

Gas exchange, membranes and transport

Revision notes · Gas exchange surfaces and Fick's law, the mammalian lung, membrane structure, osmosis and the ways substances cross membranes.

For Pearson Edexcel International AS Biology XBI11 and International A Level Biology YBI11. **A Level only** is IA2 content (Units 4 to 6), not needed for the International AS.

Gas exchange, membranes and transport **Spec 2.1-2.5**

Gas exchange surfaces and Fick's law **Spec 2.1**

Every living organism must exchange gases with its environment: oxygen in and carbon dioxide out for aerobic respiration, and the reverse in photosynthesis. The gases cross a **gas exchange surface** by diffusion, so the surface has to be built to make diffusion fast.

A small, single-celled organism has a very large **surface area to volume ratio**, so diffusion across its outer surface is enough. A large organism has a much smaller surface area to volume ratio, so it needs a specialised exchange surface (such as the lungs of a mammal) and a transport system.

Properties of a good gas exchange surface

The three properties and why each speeds up diffusion

Property	Effect on diffusion
Large surface area to volume ratio	More area for molecules to cross at the same time, so more gas is exchanged each second relative to the volume of the organism that needs it.
Thin surface (short diffusion distance)	Molecules have only a short distance to travel, so each crosses more quickly. Exchange surfaces are often one cell thick.
Large difference in concentration (steep concentration gradient)	Diffusion is the net movement down a concentration gradient. The steeper the gradient, the faster the net movement. The gradient is kept steep by removing gas on one side (blood flow) and bringing fresh supplies to the other (ventilation).

Fick's law of diffusion

Fick's law links the rate of diffusion to all three properties at once.

rate of diffusion $\propto$ (surface area $\times$ difference in concentration) $\div$ thickness of the exchange surface

- Doubling the surface area doubles the rate (all else equal).
- Doubling the concentration difference doubles the rate.
- Doubling the thickness of the surface halves the rate.

Using Fick's law to compare two surfaces

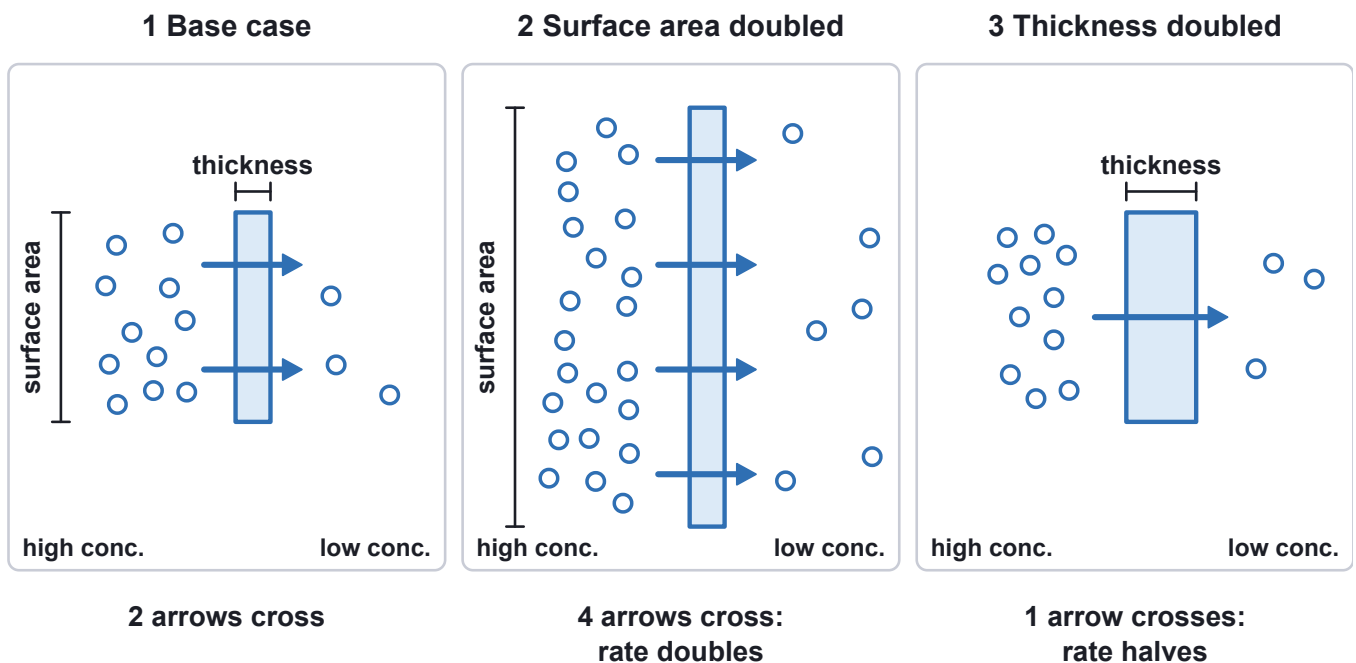
Surface A has an area of 50 mm², a concentration difference of 12 arbitrary units and a thickness of 0.5 µm. Surface B has the same area and concentration difference but is 2.0 µm thick. Calculate the relative rate of diffusion across each and state how many times faster diffusion is across A.

1. Relative rate = (area × concentration difference) ÷ thickness.
2. A: (50 × 12) ÷ 0.5 = 600 ÷ 0.5 = 1200 (arbitrary units).
3. B: (50 × 12) ÷ 2.0 = 600 ÷ 2.0 = 300 (arbitrary units).
4. Compare: 1200 ÷ 300 = 4.

Answer: A: 1200, B: 300. Diffusion is 4 times faster across A, because A is one quarter as thick.

Maths skill: Fick's law questions give you numbers and ask for a rate or a comparison. Use the same units for both surfaces, show the substitution, and give the answer in the units asked for or as a ratio.

