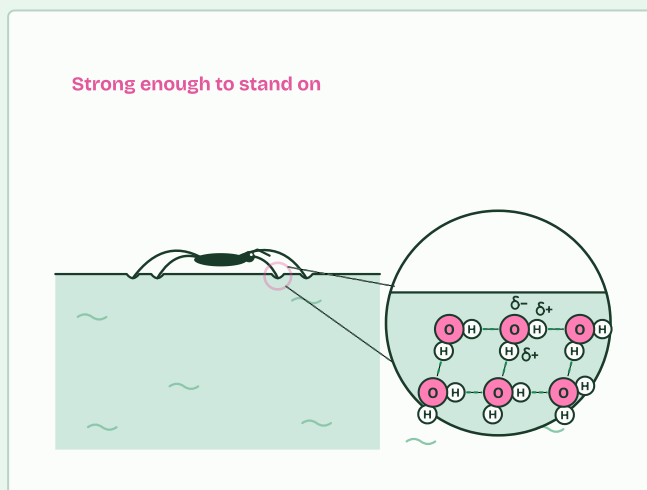


REVISION GUIDE

IB Biology, *a topic at a time*

Every interactive guide written so far, as one book: the chapters with each figure built up step by step, the mnemonics, the mistakes to avoid, the key terms and the dry labs, with the answers at the back and a link to each guide's Check.

- A1.1 **Water**
- A1.2 **Nucleic acids**
- A4.1 **Evolution and speciation**
- B1.2 **Proteins**



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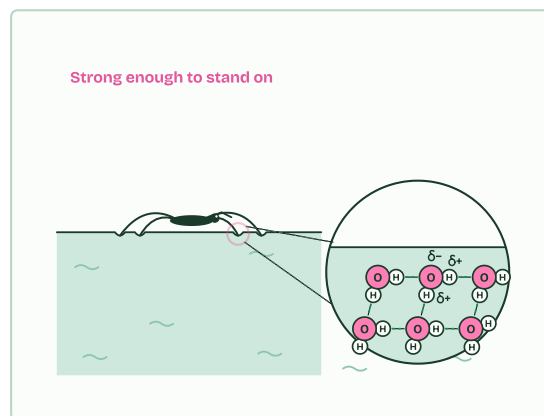
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Why life runs on *water*

Water

Life began in water, and every cell is still mostly water. Here is why one small, lopsided molecule clings to itself and to other things, dissolves what cells need, climbs to the tops of trees, and shapes the lives of a diving bird and an Arctic seal.



By the end you can

- ☐ Explain why water is the medium for life: where the first cells arose, and where life's processes still happen A1.1.1
- ☐ Explain how unequal sharing of electrons makes water polar, and draw hydrogen bonds between water molecules with partial charges A1.1.2
- ☐ Explain how cohesion lets water be pulled up xylem under tension, and lets animals live on its surface A1.1.3
- ☐ Explain how adhesion draws water through soil and plant cell walls by capillary action A1.1.4
- ☐ Explain why water is the medium for metabolism and transport, and why some molecules work because they do not dissolve A1.1.5
- ☐ Compare water with air for buoyancy, viscosity, thermal conductivity and specific heat capacity, using the black-throated loon and the ringed seal A1.1.6
- ☐ Outline how asteroids may have brought Earth's water, and why gravity and cool temperatures kept it A1.1.7
- ☐ Explain why the search for life elsewhere looks for liquid water in a star's Goldilocks zone A1.1.8

Tick each one when you can do it without the book.

01

A1.1.1 WATER AS THE MEDIUM FOR LIFE

Life began in water, and still *runs* in it

The first cells appeared in water more than 3.5 billion years ago. Where exactly, in the sea or in hot pools, is still debated. What is not in doubt is that for about three billion years every living thing stayed in water, and plants and animals reached land only in the last 500 million years or so.

Water suited them because things dissolve in it. Dissolved substances can move about, meet and react, and that is how the first cells could run their chemistry. Water is the **medium** for life, and the chemistry it carries, **metabolism**, still happens in it today.

A typical cell is about 70% water by mass. Its **cytoplasm** is an **aqueous solution**, and most of the reactions of metabolism take place in it. **Blood plasma**, about 90% water, and xylem sap carry dissolved substances round bodies and plants.

Land organisms did not leave water behind. They carry it inside them, in their cells, blood and tissue fluid, and a skin or a waxy cuticle slows its loss.

KEY TERMS

medium

The material in which something happens or is carried. Water is the medium for life: cells are mostly water, and most of their chemistry happens in it.

metabolism

All the chemical reactions that go on in a living cell.

cytoplasm

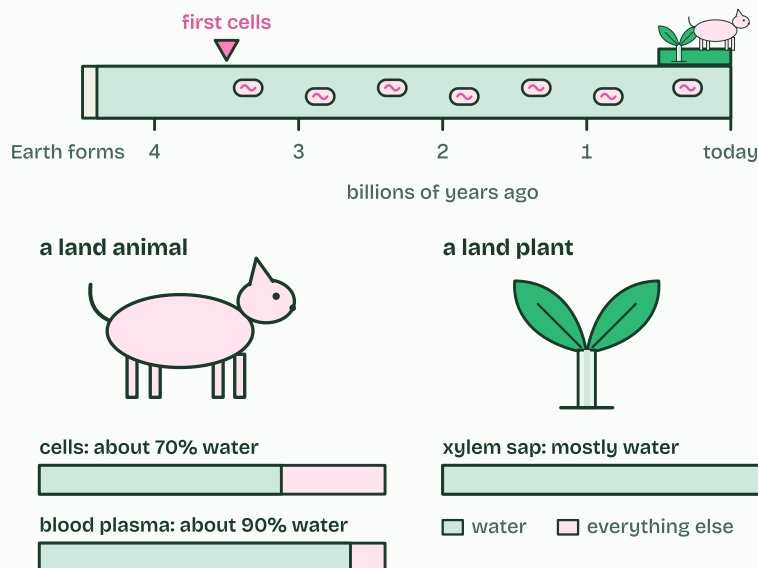
The fluid inside a cell, outside the nucleus, where many metabolic reactions take place.

aqueous solution

A mixture in which substances are dissolved in water.

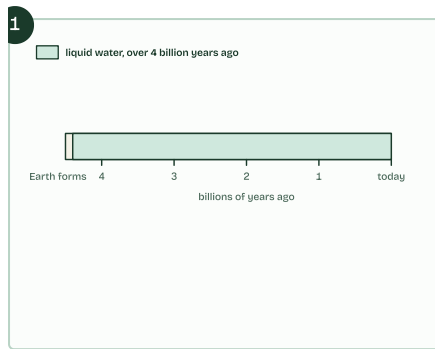
blood plasma

The pale yellow liquid part of blood. About 90% of it is water, and it carries dissolved substances round the body.

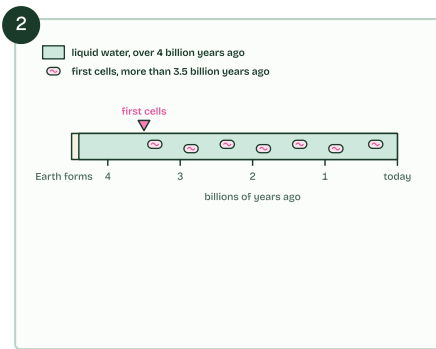


STEP BY STEP

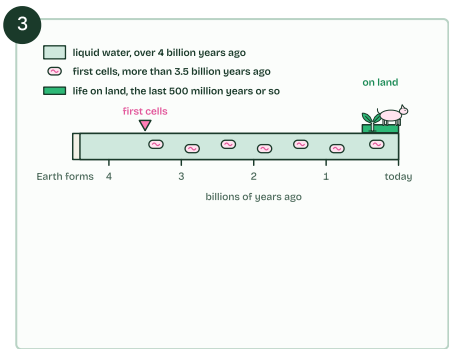
4 STEPS



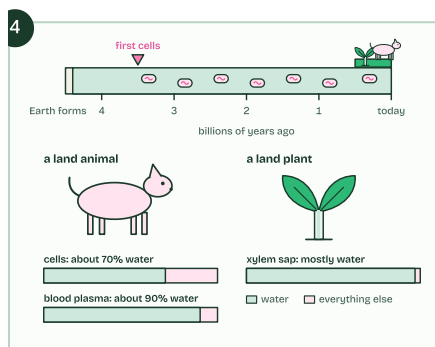
Liquid **water** appeared very early, over 4 billion years ago.



The **first cells** lived in it, more than 3.5 billion years ago, and for about three billion years every living thing stayed there.



Plants and animals reached **land** only in the last 500 million years or so.



Even there, life **carries** its water inside it: cells, blood plasma and xylem sap are all mostly water.

WATCH OUT

"Land animals live without water." They do not: they carry it inside them, and every reaction in their cells still happens in water.

IN NUMBERS

A typical cell is about 70% water by mass, an adult human about 60% and a jellyfish about 95%.

PREDICT

A packet of dry bean seeds sits in a cupboard for three years. What is happening to the metabolism inside each seed?

- (A) It runs as normal, slowly using up the seed's food store so that less is left each year
- (B) It has almost stopped: with so little water, enzymes and substrates cannot meet to react
- (C) It has stopped for good: the seeds are dead and will not grow, however much water they get

Decide before you look. Answer on page 124.

02

A1.1.2 HYDROGEN BONDS

A lopsided molecule makes *hydrogen bonds*

A water molecule is one oxygen atom joined to two hydrogen atoms by **covalent bonds**, and it is bent, with about 104.5° between the two bonds.

The sharing is unequal. Oxygen pulls on the shared electrons harder than hydrogen does, so they spend more time near the oxygen. That makes each O–H bond a **polar covalent bond**. The oxygen end gains a small negative charge and each hydrogen a small positive one: **partial charges**, written δ^- and δ^+ . The molecule is bent, so one side is negative and the other positive, and the whole thing is a **polar molecule**.

Opposite charges attract. The δ^+ hydrogen of one molecule is pulled towards the δ^- oxygen of its neighbour, and that attraction is a **hydrogen bond**. It forms between molecules, never inside one. Each is weak, about a twentieth as strong as a covalent bond, and lasts only a few trillionths of a second. But there are vast numbers, always breaking and re-forming, and one molecule can make up to four.

KEY POINTS

- Draw it the IB way: solid lines for covalent bonds, dashed lines for hydrogen bonds.
- Write δ^+ and δ^- , never a bare + or -: the molecule is neutral overall.

Why it matters: to pull water molecules apart, hydrogen bonds must be broken, and that takes energy. Water boils at 100°C , but methane, a molecule of about the same size with no hydrogen bonds, boils at -162°C . When water evaporates, its fastest molecules break their hydrogen bonds and escape, taking energy with them, so what is left behind cools. Each gram that evaporates takes about 2.4 kJ, the **latent heat of vaporisation**. That is how sweat cools skin and transpiration cools leaves.

KEY TERMS

covalent bonds

A bond in which two atoms share a pair of electrons.

polar covalent bond

A covalent bond in which the electrons are shared unequally, so one end is slightly negative and the other slightly positive.

partial charges

Charges smaller than a whole electron's, written δ^+ and δ^- . The molecule as a whole stays neutral.

polar molecule

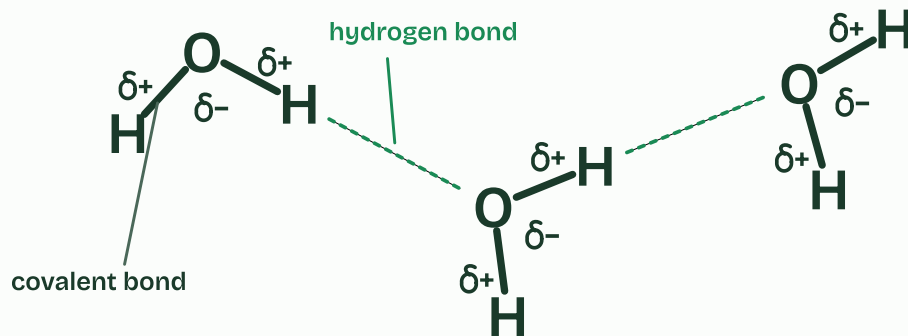
A molecule with one side slightly negative and the other slightly positive.

hydrogen bond

The weak attraction between a slightly positive hydrogen of one molecule and a slightly negative atom, here oxygen, of another.

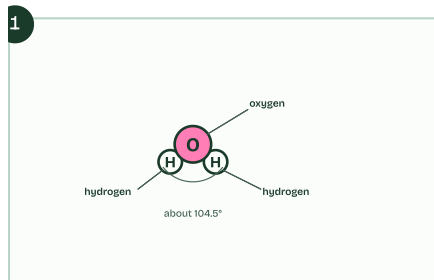
latent heat of vaporisation

The energy needed to turn 1 g of a liquid into a gas without changing its temperature.

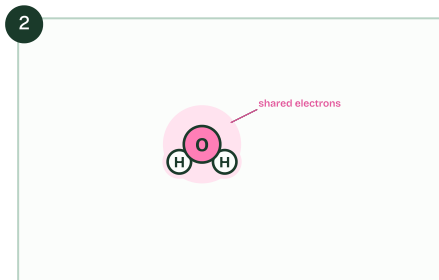


STEP BY STEP

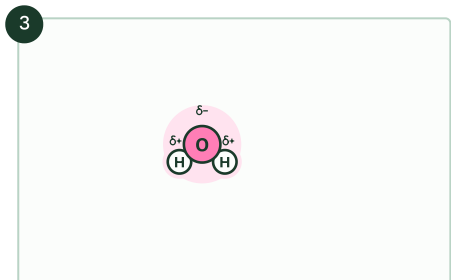
6 STEPS



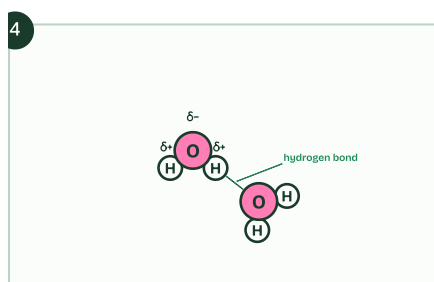
One water molecule: an oxygen with two hydrogens, **bent**, with about 104.5° between the bonds.



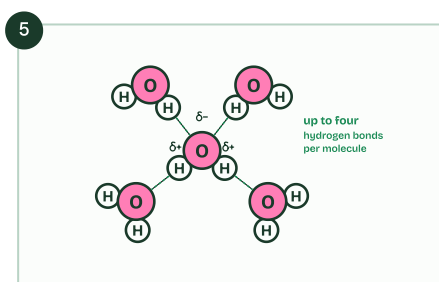
The shared **electrons** (the pink cloud) crowd round the oxygen and thin out round each hydrogen.



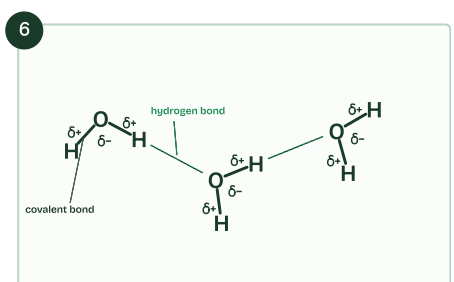
So the oxygen is slightly negative and each hydrogen slightly positive: **partial** charges, not whole ones.



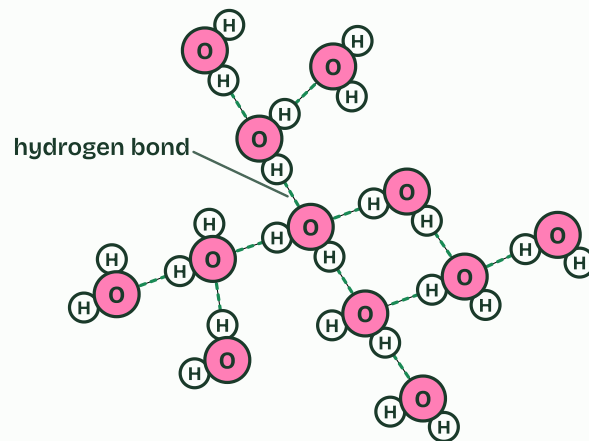
A second molecule turns its oxygen to face a hydrogen of the first, and a dashed line joins them: a **hydrogen bond**.



One molecule can make up to **four**: two through its hydrogens and two to its oxygen.



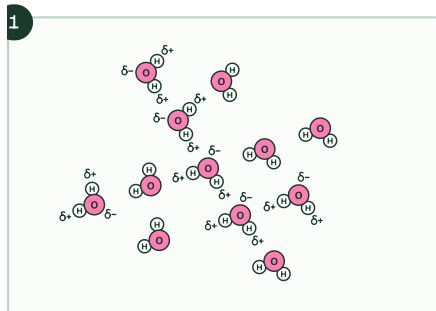
The notation the exam wants: letters, solid lines for covalent bonds, dashed lines for hydrogen bonds, and δ signs. **Draw it like this.**



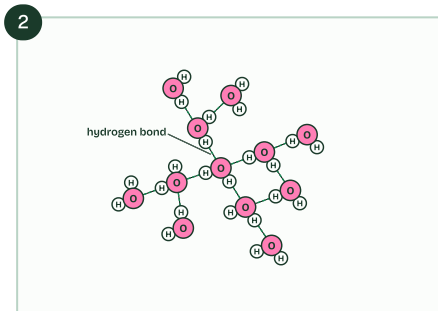
Raise the temperature: the molecules move faster and each hydrogen bond lasts a shorter time. Even so, most molecules are still held by a couple of bonds at any moment.

STEP BY STEP

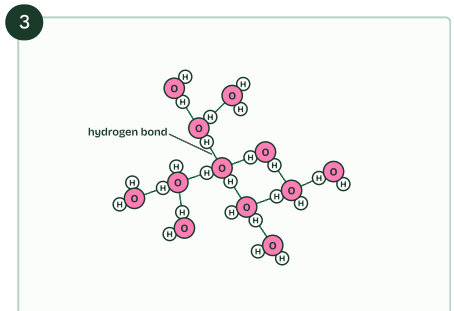
3 STEPS



Each water molecule is **polar**: the oxygen is slightly negative and the hydrogens slightly positive.



A slightly positive hydrogen is attracted to the oxygen of another molecule: a **hydrogen bond**.



Each bond lasts only a moment. They **break and form** all the time as the molecules move; in liquid water most molecules are held by several at once.

REMEMBER IT

What hydrogen bonds give water

C Cats	A Avoid	T Taking	S Showers
Cohesion water sticks to water (chapter 3)	Adhesion water sticks to polar or charged surfaces (chapter 4)	Thermal slow to warm, and takes a lot of heat to evaporate (here and chapter 6)	Solvent dissolves polar and charged substances (chapter 5)

WATCH OUT

"A hydrogen bond is the bond between O and H inside a water molecule." Those are covalent bonds. A hydrogen bond is between molecules.

WATCH OUT

" δ^+ and δ^- are the charges of ions." They are partial charges: a water molecule is neutral, so write δ , never a bare + or -.

HOW DO WE KNOW?

No one has watched a hydrogen bond form: each is far too small and lasts a few trillionths of a second. The evidence is indirect. Water boils at 100 °C, where molecules of the same size boil far lower (methane at -162 °C, hydrogen sulfide at -60 °C), and its surface tension and heat capacity are unusually high. One idea, hydrogen bonding, explains all of these at once, and X-ray and neutron studies of ice show each hydrogen pointing at an oxygen on the next molecule. A theory earns trust by explaining many observations and surviving every test so far.

LINKS

Hydrogen bonds hold the two strands of DNA together (A1.2) and help hold proteins in shape (B1.2). The same weak, numerous attractions run through the whole course.

PREDICT

Water boils in a kettle. Which bonds break as it turns to steam?

- (A) The covalent bonds inside each molecule, so the steam is hydrogen gas and oxygen gas
- (B) Both: the molecules split apart first, then the atoms join up again in the steam
- (C) The hydrogen bonds between molecules, so the steam is still made of water molecules

Decide before you look. Answer on page 124.

03

A1.1.3 COHESION

Water *holds on* to itself

Hydrogen bonds make water molecules stick to one another. That is **cohesion**.

Inside a drop, each molecule is pulled equally in every direction by its neighbours. A molecule at the surface has neighbours beside it and below it but none above, so it is pulled sideways and inwards. The surface molecules cling together and the surface acts like a stretched film that resists being broken. That is **surface tension**, and water's is higher than that of almost any other common liquid.

Small animals use the film as a habitat. A pond skater (*Gerris lacustris*) spreads its weight over long legs, and water-repellent hairs on its feet press dimples into the surface without breaking through. Mosquito larvae hang from the underside and breathe through a tube that pokes up through the film.

Cohesion also lifts water to the top of a tree. In a leaf, water evaporates from the wet walls of cells and leaves as vapour through small pores, which is **transpiration**. That pulls water out of the **xylem**. Because the molecules cohere, the whole column of water is pulled up from the roots, like a rope pulled from the top. The water is under **tension**: it is being pulled, not pushed. Cohesion keeps the column whole however tall the plant, but an air bubble breaks it, and that tube stops carrying water. (The detail of xylem vessels is B3.2.)

KEY TERMS

cohesion

The attraction between molecules of the same substance. In water it is caused by hydrogen bonds.

surface tension

The tendency of a liquid's surface to resist being broken, because the molecules at the surface are pulled together and inwards.

transpiration

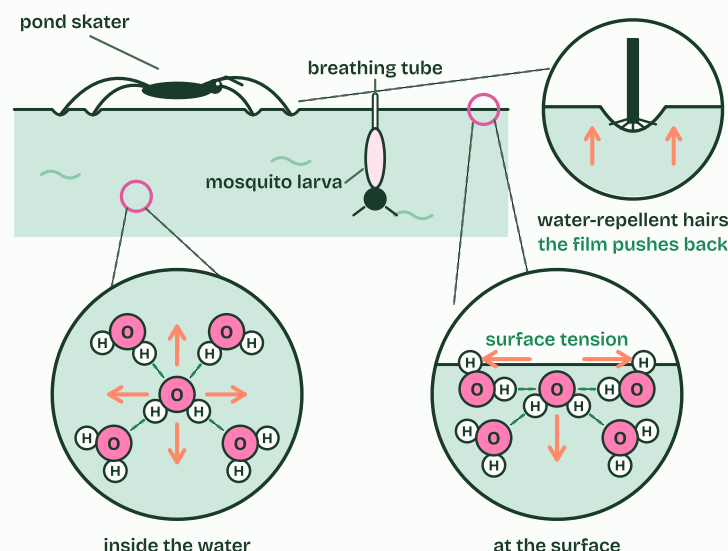
The loss of water vapour from a plant, mostly through pores in its leaves.

xylem

The tubes that carry water and dissolved minerals up a plant.

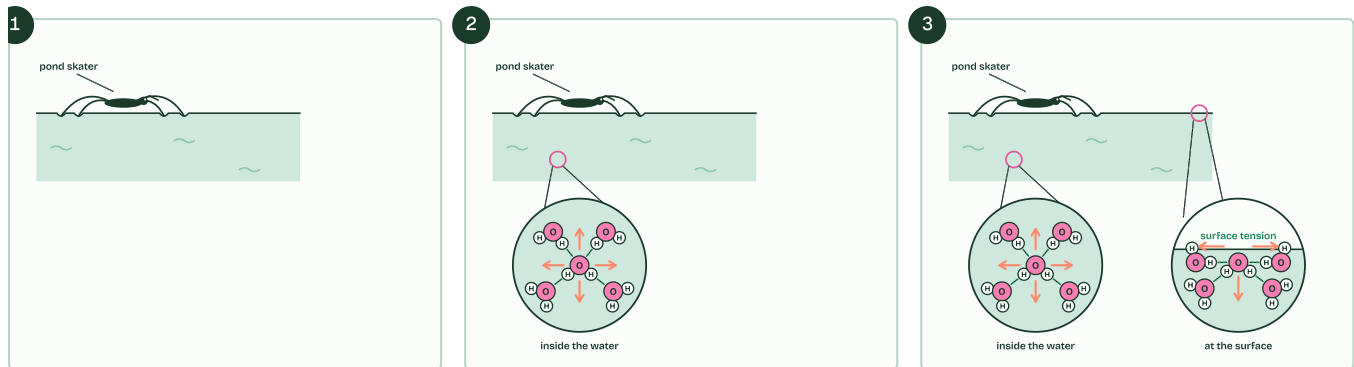
tension

A pulling force. Water in the xylem is pulled up the plant, not pushed.



STEP BY STEP

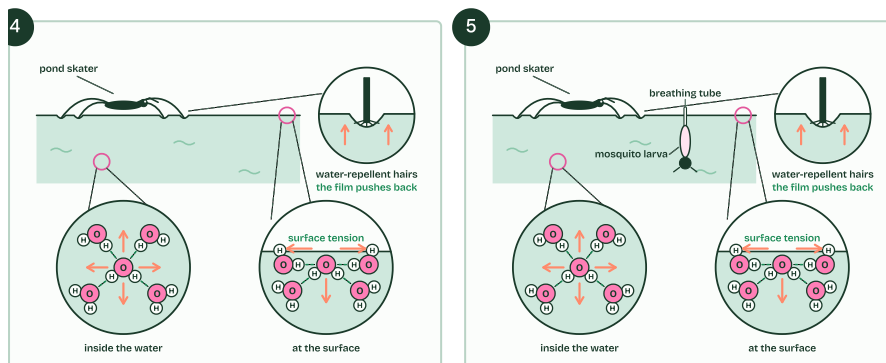
5 STEPS



A pond skater stands on water. Its long legs spread its weight, and each foot makes a small **dimple** in the surface.

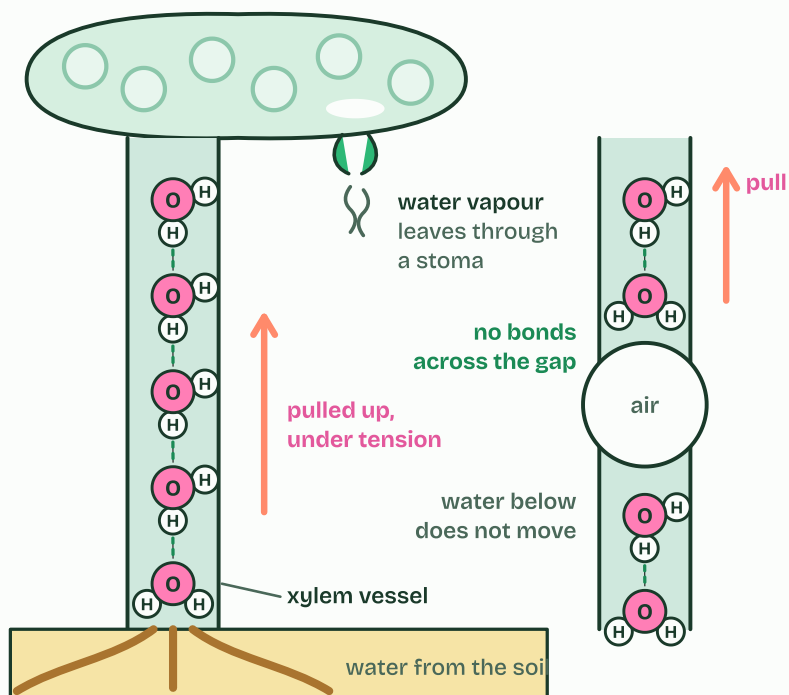
Inside the water, each molecule is pulled by its neighbours equally in **every direction**, so it stays where it is.

At the surface there are no neighbours above: the pull is **sideways and inwards**, and the surface holds together like a stretched film. That is **surface tension**.



Close up, water-repellent **hairs** on the foot press the film into a dimple without breaking it, and the film pushes back up.

A mosquito **larva** hangs from the underside of the film and breathes through a tube that pokes through it.



Evaporation at the leaf pulls the column up, and cohesion holds it together. An air bubble breaks it: below the break the water stops, because cohesion cannot pull across a gap.

WATCH OUT

"Capillary action lifts water to the top of a tree." In a xylem vessel, capillary action alone would lift water well under a metre. The pull comes from evaporation in the leaves, passed down the column by cohesion.

WATCH OUT

"Surface tension is a skin of different molecules," or "surface water is denser." It is the same water, held more tightly by hydrogen bonds at the surface.

EXAMPLE

The tallest living tree, a coast redwood in California, is about 116 m tall. Holding up a column of water that tall takes a pull of more than 1 MPa, about eleven times the pressure of the air, and cohesion holds.

LINKS

Processes at surfaces: the surface film is a habitat, and evaporation from wet cell walls drives the pull up the xylem.

PREDICT

Ground pepper floats on a bowl of water. You touch the middle of the surface with a finger dipped in washing-up liquid. What does the pepper do?

- (A) It shoots out to the edge of the bowl, dragged by the clean surface that is still pulling all round
- (B) It sinks, because the soap makes the water under it heavier than the pepper
- (C) Nothing happens: the soap mixes in and leaves the surface exactly as it was

Decide before you look. Answer on page 124.

A1.1.4 ADHESION

04 Water *clings* to polar surfaces

Water is attracted to other materials too, as long as they are polar or carry a charge. That is **adhesion**: hydrogen bonds or ionic attractions pull water on to the surface. Glass does it. So does **cellulose**, which is covered in OH groups, and so do the charged surfaces of clay and humus in soil. A waxy, non-polar surface gives water nothing to cling to, so water beads up on it instead.

Put a narrow gap between surfaces that water clings to and something useful happens. Water adheres to the walls and creeps up them, and cohesion drags the rest of the water along behind. This is **capillary action**. The narrower the gap, the higher the water rises.

In soil, rain is held in the narrow spaces between the particles by adhesion and cohesion, so it does not all drain away, and it can creep through the soil towards roots. Clay, with tiny spaces and charged particles, holds the most.

In a plant, a cell wall is a mesh of cellulose fibres with tiny gaps between them. Water soaks through the wall by capillary action and keeps it wet. In a leaf, those wet walls are where the evaporation of chapter 3 happens. (The detail of walls and leaves is B3.2.)

KEY TERMS

adhesion

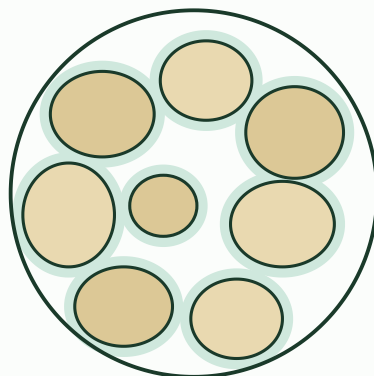
The attraction between water and a different material that is polar or charged, through hydrogen bonds or ionic attractions.

cellulose

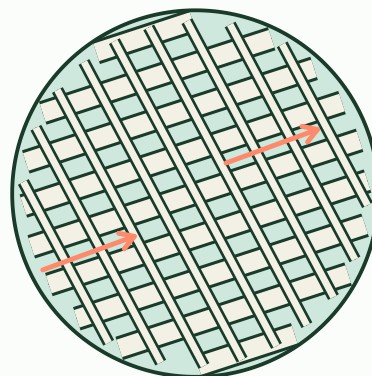
The carbohydrate that makes plant cell walls, built from long chains of glucose and covered in OH groups.

capillary action

The movement of water along a narrow space against gravity, caused by adhesion to the walls and cohesion between the water molecules.



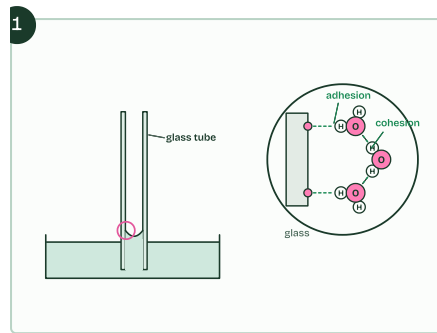
in soil
water clings to the particles
and sits in the narrow gaps



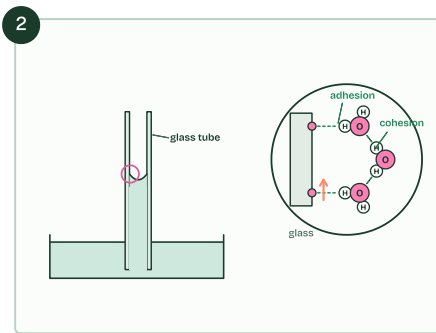
in a plant cell wall
water soaks through the gaps
between the cellulose fibres

STEP BY STEP

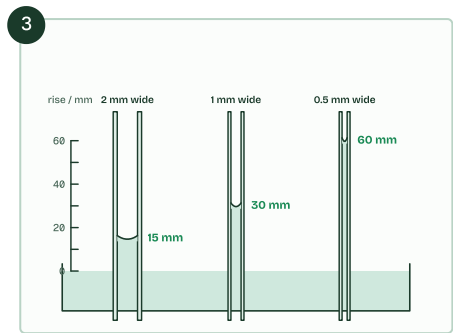
5 STEPS



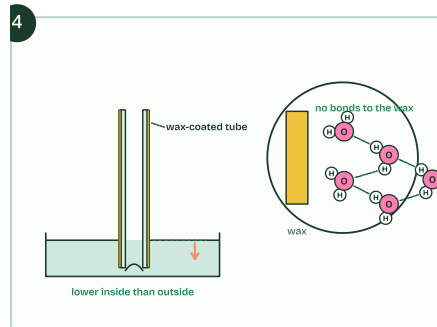
Water is attracted to the polar glass wall and forms bonds with it: **adhesion**. The water's edge curves up where it meets the glass.



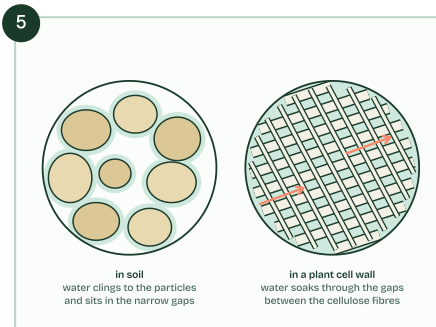
Cohesion drags more water up behind the edge, and the column rises until its weight balances the pull.



The **narrower** the tube, the higher the water climbs.



Wax has nothing for water to cling to: with no adhesion the surface curves down and sits **below** the level outside.



The same pull holds water between **soil** particles and soaks it through the gaps in a **cellulose** cell wall.

REMEMBER IT

Cohesion or adhesion?

C Clones	A Anything
Cohesion water clings to its clones: other water molecules	Adhesion water clings to anything polar or charged: glass, cellulose, soil

WATCH OUT

"Cohesion and adhesion are the same thing."
Cohesion is water to water. Adhesion is water to a different material that is polar or charged. Capillary action needs both.

EXAMPLE

A cotton towel dries you because water adheres to its cellulose fibres and creeps along the spaces between them.

LINKS

Much of biology happens at surfaces: water held on soil particles and in cell walls here, gas exchange across moist surfaces in lungs and leaves (B3.1), and reactions on membranes (B2.1).

PREDICT

Three cups in a row: red water, an empty cup, blue water. A strip of paper towel bridges each full cup and the empty one. What is in the middle cup a few hours later?

- Ⓐ Nothing: water cannot climb out of a cup by itself, whatever the paper is made of
- Ⓑ Only red water, because the red cup was filled first and so its water got there before the blue
- Ⓒ Purple water, rising until the levels even out, because water creeps along paper from both sides

Decide before you look. Answer on page 124.

05

A1.1.5 WATER AS A SOLVENT

The *solvent* cells run in

A **solution** is a **solute** dissolved in a **solvent**. Water dissolves a wide variety of substances: ions such as Na^+ , K^+ and Cl^- , and polar molecules such as glucose, amino acids and urea.

It does so because of its own charges. Water molecules crowd round an ion with their δ^- oxygens turned towards positive ions and their δ^+ hydrogens towards negative ions, and pull the ions apart. Polar molecules dissolve by forming hydrogen bonds with water. Each dissolved particle ends up wrapped in water molecules.

Substances that are polar or charged are **hydrophilic**. Substances that are non-polar, such as fats, oils and waxes, are **hydrophobic**: water molecules bond to each other instead, which pushes the non-polar molecules together, as oil forms droplets.

That makes water the medium for metabolism. Most **enzymes** catalyse reactions in aqueous solution, in the cytoplasm and in the fluids inside organelles, where dissolved enzymes and substrates move about and collide. It also makes water the medium for transport. Blood plasma carries glucose, amino acids, ions, urea and hormones dissolved in it, and xylem sap carries mineral ions such as nitrate and potassium from roots to leaves.

Some molecules work because they are hydrophobic and insoluble. The wax on a leaf stops water escaping. Fat stores energy, and insulates, without dissolving into the cell's water (the seal's insulating fat, in chapter 6). The non-polar tails of phospholipids make membranes a barrier to water-soluble substances (B1.1 and B2.1). Ten substances to sort are below.

