

Molecules (Unity and diversity) revision notes

Molecules (Unity and diversity) covers two molecules that all life shares: water and the nucleic acids. A1.1 explains how hydrogen bonding gives water the properties that make it the medium for life. A1.2 explains how the structure of DNA and RNA lets genetic information be stored, copied and expressed in every living organism.

For IB Diploma Biology SL undefined. **HL only** is additional higher level content, for HL students only.

1 Water Spec A1.1

Water as the medium for life and hydrogen bonding Spec A1.1.1, A1.1.2

Water as the medium for life

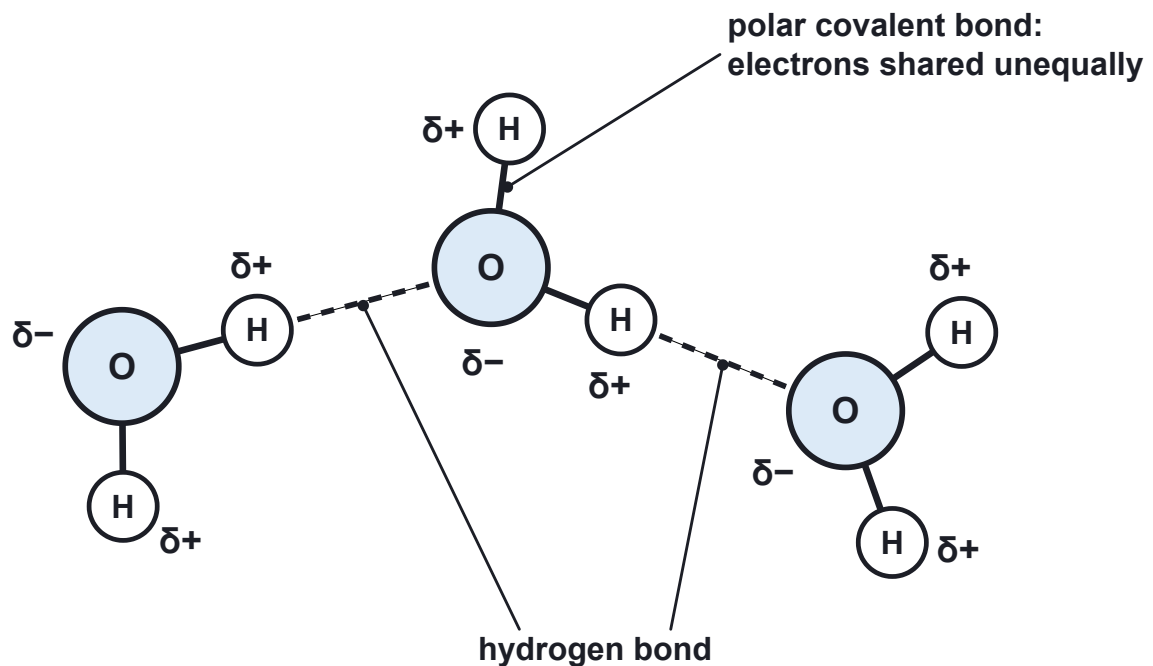
The **first cells originated in water**, and water remains the medium in which most processes of life occur. Cytoplasm is mostly water, metabolic reactions take place in aqueous solution, and substances are carried around organisms dissolved in water (blood plasma, xylem sap, phloem sap).

Polar covalent bonds

A water molecule (H_2O) has two covalent bonds between oxygen and hydrogen. The electrons in each bond are **shared unequally**: the oxygen nucleus attracts them more strongly than the hydrogen nuclei. So the oxygen end carries a **partial negative charge (δ^-)** and each hydrogen carries a partial positive charge (δ^+). Because the molecule is bent rather than straight, the charges do not cancel, and the whole molecule is **polar**.

Hydrogen bonds between water molecules

A **hydrogen bond** is the attraction between the δ^+ hydrogen of one water molecule and the δ^- oxygen of a neighbouring water molecule. It is an intermolecular force, much weaker than a covalent bond, but there are vast numbers of them in liquid water. They constantly break and re-form, and together they explain cohesion, adhesion, the solvent properties and the high specific heat capacity of water.



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Hydrogen bonds form between water molecules: the $\delta+$ hydrogen of one is attracted to the $\delta-$ oxygen of the next. IB notation shows $\delta+$ and $\delta-$ and dashed hydrogen bonds.

Exam tip: When asked to draw hydrogen bonding, draw at least two water molecules, show $\delta+$ on hydrogens and $\delta-$ on oxygen, and use a dashed line from H to O. In water, hydrogen bonds form between molecules, not within one.

