



Cells (Form and function) revision notes

Cells (Form and function) is about how the structure of a cell suits its function: how membranes are built and control what crosses them, how organelles divide a cell into compartments, and how cells specialize in size, shape and contents. HL adds membrane fluidity, gated channels and pumps, detailed organelle function, and the adaptations of pneumocytes, muscle cells and gametes.

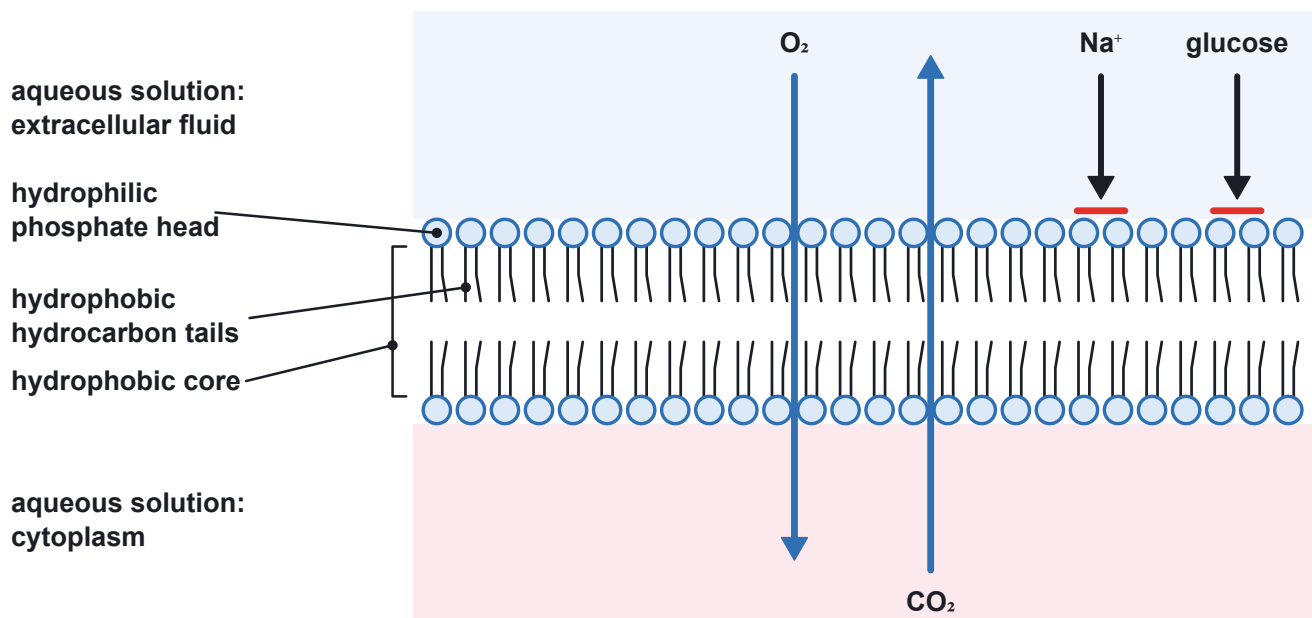
For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

1 Membranes and membrane transport Spec B2.1

Lipid bilayers, barriers and simple diffusion Spec B2.1.1-B2.1.3

A phospholipid is **amphipathic**: it has a hydrophilic (water-attracting) phosphate head and two hydrophobic (water-repelling) hydrocarbon tails. Other membrane lipids, such as cholesterol and glycolipids, are also amphipathic.

In water, phospholipids naturally arrange themselves into a **lipid bilayer**. The heads face outwards into the water on both sides and the tails point inwards, away from the water. The bilayer forms continuous sheets, which close up so that no tails are left exposed at an edge. No energy input is needed. This bilayer is the basis of every cell membrane.



O_2 and CO_2 diffuse between the phospholipids;
 Na^+ and glucose cannot enter the hydrophobic core

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Small non-polar O_2 and CO_2 cross the **hydrophobic core**; ions such as Na^+ and polar molecules such as glucose cannot.

Bilayers as barriers

The hydrocarbon chains that form the core of the membrane are non-polar. Hydrophilic particles cannot easily enter this region, so the core has **low permeability** to large molecules and to hydrophilic particles, including ions (such as Na^+ and Cl^-) and polar molecules (such as glucose). Membranes are therefore effective barriers between two aqueous solutions, such as the cytoplasm and tissue fluid.

Permeability of a lipid bilayer without membrane proteins		
Particle	Example	Crosses the hydrophobic core?
Small non-polar molecule	O_2 , CO_2	Yes, readily
Small polar molecule	H_2O	Slowly
Large polar molecule	Glucose	Hardly at all
Ion	Na^+ , K^+ , Cl^-	Hardly at all (charged)

Simple diffusion

Simple diffusion is the net movement of particles from a region of higher concentration to a region of lower concentration, caused by their random movement. It is passive: no energy from ATP is used. Oxygen and carbon dioxide are small and non-polar, so they diffuse directly between the phospholipids. In a respiring cell oxygen is used up, so it diffuses in; carbon dioxide is produced, so it diffuses out.

Common mistake: Particles do not move because of the gradient. They move randomly in all directions, but more cross from the side with the higher concentration, so the net movement is down the gradient.

Osmosis, channel proteins and pump proteins Spec B2.1.5-B2.1.8

Osmosis

Osmosis is the net movement of water molecules across a partially permeable membrane from a region of lower solute concentration to a region of higher solute concentration.

1. Water molecules move randomly and cross the membrane in both directions.
2. The membrane is impermeable to the solute, so solute particles stay on their own side.
3. On the side with the higher solute concentration, solute particles take up part of the solution, so the concentration of water molecules free to move across the membrane is lower there.
4. More water molecules therefore cross from the side with the lower solute concentration than move back, giving a net movement of water towards the higher solute concentration.
5. Osmosis is passive and continues while the difference in solute concentration remains.

Water is polar, so it crosses the lipid bilayer only slowly. **Aquaporins** are integral channel proteins that let water molecules pass through in single file, increasing the permeability of the membrane to water many times over. The pore is too narrow for most solutes, and charges inside it repel ions, so only water passes. Cells that move large volumes of water, such as kidney collecting duct cells and root cells, have many aquaporins.

Channel proteins and facilitated diffusion

Facilitated diffusion is passive diffusion of particles through a membrane protein. A **channel protein** is an integral protein with a hydrophilic pore through the membrane. The diameter of the pore and the charges lining it allow only specific ions (for example K^+) to pass. Many channels are gated: ions diffuse through when the channel is open but not when it is closed, so the cell can control permeability.

Pump proteins and active transport

Active transport is the movement of particles across a membrane against a concentration gradient, using energy from ATP. Pump proteins bind a specific particle on one side, use energy from ATP to change shape, and release the particle on the other side. Pumps move particles in one direction only, so they can build up concentration gradients.

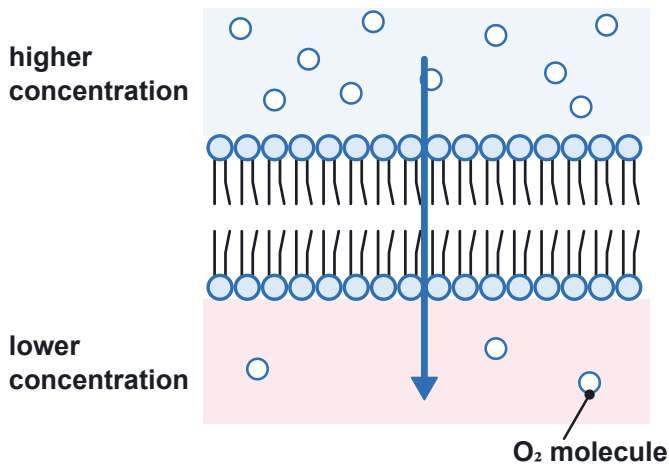
Comparing transport across membranes			
Feature	Simple diffusion	Facilitated diffusion	Active transport
Direction	Down the concentration gradient	Down the concentration gradient	Against the concentration gradient
Energy from ATP	No	No	Yes
Membrane protein	None (between phospholipids)	Channel protein	Pump protein
Selective?	No: depends only on size and polarity	Yes: specific ions	Yes: specific particles
Example	O ₂ and CO ₂	K ⁺ through a potassium channel	Mineral ions into root hair cells

Selectivity in membrane permeability

Facilitated diffusion and active transport give membranes **selective permeability**: the channel and pump proteins present decide which ions and molecules can cross. Permeability by simple diffusion is not selective. It depends only on the size of a particle and whether it is hydrophilic or hydrophobic.

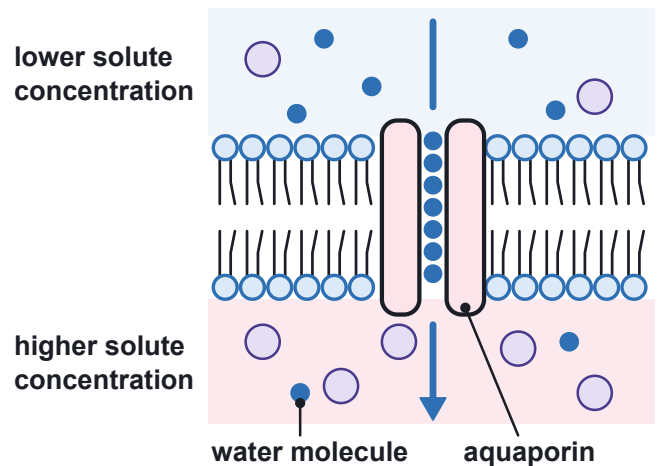
1 Simple diffusion

passive



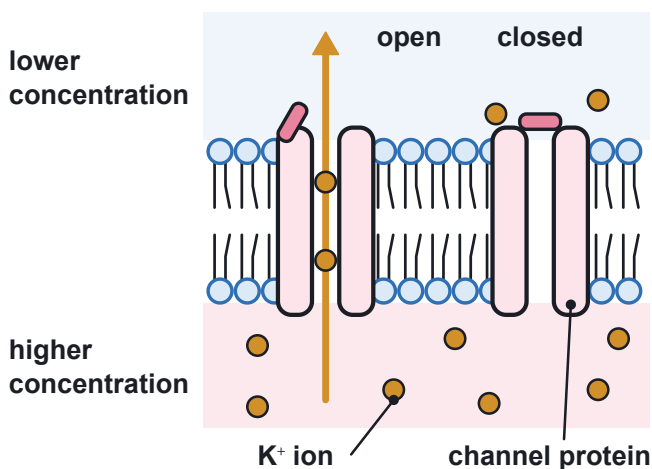
2 Osmosis (aquaporin)

passive



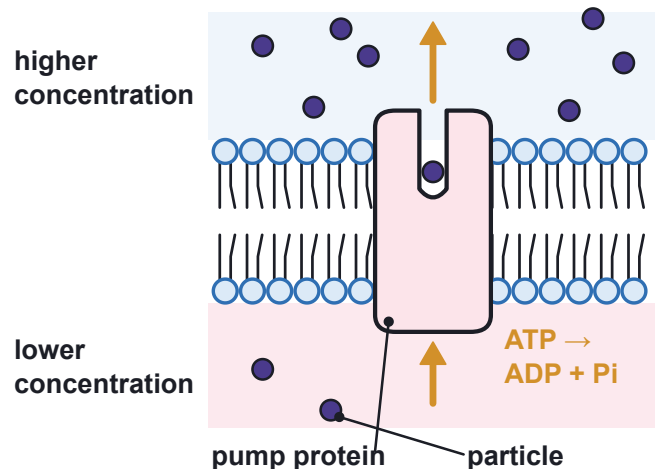
3 Facilitated diffusion

passive



4 Active transport

active



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Diffusion, osmosis and facilitated diffusion are **passive**; pump proteins use ATP for **active transport** against the gradient.