KEY TERMS

solution

A mixture of a solute dissolved in a solvent.

solute

A substance that dissolves in a solvent.

solvent

The liquid that a solute dissolves in. Water is the solvent in cells.

hydrophilic

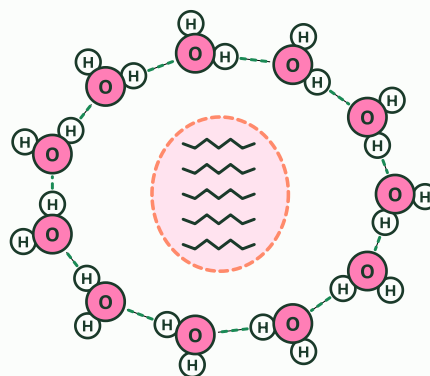
Attracted to water. Polar and charged substances are hydrophilic.

hydrophobic

Not attracted to water. Non-polar substances are hydrophobic.

enzymes

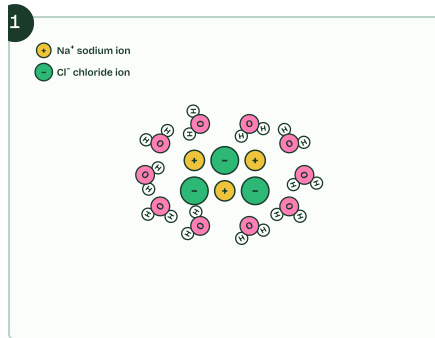
A protein that speeds up a chemical reaction in a cell without being used up.



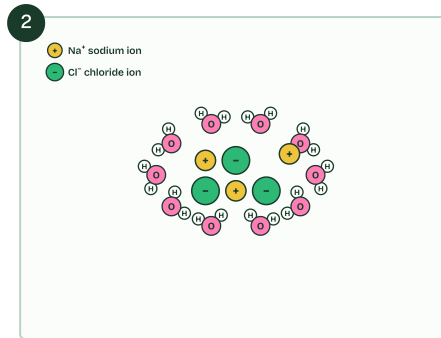
oil is non-polar
water bonds to water, not to oil

STEP BY STEP

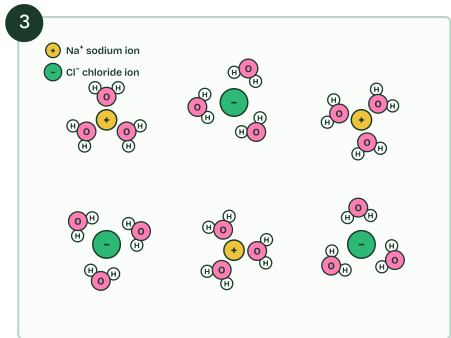
5 STEPS



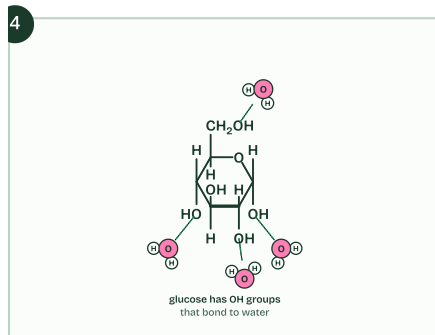
A grain of salt is a lattice of **ions**, sodium (Na⁺) and chloride (Cl⁻), held together by their opposite charges.



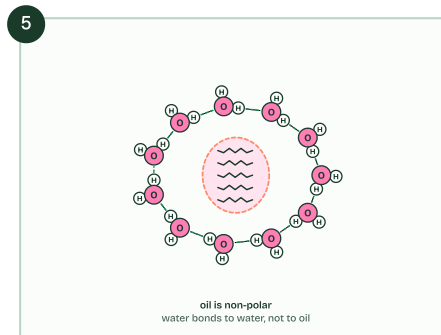
Water molecules turn to face the ions, **oxygen** towards Na⁺ and **hydrogens** towards Cl⁻, and together they pull ions loose.



Dissolved: every ion is wrapped in its own **shell** of water molecules and drifts away from the rest.



A sugar is covered in OH groups, which make **hydrogen bonds** with water, so it dissolves too.



Oil molecules are **non-polar**. Water bonds to water, not to oil, so the oil is pushed together into a droplet.

Dissolves in water

sodium chloride
ions wrapped by water

glucose
OH groups bond with water

an amino acid
charged and polar groups

urea
so urine can carry it away

vitamin C
polar, lost in urine

Does not dissolve

fat (a triglyceride)
hydrophobic

leaf wax
hydrophobic

cholesterol
hydrophobic

cellulose
hydrophilic, but insoluble

calcium phosphate
hydrophilic, but insoluble

Insoluble, and useful because of it: wax keeps water in the leaf, fat stores energy and insulates, cholesterol is part of membranes, cellulose makes cell walls that must not dissolve, and calcium phosphate makes bones that last.

WATCH OUT

"Water is the universal solvent." It dissolves more substances than any other common liquid, but not everything: fats, waxes, cellulose and bone mineral do not dissolve, and life depends on that.

WATCH OUT

"Hydrophilic means soluble." Cellulose is hydrophilic, and it is insoluble.

PREDICT

Fish get all their oxygen from water. Oxygen molecules (O_2) are non-polar. How does the oxygen get into the water?

- (A) It does not get in as a gas: fish split water molecules and take the oxygen from them
- (B) It forms hydrogen bonds with water molecules, in the same way that glucose does
- (C) Small non-polar molecules dissolve a little, and a little is enough to reach the gills

Decide before you look. Answer on page 124.

06

A1.1.6 WATER AS A HABITAT

Life in water, life in *air*

Water is a habitat as well as a medium, and living in it is very different from living in air. Four properties decide most of the difference. The values here are for 20 °C.

KEY POINTS

- **Buoyancy.** Water is over 800 times as dense as air, so it pushes up on a body with almost as much force as the body weighs. Air hardly supports a body at all.
- **Viscosity.** Water is about 55 times as viscous as air, and far denser, so a body moving through it meets much more **drag**. Streamlined shapes save energy.
- **Thermal conductivity.** Water conducts heat about 23 times as fast as air, so a warm body loses heat far faster in water than in air at the same temperature. Animals in cold water need thick insulation.
- **Specific heat capacity.** It takes about 4.2 J to warm 1 g of water by 1 °C, about four times as much as for 1 g of air, and a litre of water holds about 3,500 times as much heat for each degree as a litre of air. Much of the energy goes into breaking hydrogen bonds before the molecules can move faster. So lakes and seas change temperature slowly, from day to night and season to season, and make a stable habitat.

Two animals show the contrast. The black-throated loon (*Gavia arctica*) is a diving bird that breeds on large northern lakes, winters at sea and chases fish underwater. The ringed seal (*Pusa hispida*) is the commonest Arctic seal. It lives on and under the sea ice, keeps breathing holes open with its claws, and is kept warm in the water by a thick layer of **blubber**. The figure sets water against air for each property, and shows what it means for each animal.

KEY TERMS

buoyancy

The upward push of a fluid on an object in it. In water it is almost as large as the object's weight; in air it is tiny.

viscosity

How much a fluid resists flowing past or round an object.

drag

The force that resists movement through a fluid.

thermal conductivity

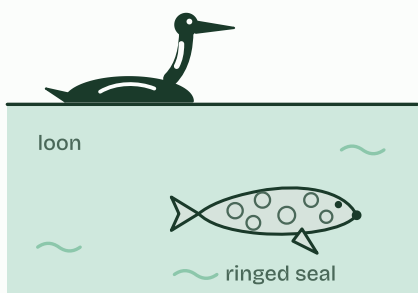
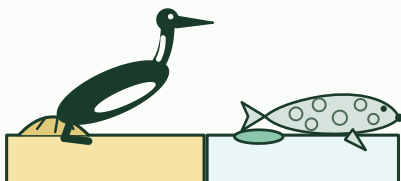
How fast heat flows through a material. Water conducts heat much faster than air.

specific heat capacity

The energy needed to warm 1 g of a substance by 1 °C. Water's is unusually high.

blubber

A thick layer of fat under the skin of a seal or whale that insulates it.

	In water		In air	
				
	loon		loon on land	seal on the ice
property at 20 °C	water	air	water against air	
Density (kg/m ³)	998	1.2	over 800 times	
Viscosity (mPa s)	1.00	0.018	about 55 times	
Thermal conductivity (W/m/K)	0.60	0.026	about 23 times	
Specific heat capacity (J/g/°C)	4.18	1.01	about 4 times	

A litre of water holds about 3,500 times as much heat for each degree as a litre of air does.

REMEMBER IT

The four properties A1.1.6 compares

B Big	V Vessels	T Turn	S Slowly
Buoyancy water holds a body up	Viscosity water resists movement: more drag	Thermal conductivity water draws heat from a body fast	Specific heat capacity water's temperature changes slowly

WATCH OUT

"Thermal conductivity and specific heat capacity are the same." Water is high in both: it drains heat from a warm body quickly, while its own temperature hardly changes.

WATCH OUT

"Fur keeps a seal warm in the water." Fur insulates by trapping air, and wet fur loses it. In water, blubber does the job.

EXAMPLE

Same bird, two names: in Britain and Ireland *Gavia arctica* is the black-throated diver. In an exam, either the common name or the scientific name is accepted.

PREDICT

Ringed seal pups are born in snow caves on the sea ice, with thick woolly fur but almost no blubber. What happens to a young pup that has to stay in the sea for a long time?

- Ⓐ It stays warm: the woolly fur traps heat in water just as it does in air, so it needs no blubber
- Ⓑ It chills fast: soaked fur holds no air, and water draws heat away about 23 times faster than air does
- Ⓒ It warms up: the sea under the ice is warmer than the winter air, so the pup gains heat from it

Decide before you look. Answer on page 124.

07

A1.1.7 HL THE ORIGIN OF EARTH'S WATER

Water from *space*, kept by gravity

Water has been abundant on Earth for billions of years, and that gave life the time it needed to arise and evolve. So where did it come from?

Earth formed about 4.5 billion years ago, and it was hot. Much of its water is thought to have come from space. **Asteroids** crashed into the young planet, and some of them had water locked inside their minerals. That is the **hypothesis** this statement asks for.

Bringing water was only half of it. Earth also kept it, for two reasons.

KEY POINTS

- **Gravity.** Earth is massive enough for its gravity to hold water vapour and the rest of the atmosphere. The Moon, with about a hundredth of Earth's mass, could not, and has almost no water: only a little ice in craters that sunlight never reaches.
- **Temperatures low enough for water to condense.** Earth is far enough from the Sun, and cooled enough, for water vapour to **condense** into liquid water. It rained out to form oceans that have lasted about four billion years.

KEY TERMS

asteroids

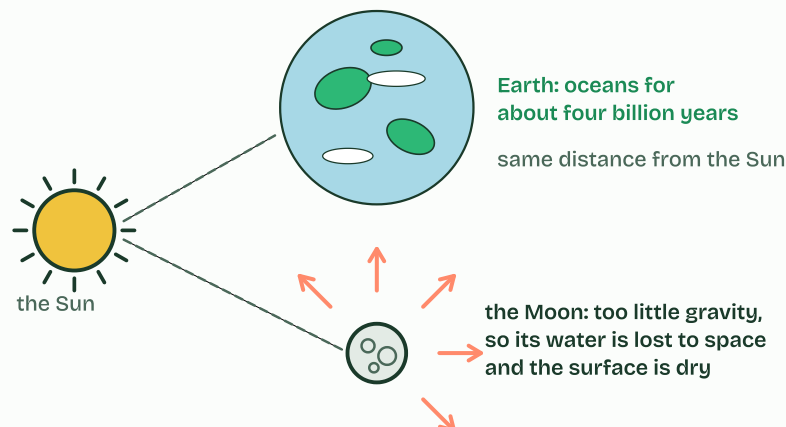
A rocky body left over from the formation of the Solar System, most of them orbiting the Sun between Mars and Jupiter.

hypothesis

An explanation that can be tested with evidence, but has not been proved.

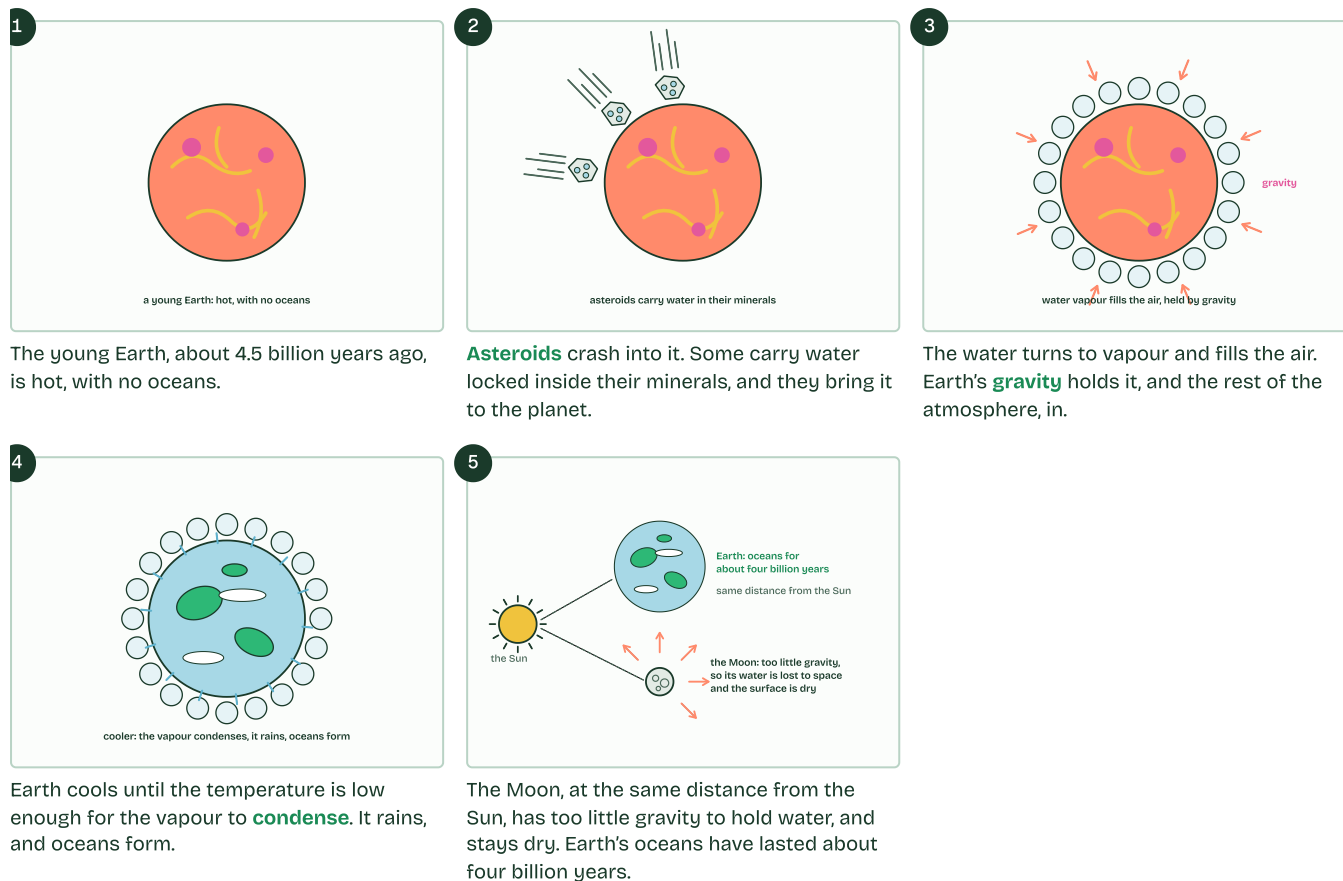
condense

Change from a gas to a liquid.



STEP BY STEP

5 STEPS



REMEMBER IT

Why Earth kept its water

G
Grip**Gravity**

holds water vapour and air to the planet

C
Chill**Cool enough to condense**

temperatures low enough for vapour to become liquid

WATCH OUT

"Earth kept its water because it has an atmosphere." The atmosphere is itself held by gravity. The two reasons to learn are gravity and temperatures low enough to condense water.

HOW DO WE KNOW?

No one saw it happen, so the hypothesis is tested with evidence. Hydrogen comes in a light form and a heavy form (deuterium), and the ratio of heavy to light hydrogen in water depends on where in the early Solar System the water formed. Water locked in some meteorites, which are fragments of asteroids, has almost the same ratio as Earth's oceans. That supports the asteroid hypothesis.

PREDICT

Venus is almost the same size and mass as Earth, but closer to the Sun. Why are there no oceans on Venus?

- ☐ A It is too hot for water vapour to condense into liquid, so any water stayed in the air as vapour
- ☐ B Its gravity is too weak to hold water vapour, so the vapour escaped into space long ago
- ☐ C No asteroids carrying water ever reached it, so it never had any water to form oceans from

Decide before you look. Answer on page 125.

08

A1.1.8 HL THE SEARCH FOR LIFE ELSEWHERE

Not too hot, not too cold: the *Goldilocks* zone

All the life we know needs liquid water as its medium (chapters 1 and 5), so the search for **extraterrestrial** life starts by looking for liquid water.

The **Goldilocks zone**, also called the habitable zone, is the band of distances round a star where a planet's surface is warm enough for water not to freeze and cool enough for it not to boil away, so water could stay liquid. Too close and it is too hot. Too far and it is too cold. The zone depends on the star: a brighter, hotter star has its zone farther out, and a dimmer, cooler star has it closer in.

Earth lies inside the Sun's zone. Venus, closer, is far too hot. Mars, just outside the zone and much smaller than Earth, is cold, with a thin atmosphere and its water frozen. Astronomers have now found more than 5,000 planets round other stars, called **exoplanets**. The rocky ones in their star's zone are the first targets in the search for life, and space agencies share their missions and data to look for them.

The zone is a model, and every model has limits. Being in the zone does not mean a planet has water: it must have received some and kept it (chapter 7). And liquid water can exist outside the zone, under ice warmed from inside, as on Jupiter's moon Europa and Saturn's moon Enceladus. Searching only the zone could miss life, like looking for lost keys only under the street light because the light is better there.

KEY TERMS

extraterrestrial

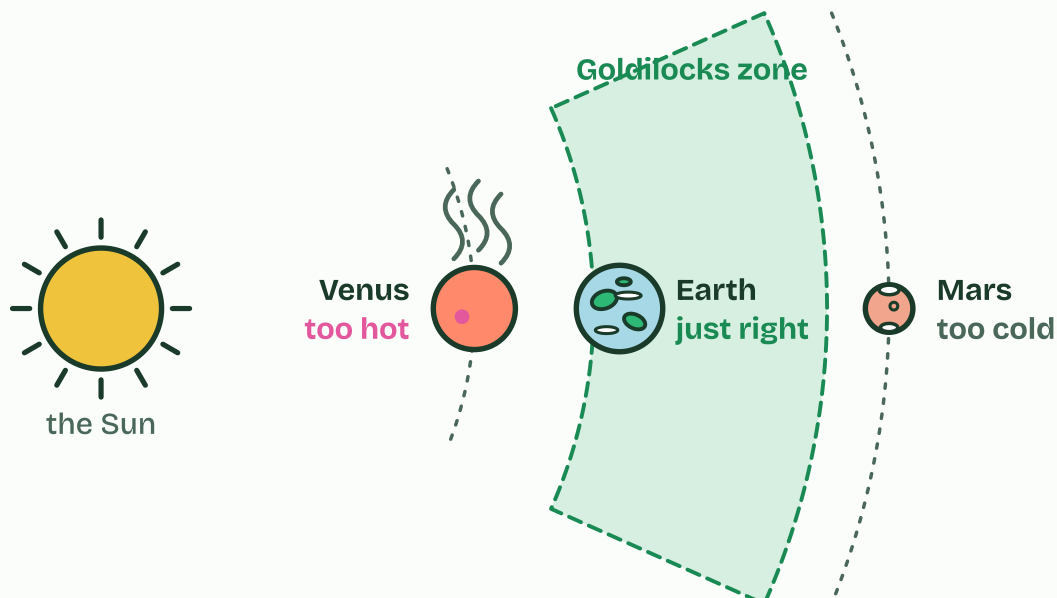
Beyond Earth.

Goldilocks zone

The band of distances from a star at which a planet's surface could be warm enough for water not to freeze and cool enough for it not to boil away. Also called the habitable zone.

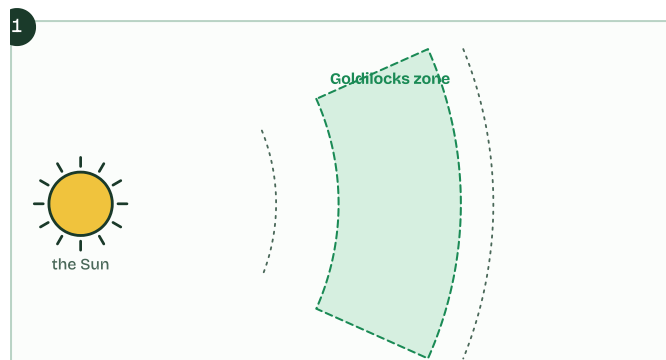
exoplanets

A planet that orbits a star other than the Sun.

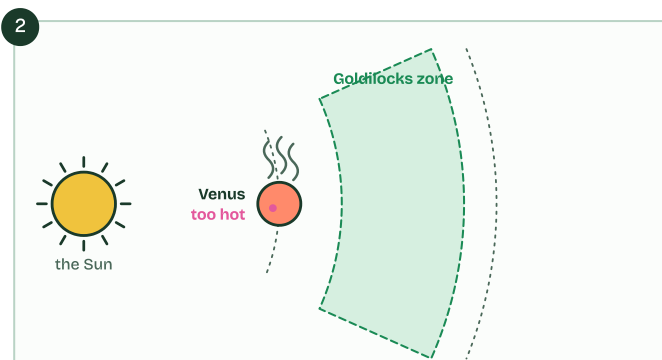


STEP BY STEP

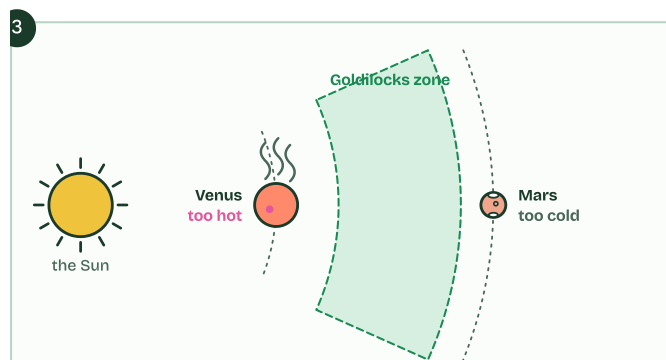
4 STEPS



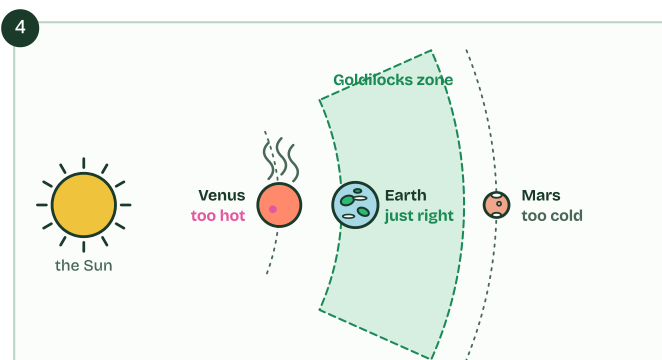
A star warms the planets round it. The pale band is its **Goldilocks zone**: the distances at which a planet's surface could keep liquid water.



Venus is closer than the zone's inner edge. It is **too hot**: water would boil away as vapour.



Mars is beyond the outer edge, and small. It is **too cold**: its water is frozen and its air is thin.



Earth is inside the zone: **just right** for liquid oceans.

the Sun

boiling away

liquid water

frozen

a small planet:
its vapour streams
away into space

How far the planet is from its star, and how big the planet is, decide whether its water boils away, stays liquid or freezes.

WATCH OUT

"Every star's Goldilocks zone is at Earth's distance." It moves with the star's brightness.

WATCH OUT

"A planet in the zone has water, so it has life." The zone says where liquid water could exist on the surface, and nothing more.

PREDICT

A star gives out much less energy than the Sun. Where would its Goldilocks zone be?

- ☐ (A) Farther out than Earth's orbit, to make up for the dim light by catching more of it
- ☐ (B) At Earth's distance, because the zone is set by the freezing and boiling points of water
- ☐ (C) Much closer to the star, so that a planet there still receives enough energy to keep water liquid

Decide before you look. Answer on page 125.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

adhesion 04

The attraction between water and a different material that is polar or charged, through hydrogen bonds or ionic attractions.

aqueous solution 01

A mixture in which substances are dissolved in water.

asteroids 07

A rocky body left over from the formation of the Solar System, most of them orbiting the Sun between Mars and Jupiter.

blood plasma 01

The pale yellow liquid part of blood. About 90% of it is water, and it carries dissolved substances round the body.

blubber 06

A thick layer of fat under the skin of a seal or whale that insulates it.

buoyancy 06

The upward push of a fluid on an object in it. In water it is almost as large as the object's weight; in air it is tiny.

capillary action 04

The movement of water along a narrow space against gravity, caused by adhesion to the walls and cohesion between the water molecules.

cellulose 04

The carbohydrate that makes plant cell walls, built from long chains of glucose and covered in OH groups.

cohesion 03

The attraction between molecules of the same substance. In water it is caused by hydrogen bonds.

condense 07

Change from a gas to a liquid.

covalent bonds 02

A bond in which two atoms share a pair of electrons.

cytoplasm 01

The fluid inside a cell, outside the nucleus, where many metabolic reactions take place.

drag 06

The force that resists movement through a fluid.

enzymes 05

A protein that speeds up a chemical reaction in a cell without being used up.

exoplanets 08

A planet that orbits a star other than the Sun.

extraterrestrial 08

Beyond Earth.

Goldilocks zone 08

The band of distances from a star at which a planet's surface could be warm enough for water not to freeze and cool enough for it not to boil away. Also called the habitable zone.

hydrogen bond 02

The weak attraction between a slightly positive hydrogen of one molecule and a slightly negative atom, here oxygen, of another.

hydrophilic 05

Attracted to water. Polar and charged substances are hydrophilic.

hydrophobic 05

Not attracted to water. Non-polar substances are hydrophobic.

hypothesis 07

An explanation that can be tested with evidence, but has not been proved.

latent heat of vaporisation 02

The energy needed to turn 1 g of a liquid into a gas without changing its temperature.

medium 01

The material in which something happens or is carried. Water is the medium for life: cells are mostly water, and most of their chemistry happens in it.

metabolism 01

All the chemical reactions that go on in a living cell.

partial charges 02

Charges smaller than a whole electron's, written δ^+ and δ^- . The molecule as a whole stays neutral.

polar covalent bond 02

A covalent bond in which the electrons are shared unequally, so one end is slightly negative and the other slightly positive.

polar molecule 02

A molecule with one side slightly negative and the other slightly positive.

solute 05

A substance that dissolves in a solvent.

solution 05

A mixture of a solute dissolved in a solvent.

solvent 05

The liquid that a solute dissolves in. Water is the solvent in cells.

specific heat capacity 06

The energy needed to warm 1 g of a substance by 1 °C. Water's is unusually high.

surface tension 03

The tendency of a liquid's surface to resist being broken, because the molecules at the surface are pulled together and inwards.

tension 03

A pulling force. Water in the xylem is pulled up the plant, not pushed.

thermal conductivity 06

How fast heat flows through a material. Water conducts heat much faster than air.

transpiration 03

The loss of water vapour from a plant, mostly through pores in its leaves.

viscosity 06

How much a fluid resists flowing past or round an object.

xylem 03

The tubes that carry water and dissolved minerals up a plant.



Check yourself

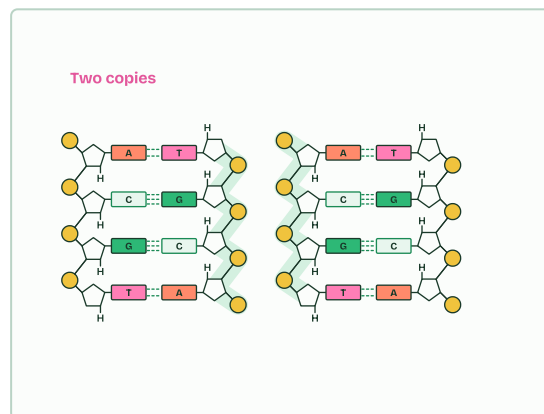
The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on A1.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

[biologybybradford.com/exam-maker/sit?
topics=A1.1&level=HL&paper=quiz&marks=15&src=ep](https://biologybybradford.com/exam-maker/sit?topics=A1.1&level=HL&paper=quiz&marks=15&src=ep)

Four letters, two strands, every *living* thing

Nucleic acids

Every living thing keeps its instructions in the same molecule, written in the same four letters. Here is how a chain of simple parts stores a whole life, copies it almost perfectly and passes it on.



By the end you can

- ☐ Explain why DNA is the genetic material of every living organism, and why RNA viruses do not break the rule A1.2.1
- ☐ Draw a nucleotide as a circle, a pentagon and a rectangle, each joined in the right place A1.2.2
- ☐ Explain how condensation builds a strand with a strong sugar–phosphate backbone, and draw a short strand of RNA A1.2.3, A1.2.5
- ☐ Name the bases of DNA and RNA, and explain how complementary pairing lets DNA be copied and read A1.2.4, A1.2.8
- ☐ Draw two antiparallel strands joined by hydrogen bonds between A and T, and C and G A1.2.6
- ☐ Give three differences between DNA and RNA, and sketch ribose against deoxyribose A1.2.7
- ☐ Explain why DNA can store limitless information, and why one genetic code in all life points to a common ancestor A1.2.9, A1.2.10
- ☐ Explain what the 5' and 3' ends are, and why nucleotides are only ever added at the 3' end A1.2.11
- ☐ Explain why a purine always pairs with a pyrimidine, and what that does for the helix A1.2.12
- ☐ Describe a nucleosome, and use molecular visualisation software to see how histones hold DNA A1.2.13
- ☐ Explain how Hershey and Chase's results show that DNA, not protein, is the genetic material A1.2.14
- ☐ Use Chargaff's data to falsify the tetranucleotide hypothesis, and explain why one result can falsify what many cannot prove A1.2.15

Tick each one when you can do it without the book.

01

A1.2.1 DNA AS THE GENETIC MATERIAL

Every living thing keeps its instructions in *DNA*

An organism inherits instructions from its parents: how to build its cells, which proteins to make, when to grow. The molecule that holds those instructions is its **genetic material**.

In every living organism studied, the genetic material is **DNA**, short for deoxyribonucleic acid. That is true of bacteria, archaea, protists, fungi, plants and animals. In a cell with a nucleus, most of the DNA is in the nucleus, with a little in the mitochondria and, in plants, the chloroplasts. In a bacterium it lies loose in the cytoplasm.

DNA belongs to the **nucleic acids**. The other one, **RNA**, does many jobs in the cell (chapter 6), and a few **viruses** use it to carry their genes: influenza, measles and the coronavirus that causes COVID-19 are RNA viruses. Other viruses carry DNA. How anyone found out that DNA, and not protein, carries genes is the story of chapter 11.

Both nucleic acids are polymers built from one kind of monomer (chapter 2), and both contain carbon, hydrogen, oxygen, nitrogen and phosphorus.

One more distinction. DNA is the whole molecule. A **gene** is one stretch of its base sequence, and a single DNA molecule carries many genes.

KEY TERMS**genetic material**

The molecule that carries the instructions an organism inherits. It is copied each time a cell divides and passed from parents to offspring.

DNA

Deoxyribonucleic acid: the nucleic acid that is the genetic material of all living organisms.

nucleic acids

Polymers built from nucleotides. DNA and RNA are the two nucleic acids.

RNA

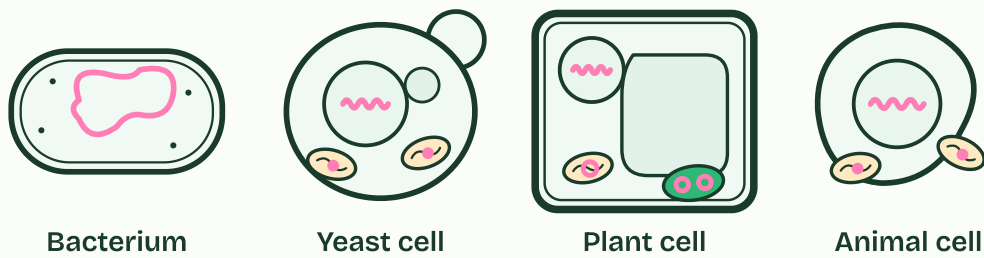
Ribonucleic acid: the other nucleic acid. It has several jobs in cells, and in some viruses it is the genetic material.

viruses

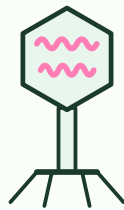
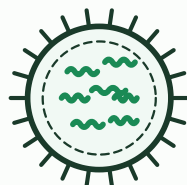
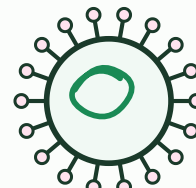
Tiny particles of genetic material inside a protein coat. A virus has no cells and can only be copied inside a host cell.

gene

A stretch of a DNA molecule: a particular base sequence that carries one piece of information.

**Viruses** not to scale

— DNA — RNA

**phage****influenza virus****coronavirus**

Pink is DNA and green is RNA. Viruses are far smaller than cells, so the strip of viruses is not to scale.

Bacterium DNA, one long loop, loose in the cytoplasm: there is no nucleus.

Plant cell DNA in the nucleus, and small loops in mitochondria and chloroplasts.

Phage A virus that infects bacteria. Its DNA lies inside a protein coat.

Coronavirus RNA inside a protein coat, with a fatty envelope. It has no cells and makes nothing for itself: it can only be copied inside a host cell.

Yeast cell DNA in the nucleus, and a little in each mitochondrion.

Animal cell DNA in the nucleus, and a little in each mitochondrion.

Influenza virus RNA inside a protein coat, with a fatty envelope. It has no cells and makes nothing for itself: it can only be copied inside a host cell.

WATCH OUT

"DNA" and "gene" are not two words for one thing. DNA is the molecule; a gene is one stretch of its base sequence, and one DNA molecule carries many genes.

PREDICT

A virus is found whose genes are made of RNA. Does that break the rule that DNA is the genetic material of all living organisms?

- (A) Yes: the rule must now say DNA or RNA
- (B) No: viruses are not counted as living organisms
- (C) No: the RNA is only a copy, and the virus keeps its real genes as DNA

Decide before you look. Answer on page 125.

02

A1.2.2 COMPONENTS OF A NUCLEOTIDE

Three parts, one *monomer*

Nucleic acids are **polymers**. The small unit, the **monomer**, is the **nucleotide**.

A nucleotide has three parts joined by covalent bonds: a **phosphate group**, a **pentose** sugar and a **nitrogenous base**. The sugar is in the middle. The phosphate is bonded to one corner of it and the base to another, and the base and the phosphate are never bonded to each other.

In DNA the sugar is deoxyribose, and in RNA it is ribose (chapter 6). The bases have names of their own (chapter 4).

Between them the three parts contain carbon, hydrogen, oxygen, nitrogen and phosphorus. Nitrogen comes only from the base and phosphorus only from the phosphate. In the cell the phosphate group carries a negative charge, a fact that matters again later in this guide.

KEY POINTS

- **Draw it the IB way.** A circle for the phosphate, a pentagon for the sugar and a rectangle for the base.
- The sugar is in the middle: the circle is at the upper left of the pentagon, on a short stalk, and the rectangle is at its right-hand corner.
- One ring round all three marks one nucleotide.

KEY TERMS

polymers

Long molecules built from many copies of a small unit, joined in a chain.

monomer

One small unit of a polymer. The monomer of a nucleic acid is the nucleotide.

nucleotide

The monomer of nucleic acids: a phosphate group, a pentose sugar and a nitrogenous base joined together.

phosphate group

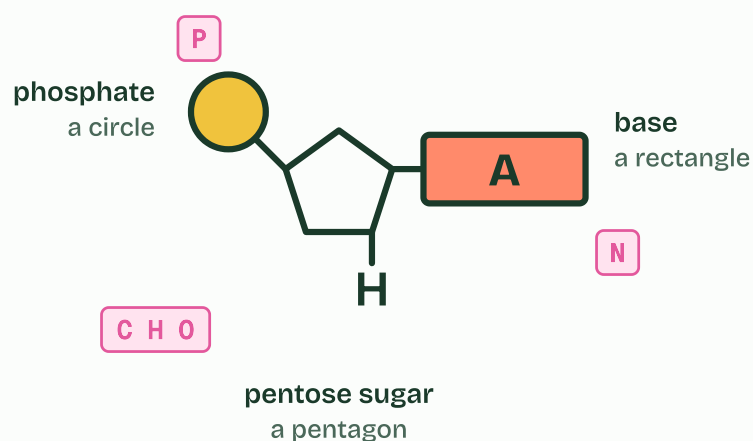
A phosphorus atom with oxygen atoms round it. In a cell it carries a negative charge.

pentose

A sugar with five carbon atoms.

