REVISION GUIDE

Open to the *air*

Gas exchange

Every animal and plant has to take in one gas and give out another, and both solve it the same way: a large, thin, moist surface, with the gradient across it kept steep. A leaf lets carbon dioxide in through pores that cost it water; your lungs move air in and out over millions of tiny sacs, and your blood carries the oxygen away. The leaf comes first, then the lungs and the blood.

16 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-b3-1-gas-exchange

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By the end you can

- [ ] Explain why every organism exchanges gases, and why being bigger makes it harder B3.1.1
- [ ] Describe the four properties of a gas-exchange surface and why each one matters B3.1.2
- [ ] Explain how a leaf's waxy cuticle, epidermis, air spaces, spongy mesophyll, guard cells and veins suit it to gas exchange B3.1.7
- [ ] Draw and label a plan diagram of a leaf in transverse section from a micrograph B3.1.8
- [ ] Explain why transpiration is the price of gas exchange, and how light, temperature, humidity and wind change its rate B3.1.9
- [ ] Find a leaf's stomatal density from a leaf cast or a micrograph, and explain why repeated counts make it more reliable B3.1.10
- [ ] Explain how blood flow and ventilation keep the gradient steep at an animal's exchange surface, with air for lungs and water for gills B3.1.3
- [ ] Relate the branching airways, the alveoli, the capillary beds, the surface area and the surfactant of a mammal's lungs to gas exchange B3.1.4
- [ ] Explain how the diaphragm, ribs, intercostal and abdominal muscles change the volume and pressure of the chest to ventilate the lungs B3.1.5
- [ ] Measure tidal volume, vital capacity and the two reserve volumes, and say what makes a result reliable B3.1.6
- [ ] Explain how cooperative binding and the binding of carbon dioxide suit haemoglobin, adult and foetal, to carrying oxygen B3.1.11
- [ ] Explain how more carbon dioxide makes haemoglobin release more oxygen (the Bohr shift) and why that helps working tissue B3.1.12
- [ ] Read an oxygen dissociation curve for affinity and explain its S shape B3.1.13

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

B3.1.1 B3.1.2 GAS EXCHANGE IN EVERY ORGANISM, AND THE SURFACES THAT DO IT

01 Every cell needs a *way in*

Every living cell respires, and aerobic respiration uses oxygen and gives out carbon dioxide. So almost every organism has to take oxygen in and get rid of carbon dioxide, all the time. That swap is **gas exchange**. Plants respire too, day and night. A leaf in the light also photosynthesises, taking carbon dioxide in and giving oxygen out, and in bright light it does this faster than it respires, so overall the leaf takes carbon dioxide in. In the dark the swap runs the other way.

Gases cross a surface by **diffusion**, from where they are more concentrated to where they are less. Diffusion is quick across a cell or two and slow over longer distances: twice as far takes about four times as long. A single cell, or a flatworm a few cells thick, is supplied through its outer surface. But as anything grows, its volume grows faster than its surface, so its **surface area to volume ratio** falls, and its centre ends up further from the outside. A large organism needs a surface made for gas exchange, and a way to carry the gases between that surface and every cell.

A **gas-exchange surface** has four properties. It is **permeable**, so oxygen and carbon dioxide can pass through it. It is **thin**, often one layer of cells, so the gases have only a short way to go. It is **moist**, because a gas has to dissolve in water before it can diffuse into a cell. And it has a **large surface area**, so a lot of gas crosses at once. Chapter 9 shows all four in a lung's alveolus. The inside of a leaf has all four (chapter 2). So do the lungs, which come later, with the human body.

KEY POINTS

- Every organism exchanges gases because every cell respires; a leaf in the light also takes in carbon dioxide for photosynthesis.
- As an organism gets bigger, its surface area to volume ratio falls and the distance from its centre to the outside rises.
- A gas-exchange surface is permeable, thin, moist and large.

KEY TERMS

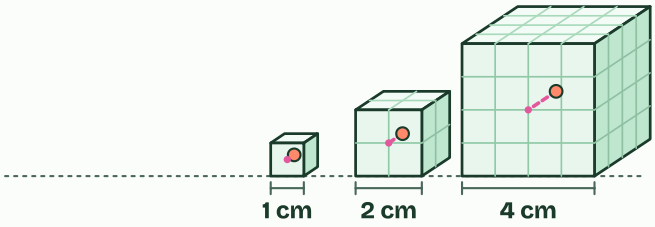
gas exchange
Taking in one gas and giving out another across a surface: oxygen in and carbon dioxide out for respiration; in a leaf in the light, carbon dioxide in and oxygen out for photosynthesis.

diffusion
The net movement of particles from where they are more concentrated to where they are less concentrated, caused by their random motion. The cell spends no energy on it.

surface area to volume ratio
The surface area of an object divided by its volume. It falls as an object of the same shape gets bigger.

gas-exchange surface
The surface where gases enter and leave an organism: the walls of the mesophyll cells in a leaf, the alveoli in a lung, the gills of a fish. Every one is permeable, thin, moist and large.

Bigger cube, smaller ratio

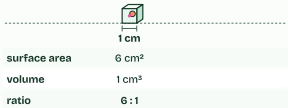


	1 cm	2 cm	4 cm
surface area	6 cm²	24 cm²	96 cm²
volume	1 cm³	8 cm³	64 cm³
ratio	6 : 1	3 : 1	1.5 : 1
centre to face	0.5 cm	1 cm	2 cm

the ratio falls ↓ — the distance rises ↑

STEP BY STEP — 4 STEPS

1



A 1 cm cube: a surface of **6 cm²** round a volume of **1 cm³**, a ratio of 6 : 1. Its centre is 0.5 cm from the nearest face.

2



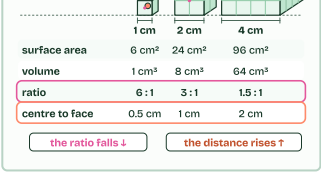
Double the side to 2 cm. The surface grows four times, to 24 cm², but the volume grows eight times, to 8 cm³: the ratio halves, to **3 : 1**.

3



Double it again, to 4 cm: 96 cm² round 64 cm³, a ratio of **1.5 : 1**. The centre is now 2 cm from the outside.

4

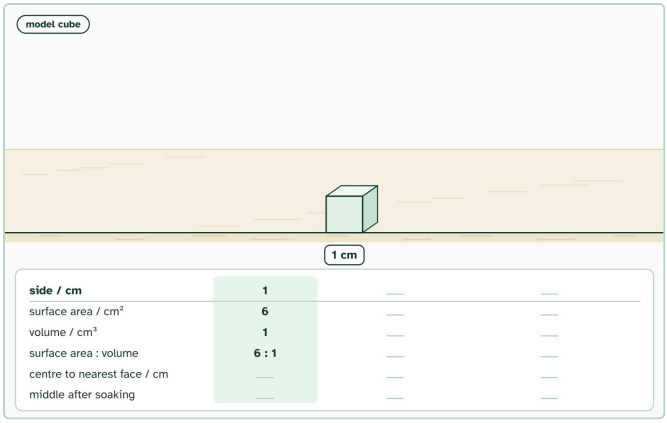


As a cube grows, each square centimetre of its surface has more volume to supply, from further away: the ratio **falls** as the distance **rises**.

ANIMATION · BIGGER BODIES, SLOWER SUPPLY

4 MOMENTS

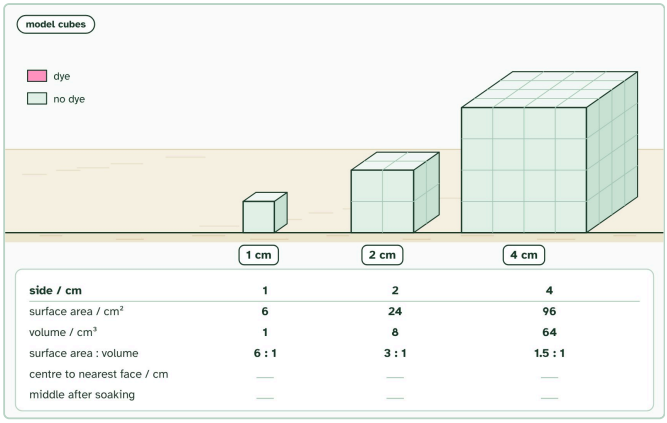
1 1 CM CUBE



side / cm	1	—	—
surface area / cm²	6	—	—
volume / cm³	1	—	—
surface area : volume	6 : 1	—	—
centre to nearest face / cm	—	—	—
middle after soaking	—	—	—

A **model** cube, not a real cell: 1 cm on each side, with 6 cm² of surface around 1 cm³ of volume.

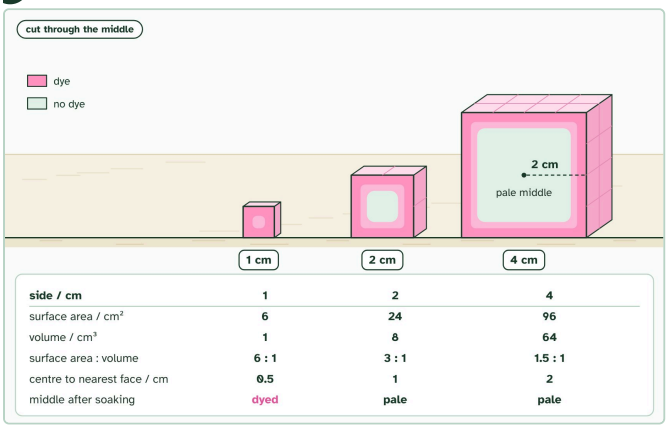
2 THREE CUBES



side / cm	1	2	4
surface area / cm²	6	24	96
volume / cm³	1	8	64
surface area : volume	6 : 1	3 : 1	1.5 : 1
centre to nearest face / cm	—	—	—
middle after soaking	—	—	—

Three cubes **soak in a dye** for the same time: just long enough for it to reach the centre of the 1 cm cube.

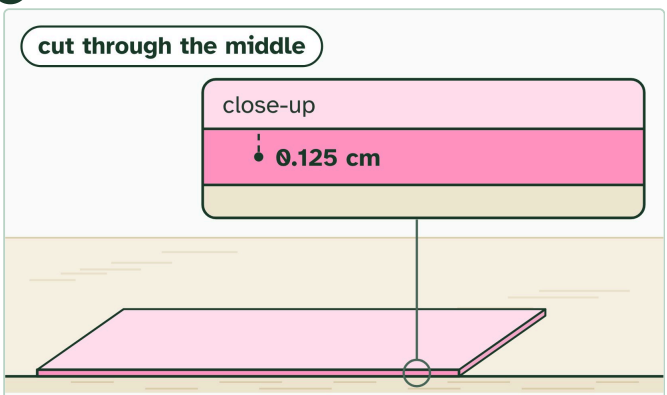
3 THREE CUBES



side / cm	1	2	4
surface area / cm²	6	24	96
volume / cm³	1	8	64
surface area : volume	6 : 1	3 : 1	1.5 : 1
centre to nearest face / cm	0.5	1	2
middle after soaking	dyed	pale	pale

Cut open, the 1 cm cube is dyed right through. The 4 cm cube is still **pale** in the middle, 2 cm from the nearest face.

4 SHEET



shape	cube	sheet
surface area / cm²	96	528
volume / cm³	64	64
surface area : volume	1.5 : 1	8.25 : 1
centre to nearest face / cm	2	0.125
middle after soaking	pale	dyed

The 4 cm cube's 64 cm³ squashed into a sheet 0.25 cm thick: after the same soak it is dyed right through, as no part is more than 0.125 cm from a surface.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#surface

REMEMBER IT

The four properties of a gas-exchange surface

T	M	P	L
Too	Many	Pink	Leaves
Thin	**Moist**	**Permeable**	**Large surface area**
a short path to cross	gases dissolve first	lets the gases through	more gas crosses at once

WATCH OUT

"Plants photosynthesise instead of respiring." Every living plant cell respires, in the light and in the dark. In bright light a leaf photosynthesises faster than it respires, which hides the respiration in its overall gas exchange; in the dark it only respires.

LINKING QUESTIONS

How do multicellular organisms solve the problem of access to materials for all their cells? Chapter 6 answers it for a leaf, and B3.2 for the whole plant. What is the relationship between gas exchange and metabolic processes in cells? Chapter 4 answers it.

PREDICT

The 4 cm cube is squashed into a sheet 16 cm by 16 cm and 0.25 cm thick, with the same volume. Compared with the cube, how quickly is every part of it supplied?

(A) More slowly: the sheet is 16 cm wide, so its middle is 8 cm from the nearest edge

(B) Quickly everywhere: there is far more surface for the volume, and no part is far from it

(C) The same: the volume decides how long the supply takes, and the volume has not changed

(D) Faster only at the edges: the middle of the sheet is as far from the air as the cube's centre

Decide before you look. Answer on page 67.

02

B3.1.7 ADAPTATIONS FOR GAS EXCHANGE IN LEAVES

A leaf is built for *gas exchange*

A leaf is a plant's organ of photosynthesis, and so of gas exchange. It is broad, which gives it a large surface to catch light and take in carbon dioxide, and thin, so the gases never have far to go. Its problem is water. Wet cells in air lose water by evaporation, and a leaf that lost water from its whole surface would soon wilt.

So the outside of a leaf is waterproofed. The **epidermis**, one layer of tightly fitted cells with few or no chloroplasts, makes a **waxy cuticle** over itself. Its cells are clear, so light passes through them. The wax keeps water in, but it keeps carbon dioxide out too, so gases need a way through: the **stomata** (one is a stoma), each a pore between two **guard cells** that can open or close it (chapter 4). Most are in the lower epidermis.

Inside, the cells are wet, and that is the point. Under the upper surface is the **palisade mesophyll**, tall cells packed with chloroplasts, where most of the light is caught. Below it, the cells of the **spongy mesophyll** are loosely packed, and the **air spaces** between them join up from every stoma to every cell. The moist walls of these **mesophyll** cells are the real gas-exchange surface: carbon dioxide dissolves in the film of water on them and diffuses into the cells, and oxygen leaves the same way. Gases diffuse thousands of times faster through air than through water, so the air spaces bring the air almost to every wet wall.

Every leaf is threaded with **veins**. Each holds xylem, which brings water to replace what evaporates from those wet walls, and phloem, which carries away the sugars the leaf makes. The veins branch so finely that no cell is far from one.

KEY POINTS

- The waxy cuticle and the epidermis keep water in, and keep gases out too.
- Stomata let gases through the epidermis, and guard cells open and close them.
- Air spaces carry gases from the stomata to every mesophyll cell; the moist walls of those cells are the exchange surface.
- Veins bring water in through the xylem and take sugars away in the phloem.

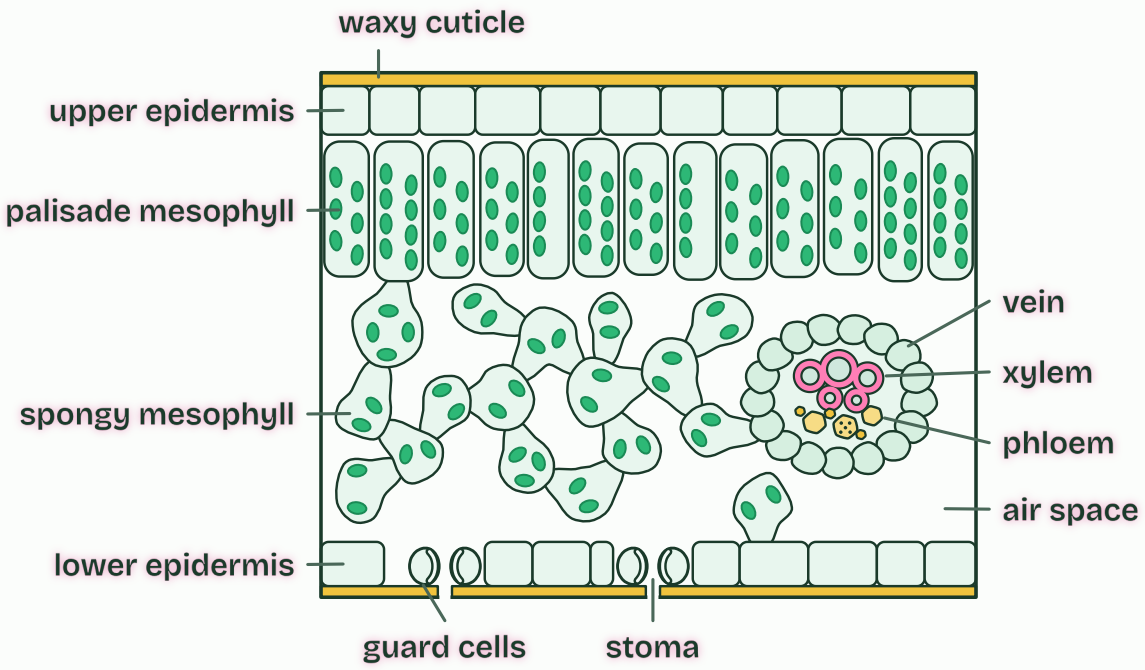
KEY TERMS

waxy cuticle
A layer of wax over the epidermis of leaves and stems. It keeps water in, and keeps gases out.

stomata
Pores in the epidermis of a leaf (one is a stoma), each between two guard cells. Gases enter and leave the leaf through them.

guard cells
The pair of cells round each stoma. They swell to open it and go limp to close it, and they have chloroplasts, where the other cells of the epidermis have few or none.

mesophyll
The tissue between a leaf's upper and lower epidermis: the palisade and spongy layers. The name means the middle of the leaf.



A leaf cut across, upper surface at the top. The cuticle is drawn thicker than it is.

Air spaces The air between the mesophyll cells, joined up from every stoma to every cell. Gases diffuse thousands of times faster through air than through water.

Palisade mesophyll Tall cells packed with chloroplasts, just under the upper surface, where the light is brightest. Most of the leaf's photosynthesis happens here.

Xylem Tubes with walls thickened by lignin (pink here). They bring water into the leaf, replacing what evaporates from the wet cell walls.

Upper epidermis One layer of tightly fitted cells with few or no chloroplasts. They are clear, so light passes through them; they make the cuticle and protect the cells below.

Guard cells A pair round each stoma, with chloroplasts, where the other epidermis cells have few or none. They open the pore to let carbon dioxide in and close it to save water (chapter 4).

Spongy mesophyll Loosely packed, rounded cells. Their wet walls are the gas-exchange surface: carbon dioxide dissolves in the water on them and diffuses in.

Vein A bundle of xylem and phloem in a sheath of cells. Veins branch all through the leaf, so no cell is far from one.

Phloem Living tubes, joined end to end through sieve plates, that carry the sugars the leaf makes (yellow here) to the rest of the plant.

Lower epidermis Like the upper epidermis, under its own cuticle, but with most of the leaf's stomata in it.

Waxy cuticle A layer of wax made by the epidermis, over both surfaces (drawn thicker than it is). It is waterproof, so the leaf does not dry out, but gases cannot cross it either.

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Waxy cuticle A layer of wax made by the epidermis, over both surfaces (drawn thicker than it is). It is waterproof, so the leaf does not dry out, but gases cannot cross it either.

REMEMBER IT

The layers of a leaf, top to bottom

C	U	P	S	L
Cats	Usually	Purr	Softly	Lazily
Cuticle waterproof wax	**Upper epidermis** one clear layer	**Palisade mesophyll** packed with chloroplasts	**Spongy mesophyll** loose, with air spaces	**Lower epidermis** most of the stomata

WATCH OUT

"Gas exchange happens across the whole surface of the leaf." The cuticle stops almost all of it. Nearly all the gas exchange of a leaf goes through its stomata, and then across the wet walls of the cells inside.

PREDICT

Why are most of a leaf's stomata in its lower surface?

(A) Carbon dioxide is denser than air, so it collects under the leaf, where the pores can take it in

(B) The upper surface needs all of its room for the palisade cells that catch most of the light

(C) The underside is shaded and cooler, so less water evaporates out through its open pores

(D) Guard cells in the upper surface would be damaged by the full sunlight falling on them

Decide before you look. Answer on page 67.

03 Drawing a leaf in *plan*

B3.1.8 DISTRIBUTION OF TISSUES IN A LEAF

Start with a prediction.

A **plan diagram** shows where the tissues are, not what their cells look like. You draw the outline of each tissue as one region, in the same proportions and positions as in the **micrograph** or slide you are drawing from, and no single cells. That makes a plan quick to draw and easy to read, and it answers the question the syllabus asks here: where is each tissue? B3.2 asks it again of a stem and a root.

In a **transverse section** of the leaf of a dicotyledonous plant (a dicot: a flowering plant with two seed leaves and net-veined leaves), the tissues lie in layers. From the top: the upper epidermis with its cuticle, the palisade mesophyll, the spongy mesophyll and the lower epidermis. The veins run through the mesophyll, and the biggest, the midrib, makes a bulge underneath, filled round its vein by packing tissue: plain, thin-walled cells that fill the space. In each vein the xylem usually lies towards the upper surface and the phloem towards the lower.

KEY POINTS

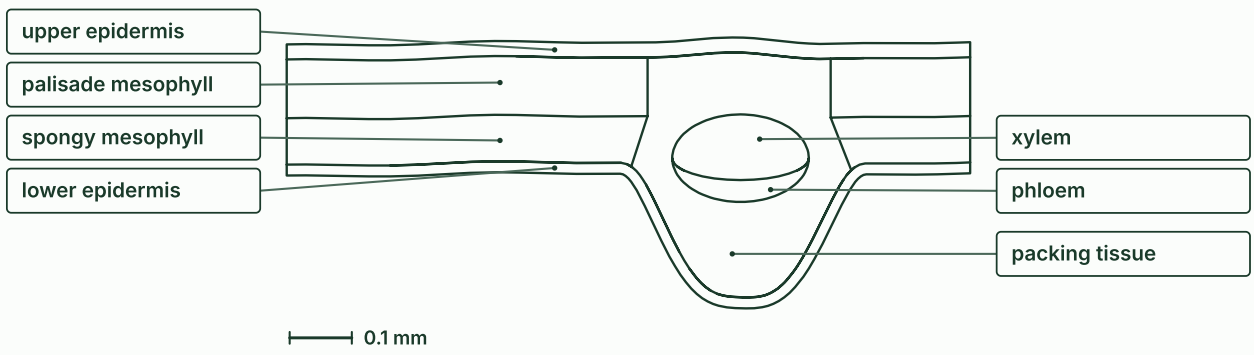
- Outlines of tissues only: no single cells.
- Proportions and positions as the micrograph shows them, not as a textbook does.
- Single, sharp, continuous lines in pencil: no sketching, no gaps, no doubled lines.
- No shading and no colour.
- Labels to the side, joined by ruled lines that touch the tissue, with no arrowheads, and never crossing.
- A title that names the organ and the section, and a scale bar or the magnification.