Exam tip: Linking question: what processes depend on active transport? Think of mineral ion uptake by roots, nerve impulses and the absorption of glucose in the gut.

Membrane proteins, glycoproteins and the fluid mosaic model Spec B2.1.4, B2.1.9, B2.1.10

Integral and peripheral proteins

Membrane proteins have diverse structures, locations and functions. **Integral proteins** are embedded in one or both of the lipid layers. Those that span both layers have hydrophobic regions in contact with the hydrocarbon core and hydrophilic regions facing the water on each side. **Peripheral proteins** are attached to one or other surface of the bilayer, often bound to an integral protein, and do not enter the hydrophobic core.

- Transport: channels and pumps (integral proteins).
- Receptors: bind signalling chemicals such as hormones or neurotransmitters.
- Enzymes: catalyse reactions at the membrane surface.
- Cell adhesion: bind cells to each other.
- Cell recognition: identify a cell to other cells.

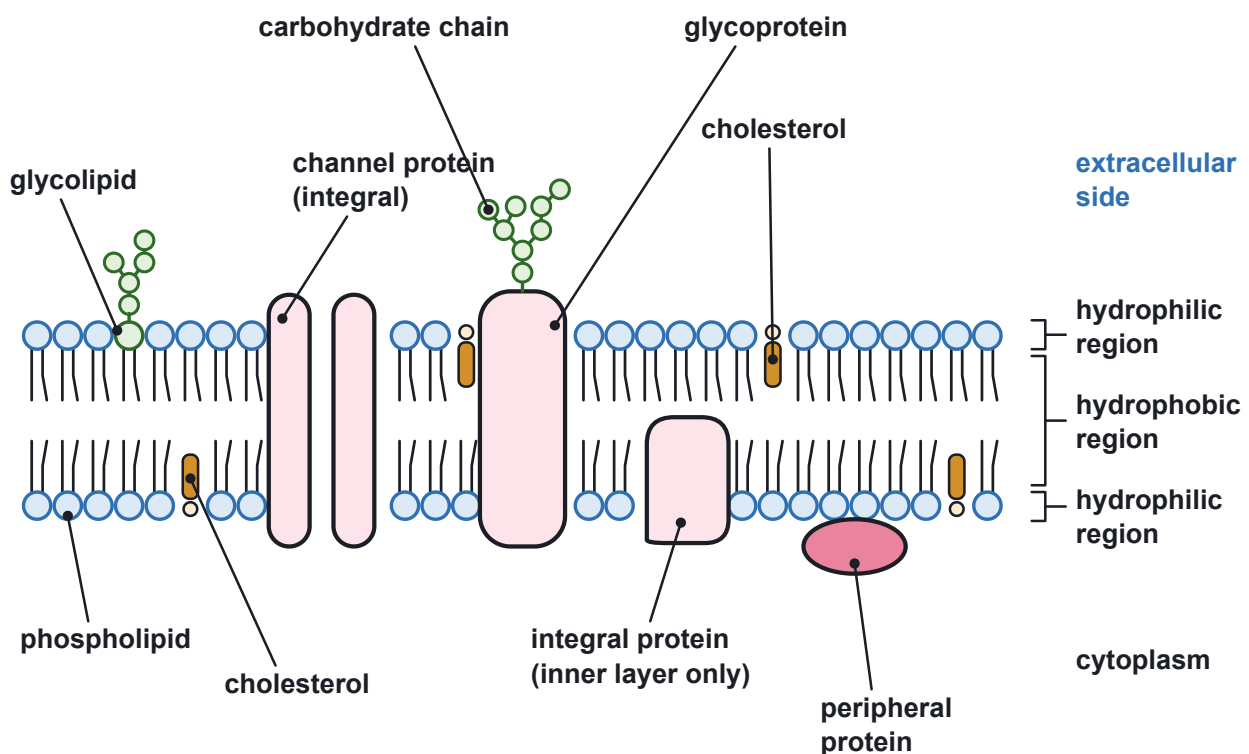
Glycoproteins and glycolipids

Glycoproteins are proteins with carbohydrate chains attached, and **glycolipids** are lipids with carbohydrate chains attached. In the plasma membrane the carbohydrate is always on the **extracellular side**, where it forms a sugary coat on the cell surface.

- Cell recognition: the carbohydrate chains act as markers, so other cells, such as cells of the immune system, can recognise a cell as self or non-self.
- Cell adhesion: carbohydrate chains help cells attach to each other to form tissues.

The fluid mosaic model

The membrane is described as **fluid** because phospholipids and many proteins can move sideways within each layer, and **mosaic** because proteins are scattered through the bilayer like tiles in a mosaic.



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The fluid mosaic model: carbohydrate chains only on the **extracellular side**, cholesterol among the tails in the **hydrophobic region**.

Exam tip: In a drawing, put carbohydrate chains only on the outside, draw cholesterol among the tails, and label the hydrophilic and hydrophobic regions, not just the heads and tails.

Membrane fluidity, cholesterol and vesicles Spec B2.1.11-B2.1.13 HL only

Fatty acids and fluidity

Unsaturated fatty acids have one or more cis double bonds, which put kinks in the hydrocarbon chain. The chains cannot pack closely, so they have **lower melting points** and the membrane stays fluid, and therefore flexible, at the temperatures the cell experiences. **Saturated fatty acids** have straight chains that pack tightly. They have higher melting points and make membranes stronger at higher temperatures.

Organisms adapt membrane composition to their habitat. Fish adapted to the near-freezing waters around Antarctica have a higher proportion of unsaturated fatty acids in their membrane phospholipids

than related fish from warmer waters, so their membranes do not become too rigid in the cold. Bacteria such as *Escherichia coli* increase the proportion of unsaturated fatty acids in their membranes when they grow at lower temperatures, and the proportion of saturated fatty acids when they grow at higher temperatures.

Cholesterol

In animal cell membranes, **cholesterol** sits within the bilayer. Its hydroxyl (-OH) group lies among the phosphate heads, and its rigid steroid rings and hydrocarbon tail lie among the fatty acid tails.

Cholesterol acts as a **modulator** (adjustor) of membrane fluidity.

- At higher temperatures it restricts the movement of the phospholipid tails, stabilising the membrane.
- At lower temperatures it stops the tails packing closely together, preventing the membrane from stiffening.

Vesicles: endocytosis and exocytosis

Because the bilayer is fluid, membranes can bend, pinch off and fuse with each other, then reseal without leaking. Endocytosis removes a small area of plasma membrane as a vesicle; exocytosis adds the vesicle membrane back to the plasma membrane.

Endocytosis	The plasma membrane folds inwards around material outside the cell and pinches off to form a vesicle inside the cell. Example: phagocytosis of bacteria by white blood cells.
Exocytosis	A vesicle moves to the plasma membrane, fuses with it and releases its contents outside the cell. Examples: secretion of digestive enzymes by pancreatic cells; release of neurotransmitter at a synapse.

Common mistake: Do not just write that cholesterol makes membranes less fluid. It reduces fluidity at high temperatures but prevents stiffening at low temperatures.

Gated ion channels, sodium-potassium pumps and cotransporters Spec B2.1.14-B2.1.16

HL only

Gated ion channels in neurons

A **gated ion channel** opens or closes in response to a stimulus. Neurons use two kinds: neurotransmitter-gated and voltage-gated channels.

Gated ion channels in neurons			
Channel	Type of gate	What opens it	Effect
Nicotinic acetylcholine receptor	Neurotransmitter-gated	Acetylcholine binding to the receptor in the post-synaptic membrane	Positive ions, mainly Na ⁺ , diffuse in, depolarising the membrane
Voltage-gated sodium channel	Voltage-gated	Depolarisation of the membrane to the threshold potential	Na ⁺ diffuses in rapidly, depolarising the membrane further; the channel soon closes again
Voltage-gated potassium channel	Voltage-gated	Depolarisation (it opens more slowly than sodium channels)	K ⁺ diffuses out, repolarising the membrane

In each case the ions move by facilitated diffusion, down their concentration gradients. The gate only controls when the channel is open.

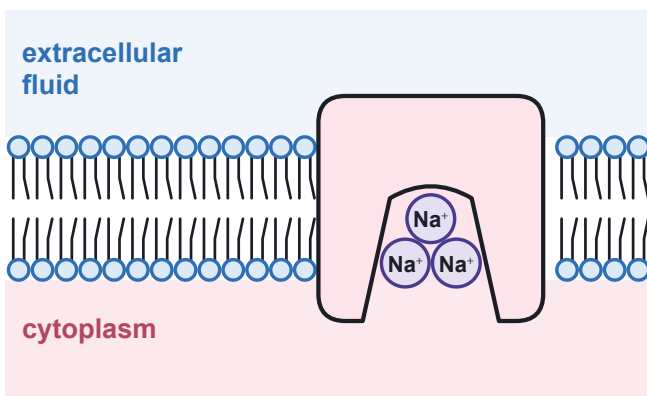
The sodium-potassium pump: an exchange transporter

The **sodium-potassium pump** is an **exchange transporter**: in each cycle it moves two different ions in opposite directions, using energy from ATP.

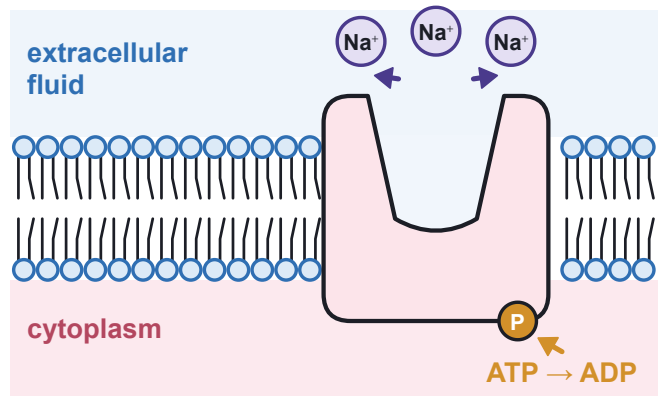
1. Three Na^+ ions from the cytoplasm bind to the pump.
2. ATP transfers a phosphate group to the pump. This changes its shape so it opens to the outside and releases the three Na^+ .
3. Two K^+ ions from outside the cell bind to the pump.
4. The phosphate is released and the pump returns to its original shape, opening to the inside.
5. The two K^+ ions are released into the cytoplasm and the cycle repeats.

