

ESAT

Biology

Plant physiology

Free lesson notes

Covers	B11.1 and B11.2
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

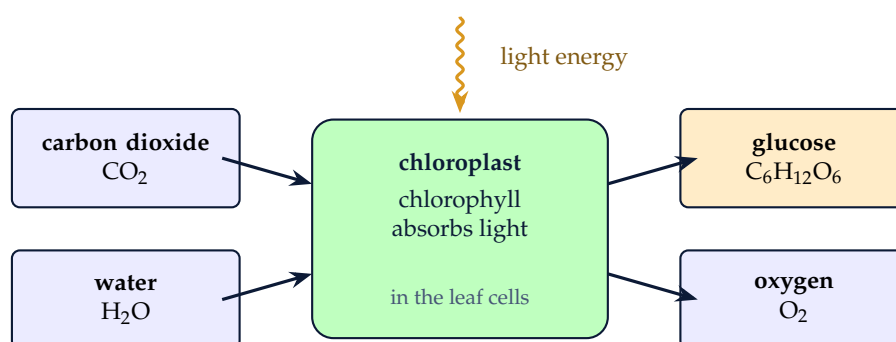
A plant is a factory that makes its own food and a plumbing system that moves water around, with no heart, no muscles and no pump. This lesson explains how. We start with **photosynthesis**, the reaction that builds sugar from carbon dioxide and water using light, and with the **limiting factors** that set how fast it can go. Then we look inside a leaf to see how its structure suits the job, how **stomata** let gases in and out, how roots take up water and mineral ions, how water is pulled up the plant in the **transpiration stream**, and how sugar is carried round by **translocation**. We finish with the rate calculations that the specification names.

How to use it. Cover each worked example and try it first. The ESAT has no calculator, so the numbers are friendly, and the data questions reward careful reading of axes, units and what a graph actually shows. Specification covered: B11.1 (photosynthesis and limiting factors) and B11.2 (xylem, phloem, uptake, transpiration and translocation, and rate calculation). Plant hormones are not in this part of the specification, so they are not covered here.

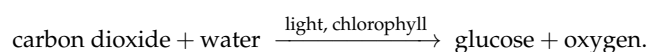
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1 Photosynthesis (B11.1)

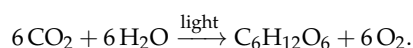
Photosynthesis is the process by which green plants and algae use light energy to make glucose from carbon dioxide and water, releasing oxygen as a by-product. It happens in **chloroplasts**, the green organelles packed with the pigment **chlorophyll**. Chlorophyll absorbs light (mostly red and blue), and that energy drives the reaction.



In words:



In symbols, and balanced:



Photosynthesis is an **endothermic** reaction: it takes energy in from the surroundings (light) and stores it in the chemical bonds of glucose. This is where almost all the energy in food chains originally comes from.

Where do the reactants come from? Carbon dioxide diffuses into the leaf from the air through the stomata. Water is absorbed from the soil by the roots and carried up in the xylem. Light comes from the Sun.

What happens to the glucose? The plant uses it in several ways:

- **Respiration:** glucose is broken down to release energy for growth and other processes. Plants respire all the time, day and night.
- **Storage:** glucose is converted to **starch**, which is insoluble, so it does not change the water balance of cells (soluble glucose would draw water in by osmosis).
- **Building materials:** glucose is made into **cellulose** for cell walls, and into fats and oils for seeds.
- **Making proteins:** glucose is combined with nitrate ions from the soil to make amino acids, and so proteins.

Photosynthesis and respiration are opposites. Photosynthesis takes in CO_2 and releases O_2 ; respiration takes in O_2 and releases CO_2 . In bright light photosynthesis is faster than respiration, so the plant gives out oxygen overall. In darkness only respiration happens and the plant takes in oxygen. At one light level in between, the two rates are equal and there is no net exchange of either gas.

Worked example: checking the balanced equation

Show that $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ is balanced.

Count atoms on each side. Left: carbon $6 \times 1 = 6$; oxygen $6 \times 2 + 6 \times 1 = 18$; hydrogen $6 \times 2 = 12$. Right: carbon 6; hydrogen 12; oxygen 6 (in glucose) + $6 \times 2 = 12$ (in O_2) = 18. Each element matches, so the equation is balanced. Notice that the six O_2 molecules come from the *water* as well as the carbon dioxide, but you only need the totals.

Key ideas

- Carbon dioxide + water $\rightarrow$ glucose + oxygen, using light energy absorbed by chlorophyll in chloroplasts. It is endothermic.
- Glucose is used for respiration, stored as starch, made into cellulose, and combined with nitrate to make proteins.
- Plants respire all the time. Photosynthesis only happens in the light.

