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Biology

for the IB Diploma

COURSEBOOK

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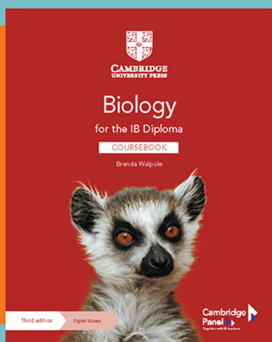
How to use this series

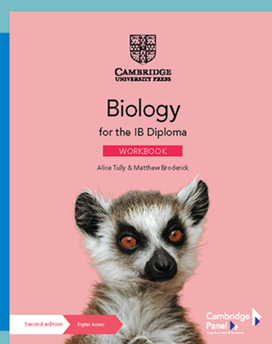
This suite of resources supports students and teachers of the IB Biology Diploma course. All of the books in the series work together to help students develop the necessary knowledge and scientific skills required for this subject.

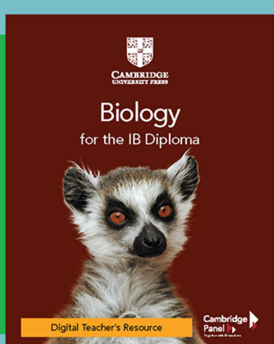


The coursebook with digital access provides full coverage of the latest IB Biology Diploma course.

It clearly explains facts, concepts and practical techniques, and uses real world examples of scientific principles. A wealth of formative questions within each chapter help students develop their understanding, and own their learning. A dedicated chapter in the digital coursebook helps teachers and students unpack the new assessment, while exam-style questions provide essential practice and self-assessment. Answers are provided on Cambridge GO, supporting self-study and home-schooling.

The workbook with digital access builds upon the coursebook with digital access with further exercises and exam-style questions, carefully constructed to help students develop the skills that they need as they progress through their IB Biology Diploma course. The exercises also help students develop understanding of the meaning of various command words used in questions, and provide practice in responding appropriately to these.





The Teacher's resource supports and enhances the coursebook with digital access and the workbook with digital access. This resource includes teaching plans, overviews of required background knowledge, learning objectives and success criteria, common misconceptions, and a wealth of ideas to support lesson planning and delivery, assessment and differentiation. It also includes editable worksheets for vocabulary support and exam practice (with answers) and exemplar PowerPoint presentations, to help plan and deliver the best teaching.

How to use this book

Throughout this book, you will find lots of different features that will help your learning. These are explained below.

UNIT INTRODUCTION

A unit is made up of a number of chapters. The key concepts for each unit are covered throughout the chapters.

LEARNING OBJECTIVES

Each chapter in the book begins with a list of learning objectives. These set the scene for each chapter, help with navigation through the coursebook and indicate the important concepts in each topic.

- A bulleted list at the beginning of each section clearly shows the learning objectives for the section.

GUIDING QUESTIONS

This feature contains questions and activities on subject knowledge you will need before starting this chapter.

The content in this book is divided into Standard and Higher Level material. A vertical line runs down the margin of all Higher Level material, allowing you to easily identify Higher Level from Standard material.

Link

These are a mix of questions and explanation that refer to other chapters or sections of the book.

Key terms are highlighted in **orange bold** font at their first appearance in the book so you can immediately recognise them. At the end of the book, there is a glossary that defines all the key terms.

KEY POINTS

This feature contains important key learning points (facts) to reinforce your understanding and engagement.

EXAM TIP

These short hints contain useful information that will help you tackle the tasks in the exam.

SCIENCE IN CONTEXT

This feature presents real-world examples and applications of the content in a chapter, encouraging you to look further into topics. You will note that some of these features end with questions intended to stimulate further thinking prompting you to consider some of the benefits and problems of these applications.

NATURE OF SCIENCE

Nature of Science is an overarching theme of the IB Biology Diploma course. The theme examines the processes and concepts that are central to scientific endeavour, and how science serves and connects with the wider community.

Throughout the book, there are ‘Nature of Science’ features that discuss particular concepts or discoveries from the point of view of one or more aspects of Nature of Science.

THEORY OF KNOWLEDGE

This section stimulates thought about critical thinking and how we can say we know what we claim to know. You will note that some of these feature end with questions intended to get you thinking and discussing these important Theory of Knowledge issues.

INTERNATIONAL MINDEDNESS

Throughout this Biology for the IB Diploma course, the international mindedness feature highlights international concerns. Science is a truly international endeavour, being practised across all continents, frequently in international or even global partnerships. Many problems that science aims to solve are international and will require globally implemented solutions.

EXTENSION

The feature highlights information in the book that is extension content and is not part of the syllabus.

TEST YOUR UNDERSTANDING

These questions appear within each chapter and help you develop your understanding. The questions can be used as the basis for class discussions or homework assignments. If you can answer these questions, it means you have understood the important points of a section.

WORKED EXAMPLE

Many worked examples appear throughout the text to help you understand how to tackle different types of questions.

REFLECTION

These questions appear at the end of each chapter. The purpose is for you as a learner to reflect on the development of your skills proficiency and your progress against the objectives. The reflection questions are intended to encourage your critical thinking and inquiry-based learning.

EXAM-STYLE QUESTIONS

Exam-style questions at the end of each chapter provide essential practice and self-assessment. These are signposted in the print coursebook and can be found in the digital version of the coursebook.

SELF-EVALUATION CHECKLIST

These appear at the end of each chapter as a series of statements. You might find it helpful to rate how confident you are for each of these statements when you are revising. You should revisit any topics that you rated 'Needs more work' or 'Almost there'.

I can	Subsection	Needs more	Almost there	Confident to move

		work		on

Free online material

Additional material to support Biology for the IB Diploma course is available online.

This includes Assessment guidance – a dedicated chapter in the digital coursebook helps teachers and students unpack the new assessment and model exam specimen papers. Additionally, answers to the Test your understanding and Exam-style questions are also available.

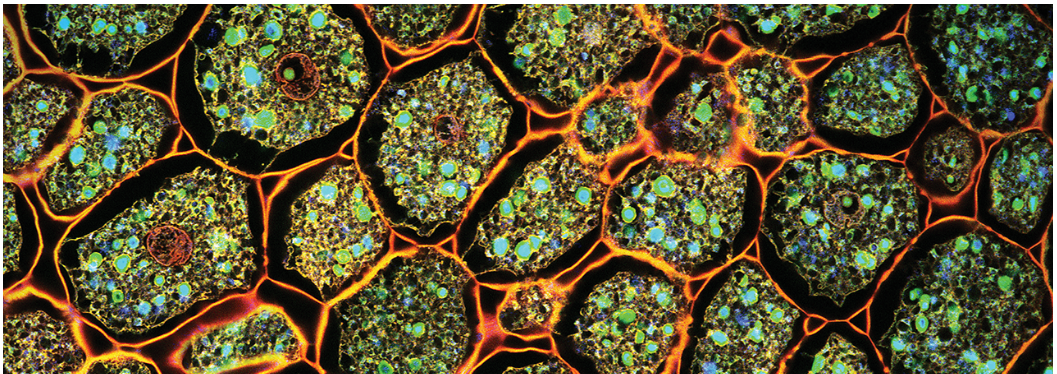
Visit Cambridge GO and register to access these resources.

Unit 1
Molecular organisation

INTRODUCTION

Living things are made up of many different elements and molecules. They are bonded together to build the millions of complex organisms we can study. All life is based on carbon compounds and, as molecules interact in different ways, they build the variety of carbohydrates, proteins, lipids and nucleic acids that we see. These molecules control the composition of the bodies of both single-celled and multicellular organisms.

In this unit we will describe how elements and molecules are arranged and how interactions between molecules form webs of chemical reactions that build up substances or break them down. These reactions are the basis of all the processes of life. Molecules of DNA and protein enable organisms to grow, reproduce and change so that living things can respond to their environments. They also give every living thing its unique characteristics, which can be passed on to the next generation.



Chapter 1

Elements, molecules and water

A1.1, A1.2, B1.1, B1.2

INTRODUCTION

Molecular biology examines the structures and reactions of the chemical substances that are important to life. Living things are composed of many chemical elements. Most elements are bonded together in organic, carbon-containing molecules and compounds. Chemical compounds are divided into two groups: organic and inorganic. Organic compounds include all the complex compounds of carbon that are found in living organisms. The four groups of macromolecules that build living things are carbohydrates, proteins, lipids and nucleic acids. Water molecules are not organic but they are vital for life and water makes up about 70% of most organisms.

1.1 Elements in living organisms

LEARNING OBJECTIVES

In this section you will:

- learn that organic molecules must contain carbon
- learn that most organic molecules also contain hydrogen and oxygen and small amounts of nitrogen, phosphorus and sulfur

GUIDING QUESTIONS

- Which are the most abundant elements and molecules in living organisms?

1.1.1 Organic molecules

Molecular biology explains the life processes that we observe and all the chemical substances that are involved and the reactions that occur between them. There are almost 100 naturally occurring elements and 25 of these are present in living organisms. The six most common elements in living things are carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur. Carbon, hydrogen and oxygen are found in all the vital organic compounds: proteins, carbohydrates, nucleic acids and lipids that build up living organisms. Nitrogen is always found in proteins and nucleic acids.

EXAM TIP

A mnemonic is a set of letters that helps us to remember something. The mnemonic CHON is a good way to remember the four key elements found in all organisms: carbon, hydrogen, oxygen and nitrogen.

The **organic compounds** form a vast group that includes gases, liquids and solid substance. Every organic compound in living organisms contains two or more atoms of carbon. As carbon atoms can easily bond with each other, organic compounds can be formed from carbon chains that differ in shape and length. Carbohydrates, proteins, lipids and nucleic acids are the main types of carbon-containing molecules on which life is based (Table 1.1.1).

Molecule	Units	Elements present
Carbohydrate	Sugar monomers	C, H, O

Proteins	Amino acids	C, H, O, N, S
Lipids	Glycerol and fatty acids	C, H, O
Nucleic acid	Nucleotide	C, H, O, N, P

Table 1.1.1: Elements present in different biological molecules.

Any compound that does not contain carbon is an **inorganic compound**. A wide variety of inorganic substances is found in living things and are important to the structure and function of different organisms.

KEY POINTS

inorganic compounds are compounds that do not contain the element carbon.

organic compounds are compounds that do contain carbon atoms. Some compounds contain carbon, but they are not organic compounds. These are carbon dioxide, carbon monoxide and carbonates.

1.1.2 Elements needed in small quantities and larger amounts

The four key elements carbon, oxygen, nitrogen and hydrogen combine and form many thousands of large molecules which make up cell structures and functional molecules (Table 1.1.1). In all organisms, the proportion of these elements is far greater than all others. They are the most abundant (that is, present in the largest quantities) by mass and the number of atoms. Table 1.1.2 shows the percentages of different elements in a human body. About 99% of the human body is made up of the four key elements plus calcium and phosphorus. Five other elements – potassium, sulfur, sodium, chlorine and magnesium – make up just under 1%. These 11 elements are necessary for life.

Element	**Symbol**	**Percentage mass**	**Percentage atoms**
Oxygen	O	65.0	24.0
Carbon	C	18.5	12.0
Hydrogen	H	9.5	62.0
Nitrogen	N	3.2	1.1
Calcium	Ca	1.5	0.22
Phosphorus	P	1.0	0.22
Potassium	K	0.4	0.03
Sulfur	S	0.3	0.38
Sodium	Na	0.2	0.37
Chlorine	Cl	0.2	0.24
Magnesium	Mg	0.2	0.07

Table 1.1.2: The mass and the number of atoms of key elements in the human body, as a percentage of the total mass and the total number of all atoms.

Similar proportions of the same elements occur in all species, from large ocean mammals to tiny single-celled organisms with very different forms. The bodies of all organisms are built from the same essential elements.

1.1.3 Trace elements

The elements iron (Fe), copper (Cu), cobalt (Co), manganese (Mn) and zinc (Zn) are **trace elements** that are needed by animals.

KEY POINT

trace elements are chemical elements that are required only in tiny amounts by living organisms for normal life.

Iron

Iron is a key trace element that almost all living organisms need for their metabolism. It is essential for cell respiration, energy production, DNA synthesis and cell division. Iron also forms part of the hemoglobin molecule (Figure 1.1.1) contained in red blood cells that transport oxygen in the blood of animals (Section 8.3). In mitochondria, which are structures in the cell where energy is released, iron is part of the electron transfer chain that allows eukaryotes to respire (Section 3.2). It is also an important component of both respiratory proteins and enzymes.

Despite the importance of its role, iron forms a tiny proportion of the body's mass. In a human, it accounts for only about 0.006% of body mass.

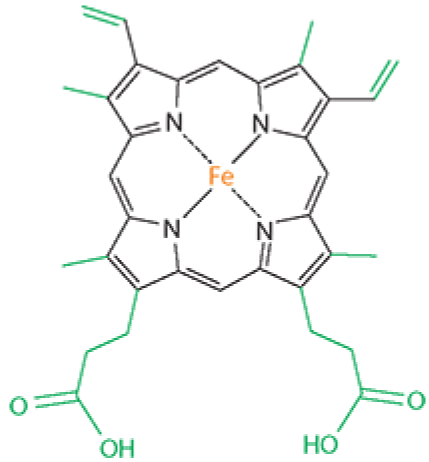


Figure 1.1.1: Hemoglobin contains iron at the centre of its molecule.