Each cycle removes one net positive charge from the cell and builds concentration gradients of Na^+ (high outside) and K^+ (high inside). This is how the pump helps to **generate membrane potentials**, including the resting potential of about -70 mV in neurons. The Na^+ gradient is also a store of energy that other transporters can use.

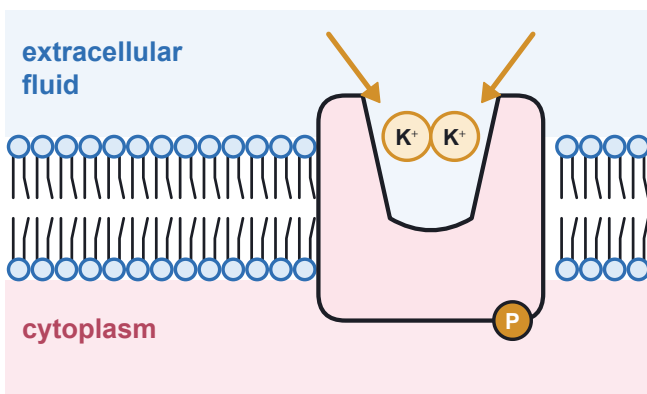
**Step 1: pump open to the cytoplasm:
3 Na^+ from the cytoplasm bind to the pump**



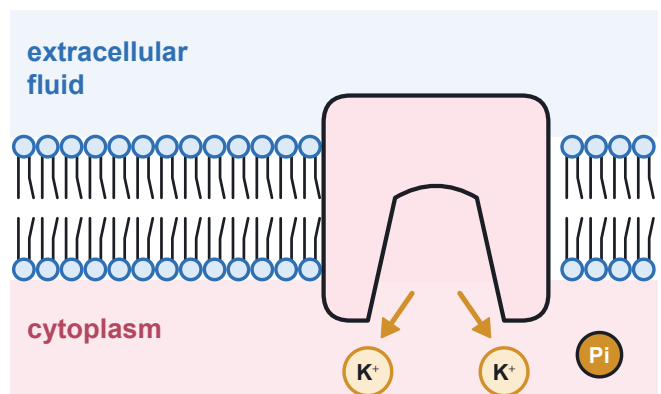
**Step 2: ATP → ADP; phosphate attaches; the
pump opens to the outside and releases 3 Na^+**



**Step 3: 2 K^+ from the extracellular fluid
bind to the pump**



**Step 4: phosphate released; the pump opens
to the cytoplasm and releases 2 K^+**



Na^+ concentration high outside the cell

K^+ concentration high inside the cell

each cycle: 3 Na^+ pumped out, 2 K^+ pumped in, 1 ATP used

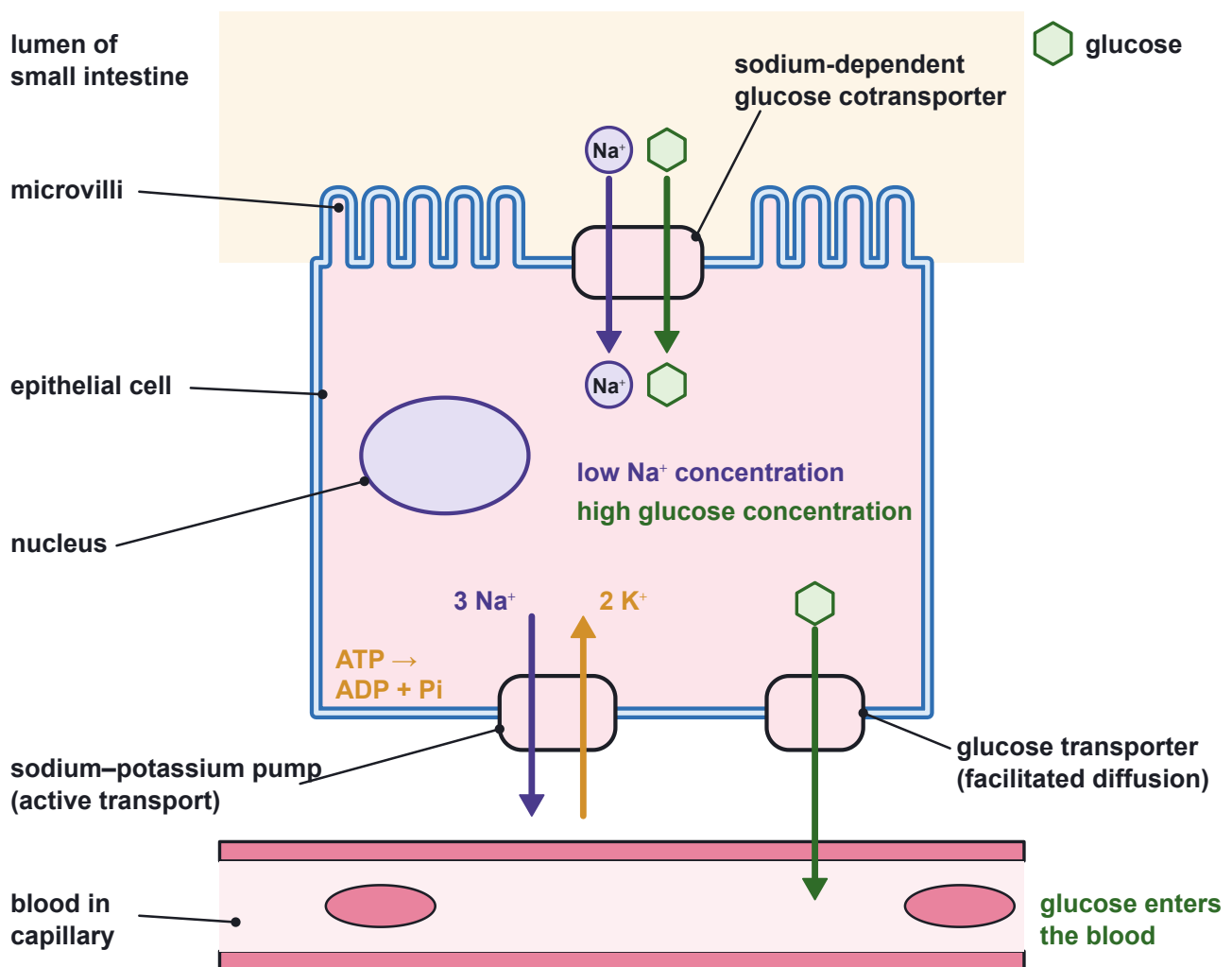
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Each cycle pumps **3 Na^+ out and 2 K^+ in** using one ATP, keeping Na^+ high outside and K^+ high inside.

Sodium-dependent glucose cotransporters

Indirect active transport uses a concentration gradient made by one pump to move another particle against its own gradient. In a **sodium-dependent glucose cotransporter**, Na^+ diffuses into the cell down its concentration gradient and the protein uses this to carry glucose in at the same time, against the glucose concentration gradient. ATP is used only by the sodium-potassium pumps that keep the Na^+ concentration inside the cell low.

- Small intestine: cotransporters in the membrane of epithelial cells facing the lumen absorb glucose from digested food. The glucose then leaves the other side of the cell by facilitated diffusion and enters the blood.
- Nephron: cotransporters in proximal convoluted tubule cells reabsorb glucose from the filtrate, so normally no glucose is lost in urine.



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Indirect active transport: the **sodium-potassium pump** keeps Na^+ low in the cell, so the **cotransporter** can bring glucose in against its gradient.

Exam tip: Call it indirect active transport: the cotransporter itself does not use ATP, but it depends on the ATP-driven sodium-potassium pump keeping Na^+ low inside the cell.

Adhesion of cells to form tissues Spec B2.1.17 HL only

In multicellular organisms, cells must stick together to form tissues. **Cell-adhesion molecules** (CAMs) are membrane proteins, usually glycoproteins, that project from the cell surface and bind to CAMs on

neighbouring cells.

There are different forms of CAM for different types of cell-cell junction. Some junctions seal adjacent cells tightly so that fluid cannot leak between them, as in the epithelium lining the gut. Others anchor cells firmly so a tissue can withstand stretching, as in skin and heart muscle.

Exam tip: You need the term cell-adhesion molecules (CAMs) and the idea that different CAMs form different junctions. Names and details of individual CAMs and junctions are not required.

Quick check

1. Which part of a phospholipid is hydrophobic?
2. Name the channel protein that lets water cross membranes rapidly.
3. What does a pump protein use to move particles against a concentration gradient?
4. On which side of the plasma membrane are the carbohydrate chains of glycoproteins?
5. **HL only** How many Na^+ and K^+ ions does the sodium-potassium pump move in one cycle?

2 Organelles and compartmentalization Spec B2.2

Organelles, the nucleus and compartments Spec B2.2.1-B2.2.3

Organelles are discrete subunits of cells that are adapted to perform specific functions. Nuclei, mitochondria, chloroplasts, the endoplasmic reticulum, the Golgi apparatus, vesicles, ribosomes and the plasma membrane are all organelles.