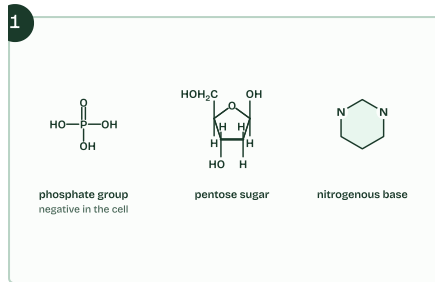
nitrogenous base

A ring of carbon and nitrogen atoms that is the part of a nucleotide that varies. Its order along a strand is the message.

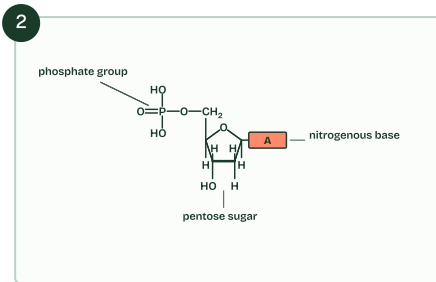


STEP BY STEP

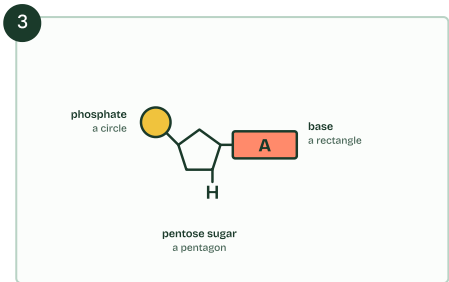
4 STEPS



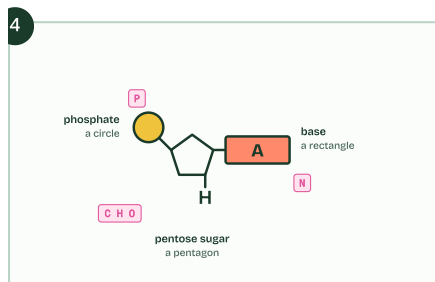
A nucleotide is built from **three parts**.



The **sugar** sits in the middle, bonded to both of the others.



The IB draws them as a **circle**, a **pentagon** and a **rectangle**, in these positions.



Nitrogen comes from the base and **phosphorus** from the phosphate.

WATCH OUT

A nucleotide is not a base. Each nucleotide contains one base, along with a sugar and a phosphate. And the base is bonded to the sugar, never to the phosphate.

PREDICT

How many different nucleotides does a cell use to build DNA?

- (A) One: every nucleotide in DNA is exactly the same as every other
- (B) Twelve: four kinds of base, four kinds of sugar and four kinds of phosphate
- (C) Four: the sugar and phosphate are the same, only the base differs

Decide before you look. Answer on page 125.

03

A1.2.3 A1.2.5 SUGAR-PHOSPHATE BONDING AND RNA

Building a strand with a strong *backbone*

Nucleotides join by **condensation**, as in the sugars and lipids of B1.1. The phosphate of each new nucleotide bonds to the sugar of the last nucleotide in the chain, and a molecule of water is released. The reverse is **hydrolysis**: water is added back and the bond breaks, which is how your digestion takes the nucleic acids in food apart.

Repeat the join and you build a **strand**: sugar, phosphate, sugar, phosphate. Every link is a **covalent bond**, so the strand is one continuous chain of covalently bonded atoms. That is the **sugar-phosphate backbone**: strong, and it fixes the order of the nucleotides along it. (Chemists call the link a phosphodiester bond; the IB does not ask for the name.)

The bases are not part of the backbone. Each sticks out sideways from its sugar, all on the same side, free to pair with another base (chapter 4). The backbone is the same all along, whatever the bases are, and any base can follow any other. Chapter 7 builds on that.

RNA is one such strand, a polymer of ribonucleotides made by condensation. DNA strands are built the same way; the enzymes that do it come in D1.1.

To draw an RNA strand, stack the nucleotides, join the lower left corner of each pentagon to the circle of the next, and point every base the same way. To mark one nucleotide, ring a circle, a pentagon and a rectangle together, not a pentagon, a rectangle and the circle below it.

One nucleotide has no order. A strand does. Order is a property of the polymer that its monomers do not have.

KEY TERMS

condensation

A reaction that joins two molecules and releases a molecule of water.

hydrolysis

A reaction in which a bond is broken by adding a molecule of water.

strand

One chain of nucleotides, also called a polynucleotide.

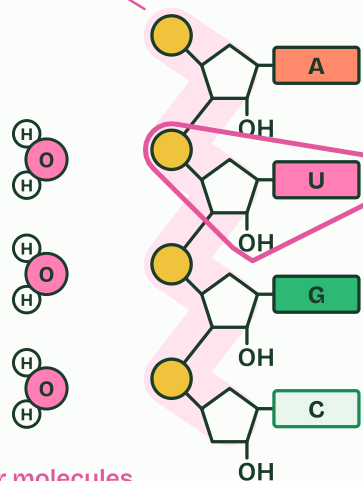
covalent bond

A bond in which two atoms share a pair of electrons. Covalent bonds are strong.

sugar-phosphate backbone

The chain of alternating sugars and phosphates, joined by covalent bonds, that runs along a nucleic acid strand.

sugar-phosphate backbone



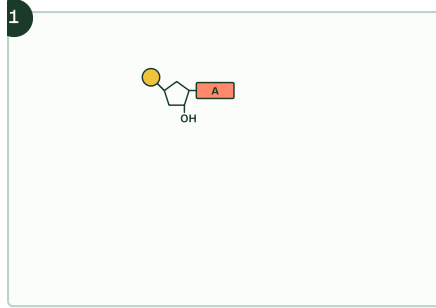
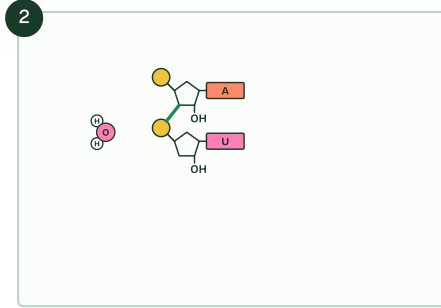
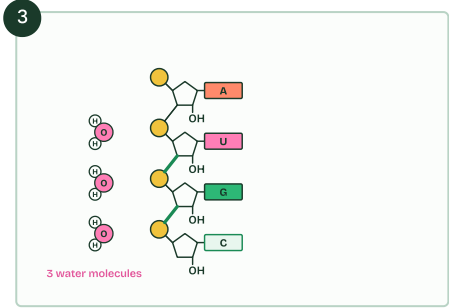
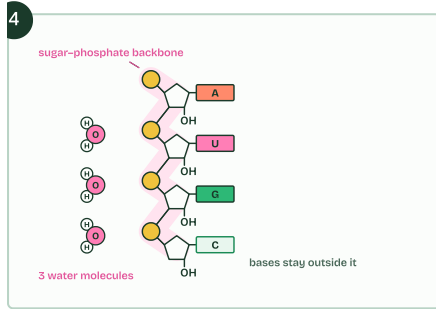
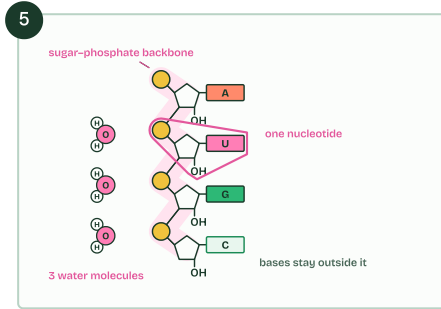
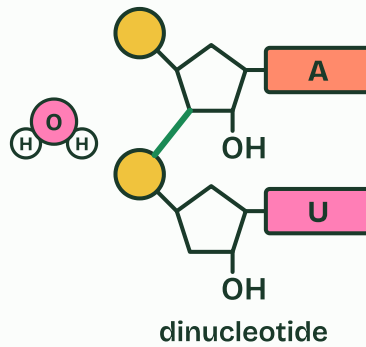
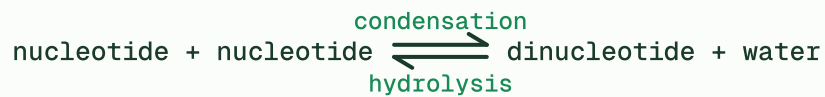
one nucleotide

3 water molecules

bases stay outside it

STEP BY STEP

5 STEPS

One **nucleotide**.**Condensation:** the phosphate bonds to the sugar above, and water leaves.Each new bond releases one **water** molecule.Sugar, phosphate, sugar, phosphate: a covalently bonded **backbone**.One nucleotide is a circle, a pentagon and a rectangle **together**.

Join nucleotides into a strand and count the water that leaves. Try a join that does not work and read why, then add water to split the strand again.

STEP BY STEP

4 STEPS

1



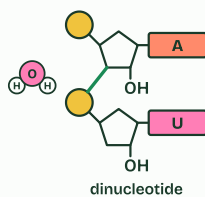
Two **nucleotides**, each a phosphate, a sugar and a base.

2



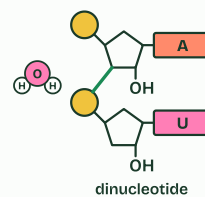
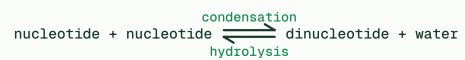
The phosphate of one and the sugar of the other face each other.

3



They leave as **water**, and a **sugar-phosphate bond** joins the sugar of one to the phosphate of the next: **condensation**, making a **dinucleotide**.

4



Add water and the bond splits again, the H to one nucleotide and the OH to the other: **hydrolysis**.

WATCH OUT

Hydrogen bonds do not hold a strand together. Inside a strand every link is covalent. Hydrogen bonds only come in between two strands (chapter 4), which is why the two strands of DNA can be parted without breaking either.

PREDICT

How many water molecules are released when 10 nucleotides join into one strand?

- (A) 9
(B) 10
(C) 20

Decide before you look. Answer on page 125.

04

Four letters that *pair*

A1.2.4

A1.2.8

BASES AND COMPLEMENTARY PAIRING

DNA uses four bases: **adenine** (A), **cytosine** (C), **guanine** (G) and **thymine** (T). RNA has A, C and G too, but **uracil** (U) takes the place of thymine. You need the names as well as the letters.

The order of the bases along a strand is the message, like letters spelling words: the **base sequence**. A gene is a stretch of that sequence, read three bases at a time to choose amino acids (D1.2).

Bases pair across between two strands by **complementary base pairing**: A with T (or with U when RNA is involved), and C with G. Complementarity rests on **hydrogen bonds**. Each base has a pattern of atoms that can give or take a hydrogen bond, and only in these two pairs do the patterns line up across the gap. A–T forms two bonds and C–G three; you do not need to memorise those numbers.

That pairing is what makes accurate copying possible. In **replication** the hydrogen bonds break and the strands separate, while the covalent backbones stay whole. Each strand is a **template**: free nucleotides pair with its exposed bases, and each new strand is complementary to its template. Each new molecule therefore has exactly the base sequence of the original. That answers the second guiding question: each strand carries what is needed to rebuild the other.

The same rule lets cells read DNA. In **transcription**, one strand of a gene is the template for an RNA copy, with an RNA base opposite each DNA base and U opposite A. In **translation**, three bases of messenger RNA pair with three bases of a transfer RNA, which brings the matching amino acid. Here both are outlined; D1.2 teaches them.

KEY TERMS

adenine

One of the four bases of DNA, written A. It pairs with thymine (uracil in RNA).

cytosine

One of the four bases of DNA, written C. It pairs with guanine.

guanine

One of the four bases of DNA, written G. It pairs with cytosine.

thymine

A base found in DNA, written T. It pairs with adenine.

uracil

A base found in RNA, written U, in the place of thymine. It pairs with adenine.

base sequence

The order of the bases along a strand of DNA or RNA.

complementary base pairing

The rule that each base pairs with one particular other base: A with T (or U), and C with G.

hydrogen bonds

Weak attractions between a slightly positive hydrogen atom on one molecule and a slightly negative atom on another.

replication

Copying a DNA molecule to make two molecules with the same base sequence.

template

A strand that new nucleotides pair with, so the new strand has the complementary sequence.

transcription

Making an RNA copy of a gene, using one DNA strand as the template.

translation

Making a chain of amino acids by reading the codons of messenger RNA.

Template strand **Partner strand**

Tray

Which base fits each empty slot?

A template strand, six empty slots for its partner, and the four bases in a tray. Which base fits each slot?

REMEMBER IT

Which base pairs with which

A Apples	T Tree	C Cars	G Garage
Adenine pairs with thymine (uracil in RNA)	Thymine in DNA only	Cytosine pairs with guanine	Guanine pairs with cytosine

WATCH OUT

Complementary does not mean identical. The two strands of one molecule have different sequences; it is the two molecules made by copying that are identical. And in RNA, uracil takes the place of thymine, not of adenine.

PREDICT

One strand of a DNA molecule reads A A T G C. The strands separate and each is copied. What does the strand built against it read, and the strand built against that one?

- (A) T T A C G, then T T A C G
 (B) T T A C G, then A A T G C
 (C) U U A C G, then A A T G C

Decide before you look. Answer on page 125.

05

A1.2.6 THE DOUBLE HELIX

Two strands, one *helix*

DNA is two strands held together by hydrogen bonds between complementary bases: A with T and G with C. The bases are on the inside and the two sugar–phosphate backbones are on the outside. A pair of bases facing each other is a **base pair**.

The strands are **antiparallel**: they run in opposite directions, like the two lanes of a road. In a drawing, the second strand's nucleotides are upside down, with the pentagons inverted and the phosphates on the other side. What direction means chemically is chapter 8.

The pair of strands winds into a **double helix**. In an exam you draw the two strands antiparallel and paired, with A opposite T and G opposite C. You do not have to draw the twist.

One hydrogen bond is weak, but millions of them hold the two strands firmly together. How that squares with copying and reading DNA, which need the strands parted, is the prediction below.

KEY TERMS

base pair

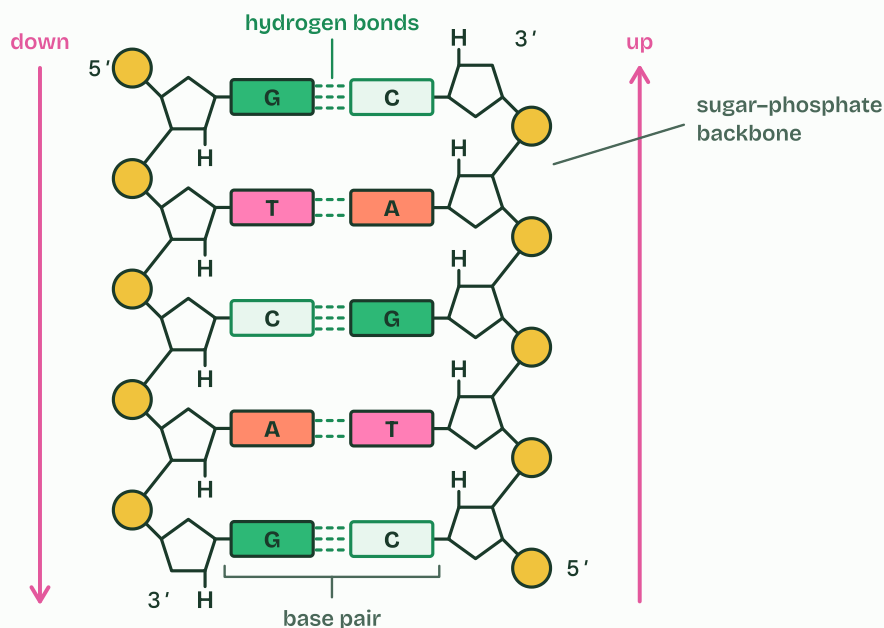
Two bases, one from each strand, held together by hydrogen bonds: A with T or G with C.

antiparallel

Running in opposite directions, like the two lanes of a road.

double helix

The shape of DNA: two strands wound round each other in a spiral.



The strands run in opposite directions: antiparallel.

The flat ladder is the drawing the exam asks for: two antiparallel strands, the second one inverted. The twist is left out.

WORKED EXAMPLE

In a double-stranded DNA molecule, 20% of the bases are adenine. Thymine pairs with adenine, so 20% are thymine. That leaves 60%, shared equally between guanine and cytosine: 30% each. Every nucleotide carries one phosphate, so the number of phosphates equals the number of bases.

WATCH OUT

Antiparallel does not mean twisted, or that the bases are opposite each other. It means the two strands run in opposite directions.

BUILT AS A MODEL

In 1953 James Watson and Francis Crick worked out this structure by building scale models of the parts and fitting them to the evidence: X-ray diffraction images of DNA made by Rosalind Franklin and Raymond Gosling, which showed a regular helix with the backbones outside, and chemical analyses showing equal amounts of A and T, and of G and C (Chargaff, chapter 12). A model is a simplification that can be tested against data. This guide's own figures leave out every atom.

PREDICT

To be copied, the two strands of DNA must come apart. Why does pulling them apart not break the strands themselves?

- Ⓐ Strong covalent bonds join the two strands, while each strand is held together by weak hydrogen bonds
- Ⓑ The bases leave the strands while they are copied, then the strands are put back together afterwards
- Ⓒ Weak hydrogen bonds join the two strands, while each strand is a chain of strong covalent bonds

Decide before you look. Answer on page 125.

06

A1.2.7 DIFFERENCES BETWEEN DNA AND RNA

DNA and RNA *compared*

DNA and RNA differ in three ways you need to be able to give: the number of strands, the bases, and the sugar.

KEY POINTS

- **Strands.** DNA has two, wound into a double helix. RNA usually has one, which can fold back and pair with itself in places: transfer RNA does.
- **Bases.** DNA has A, C, G and T. RNA has A, C, G and U.
- **Sugar.** DNA has **deoxyribose**. RNA has **ribose**.

Deoxyribose has one oxygen fewer than ribose: on carbon 2 it carries an H where ribose carries an OH, and "deoxy" means "without an oxygen". The ring oxygen is still there. Sketch both rings and mark the difference.

Cells use several kinds of nucleic acid. DNA makes up the chromosomes, with more in mitochondria and chloroplasts. **Messenger RNA** is a copy of a gene, taken to a ribosome. **Transfer RNA** brings amino acids to the ribosome. **Ribosomal RNA** is part of every ribosome. And some viruses have RNA as their genes.

KEY TERMS

deoxyribose

The pentose sugar in DNA. It has an H on carbon 2 where ribose has an OH.

ribose

The pentose sugar in RNA. It has an OH on carbon 2.

Messenger RNA

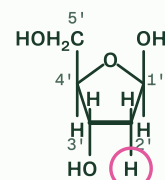
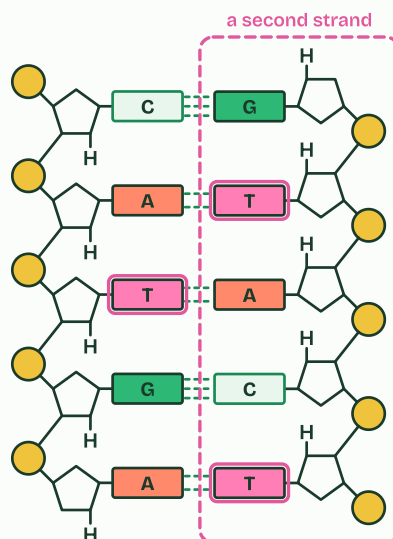
RNA that is a copy of a gene and is taken to a ribosome to be translated.

Transfer RNA

RNA that brings an amino acid to the ribosome. It folds back on itself and pairs with itself in places.

Ribosomal RNA

RNA that is part of every ribosome.

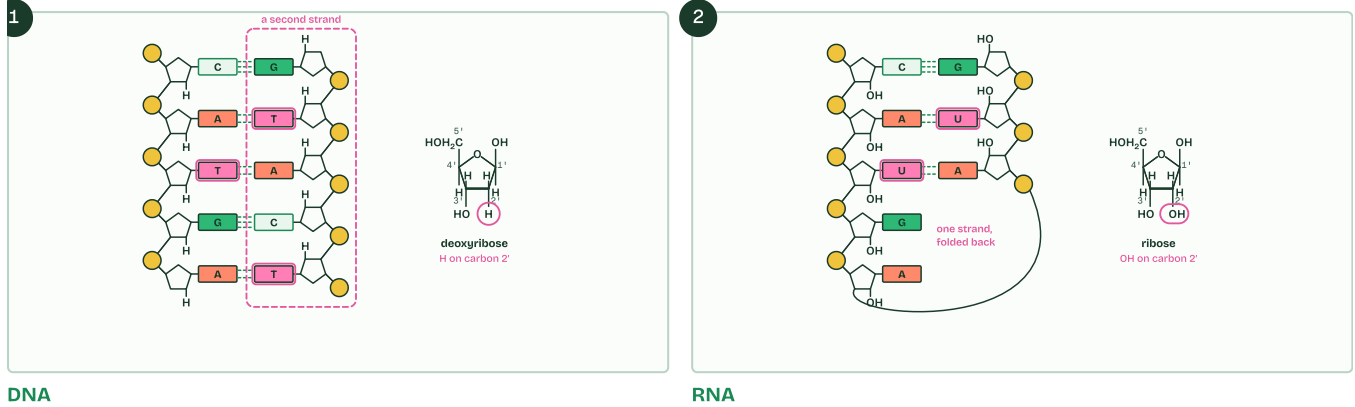


deoxyribose
H on carbon 2'

Switch between them. What differs from the other nucleic acid is outlined in pink.

SWITCH IT

2 SETTINGS



REMEMBER IT

The three differences between DNA and RNA

S Some	B Bananas	S Split
Sugar deoxyribose in DNA, ribose in RNA	Bases thymine in DNA, uracil in RNA	Strands two in DNA, usually one in RNA

LINKS

What makes RNA more likely than DNA to have been the first genetic material? A start: RNA can carry a base sequence and also act as a catalyst (some RNA molecules speed up reactions, as in the ribosome), so one molecule could have done both jobs. DNA is double-stranded and has no reactive OH on carbon 2, which makes it the steadier store, and that may be why it took over storage later. (A2.1, higher level.)

WATCH OUT

Deoxyribose still has its ring oxygen: the missing oxygen is the one on carbon 2. And RNA is not always a straight single strand: transfer RNA folds and pairs with itself.

PREDICT

A sample of nucleic acid is single-stranded and contains thymine but no uracil. What is it most likely to be?

- (A) DNA, from one of the few viruses with single-stranded DNA
- (B) RNA, because RNA is the nucleic acid that has only a single strand
- (C) A mixture of DNA and RNA, from a sample that has been contaminated

Decide before you look. Answer on page 126.

07

A1.2.9

A1.2.10

INFORMATION STORAGE AND THE GENETIC CODE

Endless sequences, *one* code

Along a strand any base can follow any other: the backbone sets no rule. And a DNA molecule can be any length. So any sequence, of any length, is possible. With four choices at every position the possibilities multiply very fast, as the slider shows. The capacity is, for every practical purpose, limitless.

That information is kept at the scale of molecules. Each human cell with a nucleus holds about 6 billion base pairs, two sets of about 3 billion, which would stretch to about 2 m if laid end to end. They are packed into a nucleus a few micrometres across. Chapter 10 shows how. (Red blood cells have no nucleus, so no DNA.) In one 2017 study, researchers stored computer files in DNA at about 215 petabytes per gram, in the laboratory.

Within a species, DNA sequences are almost the same, with small differences that are the source of different alleles. Between species they differ more. Same molecule, endless messages.

The **genetic code** is the set of rules by which a sequence of bases in messenger RNA is translated into a sequence of amino acids, three bases at a time. Each group of three is a **codon**. Almost every organism uses the same code: a codon means the same amino acid in a bacterium, a fungus, a plant and a human, with a few small variations, for example in mitochondria.

The code is arbitrary: no chemical law makes a given codon stand for a given amino acid. If life had begun separately several times, the codes would most likely differ. The best explanation for one shared code is that all life inherited it from a **universal common ancestor**. A code shared like that is **conserved** across life, and it is evidence of that shared ancestry. A gene moved from one species into another is read correctly because of it. You do not need to memorise examples: the one in the second figure is only an illustration.

That answers the first guiding question. A chain of simple units can store hereditary information because any order is possible, so the order can carry the message.

KEY TERMS

genetic code

The rules by which a sequence of bases in messenger RNA is translated into a sequence of amino acids, three bases at a time.

codon

A group of three bases in messenger RNA that stands for one amino acid.

universal common ancestor

The single ancestral population from which all living organisms are thought to be descended.

conserved

Kept the same through long periods of evolution.

$4 \times 4 \times 4 \dots (n \text{ times})$

$n = 1$ base

4

4 sequences



Slide to add bases. Each one multiplies the number of sequences by four.

SLIDE IT

8 SETTINGS

1

$4 \times 4 \times 4 \dots$ (n times)

n = 1 base

4

4 sequences



Bases in the sequence 0

2

$4 \times 4 \times 4 \dots$ (n times)

n = 2 bases

$4 \times 4 = 16$

16 sequences



Bases in the sequence 1

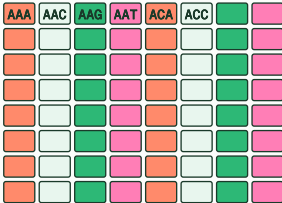
3

$4 \times 4 \times 4 \dots$ (n times)

n = 3 bases

$4 \times 4 \times 4 = 64$

64 sequences



Bases in the sequence 2

4

$4 \times 4 \times 4 \dots$ (n times)

n = 4 bases

$4 \times 4 \times 4 \times 4 = 256$

256 sequences



Bases in the sequence 3

5

$4 \times 4 \times 4 \dots$ (n times)

n = 10 bases

$4 \times 4 \times \dots \times 4$ (10 times)

1,048,576

about a million different sequences

Bases in the sequence 4

6

$4 \times 4 \times 4 \dots$ (n times)

n = 20 bases

$4 \times 4 \times \dots \times 4$ (20 times)

1,099,511,627,776

over a trillion different sequences

Bases in the sequence 5

7

$4 \times 4 \times 4 \dots$ (n times)

n = 100 bases

$4 \times 4 \times \dots \times 4$ (100 times)

about 1.6×10^{60}

a 1 followed by 60 zeros is not even close to the end of it

Bases in the sequence 6

8

$4 \times 4 \times 4 \dots$ (n times)

n = 1000 bases

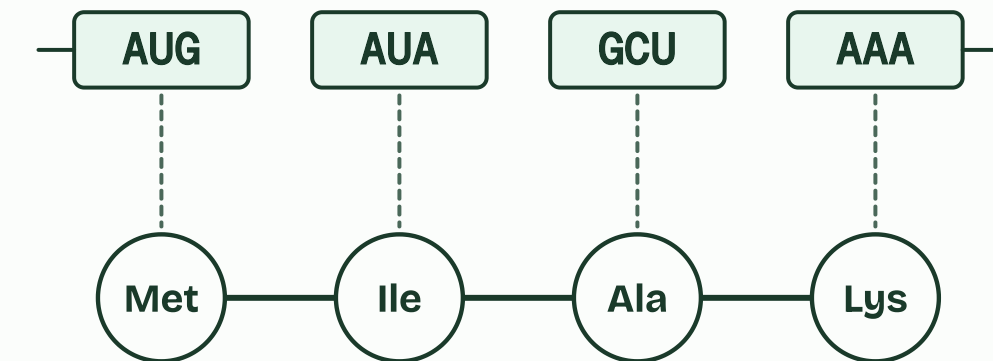
$4 \times 4 \times \dots \times 4$ (1,000 times)

a number with
603 digits

one DNA molecule can be this long and far longer

Bases in the sequence 7

Messenger RNA, read three bases at a time



Amino acids, joined into a chain

Read in a bacterium: Met, Ile, Ala, Lys

amino acid names need not be learned

The same messenger RNA read by five different ribosomes. One reader, the mitochondrion, differs in one codon.

SWITCH IT

5 SETTINGS

1

Messenger RNA, read three bases at a time

Amino acids, joined into a chain
Read in a bacterium: Met, Ile, Ala, Lys
amino acid names need not be learned

Bacterium

2

Messenger RNA, read three bases at a time

Amino acids, joined into a chain
Read in a yeast cell: Met, Ile, Ala, Lys
amino acid names need not be learned

Yeast

3

Messenger RNA, read three bases at a time

Amino acids, joined into a chain
Read in a wheat cell: Met, Ile, Ala, Lys
amino acid names need not be learned

Wheat

4

Messenger RNA, read three bases at a time

Amino acids, joined into a chain
Read in a human cell: Met, Ile, Ala, Lys
amino acid names need not be learned

Human cell

5

Messenger RNA, read three bases at a time

Amino acids, joined into a chain
Read in a human mitochondrion: Met, Met, Ala, Lys
One of the rare variations: the code is almost, not quite, universal.

Human mitochondrion

LINKS

One nucleotide holds no message. Join many and the strand has a sequence; pair two strands and the molecule can be copied. Storage and copying are properties of the polymer that its monomers do not have.

WATCH OUT

A universal code does not mean every organism has the same DNA. The dictionary is shared; the books written with it are different.

PREDICT

How many different sequences of three bases can DNA's four bases make?

- (A) 12
(B) 64
(C) 81

Decide before you look. Answer on page 126.

08

A1.2.11 HL DIRECTIONALITY

Every strand has a *direction*

The carbons of the pentose are numbered 1' to 5', said "one prime" to "five prime". The prime shows it is a carbon of the sugar and not an atom of the base. The base is on 1'. Carbon 2' carries the OH of ribose or the H of deoxyribose, 3' carries an OH, and 5', outside the ring, carries the phosphate.

In a strand, the phosphate on the 5' carbon of each nucleotide is bonded to the 3' carbon of the one before. So every link in the backbone runs the same way, and the strand has **directionality**. One end has a free phosphate on a 5' carbon, the **5' end**. The other has a free OH on a 3' carbon, the **3' end**. New nucleotides are only ever added at the 3' end, to its OH, so strands grow 5' to 3'.

Antiparallel can now be said exactly: one strand runs 5' to 3' and its partner runs 3' to 5' alongside it. A sequence is written 5' to 3', left to right, unless it is marked otherwise.

KEY POINTS

- **Replication.** Each new strand is built 5' to 3', so the two antiparallel templates are copied in opposite directions. (How that works at a replication fork is D1.1.)
- **Transcription.** RNA is built 5' to 3', so the enzyme moves along the template strand in that strand's 3' to 5' direction.
- **Translation.** A ribosome moves along messenger RNA from its 5' end towards its 3' end, so the codons are read in that order.

KEY TERMS

directionality

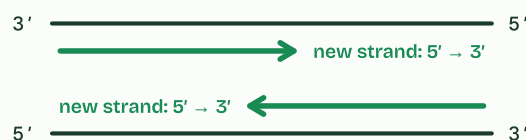
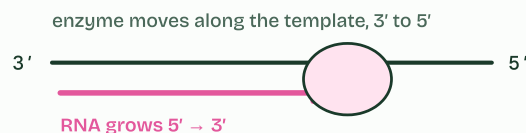
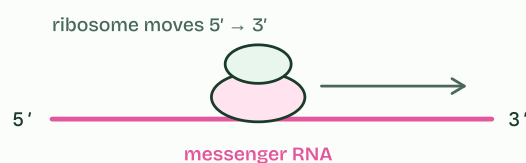
A strand has two different ends, so it runs one way: from its 5' end to its 3' end.

5' end

The end of a strand with a free phosphate on a 5' carbon.

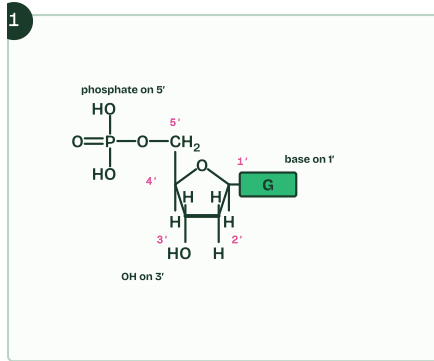
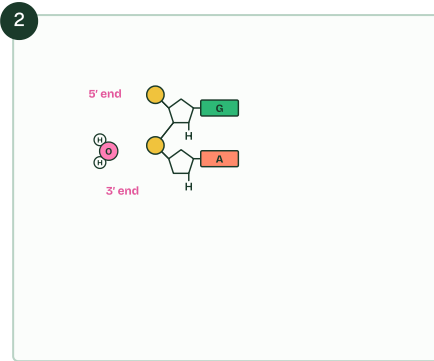
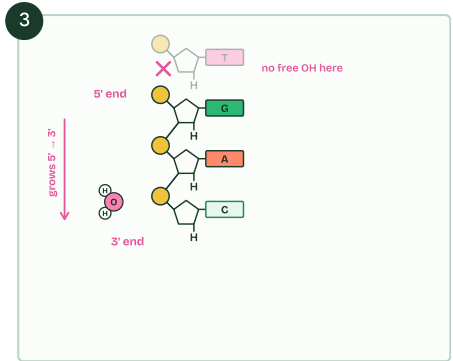
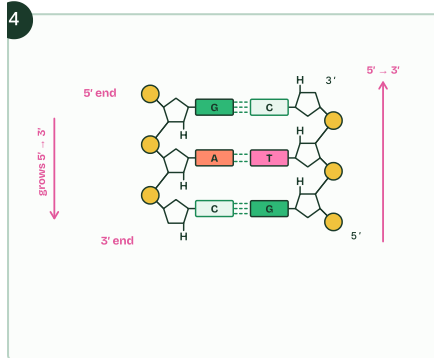
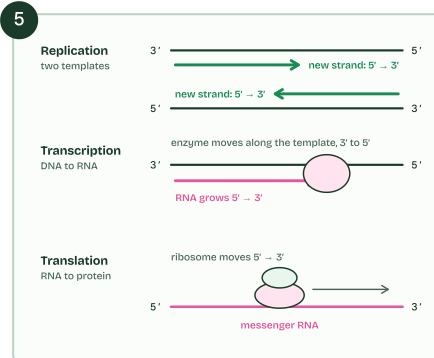
3' end

The end of a strand with a free OH on a 3' carbon. New nucleotides are added here.

Replication
two templates**Transcription**
DNA to RNA**Translation**
RNA to protein

STEP BY STEP

5 STEPS

Carbons **1' to 5'**.Each phosphate links a **5'** carbon to the **3'** carbon before it.New nucleotides join only at the **3' end**.The strands are **antiparallel**: one runs 5' to 3', the other 3' to 5'.So DNA is copied, transcribed and read in **one direction**.

WATCH OUT

5' and 3' name carbon atoms in the sugar. They are not positions along a gene. And new strands are built 5' to 3', which means their templates are read 3' to 5'.

PREDICT

One DNA strand reads 5'-ATGC-3'. Written 5' to 3', what is its partner?

- (A) 5'-TACG-3'
- (B) 5'-CGTA-3'
- (C) 5'-GCAT-3'

Decide before you look. Answer on page 126.

09

A1.2.12 HL PURINE-TO-PYRIMIDINE BONDING

A big base with a small *one*

Bases come in two shapes. **Purines** (adenine and guanine) have two rings fused together, one of six atoms and one of five. **Pyrimidines** (cytosine, thymine and uracil) have one ring of six.

Every base pair in DNA is one purine and one pyrimidine: A with T, G with C. So every pair is the same length. The two backbones stay the same distance apart all along, and the helix has the same width and the same three-dimensional shape whatever the sequence.

That matters. The helix is regular and stable along its whole length, and any sequence fits the same structure, so the sequence is free to carry information (chapter 7). Proteins that work along DNA, such as the histones of chapter 10 and the enzymes that copy and read it, meet the same shape everywhere.

Two purines would be too wide for the gap, and two pyrimidines too narrow to reach across with hydrogen bonds. A purine with the wrong pyrimidine (A with C, or G with T) is the right length, but its hydrogen bonds do not line up (chapter 4). Try each pairing in the figure.