Plants also need iron for chlorophyll to be made (or synthesised) and to maintain the structure of their chloroplasts. Almost all the iron in a plant is found in chloroplasts, with a small amount present in the cytoplasm and organelles. Without iron, photosynthesis cannot take place.

Elements' functions in different organisms

All organisms need certain essential elements but the elements may have very different functions in different organisms. For example, plants need iron for photosynthesis, but animals need iron for oxygen transport. Sodium is important in all cell membranes, but it has a special role in sending (or transmitting) the nerve impulses in animals.

Some important roles of inorganic elements are shown in Table 1.1.3.

Element	Example of role in prokaryotes	Example of role in plants	Example of role in animals

sulfur (S)	a component of two amino acids	a component of two amino acids	a component of two amino acids, needed to make some antibodies
calcium (Ca)	co-factor in some enzyme reactions	co-factor in some enzyme reactions	important constituent of bones, needed for muscle contraction
phosphorus (P)	a component of ATP, DNA and phospholipids	a component of ATP, DNA and phospholipids	a component of ATP, DNA and phospholipids
iron (Fe)	a component of cytochrome pigments used in aerobic respiration	a component of cytochrome pigments used in aerobic respiration	a component of hemoglobin and cytochrome pigments used in aerobic respiration
sodium (Na)	important in membranes, changes solute concentration and affects osmosis	important in membranes, changes solute concentration and affects osmosis	important in membranes, changes solute concentration and affects osmosis; also important in transmission of nerve impulses
magnesium (Mg)	Important in ATP and nucleic acid formation	Important in ATP and nucleic acids. In plants,	Important in ATP and nucleic acid formation

		central part of chlorophyll molecules	

Table 1.1.3: Roles of inorganic elements in living organisms.

NATURE OF SCIENCE

The impact of science

The methods used in science can have important ethical implications. This means they can have effects that are considered to be morally wrong. What is considered acceptable by one generation may not accepted by another generation. Experiments carried out in 1928 made the important discovery that copper was an essential trace element needed by living things. Scientists fed various diets to rats. The diets contained, or did not contain, different elements. Without iron the rats were unable to produce red blood cells. But with a diet that contained iron but which did not include copper, the rats became anemic, meaning that they did not have enough red blood cells to carry oxygen in their blood. When copper was added to the rats' diet, the animals recovered.

To consider:

1. Do you think experiments like this would be considered ethical today?
2. Discuss the arguments for and against such experiments.

1.1.4 Toxicity of some elements

Some essential trace elements become toxic if organisms ingest them in high doses. Heavy metals are among the most toxic elements. The most dangerous (or hazardous) include chromium (Cr), nickel (Ni), copper (Cu) and zinc (Zn). Heavy metals are released from natural sources during the weathering of rocks or volcanic eruptions, but industrial processes and agriculture have increased the amounts in the environment. **Toxic elements** remain in the environment and can accumulate, or build up, in the bodies of organisms if they are transferred through food chains and webs (Sections 12.1.1 and 12.2.2).

TEST YOUR UNDERSTANDING

1. What are the four key elements that are found in living organisms?
2. List two functions for elements that are required in very small quantities by organisms.
3. What are the main sources of toxic elements that pollute the environment?

KEY POINT

toxic elements are substances that contaminate drinking water, food and the air, making them poisonous or harmful.

Links

- How are molecules changed through metabolic processes? (Chapter 3)
- Which elements and molecules do all living things need? (Chapter 4)

1.2 Water

LEARNING OBJECTIVES

In this section you will:

- learn that water is a polar, covalent molecule that can form hydrogen bonds between its molecules
- understand that water is an important solvent and transport medium
- learn that blood and plant sap are mainly water and that they are used to transport substances in animals and plants
- describe how water has emergent properties
- learn that water has cohesive properties, which create surface tension
- learn that water has adhesive properties that are important at exchange surfaces and in plant transport
- understand that the thermal properties of water are important in controlling the temperatures of living organisms
- understand why ice has a lower density than water and has insulating properties
- recall that water is transparent and provides a habitat for living things
- learn that water is a metabolite in biochemical reactions.

GUIDING QUESTIONS

- How do the structure and properties of water make it essential for life?

1.2.1 The structure of water

Hydrogen bonds

Covalent bonds form between the hydrogen atoms and oxygen atoms in water molecules. Each of these bonds contains a shared pair of electrons. But the atoms do not share these electrons equally. Oxygen has a greater pull on the shared electrons because it has more protons and therefore a greater positive charge in its nucleus. The oxygen area of the molecule is slightly more negative than the hydrogen end.

In diagrams that represent water molecules, the slight difference in charge is shown by the Greek letter delta (δ).

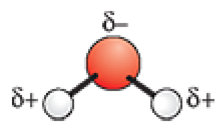


Figure 1.2.1: Diagram of a single water molecule.

Water molecules are unusual because they have a small positive charge on the two hydrogen atoms and a small negative charge on the oxygen atom. Because of this arrangement, water is said to be a polar molecule.

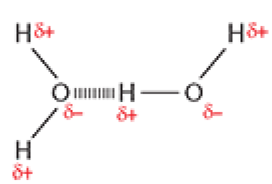


Figure 1.2.2: Hydrogen bond joins two water molecules.

KEY POINTS

covalent bonds are chemical bonds that involve the sharing of electron pairs between atoms.

hydrogen bonds are bonds that form between water molecules because they have polarity.

polar molecules are molecules that have an unevenly distributed electrical charge so that there is a positive region and a negative region. Water, sugars and amino acids are polar molecules.

A weak bond can form between the negative charge of one water molecule and the positive charge of another, as shown in Figure 1.2.2. This type of bond, known as a **hydrogen bond**, is responsible for many of the properties of water. The bond is known as an intermolecular hydrogen bond because it forms between the same types of molecules in the same substance. Hydrogen bonds are constantly forming and reforming between water molecules, which gives water its fluid property.

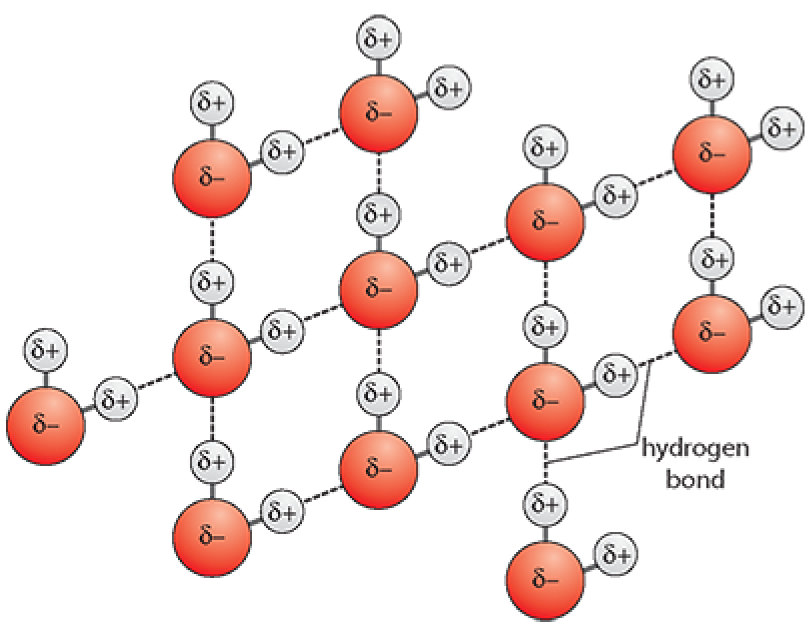


Figure 1.2.3: Hydrogen bonding in water.

1.2.2 Solvent properties of water

Water is sometimes known as a universal **solvent**. Its polarity makes it an excellent solvent for other **polar molecules**. Most inorganic ions, such as sodium, potassium and chloride ions, dissolve well in water. This is because the positive or negative charges of the ions are attracted to the charges of water molecules (Figure 1.2.4). In liquid water many water molecules are bonded together, but approximately 20% are free and able to bond with other chemical substances.

KEY POINT

solvent a substance that will dissolve a solute; for example, water is a solvent in which salt (a solute) will dissolve.

The positive and negative charges of water molecules attract ions with negative or positive charges. This means that the ions position, or orientate, themselves between water molecules and dissolve.

Polar organic molecules, such as amino acids and sugars, are also soluble in water. Water is the medium in which most biochemical reactions take place. This is because almost all substances involved dissolve well in water. Protein synthesis and most of the reactions of photosynthesis and respiration take place in an aqueous (water) solution.

Substances are classified into two groups according to their solubility in water. **Hydrophilic** substances such as sugars and salts dissolve easily.

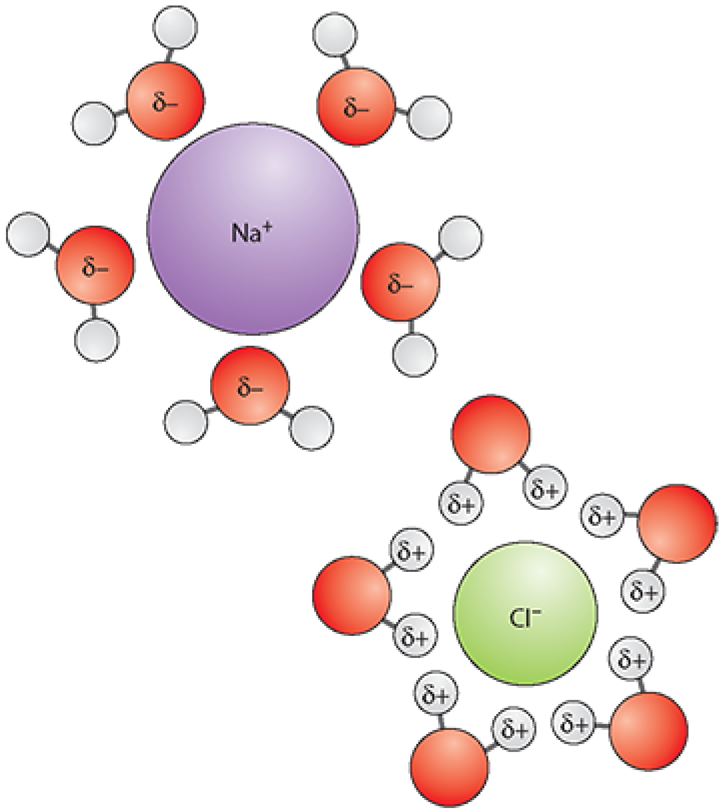


Figure 1.2.4: Diagram showing the orientation of water molecules around a positively charged sodium ion and a negatively charged chloride ion.

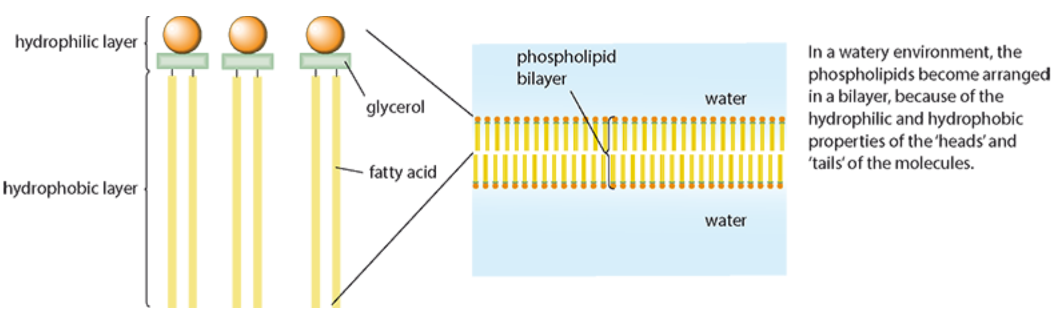


Figure 1.2.5: A phospholipid molecule includes a phosphate, glycerol and two fatty acids. In diagrams the phospholipid molecule is often simplified and shown as a circle with two tails.

THEORY OF KNOWLEDGE

The ‘memory’ of water

Homeopathy is a form of complementary medicine, which means it is not a treatment offered by conventional modern medicine. Homeopathy began in the 1790s, when a German doctor, Samuel Hahnemann, proposed the idea of ‘like cures like’ and suggested that a substance that causes symptoms can be used to treat those symptoms. A central principle of homeopathy is a process of dilution.

The ‘memory of water’ is a phrase that is usually associated with homeopathy. It was coined by Jacques Benveniste (1935–2004) who claimed that water retained a memory of substances that had been dissolved in it. Homeopathic remedies are prepared by diluting ingredients to such a low dilution that, in some cases, no molecules of the original substance are found in the solution. There is no scientific evidence to support the claim that water has a memory. The subject of homeopathy is controversial and many scientists reject it completely.

To consider:

What criteria can be used to distinguish scientific claims from false, or pseudoscientific, claims?

EXAM TIP

Make sure you can draw a single water molecule and its charges, and a group of molecules hydrogen-bonded together.

Amino acids with polar side groups also dissolve well. **Hydrophobic** substances do not dissolve in water. Hydrophobic substances are usually uncharged, and examples include fats and oils, cholesterol and some large proteins.

Non-polar substances are not very soluble in water because water molecules would rather remain hydrogen-bonded to each other, than to allow non-polar molecules to come between them. Non-polar substances such as cholesterol are packaged in spherical particles called lipoprotein (see the section on Water as a transport medium). This allows them to be carried in the blood.