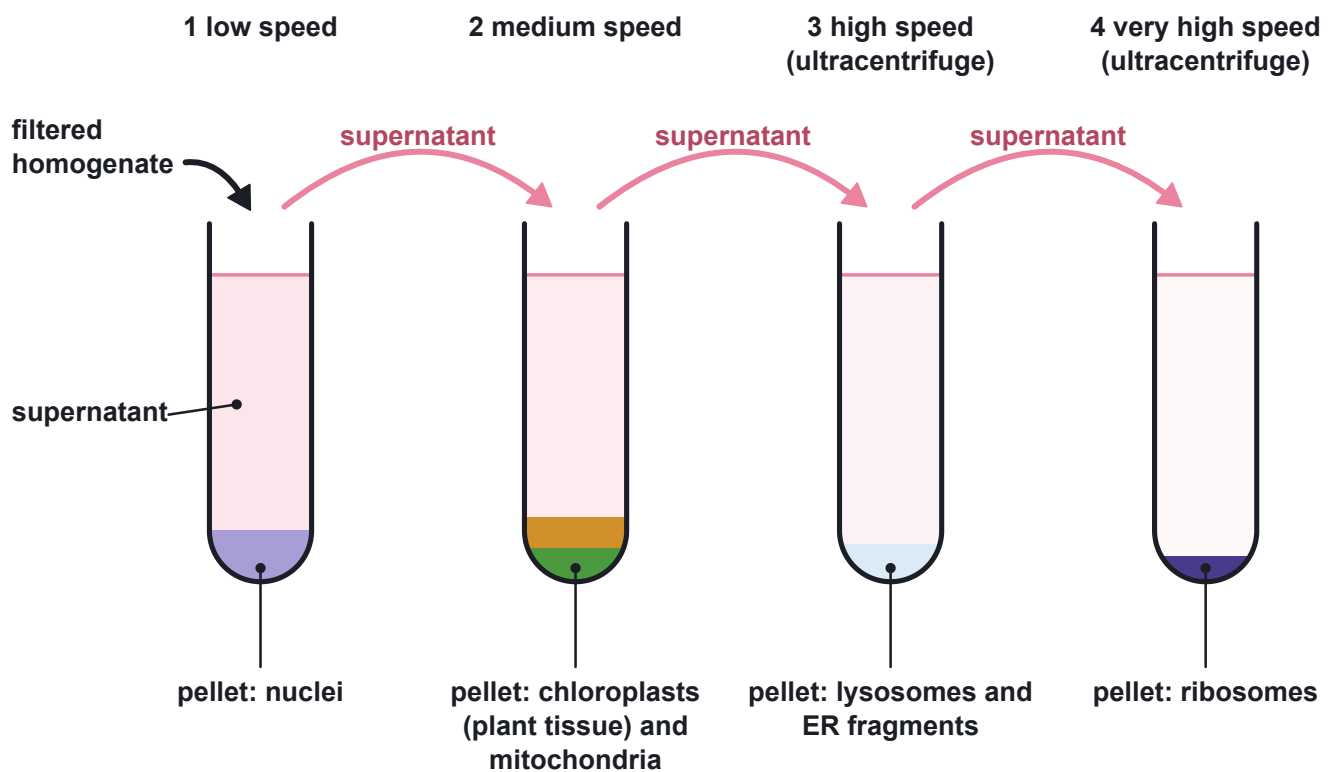
The cell wall, the cytoskeleton and the cytoplasm are **not considered organelles**. The wall lies outside the plasma membrane, the cytoskeleton is a network running through the whole cell, and the cytoplasm is the medium in which the organelles sit.

Cell fractionation

Progress in science often follows the development of new techniques. The functions of individual organelles could only be studied once **ultracentrifuges** had been invented and methods of using them for **cell fractionation** had been developed.

1. Tissue is cut up and homogenised (blended) in a cold, isotonic, buffered solution to break the cells open.
2. The homogenate is filtered to remove large debris.
3. It is spun in a centrifuge at low speed. The largest, densest organelles (nuclei) form a pellet at the bottom of the tube.
4. The liquid above the pellet (the supernatant) is spun at a higher speed to pellet chloroplasts (from plant tissue) and then mitochondria, then at even higher speeds in an ultracentrifuge for smaller parts such as fragments of ER and ribosomes.
5. Each pellet is resuspended and tested, for example by measuring the activity of enzymes, to find out what that organelle does.

Practical skill: Cold slows enzymes that would digest the organelles, an isotonic solution stops organelles gaining or losing water by osmosis, and a buffer keeps the pH constant so proteins are not denatured.



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Differential centrifugation: each faster spin pellets **smaller, less dense** organelles from the supernatant.

Separating the nucleus from the cytoplasm

In eukaryotes, **transcription** happens in the nucleus and **translation** happens at ribosomes in the cytoplasm. Because they are in separate compartments, **post-transcriptional modification** of mRNA (such as removing introns) can happen before the mRNA meets ribosomes. Prokaryotes have no nucleus, so mRNA may meet ribosomes immediately and translation can begin before transcription has finished.

Compartments in the cytoplasm

- Enzymes and their substrates (metabolites) can be concentrated in a small volume, so reactions are faster.
- Incompatible biochemical processes are kept apart, for example digestion of molecules and their synthesis.
- Conditions such as pH can be kept different in each compartment.

Lysosomes are vesicles containing hydrolytic enzymes that work best at acid pH. If these enzymes were free in the cytoplasm they would digest the cell's own molecules. **Phagocytic vacuoles** form when a cell such as a white blood cell engulfs a bacterium by endocytosis. Lysosomes then fuse with the vacuole, so the bacterium is digested inside a closed compartment.

Exam tip: Linking question: what separation techniques are used by biologists? Centrifugation separates cell parts by size and density; compare chromatography and gel electrophoresis, which separate molecules.

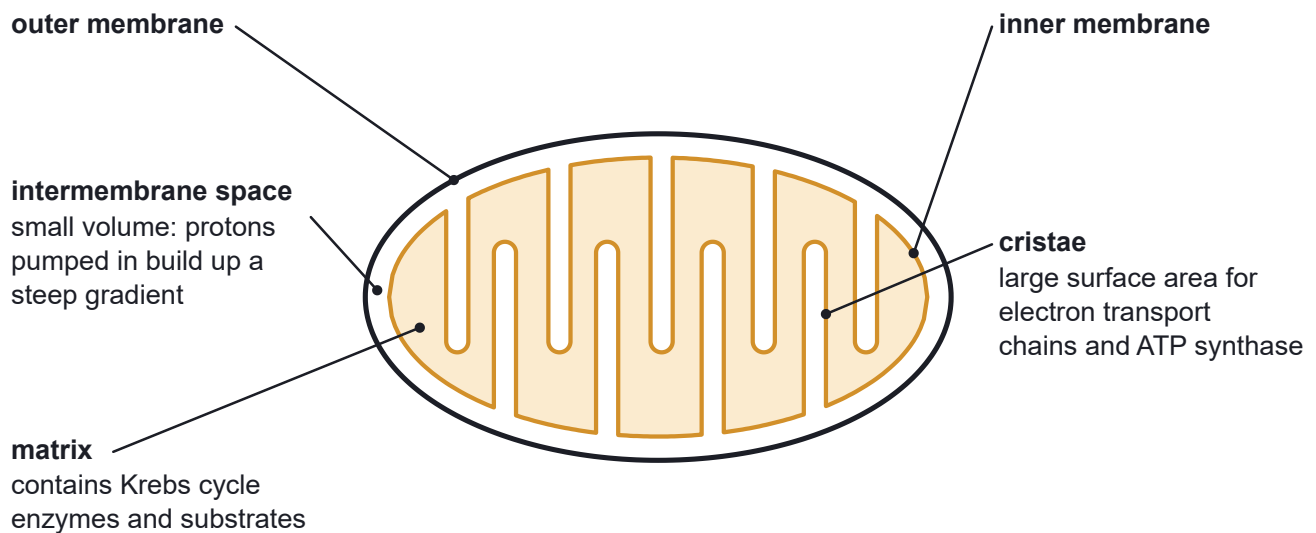
Adaptations of mitochondria and chloroplasts Spec B2.2.4, B2.2.5 HL only

Adaptations of the mitochondrion for production of ATP by aerobic cell respiration

Feature	Adaptation
Double membrane	The outer membrane separates the mitochondrion from the cytoplasm; the inner membrane holds the electron transport chain and ATP synthase.
Small volume of intermembrane space	Protons pumped into it by the electron transport chain quickly build up to a high concentration, giving a steep gradient for making ATP by chemiosmosis.
Cristae	Folds of the inner membrane give a large surface area for many electron transport chains and ATP synthase molecules.
Matrix	Compartmentalizes the enzymes and substrates of the Krebs cycle, keeping them together at high concentration.

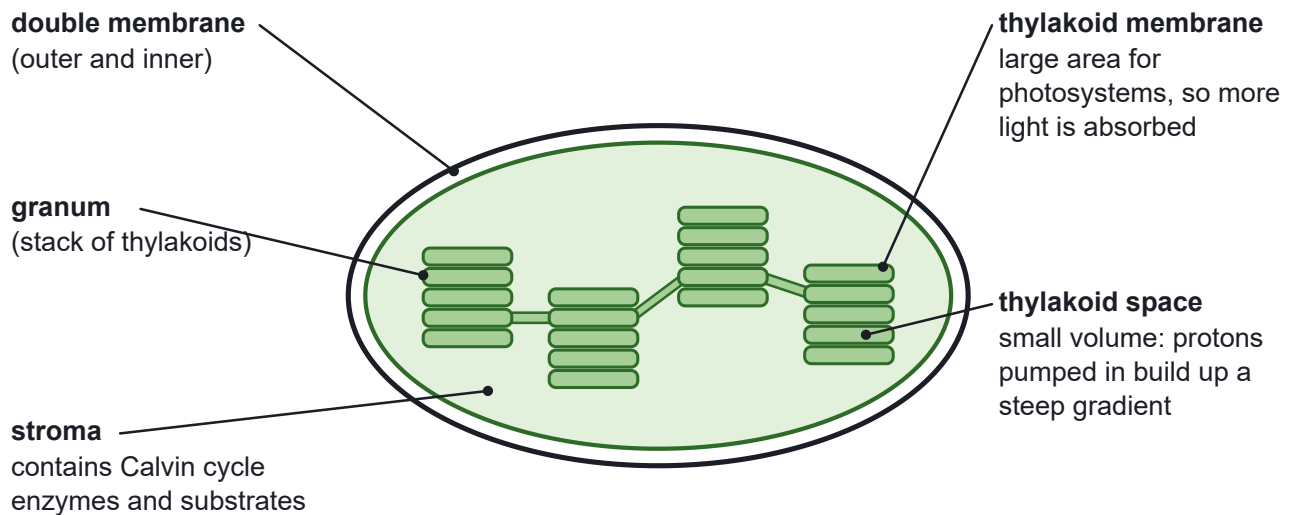
Adaptations of the chloroplast for photosynthesis

Feature	Adaptation
Thylakoid membranes	Stacked into grana, giving a large surface area for photosystems, so more light can be absorbed.
Small volume of fluid inside thylakoids	Protons pumped into the thylakoid space quickly reach a high concentration, giving a steep gradient for making ATP.
Stroma	Compartmentalizes the enzymes and substrates of the Calvin cycle , close to the ATP and NADPH made by the thylakoids.



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Mitochondrion: **cristae** give a large area for electron transport chains and ATP synthase.



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Chloroplast: stacked **thylakoids** give a large area for photosystems; the **stroma** holds the Calvin cycle enzymes.

Exam tip: For an 'explain the adaptation' question, give the feature and then its effect: for example, a small intermembrane space, so a high proton concentration builds up quickly.

The nucleus, free ribosomes and rough ER Spec B2.2.6, B2.2.7 HL only

The double nuclear membrane

The nucleus is enclosed by two membranes, together called the **nuclear envelope**. The outer membrane is continuous with the rough endoplasmic reticulum.

