Biology Units 1 & 2

Chapter 2 — Cell function and membrane transport

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Chapter 2 Cell function and membrane transport — 2A Diffusion, facilitated diffusion and active transport

Theory

A living cell is not sealed off from its surroundings. To stay alive it must constantly take in the substances it needs — such as oxygen, glucose and mineral ions — and remove the wastes it makes, such as carbon dioxide. All of this traffic has to cross the **plasma (cell) membrane**, which is **selectively permeable**: it lets some substances cross while holding others back. This subtopic is about **how substances other than water cross the membrane**. (Water has its own special route, **osmosis**, which is dealt with in 2B — this subtopic does not repeat it.)

Why the membrane lets some things cross easily and others not. The plasma membrane is built from a **phospholipid bilayer** (its full structure is covered in 1B). The important point here is that the **middle of the bilayer is a hydrophobic ("water-hating") core**, made of the fatty phospholipid tails. Whether, and how, a substance can cross depends mainly on two of its properties, together with the concentration gradient:

- **Size** — small particles cross more easily than large ones.
- **Polarity / charge (hydrophilic vs hydrophobic) — hydrophobic** ("water-hating") substances are non-polar and lipid-soluble, so they mix with the fatty core and slip straight through. **Hydrophilic** ("water-loving") substances are polar or charged (for example ions, and sugars such as glucose); they are repelled by the hydrophobic core and **cannot cross the bilayer directly** — they need a protein to help them.

So small, non-polar substances dissolve straight through the membrane, while charged or larger water-soluble substances must use one of the **transport proteins** embedded in the membrane.

The big division: passive versus active. Every way of crossing the membrane is either passive or active, depending on the direction of movement and whether the cell must spend energy:

- **Passive transport** moves a substance **down its concentration gradient** (from a **high** to a **low** concentration). It is driven by the **random motion of the particles themselves**, so the cell supplies **no energy — no ATP**. Simple diffusion, facilitated diffusion and osmosis are all passive.
- **Active transport** moves a substance **against its concentration gradient** (from a **low** to a **high** concentration). This cannot happen on its own, so the cell must **supply energy in the form of ATP**.

Simple diffusion. Diffusion is the **net movement of particles from a region of higher concentration to a region of lower concentration**, because their random motion gradually spreads them out until they are evenly distributed. Once evenly spread the particles keep moving, but there is **no further net movement** — this balanced state is called **dynamic equilibrium**. When this happens across a membrane it is called **simple diffusion**: **small, non-polar (hydrophobic, lipid-soluble)** molecules — such as **oxygen (O_2) and carbon dioxide (CO_2) — dissolve directly through the phospholipid bilayer**, moving down their gradient, with **no transport protein and no ATP**. Gas exchange is the classic example: a respiring cell uses up oxygen, so oxygen is lower inside than outside and diffuses **in**, while carbon dioxide builds up inside and diffuses **out**. The **rate** of simple diffusion is increased by a **steeper concentration gradient**, a **higher temperature** (particles have more kinetic energy and move faster), a **larger surface area**, and a **shorter distance** to cross. As a substance builds up on the far side, the gradient shrinks, the net rate falls, and at equilibrium it reaches zero.

Facilitated diffusion. Many substances a cell needs — such as **ions** and **glucose** — are **hydrophilic** and so cannot cross the bilayer directly, yet they still need to move **down their gradient**. They cross with the **help of transport proteins**; because the protein makes ("facilitates") the crossing possible, this is called **facilitated diffusion**. There are two kinds of transport protein:

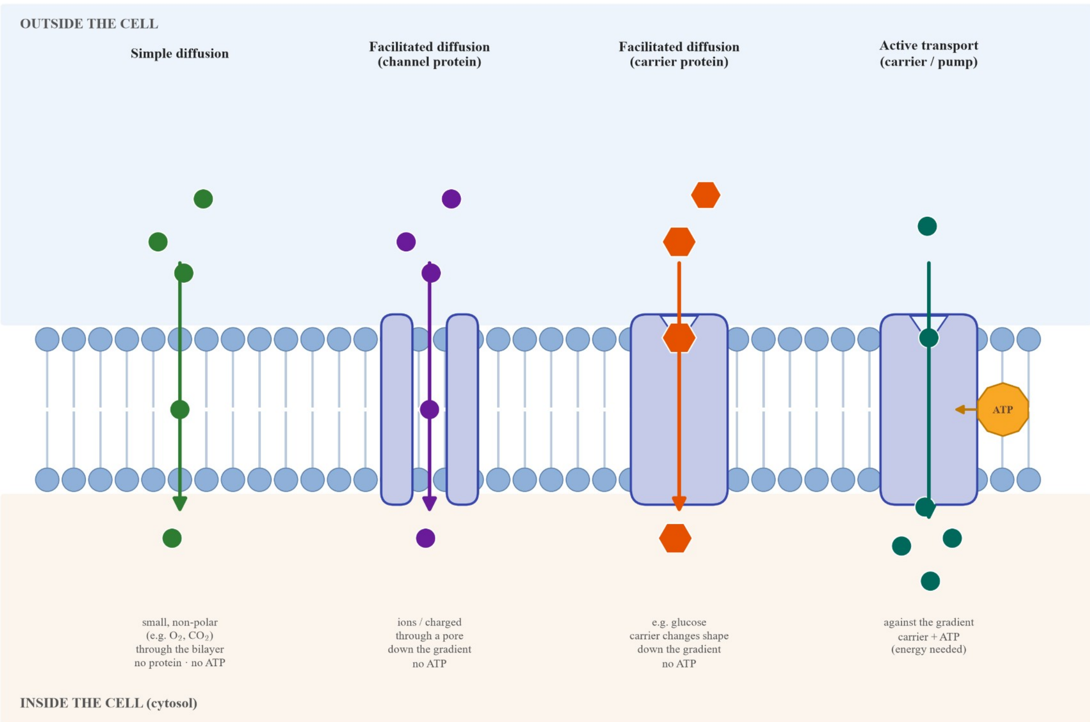
- a **channel protein** forms a **water-filled pore** through the membrane, through which specific ions or small molecules pass;
- a **carrier protein binds** the specific substance, then **changes shape** to move it to the other side and releases it.

Facilitated diffusion is still **passive** — the substance moves **down its gradient** and the cell uses **no ATP**; the protein simply provides a route through the hydrophobic core. Transport proteins are **specific** — each carries only a particular substance (or a few). Because there are only a **limited number** of them, the rate of facilitated diffusion rises as concentration increases but then **levels off (plateaus)** once every protein is working as fast as it can — a maximum rate called **saturation**. Simple diffusion has no proteins to saturate, so its rate keeps rising with the gradient.

Active transport. Sometimes a cell must move a substance **against its concentration gradient** — from where it is **scarce** to where it is **already more concentrated**. For example, a **root-hair cell absorbs mineral ions** (such as nitrate) from very dilute soil water even though the ions are already more concentrated inside the cell; and many cells keep their internal ion concentrations very different from their surroundings. Moving a substance "uphill" like this cannot happen passively, so the cell uses **active transport**: a **carrier (pump) protein** binds the substance and **energy from ATP** powers the shape change that moves it against the gradient. Active transport is **specific**, and like facilitated diffusion it can **saturate** (there are only so many pumps). Crucially, because it depends on ATP, **active transport stops if the cell can no longer respire to make ATP** — whereas passive processes, needing no ATP, carry on. This dependence on energy is the key test that tells active transport apart from diffusion.

