REVISION GUIDE

How water, sugar and blood *move*

Transport

Water climbs to the top of a tree with no pump: it is pulled up from the leaves as they lose it to the air, and sugar is pushed through the phloem by pressure. Blood has a pump, the heart, which drives it out through arteries built to hold the pressure, through capillaries where it swaps with the cells, and back through veins with valves. The plant half comes first, then the human half.

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By the end you can

- [ ] Explain how transpiration pulls water up from the roots: evaporation, capillary action in the leaf's cell walls, tension in the xylem and cohesion B3.2.7
- [ ] Explain how xylem vessels are built to carry water under tension B3.2.8
- [ ] Draw a plan diagram of a dicot stem from a micrograph and annotate what each tissue does B3.2.9
- [ ] Draw a plan diagram of a dicot root from a micrograph and identify its tissues B3.2.10
- [ ] Explain how pumping mineral ions into the root makes root pressure, and when a plant relies on it B3.2.17
- [ ] Explain how sieve tubes and companion cells load, carry and unload sap between sources and sinks B3.2.18
- [ ] Explain how capillaries are built for exchange: branched and narrow, thin-walled, with pores where exchange must be fast B3.2.1
- [ ] Tell an artery from a vein in a micrograph from the thickness of its wall against the width of its lumen B3.2.2
- [ ] Explain how the muscle and elastic fibres in their walls let arteries withstand and keep up a high pressure B3.2.3
- [ ] Find and count a pulse at the wrist or the neck, and compare counting by fingertip with digital methods B3.2.4
- [ ] Explain how valves and a flexible wall help veins return blood to the heart B3.2.5
- [ ] Explain how fatty deposits and clots block coronary arteries and what follows, and judge data on coronary heart disease B3.2.6
- [ ] Explain how tissue fluid forms from plasma by pressure filtration and drains back into the capillaries B3.2.11
- [ ] Compare plasma with tissue fluid, and explain the exchange between tissue fluid and the cells B3.2.12
- [ ] Explain how lymph vessels collect the leftover tissue fluid and return it to the blood B3.2.13
- [ ] Compare the single circulation of a bony fish with the double circulation of a mammal B3.2.14
- [ ] Relate each part of the mammalian heart to its job, identify it on a frontal diagram and trace the flow from veins to arteries B3.2.15
- [ ] Describe the cardiac cycle on the left side from the SA node, and read systolic and diastolic pressures from data B3.2.16

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

01

B3.2.7 TRANSPORT OF WATER FROM ROOTS TO LEAVES DURING TRANSPIRATION

Water is *pulled* from the top

Why is a good day for drying washing a hard day for a plant? Warm, dry, windy weather dries a towel fast, and it draws water out of leaves fast too. Leaves lose water vapour all day through the stomata they open to take in carbon dioxide. That loss is **transpiration** (B3.1). The water they lose is replaced from the soil, up through the roots and the stem: the **transpiration stream**. Nothing pumps it. It is pulled from the top.

The pull starts in the leaf. Water **evaporates** from the wet walls of the mesophyll cells into the air spaces, and the vapour diffuses out through the stomata. The walls refill by **capillary action**: water creeps through the narrow spaces between the cellulose fibres of the walls, and is drawn out of the nearest xylem vessels to take the place of the water that evaporated.

That leaves the water in the xylem being pulled. It is under **tension**: its pressure is below zero, a negative pressure potential. The tension draws the whole column of water up the stem from the roots, the way a rope moves when you pull one end. **Cohesion** keeps the column whole: hydrogen bonds hold each water molecule to its neighbours (A1.1), so a pull at the top is passed all the way down. **Adhesion** to the vessel walls helps to hold the column in place. As the column rises, water enters the roots from the soil.

The energy comes from the sun, which warms the leaves and evaporates the water. The plant spends none of its own energy lifting water up the xylem.

KEY TERMS

transpiration
The loss of water vapour from a plant, mostly from its leaves through the stomata.

transpiration stream
The flow of water from the soil, through the roots, up the xylem and out of the leaves as vapour.

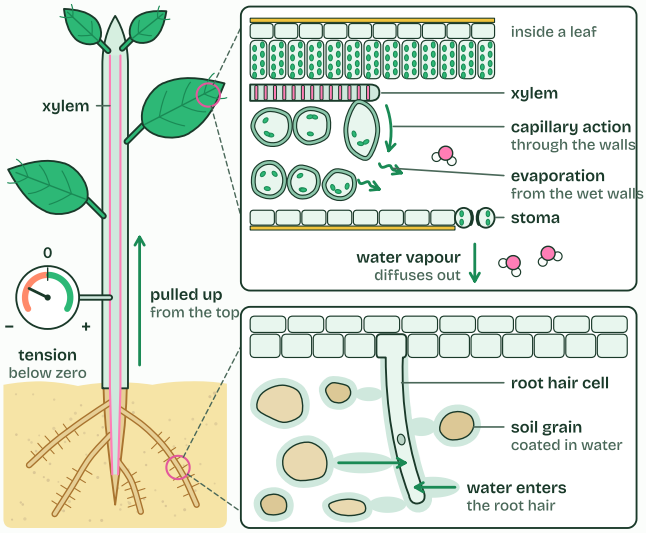
evaporates
Changes from a liquid to a gas at its surface, taking heat with it.

capillary action
Water creeping along narrow spaces, drawn by adhesion to the surfaces and held together by cohesion. In a cell wall the spaces are the gaps between the cellulose fibres.

tension
A pull on a liquid, so that its pressure is below zero. In the xylem this is a negative pressure potential.

cohesion
Water molecules sticking to each other, held together by hydrogen bonds.

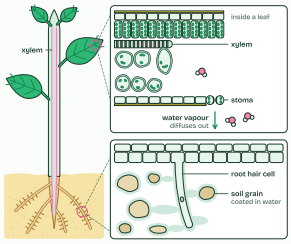
adhesion
Water molecules sticking to other substances, such as the walls of a xylem vessel.



STEP BY STEP

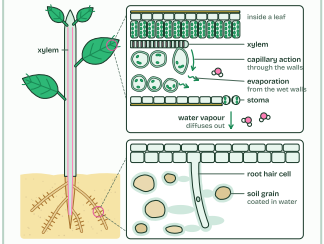
4 STEPS

1



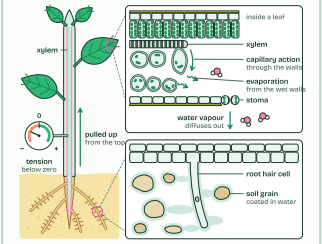
Water vapour **diffuses** out of the leaf through the stomata: transpiration.

2



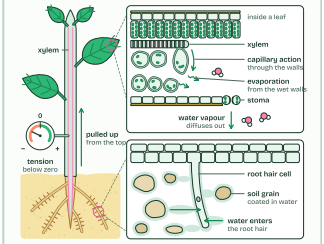
Water **evaporates** from the wet cell walls. More creeps through the walls by **capillary action**, drawn out of the xylem.

3



The water in the xylem is under **tension**: its pressure is below zero. Cohesion keeps the column whole as it is pulled up.

4

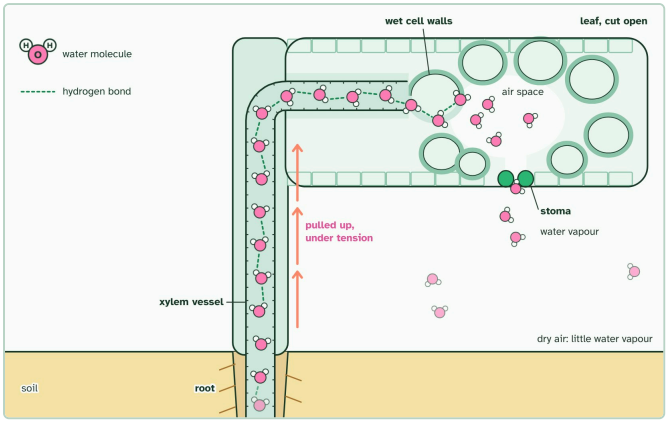


As the column rises, water enters the **root hairs** from the soil to replace it.

ANIMATION · WATER IN A XYLEM VESSEL

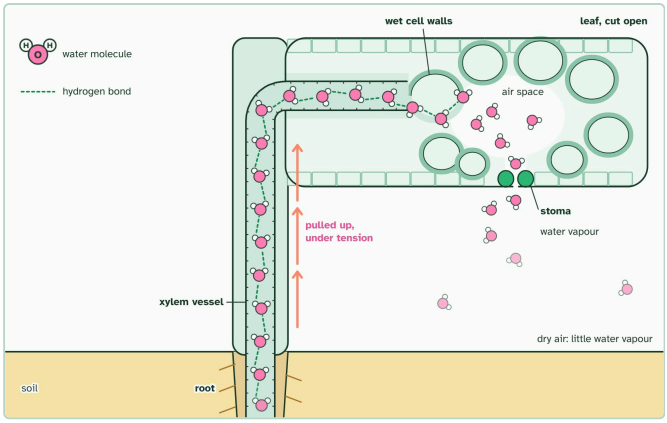
3 MOMENTS

1 FLOW: FAST



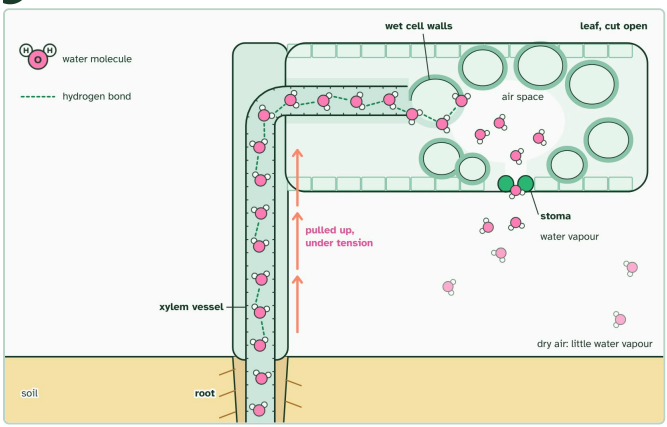
Water **evaporates** from the wet cell walls in the leaf and escapes through a stoma.

2 FLOW: FAST



Each molecule that leaves pulls on the next: **hydrogen bonds** hold the column together.

3 FLOW: FAST



The whole column is pulled up from the roots, under **tension**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#pull

REMEMBER IT

The pull, from the leaf down: Every Cool Tree Climbs

E Every	C Cool	T Tree	C Climbs
Evaporation from the wet cell walls into the air spaces	**Capillary action** water creeps through the walls, drawn from the xylem	**Tension** the water in the xylem is pulled, below zero pressure	**Cohesion** hydrogen bonds keep the column whole

WATCH OUT

"The roots pump water up the xylem." Roots can push a little (root pressure, chapter 5, higher level), but the main force is the pull from the leaves. And "capillary action in the vessels lifts water up a tree." In a tube as wide as a typical xylem vessel, capillary action alone lifts water less than a metre, nowhere near the top of a tree. The capillary action in this story is in the leaf's cell walls.

TRY IT

Warm, dry, moving air speeds evaporation, and evaporation cools the surface it leaves. Test both with the wet wicks in A1.1's dry lab. Then find where the pull starts on this guide's potometer bench: run a shoot with all its leaves, one with half of them and one with none.

PREDICT

An air bubble gets into one xylem vessel. What happens to the water in that vessel?

(A) The bubble rises with the water, and the flow carries on past it at the same speed

(B) The water speeds up, because there is less of it left in the vessel to lift

(C) Below the bubble it stops, because cohesion cannot pull across a gap

(D) The roots push the water below the bubble on past it, so the flow goes on

Decide before you look. Answer on page 80.

02 Xylem vessels are *built* for the pull

B3.2.8 ADAPTATIONS OF XYLEM VESSELS FOR TRANSPORT OF WATER

A **xylem vessel** is a long tube made from a column of cells joined end to end. While the cells are alive, they build thick walls around themselves. Then they die and their contents break down, and what is left is a tube of cell walls. Vessels are dead when they carry water, and that is what makes them good at it.

Each feature has a job:

KEY POINTS

- **No cell contents.** No cytoplasm, nucleus or vacuole is left in the **lumen**, the space inside, so nothing blocks the water.
- **End walls incomplete or gone.** The walls between the cells break down, so water flows from one cell to the next unimpeded.
- **Walls thickened with lignin.** **Lignin** is hard and strong. The water inside is under tension, which pulls the walls inwards, and lignin stops them collapsing.
- **Pits.** **Pits** are gaps in the lignin where only the thin primary wall (the original cellulose wall) is left. Water passes through them sideways, into and out of the vessel, and round a vessel that is blocked.

In a young stem that is still growing longer, the lignin goes on in rings or a spiral, which can stretch as the stem lengthens. Vessels made after the stem stops lengthening are lignified more heavily: in a net, or all over apart from the pits.

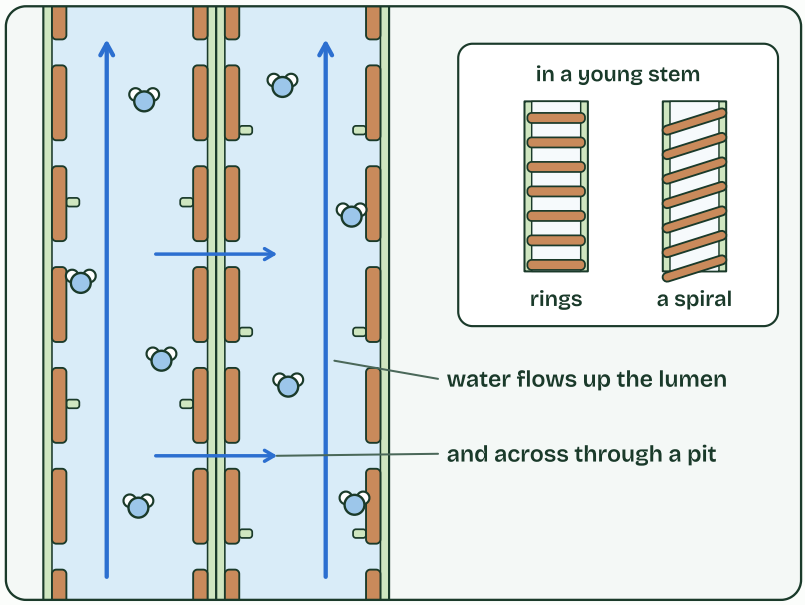
KEY TERMS

xylem vessel
A long tube in the xylem, made from a column of cells joined end to end that died once their walls were built.

lumen
The space inside a tube, such as a xylem vessel or a blood vessel.

lignin
A hard, strong polymer laid down in the walls of xylem vessels. Wood is mostly lignified xylem.

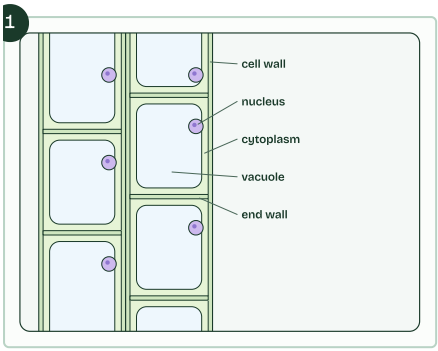
pits
Gaps in the lignin of a xylem vessel's wall, where only the thin primary wall (the original cellulose wall) is left, so water can pass through sideways.



STEP BY STEP

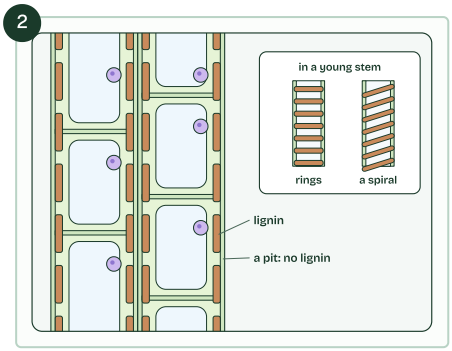
4 STEPS

1



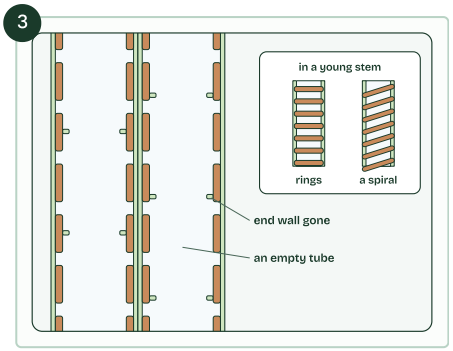
Two xylem vessels side by side, each starting as a column of **living cells** with a nucleus and cytoplasm.

2



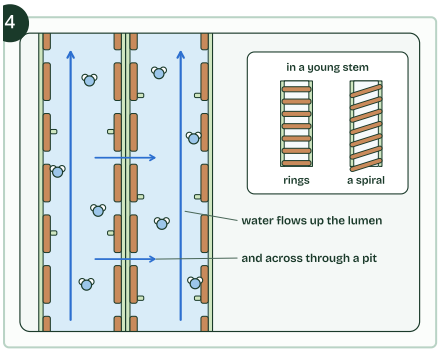
The cells thicken their walls with **lignin**, leaving gaps, the pits. In a young stem it goes on in rings or a spiral.

3



The cells die, their contents break down and the **end walls** go: an open tube.

4



Water flows up the **lumen** unimpeded, and sideways through the **pits** into the next vessel.

WATCH OUT

"Xylem vessels are living cells." They are dead when they carry water: living cells built them, then died. And "lignin is there to waterproof the vessel." Lignin does make the wall less leaky, but the job the IB asks about is strength: it stops the vessel caving in under tension.

PREDICT

A plant cannot make lignin. On a hot, windy day, what happens to its xylem vessels?

(A) They burst outwards under the pressure of all the water being pushed up them

(B) They are pulled inwards and collapse: the water in them is under tension

(C) Water leaks out through their thin walls into all the cells around them

(D) Air is sucked in through the walls, and every column of water in them breaks

Decide before you look. Answer on page 80.

B3.2.9 DISTRIBUTION OF TISSUES IN A TRANSVERSE SECTION OF THE STEM OF A DICOTYLEDONOUS PLANT

03 A stem in *section*

Cut a young stem straight across, stain the slice and look at it under a microscope. In a **dicotyledonous plant** (a dicot, such as a bean or a sunflower), the tissues are always in the same places. From the outside in:

KEY POINTS

- **Epidermis**: one layer of cells, covered in a waxy cuticle. It protects the stem, and the cuticle cuts water loss.
- **Cortex**: a band of packing cells, a few cells deep. It stores food, and its outer cells help to hold the stem up.
- **Vascular bundles**: separate bundles in a ring near the edge. Each has **phloem** on its outer side, carrying sugars and other organic compounds to where they are needed, and **xylem** on its inner side, carrying water and mineral ions up the stem; the xylem's lignin also helps support the stem. A thin layer of dividing cells, the **cambium**, lies between the two. In many stems, a sunflower's among them, each bundle also has a cap of **fibres** on the outer side of its phloem: cells with thick, lignified walls that strengthen the stem. Their walls take the same stain as the xylem's, pink in the micrograph below, so do not take them for xylem.
- **Pith**: the centre, packing cells that store food.

Why a ring near the edge? The usual explanation is mechanical. A stem must not snap when the wind bends it, and stiff material resists bending best when it is near the edge: that is why a hollow tube can be almost as stiff as a solid rod of the same width. So the bundles, with their lignified xylem, sit where they stiffen the stem most. It is an explanation, not something the section itself shows.

In a woody stem the same order holds: the phloem is in the inner bark, and the xylem is the wood inside it.

A **plan diagram** shows this layout without a single cell: one sharp line round each tissue, in the right place and proportion, labelled with ruled lines, with a title and a scale.

KEY TERMS

dicotyledonous plant
A flowering plant whose seed has two seed leaves (cotyledons). Dicots have broad, net-veined leaves, like a bean or a sunflower.

epidermis
The outer layer of cells of a stem, leaf or root.

cortex
The band of packing cells between the epidermis and the vascular tissue of a stem or root.

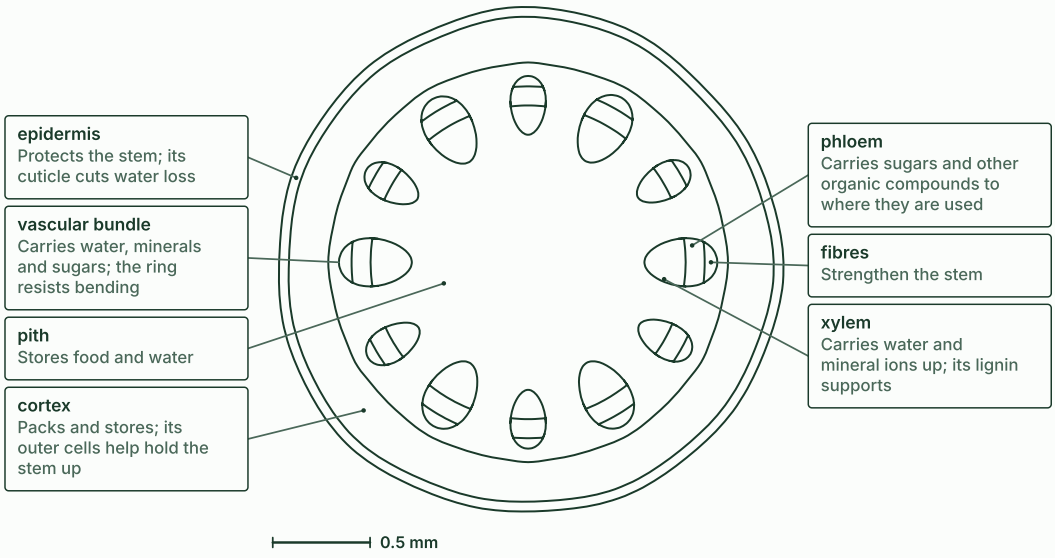
vascular bundles
A strand of xylem and phloem, with a thin layer of dividing cells (the cambium) between them, running along a stem.

cambium
A thin layer of dividing cells between the xylem and the phloem of a vascular bundle. Its divisions add new xylem and phloem.

fibres
Long, narrow cells with thick, lignified walls that strengthen a stem. In many stems a cap of them lies on the outer side of each bundle's phloem.

pith
The packing cells in the centre of a stem, which store food.

plan diagram
A drawing of a section that shows where each tissue is, as outlines only, with no cells drawn.



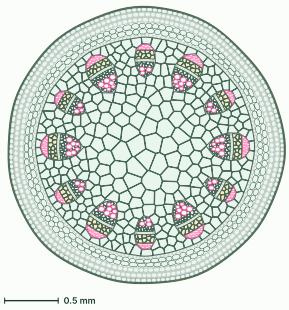
Plan diagram: transverse section of a young dicotyledonous stem

Fade the micrograph into its plan, name the tissues, give each one its job, then find the faults in a student's plan.

STEP BY STEP

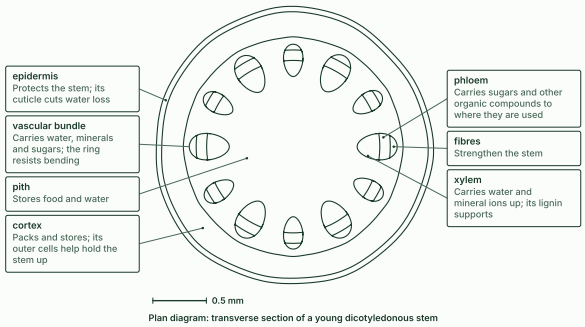
2 STEPS

1



A light micrograph, drawn: a transverse section of a young stem, every cell in view. Lignified walls are pink, as the stain colours them.

2



Plan diagram: transverse section of a young dicotyledonous stem

Its plan diagram: one clean outline for each tissue, in the micrograph's proportions, no cells and no shading; ruled label lines, each tissue's main function, a title and a scale bar.

REMEMBER IT

A stem from the outside in: Eat Cake, Pass Xmas Pudding

E Eat	C Cake	P Pass	X Xmas	P Pudding
Epidermis the skin, with its waxy cuticle	**Cortex** packing cells that store food	**Phloem** the outer side of each bundle, outside the xylem	**Xylem** the inner side of each bundle	**Pith** the centre

WATCH OUT

Two slips in plan diagrams. Phloem drawn inside the xylem: in a stem the phloem is always on the outer side of the xylem (only a cap of fibres, where there is one, lies outside it). And cells drawn in: a plan diagram shows each tissue as an outline only.

PREDICT

A cut stem stands for an hour in water with a red dye in it, then is cut across. Where is the red?

(A) In the pith at the centre, where the stem stores the water it takes up

(B) Spread evenly through every tissue, as all the cells take in water

(C) In the phloem, on the outer side of each bundle in the ring

(D) In a ring of spots near the edge: the xylem of each bundle

Decide before you look. Answer on page 80.

B3.2.10 DISTRIBUTION OF TISSUES IN A TRANSVERSE SECTION OF THE ROOT OF A DICOTYLEDONOUS PLANT

04 A root in *section*

A root anchors the plant and takes up water and mineral ions from the soil. Cut one across, a little way back from the tip, and you find three regions:

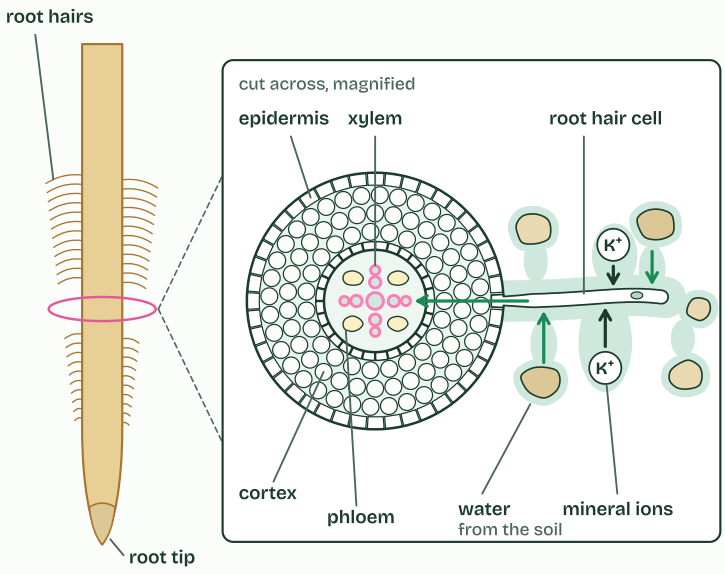
KEY POINTS

- **Epidermis**: the outer layer. Many of its cells grow a **root hair**, a long, thin outgrowth that reaches out between the soil particles. Together the hairs give the root a huge surface for taking up water and mineral ions.
- **Cortex**: a wide band of rounded packing cells. Water crosses it on its way in, and its cells store starch.
- **Vascular tissue**: all in one core in the middle. The xylem forms a star, often with four arms, and the phloem sits in the gaps between the arms. The IB calls it a vascular bundle; in a root it is one central column, not a ring of bundles.

So a stem keeps its vascular tissue in a ring near the edge, and a root keeps it in one core. The usual explanation is mechanical again: a stem has to resist bending in the wind, which material near the edge does best; a root is pulled as the plant above it sways, and a core in the middle resists pulling, like the strands of a rope. As in the stem, it is an explanation, not something the section shows.