KEY POINTS

hydrophobic refers to water hating substances.

hydrophilic are water loving substances.

Water as a metabolite

Most metabolic reactions take place in water because more kinds of substance dissolve in water than any other liquid, and it is the most effective solvent we know. **Metabolites** are substances that are formed in or are needed for metabolism. Metabolites are found in water, but water is also a reactant in photosynthesis and a product of respiration. Water is needed for hydrolysis reactions such as digestion to take place and also is produced during condensation reactions (Section 1.3).

Water as a transport medium

As water is such an excellent solvent, substances can be transported in solution around the bodies of animals and around plants. Water also has a low viscosity, which means that it flows easily through narrow tubes such as blood capillaries or the xylem of a plant.

Vertebrates all have blood that is more than 90% water and which is enclosed in a system of blood vessels. Invertebrates, such as insects, crustaceans and many molluscs, have a type of blood known as hemolymph. This fluid, which is also predominately water, is not kept in vessels but flows around the animals' bodies and into the blood spaces of their transport systems.

Blood is ideal to carry many dissolved soluble solutes, such as glucose, sodium and chloride ions, amino acids and vitamins, from the **digestive system** to other organs of the body. Blood can also transport dissolved nitrogenous waste and hormones.

Gases, such as oxygen and carbon dioxide, are not very soluble in water because they are essentially non-polar. Oxygen can dissolve in water, which allows aquatic life to exist, but its solubility is very low. Oxygen and carbon dioxide are carried in the blood, but must be held by (or bound to) hemoglobin or other pigments, or converted to soluble bicarbonate ions, to be carried in blood plasma (Section 8.3).

Many large molecules, such as lipids and proteins (Sections 1.3 and 1.4), are also mostly non-polar but can be carried through the aqueous environment of the blood. For these molecules to be sufficiently soluble, they must have some polar groups exposed on the outside of the molecule. Polar groups on the outside of soluble proteins interact with polar water molecules and make the entire protein soluble.

Cholesterol is only slightly soluble in water and dissolves in the blood in very small amounts. For this reason, cholesterol is transported by the circulatory system in lipoproteins, which are small spheres that have an outer surface made up of **amphipathic** proteins and lipids (Figure 1.2.6). The outwardfacing surfaces of these molecules are water-soluble and their inward-facing surfaces are lipid-soluble. Triglycerides (fats) are carried inside them while **phospholipids** and cholesterol, being amphipathic, are transported in the surface layer of the lipoprotein particle.

KEY POINT

amphipathic a molecule that has both polar and non-polar regions which determine how it interacts with other molecules. Phospholipids that build membranes have non-polar tails and polar heads.

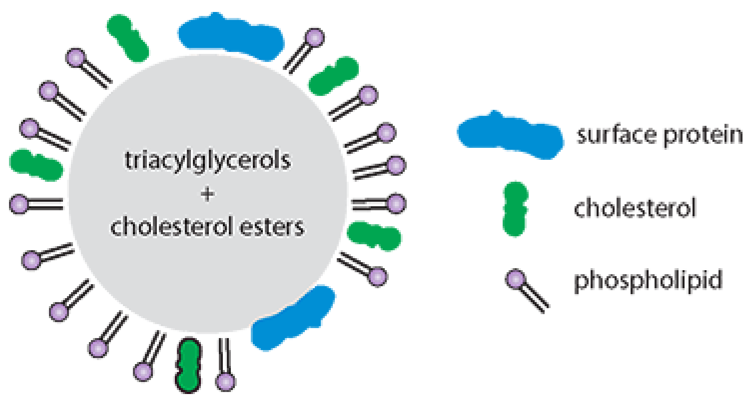


Figure 1.2.6: Simple diagram of a lipoprotein.

Substance	Solubility	Properties
sodium chloride	very soluble	ions are attracted to water molecules
glucose	very soluble	polar molecule
amino acids	very soluble	have both positive and negative charges
oxygen	low	if bound to hemoglobin it can travel in

	solubility	blood
fats and cholesterol	insoluble	fats are non-polar and cholesterol is only slightly charged. To be carried in blood fats must travel in lipoprotein complexes

Table 1.2.1: Table summarising the solubility of important molecules.

The transport system of a plant includes two types of thin, tube-like vessels called the xylem and the phloem. These tubes contain a fluid called sap, which is mostly water. The xylem carries dissolved minerals from the roots to the leaves, and the phloem transports soluble sugars up and down the plant. Liquid in the xylem contains less than 1% solutes, mostly organic acids and mineral salts. Phloem sap may contain up to 25% solutes, mainly sucrose and amino acids.

1.2.3 The physical properties of water

Emergent properties are defined as properties of a complex system that arise from simple interactions of individual component parts. In the case of water, these properties are due to interactions between individual molecules.

KEY POINT

emergent properties of water these properties are due to interactions between individual molecules.

The polar properties of water molecules, which are joined by hydrogen bonds, give water important emergent properties including:

- Cohesion of its molecules to one another
- Adhesion of its molecules to other molecules
- High specific heat capacity
- Surface tension

These properties have important consequences for many organisms, especially those which live in aquatic habitats.

1.2.4 Cohesion and its impact on organisms

Cohesion

Hydrogen bonding between water molecules holds them together in a network, resulting in a phenomenon known as cohesion (Figure 1.2.7), which gives water many of its biologically important properties. **Cohesive forces** allow water to form droplets and are also responsible for surface tension.

In the xylem of a plant, water can be drawn up inside the stem because cohesive forces keep the water together as a continuous column (Figure 1.2.7). Strong pulling forces are produced as water evaporates from the leaves at the top of tall trees. This draws water and dissolved minerals great distances up to the tips of branches high above the ground.

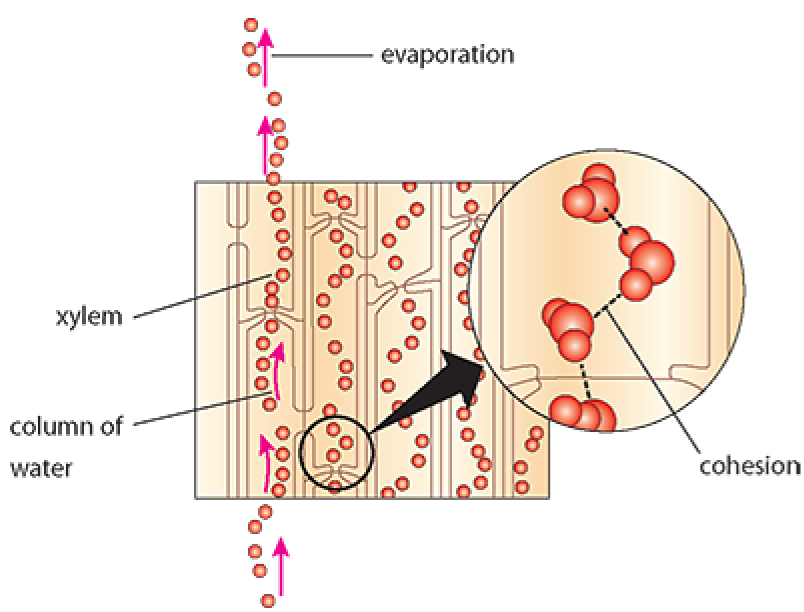


Figure 1.2.7: Cohesive forces hold water molecules in a column.

Cohesion is also responsible for surface tension. At the surface of water where it meets the air, there is a greater attraction of water molecules to one another than to the air. This forms a strong surface which enables some small organisms to walk on water. This cohesion contributes to the thermal properties of water too (Figure 1.2.8).

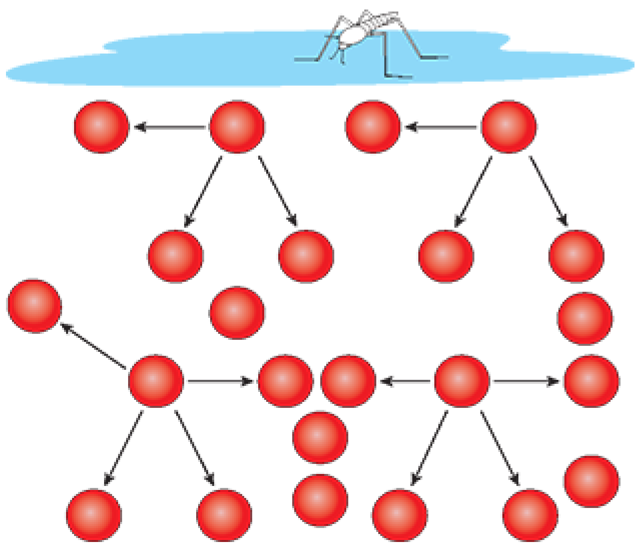


Figure 1.2.8: Surface tension attracts water molecules to one another. Pond skaters use long slender legs to distribute their body mass evenly and have tiny hydrophobic hairs on their legs.

Adhesion

Water is attracted to other polar or charged molecules. There are forces of attraction, known as **adhesive forces**, which occur between water molecules and different molecules in vessels that contain the water. This means that water tends to be attracted to and stick, or adhere, to the walls of its container. The surface of glass is polar, so it forms adhesive bonds with water.

Adhesion of water to the sides of a tube or container creates an upward force on the edges of the liquid. For this reason the surface of the water isn't flat. Instead, the surface curves downwards towards the centre of the tube, which is called a meniscus. This is because surface tension keeps the surface intact. If the adhesive force to the sides of a narrow tube is stronger than the cohesive force between molecules, water will be drawn upward against the pull of gravity. This is known as **capillary action**.

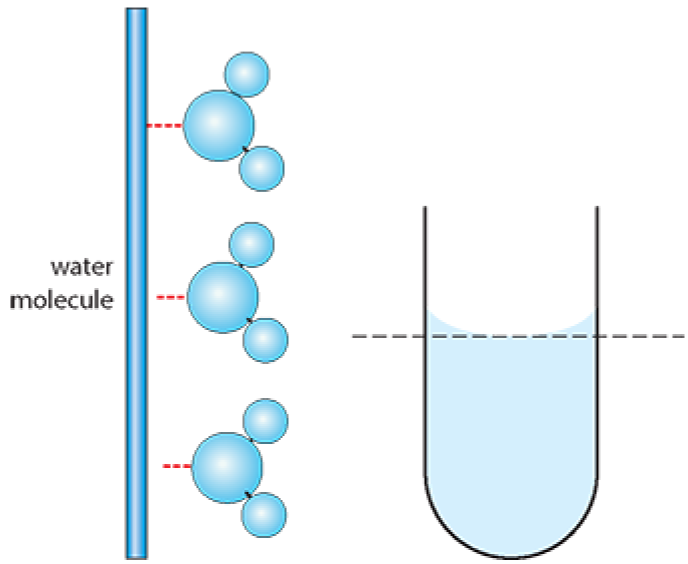


Figure 1.2.9: Adhesive forces attract water molecules to the sides of a glass container.

Water is drawn through plant cell walls and into the roots of a plant by capillary action. Adhesive forces are also important as they attract water molecules to the sides of the xylem. These forces allow water to be draw up the stem of a plant. Adhesive forces are greater in a narrow tube because relatively more water molecules are in contact with the sides. This means that adhesive forces are able to ‘hold up’ and support a substantial mass of water in the fine xylem vessels. Cohesive forces hold the water column together.

1.2.5 Thermal properties of water

Water is liquid at most temperatures at which life exists so it forms a useful habitat for living things to live in and on. Water and air are both heated through convection currents and radiation from the sun, but the ability of water to absorb heat is far greater than that of air. It is said to have a high specific heat capacity. This makes an aquatic habitat a far more stable environment for living things because the temperature of water varies less than the temperature of air.

KEY POINT

specific heat capacity is the amount of heat energy needed to raise the temperature of 1 cm^3 of water by 1 °C.

Thermal properties explained

Thermal properties are properties that materials or liquids have that are related to their ability to conduct heat. Water has special thermal properties. Water is unusual among small molecules because it is a liquid at most temperatures found on Earth. A large amount of energy is needed to break the many weak hydrogen bonds between the water molecules. This gives water a high **specific heat capacity** and means that water can absorb or give out a great deal of heat energy without its temperature changing very much. A stable temperature is important to living things because the range of temperatures in which biological reactions can occur is quite narrow. The thermal properties of water allow it to keep an organism's temperature fairly constant. In the body, water can act as a temperature regulator. Water is a major component of blood, which carries heat from warmer parts of the body, such as the liver, to cooler parts such as the feet or to the skin where is lost as radiant heat.

For liquid water to evaporate and become vapour, many hydrogen bonds between the molecules must be broken, so evaporation requires a lot of energy. As a result, water is a liquid at most temperatures found on Earth, and it has a high boiling point. When water evaporates, it carries a great deal of heat with it. For example, when sweat evaporates from the skin surface of a mammal, the process of evaporation acts cools the mammal's body.

A lot of heat must be removed from water before it freezes. This means that cell contents of organisms and the water in aquatic environments will not freeze easily in cold conditions.

