

Cambridge AS & A Level · Biology 9700 · Notes

Transport in plants

AS

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Read first: [Cell structure](#), [Biological molecules](#), [Cell membranes and transport](#)

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What you need to know

By the end of this topic you should be able to:

Structure of transport tissues

1. **Draw plan diagrams** of transverse sections (TS) of the stems, roots and leaves of herbaceous dicotyledonous plants, from microscope slides and photomicrographs.
2. **Describe where the xylem and phloem are** in transverse sections of these stems, roots and leaves.
3. **Draw and label xylem vessel elements, phloem sieve tube elements and companion cells**, from slides, photomicrographs and electron micrographs.
4. **Relate the structure** of xylem vessel elements, sieve tube elements and companion cells **to their jobs**.

Transport mechanisms

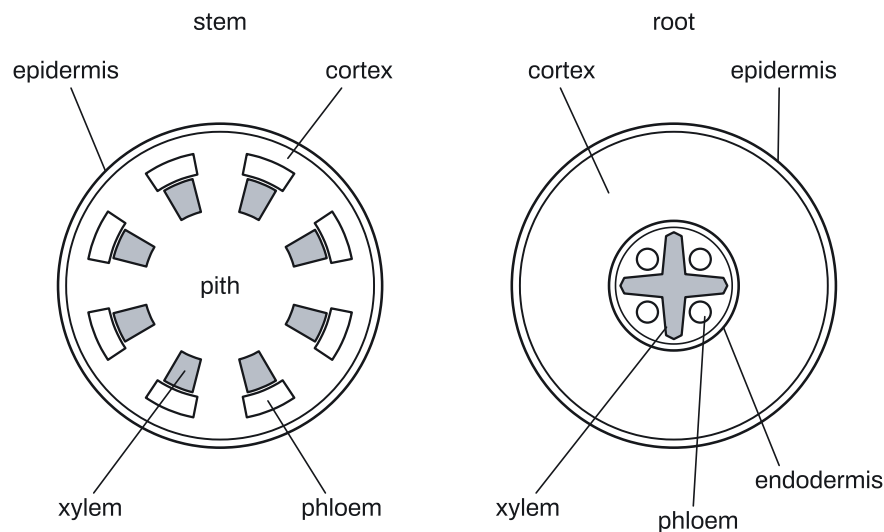
5. **State that some mineral ions and organic compounds are carried around the plant dissolved in water.**
6. **Describe how water gets from the soil to the xylem** by two routes: the **apoplast pathway** (mention cellulose and lignin) and the **symplast pathway** (mention the endodermis, the Casparian strip and suberin).
7. **Explain transpiration**: water evaporates from the surfaces inside the leaf, then the water vapour diffuses out into the air.
8. **Explain how hydrogen bonds between water molecules move water up the xylem**: cohesion and tension in the transpiration pull, and adhesion to the cellulose in cell walls.
9. **Make annotated drawings of TS leaves of xerophytes** (plants of dry places) to explain how they are adapted to cut water loss by transpiration.
10. **State that assimilates dissolved in water, such as sucrose and amino acids, move from sources to sinks in phloem sieve tubes.**
11. **Explain how companion cells load assimilates into sieve tubes**, using proton pumps and cotransporter proteins.
12. **Explain mass flow in phloem sieve tubes** down a hydrostatic pressure gradient from source to sink.

Understand it

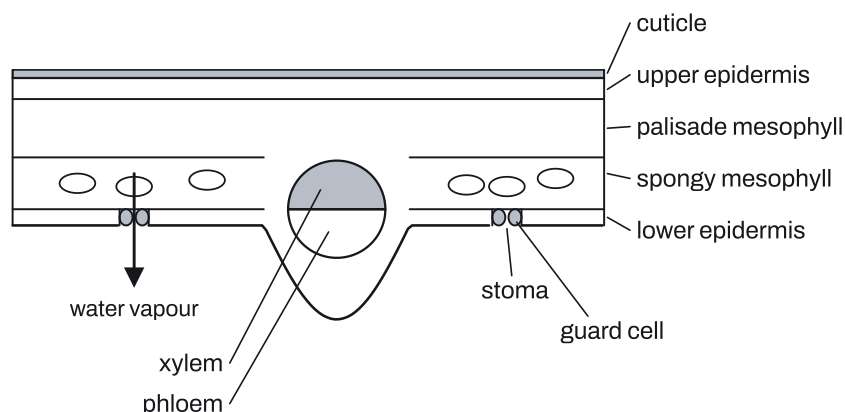
Two tissues carry substances round a plant: **xylem** carries water and mineral ions up from the roots, and **phloem** carries **assimilates** (the substances the plant has made, mainly sucrose and amino acids) from where they are made or stored to where they are used. In both tissues the substances travel **dissolved in water**, because water is a good solvent and the whole liquid flows together (**mass flow**).

Where the xylem and phloem are

Xylem and phloem run side by side in **vascular bundles** (in a root, in one central **vascular cylinder**). Their position differs in each organ, and questions often ask you to pick the organ from the layout.



- **Stem:** vascular bundles in a **ring** near the outside, around a central **pith**. In each bundle the **phloem is on the outside** and the **xylem on the inside**, with a thin layer of dividing cells (cambium) between them. There may be a cap of thick-walled supporting cells (sclerenchyma) outside the phloem.
- **Root:** the xylem and phloem are **in the centre**, in the vascular cylinder. The **xylem forms a star** (often with three or four arms) and the **phloem lies in patches between the arms**. Around the cylinder is a single layer of cells, the **endodermis**, and outside that a wide **cortex**.
- **Leaf:** the xylem and phloem are in the **midrib** and in the smaller veins. In each vein the **xylem is on the upper side** (nearer the upper epidermis) and the **phloem on the lower side**.