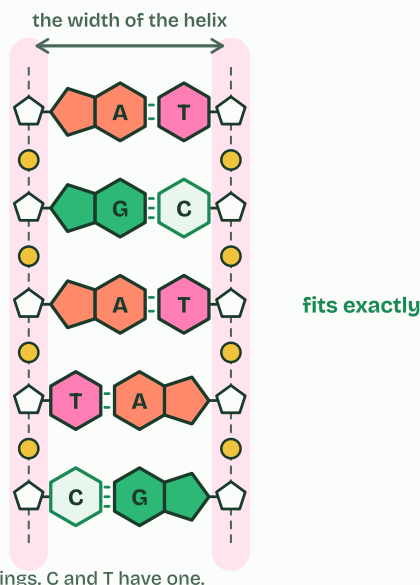
KEY TERMS

purines

Bases with two rings fused together, one of six atoms and one of five. Adenine and guanine are purines.

pyrimidines

Bases with a single ring of six atoms. Cytosine, thymine and uracil are pyrimidines.



A and G have two rings. C and T have one.

Change the middle pair. The ring shapes are drawn only here: at standard level every base is a plain rectangle.

SWITCH IT

5 SETTINGS

1

A with T

2

G with C

3

A with G

4

C with T

5

A with C

REMEMBER IT

Which bases are purines

P Pure Purines two rings	A As Adenine a purine	G Gold Guanine a purine	C CUT Pyrimidines cytosine, uracil, thymine: one ring
--	---	---	---

WATCH OUT

There is no "big pair" and "small pair". Every pair is one big base and one small one, so every pair is the same size.

PREDICT

30% of the bases in a sample of double-stranded DNA are adenine. What percentage are purines?

- (A) 30%
- (B) 50%
- (C) 60%

Decide before you look. Answer on page 126.

10

A1.2.13 HL STRUCTURE OF A NUCLEOSOME

Wound on a *spool*

In eukaryotes, the DNA in the nucleus is wound around proteins called **histones**. A **nucleosome** is a core of eight histone proteins with DNA wrapped round it, just under two turns, and one more histone attached to the **linker DNA** where the DNA enters and leaves, holding the wrapped DNA in place. The linker DNA runs on to the next nucleosome: beads on a string.

Wound this way, about 2 m of DNA fits into a nucleus. The cell can also control which stretches can be read: tags on histones are D2.2. How do the histones hold the DNA on? That is the prediction below.

KEY TERMS

histones

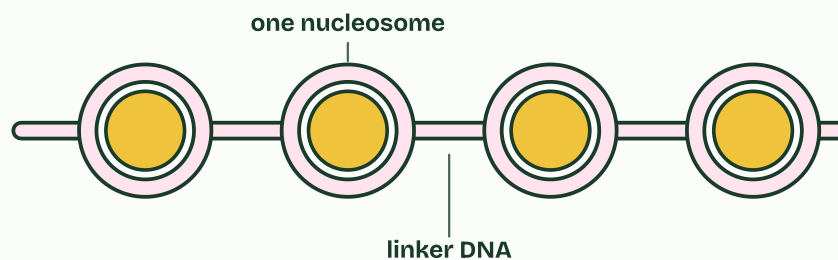
Proteins that DNA is wound around in the nuclei of eukaryotic cells.

nucleosome

A core of eight histone proteins with DNA wrapped round it, and one more histone attached to the linker DNA to hold it in place.

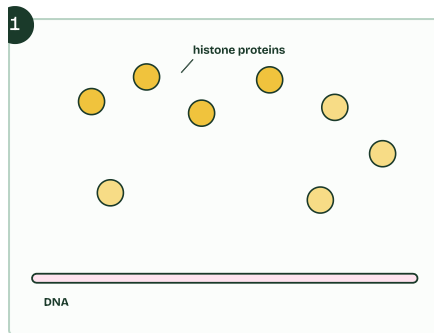
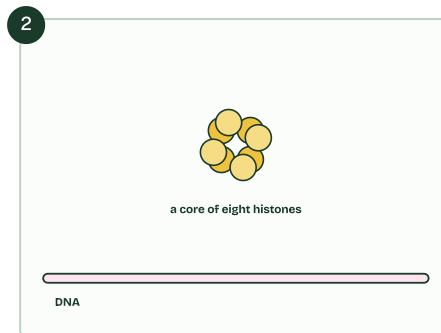
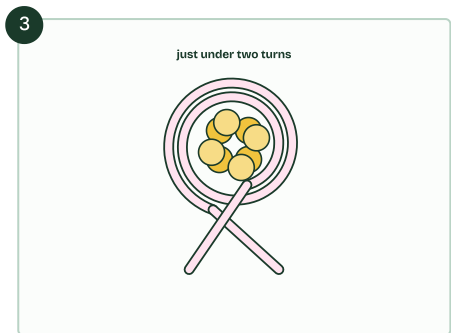
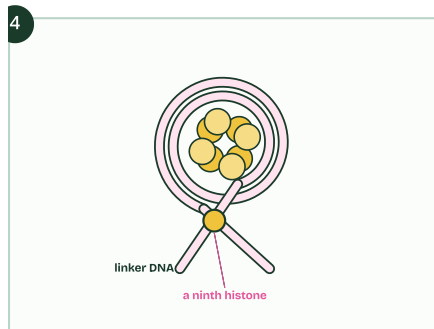
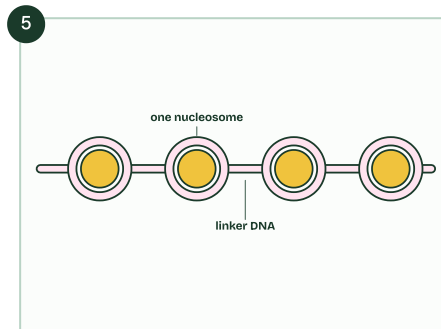
linker DNA

The stretch of DNA that leads into and out of a nucleosome and runs on to the next one.



STEP BY STEP

5 STEPS

DNA and **histone** proteins.**Eight** histones form a core.The DNA wraps round the core, just under **two turns**.A **ninth** histone, on the linker DNA, holds it in place.**Nucleosomes** along the DNA, like beads on a string.

TRY IT

Best on a laptop. The links open in a new tab.

1. Open the nucleosome core particle entry 1KX5 on the RCSB Protein Data Bank and open its 3D view.
2. Colour by chain. Count the protein chains in the core and the strands of DNA.
3. The eight proteins come as two copies each of four kinds: find each pair.
4. Where does the DNA touch the proteins: at its bases, or at its backbone?
5. Select the lysine and arginine residues and show them as sticks. Where do they point? Find the histone tails reaching out between the turns of DNA.
6. Count the turns of DNA round the core.
7. Is there a ninth histone in this structure? (In a core particle, no: the linker DNA was trimmed off before it was crystallised.) Open an entry that includes a linker histone, such as 4QLC, and find it. On a phone the 3D viewer needs a bigger screen. Answer these from the figure instead: how many histones are in the core, how many turns of DNA wrap round it, and where does the ninth histone sit?

PREDICT

A chemical is added that cancels the negative charges on DNA's phosphate groups. What would you expect to happen to the nucleosomes?

- (A) The DNA would grip the histones even more tightly than before
- (B) Nothing would change, because histones hold the bases and not the phosphates
- (C) The DNA would come away from the histones more easily

Decide before you look. Answer on page 126.

WATCH OUT

The DNA is not wrapped round one histone, and the ninth histone is not in the core: eight in the core, one on the linker DNA. Histones hold DNA by charge, not by base pairing.

11

A1.2.14 HL EVIDENCE FROM THE HERSHEY-CHASE EXPERIMENT

Hershey and Chase: which one carries the genes?

In 1952 nobody knew whether genes were made of protein or of DNA. Many expected protein: proteins are built from 20 different amino acids and vary hugely, while DNA, with only four bases, looked too simple (chapter 12 tells that story).

Alfred Hershey and Martha Chase used a **bacteriophage** called T2, a virus that infects the bacterium *E. coli*. T2 is made of only two things: a protein coat, and DNA inside it. It attaches to a bacterium and injects its genetic material, and the bacterium then makes new phages. So whatever goes into the cell is the genetic material.

They needed a way to tell the two apart. Protein contains **sulfur**, in the amino acids cysteine and methionine, but almost no phosphorus. DNA contains **phosphorus**, in its phosphate groups, but no sulfur. So phages grown with radioactive sulfur-35 had labelled protein coats, and phages grown with radioactive phosphorus-32 had labelled DNA. A **radioisotope** gives itself away by its radiation.

Each batch of labelled phages infected unlabelled bacteria. After a few minutes a blender shook the phage coats off the bacteria. A centrifuge then spun the mixture: the heavier bacteria formed a **pellet** at the bottom, and the light phage coats stayed in the liquid above, the **supernatant**. The radioactivity in each was measured. Predict what they found before you read on.

KEY TERMS

bacteriophage

A virus that infects bacteria. T2, the one used here, is a protein coat with DNA inside.

radioisotope

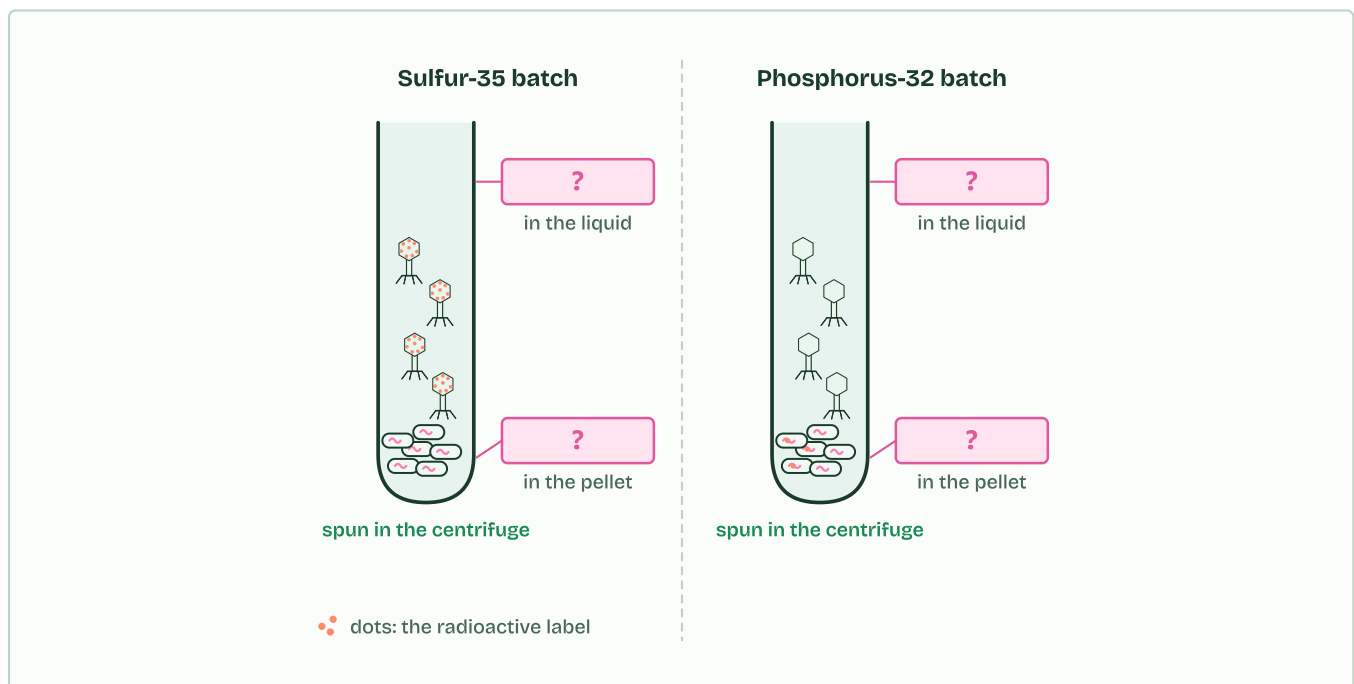
A form of an element whose atoms give out radiation, so they can be detected and followed.

pellet

The solid that collects at the bottom of a tube after centrifuging. Here it was the bacteria.

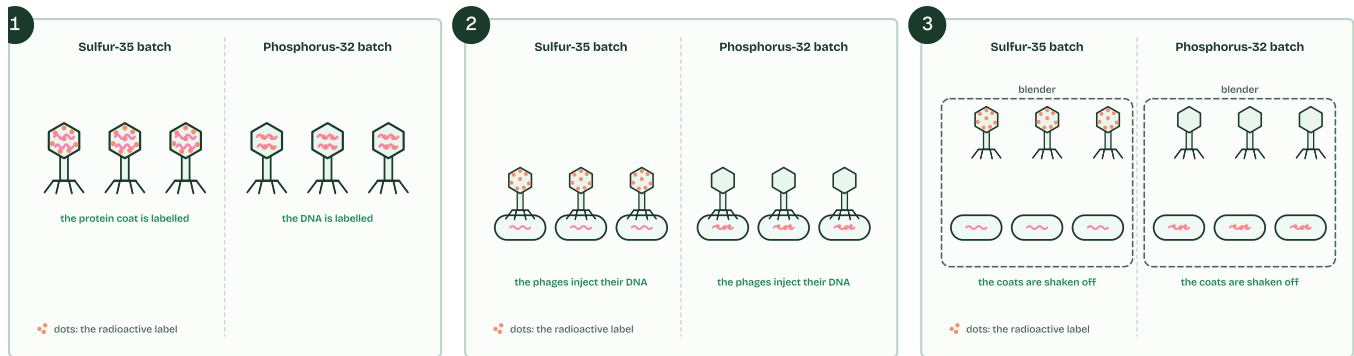
supernatant

The liquid above the pellet after centrifuging.



STEP BY STEP

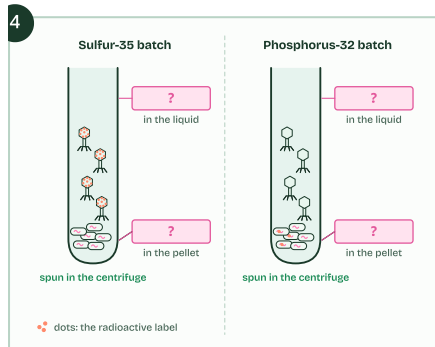
4 STEPS



Sulfur labels the protein coat; **phosphorus** labels the DNA.

The phage **injects** its genetic material.

The **blender** shakes the coats off.



The **centrifuge**: bacteria in the pellet, coats in the liquid.

PREDICT

After blending and spinning, where will most of the radioactivity be in each batch?

- (A) Both in the pellet: the whole phage goes into the bacterium
- (B) Sulfur-35 in the pellet, phosphorus-32 in the liquid
- (C) Sulfur-35 in the liquid, phosphorus-32 in the pellet

Decide before you look. Answer on page 126.

EVIDENCE, NOT PROOF

Some sulfur-35 stayed with the bacteria, and not all the phosphorus-32 went in, so the result was not perfectly clean. It persuaded most biologists, alongside other evidence and, a year later, the double helix.

WHY 1952?

Technology opens up new experiments. This one needed a way to tag protein and DNA separately, and radioisotopes only became widely available to biologists after the Second World War, made in nuclear reactors.

WATCH OUT

Sulfur labels the protein, phosphorus the DNA: swapping them is the commonest slip. The pellet is the bacteria, not the viruses. And the experiment showed that DNA is the genetic material of T2; saying the same of all life is a generalisation, which is chapter 12's subject.

12

A1.2.15 HL CHARGAFF'S DATA

Chargaff's numbers: one result can *falsify*

From the late 1940s Erwin Chargaff took DNA from many organisms, broke it into its bases, separated them and measured how much of each there was.

He found two things. First, in every species the amount of A is about equal to the amount of T, and the amount of G about equals C, so purines (A + G) equal pyrimidines (C + T). Second, the proportions differ from species to species: some DNA is rich in A and T, some in G and C, while different tissues of one species give the same proportions.

The leading idea until then was the **tetranucleotide hypothesis**, from the early 1900s: that DNA is a monotonous repeat of the four nucleotides in equal amounts. It predicts 25% of each base in every species, and a molecule too simple to carry information.

Chargaff's equalities had no explanation until the double helix, in which A pairs with T and G with C. A virus with single-stranded DNA, such as phiX174, does not show A = T: as expected, if the rule comes from pairing. Try the figure's switches, then predict.

KEY TERMS

tetranucleotide hypothesis

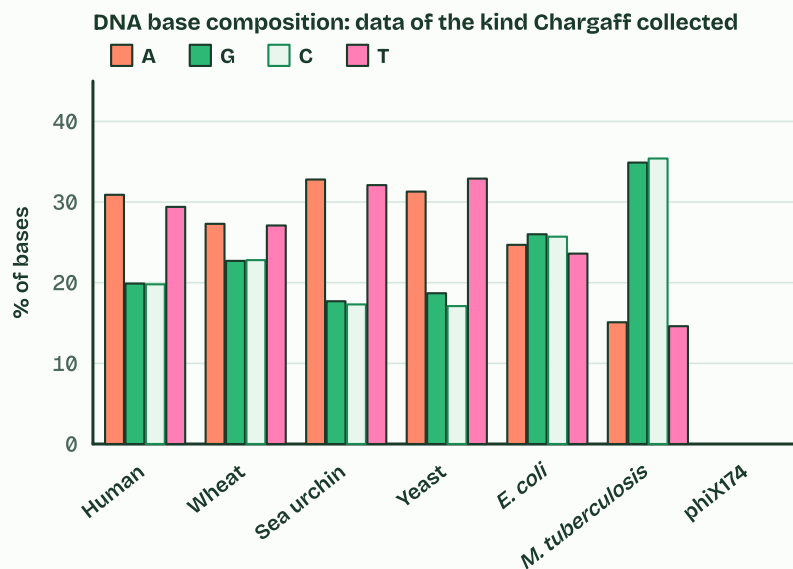
The early idea that DNA is a dull repeat of the four nucleotides in equal amounts, so 25% of each base in every species.

problem of induction

The problem that no number of observations can make a general claim certain, because the next one might differ.

certainty of falsification

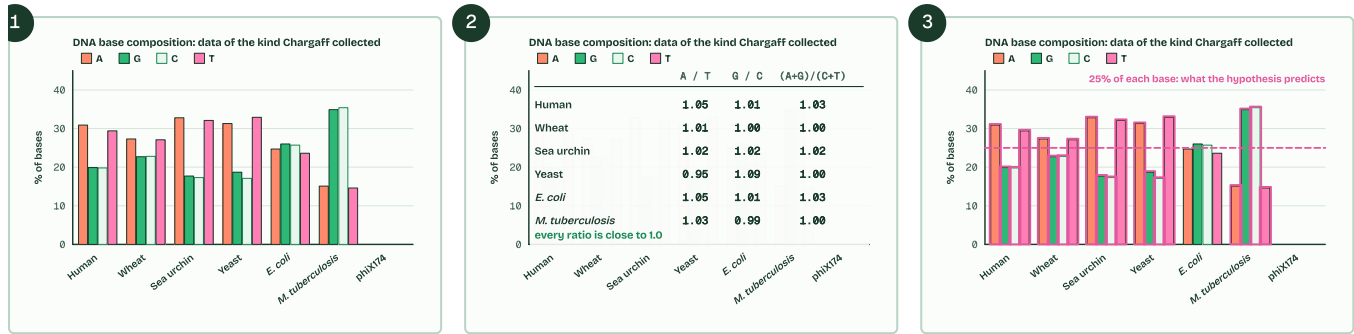
A single reliable result that contradicts a hypothesis shows with certainty that the hypothesis is wrong.



Percent of each base in the DNA of seven species, the kind of analysis Chargaff began. The values are as tabulated in biochemistry textbooks, rounded to one decimal place.

SWITCH IT

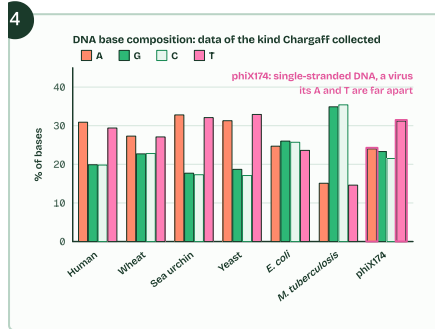
4 SETTINGS



Bases

Ratios

The hypothesis



Add a virus

PREDICT

The tetranucleotide hypothesis says every DNA molecule is 25% of each base. Which result would be enough, on its own, to falsify it?

- (A) A thousand different species, in every one of which the amount of A equals the amount of T
- (B) One species whose DNA is reliably measured as 30% adenine
- (C) One species whose DNA is measured as exactly 25% of each of the four bases

Decide before you look. Answer on page 126.

WATCH OUT

Chargaff's rule is $A = T$ and $G = C$. It is not $A = G$, and not $A + T = G + C$. It holds for double-stranded DNA, not for one strand on its own.

INDUCTION AND FALSIFICATION

However many species show A equal to T, you cannot be certain the next one will: a generalisation from observations is never certain. That is the **problem of induction**. But one reliable result that contradicts a claim is enough to reject it. A claim can be falsified with certainty in a way it can never be proved: that is the **certainty of falsification**. It is how Chargaff's data settled the tetranucleotide question without anyone testing every species.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

3' end 08

The end of a strand with a free OH on a 3' carbon. New nucleotides are added here.

5' end 08

The end of a strand with a free phosphate on a 5' carbon.

adenine 04

One of the four bases of DNA, written A. It pairs with thymine (uracil in RNA).

antiparallel 05

Running in opposite directions, like the two lanes of a road.

bacteriophage 11

A virus that infects bacteria. T2, the one used here, is a protein coat with DNA inside.

base pair 05

Two bases, one from each strand, held together by hydrogen bonds: A with T or G with C.

base sequence 04

The order of the bases along a strand of DNA or RNA.

certainty of falsification 12

A single reliable result that contradicts a hypothesis shows with certainty that the hypothesis is wrong.

codon 07

A group of three bases in messenger RNA that stands for one amino acid.

complementary base pairing 04

The rule that each base pairs with one particular other base: A with T (or U), and C with G.

condensation 03

A reaction that joins two molecules and releases a molecule of water.

conserved 07

Kept the same through long periods of evolution.

covalent bond 03

A bond in which two atoms share a pair of electrons. Covalent bonds are strong.

cytosine 04

One of the four bases of DNA, written C. It pairs with guanine.

deoxyribose 06

The pentose sugar in DNA. It has an H on carbon 2 where ribose has an OH.

directionality 08

A strand has two different ends, so it runs one way: from its 5' end to its 3' end.

DNA 01

Deoxyribonucleic acid: the nucleic acid that is the genetic material of all living organisms.

double helix 05

The shape of DNA: two strands wound round each other in a spiral.

gene 01

A stretch of a DNA molecule: a particular base sequence that carries one piece of information.

genetic code 07

The rules by which a sequence of bases in messenger RNA is translated into a sequence of amino acids, three bases at a time.

genetic material 01

The molecule that carries the instructions an organism inherits. It is copied each time a cell divides and passed from parents to offspring.

guanine 04

One of the four bases of DNA, written G. It pairs with cytosine.

histones 10

Proteins that DNA is wound around in the nuclei of eukaryotic cells.

hydrogen bonds 04

Weak attractions between a slightly positive hydrogen atom on one molecule and a slightly negative atom on another.

hydrolysis 03

A reaction in which a bond is broken by adding a molecule of water.

linker DNA 10

The stretch of DNA that leads into and out of a nucleosome and runs on to the next one.

Messenger RNA 06

RNA that is a copy of a gene and is taken to a ribosome to be translated.

monomer 02

One small unit of a polymer. The monomer of a nucleic acid is the nucleotide.

nitrogenous base 02

A ring of carbon and nitrogen atoms that is the part of a nucleotide that varies. Its order along a strand is the message.

nucleic acids 01

Polymers built from nucleotides. DNA and RNA are the two nucleic acids.

nucleosome 10

A core of eight histone proteins with DNA wrapped round it, and one more histone attached to the linker DNA to hold it in place.

nucleotide 02

The monomer of nucleic acids: a phosphate group, a pentose sugar and a nitrogenous base joined together.

pellet 11

The solid that collects at the bottom of a tube after centrifuging. Here it was the bacteria.

pentose 02

A sugar with five carbon atoms.

phosphate group 02

A phosphorus atom with oxygen atoms round it. In a cell it carries a negative charge.

polymers 02

Long molecules built from many copies of a small unit, joined in a chain.

problem of induction 12

The problem that no number of observations can make a general claim certain, because the next one might differ.

purines 09

Bases with two rings fused together, one of six atoms and one of five. Adenine and guanine are purines.

pyrimidines 09

Bases with a single ring of six atoms. Cytosine, thymine and uracil are pyrimidines.

radioisotope 11

A form of an element whose atoms give out radiation, so they can be detected and followed.

replication 04

Copying a DNA molecule to make two molecules with the same base sequence.

ribose 06

The pentose sugar in RNA. It has an OH on carbon 2.

Ribosomal RNA 06

RNA that is part of every ribosome.

RNA 01

Ribonucleic acid: the other nucleic acid. It has several jobs in cells, and in some viruses it is the genetic material.

strand 03

One chain of nucleotides, also called a polynucleotide.

sugar–phosphate backbone 03

The chain of alternating sugars and phosphates, joined by covalent bonds, that runs along a nucleic acid strand.

supernatant 11

The liquid above the pellet after centrifuging.

template 04

A strand that new nucleotides pair with, so the new strand has the complementary sequence.

tetranucleotide hypothesis 12

The early idea that DNA is a dull repeat of the four nucleotides in equal amounts, so 25% of each base in every species.

thymine 04

A base found in DNA, written T. It pairs with adenine.

transcription 04

Making an RNA copy of a gene, using one DNA strand as the template.

Transfer RNA 06

RNA that brings an amino acid to the ribosome. It folds back on itself and pairs with itself in places.

translation 04

Making a chain of amino acids by reading the codons of messenger RNA.

universal common ancestor 07

The single ancestral population from which all living organisms are thought to be descended.

uracil 04

A base found in RNA, written U, in the place of thymine. It pairs with adenine.

viruses 01

Tiny particles of genetic material inside a protein coat. A virus has no cells and can only be copied inside a host cell.



Check yourself

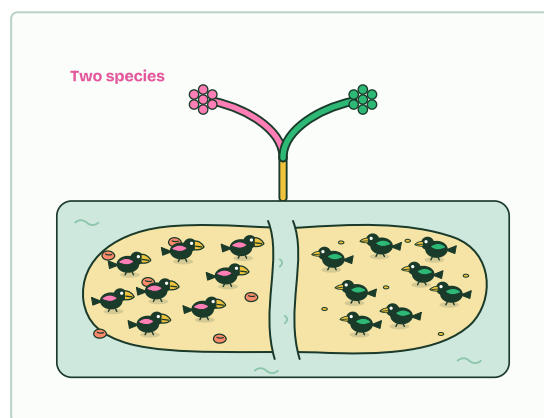
The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on A1.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

[biologybybradford.com/exam-maker/sit?
topics=A1.2&level=HL&paper=quiz&marks=15&src=ep](https://biologybybradford.com/exam-maker/sit?topics=A1.2&level=HL&paper=quiz&marks=15&src=ep)

How one species becomes *two*

Evolution and speciation

Every species alive today began as part of another. Here is the evidence that life evolves, from DNA to the bones in your arm, and how a river, a season or a doubled set of chromosomes can split one species into two.



By the end you can

- ☐ Explain why evolution is a change in the heritable characteristics of a population, and why a change gained in one lifetime is not A4.1.1
- ☐ Use differences in base and amino acid sequences to judge which species share the most recent common ancestor A4.1.2
- ☐ Explain how crops and domestic animals show how quickly heritable characteristics can change A4.1.3
- ☐ Name the bones of the pentadactyl limb and tell homologous structures from analogous ones made by convergent evolution A4.1.4, A4.1.5
- ☐ Explain why splitting is the only way new species arise, and why gradual change in one line is not speciation A4.1.6
- ☐ Explain how reproductive isolation and differential selection split bonobos from common chimpanzees A4.1.7
- ☐ Compare allopatric and sympatric speciation, and explain how adaptive radiation fills vacant niches A4.1.8, A4.1.9
- ☐ Explain why a mule is sterile, and how hybridisation and polyploidy make a new plant species at once A4.1.10, A4.1.11

Tick each one when you can do it without the book.

A4.1.1 WHAT EVOLUTION IS

01 Evolution is a change in what a population inherits

Evolution is not something one animal does in its lifetime. It is a change, over generations, in the **heritable characteristics** of a **population**. Genes carry those characteristics, so evolution shows up as some alleles becoming more common and others rarer.

The figure follows a real case. In 1977 a drought on Daphne Major, a tiny Galápagos island, left mostly big, hard seeds. Medium ground finches with deep beaks could crack them; many with shallow beaks starved. The survivors bred, their chicks inherited their alleles, and the next generation's beaks were about 4% deeper on average. No finch changed its own beak. The population changed, because some birds left more offspring than others.

KEY TERMS

heritable characteristics

Characteristics passed from parents to offspring in their genes, as alleles.

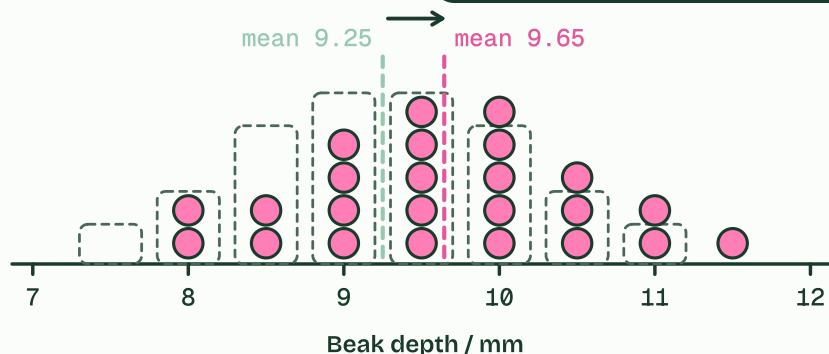
population

All the organisms of one species living in one area at the same time, able to breed with each other.

Generation 2

the population has changed:
beaks about 4% deeper on average

--- generation 1



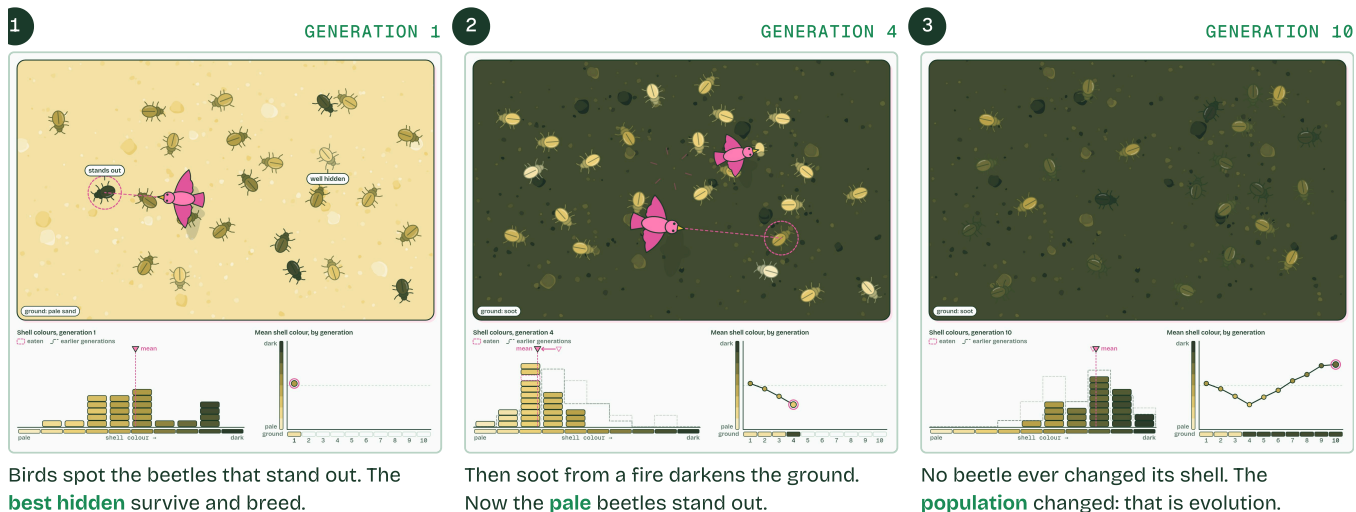
STEP BY STEP

5 STEPS



ANIMATION · WATCH IT HAPPEN: A POPULATION CHANGES

3 MOMENTS

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-a4-1-evolution-and-speciation#heritable

WATCH OUT

A change gained during a life is not passed on: a finch's chipped beak, a weightlifter's muscles, a giraffe stretching for leaves. None of these changes the alleles in eggs or sperm. Lamarck thought such changes were inherited; they are not, and they are not evolution.

WHY "THEORY"?

Evolution by natural selection explains and predicts a vast range of observations, and nothing found so far contradicts it. But science cannot prove an idea true by checking it against the whole world; it can only fail to disprove it. So it is called a theory: a pragmatic truth, true for every practical purpose and very unlikely ever to be overturned.

PREDICT

A gardener clips a hedge into a perfect cube every year for 40 years. Seeds from the hedge are sown. What shape do the seedlings grow into?

- ☐ (A) Cubes: forty years of clipping is long enough for the shape to be inherited
- ☐ (B) Slightly squarer than usual: a little of each year's change is passed on
- ☐ (C) The usual shape for the species: clipping never touched their alleles

Decide before you look. Answer on page 127.

02

A4.1.2 EVIDENCE FROM SEQUENCES

Sequences remember *common ancestors*

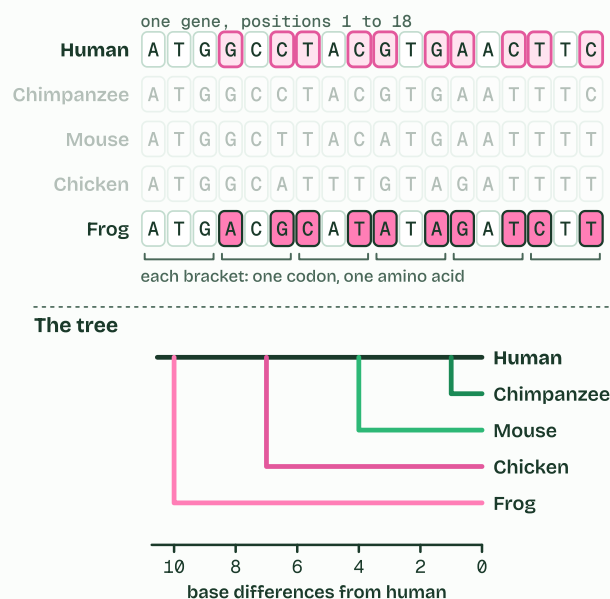
Every living thing keeps its genes in DNA, and almost all of them read it with the same genetic code. That shared machinery already points to one common ancestor. The sequences themselves hold the detail.

When a species splits in two, each new line copies its own DNA, and mutations build up separately in each. So the longer ago two species shared an ancestor, the more differences there are between the same gene in each. Compare one gene across species, count the differences, and the fewest differences mark the closest relatives.

Base sequences, in DNA or RNA, change faster than the amino acid sequences of the proteins they code for. Most amino acids have several codons, so many base changes leave the protein the same. Switch the figure to amino acids and some differences vanish: base sequences sort out close relatives, amino acid sequences reach further back.

KEY POINTS

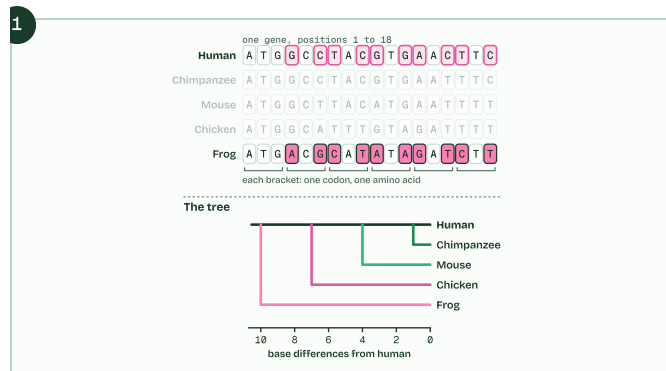
- Fewer differences: a more recent common ancestor.
- Different genes and different proteins give largely the same branching pattern, and so does the fossil record. Independent lines of evidence agreeing is what makes this powerful.



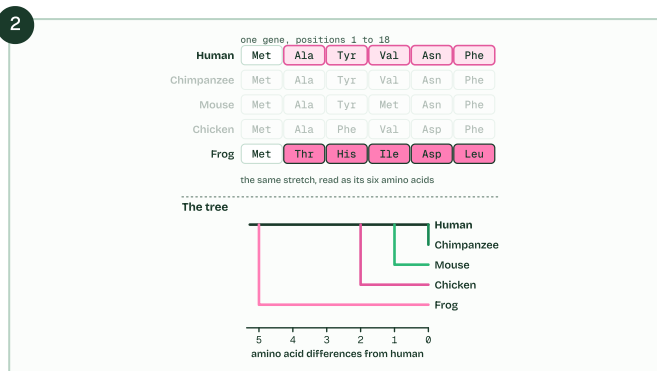
A made-up 18-base stretch of one gene, built the way real comparisons turn out. Real ones use thousands of bases and give the same pattern.