KEY TERMS

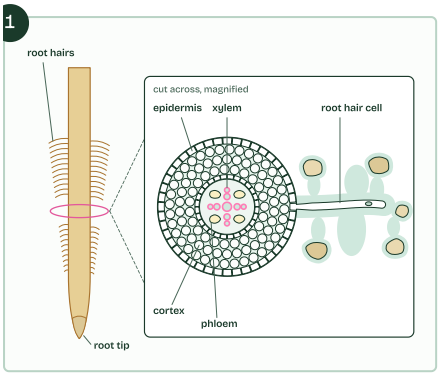
root hair
A long, thin outgrowth of one epidermal cell of a root. It reaches between soil particles and takes up water and mineral ions.



STEP BY STEP

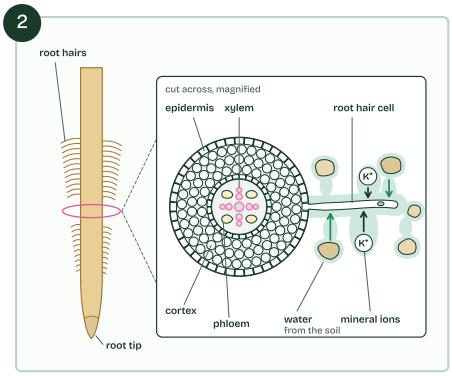
3 STEPS

1



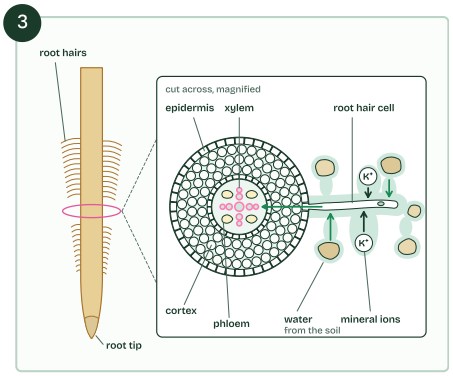
A young root. Just behind the tip, its epidermis is covered in **root hairs**.

2

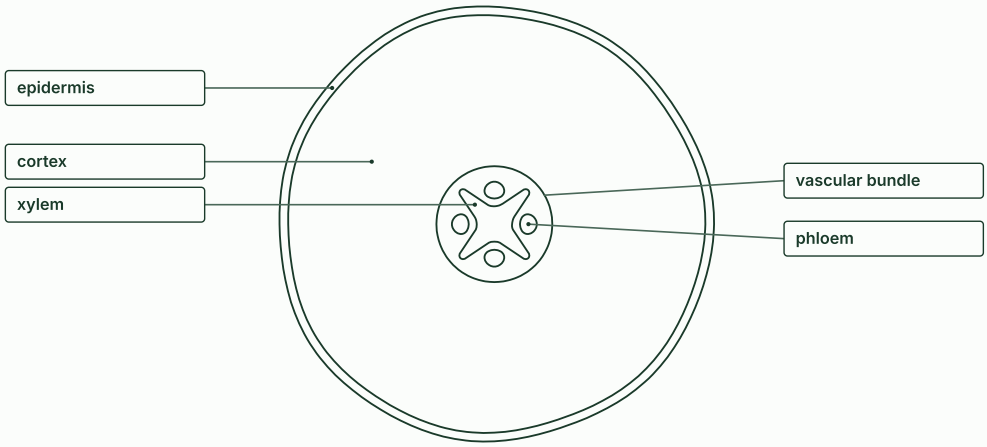


One root hair cell, close up: **water** and **mineral ions** from the soil go in through its long, thin hair.

3



From the root hair, water crosses the **cortex** to the xylem in the centre.



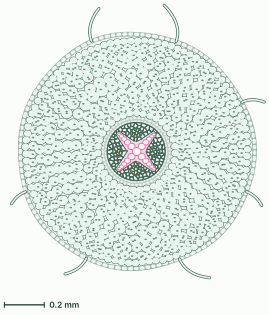
Plan diagram: transverse section of a young dicotyledonous root

Name the root's tissues, then set its plan beside the stem's: a ring near the edge against one core in the middle.

STEP BY STEP

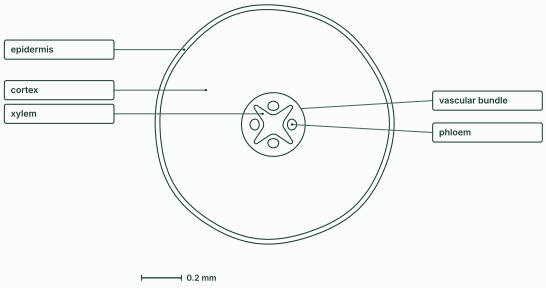
2 STEPS

1



A light micrograph, drawn: a transverse section of a young root, every cell in view. Lignified walls are pink, as the stain colours them.

2



Its plan diagram: one clean outline for each tissue, in the micrograph's proportions, no cells and no shading; ruled label lines, a title and a scale bar.

WATCH OUT

A root hair is not a cell of its own: it is part of one epidermal cell, grown out into the soil. And do not draw a root's xylem as a ring of bundles, like the stem's. In a root it is one star in the middle.

PREDICT

A seedling is moved to a new pot, and most of its root hairs are torn off. What happens over the next day?

(A) It wilts: with far less surface touching the soil water, uptake falls behind loss

(B) Nothing: water still enters through the rest of the epidermis just as fast as before

(C) It takes up more: the torn cells leak, and their solutes draw water in fast

(D) It wilts only if its xylem was torn as well, as the root hairs carry no water

Decide before you look. Answer on page 80.

B3.2.17 HL GENERATION OF ROOT PRESSURE IN XYLEM VESSELS BY ACTIVE TRANSPORT OF MINERAL IONS

05 When the leaves cannot pull: *root pressure*

The pull of transpiration needs water to be evaporating from the leaves. Sometimes almost none is. The air can be so humid that hardly any water evaporates, as in a rainforest, or on a still, humid night, when the stomata are shut as well. And in spring, before a deciduous tree's leaves have opened, there are no leaves to lose water at all. Then the roots push instead.

Root cells take up mineral ions from the soil by **active transport**, spending ATP, and pump them on into the xylem. The solute concentration in the xylem rises, so water follows by **osmosis**, from the root cells into the xylem. With no transpiration to draw it away, the water builds up there, and the pressure in the xylem rises above zero: a positive pressure potential. That is **root pressure**, and it pushes the column of water up.

Root pressure is small next to the pull of transpiration. It can push water up a few metres, but never to the top of a tall tree. It also needs energy. The ATP comes from aerobic respiration in the roots, so when the roots are short of oxygen, as in waterlogged soil, the pumps slow and root pressure falls.

You can see it. On a still, humid morning, drops of water sit along the edges of some leaves, where the veins end. They are not dew: root pressure has pushed water up the plant and out through pores at the vein endings. This is **guttation**.

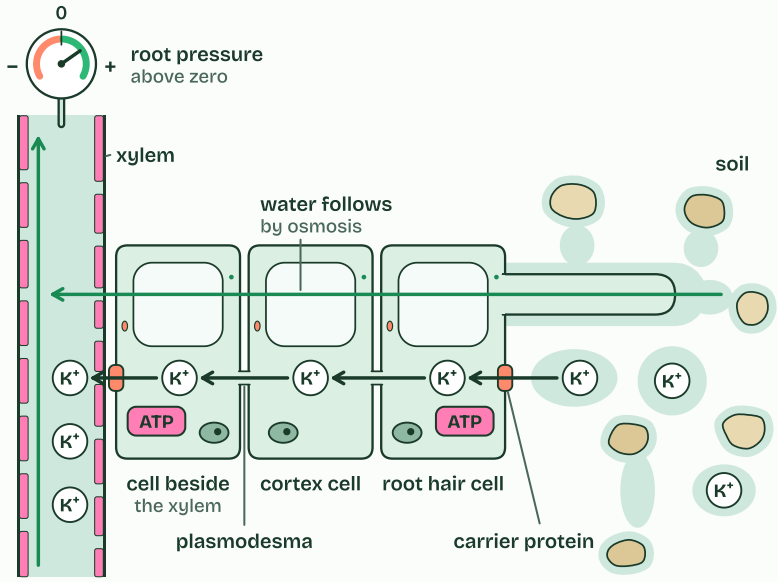
KEY TERMS

active transport
Moving a substance across a membrane against its concentration gradient, through a pump protein, using energy from ATP.

osmosis
The net movement of water across a partially permeable membrane, from a lower solute concentration to a higher one.

root pressure
A positive pressure in the xylem, made when root cells pump mineral ions into it and water follows by osmosis. It pushes water up when transpiration is too slow to pull it.

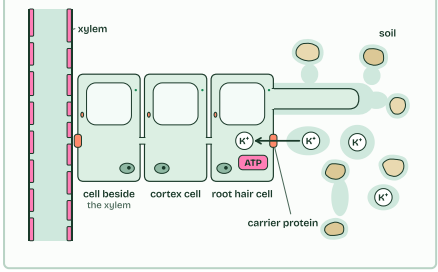
guttation
Drops of water pushed out at the edges of leaves by root pressure, usually on humid nights and early mornings.



STEP BY STEP

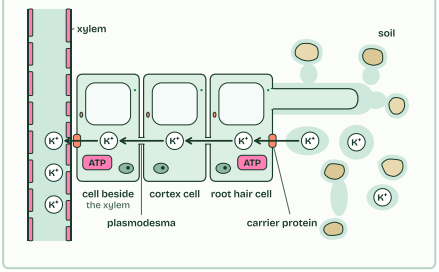
4 STEPS

1



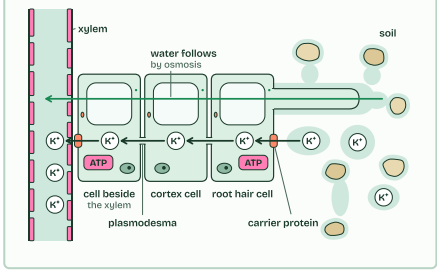
Carrier proteins in the membrane of a root hair cell pump **mineral ions** in from the soil, using ATP.

2



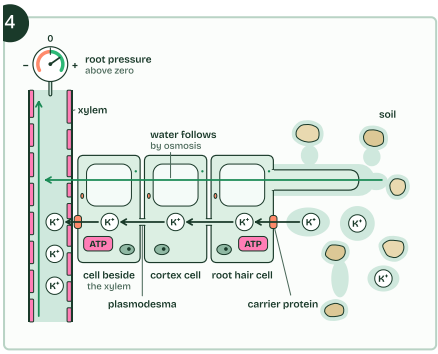
The ions pass from cell to cell through plasmodesmata, narrow channels joining the cells, and cells beside the xylem pump them on **into the xylem**, again using ATP.

3



The xylem now holds more solutes, so **water follows by osmosis**.

4

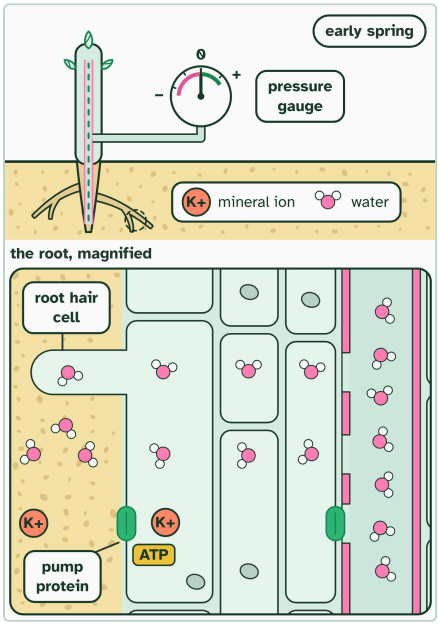


Water builds up in the xylem and its pressure rises **above zero**: root pressure pushes the column up.

ANIMATION · ROOT PRESSURE

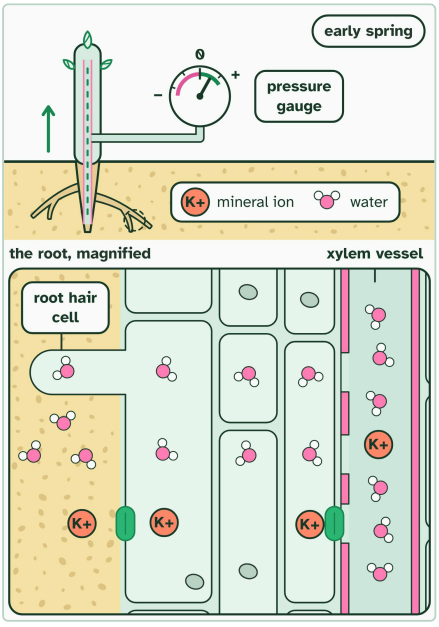
3 MOMENTS

1 XYLEM PRESSURE: ZERO



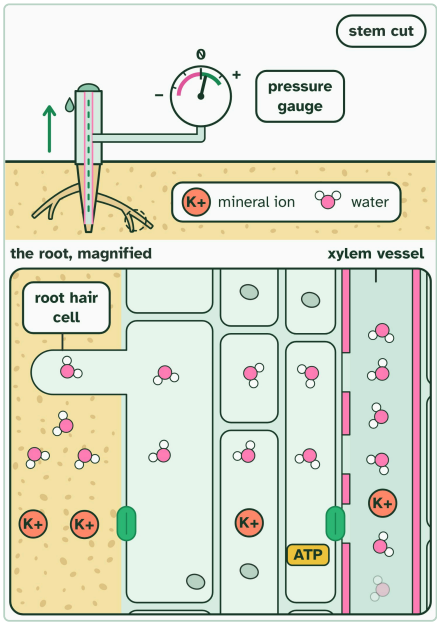
Pump proteins in the root hair cells move **mineral ions** in from the soil by **active transport**, using ATP.

2 XYLEM PRESSURE: ABOVE ZERO



Water entering the xylem raises its **pressure potential** above zero: **root pressure**, pushing the sap up the stem.

3 XYLEM PRESSURE: ABOVE ZERO



Cut the stem in early spring and **xylem sap oozes** from the stump: root pressure pushes it out.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#rootpressure

PREDICT

A grapevine is cut back in early spring, before its leaves open. What happens at the cut stump?

(A) Air is drawn into the cut, because the water in the xylem is under tension

(B) Sap oozes out of the cut, pushed up from the roots

(C) Nothing happens, as water moves only while the leaves transpire

(D) Sap is drawn back down into the roots, away from the cut end

Decide before you look. Answer on page 80.

WATCH OUT

"Water is actively transported into the xylem." The mineral ions are; water follows them by osmosis, and no pump moves the water itself. And "root pressure lifts water to the top of trees." It can push water a few metres, nowhere near the top of a tall tree. There, the pull of transpiration does the lifting.

B3.2.18 HL ADAPTATIONS OF PHLOEM SIEVE TUBES AND COMPANION CELLS FOR TRANSLOCATION OF SAP

06 Sieve tubes and *companion cells*

The xylem carries water up. The phloem carries food: the sugar a leaf makes, and other carbon compounds, to every part of the plant that needs them. This is **translocation**. Phloem **sap** is a solution, mostly of sucrose, with amino acids and other substances.

Sap moves from sources to sinks. A **source** is where sugars are made or released: a leaf in the light, or a storage organ such as a potato tuber when it sprouts in spring. A **sink** is where they are used or stored: roots, growing tips, young leaves, fruits and seeds. A sink can be above its source or below it, so sap can flow up or down, unlike the water in the xylem.

Sap travels in sieve tubes, columns of living cells called **sieve tube elements**, joined end to end. Beside each one is a **companion cell**, which does the work the element no longer can.

KEY POINTS

- **Sieve plates**: the end walls between the elements are perforated with pores, so sap flows from one element to the next.
- **Little in the way**: each element keeps only a thin layer of cytoplasm and a few organelles, and it has no nucleus, so little blocks the flow.
- **Strong walls**: they hold the sap under high pressure without bursting.
- **Companion cells**: each has a nucleus and many mitochondria.
- **Plasmodesmata**: many narrow channels through the wall between each companion cell and its element, joining their cytoplasm, so the companion cell can keep the element alive and pass it sucrose.

KEY TERMS

translocation
The movement of sap through the phloem, from sources to sinks.

sap
Phloem sap: the solution carried in the phloem, mostly sucrose, with amino acids and other substances, in water (the xylem's watery solution of mineral ions is xylem sap).

source
A part of a plant that makes or releases sugars and loads them into the phloem, such as a leaf in the light.

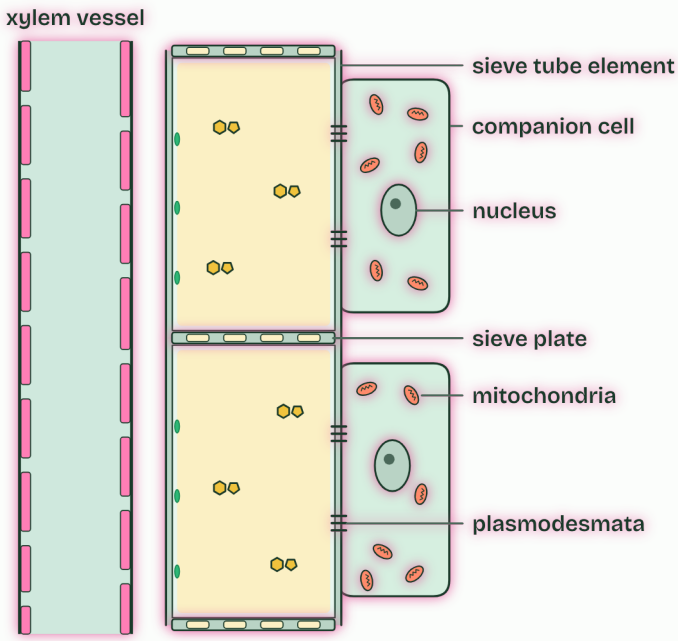
sink
A part of a plant that takes sugars out of the phloem to use or store them, such as a root, a growing tip, a fruit or a seed.

sieve tube elements
The living cells, with no nucleus and little cytoplasm, that join end to end to make a sieve tube in the phloem.

companion cell
A cell beside a sieve tube element, joined to it by many plasmodesmata. It has a nucleus and many mitochondria, and keeps the element alive.

sieve plates
The end wall between two sieve tube elements, perforated with pores so that sap can flow through.

plasmodesmata
Narrow channels through the walls between two plant cells, which join the cytoplasm of one to the other.



Xylem vessel Beside the phloem, for contrast: dead, empty, its walls lignified (pink), with no end walls left. It carries water and mineral ions up the plant.

Nucleus The companion cell has one; the sieve tube element has none. The companion cell does the work of both cells.

Sieve tube element A living cell with no nucleus and only a thin layer of cytoplasm and a few organelles round its edge, so little stands in the way of the sap. Its thick, rigid wall holds the sap under high pressure.

Plasmodesmata Narrow channels through the wall, joining the companion cell's cytoplasm to the element's. Sucrose passes through them into the sieve tube, and the companion cell keeps the element alive through them.

Companion cell One beside each sieve tube element. It has the nucleus and the organelles the element has lost, and keeps the element alive.

Mitochondria Many in each companion cell, making ATP by aerobic respiration. What the cell spends it on is the predict in the text.

Sieve plate The end wall between two elements, perforated with pores. Sap flows through the pores from one element to the next.

Xylem vessel Beside the phloem, for contrast: dead, empty, its walls lignified (pink), with no end walls left. It carries water and mineral ions up the plant.

Nucleus The companion cell has one; the sieve tube element has none. The companion cell does the work of both cells.

Sieve tube element A living cell with no nucleus and only a thin layer of cytoplasm and a few organelles round its edge, so little stands in the way of the sap. Its thick, rigid wall holds the sap under high pressure.

Plasmodesmata Narrow channels through the wall, joining the companion cell's cytoplasm to the element's. Sucrose passes through them into the sieve tube, and the companion cell keeps the element alive through them.

PREDICT

Why do companion cells have so many mitochondria?

(A) To respire the sucrose in the sieve tube for the energy the whole plant needs

(B) To warm the sap, so that it keeps flowing well in cold weather

(C) To power the sieve plates, which pump the sap along the tube

(D) To make the ATP that actively loads sucrose into the sieve tubes

Decide before you look. Answer on page 80.

B3.2.18 HL ADAPTATIONS OF PHLOEM SIEVE TUBES AND COMPANION CELLS FOR TRANSLOCATION OF SAP

07 Loading, flow and *unloading*

There is no pump along a sieve tube. Sap moves because the pressure is high at one end of the tube and low at the other, and the loading and unloading at the two ends are what make it so.

Loading. At a source, companion cells load sucrose into the sieve tubes by active transport. Proton pumps in the companion cell's membrane spend ATP pushing hydrogen ions out of the cell. The hydrogen ions flow back in through a **co-transporter** protein, which brings a sucrose molecule in with each one, from the cell walls around it, where the cells of the leaf release it, against the sucrose's own concentration gradient. The sucrose then passes into the sieve tube element through the plasmodesmata.

Pressure. The sucrose raises the solute concentration in the sieve tube, so water enters it by osmosis from the xylem close by (in the terms of D2.3, the sap's water potential has fallen). The walls hold firm, so the pressure inside rises.

Unloading. At a sink, sucrose is unloaded into the cells around it and used or stored: respired, built into new molecules such as cellulose, or stored as starch. The sap there loses solutes, water leaves it by osmosis, and the pressure at that end stays low.

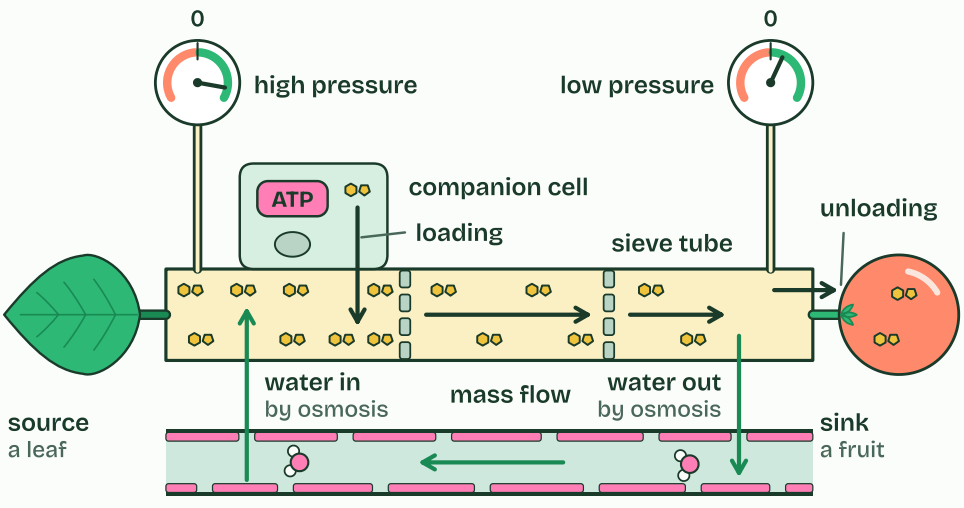
Flow. With high pressure at the source and low pressure at the sink, the sap flows from one to the other by **mass flow**: the whole solution moves together, as water does along a hose. It flows towards whichever sink is drawing: up to a fruit, down to a root. One sieve tube carries sap one way at a time, but a stem has many, so a plant moves sap both ways at once.

Compare them. Xylem and phloem side by side: fill in the table under the figure. Tap a box and choose; a right answer stays, with its reason.

KEY TERMS

co-transporter
A membrane protein that carries two substances across together. Here, a hydrogen ion flowing in down its gradient carries a sucrose molecule in with it.

mass flow
The flow of a whole fluid, solvent and solutes together, from high pressure to low, as water flows along a hose.

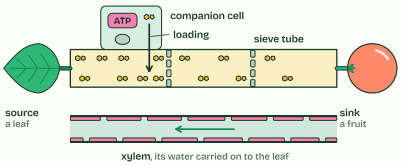


xylem, its water carried on to the leaf

STEP BY STEP

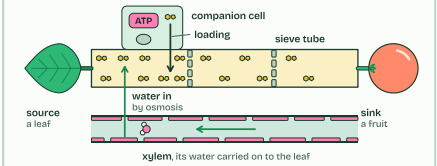
5 STEPS

1



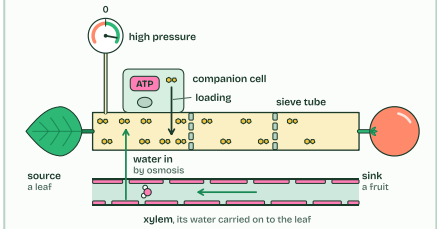
At the source, companion cells **load** sucrose into the sieve tube, spending ATP.

2



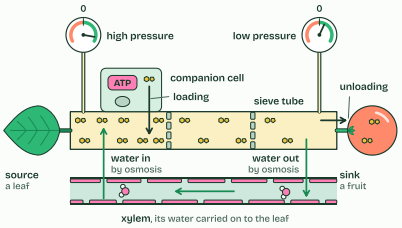
Water follows the sucrose in from the xylem by **osmosis**.

3



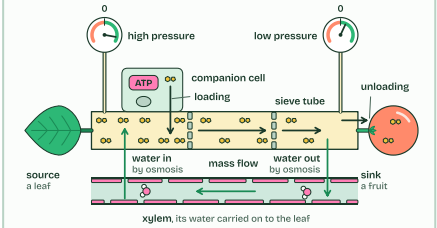
The water raises the **pressure** at the source end of the sieve tube.

4

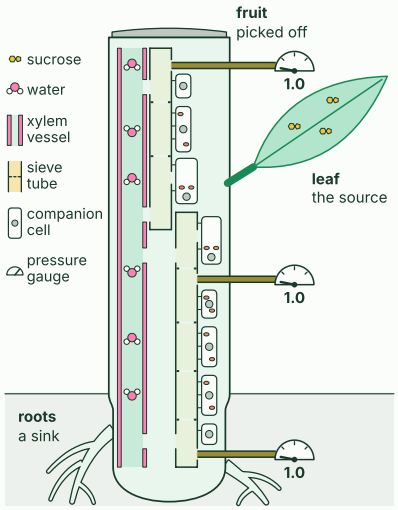


At the sink, sucrose is **unloaded** and water leaves by osmosis, so the pressure there stays low.

5



Sap **flows** by mass flow from high pressure to low: from the source to the sink.

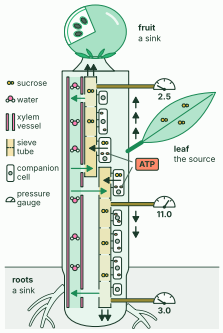


Predict first, then change the loading, the fruit, the roots or the water supply, and read the pressure at each end.