The three ways of moving substances other than water across the membrane can be summarised as follows:

Feature	Simple diffusion	Facilitated diffusion	Active transport
What moves	small, non-polar / lipid-soluble (e.g. O_2, CO_2)	polar or charged, and larger (e.g. ions, glucose)	polar or charged (e.g. ions, glucose)
Route across the membrane	directly between the phospholipids	through a **channel** or **carrier** protein	through a **carrier (pump)** protein
Direction vs the gradient	high → low (**down** the gradient)	high → low (**down** the gradient)	low → high (**against** the gradient)
Transport protein needed?	No	Yes	Yes
Energy (ATP) needed?	**No** — passive	**No** — passive	**Yes** — active



Water is the exception. Water itself also crosses the membrane passively — by **osmosis**, the special case of diffusion that applies to water — but that has its own subtopic and is **not** covered here (see **2B Osmosis**).

Worked examples

Example 1 — scaffolded

Oxygen is at a higher concentration in the fluid around a muscle cell than inside it, where oxygen is being used up during respiration. State how oxygen crosses the plasma membrane into the cell, name the type of transport, and state whether the cell must use ATP.

Working	Comment
Oxygen (O_2) is a **small, non-polar** molecule, so it can **dissolve directly through the phospholipid bilayer**.	Start from the substance's properties — size and polarity set the route.
Oxygen is **more concentrated outside** the cell than inside, so it moves **down its concentration gradient, into the cell**.	Give the direction and tie it to the gradient (high → low).
This is **simple diffusion**, and because the movement is down the gradient it is **passive**, so **no ATP** is used.	Name the process and classify it as passive.
Oxygen therefore enters the cell by **simple diffusion**, straight through the bilayer, using **no ATP**.	State the answer clearly.

Example 2 — scaffolded

A root-hair cell absorbs nitrate ions from the surrounding soil water, even though the nitrate concentration is already higher inside the cell than in the soil. Name the transport process, and explain why it requires energy.

Working	Comment
The nitrate ions are moving **from the soil (low concentration) into the cell (high concentration) —** that is, **against their concentration gradient**.	Establish the direction relative to the gradient first.
Moving a substance against its gradient **cannot happen passively**, so the cell must **supply energy (ATP)** and use a **carrier (pump) protein**.	Against the gradient ⇒ energy is required.
The process is **active transport**.	Name the process.
It requires energy because ATP is needed to power the carrier protein that pushes the ions **against their gradient**, from low to high concentration.	Answer the "why energy" part explicitly, linking ATP to the uphill movement.

Example 3 — unscaffolded

Glucose enters a cell by crossing the membrane through a carrier protein, moving from a higher glucose concentration outside to a lower concentration inside. Classify this process, and explain why glucose needs a transport protein to cross the membrane while oxygen does not.

Glucose is moving **down its concentration gradient** (from high outside to low inside) and crosses with the help of a **carrier protein**, so the process is **facilitated diffusion**; because the movement is down the gradient and uses no ATP, it is **passive**. Glucose needs a transport protein because it is a relatively **large, polar (hydrophilic) molecule**, so it is repelled by the **hydrophobic core** of the bilayer and cannot dissolve straight through. Oxygen, in contrast, is a **small, non-polar** molecule that **mixes with the fatty core and slips directly between the phospholipids**, so it needs no protein. ∴ glucose crosses by facilitated diffusion through a carrier protein because its size and polarity block the direct route that the small, non-polar oxygen can take.

Example 4 — unscaffolded

A fat-soluble (non-polar) steroid hormone and a sodium ion are both present outside a cell and both cross its plasma membrane. Explain why the two substances cross by different routes, referring to the structure of the membrane.

The plasma membrane has a **hydrophobic core** formed by the fatty phospholipid tails. The steroid hormone is **fat-soluble and non-polar (hydrophobic)**, so it **mixes with this core and dissolves straight through the bilayer** by **simple diffusion**, needing no protein. The sodium ion is **charged (hydrophilic)**, so it is **repelled by the hydrophobic**

core and **cannot cross the bilayer directly**; instead it must pass **through a transport protein** (a channel or carrier). So the same membrane presents an easy route to the non-polar hormone but an impassable core to the charged ion, which is why they take different routes. ∴ the hydrophobic core of the membrane lets non-polar substances diffuse straight through but forces charged or polar substances to use transport proteins.

Practice questions

Scaffolded

Q1. Define each of the following terms: (a) diffusion; (b) facilitated diffusion; (c) active transport.

Q2. Simple diffusion is one way substances cross the plasma membrane. (a) State whether simple diffusion requires the cell to use ATP. (b) State the direction of net movement of a substance in simple diffusion, relative to its concentration gradient. (c) Explain why simple diffusion is described as passive.

Q3. Facilitated diffusion uses proteins in the membrane. (a) Name the two types of transport protein that can carry out facilitated diffusion. (b) State why a charged ion cannot pass directly through the phospholipid bilayer. (c) Explain why facilitated diffusion is still classed as passive, even though it uses a protein.

Q4. Whether a substance can cross the bilayer directly depends on its properties. (a) State two properties of a substance that determine whether it can cross the bilayer directly, without a protein. (b) State which kind of substance, in terms of those properties, can cross the bilayer directly. (c) Explain why a large, polar molecule needs a transport protein to cross the membrane.

Q5. Active transport moves substances across the membrane. (a) State the direction a substance moves in active transport, relative to its concentration gradient. (b) Name the energy source a cell uses to drive active transport. (c) Explain why active transport, unlike diffusion, stops if the cell can no longer supply ATP.

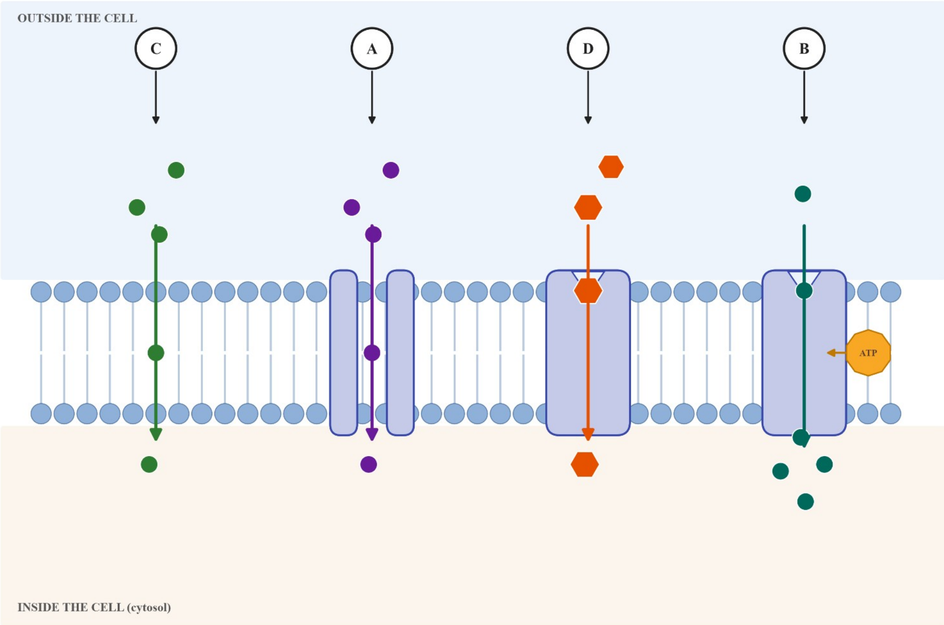
Q6. The rate of simple diffusion can vary. (a) State two factors that affect the rate of simple diffusion of a substance across a membrane. (b) Explain how a steeper concentration gradient affects the rate of simple diffusion. (c) Explain why the simple diffusion of a substance into a cell slows and eventually stops as the inside concentration rises to equal the outside concentration.