Special properties of ice

At temperatures greater than 0 °C hydrogen bonds between water molecules are easily made and broken because water is a liquid and molecules move freely within in. When the temperature falls, ice crystals form because the hydrogen bonds become permanent. Ice has a hexagonal framework of molecules with an open structure. Ice takes up more space than the volume of water that formed it, so ice is less dense than water and floats on the surface of ponds, lakes and the ocean. A layer of ice on the surface insulates the water beneath it, keeping it warmer than the cold environmental conditions above the ice. The water beneath the ice is protected from freezing, so plants and animals can survive in the slightly warmer water beneath the ice.

The properties of water are summarised in Table 1.2.2.

Property	Reason	Consequence/benefits to living organisms

cohesion	Hydrogen bonds hold water molecules together.	Water can travel in continuous columns – for example, in the stems of plants – and act as a transport medium.
adhesion	Water molecules are attracted to other different molecules.	A column of water can be held up in the narrow xylem of a plant.
solvent	The polar molecules of water can interact with other polar molecules and ions.	Ions dissolve easily. Large molecules with polar side groups, such as carbohydrates and proteins, can also dissolve. So water acts as an excellent transport medium and as a medium for metabolic reactions.
thermal	Water has a high heat capacity. Large amounts of energy are needed to break hydrogen bonds and change its temperature.	The temperature of organisms tends to change slowly. Fluids such as blood can transport heat round their bodies.
	Water has a high boiling point compared with other solvents because hydrogen bonds need large amounts of	Water is liquid at most temperatures at which life exists, so is a useful medium for metabolic reactions.

	energy to break them.	
	Water evaporates as hydrogen bonds are broken and heat is taken from the water.	Sweating and transpiration enable animals and plants to lose heat. Water acts as a coolant.
viscosity	Water has a low viscosity, molecules slide easily past one another.	Water flows easily through tiny capillaries and other very small spaces such as spaces in cell walls or in the soil.
transparency	Water allows light to pass through it.	Light can reach plants and animals below the surface of water. Plants can photosynthesise and animals such as fish, birds and seals can hunt using sight.
buoyancy	Water exerts an upthrust (force) which opposes the weight of a partially submerged body.	Water can support the weight of floating and submerged organisms, providing a habitat and also reducing the need for large supporting structures such as skeletons.

Table 1.2.2: The properties of water

1.2.6 Life on water, land and in the air

All species have body shapes and lifestyles that adapt them to the habitats in which they live. A few species live on land, in the air and in water and must adapt to life in all three areas. One bird that does this is the Black-throated loon (*Gavia arctica*) Figure 1.2.10. It is a large, streamlined diving bird that can float on water and easily dive to a depth of 5 m to hunt for fish. The bird's body shape is well-suited to diving and they have waterproof feathers for protection. They also have webbed feet with toes joined by a membrane which are suited to swimming. They nest on land around sheltered coasts in cold and temperate Arctic areas but out of water. They walk awkwardly because their legs are so far back on their bodies. Black throated loons are large birds and must run over water to take off and fly, even though they have a large wingspan, the wing surface area is small compared to its body size.

Figure 1.2.10: The black-throated loon develops black feathers on its throat in the breeding season.

The ringed seal (Figure 1.2.11) is a small earless seal that lives in the Arctic and sub-Arctic regions. Ringed seals live in frozen waters and are well-adapted to ice-covered areas. Water in various forms is essential to the seals which use liquid water to hunt in and solid water (ice) to live in and on. Seals are mammals and need to breathe air above the ice. They have strong claws on their front flippers that they use to cut breathing holes through the ice. Ringed seals stay on the ice most of the year; their streamlined bodies allow them to slide across the solid ice and swim underneath it to hunt. Thick layers of fat protect them from the cold. They dig snow caves for breeding in late winter and spring. The ice and snow caves provide protection for their young from extreme cold and polar bears which are their main predators. Loss of sea ice and snow cover on the ice poses the main threat to this species.

Figure 1.2.11: Ringed seal (*Pusa hispida*) streamlining, thick blubber and strong claws adapt this species to life on the ice

NATURE OF SCIENCE

Using theories and models to explain the properties of water

Scientific models are developed to explain patterns and observations. Models cannot be proven but are useful to explain processes that are not directly observable.

The properties water has are due to its molecular structure and energy. The detail about how molecules in water interact is a question that has been studied by scientists for many years. Techniques including infrared absorption, neutron scattering and nuclear magnetic resonance imaging (NMRI) have all been used to study the structure of water. The results along with data from theoretical calculations have led to models, theories and computer simulations that try to describe the structure of water and explain its properties.

Observations have shown that water is a small, simple molecule (H_2O) in which each hydrogen atom is covalently bonded to the central oxygen atom by a pair of electrons that are shared between them (Figure 1.2.12). Only two of the six outer-shell electrons of each oxygen atom are used to form these covalent bonds, leaving four electrons in two non-bonding pairs. These non-bonding pairs remain closer to the oxygen atom and exert a strong repulsion against the two covalently bonded pairs. The two hydrogen atoms are pushed closer together. Overall, water molecules are electrically neutral, but this model of the water molecule results in small positive and negative charges unevenly distributed over the molecule. When H_2O molecules are crowded together in liquid water, the forces between the atoms produce the properties of water that we see. Properties that are unique to water arise from the cage-like, tetrahedral hydrogen bonding among molecules that are next to each other.

New models of water are now being designed to investigate the structure of water when it contains chemicals and biomolecules. Molecular models may help us create new technologies for producing clean water, reclaiming polluted water, predicting climate and designing new drugs to cure diseases.

To consider:

1 How are models used to help scientists explain evidence that is observed or recorded?

2 How do models change when new techniques or discoveries are made?

3 Why do you think that the detail of the structure of water has been so difficult to understand?

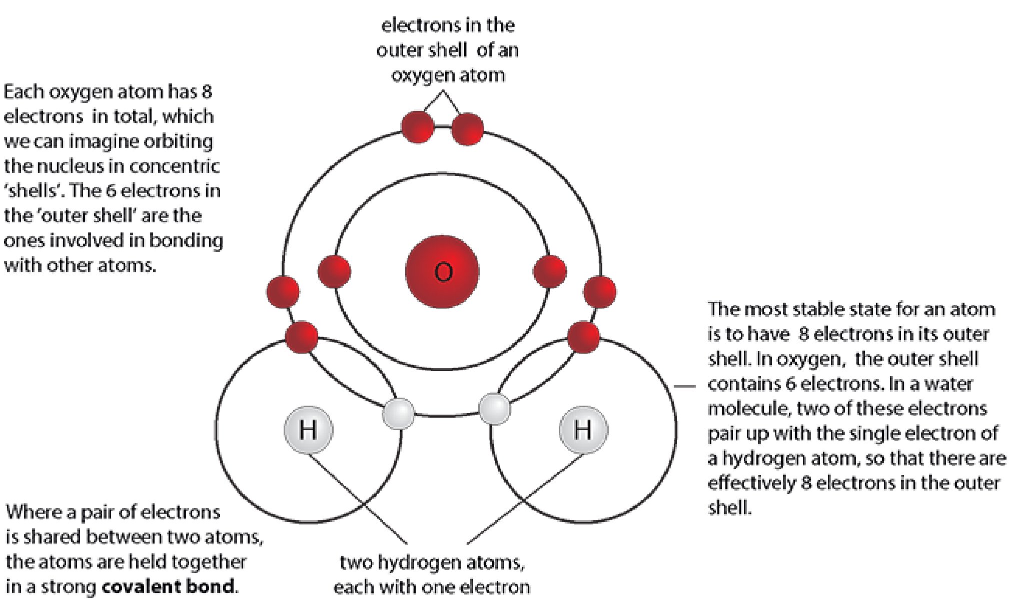


Figure 1.2.12: The two hydrogen atoms in a water molecule are pushed together on one side because of the repulsive effect of the two pairs of non-bonding electrons in the outer shell of the oxygen atom.

1.2.7 Origins of water on Earth

Most scientists believe that the water we have on Earth today originated from outside our planet. Evidence for the origin of water has come mainly from the study of material found in asteroids. Recent studies of an asteroid called 25143 Itokawa that was brought to Earth by a Japanese robot probe Hayabusa have used atom-probe tomography to examine atoms in grains of dust from the asteroid and the results suggest that at least half the water on Earth has come from interplanetary dust. The grains from the asteroid contained water that was probably created by solar wind, streams of particles that flow from the Sun. Over billions of years, as the solar system developed, the particles in the solar winds interacted with oxygen atoms in dust clouds of the solar system. As Earth orbited the Sun and passed through the clouds, water molecules slowly accumulated around and on its surface, held down by Earth's gravity. It is unlikely that all the water on Earth arrived in this way; an equally important source would probably have been the ice in comets and asteroids that crashed on Earth's surface. Evidence for this theory comes the fact that ice from comets and asteroids contain higher amounts of the hydrogen isotope deuterium compared with water on Earth, but solar dust contains relatively low levels of the isotope. If we consider the two sources together we find that the isotope balance matches that of Earth's water.

Water has remained on Earth for two important reasons; the first is the pull of Earth's gravity which retains not only water, but also water vapour drawing it back to the surface and down into reservoirs and oceans. The second reason is temperature. Temperatures are cold enough for water to condense and certain regions of the atmosphere are very cold, at high altitude the temperature can be -60o C, so that water forms crystals of ice that fall back to Earth’s surface.

Over billions of years of our planet’s history water has allowed life to evolve on Earth. But our understanding of water’s origins also suggests that other parts of the solar system could have water, possibly as ice and this knowledge is important in the search for life in other parts of the galaxy. An ice deposit is believed to have formed near the south pole of our Moon and NASA is aiming to explore this in the Artemis programme.

TEST YOUR UNDERSTANDING

4 Describe the significance of water to living organisms.

5 Define the term ‘hydrophilic’.

6 Explain how hydrogen bonding affects the force of cohesion.

7 Discuss three key properties of water that make it an ideal habitat for living organisms.

8 Why is sweat a good coolant for the body?

- **a** The small blood vessels that transfer water to sweat move closer to the skin surface when it is hot
- **b** Breaking H bonds between water molecules in sweat requires energy from body heat
- **c** Sweat contains minerals such as sodium chloride
- **d** Sweat is non-polar.

9 Explain what is meant by The Goldilocks Zone.

Extra terrestrial life and water

So far Earth is the only planet with life as we know it but there are potentially habitable worlds elsewhere. The 'Goldilocks Zone' or habitable zone is a term that astronomers use to narrow the search for such worlds. The zone was given its name from the children's fairy tale in which Goldilocks looked for porridge that was 'just right' not too hot and not too cold. Scientists define The Goldilocks Zone as the range of distance from the Sun, or other star, that an object can be before water on its surface boils away or freezes. Planets in this zone have the right temperature for water to remain liquid. There are 1,780 planets beyond our solar system that we know of. Of these about 16 are located in their star's habitable zone where conditions are not too hot or too cold to support life. A planet must also be just the right size. Too large and the atmosphere is too compacting, whilst a planet that is too small cannot maintain an atmosphere. A recently discovered planet Kepler-186f, is close to the size of Earth and orbits in its solar system's habitable zone. It is 493 light years from Earth.

Links

- How does the solubility of oxygen affect the distribution of aquatic animals? (Chapter 12)
- What are the roles of water in photosynthesis and respiration? (Chapter 3)
- How do the properties of water influence temperature control in animals? (Chapter 8)

1.3 Organic molecules in living organisms

LEARNING OBJECTIVES

In this section you will:

- learn that carbon atoms can form four covalent bonds and they can produce a wide range of different stable compounds
- understand that life is based on carbon compounds including carbohydrates, proteins, lipids and nucleic acids
- define monomers as small units that are built up into polymers
- define polymers as molecules that are built up during condensation reactions and broken down by hydrolysis
- describe glycerol and fatty acids as components of triglycerides built up by condensation reactions and triglycerides as compounds that are broken down during hydrolysis reactions
- learn that all living organisms use nucleotides to synthesise nucleic acids

> learn that functional groups such as phosphates, amines and carboxyl groups are found in many molecules and give them specific properties

- understand that the arrangement of bonds around a carbon atom allows for structural isomers with different three-dimensional forms to be made.

GUIDING QUESTIONS

- Which types of molecules are found in all living organisms?
- How are small molecules made into large ones in living organisms?
- How is carbon essential to all living organisms?

1.3.1 The importance of carbon atoms

Carbon is found in all organic molecules and forms a wide range of different compounds. Figure 1.3.1 shows how other elements can be added to a single carbon atom in one of four directions. In this way, complex three-dimensional molecules can be built up.

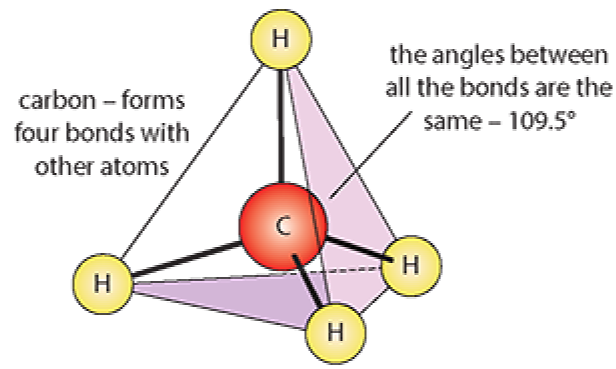


Figure 1.3.1: Hydrogen atoms (H) can bond to a single carbon atom (C) in four different directions.