STEP BY STEP

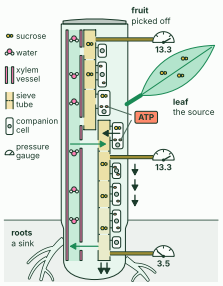
3 STEPS

1



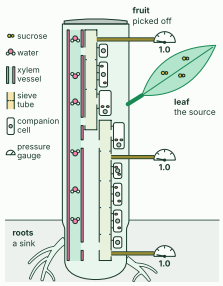
Companion cells load sucrose into two sieve tubes at the leaf, spending ATP. Water follows from the xylem by **osmosis**, so the pressure there is high (11.0). Each sink unloads, so the far end of its tube stays low, and sap flows to both: up one tube to the fruit, down the other to the roots.

2



Pick the fruit off and nothing unloads at the top: sap fills that tube's sealed end until its pressure matches the leaf's (13.3), and the flow up stops. The roots, still unloading, now get the leaf's sugar.

3



Now stop the loading too. No sucrose enters at the leaf, so no water follows it in: the pressure falls to 1.0 everywhere and no sap flows, either way. **Loading** is what drives the flow.

REMEMBER IT

Source to sink: Lazy Otters Push Fish Upstream

L Lazy	O Otters	P Push	F Fish	U Upstream
Load companion cells pump sucrose in, spending ATP	**Osmosis** water follows the sucrose in, from the xylem	**Pressure** high at the source, low at the sink	**Flow** mass flow from high pressure to low	**Unload** sucrose leaves at the sink, which may be uphill: sap goes up as well as down

PREDICT

The fruit on a branch is picked off. What happens to the flow in the sieve tube that fed it?

(A) It speeds up, because the sap now has a shorter way to go to the end

(B) It reverses at once and carries the sugar back up to the leaf

(C) It slows, then stops: with no unloading, that end's pressure rises

(D) Nothing changes, because the leaf goes on loading sucrose as before

Decide before you look. Answer on page 80.

WATCH OUT

"Phloem only flows downwards." It flows from sources to sinks, which can be up or down. "Sucrose diffuses along the phloem." It is carried by mass flow, far faster than diffusion. And "translocation is passive, like the transpiration stream." Loading costs ATP, and the flow is driven by the pressure that loading builds.

B3.2.18 HL ADAPTATIONS OF PHLOEM SIEVE TUBES AND COMPANION CELLS FOR TRANSLOCATION OF SAP

08 How we know: *aphids* and labels

Aphids feed on phloem sap. An aphid pushes its **stylet**, a mouthpart as fine as a hair, into a stem until the tip is inside a single sieve tube. The sap is under pressure, so it flows into the aphid without the aphid having to suck.

In 1953, Kennedy and Mittler cut feeding aphids away from their stylets. Sap went on oozing from the stylet stumps for hours: the pressure in the sieve tube was pushing it out. Each stump is a fine tube into one sieve tube, so the drops are pure sap, which can be collected and analysed.

A radioactive label shows where the sap goes, and how fast. One leaf is given carbon dioxide made with radioactive carbon (carbon-14), which it builds into sugars by photosynthesis, so its sucrose can be followed. With stylet stumps at measured distances along the stem, a radiation counter shows when the label first reaches each one. The label turns up both above and below the leaf.

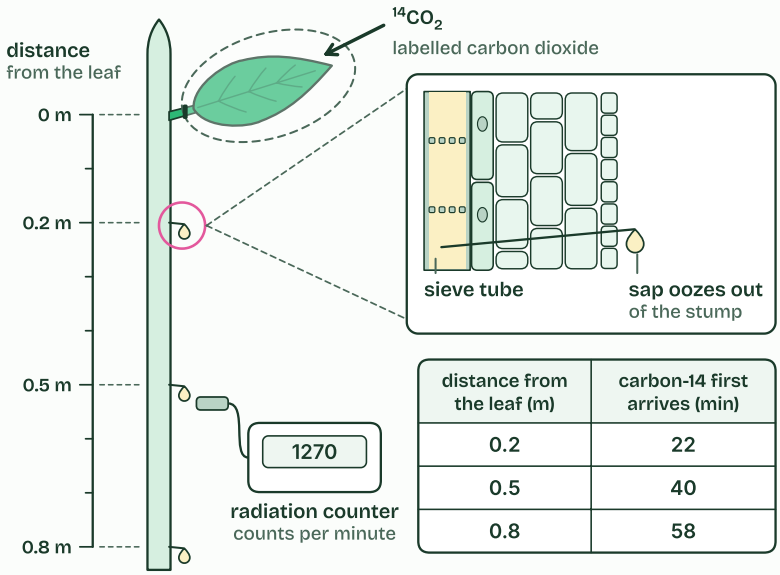
Plot the time the label reached each stump against the stump's distance from the leaf, and the points fall on a straight line. Its gradient is the time per metre, so the speed of translocation is 1 ÷ the gradient: usually between a few tens of centimetres and a metre or so an hour. The line does not pass through zero: it meets the time axis at about ten minutes, the time the leaf took to build the label into sucrose and load it before it set off down the stem. Diffusion would take decades to move sucrose a metre, so only mass flow can be that fast.

Ringing tells the same story. The phloem is in the inner bark; the xylem is the wood inside it (chapter 3). Take a complete ring of bark off a trunk, and sugar can no longer pass down. The bark just above the ring swells as sugars build up there, the roots below starve, and the tree dies, slowly, often over a year or two, though its xylem goes on carrying water up all that time (ring a shoot on the potometer bench and see). Marcello Malpighi saw the swelling in the 1600s and read it the same way: food coming down from the leaves, held up at the ring.

Two more about the label, which the bench after this chapter lets you test.

KEY TERMS

stylet
An aphid's piercing mouthpart, as fine as a hair. The aphid pushes it into a plant until the tip is inside one sieve tube.

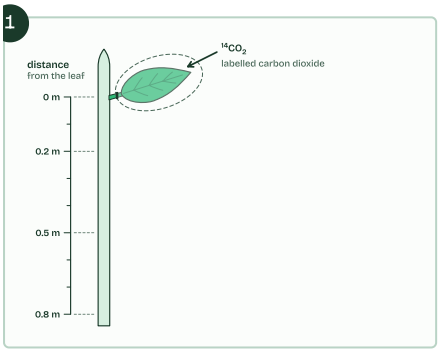


distance from the leaf (m)	carbon-14 first arrives (min)
0.2	22
0.5	40
0.8	58

STEP BY STEP

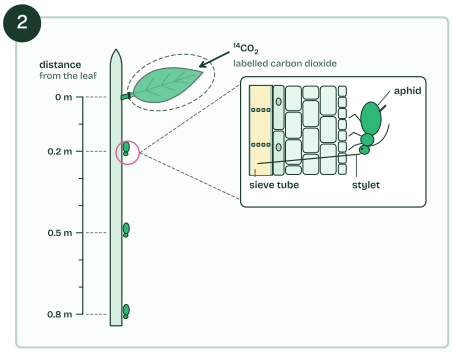
4 STEPS

1



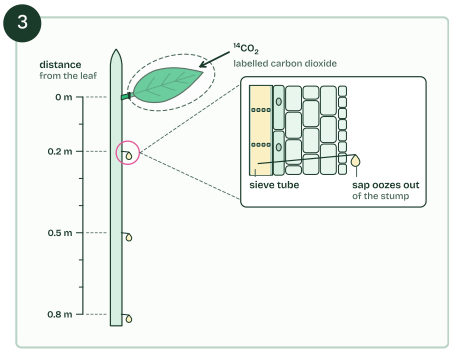
One leaf is given carbon dioxide made with **carbon-14**, and builds it into sugars.

2



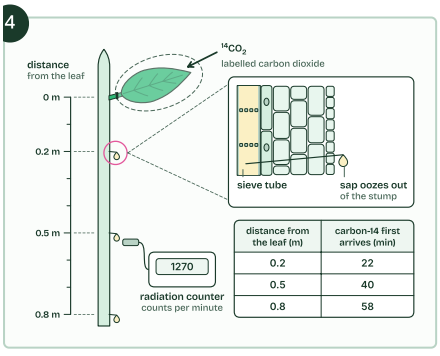
Aphids feed on the stem below it, each with its **stylet** in one sieve tube.

3

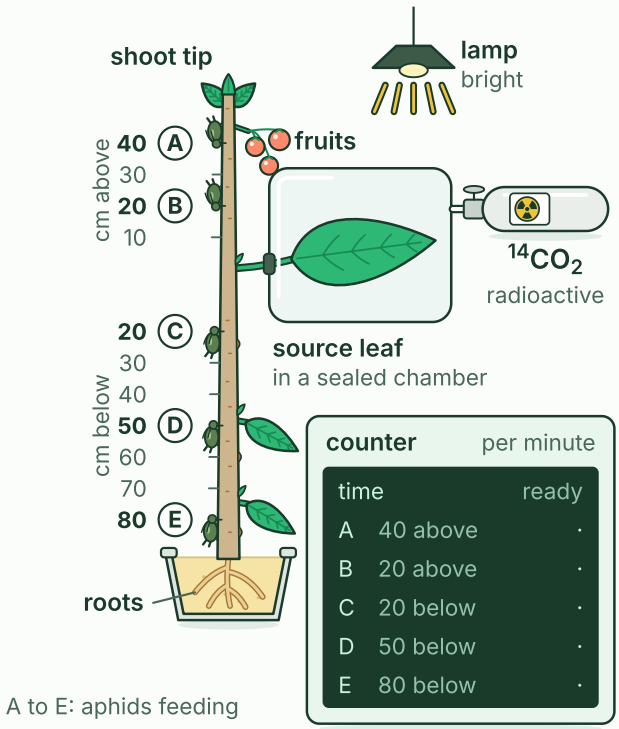


The aphids are cut away, and sap oozes from each stylet **stump**.

4



A counter checks each stump's sap. The time the label **first arrives**, counted from when the leaf was given it, goes in the table.



A to E: aphids feeding

Stylet	Distance from the leaf / cm	Arrival time / min
A	40 above	----------
B	20 above	----------
C	20 below	----------
D	50 below	----------
E	80 below	----------

Follow the label. Aphids feed at five distances above and below a source leaf. The leaf gets a 5-minute pulse of radioactive carbon dioxide; the stylets are cut and the sap from each is counted every 2 minutes, and the time each count first rises clearly above the background is its arrival.

PREDICT

Use the arrival times in the figure. How fast did the label travel down the stem?

(A) 1.0 metre an hour

(B) 0.017 metres an hour

(C) 0.83 metres an hour

(D) 60 metres an hour

Decide before you look. Answer on page 81.

PREDICT

Why does the label reach a stylet further from the leaf later?

(A) Stylets further from the leaf feed more slowly, so they collect less of the sap

(B) It is carried along in the sap at a steady speed, so further takes longer

(C) The label spreads by diffusion, which gets slower and slower over a longer path

(D) The label decays as it travels, so there is less of it left the further it goes

Decide before you look. Answer on page 81.

PREDICT

A ring of bark is removed between the leaf and the lowest stylet. The label reaches the stylets above the ring, but never the one below it. What does this show?

(A) That the label travels in the xylem, which the ring of bark cut through

(B) That the sap below the ring flows too slowly for the counter to pick up

(C) That the ring let air into the sieve tubes, which pushed the label back up

(D) That the label travels in the phloem, which is in the bark

Decide before you look. Answer on page 81.

B3.2.15 HL ADAPTATIONS OF THE MAMMALIAN HEART FOR DELIVERING PRESSURIZED BLOOD TO THE ARTERIES

09 Inside the *heart*

Your heart is two pumps side by side in one organ. The right side takes in blood that has been round the body and sends it to the lungs; the left side takes in blood from the lungs and sends it round the body. The figure draws it the way you can in five minutes, one layer at a time, and every layer is a part the IB asks you to name.

Each side has two chambers. An **atrium** on top receives blood from the veins; a **ventricle** below pumps it out into an artery. Down the middle runs the **septum**, a wall of muscle. It keeps the oxygen-poor blood on the right apart from the oxygen-rich blood on the left, and lets each side pump at its own pressure.

Four valves keep the blood moving one way. Between each atrium and its ventricle is an **atrioventricular valve**: the tricuspid on the right and the bicuspid, or mitral, on the left. Tough cords, the chordae tendineae, tie their flaps to the ventricle's wall, so a contracting ventricle cannot blow them back into the atrium. Where each ventricle opens into its artery is a **semilunar valve**, three pocket-shaped cusps: the pulmonary valve and the aortic valve. A valve has no muscle of its own. It is pushed open when the pressure behind it is higher than the pressure in front, and pushed shut when it is lower.

The heart's wall is muscle that never rests, so it needs a blood supply of its own. The blood rushing through the chambers is no help: the wall is far too thick for oxygen to diffuse through it. The **coronary arteries** branch from the aorta just above the aortic valve and run over the heart's surface in its grooves (chapter 15 is what happens when one blocks).

The right way round. A diagram in the frontal plane shows the heart as if you were facing the person, so the patient's right is on the left of the page. Trace the blood from the veins to the arteries: venae cavae, right atrium, tricuspid valve, right ventricle, pulmonary valve, pulmonary artery, the lungs; pulmonary veins, left atrium, bicuspid valve, left ventricle, aortic valve, aorta.

KEY TERMS

atrium
An upper chamber of the heart. It receives blood from the veins and passes it down to the ventricle below.

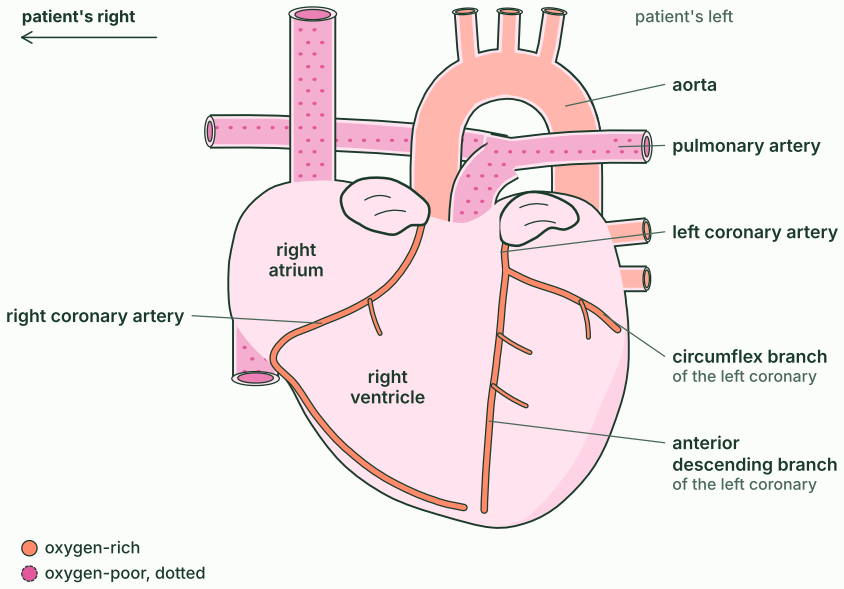
ventricle
A lower chamber of the heart, which pumps blood out into an artery.

septum
The wall of muscle between the left and right sides of the heart.

atrioventricular valve
A valve between an atrium and its ventricle: the tricuspid on the right, the bicuspid (mitral) on the left.

semilunar valve
A valve of three pocket-shaped cusps where a ventricle opens into its artery: the pulmonary valve and the aortic valve.

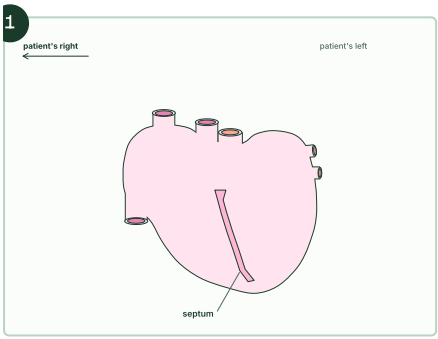
coronary arteries
The arteries that branch from the aorta just above the aortic valve and run over the surface of the heart, supplying its muscle.



STEP BY STEP

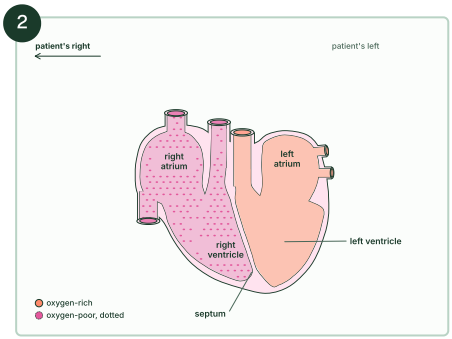
6 STEPS

1



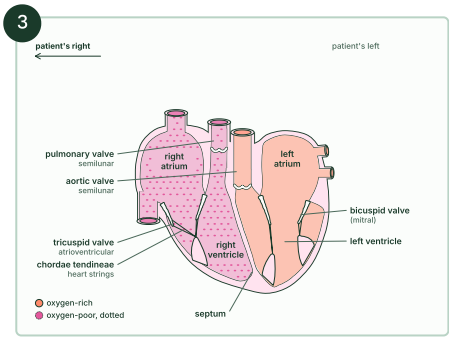
Two pumps side by side in one organ. The **septum**, a wall of muscle, divides the right side from the left. The patient's right is on the left of the drawing.

2



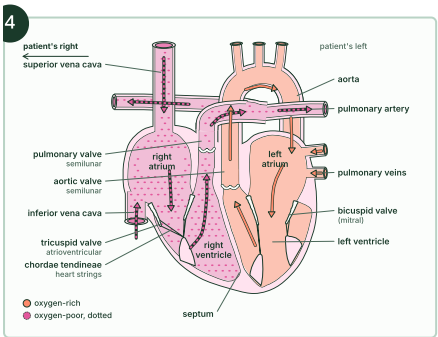
Four chambers: an **atrium** on top of each side receives blood, and a **ventricle** below pumps it out. The colours are only a code: blood is always red.

3



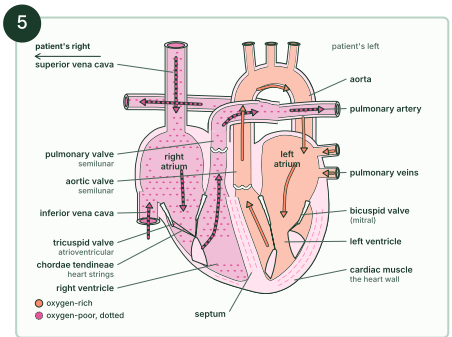
Four valves: the **atrioventricular** valves (tricuspid and bicuspid) between the atria and ventricles, held by cords, and the **semilunar** valves (pulmonary and aortic) where the arteries leave.

4



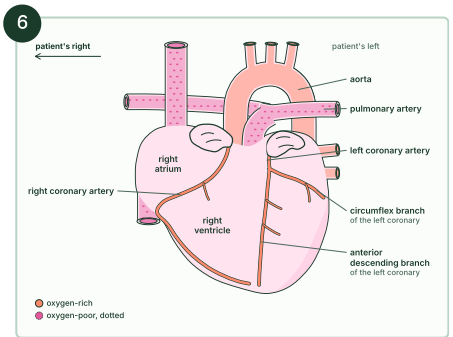
The great vessels and the flow: the **venae cavae** into the right atrium, the pulmonary artery to the lungs, the pulmonary veins back to the left atrium, and the **aorta** out to the body.

5

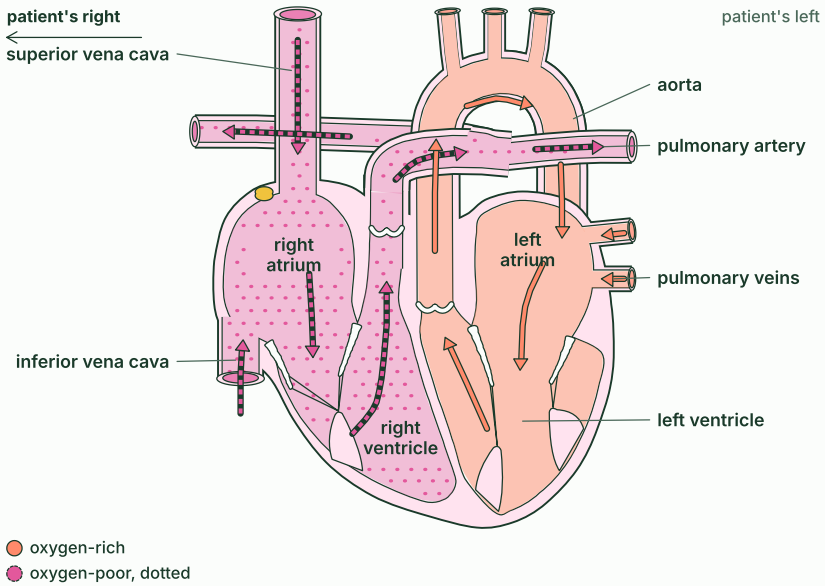


The **muscle** drawn to scale: the left ventricle's wall, about 1 cm thick, is about three times as thick as the right's, 3 to 5 mm.

6



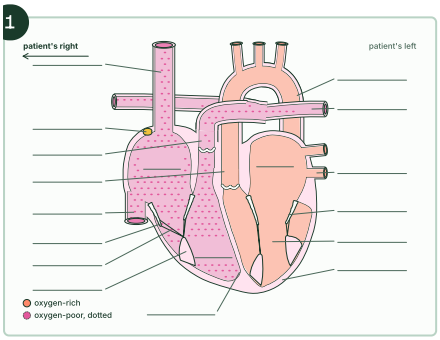
From the outside: the **coronary arteries** leave the aorta just above the aortic valve and run in the grooves over the heart, feeding its muscle.



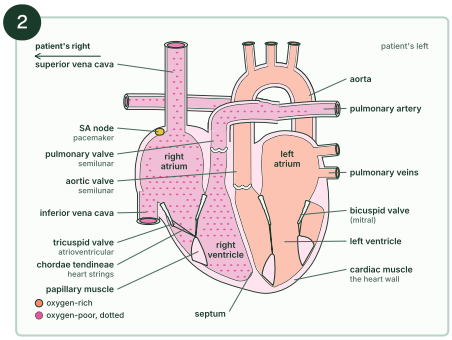
Tap each part to read its job, label it from memory, then follow one red cell from a vena cava to the aorta. Inside and Outside switch views; the Muscle layer draws the walls to scale.

STEP BY STEP

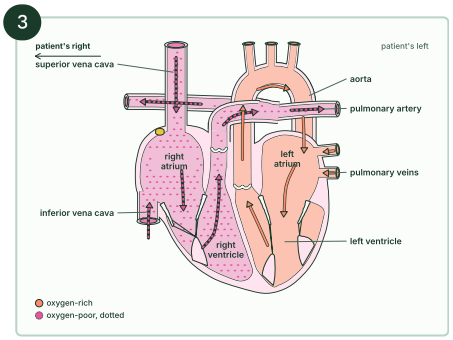
3 STEPS



The heart in the **frontal plane**, cut open from the front: the patient's right is on the left of the drawing. Label the parts on the lines.



Four chambers: **atria** above receive blood, **ventricles** below pump it out. The **septum** keeps the two sides apart; **atrioventricular** valves (tricuspid, bicuspid) and **semilunar** valves (pulmonary, aortic) let blood flow one way.



The flow, from named veins to arteries: venae cavae, right atrium, tricuspid valve, right ventricle, pulmonary valve, pulmonary artery to the lungs; pulmonary veins, left atrium, bicuspid valve, left ventricle, aortic valve, aorta.

PREDICT

Both ventricles pump the same volume of blood at each beat. Which one has the thicker wall, and why?

(A) The right, because it receives more blood from the body than the left does

(B) The left, because it pumps blood at high pressure all round the body

(C) Neither: the same volume at each beat needs the same wall on both sides

(D) The left, because oxygen-rich blood is heavier and harder to push along

Decide before you look. Answer on page 81.

REMEMBER IT

The valves in the order the blood meets them: Tiny Penguins Bake Apples

T	P	B	A
Tiny	Penguins	Bake	Apples
Tricuspid	**Pulmonary**	**Bicuspid**	**Aortic**
right atrium to right ventricle	right ventricle to pulmonary artery	left atrium to left ventricle	left ventricle to aorta

WATCH OUT

"The left of the diagram is the left side of the heart." It is the patient's right. "Valves are opened by muscles, or pulled open by their cords." Pressure opens and shuts every valve; the cords only stop the atrioventricular flaps turning inside out. "The blood on the right is blue." Blood is always red: the colours here are a code. And "the heart is fed by the blood in its chambers." The coronary arteries feed it.

B3.2.1 ADAPTATIONS OF CAPILLARIES FOR EXCHANGE OF MATERIALS BETWEEN BLOOD AND THE INTERNAL OR EXTERNAL ENVIRONMENT

10 Capillaries: where the *swap* happens

Blood does its work only where it can swap things with the cells around it, and that happens in the **capillaries**. In most of the body, oxygen, glucose and other nutrients pass out of the blood to the cells, and carbon dioxide and other wastes pass in. In the lungs the swap is with the outside world: oxygen in, carbon dioxide out. In the small intestine, digested food comes in.

Three features make a capillary bed good at exchange:

KEY POINTS

- **Branched and narrow.** An artery divides into arterioles, and each arteriole into a bed of capillaries threaded between the cells, each only 5 to 10 micrometres across. No cell is far from one, and together their walls give a huge surface area for exchange.
- **Thin walls.** The wall is a single layer of flattened **endothelium** on a thin basement membrane, so substances diffuse well under a micrometre between the blood and the tissue. Red blood cells, about 7 to 8 micrometres across, squeeze through in single file, pressed close to the wall.
- **Pores where exchange must be fastest.** Some capillaries have **fenestrations**, tiny pores through their endothelial cells: in the villi of the small intestine, where digested food is absorbed, in the kidney, where the blood is filtered, and in glands that release hormones into the blood. Most capillaries, such as those in muscle and the lungs, have none.

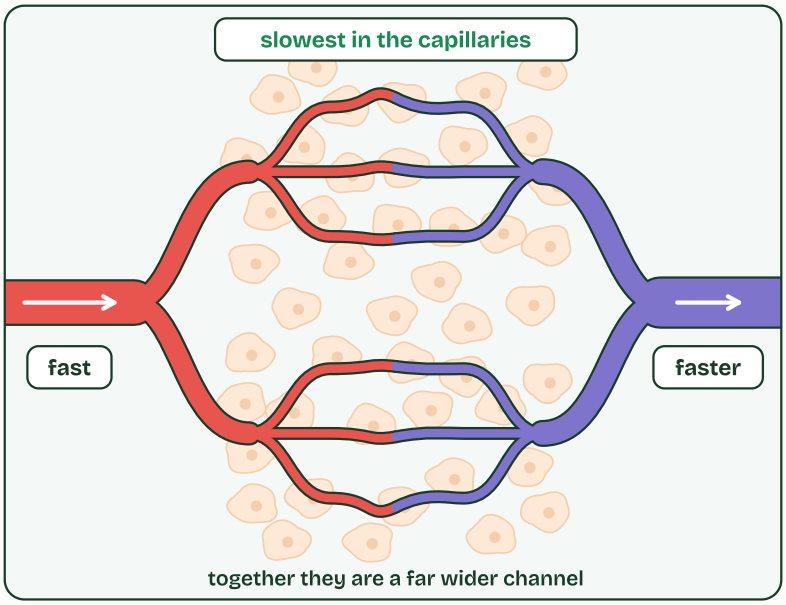
Why many small tubes and not a few wide ones? The same idea as a small cell's large surface for its volume (B3.1): thousands of narrow capillaries put far more wall against the tissue than one wide tube with the same blood in it. What leaks out through the walls becomes tissue fluid, which bathes the cells (chapter 21, higher level).