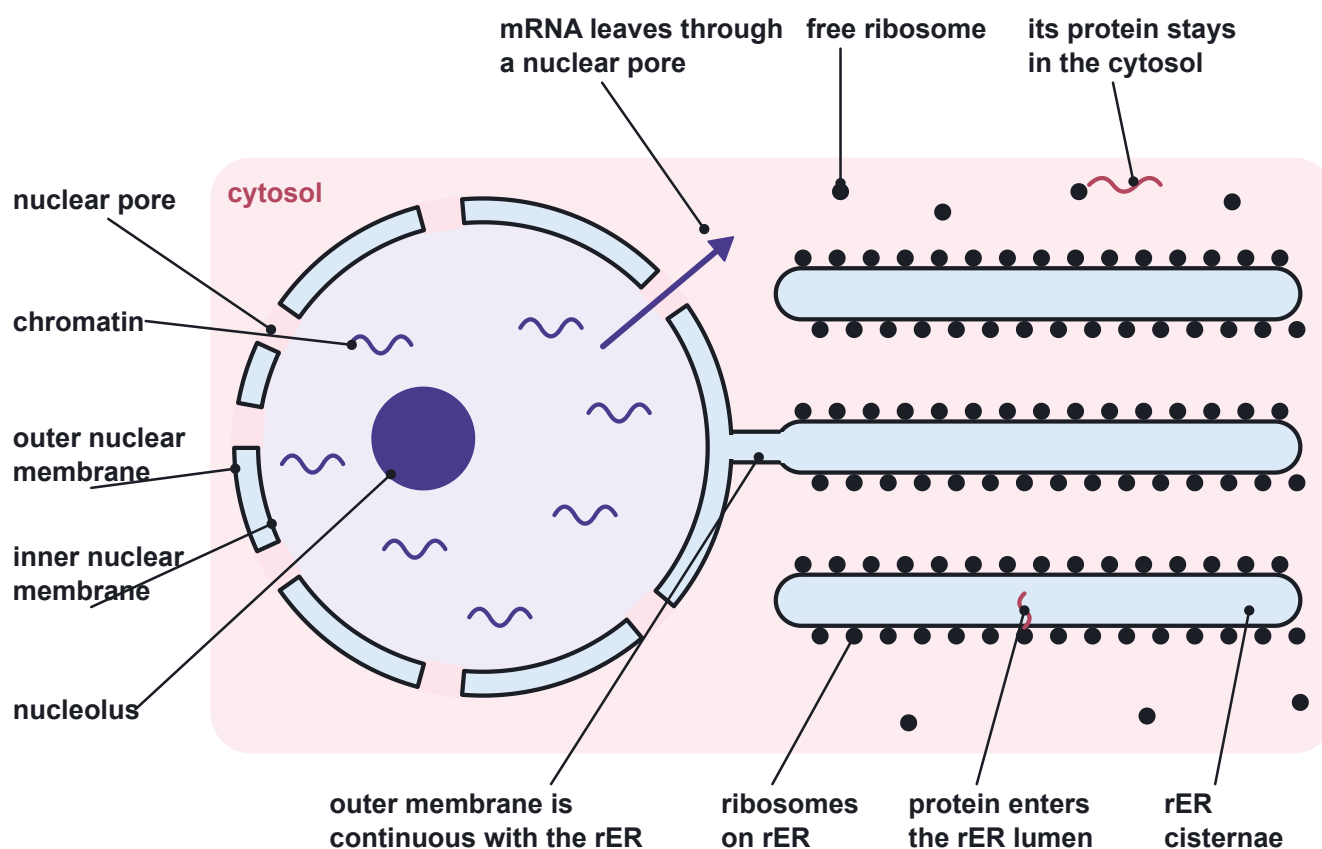
- Separation: DNA and transcription are kept apart from translation and other reactions in the cytoplasm.
- Nuclear pores: mRNA made by transcription must leave the nucleus, and proteins made in the cytoplasm (such as enzymes for DNA replication and histones) must enter. **Pores**, where the two membranes join, allow and control this traffic.
- Breakdown into vesicles: during mitosis and meiosis the nuclear membrane **breaks into vesicles** so that spindle microtubules can reach and move the chromosomes. Afterwards the vesicles fuse to form new nuclear envelopes around each set of chromosomes.

Free ribosomes and rough ER

Ribosomes are made of rRNA and protein and have no membrane. In eukaryotic cells they are found free in the cytosol or bound to the **rough endoplasmic reticulum** (rER), a network of flattened membrane sacs called cisternae.

Contrasting free ribosomes and ribosomes on the rER		
Feature	Free ribosomes	Ribosomes on the rER
Location	In the cytosol, not attached to membranes	Attached to the cytoplasmic surface of the rER
Proteins made	Proteins for retention in the cell , used in the cytoplasm or in organelles such as mitochondria and the nucleus	Proteins for transport within the cell (for example to lysosomes) or for secretion
Where the polypeptide goes	Released into the cytosol	Into the lumen of the rER, then in vesicles to the Golgi apparatus

Free and rER-bound ribosomes have the same structure, and translation always begins on a free ribosome in the cytosol. If the polypeptide being made begins with a signal sequence (a short stretch of mainly hydrophobic amino acids), the ribosome is guided to the rER and attaches to it. The growing polypeptide is fed through a pore in the rER membrane into the lumen, and the signal sequence is usually cut off. The details of this targeting are not required.



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The **outer nuclear membrane** is continuous with the rER; free ribosomes make proteins for the cytosol, rER ribosomes feed proteins into the **lumen**.

The Golgi apparatus and vesicles Spec B2.2.8, B2.2.9 HL only

The Golgi apparatus

The **Golgi apparatus** is a stack of flattened, curved membrane sacs (cisternae) that are not joined to each other. Vesicles from the rER fuse with the cis face, nearest the rER. Proteins are **processed** as they

pass through the cisternae, for example by adding or changing carbohydrate chains to make glycoproteins. At the trans face, processed proteins are packed into vesicles that bud off.

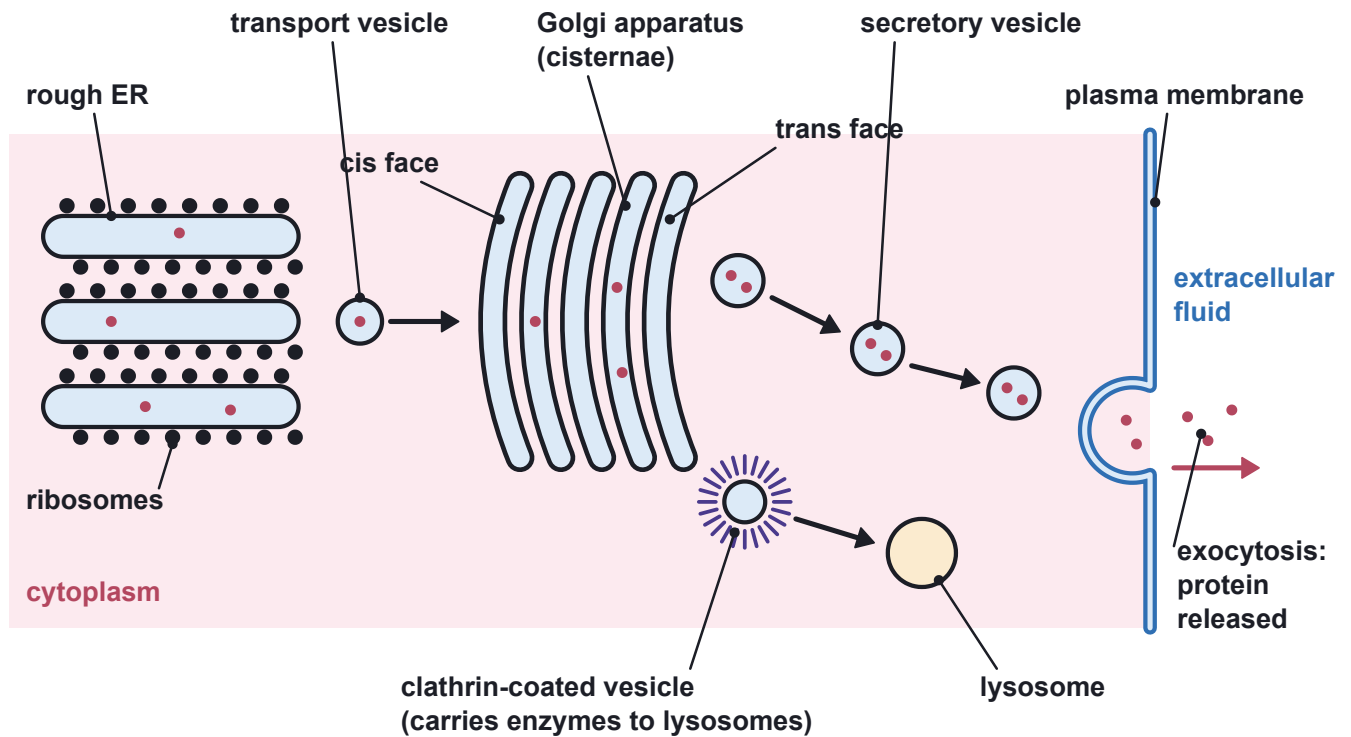
- 1 . A protein is made by ribosomes on the rER and enters the rER lumen.
- 2 . Vesicles bud off the rER and carry the protein to the cis face of the Golgi apparatus.
- 3 . The protein is processed as it moves through the Golgi cisternae.
- 4 . Secretory vesicles bud from the trans face and move to the plasma membrane.
- 5 . The vesicle membrane fuses with the plasma membrane and the protein is released by **exocytosis**.

Cells that secrete a lot of protein, such as pancreatic cells that make digestive enzymes and plasma cells that make antibodies, have extensive rER and a large Golgi apparatus.

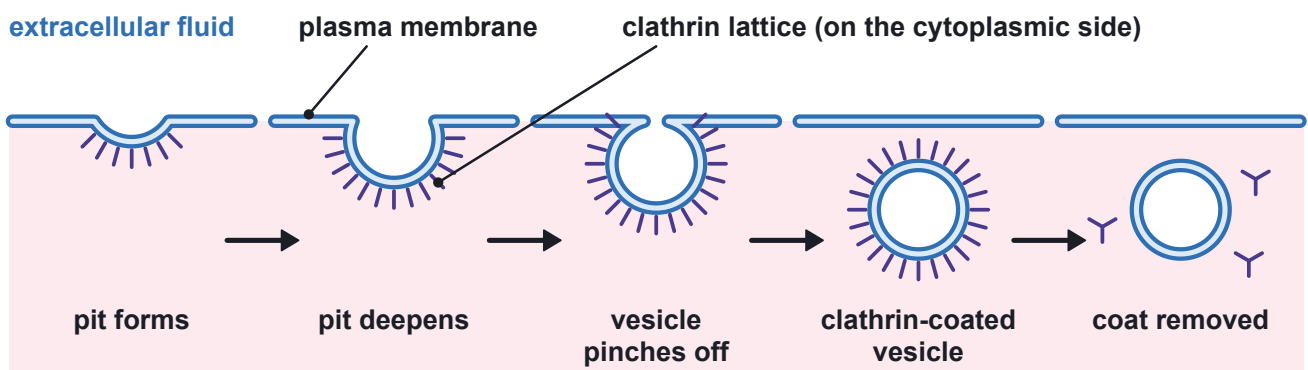
Vesicles and clathrin

Vesicles are small spheres of membrane enclosing fluid. They carry materials within the cell (for example from the rER to the Golgi apparatus), carry proteins for secretion, deliver hydrolytic enzymes as lysosomes and bring material in by endocytosis. Because membranes are fluid, vesicles can bud off one membrane and fuse with another.