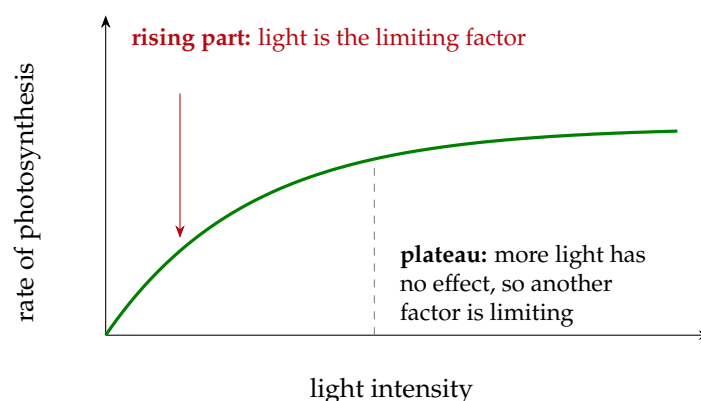
Common mistakes

- Writing that plants “breathe in carbon dioxide and breathe out oxygen” and stop there. They *also* respire, taking in oxygen and releasing carbon dioxide, all the time.
- Saying that plants get their food (their mass) from the soil. Most of the mass of a plant is built from carbon dioxide and water.
- Writing the equation backwards, or leaving out light as the energy source.
- Saying glucose is stored as glucose. It is stored as insoluble starch.

2 Limiting factors (B11.1)

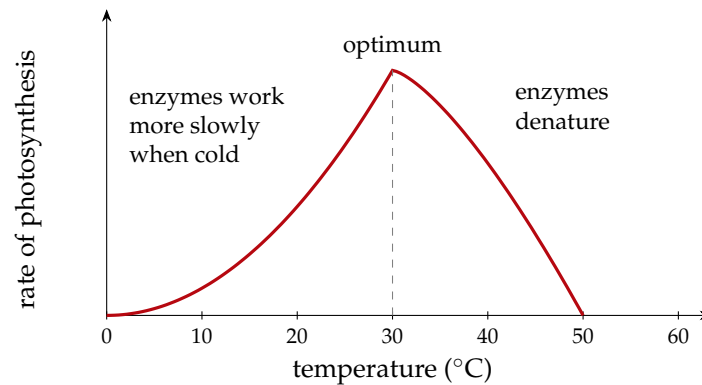
A **limiting factor** is the factor that is in shortest supply, so it sets the maximum rate of a process at that moment. Imagine a factory with plenty of workers and materials but only one machine: the machine limits output, and hiring more workers does nothing. Photosynthesis has three main limiting factors: **light intensity**, **carbon dioxide concentration** and **temperature**. (The amount of chlorophyll can also limit it.)

Light intensity. Light supplies the energy. At low light intensity the rate rises steadily as light increases, because light is the limiting factor. Eventually the rate stops rising and levels off at a **plateau**: more light no longer helps, because now something else (carbon dioxide or temperature) is limiting.

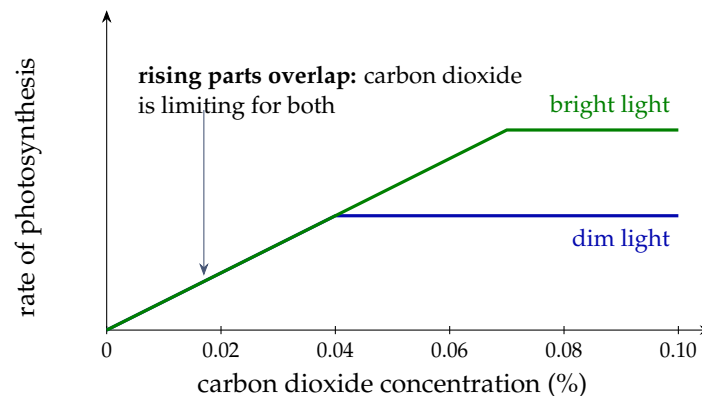


The rule for reading any limiting-factor graph: where the line is rising, the factor on the x-axis is limiting. Where the line is flat, some *other* factor is limiting.

Temperature. Photosynthesis is controlled by enzymes. As the temperature rises, particles move faster and collide more often, so the rate increases. Above the optimum (about 30°C to 40°C for many plants) the enzymes begin to **denature**: their active sites change shape and no longer fit. The rate then falls steeply.



Carbon dioxide. Air contains only about 0.04% carbon dioxide, so it is often limiting. Raising the concentration raises the rate until another factor takes over. The graph shows two light intensities. At low carbon dioxide concentrations the two lines are *the same*, because carbon dioxide is limiting both. They separate only where the dim-light line flattens: there, light has become limiting for the dim plant, while the bright plant can still use more carbon dioxide.



Light and distance. Light intensity falls with distance d from a lamp according to an **inverse square law**: intensity $\propto 1/d^2$. Doubling the distance cuts the intensity to a quarter; trebling it cuts it to a ninth. In a pondweed experiment (count the bubbles of oxygen released per minute at different distances), the rate is proportional to the light intensity *as long as light is the limiting factor*.

