

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, Standard Level and Higher Level (first assessment 2025). **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

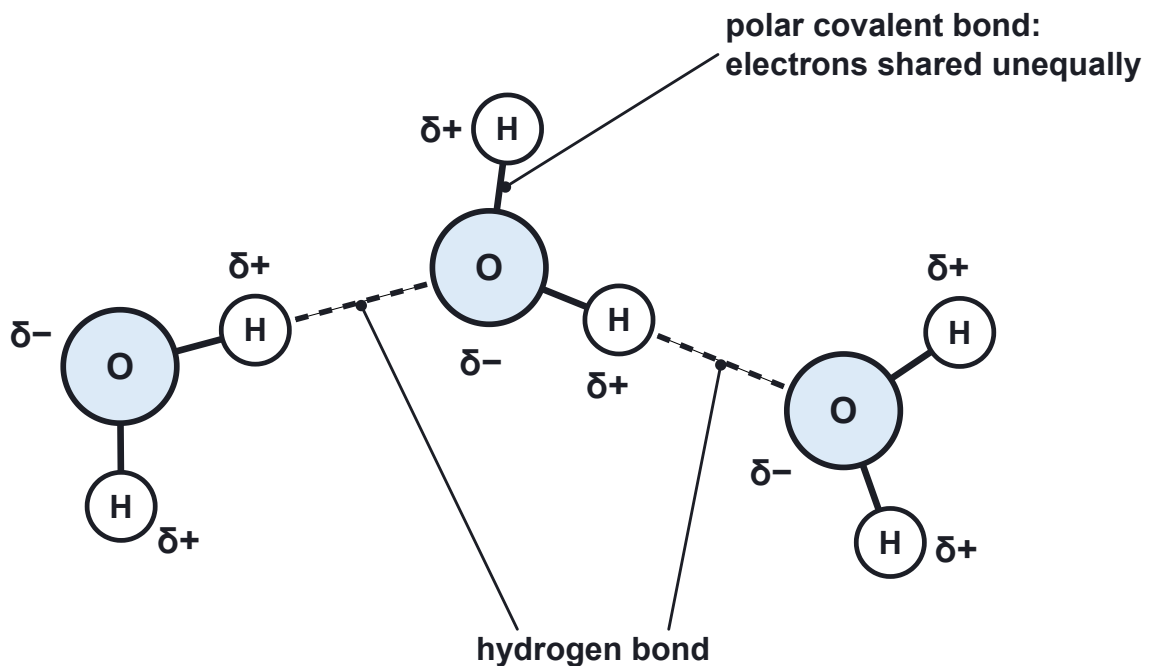
The **first cells originated in water**, and water remains the medium in which most processes of life occur. Cytoplasm is mostly water, metabolic reactions take place in aqueous solution, and substances are carried around organisms dissolved in water (blood plasma, xylem sap, phloem sap).

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.

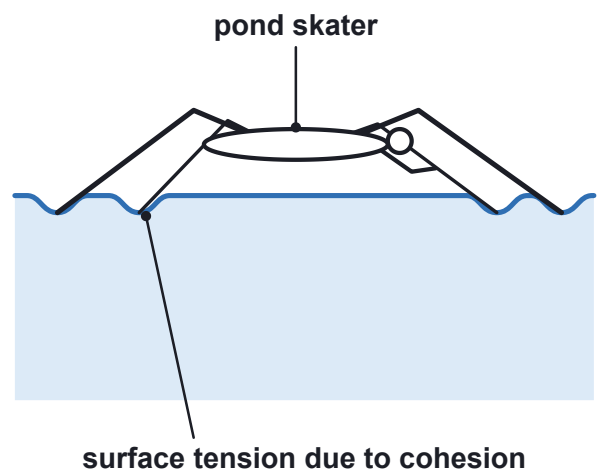
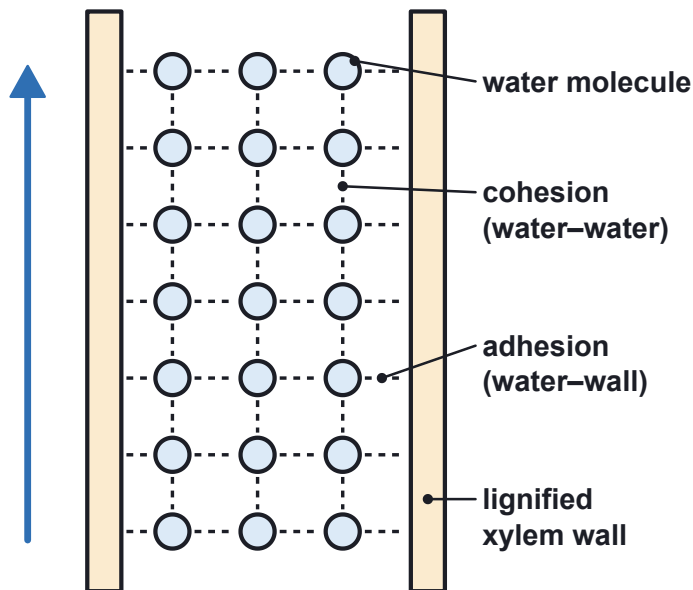
Consequences of cohesion for organisms