Common mistake: Polarity is caused by unequal sharing of electrons in the covalent bond, not by water having ions. Water molecules are uncharged overall.

Cohesion and adhesion Spec A1.1.3, A1.1.4

Cohesion	The attraction of water molecules to each other, due to hydrogen bonding.
Adhesion	The attraction of water molecules to materials that are polar or charged, by hydrogen bonds or attraction to charges.
Surface tension	The effect at a water surface where cohesion between the surface molecules makes the surface resist being broken.
Capillary action	Movement of water through narrow spaces, against gravity, caused by adhesion to the walls together with cohesion.

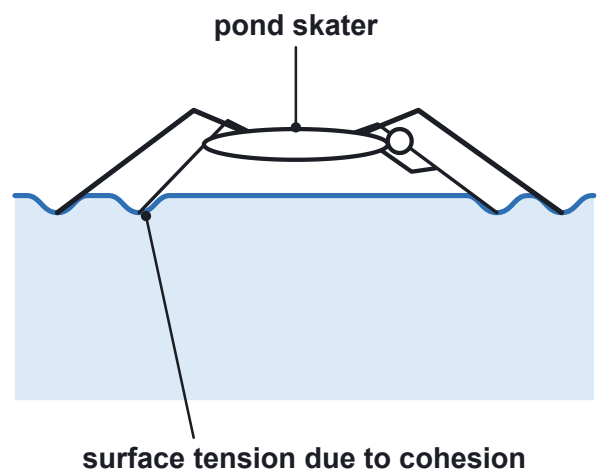
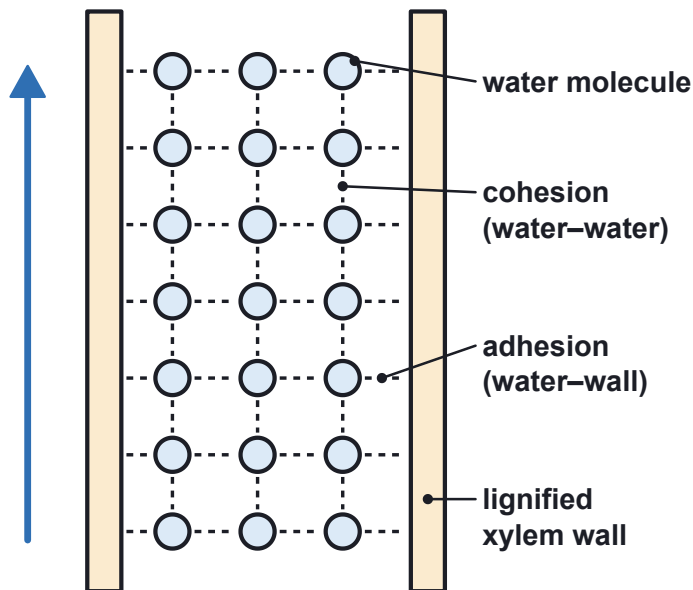
Consequences of cohesion for organisms

- **Transport under tension in xylem.** Water evaporates from leaf cells in transpiration, which pulls on the water in the xylem. Because of **cohesion**, the column of water in each vessel is pulled up as a continuous unit. The water is under tension (negative pressure), yet the column does not break.
- **Water surfaces as habitats.** Cohesion between molecules at the surface gives **surface tension**. Small, light animals such as pond skaters (water striders) can stand on the surface film without sinking, and some insect larvae hang from it to breathe.

Consequences of adhesion for organisms

- **Capillary action in soil.** Water adheres to the charged and polar surfaces of soil particles. It is drawn into the narrow pores between particles and can rise upwards from wetter layers, keeping water available to roots.
- **Capillary action in plant cell walls.** Cellulose is hydrophilic, so water **adheres** to the cellulose fibres and is drawn through the narrow spaces in cell walls. In leaves this replaces water that evaporates from the walls of mesophyll cells, keeping them moist for gas exchange.
- Adhesion to the walls of xylem vessels also helps hold the water column in place.

pulled up under tension
by transpiration



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Cohesion holds the water column together as it is pulled up the xylem; **adhesion** attracts water to the vessel wall. Cohesion at the surface gives the surface tension a pond skater stands on.

Exam tip: Keep the two words apart: cohesion is water to water, adhesion is water to another substance. In xylem answers, credit usually needs both cohesion and tension.

Solvent properties of water Spec A1.1.5

Substances that are attracted to water are **hydrophilic**. They include ions (charged) and polar molecules such as glucose and amino acids. Water molecules cluster round each ion or polar molecule, with their δ^- oxygens facing positive charges and their δ^+ hydrogens facing negative charges. This separates the particles from each other, so they dissolve.