Unscaffolded

Q7. Distinguish between simple diffusion and facilitated diffusion, with reference to the kind of substance moved and how it crosses the membrane. *(3 marks)*

Q8. Distinguish between facilitated diffusion and active transport, with reference to the direction of movement and the use of energy. *(3 marks)*

Q9. *(Stimulus.)* The diagram shows four ways in which substances cross a plasma membrane, labelled A, B, C and D. The inside of the cell is at the bottom.



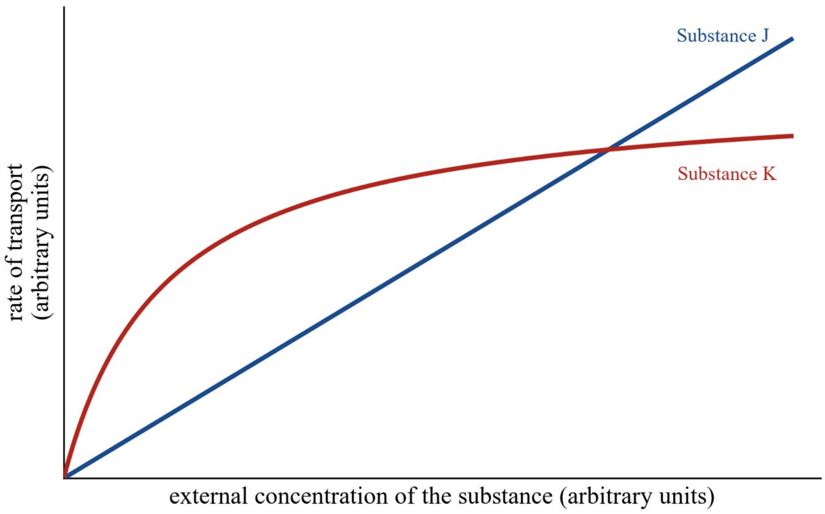
(a) Name the transport process shown at each of A, B, C and D.

(b) State one feature visible in the diagram that shows the process at B is active transport and not facilitated diffusion. *(5 marks)*

Q10. After a meal, glucose is more concentrated in the gut than inside the cells lining the gut wall, and the cells absorb it. Later, when the gut has less glucose than the cells, the cells continue to absorb glucose from the gut. (a) Name the process the cells use to absorb glucose when the gut concentration is higher than inside the cell, and state the direction of movement relative to the gradient. (b) Name and explain the process the cells must use to absorb glucose once the gut concentration is lower than inside the cell. *(4 marks)*

Q11. A muscle cell takes up calcium ions through channel proteins; the ions move from a higher concentration in the fluid outside the cell to a much lower concentration inside. (a) Name the transport process. (b) Explain why the calcium ions cross through channel proteins rather than directly through the phospholipid bilayer. (c) State, with a reason, whether this process requires ATP. *(3 marks)*

Q12. *(Data interpretation.)* The graph shows how the rate of transport of two substances, J and K, across a plasma membrane changes as the external concentration of each substance increases.



(a) Identify which substance crosses the membrane by facilitated diffusion and which by simple diffusion, justifying each choice from the graph.

(b) Explain why the rate for the substance that levels off does not keep rising at high concentration.

(c) Predict what would happen to that maximum rate if the cell made more of the transport proteins involved. *(4 marks)*

Q13. *(Investigation design.)* A student investigates how temperature affects the rate at which a coloured dye diffuses. She places one drop of dye into the centre of several identical dishes of clear gel held at different temperatures, and measures how far the colour spreads in ten minutes. (a) Identify the independent variable and the dependent variable in this investigation. (b) State one variable that must be kept constant, and explain why it must be controlled. *(4 marks)*

Q14. Carrier proteins are described as being specific. (a) Explain what is meant by saying a carrier protein is specific. (b) Suggest why a cell needs many different carrier proteins in its plasma membrane. (c) A substance blocks one type of carrier protein. Predict the effect on the transport of the substance that carrier protein normally moves. *(3 marks)*

Q15. *(Model evaluation.)* A static diagram of particles and arrows, like the one in this subtopic, is often used as a model of how substances cross the membrane. State one strength of this model, two of its limitations, and give an overall judgement of how useful it is. *(4 marks)*

Q16. Both channel proteins and carrier proteins are involved in facilitated diffusion. Describe one similarity and two differences between them. *(3 marks)*

Q17. *(Data interpretation.)* Cells were supplied with an ion, Z, and the rate at which they took it up was measured under three conditions. The results are shown below.

Condition	Rate of uptake of ion Z (arbitrary units)
Normal (cell respiring)	48
A respiratory poison stops the cell making ATP	3
Oxygen removed (so little respiration)	5

(a) State the trend in the rate of uptake when the cell can no longer make ATP.
(b) Explain what this evidence suggests about how ion Z is transported into the cell.
(c) Name the transport process used for ion Z, justifying your answer from the data. *(4 marks)*

Q18. A newly studied molecule is found to be large and highly polar, yet it enters a cell by moving from a region where it is dilute to a region where it is more concentrated. Deduce which transport process the molecule must be using, and state two features that process must have. *(3 marks)*

Q19. *(Synthesis.)* A cell lining the small intestine carries out several kinds of membrane transport at once. (a) Carbon dioxide made by respiration in the cell leaves across the plasma membrane. Name the process, and explain, in terms of concentration and the properties of carbon dioxide, why it crosses this way. (b) The gut-facing surface of this cell is folded into thousands of tiny projections called microvilli. Explain how this folding affects the rate at which substances are absorbed across that surface. (c) These cells contain far more mitochondria than most other cells of the body. Suggest, with reference to the transport this cell carries out, why so many mitochondria are needed. (d) A sample of these cells is held at 15 °C instead of 37 °C. Explain the effect this has on the rate at which carbon dioxide leaves the cells. *(8 marks)*

