

Organisms (Form and function) revision notes

How the form of whole organisms suits their function. Gas exchange in mammals and leaves, transport in blood and in xylem and phloem, and, at HL, haemoglobin, the heart, tissue fluid and how muscles, skeletons and joints produce movement.

For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

1 Gas exchange Spec B3.1

Gas exchange and exchange surfaces Spec B3.1.1, B3.1.2, B3.1.3

Every organism must take in oxygen for aerobic respiration and remove carbon dioxide, and photosynthesising organisms do the reverse in the light. **Gas exchange** happens by **diffusion**, so it depends on surface area, distance and the concentration gradient.

Why size makes it harder

- As an organism gets bigger, its volume rises faster than its surface area, so the **surface area-to-volume ratio** decreases. There is less surface for each unit of respiring tissue.
- The distance from the centre of the organism to its exterior also increases, and diffusion is only fast over very short distances.
- Small organisms (for example a unicellular organism or a flatworm) can exchange gases across their whole body surface. Large, active organisms need a specialised gas-exchange surface and a transport system to carry gases to and from every cell.

Properties of gas-exchange surfaces

The four properties of gas-exchange surfaces	
Property	Why it helps
Permeable	Oxygen and carbon dioxide can pass through the cells and membranes freely.
Thin tissue layer	A short diffusion distance makes diffusion fast.
Moist	Gases dissolve in the film of water before they diffuse across the surface.
Large surface area	More gas can diffuse across at the same time.

Keeping concentration gradients steep in animals

- **Dense networks of blood vessels** (capillaries) lie right next to the exchange surface.
- **Continuous blood flow** carries oxygenated blood away and brings deoxygenated blood with a high carbon dioxide concentration, so the gradient never levels out.
- **Ventilation** replaces the medium next to the surface: air is pumped in and out of lungs, and water is pumped over the gills of fish.

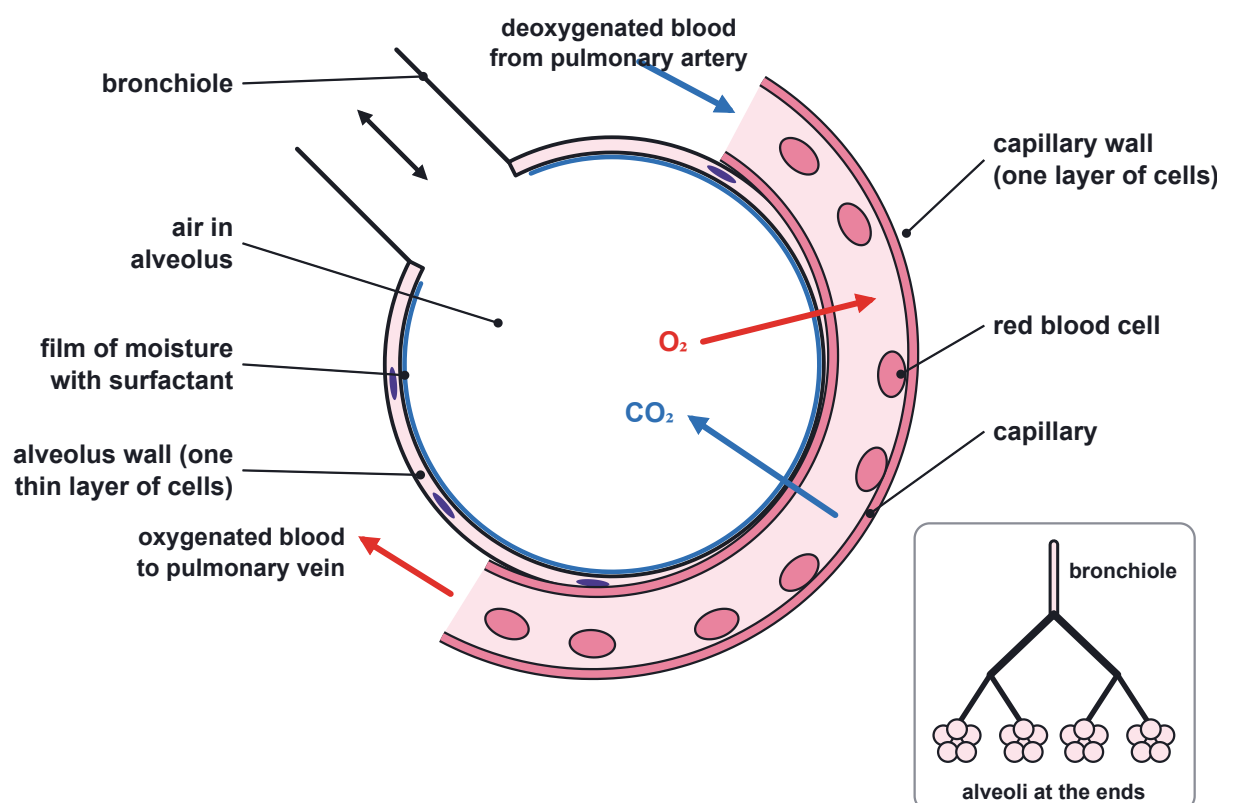
Exam tip: Linking question: how do multicellular organisms solve the problem of access to materials for all their cells? A good answer pairs a large exchange surface with a transport system that delivers to every cell.

Adaptations of mammalian lungs Spec B3.1.4

Air enters through the trachea, which divides into two bronchi, one to each lung. Each bronchus divides again and again into a **branched network of bronchioles**, which end in clusters of tiny air sacs called **alveoli**.

Adaptations of the alveolar lungs for gas exchange	
Adaptation	How it helps gas exchange
Branched network of bronchioles	Carries air to and from hundreds of millions of alveoli spread through the whole lung.
High surface area	The very large number of small alveoli gives a huge total surface for diffusion.
Extensive capillary beds	Each alveolus is covered in capillaries, so blood flows close to every part of the surface and keeps the gradient steep.
Thin walls	The alveolus wall and the capillary wall are each one layer of very thin, flattened cells, so the diffusion distance is short.
Surfactant	A fluid secreted by cells in the alveolus wall reduces the surface tension of the water lining, so the alveoli do not stick together and collapse when air is breathed out.
Moist lining	Oxygen dissolves in the film of moisture before it diffuses into the blood.

Oxygen diffuses from the air in the alveolus into the blood, and carbon dioxide diffuses from the blood into the alveolus. Ventilation and continuous blood flow keep both gradients steep.



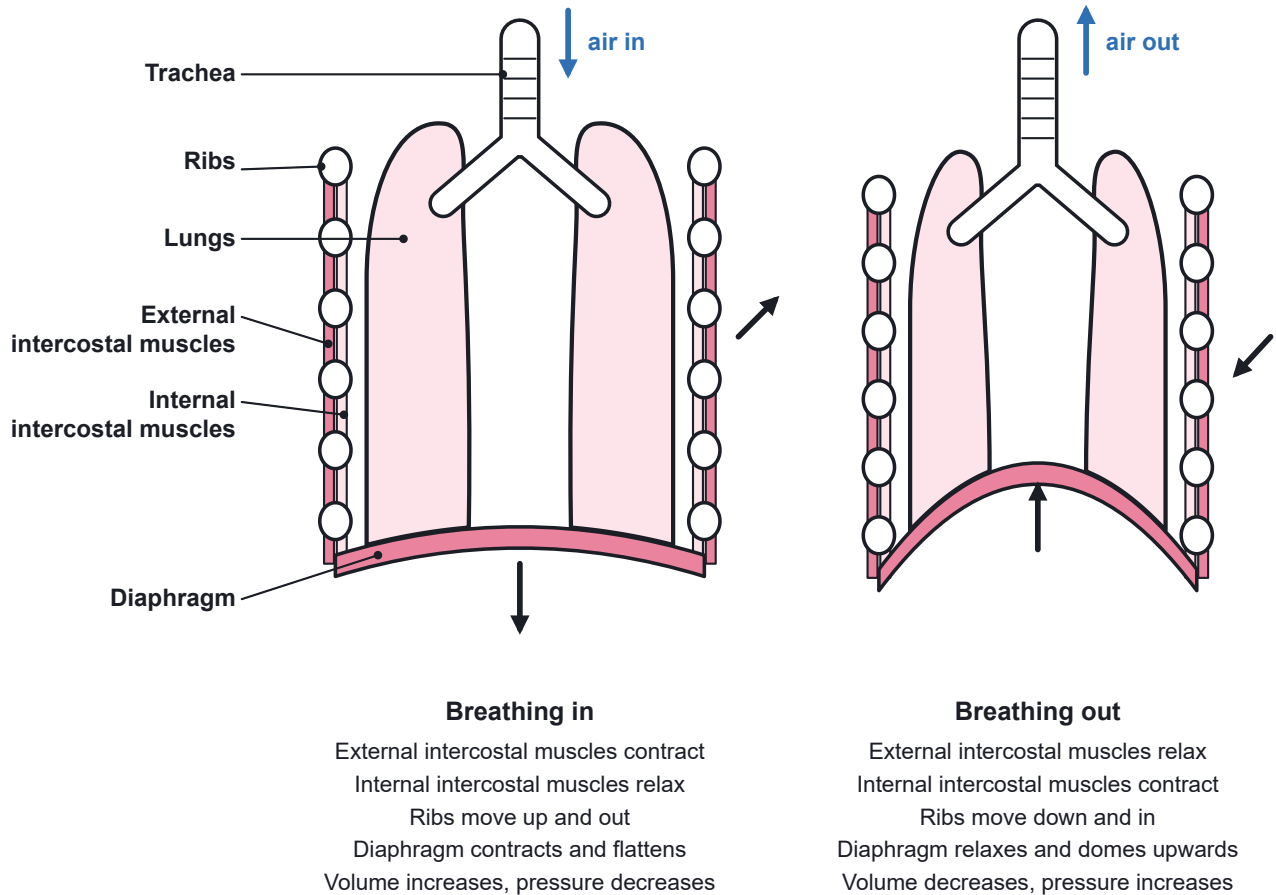
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Gas exchange in an alveolus: **two thin layers of cells** separate the air from the blood, and blood flow keeps the gradients steep.

Common mistake: Surfactant does not help gases dissolve or diffuse. Its job is to lower surface tension so the alveoli stay open.

Ventilation and lung volumes Spec B3.1.5, B3.1.6

Air always flows from higher to lower pressure. Muscles change the **volume of the thorax**, which changes the pressure inside it (pressure and volume are inversely related).



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Inspiration and expiration change the volume of the thorax. The breathing-out panel shows forced expiration: in quiet expiration the internal intercostal muscles stay relaxed. The abdominal muscles (not drawn) also contract in forced expiration.

Muscle actions during ventilation		
Structure	Inspiration (breathing in)	Expiration (breathing out)
Diaphragm	Contracts and flattens, moving down	Relaxes and is pushed back up into a dome (by elastic recoil and the abdominal organs; in forced expiration also by the abdominal muscles)
External intercostal muscles	Contract, pulling the ribcage up and out	Relax
Internal intercostal muscles	Relax	Relaxed in quiet expiration; contract in forced expiration, pulling the ribcage down and in
Abdominal muscles	Relax, so abdominal organs can be pushed down	Relaxed in quiet expiration; contract in forced expiration, pushing abdominal organs and the diaphragm up
Ribs	Move up and out	Move down and in (by gravity and elastic recoil in quiet expiration; pulled by the internal intercostals in forced expiration)
Thorax volume and pressure	Volume increases, pressure falls below atmospheric, air flows in	Volume decreases, pressure rises above atmospheric, air flows out

Quiet expiration (breathing out at rest) is mainly passive: the diaphragm and external intercostal muscles relax, and the stretched lungs and chest wall recoil elastically, so thorax volume falls. **Forced expiration** (during exercise, coughing, or when measuring vital capacity or expiratory reserve) is active: the internal intercostal muscles and the abdominal muscles contract, so more air is pushed out, faster.

Common mistake: Do not say the internal intercostal muscles contract in every breath out. They contract only in forced expiration; quiet expiration relies on muscle relaxation and elastic recoil.