- **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

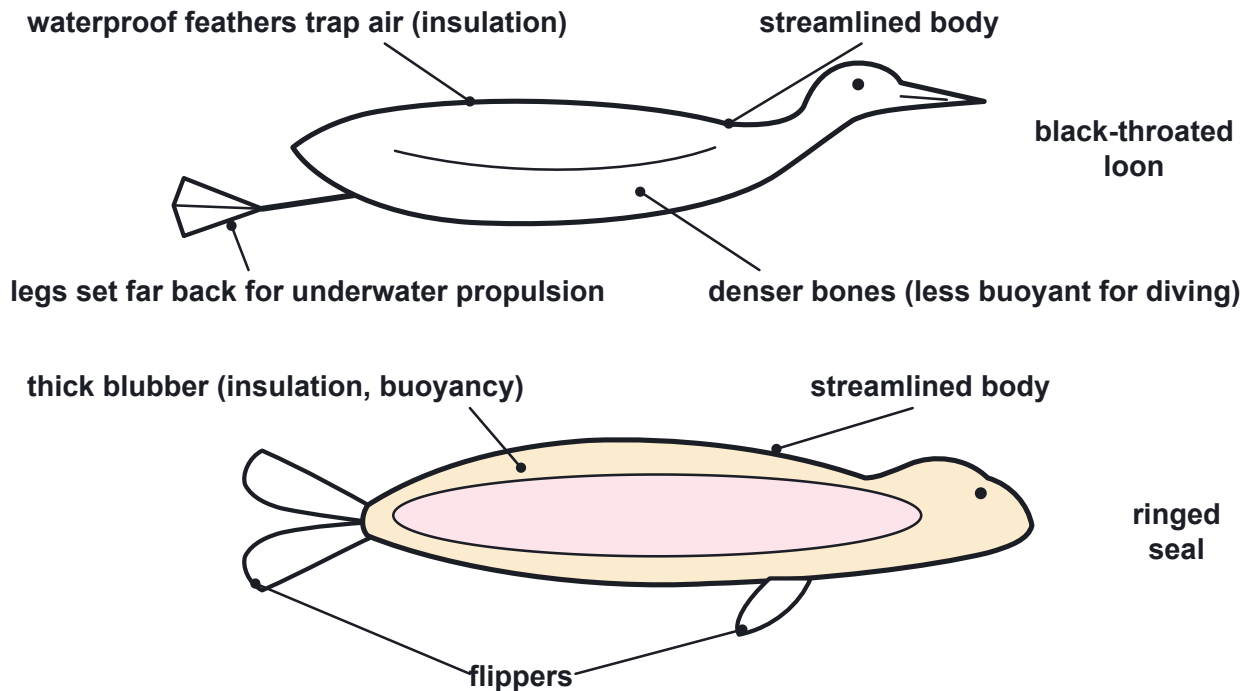
The high **specific heat capacity** of water is due to hydrogen bonding: energy is needed to break hydrogen bonds before molecules can move faster, so a lot of energy is needed to raise the temperature of water. Lakes and seas therefore change temperature much more slowly than the air above them.

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.

Origin of water on Earth and the search for life Spec A1.1.7, A1.1.8 HL only

Extraterrestrial origin of water

Earth's water is thought to have an extraterrestrial origin. The leading hypothesis is that much of it was **delivered by asteroids** that collided with the early Earth. Some asteroids contain water locked in their minerals, and in meteorites from these asteroids the ratio of deuterium (heavy hydrogen) to ordinary hydrogen in the water is similar to the ratio in Earth's oceans, which supports the hypothesis.