Answers

Q1. (a) The net movement of particles from a higher to a lower concentration, due to their random motion, until evenly spread. (b) The passive movement of a substance down its gradient through a channel or carrier protein, using no ATP. (c) The movement of a substance against its gradient, using a carrier protein and energy (ATP). **Q2.** (a) No. (b) Down its gradient — from a higher to a lower concentration. (c) It is driven by the random motion of the particles moving down their gradient, so the cell uses no ATP. **Q3.** (a) Channel proteins and carrier proteins. (b) It is charged (hydrophilic), so it is repelled by the hydrophobic core of the bilayer. (c) The substance still moves down its gradient and no ATP is used; the protein only provides a route. **Q4.** (a) Its size and its polarity/charge (whether it is hydrophobic/non-polar or hydrophilic). (b) Small, non-polar (hydrophobic, lipid-soluble) substances. (c) It is too large and/or too polar to dissolve through the hydrophobic core, so it must pass through a transport protein. **Q5.** (a) Against its gradient — from a lower to a higher concentration. (b) ATP. (c) Active transport needs energy to move a substance against its gradient; with no ATP there is no energy to do this, so it stops, whereas passive diffusion needs none and continues. **Q6.** (a) Any two of: steepness of the concentration gradient; temperature; surface area; distance across the membrane. (b) A steeper gradient increases the rate. (c) As the substance builds up inside, the gradient shrinks so the net rate falls; when inside equals outside there is no gradient and no net movement (dynamic equilibrium). **Q7.** In simple diffusion a small, non-polar substance passes directly through the bilayer; in facilitated diffusion a polar/charged substance passes through a transport protein — both are passive (down the gradient, no ATP). **Q8.** Facilitated diffusion moves a substance down its gradient with no ATP; active transport moves a substance against its gradient using ATP (both move the substance through a transport protein — facilitated diffusion through a channel or a carrier, active transport through a carrier/pump). **Q9.** (a) A = facilitated diffusion (channel protein); B = active transport; C = simple diffusion; D = facilitated diffusion (carrier protein). (b) The diagram shows B using ATP / moving the substance toward the side where it is already more concentrated (against the gradient), which D does not. **Q10.** (a) Facilitated diffusion; the glucose moves down its gradient (high gut → low cell). (b) Active transport, because the glucose now moves against its gradient (low gut → high cell), which needs ATP. **Q11.** (a) Facilitated diffusion. (b) The calcium ions are charged (hydrophilic) and are repelled by the hydrophobic core, so they need the pore of a channel protein. (c) No — the ions move down their gradient, so it is passive. **Q12.** (a) J (straight line) = simple diffusion; K (levels off) = facilitated diffusion. (b) At high concentration all the transport proteins are occupied/working at maximum (saturated), so the rate cannot rise further. (c) The maximum rate (plateau) would be higher. **Q13.** (a) IV = temperature; DV = distance the colour spreads in the fixed time (rate of diffusion). (b) E.g. volume/concentration of dye, type/amount of gel, dish size or time — kept constant so it does not also affect how far the colour spreads. **Q14.** (a) It carries only one type (or a few types) of substance that fits its binding site. (b) Because the cell must transport many different substances, each needing its own matching carrier. (c) The substance that carrier normally moves would no longer be transported (its transport stops/slows). **Q15.** Strength: it clearly shows the different routes and directions. Limitations: it is static (does not show continuous random motion); it does not show the membrane is fluid / proteins move; it is not to scale. Judgement: useful for showing routes but not a literal picture of the membrane. **Q16.** Similarity: both are specific membrane proteins used in passive facilitated diffusion. Differences: a channel forms an open pore that ions pass straight through, whereas a carrier binds the substance and changes shape; channels typically move ions, carriers move larger molecules such as glucose. **Q17.** (a) The uptake rate falls to almost zero. (b) Uptake of ion Z depends on ATP, so the ion must be moved by a process that needs energy. (c) Active transport, because stopping ATP production (or respiration) almost stops uptake. **Q18.** Active transport; it must use a carrier (transport) protein (the molecule is large and polar), and it must use ATP (it moves against its gradient). **Q19.** (a) Simple diffusion — CO_2 is small and non-polar, so it dissolves straight through the bilayer, moving down its gradient (high inside → low outside). (b) The folding greatly increases the surface area of membrane facing the gut contents, so more particles can cross per unit time and the rate of absorption is higher. (c) Mitochondria supply ATP by cellular respiration; this cell absorbs nutrients by active transport, against their gradients, which uses ATP continuously. (d) At the lower temperature the particles have less kinetic energy and move more slowly, so fewer cross per unit time and the rate of diffusion falls.

Fully-worked solutions

Q1. (a) **Diffusion** is the **net movement of particles from a region of higher concentration to a region of lower concentration**, caused by the **random motion of the particles**, continuing until they are evenly spread. (b) **Facilitated diffusion** is the **passive movement of a substance down its concentration gradient across a membrane, through a channel or carrier protein**, using **no ATP**. (c) **Active transport** is the movement of a substance **across a membrane against its concentration gradient**, using a **carrier (pump) protein** and **energy from ATP**.

Q2. (a) **No** — simple diffusion does not require the cell to use any ATP. (b) The substance moves **down its concentration gradient — from where it is more concentrated to where it is less concentrated**. (c) Simple diffusion is **passive** because it is driven by the **random motion of the particles themselves** as they move **down their own gradient**; the cell supplies **no energy**, so no ATP is used.

Q3. (a) **Channel proteins** and **carrier proteins**. (b) A charged ion is **hydrophilic** and so is **repelled by the hydrophobic (fatty) core** of the bilayer, meaning it **cannot dissolve through it**. (c) Facilitated diffusion is still **passive** because the substance moves **down its concentration gradient** and the cell uses **no ATP** — the transport protein only provides a **route** through the membrane, it does not push the substance.

Q4. (a) Any two of: the substance's **size**, and its **polarity/charge** (whether it is non-polar/ hydrophobic or polar/charged/hydrophilic); its **lipid solubility** is also acceptable. (b) **Small, non-polar (hydrophobic, lipid-soluble)** substances can cross the bilayer directly. (c) A large, polar molecule is **too big and/or too polar to dissolve through the hydrophobic core** of the bilayer, so it is **repelled by the core** and can only cross by passing **through a transport protein** that provides a suitable route.

Q5. (a) The substance moves **against its concentration gradient — from a lower to a higher concentration**. (b) **ATP**. (c) Active transport moves a substance **against its gradient**, which needs an input of **energy**; the cell gets this energy from **ATP**, so if it can no longer supply ATP there is **no energy to drive the movement** and active transport **stops**. Diffusion is **passive** (driven by the particles' own motion), needs **no ATP**, and so **continues**.

Q6. (a) Any two of: the **steepness of the concentration gradient**; the **temperature**; the **surface area** available; the **distance/thickness** to be crossed. (b) A **steeper (larger) concentration gradient increases the rate** of simple diffusion, because there is a bigger difference in concentration driving the net movement. (c) As the substance diffuses in, its **concentration inside rises**, so the **difference between inside and outside (the gradient) becomes smaller** and the **net rate falls**. When the **inside concentration equals the outside**, there is **no gradient**, so although particles still move both ways there is **no net movement** — the system is at **dynamic equilibrium**.

Q7. In **simple diffusion**, a **small, non-polar (lipid-soluble)** substance moves **directly through the phospholipid bilayer**, down its concentration gradient. In **facilitated diffusion**, a **polar or charged (hydrophilic)** substance — which cannot cross the bilayer directly — moves **through a channel or carrier protein**, again down its gradient. Both are **passive**: the substance moves **down its gradient** and **no ATP** is used; they differ in **what is moved** and **how it crosses** (bilayer vs protein). *(1 mark: simple diffusion = through the bilayer, small/non-polar; 1 mark: facilitated diffusion = through a transport protein, polar/charged; 1 mark: both passive/down the gradient/no ATP.)*

Q8. In **facilitated diffusion**, a substance moves **down its concentration gradient** (high → low) and the cell uses **no ATP** — it is passive. In **active transport**, a substance is moved **against its concentration gradient** (low → high), which requires the cell to use **energy from ATP** — it is active. Both move the substance **through a transport protein** — facilitated diffusion through **either a channel or a carrier**, active transport through a **carrier (pump)** — but only active transport needs energy. *(1 mark: facilitated diffusion = down the gradient, no ATP; 1 mark: active transport = against the gradient, uses ATP; 1 mark: a clear two-sided contrast of direction and energy.)*

Q9. (a) **A = facilitated diffusion through a channel protein** (the substance passes through a pore); **B = active transport** (a carrier protein with an ATP requirement); **C = simple diffusion** (the substance passes directly between the phospholipids, with no protein); **D = facilitated diffusion through a carrier protein** (the substance passes through a carrier). (b) The diagram shows that **B uses ATP** (the ATP marker at the carrier) and moves the substance **toward the side where it is already more concentrated — against the gradient** — whereas **D** shows no ATP and movement **down** the gradient. *(a: 1 mark each for A, B, C and D correctly named = 4 marks; b: 1 mark for one valid distinguishing feature read from the diagram.)*

Q10. (a) When the gut glucose is **higher** than inside the cell, the cell absorbs glucose by **facilitated diffusion**; the glucose moves **down its concentration gradient**, from the higher concentration in the gut to the lower concentration in the cell. (b) When the gut glucose is **lower** than inside the cell, the cell must use **active transport**. This is because the glucose is now moving **against its concentration gradient** (from the lower concentration in the gut into the higher concentration in the cell), which cannot happen passively, so the cell uses **energy from ATP** to drive a carrier protein. *(a: 1 mark — facilitated diffusion; 1 mark — down the gradient; b: 1 mark — active transport; 1 mark — because it is against the gradient and so requires ATP.)*

