DP IB Biology: SL

Your notes

2.1 Metabolism & Water

Contents

2.1.1 Molecules

Your notes

Molecular Biology

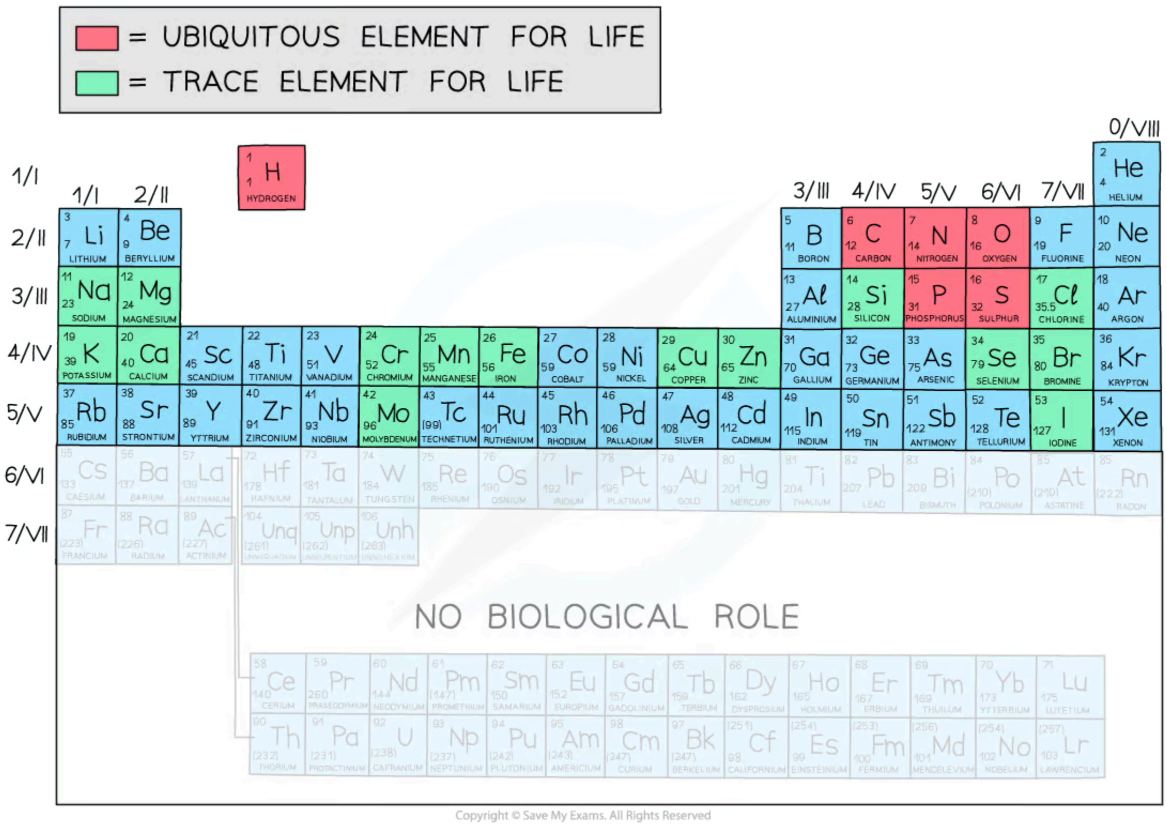
The substances of life

- There are **118 elements** in the Periodic Table
- Only the first **92 elements occur in Nature** ; the rest are artificially-synthesised in laboratories and are very unstable
- Only around **21 elements are required for life**
  - The rest have **no role** in sustaining life (some are poisonous eg. arsenic)
  - Some elements can be used in **medicine** eg. titanium for skeletal implants, thanks to its inertness, lightness and strength

- There are **4 ubiquitous elements** in biological systems (this means they are found everywhere)
- These 4 make up over 96% of living matter
  - Oxygen - 65% of body mass (humans)
  - Carbon - 18%
  - Hydrogen - 10%
  - Nitrogen - 3%

- Other **trace elements** found in organic compounds are: bromine, calcium, chlorine, chromium, copper, iodine, iron, magnesium, manganese, molybdenum, phosphorus, potassium, selenium, silicon, sodium and sulfur
- There are **other trace elements found in certain phyla only** e.g. **strontium** in certain corals (C*nidaria*)

Your notes



The elements of the Periodic Table that form parts of biological molecules

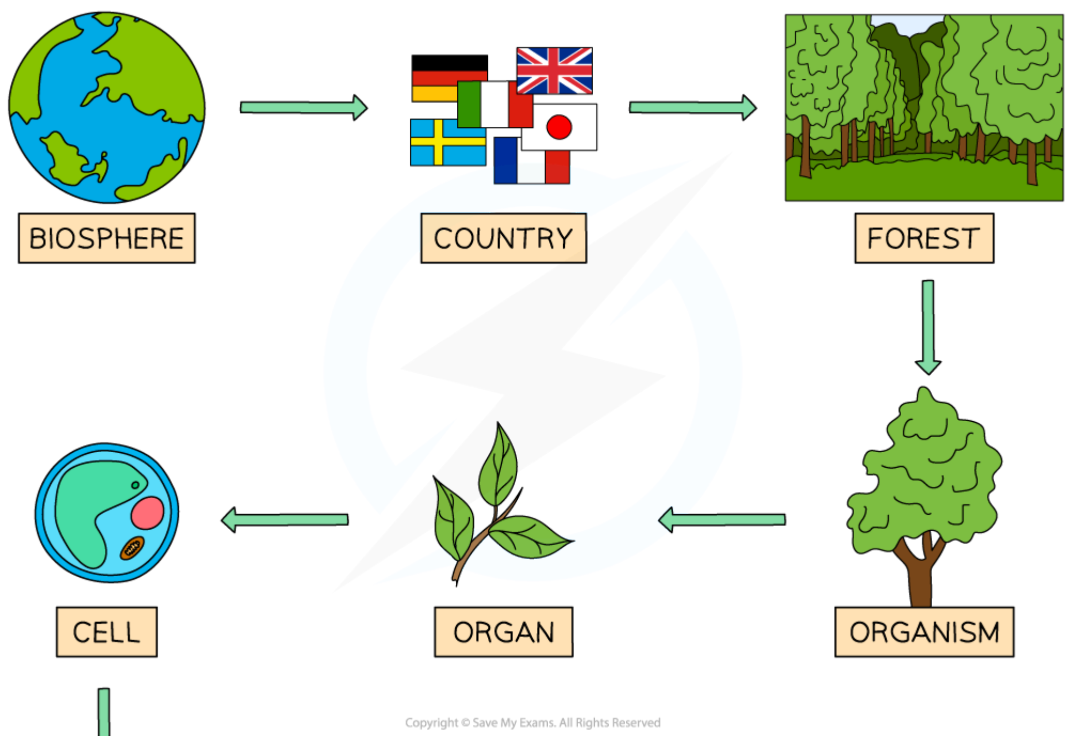
Elements in biology exist mainly in compounds