Clathrin is a protein that helps vesicles form. Clathrin molecules assemble into a basket-shaped lattice on the cytoplasmic side of a membrane: at the plasma membrane during endocytosis, and at the trans face of the Golgi apparatus for vesicles carrying enzymes towards lysosomes. The lattice pulls the membrane into a curved pit that deepens and pinches off as a clathrin-coated vesicle. The coat is then removed so the vesicle can fuse with its target membrane. Vesicles travelling from the rER to the Golgi apparatus use different coat proteins, whose names are not required.



Clathrin-coated vesicle forming at the plasma membrane (endocytosis)



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rER → Golgi → secretory vesicle → exocytosis. **Clathrin** coats vesicles at the **plasma membrane** and the **trans face** of the Golgi apparatus.

Common mistake: The Golgi apparatus does not make proteins. Ribosomes on the rER make them; the Golgi apparatus processes them and packages them into vesicles.

Quick check

1. Name two structures that are not considered organelles.
2. In cell fractionation, which organelles form a pellet first, at the lowest speed?
3. Why must the hydrolytic enzymes of lysosomes be kept in a compartment?
4. **HL only** Which part of the mitochondrion contains the enzymes of the Krebs cycle?
5. **HL only** What is the role of clathrin?

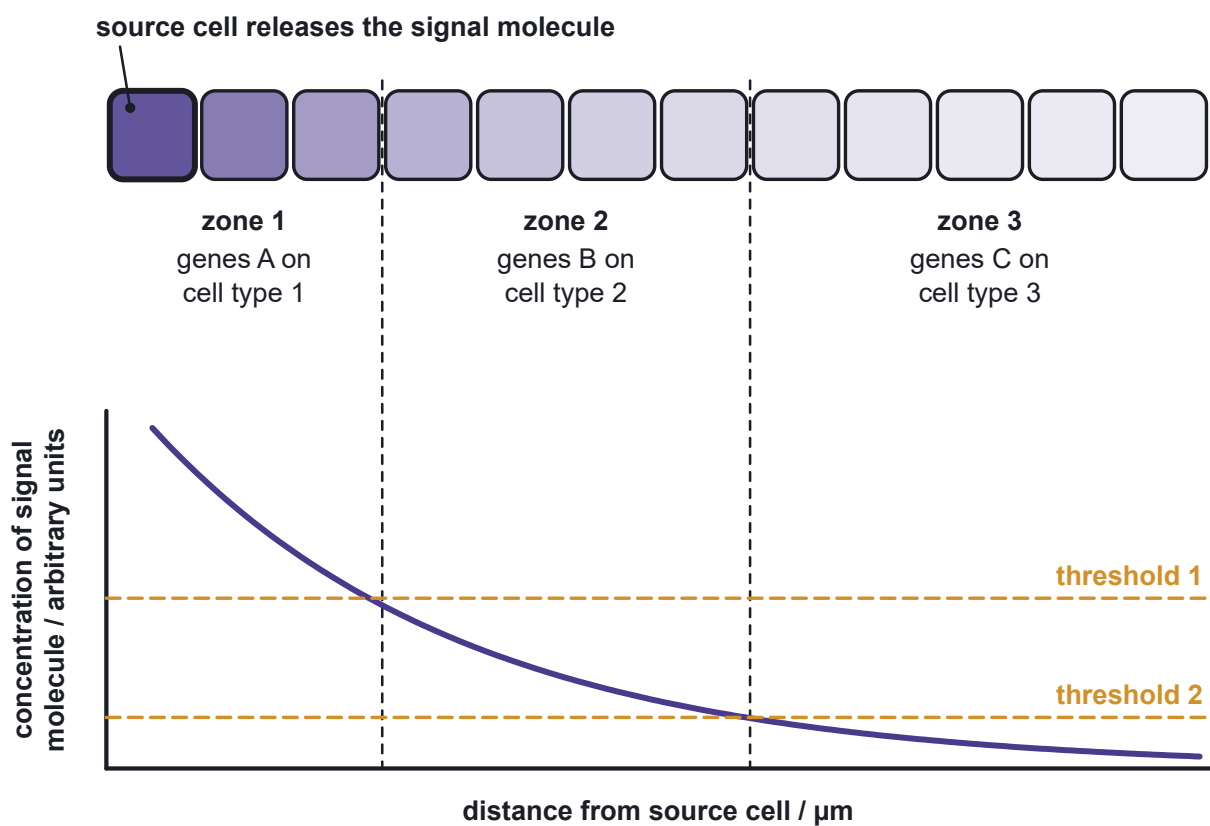
3 Cell specialization Spec B2.3

Differentiation and stem cells Spec B2.3.1-B2.3.4

From zygote to specialized cells

Fertilization produces a **zygote**, which divides by mitosis to form an embryo of unspecialized cells. These cells then develop into specialized cells by **differentiation**: each cell type expresses a different set of genes, so it makes different proteins and develops a different structure and function. All the cells still contain the same genes.

In an early-stage embryo, certain cells release signal molecules (morphogens). These diffuse away from their source, forming a **concentration gradient** across the embryo. The concentration a cell receives depends on its position, and this determines which genes it expresses. Cells in different positions therefore follow different developmental pathways, which is how body axes such as head-to-tail are set up.



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A **concentration gradient** of signal molecule tells each cell its position, so different genes are expressed in each zone (illustrative).

Properties of stem cells

Stem cells have two properties: they can **divide endlessly**, and they can **differentiate along different pathways** to become different cell types.

Stem cell niches in adult humans

A stem cell niche is a location in the body where stem cells are found. Conditions in the niche can either maintain the stem cells or promote their proliferation and differentiation, depending on the body's needs.

Two stem cell niches in adult humans

Niche	Stem cells	Function
Bone marrow	Blood-forming (haematopoietic) stem cells	Produce red blood cells, white blood cells and platelets throughout life
Hair follicles	Stem cells in a region of the follicle called the bulge	Regenerate the hair follicle in each growth cycle and help repair the skin after wounding

Totipotent, pluripotent and multipotent stem cells

Potency of stem cells

Type	Can form	Example
Totipotent	Any type of cell, including the placenta and other tissues outside the embryo; can form a whole organism	The zygote and cells of the very early embryo
Pluripotent	Any type of cell in the body, but not a whole organism	Embryonic stem cells, from the embryo a few days after fertilization
Multipotent	A limited range of related cell types	Adult stem cells, such as those in bone marrow, which form the different types of blood cell

Common mistake: Differentiated cells do not lose genes. Differentiation changes which genes are expressed, not which genes are present.

Cell size and surface area-to-volume ratio Spec B2.3.5, B2.3.6

Cell size as an aspect of specialization

Human cells vary greatly in size, and the size of each type suits its function.

Approximate sizes of some human cells

Cell	Approximate size	Link to function
Sperm (male gamete)	Head about 5 µm long; whole cell about 50–60 µm long	Small and streamlined, with little cytoplasm, so it can swim to the egg
Egg (female gamete)	About 110 µm (0.1 mm) in diameter, at the limit of what the naked eye can see	Large, with cytoplasm and nutrients for the early embryo
Red blood cell	About 7–8 µm in diameter	Small and flexible, so it can squeeze through narrow capillaries
White blood cells	About 7–20 µm in diameter, from small lymphocytes (similar to a red blood cell) to monocytes	Most are larger than red blood cells; phagocytes are large enough to engulf bacteria
Neuron	Cell body up to about 100 µm across; axons up to about 1 m long	Long axons carry impulses over long distances, such as from the spinal cord to the foot
Striated muscle fibre	Up to about 100 µm wide and many centimetres long	Long fibres contract along their whole length

Surface area-to-volume ratio

A cell exchanges materials such as oxygen, nutrients and waste across its surface, so the rate of exchange depends on its **surface area**. The need for exchange depends on how much cytoplasm is carrying out metabolism, which is the cell's **volume**.

As a cell gets larger, its volume increases faster than its surface area. For a cube of side length L , surface area = $6L^2$ but volume = L^3 , so the **surface area-to-volume ratio** ($6 \div L$) falls as L increases. A large cell may not be able to exchange materials fast enough to meet its needs, and the distance from the surface to the centre becomes long for diffusion. This constrains cell size.

surface area-to-volume ratio = surface area $\div$ volume

Calculating SA:V

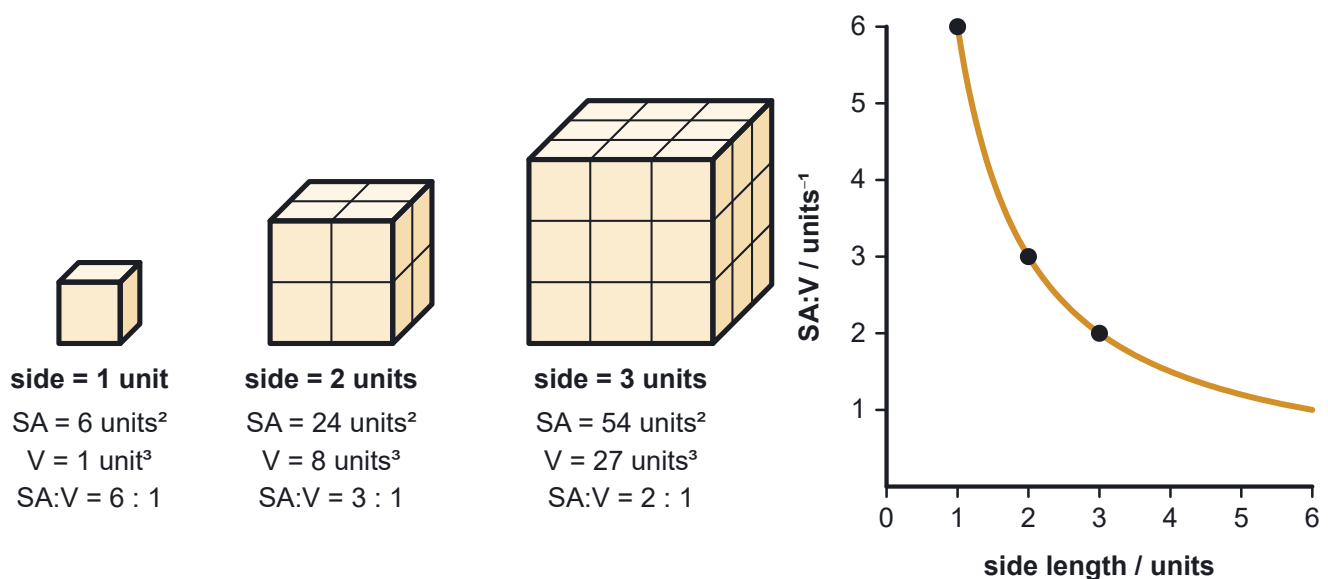
Model two cells as cubes with sides of $10\ \mu\text{m}$ and $20\ \mu\text{m}$. Calculate the surface area-to-volume ratio of each and state the effect of doubling the side length.