Water as a medium for metabolism

A wide variety of hydrophilic molecules dissolve in the water of the cytoplasm, so they can move freely and collide. **Most enzymes catalyse reactions in aqueous solution**, and water itself is a reactant in hydrolysis and a product of condensation reactions.

Water as a medium for transport

Transport in solution	
Transport medium	Examples of dissolved substances carried
Blood plasma (animals)	Glucose, amino acids, mineral ions, urea, hormones such as insulin
Xylem sap (plants)	Mineral ions such as nitrate and potassium, from roots to leaves
Phloem sap (plants)	Sucrose and amino acids, from sources to sinks

When being hydrophobic matters

Hydrophobic substances, such as fats, oils and the hydrocarbon tails of phospholipids, are non-polar and do not dissolve in water. The functions of some molecules depend on this. Phospholipid tails form the hydrophobic core of membranes, which is a barrier to ions and polar molecules. Triglycerides can be stored as fat droplets without dissolving. Hydrophobic substances that must be carried in blood, such as cholesterol and fats, travel in lipoprotein complexes, and oxygen, which dissolves only poorly in water, is mostly carried bound to haemoglobin.

Exam tip: Linking question: how do the various intermolecular forces of attraction affect biological systems? Hydrogen bonds in water and hydrophobic interactions in membranes are both examples you can use.

Physical properties of water and aquatic animals Spec A11.6

Physical properties of water and air at about 20 °C (approximate values)			
Property	Water	Air	Consequence for animals in water
Buoyancy (density)	about 1000 kg m ⁻³	about 1.2 kg m ⁻³	Water gives a large upward force, so bodies are supported and less energy is used to stay up; animals in air must support their own weight
Viscosity	about 1.0 mPa s	about 0.018 mPa s	Water is about 55 times more viscous, so there is more drag when moving through it and streamlined body shapes are an advantage
Thermal conductivity	about 0.6 W m ⁻¹ K ⁻¹	about 0.026 W m ⁻¹ K ⁻¹	Water conducts heat about 23 times faster than air, so a warm body loses heat much faster in water and endotherms need insulation
Specific heat capacity	4.18 J g ⁻¹ °C ⁻¹	about 1.0 J g ⁻¹ °C ⁻¹	Water temperature changes slowly, giving a thermally stable habitat

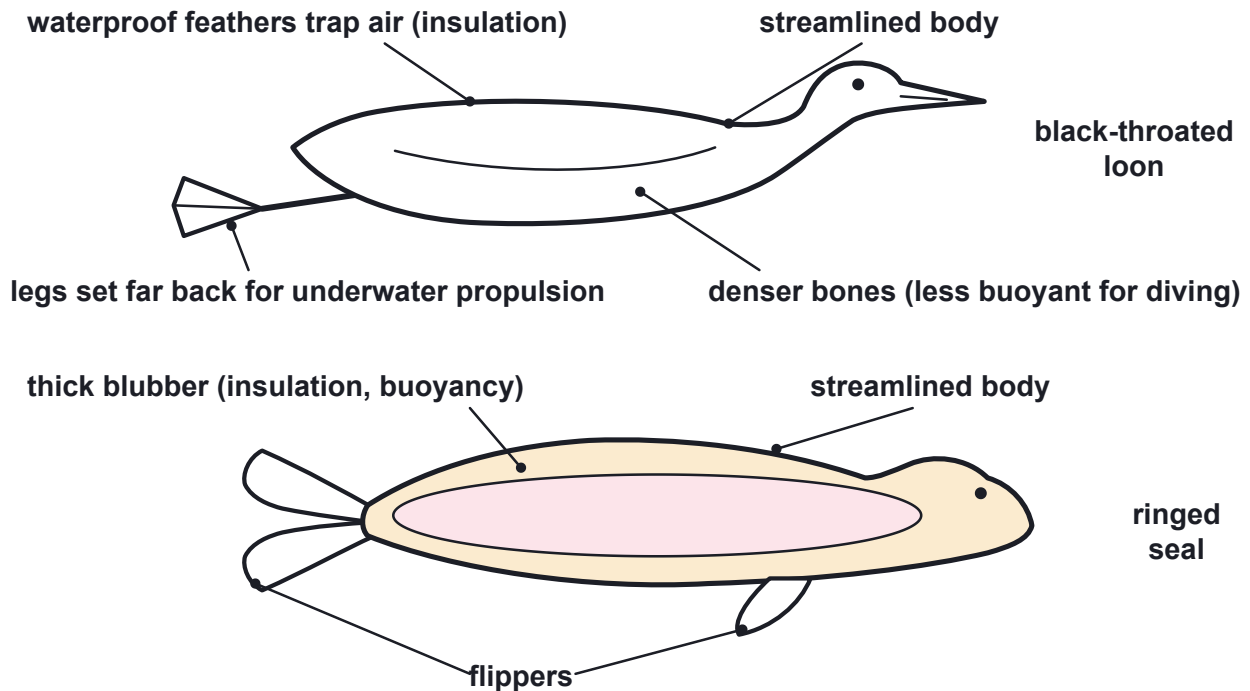
The high **specific heat capacity** of water is due to hydrogen bonding: energy is needed to break hydrogen bonds before molecules can move faster, so a lot of energy is needed to raise the temperature of water. Lakes and seas therefore change temperature much more slowly than the air above them.