- Such compounds are **mainly covalent** compounds
  - **Electrons are shared** between atoms to generate **strong bonds** within compounds
  - For example, elemental carbon only exists as graphite and diamond, which are of no direct use to organisms
  - Carbon forms **millions of different covalently-bonded compounds**, mainly with hydrogen and oxygen
  - **Oxygen** is absorbed in elemental form but is quickly converted to its compounds during **transportation** and **respiration**
- Some are **ionic** eg. sodium chloride
- Some elements form **prosthetic groups** with larger organic molecules eg. magnesium in chlorophyll, iron in haemoglobin

All of Biology can be explained at a molecular level

- The molecules in cells, and the elements that go to form them, are **the basis of all events** that occur in Nature
- Everything that is observed has a **molecular explanation**
- Imagine an all-powerful '**zoom lens**' that could look into any level of detail of life
- Such a lens could start at its most zoomed-out, looking at our **biosphere**, the Earth
  - We assume that alien life does not exist because we haven't found evidence for it yet

- We see **habitats**, **populations**, **communities** and **individual organisms** coming into view in that order, as we zoom in
- As we zoom in on one organism, we **enter its body** and see increasing levels of detail, right down to the molecular level
- The zoom model helps understand the **important interfaces** between chemistry, biology and physics
- We could zoom in further, to look at sub-atomic particles, although that begins to enter into the realms of physics!



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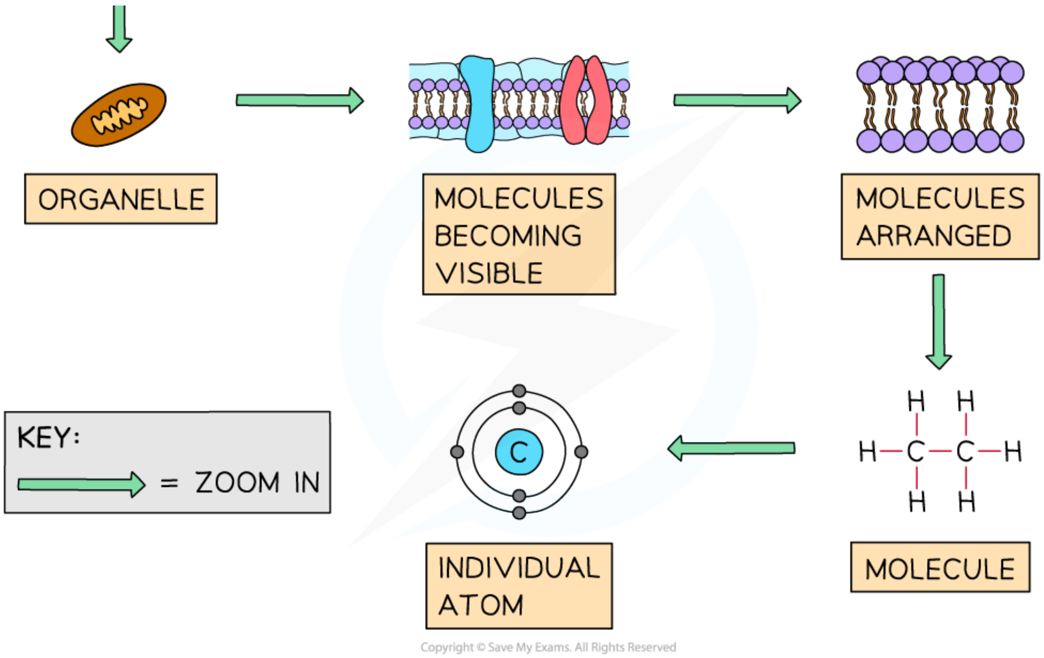


We can zoom into any part of the biosphere to identify all of Biology at a molecular (and atomic) level

Examiner Tip

Please note that you do not need to know the specific details of the Periodic Table, it is provided here for context to support your understanding of important biological compounds

Your notes

Synthesis of Organic Molecules

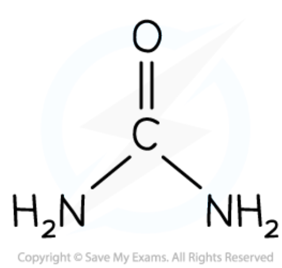
Your notes

NOS: Falsification of theories; the artificial synthesis of urea helped to falsify vitalism

- When scientists do not have all the necessary information to understand or explain a biological process/phenomenon they use their knowledge and expertise to propose a **theory**
- Other scientists or researchers will often test theories through experiments and gathering data. Sometimes this can lead to an existing theory being disproved or replaced
- In the early 1800s, the theory of **vitalism** stated that a **living force**, a mysterious non-molecular entity, was necessary for the synthesis of all **organic molecules**
- This theory advocated that all biological molecules were **exclusive to living beings** and could not be found in other branches of science
- Frederick Wöhler, a German physician, was the first to synthesise a biological molecule, **urea**, from inorganic compounds
  - Urea was **thought to be synthesised only** in living organisms
- Wöhler heated ammonium cyanate and produced urea, a well-known organic constituent of blood and urine
  - Urea had been thought to be found only in living organisms
- The formation of urea from ammonium cyanate **helped to disprove the theory of vitalism**, which has been completely **falsified** by subsequent findings
- All of the observations of biology now have a **molecular explanation**, and that is now universally accepted