Q11. (a) **Facilitated diffusion**. (b) Calcium ions are **charged (hydrophilic)**, so they are **repelled by the hydrophobic core** of the bilayer and **cannot pass directly through it**; the **channel protein provides a water-filled pore** through which they can cross. (c) **No ATP is required**: the ions are moving **down their concentration gradient** (from higher outside to lower inside), so the process is **passive**. *(1 mark: facilitated diffusion; 1 mark: ions are charged/repelled by the core so need the channel; 1 mark: no ATP because movement is down the gradient/passive.)*

Q12. (a) **Substance J** (the straight line) crosses by **simple diffusion**, because its rate **keeps rising in proportion to concentration with no upper limit**; **Substance K** (the curve that levels off) crosses by **facilitated diffusion**, because its rate **rises and then plateaus**. (b) The rate for K levels off because at high concentration **all of its transport proteins are occupied and working at their maximum rate (saturated)**, so increasing the external concentration further **cannot increase the rate**. (c) If the cell made **more transport proteins**, the **maximum rate (the height of the plateau) would be higher**, because more proteins could move more of the substance per unit time. *(a: 1 mark — J = simple diffusion with justification; 1 mark — K = facilitated diffusion with justification; b: 1 mark — proteins saturated at maximum; c: 1 mark — higher plateau/maximum rate.)*

Q13. (a) The **independent variable is the temperature**; the **dependent variable is the distance the colour spreads in the fixed time** (a measure of the rate of diffusion). (b) Any one suitable variable — for example the **volume and concentration of the dye drop**, the **type and amount of gel**, the **size of the dish**, or the **time allowed —** must be **kept constant** so that it does **not also affect how far the colour spreads**; if it changed, you could not be sure the difference was caused by temperature alone. *(a: 1 mark — IV = temperature; 1 mark — DV = distance spread / rate; b: 1 mark — names a valid controlled variable; 1 mark — explains it must be constant so it does not also affect the DV.)*

Q14. (a) Saying a carrier protein is **specific** means it has a **shape / binding site that fits and transports only one particular substance** (or a small number of closely related ones), and not others. (b) A cell needs **many different carrier proteins** because it must transport **many different substances**, and each substance needs its **own matching, specific carrier** to cross the membrane. (c) The substance that the blocked carrier normally moves would **no longer be transported** across the membrane (its transport would **stop or slow**), because there is no other carrier able to move it. *(1 mark: specific = binds/carries only its particular substance; 1 mark: many substances each need their own carrier; 1 mark: transport of that substance stops/slows.)*

Q15. A **strength** of the model is that it **clearly shows the different routes** substances take and the **direction of movement**, making an abstract idea easy to picture. Two **limitations**: it is **static**, so it does **not show that the particles are moving randomly and continuously** (or that movement can occur in both directions); and it does **not show that the membrane is fluid** (with the phospholipids and proteins able to move), nor is it drawn **to scale** (the real numbers and sizes of particles and proteins differ). **Overall judgement**: the model is **useful for teaching the routes and directions of transport**, but it should **not be taken as a literal, complete picture** of the membrane. *(1 mark: one valid strength; 2 marks: two valid limitations; 1 mark: a reasoned overall judgement.)*

Q16. Similarity: both are **specific membrane transport proteins** that carry out **passive facilitated diffusion** (moving substances down their gradient with no ATP). **Differences:** a **channel protein forms an open, water-filled pore** through which the substance passes straight across, whereas a **carrier protein binds the substance and changes shape** to move it; and **channel proteins typically transport ions**, whereas **carrier proteins transport larger molecules such as glucose**. *(1 mark: one valid similarity; 1 mark each for two valid differences = 2 marks.)*

Q17. (a) When the cell can no longer make ATP (the respiratory poison, or oxygen removed), the **rate of uptake of ion Z falls to almost zero** (from 48 down to about 3–5). (b) This evidence shows that the uptake of ion Z **depends on ATP —** when ATP can no longer be made, uptake almost stops — so ion Z must be moved by a process that **requires energy** (it is being moved against its gradient). (c) The process is **active transport**, justified because uptake is **high when the cell can respire and make ATP but almost stops when ATP production is prevented** — a passive process would not depend on ATP like this. *(a: 1 mark — uptake falls to almost zero without ATP; b: 1 mark — uptake depends on ATP; 1 mark — so the ion is moved by an energy-requiring process; c: 1 mark — active transport, justified from the ATP dependence.)*

Q18. The molecule must be using **active transport**. Because it is **moving against its concentration gradient** (from dilute to more concentrated), the process must **require energy — ATP** — since this cannot happen passively; and because the molecule is **large and highly polar**, it **cannot cross the bilayer directly**, so the process must use a **carrier (transport) protein**. *(1 mark: active transport; 1 mark: it must use ATP because movement is against the gradient; 1 mark: it must use a carrier protein because the molecule is large/polar.)*

Q19. (a) The carbon dioxide leaves by **simple diffusion**. Carbon dioxide is a **small, non-polar molecule**, so it **dissolves directly through the phospholipid bilayer**; it is **more concentrated inside** the respiring cell than outside, so it moves **down its gradient, out of the cell**, using no ATP. (b) The microvilli **greatly increase the surface area** of plasma membrane in contact with the gut contents. The **rate of transport across a membrane increases with the surface area available**, because a larger area gives the particles more membrane to cross at any moment, so **more particles cross per unit time** and the cell absorbs its nutrients faster than a flat-surfaced cell of the same volume could. (c) **Mitochondria are the site of cellular respiration**, which supplies the cell with **ATP**. This cell absorbs nutrients from the gut by **active transport**, moving them **against their concentration gradients**, and that **uses ATP continuously** — so a cell carrying out a great deal of active transport needs many mitochondria to keep up the supply of energy. (d) At **15 °C** the particles have **less kinetic energy** than at 37 °C, so they **move more slowly** and cross the membrane **less often**. Fewer carbon dioxide molecules pass out per unit time, so the **rate of simple diffusion falls —** even though the concentration gradient itself is unchanged. *(a: 1 mark — simple diffusion; 1 mark — small/non-polar, down the gradient out of the cell; b: 1 mark — the folding increases the surface area; 1 mark — so more particles cross per unit time / the rate rises; c: 1 mark — mitochondria supply ATP by respiration; 1 mark — the cell carries out much active transport against gradients, which needs ATP; d: 1 mark — less kinetic energy / slower-moving particles; 1 mark — so the rate of diffusion falls.)*

Chapter 2 Cell function and membrane transport — 2B Osmosis

Theory

Every cell is wrapped in a **plasma (cell) membrane** that is **selectively permeable** (also called partially permeable): it lets some substances cross while holding others back. Most substances a cell takes in or removes are dissolved in water, so the **movement of water itself** across this membrane is one of the most important things a cell must manage. That water movement is **osmosis**.

What osmosis is. Particles in a liquid are always moving randomly, and this random motion spreads them out from where they are crowded to where they are sparse — a process called **diffusion**. **Osmosis** is the special case of diffusion that applies to **water**:

> **Osmosis** is the **net movement of water molecules across a selectively permeable membrane, from a region of higher water concentration (a dilute solution, with less solute) to a region of lower water concentration (a concentrated solution, with more solute)**.

Two features of this definition matter. First, osmosis needs a **selectively permeable membrane** that lets water through but holds back the dissolved **solute** (such as salt or sugar). Second, the direction is set by **how much water is free to move**, not by the solute: water moves from the side where water is more concentrated (more dilute solution) to the side where water is less concentrated (more concentrated solution). Like all diffusion, osmosis is driven by the random motion of the particles themselves, so it is **passive** — it needs **no energy (no ATP)** from the cell.