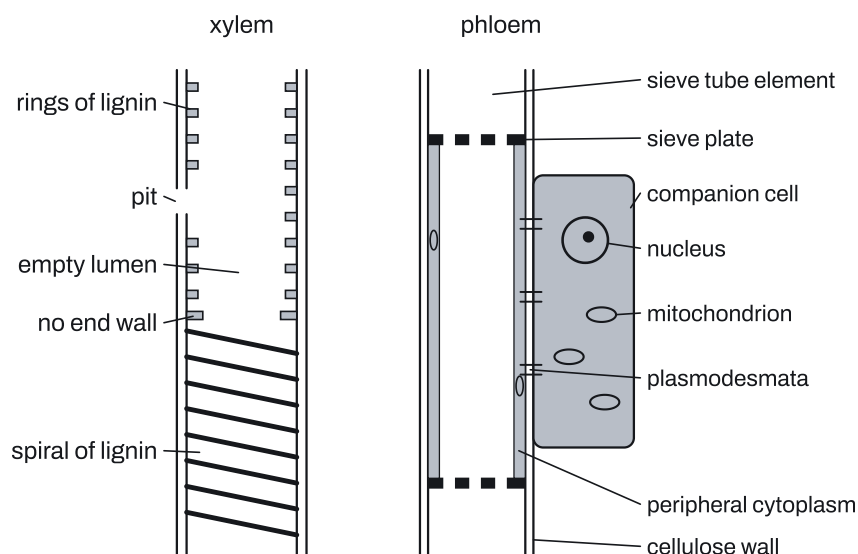
The leaf's layers, from top to bottom:

- **Cuticle:** a waxy layer made by the epidermal cells, which cuts water loss.
- **Upper epidermis:** one layer of cells, with few or no stomata on the upper side of most leaves.
- **Palisade mesophyll:** tall, column-shaped cells packed with chloroplasts; most photosynthesis happens here.
- **Spongy mesophyll:** rounded cells with large **air spaces** between them. Water evaporates from their wet cell walls.
- **Lower epidermis with stomata:** each stoma is a pore between a pair of **guard cells**, which open and close it.

Plan diagrams show only the **outlines of tissues**, never individual cells. Draw the boundaries with thin, continuous lines, keep the tissues in the right proportions, and label with ruled label lines.

Xylem vessel elements

A **xylem vessel** is a long tube made of many **vessel elements** joined end to end. As each element develops, its end walls break down, **lignin** is laid down in its walls, and its contents die and disappear. So a mature vessel element is **dead and empty**.



Feature	How it helps
No cytoplasm, no nucleus, no organelles	Nothing gets in the way of the water; the lumen is an open tube
No end walls between elements	A continuous tube, so water flows with little resistance
Lignified walls (in rings, spirals or a network)	Strong, so the vessel does not collapse under the tension of the transpiration pull; also supports the plant
Lignin is waterproof	Water stays in the vessel and moves along it

Feature	How it helps
Pits: gaps with no lignin, where only the cellulose wall remains	Let water move sideways into neighbouring vessels and cells, and round an air bubble
Narrow tube with cellulose on the inside	Water adheres to the walls, helping the column rise
Spiral or ring-shaped lignin	The vessel can still stretch as the stem grows

Phloem sieve tube elements and companion cells

A **sieve tube** is made of **sieve tube elements** joined end to end. Each one is a **living** cell, but it has lost most of what a normal plant cell has, so the sap can flow through it. Each has a **companion cell** next to it that does the work it can't do.

Sieve tube element

Feature	How it helps
Sieve plates at the ends, with sieve pores	The end walls are perforated, so sap flows from one element to the next
No nucleus , no ribosomes, no vacuole, few other organelles	Little gets in the way of the flowing sap
Thin layer of peripheral cytoplasm against the wall, with a cell surface membrane	The cell stays alive and can hold sucrose; the centre is left clear
Cellulose wall, not lignified	Water can enter and leave it by osmosis
Linked to its companion cell by many plasmodesmata	Sucrose, ATP and proteins pass in from the companion cell

Companion cell

Feature	How it helps
Nucleus	Controls the companion cell and its sieve tube element, which has no nucleus
Many mitochondria	Make the ATP for the proton pumps that load sucrose
Many ribosomes, dense cytoplasm	Make proteins, such as the proton pumps and cotransporter proteins
Many plasmodesmata to the sieve tube element	Sucrose diffuses through them into the sieve tube element

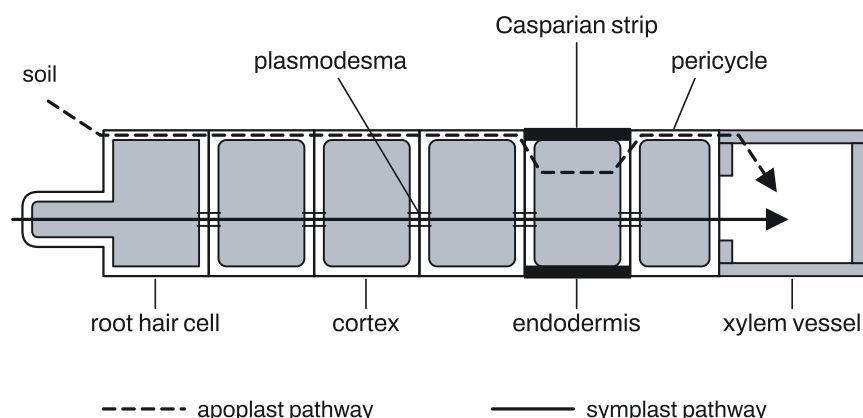
Sieve tube elements have cytoplasm, a few mitochondria and plasmodesmata, but **no nucleus and no ribosomes**; only the companion cell has many ribosomes ([9700/21/O/N/23 Q3](#) shows this as a table). Xylem vessel elements have no cytoplasm and no cell surface membrane at all.

Water from the soil to the xylem

Root hair cells give the root a huge surface area. The soil solution is dilute, while the root hair cell contains dissolved ions and sugars, so the soil water has a **higher water potential** than the cell. Water moves into the root hair cell **by osmosis**, down the water potential gradient, through its partially permeable cell surface membrane. Mineral ions are taken in by facilitated diffusion or by active transport through carrier proteins.