$$NH_4(OCN) \rightarrow NH_3 + HOCN \leftrightarrow (NH_2)_2CO$$

A balanced chemical equation showing the formation of urea



Chemical Structure of Urea

Your notes

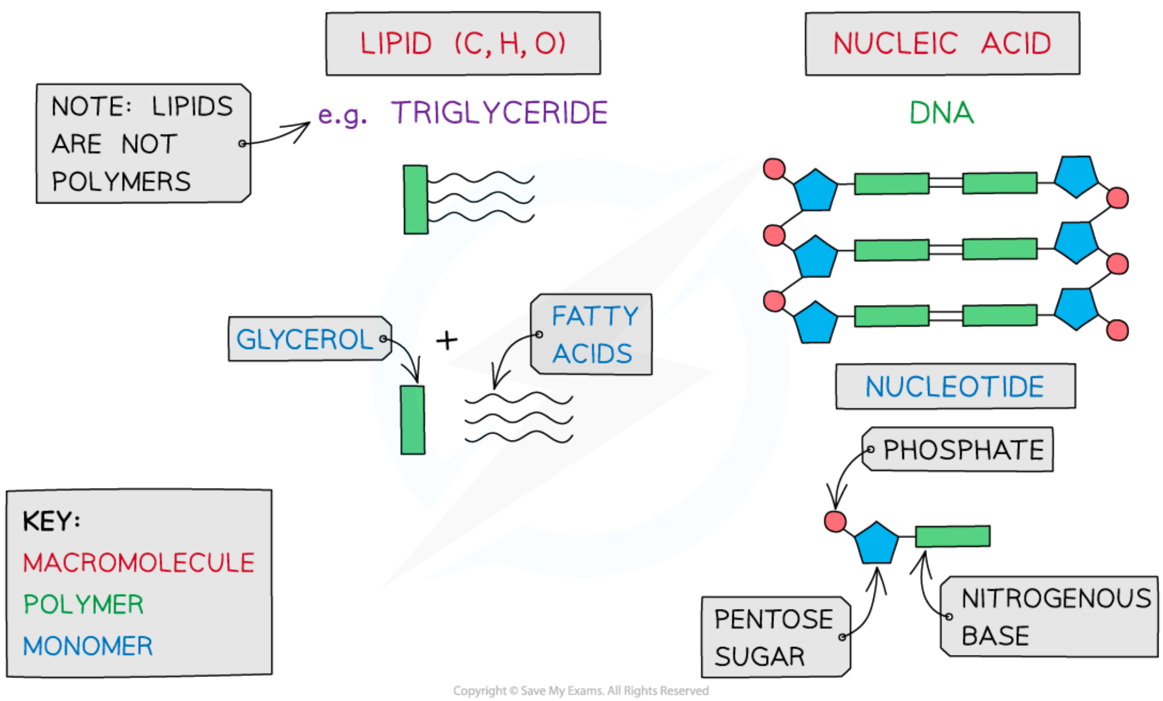
Carbon

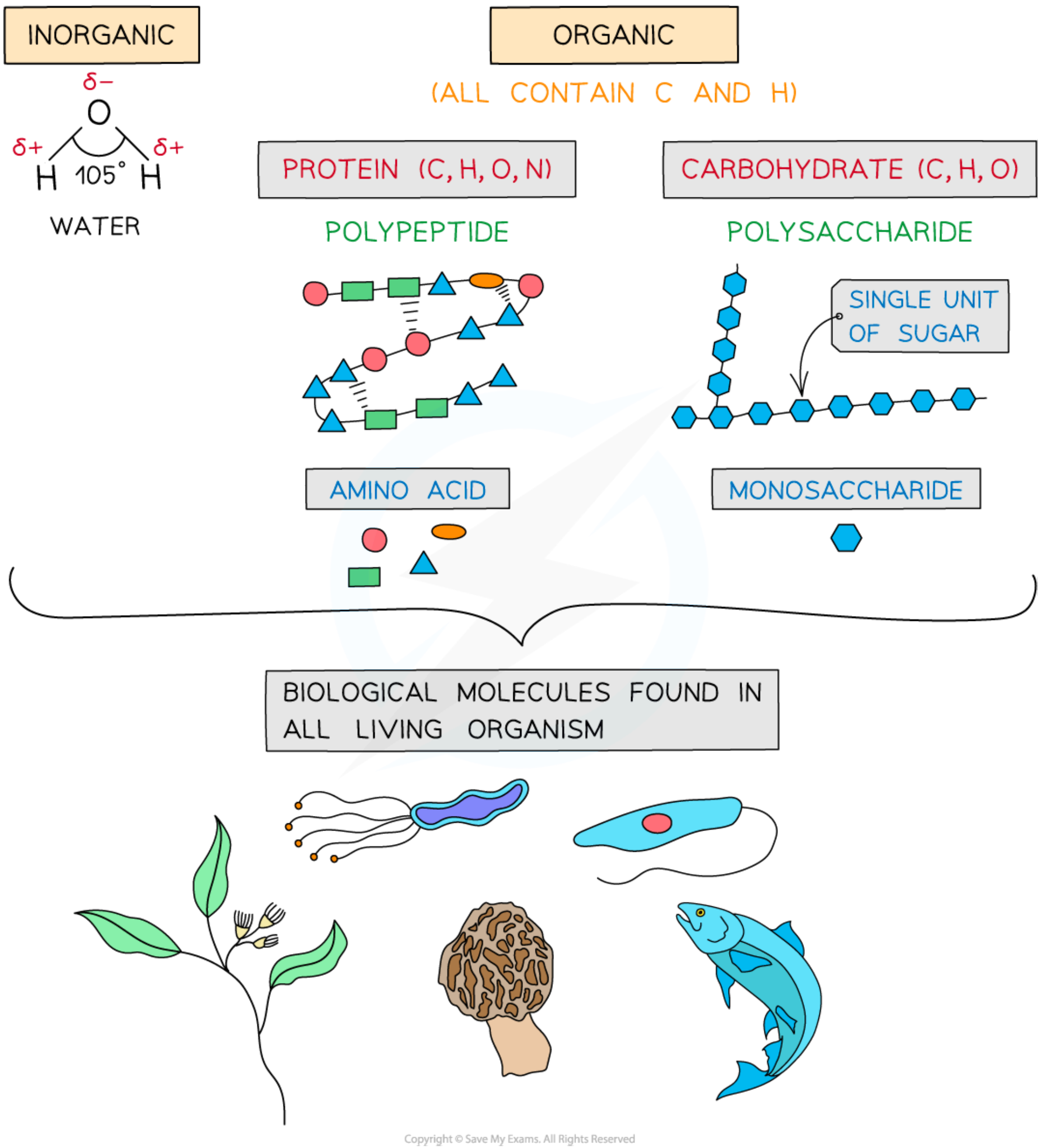
- Carbon's unique chemistry makes it the ideal basis of living systems
- The **structure and bonding** possibilities of **carbon** can be detailed as follows:
  - **Four electrons** in its outer (second) shell
  - Each atom can form four strong covalent bonds **using these 4 electrons and therefore forms very stable, large molecules**
- Bonds to **other carbon atoms**, or **other atoms** such as hydrogen, nitrogen, oxygen, sulfur and the halogens
- Forms **long-chain** and **cyclic** compounds that are stable, this allows a **very high number of possible organic compounds** to exist
- Produce a **tetrahedral structure**, due to the four bonds, which allows the formation of varied carbon compounds which have different 3-D shapes and hence, different biological properties
- **Double** and **triple bonds** can form with an adjacent carbon atom, allowing **unsaturated** compounds to form
- Can form part of (and join onto) many different **functional groups** that give organic compounds their individual properties
  - Alcohol groups
  - Hydroxyl groups
  - Ketone groups
  - Aldehyde groups
  - Carbonyl groups
  - Amino groups
  - Sulfhydryl groups
  - Phosphate groups