Black-throated loon (*Gavia arctica*)

- A diving bird that lives on water but must also fly through air and nest on land.
- Streamlined body and legs set far back on the body reduce drag and give strong propulsion underwater, against the **viscosity** of water; the same leg position makes it clumsy on land.
- Its bones are less air-filled than those of most birds, so it is less buoyant and can dive more easily; it needs fast wingbeats to stay up in air, which gives little buoyancy.
- Dense, waterproof feathers trap a layer of air, which insulates the body because air has a low thermal conductivity. Before a dive it can squeeze air out of its feathers and air sacs to reduce buoyancy.

Ringed seal (*Pusa hispida*)

- A marine mammal of Arctic seas that swims under sea ice but breathes air and rests on the ice.
- A thick layer of **blubber** insulates it against heat loss to cold water, which has a high thermal conductivity; blubber also adds buoyancy.
- Streamlined shape and flippers reduce drag in viscous water.
- In water its weight is supported by buoyancy; on ice it must support its own weight and moves slowly and awkwardly.



water compared with air

buoyancy	viscosity	thermal conductivity	specific heat capacity
			
higher in water	higher in water	higher in water	higher in water

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Adaptations of the black-throated loon and ringed seal linked to the physical properties of water, which are all higher in water than in air.

Exam tip: In an exam either the common name or the scientific name of an organism is acceptable. Link each adaptation to a named property of water, for example blubber to thermal conductivity.

Quick check

1. Why is a water molecule polar?
2. What is the difference between cohesion and adhesion?
3. Name two physical properties of water that differ from air and matter to aquatic animals.
4. Why do membranes depend on phospholipid tails being hydrophobic?

2 Nucleic acids Spec A1.2

DNA as the genetic material and nucleotides Spec A1.2.1, A1.2.2, A1.2.3, A1.2.4

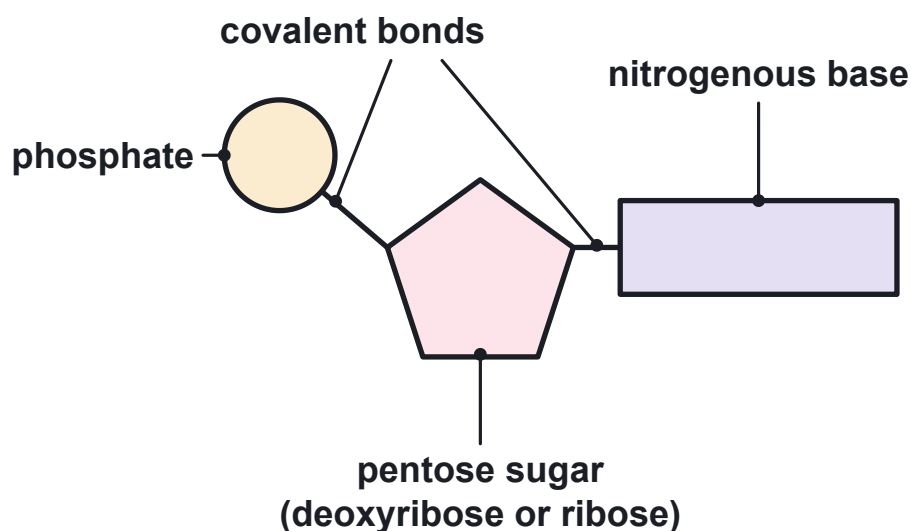
DNA as the genetic material

DNA is the genetic material of all living organisms, from bacteria to plants and animals. Some viruses use RNA as their genetic material, for example influenza virus and HIV, but viruses are not considered to be living.