Every organic compound contains two or more atoms of carbon. Carbon atoms are joined or attached (bonded) together by covalent bonds. A carbon atom can form four covalent bonds. Carbon compounds that differ in shape and length can be made, and in this way different organic molecules are created. Carbon atoms can also form double and triple bonds with other atoms. This increases the variety seen in the molecular structure of organic compounds.

KEY POINT

covalent bond is the type of bond that joins together non-metal atoms. The outer electrons of each atom are shared to fill the outer shell and make the molecule stable.

1.3.2 Carbon compounds: the building blocks of life

Carbon compounds – that is, carbohydrates, lipids, proteins and nucleic acids – form the basic molecules for all life. Carbohydrates are compounds that usually contain only the elements carbon, hydrogen and oxygen and are the most abundant group of biological molecules. Lipids contain the same three elements but with much less oxygen than a carbohydrate of the same size. Lipids may also contain small amounts of other elements such as phosphorus. Proteins, unlike carbohydrates and lipids, always contain nitrogen. Sulfur, phosphorus and other elements are also often present. Nucleotides always contain nitrogen and phosphorus (Table 1.1.1).

Many organic molecules are very large and complex but they are built up of smaller parts (subunits), which can be relatively simple. Figure 1.3.2 shows some of these building blocks. Small subunits called monomers are built into larger complex molecules called polymers in a process known as polymerisation.

Carbohydrates

Carbohydrates are the most abundant type of molecule in living things. In both plants and animals, carbohydrates have an important role as a source of energy, and in plants they also have a structural function. Carbohydrates occur in different forms. **Monosaccharides**, with the general formula $(CH_2O)_n$, where n = the number of carbon atoms in the molecule, are monomers; that is, single sugars made up of just one subunit. **Disaccharides** are sugars that have two subunits joined together by a condensation reaction (Section 1.3.3) and **polysaccharides** are long molecules consisting of a chain of monosaccharides linked together.

Proteins

Proteins are built up of units called amino acids. The atoms occurring at the fourth bond (known as the R group; see Figure 1.3.2) differ in different amino acids and give each one its own properties. The simplest amino acid is glycine, in which R is a hydrogen atom, whereas the R group in the amino acid alanine is CH_3. There are more than 100 naturally occurring amino acids but only 20 are used in the bodies of living things. Amino acids bond together in condensation reactions (Section 1.3.3) to form polypeptide chains that, in turn, are built up into proteins.

Lipids

Lipids are fats, oils, waxes and steroids. All are organic compounds that are insoluble in water but they do dissolve in organic solvents such as ethanol. An important role of lipids in living organisms is as energy storage molecules. One group known as **triglyceride** lipids includes fats and oils. Solid lipids are generally referred to as fats, whereas lipids that are liquid are known as oils. Animals store energy as fat, whereas plants store oils. Examples of plant oils include sunflower oil and olive oil. Lipid contains about twice as much energy per gram as carbohydrates such as starch, but each type of storage molecule has its own advantages. The second group of lipids includes steroids (Figure 1.3.3), which consist of four linked rings of carbon atoms. Vitamin D and cholesterol are two well known examples of steroids.

KEY POINTS

monomer refers to a small molecule that can bond to other similar small molecules, to make up repeating chains that form larger polymers.

polymer is a large, complex molecule built up of a series of monomers. Formed by condensation reactions in a process called polymerisation.

Nucleic acids

Nucleic acids are found in all living cells and viruses. Two types of nucleic acid found in cells are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) (Figure 1.3.4). DNA is found in the nucleus, mitochondria and chloroplasts of eukaryotes, whereas RNA is usually found in the cytoplasm. Nucleic acids are long molecules consisting of chains of units called nucleotides. Each nucleotide consists of a pentose sugar (which is ribose in RNA and deoxyribose in DNA) and the pentose is linked to phosphoric acid and an organic base. Nucleic acid chains are longer than those found in proteins. They are vital to inheritance and development; these aspects are discussed in Chapter 5.

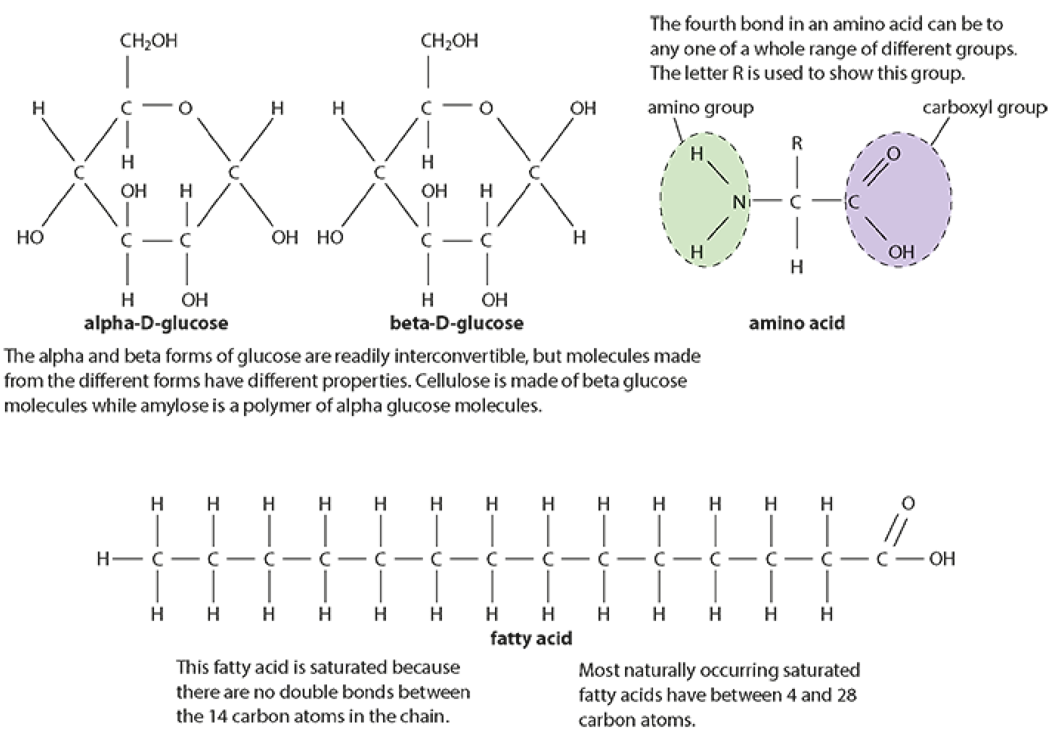


Figure 1.3.2: The basic structures of glucose, amino acids and fatty acids.

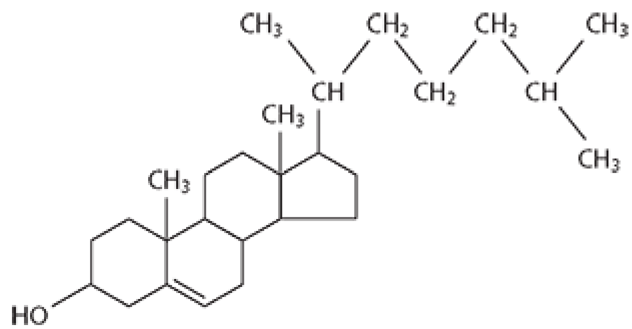


Figure 1.3.3: Like all steroids, cholesterol has four rings of carbon atoms. Other steroids differ in the side groups attached to them.

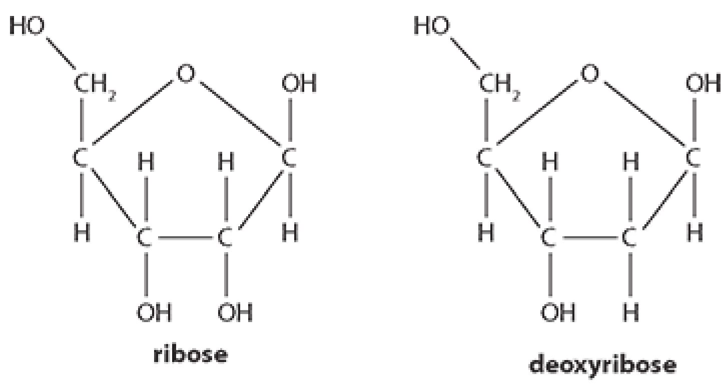


Figure 1.3.4: Ribose and deoxyribose are the building blocks of nucleic acids.

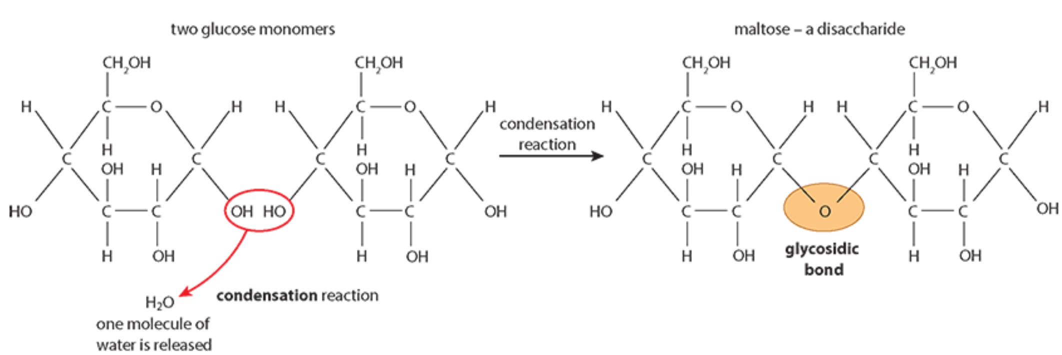


Figure 1.3.5: Monosaccharide subunits (glucose in this case) are joined in a condensation reaction, forming a disaccharide (maltose) and water.

1.3.3 Monomers and polymers

Condensation: building larger molecules

In a **condensation reaction**, two molecules are joined together by strong covalent bonds to form a larger molecule. Condensation is an example of an **anabolic** reaction, which builds up monomers to form macromolecules. Each condensation reaction requires an enzyme to catalyse the process and it produces one molecule of water. The condensation of two monosaccharide monomers produces a disaccharide. For example:

glucose	+	galactose	→	lactose + water
(monosaccharide)		(monosaccharide)		(disaccharide)

KEY POINTS

condensation reaction refers to an addition reaction in which two molecules combine to form a single molecule, and water is removed and released.

anabolic is a type of reaction in which large molecules are built up from small ones.

If further monosaccharides are added to a disaccharide, a polysaccharide is formed.

In a similar way, two amino acids can be linked to form a **dipeptide** (Figure 1.3.6):

amino acid + amino acid → dipeptide + water

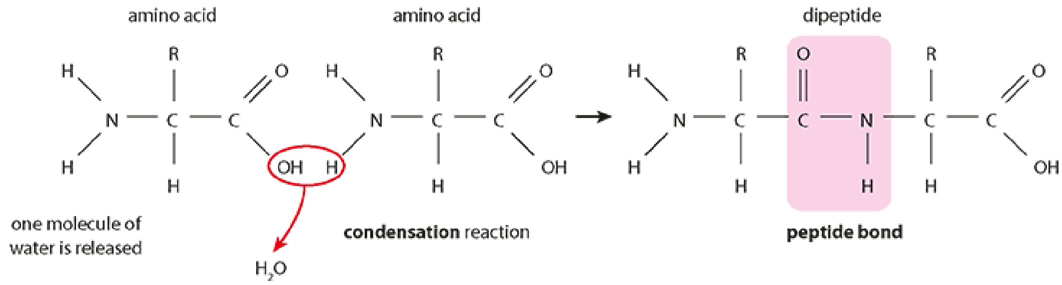


Figure 1.3.6: Two amino acids combine to form a dipeptide.

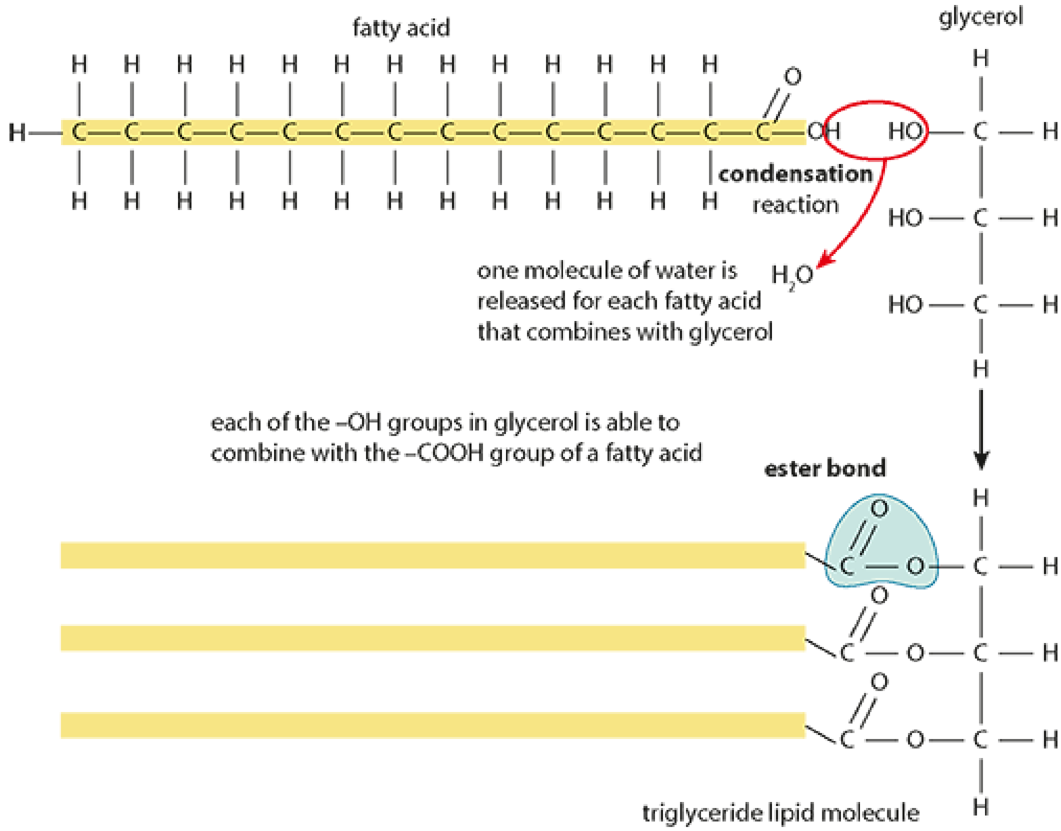


Figure 1.3.7: How a triglyceride lipid is formed from glycerol and three fatty acids.