Why adding solute drives osmosis. When a solute such as salt dissolves, its particles attract and "tie up" some of the surrounding water molecules, leaving fewer water molecules free to move. So a **concentrated** solution has a **lower free-water concentration** than a dilute one. Water therefore always moves by osmosis **towards the more concentrated solution** — the side with more solute and less free water — until the two concentrations are equal or another force stops it. (The tendency of a solution to gain or lose water in this way is formally called its **water potential**; at this level you only need the direction, not a value — water moves from a high to a low water potential.)

How water crosses the membrane. Water is a **polar** molecule, and polar substances normally cross the oily interior of the bilayer only slowly. Water is small enough, however, that some of it still slips **directly between the phospholipids**, and most of it crosses through special **water-channel proteins (aquaporins)** that give it an easy route. Because water is moving **down its own concentration gradient**, no carrier and no ATP are needed — osmosis is passive.

Tonicity — comparing a solution with the cell. Because the cell's contents are themselves a solution, what happens to a cell depends on how the **outside** solution compares with the **inside** of the cell. **Tonicity** describes the solute concentration of a solution **relative to the cell**:

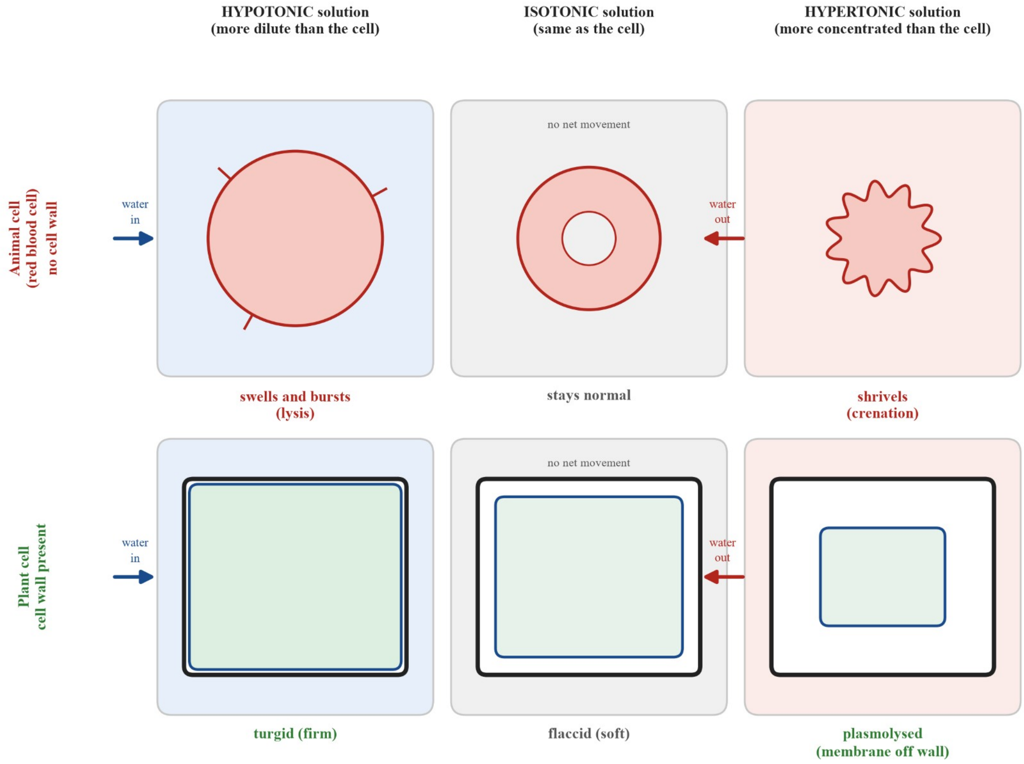
- a **hypotonic** solution has a **lower** solute concentration than the cell (more free water outside), so water moves **into** the cell;
- a **hypertonic** solution has a **higher** solute concentration than the cell (less free water outside), so water moves **out of** the cell;
- an **isotonic** solution has the **same** solute concentration as the cell, so there is **no net movement** of water (water still crosses both ways, but at equal rates).

Effect on animal cells (no cell wall). An animal cell, such as a **red blood cell**, has only its membrane holding it together. In a **hypotonic** solution water floods in, the cell swells, and — with nothing to resist the swelling — it eventually **bursts (lysis)**. In a **hypertonic** solution water leaves, and the cell **shrinks and shrivels (crenation)**. Only in an **isotonic** solution does the cell keep its normal shape. This is why body cells must be bathed in fluid that is **isotonic** to them, and why fluids given to a patient in a drip, and eye drops, are made isotonic to body cells — pure water or a strong salt solution would destroy the cells.

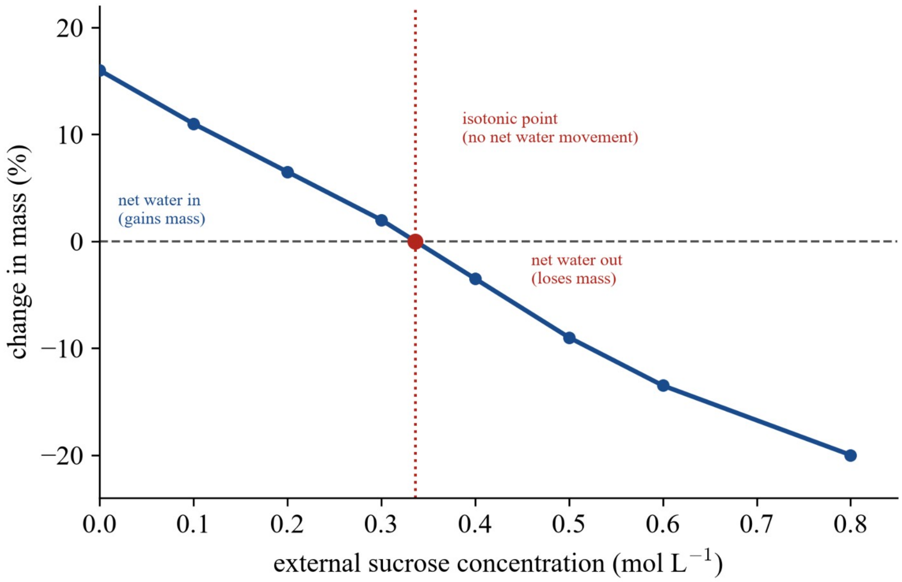
Effect on plant cells (cell wall present). A plant cell has a strong, rigid **cell wall** outside its membrane. In a **hypotonic** solution water enters and the cell contents swell, pushing the membrane hard against the wall. The wall pushes back, building up **turgor pressure**, so the cell becomes **turgid** (firm) but does **not** burst. This turgor is what holds up the soft parts of a plant; when cells lose it, the plant **wilts**. In an **isotonic** solution the cell loses turgor and becomes **flaccid** (soft). In a **hypertonic** solution so much water leaves that the membrane and cell contents shrink and **pull away from the wall** — the cell is **plasmolysed** (plasmolysis).