Lung volumes

Tidal volume	The volume of air breathed in or out in one normal breath.
Inspiratory reserve volume	The extra volume of air that can be breathed in by force after a normal inspiration.
Expiratory reserve volume	The extra volume of air that can be breathed out by force after a normal expiration.
Vital capacity	The largest volume of air that can be breathed out after the deepest possible breath in: tidal volume + inspiratory reserve + expiratory reserve.

Some air always stays in the lungs (the residual volume), so a spirometer cannot measure it and vital capacity is less than total lung volume.

Practical skill: Measure lung volumes with a digital spirometer, or by breathing out through a tube into an upturned, water-filled, calibrated bottle and reading the volume of water displaced. Repeat each measurement three times and use the mean.

Reading a spirometer trace

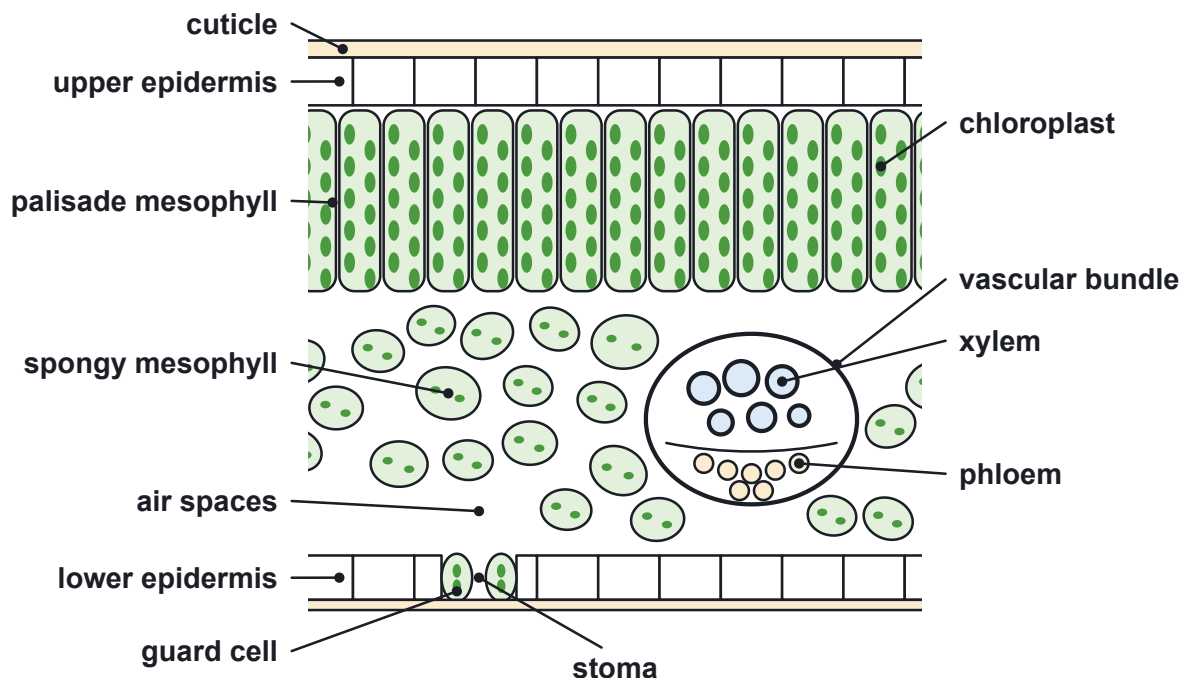
On a spirometer trace, a normal breath goes from 2.3 dm³ to 2.8 dm³. The deepest breath in reaches 5.8 dm³ and the deepest breath out falls to 1.2 dm³. Find the tidal volume, inspiratory reserve, expiratory reserve and vital capacity. (Practice data.)

1. Tidal volume = $2.8 - 2.3 = 0.5 \text{ dm}^3$
2. Inspiratory reserve = $5.8 - 2.8 = 3.0 \text{ dm}^3$
3. Expiratory reserve = $2.3 - 1.2 = 1.1 \text{ dm}^3$
4. Vital capacity = $5.8 - 1.2 = 4.6 \text{ dm}^3$ (check: $0.5 + 3.0 + 1.1 = 4.6 \text{ dm}^3$)

Answer: TV 0.5 dm³, IRV 3.0 dm³, ERV 1.1 dm³, VC 4.6 dm³

Gas exchange in leaves Spec B3.1.7, B3.1.8

In the light a leaf takes in carbon dioxide for photosynthesis and releases oxygen. The challenge is to let gases in and out without losing too much water.



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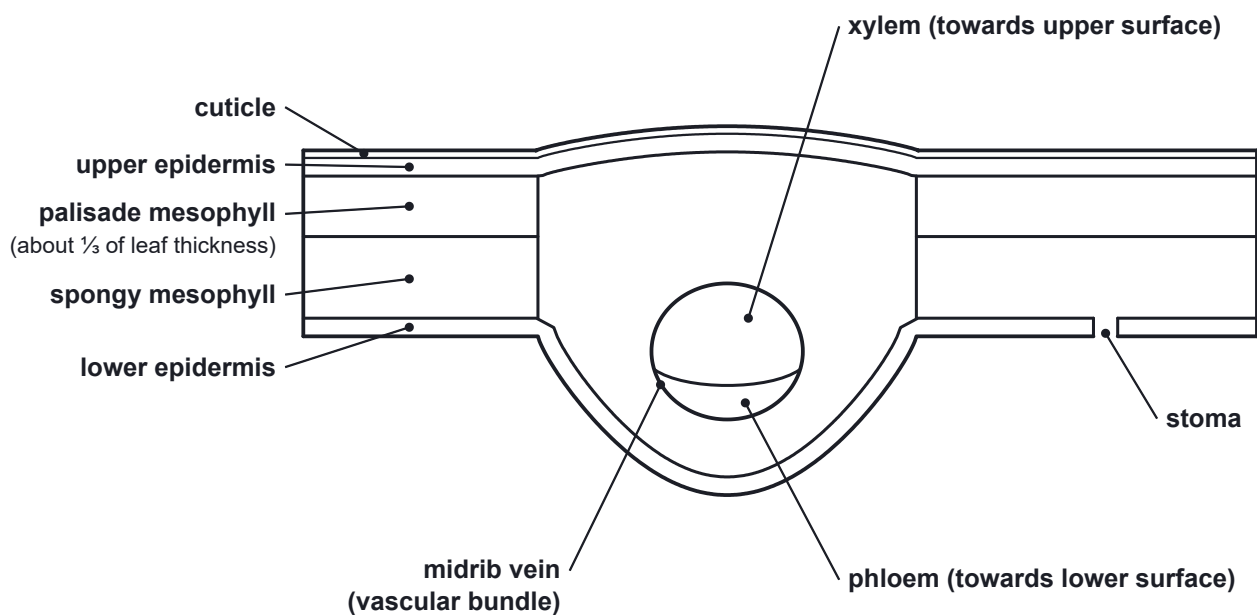
Tissues of a dicotyledonous leaf, drawn with cells. A plan diagram shows the same tissues as outlines only.

Adaptations of a leaf for gas exchange

Structure	Adaptation
Waxy cuticle	Waterproof layer on the epidermis that reduces water loss by evaporation.
Epidermis	A single, tightly packed layer of cells that secretes the cuticle and protects the leaf; it is transparent, so light reaches the mesophyll.
Stomatal guard cells	Pairs of guard cells open the stoma between them to let CO ₂ in and O ₂ out, and close it to reduce water loss.
Air spaces	Connect the stomata with the mesophyll so gases diffuse quickly through the leaf.
Spongy mesophyll	Loosely packed cells with moist walls give a large surface area for gas exchange.
Veins	Xylem brings water to replace the water lost; phloem carries away the sugars made in photosynthesis.

Plan diagram of a leaf

A **plan diagram** shows the distribution of tissues as areas outlined by single lines, with no individual cells drawn. Draw it large, use a sharp pencil, no shading, and label with ruled lines that do not cross.



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Plan diagram of a dicotyledonous leaf: tissues as outlines only. In the vein, **xylem is towards the upper surface**.

Exam tip: In the vein, xylem is towards the upper surface and phloem towards the lower surface. Examiners check this in leaf plan diagrams.

Transpiration and stomatal density Spec B3.1.9, B3.1.10

Water evaporates from the moist walls of mesophyll cells into the air spaces, then water vapour diffuses out through open stomata. Because stomata must be open for CO₂ to enter, **transpiration is a consequence of gas exchange**.

Factors affecting the rate of transpiration

Factor	Effect on rate	Reason
Light intensity	Increases	Stomata open in the light for photosynthesis.
Temperature	Increases	More evaporation from cell walls and faster diffusion of water vapour.
Humidity	Decreases	Moist air outside lowers the water vapour concentration gradient.
Wind speed	Increases	Moving air removes water vapour from around the stomata, keeping the gradient steep.
Soil water availability	Decreases if water is short	Guard cells lose turgor and stomata close.

The rate of transpiration can be estimated with a potometer, which measures water uptake by a cut shoot.

Stomatal density

$$\text{stomatal density} = \text{number of stomata} \div \text{area of field of view (mm}^2\text{)}$$

Practical skill: To make a leaf cast, paint clear nail varnish on the lower epidermis, let it dry, lift it off with clear tape and stick it to a slide. Count stomata at high power in several fields of view, or count them on a micrograph with a known scale.

Calculating stomatal density

At high power the field of view has a diameter of 0.40 mm. Counts of stomata in five fields of view are 24, 27, 22, 26 and 26. Calculate the mean stomatal density. (Practice data.)

1. Mean count = $(24 + 27 + 22 + 26 + 26) \div 5 = 125 \div 5 = 25$
2. Radius = $0.40 \div 2 = 0.20 \text{ mm}$
3. Area = $\pi r^2 = 3.14 \times 0.20^2 = 0.126 \text{ mm}^2$
4. Density = $25 \div 0.126 = 198.4$

Answer: about 200 stomata per mm^2 ($2.0 \times 10^2 \text{ mm}^{-2}$)

Maths skill: Repeated counts vary because biological material is variable. Replicate counts and a mean increase the reliability of the data; the range or standard deviation shows the spread.

Haemoglobin, the Bohr shift and oxygen dissociation curves Spec B3.1.11, B3.1.12, B3.1.13

HL only

Adult haemoglobin is made of four polypeptide chains (two alpha and two beta), each with a **haem group** containing an iron ion that binds one O_2 molecule. One haemoglobin molecule carries up to four O_2 molecules.

Cooperative binding

When the first O_2 binds, the conformation of the whole molecule changes, so the remaining haem groups bind O_2 more easily. This is **cooperative binding**. In the same way, when one O_2 is released, the others are released more easily.

Oxygen dissociation curves

An oxygen dissociation curve plots percentage saturation of haemoglobin against partial pressure of oxygen (pO_2 , kPa). It shows the affinity of haemoglobin for oxygen at different oxygen concentrations.