Exam tip: Do not write 'large surface area' on its own for an organism. Edexcel asks about surface area to volume ratio, and about thin surfaces and concentration gradients as three separate marking points.



$$\text{rate of diffusion} \propto (\text{surface area} \times \text{concentration difference}) \div \text{thickness}$$

Each blue arrow is one net movement of a gas molecule across the exchange surface.

Fick's law: rate of diffusion $\propto$ (surface area × concentration difference) ÷ thickness. Doubling the area doubles the rate; doubling the thickness halves it.

The mammalian lung Spec 2.1

Air enters the lungs by the **trachea**, which divides into two **bronchi**, one to each lung. Each bronchus branches repeatedly into smaller **bronchioles**, which end in clusters of tiny air sacs called **alveoli**. Gas exchange happens across the walls of the alveoli.

1. Air passes down the trachea, held open by rings of cartilage.
2. It moves into a bronchus, then through the many branching bronchioles.
3. It reaches the alveoli, where oxygen diffuses into the blood and carbon dioxide diffuses out.

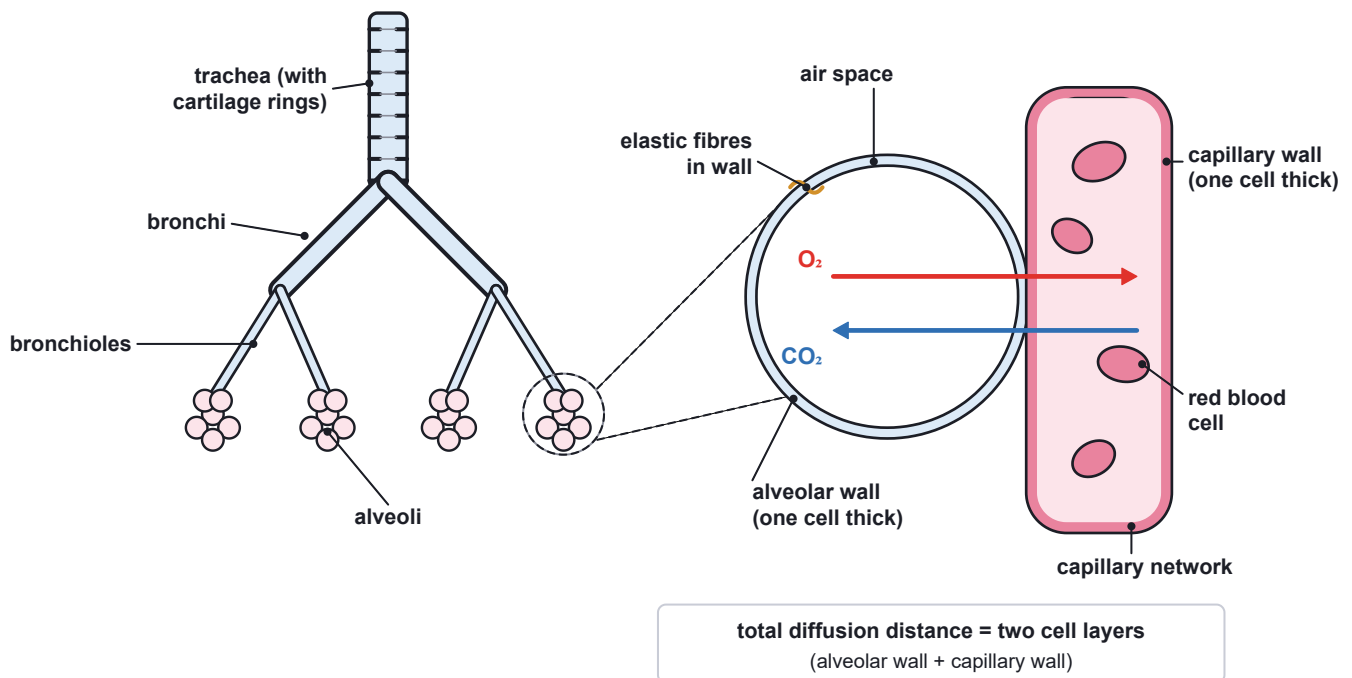
The alveolus and its blood supply

The wall of an alveolus is a single layer of flattened (squamous) epithelial cells. Next to it is the wall of a capillary, which is a single layer of flat endothelial cells. Oxygen therefore diffuses across only two very thin cells (a distance of well under 1 μm in total), from the air in the alveolus into the red blood cells in the capillary.

How the lung is adapted for rapid gas exchange	
Feature	How it helps
About 300 to 500 million alveoli in the two human lungs together (a very large number of small sacs)	Gives a very large surface area to volume ratio for gas exchange.
Alveolar wall and capillary wall each only one cell thick	Short diffusion distance, so diffusion is rapid (Fick's law: thickness is in the denominator).
Dense network of capillaries around each alveolus	Brings a large volume of blood close to the air, and carries oxygen away quickly, which keeps the oxygen concentration gradient steep.
Ventilation (breathing in and out)	Brings in fresh air with a high oxygen concentration and removes air with a high carbon dioxide concentration, maintaining both concentration gradients.
Blood flow through the capillaries	Continually removes oxygenated blood and delivers blood low in oxygen and high in carbon dioxide, maintaining the gradients.
Elastic fibres in the alveolar walls	Stretch as the alveoli fill and recoil when air is breathed out, helping to push air out.
Red blood cells squeezed through narrow capillaries	Slows their flow and brings them close to the capillary wall, giving more time for oxygen to be taken up.

Exam tip: In an 'explain how the lung is adapted' question, link every feature to a consequence for the rate of diffusion. A feature named without its effect ('so diffusion is faster because ...') may not earn the mark.

Common mistake: Ventilation does not make gas diffuse faster by itself. It maintains the concentration gradient by replacing the air in the alveoli.



The gas exchange system, and an enlarged **alveolus** beside its capillary: only **two cell layers** separate the air from the blood.