Using this: greenhouses and polytunnels. Growers raise yield by removing limiting factors: heating in winter, artificial lights, and burning paraffin or using cylinders to raise the CO_2 level. But each costs money, so a grower adds only what is limiting. There is no point paying for extra light if carbon dioxide is the factor holding the plants back.

Worked example: which factor is limiting?

A pondweed gives out 20 bubbles per minute under a lamp at 10 cm. The lamp is then moved to 20 cm, and the rate falls to 5 bubbles per minute. The lamp is moved back to 10 cm and the water is warmed by 5°C : the rate stays at 20. Explain.

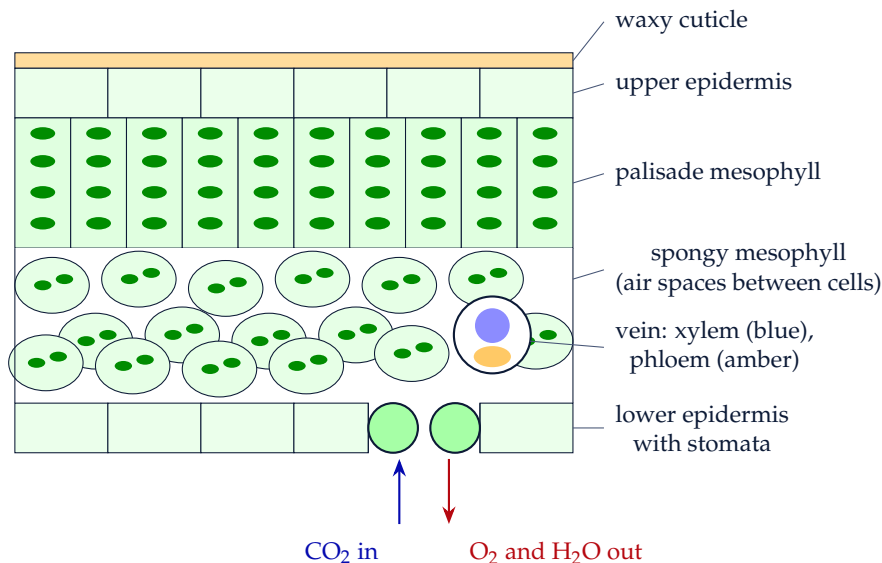
Moving the lamp from 10 to 20 cm doubles the distance, so the light intensity is $1/2^2 = 1/4$ of the original, and the rate fell to $20/4 = 5$, the same fraction: the rate is directly proportional to the intensity, so light is limiting. At 10 cm, warming the water gave no change, so temperature is not the limiting factor there. Carbon dioxide or light itself may still be limiting.

Common mistakes

- Saying the plateau means photosynthesis has *stopped*. It continues at a steady maximum rate, limited by something else.
- On a graph with a plateau, naming the x -axis factor as limiting on the flat part. It limits only on the rising part.
- Describing a falling temperature curve as “the enzymes are killed”. Enzymes are not alive; they denature.
- Forgetting that distance doubling cuts the light intensity to a *quarter*, not a half.

3 Leaf structure (B11.1)

A leaf is a thin, flat organ that is built to catch light, take in carbon dioxide and get rid of oxygen, while losing as little water as possible. Look at it in cross-section.



Read the layers from the top and match each to its job:

- **Waxy cuticle:** a waterproof layer that reduces water loss by evaporation from the upper surface.
- **Upper epidermis:** a thin, transparent layer with few or no chloroplasts, so light passes through it to the cells beneath. It protects the leaf.
- **Palisade mesophyll:** tall cells packed closely, each with *many chloroplasts*. This is where most photosynthesis happens. The cells are near the upper surface where the light is, and their tall shape means light passes through few cell walls before reaching chloroplasts.
- **Spongy mesophyll:** rounded cells with fewer chloroplasts, and between them large **air spaces**. Carbon dioxide diffuses through these air spaces to the palisade cells, and oxygen and water vapour diffuse out.
- **Lower epidermis:** contains most of the **stomata**, each controlled by two **guard cells**.
- **Veins:** bundles of **xylem** (bringing water and mineral ions in) and **phloem** (carrying sugars out). They also support the leaf.

Other adaptations: a leaf is *thin*, so gases have only a short distance to diffuse; it is *broad*, giving a large surface area to catch light; and it has a large internal surface area of cells in contact with the air spaces, because gases dissolve in the thin film of water on the cell walls before entering the cell.

Exam tip

If you are asked “how is the palisade layer adapted for photosynthesis?”, name the feature *and* link it to the function: “many chloroplasts, to absorb more light”, “near the upper surface, where light is strongest”. A feature alone earns no mark.