From there, water crosses the **cortex** to the **endodermis** by two routes:

- **Apoplast pathway:** through the **cell walls** and the **intercellular spaces**, without entering any cell. **Cellulose** walls are fully permeable: the cellulose microfibrils have spaces between them that water can move through, and water sticks to the cellulose by hydrogen bonds. Water is pulled along in a continuous stream because the molecules cling together, so this route has little resistance and carries most of the water. No membrane is crossed.
- **Symplast pathway:** through the **cytoplasm** of the cells, passing from one cell to the next through the **plasmodesmata**. Water enters the first cell by osmosis, crossing one cell surface membrane, and then moves on by osmosis from cell to cell, each with a slightly lower water potential than the one before.



The endodermis. Each endodermal cell has a band of **suberin** in its side and end walls, the **Casparian strip**. Suberin is a waxy, **waterproof** substance, so water can't pass through these walls: the **apoplast pathway is blocked**. Water (and the ions in it) must go through the **cell surface membrane into the cytoplasm** of the endodermal cells, joining the symplast. This lets the plant **control which mineral ions reach the xylem**, because the transport proteins in the membranes decide what gets through. After the endodermis, water crosses the **pericycle** and can use **either pathway** again, entering the xylem vessels through their pits.

Transpiration

Transpiration is the loss of water vapour from a plant, mostly from the leaves. It happens in two steps:

1. Water **evaporates** from the wet cellulose **cell walls of the mesophyll cells** (especially the spongy mesophyll) into the **air spaces** inside the leaf. This needs energy (water has a high **latent heat of vaporisation**, which cools the leaf).

2. The **water vapour diffuses** out of the air spaces, **through the stomata**, into the air outside, down a **water potential gradient**: the air spaces are nearly saturated with water vapour, so their water potential is higher than that of the drier outside air.

So the water potentials go down in order: **mesophyll cell > air spaces > atmosphere**. Transpiration is the unavoidable cost of **gas exchange**: stomata must open to let carbon dioxide in for photosynthesis, and once they are open water vapour gets out.

Factors that change the rate of transpiration:

Factor	Effect	Why
Higher temperature	Faster	Water molecules have more kinetic energy, so they evaporate faster and the vapour diffuses faster; warm air holds more vapour, making the gradient steeper
Lower humidity	Faster	Drier air outside, so a steeper water potential gradient for diffusion
More wind (air movement)	Faster	Moves away the humid air around the stomata, keeping the gradient steep
More light	Faster	More stomata open (for photosynthesis)

Water up the xylem: cohesion–tension

Water molecules are polar: the O has a small negative charge (δ^-) and each H a small positive charge (δ^+). The δ^+ H of one molecule is attracted to the δ^- O of another, forming a **hydrogen bond**.

- **Cohesion**: water molecules are attracted **to each other** by hydrogen bonds, so they stick together as a column.
- **Adhesion**: water molecules are attracted **to the cellulose in the xylem walls** (cellulose is hydrophilic, with many OH groups), which helps the water climb, especially in narrow vessels. Lignin is mostly hydrophobic, so it adds little adhesion.
- **Tension**: the pull on the column caused by water leaving the top of the xylem.

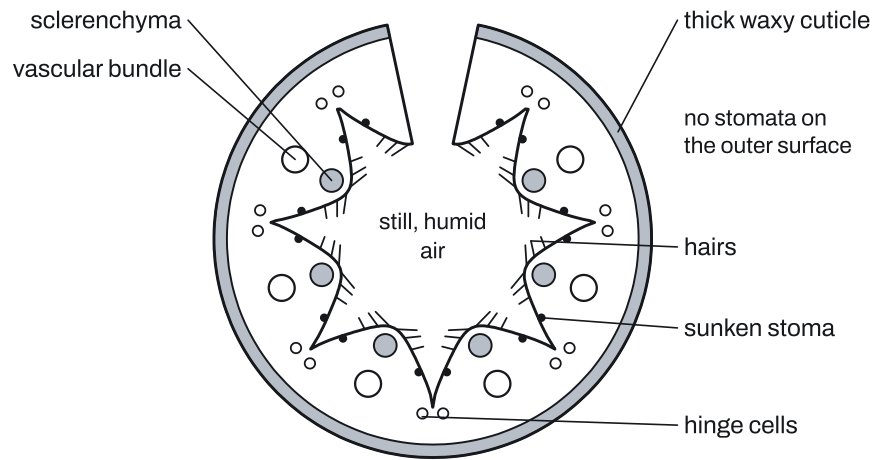
How it works:

1. Water evaporates from the mesophyll cells in the leaf, and water moves from the xylem in the leaf into them to replace it.
2. Water leaving the top of the xylem **lowers the hydrostatic pressure** there. The pressure at the top is lower than at the bottom (in fact it is **negative**: the water is under **tension**).
3. Because of **cohesion**, the water in the vessel moves up as a **continuous column**, pulled up by the tension. This is the **transpiration pull**, and the water moves by **mass flow**, down a hydrostatic pressure gradient.
4. **Adhesion** to the cellulose walls helps hold the column up and stops it pulling away from the walls.

No ATP is used: the energy comes from the heat that evaporates the water. **Lignin** stops the vessels collapsing under the tension, which is strong enough to make a tree trunk **slightly narrower** on a sunny day. An **air bubble** breaks the column, so water in that vessel stops; water goes round it through the pits.

Xerophytes

Xerophytes are plants adapted to dry places, where water is scarce and transpiration must be kept low. Their leaves have features that lengthen the diffusion path, reduce the number of stomata or trap humid air.



Adaptation	How it reduces water loss
Thick waxy cuticle	Longer diffusion distance and less permeable to water vapour, so less water is lost through the epidermis
Multilayered epidermis or a hypodermis	Longer diffusion distance
Sunken stomata (in pits, grooves or crypts)	Trap still, humid air above the stomata: a smaller water potential gradient , so less diffusion
Hairs (trichomes)	Trap a layer of still, humid air next to the leaf
Rolled or curled leaves (stomata on the inside)	Humid air is trapped inside the roll; less surface is exposed to wind
Fewer or smaller stomata (low stomatal density)	Less area for water vapour to diffuse out
Small leaves, needles or spines	Small surface area to volume ratio, so less surface to lose water from
Stomata that close at the hottest times or open only at night	Less transpiration when it would be highest

In a rolled leaf, the **hinge cells** at the bottom of the grooves lose water in dry conditions and become flaccid, so the leaf rolls up; when water is plentiful they are turgid and the leaf opens out.