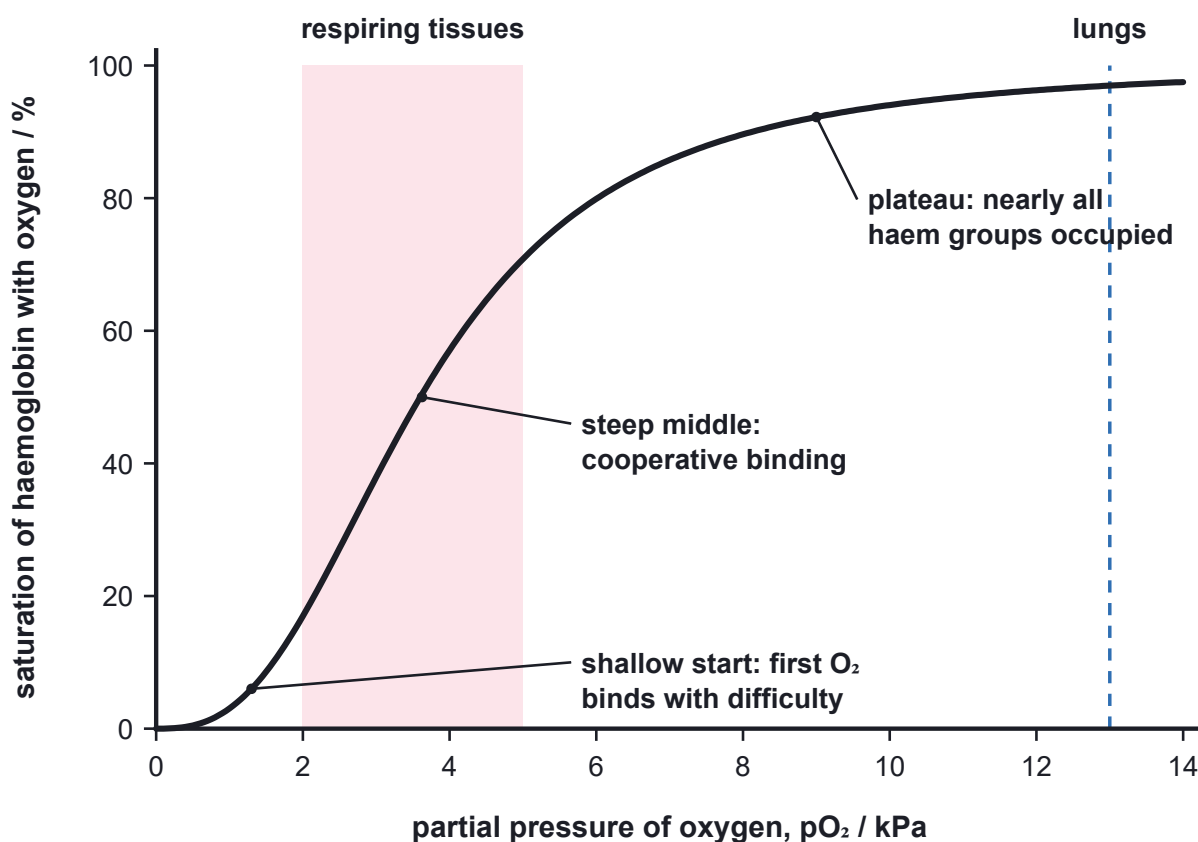
- At low pO_2 the curve is shallow: binding the first O_2 is difficult.
- In the middle the curve is steep: cooperative binding makes each further O_2 bind more easily.
- At high pO_2 the curve levels off: almost all haem groups are occupied, so in the lungs (about 13 kPa) haemoglobin is nearly saturated even if pO_2 falls a little.
- The steep part matches the pO_2 in respiring tissues, so a small drop in pO_2 releases a large amount of oxygen.

Bohr shift

Carbon dioxide binds **allosterically** to haemoglobin, at sites other than the haem groups (the amino groups at the ends of the globin chains), and this lowers its affinity for oxygen. CO_2 also reacts with water in red blood cells to form carbonic acid, and the hydrogen ions released bind to haemoglobin as well, lowering its affinity further. So a rise in CO_2 (and the fall in pH that goes with it) moves the dissociation curve to the right: the **Bohr shift**. At the same pO_2 , haemoglobin is then less saturated, so more oxygen dissociates. Actively respiring tissues produce more CO_2 , so haemoglobin releases more oxygen exactly where it is needed. In the lungs CO_2 is low, so affinity is higher and oxygen loading is efficient.

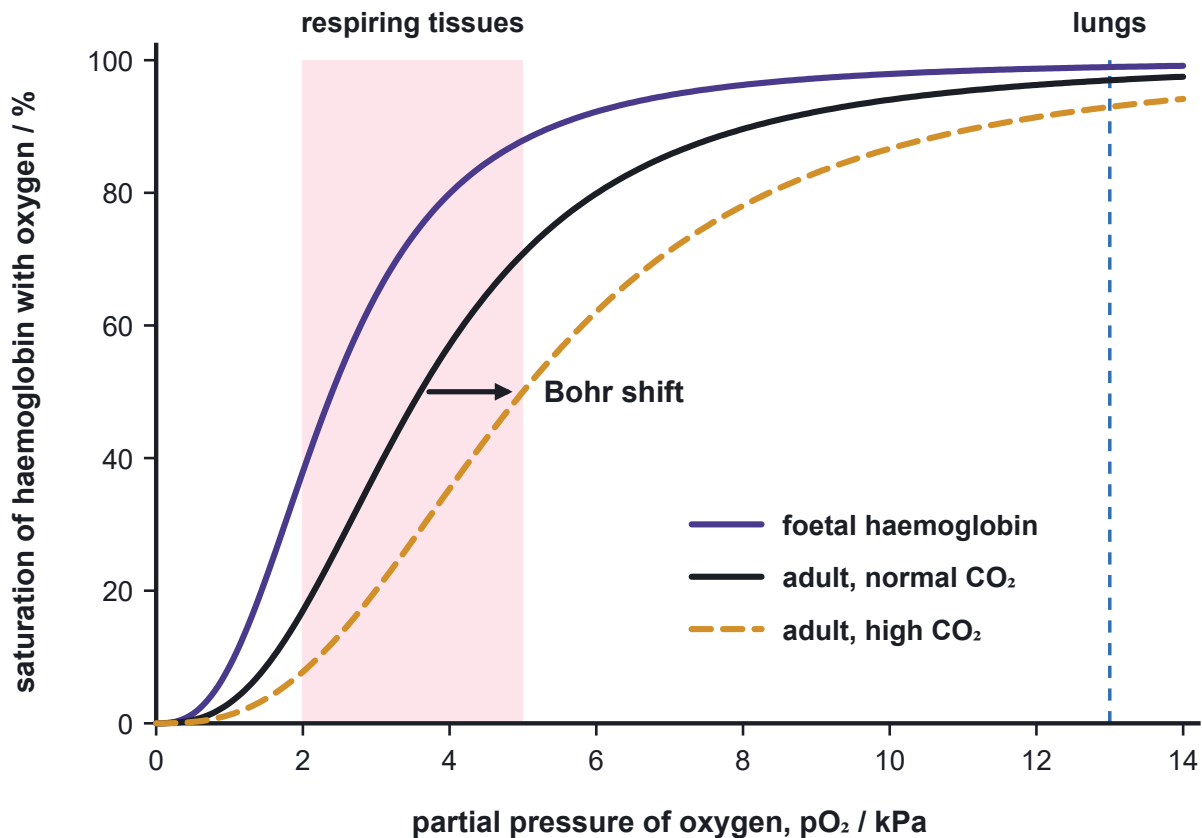
Foetal and adult haemoglobin

Foetal haemoglobin has two gamma chains in place of the beta chains, and a **higher affinity for oxygen** than adult haemoglobin. Its curve lies to the left of the adult curve, so in the placenta, at a pO_2 where maternal haemoglobin releases oxygen, foetal haemoglobin takes it up.



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The sigmoid curve of adult haemoglobin: the **steep middle (cooperative binding)** matches the pO_2 of respiring tissues. Curve shape is illustrative.



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High CO_2 moves the curve right (the **Bohr shift**, lower affinity); foetal haemoglobin lies to the left (higher affinity). Curves are illustrative.

Exam tip: Curve to the left means higher affinity (loads more easily); curve to the right means lower affinity (unloads more easily). Always say what happens to affinity.

Common mistake: The Bohr shift does not mean CO_2 competes with oxygen for the haem groups. CO_2 and hydrogen ions bind elsewhere on the globin and change the molecule's shape, lowering its affinity for oxygen.

Quick check

1. What happens to the surface area-to-volume ratio as an organism grows larger?
2. What is the function of surfactant in the alveoli?
3. Which three volumes add up to the vital capacity?
4. Why does increased humidity reduce the rate of transpiration?
5. **HL only** In which direction does high carbon dioxide shift the oxygen dissociation curve?

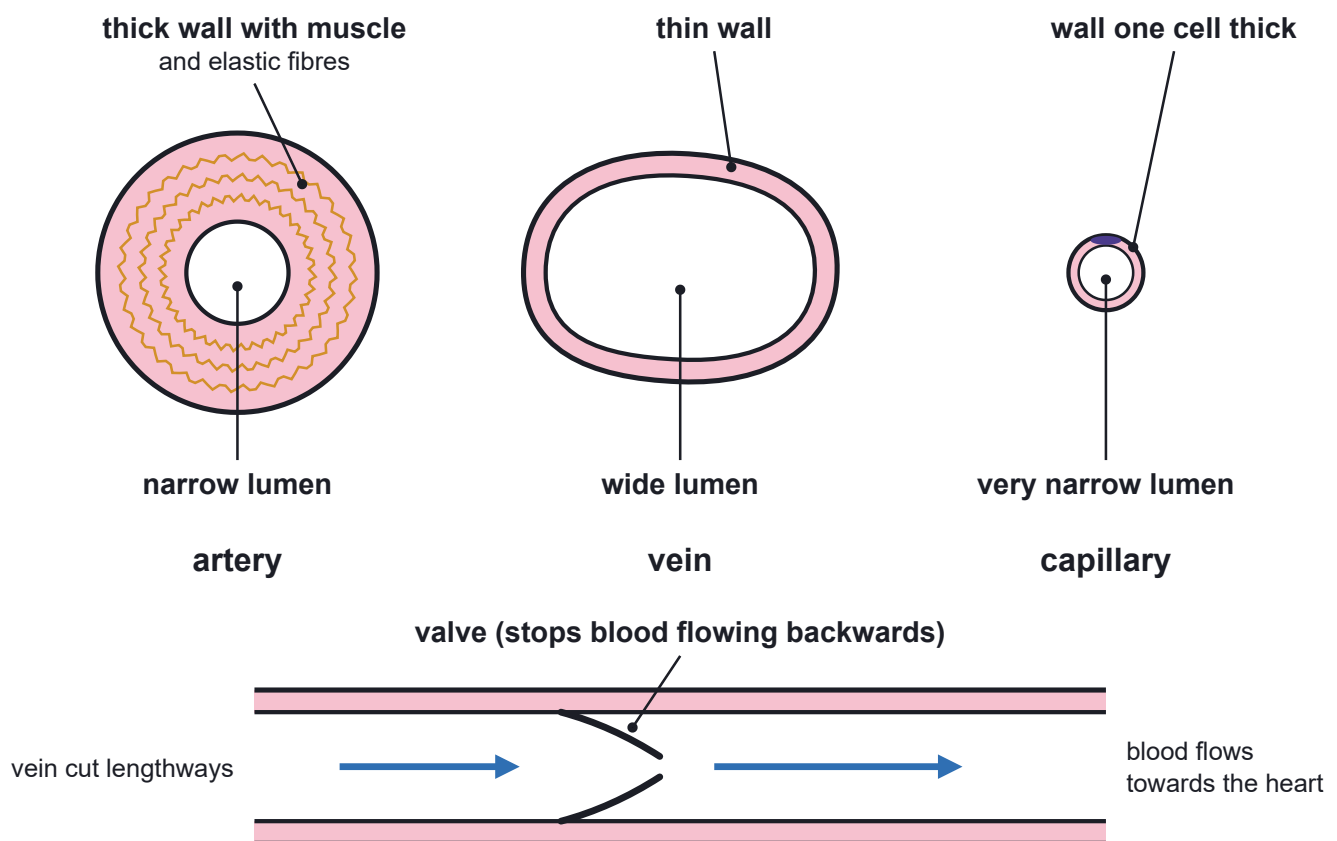
Adaptations of capillaries

Arterioles divide into networks of **capillaries** called capillary beds, which pass close to every active cell. Capillaries rejoin to form venules. All exchange between blood and tissues happens in capillaries.

Adaptations of capillaries	
Adaptation	How it helps exchange
Branching into dense networks	Gives a large total surface area and brings blood close to every cell.
Narrow diameter (about the width of a red blood cell)	Large surface area relative to volume; red blood cells pass close to the wall.
Thin wall: one layer of flattened endothelium cells on a basement membrane	Short diffusion distance.
Fenestrations (pores) in some capillaries	Allow faster exchange of fluid and solutes where exchange needs to be particularly rapid, for example in the glomerulus of the kidney and in the villi of the small intestine.
Slow blood flow	More time for exchange.