Components of a nucleotide

Nucleic acids are polymers of **nucleotides**. Every nucleotide has three parts, joined by covalent bonds:

- a **phosphate** group (drawn as a circle)
- a **pentose sugar**, a five-carbon sugar: deoxyribose in DNA, ribose in RNA (drawn as a pentagon)
- a **nitrogenous base** (drawn as a rectangle), attached to the sugar on the opposite side from the phosphate



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A nucleotide: circle = **phosphate**, pentagon = **pentose sugar**, rectangle = **base**.

The sugar-phosphate backbone

In a strand of DNA or RNA, the phosphate of one nucleotide is covalently bonded to the sugar of the next. This **sugar-phosphate bonding** makes a continuous chain of covalently bonded atoms along each strand, which forms a strong **backbone**. The bases stick out from the backbone.

Bases form the basis of a code

Nitrogenous bases in DNA and RNA	
Nucleic acid	Bases
DNA	adenine (A), thymine (T), guanine (G), cytosine (C)
RNA	adenine (A), uracil (U), guanine (G), cytosine (C)

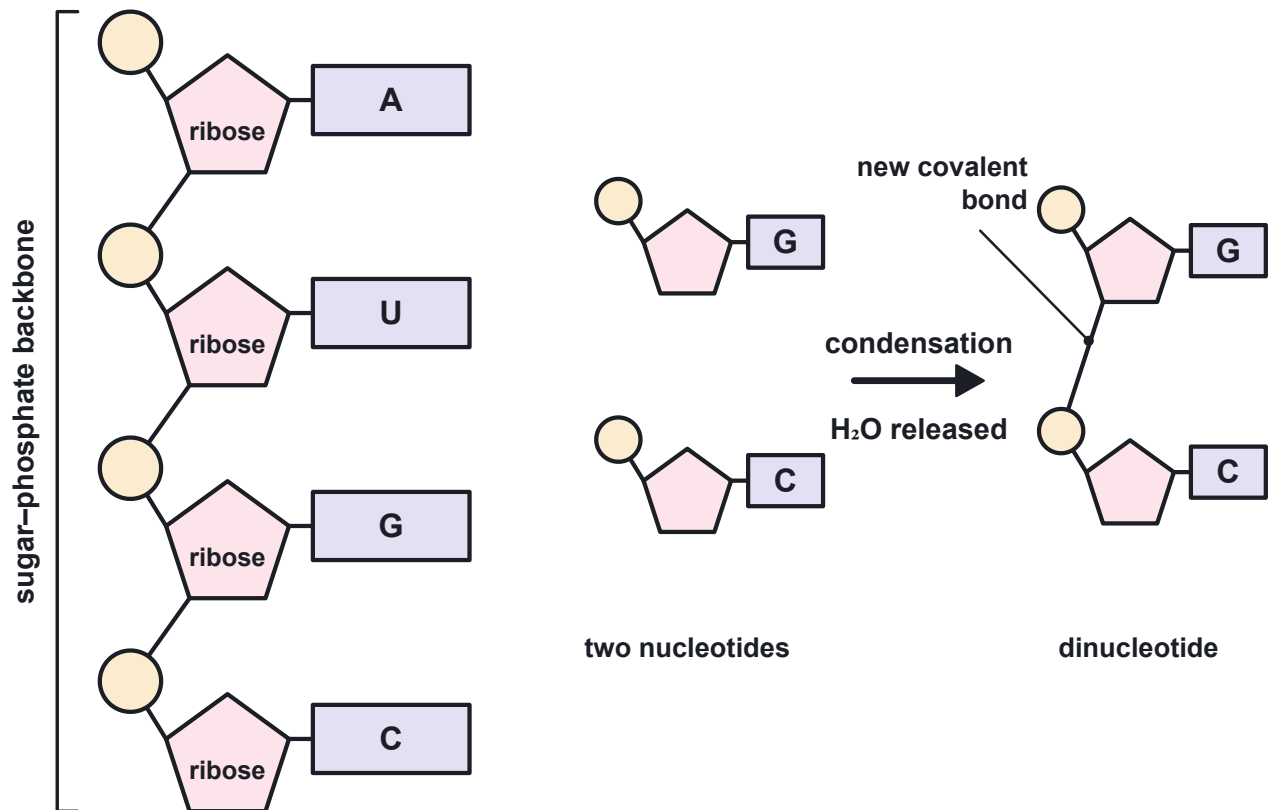
The backbone is the same in every molecule. What varies is the **sequence of bases**, and it is this sequence that stores genetic information, in the way a sequence of letters stores the meaning of a sentence.

Exam tip: You need the full names of the five bases: adenine, thymine, guanine, cytosine and uracil. Spelling matters in written answers.