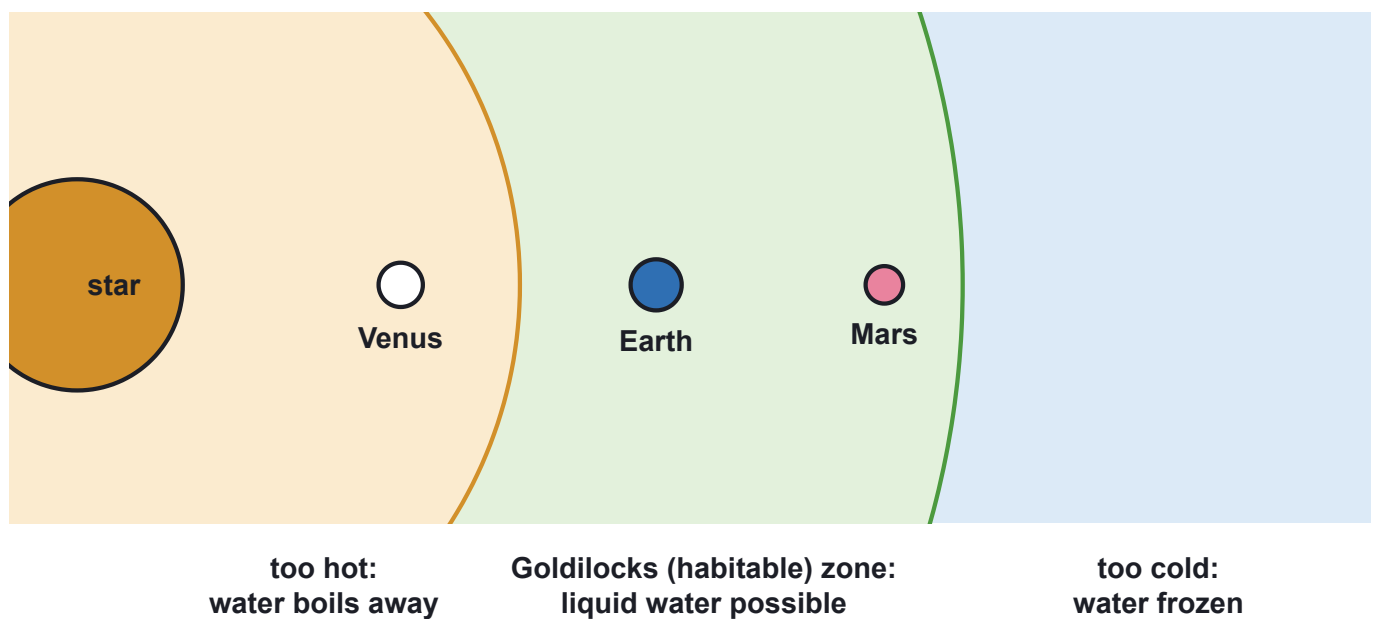
Why Earth retained its water

- **Gravity:** Earth is massive enough for its gravity to hold an atmosphere, so water vapour is not lost to space.
- **Temperature:** Earth's surface has stayed at **temperatures low enough for water to condense** into liquid, forming oceans.

The abundance of liquid water over billions of years of Earth's history has allowed life to evolve.

Water and the search for extraterrestrial life

All known life needs liquid water as its medium, so the search for life on other planets and moons starts by looking for water. The **Goldilocks zone** (habitable zone) is the range of distances from a star in which a planet's surface is neither too hot nor too cold for liquid water to exist. Planets found in this zone around other stars are priority targets. Within our solar system, evidence of past or present water on Mars and beneath the ice of some moons also makes them targets.



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The **Goldilocks zone** is the range of distances from a star where liquid water can exist on a planet's surface (not to scale).

Exam tip: The guide limits this to asteroids as the source of water, and to gravity and low enough temperatures as the reasons it was retained. Use those exact ideas.

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?
5. **HL only** What is the Goldilocks zone?

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

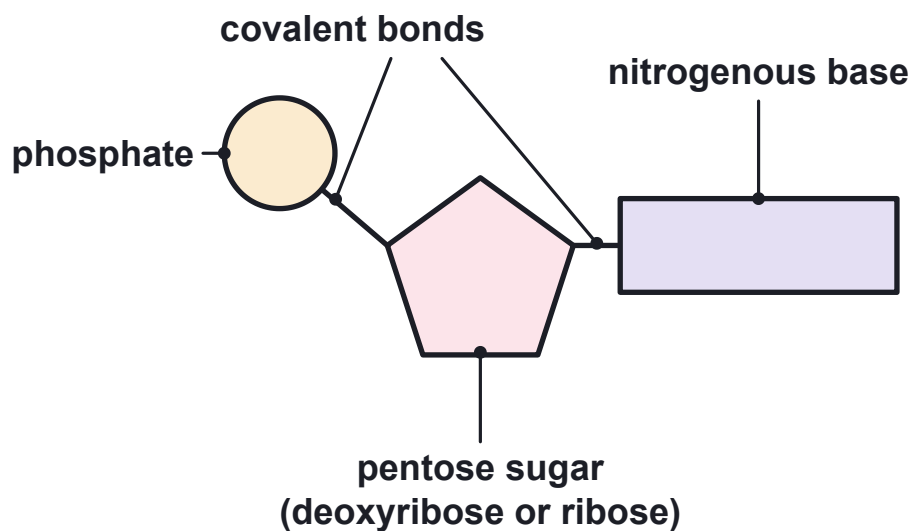
DNA as the genetic material

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)