The structure and properties of cell membranes Spec 2.2

All cells are surrounded by a **cell-surface membrane**, and eukaryotic cells also have membranes around organelles. They all share the same basic structure, which is described by the **fluid mosaic model**.

The phospholipid bilayer

A **phospholipid** has a hydrophilic (water-loving) phosphate head and two hydrophobic (water-hating) fatty acid tails. In water, phospholipids form a **bilayer**: the heads face outwards towards the water inside and outside the cell, and the tails face inwards, away from water. The bilayer is about 7 nm thick. Phospholipids are not fixed in place, so the layer is fluid: they move sideways within their own layer.

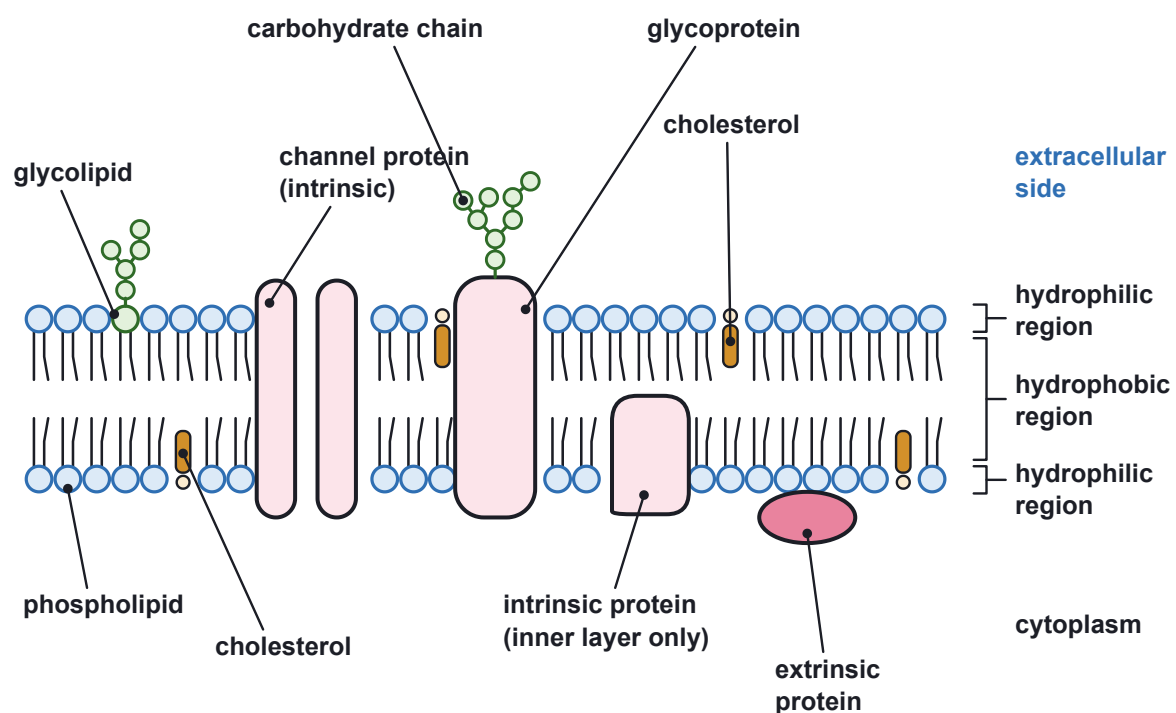
Other components

Components of the membrane and their roles		
Component	Position	Role
Phospholipids	Form the bilayer	Form a barrier to most water-soluble substances; the hydrophobic centre blocks ions and large polar molecules.
Cholesterol	Between the phospholipid tails (animal cells)	Regulates fluidity: it stops the membrane becoming too fluid at higher temperatures and stops the tails packing too closely at lower temperatures. Also makes the membrane more stable.
Intrinsic (integral) proteins	Span the whole bilayer	Form channels and carriers for transport; some are enzymes or receptors.
Extrinsic (peripheral) proteins	On one surface only	Act as enzymes, receptors or recognition sites, or link to the cell's internal framework.
Glycoproteins and glycolipids	On the outer surface, with carbohydrate chains	Act as receptors for hormones and other signals, and as cell recognition sites (antigens).

Properties of the membrane

- **Partially permeable**: small non-polar molecules such as oxygen and carbon dioxide dissolve in the lipid and pass through the bilayer. Water also crosses, in small amounts, by diffusing between phospholipids. Ions and large polar molecules cannot cross the hydrophobic core and need channel or carrier proteins.
- Fluid and flexible: the membrane can change shape and fuse with other membranes (endocytosis and exocytosis).
- Separates the cell from its surroundings and divides the cell into compartments, so that different conditions can be kept in different places.
- Contains receptors and recognition sites, so cells can respond to signals and recognise one another.

Exam tip: Use the word 'hydrophobic' for the tails and 'hydrophilic' for the heads, and say where they face. Use these scientific terms rather than 'water-hating' and 'water-loving' alone.



The **fluid mosaic model** of the cell-surface membrane, about 7 nm thick.