Carbon Compounds

Your notes

- The key molecules that are required to build structures that enable organisms to function are:
  - Carbohydrates
  - Proteins
  - Lipids
  - Nucleic Acids
  - Water
- All of these except water contain carbon





The key biological molecules for living organisms

- Carbohydrates, proteins, lipids and nucleic acids contain the elements **carbon** (C) and **hydrogen** (H) making them organic compounds
- Carbon atoms are key to organic compounds because:

Your notes

  - Each carbon atom can form **four** covalent bonds – this makes the compounds very stable (as covalent bonds are so strong they require a large input of energy to break them)
  - Carbon atoms can form covalent bonds with oxygen, hydrogen, nitrogen and sulfur
  - Carbon atoms can bond to form **straight chains**, **branched chains** or **rings**
- Carbon compounds can form small single subunits **(monomers)** that bond with many repeating subunits to form large molecules **(polymers)** by a process called polymerisation
- **Macromolecules** are very large molecules that contain 1000 or more atoms therefore having a **high molecular mass**
  - Polymers can be macromolecules, however **not all** macromolecules are polymers as the subunits of polymers have to be the **same** repeating units

Examiner Tip

When discussing monomers and polymers, you should be able to give the definition and also name specific examples eg. **nucleic acids** – the **monomer** is a **nucleotide.**

Your notes

2.1.2 Metabolism

Metabolism

- **Metabolism** is a catch-all term used to describe **all the chemical reactions** that take place within cells and organisms
- Metabolism can be thought of as **the chemical reactions of life**
  - The molecules involved are **metabolites**
- Many reactions of metabolism take place in **multiple stages**
  - Each stage is **catalysed** by a separate **enzyme**
- A series of interlinked metabolic reactions is called a **metabolic pathway**
- Metabolic reactions can be classified broadly as **anabolic** or **catabolic**

Anabolism

- Anabolic reactions are involved with the building of large molecules from smaller ones
- Examples include;
  - Photosynthesis, where CO_2 and water are built up into complex sugars
  - Protein synthesis, where amino acids are joined together in sequence
  - The buildup of fat stores ahead of animal hibernation
- Anabolic reactions often include **condensation** reactions
- Anabolic reactions are **endergonic** (they require an input of energy to take place)
  - Energy-storing products are the end result

Catabolism

Your notes

- Catabolic reactions are involved with **breaking down large molecules** into smaller ones
- These reactions are often carried out to **release energy** for cellular processes and for the **excretion** of waste
- Examples include:
  - **Respiration**, where CO_2 and water are produced from the breakdown of sugars
  - **Deamination** of proteins to release urea
  - The **depletion of fat stores** during animal hibernation
- Catabolic reactions often include **hydrolysis** reactions
- Catabolic reactions are **exergonic** (free energy is released for cellular processes or as excess heat)

Comparison of Anabolism and Catabolism Table

Anabolism	Catabolism
Requires an input of energy (endergonic)	Releases energy (exergonic)
Builds large molecules from small ones	Breaks down large molecules into smaller ones
Used to store energy in chemical form	Used to release chemical energy as heat and for movement, active transport etc
Involves condensation reactions	Involves hydrolysis reactions
Used for growth, repair, and energy storage	Performs several activities, eg. energy supply, digestion, excretion
Both are made up of enzyme-catalysed reactions	
Both are coupled to ATP, the principal energy carrier in cells	

Examiner Tip

You may be familiar with the concept of anabolic steroid drugs used by bodybuilders. This is to build muscle mass and so is a good example to remember when trying to remember the difference between anabolic and catabolic reactions.