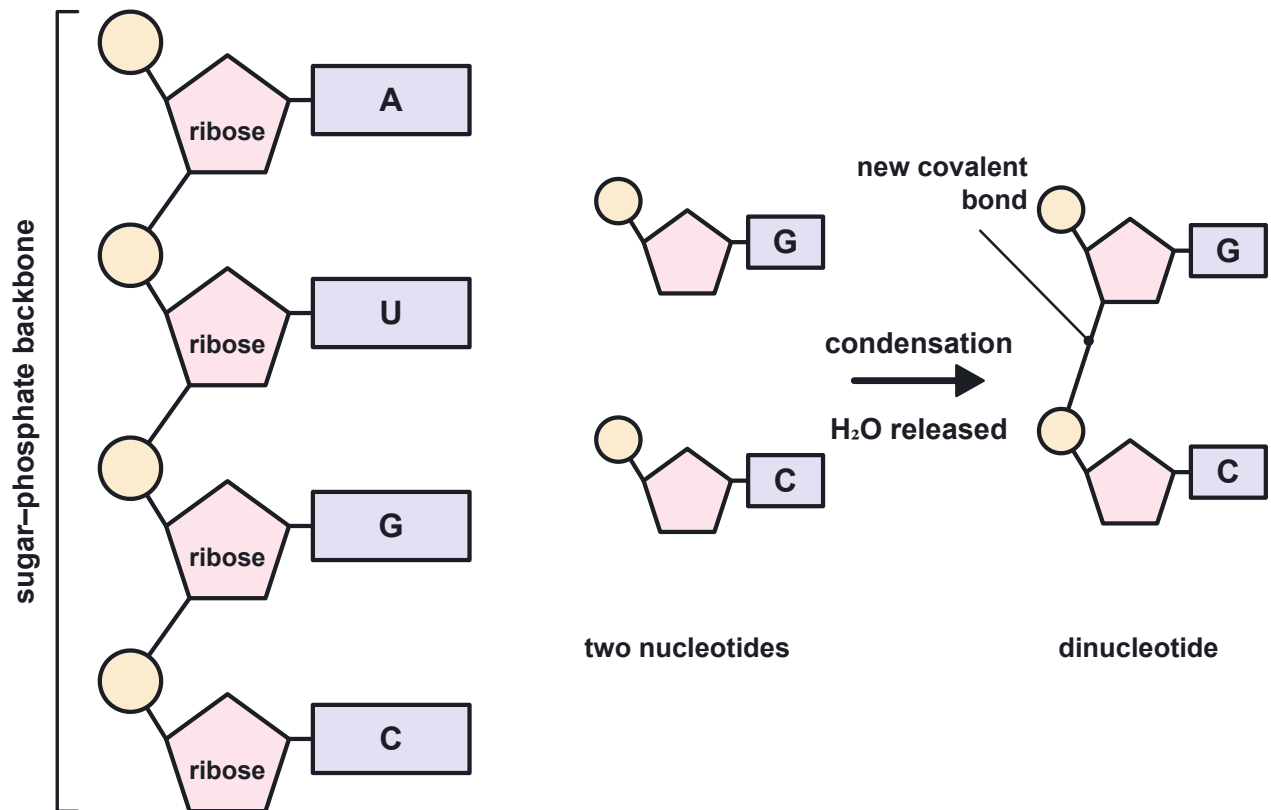
The backbone is the same in every molecule. What varies is the **sequence of bases**, and it is this sequence that stores genetic information, in the way a sequence of letters stores the meaning of a sentence.

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.

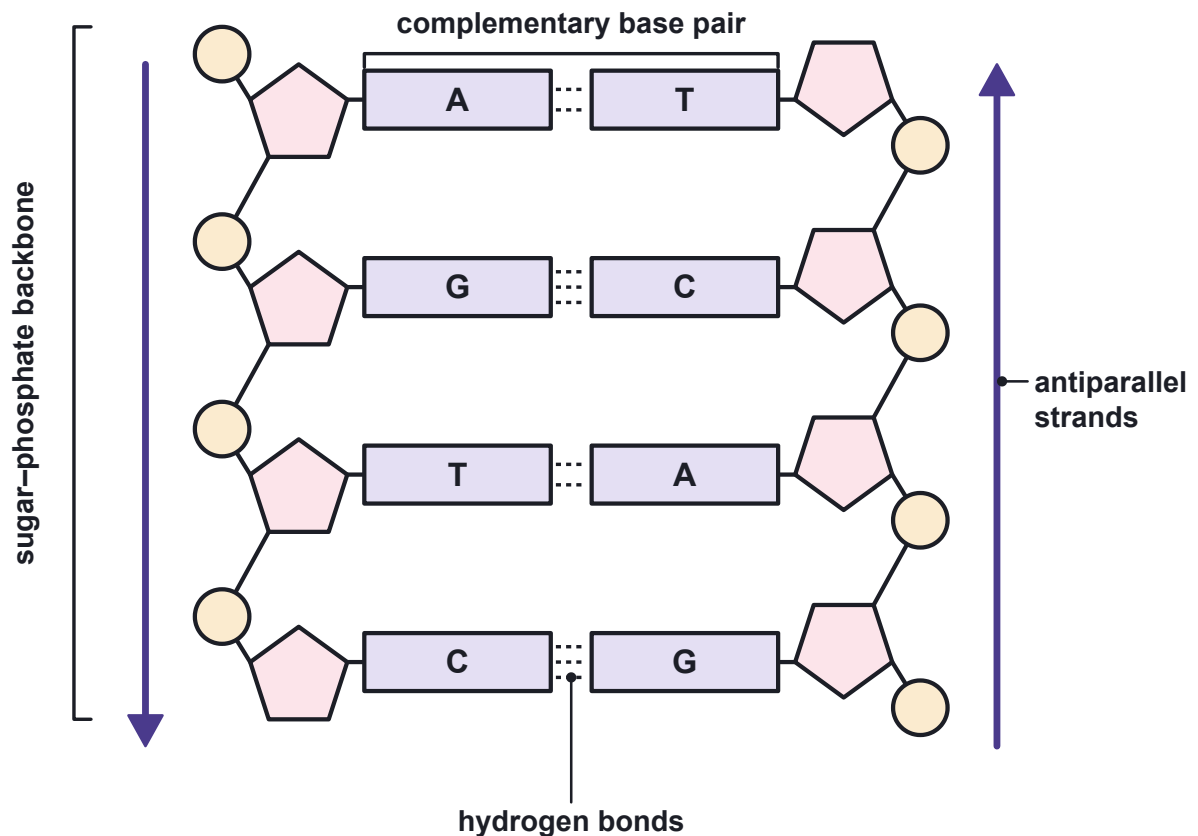


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RNA is a polymer of nucleotides. Each new sugar-phosphate bond forms by **condensation**, releasing a molecule of water.