Sources and sinks

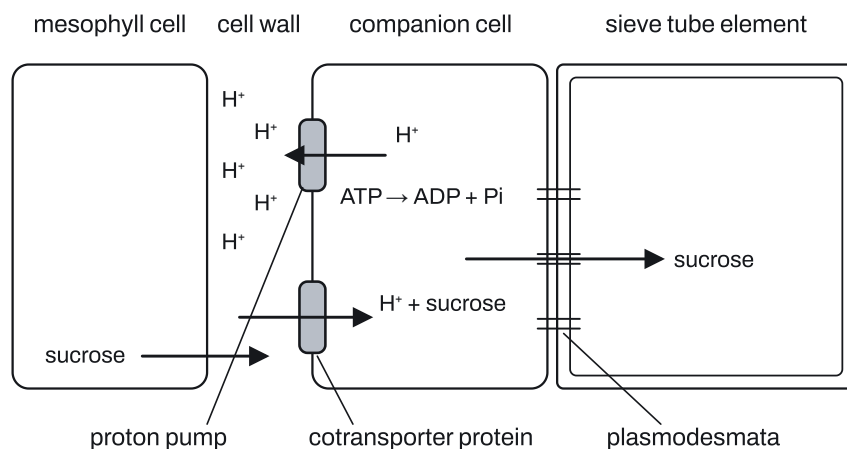
Assimilates move from **sources** to **sinks**.

- A **source** releases assimilates into the phloem: a **mature, photosynthesising leaf**, or a storage organ (root, tuber, bulb, seed) that is **mobilising** its stores, for example when a seed germinates or a bulb starts to grow in spring.
- A **sink** takes assimilates out of the phloem to use or store them: **growing** parts (young leaves, buds, shoot and root tips, developing fruits and seeds) and storage organs that are **filling up** with starch.

The same organ can be both at different times. A **young leaf** is a sink: it is growing and doesn't yet photosynthesise enough for itself, so it imports sugars. When it is mature it photosynthesises more than it needs, and becomes a source. Sinks can be above or below the source, so phloem sap can move **up or down**, and different sieve tubes can carry sap in **different directions** at the same time.

Loading the phloem: companion cells

At a source, sucrose must get into the sieve tubes, where its concentration is already high. So loading needs energy. In many plants it happens like this:

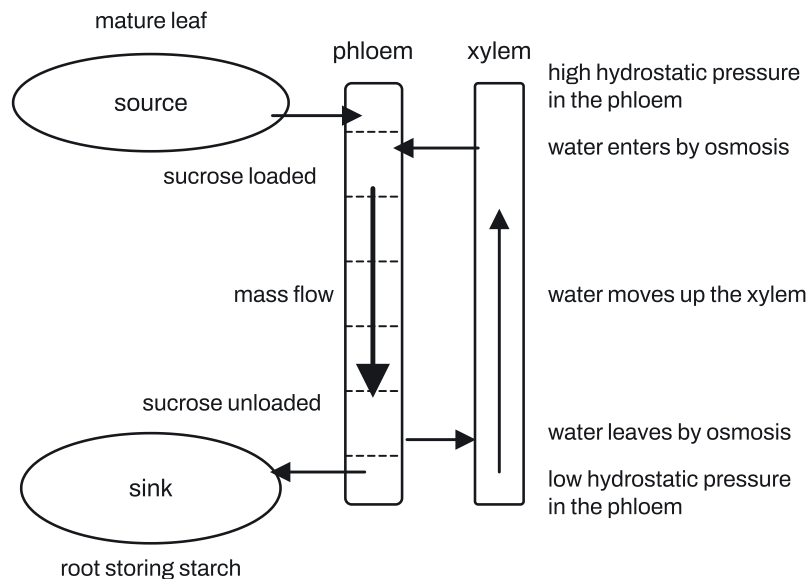


1. **Proton pumps** in the companion cell's cell surface membrane use **ATP** (from its many mitochondria) to actively pump **hydrogen ions (H^+)** out of the companion cell into its cell wall. This makes a high H^+ concentration outside (the cell wall's pH falls) and a low one inside.
2. H^+ **diffuse back in** down their concentration gradient, but only through **cotransporter proteins**. Each cotransporter carries a **sucrose** molecule in with the H^+ , **against sucrose's concentration gradient**. This is indirect active transport: ATP is used only by the pump, not by the cotransporter.
3. The sucrose concentration in the companion cell is now **higher than in the sieve tube**, so sucrose **diffuses** into the sieve tube element **through the plasmodesmata**.

Sucrose reaches the companion cell from the mesophyll cells by diffusion, through the plasmodesmata (symplast) or through the cell walls (apoplast). A respiratory poison such as cyanide stops the mitochondria making ATP, so fewer H^+ are pumped out, and less sucrose is loaded.

Mass flow in the phloem

Loading sucrose starts the sap moving:



1. **At the source**, sucrose is loaded into the sieve tube. This **lowers the water potential** in the sieve tube.
2. **Water enters** the sieve tube **by osmosis** from the nearby xylem (and surrounding cells). The **volume** of liquid in the sieve tube increases, so the **hydrostatic pressure rises**.
3. **At the sink**, sucrose is removed (by diffusion or active transport) and used in respiration or turned into starch. This **raises the water potential** in the sieve tube, so **water leaves** by osmosis, the volume falls, and the **hydrostatic pressure falls**.
4. So the pressure is **high at the source and low at the sink**. The sap flows **by mass flow down this hydrostatic pressure gradient**, from source to sink, carrying the sucrose, amino acids and other solutes with it.