KEY TERMS

capillaries
The narrowest blood vessels, joining arterioles to venules, where substances pass between the blood and the tissues.

endothelium
The single layer of flattened cells lining every blood vessel. In a capillary it is the whole wall, with a basement membrane under it.

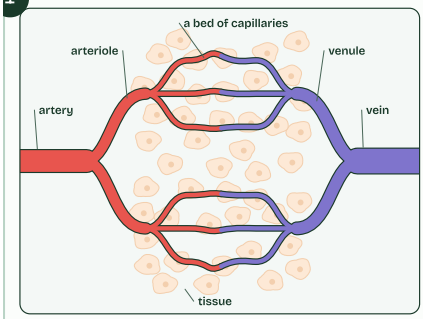
fenestrations
Small pores through the endothelial cells of some capillaries, which let fluid and small molecules out and in faster.



STEP BY STEP

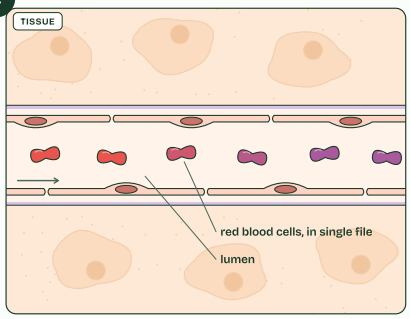
5 STEPS

1



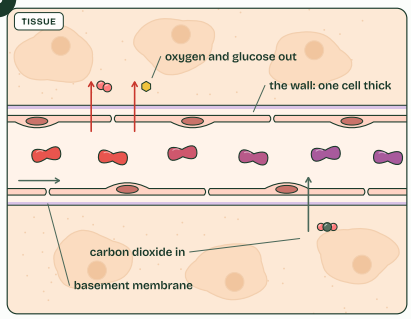
An **artery** divides into arterioles, and each arteriole into a **bed of capillaries** threaded through the tissue. They join again into venules and a vein.

2



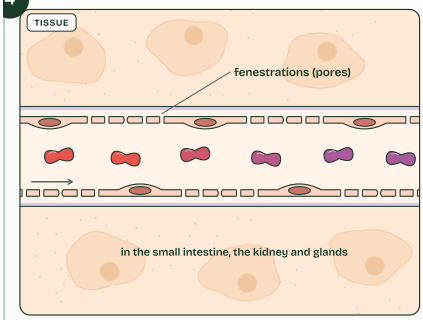
One capillary, close up. Its lumen is just wide enough for **red blood cells** in single file.

3



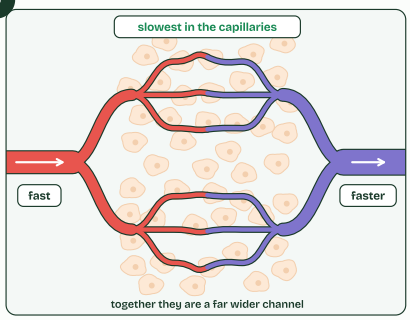
Its wall is **one cell thick**, flat endothelial cells on a basement membrane, so oxygen and glucose diffuse out a very short way, and carbon dioxide in.

4



Where exchange must be fastest (the small intestine, the kidney, glands), capillaries have **fenestrations**: pores through the wall.

5



The blood is **slowest in the capillaries**: together they are a far wider channel than the artery, so it has time to exchange.

PREDICT

Blood leaves the heart fast. How fast is it moving by the time it reaches the capillaries, and why does that matter?

(A) Faster, because the vessels are so narrow that the blood is squeezed along them

(B) Far slower: together the capillaries are a much wider channel, so there is time to exchange

(C) About the same, because the heart's push is just as strong everywhere in the body

(D) Slower, but only because the capillaries lose so much of the blood through their walls

Decide before you look. Answer on page 81.

WATCH OUT

"Capillary walls have muscle in them." They are one cell thick; only arteries and veins have muscle. "All capillaries have pores." Only some do, where exchange has to be fast. And "the blood is fastest where the vessels are narrowest." In the body it is the other way round: the capillary beds, the narrowest vessels, are where it is slowest.

11

B3.2.3 ADAPTATIONS OF ARTERIES FOR THE TRANSPORT OF BLOOD AWAY FROM THE HEART

Arteries: built to hold the *pressure*

Arteries carry blood away from the heart: to the lungs in the pulmonary artery, and to the rest of the body in the aorta and its branches. The blood comes in surges, one with each beat, at a high pressure: in the aorta of a resting young adult it rises to about 120 mmHg as the **left ventricle**, the heart's main pumping chamber, contracts and pushes blood out through the **aortic valve**.

The wall has three layers. Tap each one in the figure.

KEY POINTS

- **A smooth lining.** The endothelium, one layer of flat cells, gives the blood a smooth surface to flow over.
- **A thick middle layer of smooth muscle and elastic fibres.** The muscle makes the wall thick and strong, so it can withstand the high pressure without bursting, and it can narrow the artery a little. The elastic fibres stretch with each surge and then recoil. This **elastic recoil** pushes the blood on between beats, so it maintains the pressure and evens out the surges.
- **A tough outer coat.** Collagen fibres stop the artery from overstretching.

So an artery is a thick wall round a narrow lumen. The wall is the adaptation: thick and muscular to withstand the pressure, elastic to maintain it. The narrow lumen comes with it. (The three layers have Latin names, tunica intima, media and externa, which you will not need.)

KEY TERMS

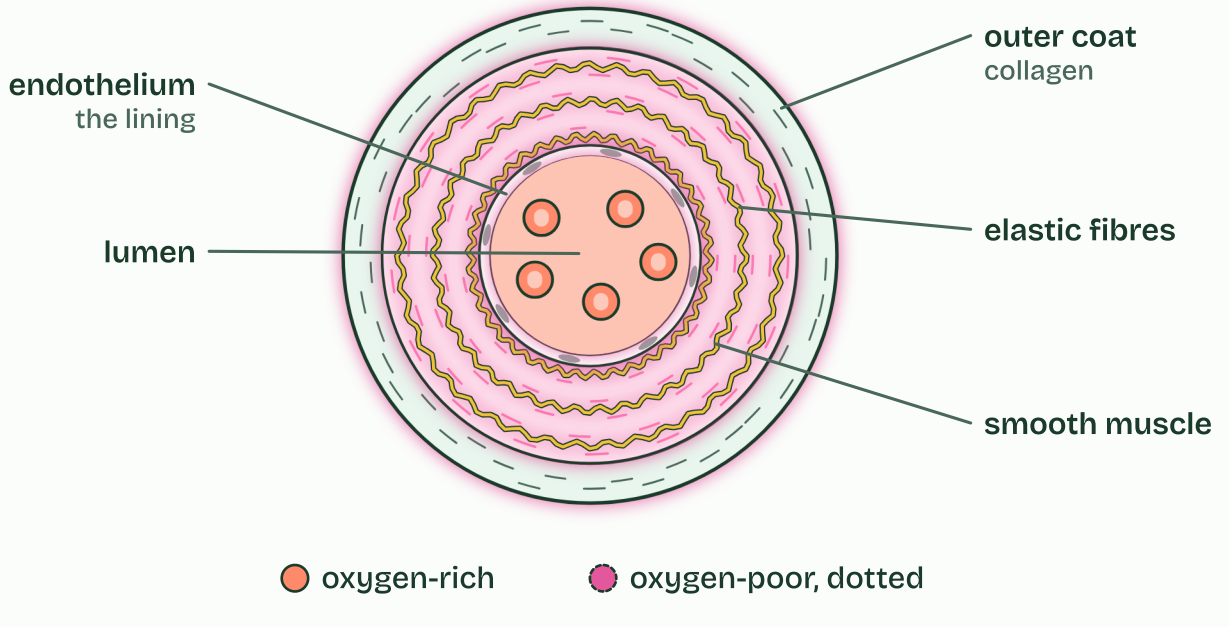
arteries
A vessel carrying blood away from the heart, at high pressure.

left ventricle
The lower chamber on the left of the heart, its main pump: it pushes oxygen-rich blood out into the aorta and round the body.

aortic valve
The valve where the left ventricle opens into the aorta. Its three pocket-shaped cusps let blood out and shut against it falling back.

elastic fibres
Fibres of the protein elastin in the wall of an artery, which stretch and spring back like a rubber band.

elastic recoil
The springing back of a stretched artery wall between beats, which keeps the blood moving and the pressure up.



Outer coat A tough layer of collagen fibres. It stops the artery from overstretching, and anchors it to the tissue around it.

Elastic fibres Sheets and fibres of the protein elastin in the middle layer, wavy while the artery is relaxed. They let the wall stretch as each surge of blood arrives, instead of bursting.

Lumen The space the blood flows through: narrow for the thickness of the wall round it. The blood here is oxygen-rich (coral is only a code: blood is always red).

Smooth muscle Most of the thick middle layer. It makes the wall thick and strong enough to withstand the high pressure of each surge without bursting, and it can narrow the artery a little.

Endothelium The lining: one layer of flat cells, which gives the blood a smooth surface to flow over.

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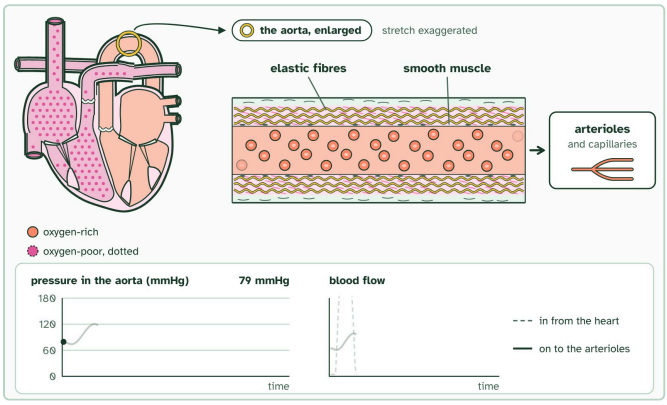
Elastic fibres Sheets and fibres of the protein elastin in the middle layer, wavy while the artery is relaxed. They let the wall stretch as each surge of blood arrives, instead of bursting.

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ANIMATION · SURGE IN, STEADY OUT

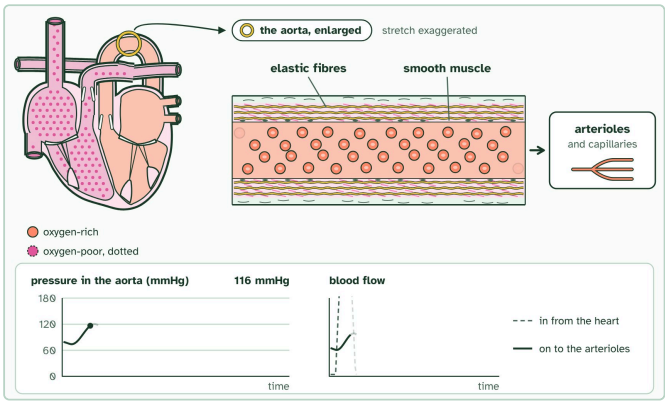
3 MOMENTS

1 VENTRICLE FULL



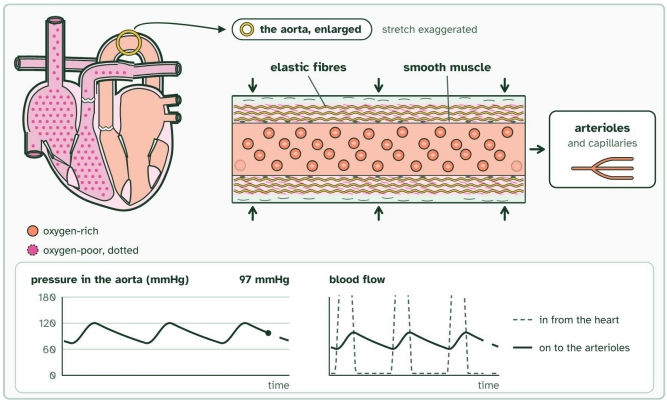
The left ventricle is full and the **aortic valve** is shut. The film is slowed down six times, and the ringed piece of aorta enlarged.

2 SURGE



The wall **stretches** to take the surge: its elastic fibres are pulled out straighter, and its muscle and tough outer coat stop it bursting.

3 BETWEEN BEATS



Between beats: the stretched wall springs back (**elastic recoil**) and squeezes the blood on, so it keeps flowing and the pressure stays up until the next surge.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#arteries

PREDICT

Between heartbeats the ventricles relax and the aortic valve is shut, yet the blood in your arteries keeps flowing on. What keeps it moving?

(A) The artery wall, stretched by the last surge, springs back and squeezes it on

(B) The muscle in the artery wall contracts in waves, like the wall of the gut

(C) Valves all along the arteries squeeze the blood forward from one to the next

(D) The atria are still contracting, and push more blood through into the arteries

Decide before you look. Answer on page 81.

WATCH OUT

"Arteries carry oxygen-rich blood." Most do, but the pulmonary artery carries oxygen-poor blood to the lungs: an artery is defined by its direction, away from the heart. "Artery walls pump the blood." They stretch and recoil; the heart does the pumping. And "arteries have valves along them." The only ones are the semilunar valves where they leave the heart.

12 Veins: the way *home*

B3.2.5 ADAPTATIONS OF VEINS FOR THE RETURN OF BLOOD TO THE HEART

Veins carry blood back to the heart. By the time blood has been through the capillaries, the surge of each beat is gone and its pressure has fallen to a few mmHg, too little on its own to lift blood from your feet to your chest. So veins are built to need very little push, and to take help from elsewhere.

A vein has the same three layers as an artery, but its wall is thin, with little muscle or elastic tissue, around a wide lumen. A wide lumen gives the slow, low-pressure blood little resistance to flow through.

KEY POINTS

- **A flexible wall.** Thin and with little muscle, so the skeletal muscles around it can squeeze it flat as they contract.
- **Pocket valves.** Two or three flaps, each shaped like a pocket. Blood moving towards the heart presses them flat against the wall; blood falling back fills the pockets, which meet in the middle and shut the vein. So any squeeze moves blood one way only, and the valves stop **backflow** between squeezes.
- **Help from breathing.** Each breath in lowers the pressure in the chest, which draws blood up the large veins towards the heart.

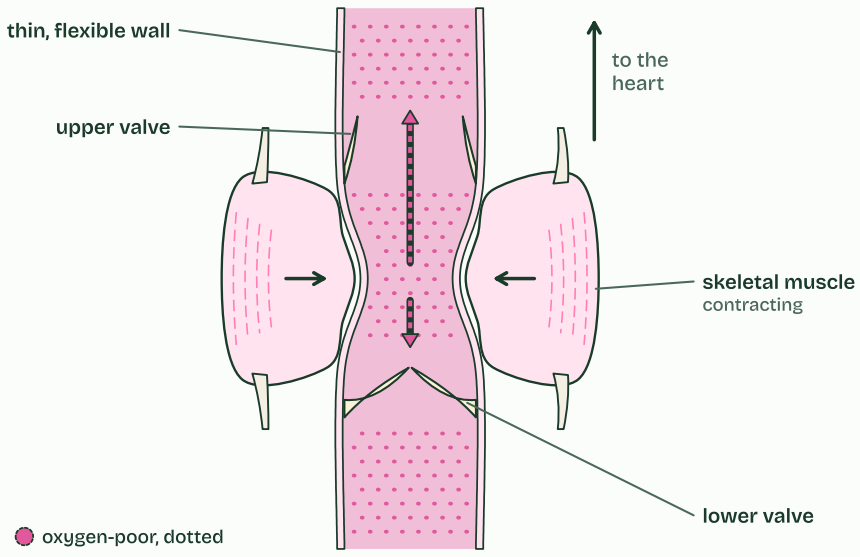
Valves are most common in the veins of the legs, which work against gravity. Where they fail, blood pools and the veins bulge: varicose veins. Compare veins with arteries and capillaries in the table in chapter 13.

KEY TERMS

veins
A vessel carrying blood back to the heart, at low pressure.

pocket valves
Flaps in a vein, shaped like pockets, that let blood through towards the heart and shut against it flowing back.

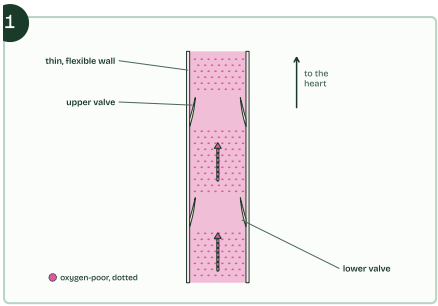
backflow
Blood flowing the wrong way, away from the heart.



STEP BY STEP

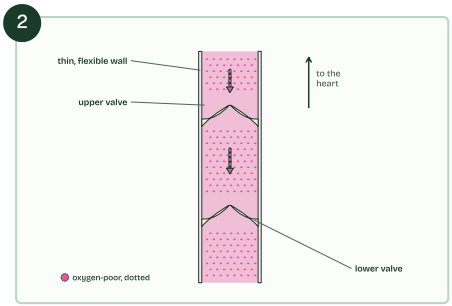
4 STEPS

1



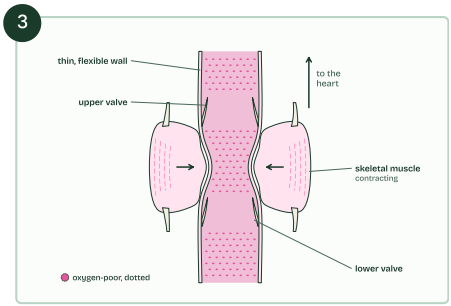
A vein cut along its length, with two **pocket valves**. Blood moving towards the heart presses their flaps flat against the wall.

2



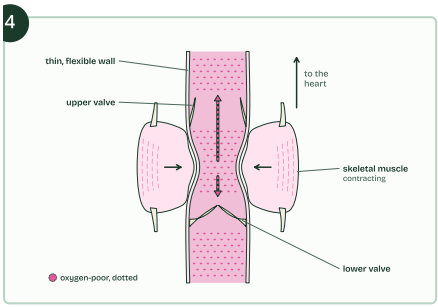
Blood falling back fills the pockets: the flaps meet in the middle and the valves **shut**. No backflow.

3



The skeletal **muscles** on either side contract, and the thin, flexible wall is squeezed in.

4

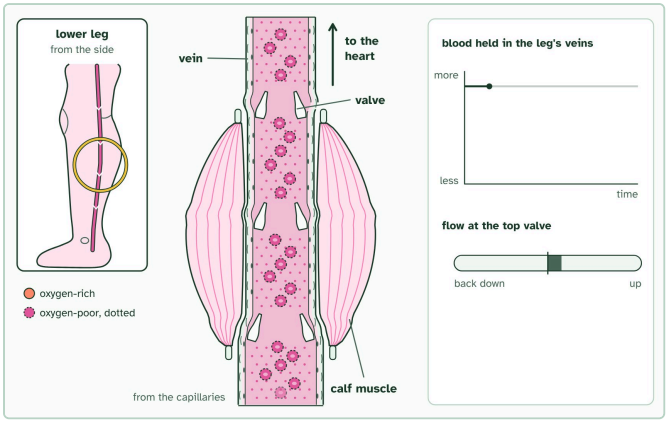


The squeeze pushes blood both ways, but the lower valve shuts and the upper one opens: it can go only **towards the heart**.

ANIMATION · THE MUSCLE PUMP AND THE VALVES

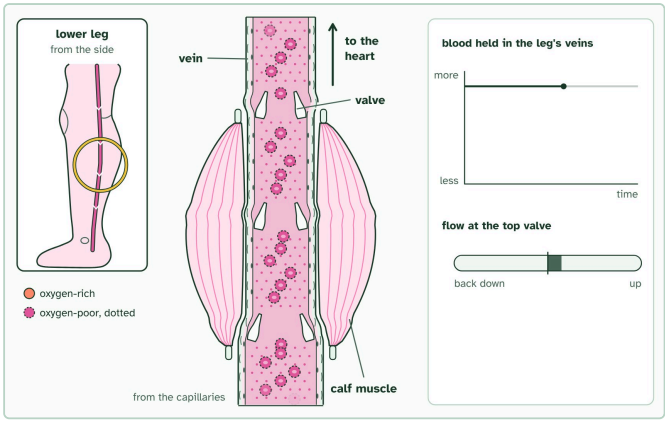
3 MOMENTS

1 STANDING STILL



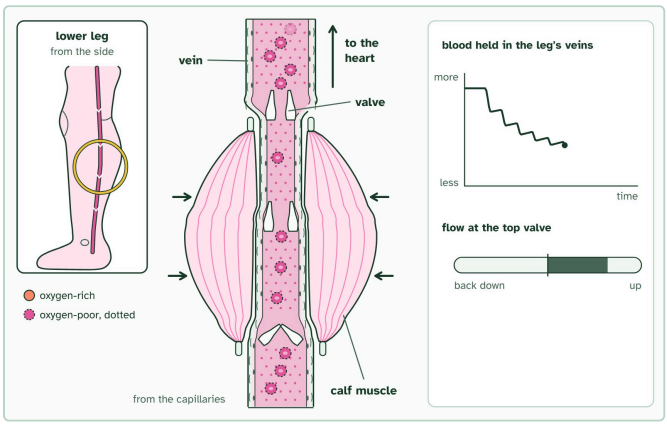
Standing still. Blood from the capillaries of the lower leg seeps into a deep vein, at low pressure: the surge from the heart is long gone.

2 STANDING STILL



Only a gentle push is left, so the blood creeps up towards the heart, slowed down two times here. The veins fill and stretch: blood pools in the legs.

3 MUSCLE CONTRACTING



Walking: each time the calf muscle contracts it squeezes the vein and pushes blood up towards the heart, and the **valves** stop it falling back.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#veins

PREDICT

You are walking. Each time your calf muscle contracts, what happens to the blood in a vein that runs through it?

(A) It is squeezed in both directions equally, until the heart draws it upwards

(B) It is squeezed towards the heart, and valves stop it dropping back afterwards

(C) It is pushed out through the thin wall of the vein into the muscle around it

(D) The vein itself contracts and drives the blood upwards, as the heart does

Decide before you look. Answer on page 81.

WATCH OUT

"All veins carry oxygen-poor blood." The pulmonary veins bring oxygen-rich blood from the lungs: a vein is defined by its direction, towards the heart. "Veins pulse." The pulse is lost in the capillaries. "Peristalsis moves blood up the veins." Veins have no waves of muscle contraction: the muscles around them squeeze them. And "valves are only in the heart."

B3.2.2 STRUCTURE OF ARTERIES AND VEINS

13 Which is which? Reading a vessel in *section*

Arteries and veins often run side by side, so a slide of almost any tissue cut across shows the two together, with capillaries between. The IB asks you to tell them apart in a micrograph. Start as you would a plan diagram: trace round the outside of each vessel, then round its lumen, and look at what lies between.

KEY POINTS

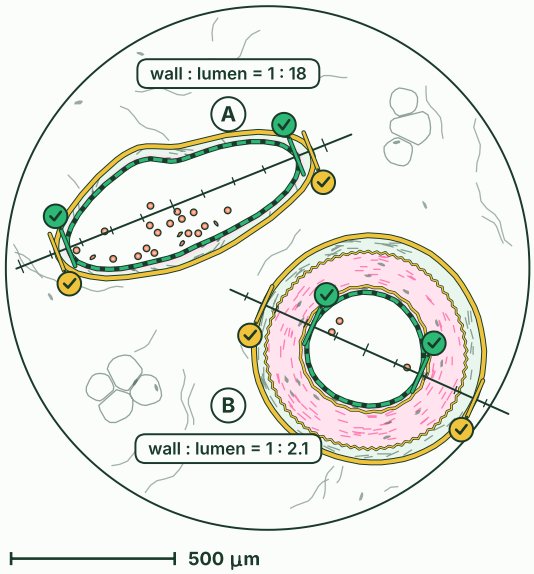
- **Artery**: a thick wall for the size of its lumen, most of it the muscle and elastic middle layer, often with wavy lines of elastic tissue. The lumen is usually small and round, its lining slightly scalloped.
- **Vein**: a thin wall round a wide lumen that is often flattened or crumpled, because the thin wall collapses when the tissue is cut. In a section along its length you may catch a valve.
- **Capillary**: a lumen only just wide enough for one red blood cell, and a wall of one flattened cell.

To judge the wall against the lumen, measure both across the same line with the eyepiece scale or the scale bar. Then put your call into words: name the evidence, not just the answer.

Artery, capillary or vein? Fill in the table under the tool. Tap a box and choose; a right answer stays, with its reason.

KEY TERMS

micrograph
A photograph taken through a microscope. Here, a thin slice of tissue, stained so that its layers show.

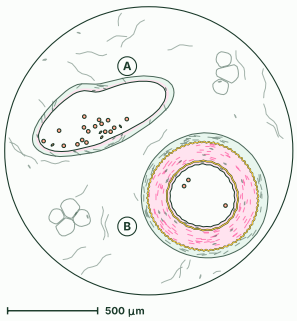


Outline each vessel, measure its wall and lumen on the scale bar, decide which is which, then pick the evidence that backs your call. Practise on four more.

STEP BY STEP

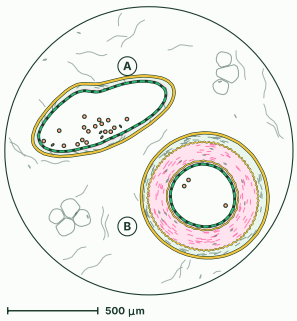
3 STEPS

1



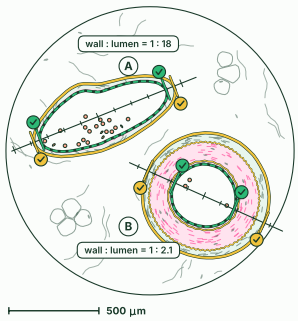
A transverse section as it looks down a light microscope, stained: two vessels, A and B, about the same width overall. The scale bar gives the size.

2



Outline first: the outside edge of each vessel (yellow) and the edge of its lumen (green, dashed). The **wall** is the band between them.

3



Measured across the widest part, the wall both sides and the lumen between: A: wall about 42 µm, lumen about 750 µm; B: wall about 170 µm, lumen about 360 µm. B, with a thick wall for its lumen, is the artery; A, with a thin wall round a wide, flattened lumen, is the vein.

PREDICT

Two vessels in a micrograph are about the same width overall. Which single measurement best tells you which one is the artery?

(A) The overall width of each vessel, measured across from outside to outside

(B) The colour of the blood cells left in each lumen, red or a darker purple

(C) The thickness of each vessel's wall, compared with the width of its lumen

(D) Whether each lumen is perfectly round, as only an artery's can stay open

Decide before you look. Answer on page 82.

WATCH OUT

"The bigger vessel is the artery." Size alone tells you little: a vein is often the wider of a pair. "Arteries are red and veins blue in a micrograph." Every colour on a slide is a stain. And "a round lumen proves it is an artery." It is a clue, never proof on its own.