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.

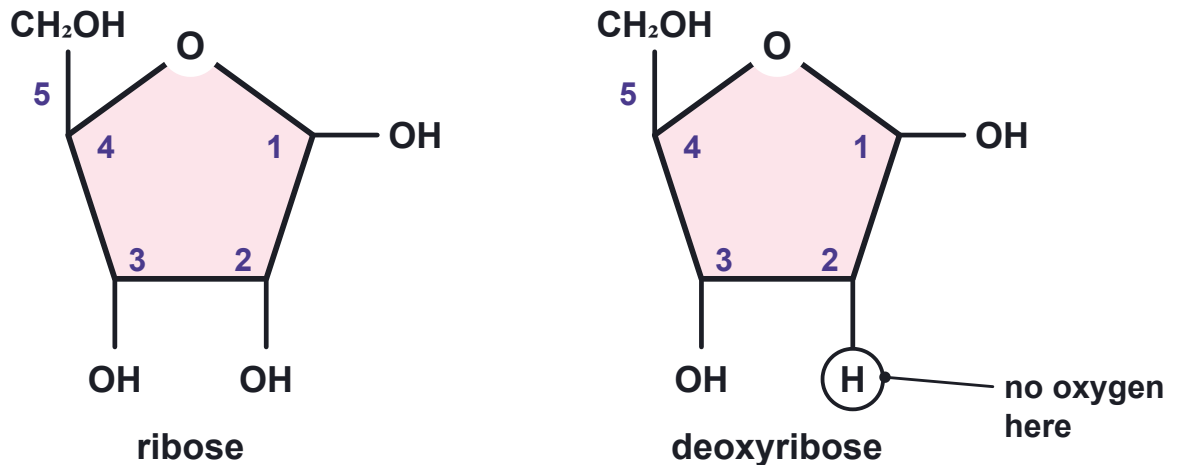
Exam tip: Linking question: how can polymerization result in emergent properties? A single nucleotide stores no information, but a polymer of thousands of them stores a whole gene.

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?

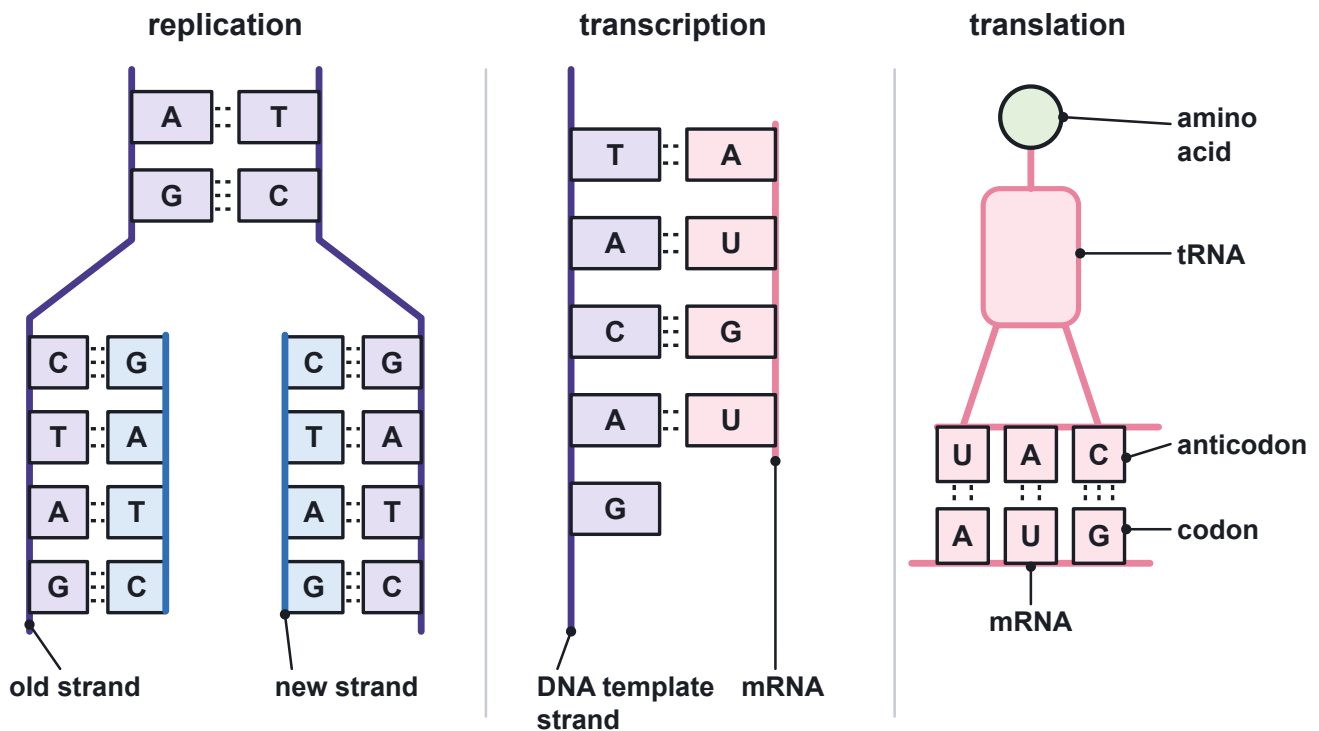
1. Each position can hold any one of 4 bases.
2. Number of sequences = $4 \times 4 \times \dots$ (10 times) = 4^{10} .
3. $4^{10} = 1\,048\,576$.