KEY TERMS

plan diagram
A drawing that shows where the tissues of an organ are, as outlines of regions, with no single cells drawn.

micrograph
An image taken through a microscope. A light micrograph of a leaf shows its tissues stained in colour.

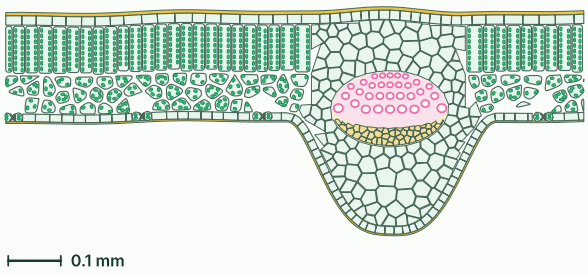
transverse section
A thin slice cut straight across an organ, at right angles to its length.



Plan diagram: transverse section of a dicotyledonous leaf, through the midrib

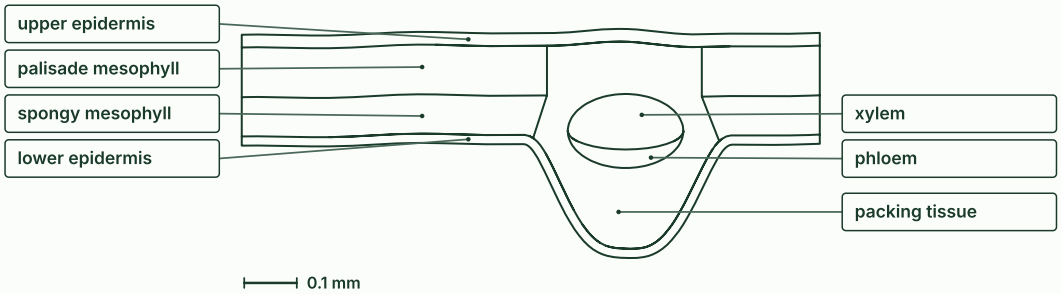
STEP BY STEP
2 STEPS

1



A light micrograph, drawn: a transverse section of a leaf through its midrib, every cell in view. Lignified walls are pink, as the stain colours them; the cuticle is shown yellow and thicker than true scale.

2



Plan diagram: transverse section of a dicotyledonous leaf, through the midrib

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.

PREDICT

A plan diagram shows where each tissue of an organ is. A student draws every palisade cell in their plan of a leaf. What is wrong?

(A) The cells should be shaded in green, to show which of the leaf's cells hold its chloroplasts

(B) The palisade layer belongs below the spongy layer, nearer to the stomata that supply its air

(C) The cells should be drawn at a higher magnification, so that each one is large enough to see

(D) A plan shows the outline of each tissue, and none of the separate cells inside it at all

Decide before you look. Answer on page 67.

WATCH OUT

Draw what the micrograph shows, not what you remember from a textbook. If its palisade layer is thinner than its spongy layer, so is yours: the proportions are checked against the image.

04 Guard cells open and close the *door*

B3.1.7 STOMATAL GUARD CELLS

How open a stoma is depends on how much water its two guard cells hold. Each guard cell's wall is thicker on the side facing the pore. When the guard cells take in water they swell and become **turgid**. Their thin outer walls stretch more than the thick inner ones, so the two cells bow apart and the pore opens. When they lose water they become **flaccid**, straighten, and the pore closes.

What moves the water is potassium. In the light, guard cells take up potassium ions (K^+) from the cells around them. That raises the concentration of solutes inside them, and water follows by **osmosis**. In the dark they lose potassium ions, the water leaves, and the pore closes.

Open or shut, there is a price. Open stomata let carbon dioxide in for photosynthesis, and let water vapour out. Shut, they save water but cut off the carbon dioxide. A plant balances the two all day, and chapter 6 follows the water.

The signal is a plant hormone, **abscisic acid**. A plant short of water makes more of it, and it makes the guard cells lose potassium ions, so the stomata close even in bright light. Higher level students meet plant hormones again in C3.1.

KEY POINTS

- A guard cell's wall is thickest on the pore side, so turgid guard cells bow apart and open the stoma.
- Potassium ions taken up in the light draw water in by osmosis; losing them lets the water out and closes the pore.
- Abscisic acid closes the stomata when the plant is short of water, even in the light.

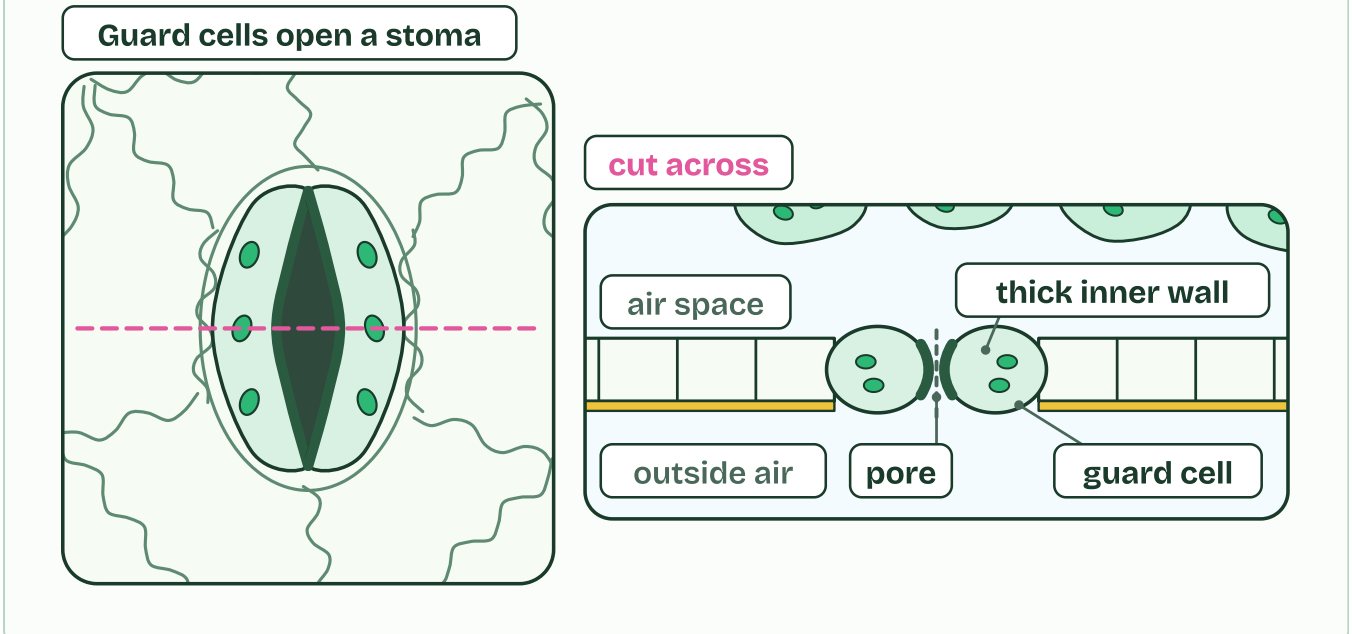
KEY TERMS

turgid
Swollen with water, so the cell pushes on its wall. Turgid guard cells bow apart and open their stoma.

flaccid
Short of water, so the cell no longer presses on its wall. Flaccid guard cells straighten and close their stoma.

osmosis
The net movement of water across a partially permeable membrane, from a less concentrated solution to a more concentrated one.

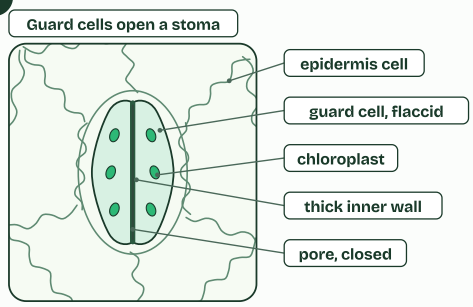
abscisic acid
A plant hormone made when a plant is short of water. It makes guard cells lose potassium ions, so the stomata close.



STEP BY STEP

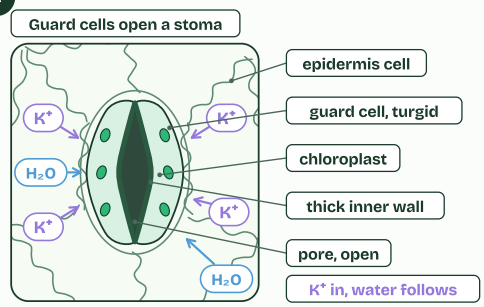
3 STEPS

1



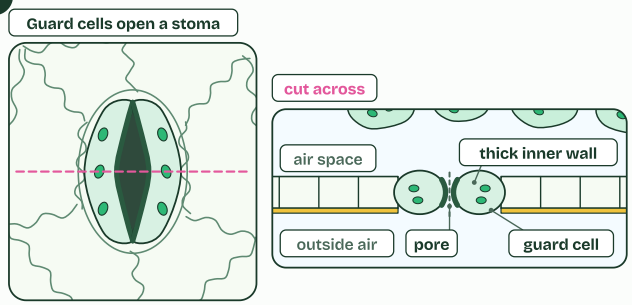
A stoma seen from outside the leaf, closed. Its two guard cells are **flaccid**: they hold little water, lie straight and meet along the pore. Each has chloroplasts, and a thick wall on the side facing the pore.

2



In the light, potassium ions (K^+) move into the guard cells and water follows by **osmosis**. The cells swell and become **turgid**. Their thin outer walls stretch more than the thick inner ones, so the cells bow apart and the pore opens.

3

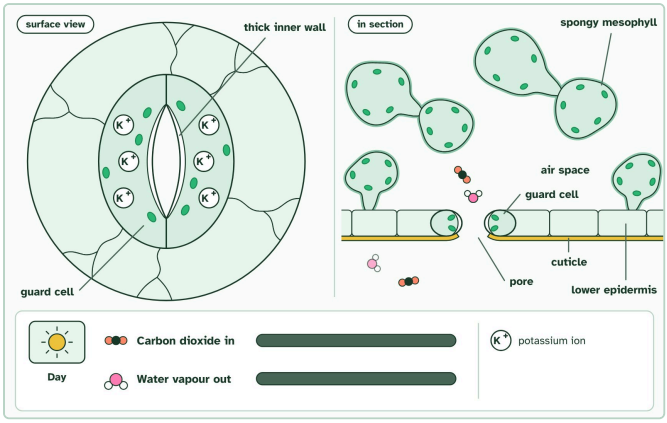


The same open pair cut across the middle, as in the leaf of chapter 2. The thick walls line the pore, and the pore opens into an air space inside the leaf.

ANIMATION · OPEN, CLOSED, AND THE PRICE OF EACH

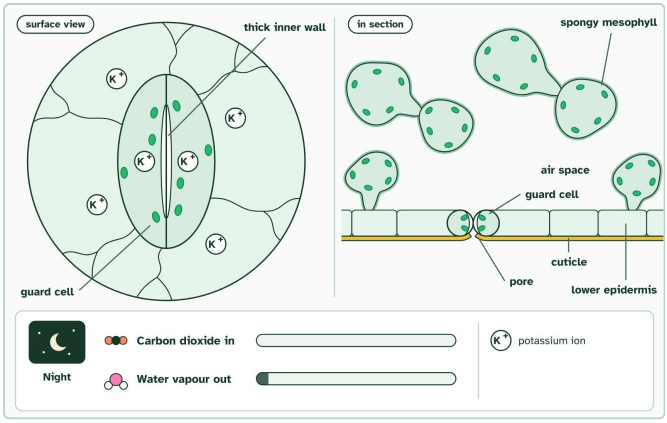
3 MOMENTS

1 DAY



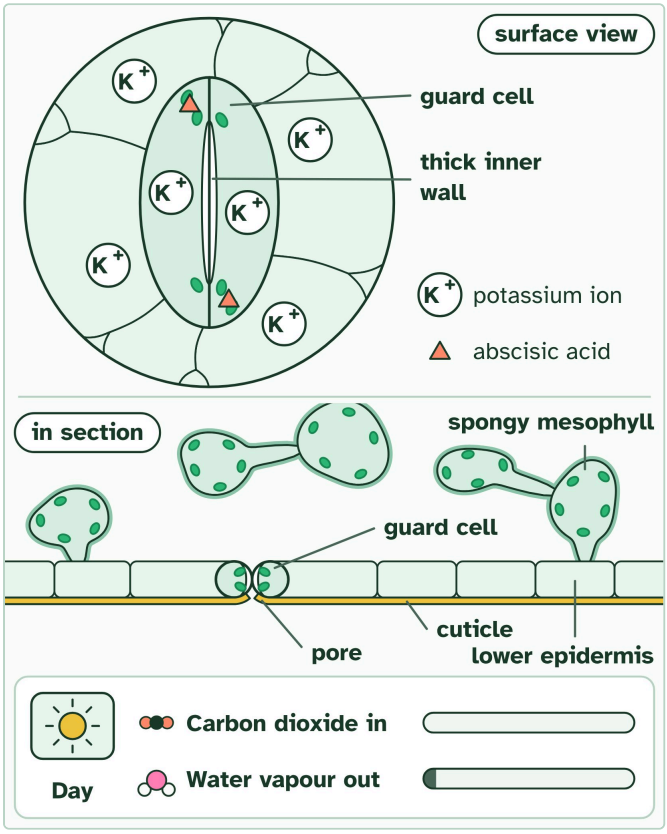
Carbon dioxide diffuses in through the open pore for photosynthesis, and water vapour diffuses out.

2 NIGHT



Night. With no light, the guard cells have lost potassium ions and water, and the pore is closed: far less water vapour escapes, though a little still gets out through the cuticle.

3 SHORT OF WATER



Short of water in daylight: abscisic acid has made the guard cells lose potassium ions, and the pore has closed. Water is saved, but carbon dioxide is shut out too.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#stomata

PREDICT

A plant in bright sunshine runs short of water. What do its stomata do?

(A) They open wider, so that more water evaporates and keeps the leaf cool in the sun

(B) They stay open: light makes guard cells take up potassium ions, whatever else happens

(C) They open and close faster, taking in carbon dioxide between the bursts of water loss

(D) They close: holding on to water now matters more than taking in carbon dioxide

Decide before you look. Answer on page 67.

LINKING QUESTION

What is the relationship between gas exchange and metabolic processes in cells? The carbon dioxide that comes in through an open stoma is fixed into sugar in the chloroplasts of the mesophyll, and some of the oxygen given off is used in the same cells' respiration (C1.2). C1.3's film Follow one carbon atom (a higher level chapter there) takes one carbon from the air into a sugar.

WATCH OUT

"Guard cells pull the pore open like muscles." Plants have no muscles. Guard cells change shape because water moves into or out of them by osmosis, and their uneven walls turn that swelling into a gap.

05 Counting *stomata*

B3.1.10 STOMATAL DENSITY

Stomatal density is the number of stomata in a unit area of leaf surface, usually given per mm². You can find it from a micrograph that has a scale, or from a **leaf cast**: paint a thin layer of clear nail varnish on the leaf, let it dry, press clear tape onto it, peel the varnish off with the tape and stick it on a slide. The varnish keeps the shape of the epidermis, guard cells and all.

Find the cast at low power, then count at high power. Decide before you start what to do with a stoma cut by the edge of the **field of view** (one rule, the one used here: count it only if more than half of it is inside) and keep to it. To turn a count into a density you need the field's area. Measure its diameter with a **stage micrometer**, a slide ruled in hundredths of a millimetre, or measure it at low power against a clear ruler and divide by how many times more the high-power objective magnifies. The radius is half the diameter, the area is πr², and the density is the mean count divided by the area.

Then compare. In many dicot leaves the lower surface has far more stomata than the upper, and leaves of one plant grown in sun or in shade can differ.

KEY POINTS

- Stomatal density = mean number of stomata per field ÷ area of the field (πr²), usually per mm².
- Count several random fields at high power, with a rule for stomata cut by the edge, decided first.
- Repeated counts make the mean more reliable and show how much the leaf varies.

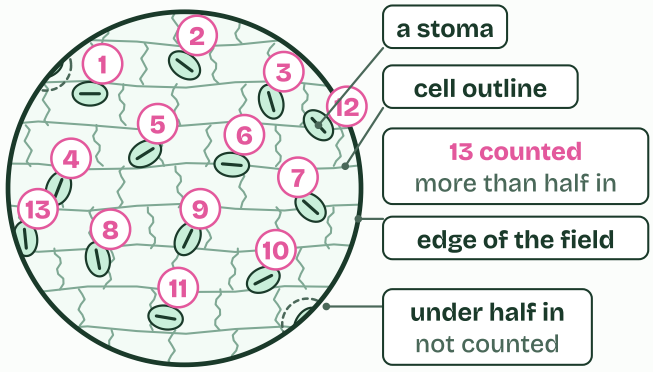
KEY TERMS

stomatal density
The number of stomata in a unit area of leaf surface, usually per square millimetre.

field of view
The circle you see through the microscope. Its diameter shrinks as the magnification rises.

stage micrometer
A slide with a tiny ruled scale, usually 1 mm divided into 100 parts, used to measure what a microscope shows.

Counting stomata in a field



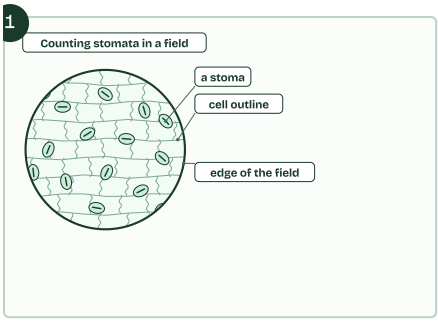
field across: 0.45 mm
so r = 0.225 mm
area = π × 0.225²
= 0.159 mm²

five fields: 12, 15, 11, 14, 13
mean 13
density = 13 ÷ 0.159
≈ 82 per mm²

STEP BY STEP

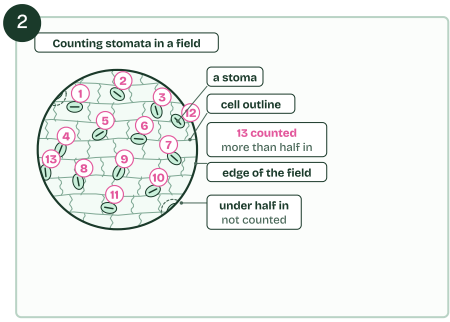
4 STEPS

1



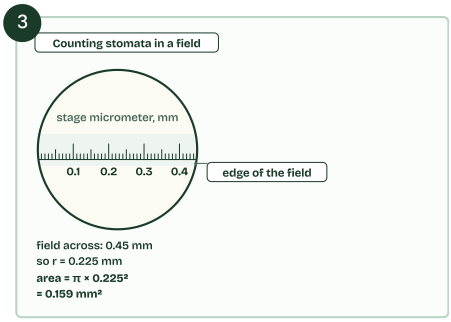
A leaf cast at high power: the outlines of the epidermis cells and the stomata, each a pair of guard cells round a pore. Some stomata are cut by the **edge of the field**.

2



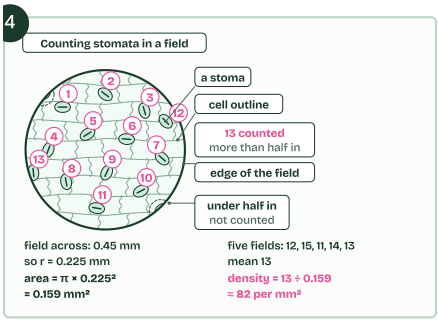
Count every stoma, keeping to one rule at the edge: count it only if **more than half** of it is inside. This field holds **13**.

3

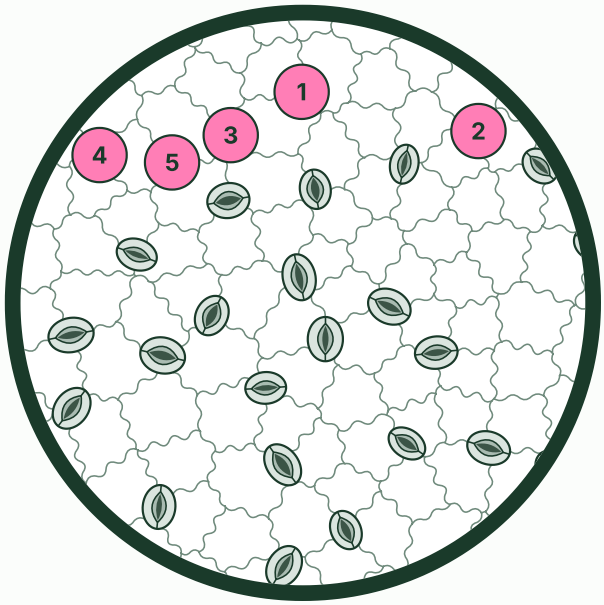


A stage micrometer at the same magnification, ruled in hundredths of a millimetre, shows the field is **0.45 mm** across: its far edge falls halfway between 0.4 and 0.5. So its radius is 0.225 mm, and its area is π × 0.225² = **0.159 mm²**.

4



Count five fields chosen at random: 12, 15, 11, 14 and 13, a mean of 13. Density = mean count ÷ area = 13 ÷ 0.159, about **82 stomata per mm²**. (Invented counts, to show the method.)



Count a stoma only if more than half of it is inside the circle.

Field	Leaf	Surface	Stomata	Density / mm^{-2}

Count the stomata: on the page, tap each one inside the field (the bench numbers it) and press Record; measure the field with a stage micrometer, and the table, the means, the densities and the graph fill in.

PREDICT

Why count five fields, chosen at random, instead of one?

(A) Stomata are not spread evenly, so the mean of random fields is more reliable and shows the spread

(B) One field cannot be focused sharply enough at high power to count every stoma in it accurately

(C) Five counts cancel out the microscope's own error, which is the same in every one of the fields

(D) Choosing the fields at random means the hard ones can be skipped, which makes the counting faster

Decide before you look. Answer on page 67.

NATURE OF SCIENCE

Repeating a measurement makes a result more reliable. Here the repeats are counts of fields at high power, and their spread is real biology, not only error: stomata are not spaced evenly over a leaf, so one field can land on a crowded patch or a sparse one. Choose the fields at random, not the clearest-looking ones, count enough of them for the mean to settle, and sample more than one leaf, because leaves differ just as fields do.