RNA polymers and the DNA double helix Spec A1.2.5, A1.2.6

RNA as a polymer

RNA is a **polymer formed by condensation of nucleotide monomers**. When two nucleotides are joined, the phosphate of one bonds covalently to the sugar (ribose) of the other and a molecule of water is released. Repeating this builds a single strand of any length, with a sugar-phosphate backbone and one base on each nucleotide.

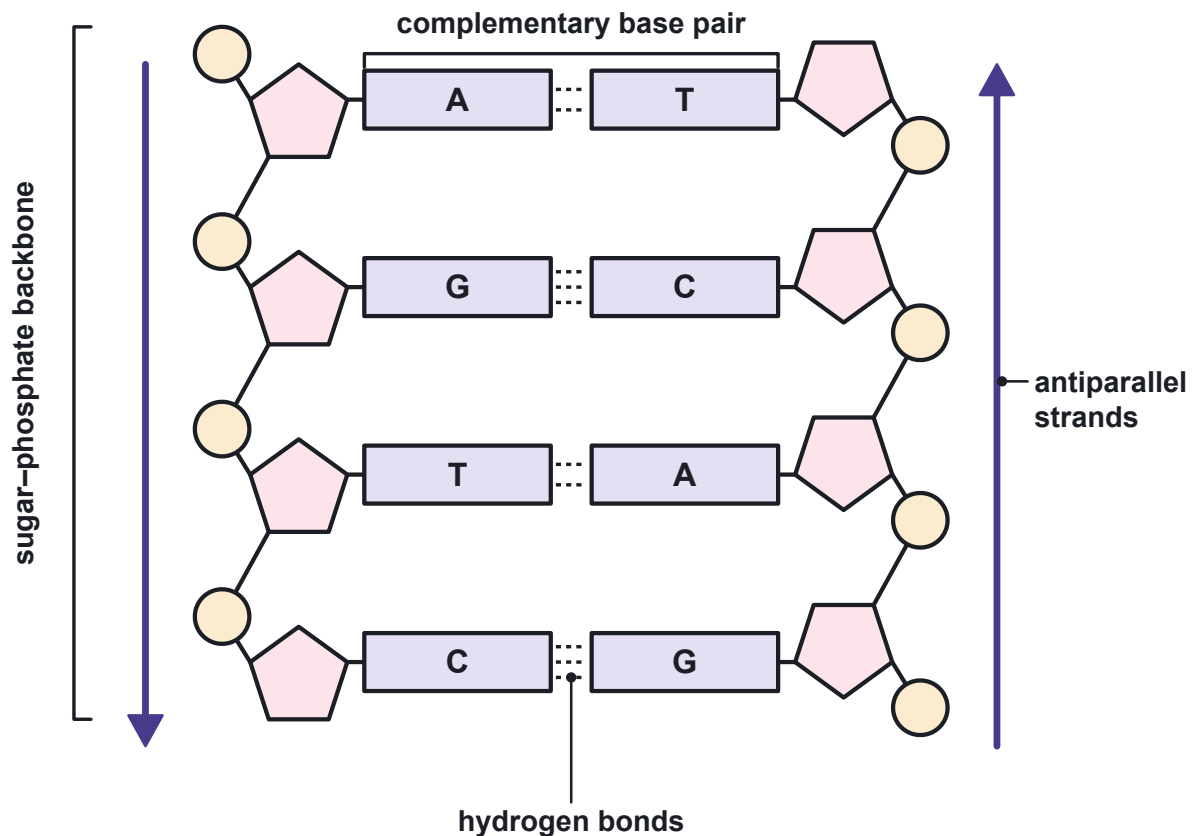


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RNA is a polymer of nucleotides. Each new sugar-phosphate bond forms by **condensation**, releasing a molecule of water.

DNA as a double helix

- DNA has **two strands** of nucleotides, wound into a **double helix**.
- The two strands are **antiparallel**: they run in opposite directions.
- The bases face inwards and the two strands are linked by **hydrogen bonds** between bases.
- Pairing is complementary: **adenine (A) pairs with thymine (T)** and guanine (G) pairs with cytosine (C).



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DNA: two **antiparallel** strands (one drawn upside down), linked by hydrogen bonds between complementary base pairs, A with T and G with C.

Exam tip: In DNA diagrams draw the two strands antiparallel (one strand upside down) and pair A with T and G with C. You do not need to draw the helix, the relative sizes of the bases or the number of hydrogen bonds.