Your notes

2.1.3 Hydrogen Bonds

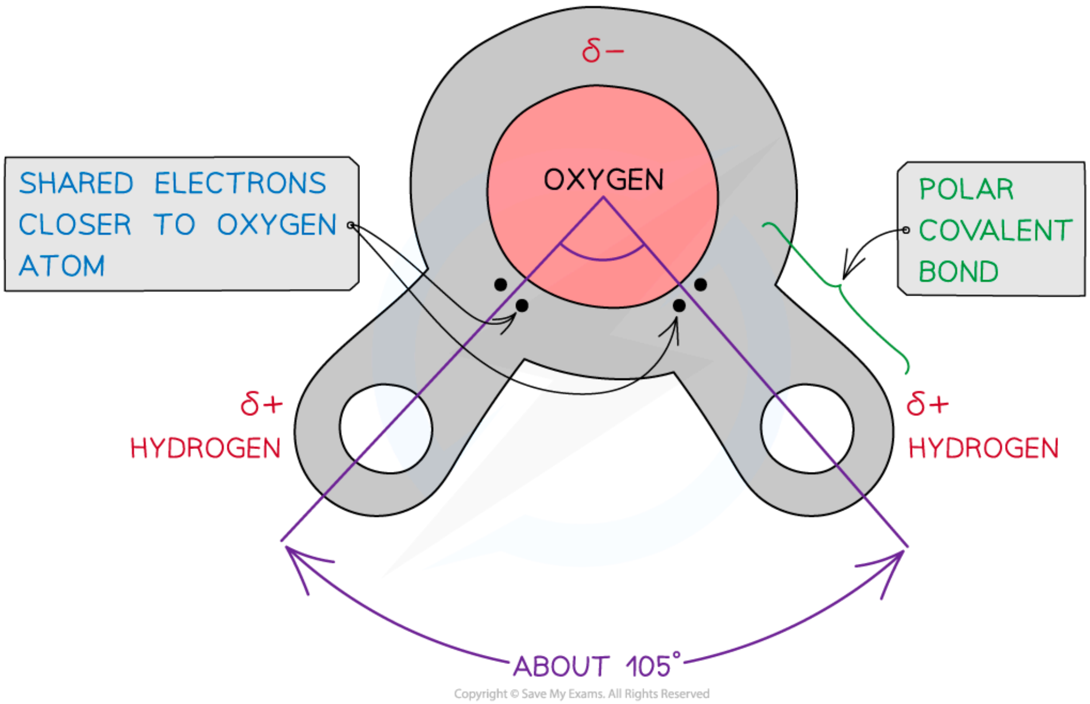
Hydrogen Bonds

- Hydrogen bonding plays an important role between many biological molecules
- Some key functions include:
  - **Dissolving of solutes** in water
  - The **cohesion** and **adhesion** of water molecules
    - These properties allow water to move up the trunks of really tall trees
  - **Base-pairing** between the two strands of DNA
  - Structure:
    - Hydrogen bonds help to form part of the **secondary** and **tertiary** levels of structure in proteins
    - The hydrogen bonds found between strands of **cellulose** and **collagen** give those molecules their **tensile strength**
  - Interactions between **mRNA** and **tRNA** during **protein synthesis**
  - **Surface effects** on membranes between **polar phosphate groups** and **water**

Hydrogen bonding in water

- Hydrogen bonding is a fundamental property of **water**
- Water is of the **utmost biological importance**
  - It is the **medium** in which all metabolic reactions take place in cells
  - Between 70% to 95% of the mass of a cell is water
  - Water is **so fundamental to life** that astronomers look for **signs of water** on other planets and moons, as indicators of possible extra-terrestrial life
  - As 71% of the Earth's surface is covered in water it is a **major habitat** for organisms
- Water is composed of atoms of hydrogen and oxygen
  - One atom of oxygen combines with two atoms of hydrogen by sharing electrons (**covalent bonding**)
- Although water as a whole is electrically neutral, the **sharing** of the **electrons** is **uneven** between the oxygen and hydrogen atoms
  - The oxygen atom attracts the electrons more strongly than the hydrogen atoms, resulting in a **weak negatively charged region** on the oxygen atom (δ^-) and a **weak positively charged region** on the hydrogen atoms(δ^+), this also results in the molecule's asymmetrical shape
- This separation of charge due to the electrons in the covalent bonds being unevenly shared is called a **dipole**
- When a molecule has **one** end that is negatively charged and **one** end that is positively charged it is also a **polar molecule**
- Water is therefore a **polar molecule**

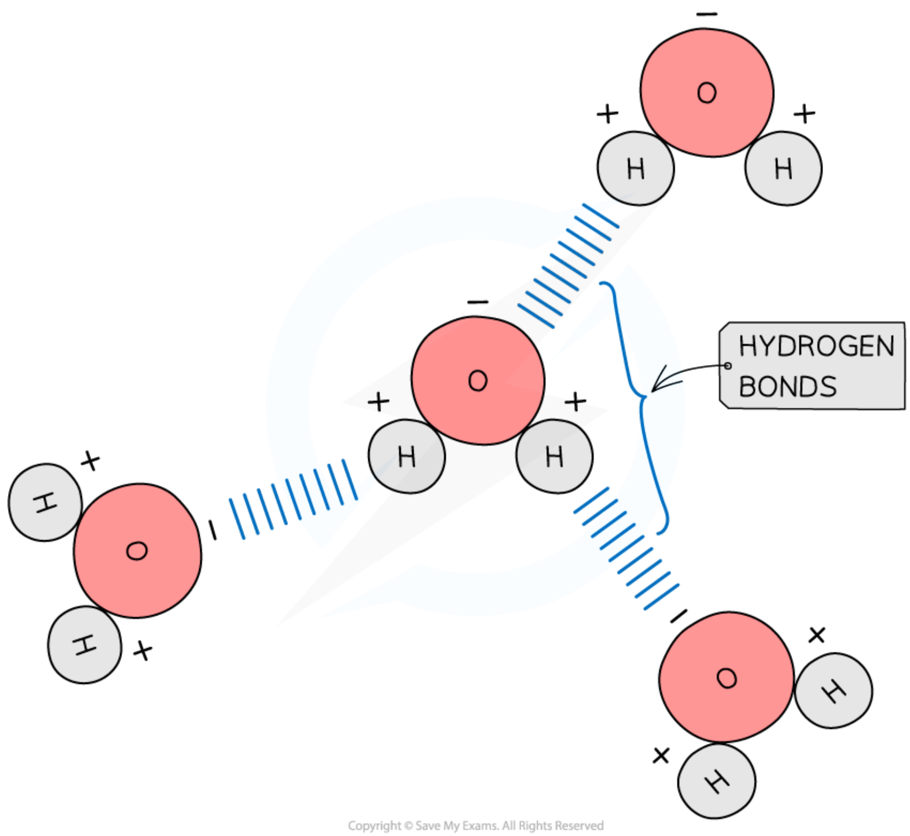
Your notes



The covalent bonds of water make it a polar molecule

- **Hydrogen bonds** form between water molecules
  - As a result of the polarity of water, **hydrogen bonds form** between the positive and negatively charged regions of adjacent water molecules
- Hydrogen bonds are weak, when there are few, so they are **constantly breaking and reforming**
- However, when there are large numbers present they form a strong structure
- Hydrogen bonds **cause many of the properties of water molecules**, that make them so important to living organisms:
  - Excellent **solvent** – many polar substances can dissolve in water
  - A relatively **high specific heat capacity**
  - A relatively **high latent heat of vaporisation**
  - Water is less dense when a solid (ice floats, allowing aquatic life to flourish beneath)
  - Water has **high surface tension** and cohesion
  - It acts as a **reagent**