WORKED EXAMPLE

Five random fields at high power (×400) hold 12, 15, 11, 14 and 13 stomata: a mean of 13. The field is 0.45 mm across, so its radius is 0.225 mm and its area is $\pi \times 0.225^2 = 0.159$ mm². The density is $13 \div 0.159 \approx 82$ stomata per mm². (The counts are invented, to show the arithmetic.)

WATCH OUT

Measure the field at the magnification you counted at. Going from a ×10 to a ×40 objective makes the field a quarter as wide and a sixteenth of the area, so dividing a high-power count by the low-power area makes the density sixteen times too small.

PREDICT

Some stomata lie across the edge of the field, part in and part out. Why decide on a rule for them before you start counting?

(A) Stomata on the edge are always out of focus, and cannot be counted with any certainty

(B) So that every field is counted the same way, and counts from different fields compare

(C) An edge stoma belongs to the next field along, and would be counted twice over there

(D) The rule makes every count higher, which gives a density nearer to the leaf's real one

Decide before you look. Answer on page 67.

PREDICT

At the same magnification, a leaf's upper surface gives a mean of 3 stomata a field and its lower surface 15. Why can you say the lower surface has five times the density without measuring the field?

(A) Density is the count itself, so a mean of 15 stomata a field is a density of 15 stomata per mm² on that surface

(B) A field of view at high power is always exactly 1 mm², so each mean count is already that surface's density

(C) The field is so small that leaving its area out changes each of the two densities by well under one percent

(D) Both counts come from fields of the same area, so the area cancels when one density is divided by the other

Decide before you look. Answer on page 67.

06 The price of gas exchange: *transpiration*

B3.1.9 TRANSPIRATION AS A CONSEQUENCE OF GAS EXCHANGE IN A LEAF

Start with a prediction about a leaf in the sun.

Transpiration is the loss of water vapour from the leaves and stems of a plant. It is not a job the plant does: it is a consequence of gas exchange. Carbon dioxide can only get into the mesophyll cells by dissolving in the water on their walls, so those walls must be wet. Water evaporates from them into the air spaces, and the air inside a leaf is nearly saturated with water vapour. When the stomata open to let carbon dioxide in, water vapour diffuses out, down its concentration gradient into the drier air outside. A plant can only cut it down by closing its stomata, and that cuts down its gas exchange too.

The rate depends on that gradient, and on how open the stomata are. **Light** opens the stomata, so transpiration is fastest by day and slows right down at night. A higher **temperature** speeds up evaporation and diffusion, and the warmer air spaces hold more vapour before they are saturated, so the gradient to the outside air is steeper. **Humid** air already holds a lot of vapour, so the gradient is shallower and the rate falls. **Wind** carries away the humid layer of air next to the leaf, which keeps the gradient steep. Switch the figure between them.

To measure the rate, use a **potometer**: a leafy shoot sealed into a tube of water, with an air bubble that moves along a scale as the shoot takes water up. It measures uptake, not loss, but almost all the water a shoot takes up is lost by transpiration, so the uptake stands in for it. The dry lab below is a potometer: try it with the lamp, the fan, the humidity or the temperature. How the water lost from the leaves pulls more up the stem is the subject of B3.2.

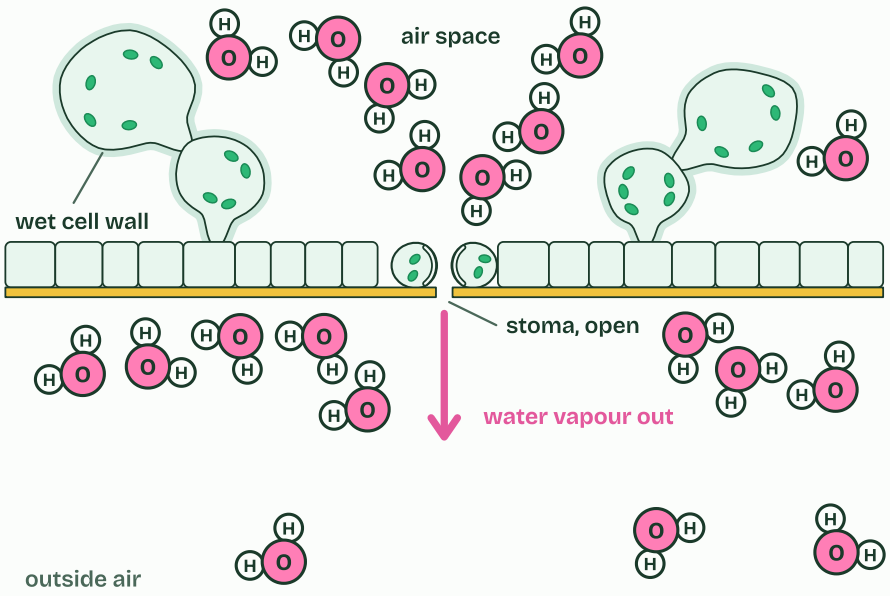
KEY POINTS

- Transpiration is the loss of water vapour from leaves and stems, a consequence of the open stomata that gas exchange needs.
- Water evaporates from the wet walls of the mesophyll cells into the air spaces, then diffuses out through the stomata.
- Light, a higher temperature, dry air and wind raise the rate; humid air lowers it.
- A potometer measures water uptake, which is close to the water lost.

KEY TERMS

transpiration
The loss of water vapour from the leaves and stems of a plant. Most of it goes out through the stomata.

potometer
Apparatus that measures how fast a leafy shoot takes up water: the shoot is sealed into a tube of water, and an air bubble moves along a scale as the water is taken up.

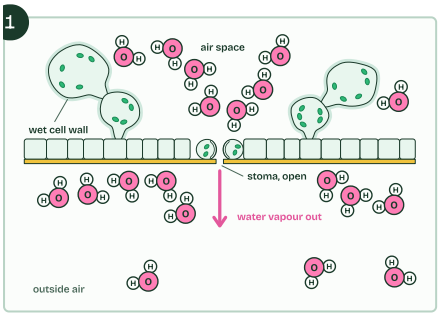


One stoma in a leaf's lower surface, and the air under it. The arrow's weight shows how fast water vapour leaves.

SWITCH IT

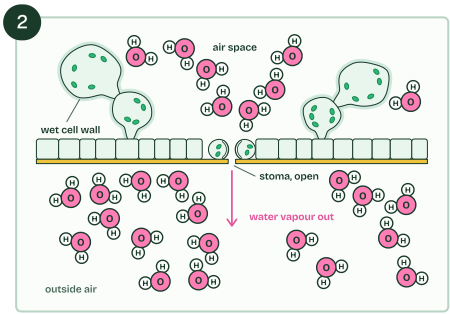
5 SETTINGS

1



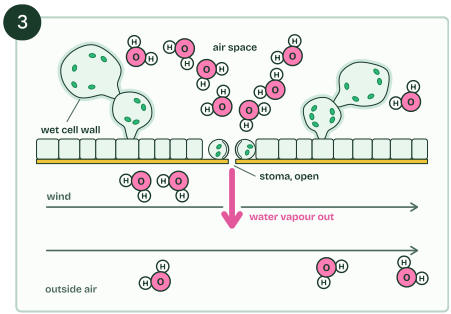
Still air

2



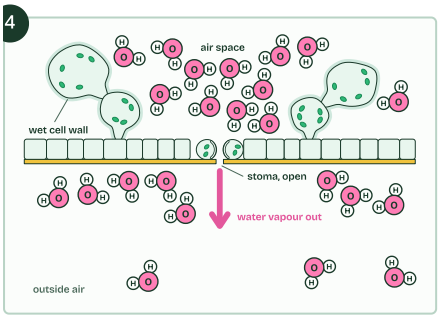
Humid air

3



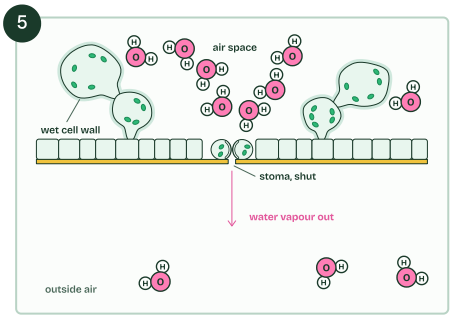
Windy

4



Warm

5



Dark

PREDICT

One leaf on a plant in sunshine has its lower surface smeared with petroleum jelly. Compared with a leaf left alone, it becomes...

(A) cooler, because the shiny layer of jelly reflects more of the sunlight that reaches the leaf

(B) warmer, because less water can evaporate out through its stomata and carry heat away

(C) no warmer and no cooler, because the jelly blocks only carbon dioxide, which carries no heat

(D) cooler, because less water is pulled up into it, and the water in the xylem carries the heat

Decide before you look. Answer on page 68.

REMEMBER IT

Four factors that change the rate of transpiration

L Lazy	T Teens	H Hate	W Wednesdays
Light opens the stomata	**Temperature** faster evaporation and diffusion	**Humidity** more humid air, a slower rate	**Wind** blows the humid air away

WATCH OUT

"Transpiration stops in the dark." Water evaporates from the wet walls of the mesophyll cells in the dark as well as in the light. In the dark the stomata close, so far less of the vapour gets out, but some still does. By day, light speeds transpiration up in two ways: it opens the stomata, and the sunshine a leaf absorbs warms it, so the water evaporates faster.

LINKING QUESTION

How do multicellular organisms solve the problem of access to materials for all their cells? A leaf gets carbon dioxide to every cell through its stomata and air spaces, and loses water doing it. The xylem brings that water up from the roots, and the phloem carries the sugars away: B3.2. The second guiding question for B3.1, the similarities and differences between gas exchange in a flowering plant and in a mammal, is answered at the end of the guide, in Putting it together.

07 Keeping the gradient *steep*

B3.1.3 MAINTENANCE OF CONCENTRATION GRADIENTS AT EXCHANGE SURFACES IN ANIMALS

Gases cross an exchange surface by diffusion, and the cell spends nothing on it (chapter 1). That makes it cheap, but it only works while there is a **concentration gradient**: more oxygen on the air side of the wall than on the blood side, and more carbon dioxide on the blood side than in the air.

So an animal keeps both sides of the wall changing. Three things do it, and the IB names all three:

KEY POINTS

- **A dense network of blood vessels.** Capillaries wrap the exchange surface so closely that almost every part of the wall has blood just behind it, a short way to diffuse.
- **Continuous blood flow.** Blood carries the oxygen away as fast as it arrives and brings carbon dioxide from the body's cells, so the blood at the wall never catches up with the air.
- **Ventilation.** Moving fresh air (or water) past the surface, so the outside never runs short of oxygen or fills up with carbon dioxide.

Ventilation is not gas exchange. Ventilation moves the air; gas exchange is the diffusion across the wall. What keeps using the oxygen up and making more carbon dioxide is respiration in every cell of the body (C1.2), which is why the blood coming back to the lungs is always lower in oxygen than the air in the alveoli.

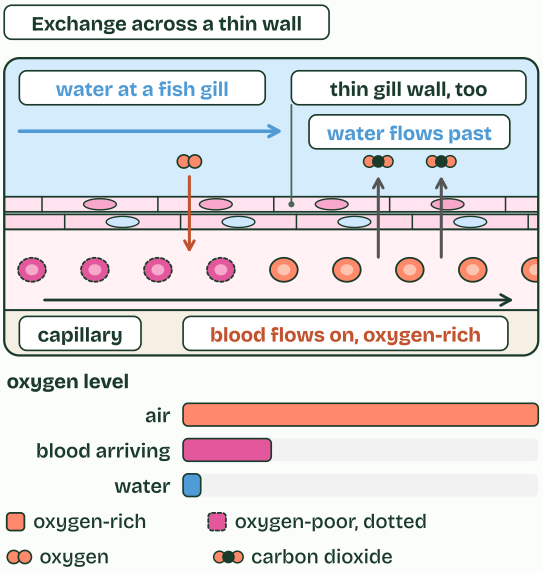
Water and gills. A fish does the same with water. Its **gills** are rows of thin filaments, each packed with capillaries, and the fish pumps water over them in a one-way stream, in through the mouth and out under the gill covers. Water is a harder medium than air: a litre of it holds about thirty times less oxygen than a litre of air, and it is far denser and more viscous, so a fish must move a large volume of water to get enough. The blood in the gill capillaries flows the opposite way to the water, which keeps a gradient along the whole filament (*counter-current flow*, not needed for the exam, and B3.2 has the fish's single circulation).

KEY TERMS

concentration gradient
A difference in concentration between two places. A substance diffuses down it, from where it is more concentrated to where it is less; the steeper the gradient, the faster the net movement.

ventilation
Moving air or water over a gas-exchange surface: breathing in and out in a mammal, pumping water over the gills in a fish.

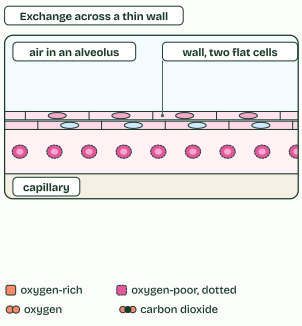
gills
The gas-exchange organ of a fish: thin filaments packed with capillaries, with water pumped over them.



STEP BY STEP

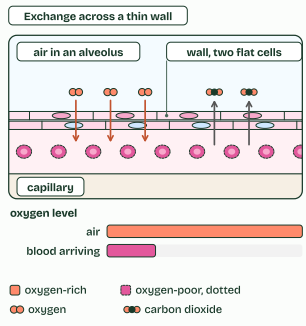
5 STEPS

1



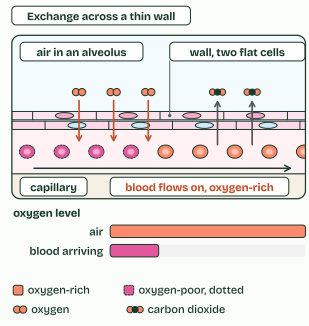
An exchange surface: **air** in an alveolus over a wall two flat cells thick, and a **capillary** under it.

2



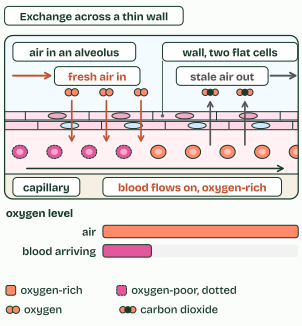
Oxygen diffuses **in** across the wall, down its gradient, and carbon dioxide diffuses **out**. The bars show the oxygen level either side.

3



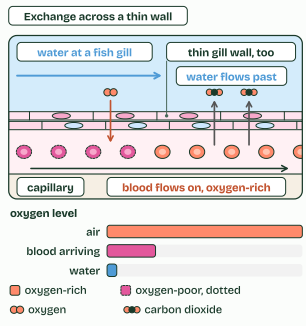
The blood keeps **flowing**: it carries each load of oxygen away and brings blood low in oxygen to the wall, so the gradient stays steep.

4



Ventilation replaces the air, so the air side stays high in oxygen and low in carbon dioxide.

5

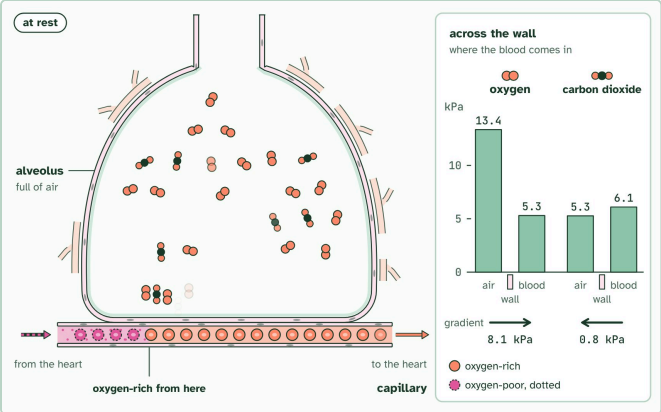


A fish's **gill** works the same way, with water pumped past in place of air. Water holds far less oxygen than air, so a fish must move a lot of it.

ANIMATION · KEEPING THE GRADIENT STEEP

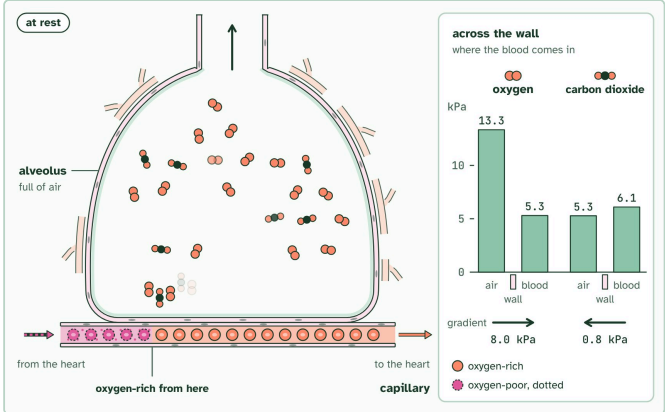
3 MOMENTS

1 BREATHING IN



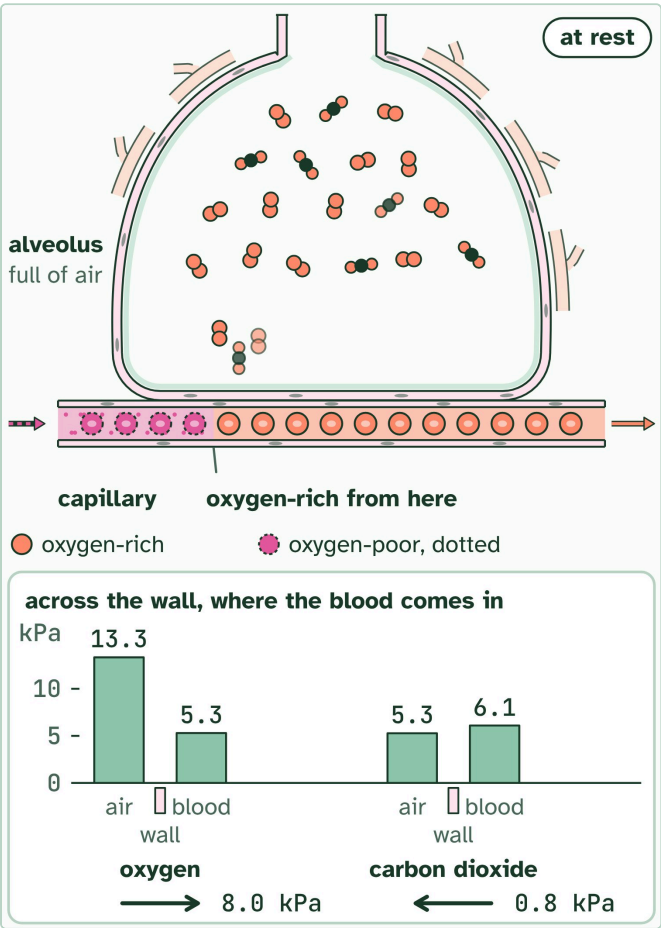
One alveolus and the capillary on its wall. The air in the alveolus is rich in oxygen; the blood arrives **oxygen-poor**.

2 BREATHING OUT



Oxygen diffuses down its **concentration gradient**: from the air, across the thin wall, into the blood. A short way along, the blood is oxygen-rich.

3 BREATHING IN



The blood flows on and breathing brings fresh air, so the gradients stay steep. What if one of them stopped? Try **Blood flow** or **Ventilation**. (The blood is slowed down about ten times here, and the breaths sped up: the film's clock is not to scale.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#gradient

PREDICT

The blood in a capillary beside an alveolus stops flowing, but breathing carries on. What happens to the gradient across the wall?

(A) It fades away, as the still blood soon reaches the air's oxygen level

(B) It becomes steeper, because the alveolus keeps being filled with fresh air

(C) It stays the same, because breathing alone keeps the air's oxygen high

(D) It reverses, because the still blood gives its oxygen back to the air

Decide before you look. Answer on page 68.

REMEMBER IT

The three things that keep the gradient steep

V Very	F Fast	V Vans
Vessels a dense network at the wall	**Flow** blood that never stops	**Ventilation** fresh air, or water, at the surface

WATCH OUT

"Breathing is gas exchange." Breathing is ventilation; gas exchange is the diffusion across the alveolus wall. "The lungs suck the oxygen in." Nothing pulls oxygen across: it diffuses down its gradient. "The blood in the lung capillaries is already full of oxygen." It arrives low, which is why oxygen diffuses into it. And "fish breathe water by taking the oxygen out of the water molecules." They take up the oxygen gas dissolved in the water; the oxygen in H_2O stays where it is.

08 Down the branching *tree*

B3.1.4 ADAPTATIONS OF MAMMALIAN LUNGS FOR GAS EXCHANGE

Air comes in through your nose or mouth, down the throat and into the **trachea**, the windpipe, which C-shaped rings of cartilage hold open as the pressure inside it changes. In the chest it divides into two **bronchi**, one to each lung. Inside the lung each bronchus divides, and divides again, over twenty times in all, into ever narrower **bronchioles**. The finest end in clusters of tiny air sacs, the **alveoli**, like bunches of grapes on their stalks.

Why a tree, then? Two reasons. Branching carries air to every part of the lung, so no alveolus is far from an airway. And it packs an enormous surface into the chest: hundreds of millions of alveoli, each a fraction of a millimetre across. The airways themselves exchange no gas, because their walls are too thick; the trachea, bronchi and bronchioles only carry the air in and out. The bronchioles have no cartilage. Their walls have smooth muscle that can narrow them, which is what goes wrong in an asthma attack.

Every alveolus is wrapped in capillaries, so the lungs hold an extensive **capillary bed**: the third adaptation the IB lists. The fourth, surfactant, is in chapter 9.