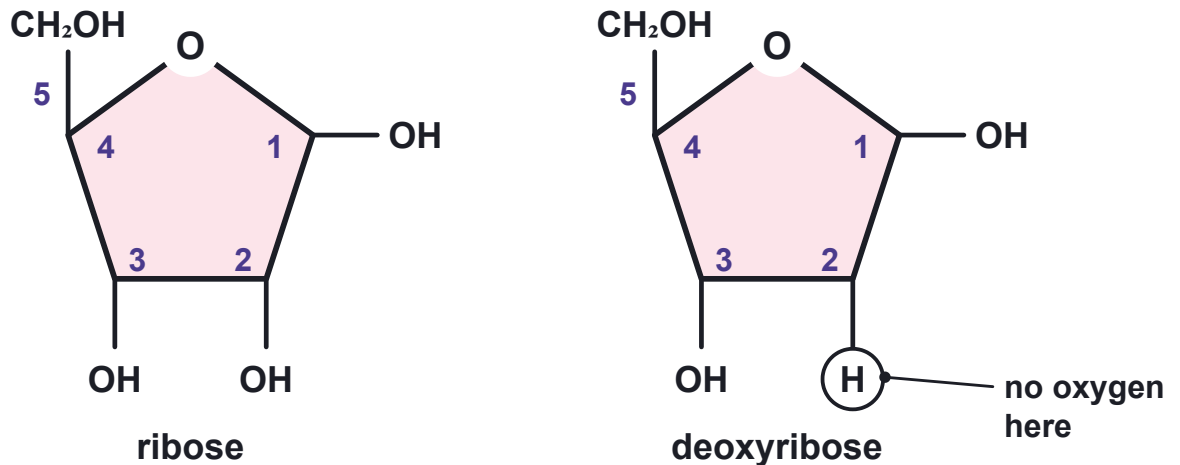
Exam tip: Linking question: how can polymerization result in emergent properties? A single nucleotide stores no information, but a polymer of thousands of them stores a whole gene.

Differences between DNA and RNA Spec A1.2.7

Differences between DNA and RNA		
Feature	DNA	RNA
Number of strands	Two (double helix)	One
Nitrogenous bases	A, T, G, C	A, U, G, C (uracil instead of thymine)
Pentose sugar	Deoxyribose	Ribose

Ribose and deoxyribose

Both sugars are pentoses with a five-membered ring containing an oxygen atom. The difference is on carbon 2: **ribose has an OH group** there, while **deoxyribose has only H**, so it has one oxygen atom fewer ('deoxy' means without oxygen).



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Ribose has an **OH** on carbon 2; deoxyribose has only **H** there, so it has one oxygen fewer.

Examples of nucleic acids

- **DNA:** the genetic material, found in chromosomes in the nucleus, and in mitochondria, chloroplasts and the cytoplasm of prokaryotes.
- **Messenger RNA (mRNA):** a copy of a gene, carried to ribosomes.
- **Transfer RNA (tRNA):** carries amino acids to the ribosome during translation.
- **Ribosomal RNA (rRNA):** part of the structure of ribosomes.

Common mistake: In a compare question, write each difference as a matched pair, such as 'DNA contains deoxyribose but RNA contains ribose'. Stating only one side rarely scores.

Base pairing, information storage and the genetic code Spec A1.2.8, A1.2.9, A1.2.10

Complementary base pairing

Complementarity is based on hydrogen bonding: A and T (or A and U in RNA) form hydrogen bonds with each other, and so do G and C. Other combinations do not fit and do not bond properly. So the sequence on one strand fixes the sequence on the other.

- **Replication:** the two strands separate and each acts as a template. Free nucleotides pair with complementary bases, so two identical DNA molecules are produced.
- **Transcription** (expression): an mRNA molecule is built with bases complementary to one strand of a gene, with U pairing with A.
- **Translation** (expression): each tRNA anticodon pairs with a complementary mRNA codon, so amino acids are added in the order the code specifies.

Limitless capacity for storing information

There is no restriction on the order of bases along a strand, and a DNA molecule can be any length. So **any base sequence is possible** and the diversity of possible sequences is effectively limitless. With 4 bases, the number of possible sequences of length n is 4^n . DNA also stores data with great economy: the human genome of about 3 billion base pairs fits inside a nucleus only a few micrometres across.

Number of possible base sequences

How many different base sequences are possible for a DNA strand 10 nucleotides long?