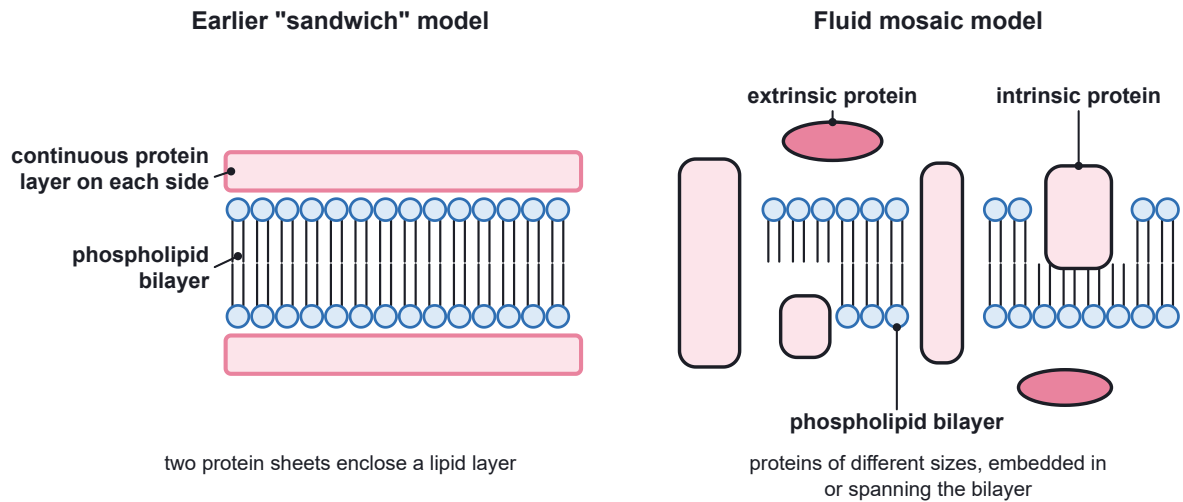
Models of membrane structure and the evidence for them Spec 2.2

Scientists cannot see molecules in a membrane directly. A **model** is an explanation built from the data available. When new data do not fit, the model is changed or replaced. This is how the fluid mosaic model came to be accepted.

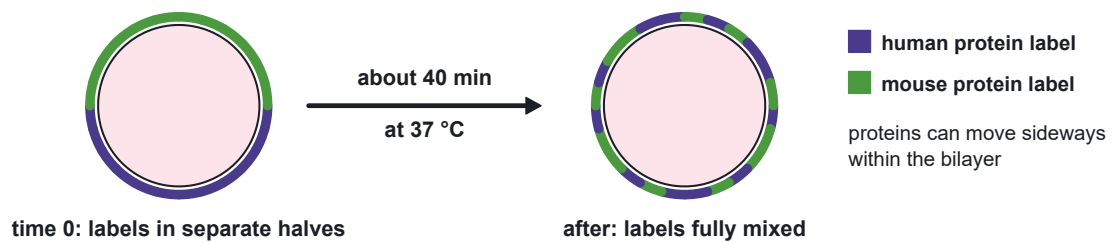
How data have been interpreted		
Evidence	What it showed	How it was interpreted
Early electron micrographs of membranes	Two dark lines with a lighter band between them.	Taken to show a layer of protein on each side of a lipid layer, an early 'sandwich' model with continuous protein layers.
Freeze-fracture electron microscopy	Bumps (protein molecules) scattered within the lipid layers, which split apart between the two layers.	Proteins are embedded within the bilayer, and not in continuous layers on the surface. This supports the mosaic.
Biochemical analysis of membrane proteins	Many proteins have large hydrophobic regions and are not soluble in water.	Hard to explain if all proteins lay on the surface; consistent with proteins spanning the hydrophobic interior.
Cell fusion experiment: a mouse cell and a human cell fused and their surface proteins labelled with different fluorescent markers	At 37 °C the two labels mixed completely over about 40 minutes. At low temperature, mixing was greatly slowed.	Proteins can move sideways in the membrane, so the membrane is fluid. Slower movement at low temperature fits with the lipid becoming more rigid.

The model is named for these two ideas: the bilayer is **fluid** because the phospholipids and many proteins move, and **mosaic** because the proteins are scattered through the bilayer in a pattern like the tiles of a mosaic.

Exam tip: In 'how does the data support the model' questions: first state what the data show (with a value if the data allow), then say what that means about the membrane, then name the feature of the model it supports.



Cell-fusion experiment (human and mouse cells fused, proteins labelled with different fluorescent dyes)



The **sandwich model** against the **fluid mosaic model**. In the cell-fusion experiment the labels mix, so proteins can move within the bilayer.

Core practical 3: membrane permeability, alcohol and temperature Spec 2.3

Core practical: *Core practical 3: investigate membrane properties including the effect of alcohol and temperature on membrane permeability.*

Beetroot cells contain a red-purple pigment, **betalain**, inside the vacuole. While the vacuole membrane (tonoplast) and the cell-surface membrane are intact, the pigment cannot leave the cell. If the membranes are damaged and become more permeable, pigment leaks out. The more colour in the surrounding liquid, the greater the permeability.

Method (temperature version)

1. Use a cork borer to cut cylinders of beetroot of the same diameter. Cut them to the same length with a scalpel on a white tile. Rinse them in distilled water until the water runs clear, to remove pigment released from cut cells.
2. Set up water baths at a range of temperatures (for example 0, 10, 20, 30, 40, 50, 60, 70 °C). Check each temperature with a thermometer.
3. Put the same volume of distilled water (for example 10 cm³) into each of a set of test tubes, and bring them to temperature in the water baths.
4. Add one beetroot cylinder to each tube and leave for the same time (for example 10 minutes).
5. Remove the cylinders. Shake each tube gently to mix the liquid, and pour it into a cuvette.
6. Measure the absorbance of each liquid in a colorimeter with a blue-green filter, after zeroing it on distilled water. (Or compare colours with a set of colour standards.)
7. Repeat at least three times at each temperature and calculate a mean.

For the alcohol version, keep the temperature constant (for example 20 °C) and instead use a set of ethanol concentrations (for example 0, 10, 20, 30, 40, 50 %), made by diluting ethanol with distilled water to the same total volume.