KEY TERMS

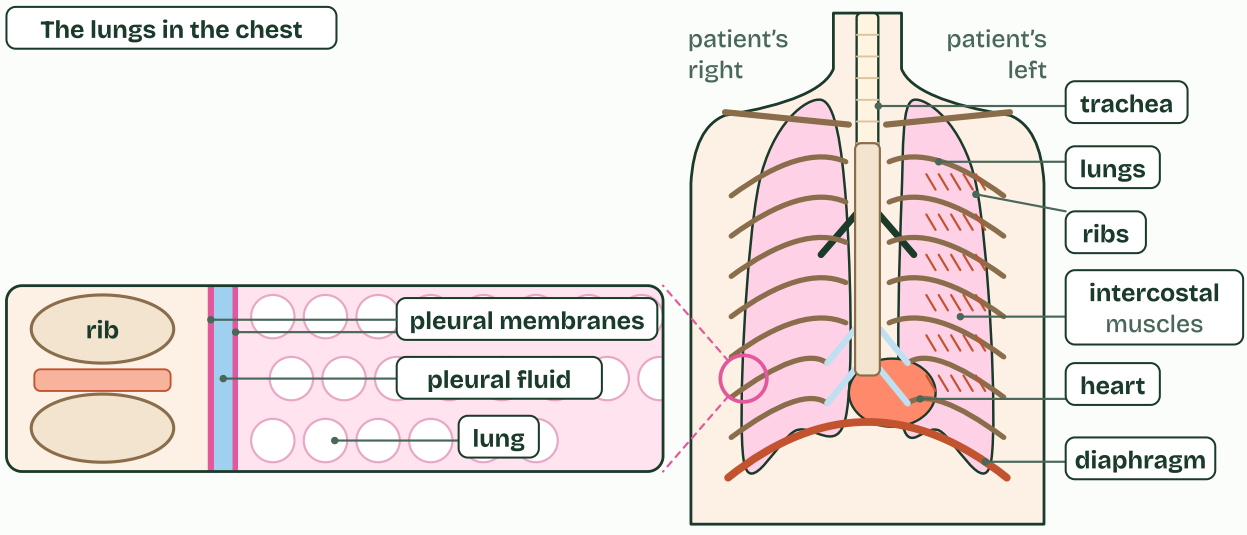
trachea
The windpipe: the tube from the larynx to the chest, held open by C-shaped rings of cartilage.

bronchi
One of the two branches of the trachea, one to each lung (plural bronchi). Their walls have cartilage too.

bronchioles
The narrow airways that branch from the bronchi through the lung. They have smooth muscle in their walls and no cartilage, and the finest ones end in clusters of alveoli.

alveoli
The tiny air sacs at the ends of the bronchioles, each wrapped in capillaries, where gases are exchanged with the blood (singular alveolus).

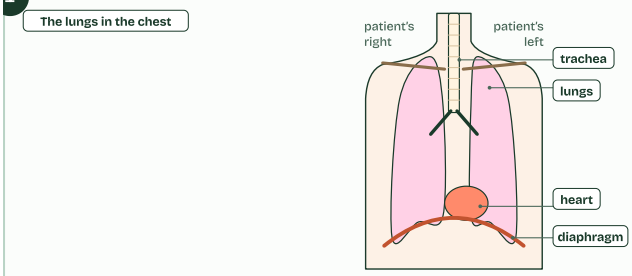
capillary bed
A dense network of capillaries over a surface or through a tissue.



STEP BY STEP

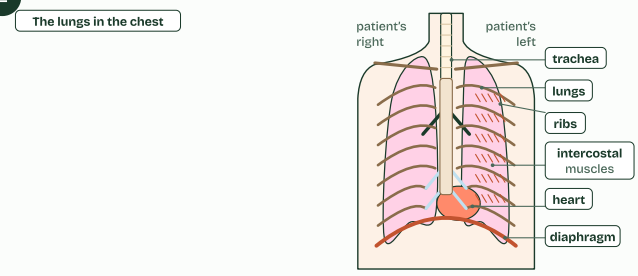
3 STEPS

1



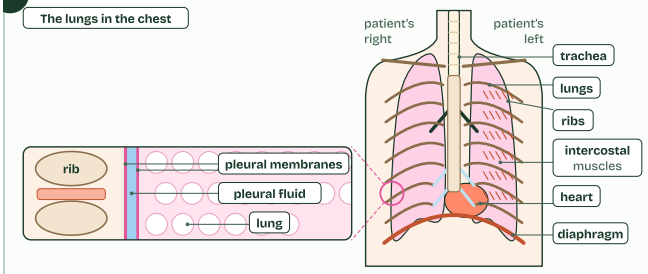
The **lungs** fill the chest, from just above the collarbones down to the domed **diaphragm**. The **trachea** runs down the neck between them, and the **heart** sits between them on the diaphragm, a little to the patient's left.

2

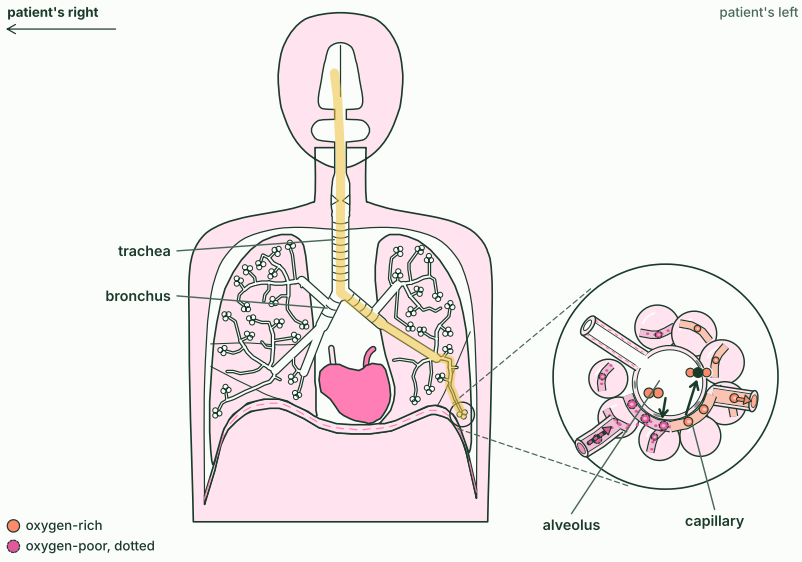


The **ribs** cage the lungs. Each joins the breastbone at the front, the lower ones through bars of cartilage, and the **intercostal muscles** fill the gaps between them (chapter 10 shows what they do).

3



The ringed spot magnified, cut across: two **pleural membranes**, one covering the lung and one lining the chest wall, with a thin layer of **pleural fluid** between them. The fluid lets the lung slide as you breathe but holds it to the wall, so the lung follows the chest as it moves (chapter 10).

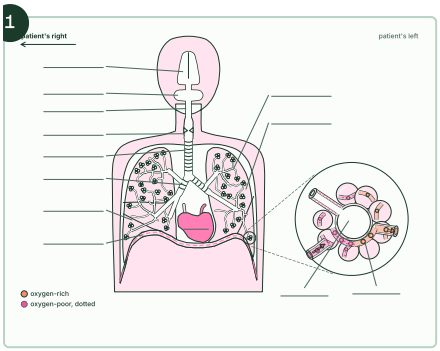


Tap each part to read its job, label it from memory, then follow one oxygen molecule from the nose to a red cell, and a carbon dioxide molecule back out. Answer the question above before you switch on Area.

STEP BY STEP

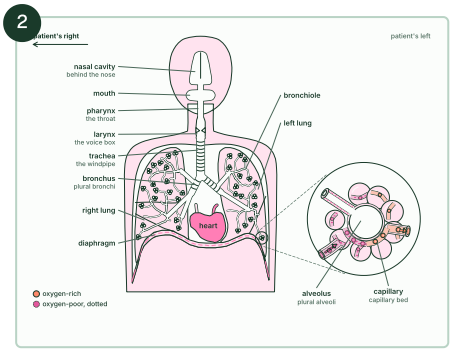
3 STEPS

1



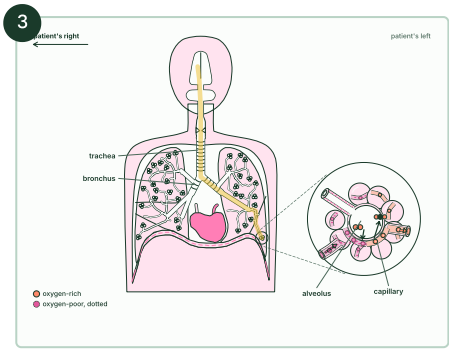
The airways in the **frontal plane**: the patient's right is on the left of the drawing. Label the parts on the lines.

2



Air passes the nose or mouth, the **pharynx** and **larynx**, the **trachea** (held open by rings of cartilage), two **bronchi** and branching **bronchioles** to clusters of **alveoli**, each wrapped in **capillaries**.

3



A breath in, to one cluster of alveoli. There **oxygen** crosses the alveolus wall and the capillary wall, each one cell thick, into a red cell; **carbon dioxide** crosses the other way.

PREDICT

A lung is a tree of ever narrower tubes ending in millions of tiny sacs, not one big bag. What does this gain?

(A) The air moves faster through narrow tubes, so it reaches the blood sooner

(B) More tubes mean more rings of cartilage to keep the lung open against the pressure outside

(C) A far greater surface area in the same volume, so more oxygen can cross each second

(D) The narrow tubes slow the blood, and that gives it time to pick up the oxygen

Decide before you look. Answer on page 68.

WATCH OUT

"Gas is exchanged all along the airways." Only in the alveoli. "The lungs are two empty bags." They are spongy: a tree of tubes and sacs. "The bronchioles have cartilage rings like the windpipe." Only the trachea and bronchi do. And "your lungs would cover a tennis court." A favourite claim, but the measured area is about 70 square metres, about a quarter of a tennis court.

09

B3.1.4 ADAPTATIONS OF MAMMALIAN LUNGS FOR GAS EXCHANGE

One alveolus, *close up*

An alveolus is a sac about a quarter of a millimetre across, and its wall is a single layer of very flat cells. Over it lies a net of capillaries whose walls are also one cell thick, so between the air and the blood there is a barrier less than a micrometre thick where the gases cross. Before you look at the figure, draw one from memory: the sac, its wall, the capillary, a red cell. Then check your drawing against it, and tap each part.

Chapter 1's four properties of an exchange surface, one by one:

KEY POINTS

- **Permeable.** Oxygen and carbon dioxide pass straight through the thin cells of the wall.
- **Thin.** One flat cell of alveolus wall and one of capillary wall: a short path to diffuse.
- **Moist.** A thin film of water lines every alveolus, and the gases dissolve in it before they diffuse.
- **A large surface area.** Hundreds of millions of alveoli (chapter 8).

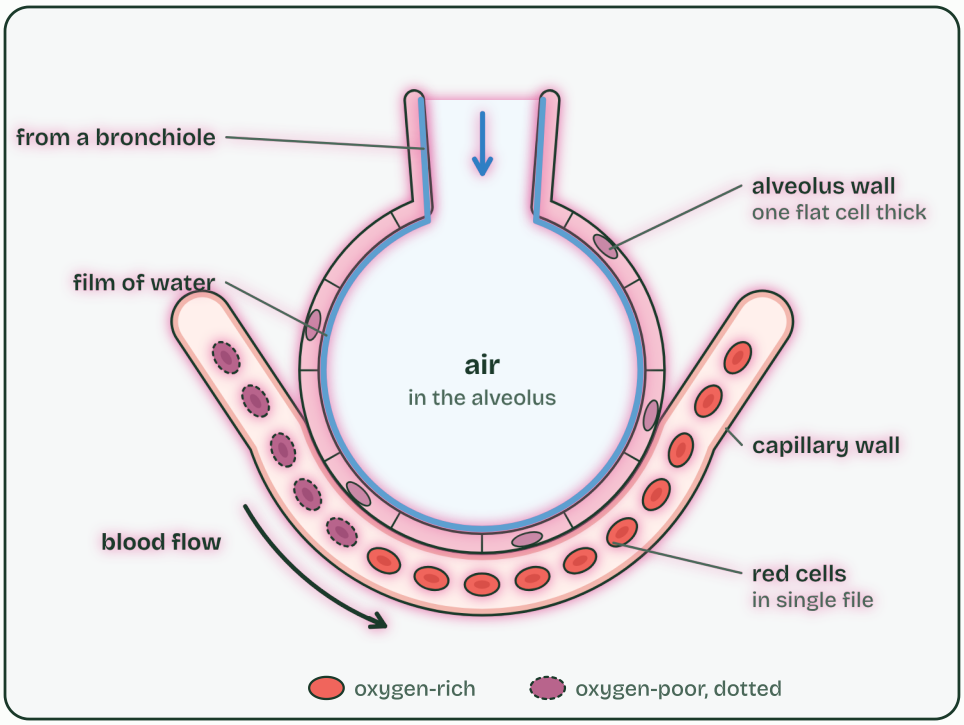
The gradient across the wall is kept by the blood and the breathing (chapter 7), not by the alveolus itself.

Surfactant is the fourth adaptation the IB names. The film of water inside an alveolus pulls on itself, which tends to draw the wall in. Cells in the wall make surfactant, a mixture of phospholipids and proteins, which spreads over the water and weakens its pull. So the alveoli stay open as you breathe out, and open again easily as you breathe in. The cells that make it, and the ones that form the thin wall, are B2.3's pneumocytes (higher level there).

Match the feature to what it does. Fill in the table under the figure: tap a box and choose; a right answer stays, with its reason.

KEY TERMS

surfactant
A mixture of phospholipids and proteins made by cells in the alveolus wall. It spreads over the film of water lining the alveoli and weakens its pull, so the alveoli do not collapse when you breathe out.



The capillary wall One flat cell thick, pressed against the alveolus wall. A net of capillaries covers every alveolus.

Air in the alveolus Fresh air arrives with each breath, down the airways. Oxygen dissolves in the film of water and diffuses across the wall into the blood; carbon dioxide diffuses the other way.

A film of water lines the alveolus, so the surface is moist: a gas dissolves in it before it diffuses. Surfactant spreads over it (the film below).

The blood keeps flowing , carrying each load of oxygen away and bringing more blood low in oxygen, so the gradient stays steep (chapter 7).

Red blood cells squeeze through in single file, close to the wall. They arrive oxygen-poor and are oxygen-rich within the first stretch of the capillary.

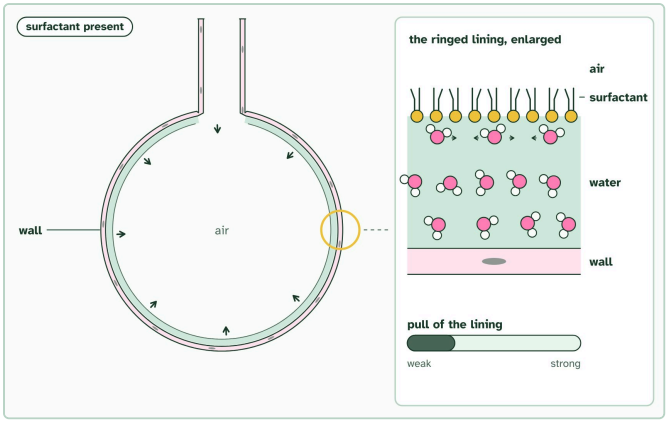
The alveolus wall One layer of very flat cells. With the capillary wall, the gases cross well under a micrometre.

The way in The alveolus opens from the end of a bronchiole, so its air is changed with every breath.

ANIMATION · WHY THE ALVEOLI STAY OPEN

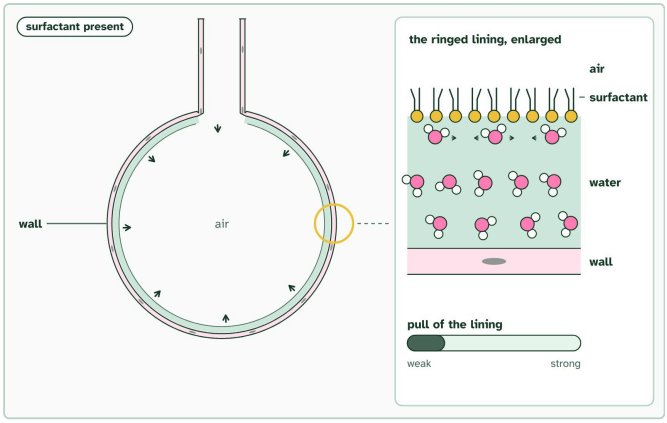
3 MOMENTS

1 BREATHING OUT



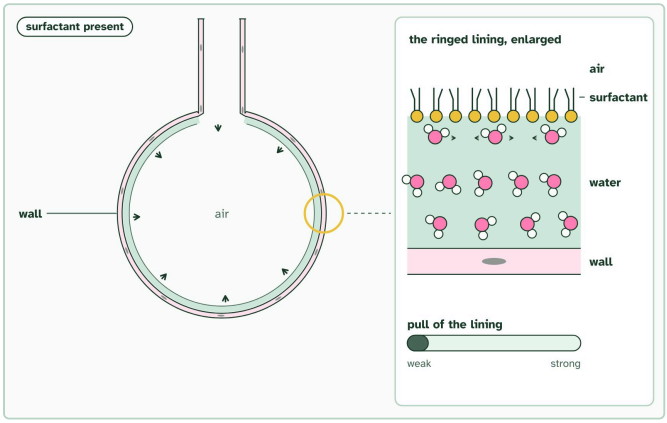
An alveolus cut open, and a ringed piece of its lining enlarged. A thin film of water lines every alveolus: the gases dissolve in it to cross the wall.

2 BREATHING IN



An alveolus cut open, and a ringed piece of its lining enlarged. A thin film of water lines every alveolus: the gases dissolve in it to cross the wall.

3 BREATHING IN



So as you breathe out and the alveolus gets smaller, it stays open, and the next breath fills it easily. Choose **Absent** to compare.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#alveolus

PREDICT

A baby is born weeks early with too little surfactant. What goes wrong in its alveoli when it breathes out?

(A) The walls swell with fluid and become too thick for the oxygen to diffuse across into the blood

(B) The capillaries leak blood out into the air spaces of the lungs each time the baby breathes out

(C) The alveoli swell a little more with every breath, until some of them burst open

(D) The watery lining pulls the walls together, so the alveoli collapse and are hard to reopen

Decide before you look. Answer on page 68.

WATCH OUT

"Surfactant is a soap that cleans the lungs." It weakens the water's pull; it cleans nothing. "The alveolus has a cell wall." Its "wall" is a layer of animal cells, with no cell walls at all. "The alveoli are dry inside." They must be moist for the gases to dissolve. And "the alveoli keep the gradient steep." The blood flow and the breathing do.

10 Pressure moves the *air*

B3.1.5 VENTILATION OF THE LUNGS

Air flows from where its pressure is higher to where it is lower. Ventilation changes the pressure in your lungs by changing the size of your chest. Your lungs have no muscle that can expand them. They sit in a sealed chest, floored by the **diaphragm** and walled by the ribs, and they are stretched with it.

Breathing in (inspiration). The diaphragm contracts: it flattens and moves down. The **external intercostal muscles**, between the ribs, contract and lift the ribs up and out. The chest gets bigger, the pressure in the lungs falls below the air outside, and air flows in.

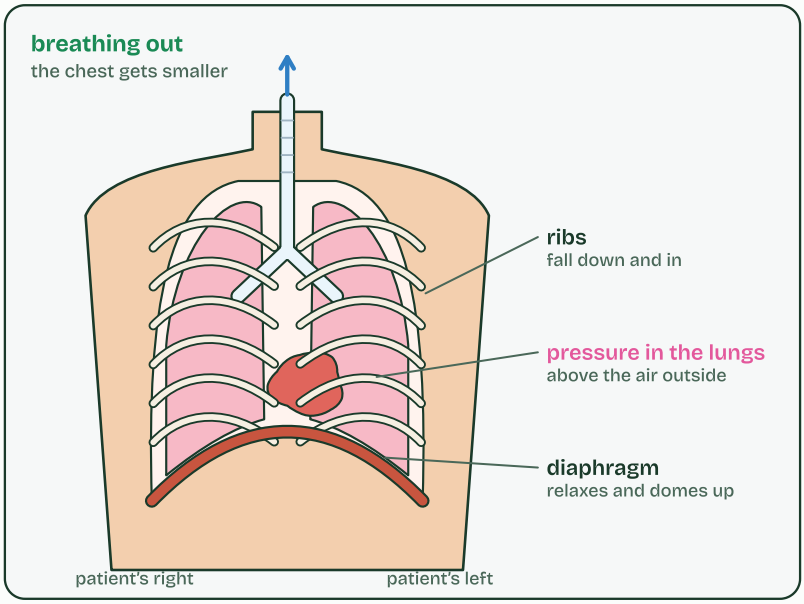
Breathing out at rest (expiration). The diaphragm and the external intercostals relax. The ribs fall back, the diaphragm domes up again, and the stretched lungs recoil like an elastic band. The chest gets smaller, the pressure rises above the air outside, and air flows out. No muscle contracts for it: quiet breathing out is passive.

A model lung shows the idea: a bottle with its base cut off, a rubber sheet over the base for the diaphragm, and a balloon inside for a lung. Pull the sheet down and the balloon fills. It leaves a lot out: no ribs and no intercostal muscles, and a balloon that hangs free in the bottle, where a real lung is held against the inside of the chest wall. The film below has one beside the chest.

KEY TERMS

diaphragm
The domed sheet of muscle under the lungs that separates the chest from the abdomen. It flattens as it contracts.

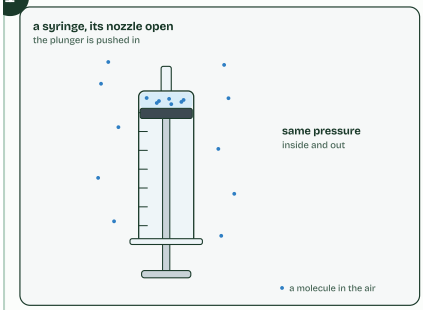
external intercostal muscles
The muscles between the ribs, in two layers: the external intercostals lift the ribs up and out; the internal intercostals pull them down and in.



STEP BY STEP

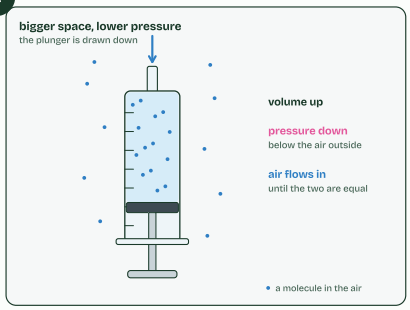
4 STEPS

1



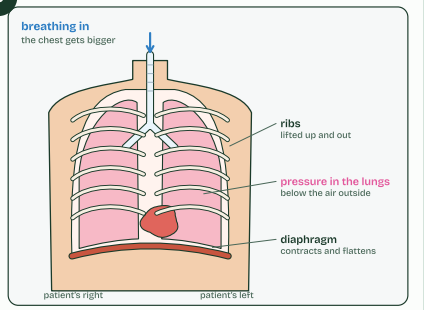
A **syringe**, its nozzle open and its plunger pushed in. The air inside is at the same pressure as the air outside.