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.

Directionality and purine-pyrimidine pairing Spec A1.2.11, A1.2.12 HL only

Directionality of RNA and DNA

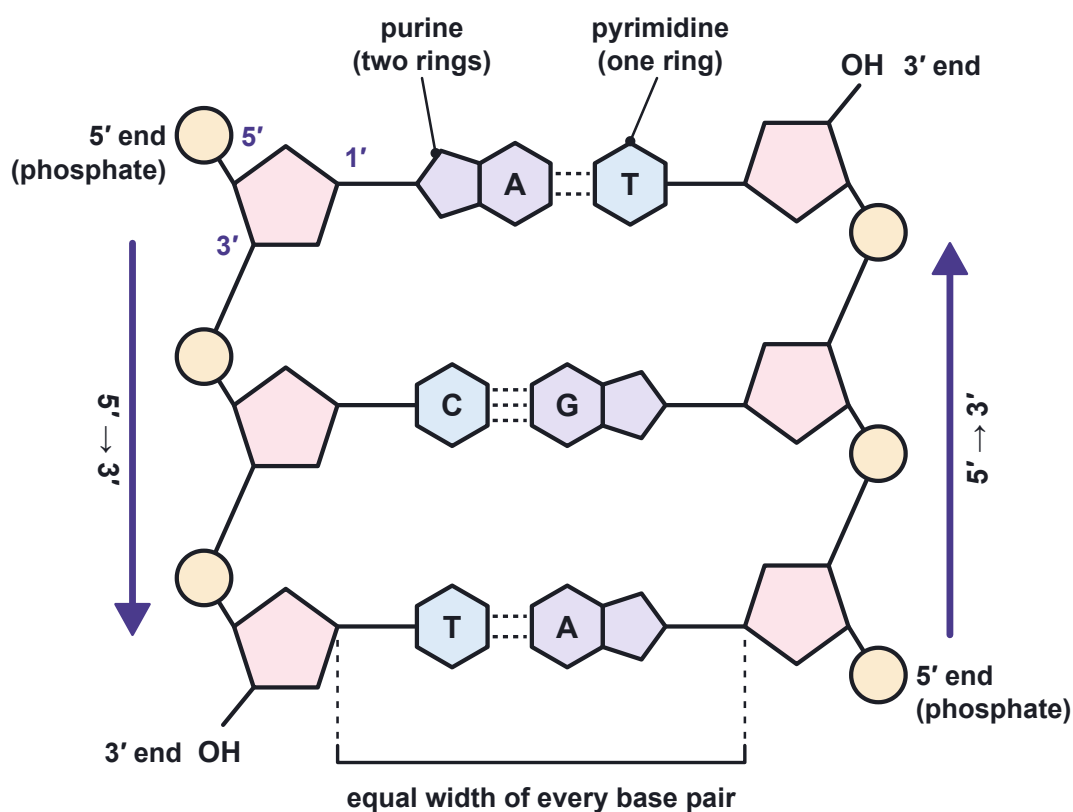
The carbons of the pentose sugar are numbered 1' to 5'. The base is attached to carbon 1', the phosphate of the same nucleotide to carbon 5', and the phosphate of the next nucleotide to carbon 3'. So every link in the backbone runs **from carbon 3' of one sugar to carbon 5' of the next**. One end of a strand has a free phosphate on carbon 5' (the **5' end**) and the other a free OH on carbon 3' (the **3' end**). In DNA the two strands run in opposite directions: this is what antiparallel means.

Why directionality matters

Process	Significance of 5' to 3'
Replication	DNA polymerase can only add nucleotides to the 3' end of a growing strand, so new DNA is built 5' to 3'
Transcription	RNA polymerase builds mRNA 5' to 3', so it moves along the template strand reading it 3' to 5'
Translation	Ribosomes read mRNA from the 5' end towards the 3' end, codon by codon

Purine-to-pyrimidine bonding

Adenine and guanine are **purines**, with two rings. Cytosine, thymine and uracil are **pyrimidines**, with one ring. Each base pair in DNA is one purine bonded to one pyrimidine (A-T and C-G), so all base pairs have equal length. The two backbones are therefore always the same distance apart and the DNA helix has the same three-dimensional structure, regardless of the base sequence. This uniformity contributes to the stability of the helix.



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Each strand runs **5' to 3'**, in opposite directions. Every base pair is a purine (two rings) with a pyrimidine (one ring), so all base pairs have **equal width**.

Common mistake: A purine never pairs with a purine. Two purines would be too wide to fit between the backbones and two pyrimidines too narrow.