Variables		
Type	Temperature version	Alcohol version
Independent	Temperature of the water	Concentration of ethanol
Dependent	Absorbance of the liquid (a measure of pigment released)	Absorbance of the liquid
Controlled	Size and shape (surface area) of beetroot piece, same beetroot, volume of liquid, time in liquid, colorimeter filter, rinsing	As temperature version, plus a constant temperature

Risk management

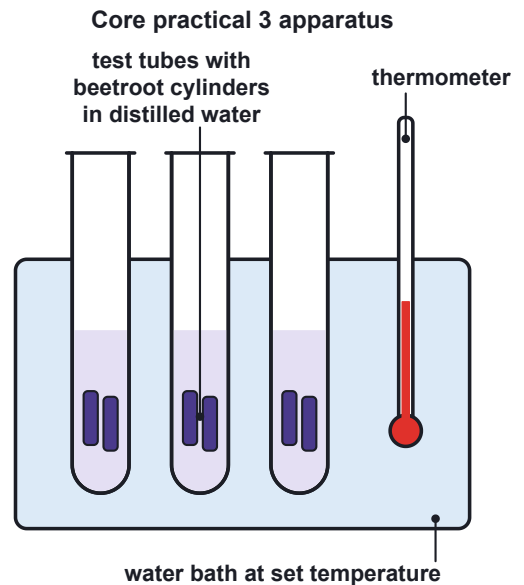
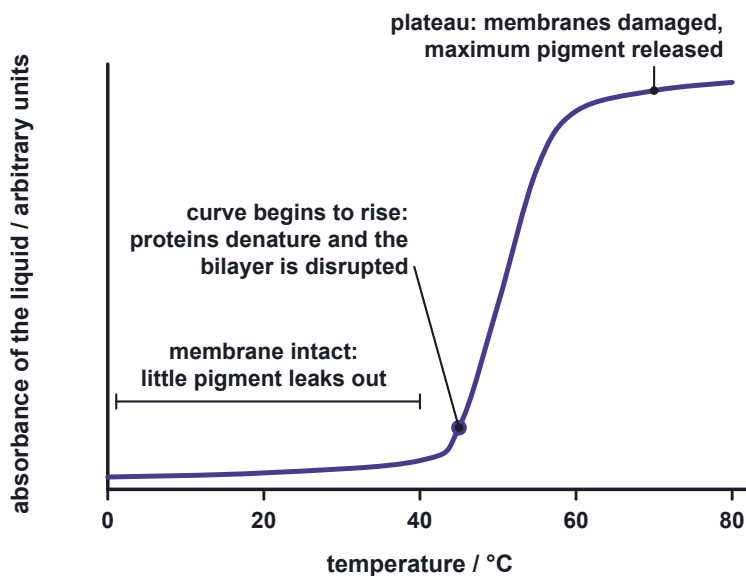
- Ethanol is flammable: keep it away from flames and wear eye protection.
- Hot water can scald: use a thermostatically controlled bath where possible and do not carry hot water across the room.
- Scalpels and cork borers are sharp: cut on a tile, away from the hand holding the beetroot.
- Beetroot juice stains: wear a lab coat.

Processing and explaining results

- Calculate the mean absorbance at each value of the independent variable. Plot a graph with the independent variable on the x axis and mean absorbance on the y axis. Include units.
- Temperature: little leakage at low temperatures (the membrane is intact and its proteins are not damaged). Above about 40 °C the absorbance rises sharply, because proteins in the membrane denature, which opens gaps, and the phospholipids move more, so the bilayer becomes more fluid and leaky.
- Alcohol: ethanol dissolves lipids and disrupts the phospholipid bilayer (and at higher concentrations denatures membrane proteins), so the membrane becomes more permeable and absorbance rises as the concentration rises.
- Compare with a control (beetroot in distilled water at room temperature) to show that the pigment is not just leaking out anyway.

Maths skill: Calculate a mean of repeats, and ignore anomalous results (explain why you did). When comparing treatments, you can work out the percentage change in absorbance relative to the control: $(\text{value} - \text{control}) \div \text{control} \times 100$.

Common mistake: Do not say the membrane 'melts' or that the pigment 'breaks down'. Say that the proteins denature and the phospholipid bilayer is disrupted, so permeability increases.



after a fixed time, measure the absorbance of the liquid with a colorimeter

Core practical 3. **Illustrative data:** above about 40 °C the membranes are damaged and more pigment leaks out, until the curve plateaus.

Osmosis and water potential Spec 2.4

Water potential (symbol ψ , the Greek letter psi) is a measure of the tendency of water molecules to move from one place to another. It is measured in **kilopascals (kPa)**. Pure water has the highest water potential, which is defined as zero. Dissolved solutes attach to some of the water molecules, so fewer water molecules are **free** to move. Adding solute lowers the water potential, so the water potential of any solution is negative.

Osmosis is the net movement of free water molecules through a partially permeable membrane, down a water potential gradient. Water molecules move in both directions across the membrane, but more move from the region of higher (less negative) water potential to the region of lower (more negative) water potential. Osmosis is a passive process and needs no ATP.

What happens to cells in solutions of different water potential

Solution compared with the cell	Net movement of water	Animal cell (no cell wall)	Plant cell (cellulose cell wall)
Higher water potential (more dilute, such as pure water)	Into the cell	Swells and may burst (lysis).	Swells until the wall resists: turgid.
Same water potential	No net movement	Stays the same.	Stays the same.
Lower water potential (more concentrated)	Out of the cell	Shrinks and the surface looks shrivelled (crenation).	Cytoplasm shrinks and pulls away from the cell wall: plasmolysed.

Recommended practical: tissue water potential using plant tissue

The specification recommends an investigation of tissue water potentials using plant tissue and graded concentrations of a solute. Cylinders of potato are cut to the same size, blotted, weighed, left in sucrose solutions of different concentrations for the same time, then blotted and weighed again. In dilute solutions the cylinders gain mass; in concentrated solutions they lose mass.

$$\text{percentage change in mass} = (\text{final mass} - \text{initial mass}) \div \text{initial mass} \times 100$$

Percentage change in mass

A potato cylinder has a mass of 2.40 g before and 2.70 g after 24 hours in a sucrose solution. Calculate the percentage change in mass.