2



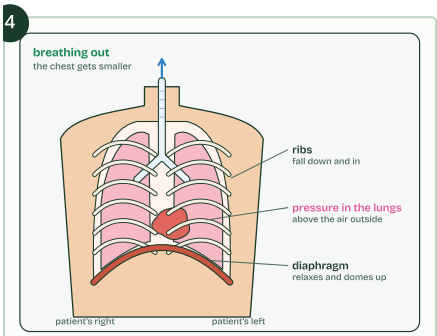
Draw the plunger down: the space inside gets bigger, so the air in it is at a **lower pressure** than the air outside, and air flows in until the two are equal.

3



Your chest works the same way. Breathing in, the **diaphragm** contracts and flattens and the **external intercostals** lift the ribs up and out. The chest gets bigger, the pressure in the lungs falls, and air flows in.

4

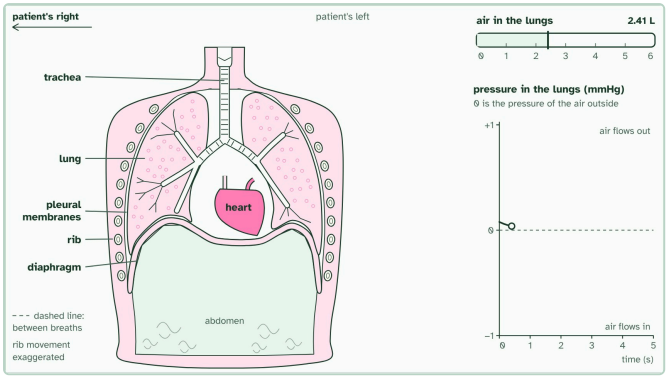


Breathing out at rest, the muscles **relax**: the ribs fall, the diaphragm domes up and the stretched lungs recoil. The chest gets smaller, the pressure rises above the air outside, and air flows out.

ANIMATION · BREATHING IN AND OUT AT REST

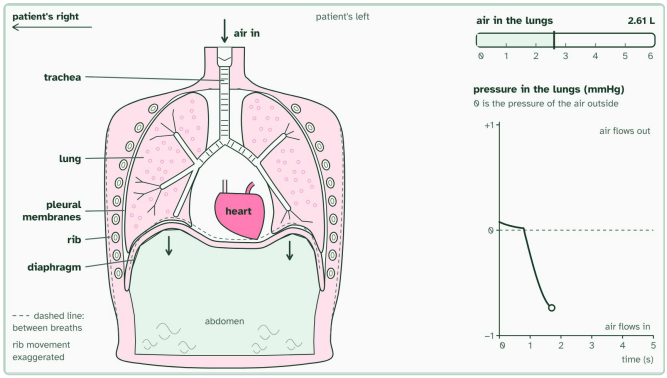
3 MOMENTS

1 BETWEEN BREATHS



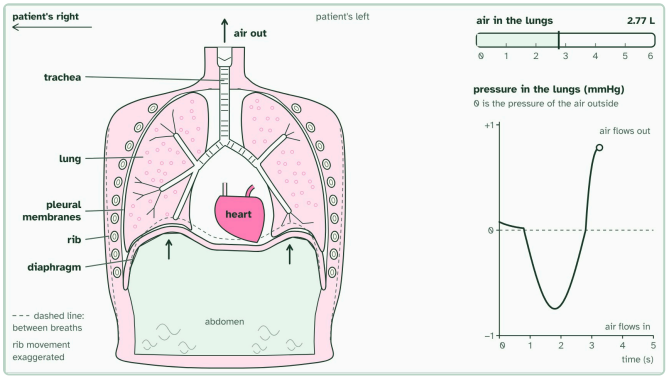
Between breaths. The muscles are relaxed, and the air in the lungs is at the same pressure as the air outside, so no air moves.

2 BREATHING IN



The chest gets bigger and the lungs stretch with it: their **volume** rises, the **pressure** in them falls below the air outside, and air flows in.

3 BREATHING OUT



Breathing out: the muscles **relax**. The ribs drop, the diaphragm domes up again and the stretched lungs **recoil**, so the volume falls.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#breathe

PREDICT

The diaphragm contracts. What does that do to the pressure of the air in the lungs, and so to the air?

(A) The diaphragm pulls the air in directly as it moves down, the way a hand pulls in a rope

(B) It flattens, the chest gets bigger, the pressure falls below the air outside, and air flows in

(C) It pushes down on the air in the lungs, raises its pressure and so forces it in

(D) The lungs expand first by themselves, and they pull the wall of the chest and the diaphragm out with them

Decide before you look. Answer on page 68.

BOYLE'S LAW

For a fixed amount of gas at a steady temperature, pressure × volume stays the same: double the volume and the pressure halves. In a quiet breath the pressure in your lungs falls only about 1 mmHg below the air outside, a fraction of a per cent, but air flows in until the two are equal: about half a litre of it.

REMEMBER IT

Breathing in, in order

D	L	W	F
Drop	**Lift**	**Widen**	**Fill**
Diaphragm contracts flattens and moves down	**External intercostals contract** ribs up and out	**Chest volume rises** so the pressure in the lungs falls	**Air flows in** from higher pressure to lower

WATCH OUT

"The diaphragm rises when you breathe in." It contracts, flattens and moves down. "The lungs have muscles and pull themselves open." They have no muscle that expands them: they follow the chest. "Air is pushed into the lungs." It flows in because the pressure inside has fallen. And "quiet breathing out is hard work." At rest it is passive: the muscles relax and the lungs recoil.

11

B3.1.5 VENTILATION OF THE LUNGS

Working *harder*

Run up a flight of stairs and your breathing changes at once. Your muscles respire faster, using more oxygen and making more carbon dioxide, so you need to move more air: each breath goes deeper (a bigger tidal volume, chapter 12) and comes faster (a higher ventilation rate). Quiet breathing cannot do that. Breathing hard needs muscles that sit still at rest.

Muscles can only pull, so each one that moves the ribs one way has a partner that moves them back: an **antagonistic pair**. The external intercostals lift the ribs; the internal intercostals pull them down.

KEY POINTS

- **Forced breathing in.** The diaphragm and the external intercostals contract harder and further, and muscles in the neck and chest help to lift the ribs higher.
- **Forced breathing out** (exercise, a cough, blowing out a candle). The internal intercostals contract and pull the ribs down and in; the abdominal muscles contract and push the diaphragm up. Breathing out is now active.

What tells your body to breathe harder? Sensors detect the rise in carbon dioxide in the blood, and the fall in pH that goes with it, and the brain sends faster signals to the breathing muscles. That control belongs to C3.1. Your pulse rises with your breathing: B3.2's pulse bench measures it.

Which muscles act? Fill in the table under the figure: for each kind of breath, choose the muscles that contract.

All four together. Once the table is filled in, the last film shows the chest from the side, where you can see what the front view hides: the fibres of the two intercostal layers running at right angles, the sternum swinging up and forward with the ribs, and the wall of the abdomen moving out as the diaphragm flattens and in as its muscles contract. Beside it are the volume and the pressure of the air in the lungs, moving opposite ways, as Boyle's law says.

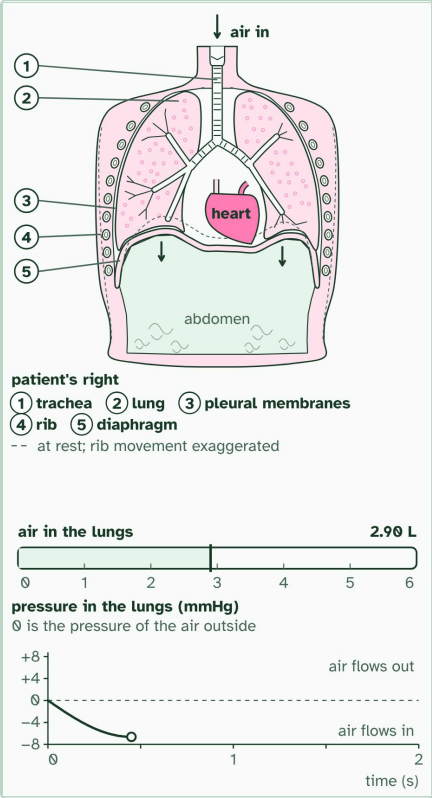
KEY TERMS

antagonistic pair
Two muscles that pull in opposite directions, so that when one contracts the other is stretched: the external and internal intercostals, for example.

ANIMATION · BREATHING HARD

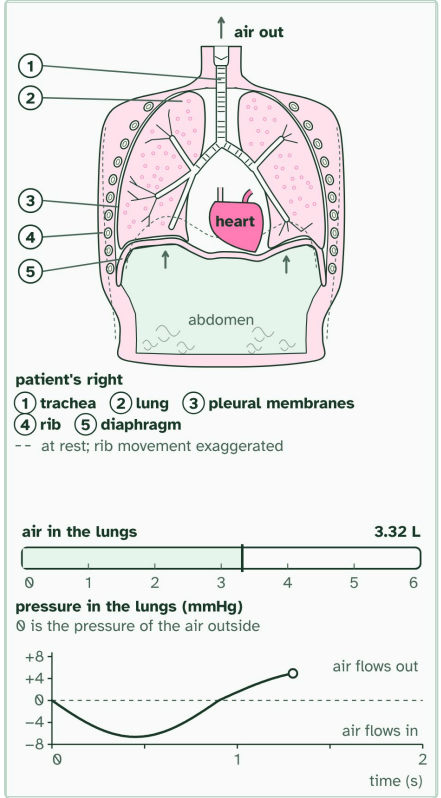
3 MOMENTS

1 BREATHING IN, HARD



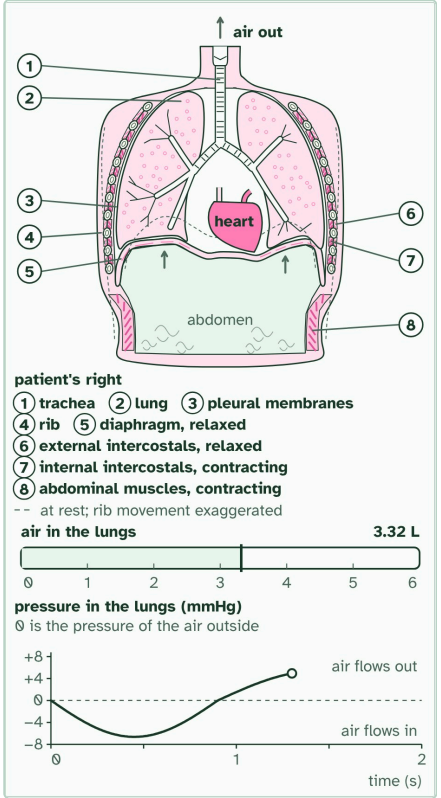
The pressure in the lungs falls much further below the air outside, so more air rushes in, faster.

2 BREATHING OUT, HARD



Breathing out is now **forced**: muscles squeeze the chest smaller, faster and further than recoil alone. Which ones? Turn on **Muscles**.

3 BREATHING OUT, HARD



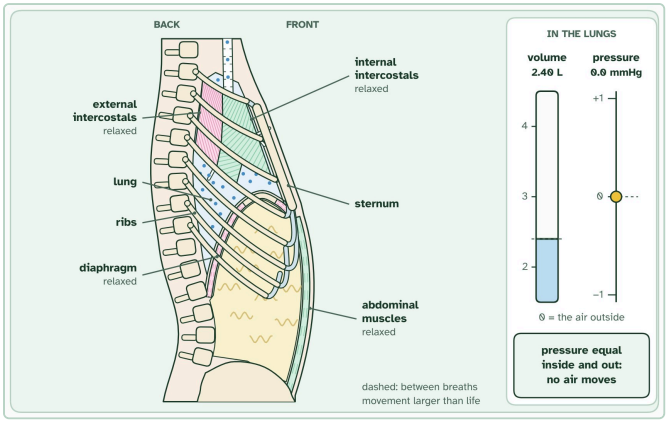
Breathing out hard: the **internal intercostals** pull the ribs down and in, and the **abdominal muscles** push the diaphragm up. A quiet breath out uses neither.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#forced

ANIMATION · FOUR MUSCLES, ONE BREATH

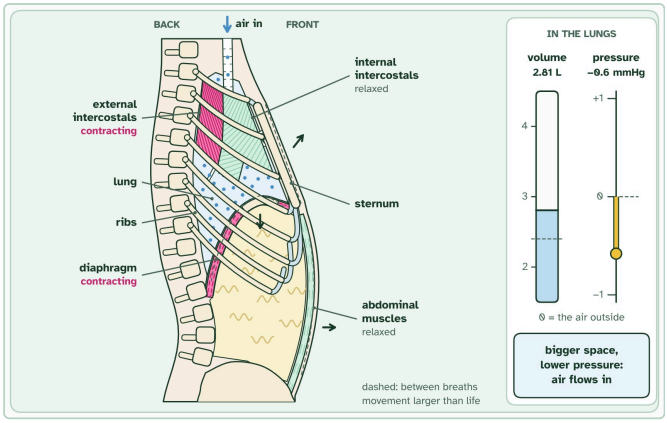
4 MOMENTS

1 PAUSE



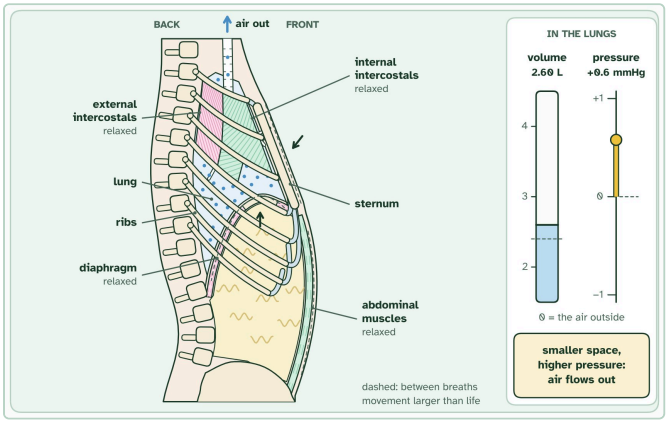
Between breaths, seen from the side. Every muscle is relaxed, and the air in the lungs is at the same pressure as the air outside, so no air moves.

2 BREATHING IN



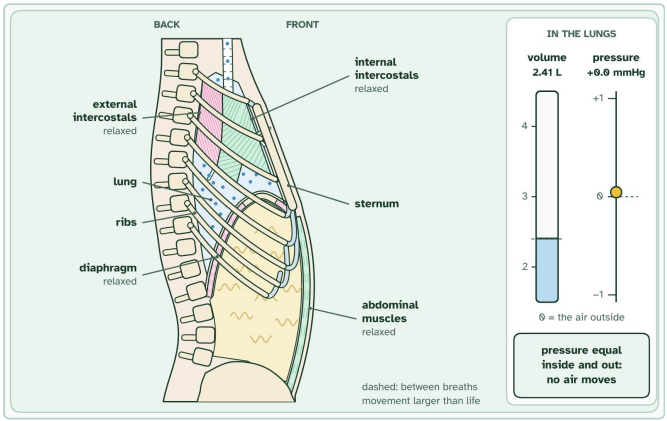
The chest is bigger, so the air in the lungs has more space: its **pressure falls** below the air outside (Boyle's law), and air flows in until the two are equal.

3 BREATHING OUT



Breathing out at rest. Both muscles **relax**. The ribs drop, the diaphragm domes up and the stretched lungs recoil: less space, so the **pressure rises** and air flows out.

4 PAUSE



No muscle did that: a quiet breath out is **passive**. The internal intercostals and the abdominal muscles stayed relaxed throughout. Now set Breathing to **Hard**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#forced

PREDICT

Quiet breathing out uses no muscle effort. In a sprint, which extra muscles help you breathe out?

(A) The abdominal muscles and the internal intercostals, which pull the chest smaller

(B) The diaphragm, which contracts harder and squeezes the air up and out of the lungs

(C) The external intercostals, which contract harder and push the ribs down and in

(D) The muscle in the lungs' own walls, which squeezes the air out of the alveoli

Decide before you look. Answer on page 68.

REMEMBER IT

IEEI: Inhale External, Exhale Internal

I	E
IE	EI
Inhale: External	**Exhale: Internal**
the external intercostals lift the ribs up and out	the internal intercostals pull the ribs down and in (forced breathing out only)

WATCH OUT

"You breathe in with muscles and out by relaxing, always." Only at rest; hard breathing out is muscular too. "The abdominal muscles have nothing to do with breathing." They drive forced breathing out. And "a lack of oxygen is what makes you breathe faster." In everyday life it is mainly the rise in carbon dioxide, and the fall in pH, that does it.

12 How much *air*?

B3.1.6 MEASUREMENT OF LUNG VOLUMES

A **spirometer** measures how much air you move. A digital one is a mouthpiece on a flow sensor: you breathe through it with a clip on your nose, and the screen draws the volume breathed against time. Up the trace is a breath in, down a breath out. A cheaper version is an upturned bottle of water: you breathe out through a tube into it, and the air you push out takes the place of the water.

KEY POINTS

- **Tidal volume**: the air moved in or out in one ordinary breath.
- **Inspiratory reserve volume**: the extra you can breathe in after an ordinary breath in.
- **Expiratory reserve volume**: the extra you can breathe out after an ordinary breath out.
- **Vital capacity**: the most air you can move in one breath, from the deepest breath in to the hardest breath out: the other three added together.

Count the breaths in a minute and you have the **ventilation rate**: about 12 to 16 at rest in an adult, with a tidal volume of about half a litre (0.5 dm^3: a litre is 1 dm^3, the unit the IB writes volumes in). Tidal volume × rate gives the air moved in a minute, about 6 litres at rest.

Two questions to try first, which the bench after this chapter lets you test.

Even after your hardest breath out, about a litre of air stays in your lungs, the *residual volume*: the alveoli never empty completely. A spirometer only measures air that moves through it, so it cannot measure this, and the vital capacity is not all the air in your lungs.

Making it reliable. Zero the sensor first and check it with a known volume, such as a calibration syringe. Lung volumes differ with height, sex, age, fitness and posture, and with effort and technique, so record who the volunteer is and how they sat or stood. One deep breath is not enough: take three good ones and use the best or the mean, and say how far the repeats spread. Breathing rises with exercise in two ways at once, deeper and faster. The bench after this chapter measures both.

KEY TERMS

spirometer
Apparatus that measures the volume of air breathed in and out. A digital one has a mouthpiece and a flow sensor and draws the volume against time.

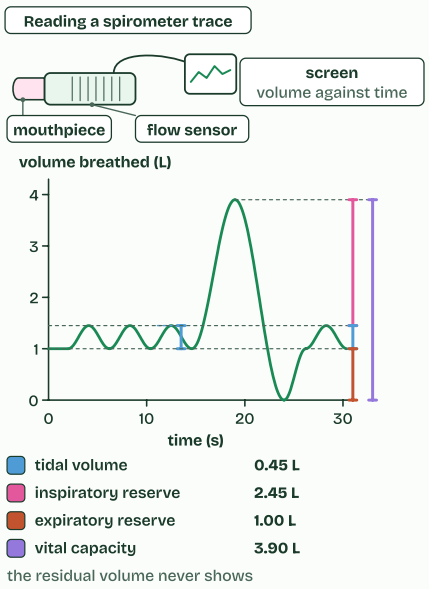
tidal volume
The volume of air breathed in, or out, in one ordinary breath: about half a litre at rest.

inspiratory reserve volume
The extra volume of air you can breathe in, after an ordinary breath in.

expiratory reserve volume
The extra volume of air you can breathe out, after an ordinary breath out.

vital capacity
The most air you can move in one breath: from the deepest breath in to the hardest breath out. It is the tidal volume and the two reserve volumes added together.

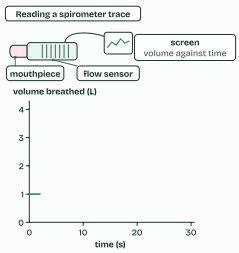
ventilation rate
The number of breaths taken in a minute.



STEP BY STEP

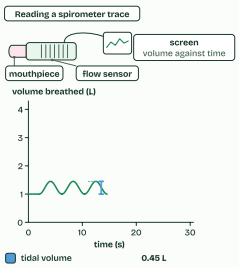
5 STEPS

1



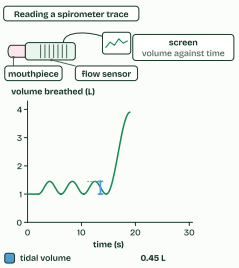
The volunteer breathes through the mouthpiece with a clip on the nose. The sensor is zeroed, and the trace starts flat.

2



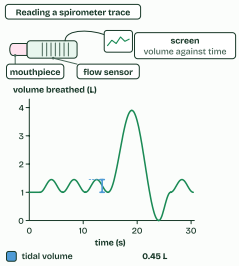
Three ordinary breaths: up the trace is a breath in, down a breath out. The height of one is the **tidal volume**.

3



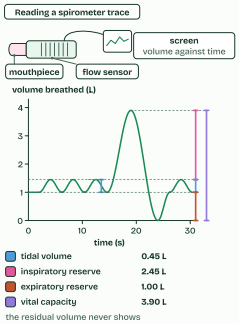
Then the deepest breath in they can take: the trace climbs far above the top of an ordinary breath.

4



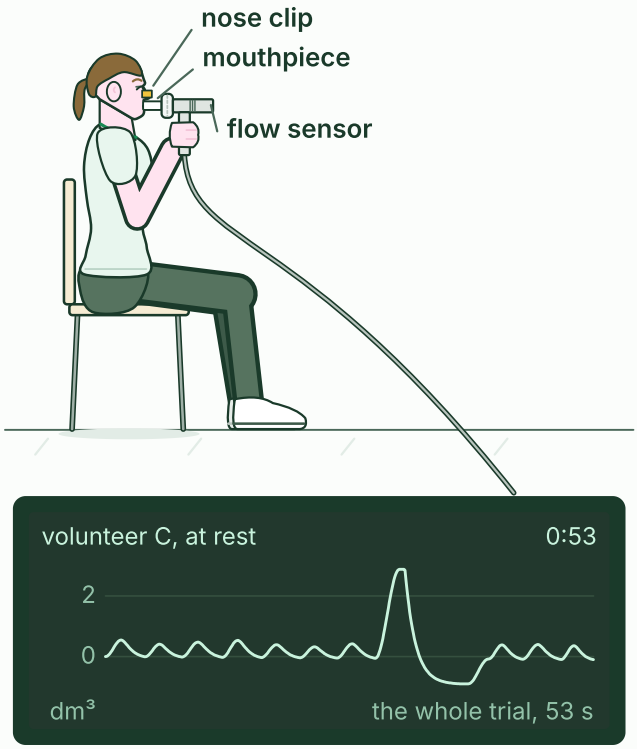
Then out as hard as they can: the trace falls far below where an ordinary breath out ends, before quiet breathing starts again.