Common mistake: Write 'the capillary wall is one cell thick', not 'the capillary has a cell wall'. Animal cells have no cell walls.

Structure and adaptations of arteries and veins Spec B3.2.2, B3.2.3, B3.2.5



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Arteries have thick walls and narrow lumens; veins have thin walls, wide lumens and valves.

Arteries and veins compared		
Feature	Artery	Vein
Wall thickness relative to lumen	Thick wall, narrow lumen	Thin wall, wide lumen
Tunica media (smooth muscle and elastic fibres)	Thick layer	Thin layer
Shape in a micrograph	Round, with a folded inner lining	Often flattened or irregular
Valves	None along their length	Present
Blood pressure	High, pulsing	Low, steady

Practical skill: To identify a vessel in a micrograph, compare the thickness of the wall with the diameter of the lumen. In an artery the wall is thick relative to a narrow, round lumen; in a vein the wall is much thinner than the width of its wide, often flattened lumen.

Adaptations of arteries

- Elastic fibres** stretch when the ventricles pump blood in, then recoil between beats. The recoil pushes blood on and keeps the pressure up, so flow is less pulsing further from the heart.
- A thick layer of **smooth muscle** can contract to narrow the lumen, helping to maintain blood pressure.

- The thick wall, with a tough outer layer of collagen fibres, withstands high pressure without bursting.
- The narrow lumen helps maintain high pressure.

Adaptations of veins

- Pressure in veins is too low to push blood back to the heart unaided.
- Pocket **valves** close if blood starts to flow backwards, so blood moves only towards the heart.
- The thin, **flexible wall** is compressed when nearby skeletal muscles contract, squeezing blood towards the heart.
- A wide lumen offers little resistance to flow.

Pulse rates and occlusion of the coronary arteries Spec B3.2.4, B3.2.6

Measuring pulse rate

Each heartbeat sends a surge of blood along the arteries, felt as a **pulse**. The pulse rate equals the heart rate.

Practical skill: Press two fingertips (not the thumb, which has its own pulse) on the radial artery on the inside of the wrist or the carotid artery in the neck. Count beats for 30 s and multiply by 2, repeat and find the mean. Compare the result with a digital heart rate monitor or pulse oximeter.

Pulse rate

A student counts 19 beats in 15 seconds. Calculate the pulse rate. (Practice data.)

1. Beats per minute = $19 \times (60 \div 15)$
2. = $19 \times 4 = 76$

Answer: 76 beats per minute

Occlusion of the coronary arteries

The **coronary arteries** branch from the aorta and supply cardiac muscle with oxygen and glucose.

1. Fatty deposits (atheroma or plaque) build up in the wall of a coronary artery, under the endothelium: atherosclerosis.
2. The lumen narrows and the wall hardens, so blood flow is reduced.
3. If a plaque ruptures, a blood clot (thrombus) can form and block the artery completely: **occlusion**.
4. Cardiac muscle beyond the blockage gets too little oxygen for aerobic respiration, causing chest pain (angina) or, if severe, a heart attack (myocardial infarction), when part of the heart muscle dies.

Risk factors include a diet high in saturated fat, high blood cholesterol, smoking, high blood pressure, obesity, lack of exercise, increasing age, male sex and family history.

Exam tip: A correlation coefficient (r) from -1 to +1 measures how strongly two variables are correlated. Even a strong correlation, such as between saturated fat intake and coronary heart disease, does not prove that one causes the other; a low r or no correlation can be evidence against a hypothesis.

Water transport in xylem Spec B3.2.7, B3.2.8

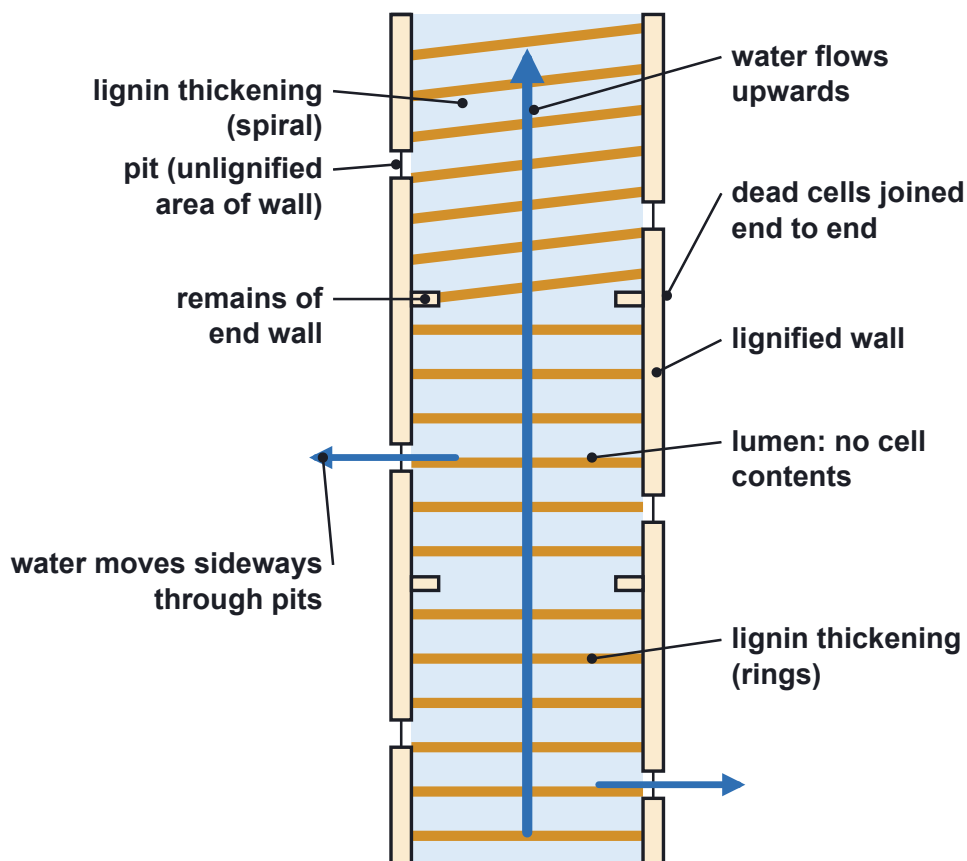
1. Water evaporates from the cell walls of spongy mesophyll cells and diffuses out of the leaf through stomata (transpiration).
2. Water is drawn out of the xylem vessels in the leaf veins and through the cell walls to replace it, by **capillary action** (adhesion of water to cellulose).
3. This generates **tension** (a negative pressure potential) in the xylem.
4. The tension pulls water up the xylem from the roots.

5. **Cohesion** between water molecules, due to hydrogen bonding, keeps the column of water continuous so it does not break.

This is the cohesion-tension mechanism. It is passive: the energy comes from evaporation, driven by heat from the sun, not from ATP.

Adaptations of xylem vessels

Xylem vessel adaptations	
Feature	Function
No cell contents (dead cells, no cytoplasm or nucleus)	Unimpeded flow of water.
Incomplete or absent end walls	Cells form a continuous tube, so water flows without obstruction.
Lignified walls (thickened in rings, spirals or networks)	Withstand the tension without collapsing inwards.
Pits (unlignified areas of wall)	Allow water to enter and leave the vessel, and pass between neighbouring vessels.



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A xylem vessel: a continuous tube of dead cells with **lignified walls** that resist tension, and pits for lateral movement of water.

Exam tip: Linking question: how do pressure differences contribute to the movement of materials?
Xylem uses negative pressure (tension); blood and phloem sap use positive pressure.

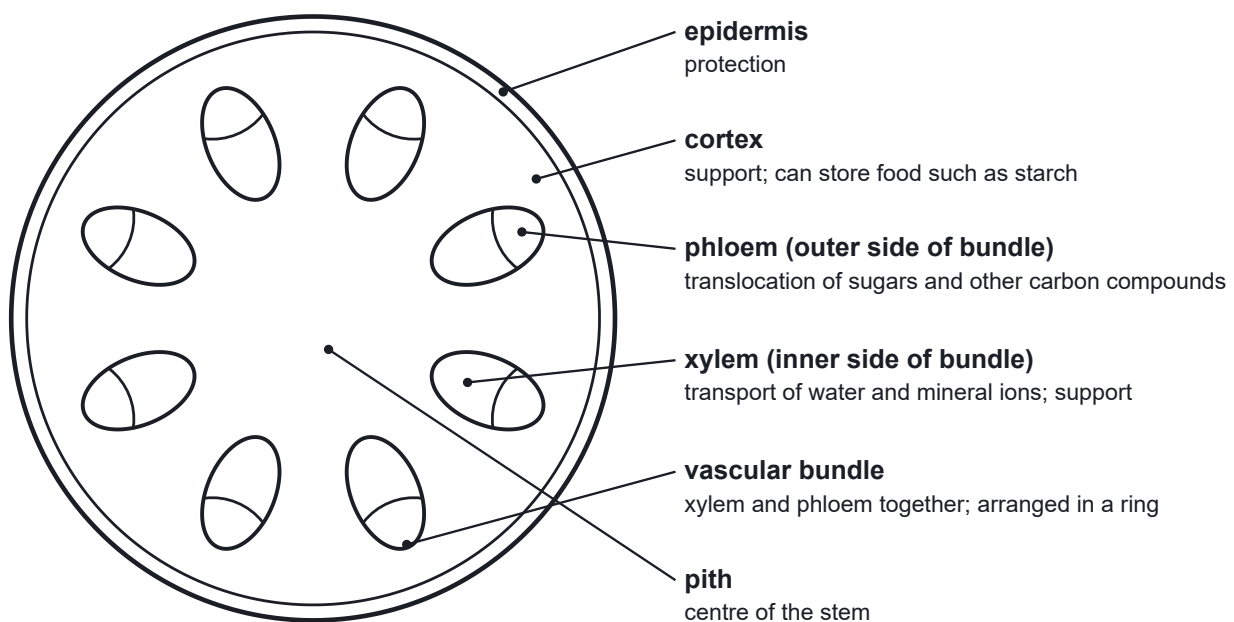
Tissues in dicotyledonous stems and roots Spec B3.2.9, B3.2.10

Functions of tissues in stems and roots

Tissue	Main function
Epidermis	Protective outer layer; in roots it bears root hairs that absorb water and mineral ions.
Cortex	Packing and support tissue between epidermis and vascular tissue; can store food such as starch; in roots water crosses it to reach the xylem.
Xylem	Transports water and mineral ions from roots to leaves; lignified walls give support.
Phloem	Transports sap containing sugars and other carbon compounds by translocation.
Vascular bundle	A strand of xylem and phloem together.

Stem

- Vascular bundles are arranged in a **ring** near the outside of the stem.
- In each bundle, phloem is on the outside and xylem on the inside.
- Cortex lies between the epidermis and the ring of bundles; the centre of the stem is pith.