Mass flow in the phloem needs energy (for loading), unlike the flow in the xylem.

	Xylem	Phloem
Carries	Water and mineral ions (and some plant hormones)	Assimilates (sucrose, amino acids) dissolved in water, with some ions
Direction	Up only, from roots to leaves	From source to sink: up or down
Cells	Dead, empty vessel elements	Living sieve tube elements with companion cells
Walls	Lignified	Cellulose
Driven by	Transpiration pull (tension): passive	Hydrostatic pressure made by active loading
How it moves	Mass flow	Mass flow

Blood in arteries and veins also moves by mass flow.

Measuring transpiration with a potometer

A **potometer** measures how fast a leafy shoot **takes up water**. Almost all the water taken up is lost by transpiration, so the rate of uptake is used as an **estimate of the rate of transpiration**.

Cut and fit the shoot **under water** so **no air enters the xylem**, and seal the joints. Measure the **distance** an air bubble moves along the capillary in a set time, reset it with the reservoir, repeat and take the mean. Change one factor (such as wind, with a fan) and keep the others constant.

$$\text{rate of water uptake} = \frac{\text{volume of water taken up}}{\text{time}}, \quad \text{volume} = \pi r^2 \times \text{distance moved by the bubble}$$

where r is the internal radius of the capillary tube. To compare shoots of different sizes, divide by the **total leaf area** (draw round the leaves on squared paper and count the squares).

Key facts and formulas

None of these are in the syllabus's list of mathematical formulae, so they are all "Learn it".

Formula	Status
Volume of water taken up = $\pi r^2 \times \text{distance moved by the bubble}$ (r = radius of the capillary)	Learn it
Rate = $\frac{\text{distance or volume}}{\text{time}}$; rate per unit leaf area = $\frac{\text{rate}}{\text{leaf area}}$	Learn it
Percentage change = $\frac{\text{new} - \text{original}}{\text{original}} \times 100$	Learn it
Magnification = $\frac{\text{image size}}{\text{actual size}}$ (for drawings and scale bars)	Learn it
Water moves from higher (less negative) to lower (more negative) water potential	Learn it
Transpiration: ψ of mesophyll cell > air spaces > atmosphere	Learn it
Loading at a source: sieve tube ψ falls, water enters, volume and pressure rise	Learn it
Unloading at a sink: sieve tube ψ rises, water leaves, volume and pressure fall	Learn it
Pressure in the xylem of a transpiring plant is negative (tension), lowest at the top	Learn it

How to do it

We have tagged 191 questions on this topic from 2021–2025: 160 multiple choice on Paper 1 and 31 structured questions on Paper 2. 25 of them mix types, so the counts add up to 225.

Question type	Questions
Describe water movement from soil to xylem (apoplast, symplast, endodermis)	29
Predict sieve-tube changes; explain mass flow from source to sink	27

Question type	Questions
Relate the structure of xylem and phloem cells to their functions	27
Identify tissues and cells; know where xylem and phloem are	26
Explain phloem loading by companion cells	25
Explain water movement up the xylem (cohesion–tension)	24
Explain transpiration and the factors that change its rate	15
State and explain xerophyte leaf adaptations	13
Identify sources and sinks	8
State the roles of lignin, suberin and cellulose	8
Interpret data from transport investigations	7
State what xylem and phloem carry	7
Draw or judge plan diagrams and cell drawings	5
Use a potometer and work out rates	4

1. Describe water movement from soil to xylem (29 questions)

Describe the route in order: osmosis into the root hair cell → across the cortex by the apoplast (cellulose walls) and symplast (cytoplasm, plasmodesmata) → Casparian strip blocks the apoplast, so water crosses a membrane into the endodermal cells → **say why**: the plant controls which ions reach the xylem → either pathway into the xylem through pits.

Variations you will meet:

- **Checking statements** (the most common multiple-choice form). The apoplast is **never** through plasmodesmata, cytoplasm or vacuoles, and does not involve osmosis. The symplast is **never** through intercellular spaces. Water does not cross a membrane by squeezing between phospholipids in the symplast, and it does not enter the xylem "by osmosis through the cell wall". After the endodermis, water can take **either** pathway.
- **Order of tissues**: root hair (epidermis) → cortex → endodermis → pericycle → xylem.
- **Name structures on a diagram**: a strand crossing two cell walls is a **plasmodesma** (singular); the band in the endodermal walls is the **Casparian strip**.
- **Why the apoplast is fast**: no membranes to cross; cellulose microfibrils leave spaces; water sticks to the hydrophilic walls and is pulled along by cohesion.
- **Which component the apoplast uses**: **cellulose**, not suberin.
- **Arrows across a root**: an arrow that crosses from a cell wall into cytoplasm cannot be apoplast only.
- **Ions**: an ion such as NH_4^+ or Fe^{2+} travelling in the apoplast is stopped at the Casparian strip and must be taken into the endodermal cells by transport proteins. A mutant with no Casparian strip lets more (unwanted) ions reach the xylem.

- **Water potentials given:** water moves towards the **more negative** value, for example from -120 kPa to -350 kPa.
- **Root hairs:** many long, thin hairs give a large surface area for uptake of water and ions.

2. Predict sieve-tube changes; explain mass flow (27 questions)

1. **Source or sink?** Into the sieve tube (source): ψ **lower**, water in, **volume increases**. Out of it (sink): ψ **higher**, water out, **volume decreases**.
2. **Explain mass flow** as the chain in "Mass flow in the phloem", giving the cause of each change.

Variations you will meet:

- **"Which row shows the cause and direction?":** a **hydrostatic pressure** gradient (not a water potential gradient), from **source to sink**.
- **"Which process moves sucrose through the sieve tube?":** **mass flow**, not diffusion or active transport.
- **Why different substances can move in different directions:** different sieve tubes can carry sap to different sinks at the same time.
- **Graph axes:** hydrostatic pressure (y-axis) against distance from the source (x-axis), falling towards the sink.
- **A physical model:** two partially permeable bags joined by a tube, in water. The bag with the concentrated sucrose solution takes in water by osmosis, its pressure rises, and liquid flows along the tube to the dilute bag, as from source to sink.