Your notes

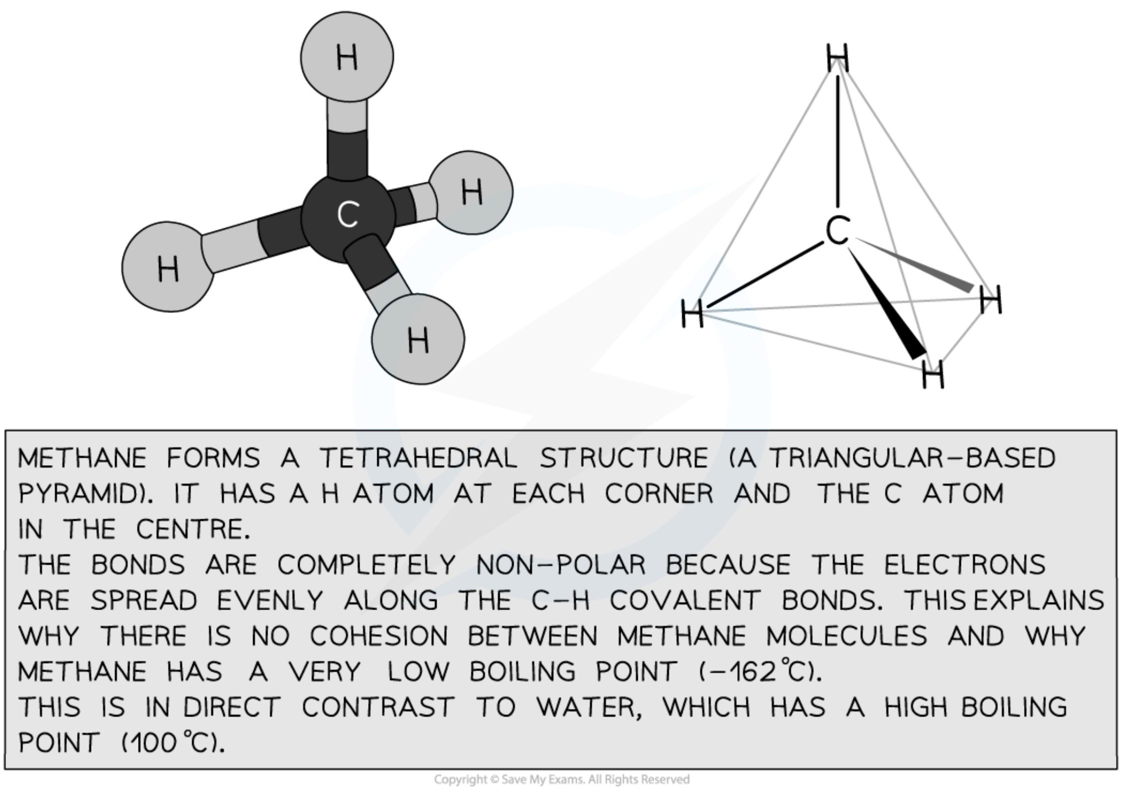


The polarity of water molecules allows hydrogen bonds to form between adjacent water molecules

Comparison: Water & Methane

Your notes

- Both **methane** (CH_4) and **water** (H_2O) are **small**, covalently-bonded molecules
- Methane is the **simplest organic compound**
- They have similar molecular weights, 16 and 18 respectively
- **But** water is polar and so forms hydrogen bonds, whereas methane is **not polar** and so does not form hydrogen bonds
- **Water is liquid** at room temperature, whereas **methane is a gas**
  - Other compounds, with a small molecular weight, such as ammonia (NH_3) and carbon dioxide (CO_2) are gases at room temperature
    - These compounds also **do not form hydrogen bonds**
  - This shows how **water molecules are held together by hydrogen bonds**, whereas the other gas molecules are free to move around in the gaseous state
  - Methane is a **fuel** with a **high energy content** in its bonds, whereas water is a **final product** of combustion and respiration
- Understanding the molecular properties of methane underlines **the significance of hydrogen bonding** in water



Methane's structure determines its properties

Your notes

Comparison of the Properties of Water and Methane Table

	Water	Methane
Formula	H_2O	CH_4
Molecular Weight	18	16
Polarity	High	Low
Latent Heat of Vaporisation / kJ kg^{-1}	2 260	510
Specific Heat Capacity / kJ kg^{-1} °C^{-1}	4.2*	2.2
Melting Point / °C	0	−182
Boiling Point / °C	100	−162

* Water has the highest Specific Heat Capacity of any known substance

Examiner Tip

It is important to know where the hydrogen bonds form between water molecules (oxygen of one water molecule to the hydrogen atom of another).

2.1.4 Water

Your notes

Properties of Water

Water as the medium for life

- The first cells evolved in a watery environment
- This is believed to have been in the deep oceans, close to hydrothermal vents in the Earth's crust
- Some water and solutes got trapped within a membrane
- Chemical reactions began occurring within the membrane-bound structure
- This led to the evolution of cells
- Water in its liquid state allows dissolved molecules to move around, so they are easily able to collide and react with each other
- Most life processes occur in water
- The link between water and life is so strong that scientists looking for life on other planets and moons look for evidence of water to suggest that life could have occurred there

The properties of water

Solvent

- As water is a **polar molecule** many ions (e.g. sodium chloride) and covalently bonded polar substances (e.g. glucose) will dissolve in it
  - This allows **chemical reactions** to occur within the **cytoplasm** of cells (as the dissolved solutes are more chemically reactive when their individual molecules are free to move about)
  - **Metabolites** can be transported efficiently (except non-polar molecules which are hydrophobic)
- Water molecules 'surround' individual solute particles to ensure each solute particle is isolated from others
  - This explains why **solutions are clear** - we can't see individual molecules that are separated from their crystal structures
- This is also why concentrated solutions have a **lower water potential** or a higher **osmolarity**
  - Because many water particles are 'occupied' in keeping a solute molecule in solution, **fewer water molecules are free to diffuse** across partially permeable membranes

Water has a high specific heat capacity

- Specific heat capacity is a measure of the **energy required to raise the temperature of 1 kg of a substance by 1°C**
- Water has a **high** specific heat capacity of 4200 J/kg/°C meaning a relatively large amount of energy is required to raise its temperature
- The high specific heat capacity is due to the **many hydrogen bonds** present in water