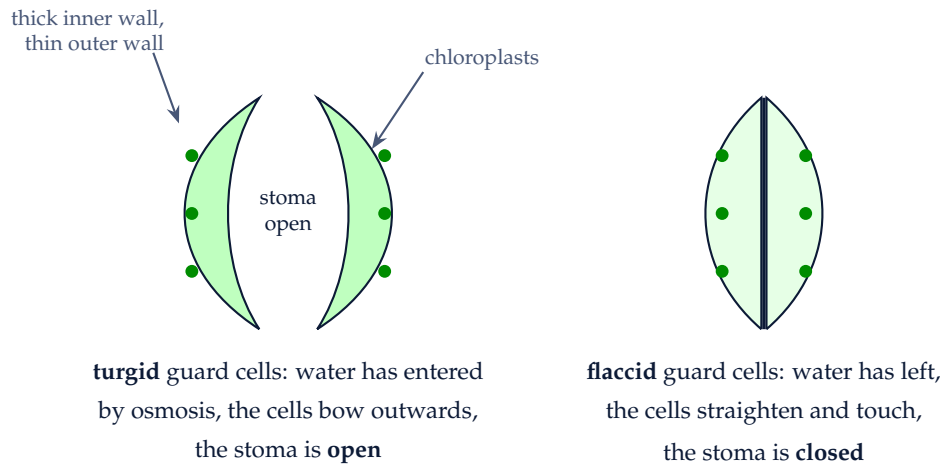
Common mistakes

- Putting the stomata on the upper surface. Most are on the lower surface, where it is cooler and less water is lost.
- Saying the spongy layer is where most photosynthesis happens. It is the palisade layer, because it has most of the chloroplasts.
- Thinking the air spaces are wasted gaps. They are the route by which carbon dioxide reaches the cells.
- Confusing xylem and phloem in the vein. Xylem brings *water* in, phloem takes *sugar* out.

4 Stomata and gas exchange (B11.1, B11.2)

A **stoma** (plural *stomata*) is a small pore, usually on the underside of a leaf, surrounded by a pair of **guard cells**. Gases pass through it *by diffusion*. In the light, carbon dioxide diffuses in because photosynthesis uses it up inside the leaf, keeping the concentration there lower than outside. Oxygen diffuses out for the opposite reason. Water vapour also diffuses out, because the air spaces are saturated with water and the outside air is usually drier.

How the guard cells open and close the stoma. The inner wall of each guard cell (next to the pore) is thicker and less stretchy than the outer wall.



When water enters the guard cells by osmosis, they become **turgid** (swollen and firm). The thin outer wall stretches more than the thick inner wall, so each cell bends outwards and the pore opens. When water leaves, the cells become **flaccid** and straighten, closing the pore. Stomata usually open in the light and close in the dark, or when the plant is short of water.

A trade-off. Open stomata allow carbon dioxide in, which the plant needs, but also let water vapour out, which it cannot afford to lose. On a hot, dry day the plant closes its stomata to save water; this lowers its photosynthesis because carbon dioxide can no longer get in. So a plant is always balancing two needs. Plants in dry places are adapted to this with thicker cuticles, fewer stomata, or stomata sunk into pits.

Estimating the number of stomata. A sample of the leaf surface is viewed under a microscope. Count the stomata in a field of view of known area, calculate the number per square millimetre, and scale up.

Worked example: counting stomata

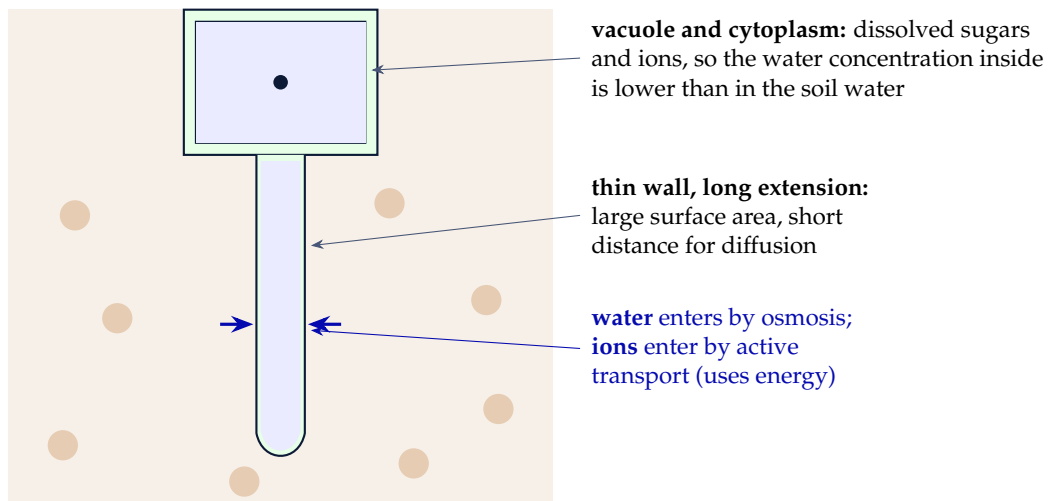
A student counts 18 stomata in a field of view of area 0.05 mm^2 on the lower surface of a leaf. The lower surface has area 20 cm^2 . Estimate the number of stomata on the lower surface.
 Density = $18 \div 0.05 = 360$ per mm^2 . Convert the area: $1 \text{ cm}^2 = 10 \times 10 = 100 \text{ mm}^2$, so $20 \text{ cm}^2 = 2000 \text{ mm}^2$.
 Number = $360 \times 2000 = 720\,000$, or 7.2×10^5 . This is an estimate because stomata are not spread perfectly evenly, so the student would count several fields and take the mean.