When more than two amino acids are joined in this way, a **polypeptide** is formed. Polypeptide chains form protein molecules.

In another condensation reaction, glycerol links to fatty acids to produce triglyceride lipid molecules (Figure 1.3.7):

glycerol + 3 fatty acids → triglyceride lipid + water

EXAM TIP

Notice how the carbon atoms in the pentose sugar are labelled 1 to 5. These numbers will help you remember how other molecules bond in the nucleotide.

Nucleotides build nucleic acids

Nucleic acids are large polymers that are essential to all forms of living organism. The term nucleic acid includes DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). Each monomer subunit of a DNA or RNA molecule is called a nucleotide (Figure 1.3.8). All organisms use nucleotides in the synthesis of their nucleic acids (Section 2.7).

Nucleotides are the building blocks of DNA. Each pentose sugar contains a ring of five carbon atoms. Two carbon atoms are linked to either a phosphate group or a pentose sugar, and one carbon atom is bonded to one of four nitrogenous bases. These bases are adenine, guanine, cytosine and thymine.

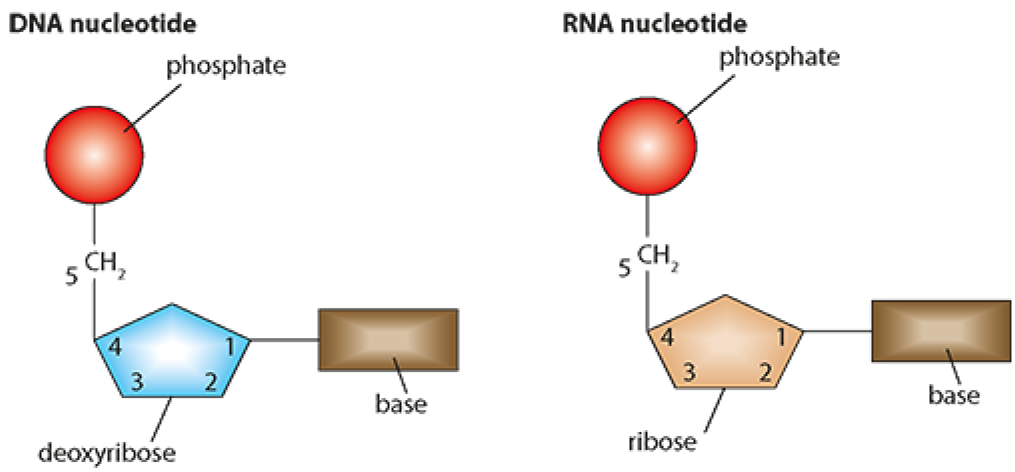


Figure 1.3.8: The general structure of DNA and RNA nucleotides.

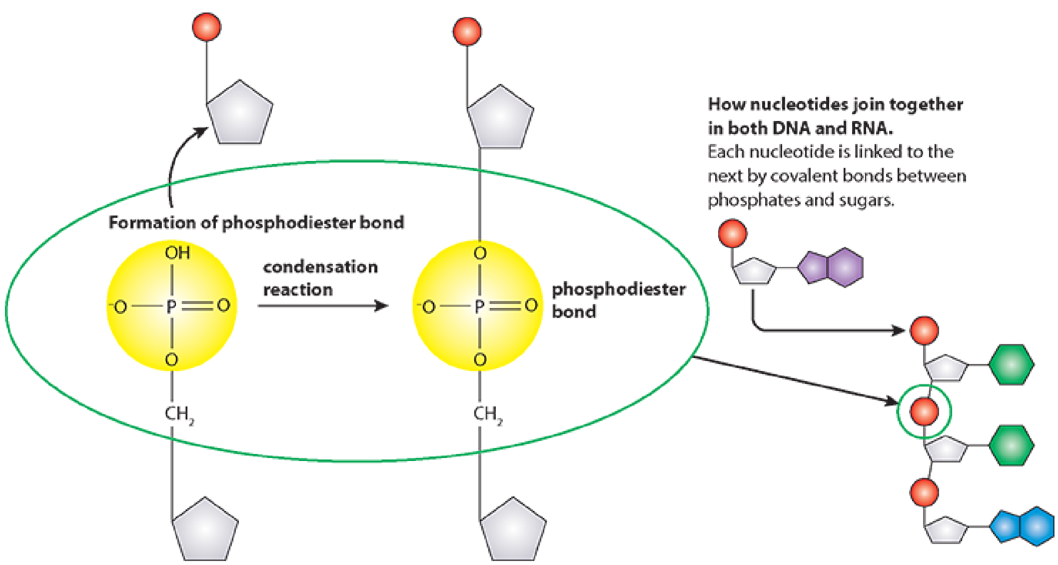


Figure 1.3.9: As nucleotides are joined together, a phosphate group is bonded to a sugar molecule, and water is released. This makes a sugar phosphate that forms the backbone of RNA and DNA. This is another example of a condensation reaction.

RNA nucleotides have a similar structure but the pentose sugar found in RNA is ribose, a five-carbon sugar that has an hydroxyl (–OH) group attached to the second carbon atom. DNA has a single –H in this position. Another difference is that RNA nucleotides have uracil instead of thymine as one of their nitrogenous bases.

Condensation reactions bond nucleotides together to form a DNA molecule. The phosphate group of one nucleotide links to the deoxyribose ring of the adjacent molecule to form a chain of nucleotides, as shown in Figure 1.3.9.

The sugar and phosphate groups are identical all along the nucleotide chain and form the 'backbone' of DNA and RNA molecules, as shown on the right of Figure 1.3.9.

Hydrolysis: breaking down macromolecules

Hydrolysis reactions break down polymers into smaller units. They are the reverse of condensation reactions. Hydrolysis reactions separate polysaccharides, polypeptides and triglycerides into their monomers.

Reactions like this take place every time food is digested. Hydrolysis is an example of a catabolic reaction in which macromolecules are broken down into monomers. Water molecules are used in **hydrolysis reactions**. Enzymes are required to catalyse the reactions:

- Hydrolysis of starch (a polysaccharide) uses water and produces many molecules of glucose.
- Hydrolysis of protein (made of polypeptide chains) uses water and produces many amino acids.
- Hydrolysis of a triglyceride (a lipid) uses water and produces fatty acids and glycerol molecules.

TEST YOUR UNDERSTANDING

10 State the number of covalent bonds that can be formed by a carbon atom.

11 State what is meant by the term monomer.

12 Name the type of reaction which builds monomers into polymers.

13 What are the three components that organisms use in the synthesis of nucleic acids?

14 Fill in the gaps in this sentence:

Triglycerides are broken down into .... and .... during hydrolysis reactions.

15 Which molecule do all organisms use as a source of energy?

KEY POINTS

hydrolysis reactions are those reactions that break down polymers into smaller units. Water is used in the reaction. Hydrolysis reactions are made faster (or catalysed) in living organisms by proteins called enzymes.

catabolism is a type of reaction in which complex molecules are broken down into simpler ones.

1.3.4 Functional groups

Three examples of important **functional groups** in living organisms are **carboxyl groups**, amines and phosphates.

Carboxyl groups

A carboxyl group is a functional group that binds to larger molecules and gives them specific properties. It occurs in carboxylic acids, which have important roles in biological systems. The carboxyl group consists of a carbon bonded to oxygen and an hydroxyl (OH) group and is usually written as –COOH or –CO_2H (Figure 1.3.10).

Carboxyl groups are **polar** and strongly hydrophilic so they can participate in creation of **hydrogen bonds** and many other important reactions. The R in Figure 1.3.10 can be a single H atom or one of many carbon-containing molecules. Carboxyl groups are important in protein synthesis (Section 4.2).

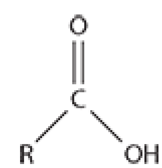


Figure 1.3.10: The structure of a carboxyl group.

KEY POINTS

functional group is a group of atoms in a molecule that has similar chemical properties in every compound in which it appears.

carboxyl group is a functional group consisting of a carbon atom linked by a double bond to an oxygen atom and by a single bond to a hydroxyl group.

polar means relating to a molecule in which the distribution of electrons is not even, so that one part of the molecule is more positively charged than another part.

hydrogen bond is a bond found in macromolecules formed by the attraction of a small positive change on a hydrogen atom and a small negative charge on an oxygen or nitrogen atom.

Every amino acid contains both a carboxyl group and an amino group. Bonds form between the amino group of one amino acid and the carboxyl group of the next. The bond is called a peptide bond and links amino acids together to form polypeptides. Carboxyl groups are also found in a large variety of other molecules including fatty acids.

Amines

Amines are functional groups that contain a nitrogen atom with a lone pair of electrons in their outer shell (Figure 1.3.11, shown in red). Amines are derived from (meaning they come from) ammonia (NH_3), with one or more hydrogen atoms replaced by a different group. The most important group that contains amines are the amino acids. The $–NH_2$ group is called an amino group.

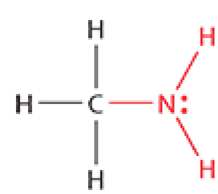


Figure 1.3.11: The structure of an amine group.

Phosphate groups

A phosphate is an ion that contains one phosphorus and four oxygen atoms (usually written PO_4^{3-}). When it is attached to a carbon-containing molecule it is called a phosphate group (Figure 1.3.12).

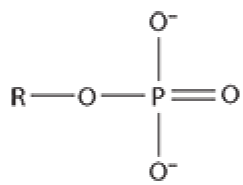


Figure 1.3.12: The arrangement of atoms in a phosphate group.

Phosphate groups are found in DNA and RNA and also in adenosine triphosphate (ATP), which provides energy to cells. Phosphate groups also form part of phospholipid molecules in cell membranes (Section 6.1). Each phospholipid is made up of a lipid molecule and a phosphate group. Phosphate is also an important nutrient resource in ecosystems, especially in freshwater environments (Section 12.2).

KEY POINT

isomers are molecules that have the same molecular formula, but different molecular shapes. There are two major classes of isomers: structural isomers and stereoisomers.

Phosphate groups activate proteins through phosphorylation (the addition of a phosphate group) so that the proteins can carry out their functions in cells. De-phosphorylation is the removal of a phosphate group and this deactivates proteins. ATP is made up of adenosine and three phosphate groups. One phosphate group is removed and then replaced during the process of energy release.

EXTENSION

Phosphate acts as important buffer in cells. A buffer keeps the pH neutral (not acidic or alkaline), a state that living cells require because most biological processes only occur at a neutral pH. Phosphate-buffered saline, a solution containing water, salt and phosphate, is often used in research into cell activities.

TEST YOUR UNDERSTANDING

16 Define a functional group.

17 Draw a carboxyl group and state one type of molecule that contains it.

NATURE OF SCIENCE

As you read this book and other scientific texts you will come across many examples of scientific conventions that are agreed internationally. One of these is the international system (SI) of metric units and prefixes which are used by all scientists worldwide.

SI – International System of length and volume

1 metre (m) = 1m

1 millimetre (mm) = 10^{-3}m

1 micrometre (mm) = 10^{-6}m

1 nanometre = 10^{-9}m

1 centimetre cubed = 1 cm^3

1 decimetre cubed = 1 dm^3

The convention is also applied to time which is measured in seconds (s), minutes (mins) and hours (h) and to concentration which is measured in mol dm^{-3}

Links

Relatively few elements are found in living organisms and yet a wide range of different molecules can be made from them. How can this be? (Chapter 1)

- How does the solubility of oxygen affect the distribution of aquatic animals? (Chapter 12)
- What are the roles of water in photosynthesis and respiration? (Chapter 2)
- How do the properties of water influence temperature control in animals? (Chapter 8)

1.4 Carbohydrates

LEARNING OBJECTIVES

In this section you will:

- learn that carbohydrates exist in different forms, which give them a variety of properties
- understand that monomers are linked together by condensation reactions to form disaccharides and polysaccharides
- understand that larger carbohydrates are less soluble in water
- compare the storage polysaccharides glycogen and starch which have compact molecular structures
- learn that cellulose is a structural polysaccharide with a molecular structure that is related to its function
- understand that carbohydrates are an efficient short-term energy store
- recall that monosaccharides are metabolised to release energy

> learn that different monosaccharides, including glucose, ribose and deoxyribose, have different properties determined by the way in which they bond together

- understand how the hydroxyl groups of monosaccharides allow the condensation reactions that form polymers
- understand how the arrangement of branching in polysaccharide molecules is related to their structural and energy storage roles.