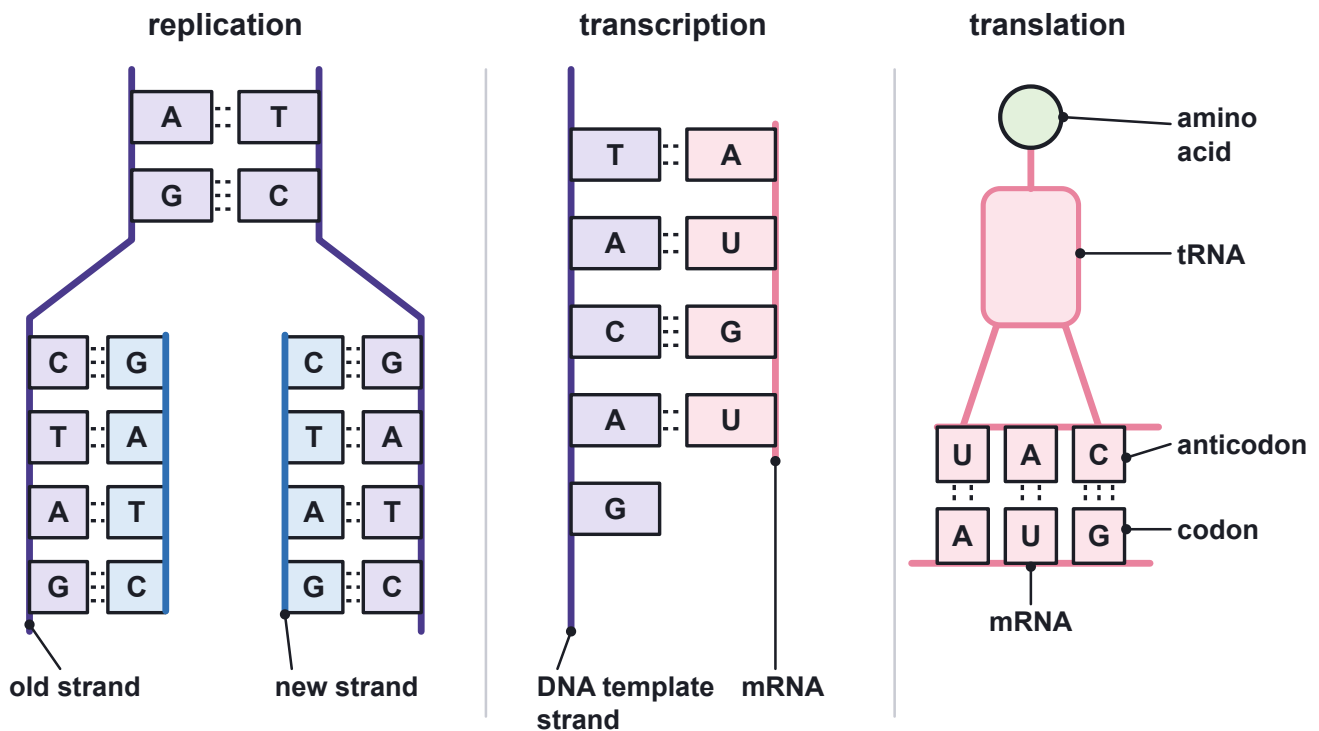
1. Each position can hold any one of 4 bases.
2. Number of sequences = $4 \times 4 \times \dots$ (10 times) = 4^{10} .
3. $4^{10} = 1\,048\,576$.

Answer: About one million (1 048 576) sequences, from just 10 nucleotides.

Maths skill: Possible sequences = 4^n for DNA of length n nucleotides. Each extra nucleotide multiplies the number of possibilities by 4.

A universal genetic code

The genetic code, the way base triplets (codons) correspond to amino acids, is **conserved across all life forms**, with only a few minor variations. It is very unlikely that so many organisms would arrive at the same arbitrary code independently. The best explanation is that all living organisms inherited it from a **universal common ancestor**. This is also why a gene from one species can be expressed in another.



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Complementary base pairing by **hydrogen bonds** in replication, transcription and translation.

Quick check

1. What are the three components of a nucleotide?
2. State three differences between DNA and RNA.
3. What does antiparallel mean in DNA?

Quick check answers

Water

1. Electrons in the O-H covalent bonds are shared unequally, so oxygen is δ^- and the hydrogens are δ^+ , and the bent shape means the charges do not cancel.
2. Cohesion is attraction between water molecules; adhesion is attraction of water to polar or charged materials.
3. Any two of: buoyancy, viscosity, thermal conductivity, specific heat capacity.
4. The hydrophobic tails do not dissolve in water, so they form a barrier to ions and polar molecules.

Nucleic acids

1. A phosphate group, a pentose sugar and a nitrogenous base.
2. DNA has two strands, RNA one; DNA has thymine, RNA uracil; DNA has deoxyribose, RNA ribose.
3. The two strands run in opposite directions.