Common mistakes

- Saying the guard cells open when they are flaccid. Turgid (full of water) cells open the stoma.
- Believing that water moves into guard cells because they “want” to open. Water follows osmosis, after the guard cells accumulate solutes.
- Converting 1 cm^2 to 10 mm^2 . Areas scale with the *square*: $1 \text{ cm}^2 = 100 \text{ mm}^2$.
- Forgetting that closed stomata also reduce photosynthesis, not just water loss.

5 Roots: water and mineral ions (B11.2)

Plants take up water and **mineral ions** from the soil through the **root hair cells**. Each root hair cell has a long, thin projection that pushes between soil particles, giving a huge surface area and a short diffusion distance.



Water enters by **osmosis**. The soil water is a dilute solution; the cell sap in a root hair cell contains dissolved sugars and ions, so it has the lower concentration of water. Water therefore moves from the soil into the cell down this concentration gradient, through the partially permeable membrane, then across the root cortex to the xylem. No energy is needed.

Mineral ions are usually in a *lower* concentration in the soil than inside the root hair cell, so diffusion would carry them the wrong way (out). Plants take them in by **active transport**: carrier proteins in the membrane move ions *against* the concentration gradient. This needs **energy from respiration**, so it stops if the root runs short of oxygen (as in waterlogged soil) or if respiration is poisoned.

What the ions are for. Plants need only small amounts, but cannot grow properly without them:

- **Nitrate** ions: to make amino acids and so proteins (and DNA bases). Shortage: stunted growth and yellow older leaves.
- **Magnesium** ions: to make chlorophyll. Shortage: yellow leaves (chlorosis) because chlorophyll cannot be made.
- **Phosphate** ions: to make DNA, ATP (the energy carrier) and cell membranes. Shortage: poor root growth and purple leaves.

This is why farmers use fertilisers containing nitrates, phosphates and potassium. Remember the link to ecosystems: too much fertiliser washing into a lake causes eutrophication.

Worked example: which transport process?

A student places roots in a solution of potassium ions and measures the uptake rate. Uptake continues when the solution is much more concentrated than the root, but stops when she adds a poison that stops respiration, and starts again if the poison is removed. Which process is responsible, and why?

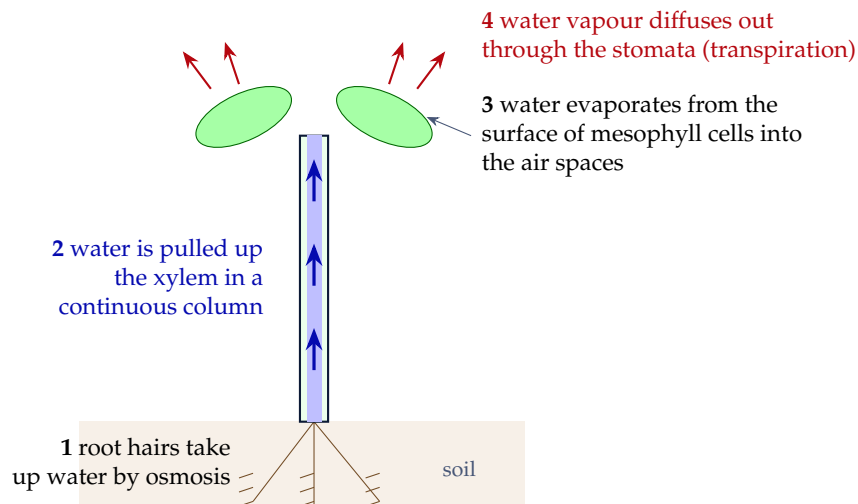
Uptake against the concentration gradient (into the already concentrated cells) rules out simple diffusion. Poisoning respiration stops uptake, so the process needs energy from respiration. The process is **active transport**.

Common mistakes

- Saying water enters root hairs by active transport. It enters by osmosis and needs no energy.
- Saying that mineral ions enter by diffusion. They are taken in against the gradient by active transport.
- Describing water as moving from a high concentration of solute to a lower one. Water moves from where its own concentration is higher (dilute solution) to lower (concentrated solution).
- Thinking plants need minerals “for energy”. Minerals build molecules; they are not a fuel.