3. Relate the structure of xylem and phloem cells to their functions (27 questions)

1. **Recall the features** of each cell (the tables in "Understand it").
2. **Link each feature to the job**, in one sentence: "no end walls, **so** a continuous tube with little resistance to flow".

Variations you will meet:

- **Tick tables** of which cells have cytoplasm, a nucleus, mitochondria, plasmodesmata, lignin, pits. Xylem vessel elements: none of the living features, but lignin and pits. Sieve tube elements: cytoplasm, a few mitochondria and plasmodesmata, but **no nucleus, no ribosomes** and no lignin. Companion cells: all the living features, no lignin.
- **Which feature lowers resistance in xylem?:** **no cross (end) walls**. "Narrow tubes" is a distractor; narrow tubes do not reduce resistance.
- **Which feature helps adhesion?:** the cellulose in the walls (lignin replacing cellulose does not help).
- **The main job of the companion cell:** loading sucrose into the sieve tube (with ATP from its mitochondria), and keeping the sieve tube element alive.
- **A heated band round a stem** kills the living phloem cells there, so phloem transport stops, but xylem (dead already) keeps working.

- **Matching leaf cells to descriptions:** a cell that is one of a pair forming a stoma is a **guard cell**; a column-shaped photosynthesising cell is a **palisade mesophyll** cell; a cell that secretes the waxy cuticle is an **epidermal** cell; a thick-walled supporting cell is **sclerenchyma**; the cell that receives water to build up hydrostatic pressure for mass flow is the **sieve tube element**.

4. Identify tissues and cells; know where xylem and phloem are (26 questions)

1. **Decide the organ from the layout:** vascular bundles in a ring = **stem**; xylem as a central star with phloem between its arms = **root**; xylem on the upper side of a bundle in a thin flat structure = **leaf**.
2. **Identify cells in sections:** xylem vessel elements are wide, empty, with thick (often darkly stained, spiral or ring) walls; sieve tube elements are narrower, with sieve plates; companion cells are small, with dense cytoplasm and a nucleus, beside a sieve tube element.

Variations you will meet:

- **Label lines** must **touch** the xylem, phloem or Casparian strip; candidates often label the phloem instead of the xylem.
- **Name a cell, not a tissue:** "xylem vessel element", not just "xylem"; "endodermal cell".
- **Longitudinal sections (LS):** xylem shows spiral or ring thickening; phloem shows sieve plates across the tubes.
- **Two sieve tube elements look different in TS:** one has been cut through its sieve plate, the other through the middle.
- **A lignin stain** colours the xylem (and sclerenchyma) only.

5. Explain phloem loading by companion cells (25 questions)

Give the four steps from "Loading the phloem" **in order**, naming ATP, proton pump, H^+ out, cotransporter, sucrose against its gradient, plasmodesmata.

Variations you will meet:

- **What X and Y are** in a diagram: the ion pumped out is H^+ ; the molecule carried in with it is sucrose.
- **Which step uses ATP directly?** Only the proton pump. The first event is pumping H^+ out, **not** H^+ diffusing in.
- **Relative sucrose concentrations:** highest in the companion cell, then the sieve tube, lowest in the mesophyll cell.
- **A metabolic poison** (cyanide): less ATP, so fewer H^+ pumped out, the pH in the cell wall **rises** (H^+ concentration falls), and less sucrose is loaded.
- **Which cells have proton pumps:** companion cells (in the phloem), so in a plan diagram choose the phloem.
- **What is cotransported:** small molecules such as sucrose (a disaccharide) and amino acids (monomers), never polysaccharides or proteins.

6. Explain water movement up the xylem (24 questions)

Write the cohesion–tension chain from "Understand it": evaporation in the leaf → lower hydrostatic pressure at the top (tension) → cohesion keeps a continuous column → adhesion to cellulose → mass flow; lignin stops collapse.

Variations you will meet:

- **Name the term:** attraction between water molecules = **cohesion**; attraction to the vessel walls = **adhesion**; the pull made by evaporation = **tension**.
- **Pressure and water potential:** the pressure in the xylem is **negative**, and the water potential in root hair cells is **negative** too.
- **The method** is **cohesion–tension**, not osmosis or cotransport.
- **An air bubble** (cavitation) breaks the column: cohesion is lost (and with it the tension that pulls the water); pits let water go round it.
- **A tree trunk narrows by day:** high transpiration (warm, sunny, windy, dry air) increases the tension, pulling the vessel walls in slightly.
- **How a hydrogen bond forms:** between the δ^+ hydrogen of one water molecule and the δ^- oxygen of another.

7. Explain transpiration and the factors that change its rate (15 questions)

1. **Define it:** loss of **water vapour** from the plant; water **evaporates** from mesophyll cell walls into the air spaces, then the vapour **diffuses** out through the **stomata**.
2. **Explain a factor** with the steps: what changes → faster (or slower) evaporation or diffusion → steeper (or shallower) water potential gradient → more (or less) water vapour lost.

Variations you will meet:

- **Where does water evaporate from?:** the **mesophyll cell walls**, not the leaf surface, the air spaces or the stomatal pores.
- **Which process at each step:** osmosis into the root hair, mass flow up the xylem, evaporation in the leaf, diffusion out of the stomata.
- **Why transpiration is unavoidable:** stomata must be open for gas exchange (CO_2 in).
- **Temperature data:** more kinetic energy → faster evaporation from spongy mesophyll walls → steeper gradient for diffusion of water vapour out → more stomata open.

8. State and explain xerophyte leaf adaptations (13 questions)

1. **Name the feature** (from the list or the photomicrograph).
2. **Pair it with its explanation:** longer diffusion distance, less permeable, humid air trapped (smaller water potential gradient), fewer stomata, or smaller surface area.