14 Feeling the *pulse*

B3.2.4 MEASUREMENT OF PULSE RATES

Each time the left ventricle contracts, it sends a surge of blood into the aorta, and a wave of stretch runs along the arteries, far faster than the blood itself. Where an artery runs close to the skin over a bone, you can feel each wave as a tap: that is your **pulse**. One tap is one heartbeat, so counting them gives your heart rate.

Two places are easiest. The **radial** pulse is at the wrist, on the thumb side, just below the base of the thumb. The **carotid** pulse is in the neck, in the groove beside the windpipe, under the angle of the jaw. Use two fingertips, never your thumb, which has a pulse of its own, and press lightly. At the neck, use one side only.

Count the taps in 15, 30 or 60 seconds with a stopwatch, and scale up to beats a minute. That is the traditional method: cheap, and needing nothing but a watch. Digital methods take a reading for you. A **pulse oximeter** on a fingertip, a smartwatch or a chest strap count beats continuously and average them, but they need a moment to settle, and a watch on a cold or small wrist can misread.

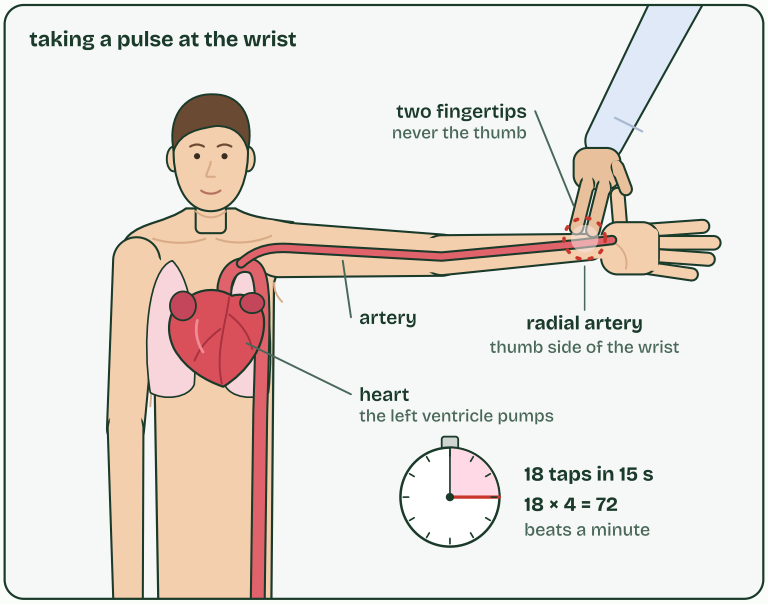
A resting pulse in adults is usually between 60 and 100 a minute, lower in very fit people, and it changes with age, fitness, posture, stress, caffeine and the time of day. So repeat a count and give the mean.

Two more, which the bench after this chapter lets you test: a stepping test with six volunteers, by fingertip and by meter.

KEY TERMS

pulse
The wave of stretch that runs along the arteries with each beat of the heart, felt as a tap where an artery is near the skin.

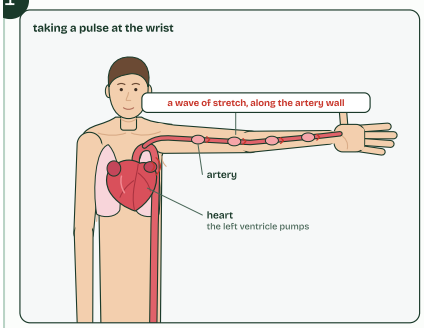
pulse oximeter
A clip on a fingertip that shines light through it. The pulsing blood absorbs more light with each beat, so the clip counts the beats (and estimates how much oxygen the blood carries).



STEP BY STEP

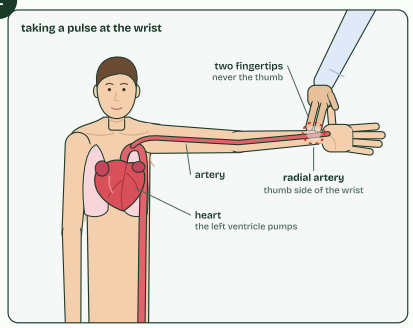
3 STEPS

1



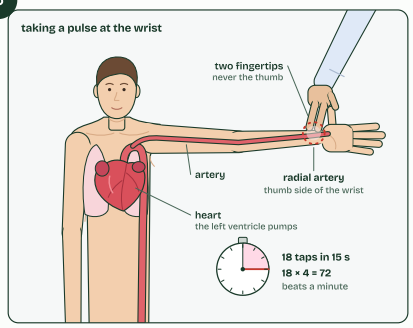
Each beat of the left ventricle sends a **wave of stretch** along the arteries, far faster than the blood itself.

2

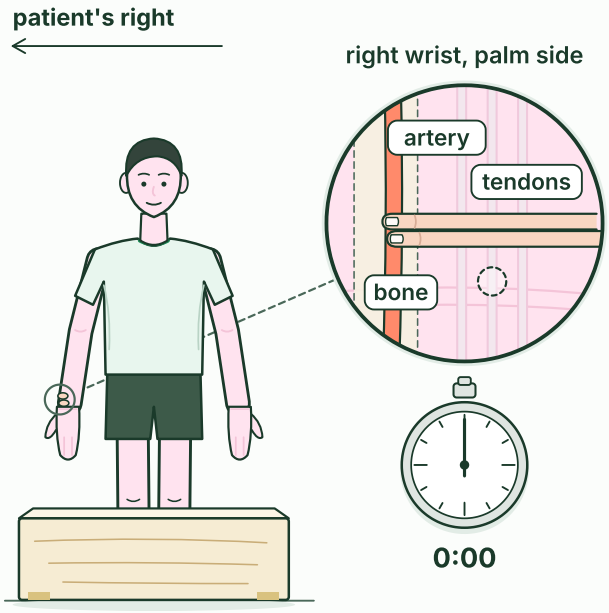


At the wrist the **radial artery** runs close to the skin, on the thumb side. Two fingertips, pressing lightly, feel each wave as a tap.

3



Count the taps for 15 seconds and multiply by 4 to give the rate in **beats a minute**.



volunteer B ready
count for 15 s
beats .
× 4 = .

Time after stepping / min	Beats in 15 s	Pulse rate / beats min^{-1}
before 1	----------	----------
before 2	----------	----------
before 3	----------	----------
0	----------	----------
0.5	----------	----------
1.0	----------	----------
1.5	----------	----------

Pulse and effort. A volunteer stands behind a step. Two fingertips find the pulse at the wrist, on the thumb side; it is counted for 15 seconds three times at rest, then straight after stepping and every half minute until it is back within 5 beats a minute of resting. Each count times 4 is the pulse rate a minute.

PREDICT

You count your pulse for 15 seconds and get 18 beats. A friend counts theirs for a whole minute and gets 68. Whose estimate of the resting rate is likely to be more precise, and why?

(A) Yours, because a short count catches the true rate before it has time to change

(B) Neither, because the pulse at the wrist and the heart rate are different things

(C) Both the same, because each result is rounded off to a whole number of beats

(D) Your friend's, because a beat miscounted in 15 seconds is an error of 4 a minute

Decide before you look. Answer on page 82.

WATCH OUT

"The pulse is the blood rushing past." It is a pressure wave in the artery's wall, far faster than the blood. "Use your thumb." It has a pulse of its own. And "pulse and blood pressure are the same thing." The pulse is a rate, in beats a minute; blood pressure is a pressure, in mmHg (chapter 20).

PREDICT

A volunteer steps up and down for a few minutes. What happens to their pulse straight afterwards, and over the next few minutes?

(A) It drops below the resting rate, then climbs slowly back up to it again

(B) It is well above resting, then falls back, fastest at first, over minutes

(C) It is well above resting and stays there until the volunteer next eats

(D) It stays at the resting rate, since the exercise has stopped by the count

Decide before you look. Answer on page 82.

PREDICT

You want to compare counting by fingertip with a pulse oximeter. What makes the comparison fair?

(A) Use a different volunteer for each method, so that neither result biases the other

(B) Count by fingertip after exercise and use the meter at rest, when it reads best

(C) Take both on the same person at the same time, at rest, and repeat each reading

(D) Take a single reading by each method, since the pulse never changes from minute to minute

Decide before you look. Answer on page 82.

15 When a coronary artery *blocks*

B3.2.6 CAUSES AND CONSEQUENCES OF OCCLUSION OF THE CORONARY ARTERIES

The **coronary arteries** feed the heart's own muscle. They branch from the aorta where it leaves the heart and run over the heart's surface. They are narrow, and the heart takes oxygen from their blood more fully than almost any other organ.

Over years, fatty deposits can build up in the wall of an artery, under its lining. This is **atherosclerosis**. The deposit, an **atheroma** or plaque, grows, hardens as calcium is laid down in it, and bulges into the lumen, narrowing it.

Narrowing is not the only danger. The plaque roughens and damages the lining, and if it cracks, a blood clot, a **thrombus**, forms on it. A clot can block the artery completely: the coronary artery is **occluded**.

KEY POINTS

- **Consequences.** Muscle beyond a narrowed artery gets too little oxygen when it works hard (ischaemia), felt as **angina**. When an artery is occluded, the muscle it feeds gets no oxygen at all and starts to die within about half an hour: a heart attack, or **myocardial infarction**. The dead muscle cannot contract, so the heart pumps less well, and a large infarct can be fatal. All of this is coronary heart disease (CHD).
- **Causes, or risk factors.** High levels of LDL cholesterol in the blood, linked to diets high in saturated and trans fats (B1.1); smoking; high blood pressure, which damages the lining; too little exercise; obesity and type 2 diabetes; and some you cannot change: age, being male, and family history.

KEY TERMS

coronary arteries
The arteries that branch from the aorta where it leaves the heart and run over the surface of the heart, supplying its muscle.

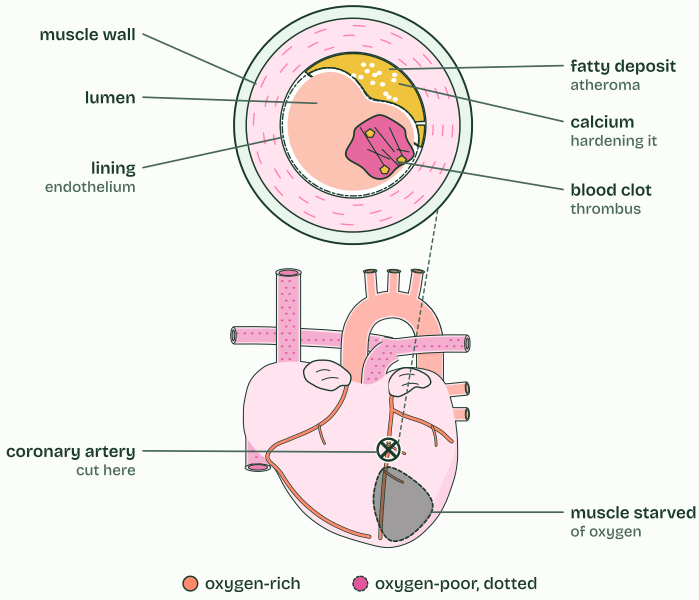
atherosclerosis
The build-up of fatty deposits (atheroma, or plaque) in the walls of arteries, narrowing and hardening them.

atheroma
A fatty deposit in the wall of an artery, under its lining; also called a plaque.

thrombus
A blood clot formed inside a blood vessel.

angina
Chest pain on effort, when narrowed coronary arteries cannot bring the heart muscle enough oxygen. It eases with rest.

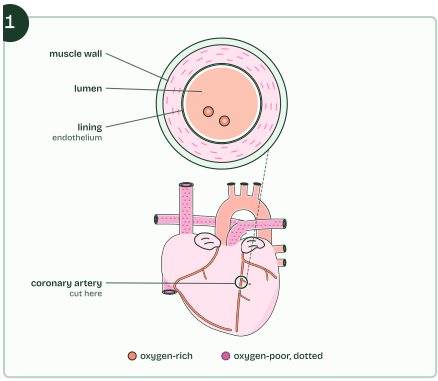
myocardial infarction
The death of part of the heart muscle when its blood supply is blocked: a heart attack.



STEP BY STEP

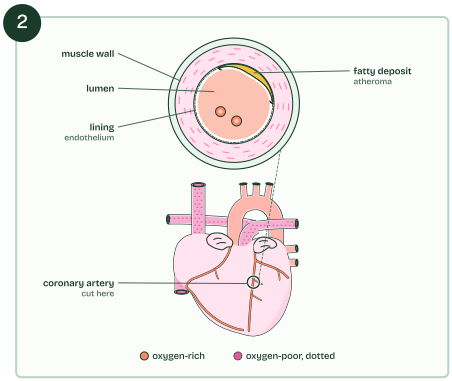
5 STEPS

1



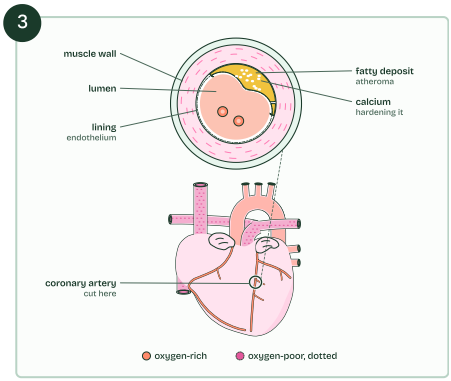
A **coronary artery** cut across, where it runs over the front of the heart: a round lumen, a smooth lining, a muscular wall.

2



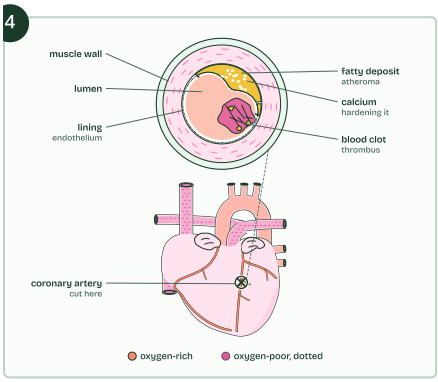
The lining is damaged, and a **fatty deposit** starts to build up under it.

3



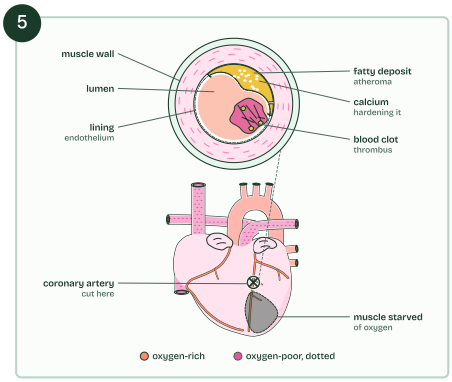
Over years the deposit, an **atheroma**, grows and hardens with calcium. It bulges into the lumen and narrows it.

4



The rough surface can crack, and a **blood clot** forms on it, blocking the artery: occlusion.

5

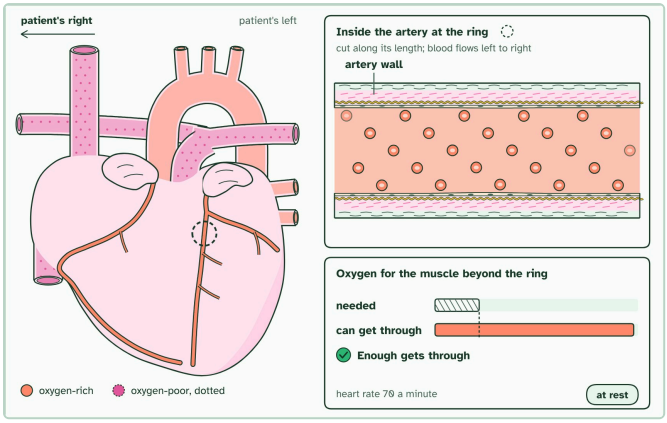


The heart muscle beyond the block gets no oxygen and starts to die: a **heart attack**.

ANIMATION · A CORONARY ARTERY, OVER THE YEARS

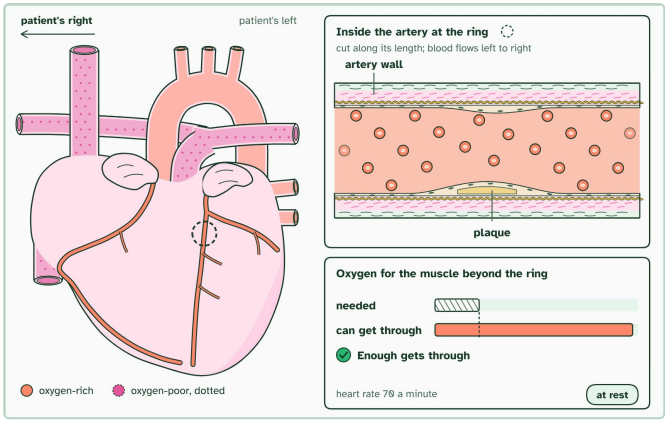
5 MOMENTS

1 AGE 25, NARROWED 1%



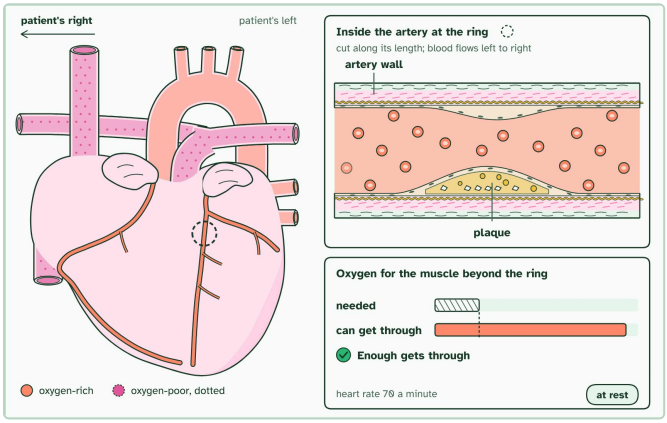
Age 20. A **coronary artery** runs over the heart's surface and feeds the heart's own muscle. The panel shows a short length of it, cut open.

2 AGE 44, NARROWED 20%



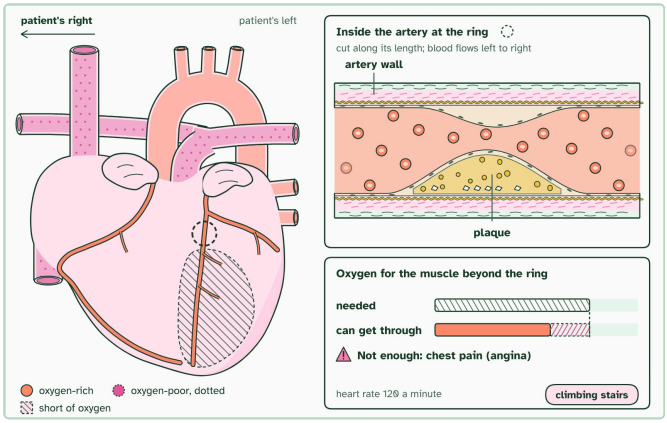
Year by year the plaque grows into the lumen, and calcium hardens it. This is **atherosclerosis**.

3 AGE 65, NARROWED 45%



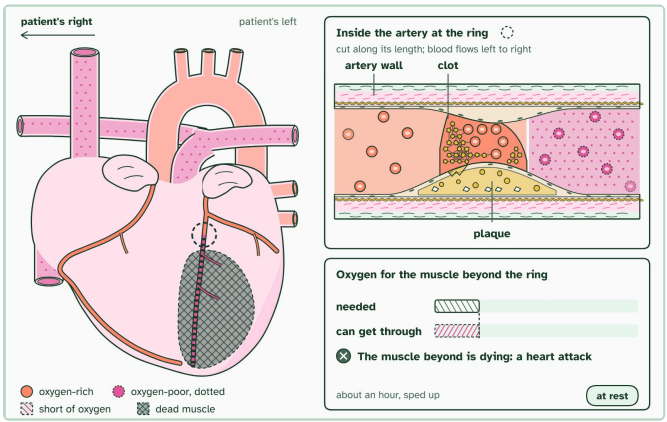
The gauge compares the oxygen the muscle beyond the ring needs with the most the artery can bring it.

4 AGE 64, NARROWED 73%



Climbing stairs at 64, with three risks: the narrowed artery cannot bring the extra oxygen, so the muscle beyond is short of it and there is **chest pain (angina)**.

5 AGE 58, PLAQUE CRACKED



A plaque cracked at 58: the clot blocks the artery, and the muscle beyond it has died, a **heart attack**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#coronary

PREDICT

A man's coronary artery is narrowed by about two thirds. At rest he feels nothing, but climbing the stairs gives him chest pain. Why?

(A) Climbing the stairs squeezes the narrowed artery shut while his legs are working

(B) The plaque rubs on the artery wall when the heart beats faster, and that hurts

(C) On the stairs his heart muscle needs far more oxygen than the narrow artery brings

(D) His heart has less blood in its chambers while the rest of his body is moving

Decide before you look. Answer on page 82.

WATCH OUT

"A heart attack is when the heart stops." That is cardiac arrest, which a heart attack can cause but is not the same thing: in a heart attack part of the muscle dies, and the heart usually keeps beating. "Angina is a small heart attack." In angina no muscle dies, and the pain passes with rest. And "cholesterol is a poison." Every cell membrane needs it; the harm comes from too much LDL in the blood, laid down in artery walls.

B3.2.6 CAUSES AND CONSEQUENCES OF OCCLUSION OF THE CORONARY ARTERIES

16 Fat and heart disease: what the *data* can show

How do we know what raises the risk of coronary heart disease? Much of the evidence comes from **epidemiology**: counting how often a disease occurs in different groups and looking for what goes with it. The count is often given as the **incidence**, new cases per 100 000 people a year, so groups of different sizes can be compared.

A common first look is a scatter graph: one point for each country, say, with how much of something people eat on one axis and the incidence of CHD on the other. If the points rise together, the two are **correlated**.

The strength of a correlation is measured by the **correlation coefficient**, r. It runs from −1 to +1: its sign gives the direction (+ both rise together, − one falls as the other rises) and its size the strength (near 1 or −1, the points lie close to a line; near 0, no straight-line link). A spreadsheet may give r^2 instead, the share of the variation in one variable that goes with the other.

KEY POINTS

- **A weak or no correlation** can count against a hypothesis: if a factor caused a disease, the disease should be commoner where the factor is commoner.
- **A strong correlation does not prove a cause.** Countries that eat more saturated fat also tend to be richer, to live longer, and to smoke and exercise differently; any of these could raise CHD too. The cause could run the other way, the sample could be small, and the way the data were collected matters: a country's average diet says nothing about the people who actually fell ill.
- **What moves evidence towards a cause**: a mechanism that makes sense (atheroma, chapter 15); a dose-response, more of the factor and more disease; the same link found in many studies of different kinds; and trials that change the factor and watch what happens.

The link between saturated fat and CHD is the IB's own example: scientists use correlation coefficients to measure how strong a relationship is, but even a strong one does not prove a causal link. Work through it in the tool, on data invented to show the idea.

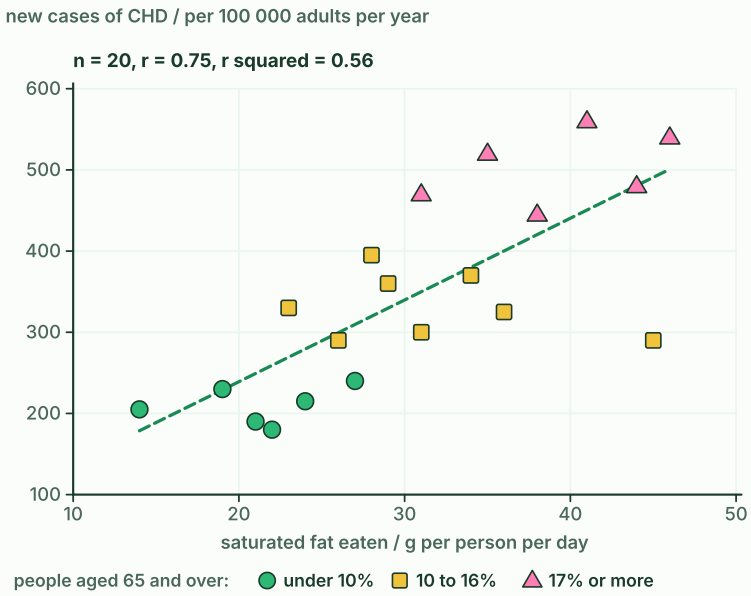
KEY TERMS

epidemiology
The study of how often a disease occurs in different groups of people, and what goes with it.

incidence
The number of new cases of a disease in a population in a given time, often per 100 000 people a year.

correlated
Two variables are correlated when they tend to change together: both up (positive), or one up as the other goes down (negative).

correlation coefficient
A number from minus 1 to plus 1 that measures how closely two variables follow a straight line together. Its sign gives the direction; its size, the strength.

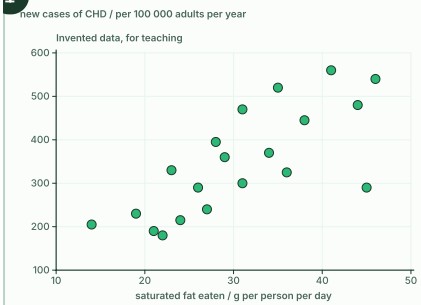


Start with the ice-cream towns, then the fat and heart disease data, every number invented. Take a point out, colour the points by a hidden factor, and use fewer countries.

STEP BY STEP

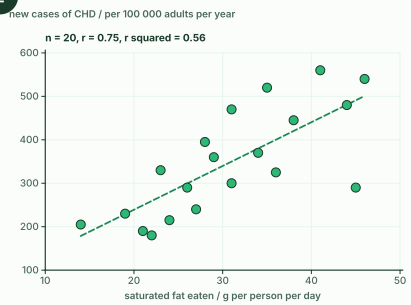
3 STEPS

1



Invented data: Twenty made-up countries: the saturated fat eaten, and new cases of coronary heart disease (CHD) a year, its incidence. Each point is one of the 20 countries. Describe the pattern before you calculate anything.

2



The trend line and the **correlation coefficient**: r = 0.75, a strong positive correlation. r squared = 0.56: about 56% of the variation in new cases of CHD goes with saturated fat eaten. That says nothing about which, if either, is the cause.

3



A **third factor**, people aged 65 and over, as a shape for each group (the key). In these invented data, countries with older populations eat more saturated fat and have more CHD, which becomes far more common with age. Inside each age group the link is much weaker, so part of the pattern is age. Real studies compare age-standardised rates to take this out. Inside the groups r is 0.31, −0.28 and 0.41.

PREDICT

Across 30 seaside towns, ice-cream sales and cases of sunburn rise and fall together through the year. The correlation coefficient is 0.9. What can you conclude?

(A) Eating ice cream makes the skin more likely to burn in the sun

(B) Being sunburnt makes people want to buy more ice creams

(C) They go together, but something else could drive both

(D) Nothing, because 0.9 is too weak a correlation to mean much

Decide before you look. Answer on page 82.