6 Transpiration (B11.2)

Transpiration is the loss of water vapour from the leaves of a plant, mostly through the stomata. It is a result of the plant’s need to open its stomata. The path of the water is a continuous **transpiration stream**.



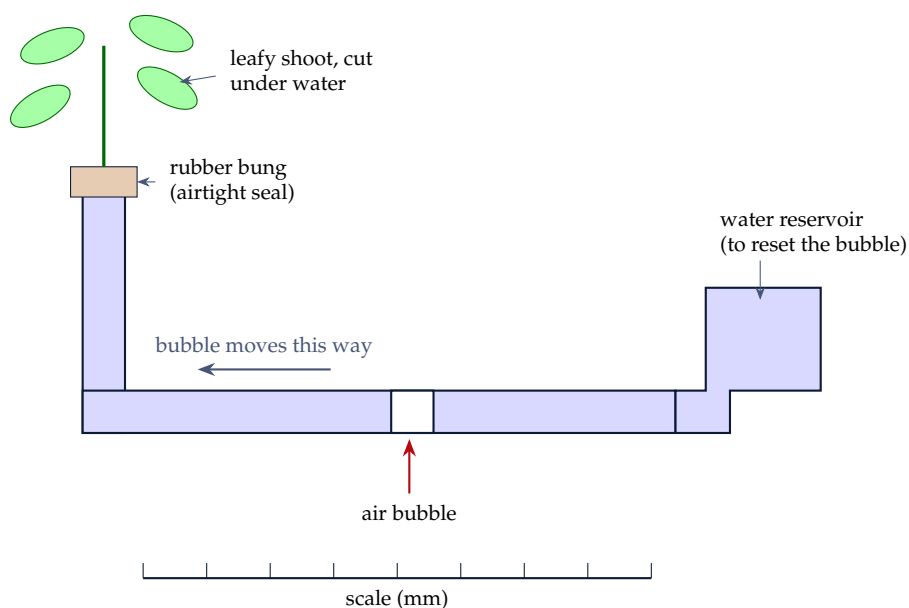
Follow it step by step. Water is absorbed by root hairs and enters the xylem. In the leaf, water evaporates from the wet surfaces of the mesophyll cells into the air spaces, and the vapour diffuses out through the stomata. The water lost is replaced by water pulled up the xylem. Water molecules **stick together** (cohesion) and also stick to the walls of the xylem, so the column does not break: the evaporation at the top pulls the whole column up like a rope. This is why the stream is also called a *transpiration pull*.

Why is it useful? The stream brings in the water needed for photosynthesis, supports the plant by keeping cells turgid, cools the leaf as water evaporates, and carries dissolved mineral ions from the roots to the leaves. If more water is lost than is taken up, cells become flaccid and the plant **wilts**.

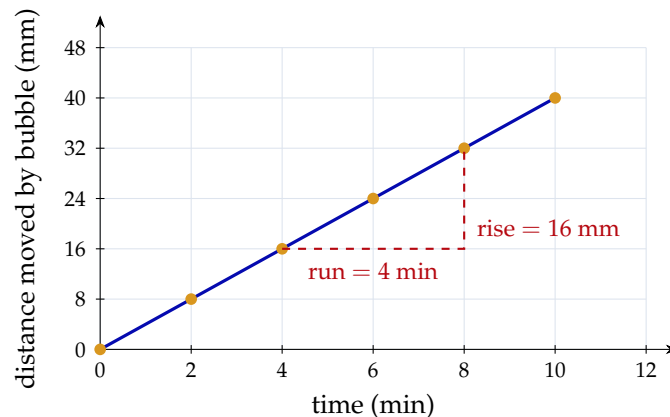
What affects the rate? Anything that speeds evaporation and diffusion of water vapour out of the leaf.

- **Light:** more light, more open stomata, faster transpiration.
- **Temperature:** warmer, water molecules evaporate faster and diffuse faster.
- **Humidity:** in humid air the concentration gradient of water vapour is smaller, so less diffuses out. Dry air increases the rate.
- **Air movement (wind):** wind blows away the humid air next to the leaf, keeping the gradient steep, so the rate increases.

Measuring it: the potometer. A cut leafy shoot is sealed in a tube connected to a horizontal capillary tube containing an air bubble, as shown. As the shoot takes up water, the bubble moves along the scale. Strictly a potometer measures *water uptake*, but nearly all the water taken up is lost by transpiration, so it is a good estimate of the rate. Cutting the shoot under water avoids air bubbles in the xylem, and a water reservoir is used to push the bubble back to the start for repeats.



Rate calculations. A rate is a quantity divided by time. The speed of the bubble is **distance moved** $\div$ **time**, which is the **gradient** of a distance–time graph. A straight line means a constant rate.