SWITCH IT

2 SETTINGS



Bases



Amino acids

EXAMPLE

Cytochrome c, a protein every aerobic cell uses, is 104 amino acids long in humans. A chimpanzee's is identical, a rhesus monkey's differs at one position, and a yeast's at more than 40.

WATCH OUT

Similar sequences do not mean one living species came from the other. Humans did not evolve from chimpanzees: both evolved from an ancestor that lived about 6 to 7 million years ago, and both lines have changed since.

PREDICT

Before you compare: which species' sequence will differ from the human one at the most positions?

- (A) Chimpanzee
- (B) Mouse
- (C) Chicken
- (D) Frog

Decide before you look. Answer on page 127.

03

A4.1.3 EVIDENCE FROM SELECTIVE BREEDING

Six vegetables, one wild *weed*

Wild cabbage grows on sea cliffs in western Europe: a straggly, leafy plant with yellow flowers. Over the last few thousand years, farmers kept seed only from the plants they liked best. This is **selective breeding**.

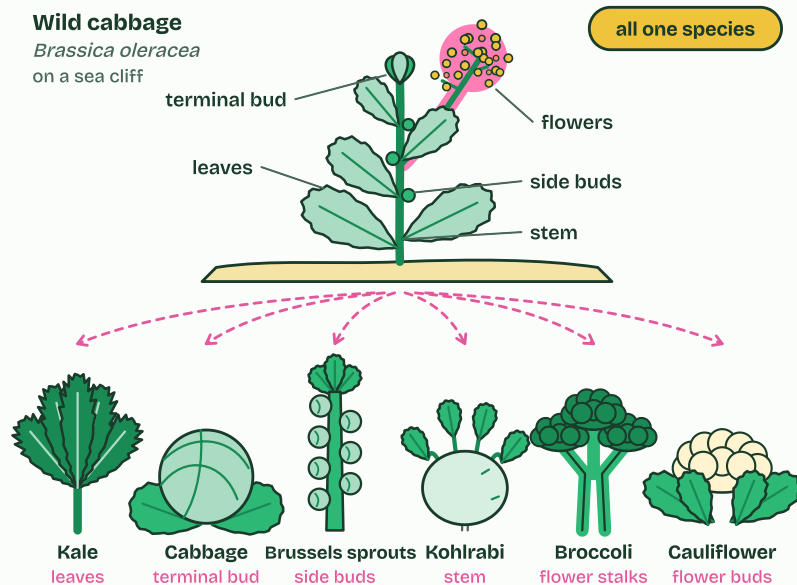
Choose the plants with the biggest leaves, generation after generation, and you get kale. Choose a fat terminal bud and you get cabbage; fat side buds, Brussels sprouts; a swollen stem, kohlrabi; thick flower stalks, broccoli; a dense mass of flower buds, cauliflower. Every one is still *Brassica oleracea*.

Why is this evidence for evolution? The cultivars differ from each other, and from wild cabbage, far more than the wild plant varies, and the changes are heritable: their seeds grow true. People choosing which plants breed changed a species this much in a few thousand years. Natural selection, choosing by survival and reproduction over millions of years, can change species far more.

KEY TERMS

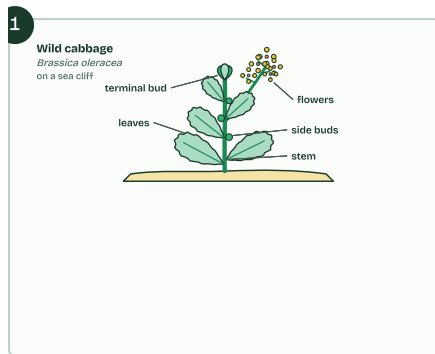
selective breeding

Humans choosing which plants or animals breed, so the characteristics they want become commoner in each generation. Also called artificial selection.

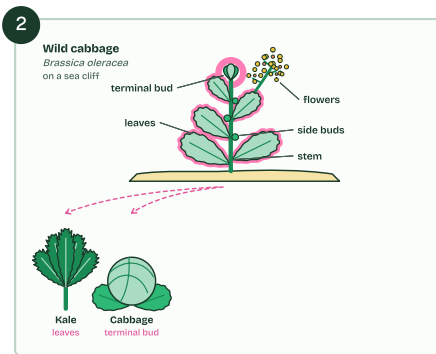


STEP BY STEP

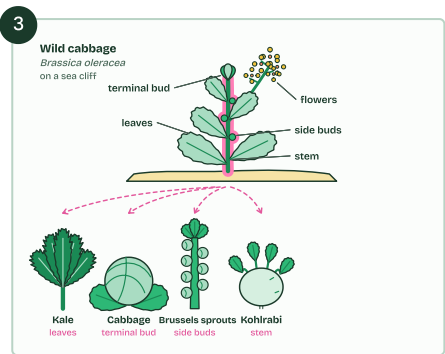
4 STEPS



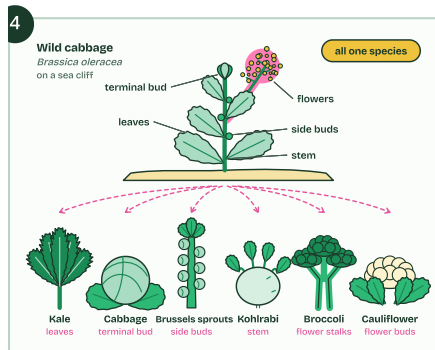
Wild cabbage: **leaves**, buds at the tip and along the stem, and yellow flowers.



Selected for **leaves**: kale. Selected for a big **terminal bud**: cabbage.



Selected for **side buds**: brussels sprouts. Selected for a swollen **stem**: kohlrabi.



Selected for **flower stalks and buds**: broccoli and cauliflower. All six can still interbreed: **one species**.

EXAMPLE

Maize was bred from teosinte, a wild grass of Mexico. A teosinte ear holds fewer than a dozen kernels, each in a stone-hard case; a cob of maize holds hundreds of soft ones. Dogs were domesticated from wolves more than 15,000 years ago, and most of today's breeds, from chihuahua to Great Dane, were bred in the last few hundred years.

WATCH OUT

Dog breeds and cabbage cultivars look like different species but are not: a chihuahua and a Great Dane share one gene pool, which their alleles can still cross through dogs of in-between sizes. Selective breeding shows how fast heritable characteristics can change. It is not an example of new species forming.

REMEMBER IT

The three lines of evidence for evolution in A4.1

D Darwin's DNA and protein sequences fewer differences, closer relatives	B Big Breeding big heritable changes, fast	H Hunch Homologous structures one bone plan, many jobs
--	--	--

PREDICT

Kohlrabi and Brussels sprouts look nothing alike. A grower lets them cross-pollinate. What happens?

- ☐ A No seeds form at all: by now they are different species
- ☐ B Seeds form and grow into fertile plants: one species
- ☐ C Seeds form but grow into sterile plants, like a mule

Decide before you look. Answer on page 127.

04

A4.1.4

A4.1.5

HOMOLOGOUS AND ANALOGOUS STRUCTURES

Same bones, different jobs, and the *reverse*

Your arm, a bat's wing, a whale's flipper and a horse's front leg do very different jobs. Inside, they are built from the same bones in the same order: one upper arm bone, two in the forearm, a block of wrist bones, a row of palm bones, then the digits. This shared plan is the **pentadactyl limb**, and structures built on a plan inherited from a common ancestor are **homologous structures**.

No engineer would build a wing, a paddle and a leg from the same parts. Evolution does not design from scratch: it modifies what an ancestor already had. The shared plan makes sense only if all four limbs were inherited from one common ancestor, an early four-legged vertebrate, and each line then modified it for its own way of life.

Now switch the figure. A bird's wing and an insect's wing both fly, but one is a forelimb full of bones and the other a thin fold of the body wall with no bones at all. Features with the same function but different evolutionary origins are **analogous structures**, and they arise by **convergent evolution**: unrelated lines meeting similar demands with similar solutions. The camera eyes of octopuses and vertebrates are another pair.

KEY TERMS

pentadactyl limb

The limb plan of amphibians, reptiles, birds and mammals: one upper bone, two lower bones, wrist or ankle bones, then up to five digits.

homologous structures

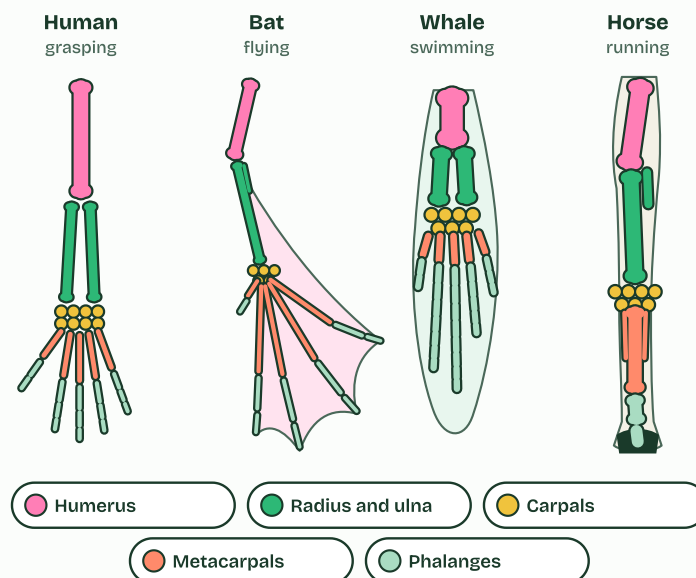
Structures built on one plan inherited from a common ancestor, whatever job each one now does.

analogous structures

Structures that do the same job but evolved separately in each line, so they were not inherited in that form from a common ancestor.

convergent evolution

Unrelated lines evolving similar features because they face similar demands, such as flight or swimming.



Humerus One upper arm bone, in every limb. Short and thick in the whale, a strut for the wing in the bat.

Carpals A block of small wrist bones: eight in your wrist. In the horse they make the joint people call its knee.

Radius and ulna Two forearm bones. In the horse they have fused into one strong support, with only the top of the ulna (the point of the elbow) still clear; in the bat the ulna is a thin splint.

Metacarpals The palm bones. Very long in the bat, holding the wing out. The horse stands on one, the cannon bone, with two thin splint bones beside it: what is left of two more.

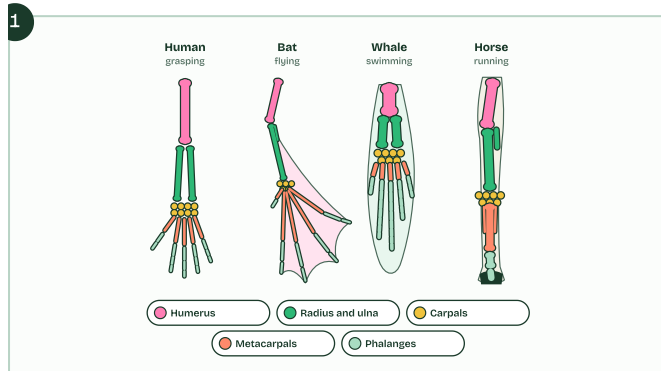
Phalanges The finger bones. Long and spread in the bat, extra ones in the whale, and in the horse just three in a single digit, the last inside the hoof.

Insect wing No bones and no muscles inside: a thin double layer of cuticle, the insect's outer skeleton, stiffened by veins. Muscles in the thorax drive it.

Bird wing A forelimb: humerus, radius and ulna, wrist and hand bones (fewer digits, partly fused), with feathers for the flight surface. It is homologous with your arm.

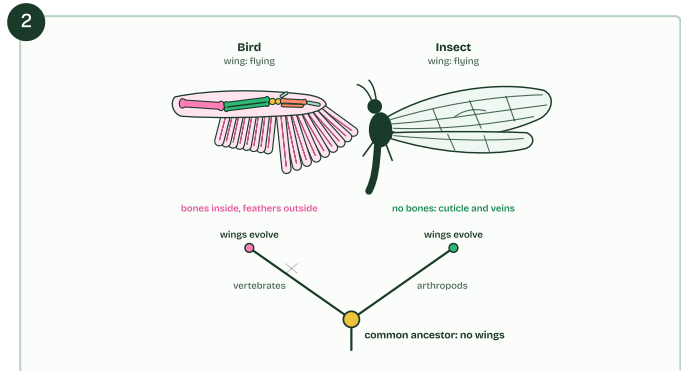
Their last common ancestor A small animal living more than 550 million years ago, with no wings at all. Wings evolved separately in the two lines, from different starting parts: convergent evolution.

SWITCH IT



Homologous

2 SETTINGS



Analogous

WATCH OUT

Penguin, turtle and whale flippers are often given as analogous structures, but all three are forelimbs with the pentadactyl bones inside: homologous as limbs, with only the flipper shape converging. And "pentadactyl" names the plan, not a count: the horse has one digit left, on the same plan.

REMEMBER IT

The pentadactyl limb, shoulder to fingertip

H Hungry	R Rats	C Chew	M My	P Pencils
Humerus upper arm, one bone	Radius and ulna forearm, two bones	Carpals wrist	Metacarpals palm	Phalanges fingers

PREDICT

A bat's wing and a bird's wing: homologous or analogous?

- (A) Analogous only: they look different and are built differently
- (B) Homologous only: both are forelimbs, so nothing about them converged
- (C) Both: homologous as forelimbs, analogous as wings for flight

Decide before you look. Answer on page 127.

05

A4.1.6 SPECIATION

New species arise only by *splitting*

A **species**, in the definition biologists use most, is a group of organisms that can interbreed and produce fertile offspring. Its populations share one pool of alleles, because individuals move and mate between them.

Speciation happens when that sharing stops. Split a species into two populations that no longer interbreed and each changes in its own way: different mutations, different chance events, different selection. Given long enough, they differ so much that they could not interbreed even if they met again. One species has become two.

Every new species has appeared like this, by splitting from one that already existed. Speciation adds to the number of species on Earth and extinction takes species away; the diversity alive today is the balance of the two.

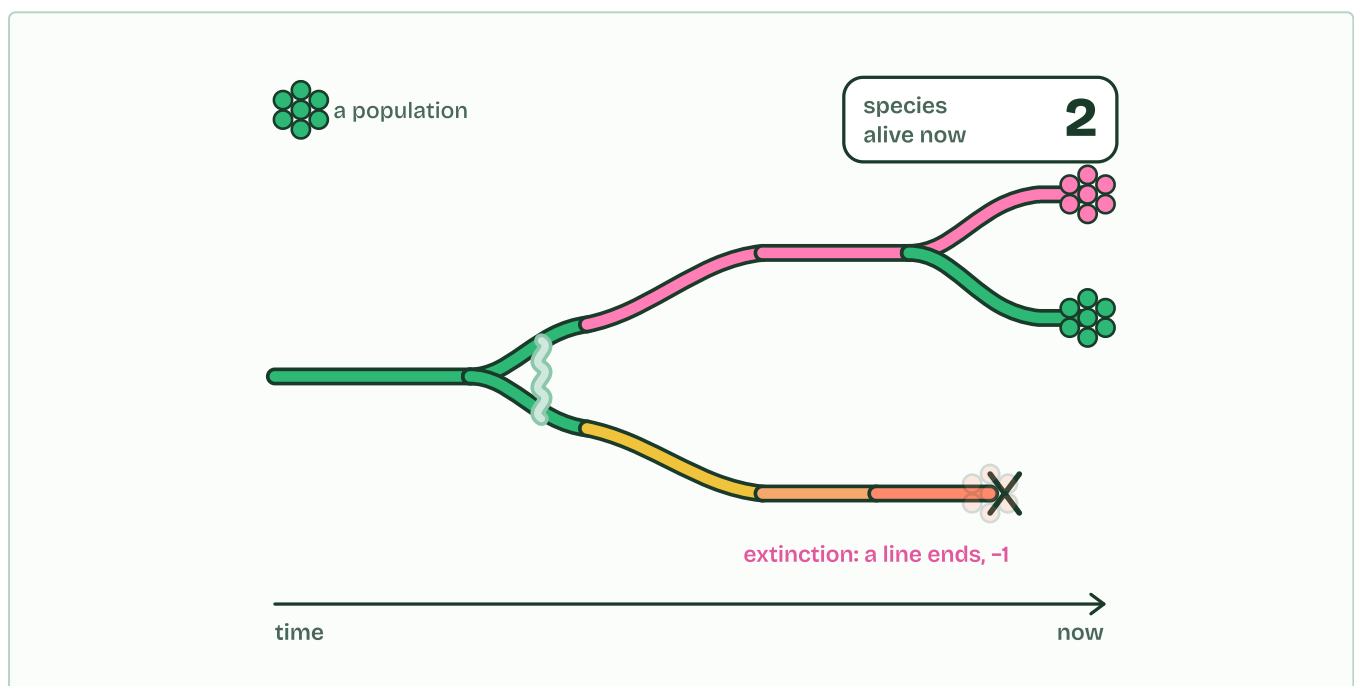
KEY TERMS

species

A group of organisms that can interbreed and produce fertile offspring. This is the biological species concept, the one used most.

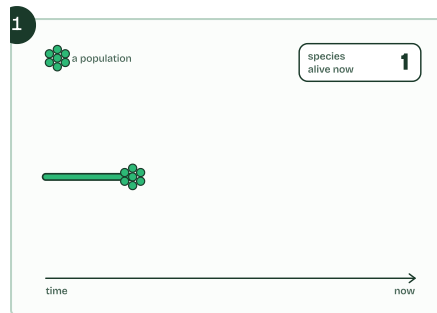
speciation

How new species arise: one existing species splits into two or more groups that can no longer interbreed.

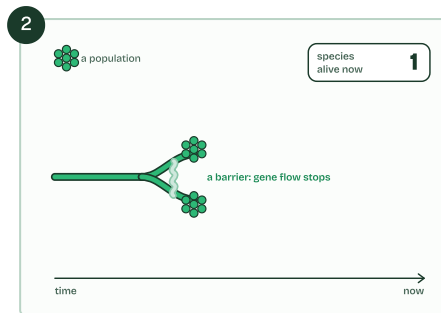


STEP BY STEP

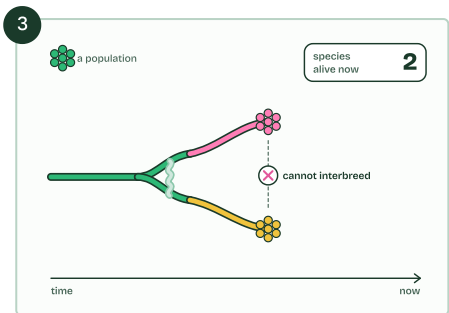
6 STEPS



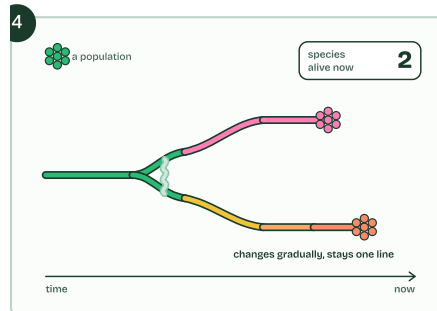
One species: every population can interbreed with every other.



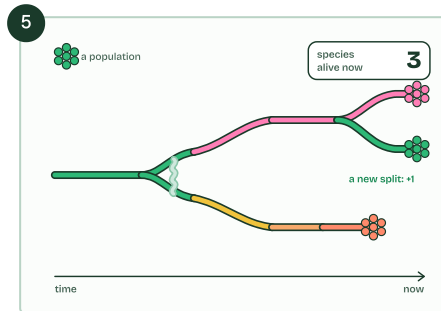
A barrier divides it into two populations.
Gene flow stops, but for now they are still one species.



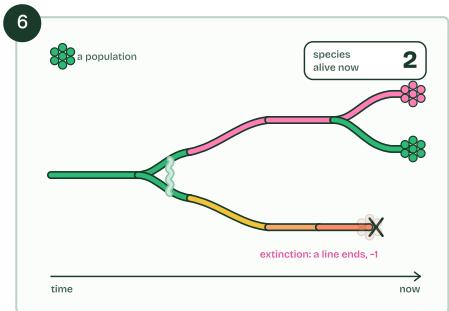
Each population changes separately until they **cannot interbreed**: two species.



The lower species changes **gradually** but never splits: still one species, so the count stays at two.



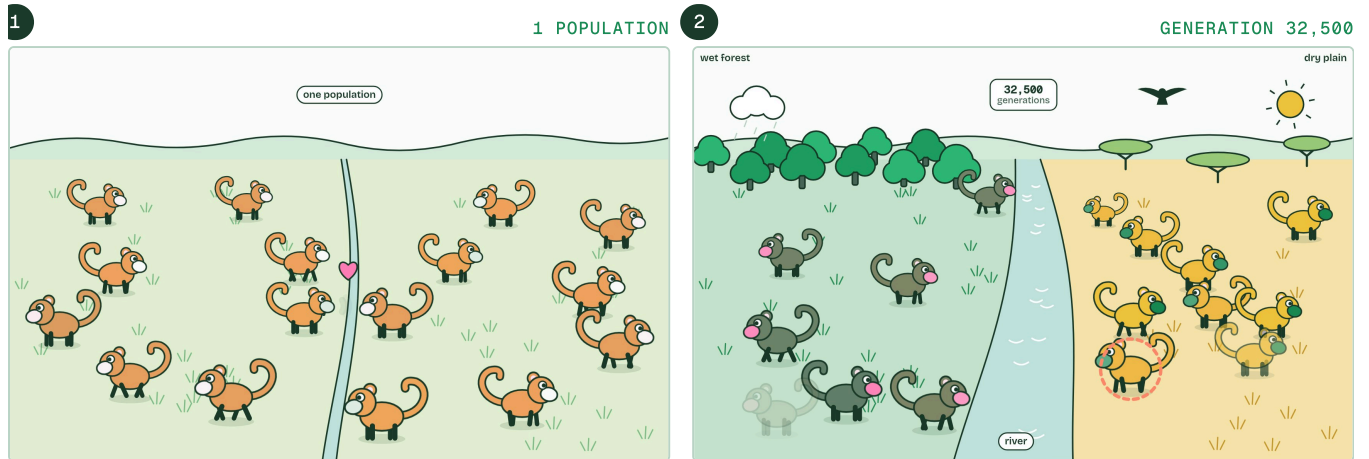
The upper species **splits** again: three.



The lower species dies out: **extinction** takes the count back to two.

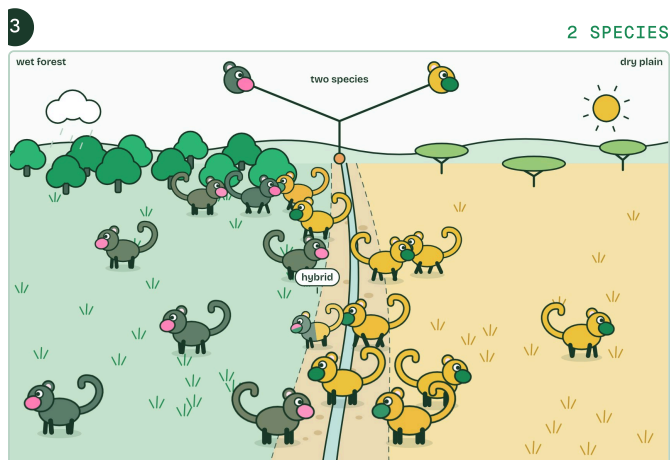
ANIMATION · WATCH IT HAPPEN: ONE POPULATION BECOMES TWO

3 MOMENTS



One population: any two can meet and mate, so genes flow across the valley.

Different selection each side: coats match the ground, displays drift apart.



Hybrids are rare, weak and often sterile, so the two never merge: **two species**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-a4-1-evolution-and-speciation#splitting

WATCH OUT

A species that changes gradually without splitting is still one line. It has evolved, but no species has been added, so that is not speciation. Play the figure to step 4.

WHERE THE DEFINITION STRUGGLES

Organisms that reproduce asexually, like bacteria, do not interbreed, and fossils cannot be tested, so these are grouped by their characteristics and sequences instead. And because splitting takes time, some pairs of populations are part-way: they interbreed a little where they meet, and whether they count as one species or two is a judgement.

PREDICT

A line of snails changes its shell shape steadily for two million years and never splits. The oldest and newest shells look so different that fossil experts give them different names. How many species has the line added to the Earth?

- ☐ (A) One: the oldest and newest shells now carry different names
- ☐ (B) None: at every moment there was still only one species
- ☐ (C) It depends on how different the oldest and newest shells look

Decide before you look. Answer on page 127.

06

A4.1.7 REPRODUCTIVE ISOLATION AND DIFFERENTIAL SELECTION

One river, two *apes*

Speciation needs two things. First, **reproductive isolation**: the populations must stop interbreeding, so alleles no longer pass between them. A sea, a mountain range or a river can do it: **geographical isolation**. Second, **differential selection**: different conditions on each side favour different characteristics, so the populations diverge. New mutations and chance (genetic drift), different on each side, add to it.

The Congo River is a real case. Common chimpanzees live north of it and beyond its upper reaches; bonobos live only in the forests south of its great bend. Neither ape can swim, and the river is wide and deep. Genetic evidence suggests their ancestors were divided roughly 1 to 2 million years ago, perhaps when a few reached the south bank during a dry spell and were then cut off.

South of the river there are no gorillas, and plants on the forest floor, which the apes eat when fruit is scarce, are plentiful. North of it, chimpanzees share the forest with gorillas and food is patchier. One widely held explanation is that these differences selected for different behaviour: bonobos live in large, calm groups in which females form strong alliances, while chimpanzee groups are led by males and compete more fiercely. Their bodies differ too: bonobos are more slender, with longer legs and smaller skulls.

KEY TERMS

reproductive isolation

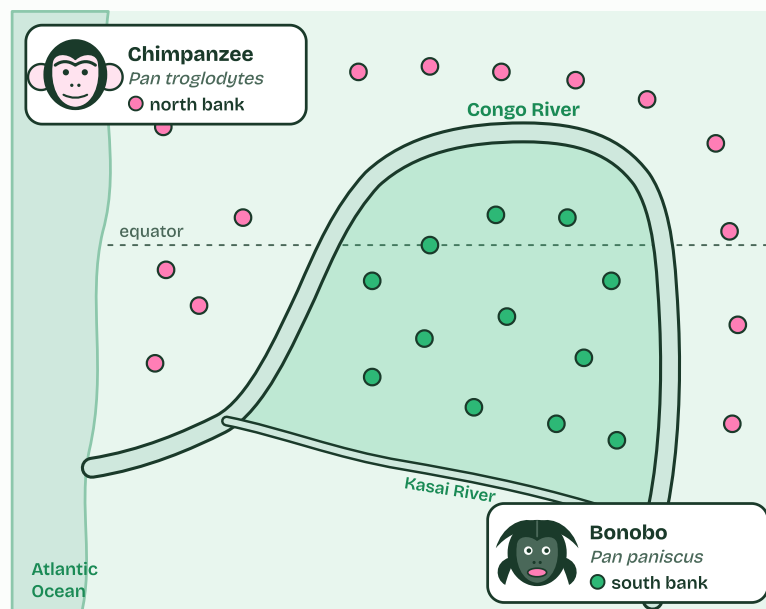
When two populations no longer interbreed, so no alleles pass between them.

geographical isolation

Reproductive isolation caused by a physical barrier, or distance, that keeps populations apart.

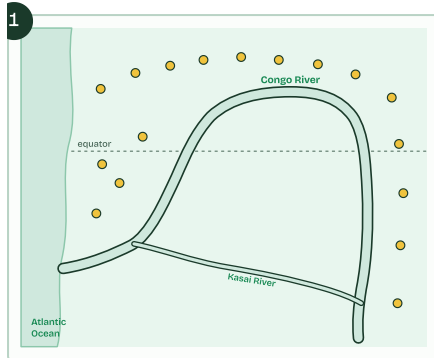
differential selection

Natural selection favouring different characteristics in different populations, because their environments differ.

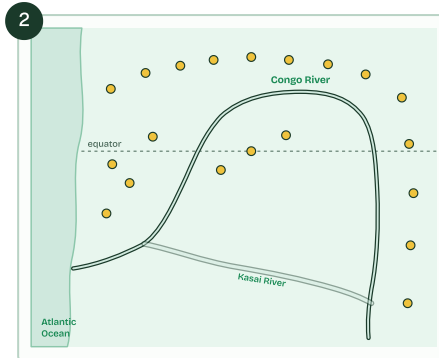


STEP BY STEP

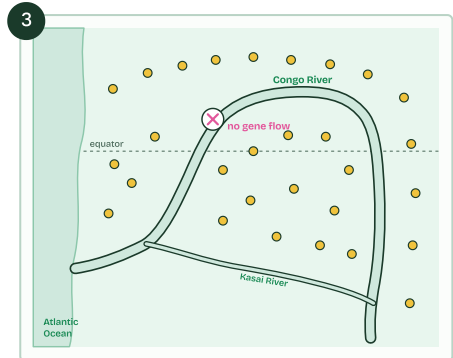
5 STEPS



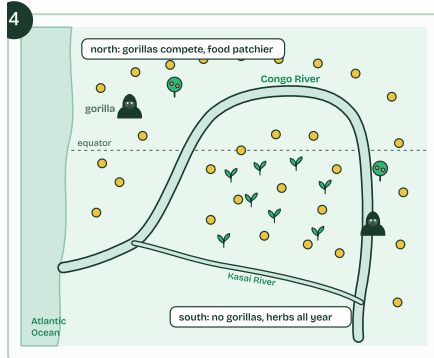
Long ago: one population of **ancestral apes**, north of the Congo River.



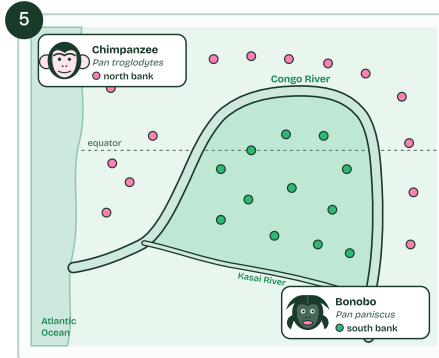
Perhaps in a dry spell, the river runs low and a few apes reach the **south bank**.



The water rises. Neither side can cross: **no gene flow** between the populations.



Different conditions on each bank: **differential selection** favours different behaviour and bodies.



Over about 1 to 2 million years they diverge into **two species**: chimpanzees north, bonobos south.

WATCH OUT

The river did not make the apes change. It stopped gene flow. Different selection on each side, with mutation and chance, did the changing.

HOW CLEAN WAS THE SPLIT?

Their genomes show that a few apes did cross the river long after the split, a few hundred thousand years ago, but too rarely to stop the two populations diverging.

PREDICT

Suppose the river had divided the apes but the forests on both banks were identical. What would you expect after a million years?

- (A) No differences at all: without selection, nothing in them would change
- (B) Some differences, from mutation and drift, but less divergence
- (C) Just as much divergence: isolation on its own does all the work

Decide before you look. Answer on page 127.

07

A4.1.8 HL ALLOPATRIC AND SYMPATRIC SPECIATION

Apart or together: *two routes* to a new species

Every speciation needs the same first step: gene flow between two groups has to stop, so they can change separately. The two routes differ in what stops it.

In **allopatric speciation** ("other homeland") a geographical barrier does it: a sea, a mountain range, or a river, as for the bonobos. In **sympatric speciation** ("same homeland") the groups live side by side, and something else keeps them from mating. They may breed at different times (**temporal isolation**) or choose mates differently (**behavioural isolation**).

Apple maggot flies in North America show it happening. They used to lay their eggs only in hawthorn fruit, and adults find mates on the kind of fruit they grew up in. After apple trees were planted in North America, some flies switched to apples; apple-infested fruit was first recorded in the 1860s. Apples ripen weeks before hawthorns, so apple flies now emerge, meet and mate earlier, on apples. The two groups share the same orchards, yet interbreed far less than they would by chance: they are on their way to becoming separate species.

KEY TERMS

allopatric speciation

Speciation in populations kept apart by geography: a sea, a mountain range, a river, or sheer distance.

sympatric speciation

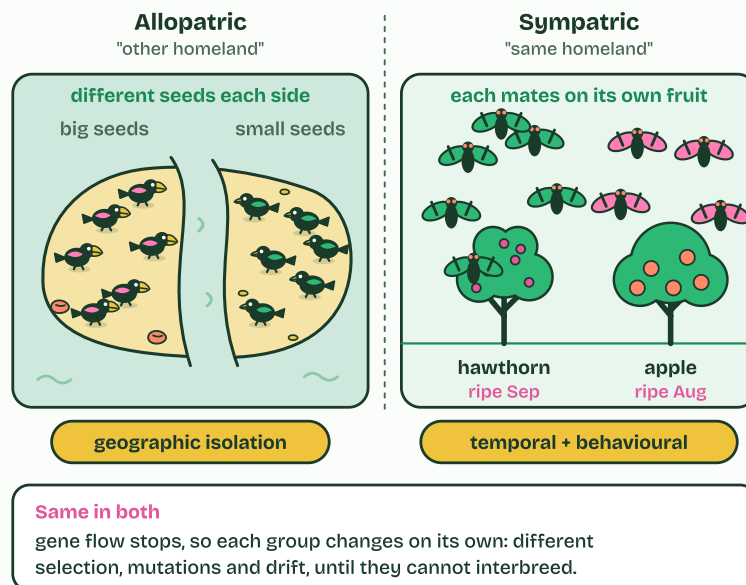
Speciation within one area: the groups could meet, but stop interbreeding, for example because they breed at different times, choose different mates or, in plants, have doubled their chromosomes.

temporal isolation

Isolation because populations breed at different times of day or year.

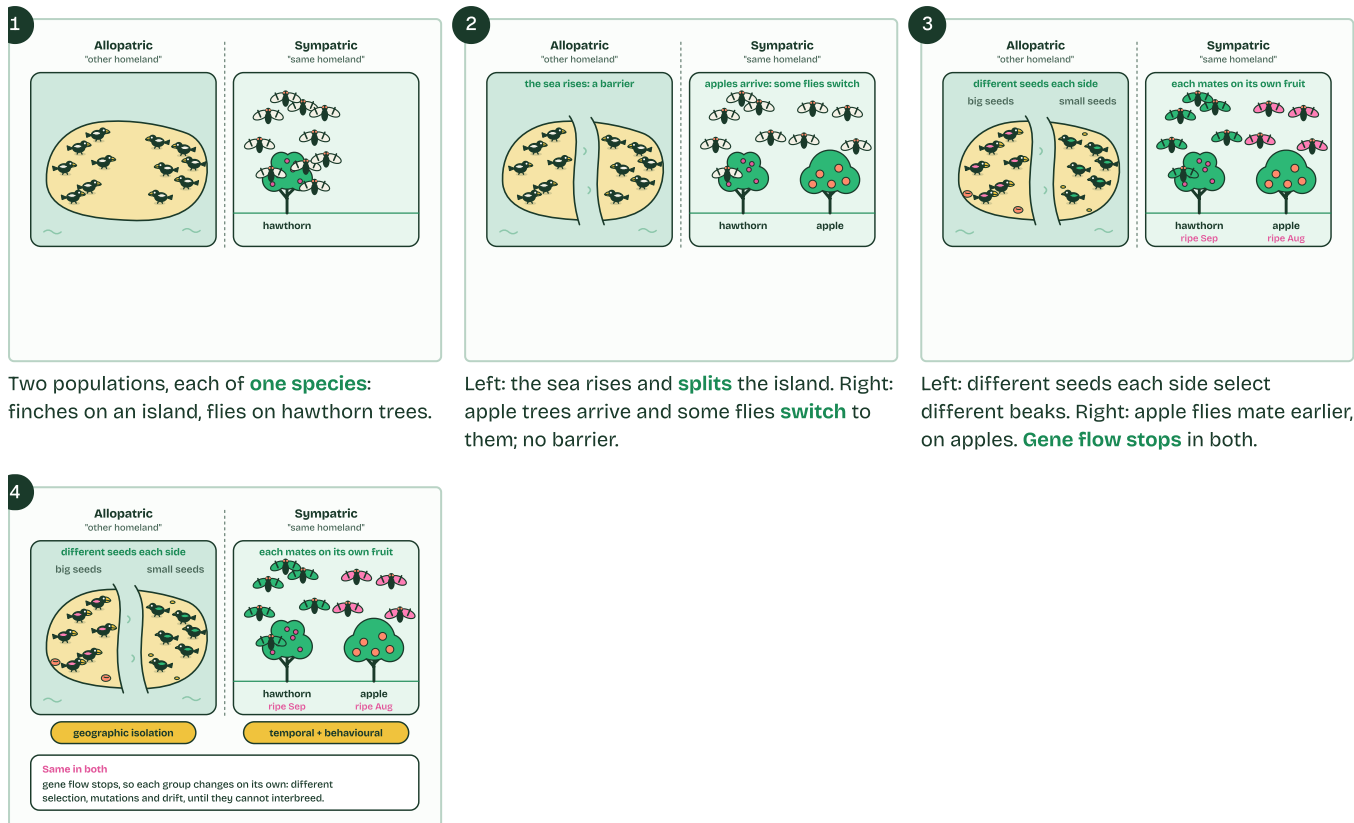
behavioural isolation

Isolation because populations court or choose mates differently, so they do not mate with each other.