WATCH OUT

"Correlation means causation." It can be a clue, never a proof. "No correlation means no link." r measures only straight-line links: points on a curve can give r near 0, so always look at the graph. And "r = 0.9 proves it." The ice-cream towns have that too.

B3.2.14 HL DIFFERENCES BETWEEN THE SINGLE CIRCULATION OF BONY FISH AND THE DOUBLE CIRCULATION OF MAMMALS

17 One loop or *two*

Blood has to pass through two kinds of capillary bed on its way round: one where it takes up oxygen (the gills of a fish, the lungs of a mammal) and the ones in the body's tissues, where it gives oxygen up. The question is how the heart is placed between them.

A bony fish has a heart with one atrium and one ventricle. The ventricle pumps oxygen-poor blood to the gills, where it takes up oxygen. From the gills the blood flows straight on to the body's organs and back to the heart. This is a **single circulation**: heart, gills, body, heart.

A mammal has a **double circulation**. The right side of the heart pumps blood to the lungs and back to the left side: the pulmonary circulation. The left side pumps it round the body and back to the right side: the systemic circulation. Heart, lungs, heart, body, heart.

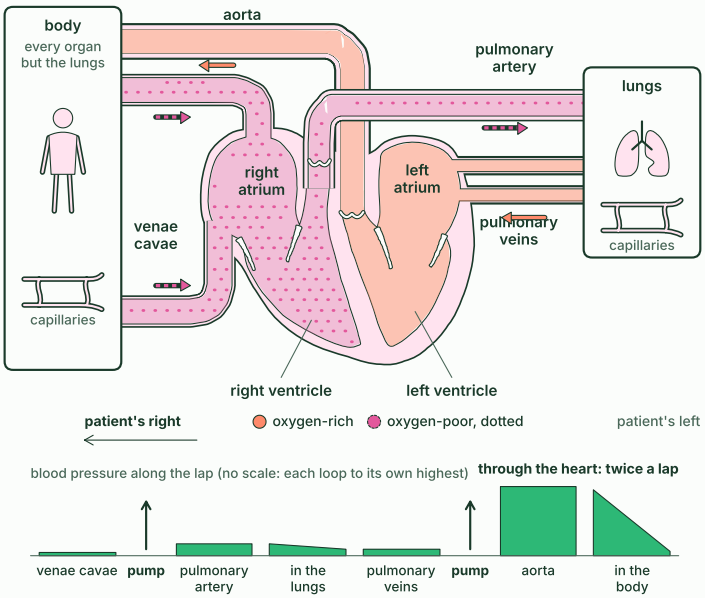
KEY POINTS

- **Pressure.** Blood loses most of its pressure squeezing through a capillary bed. In a fish it reaches the body's organs at the low pressure left after the gills. In a mammal it comes back to the heart after the lungs and is pumped again, so the body's tissues get blood at high pressure, fast enough to supply a high metabolic rate and to keep a body warm.
- **Two pressures.** The two sides of a mammal's heart work at their own pressures: the left high, for the whole body, and the right low, for the lungs, whose delicate capillaries a high pressure would damage.
- **Kept apart.** The septum keeps oxygen-rich and oxygen-poor blood apart, so the body gets blood that is fully oxygen-rich.

KEY TERMS

single circulation
A circulation in which the blood passes through the heart once on each complete lap of the body, as in a bony fish.

double circulation
A circulation in which the blood passes through the heart twice on each lap: once to the lungs and back (pulmonary), once to the body and back (systemic).

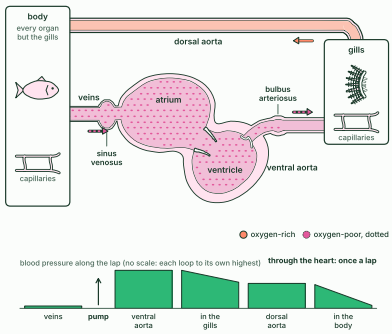


Build each loop by tapping the organs in order, then follow a red cell round: count its passes through the heart and watch the pressure fall and rise.

STEP BY STEP

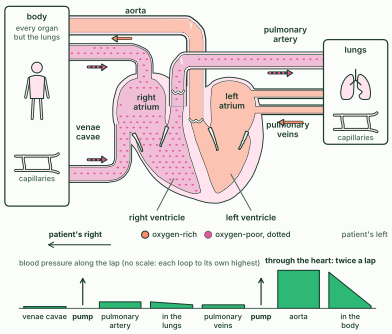
2 STEPS

1



A bony fish: a **single circulation**. The two-chambered heart pumps blood to the gills; it flows straight on to the body and back. Once through the heart a lap, and the body gets blood that has lost pressure in the gill capillaries.

2



A mammal: a **double circulation**. The right side pumps blood to the lungs and back (pulmonary), the left side to the body and back (systemic). Twice through the heart a lap: the body gets freshly pumped, high-pressure blood.

PREDICT

On one complete lap round the body, how many times does the blood pass through the heart in a bony fish, and in a mammal?

(A) Twice in a fish and once in a mammal

(B) Once in both, since a heart is one pump

(C) Once in a fish and twice in a mammal

(D) Once in a fish, four times in a mammal

Decide before you look. Answer on page 83.

WATCH OUT

"A fish's heart has four chambers." A bony fish's heart has one atrium and one ventricle (with two small chambers before and after them that you will not need). "A mammal has two hearts." It has one heart that is two pumps. And "double circulation means the blood mixes." It means the opposite: the two loops stay apart.

B3.2.15 HL ADAPTATIONS OF THE MAMMALIAN HEART FOR DELIVERING PRESSURIZED BLOOD TO THE ARTERIES

18 A muscle that sets its own *pace*

The heart's wall is **cardiac muscle**, found nowhere else in the body. It contracts about 100 000 times a day for a lifetime, and it has to contract as one, so that the chambers squeeze their blood out instead of just twitching.

KEY POINTS

- **Branched cells, joined end to end.** The cells branch and meet at **intercalated discs**, where gap junctions let the electrical signal pass straight from one cell to the next. So a signal spreads through the wall as a wave and the wall contracts as one.
- **Striated, with many mitochondria.** Like skeletal muscle it has stripes, but it never rests, so it is packed with mitochondria for aerobic respiration and has a rich supply of capillaries from the coronary arteries. It does not tire.
- **Myogenic.** The beat starts in the muscle, not in a nerve.

Each beat starts at the **sinoatrial (SA) node**, the pacemaker, a patch of special muscle cells in the wall of the right atrium where the superior vena cava enters. Its cells fire on their own, regularly, and each firing sends a signal across both atria, so they contract together. The signal cannot cross straight into the ventricles: a layer of tissue that does not conduct lies between them. Its only way through is the atrioventricular (AV) node, which holds it for about a tenth of a second, so the atria finish emptying into the ventricles first. Then fibres carry it fast down the septum to the apex, and up through the ventricles' walls. So the ventricles contract from the apex upwards, squeezing their blood up towards the arteries at the top, as you squeeze toothpaste from the end of the tube.

If the SA node fails, an artificial pacemaker, a small battery-powered device under the skin, can send the signal instead.

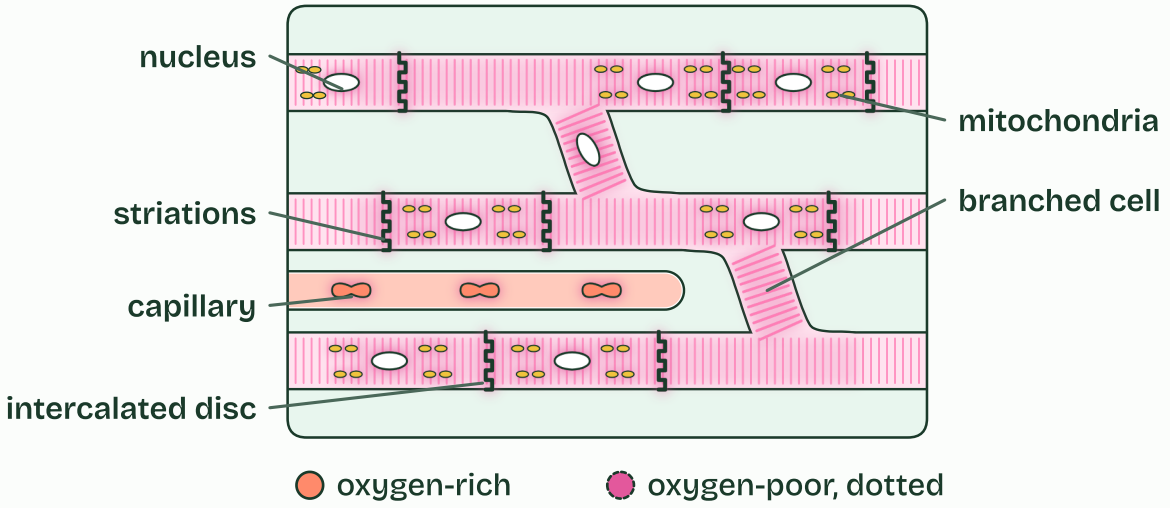
KEY TERMS

cardiac muscle
The muscle of the heart wall: striated, with branched cells joined end to end at intercalated discs.

intercalated discs
The joins between cardiac muscle cells, with gap junctions through which the signal passes from one cell to the next.

myogenic
Starting its own contractions, with no signal from a nerve.

sinoatrial (SA) node
The sinoatrial node: a patch of special cardiac muscle cells in the wall of the right atrium that starts each heartbeat; the pacemaker.



Capillary A rich supply of blood from the coronary arteries runs between the fibres, bringing oxygen and glucose to muscle that works without a break.

Branched cell Each cell branches, and is joined end to end with the cells around it, so the cells make a network through the wall of the heart.

Nucleus One, or sometimes two, near the middle of each cell.

Striations The stripes: bundles of protein filaments in repeating units, which slide past each other to contract, as in skeletal muscle.

Intercalated disc Where two cells join, end to end. Gap junctions in the disc let the electrical signal pass straight from one cell to the next, so it spreads through the wall as a wave and the cells contract together.

Mitochondria Packed between the filaments, far more than in skeletal muscle. Aerobic respiration in them supplies the ATP for every contraction, so the muscle does not tire.

Capillary A rich supply of blood from the coronary arteries runs between the fibres, bringing oxygen and glucose to muscle that works without a break.

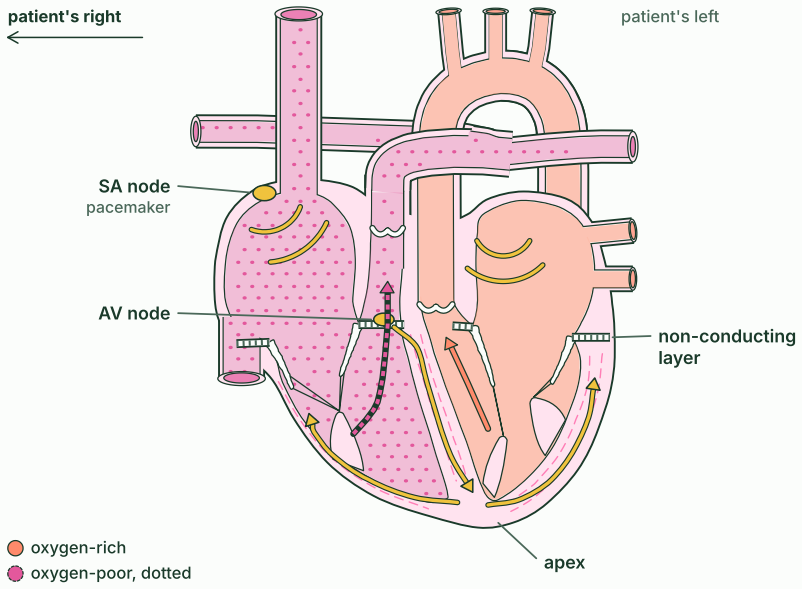
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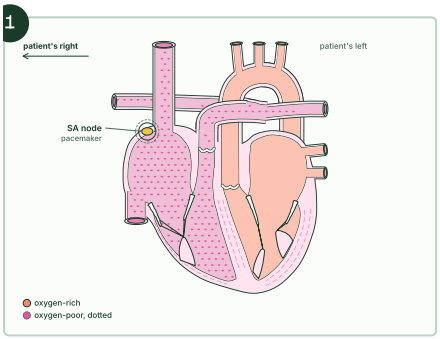
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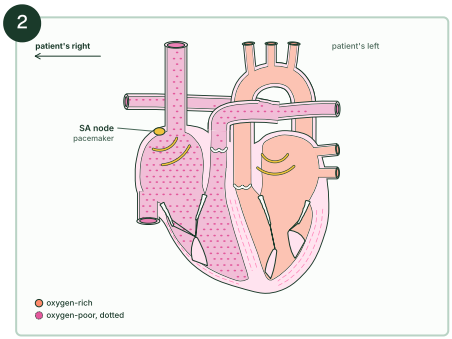


STEP BY STEP

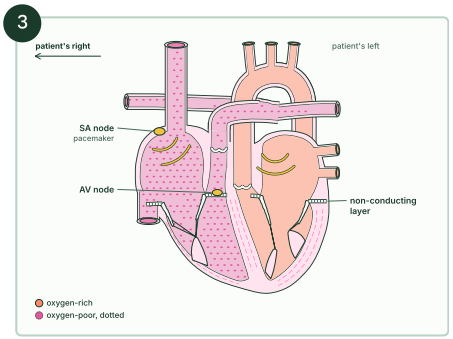
6 STEPS



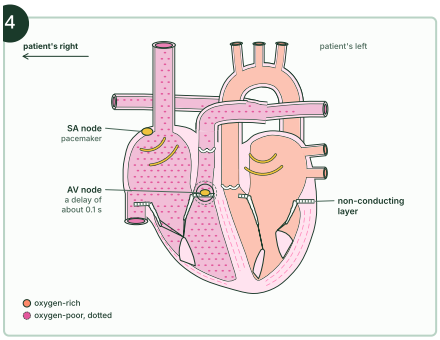
The **SA node**, the pacemaker: a patch of special muscle in the wall of the right atrium. Each beat starts when it fires.



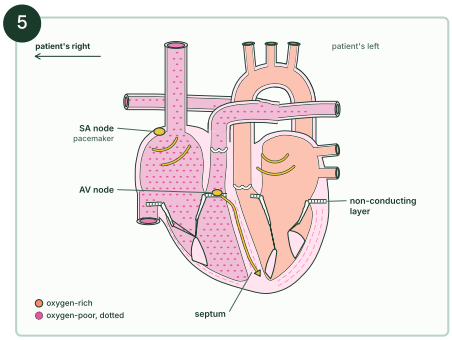
The signal spreads through the walls of **both atria**, and they contract together.



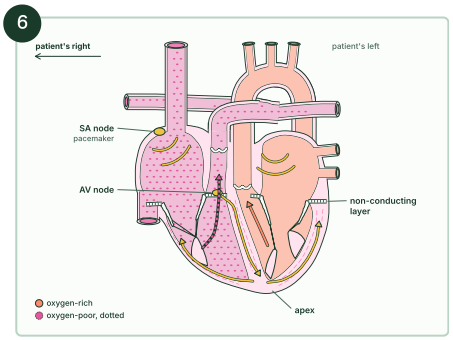
A **non-conducting layer** between the atria and the ventricles blocks it. Its only way through is the **AV node**.



The AV node holds the signal for about **0.1 s**, while the atria finish emptying into the ventricles.



Fibres carry it fast **down the septum** to the apex.



From the **apex** it spreads up the walls of both ventricles, so they contract from the bottom up and squeeze the blood up into the arteries.

PREDICT

A heart is taken out of an animal and kept in a warm salt solution with oxygen bubbled through it. It goes on beating for some time. What does this show?

(A) The heart stores up signals from the brain and lets them out slowly, one by one

(B) The beat is driven by the blood still inside its chambers, pressing on the walls

(C) The salt solution itself is sending the signals that make the muscle contract

(D) The signal for each beat starts inside the heart itself, not in the brain or nerves

Decide before you look. Answer on page 83.

WATCH OUT

"The brain makes the heart beat." The brain changes the rate; the SA node starts each beat. "Cardiac muscle is the same as skeletal muscle." Both are striated, but cardiac cells branch, join at intercalated discs, beat on their own and never tire. And "the ventricles contract from the top down." They contract from the apex up, towards the arteries.

19 B3.2.16 HL STAGES IN THE CARDIAC CYCLE

The cardiac *cycle*

One heartbeat is one **cardiac cycle**. At 75 beats a minute it takes 0.8 seconds. A chamber contracting is in **systole**; relaxing, it is in **diastole**. The IB asks for the events on the left side of the heart, from the moment the SA node fires.

So one rule runs every valve: **a valve opens when the pressure behind it is higher than the pressure in front, and shuts when it is lower.** Follow the left side through one beat:

KEY POINTS

- **Atrial systole.** The SA node fires and the atria contract, topping up the ventricle, which has already filled most of the way on its own as blood flowed in from the veins. The bicuspid valve is open; the aortic valve is shut.
- **Ventricular systole.** The signal reaches the ventricle and it contracts. Its pressure rises above the atrium's, so the bicuspid valve shuts: the first heart sound, "lub". For a moment every valve is shut and the pressure climbs fast. When it passes the aorta's, the aortic valve opens and blood is pushed out. The aorta's pressure peaks: the systolic pressure.
- **Diastole.** The ventricle relaxes and its pressure falls. Below the aorta's, the aortic valve shuts: the second heart sound, "dub". Below the atrium's, the bicuspid valve opens and the ventricle fills again, while the aorta's elastic wall keeps the blood moving on, its pressure sinking to its lowest, the diastolic pressure, before the next beat.

The heart sounds are valves closing, not blood rushing. At a faster heart rate the cycle is shorter, and it is mostly diastole, the filling time, that is cut.

Put the beat in order. Under the film: tap the events of one beat on the left side in the order they happen. A right one stays, with the pressure that makes it happen.

KEY TERMS

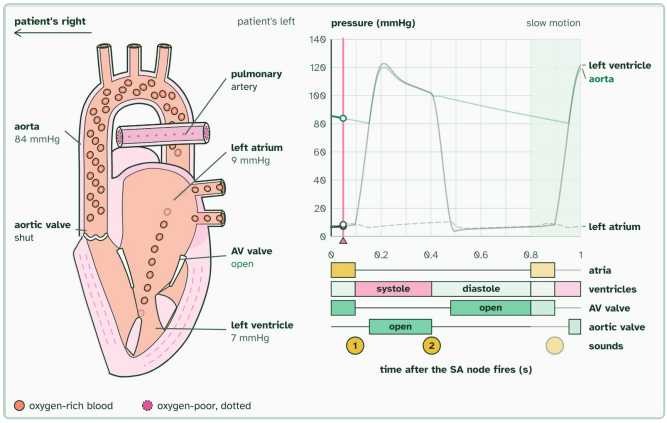
cardiac cycle
The sequence of events in one heartbeat: the atria contract, then the ventricles, then the whole heart relaxes and refills.

systole
The part of the cardiac cycle when a chamber contracts.

diastole
The part of the cardiac cycle when a chamber relaxes and fills with blood.

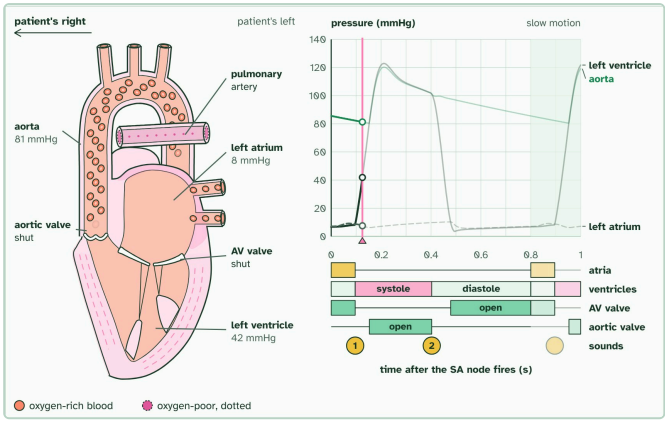
ANIMATION · ONE HEARTBEAT, LEFT SIDE
4 MOMENTS

1 ATRIAL SYSTOLE, 0.05 S



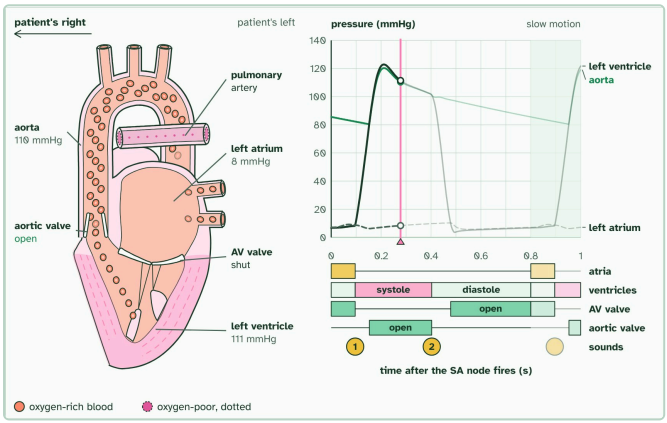
The SA node fires. The **atrium contracts** and tops up the ventricle, which is already mostly full.

2 VENTRICULAR SYSTOLE, 0.13 S



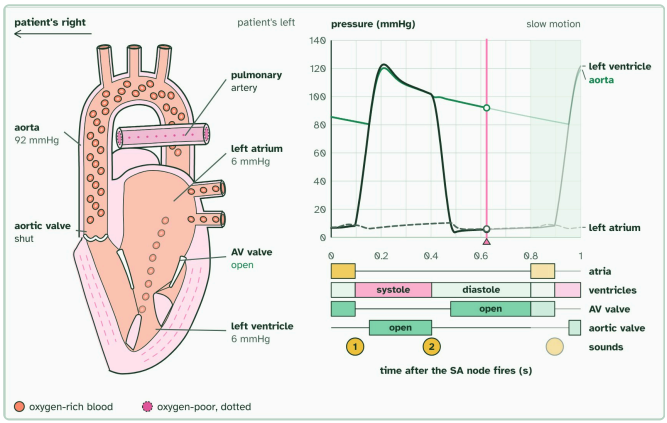
The **ventricle contracts.** Its pressure rises above the atrium's, so the **AV valve shuts:** the first heart sound.

3 VENTRICULAR SYSTOLE, 0.28 S



Its pressure rises above the aorta's: the **aortic valve opens** and blood is pushed out into the aorta.

4 DIASTOLE, 0.62 S



Its pressure falls below the atrium's: the **AV valve opens** and the ventricle fills. This is diastole.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#cycle

PREDICT

The left ventricle starts to contract. A moment later the aortic valve opens. What opens it?

(A) The pressure in the ventricle rises above the aorta's pressure

(B) The signal from the SA node reaches the valve and makes it open

(C) The left atrium contracts, and the push forces the valve open

(D) Muscles in the valve pull it open as the ventricle's wall tightens

Decide before you look. Answer on page 83.

REMEMBER IT

One beat on the left side: All Valves Swing Open Shut Fill

A All	V Valves	S Swing	O Open	S Shut	F Fill
Atria contract the ventricle is topped up	**Ventricle contracts** bicuspid valve shuts: lub	**Squeeze, all shut** pressure climbs with no blood moving	**Outflow** aortic valve opens, blood ejected	**Slackens** ventricle relaxes, aortic valve shuts: dub	**Fills** bicuspid valve opens, the ventricle refills

WATCH OUT

"The ventricles fill only when the atria contract." Most of their filling happens before that, while the whole heart is relaxed. "Diastole is a rest when nothing happens." It is when the heart refills. "The heart sounds are the blood rushing." They are valves shutting. And "valves are muscles." They are flaps moved by pressure.

20 Reading blood *pressure*

B3.2.16 HL STAGES IN THE CARDIAC CYCLE

The pressure in your arteries rises and falls with every beat. It peaks as the left ventricle pushes blood into the aorta: the **systolic pressure**. It sinks to its lowest just before the next beat, held up by the elastic recoil of the artery walls (chapter 11): the **diastolic pressure**. Blood pressure is measured in millimetres of mercury, mmHg, and written systolic over diastolic: about 120/80 for a healthy young adult at rest. That is the usual textbook figure; the American Heart Association calls anything below 120/80 normal, and the NHS puts the ideal at 90/60 up to just under 120/80.

To read either from a trace of arterial pressure, find the tops of the waves (systolic) and the bottoms of the troughs (diastolic). Try it on the two traces in the figure, then the questions below.

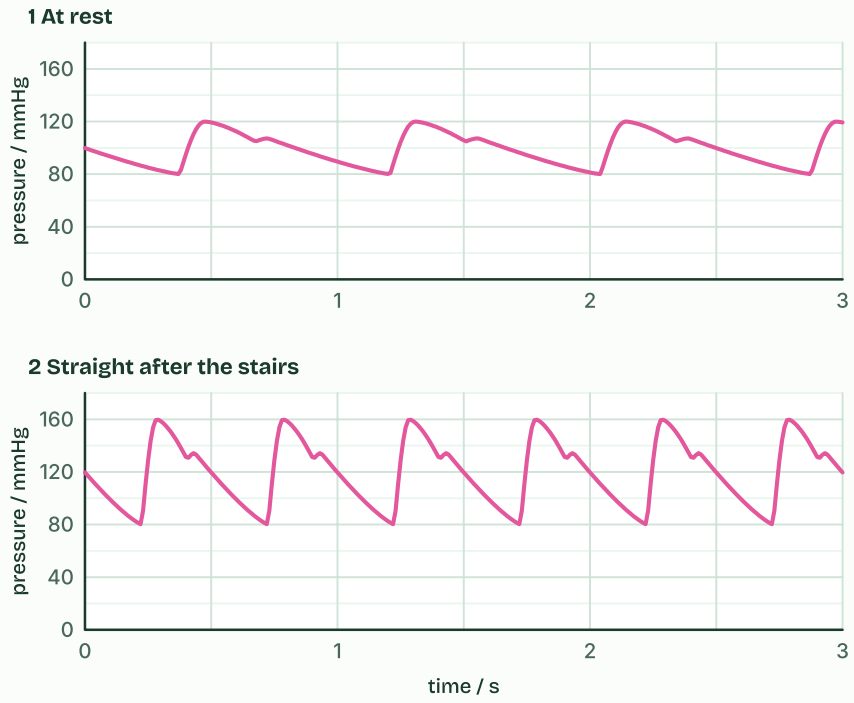
Measuring it. A doctor uses a cuff round the upper arm, a gauge, and a stethoscope over the artery below the cuff. Before the film, decide what the first sound means.

A digital monitor does it without a stethoscope: it senses the small pulses of pressure in the cuff as the artery opens and works the two numbers out. High blood pressure, kept up for years, strains the heart and damages the lining of the arteries, one of the risk factors for coronary heart disease (chapter 15).

KEY TERMS

systolic pressure
The highest pressure in the arteries in each beat, as the left ventricle contracts.

diastolic pressure
The lowest pressure in the arteries in each beat, just before the next contraction.