GUIDING QUESTIONS

- How do living organisms use carbohydrates as storage and structural molecules?
- Why are carbohydrates good sources of energy?

1.4.1 Carbohydrates

Carbohydrates are the most abundant category of molecule in living things. In both plants and animals carbohydrates have an important role as a source of energy, and in plants they also have a structural function. Carbohydrates occur in various forms and different carbohydrates have different properties and roles in living organisms. Monosaccharides have the general formula $(CH_2O)_n$, where n = the number of carbon atoms in the molecule. They are monomers, which means that they are single sugars made up of just one subunit. Glucose, fructose and galactose are three examples of common monosaccharides. Glucose is the most common monosaccharide and it has the chemical formula $C_6H_{12}O_6$.

Linking together monosaccharide monomers to build up polymers produces different types of carbohydrate. The condensation reactions involved in this process result in the production of either disaccharides or polysaccharides. Disaccharides consist of two monomers and polysaccharides are formed from long chains of monosaccharide monomers (Figure 1.4.1). The strong covalent bond between two monomers in a carbohydrate is known as a glycosidic bond and a water molecule is released in the condensation reaction.

In a condensation reaction, two molecules are joined together by strong covalent bonds to form a larger molecule. Condensation is an example of an anabolic reaction, which builds up monomers to form macromolecules. Each condensation reaction requires an enzyme to catalyse the process and it produces one molecule of water.

The condensation of two monosaccharide monomers produces a disaccharide.

For example:

glucose + galactose → (monosaccharide) (monosaccharide)
lactose + water (disaccharide)

Glycosidic bonds can also form between a sugar molecule and another molecule such as a lipid or amino acid to produce glycolipids and glycoproteins. Glycolipids and glycoproteins are found on the outer surface of cell membranes and are important in enabling cells to recognise one another. You can read more about cell to cell recognition in Chapter 6.

KEY POINT

glycosidic bond a type of covalent bond that links a carbohydrate molecule to another carbohydrate, or another group.

In any condensation reaction, two molecules can be joined to form a larger molecule, held together by a covalent bond. Condensation is an example of an anabolic reaction, in which monomers are built up to form macromolecules. Each condensation reaction requires an enzyme to catalyse the process and every reaction produces one molecule of water.

Different combinations of monosaccharide monomers produce a range of disaccharides. When a bond is formed between two glucose monomers, a disaccharide called maltose is produced. Maltose is found in seeds such as barley. Other monosaccharides include fructose, found in fruits, and galactose, which is present in milk. The equations here show some disaccharides that can be formed.

NATURE OF SCIENCE

Healthy eating and scientific literacy

Scientists have a responsibility to inform people about their work. Responsible citizens need to be able to evaluate information critically. What do you know about healthy eating?

It is difficult to say which parts of our diet are most likely to cause obesity. Studies show that the answer is not simple. Too much carbohydrate in a person's diet can cause them to become overweight, but this explanation may be too simple. The type of carbohydrate a food contains is important as well.

Simple carbohydrates (sugars, such as glucose and sucrose) are typically found in processed foods with low nutritional value, such as sugary drinks or food with added sugar. Adding sugar to food increases its calorie content, but does not provide any additional nutrition. But simple carbohydrates are not only found in low-nutrient foods. Milk and milk products contain lactose, which is a type of simple carbohydrate, but milk is also rich in protein, calcium and vitamin D. Other simple carbohydrates are present in fruits and vegetables that contain a variety of other vitamins and minerals, and nutrients such as fibre.

Complex carbohydrates, such as starch, are found in food such as bread and pasta. They contain longer chains of sugar molecules than simple carbohydrates. The body converts these molecules into glucose, which it uses for energy. As complex carbohydrates have longer chains, they take longer to digest and provide a more lasting source of energy than simple carbohydrates. Complex carbohydrates found in wholefoods tend to be highly nutritious. For example, wholegrain foods such as brown rice, barley and oats also provide fibre, vitamin B and E. Wholegrain foods may also reduce the risk of serious health conditions, such as type 2 diabetes and cardiovascular disease.

But not all complex carbohydrates are healthier choices: they are also found in processed foods such as white flour and white rice.

This means that some forms of simple carbohydrates are healthier than some complex carbohydrates. As you choose what to eat, consider the overall nutrition in each food, not just the type of carbohydrate it contains.

To consider:

1 How do you make informed choices about your own diet?

2 Discuss the importance of labelling on processed foods. Do labels help people learn about healthy options?

glucose	+	glucose	→	maltose + water
(monosaccharide)		(monosaccharide)		(disaccharide)
glucose	+	fructose	→	sucrose + water
glucose	+	galactose	→	lactose + water

If further monosaccharides are added to a disaccharide, a polysaccharide is formed, as you can see in Figure 1.4.1. Types of carbohydrate are summarised in Table 1.4.1.

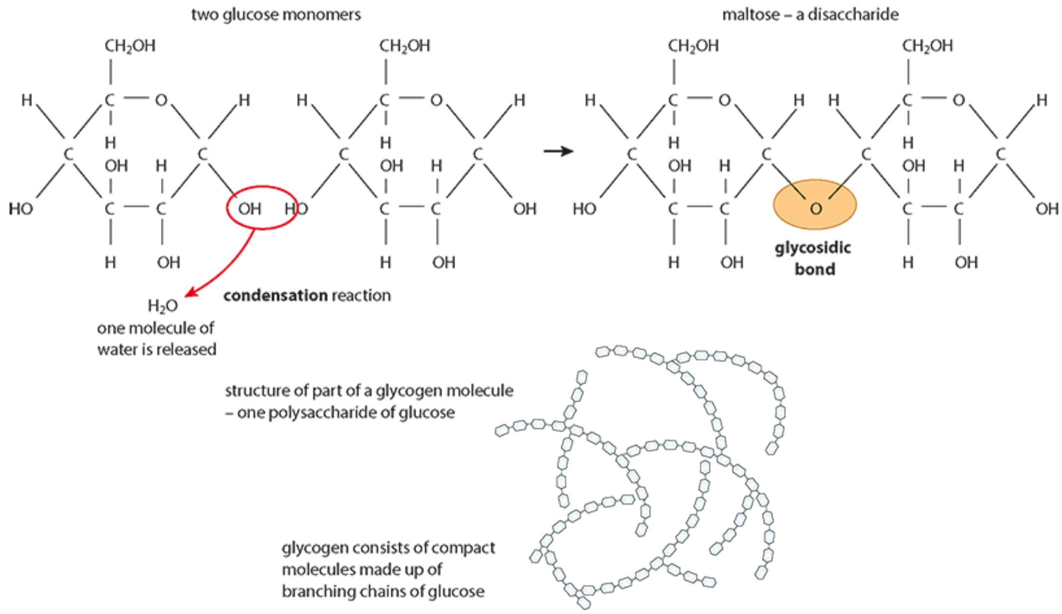


Figure 1.4.1: Monosaccharide subunits (glucose in this case) are joined in a condensation reaction, forming a disaccharide (maltose) and water. Glycogen is a polysaccharide, formed from long chains of glucose subunits.

Form of carbohydrate	Examples	Example of use in plants	Example of use in animals
monosaccharide	glucose, galactose, fructose	fructose is found in many fruits, making them taste sweet and attracting animals to eat them; this helps seeds in the fruit to be dispersed, or spread	glucose is the source of energy for cell respiration it is obtained from the digestion of carbohydrate foods
disaccharide	maltose,	sucrose is	lactose is

	lactose, sucrose	transported from leaves to storage tissues and other parts of the plant to provide an energy source	found in milk and provides energy for young mammals
polysaccharide	starch, glycogen, cellulose	cellulose is a structural component of plant cell walls starch is used as a food store	glycogen is the storage carbohydrate of animals, found in the liver and muscles

Table 1.4.1: Examples and roles of carbohydrates.

Form and function of monosaccharides

Monosaccharides can be either pentoses or hexoses. Pentose have a ring of 5 carbon atoms (Fig 1.4.9), while hexoses such as glucose are formed of a ring of 6 carbon atoms.(Figure 1.4.1)

1.4.2 Size, solubility and energy storage

Small carbohydrates such as glucose are very soluble in water, but larger molecules are less soluble. Glucose and other monosaccharides are an important source of energy for metabolism, their solubility makes them easy to transport. As part of larger molecules, they can form storage molecules. Large polysaccharides are those which contain from 40 to 1000 monomers.

Starch, glycogen and cellulose are all polymers of glucose monomers. Glycogen and starch are **storage carbohydrates** that act as an energy reserve.

Glycogen is stored in animals, fungi and prokaryotes, and starch is stored in plants. Both molecules have a compact shape and are insoluble because of their large size (Figure 1.4.1). Glycogen is made of branching chains of glucose monomers (Figure 1.4.1) and starch has long chains of glucose that coil into a helical shape (Figure 1.4.2).

Glycogen and starch are excellent for energy storage because they are easily put together, or assembled, and easily broken down by enzymes. In animals glycogen is stored in the liver and muscles. It can be used quickly and efficiently to release energy if it is needed. In plants starch is stored in all cells and is a useful reserve for the plant. Starch also provides food for animals in the form of potatoes and seeds, such as wheat and maize.

Both glycogen and starch take up less space than the same number of free glucose molecules. Small differences in the bonding between monomers produce the differences in shape between glycogen and starch.

Starch is a mixture of **amylose** and **amylopectin**. Amylose is a linear molecule with between 500 and 20 000 of glucose molecules. Amylopectin is branched and contains over 1 million glucose molecules (Figure 1.4.2).

When glycogen and starch are hydrolysed (broken down; see Section 1.3) glucose monomers are released. Glucose can be metabolised in cells in the reactions of respiration that release the energy living organisms need.

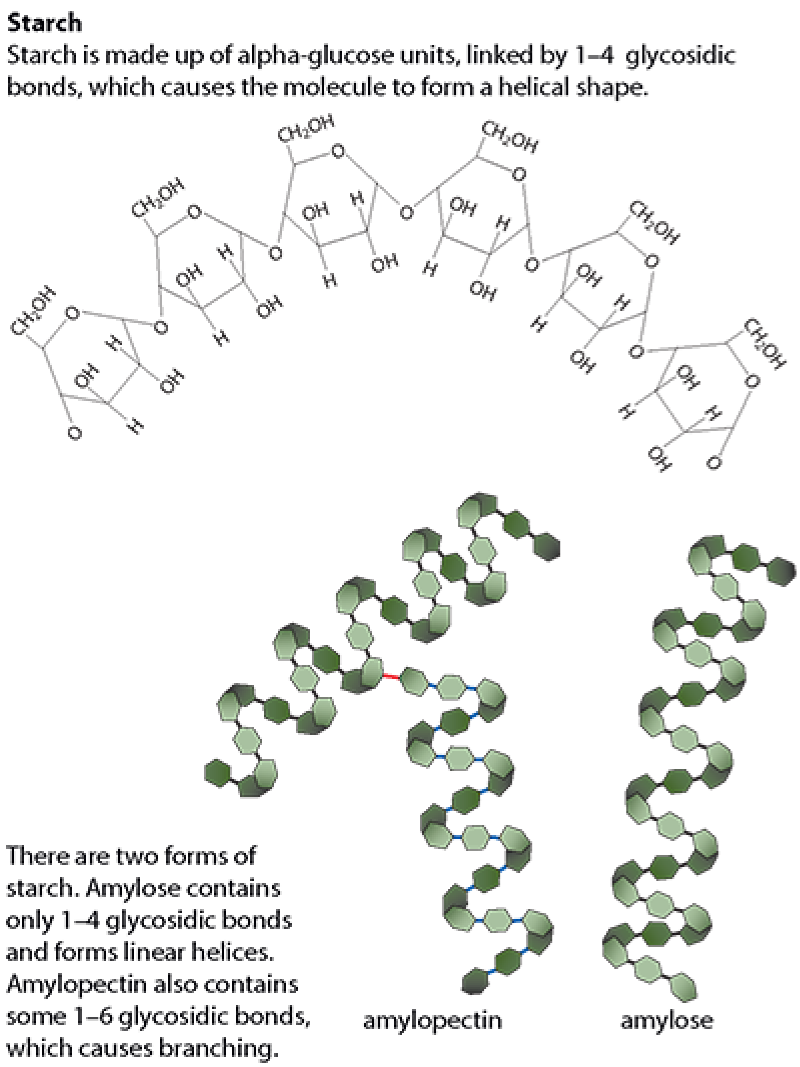


Figure 1.4.2: Starch is a polysaccharide found in plants.

Cellulose

Cellulose is polysaccharide with a different arrangement of bonding between glucose monomers. As a result, cellulose has very different properties from starch and glycogen. Cellulose is a **structural polysaccharide** that is used to build the cell walls of plants. It is made up of long, straight chains of glucose molecules but the glycosidic linkages between glucose monomers produce flat, linear strands. Hydrogen bonds can form cross-links between adjacent, parallel chains, which gives the polysaccharide its strength and structural properties (Figure 1.4.3). Cellulose strands form tightly packed, rigid bundles that support stems and hold plants upright.