STEP BY STEP

4 STEPS



Both groups diverge. What stopped gene flow differs: **geography**, or **timing and behaviour**.

WATCH OUT

Sympatric does not mean the groups never meet; it means they could meet and still do not mate. It is rarer than allopatric in animals, because any interbreeding mixes their alleles again. In plants it is common, by polyploidy (chapter 9).

REMEMBER IT**Three kinds of reproductive isolation**

G Grumpy	B Birds	T Tweet
Geographic a barrier between them	Behavioural different courtship	Temporal breed at different times

PREDICT

Two populations of a cricket share one meadow. One sings and mates in spring, the other in late summer. Which kind of isolation is this, and which route to speciation?

- ☐ (A) Geographic isolation: allopatric speciation
- ☐ (B) Temporal isolation: sympatric speciation
- ☐ (C) Behavioural isolation: allopatric speciation

Decide before you look. Answer on page 127.

08

A4.1.9 HL ADAPTIVE RADIATION

One ancestor, many *niches*

When a species reaches a place with food and ways of life that nothing else is using, its descendants can split again and again, each line adapting to a different way of life. This is **adaptive radiation**. The unused ways of life are **vacant niches**.

About 1 to 2 million years ago a few seed-eating finches reached the Galápagos from the American mainland. The islands had few other small birds, so niches stood empty: big seeds, small seeds, cactus flowers, buds and fruit, insects, grubs hidden in bark. Today about 18 species of Darwin's finches descend from that one ancestor, each with a beak suited to its food. The woodpecker finch even pries out grubs with a cactus spine held in its beak.

Because each species uses a different food, closely related species can live on the same island without competing much. That is why adaptive radiation raises biodiversity: one species has become many, living side by side. In Lake Malawi, cichlid fish have radiated into hundreds of species in one lake, scraping algae, crushing snails, eating scales or other fish.

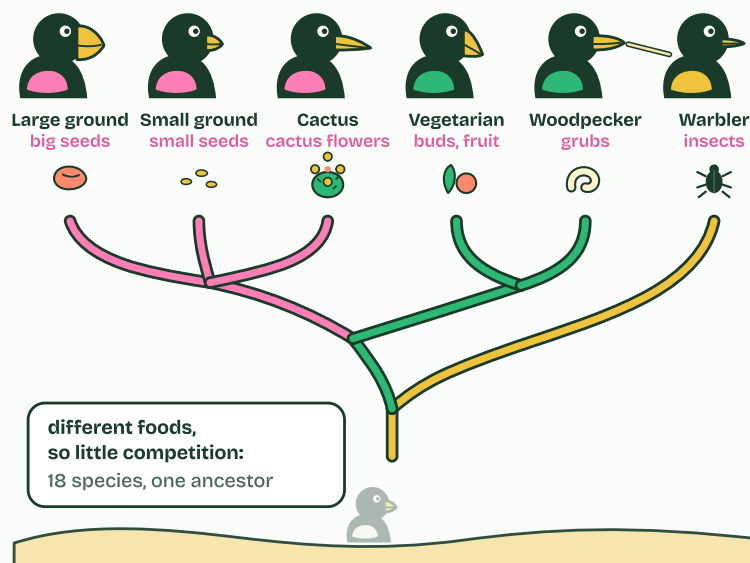
KEY TERMS

adaptive radiation

One ancestral species giving rise, fairly quickly, to many species, each suited to a different way of life (niche).

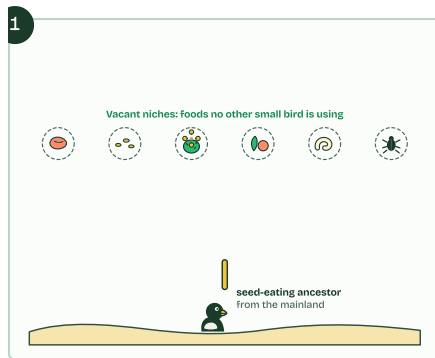
vacant niches

A niche is the role of a species in its ecosystem: what it eats, where and when it lives, how it interacts with others. A vacant niche is one no species is filling.

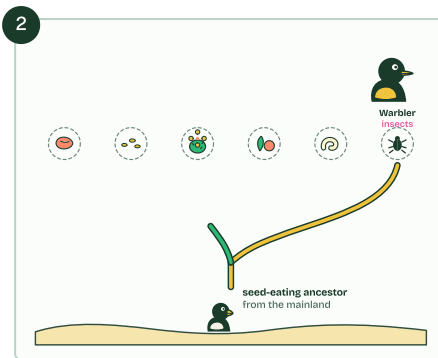


STEP BY STEP

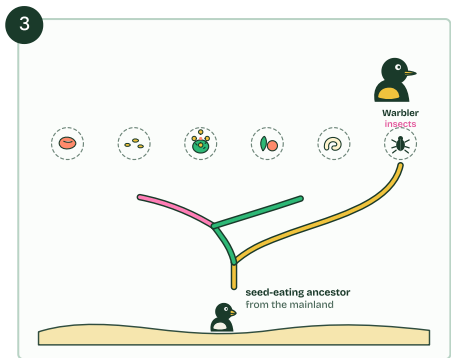
5 STEPS



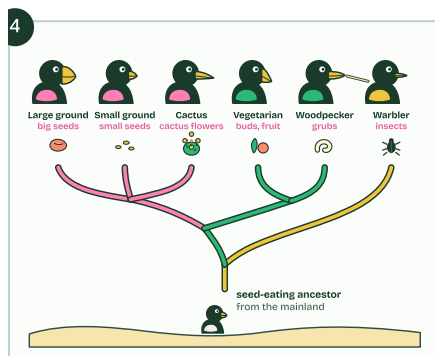
A seed-eating finch arrives on islands with **vacant niches**: foods no other small bird is using.



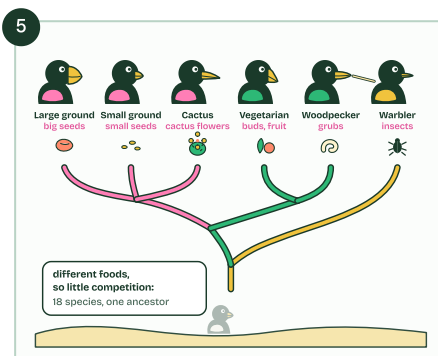
The first split: one line takes to eating **insects**, with a thin, pointed beak.



The rest split into **ground finches** and **tree finches**.



Each line splits again, each species with a beak **suited to its food**.



Different foods mean **little competition**: many related species live side by side.

WATCH OUT

The finches did not grow new beaks because they needed them. In each population, birds whose beaks happened to suit an unused food survived and bred better: natural selection acting on variation that was already there.

PREDICT

Suppose the first finches had landed on islands already full of small birds of many kinds. What would you expect?

- (A) Fewer finch species: most niches would already be filled
- (B) More finch species: competition makes new species faster
- (C) The same number: radiation depends only on the finches' genes

Decide before you look. Answer on page 128.

09

A4.1.10 HL

A4.1.11 HL

HYBRIDS AND POLYPLOIDY

The mule's *dead end*, the plant's way out

Even where two species meet, their alleles rarely mix. Barriers act before fertilisation and after it. Before, courtship usually prevents **hybridisation**: many animals choose mates by songs, dances, colours or scents that belong to their own species, and ignore the rest. Each firefly species flashes its own code, and a female answers only her own species' code.

After fertilisation, a hybrid may die young, or live but be sterile. A horse ($2n = 64$) and a donkey ($2n = 62$) can produce a mule, with 32 chromosomes from the horse and 31 from the donkey: 63. A mule is strong and healthy, but at meiosis its chromosomes cannot all pair up, because horse and donkey chromosomes differ in number and arrangement. Its gametes get unbalanced sets and almost never work, so horse and donkey alleles go no further.

Plants have a way out. A hybrid of two plant species is usually sterile for the same reason. But if its chromosome number doubles, every chromosome gains an identical partner, meiosis works, and the plant is fertile. It is a **polyploid**, and it cannot breed successfully with either parent: a new species in a generation or two. This is **abrupt speciation**.

The smartweeds and knotweeds, genus *Persicaria*, are full of examples: DNA studies show that several of their species, some of them common weeds, began as hybrids like this. Redshank, *Persicaria maculosa* ($2n = 44$), is one, with pale persicaria ($2n = 22$) as one of its parents.

KEY TERMS

hybridisation

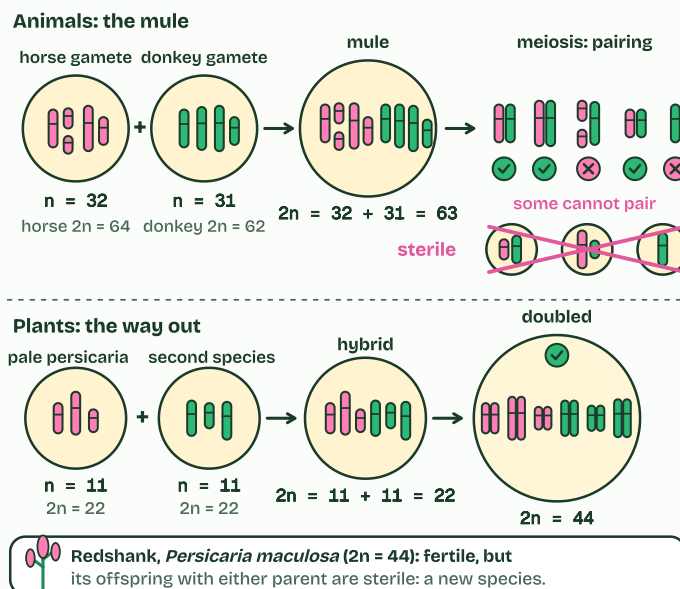
Mating between two different species, producing a hybrid.

polyploid

Having more than two complete sets of chromosomes.

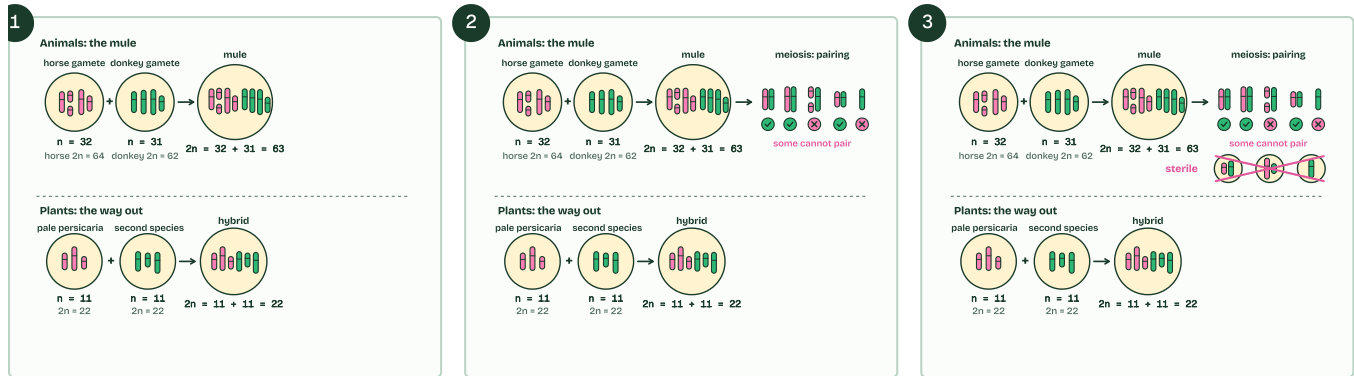
abrupt speciation

A new species formed in one or a few generations, as when a hybrid plant doubles its chromosomes, rather than by gradual divergence.



STEP BY STEP

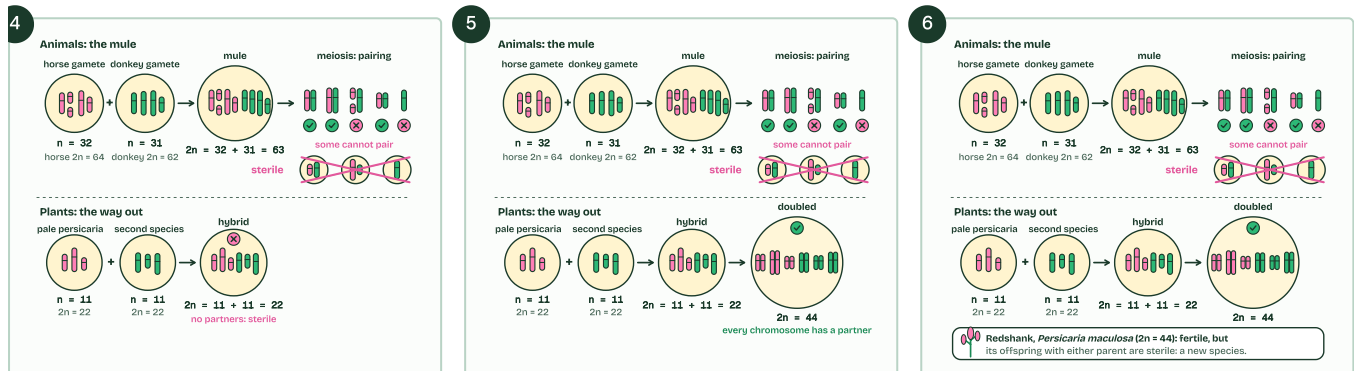
6 STEPS



A horse gamete (32 chromosomes) and a donkey gamete (31) make a **mule** with 63. A few of each set are drawn.

At meiosis, matching chromosomes pair up, but horse and donkey sets differ in **number and arrangement**: some cannot pair.

So the gametes get **unbalanced** sets and do not work: the mule is sterile.



Two smartweed species make a hybrid with 11 + 11 = 22. No chromosome has a matching partner: **sterile**, like the mule.

The chromosome number **doubles** to 44: every chromosome now has an identical partner, so meiosis works.

A fertile **polyploid** whose offspring with either parent are sterile: a new species, made in a generation or two.

WATCH OUT

The hybrid's number is the sum of the gametes, not of the parents: 32 + 31 = 63 for the mule, 11 + 11 = 22 for the smartweed hybrid. Doubling then gives 44. Japanese knotweed, the invasive garden weed, is a polyploid too, but it belongs to a different genus (*Reynoutria*, also called *Fallopia*); name a *Persicaria* for this example.

PREDICT

Redshank (2n = 44) is crossed with one of its parents, pale persicaria (2n = 22). How many chromosomes do the offspring have, and are they fertile?

- (A) 44: they take after redshank, so they are fertile
(B) 33: three sets that cannot pair evenly, so sterile
(C) 66: six sets, so fertile, like any polyploid

Decide before you look. Answer on page 128.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

abrupt speciation 09

A new species formed in one or a few generations, as when a hybrid plant doubles its chromosomes, rather than by gradual divergence.

adaptive radiation 08

One ancestral species giving rise, fairly quickly, to many species, each suited to a different way of life (niche).

allopatric speciation 07

Speciation in populations kept apart by geography: a sea, a mountain range, a river, or sheer distance.

analogous structures 04

Structures that do the same job but evolved separately in each line, so they were not inherited in that form from a common ancestor.

behavioural isolation 07

Isolation because populations court or choose mates differently, so they do not mate with each other.

convergent evolution 04

Unrelated lines evolving similar features because they face similar demands, such as flight or swimming.

differential selection 06

Natural selection favouring different characteristics in different populations, because their environments differ.

geographical isolation 06

Reproductive isolation caused by a physical barrier, or distance, that keeps populations apart.

heritable characteristics 01

Characteristics passed from parents to offspring in their genes, as alleles.

homologous structures 04

Structures built on one plan inherited from a common ancestor, whatever job each one now does.

hybridisation 09

Mating between two different species, producing a hybrid.

pentadactyl limb 04

The limb plan of amphibians, reptiles, birds and mammals: one upper bone, two lower bones, wrist or ankle bones, then up to five digits.

polyploid 09

Having more than two complete sets of chromosomes.

population 01

All the organisms of one species living in one area at the same time, able to breed with each other.

reproductive isolation 06

When two populations no longer interbreed, so no alleles pass between them.

selective breeding 03

Humans choosing which plants or animals breed, so the characteristics they want become commoner in each generation. Also called artificial selection.

speciation 05

How new species arise: one existing species splits into two or more groups that can no longer interbreed.

species 05

A group of organisms that can interbreed and produce fertile offspring. This is the biological species concept, the one used most.

sympatric speciation 07

Speciation within one area: the groups could meet, but stop interbreeding, for example because they breed at different times, choose different mates or, in plants, have doubled their chromosomes.

temporal isolation 07

Isolation because populations breed at different times of day or year.

vacant niches 08

A niche is the role of a species in its ecosystem: what it eats, where and when it lives, how it interacts with others. A vacant niche is one no species is filling.

Dry lab: *Finches on islands*

Split a population of finches, decide what acts on each side, run the generations, then bring them back together and test whether you have made a new species.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. biologybybradford.com/guides/ib-biology-a4-1-evolution-and-speciation#lab

Your question

What does it take to turn one population into two species? Is cutting off gene flow enough, or do the two sides also need different selection? How much gene flow undoes it?

What you can change

The scenario (split by the sea, a control with the same food both sides, and at higher level one island with two foods), the difference in food, the number of birds, how many cross each generation, how strongly females choose mates by song, mutation, and how many generations to run.

What to record

For each run: the settings, the difference in mean beak depth when you stop, and the isolation index and verdict when you reunite them. Change one setting at a time and repeat each set-up at least three times: the runs scatter, as real populations do.

Find out

- **Is isolation alone enough?** Run the control (same food both sides) three times with no birds crossing, then the split with very different food three times. Reunite them after each run. Compare the isolation indexes.
- **How much gene flow undoes it?** Keep the food very different and raise the birds crossing each generation: 0, 1, 2, 4, 8. Three runs at each. At what rate does the verdict change from two species to one?
- **Small or large?** Run the control with 20 birds per island and with 300. Which pair of islands drifts further apart by chance alone?
- **Higher level: one island, two foods.** Set mate choice to none, then moderate, then very strong. When does the population split into two groups that do not interbreed?

Record

- For every run: the scenario, the settings you changed, the generations, the difference in mean beak depth, and the isolation index and verdict when you reunite or test them.
- Change one setting at a time and keep the rest fixed.
- Repeat each set-up at least three times and take a mean: no two runs are the same, because chance is part of the model, as it is of real populations.
- Use **Graph your results** under the lab to see the mean isolation index for each number of birds crossing each generation, or download the CSV and plot it yourself.

QUESTIONS ON THE LAB

QUESTION 1

In the control, the islands have the same food. After 200 generations the mean beaks usually differ a little, but the test says one species. Why?

- (A) With the same food on both islands, mutation stops, so nothing can change
- (B) Only drift and mutation differ, so the beaks wander slowly and at random
- (C) The sea between them is not a real barrier, so the birds still interbreed

Answer on page 128.

QUESTION 2

With very different food, a handful of birds crossing each generation is enough to keep the two islands one species. How?

- (A) The crossing birds eat the other island's seeds, so that island runs out of food
- (B) The crossing birds cannot survive on the other island, so nothing there changes
- (C) Each crossing bird brings its alleles, mixing the gene pools every generation

Answer on page 128.

QUESTION 3

Higher level. On one island with two foods, the population only splits into two groups when mate choice is strong. Why is mate choice needed here, but not when the sea splits the island?

- (A) On one island nothing else stops the two groups mating, so behaviour must
- (B) Mate choice causes the mutations that make beaks deeper or shallower
- (C) Strong mate choice makes the birds move to the other side of the island

Answer on page 128.



Check yourself

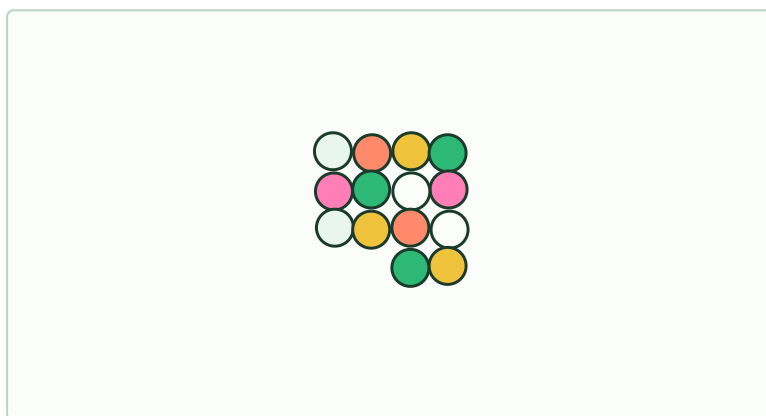
The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on A4.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=A4.1&level=HL&paper=quiz&marks=15&src=ep

Twenty amino acids, *endless* shapes

Proteins

Every protein in you is a chain of the same twenty building blocks. The order they are joined in decides the shape the chain folds into, and the shape decides the job. Heat or the wrong pH and the shape, and the job, are gone.



By the end you can

- ☐ Draw a generalised amino acid and name the four groups on its alpha carbon B1.2.1
- ☐ Explain how condensation joins amino acids with peptide bonds, write the word equation and draw a dipeptide B1.2.2
- ☐ Explain why some amino acids must come from food, and what that means for a vegan diet B1.2.3
- ☐ Explain why the number of possible polypeptides is practically endless B1.2.4
- ☐ Explain how heat and pH denature a protein, and why it then stops working B1.2.5
- ☐ Classify R groups and explain how they set the properties of a polypeptide B1.2.6
- ☐ Explain how the sequence of amino acids gives every copy of a protein the same precise shape B1.2.7
- ☐ Describe the alpha helix and beta-pleated sheet and the hydrogen bonds that hold them B1.2.8
- ☐ Name the four kinds of bond that hold a tertiary structure, and say where polar and non-polar R groups end up B1.2.9, B1.2.10
- ☐ Compare insulin, collagen and haemoglobin: chains, conjugated or not, globular or fibrous, and how form suits function B1.2.11, B1.2.12

Tick each one when you can do it without the book.

01

B1.2.1 GENERALISED STRUCTURE OF AN AMINO ACID

Every amino acid is built on the same *core*

A protein is a polymer (B1.1), a long chain of the same kind of unit joined end to end. The units are **amino acids**, and every one of them starts from the same pattern.

At the middle sits one carbon atom, the **alpha carbon**. Carbon always makes four bonds, and here they go to four different things: an **amine group** (-NH_2), a **carboxyl group** (-COOH), a single hydrogen atom and an **R group**. The name says it: "amino" from the amine group, "acid" from the carboxyl group, which can give up a hydrogen ion.

The R group is the only part that varies. The genetic code uses twenty different R groups, so there are twenty amino acids. The smallest R group is a single hydrogen atom, and others are chains or rings, some containing oxygen, nitrogen or sulfur. At standard level you do not need to name any of them.

KEY POINTS

- Draw the alpha carbon in the middle, the amine group on one side and the carboxyl group on the other, hydrogen and R above and below.
- Show every atom and every bond, in the un-ionised form (-NH_2 and -COOH), as the markschemes do.
- Count the bonds: four on carbon, three on nitrogen, two on oxygen, one on hydrogen.

KEY TERMS

amino acids

The monomers of proteins. Each has an amine group, a carboxyl group, a hydrogen atom and an R group on one central carbon.

alpha carbon

The central carbon of an amino acid. It makes four single bonds, to an amine group, a carboxyl group, a hydrogen atom and an R group.

amine group

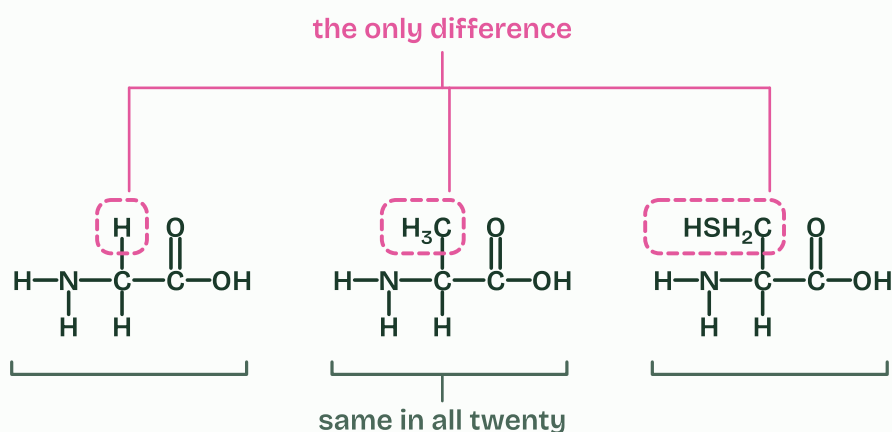
The group -NH_2 : a nitrogen atom bonded to two hydrogens. It is the amino part of the name.

carboxyl group

The group -COOH : a carbon with a double bond to one oxygen and a single bond to an OH. It can give up a hydrogen ion, which is why it is an acid.

R group

The side chain of an amino acid: the one part that differs between the twenty. R stands for whatever group it is, not for an element.



STEP BY STEP

6 STEPS

1

The **alpha carbon** makes four bonds.

2

An **amine group** goes on the left bond: a nitrogen with two hydrogens.

3

A **carboxyl group** goes on the right bond: a carbon with a double bond to one oxygen and a single bond to an OH.

4

One **hydrogen** atom goes on the bottom bond.

5

The last bond carries the **R group**. It stands for whatever side chain this amino acid has.

6

Three different amino acids: the same core in each, and only the **R group** differs.

REMEMBER IT

The four groups on the alpha carbon

A A	C Cat	H Has	R Rhythm
Amine group -NH ₂ , on one side	Carboxyl group -COOH, on the other side	Hydrogen one H atom	R group the only part that varies

WATCH OUT

R is not an element. It stands for the side chain, whatever it is in that amino acid. And check every drawing by counting bonds: four on every carbon, three on nitrogen, two on oxygen, one on hydrogen.

PREDICT

A student draws an alpha carbon bonded to -NH₂, -COOH, R and -OH. What is wrong with the drawing?

- (A) Nothing is wrong: the alpha carbon can carry any four groups, as long as it makes four bonds
- (B) The fourth group should be a single hydrogen atom, not -OH
- (C) The R group is in the wrong place: it should be bonded to the nitrogen of the amine group

Decide before you look. Answer on page 128.

B1.2.2 CONDENSATION REACTIONS FORMING DIPEPTIDES AND LONGER CHAINS

02 Peptide bonds join amino acids, and *water* leaves

Amino acids join by the same move as every other monomer in B1.1, a condensation reaction. The OH from the carboxyl group of one amino acid and an H from the amine group of the next leave together as a molecule of water. The carbon of the carboxyl group is then left bonded to the nitrogen of the amine group, and that C-N bond is a **peptide bond**, a strong covalent bond. Two amino acids make a **dipeptide**.

The word equation is **amino acid + amino acid → dipeptide + water**.

The dipeptide still has a free amine group at one end and a free carboxyl group at the other, so more amino acids can join on in the same way. A long chain is a **polypeptide**. A chain of n amino acids has $n - 1$ peptide bonds, and $n - 1$ molecules of water were released making it. Hydrolysis, adding water back, reverses it, which is what digestion does to the proteins in food. In cells, ribosomes make the peptide bonds, in the order a gene sets (D1.2).

A protein is one or more polypeptides folded into a working shape. Model this reaction with a kit first (see Teach), then try the bond builder below and draw a dipeptide.

KEY TERMS

peptide bond

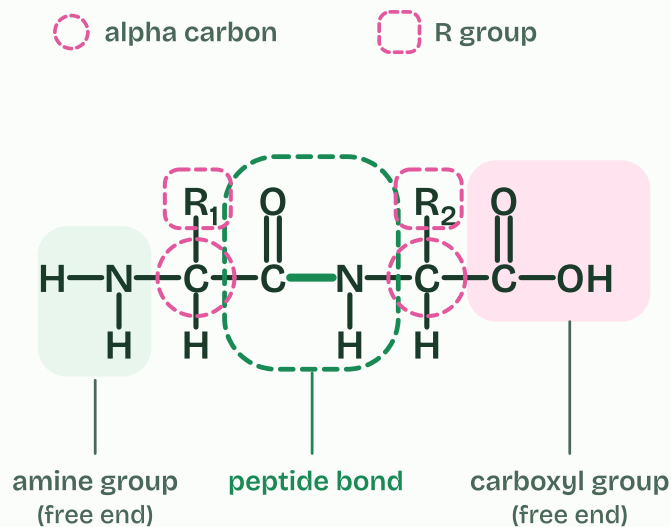
The covalent bond between the carbon of one amino acid's carboxyl group and the nitrogen of the next amino acid's amine group. It forms in a condensation reaction.

dipeptide

Two amino acids joined by one peptide bond.

polypeptide

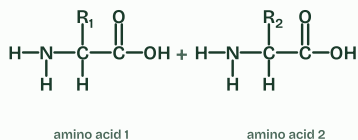
A chain of many amino acids joined by peptide bonds.



STEP BY STEP

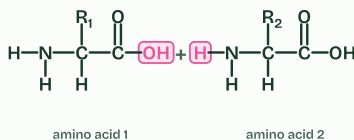
4 STEPS

1



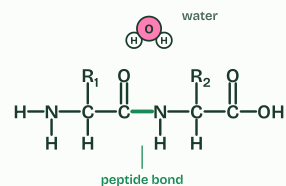
Two amino acids, **R₁** and **R₂**, with the carboxyl group of the first facing the amine group of the second.

2



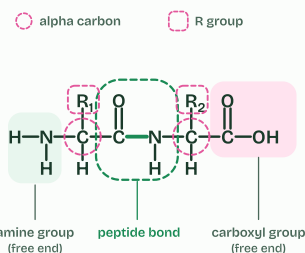
The **OH** from the carboxyl group and one **H** from the amine group are lit: they will leave as **water**.

3

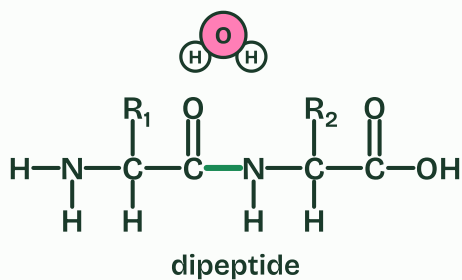
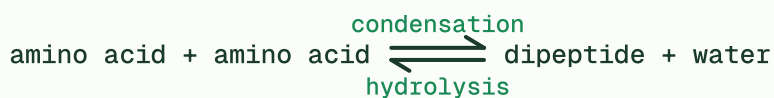


The carbon bonds to the nitrogen and the water drifts away. The new C-N bond is a **peptide bond**.

4



A **dipeptide**, drawn as an examiner wants it. It still has an amine group at one end and a carboxyl group at the other.

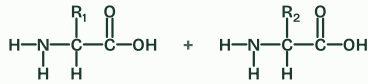


Join the amino acids, both ways round, then add water to split them again. Count the peptide bonds and the water released.

STEP BY STEP

4 STEPS

1

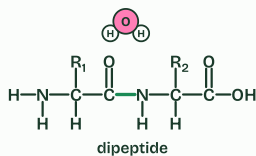


Two amino acids.

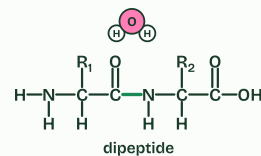
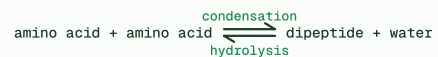
2

The OH of one's **carboxyl group** and an H of the other's **amine group** face each other.

3

They leave as **water**, and a **peptide bond** joins the carbon to the nitrogen: **condensation**, making a **dipeptide**.

4

Add water and the peptide bond splits again, the OH back to the carbon and the H to the nitrogen: **hydrolysis**.

WATCH OUT

The peptide bond is not between the two alpha carbons, not through an oxygen (C-O-N), and never involves an R group. And the water takes its OH from one amino acid and its H from the other, not both from the same one.

EXAMPLE

Insulin has two polypeptides. The shorter has 21 amino acids and so 20 peptide bonds, and the longer has 30 and so 29. (Insulin itself comes back at higher level.)

PREDICT

Two different amino acids, A and B, are joined by one peptide bond. How many different dipeptides could they make?

- (A) One: A joined to B is the same molecule as B joined to A, because the same two amino acids are used
- (B) Four: any group on one amino acid can join any group on the other, so there are four ways to do it
- (C) Two: A's carboxyl to B's amine, or B's carboxyl to A's amine, and these are different molecules

Decide before you look. Answer on page 129.

03

B1.2.3 DIETARY REQUIREMENTS FOR AMINO ACIDS

Some amino acids you must *eat*

Your cells need all twenty amino acids to build their proteins. They can make some of them from other amino acids: these are **non-essential amino acids**. They cannot make the rest, which must come from food: **essential amino acids**. For an adult, nine of the twenty are essential. You do not need to name any of them.

“Essential” is about the diet, not importance: a protein needs every amino acid in its sequence, so the non-essential ones matter just as much. You just do not need to eat them.

The body keeps no store of spare amino acids, as it does for glycogen and fat, so essential ones are needed regularly. Food protein is digested (hydrolysed) to amino acids, which are absorbed and built into your own proteins. If one essential amino acid runs short, every protein that needs it cannot be finished: the gene sets the sequence, and no other amino acid can stand in.

Vegan diets take all their protein from plants. Most plant foods contain every essential amino acid, but some have little of one: cereals are low in one, and beans and lentils in a different one. A variety over the day, such as rice with lentils or hummus with bread, supplies them all, and soya and quinoa have all of them in good amounts. A vegan diet needs attention, not luck. Meat, eggs and dairy carry all of them in proportions close to what we need.

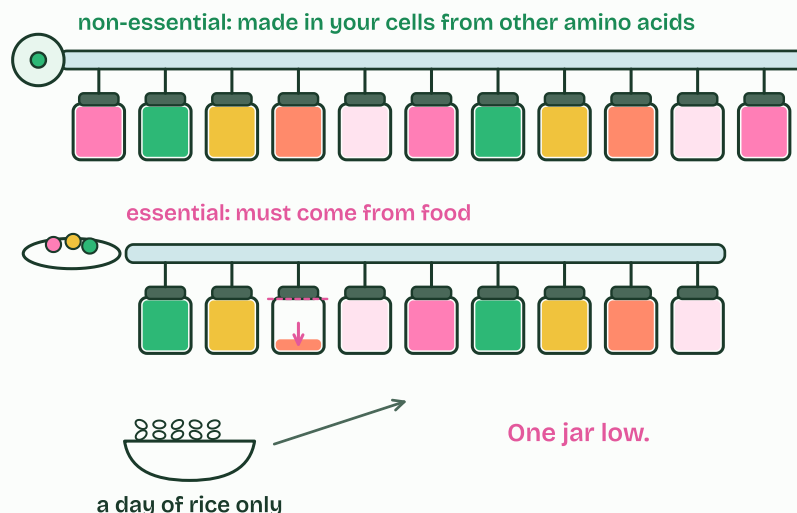
KEY TERMS

non-essential amino acids

Amino acids that the body can make from other amino acids, so they do not have to come from food.

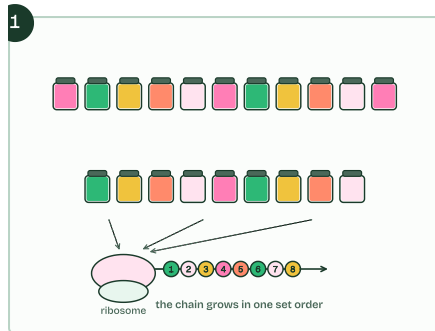
essential amino acids

Amino acids that the body cannot make, so they must be obtained from food.