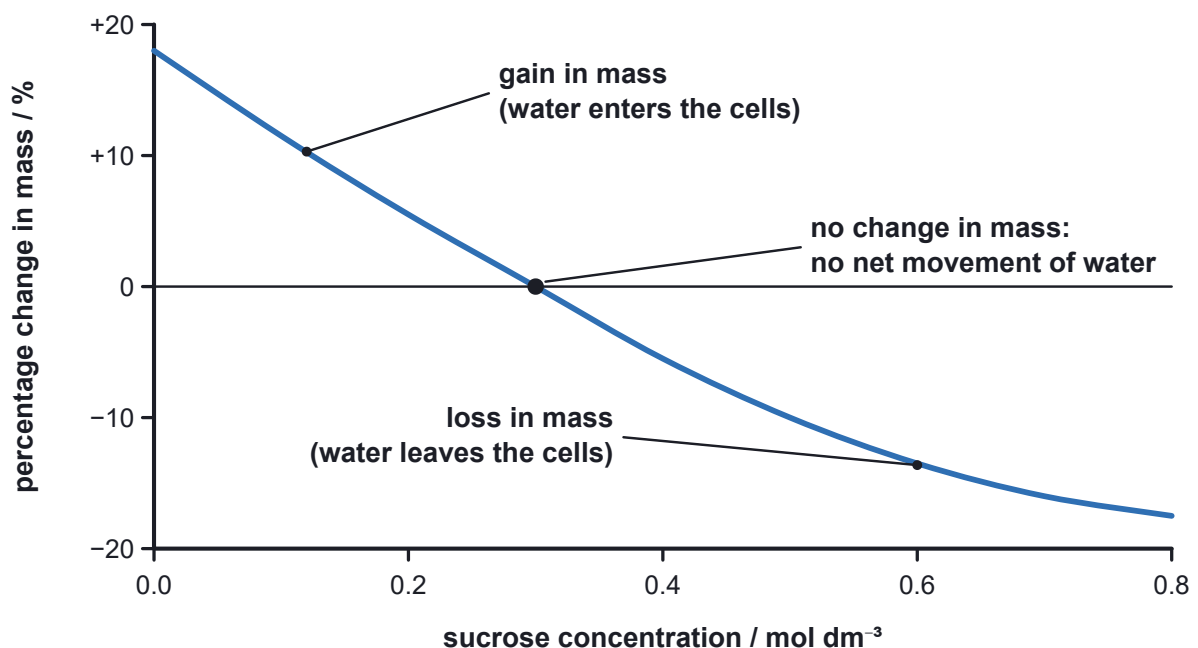
1. Change in mass = $2.70 - 2.40 = +0.30$ g.
2. Divide by the initial mass: $0.30 \div 2.40 = 0.125$.
3. Multiply by 100: 12.5 %.

Answer: +12.5 % (an increase, so water entered by osmosis).

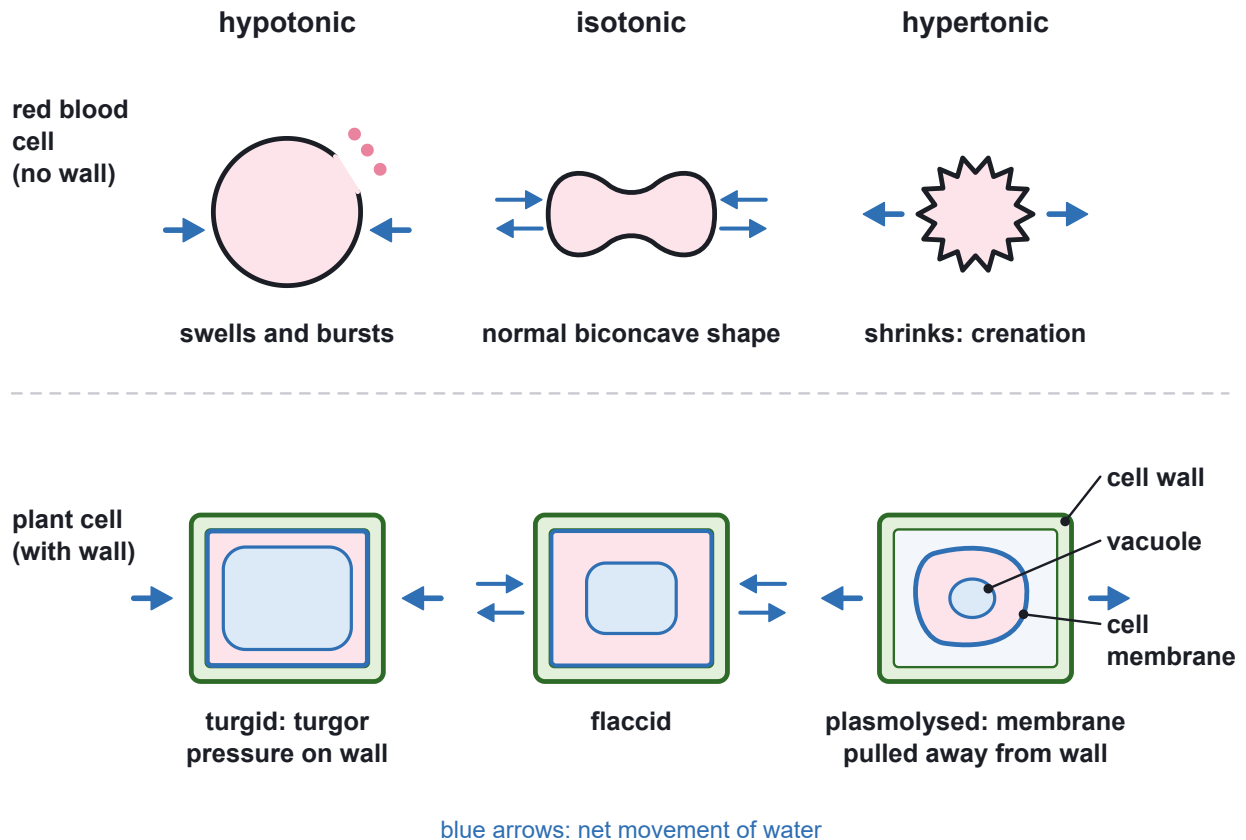
Plot percentage change in mass (y axis) against sucrose concentration (x axis). Where the line crosses zero, there is no net movement of water, so the water potential of the potato tissue equals that of the solution. Read off the concentration at the intercept, then use a calibration table to find the water potential.