To convert distance to a *volume*, treat the capillary as a cylinder: $\text{volume} = \pi r^2 \times \text{length}$, where r is the internal radius of the tube.

Worked example: the rate of water uptake

The graph above shows a bubble moving along a capillary tube of internal radius 0.5 mm. (a) Find the speed of the bubble. (b) Find the volume of water taken up per minute, leaving your answer in terms of π . (c) The shoot has a total leaf area of 50 cm². Find the volume per hour per square centimetre of leaf.

(a) Gradient = $(32 - 16) \div (8 - 4) = 16 \div 4 = 4$ mm/min (also $40 \div 10 = 4$ from the last point). (b) Volume per minute = $\pi r^2 \times 4 = \pi \times 0.25 \times 4 = \pi$ mm³ per minute. (c) Per hour: 60π mm³. Per cm²: $60\pi \div 50 = 1.2\pi \approx 3.8$ mm³ per hour per cm². (Using $\pi \approx 3.14$.)

Worked example: water loss per unit area

A potted plant is sealed in a bag so that only water lost from the leaves is measured. Over 4 hours, the pot and plant lose 60 g in mass. The leaves have a total area of 0.3 m². Find the rate of water loss in grams per square metre per hour.

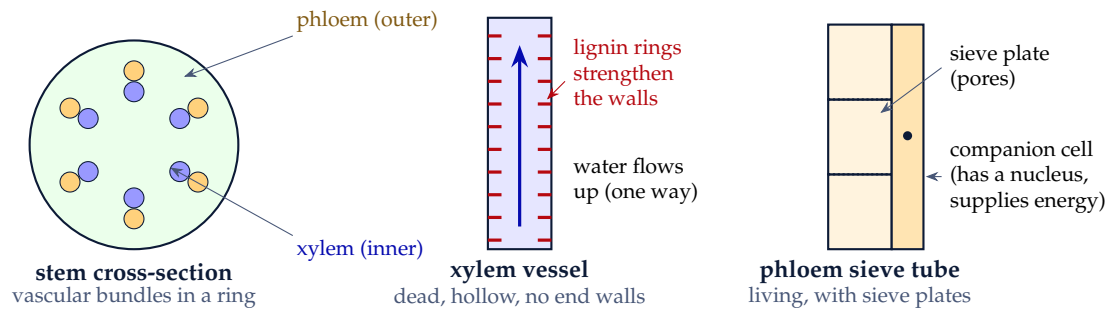
Per hour: $60 \div 4 = 15$ g. Per m²: $15 \div 0.3 = 50$ g/(m² · h). Divide by time, then by area. A check on units: g m⁻² h⁻¹ means grams, per square metre, per hour.

Common mistakes

- Saying transpiration is the movement of water up the xylem. It is the *loss of water vapour* from the leaf; the upward movement is the transpiration stream.
- Saying wind decreases transpiration because the leaf is cooled. Wind removes the humid air layer and increases the rate.
- Saying humidity increases transpiration because there is more water in the air. More water in the air means a smaller gradient and a slower rate.
- In a rate calculation, forgetting to divide by time, or using diameter in place of radius in πr^2 .

7 Xylem, phloem and translocation (B11.2)

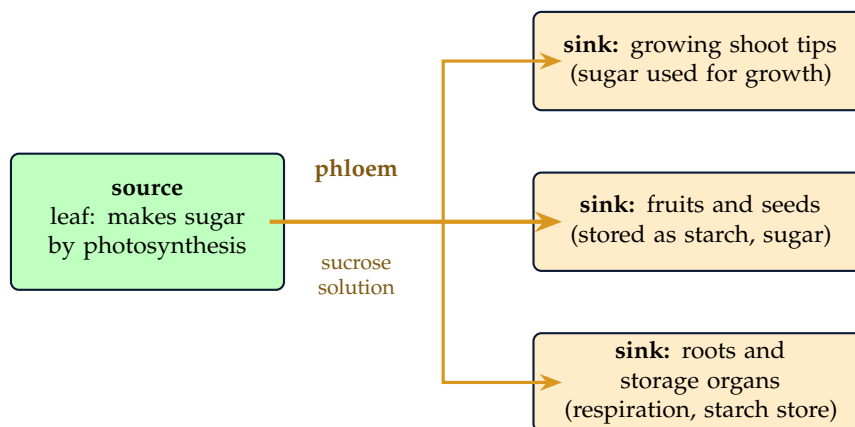
Plants have two transport tissues, found together in the **vascular bundles** of the roots, stems and leaves. They are quite different.



Xylem carries water and mineral ions from the roots to the shoots, in one direction only (upwards). Xylem vessels are formed from cells that have **died**: the end walls break down, leaving a hollow tube, with no cytoplasm to get in the way of flow. The walls are thickened and strengthened with a tough waterproof material called **lignin**, which stops the vessel collapsing under the low pressure of the transpiration pull and also supports the plant.