Your notes

    - It takes **a lot of thermal energy** to break these bonds and a lot of energy to build them, thus the temperature of water does not fluctuate greatly
- The advantage for living organisms is that it:
    - Provides suitable, **stable habitats**
    - Is able to maintain a **constant temperature** as water is able to absorb a lot of heat without wide temperature fluctuations
        - This is vital in maintaining temperatures that are optimal for **enzyme activity**
    - Water in blood plasma is also essential in **transferring heat** around the body, helping to **maintain a fairly constant temperature**, especially at body extremities eg. fingertips
        - As blood passes through more metabolically active ('warmer') regions of the body, heat energy is absorbed but the temperature remains fairly constant
        - Water in **tissue fluid** also plays an important regulatory role in maintaining a constant body temperature

Water has a high latent heat of vaporisation

- In order to change state (from liquid to gas) a large amount of thermal energy must be absorbed by water to break the **hydrogen bonds** and allow individual gas particles to escape (evaporate)
- This explains water's **high boiling point** (100°C)
- Water is present on Earth in **all three physical states** (solid, liquid and gas) thanks to this characteristic
    - **Ice**, **liquid water** and **water vapour** all play a vital role in the biosphere
    - This is an advantage for living organisms as **only a little water is required** to evaporate for the organism **to dissipate a great amount of heat**
    - This provides a **cooling** effect for living organisms, for example, the transpiration from leaves or evaporation of water in sweat from the skin

Properties of Water & its Role in Living Organisms Table

Your notes

Property	Role in living organisms	Reason
Solvent	○ Allows chemical reactions to occur ○ Transport medium	Polarity of water
High specific heat capacity	○ Allows water to be a suitable habitat ○ Optimal temperature maintained within cells and bodies	Presence of many hydrogen bonds
High latent heat of vaporisation	○ Coolant	Presence of many hydrogen bonds

Cohesion and adhesion

- Hydrogen bonds between water molecules allows for strong **cohesion between water molecules**
  - Allowing **columns of water** to move (called **mass transport**) through the xylem of plants and through blood vessels in animals
  - Enabling **surface tension** where a body of water meets the air, these hydrogen bonds occur between the top layer of water molecules to create a sort of film on the body of water
    - This layer is what allows insects such as **pond skaters** to move across the surface of water
- Water is also able to hydrogen bond to **other molecules**, such as cellulose, which is known as **adhesion**
  - This also enables water to move up the **xylem** during **transpiration**
  - Cohesion and adhesion both contribute to water forming a **meniscus** in glassware, where water molecules adhere to polar molecules in the glass
  - Water adheres to the xylem walls (made of lignin) by **capillary action**

Examiner Tip

COhesion = water particles sticking to **each other. AD**hesion = water particles sticking to **other materials**

Hydrophilic & Hydrophobic

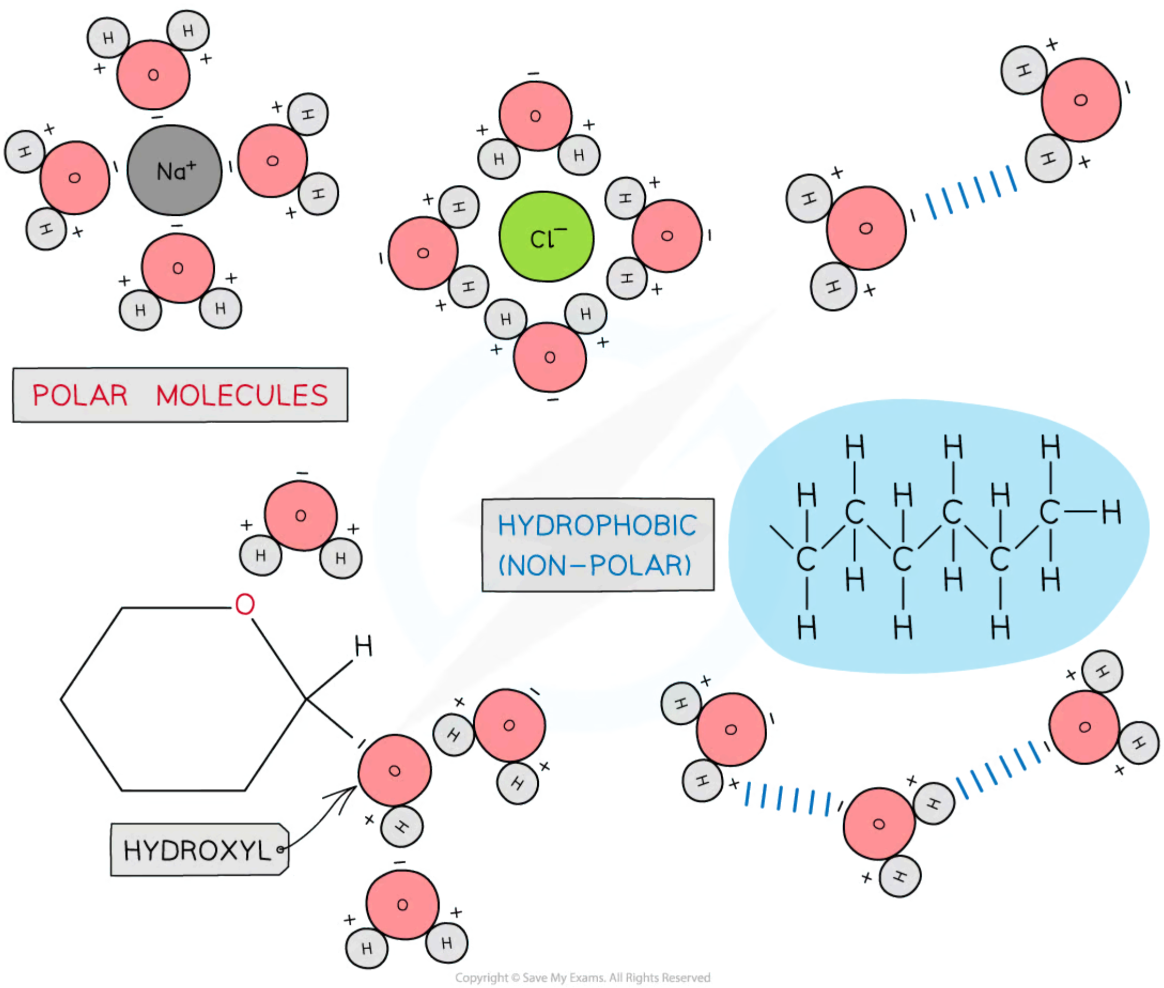
Your notes

- Biological molecules can be hydrophilic or hydrophobic (and sometimes both)
  - Hydrophilic = "water-loving"
  - Hydrophobic = "water-hating"