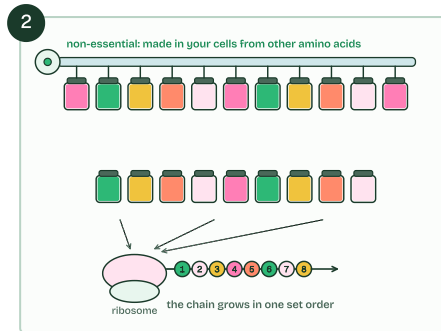


STEP BY STEP

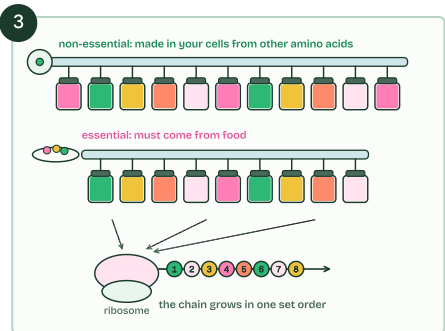
5 STEPS



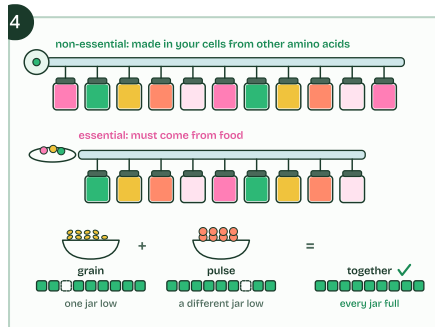
Twenty jars feed the line, and the chain grows in **one order**, set by the gene.



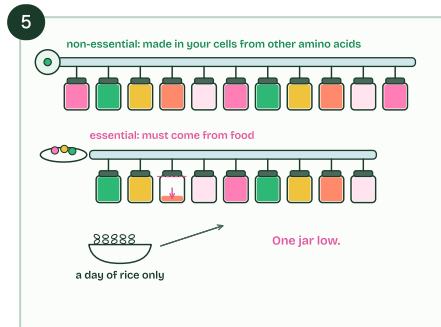
Eleven jars are filled by a pipe from the cells: **non-essential** amino acids, which your cells can make from other amino acids.



Nine jars are filled only from the plate: **essential** amino acids, which must come from food.



A varied plant plate: grain runs a little low in one jar and pulses in a different one, and together they fill every jar. A **vegan** diet covers all nine with **variety**.



A day of rice only: one jar runs low.

WATCH OUT

Non-essential amino acids are not unimportant: they are in your proteins too, you just do not need them in food. And “vegans cannot get essential amino acids” is false: they need a variety of plant proteins.

PREDICT

You eat plenty of protein, but it lacks one essential amino acid. What happens to the proteins that need it?

- (A) They cannot be completed, because no other amino acid can take its place in the sequence
- (B) Your cells make the missing amino acid from other amino acids that are in plentiful supply
- (C) Nothing changes, as long as the total amount of protein eaten is high enough
- (D) A different amino acid is put in its place, so the proteins are still finished, if slightly altered

Decide before you look. Answer on page 129.

B1.2.4 INFINITE VARIETY OF POSSIBLE PEPTIDE CHAINS

04 Twenty amino acids, *endless* chains

The **genetic code** (A1.2) codes for twenty amino acids. A polypeptide can have any number of them, from a few to thousands, in any order, and the same amino acid can appear again and again.

That makes the number of possible chains enormous. There are $20 \times 20 = 400$ different dipeptides, $20 \times 20 \times 20 = 8,000$ tripeptides, and 20^n chains of length n . Past about 60 amino acids there are more possible sequences than there are atoms in the observable universe, and real proteins are much longer than that.

Living things use only a tiny fraction of the possible sequences. Each gene codes for one polypeptide, and all the proteins an organism makes are its **proteome**. You should know some examples of polypeptides:

KEY POINTS

- **Glucagon**, a hormone, has 29 amino acids.
- **Insulin**, a hormone, has 51 in two chains of 21 and 30.
- **Lysozyme**, an enzyme in egg white and tears, has 129.
- Each **haemoglobin** chain has 141 or 146.
- A **collagen** chain has about 1,000.
- **Titin**, a springy protein inside muscle, has about 34,000, the largest known in humans.

KEY TERMS

genetic code

The rules a cell uses to turn the sequence of bases in a gene into the sequence of amino acids in a polypeptide. It codes for twenty amino acids.

proteome

All the proteins that an organism, or a cell, makes.

choices at each position

20 20



2 amino acids

SWITCH IT

6 SETTINGS

1

choices at each position

20 20 20 20 20 20 20 20 20 20 20 20 ...



150 amino acids (12 drawn)

2

choices at each position

20 20 20 20 20 20 20 20 20 20 20 20 ...



150 amino acids (12 drawn)

10

3

choices at each position

20 20 20 20 20 20 20 20 20 20 20 20 ...



150 amino acids (12 drawn)

51

4

choices at each position

20 20 20 20 20 20 20 20 20 20 20 20 ...

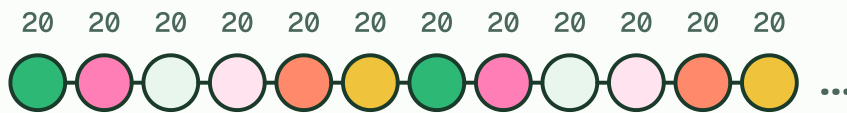


150 amino acids (12 drawn)

62

5

choices at each position

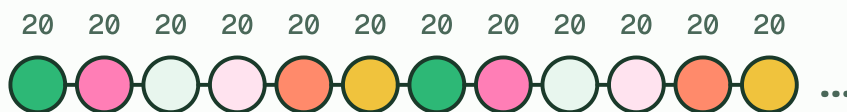


150 amino acids (12 drawn)

100

6

choices at each position



150 amino acids (12 drawn)

146

WATCH OUT

Twenty amino acids do not mean twenty proteins. And a protein's identity is its order: the same amino acids in a different order make a different polypeptide.

LINKING QUESTION

What is the relationship between the genome and the proteome? The genome is all of an organism's genes, and most of them code for a polypeptide, so the genome sets which proteins the organism can make, its proteome. Different cells use different parts of it, so a liver cell's proteins differ from a muscle cell's (D1.2, and D2.2 at higher level).

PREDICT

How many different dipeptides can be made from the 20 amino acids?

- (A) 20, because there are only twenty amino acids to choose from
- (B) 40, because each of the twenty amino acids can sit first or second
- (C) 190, because a pair in either order counts once and a repeated amino acid is not allowed
- (D) 400, because there are twenty choices at each of the two positions

Decide before you look. Answer on page 129.

05

B1.2.5 EFFECT OF PH AND TEMPERATURE ON PROTEIN STRUCTURE

Heat and pH *unfold* a protein

A protein works because of its precise three-dimensional shape: a pocket that fits one molecule, a surface that binds one partner. That shape is held in place by many weak bonds between parts of the folded chain, hydrogen bonds (met in A1.1) and attractions between charged groups.

At higher level you will meet the four kinds of bond in chapter 9.

Heat. The atoms vibrate more and more, and past a point the weak bonds break. The chain unfolds, its shape is lost and it can no longer do its job: it is **denatured**. The peptide bonds are covalent and much stronger, so the sequence of amino acids is unchanged.

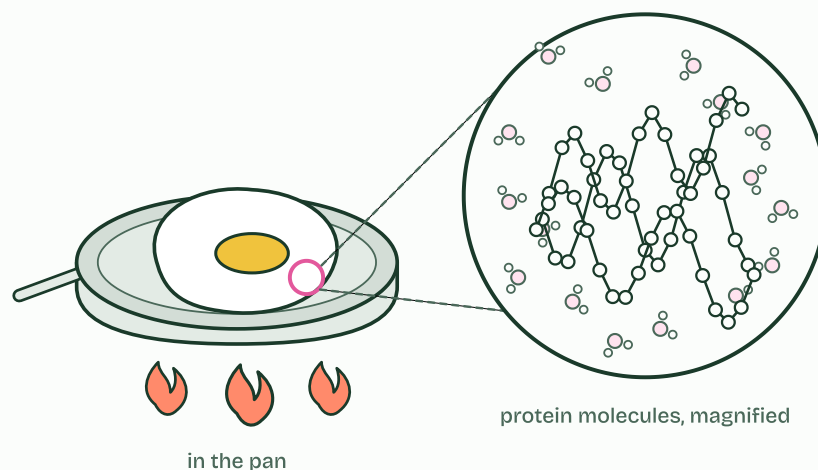
pH. Hydrogen ions attach to groups in the R groups, or leave them, and so change their charges. The attractions between oppositely charged groups are lost and the shape changes. Each protein keeps its shape over a range of pH, and far outside it the protein denatures.

Denaturation is usually permanent. Heated chains tangle with each other and do not refold when cooled, which is why an egg white stays white and solid. Each protein's limits suit where it works: proteins in the stomach keep their shape at about pH 2, and the proteins of microbes in hot springs stay folded at temperatures that would denature ours. Cooling slows a protein down but does not unfold it.

KEY TERMS

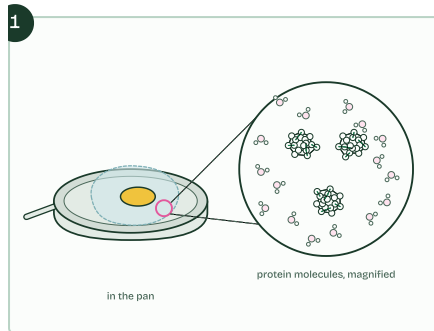
denatured

Having lost its three-dimensional shape because the bonds that hold it have broken, so that the protein can no longer do its job. The amino acid sequence is unchanged.

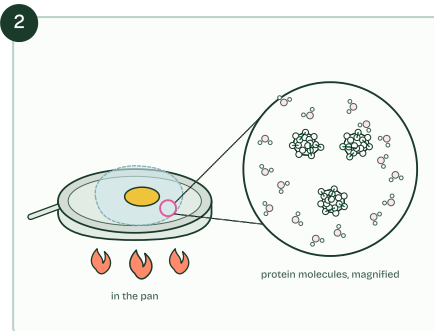


STEP BY STEP

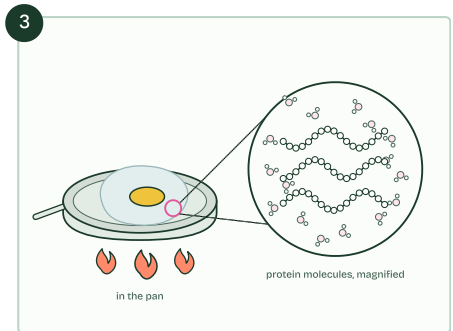
4 STEPS



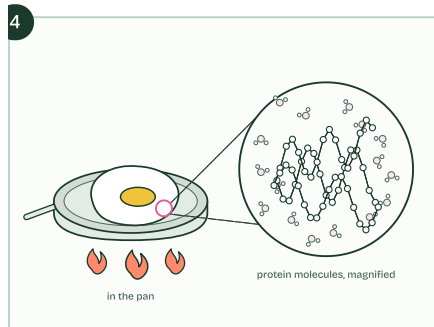
Raw egg white: clear and runny. Magnified, the proteins are **folded**, each on its own among the water molecules.



Heat makes the molecules jiggle harder and breaks the bonds that hold the folds.

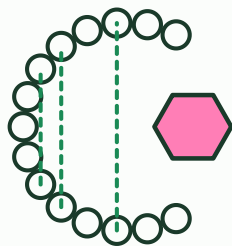


The chains **unfold**: with the bonds gone, their shape is gone.



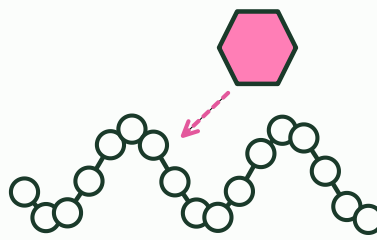
Unfolded chains **tangle** together and the egg white sets, white and solid. The proteins are **denatured**.

37 °C: folded



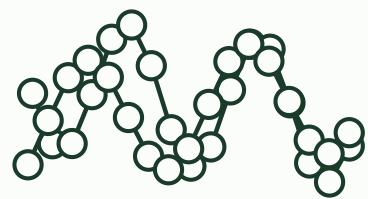
one precise shape
the partner fits

hot: unfolded



the fold is gone
it no longer fits

cooled again: tangled



no refolding
the chains tangle

Too acid or too alkaline does much the same: the charges change and the fold opens.

Heat unfolds a protein, and cooling it again does not bring the shape back: the chains tangle instead. The same happens, by a different route, when the pH moves too far.

WATCH OUT

Denatured does not mean dead (a protein was never alive), melted or dissolved. Cold does not denature: a protein in the fridge is slow but whole. And cooling a heat-denatured protein does not usually bring its shape back.

TRY IT

The enzyme in your spit, a home lab in C1.1, times salivary amylase breaking down starch at cold, room and warm temperatures. Amylase is a protein, and denaturation is the reason the hottest tube behaves as it does.

LINKING QUESTION

How do abiotic factors influence the form of molecules? Temperature and pH change a protein's shape by breaking the bonds that hold it. The same idea runs through the course: heat breaks hydrogen bonds between water molecules (A1.1), warmth melts fats with more C=C bonds sooner (B1.1), and every enzyme has an optimum (C1.1).

PREDICT

When an egg sets in a hot pan, which bonds break?

- (A) The peptide bonds, so the chains fall apart into separate amino acids as the egg cooks
- (B) Neither: the protein just melts, like fat, and goes solid again as it cools
- (C) The weak bonds that hold the fold, while the peptide bonds stay intact
- (D) Both the weak bonds and the peptide bonds, so everything comes apart

Decide before you look. Answer on page 129.

06

B1.2.6 HL CHEMICAL DIVERSITY IN THE R GROUPS

The R groups decide how a chain *behaves*

R groups differ in size, shape and chemistry, and those differences give a polypeptide its properties: which parts face water, what binds to what, and where the chain carries charge. You do not need to name any R group, but you do need to sort them.

There are two big classes. **Hydrophobic** R groups are non-polar, mostly carbon and hydrogen, and water does not attract them. **Hydrophilic** R groups are attracted to water, and they are either **polar**, with partial charges that let them form hydrogen bonds, or **charged**.

Charged R groups are **acidic** or **basic**. An acidic R group contains a carboxyl group, which loses a hydrogen ion and becomes negative (-COO^-). A basic R group contains an amine group, which gains a hydrogen ion and becomes positive (-NH_3^+). At the pH inside a cell both are charged, and a change in pH changes that (chapters 5 and 9).

KEY TERMS

hydrophobic

Not attracted to water.

Hydrophobic R groups are non-polar, made mostly of carbon and hydrogen.

hydrophilic

Attracted to water. Hydrophilic R groups are either polar or charged.

polar

Having slightly positive and slightly negative regions, as in an O-H or N-H group, so that it can form hydrogen bonds with water.

charged

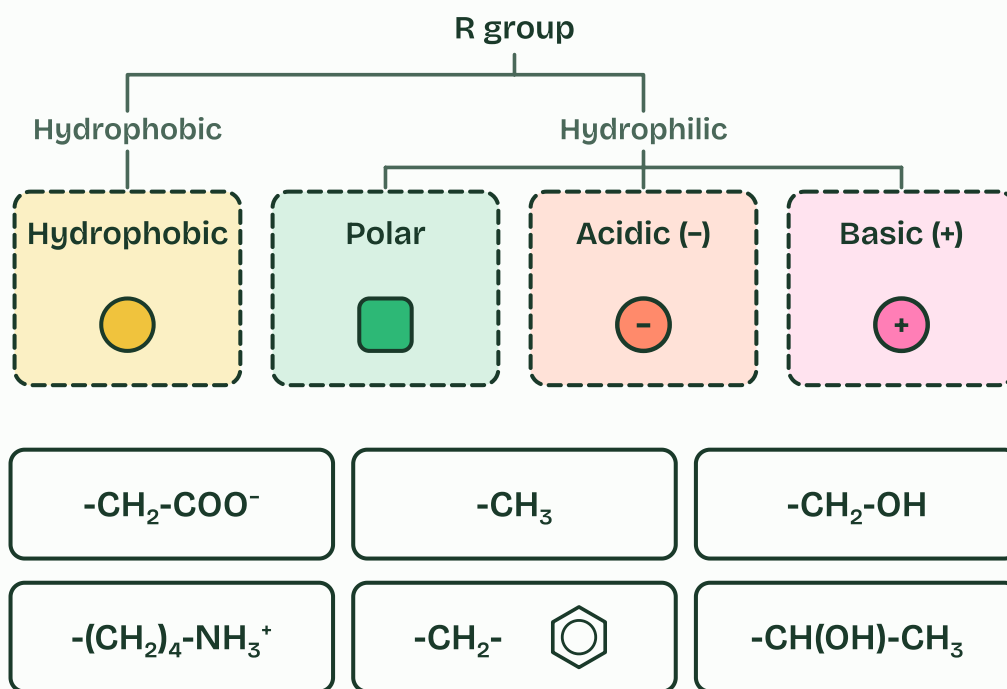
Carrying a whole positive or negative charge, because a group in the R group has gained or lost a hydrogen ion.

acidic

An acidic R group contains a carboxyl group, which loses a hydrogen ion and becomes negatively charged.

basic

A basic R group contains an amine group, which gains a hydrogen ion and becomes positively charged.



Six R groups, drawn as condensed formulas, and four bins. Which bin does each belong in, and what tells you?

REMEMBER IT

The four kinds of R group

H Hungry	P Pandas	A Ate	B Bamboo
Hydrophobic non-polar, hides from water	Polar partial charges, hydrogen bonds	Acidic loses H ⁺ , negative	Basic gains H ⁺ , positive

WATCH OUT

Hydrophilic does not mean charged: polar R groups are hydrophilic with no overall charge. Acidic R groups are negative, not positive. And a charge can come and go with pH.

PREDICT

An R group contains a carboxyl group. Inside a cell, at about pH 7, it is:

- ☐ (A) Uncharged and hydrophobic, so water does not attract it
- ☐ (B) Negatively charged, because it has lost a hydrogen ion
- ☐ (C) Positively charged, because it has gained a hydrogen ion

Decide before you look. Answer on page 129.

07

B1.2.7 HL IMPACT OF PRIMARY STRUCTURE ON CONFORMATION

The sequence sets the *shape*

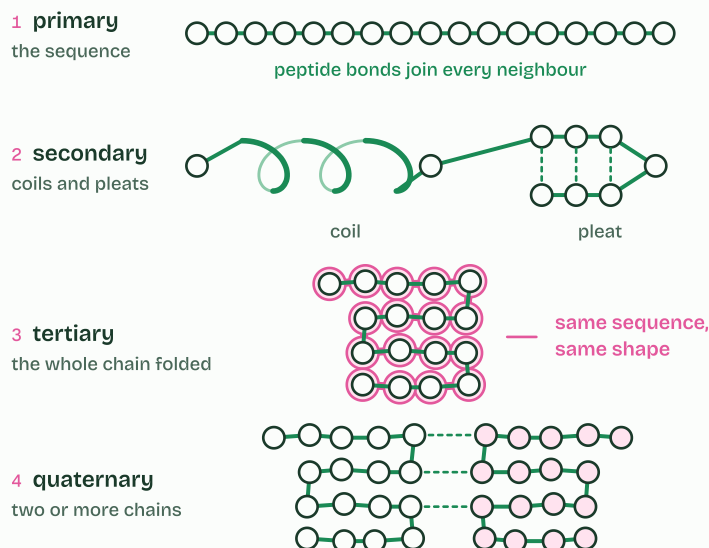
The **primary structure** of a protein is the sequence of amino acids in its polypeptide, and a gene sets it. The sequence, and the exact position of each amino acid in it, decide the three-dimensional shape: where the chain coils or pleats (secondary structure, chapter 8), how the whole chain folds (tertiary, chapters 9 and 10) and how chains fit together (quaternary, chapter 11).

So proteins have precise, predictable and repeatable structures, despite their complexity. Every insulin molecule your pancreas makes has the same shape, and fits insulin receptors anywhere in your body. Change one amino acid in a key position and the shape can change: in D1.3 you will meet a single changed amino acid in haemoglobin with large effects.

KEY TERMS

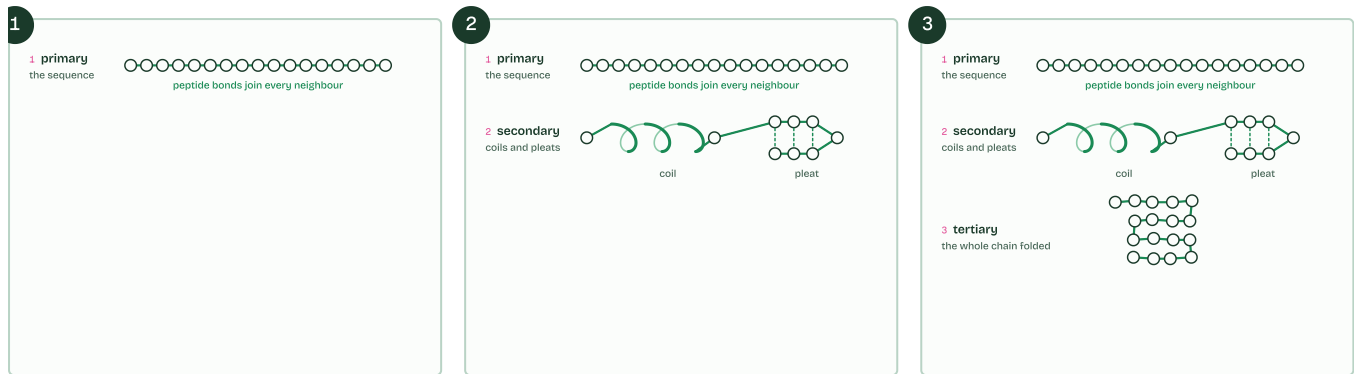
primary structure

The sequence of amino acids in a polypeptide, set by its gene.



STEP BY STEP

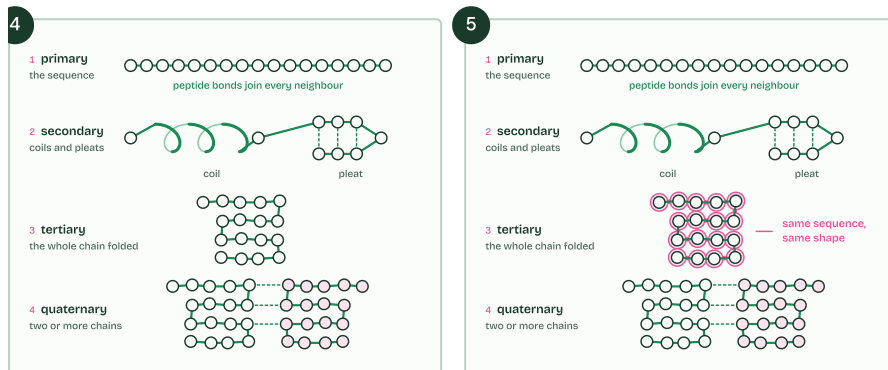
5 STEPS



Primary structure: a sequence of amino acids, each joined to the next by a peptide bond.

Secondary structure: one stretch coils and another pleats beside itself, held by dashed hydrogen bonds.

Tertiary structure: the whole chain folded into a compact shape.



Quaternary structure: two or more folded chains together. Not every protein has one.

A second copy of the same sequence folds into the same shape: same sequence, **same shape**, every time.

WATCH OUT

Primary structure is the sequence, not a shape, but it decides every level after it. Folding is not random.

HOW WE KNOW

Christian Anfinsen unfolded the enzyme ribonuclease with chemicals and then removed them. The chains refolded by themselves into the working shape, so the information for the shape is in the sequence (Nobel Prize in Chemistry, 1972). Since 2020 a computer model trained on known structures, AlphaFold, has predicted the shape of many proteins from their sequence alone, often close to what experiments find, and its database holds predictions for over 200 million proteins. Models earn trust by being tested against evidence.

PREDICT

**Two people make insulin from the same gene sequence.
Do their insulin molecules have the same shape?**

- ☐ A Yes, exactly: the same sequence folds the same way every time
- ☐ B Roughly: folding is random, so every molecule differs a little from the next
- ☐ C Only if the two people are related, because they share the same alleles for it

Decide before you look. Answer on page 129.

08

B1.2.8 HL PLEATING AND COILING OF SECONDARY STRUCTURE

Coils and pleats held by *hydrogen bonds*

Every peptide bond sits between a C=O group, whose oxygen is slightly negative, and an N-H group, whose hydrogen is slightly positive. These backbone groups are polar (A1.1), so a C=O and an N-H further along the chain can form a hydrogen bond. Where the chain makes these bonds in regular positions, it settles into a regular shape, its **secondary structure**.

In an **alpha helix** the chain coils, and each C=O bonds with the N-H four amino acids further along. The bonds fall in regular positions along the coil, and the R groups point outwards. In a **beta-pleated sheet**, stretches of the chain lie side by side, running the same way or opposite ways, and C=O groups in one stretch bond to N-H groups in the next. The chain zigzags, which makes the pleats, and the R groups point alternately above and below the sheet.

Each bond is weak, but hundreds in regular positions make the structure stable. One protein usually has stretches of both, joined by less regular loops.

KEY TERMS

secondary structure

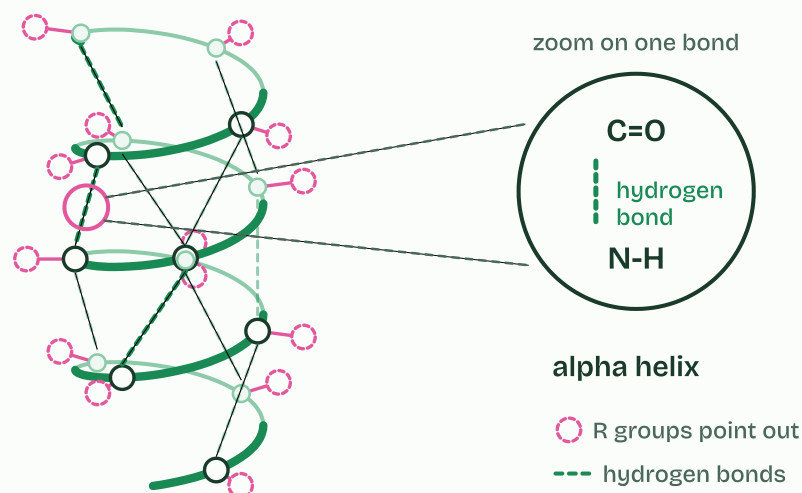
The regular coils and pleats that a polypeptide forms, held by hydrogen bonds between groups in the backbone.

alpha helix

A secondary structure in which the polypeptide is coiled like a spring. Each C=O forms a hydrogen bond with the N-H four amino acids further along.

beta-pleated sheet

A secondary structure in which stretches of the polypeptide lie side by side, held by hydrogen bonds between their backbones. The chain zigzags, so the sheet is pleated.



Hydrogen bond the O of a C=O group in one amino acid and the H of an N-H group four amino acids further along. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one amino acid and the H of an N-H group four amino acids further along. Both groups are in the backbone.

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Hydrogen bond the O of a C=O group in one amino acid and the H of an N-H group four amino acids further along. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Beta-pleated sheet stretches of the chain side by side, held by hydrogen bonds between backbone groups.

Hydrogen bond the O of a C=O group in one amino acid and the H of an N-H group four amino acids further along. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Hydrogen bond the O of a C=O group in one strand and the H of an N-H group in the strand beside it. Both groups are in the backbone.

Alpha helix one stretch of the chain coiled, held by hydrogen bonds between backbone groups in regular positions.

Loops the less regular stretches that join the helices and sheets together.

SWITCH IT

3 SETTINGS

1

zoom on one bond

C=O
hydrogen bond
N-H

alpha helix

R groups point out
hydrogen bonds

Helix

2

beta-pleated sheet

three strands side by side, running opposite ways

R groups alternate above and below

Sheet

3

alpha helix

beta-pleated sheet

loops

One chain usually has stretches of both, joined by less regular loops.

In a protein

WATCH OUT

Secondary structure bonds are between backbone groups, not R groups. An alpha helix is one coiled polypeptide, nothing to do with the double helix of DNA. And collagen's helix is not an alpha helix (chapter 11).

PREDICT

Which groups form the hydrogen bonds that hold an alpha helix?

- (A) The R groups of neighbouring amino acids, in regular positions
- (B) Water molecules around the helix, bonded to two parts of the chain
- (C) The amine and carboxyl groups at the two ends of the chain
- (D) The C=O and N-H groups of the peptide bonds in the backbone

Decide before you look. Answer on page 129.

09

B1.2.9 HL DEPENDENCE OF TERTIARY STRUCTURE ON FOUR KINDS OF BOND

Four kinds of bond hold the *fold*

Tertiary structure is the three-dimensional shape of the whole polypeptide. It is held by bonds between R groups, often far apart in the sequence.

KEY POINTS

- **Hydrogen bonds** between polar R groups.
- **Ionic bonds** between a positively charged (basic) and a negatively charged (acidic) R group. The amine and carboxyl groups in R groups become charged by gaining or losing a hydrogen ion, and only then can they form ionic bonds.
- **Disulfide bonds**, covalent bonds between the sulfur atoms of two **cysteines**, the only amino acid you need to name. This is the strongest of the four.
- **Hydrophobic interactions**: non-polar R groups cluster together, away from water.

This links back to chapter 5. Heat breaks hydrogen bonds, ionic bonds and hydrophobic interactions, and a change of pH alters charges and so breaks ionic bonds. The disulfide bonds are covalent, so they survive much more.

KEY TERMS

tertiary structure

The three-dimensional shape of a whole polypeptide, held by bonds between R groups that are often far apart in the sequence.

ionic bonds

The attraction between a positively charged R group and a negatively charged one.

disulfide bonds

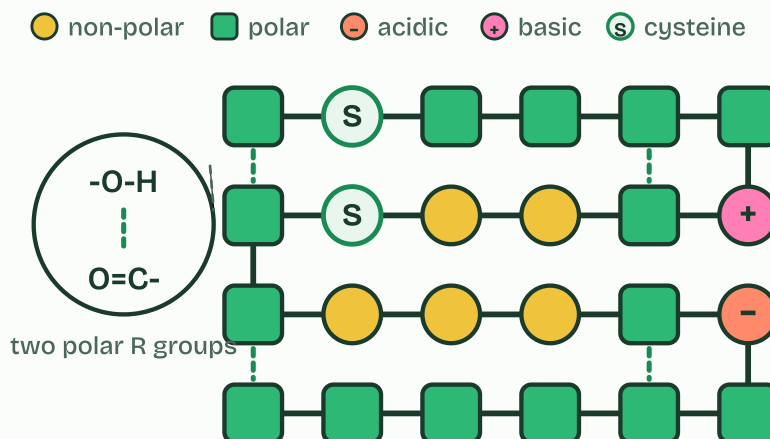
A covalent bond between the sulfur atoms of two cysteines.

cysteines

The amino acid whose R group ends in a sulfur atom, so that two of them can form a disulfide bond. It is the only amino acid you need to name.

hydrophobic interactions

The clustering of non-polar R groups together, away from water, in the middle of a folded protein.



SWITCH IT

6 SETTINGS

1

two polar R groups

Hydrogen

2

acidic meets basic

Ionic

3

two cysteines

Disulfide

4

Hydrophobic

5

All

6

the carboxyl gains H⁺

Lower the pH

REMEMBER IT

The bonds that hold a tertiary structure

H Happy	H Hippos	I Ignore	D Dentists
Hydrogen bonds between polar R groups	Hydrophobic interactions non-polar R groups huddle away from water	Ionic bonds between + and - R groups	Disulfide bonds two cysteines; the only covalent one

WATCH OUT

A disulfide bond is covalent and forms only between two cysteines: it is not a kind of hydrogen bond. Ionic bonds need charged R groups, not just polar ones. And hydrophobic interactions are not attractions between the R groups and water.

PREDICT

An ionic bond holds two parts of a protein together. The pH falls to 2. Why might the bond break?

- (A) Acid breaks the peptide bonds, so the chain falls apart into amino acids
- (B) The negative carboxyl R group gains a hydrogen ion and loses its charge
- (C) The positive R group loses its charge, so nothing is left to attract the negative one
- (D) Hydrogen ions break the disulfide bonds, which are the weakest of the four

Decide before you look. Answer on page 129.

10

B1.2.10 HL EFFECT OF POLAR AND NON-POLAR AMINO ACIDS ON TERTIARY STRUCTURE

Oily inside, *watery* outside

In proteins that dissolve in water, such as the globular proteins of chapter 12, the hydrophobic R groups cluster in the core, away from the water. The hydrophilic R groups, polar and charged, sit on the surface, where they interact with water. That watery surface is why the protein dissolves.

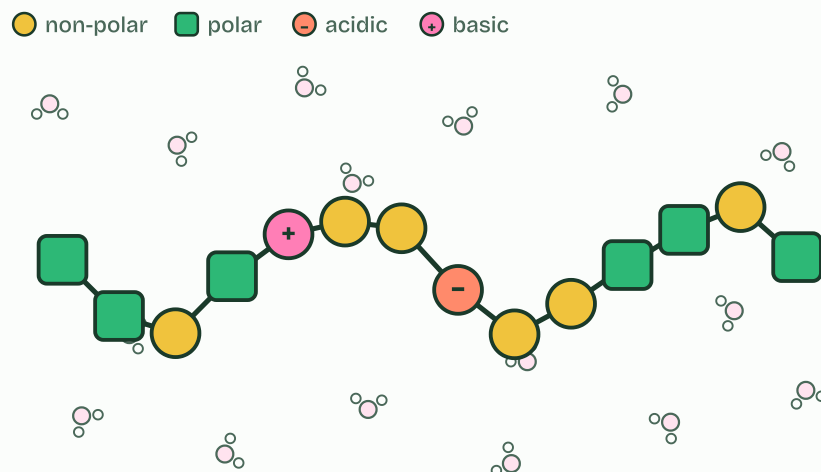
Why? Water molecules form hydrogen bonds with each other and with polar groups, but not with non-polar ones, so the non-polar R groups end up pushed together. This drives much of the folding. Water does not push them away as a magnet would: it simply bonds to itself and to polar groups instead.

Integral proteins work the other way round. They have regions of hydrophobic amino acids where they cross the membrane, lying among the hydrophobic tails of the phospholipids (B1.1), and hydrophilic regions where the protein meets water on each side (B2.1). A stretch of about 20 hydrophobic amino acids, coiled as a helix, is enough to cross the bilayer once.

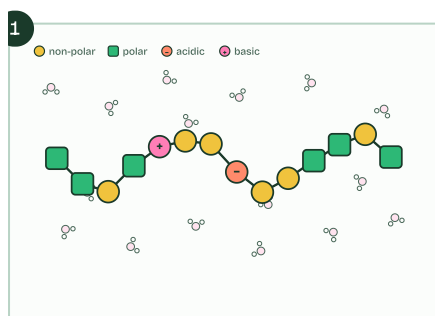
KEY TERMS

integral proteins

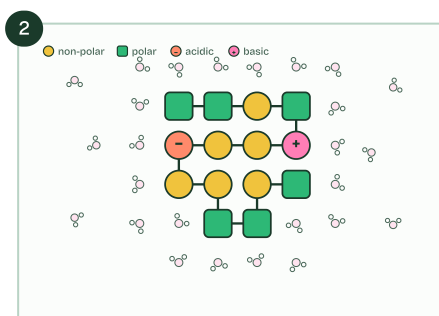
Proteins that are embedded in a cell membrane, with part of the chain lying among the hydrophobic tails of the phospholipids.