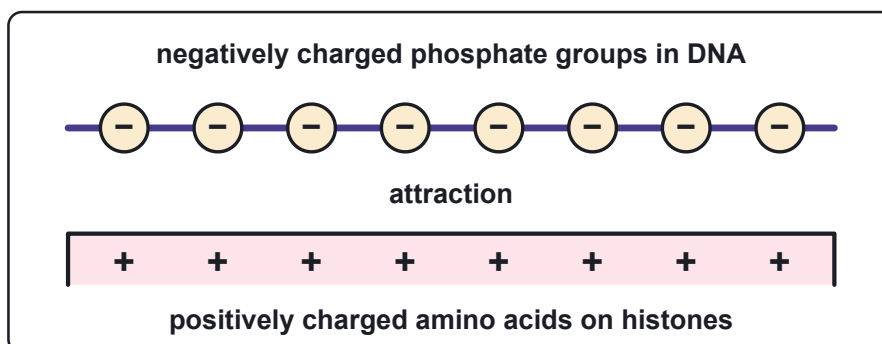
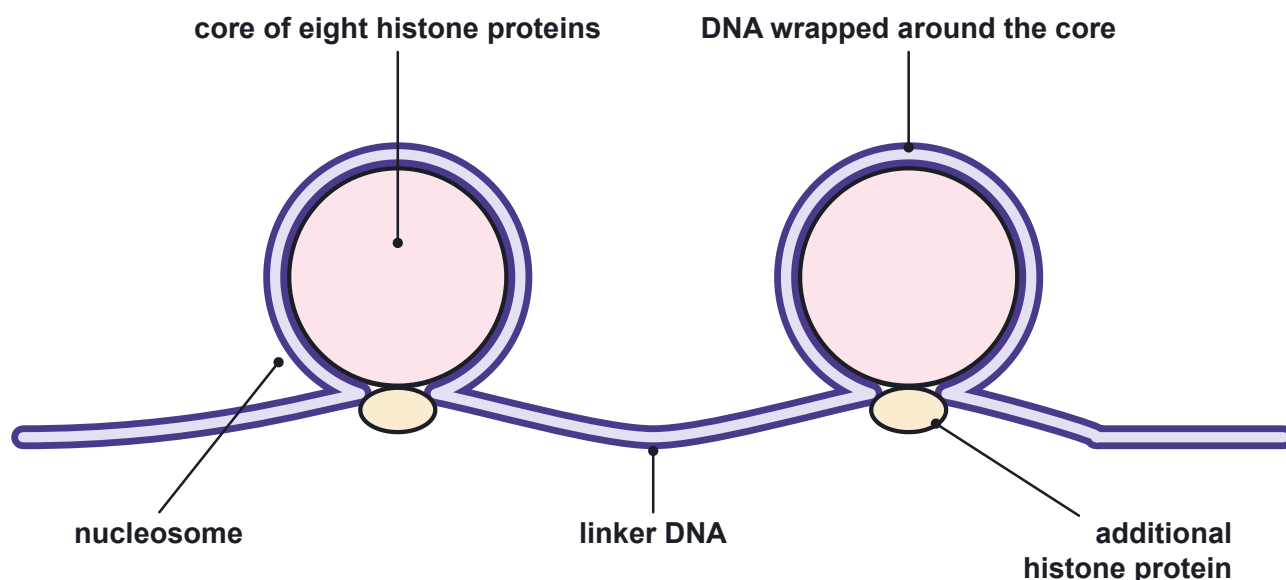
Structure of a nucleosome Spec A1.2.13 HL only

In eukaryotes, DNA in the nucleus is associated with proteins called **histones**. The basic unit of packaging is the **nucleosome**.

- A core of **eight histone proteins**.
- A length of DNA **wrapped around** the core.

- An **additional histone protein** attached to the **linker DNA** where it enters and leaves, holding the DNA in place.
- Linker DNA continues to the next nucleosome, like beads on a string.

The histones have many positively charged amino acids on their surface. These are attracted to the **negatively charged phosphate groups** in the DNA backbone, which is why DNA binds so tightly around the histone core.



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Nucleosomes: DNA wrapped around a core of eight histones, held by an additional histone and joined by **linker DNA**. Positive histones attract negative DNA phosphates.

Practical skill: Use molecular visualization software (for example JSmol with the nucleosome core particle structure, PDB entry 1A0I) to study how the protein and DNA associate. Colour the histones and DNA separately and look for positive amino acids next to the DNA phosphates.

Hershey-Chase experiment and Chargaff's data Spec A1.2.14, A1.2.15 HL only

The Hershey-Chase experiment

By the early 1950s it was still debated whether genes were made of protein or DNA. Hershey and Chase used **T2 bacteriophage**, a virus made only of a protein coat and DNA, which infects the bacterium *Escherichia coli*. Proteins contain sulfur but almost no phosphorus; DNA contains phosphorus but no sulfur.

1. One batch of viruses was grown with radioactive sulfur (^{35}S), which labelled their **protein coats**. Another batch was grown with radioactive phosphorus (^{32}P), which labelled their **DNA**.

2. Each batch was allowed to infect bacteria.
3. The mixture was agitated in a blender to detach the virus coats from the outside of the bacteria.
4. It was centrifuged: the heavier bacteria formed a pellet and the lighter virus coats stayed in the supernatant liquid.
5. The radioactivity of the pellet and the supernatant was measured.