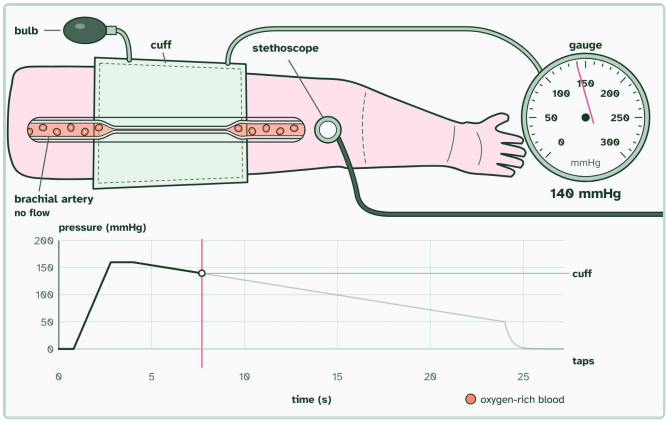


The pressure in an artery in one person over 3 seconds, at rest and straight after running up three flights of stairs. The traces are drawn for this guide.

ANIMATION · TAKING A BLOOD PRESSURE

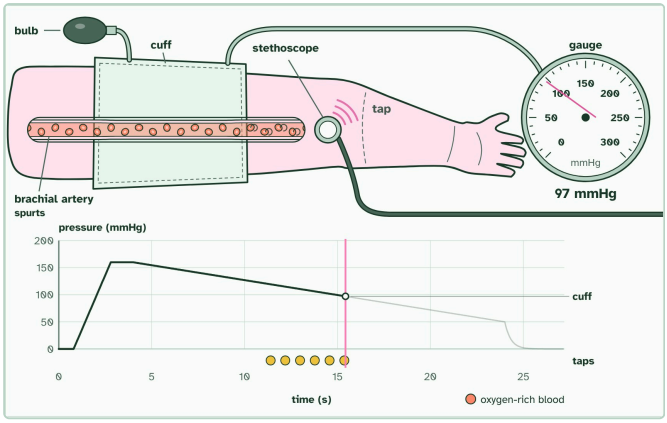
3 MOMENTS

1 GAUGE 140 MMHG



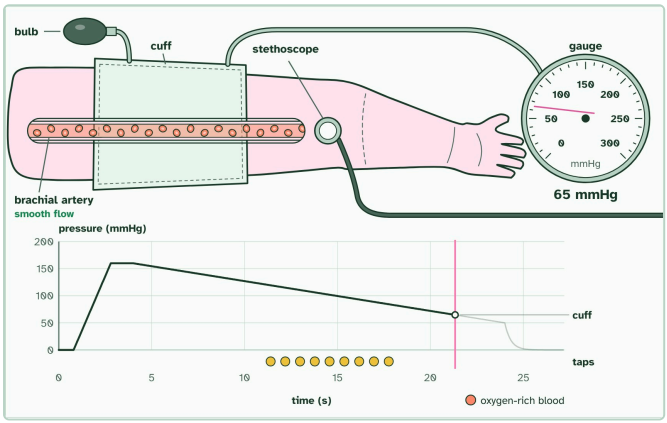
No blood gets past the cuff, so there is nothing to hear below it. The cuff is let down slowly.

2 GAUGE 97 MMHG



A **tapping**: at each beat blood spurts past the cuff, and the stethoscope picks it up.

3 GAUGE 65 MMHG



The tapping has **stopped**: blood flows past the cuff smoothly, all the time.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-2-transport#pressure

PREDICT

Read the figure's first trace, the person at rest. What is their blood pressure?

(A) 80/120 mmHg

(B) 120/80 mmHg

(C) 72 beats a minute

(D) 120/0 mmHg

Decide before you look. Answer on page 83.

PREDICT

Now the second trace, the same person straight after running up three flights of stairs. What has changed?

(A) The systolic pressure has risen a lot, the diastolic little, and the beats come faster

(B) Only the heart rate: each beat now reaches the same pressures as before

(C) Both pressures have fallen, because the blood is spread out to the working muscles

(D) The diastolic pressure has risen above the systolic, since the heart is filling faster

Decide before you look. Answer on page 83.

PREDICT

The cuff is pumped up until no sound at all can be heard in the artery, then let down slowly. The first tapping sound comes when the cuff's pressure has fallen to which pressure?

(A) The diastolic pressure, the lowest in each beat

(B) The systolic pressure, the highest in each beat

(C) The average of the systolic and the diastolic

(D) The pressure of the air outside, at sea level

Decide before you look. Answer on page 83.

WATCH OUT

"The top number is the pulse rate." Both numbers are pressures, in mmHg. "Systolic is the pressure inside the heart." It is the pressure in the arteries; the left ventricle's peak is close to it. And "one reading in class says whether someone's blood pressure is healthy." It takes repeated readings, at rest, to say that.

B3.2.11 HL B3.2.12 HL RELEASE AND REUPTAKE OF TISSUE FLUID IN CAPILLARIES; EXCHANGE OF SUBSTANCES BETWEEN TISSUE FLUID AND CELLS IN TISSUES

21 Tissue fluid: out and *back*

Capillaries do not touch every cell. Between them and the cells is a thin layer of liquid, **tissue fluid**, and everything the blood brings and takes away passes through it. Tissue fluid is made from the blood's own plasma, which leaks out of the capillaries and, mostly, goes back in again.

Out. Blood arrives at the arteriolar end of a capillary at a fairly high pressure, about 35 mmHg, from the arterioles. That pressure forces plasma out through the wall: **pressure filtration**. The proteins and cells stay in.

Exchange. The cells take what they need from the tissue fluid, oxygen and glucose, amino acids and ions, and give up their wastes into it, carbon dioxide above all. Each substance crosses the cell's membrane by diffusion or by transport through proteins, down or against its gradient. (Urea is made only in the liver; from there it travels in the plasma to the kidneys.)

Back. Along the capillary the blood's pressure falls, to about 15 mmHg at the venular end. There the pressure pushing fluid out is lower, and most of the tissue fluid drains back into the capillary, carrying the wastes with it. What does not go back drains into the lymph (chapter 22).

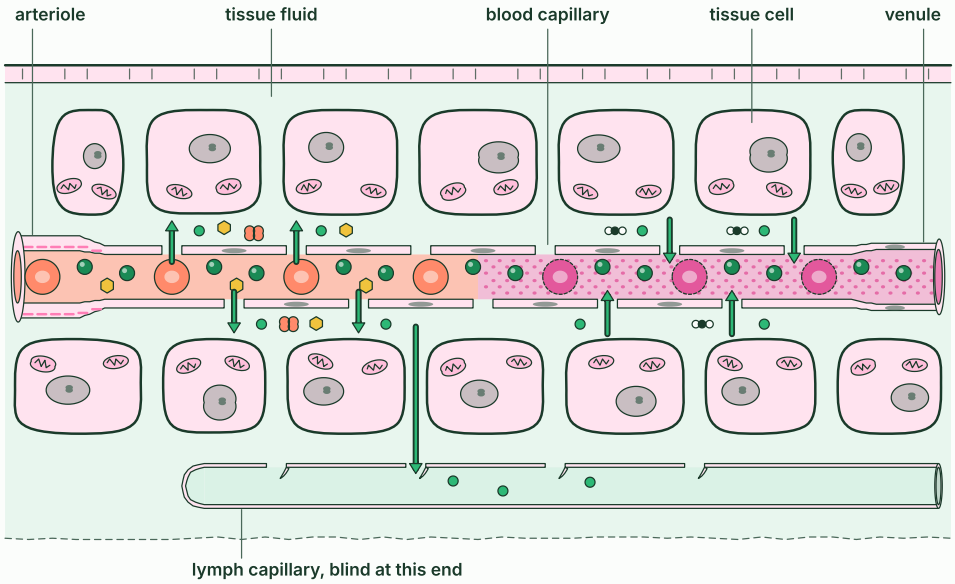
Why does the fluid go back at all, and not just stop? The proteins left in the plasma give it a lower water potential than the tissue fluid, so they draw water back in by osmosis (D2.3). At the arteriolar end the pressure outweighs that pull; at the venular end the pull outweighs the pressure. That goes a little beyond the course, which asks only for the pressures. The pressures are the course's model. Measurements in many tissues show that more of the fluid leaves along the whole capillary than this account says, and that more of it returns by the lymph (the tool has a note on it).

So tissue fluid is plasma without most of its proteins, and with no red blood cells or platelets, although white blood cells can squeeze out into it. Near busy cells it has less oxygen and glucose, and more carbon dioxide, than the plasma arriving. Fill in the table under the tool to compare them.

KEY TERMS

tissue fluid
The liquid that bathes the cells of a tissue, formed from plasma that has passed out of the capillaries.

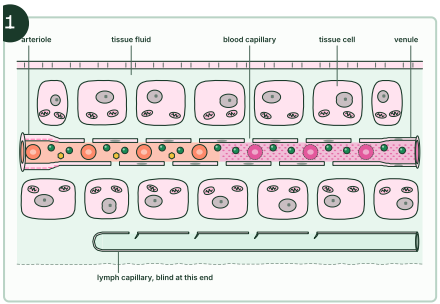
pressure filtration
Fluid forced through a barrier by pressure, the barrier holding back what is too big to pass.



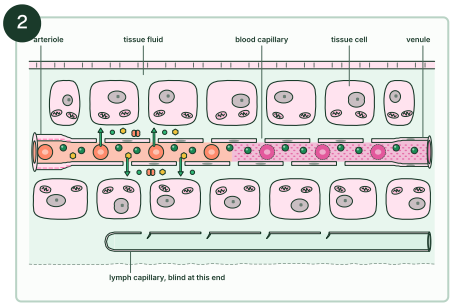
Watch what leaves the capillary and what comes back, change the pressure from the arteriole, then switch to Exchange and see what the cells take and give.

STEP BY STEP

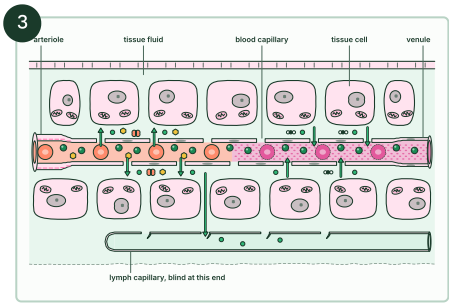
3 STEPS



A capillary bed: blood arrives from the **arteriole** at a high pressure, about 35 mmHg, and runs on through a capillary whose wall is one cell thick. Predict: what will the pressure force out?



Pressure filtration. At the arteriolar end the pressure forces plasma out through the gaps in the wall: water with small molecules such as glucose, oxygen and ions. Proteins and blood cells are too big and stay in. The fluid that leaves is **tissue fluid**.



By the **venular end** the pressure has fallen, and most of the tissue fluid drains back into the capillary, bringing carbon dioxide and other wastes. The rest drains into a **lymph capillary**.

PREDICT

At the arteriolar end of a capillary, the start of it, fluid is forced out into the tissue. What does that fluid carry?

(A) All of the blood, its red and white blood cells included, through the pores

(B) Only water, because the capillary wall is a membrane that lets through only water

(C) Water and small solutes, such as glucose, ions and oxygen, but not the large proteins

(D) Everything but the oxygen, which can only ever leave the blood by diffusion

Decide before you look. Answer on page 83.

WATCH OUT

"Tissue fluid is blood." It is plasma that has left the blood, without its cells or most of its proteins. "Red blood cells leave through the capillary's pores." They are far too big. And "the tissue fluid is pumped back." Nothing pumps it: it drains back where the pressure is lower.

22 Lymph: the *drain*

B3.2.13 HL DRAINAGE OF EXCESS TISSUE FLUID INTO LYMPH DUCTS

Not all of the tissue fluid drains back into the capillaries. The rest, a few litres a day across the whole body, would build up in the tissues if nothing took it away. It is taken up by the **lymphatic system**, and once it is inside a lymph vessel it is called **lymph**.

Lymph capillaries start among the cells and blood capillaries, as blind-ended tubes. Their walls are very thin, a single layer of cells, with gaps between the cells: the edges overlap like flaps, and fluid pushing in from the tissue opens them. Fluid, and molecules too big to get back into a blood capillary, can get in, and the flaps close against them getting out. The lymph capillaries join into larger lymph vessels, which have **valves**, as veins do.

Lymph flows slowly through ever larger vessels to two ducts in the chest, which empty it into the large veins at the base of the neck, just before they reach the heart. So the fluid that left the blood in the tissues gets back to the blood. If drainage fails, fluid collects in the tissues and they swell: **oedema**.

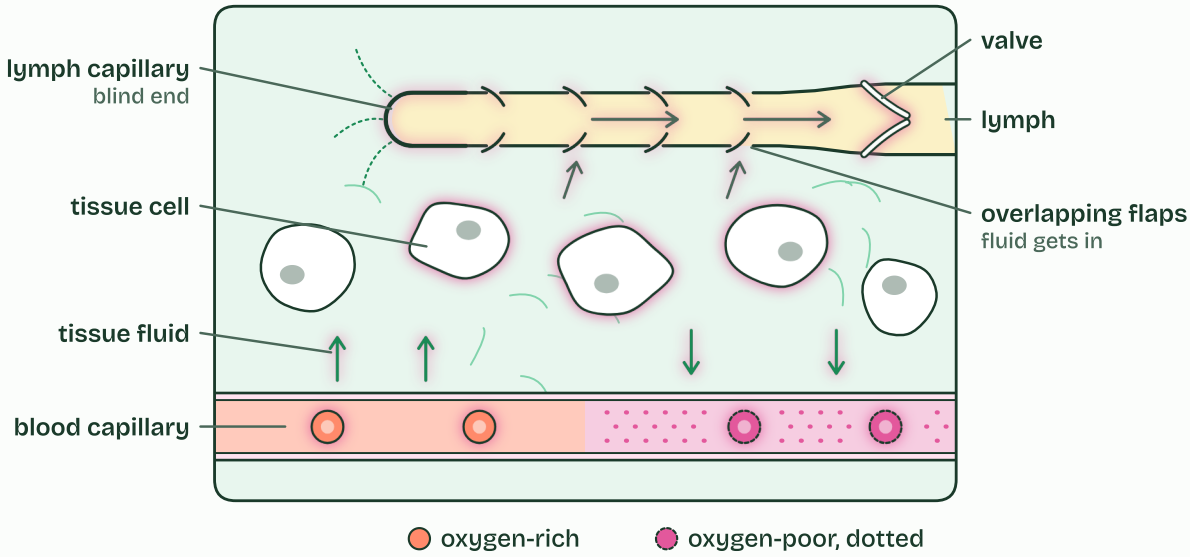
On its way, lymph passes through lymph nodes, where white blood cells check it for pathogens (C3.2), and from the small intestine it carries fat away from digestion. Neither is needed here.

KEY TERMS

lymphatic system
The network of thin-walled vessels that collects excess tissue fluid and returns it to the blood.

lymph
Tissue fluid that has entered the lymph vessels.

oedema
Swelling of a tissue with excess tissue fluid.



Tissue cell A body cell, taking what it needs from the tissue fluid and giving its wastes up to it.

Tissue fluid Fluid that has left the blood capillary bathes the cells. Most of it drains back into the blood capillary; what is left over drains into the lymph capillary.

Blood capillary Oxygen-rich blood arrives from the left. Tissue fluid is forced out near this end, and most of it returns near the other.

Lymph Tissue fluid that has got into a lymph vessel. It has no red blood cells and carries some protein.

Lymph capillary It starts among the cells as a blind-ended tube, closed at this end, so fluid can get in only through its thin wall.

Valve The larger lymph vessels have valves, like veins: they let lymph pass one way only, on towards the chest.

Blood capillary Oxygen-rich blood arrives from the left. Tissue fluid is forced out near this end, and most of it returns near the other.

Lymph Tissue fluid that has got into a lymph vessel. It has no red blood cells and carries some protein.

Overlapping flaps The wall is one layer of thin cells whose edges overlap. Fluid pushing in from the tissue opens the flaps, and pressure from inside closes them, so fluid gets in but not out. Molecules too big to get back into a blood capillary get in here too.

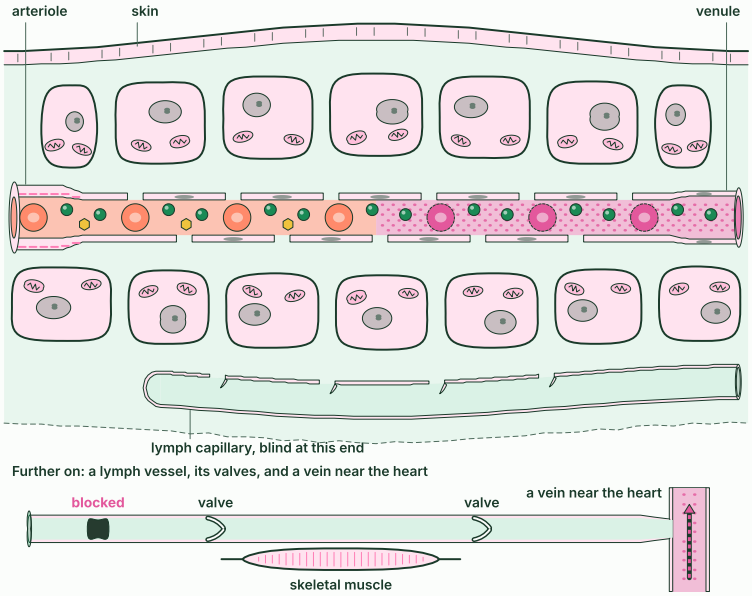
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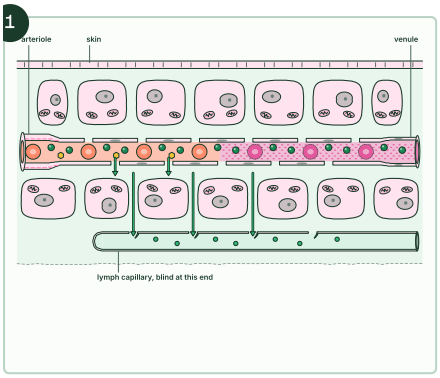
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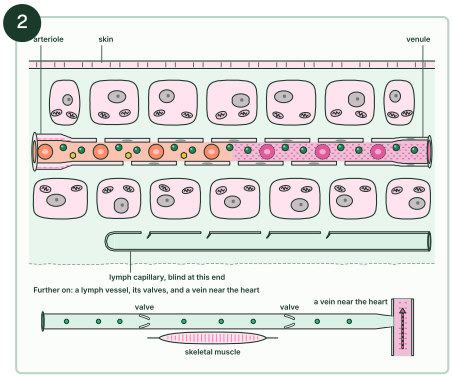


Follow the tissue fluid the capillary does not take back into the lymph. Set the muscles moving, then block the lymph and watch the tissue.

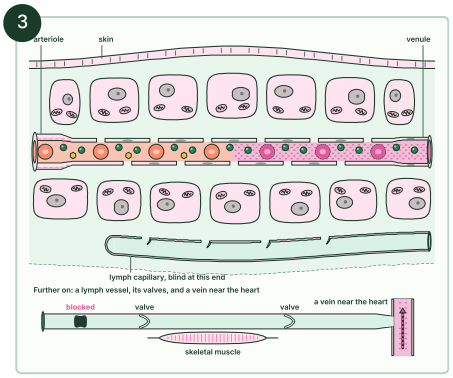
STEP BY STEP
3 STEPS



Not all the tissue fluid goes back into the capillary. The rest drains into a **lymph capillary**: a blind-ended tube with a very thin wall, whose cells overlap leaving **gaps** that let fluid in but not out. Inside it the fluid is called **lymph**.



Lymph capillaries join into larger lymph vessels with **valves**, which let lymph go one way only; the vessels empty into a **vein near the heart**, so the fluid is returned to the blood.



If the lymph is **blocked**, the surplus fluid stays in the tissue, the spaces between the cells widen and the tissue swells: oedema.

PREDICT

Lymph vessels have valves, but there is no heart pumping lymph. What keeps it moving?

(A) The pressure of each heartbeat, carried on through the walls of the capillaries

(B) Gravity, which draws it down from the head and arms towards the feet

(C) The body's muscles squeezing the vessels, with valves that stop it falling back

(D) Diffusion, from where the lymph is more concentrated to where it is less so

Decide before you look. Answer on page 84.

WATCH OUT

"Lymph vessels carry blood." They carry lymph: tissue fluid, with no red cells. "Lymph is pumped by the heart." Muscles squeeze it and valves keep it moving one way. And "lymph is the same as tissue fluid." It is tissue fluid that has entered a lymph vessel.

Key terms

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

active transport 05
Moving a substance across a membrane against its concentration gradient, through a pump protein, using energy from ATP.

adhesion 01
Water molecules sticking to other substances, such as the walls of a xylem vessel.

angina 15
Chest pain on effort, when narrowed coronary arteries cannot bring the heart muscle enough oxygen. It eases with rest.

aortic valve 11
The valve where the left ventricle opens into the aorta. Its three pocket-shaped cusps let blood out and shut against it falling back.

arteries 11
A vessel carrying blood away from the heart, at high pressure.

atheroma 15
A fatty deposit in the wall of an artery, under its lining; also called a plaque.

atherosclerosis 15
The build-up of fatty deposits (atheroma, or plaque) in the walls of arteries, narrowing and hardening them.

atrioventricular valve 09
A valve between an atrium and its ventricle: the tricuspid on the right, the bicuspid (mitral) on the left.

atrium 09
An upper chamber of the heart. It receives blood from the veins and passes it down to the ventricle below.

backflow 12
Blood flowing the wrong way, away from the heart.

cambium 03
A thin layer of dividing cells between the xylem and the phloem of a vascular bundle. Its divisions add new xylem and phloem.

capillaries 10
The narrowest blood vessels, joining arterioles to venules, where substances pass between the blood and the tissues.

capillary action 01
Water creeping along narrow spaces, drawn by adhesion to the surfaces and held together by cohesion. In a cell wall the spaces are the gaps between the cellulose fibres.

cardiac cycle 19
The sequence of events in one heartbeat: the atria contract, then the ventricles, then the whole heart relaxes and refills.

cardiac muscle 18
The muscle of the heart wall: striated, with branched cells joined end to end at intercalated discs.

co-transporter 07
A membrane protein that carries two substances across together. Here, a hydrogen ion flowing in down its gradient carries a sucrose molecule in with it.

cohesion 01
Water molecules sticking to each other, held together by hydrogen bonds.

companion cell 06
A cell beside a sieve tube element, joined to it by many plasmodesmata. It has a nucleus and many mitochondria, and keeps the element alive.

coronary arteries 09
The arteries that branch from the aorta just above the aortic valve and run over the surface of the heart, supplying its muscle.

correlated 16
Two variables are correlated when they tend to change together: both up (positive), or one up as the other goes down (negative).

correlation coefficient 16
A number from minus 1 to plus 1 that measures how closely two variables follow a straight line together. Its sign gives the direction; its size, the strength.

cortex 03
The band of packing cells between the epidermis and the vascular tissue of a stem or root.

diastole 19
The part of the cardiac cycle when a chamber relaxes and fills with blood.

diastolic pressure 20
The lowest pressure in the arteries in each beat, just before the next contraction.

dicotyledonous plant 03
A flowering plant whose seed has two seed leaves (cotyledons). Dicots have broad, net-veined leaves, like a bean or a sunflower.

double circulation 17
A circulation in which the blood passes through the heart twice on each lap: once to the lungs and back (pulmonary), once to the body and back (systemic).

elastic fibres 11
Fibres of the protein elastin in the wall of an artery, which stretch and spring back like a rubber band.

elastic recoil 11
The springing back of a stretched artery wall between beats, which keeps the blood moving and the pressure up.

endothelium 10
The single layer of flattened cells lining every blood vessel. In a capillary it is the whole wall, with a basement membrane under it.

epidemiology 16
The study of how often a disease occurs in different groups of people, and what goes with it.

epidermis 03
The outer layer of cells of a stem, leaf or root.

evaporates 01
Changes from a liquid to a gas at its surface, taking heat with it.

fenestrations 10
Small pores through the endothelial cells of some capillaries, which let fluid and small molecules out and in faster.

fibres 03
Long, narrow cells with thick, lignified walls that strengthen a stem. In many stems a cap of them lies on the outer side of each bundle's phloem.

guttation 05
Drops of water pushed out at the edges of leaves by root pressure, usually on humid nights and early mornings.

incidence 16
The number of new cases of a disease in a population in a given time, often per 100 000 people a year.

intercalated discs 18
The joins between cardiac muscle cells, with gap junctions through which the signal passes from one cell to the next.

left ventricle 11
The lower chamber on the left of the heart, its main pump: it pushes oxygen-rich blood out into the aorta and round the body.

lignin 02
A hard, strong polymer laid down in the walls of xylem vessels. Wood is mostly lignified xylem.

lumen 02
The space inside a tube, such as a xylem vessel or a blood vessel.

lymph 22
Tissue fluid that has entered the lymph vessels.

lymphatic system 22
The network of thin-walled vessels that collects excess tissue fluid and returns it to the blood.

mass flow 07
The flow of a whole fluid, solvent and solutes together, from high pressure to low, as water flows along a hose.

micrograph 13
A photograph taken through a microscope. Here, a thin slice of tissue, stained so that its layers show.

myocardial infarction 15
The death of part of the heart muscle when its blood supply is blocked: a heart attack.

myogenic 18
Starting its own contractions, with no signal from a nerve.

oedema 22
Swelling of a tissue with excess tissue fluid.

osmosis 05
The net movement of water across a partially permeable membrane, from a lower solute concentration to a higher one.

pith 03
The packing cells in the centre of a stem, which store food.

pits 02
Gaps in the lignin of a xylem vessel's wall, where only the thin primary wall (the original cellulose wall) is left, so water can pass through sideways.

plan diagram 03
A drawing of a section that shows where each tissue is, as outlines only, with no cells drawn.

plasmodesmata 06
Narrow channels through the walls between two plant cells, which join the cytoplasm of one to the other.

pocket valves 12
Flaps in a vein, shaped like pockets, that let blood through towards the heart and shut against it flowing back.

pressure filtration 21
Fluid forced through a barrier by pressure, the barrier holding back what is too big to pass.

pulse 14
The wave of stretch that runs along the arteries with each beat of the heart, felt as a tap where an artery is near the skin.

pulse oximeter 14
A clip on a fingertip that shines light through it. The pulsing blood absorbs more light with each beat, so the clip counts the beats (and estimates how much oxygen the blood carries).

root hair 04
A long, thin outgrowth of one epidermal cell of a root. It reaches between soil particles and takes up water and mineral ions.

root pressure 05
A positive pressure in the xylem, made when root cells pump mineral ions into it and water follows by osmosis. It pushes water up when transpiration is too slow to pull it.

sap 06
Phloem sap: the solution carried in the phloem, mostly sucrose, with amino acids and other substances, in water (the xylem's watery solution of mineral ions is xylem sap).

semilunar valve 09
A valve of three pocket-shaped cusps where a ventricle opens into its artery: the pulmonary valve and the aortic valve.

septum 09
The wall of muscle between the left and right sides of the heart.

sieve plates 06
The end wall between two sieve tube elements, perforated with pores so that sap can flow through.

sieve tube elements 06
The living cells, with no nucleus and little cytoplasm, that join end to end to make a sieve tube in the phloem.

single circulation 17
A circulation in which the blood passes through the heart once on each complete lap of the body, as in a bony fish.

sink 06
A part of a plant that takes sugars out of the phloem to use or store them, such as a root, a growing tip, a fruit or a seed.

sinoatrial (SA) node 18
The sinoatrial node: a patch of special cardiac muscle cells in the wall of the right atrium that starts each heartbeat; the pacemaker.

source 06
A part of a plant that makes or releases sugars and loads them into the phloem, such as a leaf in the light.

stylet 08
An aphid's piercing mouthpart, as fine as a hair. The aphid pushes it into a plant until the tip is inside one sieve tube.

systole 19
The part of the cardiac cycle when a chamber contracts.

systolic pressure 20
The highest pressure in the arteries in each beat, as the left ventricle contracts.

tension 01
A pull on a liquid, so that its pressure is below zero. In the xylem this is a negative pressure potential.

thrombus 15
A blood clot formed inside a blood vessel.

tissue fluid 21
The liquid that bathes the cells of a tissue, formed from plasma that has passed out of the capillaries.

translocation 06
The movement of sap through the phloem, from sources to sinks.

transpiration 01
The loss of water vapour from a plant, mostly from its leaves through the stomata.

transpiration stream 01
The flow of water from the soil, through the roots, up the xylem and out of the leaves as vapour.

vascular bundles 03
A strand of xylem and phloem, with a thin layer of dividing cells (the cambium) between them, running along a stem.