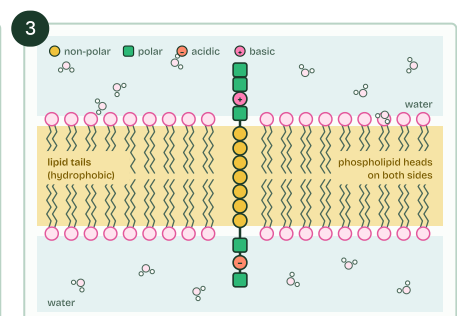
SWITCH IT



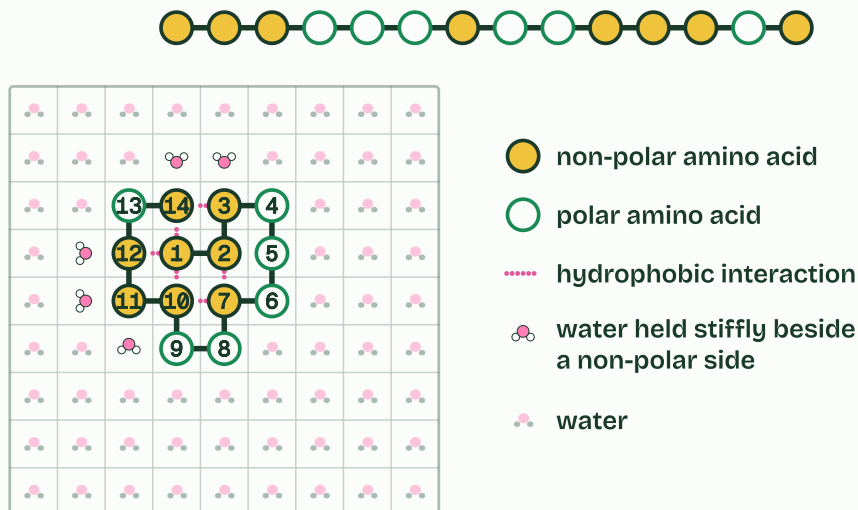
Unfolded



In water



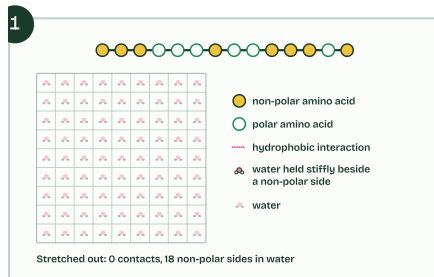
In a membrane



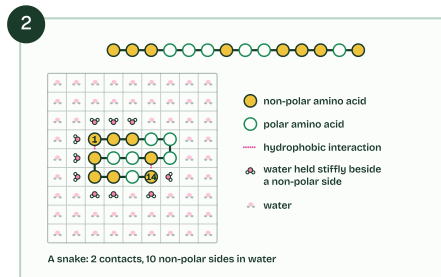
The best fold: 6 contacts, 5 non-polar sides in water

Lay the chain one residue at a time. Bring the non-polar ones together, out of the water.

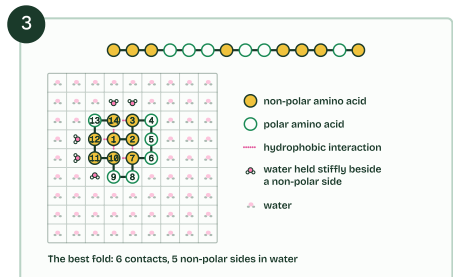
STEP BY STEP



The chain as it is made: its order of **non-polar** and **polar** amino acids. Stretched out, 18 non-polar sides touch water.



A first try: 2 contacts between non-polar residues, 10 non-polar sides still in water.



The best fold for this chain: the non-polar residues meet in a **core**, 6 contacts, only 5 sides left in water; the polar ones face outwards.

WATCH OUT

Hydrophobic amino acids are not "bad": without them there would be no core and no membrane protein. And a chain does not fold because someone puts it there: it folds by itself as it jostles in water.

PREDICT

A protein dissolves in blood plasma. Where are most of its hydrophobic R groups?

- (A) On the surface, where they touch the water and help the protein to dissolve
- (B) At the two ends of the chain, where they are free to move about
- (C) Clustered in the core of the protein, away from the water
- (D) Spread evenly through it, so that no part of the chain is more water-loving

Decide before you look. Answer on page 129.

11

B1.2.11 HL QUATERNARY STRUCTURE OF NON-CONJUGATED AND CONJUGATED PROTEINS

More than one chain: *quaternary* structure

Some proteins are a single polypeptide. Others are two or more polypeptides held together, and their arrangement is the **quaternary structure**, held by the same kinds of bond as the tertiary.

A **non-conjugated protein** is made of polypeptide only. **Insulin** has two polypeptides, of 21 and 30 amino acids, linked by two disulfide bonds, with a third disulfide bond within the shorter chain. **Collagen** has three polypeptides, each about 1,000 amino acids long, wound round each other into a triple helix like a rope. Every third amino acid is the smallest one, which lets the chains pack tightly, and hydrogen bonds between the chains hold the rope together.

A **conjugated protein** includes a part that is not polypeptide, a **prosthetic group**. **Haemoglobin** has four polypeptides, two of one kind and two of another, each holding a haem group with an iron ion at its centre. Each haem binds one oxygen molecule, so one haemoglobin carries up to four.

KEY TERMS

quaternary structure

The arrangement of two or more polypeptides in one protein, held by the same kinds of bond as the tertiary structure.

non-conjugated protein

A protein made of polypeptide only.

conjugated protein

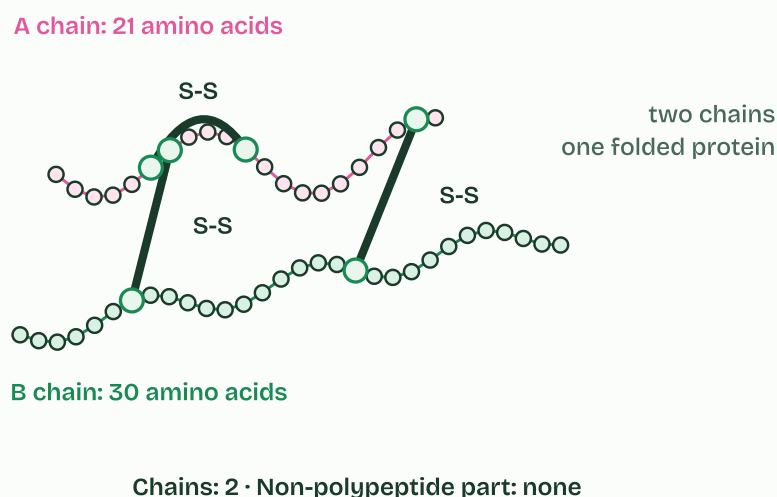
A protein that includes a part that is not polypeptide, called a prosthetic group.

prosthetic group

The non-polypeptide part of a conjugated protein, such as the haem group of haemoglobin.

cryogenic electron microscopy

Cryo-EM: freezing proteins so fast that the water around them turns to glass-like ice, then imaging single molecules with electrons and combining thousands of images into a 3D structure.



SWITCH IT

3 SETTINGS

1

Insulin

2

Collagen

3

Haemoglobin

REMEMBER IT

The three named proteins, in order of chains

I I	S See	H Him
Insulin 2 chains; globular; non-conjugated	Collagen 3 chains; fibrous; non-conjugated	Haemoglobin 4 chains plus haem; globular; conjugated

WATCH OUT

Quaternary means more than one chain, not four (haemoglobin just happens to have four). Conjugated means joined to a non-protein group, not to another protein. And collagen's triple helix is not three alpha helices: each chain is a narrower helix of its own.

HOW WE KNOW

Technology lets us see what our senses cannot. A haemoglobin molecule is about 5 to 6 nm across, and a light microscope cannot resolve anything smaller than about 200 nm. **Cryogenic electron microscopy** (cryo-EM) freezes proteins so fast that the water around them turns to glass-like ice, not crystals, then images single molecules with electrons. A computer combines thousands of images of molecules lying at different angles into a 3D structure, so it shows single proteins and the molecules they bind without growing crystals, as X-ray crystallography needs (Nobel Prize in Chemistry, 2017).

PREDICT

A haemoglobin molecule is about 5 to 6 nm across.

Could you see one with the best light microscope?

- (A) Yes, at the highest magnification, if the best objective lens and a bright enough light are used
- (B) No: it is far smaller than the smallest thing light can resolve, about 200 nm
- (C) Only if it is stained, because a stain makes any molecule large enough to see

Decide before you look. Answer on page 130.

12

B1.2.12 HL RELATIONSHIP OF FORM AND FUNCTION IN GLOBULAR AND FIBROUS PROTEINS

Balls and ropes: globular and *fibrous* proteins

Globular proteins are folded into compact, rounded shapes. Their hydrophilic surfaces make most of them soluble, and their precise shapes let them bind specific molecules: enzymes, hormones, transport proteins and antibodies.

Insulin shows how form suits function. It is small and compact. It is soluble, so it is carried dissolved in the blood plasma from the pancreas to every tissue. Its precise shape binds the insulin receptor on target cells (liver, muscle and fat cells), and its disulfide bonds keep that shape stable.

Fibrous proteins are long and narrow, often with a repeating sequence, usually insoluble and strong, and have structural jobs. **Collagen** is three chains wound into a rope. The ropes lie side by side, staggered, and are cross-linked into fibrils, which are bundled into fibres. It is insoluble and has great tensile strength, which means it resists pulling. It is in skin, tendons, ligaments, bone, cartilage and blood vessel walls, and it is the most abundant protein in the human body.

The rule of thumb is that globular proteins do something and fibrous ones are something. It has exceptions: actin and tubulin are globular units that link into structural filaments.

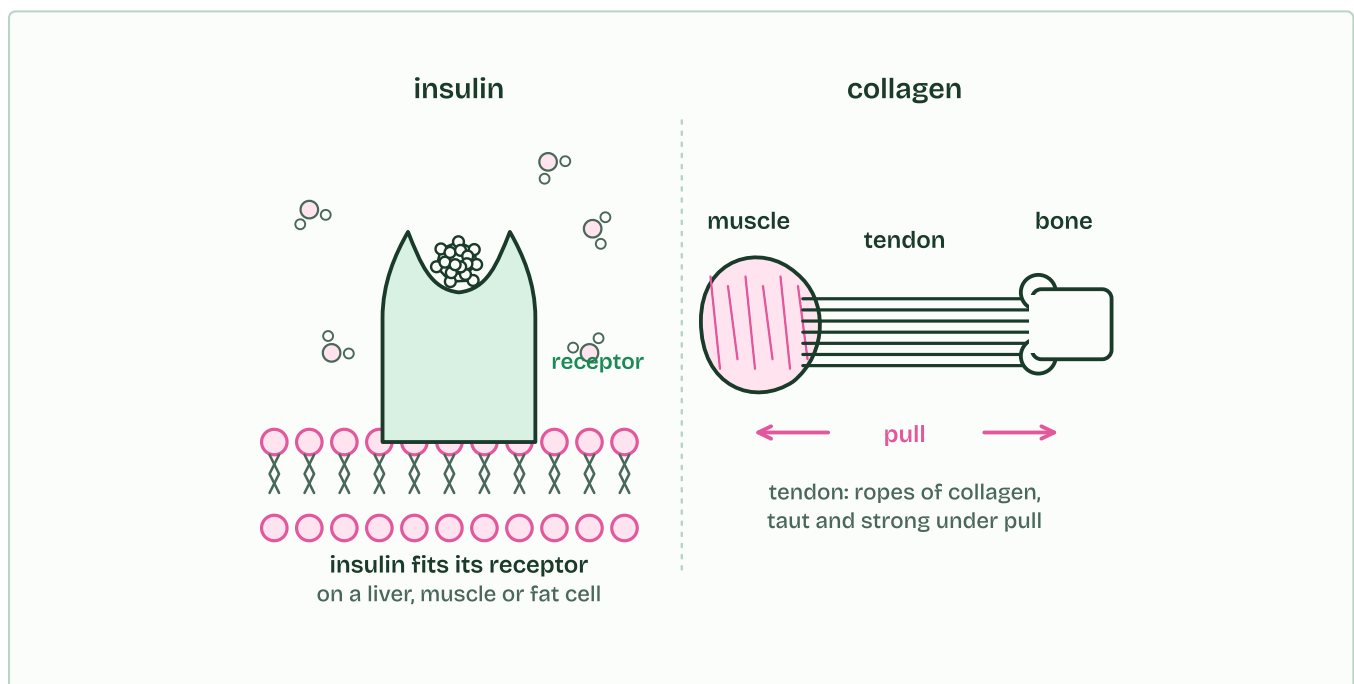
KEY TERMS

globular proteins

Proteins folded into compact, rounded shapes. Most are soluble in water and bind specific molecules: enzymes, hormones, transport proteins and antibodies.

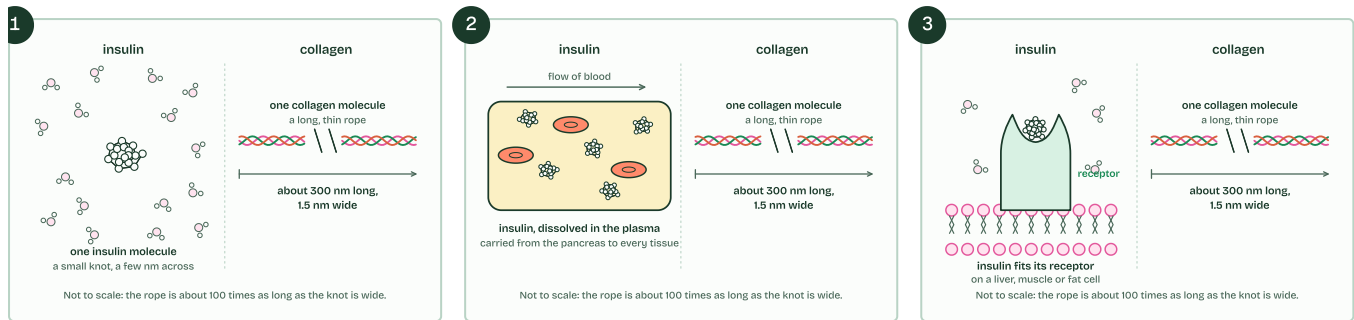
fibrous proteins

Proteins that are long and narrow, often with a repeating sequence. Most are insoluble and strong, and have structural jobs.



STEP BY STEP

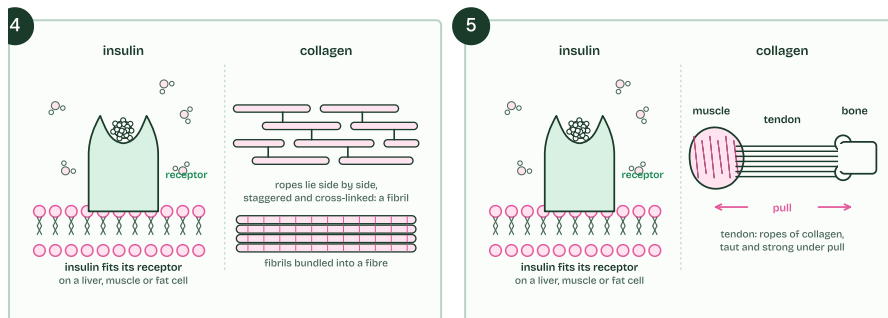
5 STEPS



One **insulin** molecule is a small rounded knot among water molecules. One **collagen** molecule is a long, thin rope, about 100 times longer than the knot is wide.

Insulin is **soluble**: dissolved in the plasma, it is carried round the body in the blood.

Insulin has a **precise shape** that fits the receptor on its target cells, liver, muscle and fat cells, like a key in a lock.



Collagen ropes lie side by side, staggered and **cross-linked**, into fibrils, and fibrils are bundled into fibres.

In a tendon, collagen fibres are **insoluble** and strong: they stay taut when muscle pulls on bone.

WATCH OUT

The functional and structural rule is only a rule of thumb (actin and tubulin). And a fibrous protein is fibrous in shape as a single molecule: it is not "made of fibres".

PREDICT

A protein is long and thin, has a repeating sequence and does not dissolve in water. What is its most likely job?

- (A) A hormone carried in the blood, because it has to dissolve and reach its target
- (B) An enzyme, because enzymes are always long and thin so that they reach their substrate
- (C) An antibody, which has to be long and thin to wrap round the microbes it destroys
- (D) A structural protein, as found in tendons, skin and blood vessel walls

Decide before you look. Answer on page 130.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

acidic 06

An acidic R group contains a carboxyl group, which loses a hydrogen ion and becomes negatively charged.

alpha carbon 01

The central carbon of an amino acid. It makes four single bonds, to an amine group, a carboxyl group, a hydrogen atom and an R group.

alpha helix 08

A secondary structure in which the polypeptide is coiled like a spring. Each C=O forms a hydrogen bond with the N-H four amino acids further along.

amine group 01

The group -NH₂: a nitrogen atom bonded to two hydrogens. It is the amino part of the name.

amino acids 01

The monomers of proteins. Each has an amine group, a carboxyl group, a hydrogen atom and an R group on one central carbon.

basic 06

A basic R group contains an amine group, which gains a hydrogen ion and becomes positively charged.

beta-pleated sheet 08

A secondary structure in which stretches of the polypeptide lie side by side, held by hydrogen bonds between their backbones. The chain zigzags, so the sheet is pleated.

carboxyl group 01

The group -COOH: a carbon with a double bond to one oxygen and a single bond to an OH. It can give up a hydrogen ion, which is why it is an acid.

charged 06

Carrying a whole positive or negative charge, because a group in the R group has gained or lost a hydrogen ion.

conjugated protein 11

A protein that includes a part that is not polypeptide, called a prosthetic group.

cryogenic electron microscopy 11

Cryo-EM: freezing proteins so fast that the water around them turns to glass-like ice, then imaging single molecules with electrons and combining thousands of images into a 3D structure.

cysteines 09

The amino acid whose R group ends in a sulfur atom, so that two of them can form a disulfide bond. It is the only amino acid you need to name.

denatured 05

Having lost its three-dimensional shape because the bonds that hold it have broken, so that the protein can no longer do its job. The amino acid sequence is unchanged.

dipeptide 02

Two amino acids joined by one peptide bond.

disulfide bonds 09

A covalent bond between the sulfur atoms of two cysteines.

essential amino acids 03

Amino acids that the body cannot make, so they must be obtained from food.

fibrous proteins 12

Proteins that are long and narrow, often with a repeating sequence. Most are insoluble and strong, and have structural jobs.

genetic code 04

The rules a cell uses to turn the sequence of bases in a gene into the sequence of amino acids in a polypeptide. It codes for twenty amino acids.

globular proteins 12

Proteins folded into compact, rounded shapes. Most are soluble in water and bind specific molecules: enzymes, hormones, transport proteins and antibodies.

hydrophilic 06

Attracted to water. Hydrophilic R groups are either polar or charged.

hydrophobic 06

Not attracted to water. Hydrophobic R groups are non-polar, made mostly of carbon and hydrogen.

hydrophobic interactions 09

The clustering of non-polar R groups together, away from water, in the middle of a folded protein.

integral proteins 10

Proteins that are embedded in a cell membrane, with part of the chain lying among the hydrophobic tails of the phospholipids.

ionic bonds 09

The attraction between a positively charged R group and a negatively charged one.

non-conjugated protein 11

A protein made of polypeptide only.

non-essential amino acids 03

Amino acids that the body can make from other amino acids, so they do not have to come from food.

peptide bond 02

The covalent bond between the carbon of one amino acid's carboxyl group and the nitrogen of the next amino acid's amine group. It forms in a condensation reaction.

polar 06

Having slightly positive and slightly negative regions, as in an O-H or N-H group, so that it can form hydrogen bonds with water.

polypeptide 02

A chain of many amino acids joined by peptide bonds.

primary structure 07

The sequence of amino acids in a polypeptide, set by its gene.

prosthetic group 11

The non-polypeptide part of a conjugated protein, such as the haem group of haemoglobin.

proteome 04

All the proteins that an organism, or a cell, makes.

quaternary structure 11

The arrangement of two or more polypeptides in one protein, held by the same kinds of bond as the tertiary structure.

R group 01

The side chain of an amino acid: the one part that differs between the twenty. R stands for whatever group it is, not for an element.

secondary structure 08

The regular coils and pleats that a polypeptide forms, held by hydrogen bonds between groups in the backbone.

tertiary structure 09

The three-dimensional shape of a whole polypeptide, held by bonds between R groups that are often far apart in the sequence.



Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on B1.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

[biologybybradford.com/exam-maker/sit?
topics=B1.2&level=HL&paper=quiz&marks=15&src=ep](https://biologybybradford.com/exam-maker/sit?topics=B1.2&level=HL&paper=quiz&marks=15&src=ep)

Answers

A1.1 Water

PREDICTIONS IN THE CHAPTERS

01 A packet of dry bean seeds sits in a cupboard for three years. What is happening to the metabolism inside each seed?

B It has almost stopped: with so little water, enzymes and substrates cannot meet to react

Almost stopped. A dry seed holds only about a tenth of its mass as water, too little for most reactions. Soak it, and within hours water floods in, its enzymes start working and the seed begins to germinate. Metabolism needs water as its medium, which is what this statement means.

02 Water boils in a kettle. Which bonds break as it turns to steam?

C The hydrogen bonds between molecules, so the steam is still made of water molecules

Only the hydrogen bonds. Boiling and evaporation separate whole molecules from one another, and the covalent bonds, about twenty times stronger, stay as they are. Breaking all those hydrogen bonds is why water needs so much heat to boil or evaporate, and why sweat cools you. The dry lab puts a number on it.

03 Ground pepper floats on a bowl of water. You touch the middle of the surface with a finger dipped in washing-up liquid. What does the pepper do?

A It shoots out to the edge of the bowl, dragged by the clean surface that is still pulling all round

It shoots outwards. Soap molecules crowd into the surface where you touch it and weaken the hydrogen bonding there, so the surface tension falls in the middle. The clean surface all round still pulls strongly and drags the water, and the pepper on it, to the edges. Detergent in a pond does the same to a pond skater: with less surface tension to stand on, it sinks.

04 Three cups in a row: red water, an empty cup, blue water. A strip of paper towel bridges each full cup and the empty one. What is in the middle cup a few hours later?

C Purple water, rising until the levels even out, because water creeps along paper from both sides

Purple water. Paper towel is cellulose. Water adheres to its fibres and creeps up and along the strip by capillary action, cohesion pulling the rest behind, and drips into the empty cup until the levels even out. Both colours arrive and mix. The same process keeps the walls of a leaf's cells wet and moves water through soil.

05 Fish get all their oxygen from water. Oxygen molecules (O_2) are non-polar. How does the oxygen get into the water?

C Small non-polar molecules dissolve a little, and a little is enough to reach the gills

A little dissolves. A litre of water at 20 °C holds only about 9 mg of oxygen, about a thirtieth of the oxygen in a litre of air. Small non-polar molecules such as oxygen slip in between water molecules in small amounts. It is enough for fish, which pass a great deal of water over large gills. Warm water holds even less, which is why fish gasp at the surface in a heatwave.

06 Ringed seal pups are born in snow caves on the sea ice, with thick woolly fur but almost no blubber. What happens to a young pup that has to stay in the sea for a long time?

B It chills fast: soaked fur holds no air, and water draws heat away about 23 times faster than air does

It chills fast. The woolly fur keeps a pup warm in the snow cave because it traps air, a poor conductor of heat. Soaked, it holds water instead, and the pup has almost no blubber yet. The sea, at about -1.8 °C, is indeed warmer than the winter air, but water draws heat away so much faster that the pup loses heat far more quickly in it. That is why the snow caves matter.

- 07 Venus is almost the same size and mass as Earth, but closer to the Sun. Why are there no oceans on Venus?

A It is too hot for water vapour to condense into liquid, so any water stayed in the air as vapour

Too hot. Venus's gravity is nearly as strong as Earth's, so gravity is not the problem. Its surface is about 460 °C today, so its water stayed as vapour and has since been lost. A planet needs both: enough gravity, and temperatures low enough for water to condense.

- 08 A star gives out much less energy than the Sun. Where would its Goldilocks zone be?

C Much closer to the star, so that a planet there still receives enough energy to keep water liquid

Much closer. A planet must be near a dim star to receive enough energy to keep water liquid. Round red dwarfs, the commonest stars in our galaxy, the zone is so close that a planet's year there lasts only days or weeks.

A1.2

Nucleic acids

PREDICTIONS IN THE CHAPTERS

- 01 A virus is found whose genes are made of RNA. Does that break the rule that DNA is the genetic material of all living organisms?

B No: viruses are not counted as living organisms

No. A virus has no cells and no metabolism of its own, and it can only be copied inside a host cell, so biologists do not count it as alive. The rule is about living things, and in every one studied so far the genetic material is DNA. In an RNA virus the genes really are RNA: there is no hidden DNA original.

- 02 How many different nucleotides does a cell use to build DNA?

C Four: the sugar and phosphate are the same, only the base differs

Four. Every DNA nucleotide has the same phosphate and the same sugar, deoxyribose; only the base differs, and DNA has four bases. RNA has its own four, built on ribose, so a cell's nucleic acids use eight nucleotides in all.

- 03 How many water molecules are released when 10 nucleotides join into one strand?

A 9

Nine. Each bond releases one water molecule, and ten nucleotides in a row have nine bonds between them: n nucleotides make $n - 1$ bonds and release $n - 1$ water molecules. Taking the strand apart again by hydrolysis would use nine water molecules.

- 04 One strand of a DNA molecule reads A A T G C. The strands separate and each is copied. What does the strand built against it read, and the strand built against that one?

B T T A C G, then A A T G C

Pairing makes a complementary copy, and the complement of the complement is the original. So every molecule made by copying has the same sequence as the one it came from: this is how complementary pairing keeps genetic information exact through replication. (U belongs in RNA, not in a DNA copy.)

- 05 To be copied, the two strands of DNA must come apart. Why does pulling them apart not break the strands themselves?

C Weak hydrogen bonds join the two strands, while each strand is a chain of strong covalent bonds

The bonds between the strands are hydrogen bonds: weak one by one, so the strands can be unzipped. The bonds along each strand are covalent, so each strand, and the sequence it carries, stays whole. Both strands then serve as templates (chapter 4).

- 06 A sample of nucleic acid is single-stranded and contains thymine but no uracil. What is it most likely to be?

A DNA, from one of the few viruses with single-stranded DNA

Thymine is the clue: it is a DNA base. Most DNA is double-stranded, but a few viruses carry single-stranded DNA, so the number of strands is the least reliable of the three differences. The sugar would settle it: deoxyribose means DNA.

- 07 How many different sequences of three bases can DNA's four bases make?

B 64

Four choices for the first base, four for the second and four for the third: $4 \times 4 \times 4 = 64$. (12 adds when it should multiply; 81 is 3 to the power 4, the right numbers the wrong way round.) Each extra base multiplies the possibilities by four again, which is why the capacity of DNA is limitless.

- 08 One DNA strand reads 5'-ATGC-3'. Written 5' to 3', what is its partner?

C 5'-GCAT-3'

The partner pairs base by base, T A C G, but runs the other way: 3'-TACG-5'. Read from its own 5' end, that is 5'-GCAT-3'. (5'-CGTA-3' is the first strand backwards, with no pairing at all.)

- 09 30% of the bases in a sample of double-stranded DNA are adenine. What percentage are purines?

B 50%

50%, whatever the sequence. Every base pair is one purine and one pyrimidine, so purines are always half the bases in double-stranded DNA: here 30% adenine and 20% guanine. In symbols, $A + G = C + T$. Chapter 12 picks this up.

- 10 A chemical is added that cancels the negative charges on DNA's phosphate groups. What would you expect to happen to the nucleosomes?

C The DNA would come away from the histones more easily

The DNA would loosen. Histones are rich in positively charged amino acids (lysine and arginine), and DNA's phosphate groups are negatively charged, so the two attract. Because the backbone is on the outside and every base pair is the same width (chapter 9), histones can hold any sequence. Take away the negative charges and the attraction goes. Cells do something like this on purpose, tagging histones to loosen or tighten the wrapping (D2.2).

- 11 After blending and spinning, where will most of the radioactivity be in each batch?

C Sulfur-35 in the liquid, phosphorus-32 in the pellet

Only the DNA goes in. The protein coats, carrying the sulfur-35, are shaken off and stay in the liquid; the bacteria, now holding the phage DNA with its phosphorus-32, sink to the pellet. The DNA that went in is what made the new phages: phosphorus-32 turned up in the next generation of phages, and sulfur-35 hardly at all. So DNA, not protein, is the genetic material of T2.

- 12 The tetranucleotide hypothesis says every DNA molecule is 25% of each base. Which result would be enough, on its own, to falsify it?

B One species whose DNA is reliably measured as 30% adenine

One reliable contradiction is enough to reject a claim about all DNA. Human DNA is about 30% adenine and 20% guanine, not 25% of each, and the proportions vary between species. A thousand species with A equal to T cannot prove anything about every species, and do not even test the 25% prediction; a species at exactly 25% agrees with the hypothesis, so it cannot falsify it.

A4.1

Evolution and speciation

PREDICTIONS IN THE CHAPTERS

- 01** A gardener clips a hedge into a perfect cube every year for 40 years. Seeds from the hedge are sown. What shape do the seedlings grow into?

C The usual shape for the species: clipping never touched their alleles

The usual shape. Clipping changes the hedge's body, not the alleles in its pollen and ovules, so nothing about it reaches the seeds. Only changes to the alleles in gametes can be inherited, which is why only they count as evolution.

- 02** Before you compare: which species' sequence will differ from the human one at the most positions?

D Frog

The frog. Our line split from the chimpanzee's about 6 to 7 million years ago, from the mouse's about 90 million, from the birds' about 310 million and from the amphibians' about 350 million. The frog's line has had longest for differences to build up.

- 03** Kohlrabi and Brussels sprouts look nothing alike. A grower lets them cross-pollinate. What happens?

B Seeds form and grow into fertile plants: one species

They cross easily and the offspring are fertile, which is why seed growers keep the cultivars far apart. However different they look, they are still one species with one gene pool.

- 04** A bat's wing and a bird's wing: homologous or analogous?

C Both: homologous as forelimbs, analogous as wings for flight

Both. As forelimbs they share the pentadactyl plan from a common ancestor: homologous. But that ancestor could not fly, so wings evolved separately in bats (skin stretched over long fingers) and birds (feathers on a shortened hand): as wings, analogous.

- 05** A line of snails changes its shell shape steadily for two million years and never splits. The oldest and newest shells look so different that fossil experts give them different names. How many species has the line added to the Earth?

B None: at every moment there was still only one species

None. At every moment there was one species of these snails, so the count never went up. The two names are a convenience for describing change along one line. Gradual change within one line is evolution, but only a split adds a species.

- 06** Suppose the river had divided the apes but the forests on both banks were identical. What would you expect after a million years?

B Some differences, from mutation and drift, but less divergence

Some differences. Mutations and drift still differ on each side, so the populations slowly drift apart, but with no differential selection nothing pushes them in different directions. Try it in the dry lab: the control has the same food on both islands.

- 07** Two populations of a cricket share one meadow. One sings and mates in spring, the other in late summer. Which kind of isolation is this, and which route to speciation?

B Temporal isolation: sympatric speciation

Temporal isolation, and sympatric, because they live in the same place. Nothing separates them but the time of year when they breed, which is enough to stop gene flow.

- 08** Suppose the first finches had landed on islands already full of small birds of many kinds. What would you expect?

A Fewer finch species: most niches would already be filled

Fewer. A finch with a beak suited to insects would compete with established insect-eaters, which already do that job well, so selection would not favour it. Vacant niches are what let a radiation happen.

- 09** Redshank ($2n = 44$) is crossed with one of its parents, pale persicaria ($2n = 22$). How many chromosomes do the offspring have, and are they fertile?

B 33: three sets that cannot pair evenly, so sterile

33. A redshank gamete carries 22 and a pale persicaria gamete 11. The offspring have three sets of 11, and an odd number of sets cannot pair evenly at meiosis, so they are sterile. That is why the new polyploid is reproductively isolated from its parents straight away.

QUESTIONS ON THE DRY LAB

- Q1** In the control, the islands have the same food. After 200 generations the mean beaks usually differ a little, but the test says one species. Why?

B Only drift and mutation differ, so the beaks wander slowly and at random

Isolation stops gene flow, but with the same food there is no differential selection to push the two populations in different directions. Drift and new mutations still differ on each side, so the beaks wander apart a little, slowly and in no particular direction: far too little, in 200 generations, for the birds to prefer their own kind. It is the bonobos' lesson (A4.1.7): isolation lets populations diverge, and different selection drives them apart.

- Q2** With very different food, a handful of birds crossing each generation is enough to keep the two islands one species. How?

C Each crossing bird brings its alleles, mixing the gene pools every generation

Gene flow. Every bird that crosses and breeds carries its alleles into the other gene pool, undoing some of the divergence that selection builds. A few migrants each generation can hold two populations together as one species, even when selection on each side is strong. That is why reproductive isolation comes first in speciation (A4.1.6 and A4.1.7).

- Q3** Higher level. On one island with two foods, the population only splits into two groups when mate choice is strong. Why is mate choice needed here, but not when the sea splits the island?

A On one island nothing else stops the two groups mating, so behaviour must

Without a barrier, deep-beaked and shallow-beaked birds meet and mate, and their chicks have middling beaks, mixing the two groups back together every generation. Only behavioural isolation, choosing a mate that sounds like your own kind, stops that gene flow. With the sea, geography does that job. This is the difference between sympatric and allopatric speciation (A4.1.8).

B1.2

Proteins

PREDICTIONS IN THE CHAPTERS

- 01** A student draws an alpha carbon bonded to $-\text{NH}_2$, $-\text{COOH}$, R and $-\text{OH}$. What is wrong with the drawing?

B The fourth group should be a single hydrogen atom, not $-\text{OH}$

The alpha carbon always carries a single hydrogen atom. With $-\text{OH}$ in its place the drawing is not an amino acid, and an examiner would not award the mark for the alpha carbon's groups. Check every drawing for the H.

02 Two different amino acids, A and B, are joined by one peptide bond. How many different dipeptides could they make?

C Two: A's carboxyl to B's amine, or B's carboxyl to A's amine, and these are different molecules

Two. A peptide bond always joins a carboxyl group to an amine group, so every dipeptide has an amine end and a carboxyl end. In A-B, A keeps its free amine group; in B-A, B does. The same amino acids make different molecules, which is why the order of amino acids matters (chapter 4). Try both ways round in the bond builder.

03 You eat plenty of protein, but it lacks one essential amino acid. What happens to the proteins that need it?

A They cannot be completed, because no other amino acid can take its place in the sequence

They cannot be completed. Your cells cannot make an essential amino acid, and the gene sets the sequence, so no other amino acid can take its place. Every protein that needs it stalls at that point. That is why the total amount of protein is not the whole story: the mix matters.

04 How many different dipeptides can be made from the 20 amino acids?

D 400, because there are twenty choices at each of the two positions

400. There are 20 choices for the first amino acid and 20 for the second. Order matters (one way round is a different molecule from the other), and the same amino acid can appear twice. Move the slider to 2 to check, then try 3.

05 When an egg sets in a hot pan, which bonds break?

C The weak bonds that hold the fold, while the peptide bonds stay intact

Only the weak bonds that hold the fold. The chain of amino acids is still whole: a cooked egg is digested into exactly the same amino acids as a raw one. What heat destroys is the shape, and with it the job.

06 An R group contains a carboxyl group. Inside a cell, at about pH 7, it is:

B Negatively charged, because it has lost a hydrogen ion

Negatively charged. A carboxyl group gives up its hydrogen ion and is left negative: an acidic R group. An amine group does the opposite, gaining a hydrogen ion to become positive: a basic R group. Both are hydrophilic.

07 Two people make insulin from the same gene sequence. Do their insulin molecules have the same shape?

A Yes, exactly: the same sequence folds the same way every time

Yes. Proteins have precise, repeatable shapes. The sequence of R groups decides which bonds can form and where, so the same sequence folds the same way every time. That is why one hormone fits the same receptor in every cell, and why a protein's shape can be predicted from its sequence.

08 Which groups form the hydrogen bonds that hold an alpha helix?

D The C=O and N-H groups of the peptide bonds in the backbone

The backbone's own C=O and N-H groups, in regular positions four amino acids apart. That is why almost any stretch of chain can coil or pleat: the groups that bond are in every amino acid. The R groups decide which stretches do.

09 An ionic bond holds two parts of a protein together. The pH falls to 2. Why might the bond break?

B The negative carboxyl R group gains a hydrogen ion and loses its charge

In acid, a -COO^- picks up a hydrogen ion and becomes -COOH , with no charge, so nothing attracts it to the positive R group. Press Lower the pH to watch it. In strong alkali the opposite happens: -NH_3^+ loses its hydrogen ion.

10 A protein dissolves in blood plasma. Where are most of its hydrophobic R groups?

C Clustered in the core of the protein, away from the water

In the core. Hydrophobic R groups are not attracted to water, so in the folded protein they end up together inside, while hydrophilic ones cover the surface and keep it in solution. Play the puzzle below and you will find yourself doing the same.

11 A haemoglobin molecule is about 5 to 6 nm across. Could you see one with the best light microscope?

B **No: it is far smaller than the smallest thing light can resolve, about 200 nm**

No. A light microscope cannot separate details closer than about 200 nm, some 40 times the size of a haemoglobin molecule. Electron microscopes, and now cryo-EM, image single molecules: technology extends our senses.

12 A protein is long and thin, has a repeating sequence and does not dissolve in water. What is its most likely job?

D **A structural protein, as found in tendons, skin and blood vessel walls**

A structural one. Long, repetitive and insoluble are the marks of a fibrous protein: strength, not binding. Hormones, enzymes and antibodies have to dissolve and fit specific molecules, which needs a compact, globular shape.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.