5



The volumes, read between the lines: tidal 0.45 L, **inspiratory reserve** 2.45 L, **expiratory reserve** 1.00 L, and the **vital capacity**, all three together, 3.90 L. The air that never leaves, the residual volume, never shows.

volunteer C
female, 17
170 cm



Trial	TV / dm³	IRV / dm³	ERV / dm³	VC / dm³
1	----------	----------	----------	----------
2	----------	----------	----------	----------
3	----------	----------	----------	----------
mean	----------	----------	----------	----------

Lung volumes. A volunteer sits with a nose clip on and breathes through a mouthpiece into a flow sensor; the screen draws the volume breathed against time: half a minute of normal breathing, one breath in as deep as possible, one out as far as possible, then normal again. Read each volume between two points on the trace; repeat the trial and take the means.

PREDICT

After an ordinary breath out you push out as much more air as you can. Which volume is that extra air?

(A) The tidal volume

(B) The inspiratory reserve volume

(C) The expiratory reserve volume

(D) The whole vital capacity

Decide before you look. Answer on page 68.

PREDICT

On the bench, the volunteer breathes out as hard as they can, and the trace stops falling. Are their lungs completely empty?

(A) Yes: the trace stops because the lungs are empty, and that is the vital capacity

(B) No: the sensor stops reading once the flow is slow, so the end of the trace is lost

(C) Yes, but only in a fit volunteer, whose stronger muscles can empty their lungs fully

(D) No: about a litre stays in, which no spirometer can measure, as it never moves

Decide before you look. Answer on page 68.

PREDICT

You want to compare the vital capacities of two volunteers. What makes the comparison fair?

(A) The same posture and instructions, three good tries each, and their heights, ages and sexes recorded

(B) One deep breath each, taken as soon as they arrive, so that neither has had time to practise

(C) The taller volunteer stands and the shorter one sits, so that the two traces come out about the same size

(D) Each volunteer measured on a different spirometer, so that a fault in one machine cannot spoil both

Decide before you look. Answer on page 68.

WATCH OUT

"Vital capacity is all the air in the lungs." The residual volume is left behind. "A bigger chest always means a bigger vital capacity." Height matters most, but age, sex and fitness change it too. "Tidal volume is the same in everyone." It varies from person to person and with effort. And "exercise only makes you breathe faster." Each breath gets deeper too.

13 A carrier with four *hands*

B3.1.11 HL ADAPTATIONS OF FOETAL AND ADULT HAEMOGLOBIN FOR THE TRANSPORT OF OXYGEN

Oxygen dissolves poorly in water, so the plasma could carry only a small fraction of what an active mammal needs. Almost all of it travels bound to **haemoglobin**, which packs every red blood cell. A haemoglobin molecule is four polypeptide chains held together, each folded round a **haem group** with an iron ion at its centre, and each iron binds one oxygen molecule. So one haemoglobin carries up to four. It is B1.2's example of a protein with quaternary structure and a non-protein part, a conjugated protein. In the lungs it loads oxygen; in the tissues it unloads it.

That is **cooperative binding**. It runs in reverse too: once one oxygen leaves, the others leave more easily. So haemoglobin loads fully where there is plenty of oxygen and lets most of it go where oxygen is short, which is the S-shaped curve of chapter 14.

Carbon dioxide also binds to haemoglobin, but not at the haem: it binds at other sites, on the chains themselves. Binding at a site other than the one a molecule works at is called **allosteric** binding, "another site". It changes the shape so that the haem groups hold oxygen less tightly. Hydrogen ions, which carbon dioxide makes in the blood (chapter 16), bind at other sites too, and do more of this than the carbon dioxide itself.

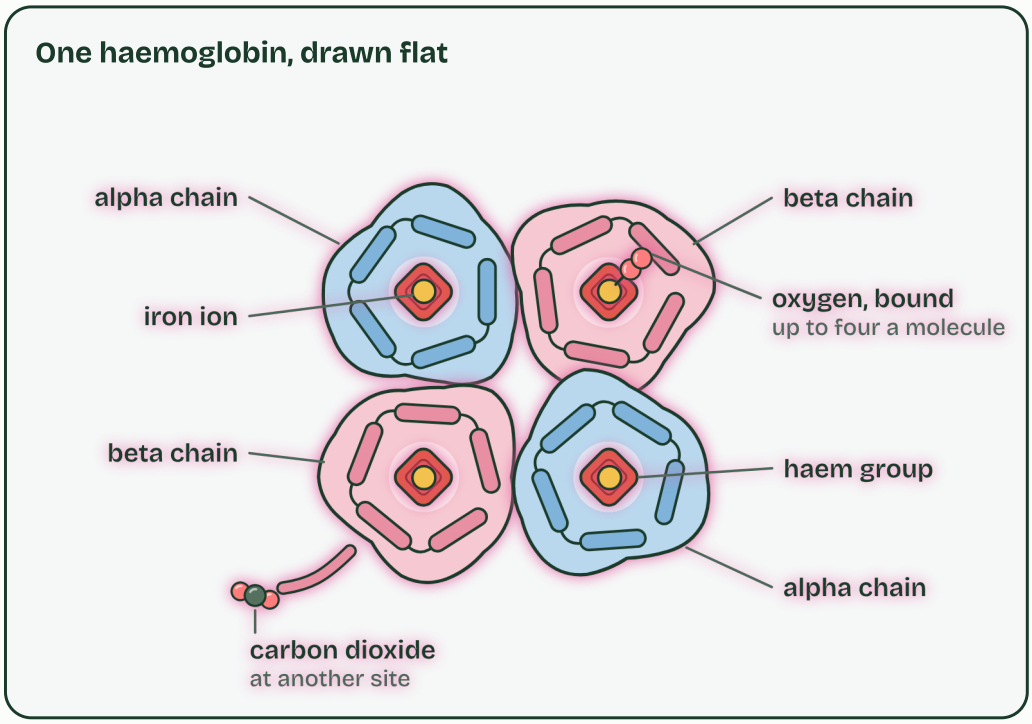
KEY TERMS

haemoglobin
The protein that fills red blood cells and carries oxygen. Four polypeptide chains, each holding a haem group with an iron ion that binds one oxygen molecule.

haem group
The flat, iron-containing group held in each of haemoglobin's four chains. Its iron ion binds one oxygen molecule.

cooperative binding
The binding of one oxygen to haemoglobin making the next bind more easily, because each one bound changes the shape of the whole molecule; and in reverse, each one released making the next leave more easily.

allosteric
Binding at a site other than the active site (here, other than the haem), which changes the protein's shape and so its activity.



An alpha chain One of the four polypeptide chains. Two are alpha chains and two are beta, and each is folded round its own haem group. Held together, the four make one molecule: its quaternary structure (B1.2).

A beta chain Another of the four chains. In a foetus two gamma chains take the place of these two, which changes how tightly the molecule holds oxygen (chapter 15).

Another site Carbon dioxide binds here, at the end of a chain, never at the haem. Binding at another site (allosteric binding) changes the shape so the haem groups hold oxygen less tightly. Hydrogen ions bind at sites of their own and do the same.

The iron ion at the centre of each haem binds one oxygen molecule. Four haem groups, so one haemoglobin carries up to four oxygen molecules.

A beta chain Another of the four chains. In a foetus two gamma chains take the place of these two, which changes how tightly the molecule holds oxygen (chapter 15).

An alpha chain One of the four polypeptide chains. Two are alpha chains and two are beta, and each is folded round its own haem group. Held together, the four make one molecule: its quaternary structure (B1.2).

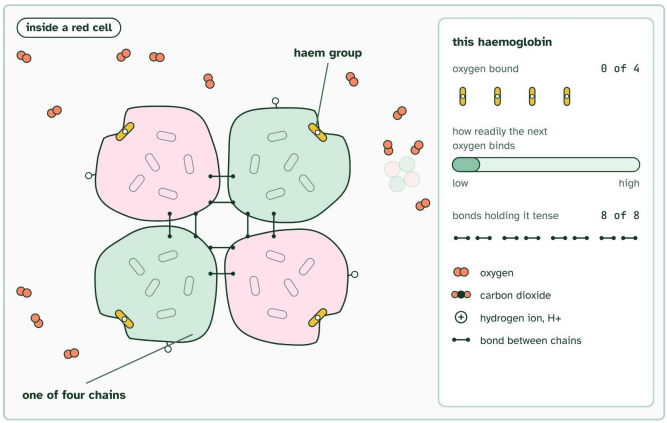
A haem group A flat ring that is not made of amino acids, held in a pocket of its chain. Every haemoglobin has four, so it is a conjugated protein.

Oxygen, bound to an iron. Binding changes its chain's shape a little, and the change spreads through the joined chains so the next oxygen binds more easily: cooperative binding.

ANIMATION · ONE HAEMOGLOBIN TAKES UP OXYGEN

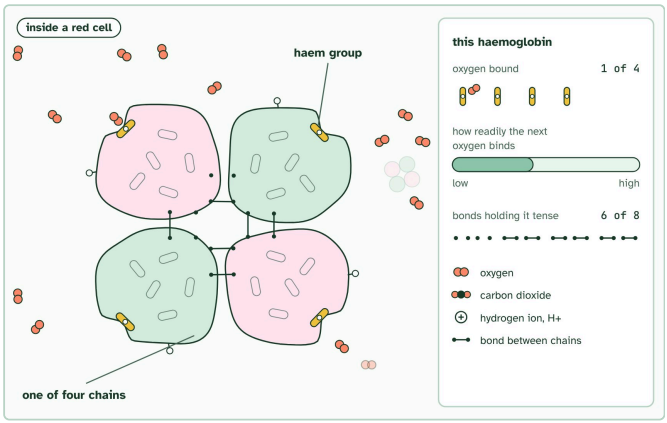
3 MOMENTS

1 0 OF 4 BOUND



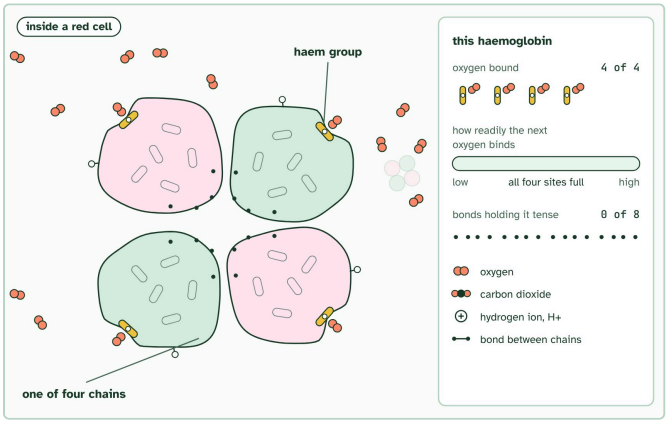
One haemoglobin inside a red cell: four chains, each holding a **haem group**. It has no oxygen yet, and bonds between its chains hold it in a tense shape.

2 1 OF 4 BOUND



The first oxygen binds to the iron of one haem. That chain changes shape and breaks its bonds, so the whole molecule relaxes a little.

3 4 OF 4 BOUND



The fourth binds the most easily of all. Full: four oxygen molecules, one on each haem.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#haemoglobin

PREDICT

A haemoglobin has four haem groups. What does the first oxygen to bind do to how easily the others bind?

(A) It makes it harder, because the oxygen already bound blocks the way to the others

(B) It makes it easier, because binding changes the shape of the whole molecule

(C) It changes nothing, because each of the four haem groups binds on its own

(D) It makes it easier, but only for an oxygen that arrives within the same second

Decide before you look. Answer on page 69.

WATCH OUT

"Each red cell carries one oxygen." Each is packed with hundreds of millions of haemoglobin molecules, each carrying up to four. "Haemoglobin is in the plasma." It is inside the red cells. "Carbon dioxide takes oxygen's place on the haem." It binds elsewhere. And "oxygen is carried dissolved in the blood." Only about 2 per cent is.

B3.1.13 HL OXYGEN DISSOCIATION CURVES AS A MEANS OF REPRESENTING THE AFFINITY OF HAEMOGLOBIN FOR OXYGEN AT DIFFERENT OXYGEN CONCENTRATIONS

14 The S-shaped *curve*

How much oxygen haemoglobin holds depends on how much oxygen is around it. An **oxygen dissociation curve** shows it. Up the side is the **saturation**: the percentage of the haem groups carrying oxygen. Along the bottom is the **partial pressure** of oxygen, pO_2, in kilopascals (kPa): how much oxygen there is. In the alveoli pO_2 is about 13 kPa; in a resting tissue the blood leaves at about 5 kPa; in a hard-working muscle it can fall to 2 or 3.

Read the shape for what it does:

KEY POINTS

- **The flat top: loading in the lungs.** At the lungs' pO_2, haemoglobin is nearly saturated, and the flat top means a small fall in the lungs' oxygen (high up a mountain, or in a stuffy room) costs it very little.
- **The steep middle: unloading in the tissues.** Where pO_2 is low, a small fall makes haemoglobin let go of a lot more oxygen, so a tissue that uses more oxygen gets more.
- **Affinity.** How tightly haemoglobin holds oxygen. A curve further to the left holds more oxygen at the same pO_2: a higher affinity. A curve further to the right holds less and gives more away: a lower affinity.

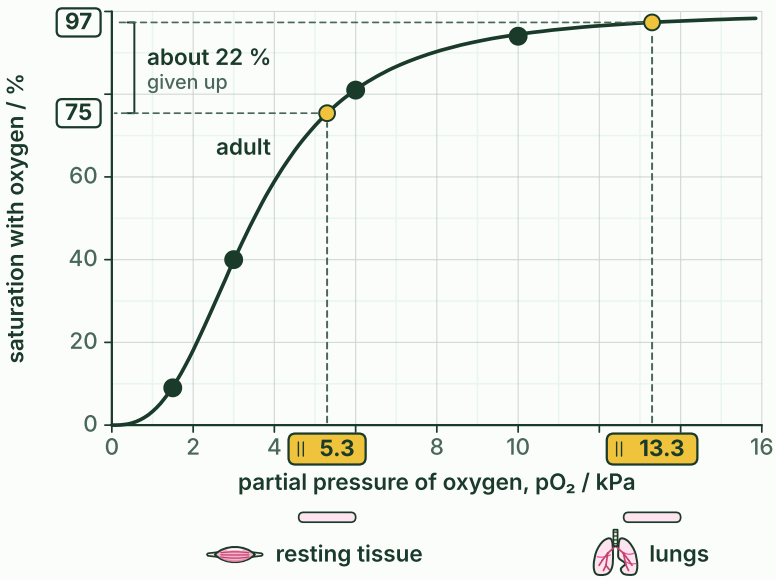
The oxygen given up between two places is the saturation at one minus the saturation at the other. Find it in the tool for the lungs and a resting tissue.

KEY TERMS

oxygen dissociation curve
A graph of the percentage saturation of haemoglobin with oxygen (y) against the partial pressure of oxygen around it (x).

saturation
The percentage of the haem groups in a sample of blood that are carrying oxygen.

partial pressure
The share of a gas mixture's pressure that comes from one gas, a measure of how much of that gas there is: oxygen's, written pO2, in kilopascals (kPa).

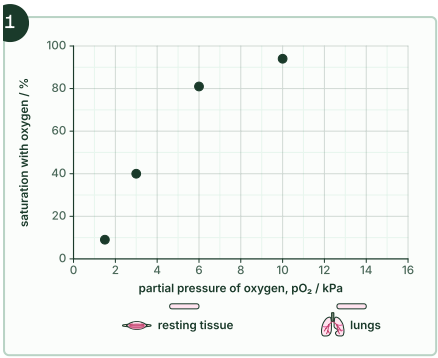


Plot four points and watch the S draw, then move the marker to read the saturation at the lungs and at a resting tissue, and the oxygen given up between them.

STEP BY STEP

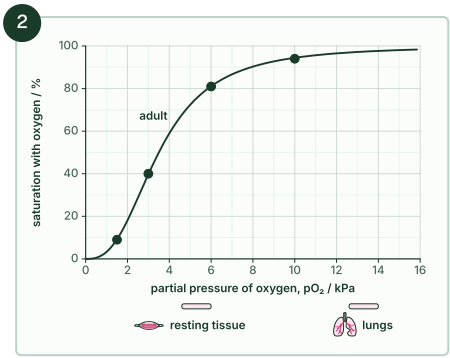
3 STEPS

1



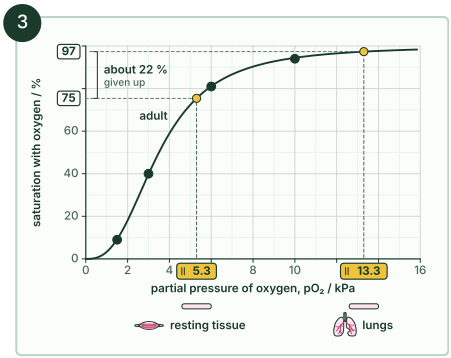
Four measurements of blood at different partial pressures of oxygen (pO_2), plotted as the percentage of its haemoglobin carrying oxygen: its **saturation**.

2



The curve through them is **S-shaped**: shallow at the lowest pO_2, steep in the middle, flat at the top. This is the oxygen dissociation curve of adult haemoglobin.

3



Read it: blood leaving the **lungs** (13.3 kPa) is about 97 % saturated; blood leaving **resting tissue** (5.3 kPa) about 75 %. About 22 % of the haemoglobin gave up its oxygen there.

PREDICT

The curve is shallow at low pO_2, steep in the middle and flat at the top. What makes the middle so steep?

(A) More oxygen dissolves in the plasma as the pressure rises, and the plasma passes it on to the red cells

(B) The red cells swell as the pressure rises, and a bigger red cell takes up more oxygen

(C) The carbon dioxide in the middle of the range pushes oxygen onto the haem groups

(D) Once some haem groups hold oxygen, the rest bind it much more easily: cooperative binding

Decide before you look. Answer on page 69.

REMEMBER IT

Which way the curve moves

L Left	**R** Right
Loads	**Releases**
higher affinity: holds oxygen tighter	lower affinity: gives oxygen up

WATCH OUT

"The y-axis is the amount of oxygen in the blood." It is the percentage of haemoglobin saturated. "A curve to the right means a higher affinity." Lower. "The curve is a straight line." Cooperative binding makes it an S. And "haemoglobin is fully saturated in the lungs." Close, at about 97 per cent, but not quite.

15 Foetal against *adult*

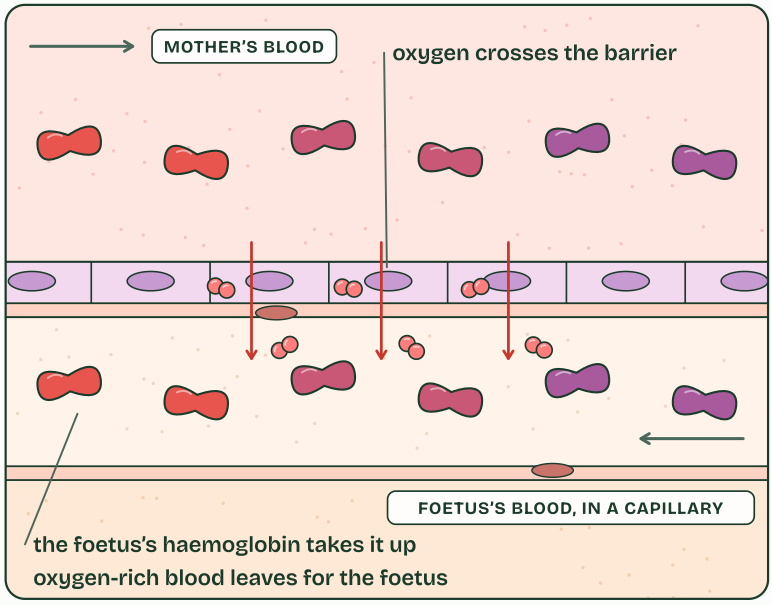
B3.1.11 HL ADAPTATIONS OF FOETAL AND ADULT HAEMOGLOBIN FOR THE TRANSPORT OF OXYGEN

A foetus cannot breathe: it gets its oxygen from its mother's blood, in the placenta. There the mother's blood and the foetus's blood run close together, separated by a thin barrier, and never mix. Oxygen leaves the mother's haemoglobin, diffuses across, and has to be taken up by the foetus's. But the mother's blood in the placenta has already lost some of its oxygen, so the pO_2 there is low.

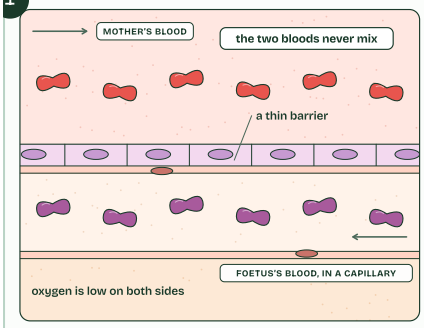
Foetal haemoglobin is built from different chains: two of the same alpha chains as an adult's, but two gamma chains in place of the adult's beta chains. Its dissociation curve lies to the left of the adult's, so at every pO_2 in the placenta it is more saturated. After birth, the baby breathes for itself, and over the first months its red cells come to be filled with adult haemoglobin instead. The placenta itself is D3.1's.

KEY TERMS

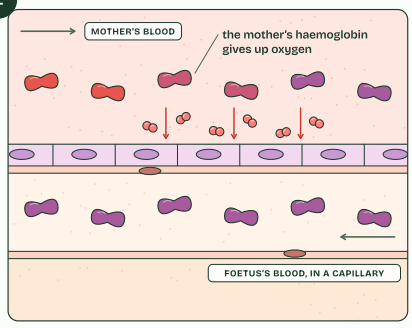
foetal haemoglobin
The haemoglobin of a foetus. It is made of two alpha and two gamma chains (adult haemoglobin has beta chains in place of the gamma), and has a higher affinity for oxygen.