The two cell types therefore respond very differently to the same solution:

Solution	Animal cell (e.g. red blood cell)	Plant cell
Hypotonic — water enters	Swells and bursts — **lysis**	Swells; wall resists → **turgid** (firm), does not burst
Isotonic — no net movement	Keeps normal shape	**Flaccid** (soft; no turgor)
Hypertonic — water leaves	Shrinks and shrivels — **crenation**	Membrane pulls off the wall — **plasmolysed**



Measuring osmosis — plant-tissue investigations. Osmosis can be followed by weighing plant tissue. Identical cylinders cut from a plant (for example, potato) are weighed, left in solutions of different solute concentration, then blotted dry and reweighed. In a **hypotonic** (dilute) solution water enters the cells by osmosis and the tissue **gains mass**; in a **hypertonic** (concentrated) solution water leaves and the tissue **loses mass**. Somewhere in between is the **isotonic point** — the external concentration at which the tissue shows **no change in mass**, because the solution has the **same solute concentration as the cells** and there is no net water movement. The result is usually reported as a **percentage change in mass** rather than a raw change, so that cylinders that started at slightly different masses can be compared fairly. Plotting percentage change in mass against concentration gives a line that crosses zero at the isotonic point:



Osmosis in living things. Osmosis matters everywhere water and cells meet:

- **Water uptake in plants.** The cytosol of a **root hair cell** holds more solute than the surrounding soil water, so soil water is hypotonic to the cell and water moves **in** by osmosis — this is how plants take up most of their water.
- **Food preservation.** Coating food in **salt**, or turning fruit into high-**sugar** jam, makes the surroundings strongly hypertonic to any microbe that lands on it. Water is drawn **out** of the microbes' cells by osmosis, so they dehydrate and cannot grow — which is why heavily salted or sugared food keeps.
- **Freshwater single-celled organisms.** A single-celled organism living in fresh (pond) water is hypertonic to its surroundings, so water constantly floods **in** by osmosis and could burst the cell. Many such organisms bail this water out using a **contractile vacuole** that collects water and pumps it back out — and because this pumps water *against* the direction osmosis is pushing it, it needs **energy (ATP)**; it is not osmosis.

Worked examples

Example 1 — scaffolded

Two sugar solutions are separated by a membrane that lets water through but not sugar. Solution X is 0.1 mol L^{-1} sucrose and solution Y is 0.5 mol L^{-1} sucrose. State the direction of net water movement across the membrane and explain your answer.

Working	Comment
Solution Y (0.5 mol L^{-1}) has **more solute** than solution X (0.1 mol L^{-1}), so Y has the **lower free-water concentration**.	Compare the solute concentrations first — this sets which way water moves.
Water moves by **osmosis** from the higher free-water side (X) to the lower free-water side (Y), so the net movement is **from X to Y**.	Water always moves towards the more concentrated solution.
The membrane lets **water** through but not sucrose, so only water crosses; the movement needs **no ATP** because it is down the water gradient.	Note that osmosis is passive and that the solute stays put.
Net water movement is therefore **from solution X into solution Y**.	State the direction clearly as the answer.

Example 2 — scaffolded

A plant cell is placed in a strongly hypertonic solution. Predict what happens to the cell, name the condition, and explain your reasoning.

Working	Comment
The solution is **hypertonic** — it has a higher solute concentration than the cell (less free water outside).	Establish the tonicity relative to the cell.
Water therefore moves **out of the cell by osmosis**, from the higher free-water inside to the lower free-water outside.	Give the direction of net water movement and name the process.
As the cytoplasm and vacuole lose water and shrink, the membrane is pulled **away from the rigid cell wall**.	Link the water loss to the visible change; the wall does not shrink.
The cell is **plasmolysed** (plasmolysis).	Use the correct term for a plant cell that has lost water this way.

Example 3 — unscaffolded

A red blood cell is placed in a beaker of pure (distilled) water. Predict and explain what happens to the cell, and explain why fluids given to a patient through a drip are made isotonic to the patient's cells instead.

Pure water contains no solute, so it is **hypotonic** to the red blood cell (the cell's cytosol has far more solute). Water therefore moves **into the cell by osmosis**, from the higher free-water region outside to the lower free-water region inside. The cell **swells**, and because an animal cell has **no cell wall** to resist the swelling, it keeps taking in water until it **bursts — lysis**. A fluid given through a drip is made **isotonic** to the patient's cells so that there is **no net movement of water** into or out of the blood cells: an isotonic fluid neither swells the cells (as pure water would, causing lysis) nor shrivels them (as a hypertonic fluid would, causing crenation), so the cells keep their normal shape and function. ∴ a red blood cell bursts in pure water, and isotonic fluids are used medically to protect cells from osmotic damage.

Example 4 — unscaffolded

Explain, in terms of osmosis, why coating fresh meat in salt, or preserving fruit as high-sugar jam, stops bacteria and moulds from growing on it.

Coating food in salt, or setting it in concentrated sugar, surrounds the food with a solution that is strongly **hypertonic** to any bacterium or mould that lands on it — the outside now has a much higher solute concentration (much less free water) than the inside of the microbes' cells. Water is therefore drawn **out of the microbes' cells by osmosis**, moving from the higher free-water region inside the cell to the lower free-water region outside. Losing this water, the microbes' cells shrink and dehydrate, so the microbes **cannot grow or reproduce** and the food does not spoil. ∴ salting or sugaring preserves food because the hypertonic surroundings remove water from spoilage microbes by osmosis.

Practice questions

Scaffolded

Q1. Define each of the following terms: (a) osmosis; (b) selectively permeable membrane; (c) isotonic solution.

Q2. Osmosis is one way substances cross the plasma membrane. (a) State whether osmosis requires the cell to use energy (ATP). (b) State the direction of net water movement in osmosis, relative to the solute concentrations of the two solutions. (c) Explain why the movement of water in osmosis is described as passive.

Q3. The tonicity of a solution is described relative to a cell. (a) Define the term hypotonic. (b) Define the term hypertonic. (c) State what happens to the mass of a cell placed in a solution that is isotonic to it, and explain why.

Q4. A red blood cell can be placed in solutions of different tonicity. (a) State what happens to the cell in a hypotonic solution, and name this outcome. (b) State what happens to the cell in a hypertonic solution, and name this outcome. (c) Explain why there is no net movement of water when the cell is in an isotonic solution.

Q5. A plant cell responds to osmosis differently from an animal cell. (a) Name the condition of a plant cell that has taken in water and become firm. (b) Name the condition of a plant cell that has lost so much water that its membrane pulls away from the cell wall. (c) Explain why a plant cell placed in a hypotonic solution does not burst.

Q6. Cylinders of potato are weighed, left in sucrose solutions of different concentration, then blotted and reweighed. The percentage change in mass of each is calculated. (a) Explain what a percentage change in mass of zero tells you about the solution, relative to the cells. (b) Explain why the percentage change in mass is calculated, rather than using the raw change in mass in grams. (c) State why several potato cylinders are tested at each concentration.

Unscaffolded

Q7. Define osmosis, and explain how osmosis differs from the simple diffusion of a dissolved substance. *(3 marks)*

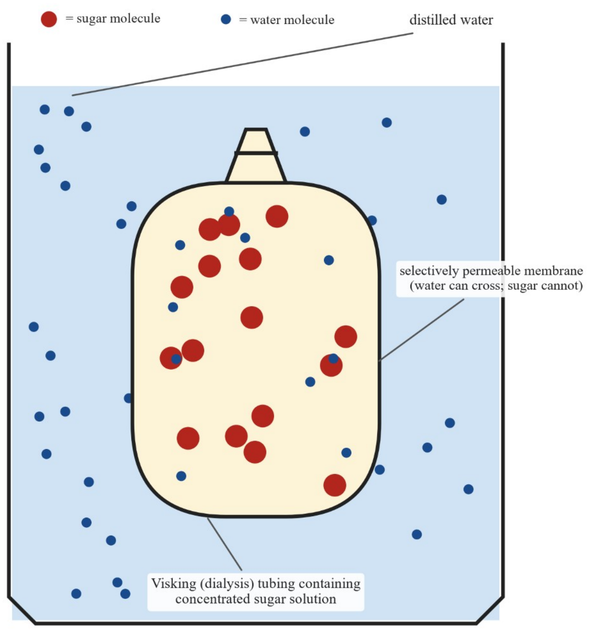
Q8. Both osmosis and active transport move substances across the plasma membrane. Distinguish between them, with reference to what is moved, the direction of movement, and the use of energy. *(3 marks)*

Q9. A red blood cell and a plant cell are each placed in the same concentrated salt solution, which is hypertonic to both. For each cell, describe and name what happens, and explain why the two outcomes look different. *(4 marks)*

Q10. A gardener adds far too much fertiliser to the soil around a healthy plant, so that the soil water becomes hypertonic to the plant's root cells. Within hours the plant wilts. (a) Explain, in terms of osmosis, why the plant wilts. (b) Name the condition of the root cells if a large amount of water is lost. *(4 marks)*

Q11. A leafy houseplant with drooping, floppy leaves becomes firm and upright again a few hours after it is watered. Explain this recovery in terms of water movement and the plant cells. *(3 marks)*

Q12. *(Stimulus.)* A bag made of Visking (dialysis) tubing is filled with a concentrated sugar solution, tied, and placed in a beaker of distilled water. The tubing is a selectively permeable membrane that lets water through but not sugar. The set-up is shown below.