1. $10\ \mu\text{m}$ cube: surface area = $6 \times 10^2 = 600\ \mu\text{m}^2$; volume = $10^3 = 1000\ \mu\text{m}^3$
2. SA:V = $600 \div 1000 = 0.6\ \mu\text{m}^{-1}$ (0.6 : 1)
3. $20\ \mu\text{m}$ cube: surface area = $6 \times 20^2 = 2400\ \mu\text{m}^2$; volume = $20^3 = 8000\ \mu\text{m}^3$
4. SA:V = $2400 \div 8000 = 0.3\ \mu\text{m}^{-1}$ (0.3 : 1)

Answer: Doubling the side length multiplies surface area by 4 but volume by 8, so SA:V halves, from 0.6 to $0.3\ \mu\text{m}^{-1}$.

Maths skill: Give SA:V in μm^{-1} (or cm^{-1}) or as a ratio such as 0.6 : 1. Work out surface area (squared units) and volume (cubed units) separately before dividing.

Practical skill: Model SA:V with agar cubes of different side lengths containing an indicator, placed in acid. The percentage of each cube's volume that changes colour in a fixed time shows how exchange falls behind as cubes get larger. Models are simplified: cubes are simpler than real cells, but scale factors work in the same way.



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As side length increases, volume grows faster than surface area, so the **SA:V ratio falls**.

Exam tip: Linking question: what are the advantages of small size and large size in biological systems? Small cells exchange materials quickly; large organisms need extra adaptations such as lungs and a circulatory system.

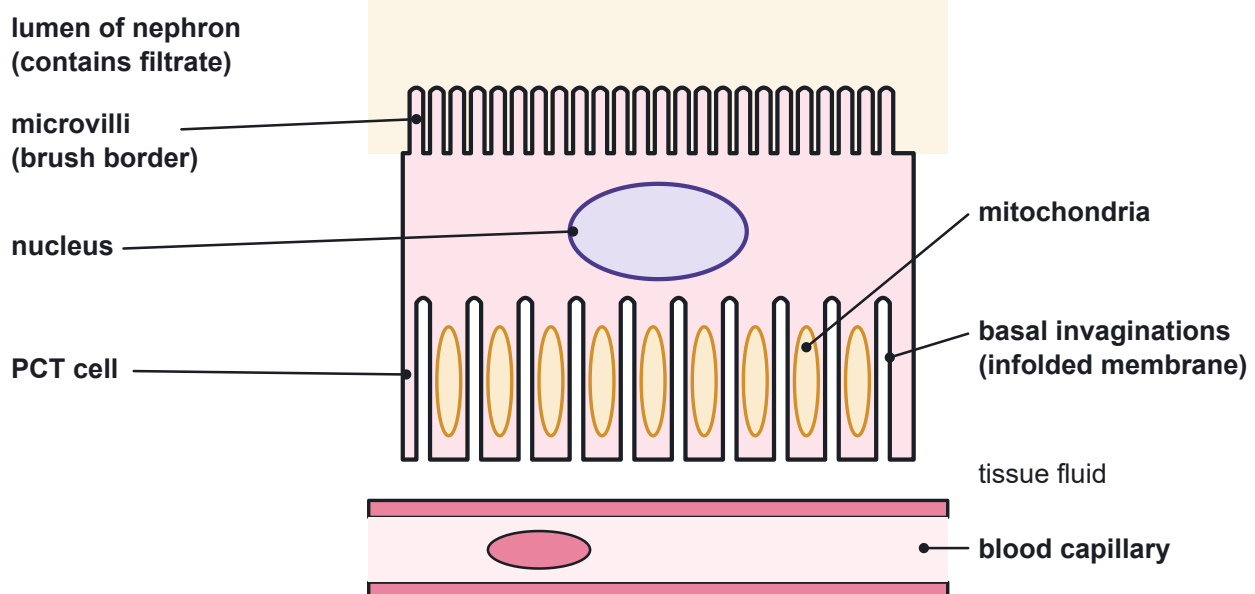
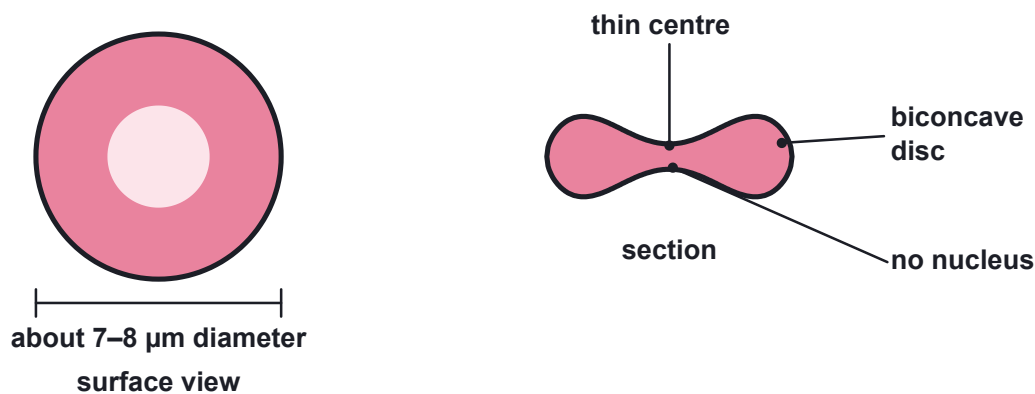
Surface area adaptations and pneumocytes

Spec B2.3.7, B2.3.8

HL only

Adaptations that increase SA:V

Increasing the surface area-to-volume ratio of cells		
Adaptation	Example	How it helps
Flattening	Erythrocytes (red blood cells) are biconcave discs	A larger surface area for the same volume, and no part of the cytoplasm is far from the surface, so oxygen loads and unloads quickly
Microvilli	Proximal convoluted tubule (PCT) cells in the nephron have a brush border of microvilli on the membrane facing the filtrate	Greatly increases the area for reabsorbing substances such as glucose, ions and water from the filtrate
Invagination	In PCT cells, the basal membrane facing the tissue fluid and blood capillaries is folded inwards	Increases the area for pumping reabsorbed substances out of the cell; many mitochondria nearby supply ATP



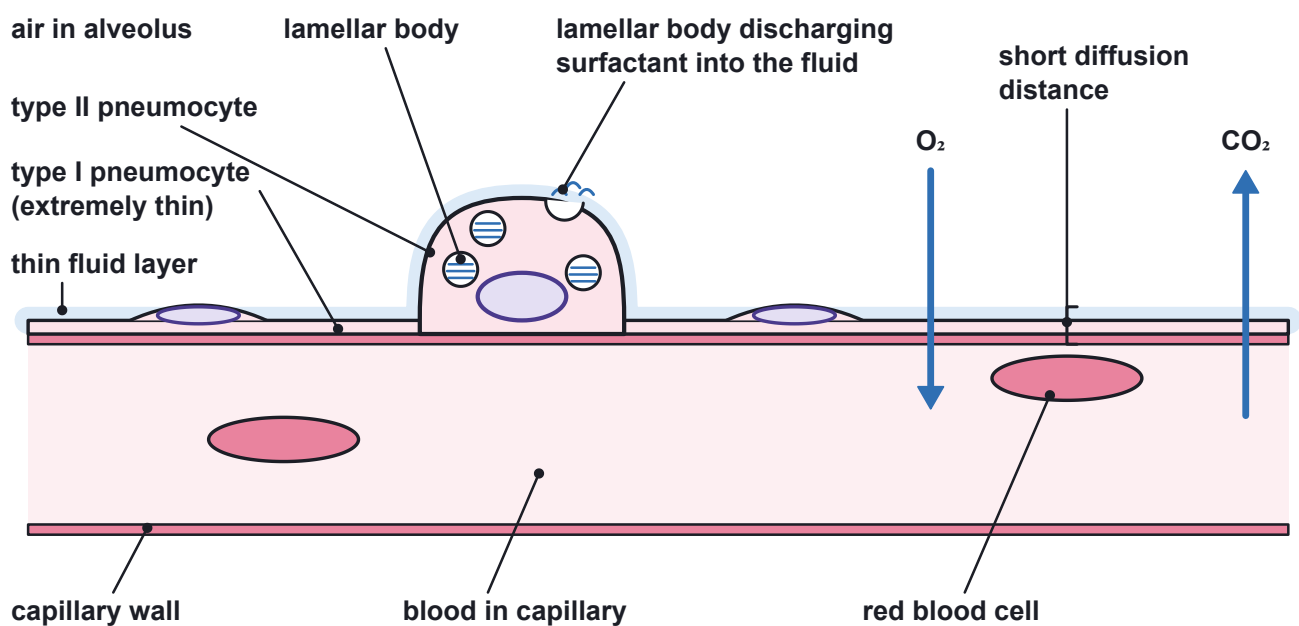
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Flattening (biconcave erythrocytes), microvilli and basal invaginations all increase the SA:V ratio.

Type I and type II pneumocytes

The alveolar epithelium is an example of a tissue with **more than one cell type**, because different adaptations are needed for the overall function of the tissue.

Pneumocytes in the alveolar wall		
Feature	Type I pneumocytes	Type II pneumocytes
Shape	Extremely thin, flattened cells covering about 95% of the alveolar surface	Rounded (cuboidal) cells; at least as numerous as type I cells but covering only about 5% of the surface
Key adaptation	Extreme thinness: the cytoplasm is much less than 1 μm thick	Many secretory vesicles, called lamellar bodies , in the cytoplasm
Function	A short distance for diffusion of O_2 and CO_2 between air in the alveolus and blood in the capillaries	Lamellar bodies discharge surfactant into the alveolar lumen; surfactant reduces surface tension in the moist lining, which helps stop the alveoli collapsing



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Thin **type I pneumocytes** give a short diffusion distance; **type II pneumocytes** secrete surfactant from lamellar bodies.

Exam tip: Name the vesicles: type II pneumocytes contain lamellar bodies that discharge surfactant. Gas exchange happens mainly across the type I cells.

Cardiac muscle cells and striated muscle fibres Spec B2.3.9 HL only

Both types contain **contractile myofibrils**, which give a striped (striated) appearance and shorten when the muscle contracts. They differ in branching, length and number of nuclei.