Variations you will meet:

- **A table with a different adaptation for each structure:** cuticle → thicker; upper epidermis → several layers of cells or hairs; lower epidermis → sunken stomata, fewer stomata or hairs. Each example must be different.
- **Which features reduce the water potential gradient?:** those that trap humid air (sunken stomata, hairs, rolled leaves). A thick cuticle works differently, by lengthening the diffusion path.
- **Hinge cells in a rolled leaf** (layer Y): in dry conditions they lose water, so their water potential and turgor fall and the leaf rolls; when water is plentiful they are turgid and the leaf is flat.
- **A leaf in a photomicrograph:** look for thick cuticle, rolled shape, hairs, stomata in grooves, few air spaces.

9. Identify sources and sinks (8 questions)

1. **Is the organ releasing assimilates or taking them in?** Releasing = source; taking in = sink.
2. **Give a reason:** for a sink, it is growing, not yet photosynthesising enough, or storing; for a source, it is mature and photosynthesising, or breaking down stores.

Variations you will meet: a young leaf (sink) that becomes a mature leaf (source), needing more water as it grows because it photosynthesises and transpires more; a bulb or tuber that is a sink while storing and a source when it sprouts; a germinating seed's store, which is a source. A leaf that is a sink for sucrose is a sink for amino acids too.

10. State the roles of lignin, suberin and cellulose (8 questions)

Give the substance, **where** it is and **what it does** to water, as in "Understand it": lignin (xylem walls: strong, waterproof), suberin (Casparian strip: blocks the apoplast), cellulose (all walls: permeable, water adheres to it).

11. Interpret data from transport investigations (7 questions)

1. **Describe the pattern with figures and units:** quote pairs of values ("at 20 °C the rate was 5 mmol m⁻² s⁻¹, rising to 17 at 40 °C").
2. **Compare** where there are two sets of data.
3. **Explain** using the mechanism: tension in the xylem, mass flow in the phloem, the phloem being outside the xylem in a stem.

Examples of what you may see: radioactive tracers in xylem and phloem separated by waxed paper; removing a ring of bark (the phloem) so sugars build up above the ring; transpiration curves; water uptake that lags behind water loss during the day; xylem sap flow against leaf area.

12. State what xylem and phloem carry (7 questions)

Use the xylem–phloem table in "Understand it". A sample rich in sucrose and amino acids is phloem sap; water is the main part of both saps because the solutes travel **dissolved in it**.

13. Draw or judge plan diagrams and cell drawings (5 questions)

1. **Plan diagrams**: tissue outlines only, **no cells**; correct proportions; xylem towards the upper side in a leaf vein.
2. **Cell drawings**: a sieve tube element needs sieve plates and thin peripheral cytoplasm, and **no nucleus**, no vacuole and no lignin.
3. **Scale**: use magnification = image size $\div$ actual size, in the same units (1 mm = 1000 μ m).

14. Use a potometer and work out rates (4 questions)

Find the mean distance, then rate = distance $\div$ time; for volume use $\pi r^2 \times$ distance, then divide by time (and leaf area if asked). Say why the shoot is cut under water (see "Measuring transpiration with a potometer") and that uptake only estimates transpiration (Example 2 (e)).

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

(a) Describe how water moves from the cortex of a root into the xylem by the apoplast pathway. **[4]**

(b) Explain how water moves up the xylem of a tall plant. **[4]**

(a) Water moves through the **cellulose cell walls** and the spaces between cells of the cortex, without crossing any membrane. **B1** At the **endodermis**, the **Casparian strip** of **suberin** is waterproof, so the apoplast pathway is blocked. **B1** Water has to cross the **cell surface membrane** into the cytoplasm of the endodermal cells (joining the symplast), which lets the plant control which ions enter the xylem. **B1** After the endodermis water can move through the walls again and enters the xylem vessels through the pits. **B1**

(b) Water **evaporates** from the mesophyll cell walls in the leaves and is replaced by water from the xylem. **B1** This **lowers the hydrostatic pressure** at the top of the xylem, so the water is under **tension**. **B1** **Cohesion**, from hydrogen bonds between water molecules, keeps the water as a continuous column that is pulled up by **mass flow**. **B1** **Adhesion** of water to the cellulose walls also helps it rise. **B1**

Example 2

A student used a potometer to measure the rate of water uptake by a leafy shoot. The internal radius of the capillary tube was 0.40 mm. In still air the bubble moved 45 mm, 52 mm and 47 mm in three separate 5-minute periods. With a fan blowing on the shoot the mean distance in 5 minutes was 92 mm.

- (a) Calculate the mean rate of movement of the bubble in still air, in mm min^{-1} . **[2]**
 - (b) Calculate the volume of water taken up per minute in still air. Give your answer to 3 significant figures. **[2]**
 - (c) Calculate the percentage increase in the rate of uptake caused by the fan. **[1]**
 - (d) Explain the effect of the fan. **[2]**
 - (e) State **one** reason why the rate of water uptake is only an estimate of the rate of transpiration. **[1]**
- (a)** Mean distance = $(45 + 52 + 47) \div 3 = 48 \text{ mm}$. **M1** Rate = $48 \div 5 = 9.6 \text{ mm min}^{-1}$. **A1**
- (b)** Volume per minute = $\pi r^2 \times 9.6 = \pi \times 0.40^2 \times 9.6$. **M1** = $4.83 \text{ mm}^3 \text{ min}^{-1}$. **A1**
- (c)** With the fan: $92 \div 5 = 18.4 \text{ mm min}^{-1}$. Increase = $\frac{18.4 - 9.6}{9.6} \times 100 = 91.7\%$. **B1**
- (d)** The moving air carries away the humid air around the stomata, so the air outside the leaf stays dry. **B1** The **water potential gradient** between the air spaces and the air outside stays steep, so water vapour diffuses out through the stomata faster, and more water is pulled up the xylem. **B1**
- (e)** Some of the water taken up is used in photosynthesis or stays in the cells (to keep them turgid), so not all of it is lost by transpiration. **B1**

Example 3

A scientist measured the rate at which sucrose was carried in the phloem of a stem, before and after the leaves were treated with cyanide, which stops aerobic respiration. The rate fell from 1.8 to 0.3 mg h^{-1} .