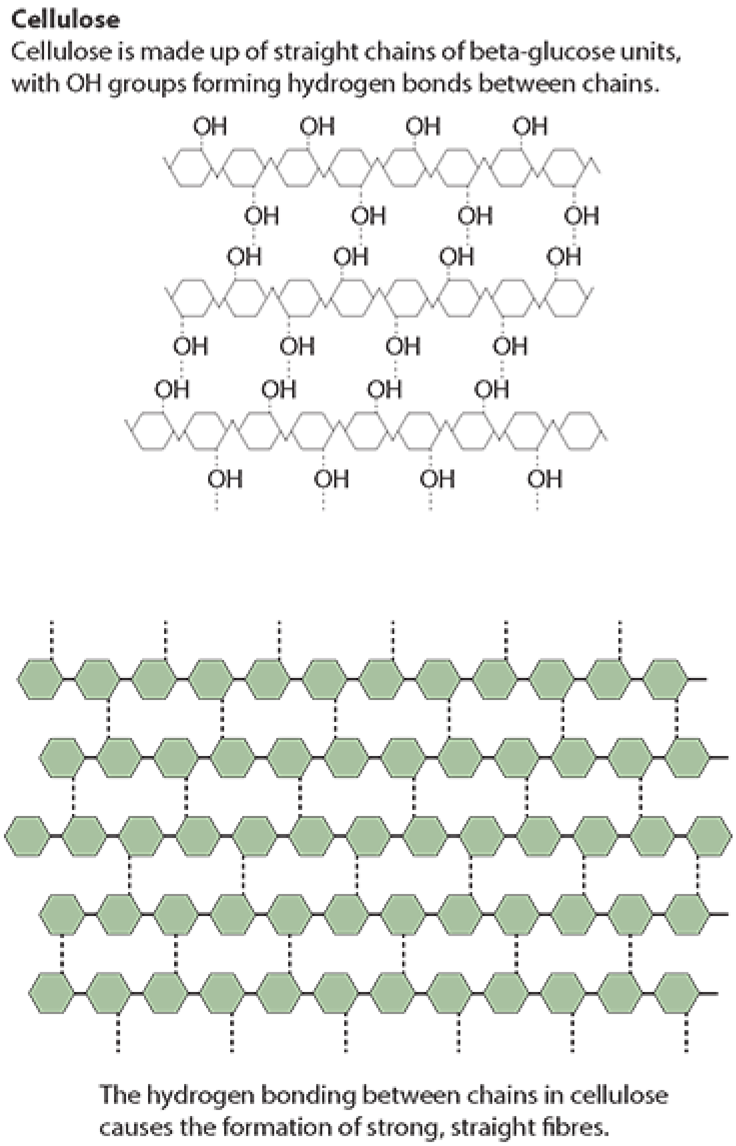


Figure 1.4.3: Cellulose is a structural polysaccharide found in plants.

SCIENCE IN CONTEXT

The abundance of cellulose

Cellulose, found in the cell walls of all plants, is probably the most abundant organic molecule on Earth. Paper and cotton are almost pure cellulose and wood contains cellulose and lignin.

Cotton is a fluffy fibre which surrounds the seeds of cotton plants to help them disperse. Cotton is found naturally in tropical and subtropical regions of Africa, Egypt, India and the Americas.

Cotton has been spun and woven into fabric for more than 2500 years: fragments of cotton from 500 BCE have been found in Peru and dyed cotton clothing was used in ancient India, Egypt and China.

Today cotton is the most commonly used natural fibre and around 25 million tonnes are produced annually. India is the largest producer and the USA is the largest exporter of cotton. In recent years genetically modified cotton plants have been developed in an effort to reduce the use of pesticides. It was recently estimated that 25 million hectares of land, almost 70% of the total, are planted with GM cotton plants.

Long ago, paper was also made from cotton rags and linen from flax plants. Cotton paper from the year 751 has been found in Samarkand in Uzbekistan, but by the turn of the 20th century wood pulp became the primary material used. Cotton is still used to make some speciality paper for important documents because it will last for many years and not deteriorate.

To consider:

1 Thousands of years ago, cotton plants were cultivated independently in several part of the world. Investigate the reasons why cotton was such a useful plant to domesticate.

2 Why do you think that waste fabric is not used to make paper today?

3 Thinking about your own clothing, are you wearing any items that are made from cotton fibres?

TEST YOUR UNDERSTANDING

18 State two examples of disaccharides.

19 Which of the following statements is true?

All carbohydrates:

A are polymers

B are simple sugars

C consist of one or more simple sugar

D are soluble in water

20 Fill in the gaps in this description of the formation of polysaccharides.

Two monosaccharide monomers are linked together by ....reactions to form a …………........... . If further monomers are added a …………………. is formed.

21 Give two examples of polysaccharides and outline their functions.

22 Explain why plants store starch and animals store glycogen rather than glucose molecules.

EXTENSION

Bonding arrangements of monosaccharides

Isomers of glucose

Glucose has two structural isomers, alpha (α) and beta (β) glucose (Figure 1.4.4).

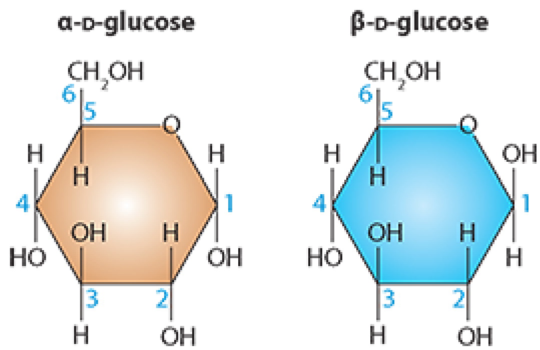


Figure 1.4.4: The isomers of glucose.

Notice how the carbon atoms in the molecules are numbered. These numbers are used to describe the linkages that the molecules can form. The positions of the side groups in the two molecules give the molecules abilities to bond in different ways. Bonding patterns produce the different polysaccharides that form amylose and amylopectin in starch molecules, and cellulose. Starch is built up of alpha-D-glucose monomers and cellulose of beta-D-glucose monomers.

Amylose (Figure 1.4.2) consists of a linear, helical chains of between 500 and 20 000 alpha-D-glucose monomers linked together through glycosidic bonds between the 1 carbon on one molecule and the 4 carbon on the next molecule. The bonds are called 1–4 glycosidic bonds. The hydroxyl (–OH) groups allow **condensation reactions** to link adjacent monomers and release water as they form.

Amylopectin molecules are much larger polymers each containing over a million glucose monomers. Amylopectin is branched because it forms 1–6 glycosidic bonds as well as 1–4 bonds (Figure 1.4.6).

Condensation reactions occur between sugar monomers. Here a 1–4 linkage is made between two alpha glucose monomers to form maltose. A glycosidic bond is made and water is released from the hydroxyl groups.

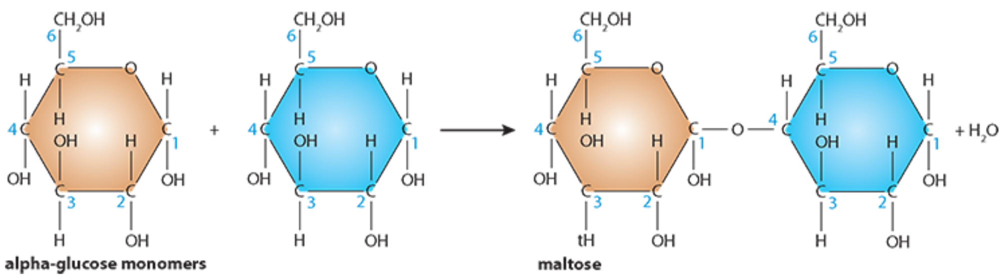


Figure 1.4.5: Two alpha glucose monomers are joined in a condensation reaction to produce maltose.

Cellulose molecules are linear chains of hundreds or thousands of beta-D-glucose monomers joined through 1–4 linkages (Figure 1.4.7). Notice that in cellulose alternate glucose monomers are ‘upside down’. Compare this structure with the structure of glucose which has alpha glucose monomers joined through 1–4 linkages.

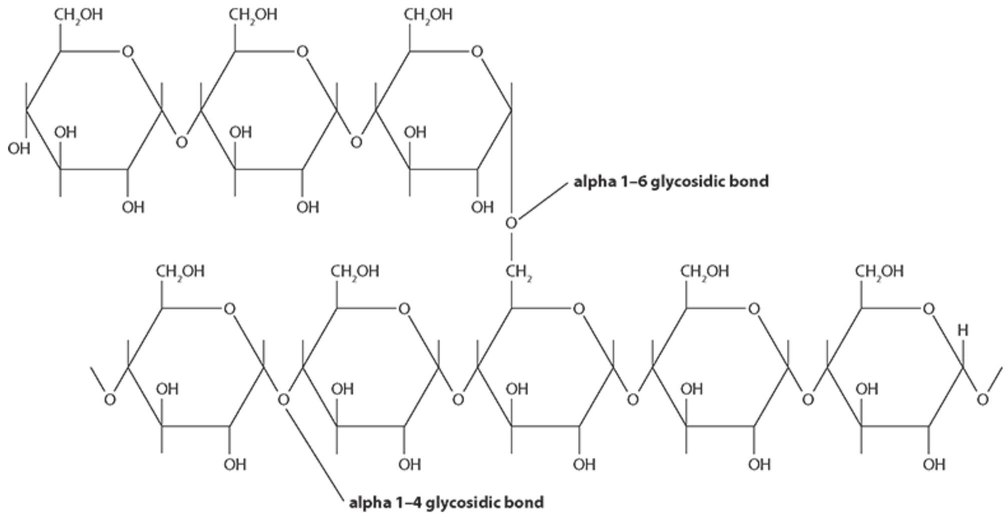


Figure 1.4.6: Amylopectin.

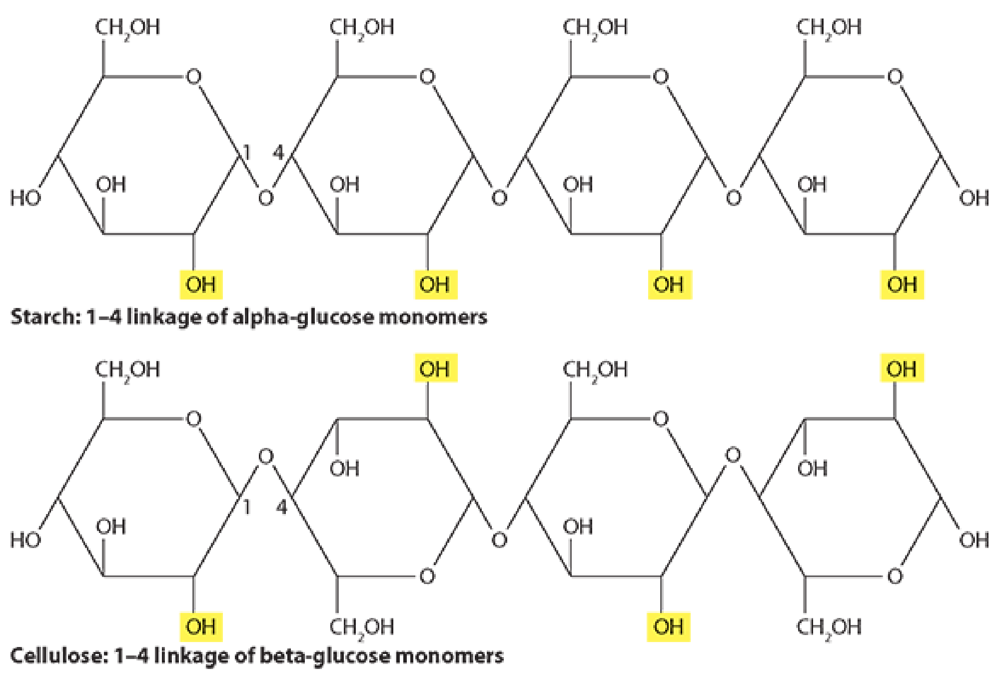


Figure 1.4.7: Comparing the linkages in starch and cellulose.

Table 1.4.2 summarises the different structures and functions of the important polysaccharides amylose, amylopectin, cellulose and glycogen.

Polysaccharide	Structure	Function
amylose	Linear, helical chains 500–20 000 alpha-D-glucose monomers linked together through the bonds are called 1–4 glycosidic bonds.	Energy storage in plants, part of starch.
amylopectin	Branched molecules of over a million alpha-d-glucose monomers with 1–6 glycosidic bonds.	Energy storage in plants, part of starch.
glycogen	Compact branching chains of alpha-d-glucose monomers with 1–4 glycosidic linkages. Branches with alpha-1–6 linkages occur approximately every 10 units.	Short-term energy storage in animals, fungi and prokaryotes.
cellulose	Straight chains of beta-D-glucose monomers. Hydrogen bonding occurs between polar hydroxyl groups in the chains.	Structural polysaccharide forming strong rigid fibres of plant cell walls.
chitin	Long chains of sugar molecules derived from glucose by replacing one hydroxyl group with a nitrogen-containing group. Linkages are similar to those	Structural polysaccharide found in cell walls of fungi, exoskeletons of arthropods