Results and conclusion		
Label	Where most radioactivity was found	What it shows
³⁵ S (protein)	Supernatant	Protein stayed outside the bacteria
³² P (DNA)	Pellet (inside bacteria)	DNA entered the bacteria

Because the infected bacteria went on to produce new viruses, the material that entered them must carry the instructions. Only DNA entered, so **DNA is the genetic material**.

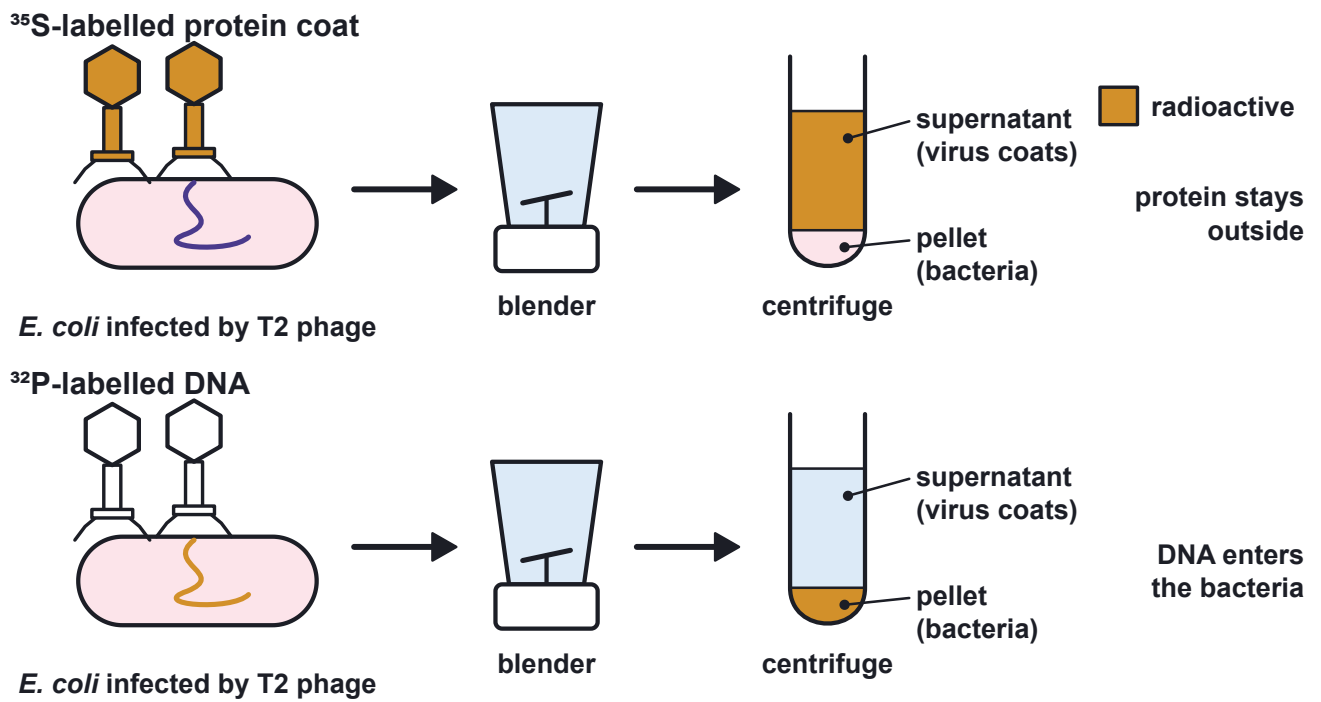
Exam tip: Nature of science: technological developments open up new experiments. The Hershey–Chase experiment only became possible once radioisotopes were available to scientists as research tools.

Chargaff's data

Chargaff measured the relative amounts of the four bases in DNA from diverse life forms. He found that in every species the amount of **adenine was about equal to thymine** and guanine about equal to cytosine, so purines equalled pyrimidines. But the proportion of A + T compared with G + C **varied between species**.

The earlier **tetranucleotide hypothesis** proposed that DNA was a repeating sequence of the four bases, which would mean all four bases are present in equal amounts in every species. Chargaff's data did not fit, so they falsified it, and the idea that DNA was too simple to carry genetic information was abandoned. The A = T and G = C pattern later supported complementary base pairing in the double helix.

Exam tip: Nature of science: the problem of induction is that no number of agreeing observations can prove a general theory true. Falsification is more certain: one reliable set of contrary data, such as Chargaff's, is enough to show a hypothesis is false.



DNA enters the bacteria and is the genetic material

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Hershey-Chase: ³⁵S (protein) stayed in the **supernatant**, ³²P (DNA) went into the **pellet**, so DNA enters the bacteria and is the genetic material.

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?
4. **HL only** Why does an A-T pair have the same width as a C-G pair?
5. **HL only** Which isotope labelled DNA in the Hershey-Chase experiment?

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.
5. The range of distances from a star where temperatures allow liquid water on a planet's surface.

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.
4. Each pair is one purine (two rings) bonded to one pyrimidine (one ring).
5. Radioactive phosphorus, ^{32}P .