- (a) Calculate the percentage decrease in the rate. **[1]**
 - (b) Explain how companion cells load sucrose into phloem sieve tubes, and use this to explain the effect of cyanide. **[5]**
 - (c) Explain how loading sucrose at the source causes the sap to move to a sink. **[4]**
- (a)** $\frac{1.8 - 0.3}{1.8} \times 100 = 83.3\%$. **B1**
- (b)** **Proton pumps** in the companion cell membrane use **ATP** to pump **H⁺ out** of the companion cell, into the cell wall. **B1** This makes a **H⁺ concentration gradient**, and **H⁺ diffuse back in** through **cotransporter proteins**. **B1** Each cotransporter carries **sucrose** in with the **H⁺**, **against the sucrose concentration gradient**. **B1** Sucrose then **diffuses** into the sieve tube element through **plasmodesmata**. **B1** Cyanide stops respiration in the mitochondria, so little ATP is made and fewer **H⁺** are pumped; less sucrose is loaded and less is carried away. **B1**

(c) Loading sucrose **lowers the water potential** in the sieve tube at the source. **B1** Water enters by **osmosis** from the xylem, which raises the **hydrostatic pressure**. **B1** At the sink sucrose is removed, so water leaves and the pressure is lower. **B1** The sap moves by **mass flow down the hydrostatic pressure gradient**, from the source to the sink. **B1**

Common mistakes

- **Mixing up cohesion and adhesion.** Cohesion is water sticking to water; adhesion is water sticking to the **cellulose** walls. Say "cellulose", not just "the wall" or "lignin".
- **Saying adhesion and cohesion alone move water up.** They hold the column together; the **tension** from evaporation in the leaf provides the pull. Don't lean on root pressure.
- **Thinking water can cross the Casparian strip.** It can't: suberin is waterproof, so water must go through the cell surface membranes of the endodermal cells. Then **explain why that matters** (control of which ions reach the xylem); many answers stop too early.
- **Thinking sieve tube elements have no cytoplasm**, or that they contain lignin, a vacuole or a nucleus. They have a thin layer of peripheral cytoplasm and a cell surface membrane, cellulose walls, and no nucleus or vacuole. Xylem vessel elements are the ones with no cytoplasm.
- **Getting the sieve-tube changes backwards.** Loading (source): ψ lower, volume up. Unloading (sink): ψ higher, volume down. In one paper nine tenths of weaker candidates got this kind of question wrong.
- **Saying mass flow in the phloem goes down a water potential gradient.** It goes down a **hydrostatic pressure** gradient.
- **Starting phloem loading with H^+ diffusing in.** The first step is **pumping H^+ out**, using ATP.
- **Answering a loading question with mass flow**, or a mass flow question with proton pumps. Answer the step asked about, and in the mass flow chain give the **cause** of each change ("sucrose loaded **so** ψ lowered **so** water enters by osmosis **so** pressure rises").
- **Writing "concentration gradient" for water vapour.** Mark schemes credit a **water potential gradient** (or diffusion of water vapour) and ignore "concentration gradient".
- **Saying water evaporates from the leaf surface or the stomata.** It evaporates from the **mesophyll cell walls** into the air spaces.

How to get the marks

- **"Explain"** a process: write it as a chain of cause and effect, one mark-worthy step per sentence, in order. Mass flow and cohesion–tension answers get **one mark per link**.
- **"Describe"** data: give the trend and **quote paired figures with units**; for a comparison, compare at the same value ("at 35 °C, plant A lost 18 but plant B only 9 mmol m⁻² s⁻¹").
- **"State and explain"** an adaptation: give the feature, then how it cuts water loss. Marks go to the **pair**; the feature alone earns little. Use "water potential gradient" and "diffusion distance".
- **"Relate structure to function"**: name the feature **and** say what it does ("no end walls, **so** less resistance to flow").

- **Calculations:** show the working, give units (mm min^{-1} , $\text{mm}^3 \text{min}^{-1}$), and round only at the end.
- **"Suggest":** apply the ideas here to the new plant or situation in the question (a parasite tapping the phloem, a mutant without a Casparian strip, a heated stem).

Quick check

1. In a transverse section, the xylem forms a star in the centre and the phloem lies between its arms. Name the organ, and name the layer of cells around the vascular tissue that contains the Casparian strip.
2. A potometer's capillary tube has an internal radius of 0.50 mm. The bubble moves 30 mm in 4 minutes. Calculate the rate of water uptake in $\text{mm}^3 \text{min}^{-1}$, to 3 significant figures.
3. Amino acids are unloaded from a sieve tube into a growing shoot tip. State what happens to the water potential and to the volume of liquid in the sieve tube element.
4. A student's plan diagram of a leaf shows the midrib as 90 mm wide. The midrib is actually 1.5 mm wide. Calculate the magnification of the drawing.
5. Explain how sunken stomata reduce the rate of transpiration.

Answers

1. A **root**; the **endodermis** (the Casparian strip is suberin in the walls of its cells).
2. $\text{Volume} = \pi \times 0.50^2 \times 30 = 23.56 \text{ mm}^3$; $\text{rate} = 23.56 \div 4 = 5.89 \text{ mm}^3 \text{ min}^{-1}$.
3. The water potential becomes **higher** (less negative), because solutes leave; water leaves by osmosis, so the **volume decreases**.
4. $\text{Magnification} = 90 \div 1.5 = \times 60$ (same units: both in mm).
5. The stomata sit in pits, where still, humid air is trapped. The water potential of the air just outside the stomata stays high, so the **water potential gradient** between the air spaces and the air outside is smaller, and less water vapour diffuses out.

Past questions to try

- [9700/22/O/N/24 Q6](#): apoplast and symplast pathways across a root.
- [9700/23/O/N/22 Q3](#): how water moves up xylem vessels, and air bubbles in the xylem.
- [9700/23/O/N/23 Q5](#): sources and sinks, and mass flow in the phloem.
- [9700/21/O/N/21 Q5](#): transpiration and a potometer investigation.