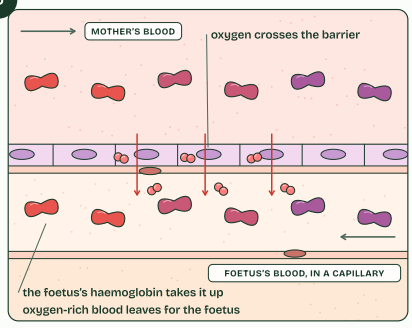
STEP BY STEP 3 STEPS

1


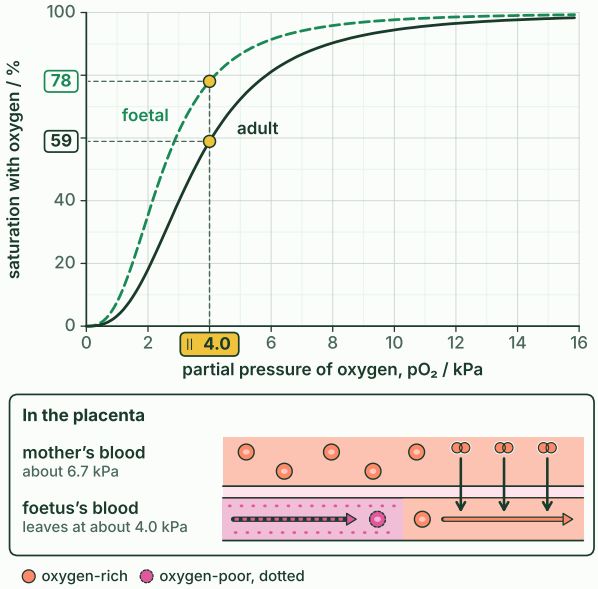
In the placenta the mother's blood flows past a thin barrier, and the foetus's blood flows the other way in capillaries beneath it. The two never mix. On both sides the oxygen is low.

2


The mother's haemoglobin, at this low pO_2, **gives up** some of its oxygen, which diffuses towards the barrier.

3


The oxygen crosses, and the foetus's haemoglobin **takes it up** at the low pO_2 there: it holds oxygen more tightly than the mother's. Its red cells leave oxygen-rich, for the foetus.

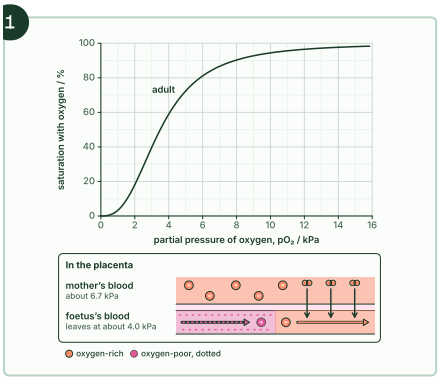


The foetal and the adult curve together. Read both at the placenta's pO_2 and see which way oxygen goes.

STEP BY STEP

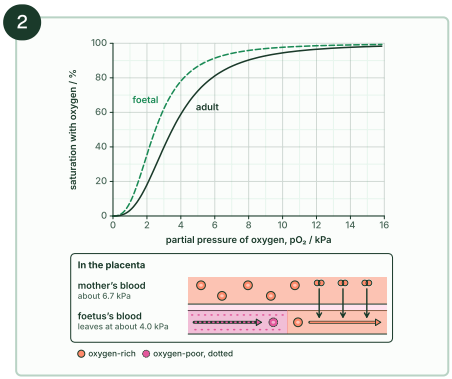
3 STEPS

1



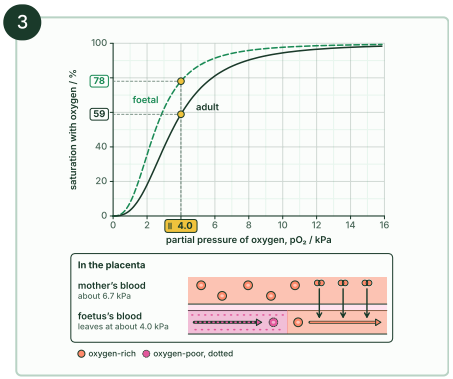
In the placenta the mother's blood and the foetus's blood come close but never mix. The mother's is at about 6.7 kPa there; the foetus's leaves at only about 4.0 kPa.

2



Foetal haemoglobin's curve lies to the **left** of the adult curve: at the same pO_2 it is more saturated. It has a higher **affinity** for oxygen.

3



At 4.0 kPa adult haemoglobin is about 59 % saturated and foetal haemoglobin about 78 %: oxygen the mother's haemoglobin lets go is taken up by the foetus's.

PREDICT

In the placenta the mother's blood and the foetus's blood are both at low oxygen levels. For oxygen to pass to the foetus, what must be true of foetal haemoglobin?

(A) It must hold oxygen less tightly, so that it can pass it on to the foetus's tissues quickly

(B) It must have the same affinity, because oxygen moves by pressure alone and not by binding

(C) It must hold oxygen more tightly than the mother's haemoglobin does at that low level

(D) It must have more haem groups than adult haemoglobin, so that each molecule carries more

Decide before you look. Answer on page 69.

DISCUSS

Why must the foetal curve lie to the left of the adult's? Read both curves in the tool at the placenta's pO_2. Then read the foetal curve at a foetal tissue's pO_2, which is lower still: does foetal haemoglobin still give up oxygen there?

WATCH OUT

"The foetus's blood is its mother's." The two never mix: only substances cross the barrier. "The foetus breathes through the placenta." Its lungs are full of fluid and exchange no gas until birth; the placenta does it. And "foetal haemoglobin carries more oxygen when full." Full, both carry four oxygen molecules; the foetal one holds them more tightly.

16 More carbon dioxide, more oxygen *delivered*

B3.1.12 HL BOHR SHIFT

A muscle that works hard respires fast, so it makes a lot of carbon dioxide. That carbon dioxide diffuses into the blood and into the red cells. There an enzyme, *carbonic anhydrase*, combines it with water to make carbonic acid, which splits into hydrogen ions and hydrogen carbonate ions. The blood becomes a little more acidic.

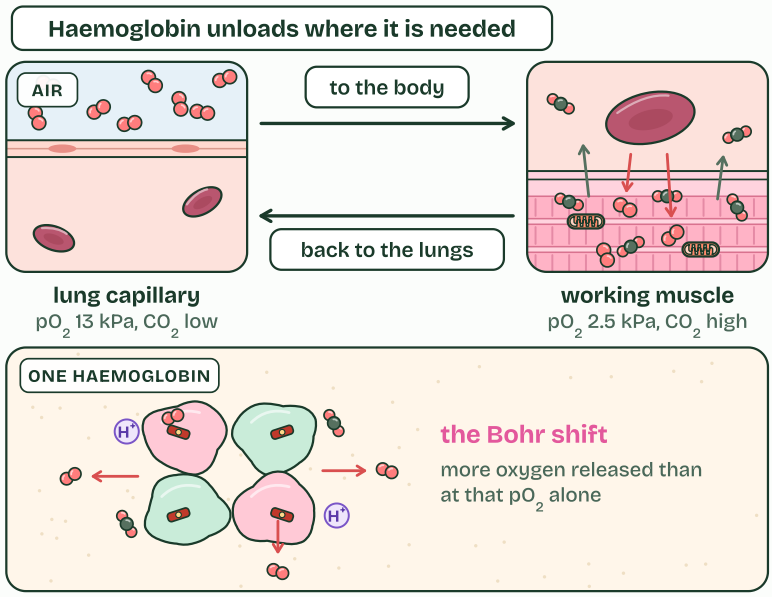
That move of the curve to the right is the **Bohr shift**. It does exactly what a working tissue needs: the harder a muscle works, the more carbon dioxide it makes, and the more oxygen the blood passing through it gives up. In the lungs the reverse happens. Carbon dioxide diffuses out into the alveoli, the curve moves back to the left, and haemoglobin loads oxygen easily again.

KEY POINTS

- More carbon dioxide, more hydrogen ions, lower affinity, more oxygen released.
- The benefit: oxygen is delivered where respiration is fastest, without the pO_2 having to fall further.
- In the lungs the carbon dioxide leaves, and loading is easy again.

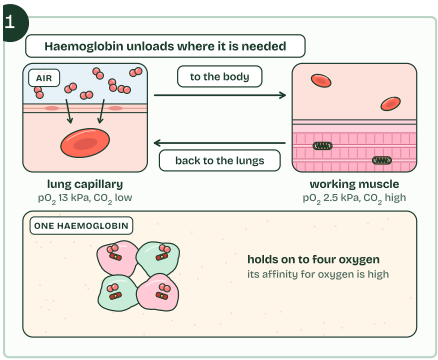
KEY TERMS

Bohr shift
The move of the oxygen dissociation curve to the right when carbon dioxide (and so acidity) rises: haemoglobin's affinity for oxygen falls, so it releases more oxygen in respiring tissue.

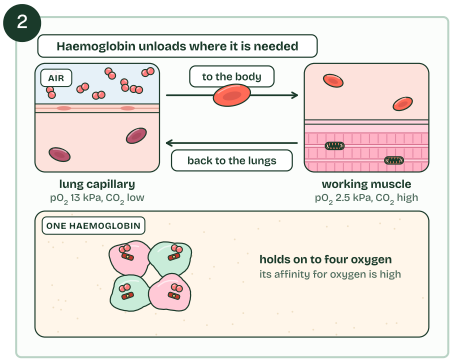


STEP BY STEP

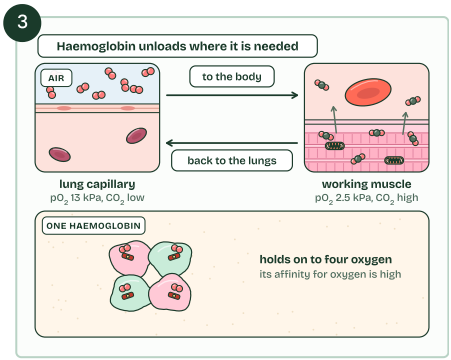
5 STEPS



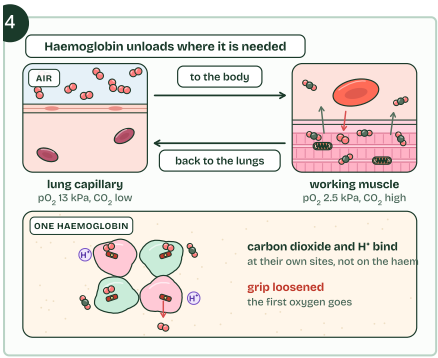
A red cell in a lung capillary. Oxygen is high and carbon dioxide low, so its haemoglobin loads fully: each molecule carries four oxygen.



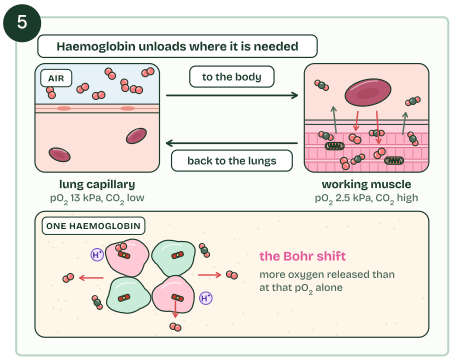
It leaves the lung oxygen-rich and is carried out to the body.



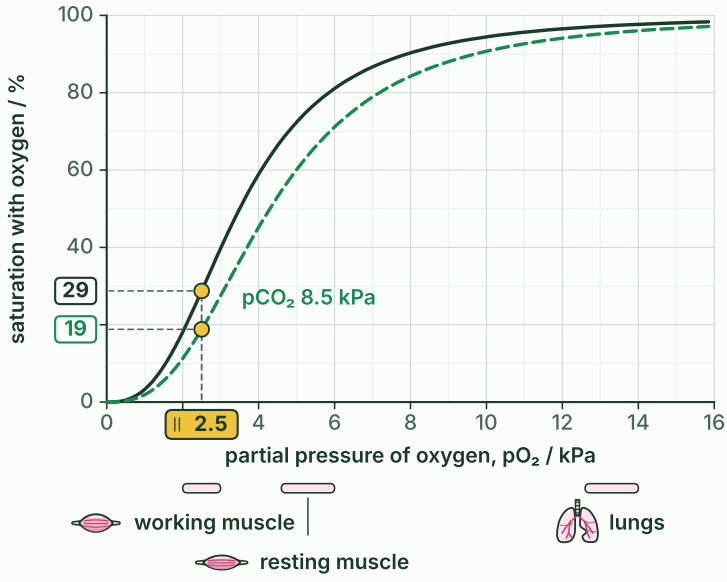
In a working muscle the pO_2 is low and the muscle's respiration has made a lot of carbon dioxide, which diffuses into the blood and the cell.



Carbon dioxide, and the hydrogen ions made from it in the cell, bind to the haemoglobin at their own sites. Its grip on oxygen loosens: its **affinity falls**, and the first oxygen goes.



So it releases **more oxygen** than it would at that pO_2 alone, into the muscle that needs it most: the Bohr shift. The cell goes back to the lungs oxygen-poor, where the carbon dioxide leaves and it loads again.

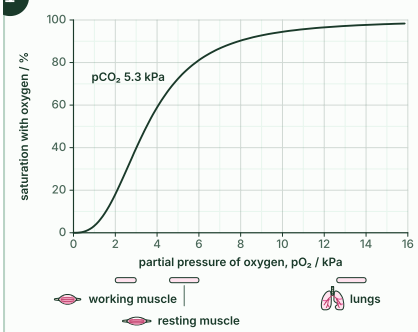


Raise the carbon dioxide and watch the curve move. Compare the oxygen given up at a resting and a working muscle, then sketch the shifted curve yourself.

STEP BY STEP

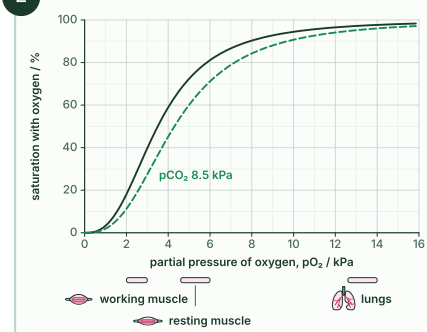
3 STEPS

1



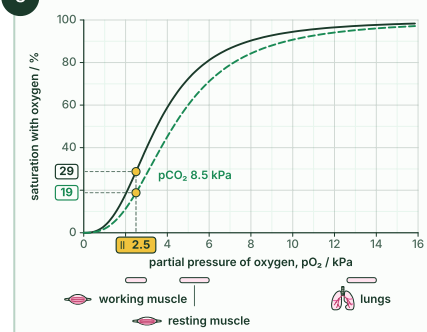
Adult haemoglobin with the carbon dioxide of blood in the lungs (pCO_2 5.3 kPa).

2



With the carbon dioxide of blood in working muscle (pCO_2 about 8.5 kPa) the curve moves to the **right**: a lower affinity for oxygen. This is the **Bohr shift**.

3

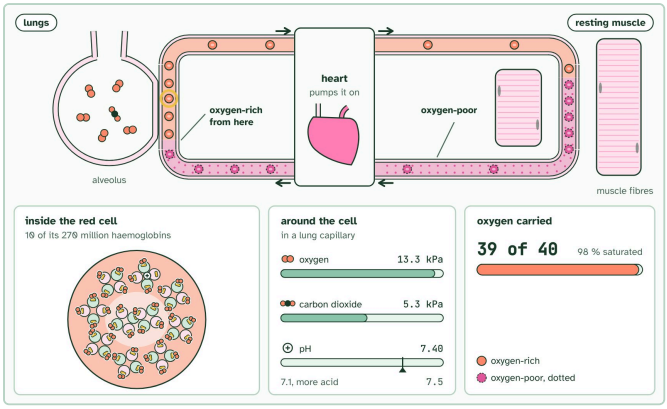


At working muscle's pO_2 (2.5 kPa) the shifted curve is about 19 % saturated against 29 % without the shift: more oxygen is given up where the muscle needs it.

ANIMATION · FROM LUNG TO WORKING MUSCLE

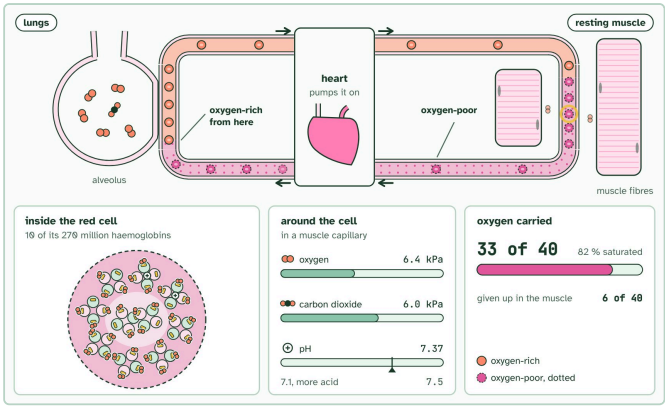
3 MOMENTS

1 IN A LUNG CAPILLARY



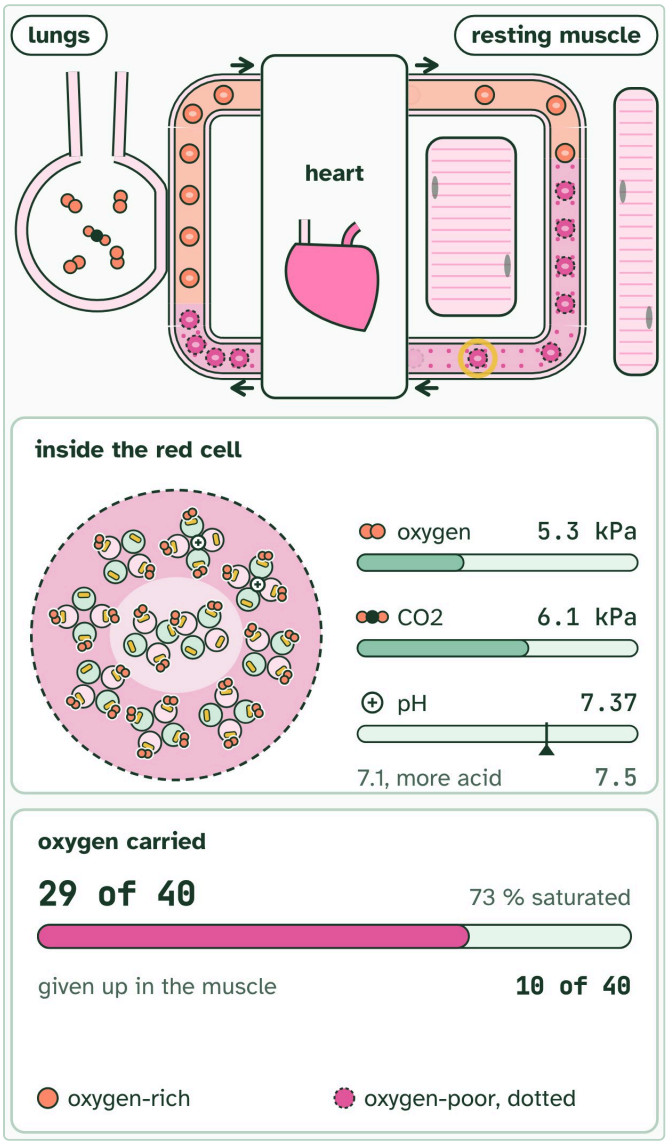
Beside the alveolus the oxygen level is high and carbon dioxide leaves: the haemoglobin fills to nearly 100 per cent.

2 IN A MUSCLE CAPILLARY



In the muscle capillary the oxygen level is lower, and carbon dioxide from respiration comes in. The haemoglobin gives up some of its oxygen.

3 ON ITS WAY TO THE HEART



A resting muscle takes only about a quarter of the oxygen. The rest goes back to the lungs: a reserve for harder work. Try **Working**. (The film's clock is not to scale: at rest a red cell goes round the body in about a minute.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#bohr

PREDICT

A muscle is working hard and its carbon dioxide is high. At the same pO_2, what does this do to the haemoglobin passing through?

(A) It raises its affinity, so more oxygen is held back for the next muscle along

(B) It lowers its affinity, so the haemoglobin releases more oxygen to the muscle

(C) It makes no difference, because only the pO2 sets how saturated it is

(D) It releases oxygen only where the carbon dioxide has already left the blood

Decide before you look. Answer on page 69.

GO FURTHER

Carbon dioxide travels back to the lungs three ways: most of it, about 70 per cent, as hydrogen carbonate ions in the plasma; about a fifth bound to haemoglobin; and the rest, under a tenth, dissolved.

EXAM PRACTICE

Explain, with an annotated sketch of the dissociation curve, how exercise changes haemoglobin's affinity for oxygen, and why this helps the muscles (6 marks). Sketch the shifted curve in the tool below first.

WATCH OUT

"The curve moves right, so haemoglobin takes up more oxygen." It gives more up. "The Bohr shift happens in the lungs." It matters most in respiring tissue; in the lungs it is undone. "Carbon dioxide takes the place of oxygen on the haem." It binds elsewhere. And "the acid damages the haemoglobin." The change in pH is small and the shape change reverses in the lungs.

Key terms

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

abscisic acid 04
A plant hormone made when a plant is short of water. It makes guard cells lose potassium ions, so the stomata close.

allosteric 13
Binding at a site other than the active site (here, other than the haem), which changes the protein's shape and so its activity.

alveoli 08
The tiny air sacs at the ends of the bronchioles, each wrapped in capillaries, where gases are exchanged with the blood (singular alveolus).

antagonistic pair 11
Two muscles that pull in opposite directions, so that when one contracts the other is stretched: the external and internal intercostals, for example.