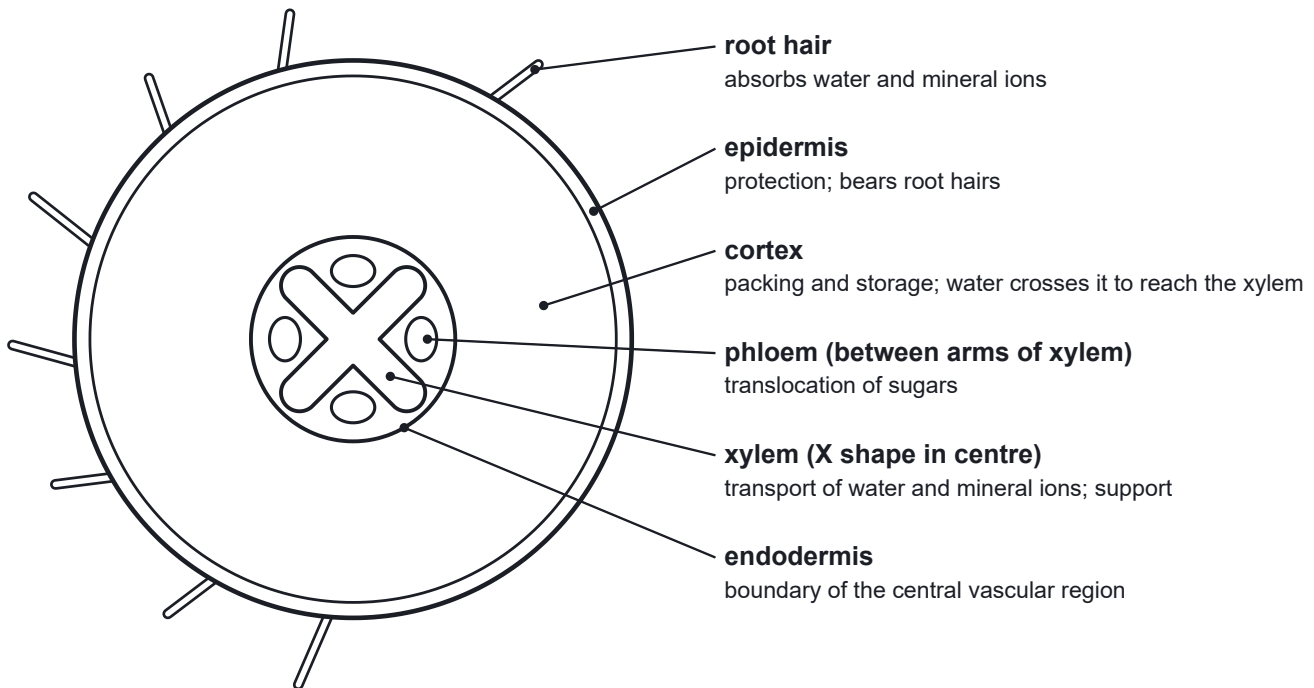


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Plan diagram of a dicotyledonous stem: vascular bundles in a **ring**, phloem outside and xylem inside each bundle.

Root

- Xylem and phloem form a **central vascular region**, not a ring: xylem in a star or X shape with phloem between its arms.
- The guide asks you to identify vascular bundles in the root too. In a root they are **radial**: the groups of xylem and phloem alternate on different radii inside one central vascular cylinder (the stele), instead of xylem and phloem sharing a bundle as in the stem.
- A wide cortex surrounds the vascular region, with the epidermis and root hairs on the outside.
- The central position of vascular tissue resists the pulling forces on a root.



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Plan diagram of a dicotyledonous root: xylem and phloem form a **central vascular region**, with phloem between the arms of the xylem.

Practical skill: Draw plan diagrams from micrographs: outline each tissue with a single clear line, keep proportions accurate, no cells and no shading. Label the tissues the guide lists (epidermis, cortex, vascular bundles, xylem and phloem; pith in the stem) and, for the stem, annotate each label with its main function.

Tissue fluid and lymph Spec B3.2.11, B3.2.12, B3.2.13 HL only

Release and reuptake of tissue fluid

1. At the arteriole end of a capillary bed, blood pressure is high.
2. Plasma is forced out through gaps in the capillary wall: **pressure filtration**. This fluid is **tissue fluid**.
3. Large plasma proteins and blood cells stay in the capillary.
4. Along the capillary, pressure falls. At the venule end the pressure is lower, so tissue fluid drains back into the capillary (the plasma proteins left in the blood help draw water back in by osmosis).

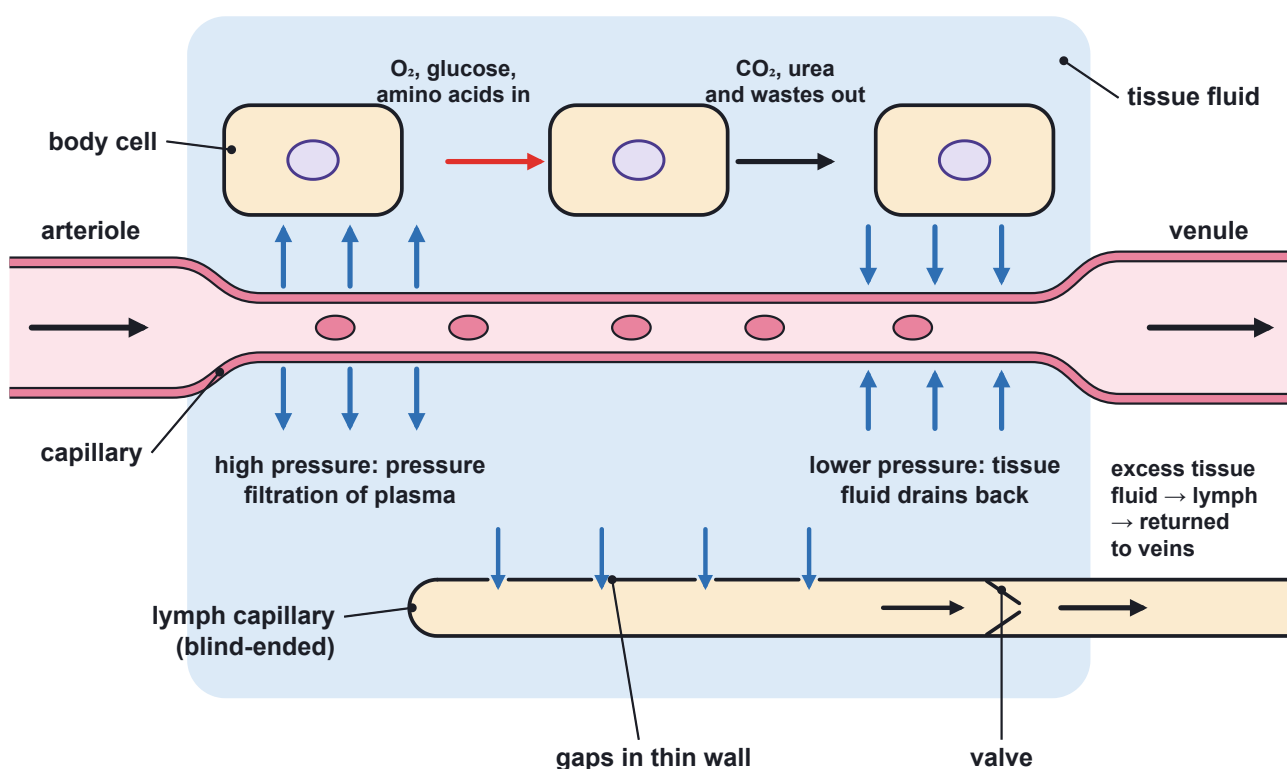
Exchange between tissue fluid and cells

Tissue fluid bathes every cell. Oxygen, glucose, amino acids and ions diffuse or are transported from the fluid into cells; carbon dioxide, urea and other wastes pass from cells into the fluid and then into the blood.

Composition of plasma and tissue fluid		
Component	Plasma	Tissue fluid
Water, ions, glucose, amino acids	Present	Present, at similar concentrations
Large proteins	High concentration	Very little
Oxygen	Higher	Lower (used by cells)
Carbon dioxide and wastes	Lower	Higher (released by cells)
Red blood cells	Carried in the blood but not part of plasma	Absent

Drainage into lymph ducts

- Not all tissue fluid returns to the capillaries. The excess drains into blind-ended lymph capillaries, which have **thin walls with gaps** that let fluid in. The fluid is now lymph.
- Lymph ducts have valves, so lymph flows in one direction only, squeezed along by surrounding muscles.
- Lymph is returned to the blood circulation in veins near the heart (the subclavian veins).



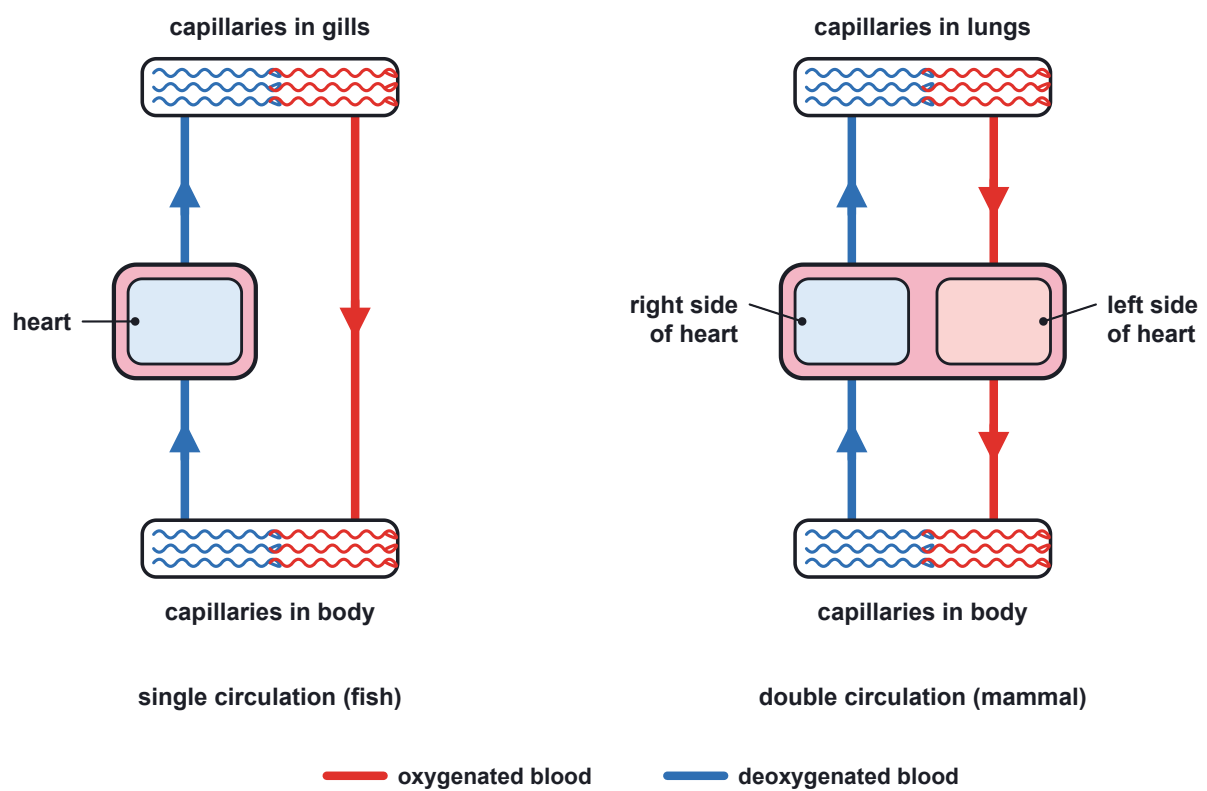
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Pressure filtration forms tissue fluid at the arteriole end; most drains back at the venule end and the excess becomes lymph.