Comparing cardiac muscle cells and striated muscle fibres

Feature	Cardiac muscle cells	Striated (skeletal) muscle fibres
Contractile myofibrils	Present	Present
Branching	Branched	Unbranched
Length	Short (about 0.1 mm)	Very long (up to many centimetres)
Nuclei	Usually one, near the centre	Many, near the edge of the fibre
Connections	Joined end to end at intercalated discs	Lie side by side, each stimulated by a motor neuron

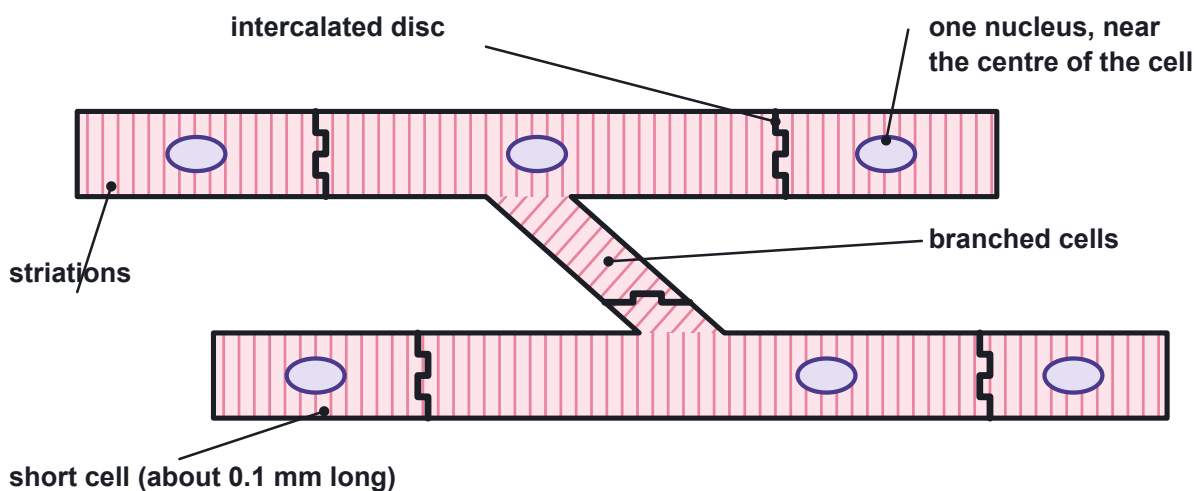
Hypotheses for the differences

- Branching: cardiac cells branch and join at intercalated discs, forming a network, so impulses spread quickly through the heart wall and the heart contracts as a coordinated unit.
- Length: a striated muscle fibre is long so that one stimulus makes the whole fibre contract along its length at the same time.
- Number of nuclei: one nucleus may not be able to supply enough mRNA for the proteins of a very large volume of cytoplasm, so a long fibre has many nuclei spread along it. A short cardiac cell needs only one.

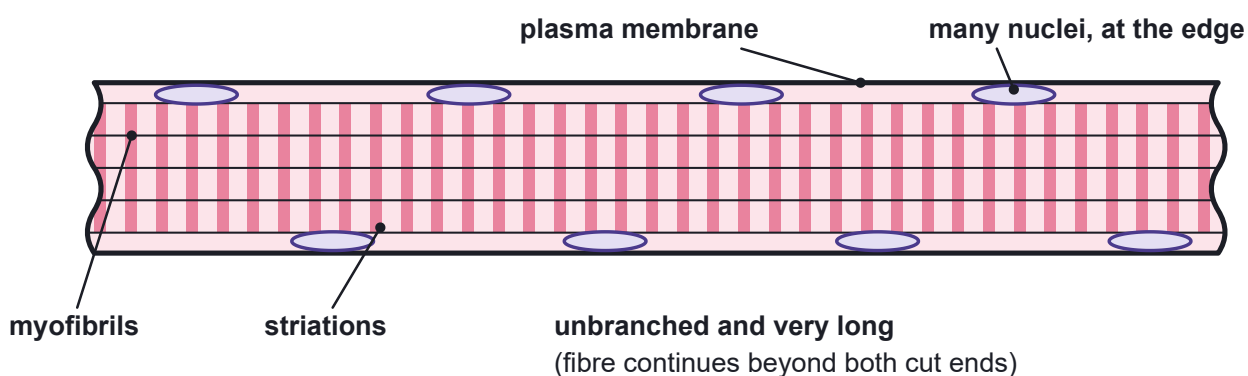
Is a striated muscle fibre a cell?

A striated muscle fibre is surrounded by one continuous plasma membrane, as a cell is. But it forms during development when many muscle precursor cells **fuse** together, and it contains many nuclei, so it does not fit the usual idea of a cell as a unit with one nucleus. It can be argued either way: it is often described as an **atypical cell**, an exception to the cell theory, or as a fused structure rather than a single cell.

Cardiac muscle



Striated (skeletal) muscle fibre



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Cardiac cells are short, **branched** and joined by **intercalated discs**; striated fibres are long, unbranched and **multinucleate**.

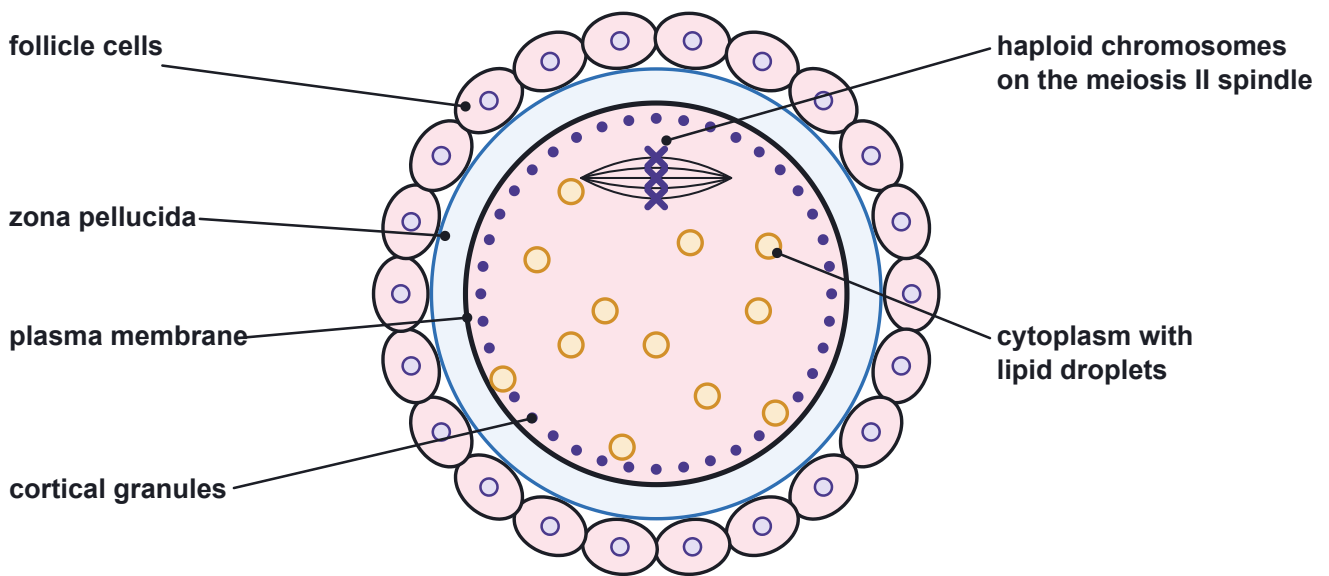
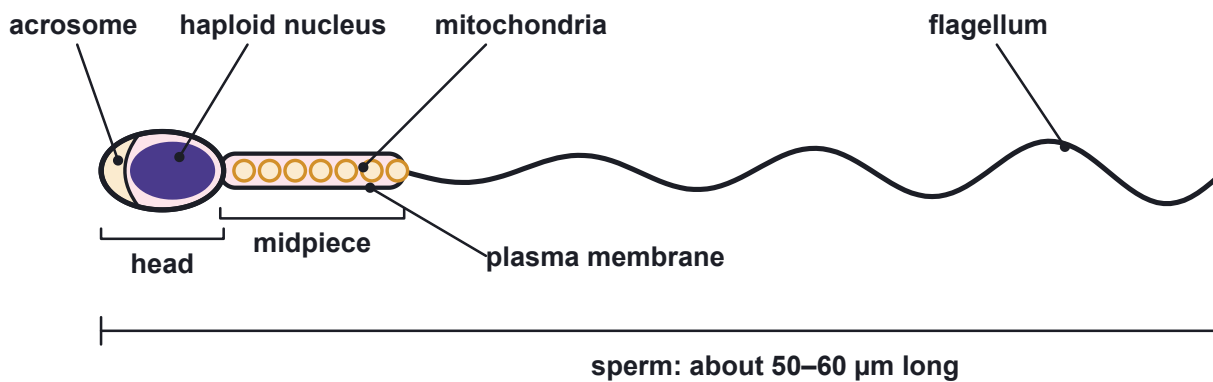
Exam tip: In a 'discuss' question on whether a muscle fibre is a cell, give evidence on both sides and finish with a reasoned conclusion.

Adaptations of sperm and egg cells Spec B2.3.10 HL only

Adaptations of the human sperm	
Structure	Adaptation
Haploid nucleus in the head	Carries one set of chromosomes; the DNA is tightly packed so the head is small
Acrosome	A large vesicle at the tip of the head containing enzymes that digest a path through the zona pellucida
Midpiece	Packed with mitochondria that produce ATP by aerobic respiration to power the flagellum
Flagellum (tail)	Beats to propel the sperm through fluid in the female reproductive tract
Little cytoplasm	A small, streamlined cell that swims efficiently; very large numbers are produced

Adaptations of the human egg

Structure	Adaptation
Large size (about 110 μm)	Plenty of cytoplasm, with nutrients such as lipid droplets and organelles, to support the early embryo
Haploid set of chromosomes	One set of chromosomes, combined with the sperm's set at fertilization (the ovulated egg is a secondary oocyte that completes meiosis II only after a sperm enters)
Zona pellucida	A layer of glycoprotein around the egg; sperm bind to it, and it protects the egg
Cortical granules	Vesicles under the plasma membrane; after one sperm enters, they release their contents by exocytosis, which hardens the zona pellucida and prevents polyspermy
Follicle cells	A layer of cells around the egg that supports it



egg: about 110 μm in diameter

The sperm and the egg are not drawn to the same scale.

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Sperm and egg are adapted for **movement** and **supporting the early embryo**; not drawn to the same scale.

Exam tip: Pair each structure with its function, for example 'many mitochondria in the midpiece, to provide ATP for movement of the flagellum'. A structure alone rarely earns the mark.

Quick check

1. State the two properties of stem cells.
2. Name two stem cell niches in adult humans.
3. What type of stem cell is found in adult bone marrow?
4. What happens to the SA:V of a cube when its side length doubles?
5. **HL only** What do type II pneumocytes secrete?

Quick check answers

Membranes and membrane transport

1. The two hydrocarbon (fatty acid) tails.
2. Aquaporin.
3. Energy from ATP.
4. The extracellular side.
5. Three Na^+ out and two K^+ in.

Organelles and compartmentalization

1. Any two of: the cell wall, the cytoskeleton, the cytoplasm.
2. Nuclei.
3. So they do not digest the cell's own molecules, and so they can be concentrated at their acid optimum pH.
4. The matrix.
5. It forms a coat that curves a membrane into a bud, forming a vesicle.

Cell specialization

1. They can divide endlessly and differentiate along different pathways.
2. Bone marrow and hair follicles.
3. Multipotent.
4. It halves.
5. Surfactant, from lamellar bodies.