Bohr shift 16
The move of the oxygen dissociation curve to the right when carbon dioxide (and so acidity) rises: haemoglobin's affinity for oxygen falls, so it releases more oxygen in respiring tissue.

bronchi 08
One of the two branches of the trachea, one to each lung (plural bronchi). Their walls have cartilage too.

bronchioles 08
The narrow airways that branch from the bronchi through the lung. They have smooth muscle in their walls and no cartilage, and the finest ones end in clusters of alveoli.

capillary bed 08
A dense network of capillaries over a surface or through a tissue.

concentration gradient 07
A difference in concentration between two places. A substance diffuses down it, from where it is more concentrated to where it is less; the steeper the gradient, the faster the net movement.

cooperative binding 13
The binding of one oxygen to haemoglobin making the next bind more easily, because each one bound changes the shape of the whole molecule; and in reverse, each one released making the next leave more easily.

diaphragm 10
The domed sheet of muscle under the lungs that separates the chest from the abdomen. It flattens as it contracts.

diffusion 01
The net movement of particles from where they are more concentrated to where they are less concentrated, caused by their random motion. The cell spends no energy on it.

expiratory reserve volume 12
The extra volume of air you can breathe out, after an ordinary breath out.

external intercostal muscles 10
The muscles between the ribs, in two layers: the external intercostals lift the ribs up and out; the internal intercostals pull them down and in.

field of view 05
The circle you see through the microscope. Its diameter shrinks as the magnification rises.

flaccid 04
Short of water, so the cell no longer presses on its wall. Flaccid guard cells straighten and close their stoma.

foetal haemoglobin 15
The haemoglobin of a foetus. It is made of two alpha and two gamma chains (adult haemoglobin has beta chains in place of the gamma), and has a higher affinity for oxygen.

gas exchange 01
Taking in one gas and giving out another across a surface: oxygen in and carbon dioxide out for respiration; in a leaf in the light, carbon dioxide in and oxygen out for photosynthesis.

gas-exchange surface 01

The surface where gases enter and leave an organism: the walls of the mesophyll cells in a leaf, the alveoli in a lung, the gills of a fish. Every one is permeable, thin, moist and large.

gills 07

The gas-exchange organ of a fish: thin filaments packed with capillaries, with water pumped over them.

guard cells 02

The pair of cells round each stoma. They swell to open it and go limp to close it, and they have chloroplasts, where the other cells of the epidermis have few or none.

haem group 13

The flat, iron-containing group held in each of haemoglobin's four chains. Its iron ion binds one oxygen molecule.

haemoglobin 13

The protein that fills red blood cells and carries oxygen. Four polypeptide chains, each holding a haem group with an iron ion that binds one oxygen molecule.

inspiratory reserve volume 12

The extra volume of air you can breathe in, after an ordinary breath in.

mesophyll 02

The tissue between a leaf's upper and lower epidermis: the palisade and spongy layers. The name means the middle of the leaf.

micrograph 03

An image taken through a microscope. A light micrograph of a leaf shows its tissues stained in colour.

osmosis 04

The net movement of water across a partially permeable membrane, from a less concentrated solution to a more concentrated one.

oxygen dissociation curve 14

A graph of the percentage saturation of haemoglobin with oxygen (y) against the partial pressure of oxygen around it (x).

partial pressure 14

The share of a gas mixture's pressure that comes from one gas, a measure of how much of that gas there is: oxygen's, written pO2, in kilopascals (kPa).

plan diagram 03

A drawing that shows where the tissues of an organ are, as outlines of regions, with no single cells drawn.

potometer 06

Apparatus that measures how fast a leafy shoot takes up water: the shoot is sealed into a tube of water, and an air bubble moves along a scale as the water is taken up.

saturation 14

The percentage of the haem groups in a sample of blood that are carrying oxygen.

spirometer 12

Apparatus that measures the volume of air breathed in and out. A digital one has a mouthpiece and a flow sensor and draws the volume against time.

stage micrometer 05

A slide with a tiny ruled scale, usually 1 mm divided into 100 parts, used to measure what a microscope shows.

stomata 02

Pores in the epidermis of a leaf (one is a stoma), each between two guard cells. Gases enter and leave the leaf through them.

stomatal density 05

The number of stomata in a unit area of leaf surface, usually per square millimetre.

surface area to volume ratio 01

The surface area of an object divided by its volume. It falls as an object of the same shape gets bigger.

surfactant 09

A mixture of phospholipids and proteins made by cells in the alveolus wall. It spreads over the film of water lining the alveoli and weakens its pull, so the alveoli do not collapse when you breathe out.

tidal volume 12

The volume of air breathed in, or out, in one ordinary breath: about half a litre at rest.

trachea 08

The windpipe: the tube from the larynx to the chest, held open by C-shaped rings of cartilage.

transpiration 06

The loss of water vapour from the leaves and stems of a plant. Most of it goes out through the stomata.

transverse section 03

A thin slice cut straight across an organ, at right angles to its length.

turgid 04

Swollen with water, so the cell pushes on its wall. Turgid guard cells bow apart and open their stoma.

ventilation 07

Moving air or water over a gas-exchange surface: breathing in and out in a mammal, pumping water over the gills in a fish.

ventilation rate 12

The number of breaths taken in a minute.

vital capacity 12

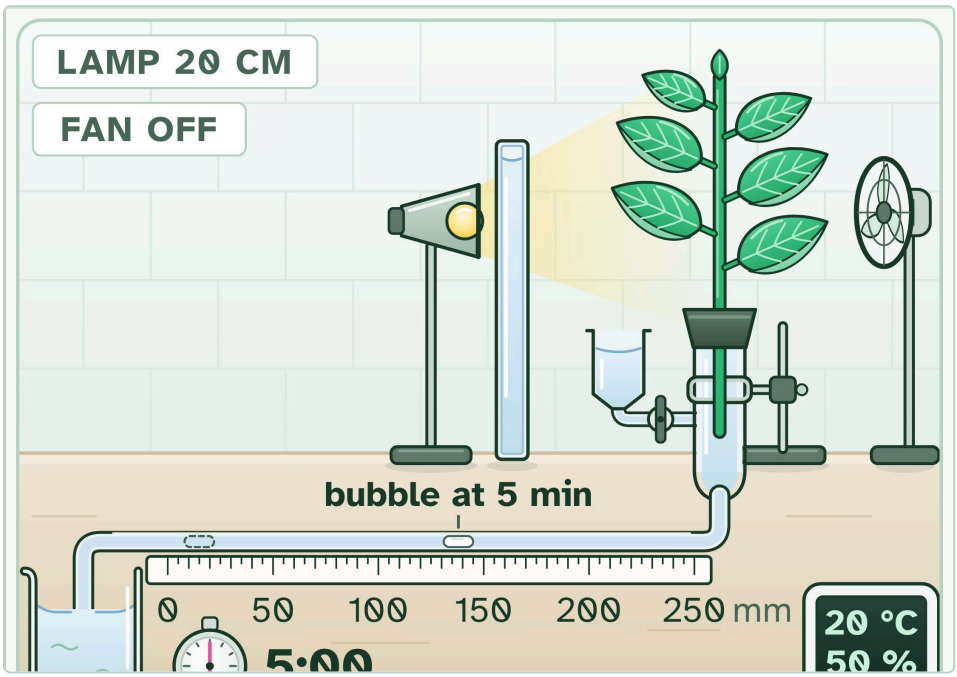
The most air you can move in one breath: from the deepest breath in to the hardest breath out. It is the tidal volume and the two reserve volumes added together.

waxy cuticle 02

A layer of wax over the epidermis of leaves and stems. It keeps water in, and keeps gases out.

Dry lab: *The potometer*

A leafy shoot sealed into a tube of water takes up water as its leaves lose it, and an air bubble creeps along the scale. Change the light, the wind, the humidity or the temperature, read the bubble every minute, then plan and write it up as an investigation with the coach beside you.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-b3-1-gas-exchange#lab`

Your question

How does one condition change how fast a leafy shoot takes up water, and so how fast it transpires? The bench starts with light: how does the rate change as the lamp comes from 80 cm to 10 cm?

What you can change

One independent variable at a time: the lamp's distance (10 to 80 cm), the fan (off, low or high), the humidity of the air (30 to 90 %) or its temperature (15 to 30 °C). Keep everything else the same unless you mean to change it: the heat shield, the bag, the capillary's bore and how long you wait before you read. Give the shoot time to settle after every change.

What to record

The bubble's position on the scale every minute, then the rate as a volume of water a minute, and per cm² of leaf. At least three runs at each value, a mean and a standard deviation, and a graph of the means with error bars. A potometer measures water uptake, not water loss. A little of the water a shoot takes up stays in it, so uptake is a little more than transpiration, though close enough to stand in for it.

Find out

- **How much does light matter?** The lamp at five or more distances between 80 cm and 10 cm, three runs at each, with the heat shield in place. Wait for the rate to settle after every move before you read.
- **Does moving air speed it up?** The fan off, low and high, three runs at each, with the lamp and the room kept the same.
- **Humid air or dry?** The air from 30 to 90 % humidity. Then, at the room's own humidity, tie a clear bag over the leaves and read the bubble every minute.
- **Is a warmer room faster?** The air from 15 to 30 °C, at the same humidity.
- **Run the controls.** A potometer with no shoot in it, its bung sealed, whatever you change; for light, the shoot in a light-proof box with the lamp off as well.

Record

- For every run: the variable you changed, its value, and the settings you kept the same.
- The bubble's position on the scale each minute. How far it moves ÷ the time is its rate in mm min^{-1}.
- Turn that into a volume: the distance × the bore's cross-section, πr^2, which is 0.785 mm^2 for a 1.0 mm bore. A bubble moving 24 mm a minute along it means 24 × 0.785 ≈ 19 mm^3 of water a minute.
- Divide by the leaf area, traced on 1 cm squared paper, for the rate per cm^2 of leaf.
- Three or more runs at each value, with a mean and its standard deviation. The table and the graph fill in as you record, or download the CSV and plot your own. When you are done, the IA coach below the dry lab helps you write it up as an investigation.

Your question How does one condition change how fast a leafy shoot takes up water, and so how fast it transpires? The bench starts with light: how does the rate change as the lamp comes from 80 cm to 10 cm?**What you can change**One independent variable at a time: the lamp's distance (10 to 80 cm), the fan (off, low or high), the humidity of the air (30 to 90 %) or its temperature (15 to 30 °C). Keep everything else the same unless you mean to change it: the heat shield, the bag, the capillary's bore and how long you wait before you read. Give the shoot time to settle after every change.**What to record**The bubble's position on the scale every minute, then the rate as a volume of water a minute, and per cm^2 of leaf. At least three runs at each value, a mean and a standard deviation, and a graph of the means with error bars. A potometer measures water uptake, not water loss. A little of the water a shoot takes up stays in it, so uptake is a little more than transpiration, though close enough to stand in for it.

Back to the leaf

Transpiration is a consequence of gas exchange in a leaf. Use your results to explain why the shoot took up water faster as the lamp came closer.

QUESTIONS ON THE LAB

QUESTION 1

A lamp warms whatever it shines on. Why does the bench keep a heat shield, a glass tank of water, between the lamp and the shoot?

(A) So that the water in it keeps the air round the shoot humid, the same in every run

(B) So that every distance gives the leaves the same light, and only the lamp's heat changes

(C) So that moving the lamp changes the light on the leaves, and not their temperature too

(D) So that the water focuses the lamp's light like a lens, and the leaves get more of it

Answer on page 69.

QUESTION 2

With the fan on low, the shoot takes up water much faster than in still air. What do you expect the high setting to add?

(A) As much again as low added, because the rate rises in step with the speed of the air

(B) Less than low added, because once the humid layer has gone, the stomata set the limit

(C) Nothing, because any moving air makes the guard cells close the stomata straight away

(D) More than low added, because faster air also pulls the vapour out through the stomata

Answer on page 70.

QUESTION 3

Why run a potometer with no shoot in it, its bung sealed, alongside the real ones?

(A) To find how much water a stem alone takes up, so that it can be taken off every reading

(B) To give a rate for the dark, which the rates under the lamp can then be compared with

(C) To show how much water is lost through the cuticle alone, with no stomata in the way

(D) To check the bubble stays still on its own, so all the movement you read is the shoot's

Answer on page 70.

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: distance from the lamp			
Dependent: rate of water uptake			
Kept the same: air movement (the fan)			
Kept the same: humidity of the air			
Kept the same: temperature of the air			
Kept the same: heat shield between the lamp and the shoot			
Kept the same: no bag over the shoot			
Kept the same: the same shoot, and its leaf area			
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 B3.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=B3.1&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 The 4 cm cube is squashed into a sheet 16 cm by 16 cm and 0.25 cm thick, with the same volume. Compared with the cube, how quickly is every part of it supplied?

B Quickly everywhere: there is far more surface for the volume, and no part is far from it

Quickly everywhere. The sheet keeps the cube's 64 cm³, but its surface is 528 cm² instead of 96 cm², a ratio of 8.25 : 1 instead of 1.5 : 1. And no part of it is more than 0.125 cm from a surface, where the cube's centre was 2 cm in. Flattening is how a leaf gets round the problem: it is broad and thin.

02 Why are most of a leaf's stomata in its lower surface?

C The underside is shaded and cooler, so less water evaporates out through its open pores

The lower surface is out of the direct sun, so it is cooler, and pores there lose less water for the carbon dioxide they let in. Nothing is lost by putting them underneath: the air spaces carry the gas up to the palisade cells in a moment.

03 A plan diagram shows where each tissue of an organ is. A student draws every palisade cell in their plan of a leaf. What is wrong?

D A plan shows the outline of each tissue, and none of the separate cells inside it at all

A plan diagram outlines each tissue as one region. Cells belong in a different drawing, a detailed one of a small part of a tissue at high power. Neither kind is ever shaded.

04 A plant in bright sunshine runs short of water. What do its stomata do?

D They close: holding on to water now matters more than taking in carbon dioxide

They close. The plant makes abscisic acid, the guard cells lose potassium ions and then water, and the pores shut even in full light. The plant keeps its water, but takes in less carbon dioxide, so photosynthesis slows: the price of not drying out.

05 Why count five fields, chosen at random, instead of one?

A Stomata are not spread evenly, so the mean of random fields is more reliable and shows the spread

Stomata are scattered unevenly, so some fields hold more than others. The mean of several random fields is closer to the leaf's true density than any one count, and the spread of the counts tells you how much they vary. Choosing the fields yourself could pick the clearest, which may not be typical.

05 Some stomata lie across the edge of the field, part in and part out. Why decide on a rule for them before you start counting?

B So that every field is counted the same way, and counts from different fields compare

Without a rule you would count some edge stomata and not others, so fields would not be counted alike, and counts from different fields, leaves or people would not compare. Counting every stoma the edge touches makes the density too high, and counting none of them makes it too low. Counting one only when more than half of it is inside is, for something so small next to the field, the same as counting the stomata whose centres lie inside the circle, so the count fits the area πr^2 you divide it by.

05 At the same magnification, a leaf's upper surface gives a mean of 3 stomata a field and its lower surface 15. Why can you say the lower surface has five times the density without measuring the field?

D Both counts come from fields of the same area, so the area cancels when one density is divided by the other

Density is count ÷ area, and both counts come from fields of the same area, so in the ratio of the two densities the area cancels: 15 ÷ 3 = 5. You need the area to give each density in stomata per mm² (with a 0.159 mm² field, about 19 and 94), but not to compare them. Most of the pores are on the shaded, cooler lower surface, where they lose less water for the carbon dioxide they let in (chapter 2).

06 One leaf on a plant in sunshine has its lower surface smeared with petroleum jelly. Compared with a leaf left alone, it becomes...

B **warmer, because less water can evaporate out through its stomata and carry heat away**

Warmer. Water takes heat with it when it evaporates. Jelly on the lower surface blocks most of the stomata, so the leaf loses far less water, loses most of that cooling, and warms up in the sun. An infrared thermometer shows the difference, and the physics is A1.1's dry lab, Wet wicks.

07 The blood in a capillary beside an alveolus stops flowing, but breathing carries on. What happens to the gradient across the wall?

A **It fades away, as the still blood soon reaches the air's oxygen level**

It fades away. The air keeps its oxygen, but the blood that sits against the wall takes up oxygen until it holds as much as the air, and then net diffusion stops: no gradient, no exchange. The gradient needs both sides refreshed. Breathing keeps the air side high in oxygen; flowing blood carries each load away and brings blood that is low in oxygen to the wall. The film below lets you stop either one.

08 A lung is a tree of ever narrower tubes ending in millions of tiny sacs, not one big bag. What does this gain?

C **A far greater surface area in the same volume, so more oxygen can cross each second**

A far greater surface area for the same volume. Chapter 1's cubes showed it: one big bag has a small surface for what it holds, and many small sacs have a huge one. Your two lungs hold a few litres of air, yet the walls of their alveoli add up to about 70 square metres (estimates run from about 50 to 100, by method), enough to carpet a large classroom. The Area switch in the tool below sets a few small sacs beside one bag of the same air.

09 A baby is born weeks early with too little surfactant. What goes wrong in its alveoli when it breathes out?

D **The watery lining pulls the walls together, so the alveoli collapse and are hard to reopen**

They collapse. The film of water lining each alveolus pulls on itself, as the water in a soap bubble does, and that pull draws the wall inwards. Surfactant weakens the pull. Without enough of it, the alveoli fold shut as the baby breathes out, and every breath in is a struggle to open them again. Babies born very early can be given surfactant, and their mothers a steroid injection before the birth that speeds up the lungs' own production. Switch Surfactant to Absent in the film below.

10 The diaphragm contracts. What does that do to the pressure of the air in the lungs, and so to the air?

B **It flattens, the chest gets bigger, the pressure falls below the air outside, and air flows in**

It flattens and the chest gets bigger. The air in the lungs now has more room, so its pressure falls a little below the air outside, and air flows in until the two are equal. The diaphragm never touches the air: it changes the size of the chest, and the pressure does the rest. The lungs follow the chest wall out; they cannot pull themselves open.

11 Quiet breathing out uses no muscle effort. In a sprint, which extra muscles help you breathe out?

A **The abdominal muscles and the internal intercostals, which pull the chest smaller**

The abdominal muscles and the internal intercostals. The internal intercostals pull the ribs down and in, and the abdominal muscles squeeze the abdomen's contents up against the relaxed diaphragm, pushing it higher than a quiet breath out would. The chest shrinks further and faster. A contracting diaphragm can only flatten, which makes the chest bigger; the external intercostals lift the ribs; and the lungs have no muscle that can squeeze the air out.

12 After an ordinary breath out you push out as much more air as you can. Which volume is that extra air?

C **The expiratory reserve volume**

The expiratory reserve volume: the extra you can breathe out beyond an ordinary breath out. Expiration is breathing out, and the reserve is what you keep back when you breathe quietly. The tidal volume is the ordinary breath itself, the inspiratory reserve is the extra you can breathe in, and the vital capacity is all three together.

12 On the bench, the volunteer breathes out as hard as they can, and the trace stops falling. Are their lungs completely empty?

D No: about a litre stays in, which no spirometer can measure, as it never moves

No. The residual volume, about a litre in an adult, stays in the lungs even after the hardest breath out, so the alveoli never collapse empty. A spirometer measures only air that moves through it, so it can measure the vital capacity but never the residual volume, and no amount of fitness empties the lungs.

12 You want to compare the vital capacities of two volunteers. What makes the comparison fair?

A The same posture and instructions, three good tries each, and their heights, ages and sexes recorded

Keep everything you can the same (posture, the instructions, the same spirometer, zeroed), take three good tries each and use the best or the mean, and record what you cannot keep the same: height, age and sex, which all change vital capacity. Then a difference can be put down to the person, not to the method. One try catches a poor breath; two machines add their own differences.

13 A haemoglobin has four haem groups. What does the first oxygen to bind do to how easily the others bind?

B It makes it easier, because binding changes the shape of the whole molecule

Easier. When an oxygen binds to one haem group, its chain changes shape a little, and because the four chains are joined, the change spreads to the others and opens up their haem groups. The second binds more easily than the first, the third more easily still, and the fourth most easily of all. The film below plays it.

14 The curve is shallow at low pO_2, steep in the middle and flat at the top. What makes the middle so steep?

D Once some haem groups hold oxygen, the rest bind it much more easily: cooperative binding

Cooperative binding (chapter 13). At low pO_2 the first oxygen binds with difficulty, so the curve starts shallow. Once one is on, the rest bind much more easily, so a small rise in pO_2 fills a lot of haem groups: the steep middle. Near the top almost every group is full, so the curve flattens. Plot the points in the tool below and watch the S appear.

15 In the placenta the mother's blood and the foetus's blood are both at low oxygen levels. For oxygen to pass to the foetus, what must be true of foetal haemoglobin?

C It must hold oxygen more tightly than the mother's haemoglobin does at that low level

It must hold oxygen more tightly: a higher affinity. At the low pO_2 in the placenta the mother's haemoglobin lets go of oxygen, and the foetus's, which holds it more tightly, takes it up, so oxygen passes one way across the placenta. If the two had the same curve, they would hold the same share of oxygen at the same pO_2, and little would pass. Both have four haem groups.

16 A muscle is working hard and its carbon dioxide is high. At the same pO_2, what does this do to the haemoglobin passing through?

B It lowers its affinity, so the haemoglobin releases more oxygen to the muscle

It lowers the affinity, so the haemoglobin releases more oxygen. The hydrogen ions and the carbon dioxide bind to haemoglobin at their own sites (chapter 13) and hold it in the shape that grips oxygen less tightly. At the same pO_2 it is less saturated, so it has given more of its oxygen up. The whole curve has moved to the right.

QUESTIONS ON THE DRY LAB

Q1 A lamp warms whatever it shines on. Why does the bench keep a heat shield, a glass tank of water, between the lamp and the shoot?

C So that moving the lamp changes the light on the leaves, and not their temperature too

A lamp gives out heat as well as light, and the closer it is, the more it warms the leaves. A warmer leaf transpires faster, so without the shield the rate would rise for two reasons at once, and you could not tell how much of the rise was the light. Water lets light through but takes up much of the heat. With the shield in place, the lamp's distance changes the light and little else: keep it there for every run, and say so in your method.

Q2 With the fan on low, the shoot takes up water much faster than in still air. What do you expect the high setting to add?

B **Less than low added, because once the humid layer has gone, the stomata set the limit**

Less. In still air, the vapour coming out of the stomata builds up in a thin layer of humid air on the leaf, and the vapour behind it has to cross that layer. A breeze sweeps most of it away, so the low setting adds a lot. Faster air thins the layer further, but the vapour still has to get out through the stomata, and they are open no wider than before, so each step up in wind adds less. Check that the difference between low and high is bigger than the spread of your repeats before you claim it.

Q3 Why run a potometer with no shoot in it, its bung sealed, alongside the real ones?

D **To check the bubble stays still on its own, so all the movement you read is the shoot's**

With no shoot, nothing takes water up, so the bubble should not move. If it does, something other than a shoot is moving it, the water in the apparatus warming and expanding, say, and the same error would be in every reading you take with a shoot. A bubble that stays still shows that what you read is the shoot's uptake. The light-proof box is a different control: it gives the rate with no light at all, for the runs under the lamp to be compared with.

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.