Practical skill: Control the size of the cylinders, the volume of solution, the time, the temperature and the way the pieces are blotted. Use percentage change rather than change in mass, so that pieces of slightly different starting mass can be compared.

Common mistake: Do not say water moves 'from a high concentration of water to a low concentration of water'. Say 'from a higher (less negative) water potential to a lower (more negative) water potential'. And keep the sign: -200 kPa is a higher water potential than -500 kPa.



Where the line crosses zero, **no net movement of water** occurs: the water potential of the tissue equals that of the solution.
Illustrative data.



Plant cells in different solutions: **turgid**, flaccid and **plasmolysed**.

Passive transport: diffusion, facilitated diffusion, channel and carrier proteins

Spec 2.5

Passive transport is the movement of substances across a membrane without the cell supplying metabolic energy (no ATP is used). The substance moves down its concentration (or electrochemical) gradient, using the kinetic energy of its own molecules. There are two kinds: diffusion and facilitated diffusion.

Diffusion

Diffusion is the net movement of molecules or ions from a region of higher concentration to a region of lower concentration, down a concentration gradient. Small non-polar molecules such as oxygen and carbon dioxide diffuse directly through the phospholipid bilayer.

Facilitated diffusion

Ions and polar molecules (such as glucose) cannot cross the hydrophobic centre of the bilayer.

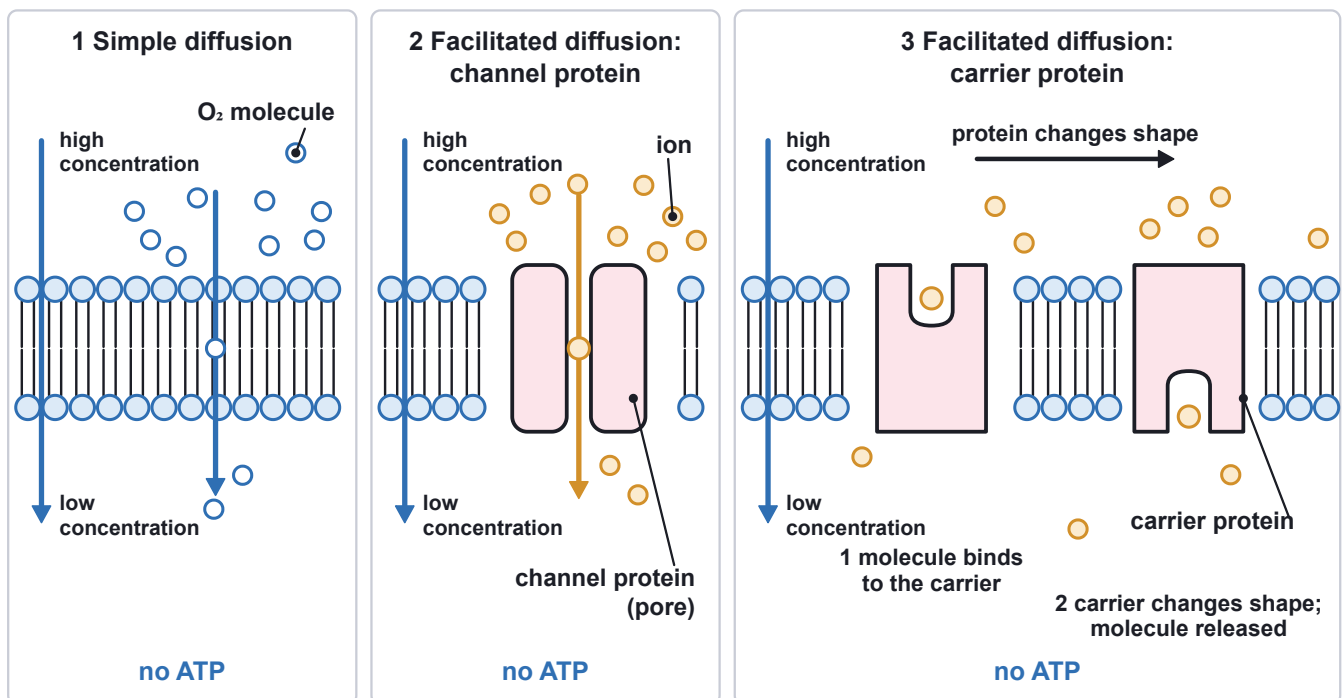
Facilitated diffusion is passive transport through the membrane with the help of transport proteins. There are two types of protein.

Channel proteins compared with carrier proteins

Feature	Channel protein	Carrier protein
Structure	Water-filled pore through the membrane, lined with hydrophilic amino acids; often gated (opens and closes).	Has a binding site specific to one molecule or ion, on one side of the membrane.
How it works	Ions or small polar molecules of the right size and charge pass through the pore.	The molecule binds, the protein changes shape (conformation) and releases the molecule on the other side.
Specificity	Specific to particular ions by pore size and charge.	Specific to a particular molecule by the shape of the binding site.
Energy	Passive: no ATP.	Passive in facilitated diffusion: no ATP.

The rate of facilitated diffusion rises with the concentration gradient, but only up to a point. When all the carrier proteins are working at their maximum rate (saturated), adding more of the substance does not increase the rate. The rate also depends on the number of transport proteins in the membrane.