Single and double circulation and the mammalian heart

Spec B3.2.14, B3.2.15

HL only



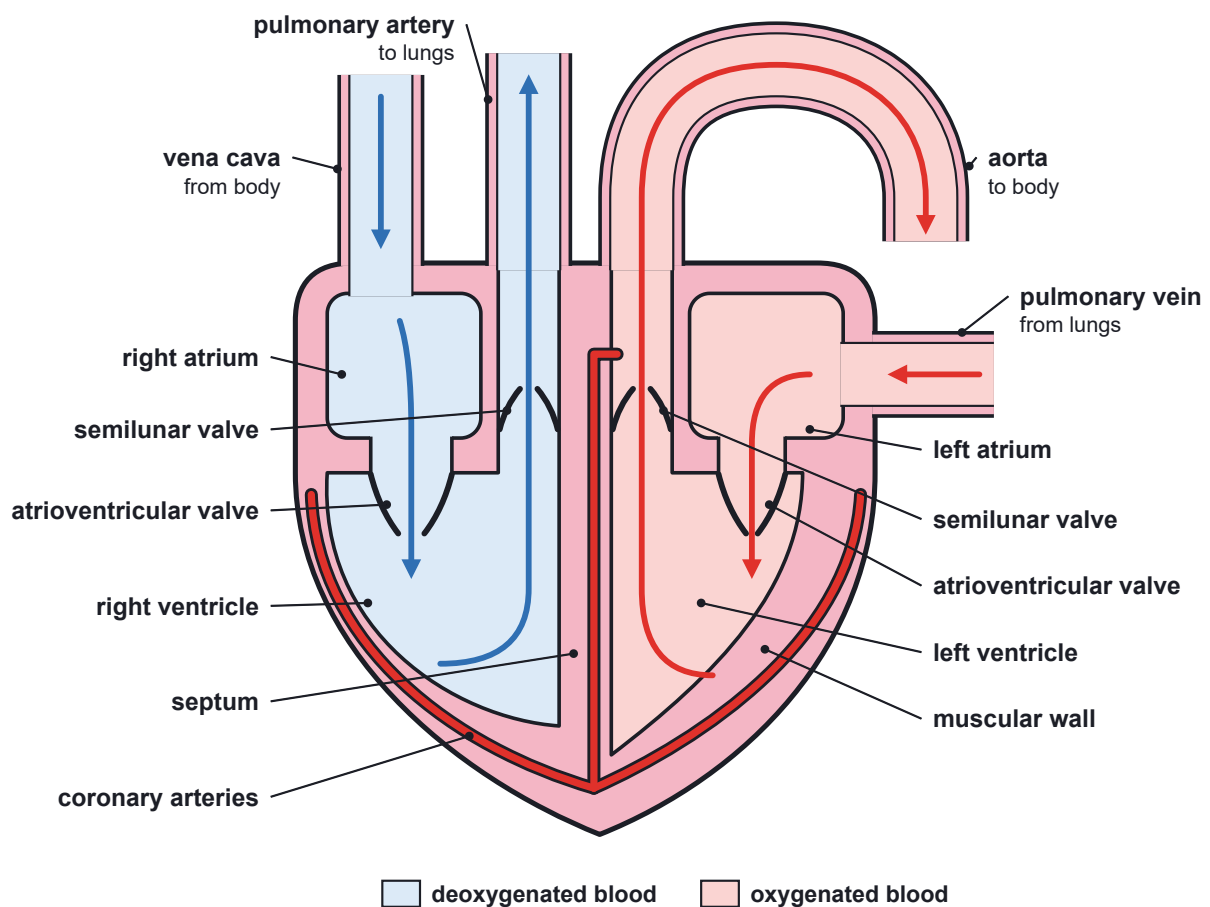
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In a fish blood passes through the heart once per circuit; in a mammal it passes through twice.

Single and double circulation		
Feature	Bony fish (single)	Mammal (double)
Sequence of organs	Heart → gills → body → heart	Heart (right side) → lungs → heart (left side) → body → heart
Passes through heart per circuit	Once	Twice
Pressure of blood reaching the body	Low, because pressure is lost in the gill capillaries	High, because blood is pumped again after the lungs
Separation of blood	Only deoxygenated blood in the heart	Septum keeps oxygenated and deoxygenated blood apart

Adaptations of the mammalian heart

Form and function in the heart	
Structure	Adaptation
Cardiac muscle	Contracts without nerve stimulation (myogenic); branched, connected cells pass impulses rapidly so the walls contract together; does not fatigue.
Pacemaker (sinoatrial node)	A group of specialised cells in the wall of the right atrium that initiates each heartbeat.
Atria	Thin-walled chambers that collect blood from veins and pump it a short distance into the ventricles.
Ventricles	Thick muscular walls generate high pressure; the left ventricle wall is thicker because it pumps blood around the whole body.
Atrioventricular valves	Close when ventricles contract, preventing backflow into the atria.
Semilunar valves	In the aorta and pulmonary artery; close when ventricles relax, preventing backflow into the ventricles.
Septum	Wall separating left and right sides, keeping oxygenated and deoxygenated blood apart.
Coronary vessels	Supply cardiac muscle with oxygen and glucose and remove CO ₂ .



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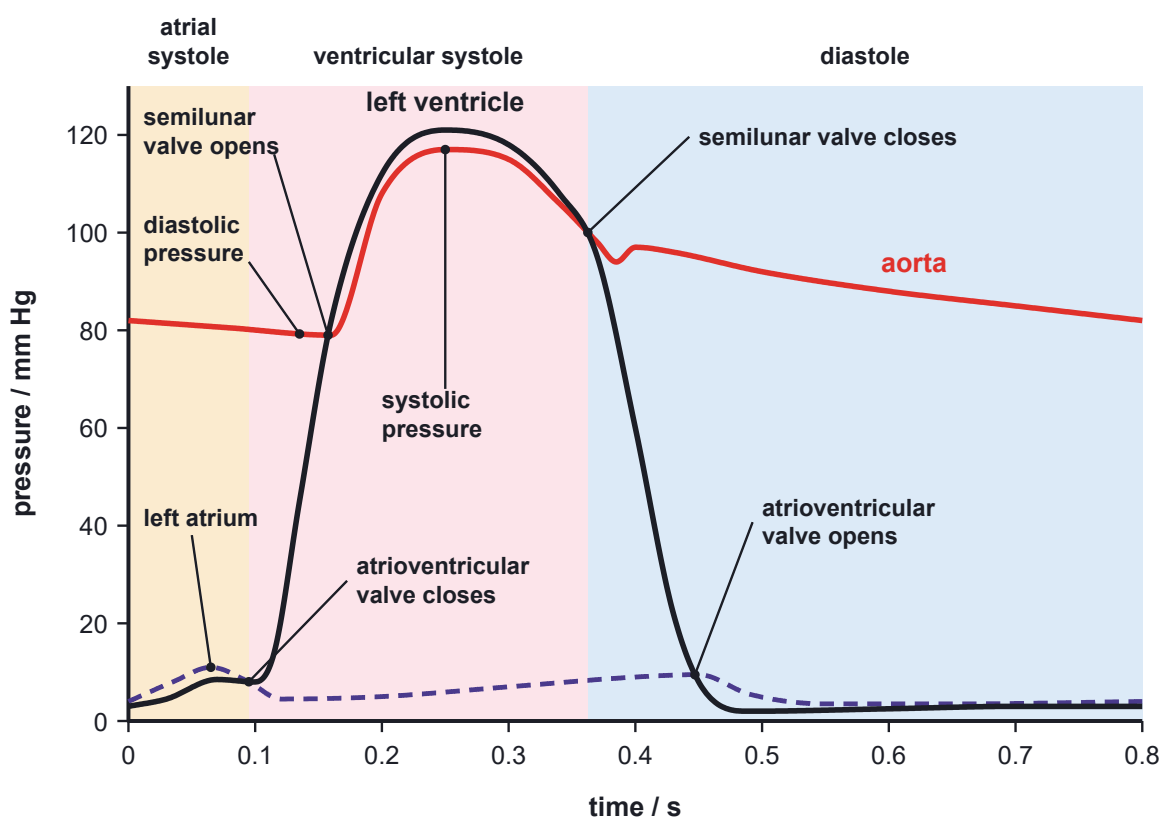
The heart in the frontal plane is drawn as if facing the person, so its left side is on the right of the page. The coronary arteries are drawn schematically (in life they branch from the base of the aorta and run over the outer surface), and the sinoatrial node, in the wall of the right atrium near the vena cava, is not drawn.

1. Vena cava → right atrium → atrioventricular valve → right ventricle → semilunar valve → pulmonary artery → lungs.
2. Pulmonary veins → left atrium → atrioventricular valve → left ventricle → semilunar valve → aorta → body.

Stages in the cardiac cycle Spec B3.2.16 HL only

The **sinoatrial node** (the pacemaker) sends out an electrical signal that spreads across the walls of both atria. After a short delay at the atrioventricular node, it spreads through the ventricle walls from the apex (the bottom) upwards. Events in the left side of the heart:

1. **Atrial systole:** the left atrium contracts, raising its pressure slightly above ventricular pressure. The atrioventricular valve is open, so blood is pushed into the left ventricle, topping it up.
2. **Ventricular systole begins:** the ventricle contracts. When ventricular pressure rises above atrial pressure, the **atrioventricular valve closes**.
3. With both valves closed, ventricular pressure rises steeply.
4. When ventricular pressure exceeds aortic pressure, the **semilunar valve opens** and blood is ejected into the aorta.
5. **Diastole:** the ventricle relaxes. When its pressure falls below aortic pressure, the semilunar valve closes, preventing backflow.
6. When ventricular pressure falls below atrial pressure, the atrioventricular valve opens and blood flows passively from the left atrium into the ventricle, which fills before the next atrial systole.



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Pressure changes in the left side of the heart. Each valve opens or closes where **two pressure lines cross**. Values are illustrative.

Systolic and diastolic blood pressure

- **Systolic pressure** is the highest arterial pressure, during ventricular systole.
- **Diastolic pressure** is the lowest arterial pressure, during diastole; it stays well above zero because the elastic artery walls recoil.
- A typical healthy adult reading is about 120/80 mm Hg (systolic/diastolic). Readings persistently above about 140/90 mm Hg indicate hypertension.

Heart rate from a pressure graph

On a pressure graph, the peaks of ventricular pressure are 0.75 s apart. Calculate the heart rate. (Practice data.)

1. One cycle lasts 0.75 s
2. Heart rate = $60 \div 0.75 = 80$

Answer: 80 beats per minute

Exam tip: Valves open and close because of pressure differences on either side of them. Always say which pressure is higher when explaining a valve movement.

Root pressure and phloem transport Spec B3.2.17, B3.2.18 HL only

Root pressure

1. Root cells use ATP to **actively transport mineral ions** into the xylem vessels.
2. The solute concentration in the xylem rises, so water enters the xylem from surrounding cells by osmosis.
3. This generates a **positive pressure potential** (root pressure) that pushes water up the xylem.

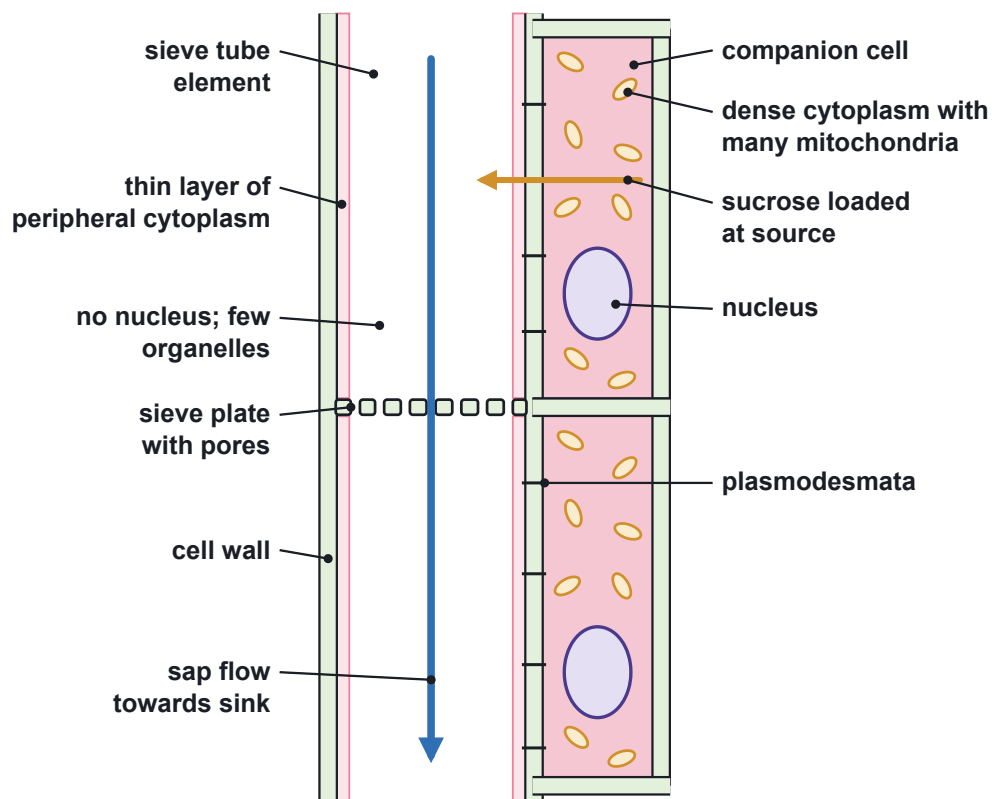
Root pressure matters when transport by transpiration is insufficient: for example when high humidity prevents transpiration, or in spring before the leaves of deciduous plants have opened.