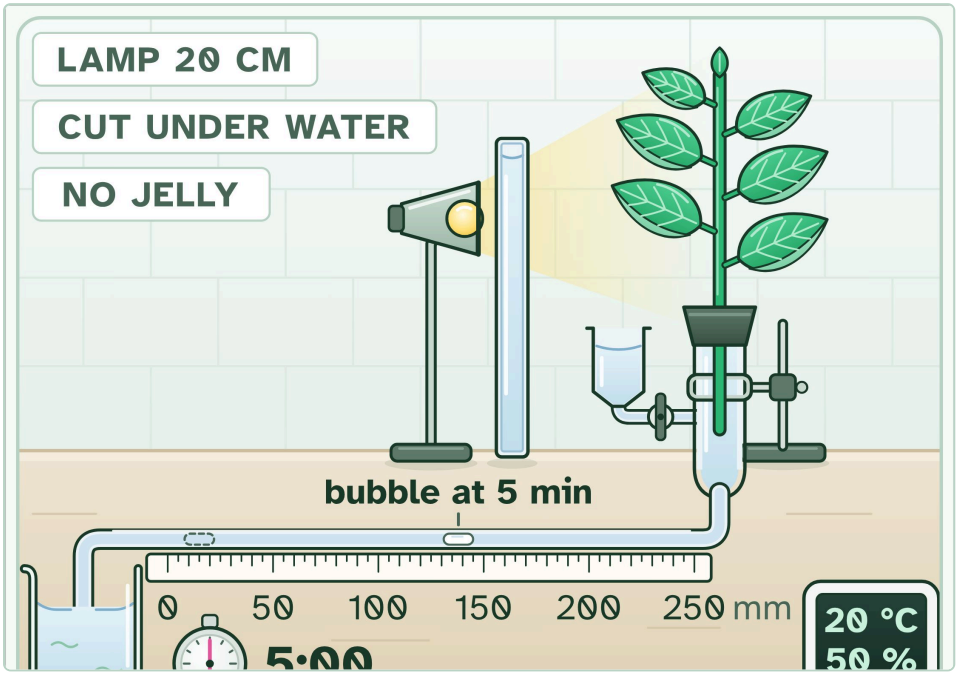
veins 12
A vessel carrying blood back to the heart, at low pressure.

ventricle 09
A lower chamber of the heart, which pumps blood out into an artery.

xylem vessel 02
A long tube in the xylem, made from a column of cells joined end to end that died once their walls were built.

Dry lab: *What drives the water?*

A leafy shoot sealed into a potometer, with an air bubble that creeps along a scale as the shoot takes up water. Strip its leaves, coat them in petroleum jelly, cut the shoot in air or ring its bark, and find out where the pull on the water comes from.



Run it online: change the variables, run the trials, and the table and graph fill in as you go.
`biologybybradford.com/guides/ib-biology-b3-2-transport#lab`

Your question

Where does the pull on the water in a shoot come from, and which part of the stem carries the water? Change one thing about the shoot at a time and see what happens to the rate at which it takes up water.

What you can change

The leaves (all on, half removed, all removed), petroleum jelly on the leaves (none, upper surfaces, lower surfaces, both), how the shoot was cut (under water or in air) and a ring of bark (left whole, or removed). Each run is a fresh shoot, matched to the others: change one thing at a time, and compare it with the untreated shoot, your control.

What to record

For each run: the settings, and the bubble's position on the scale against time. Work out the rate as a distance a minute, then as a volume a minute. Repeat each set-up at least three times: the runs scatter, as real shoots do. The coach under the bench helps you plan, process and evaluate.

Find out

- **Where does the pull come from?** Run a shoot with all its leaves, one with half of them removed and one with none. Write down what you expect before each run. How does the rate change as the leaves go?
- **Which surface loses the water?** Coat the leaves of one shoot with petroleum jelly on their upper surfaces, another's on the lower surfaces, and a third's on both. Which coat cuts the rate most, and what does that tell you about where the stomata are?
- **What does air do to the xylem?** Compare a shoot cut under water with one cut in air before it was fitted. How much less does the second shoot take up?
- **Is the water in the bark?** Remove a ring of bark below the leaves of a shoot and run it. Compare its rate with the rate of a shoot left whole.
- **Keep it fair.** Every run is a fresh shoot, chosen to match the others. The untreated shoot (all its leaves, no jelly, cut under water, its bark whole) is the control for each comparison.

Record

- For every run: the settings (the leaves, the petroleum jelly, how the shoot was cut, the bark) and the bubble's position on the scale each time you read it.
- Once a shoot is fitted, wait before you start timing: it takes a few minutes to settle at a steady rate.
- The rate as the distance the bubble moves a minute, then as a volume a minute: the distance times the capillary's cross-sectional area (πr^2, with r half the bore).
- Repeat each set-up at least three times, and give the mean and the standard deviation. No two runs match, just as no two real shoots do.
- A potometer measures the water a shoot takes up, not the water it loses. Most of it is lost again by transpiration, but a little stays in the shoot, so say "uptake" when you write up your results.

Your question Where does the pull on the water in a shoot come from, and which part of the stem carries the water? Change one thing about the shoot at a time and see what happens to the rate at which it takes up water.**What you can change**The leaves (all on, half removed, all removed), petroleum jelly on the leaves (none, upper surfaces, lower surfaces, both), how the shoot was cut (under water or in air) and a ring of bark (left whole, or removed). Each run is a fresh shoot, matched to the others: change one thing at a time, and compare it with the untreated shoot, your control.**What to record**For each run: the settings, and the bubble's position on the scale against time. Work out the rate as a distance a minute, then as a volume a minute. Repeat each set-up at least three times: the runs scatter, as real shoots do. The coach under the bench helps you plan, process and evaluate.

Back to the xylem

Use your results to explain where the pull that draws water up a shoot comes from, and how the xylem carries the water.

QUESTIONS ON THE LAB

QUESTION 1

A shoot with every leaf taken off goes into the potometer. The bubble barely moves. What does this show?

(A) The stem pumps the water up, and the pump stops working once the leaves are taken off

(B) The pull on the water comes from the leaves, as water evaporates from them

(C) The cut ends of the vessels close up when the leaves are removed, which blocks the flow

(D) A shoot with no leaves has no living cells left to drive the water up by active transport

Answer on page 84.

QUESTION 2

One shoot is cut in air before it is fitted to the potometer; another is cut under water. The shoot cut in air takes up much less. Why?

(A) The air dries the cut end, so its cells shrink and squeeze the vessels shut all along the stem

(B) Cutting it in air lets sap leak out of the phloem, which leaves too little water for the xylem

(C) Air gets into the cut vessels and breaks their columns of water, so the pull cannot lift them

(D) The cut end cools in the air, and cold water is too thick to move up such narrow vessels

Answer on page 84.

QUESTION 3

A ring of bark is removed from the stem below the leaves. The uptake hardly changes. Why not?

(A) The phloem in the bark carries water too, but a narrow ring is too short to stop it flowing

(B) Water goes round the ring through the pith instead, passing from cell to cell by osmosis

(C) The ring does stop the water, but the leaves make up for it by opening more of their stomata

(D) Water travels up in the xylem, which is in the wood inside the bark, not in the bark itself

Answer on page 84.

WRITE IT UP AS AN INVESTIGATION

Your results from this dry lab can be written up the way an IB scientific investigation is: four criteria, each worth 6 marks. Tick each line as your write-up does it. The coach on the page checks these as you go; it never gives a mark.

1 Research design

A focused question set in its biology; your choices of what to measure, how, over what range and how often, explained rather than listed; what you kept the same and how; safety, ethics and the environment; a method someone else could follow and repeat.

- [ ] My question names what I changed.
- [ ] It gives the range I used, with units.
- [ ] It names what I measured and how.
- [ ] It names the organism or system.
- [ ] My background explains, with the biology, why the two should be linked.
- [ ] I cite my sources, and each reference can be traced.
- [ ] If I give a hypothesis, it predicts and explains.
- [ ] Every variable has its How, Why and Units.
- [ ] For each thing kept the same, I say how I kept it so.
- [ ] I list at least three things I kept the same.
- [ ] I name the apparatus that set what I changed, and the instrument that measured.
- [ ] I test enough values.
- [ ] My values spread wide enough.
- [ ] I run at least three trials at every value.
- [ ] I run a control.
- [ ] I explain why these values, this many and this often.
- [ ] Someone else could repeat my method.
- [ ] I deal with safety, ethics and the environment.

2 Data analysis

Raw data recorded clearly, with titles, units, uncertainties and the same decimal places down a column; what you saw as well as what you measured; processing that suits the question, shown with a worked example; the spread shown; a graph a reader can trust.

- [ ] Each table has a numbered title that says what it shows.
- [ ] Every heading has its quantity and its unit.
- [ ] Every raw data heading has its uncertainty.
- [ ] Each uncertainty is realistic for the instrument.
- [ ] Each uncertainty has the same decimal places as its readings.
- [ ] I record what I saw as well as what I measured.
- [ ] I show one worked example of my processing, and it is right.
- [ ] I say why I left out any trial.
- [ ] My error bars show a spread my repeats can support.
- [ ] My graph has a numbered title and labelled axes with units.
- [ ] I say what the error bars show.
- [ ] A straight line, if I draw one, has its R^2.
- [ ] A statistical test, if I run one, has its hypotheses and suits the data.

3 Conclusion

Your question answered from the processed data, with numbers quoted and the spread taken into account; the biology that explains the pattern; a comparison with published work; no claim bigger than the data.

- [ ] I answer my question in a sentence, naming both variables.
- [ ] I quote my processed numbers.
- [ ] I say how sure the spread lets me be.
- [ ] I say whether my hypothesis is supported.
- [ ] I explain the pattern with biology.
- [ ] I compare my result with published work, and cite it.
- [ ] I claim no more than my data show.

4 Evaluation

Weaknesses and limitations of this method (not slips in carrying it out), with evidence from your own data, the effect each had on the results, which mattered most and why, and a realistic improvement for each.

- [ ] I give at least three weaknesses or limitations.
- [ ] Every row is filled in.
- [ ] No slips in carrying it out: weaknesses of the method itself.
- [ ] Each improvement is specific: which instrument, how many, what changes.
- [ ] Each effect says what it did to my data.
- [ ] At least two rows point to evidence in my own data.
- [ ] At least one limitation: what this experiment cannot tell me.
- [ ] I say which mattered most, and why.
- [ ] I deal with what stands out in my data.
- [ ] My improvements improve this investigation, not a new one.

Variables

Variable	How?	Why?	Units
Independent: leaves on the shoot			
Dependent: rate of water uptake			
Kept the same: no petroleum jelly on the leaves			
Kept the same: cutting the shoot under water			
Kept the same: the bark left whole			
Kept the same: size and kind of shoot			
Kept the same: distance from the lamp			
Kept the same: still air (no fan)			
Kept the same: temperature of the air			
Kept the same: humidity of the air			
Kept the same: capillary bore			
Kept the same: time left to settle before reading			
Kept the same: length of the run			

Evaluation

Weakness or limitation	Which?	Evidence in my data	Effect on my results	Improvement

Data generated with the potometer dry lab, biologybybradford.com (a simulation). These checks catch what is missing. They cannot judge how good it is: that is what your teacher does.

Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on B3.2 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=B3.2&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 An air bubble gets into one xylem vessel. What happens to the water in that vessel?

C Below the bubble it stops, because cohesion cannot pull across a gap

Below the bubble the water stops. The pull from the leaf passes down the column only through the hydrogen bonds between molecules, and they cannot pull across a gap of air. The water above the bubble is still drawn up and out, so that vessel stops carrying water. The plant survives it: water goes round the blocked vessel through the pits in the walls (chapter 2). The film below lets you switch the bubble on.

02 A plant cannot make lignin. On a hot, windy day, what happens to its xylem vessels?

B They are pulled inwards and collapse: the water in them is under tension

They collapse inwards. A hot, windy day means fast transpiration, so the water in the xylem is under strong tension, pulling on the walls. Without lignin to stiffen them, the walls cave in, the tube closes and the water stops moving. Lignin is what lets a vessel carry water under tension.

03 A cut stem stands for an hour in water with a red dye in it, then is cut across. Where is the red?

D In a ring of spots near the edge: the xylem of each bundle

In a ring of spots near the edge. The dye travels with the water, and water travels up the stem in the xylem, on the inner side of each vascular bundle. The bundles form a ring near the edge, so the red shows as a ring of dots. A celery stalk in coloured water shows the same thing; it is a leaf stalk, not a stem, but its bundles also sit near the edge.

04 A seedling is moved to a new pot, and most of its root hairs are torn off. What happens over the next day?

A It wilts: with far less surface touching the soil water, uptake falls behind loss

It wilts. Root hairs give a root most of its surface for taking up water and mineral ions. With most of them torn off, uptake falls below what the leaves lose until new hairs grow, which is why a transplant is watered well and kept out of strong sun for a few days.

05 A grapevine is cut back in early spring, before its leaves open. What happens at the cut stump?

B Sap oozes out of the cut, pushed up from the roots

Sap oozes out, and can go on oozing for days. With no leaves, nothing is pulling on the xylem. The roots are pumping ions in, water follows, and root pressure pushes it out of the cut. Gardeners call it bleeding, and birch trees bleed in spring the same way. In summer, with the leaves transpiring, the same cut would draw air in instead, because the column would be under tension.

06 Why do companion cells have so many mitochondria?

D To make the ATP that actively loads sucrose into the sieve tubes

Loading sucrose into a sieve tube is active transport, which needs ATP, and the companion cell's mitochondria make it by aerobic respiration. The sieve tube element has too few organelles to do it for itself. The sieve plates pump nothing: they are perforated end walls that let the sap through.

07 The fruit on a branch is picked off. What happens to the flow in the sieve tube that fed it?

C It slows, then stops: with no unloading, that end's pressure rises

It slows, then stops. With no fruit taking sucrose out, sucrose builds up at that end of the tube, water stops leaving, and the pressure there rises until it matches the source's. The flow depends on the difference in pressure between the ends: with no difference, nothing flows to that end, and the sap goes to the sinks that are left.

08 Use the arrival times in the figure. How fast did the label travel down the stem?

A 1.0 metre an hour

1.0 metre an hour. Use the difference between two stumps: from the first to the last, the label covered 0.8 − 0.2 = 0.6 m in 58 − 22 = 36 minutes. 0.6 ÷ 36 = 0.017 m a minute, and × 60 = 1.0 m an hour. One stump on its own gives too low a speed (0.8 m in 58 minutes is 0.83 m an hour), because its time includes the 10 minutes or so before the label entered the stem. 0.017 is the speed per minute, not per hour, and 60 is the minutes per metre, turned upside down.

08 Why does the label reach a stylet further from the leaf later?

B It is carried along in the sap at a steady speed, so further takes longer

The labelled sucrose is carried along by mass flow at a fairly steady speed, so each extra 0.3 m takes the same extra 18 minutes, and the points fall on a straight line. If the label spread by diffusion, the time would grow with the square of the distance: twice as far would take about four times as long. And carbon-14 decays far too slowly (its half-life is about 5,700 years) to fade on the way.

08 A ring of bark is removed between the leaf and the lowest stylet. The label reaches the stylets above the ring, but never the one below it. What does this show?

D That the label travels in the phloem, which is in the bark

The phloem is in the bark, so taking off a ring of bark takes away the phloem, and nothing labelled can pass it. The xylem, the wood inside, is untouched, so if the label travelled in the xylem it would still arrive. It is the ringing result again, with a label to make it visible.

09 Both ventricles pump the same volume of blood at each beat. Which one has the thicker wall, and why?

B The left, because it pumps blood at high pressure all round the body

The left. It drives blood all round the body, through every organ, so it must make a much higher pressure, and a thicker wall of muscle squeezes harder. The right ventricle sends blood only to the lungs next door, and their thin capillaries would be damaged by a high pressure. Step 5 of the figure draws the walls to scale: the left one is about three times as thick as the right.

10 Blood leaves the heart fast. How fast is it moving by the time it reaches the capillaries, and why does that matter?

B Far slower: together the capillaries are a much wider channel, so there is time to exchange

Far slower, hundreds of times slower than in the aorta. Each capillary is narrow, but there are so many of them that their lumens added together are a far wider channel than the artery that feeds them, and the same volume of blood a second spread over a wider channel moves more slowly. Slow blood spends longer next to the cells, so there is time for oxygen, glucose and wastes to diffuse. Step 5 of the figure compares the speeds.

11 Between heartbeats the ventricles relax and the aortic valve is shut, yet the blood in your arteries keeps flowing on. What keeps it moving?

A The artery wall, stretched by the last surge, springs back and squeezes it on

The wall springs back. Each surge stretches the elastic fibres in the artery's wall; between beats they recoil, squeezing the blood on. So the flow does not stop between beats and the pressure stays up, at about 80 mmHg in the aorta, instead of falling to zero. Arteries have no valves along them and their muscle does not pump. The film below plays it: Beat after beat shows the wall springing back.

12 You are walking. Each time your calf muscle contracts, what happens to the blood in a vein that runs through it?

B It is squeezed towards the heart, and valves stop it dropping back afterwards

It is squeezed towards the heart. The vein's wall is thin and flexible, so the contracting muscle squashes it. Blood is pushed both ways, but the valve below shuts against it, so it can go only up. When the muscle relaxes, the valve above shuts and the blood cannot fall back. Walking pumps the blood home a step at a time. The film below runs it.

13 Two vessels in a micrograph are about the same width overall. Which single measurement best tells you which one is the artery?

C **The thickness of each vessel's wall, compared with the width of its lumen**

The wall's thickness compared with the width of the lumen. An artery has a thick wall round a narrow lumen; a vein a thin wall round a wide lumen. Overall width does not help when the two are the same size, and the colours in a micrograph come from the stain, not from the blood. A round lumen is a clue, but cutting and fixing can squash either vessel, so it is not proof on its own.

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14 You count your pulse for 15 seconds and get 18 beats. A friend counts theirs for a whole minute and gets 68. Whose estimate of the resting rate is likely to be more precise, and why?

D **Your friend's, because a beat miscounted in 15 seconds is an error of 4 a minute**

Your friend's. Your 18 beats in 15 seconds become 72 a minute only by multiplying by 4, so a beat too many or too few makes the rate 4 out. Counted over a whole minute, the same slip is 1 a minute. The pulse is the heart rate: each tap is one beat. A longer count is more precise, but the rate can drift during it, so repeat it and take the mean.

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14 A volunteer steps up and down for a few minutes. What happens to their pulse straight afterwards, and over the next few minutes?

B **It is well above resting, then falls back, fastest at first, over minutes**

It is well above resting, then falls back, fastest at first. During the exercise the muscles respire faster, so they need more oxygen and make more carbon dioxide, and the heart beats faster to carry them. Afterwards the rate falls as the muscles catch up, quickly at first and then more slowly. A fitter volunteer usually rises less and recovers faster. Recovery is measured from the readings each minute until the rate is back near resting.

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14 You want to compare counting by fingertip with a pulse oximeter. What makes the comparison fair?

C **Take both on the same person at the same time, at rest, and repeat each reading**

Measure the same person at the same moment, sitting still, with both methods, and repeat the pair several times. Sitting still matters for the meter too: it loses the signal when the person moves. Then any difference is the method's, not the person's or the time's. A different volunteer, or readings at different times, would mix the method up with everything that changes the pulse, which is a lot. Compare the means, and how widely each method's repeats spread.

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15 A man's coronary artery is narrowed by about two thirds. At rest he feels nothing, but climbing the stairs gives him chest pain. Why?

C **On the stairs his heart muscle needs far more oxygen than the narrow artery brings**

At rest the narrowed artery still brings enough blood for the muscle's needs. Climbing stairs, the heart beats faster and harder, so its muscle needs much more oxygen, and the narrowed artery cannot carry enough. Short of oxygen, that patch of muscle hurts: this is angina. It eases with rest, when the demand falls back. The heart muscle is fed by the coronary arteries, not by the blood in its chambers.

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16 Across 30 seaside towns, ice-cream sales and cases of sunburn rise and fall together through the year. The correlation coefficient is 0.9. What can you conclude?

C **They go together, but something else could drive both**

They go together, strongly: 0.9 is close to the maximum of 1. But that does not show that either one causes the other. Hot, sunny weather sends up both, so the two rise and fall together with no link between them at all. A third factor like this is a confounding variable, and it is the first thing to look for in any correlation.

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17 On one complete lap round the body, how many times does the blood pass through the heart in a bony fish, and in a mammal?

C **Once in a fish and twice in a mammal**

Once in a fish, twice in a mammal. The fish's heart pumps blood to the gills, and from the gills it flows straight on round the body before it comes back. A mammal's blood goes from the right side of the heart to the lungs, back to the left side, out round the body and back to the right side: two passes. Four chambers do not mean four passes: on each pass the blood goes through one atrium and one ventricle.

18 A heart is taken out of an animal and kept in a warm salt solution with oxygen bubbled through it. It goes on beating for some time. What does this show?

D **The signal for each beat starts inside the heart itself, not in the brain or nerves**

The beat starts in the heart itself. Cut off from every nerve, the heart still beats, so its signal cannot come from the brain. Cardiac muscle is myogenic: the beat begins in the muscle. Nerves and hormones can speed it up or slow it down (C3.1), but they do not start it. The salt solution and the oxygen only keep the cells alive.

19 The left ventricle starts to contract. A moment later the aortic valve opens. What opens it?

A **The pressure in the ventricle rises above the aorta's pressure**

Pressure. As the ventricle contracts its pressure rises, and once it is higher than the pressure in the aorta, the blood pushes the valve's cusps apart. Valves have no muscle and no nerves; the SA node's signal only makes the muscle of the chambers contract. Every valve in the cycle works this way, as the rest of the chapter shows.

20 Read the figure's first trace, the person at rest. What is their blood pressure?

B **120/80 mmHg**

120/80 mmHg: the peaks reach 120 (systolic) and the troughs sink to 80 (diastolic), written systolic first. The pressure never falls to 0 between beats, because the arteries' elastic walls keep it up. A rate in beats a minute is the pulse, which you would count from the number of peaks in a minute, not read off the pressure axis.

20 Now the second trace, the same person straight after running up three flights of stairs. What has changed?

A **The systolic pressure has risen a lot, the diastolic little, and the beats come faster**

The peaks are higher, at about 160 mmHg, while the troughs have not moved, at about 80, and there are more beats in the same time: six peaks in the 3 seconds against four, a beat every half second against one every 0.83 seconds, so about 120 a minute against 72. In exercise the heart beats harder and faster, so systolic pressure rises; the arterioles in the working muscles widen and let blood through more easily (C3.1), so the diastolic pressure stays about the same. Within minutes of stopping it falls back.

20 The cuff is pumped up until no sound at all can be heard in the artery, then let down slowly. The first tapping sound comes when the cuff's pressure has fallen to which pressure?

B **The systolic pressure, the highest in each beat**

The systolic pressure. While the cuff squeezes harder than the artery's highest pressure, the artery stays shut and silent. As the cuff falls just below the peak, blood spurts through at the top of each beat, and each spurt taps. The taps go on until the cuff falls below the diastolic pressure; then the artery stays open all through the beat, the flow is smooth, and the sounds stop. So the first tap is systolic and the last is diastolic.

21 At the arteriolar end of a capillary, the start of it, fluid is forced out into the tissue. What does that fluid carry?

C **Water and small solutes, such as glucose, ions and oxygen, but not the large proteins**

Water and the small molecules dissolved in it: glucose, amino acids, ions, oxygen, hormones. The gaps between the capillary's cells, and its pores, are big enough for these but too small for the plasma proteins and the red blood cells, which stay behind in the blood. Only the wall's gaps sort them, by size: pressure pushes the fluid through.

22 Lymph vessels have valves, but there is no heart pumping lymph. What keeps it moving?

C **The body's muscles squeezing the vessels, with valves that stop it falling back**

Squeezing. As you move, your skeletal muscles squeeze the thin-walled lymph vessels, as they squeeze veins, and the valves let the lymph go one way only, towards the chest. Breathing helps, and the walls of the larger lymph vessels contract in rhythm too, which in some tissues does much of the work. That is why the lymph moves most when you move: keep still for hours, as on a long flight, and the ankles swell. The tool below shows it.

QUESTIONS ON THE DRY LAB

Q1 A shoot with every leaf taken off goes into the potometer. The bubble barely moves. What does this show?

B **The pull on the water comes from the leaves, as water evaporates from them**

The pull comes from the leaves. Water evaporates from the wet cell walls inside each leaf and diffuses out through the stomata, and that loss is what pulls the column of water up the xylem. With the leaves gone almost nothing pulls, so the bubble nearly stops. The stem has no pump, and a cut shoot has no roots to push, so the pull must come from the top.

Q2 One shoot is cut in air before it is fitted to the potometer; another is cut under water. The shoot cut in air takes up much less. Why?

C **Air gets into the cut vessels and breaks their columns of water, so the pull cannot lift them**

Air is drawn into the cut ends of the xylem vessels and breaks the columns of water in them. Cohesion holds a column together only while it is unbroken, so the tension from the leaves can no longer pull water up those vessels, and uptake falls. Cutting the shoot under water, and keeping the cut end wet while it is fitted, keeps the air out. That is why a potometer's shoot is always cut under water.

Q3 A ring of bark is removed from the stem below the leaves. The uptake hardly changes. Why not?

D **Water travels up in the xylem, which is in the wood inside the bark, not in the bark itself**

Ringing takes off the bark, and the phloem with it, but the xylem is in the wood inside the ring and is left whole. Water goes up in the xylem, so uptake carries on. What a ring does stop is sugar travelling down in the phloem, which is why a ringed tree dies slowly as its roots starve (chapter 8, higher level).

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.