Phloem carries dissolved sugars (mainly **sucrose**) and amino acids from where they are made to where they are needed. This is **translocation**. Phloem is made of living cells called **sieve tube elements**, joined end to end, with perforated end walls (**sieve plates**) that let the contents flow through. Each is helped by a **companion cell** which has a nucleus and many mitochondria, and supplies the energy for loading the sugar. Translocation can go in *both directions* in the plant, and it needs energy, unlike transpiration.

Sources and sinks. A **source** is a part of the plant that makes or releases sugar, for example a leaf in daylight. A **sink** is a part that uses or stores it: growing shoot tips and roots, developing fruits and seeds, storage organs such as potato tubers. Sugar moves from sources to sinks, so the direction depends on the season: in spring, stored sugar moves *up* from the roots to the new buds (roots are the source); in summer, it moves *down* from the leaves.



	Xylem	Phloem
Carries	water and mineral ions	sucrose and amino acids
Direction	upwards only	both directions
Cells	dead, hollow, lignified	living, sieve plates, companion cells
Driven by	evaporation (transpiration pull)	active loading (needs energy)

Evidence. If a ring of bark (which contains the phloem) is removed from around a stem, the xylem inside is untouched, so water still reaches the leaves. Sugar made in the leaves cannot pass the gap, so it *builds up and the stem swells above the ring*, and the roots below slowly starve. This shows that sugar travels in the phloem. Aphids insert their mouthparts into phloem and feed on the sugary sap; a severed mouthpart leaks sap which can be analysed.

Worked example: interpreting a ringing experiment

A ring of bark is removed from a young tree trunk. After a few weeks the bark just above the ring has swollen, and the tree is still alive, with green leaves. Explain both observations.

The bark contains the phloem. Sugar made in the leaves travels down in the phloem but cannot cross the gap where the phloem has been removed, so it accumulates just above the ring, which swells. The xylem lies inside the bark and is not damaged, so water still flows up to the leaves, and they stay green. Eventually the roots, which get no

sugar, would starve and the tree would die.

Exam tip

For a “compare xylem and phloem” question, give a pair of contrasts in *each* row (what is carried, direction, living or dead). Saying “xylem carries water and phloem carries sugar” once will only earn half the marks.

Common mistakes

- Saying xylem carries sugars, or that phloem carries water. Xylem: water and minerals. Phloem: sugars and amino acids.
- Saying phloem is dead tissue. Xylem is dead; phloem is made of living cells.
- Saying phloem moves things only down. It moves sugar from sources to sinks, in whichever direction that is.
- Removing a ring of bark and expecting the leaves to wilt. The xylem is not removed, so water still flows.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. Write the word equation and the balanced symbol equation for photosynthesis. State two things that glucose is used for.
2. A graph of photosynthesis against light intensity rises and then levels off. Explain both parts.
3. Why does the rate of photosynthesis fall steeply above about 40 °C?
4. A lamp is moved from 10 cm to 30 cm from a plant in which light is limiting. By what factor does the rate change?
5. Give two ways in which the palisade layer is adapted for photosynthesis.
6. Explain how guard cells open a stoma, and why the stomata close on a hot, dry day.
7. Explain how plants take up (a) water and (b) mineral ions into root hair cells.
8. A bubble in a potometer moves 18 mm in 6 minutes. State the speed, and name two conditions that would increase it.

Answers to the self-check

1. Carbon dioxide + water → glucose + oxygen; $6\text{CO}_2 + 6\text{H}_2\text{O} \longrightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$, with light and chlorophyll. Glucose is used for respiration, stored as starch, made into cellulose, or made into proteins with nitrate.
2. On the rising part light is the limiting factor. On the plateau, another factor (carbon dioxide concentration or temperature) is limiting, so more light has no effect.
3. The enzymes that control the reactions denature: their active sites change shape and no longer fit the substrate.
4. The distance is trebled, so the intensity is $1/3^2 = 1/9$ of the original. The rate falls to one ninth.
5. It has many chloroplasts to absorb light, and it is near the upper surface where the light is strongest (the cells are tall and packed closely, so light passes through few cell walls).
6. Water enters by osmosis, so the guard cells become turgid and bend apart because of the thick inner walls. On a hot day they lose water and close, which reduces water loss.
7. (a) Osmosis, down a concentration gradient of water. (b) Active transport, against the concentration gradient, using energy from respiration.
8. $18 \div 6 = 3 \text{ mm/min}$. A higher temperature, drier air, more wind or brighter light all increase the rate.

Next step

Heurisco's *ESAT Biology: Plant Physiology Practice Set* has twenty original exam-style questions on this lesson, with leaf diagrams, limiting-factor graphs, potometer data and rate calculations, in order of difficulty, with a full worked solution, a common-trap note and the specification code for every question.