Phloem: sieve tubes and companion cells

Phloem carries sap containing sucrose and other carbon compounds from **sources** (for example photosynthesising leaves) to **sinks** (for example roots, fruits and growing tissues). This is **translocation**.

Adaptations of phloem	
Feature	How it helps translocation
Sieve tube elements joined end to end	Form a continuous sieve tube for sap flow.
Sieve plates (perforated end walls)	Let sap flow from one element to the next.
Reduced cytoplasm and organelles, no nucleus in sieve tube elements	Less resistance, so sap flows more easily.
Companion cells with many mitochondria	Produce ATP for active transport to load sugars into sieve tubes at sources.
Plasmodesmata between companion cells and sieve tube elements	Connect their cytoplasm, so the companion cell can keep the sieve tube element alive and pass loaded sugars into it.

Loading carbon compounds at the source raises the solute concentration, so water enters by osmosis and pressure rises. Unloading at the sink lowers it. Sap flows from high to low pressure.



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Sieve tube elements carry the sap; **companion cells** supply the ATP for loading sucrose at the source.

Quick check

1. What are fenestrations in capillaries?
2. How do elastic fibres in artery walls help maintain blood pressure?
3. What causes tension in the xylem?
4. Where is xylem found in a dicotyledonous root?
5. **HL only** Which node initiates each heartbeat?

3 Muscle and motility Spec B3.3 HL only

Movement and reasons for locomotion Spec B3.3.1, B3.3.9

All living things move in some way, from cytoplasm streaming inside cells to whole animals travelling thousands of kilometres. Organisms are either **motile** (able to move from place to place) or **sessile** (fixed in one place).

A motile and a sessile species		
Species	Type	Adaptations for movement
Atlantic salmon (<i>Salmo salar</i>)	Motile	Streamlined body; blocks of muscle along each side contract alternately to bend the body and tail from side to side; fins give stability and steering. Adults migrate from the sea up rivers to spawn.
Venus flytrap (<i>Dionaea muscipula</i>)	Sessile	Rooted in the soil, so it cannot move from place to place. The two lobes of each modified leaf snap shut in about a tenth of a second when trigger hairs are touched twice in quick succession, trapping insects. Plants have no muscle: the movement comes from rapid changes in turgor that make the curved lobes flip shape.

Locomotion is movement of the whole organism from one place to another.

Reasons for locomotion	
Reason	Example
Foraging for food	Honeybee workers fly from the hive to flowers to collect nectar and pollen.
Escaping from danger	Squid escape predators by jet propulsion, forcing water out of the mantle cavity.
Searching for a mate	Male silk moths fly towards females by following the pheromone the females release.
Migration	Arctic terns fly between Arctic breeding grounds and the Antarctic each year.

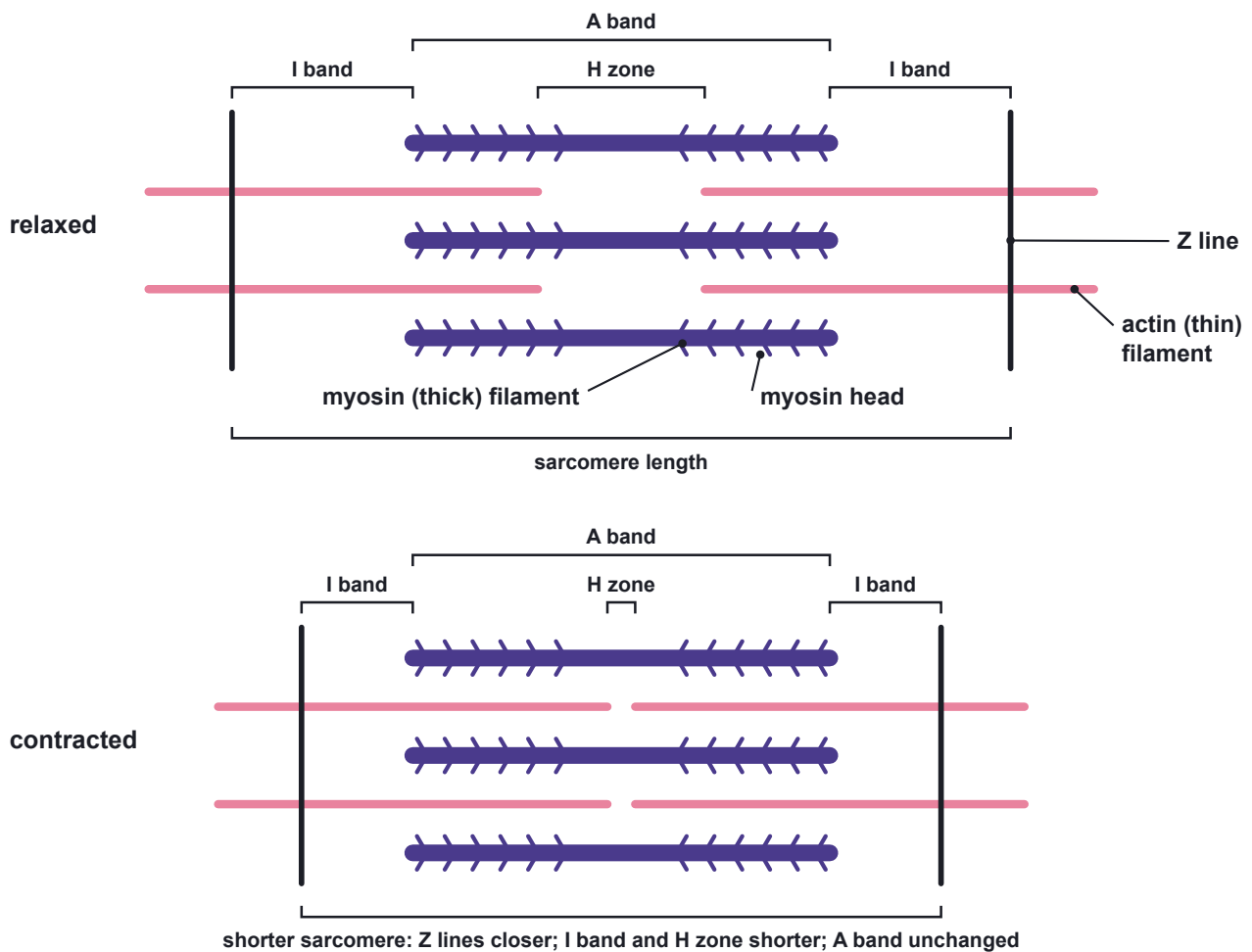
Exam tip: Linking question: in what ways does locomotion contribute to evolution? Moving to find mates, food or new habitats affects which individuals survive and reproduce, and so which alleles are passed on.

Sliding filament model of muscle contraction Spec B3.3.2

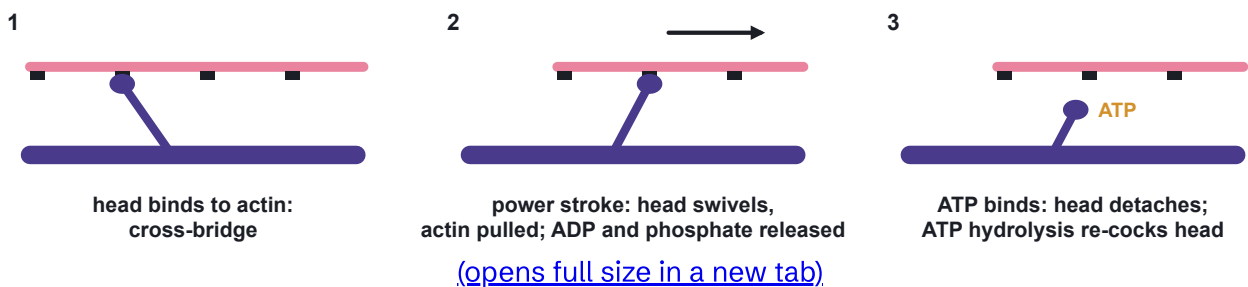
A skeletal muscle fibre contains many myofibrils. Each myofibril is a chain of repeating units called **sarcomeres**, separated by **Z lines**.

- Thin **actin** filaments are attached to the Z lines and point towards the centre of the sarcomere.
 - Thick **myosin** filaments lie in the centre, overlapping the actin. Each has many myosin heads.
 - The dark band (A band) is the length of the myosin; the light bands (I bands) contain only actin; the H zone in the centre contains only myosin.
1. A nerve impulse causes calcium ions to be released from the sarcoplasmic reticulum. They bind to regulatory proteins on the actin, exposing binding sites for myosin.
 2. Myosin heads, already energised by hydrolysing ATP, bind to the binding sites on actin, forming **cross-bridges**.
 3. The heads swivel (the power stroke), pulling the actin filaments towards the centre of the sarcomere. ADP and phosphate are released.
 4. A new ATP binds to each myosin head, which then detaches from the actin.
 5. Hydrolysis of ATP re-cocks the head, ready to bind further along the actin. The cycle repeats while calcium is present.

The filaments **slide past each other**; neither changes length. During contraction the Z lines move closer together, the I band and H zone shorten, and the A band stays the same length.



Cross-bridge cycle (one myosin head)



Sliding filaments: the sarcomere shortens but the **A band stays the same length**, because actin slides past myosin.

Common mistake: The filaments do not shorten or contract. They slide past each other, so only the sarcomere shortens.

Titin, antagonistic muscles and the intercostal muscles Spec B3.3.3, B3.3.8

Titin

- **Titin** is the largest known protein. Each molecule runs from the Z line to the centre of the sarcomere, alongside the myosin filament.
- When a sarcomere is stretched, titin is stretched too and stores potential energy, like a spring.
- When the stretching force stops, titin **recoils**, helping the sarcomere return to its resting length.

- Titin also **prevents overstretching**, which could pull the actin and myosin filaments apart.

Antagonistic muscles

Muscle tissue can only exert force when it contracts: it pulls but cannot push. A relaxed muscle is lengthened again by a second muscle that pulls the other way. Muscles that produce opposite movements are **antagonistic**, for example the biceps (flexes the elbow) and triceps (extends it).

Internal and external intercostal muscles

The intercostal muscles lie in two layers between the ribs. Their muscle fibres run in different orientations, at roughly right angles to each other, so they move the ribcage in opposite directions.

Intercostal muscles as an antagonistic pair		
Muscle	When it contracts	Effect on the other layer
External intercostal muscles	Pull the ribcage up and out (inspiration)	Stretch the internal intercostals, storing potential energy in titin
Internal intercostal muscles	Pull the ribcage down and in (forced expiration)	Stretch the external intercostals, storing potential energy in titin

This is an example of antagonistic muscle action that moves part of the body internally rather than moving the body from place to place.

Exam tip: Link to B3.1.5: in ventilation answers, name the external intercostals for inspiration and the internal intercostals (with abdominal muscles) for forced expiration.