- **Polar molecules** and molecules with **positive or negative charges** can form hydrogen bonds with water (and dissolve) so are generally **hydrophilic**
- **Non-polar molecules** with no **positive or negative charge**, cannot form hydrogen bonds with water so are generally **hydrophobic**
  - These molecules tend to join together in groups due to **hydrophobic interactions** where hydrogen bonds form between water particles but not with the non-polar molecule

- Because most biological molecules are hydrophilic and can be dissolved, water is regarded as the **universal solvent**
- Some large molecules have **different groups** with **different characteristics**
  - **Phospholipids** have hydrophilic (phosphate group) heads and hydrophobic (hydrocarbon chain) tails. This dual character is a key feature in the structure and function of **cell membranes**

Your notes

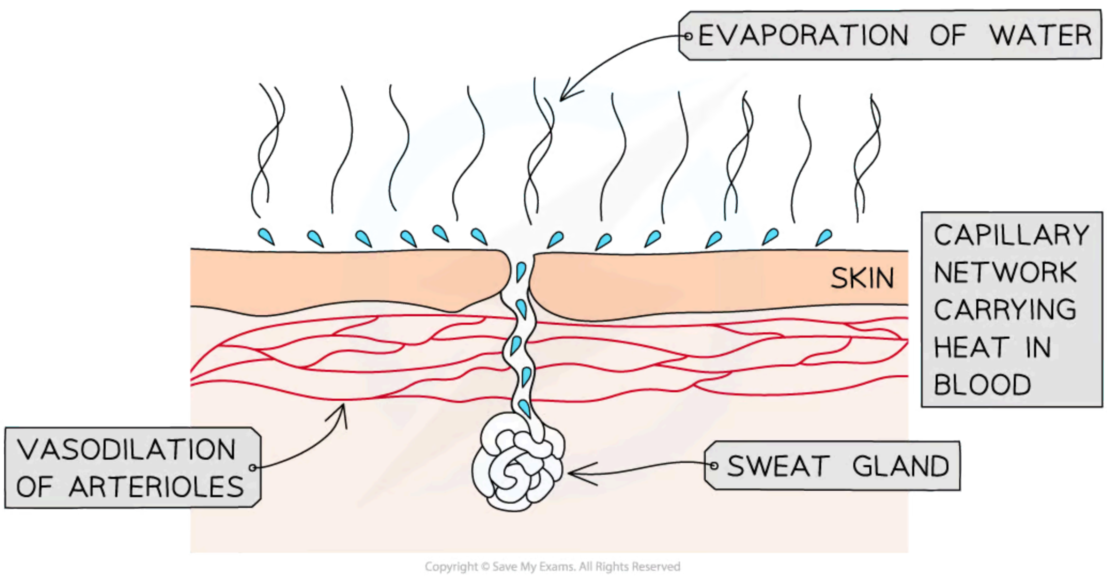


Due to its polarity water is considered a universal solvent

Focus on Water as a Coolant

Your notes

- Water's high latent heat of vaporisation makes it an excellent coolant
- **Animals** have evolved **sweating** (perspiration) as a way of disposing of excess heat generated through physical activity
- The **hypothalamus** detects changes to blood temperature and when temperatures rise, it stimulates the secretion of sweat
- Small droplets of water are secreted from **sweat glands** onto the skin's surface
- **Vasodilation** of arterioles just beneath the skin carries more blood close to the surface
- Sweat (mainly water, also contains salts and other solutes) **evaporates**, carrying the excess heat away into the surrounding air and reducing the temperature of the organism
- Water's high latent heat of vaporisation allows only **small volumes of water to be needed** to carry away a lot of heat



The excess heat carried in blood causes the evaporation of sweat from the skin surface

Water as a coolant in plants

- **Plants transpire**
- A large tree will stand in direct sunlight all day, so **will absorb a huge amount of heat** (as infra-red radiation from the Sun) on a hot day
  - A tree cannot seek shade, because it **requires light energy** for photosynthesis
  - A tree is also **immobile** and provide shade for other organisms
  - A **transpiration stream** of water flows up the tree, from roots to xylem to leaves, throughout the day

- Water **evaporates inside the spongy mesophyll layer** of leaves, so water vapour can **diffuse out** via the stomata
- For example, a large oak tree can absorb around 500 litres of water per day from the soil, around **90% of which is evaporated in transpiration** to dissipate heat
  - The remainder is used to keep cells turgid and as a raw material for photosynthesis

Examiner Tip

Sweat and **transpiration** have a lot of parallels in keeping animals and plants cool. This is why the French use the same word for both; the French word for "sweating" is "***transpiration***"!

Focus on Water as a Solvent

- Different solutes behave differently with water as a solvent
- Even though water is a universal solvent, different metabolites have **different solubilities in water**
- Different solutes have **different hydrophobic and hydrophilic properties** which affect their solubility in water

Highly soluble metabolites

- Some are **highly soluble** (eg. sodium chloride, urea), some are **insoluble** (eg. fats) and some have **intermediate solubility** (eg. oxygen and certain amino acids with a large R group)
- Highly soluble metabolites simply travel dissolved in the **blood plasma**
  - eg. salts, glucose, amino acids
    - Even the amino acids with hydrophobic R groups are soluble enough to be freely transported in water
- Different transport mechanisms have evolved to assist in the transportation of the **less soluble metabolites**

Less soluble metabolites

- A low solubility metabolite such as **oxygen requires assistance** through **combining with haemoglobin**, to allow more oxygen to be carried than directly in blood plasma
  - Oxygen is less soluble at body temperature (37°C) than at 20°C
  - Oxygen is **sparingly soluble** but **soluble enough to allow enough to dissolve** in oceans, rivers and lakes for aquatic animals to **breathe**
  - Haemoglobin can **bind oxygen** to allow sufficient oxygen to be transported to all body cells
- **Insoluble** metabolites like fats require **emulsification**, and transport in **lacteals**, or by being converted to **soluble phospholipids**
- **Cholesterol**, which is insoluble, is **converted to lipoproteins** by combining with proteins

Your notes