Exam tip: 'Facilitated diffusion' still needs a concentration gradient and still uses no ATP. Say 'down a concentration gradient through a channel or carrier protein' to earn the marks.



Passive transport: all three move down a concentration gradient and use no ATP.

Active transport, endocytosis and exocytosis Spec 2.5

Active transport

Active transport is the movement of molecules or ions across a membrane against a concentration gradient, using energy from ATP and a carrier protein. **ATP** is the immediate source of energy for the cell. It is hydrolysed to ADP and inorganic phosphate (P_i), which releases energy.

1. The molecule or ion to be moved binds to a specific site on a carrier protein.
2. ATP binds to the carrier protein and is hydrolysed to ADP + P_i , which releases energy.
3. The protein changes shape and releases the molecule on the other side of the membrane, against the gradient.

4. The protein returns to its original shape, ready to bind again.

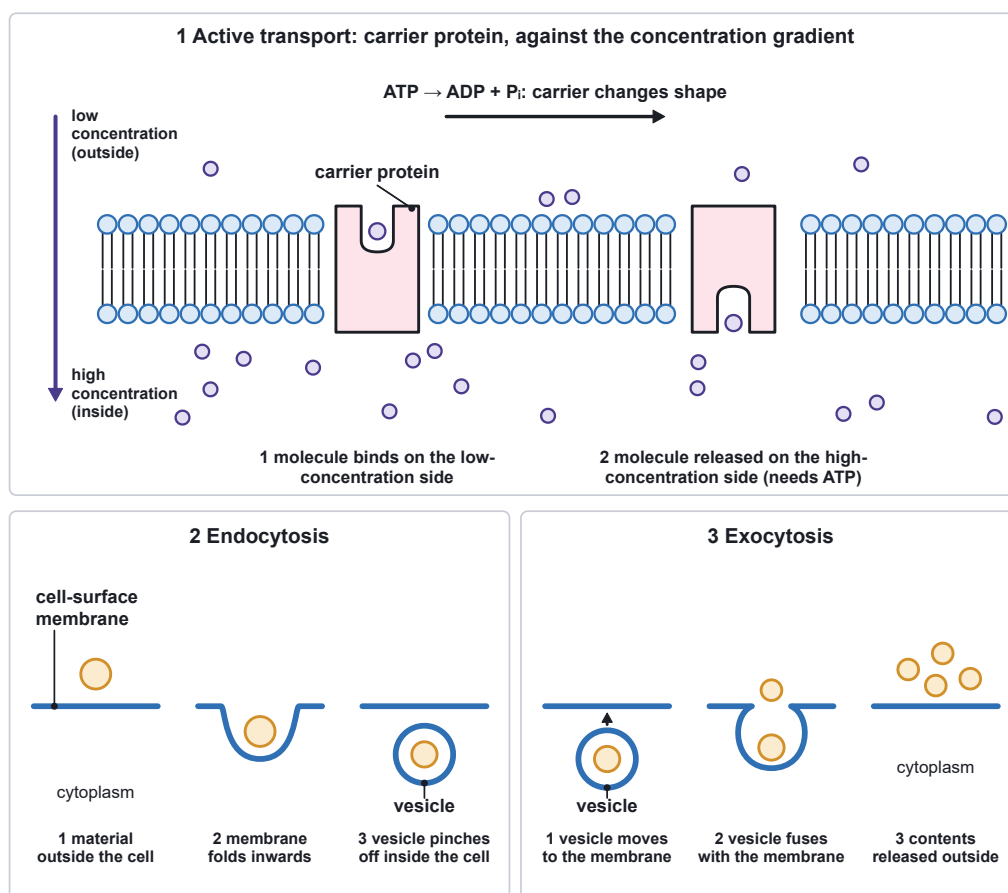
Endocytosis and exocytosis

- **Endocytosis** is the bulk transport of material into a cell. A region of the cell-surface membrane folds inwards around the material and pinches off to form a vesicle inside the cell. Cells use it to take in large particles or fluid droplets; ATP is needed.
- **Exocytosis** is the bulk transport of material out of a cell. A vesicle (often from the Golgi apparatus) moves to the cell-surface membrane, fuses with it and releases its contents outside. Cells use it to secrete substances such as enzymes and hormones; ATP is needed.

Comparing the transport processes			
Feature	Diffusion	Facilitated diffusion	Active transport
Direction relative to gradient	Down	Down	Against
ATP needed	No	No	Yes
Protein needed	No	Yes (channel or carrier)	Yes (carrier)
Specific	No	Yes	Yes

Exam tip: A good mark point for active transport is 'ATP is hydrolysed to ADP and P_i, which releases energy'. An answer that only says 'uses energy' is not enough. Cells with a lot of active transport have many mitochondria.

Common mistake: Endocytosis and exocytosis are not diffusion or osmosis, and they do not use channel or carrier proteins. They move bulk material in vesicles and they need ATP.



Active transport needs ATP; **endocytosis** and **exocytosis** move bulk material in vesicles and also need ATP.

Quick check

1. State the three properties of a gas exchange surface.
2. What happens to the rate of diffusion if the thickness of the exchange surface doubles?
3. Why can oxygen cross the phospholipid bilayer, but sodium ions cannot?
4. Define osmosis.
5. What is the role of ATP in active transport?

Quick check answers

Gas exchange, membranes and transport

1. A large surface area to volume ratio, a thin surface (short diffusion distance) and a large concentration difference.
2. It halves, because the rate is inversely proportional to the thickness (Fick's law).
3. Oxygen is small and non-polar, so it dissolves in the hydrophobic centre. Ions are charged and are repelled by it.
4. The net movement of free water molecules through a partially permeable membrane, down a water potential gradient.
5. It is hydrolysed to ADP and P_i , releasing the energy that changes the shape of the carrier protein.