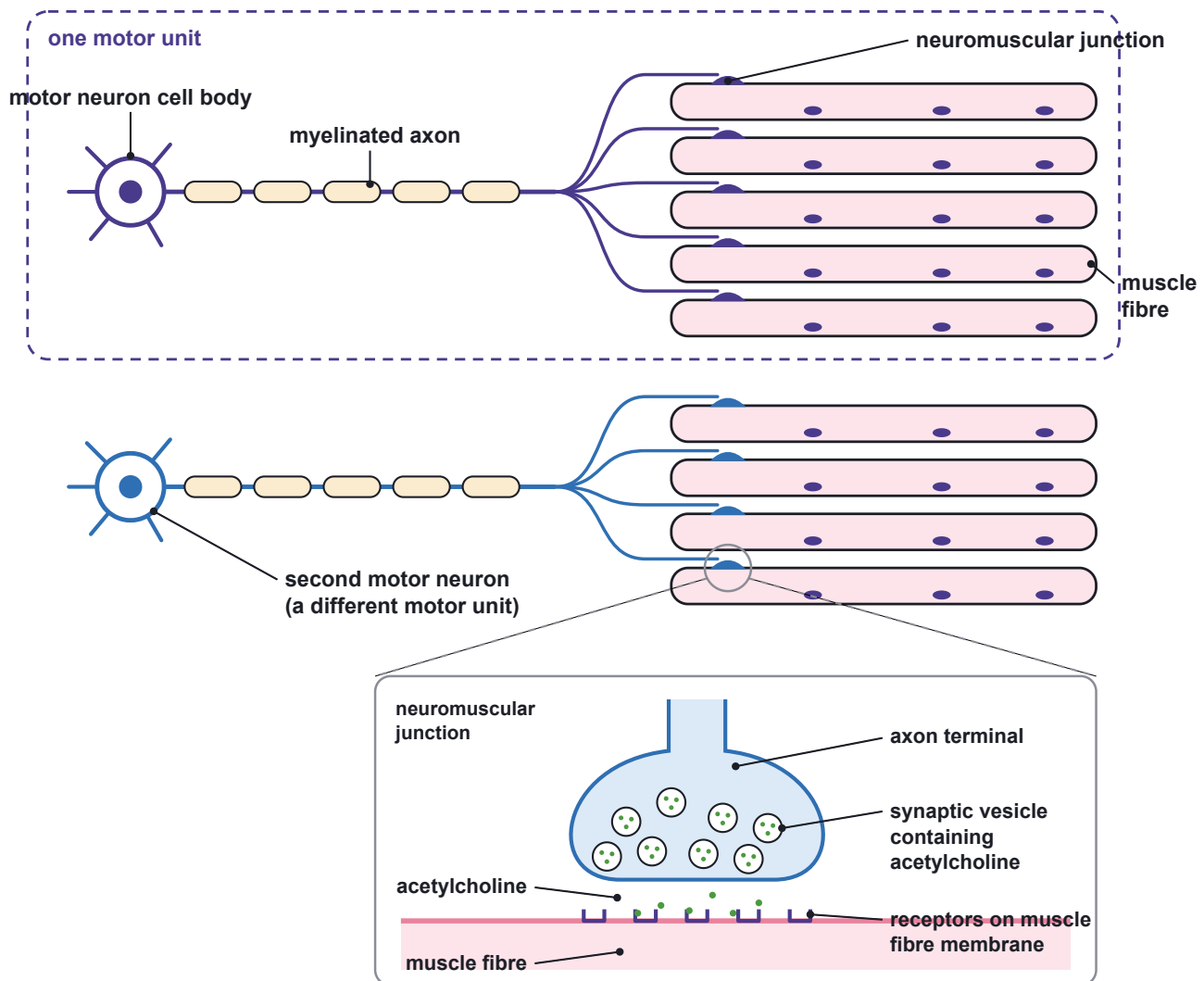
Motor units in skeletal muscle Spec B3.3.4

A **motor unit** consists of:

- **One motor neuron**, whose cell body is in the spinal cord or brainstem and whose axon branches at its end.
- **The muscle fibres** it controls: long, multinucleate cells packed with myofibrils.
- **Neuromuscular junctions**: the synapses where each axon branch meets a muscle fibre.

1. An action potential travels along the motor neuron to its axon terminals.
2. At each **neuromuscular junction** the neurotransmitter **acetylcholine** is released and diffuses across the gap.
3. It binds to receptors on the muscle fibre membrane, which depolarises and passes an impulse along the fibre.
4. Calcium ions are released inside the fibre and the sarcomeres contract.

All the fibres in one motor unit contract at the same time. Muscles that need fine control, such as those moving the eye, have small motor units with few fibres each. Large leg muscles have large motor units. The nervous system controls the strength of contraction by changing how many motor units are active.



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A motor unit is **one motor neuron and all the muscle fibres it controls**; they all contract together.

Skeletons, the hip joint and range of motion Spec B3.3.5, B3.3.6, B3.3.7

Skeletons as anchorage and levers

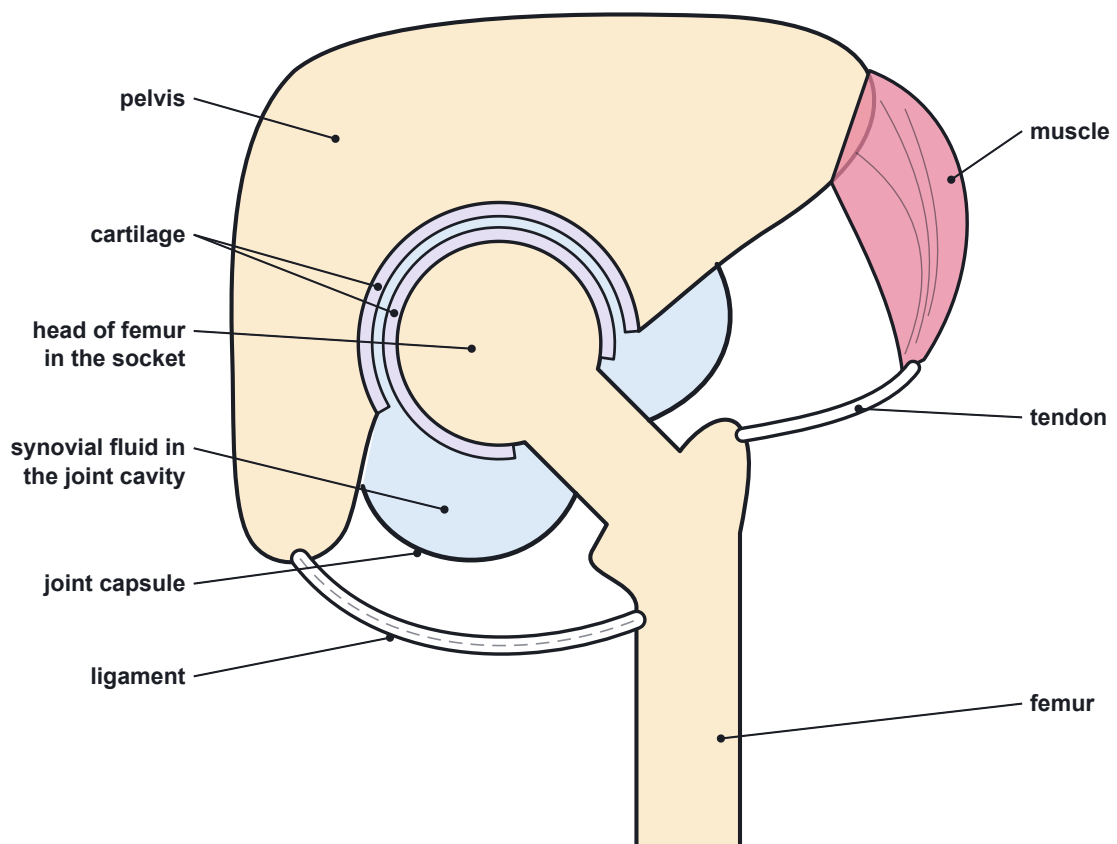
- **Anchorage:** muscles are attached to the skeleton, so when they contract they pull on something firm.
- **Levers:** rigid parts of the skeleton pivot at joints. A muscle applies force to one point and the bone transmits it to another, changing the size or direction of the force or movement.
- **Arthropods** (such as insects and crabs) have an **exoskeleton** on the outside of the body; the muscles are attached to its inner surface.
- **Vertebrates** have an **endoskeleton** of bone and cartilage inside the body; muscles are attached to its outer surface by tendons.

Movement at the hip joint

The hip is a ball-and-socket synovial joint: the rounded head of the **femur** fits into a socket in the **pelvis**.

Roles of the parts of a synovial joint

Part	Role
Bones (femur and pelvis)	Rigid levers that move relative to each other.
Cartilage	Smooth layer covering the bone ends; reduces friction and absorbs shock.
Synovial fluid	Lubricates the joint to reduce friction; secreted by the membrane of the joint capsule.
Ligaments	Tough bands connecting bone to bone; stabilise the joint and limit movement.
Muscles	Contract in antagonistic groups to move the femur.
Tendons	Connect muscles to bones and transmit the force of contraction.



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The hip is a **ball-and-socket synovial joint**: cartilage and synovial fluid reduce friction; ligaments join bone to bone, tendons join muscle to bone.

Range of motion

Range of motion is how far a joint can move, measured as an angle in degrees, in each plane. The hip moves in several dimensions: flexion and extension (forwards and backwards), abduction and adduction (away from and towards the midline) and rotation. A hinge joint such as the knee moves mainly in one plane.

Practical skill: Measure joint angles with a goniometer: place its pivot over the centre of the joint, line one arm up with the fixed bone and the other with the moving bone, and read the angle. Alternatively, photograph or film the movement and measure the angles with image-analysis software. Repeat three times and compare each dimension.

Comparing range of motion

A student measured hip flexion of a classmate three times with a goniometer: 112°, 118° and 115°. Hip abduction was 38°, 42° and 40°. Calculate the mean of each and how many times larger the flexion range is. (Practice data.)

1. Mean flexion = $(112 + 118 + 115) \div 3 = 115^\circ$
2. Mean abduction = $(38 + 42 + 40) \div 3 = 40^\circ$
3. Ratio = $115 \div 40 = 2.9$

Answer: flexion 115°, abduction 40°; flexion range is about 2.9 times larger

Adaptations for swimming in marine mammals Spec B3.3.10

Marine mammals, such as the bottlenose dolphin (*Tursiops truncatus*), evolved from land mammals but are adapted to swim and dive.

Swimming adaptations of marine mammals	
Adaptation	How it helps
Streamlining	A smooth, tapering body with no external ears and little hair reduces drag (water resistance).
Forelimbs form flippers	The bones of the forelimb are enclosed in a stiff, flat flipper used for steering and balance.
Tail forms a fluke	A wide, horizontal tail fluke is moved up and down by powerful back muscles to push the animal forwards; fish tails move from side to side.
Hind limbs reduced	In whales and dolphins the hind limbs are absent externally, improving streamlining.
Changes to the airways	The nostrils have moved to the top of the head as a blowhole, closed by a muscular flap during dives; air can be exchanged rapidly at the surface, so the animal breathes periodically between dives.

Exam tip: When asked to compare with fish, say that the fluke moves up and down (vertical movement) whereas a fish tail fin moves from side to side.

Quick check

1. **HL only** What is the difference between motile and sessile organisms?
2. **HL only** Which bands of a sarcomere shorten during contraction?
3. **HL only** What two roles does titin have in the sarcomere?
4. **HL only** What does a motor unit consist of?
5. **HL only** Which two bones meet at the hip joint?

Quick check answers

Gas exchange

1. It decreases.
2. It reduces surface tension so the alveoli do not stick together and collapse when air is breathed out.
3. Tidal volume, inspiratory reserve volume and expiratory reserve volume.
4. It reduces the concentration gradient of water vapour between the air spaces and the outside air.
5. To the right (lower affinity, more oxygen released): the Bohr shift.

Transport

1. Pores in the capillary wall that allow particularly rapid exchange, for example in the kidney glomerulus.
2. They stretch when blood is pumped in and recoil between beats, pushing blood on and keeping the pressure up.
3. Loss of water by transpiration from leaf cell walls draws water out of the xylem by capillary action.
4. In the centre, in a star or X shape, with phloem between its arms.
5. The sinoatrial node (the pacemaker) in the wall of the right atrium.

Muscle and motility

1. Motile organisms can move from place to place; sessile organisms are fixed in one place but can still move parts of their bodies.
2. The I band and the H zone shorten; the A band stays the same.
3. It helps the sarcomere recoil after stretching and prevents overstretching.
4. One motor neuron, the muscle fibres it stimulates and the neuromuscular junctions connecting them.
5. The femur and the pelvis.