(a) State the direction of net water movement between the beaker and the bag.
(b) Predict and explain what happens to the mass of the bag over the next hour.
(c) Explain what happens to the rate of net water movement as time goes on. *(4 marks)*

Q13. *(Data interpretation.)* Identical cylinders of a root vegetable were weighed, left in sucrose solutions for two hours, blotted, and reweighed. The percentage change in mass is shown.

Sucrose concentration (mol L^{-1})	Change in mass (%)
0.0	+15
0.2	+6
0.3	0
0.4	−8

Sucrose concentration (mol L^{-1})	Change in mass (%)
0.6	−17

(a) Explain why the cylinders in 0.0 and 0.2 mol L^{-1} gained mass, while those in 0.4 and 0.6 mol L^{-1} lost mass.
(b) Estimate the sucrose concentration that is isotonic to the cells, and justify your answer using the data.
(c) Predict, with a reason, what would happen to the mass of a cylinder left in a 1.0 mol L^{-1} solution. *(4 marks)*

Q14. A single-celled organism that lives in fresh (pond) water has a cytosol that is hypertonic to the surrounding water. (a) State the direction of net water movement between the pond water and the organism, and explain why. (b) Explain the problem this continual water movement would cause if it were not controlled. (c) The organism uses a contractile vacuole that collects water and expels it from the cell, a process that requires ATP. Explain why expelling this water is **not** osmosis. *(4 marks)*

Q15. Explain how water enters a root hair cell from the soil. In your answer, name the process, and refer to the solute concentrations of the soil water and the cell. *(3 marks)*

Q16. Water is a polar molecule, yet it is still able to cross the plasma membrane during osmosis. Explain how water crosses the membrane, and explain why its movement is classed as passive. *(3 marks)*

Q17. *(Investigation design.)* A student investigates how the concentration of a salt solution affects the change in mass of potato cylinders. She cuts cylinders, weighs each, leaves them in different salt solutions for 30 minutes, then reweighs them. (a) Identify the independent variable and the dependent variable in this investigation. (b) State one variable that must be kept constant, and explain why. (c) Before reweighing, each cylinder should be gently blotted dry. Explain why failing to do this would introduce an error into the results. *(4 marks)*

Q18. *(Data interpretation.)* Cylinders of two vegetables, P and Q, were tested by the potato-cylinder method. Vegetable P had an isotonic point at 0.30 mol L^{-1} sucrose; vegetable Q had an isotonic point at 0.15 mol L^{-1} sucrose. (a) State which vegetable's cells have the higher internal solute concentration, and justify your answer. (b) Predict, with a reason, what would happen to cylinders of vegetable Q placed in a 0.30 mol L^{-1} sucrose solution. *(4 marks)*

Q19. *(Synthesis.)* A student investigates osmosis using identical cylinders cut from a fresh carrot. She weighs each cylinder, places them in salt solutions ranging from distilled water to a very concentrated solution, and after 30 minutes measures the change in length and firmness of each cylinder. (a) Explain, in terms of osmosis, why the cylinders in distilled water became longer and firmer, while those in the most concentrated solution became shorter and floppy. (b) One cylinder showed no change in length or firmness. State what this tells you about the solution it was in, relative to the carrot cells. (c) The student judges “firmness” by hand. Explain **two** reasons why recording the change in mass of each cylinder would be a more reliable and more valid measure of the effect of the solutions. (d) The student repeats the experiment using carrot that had been stored for a week in salty water, so that its cells now contain more solute than fresh carrot. Predict, with reasoning, how the isotonic point of this carrot would compare with that of fresh carrot. *(8 marks)*

Answers

Q1. (a) The net movement of water across a selectively permeable membrane from a higher water concentration (dilute) to a lower water concentration (concentrated). (b) A membrane that lets some substances (such as water) through while holding others (such as solutes) back. (c) A solution with the same solute concentration as the cell, so there is no net movement of water. **Q2.** (a) No. (b) From the more dilute (lower-solute) solution to the more concentrated (higher-solute) solution. (c) It is driven by the random motion of water molecules moving down their own gradient, so it uses no ATP. **Q3.** (a) A solution with a lower solute concentration than the cell. (b) A solution with a higher solute concentration than the cell. (c) No change in mass, because the solution is isotonic to the cell, so there is no net movement of water. **Q4.** (a) Water enters, the cell swells and bursts — lysis. (b) Water leaves and the cell shrivels — crenation. (c) The solution has the same solute concentration as the cell, so water crosses both ways at equal rates and there is no net movement. **Q5.** (a) Turgid. (b) Plasmolysed (plasmolysis). (c) The rigid cell wall resists the swelling and builds up turgor pressure, stopping the cell bursting. **Q6.** (a) The solution is isotonic to the cells — same solute concentration, so no net water movement. (b) So cylinders that started at different masses can be compared fairly. (c) To make the results more reliable/repeatable (able to spot and reduce the effect of any anomalous cylinder). **Q7.** Osmosis is the net movement of water across a selectively permeable membrane from a higher to a lower water concentration; it differs from simple diffusion in that it involves water specifically and requires a selectively permeable membrane, whereas simple diffusion is the spreading of any substance down its own gradient and needs no membrane. **Q8.** Osmosis moves water down its gradient with no ATP; active transport moves a solute against its gradient using ATP. **Q9.** Red blood cell: water leaves, it shrivels — crenation; plant cell: water leaves and the membrane pulls off the wall — plasmolysis. They differ because the plant cell has a rigid wall (which stays in place while the membrane pulls in) and the animal cell does not. **Q10.** (a) The soil is hypertonic, so water leaves the root cells by osmosis; the cells lose turgor and the plant wilts. (b) Plasmolysed (plasmolysis). **Q11.** The watered soil is hypotonic to the cells, so water enters by osmosis; the cells regain turgor (become turgid) and the leaves become firm and upright again. **Q12.** (a) From the beaker (distilled water) into the bag. (b) The bag gains mass, because water enters the concentrated sugar solution by osmosis while the sugar cannot leave. (c) It slows down as the concentrations become closer together. **Q13.** (a) 0.0 and 0.2 mol L^{-1} are hypotonic, so water entered and mass rose; 0.4 and 0.6 mol L^{-1} are hypertonic, so water left and mass fell. (b) About 0.3 mol L^{-1} — the mass change there is zero (isotonic). (c) It would lose mass (more than at 0.6), because 1.0 mol L^{-1} is even more hypertonic, so more water leaves. **Q14.** (a) Water moves into the organism, because the pond water is hypotonic to the cytosol. (b) Water would keep entering and the cell could swell and burst. (c) Expelling water pushes it against the direction osmosis drives it (out of a cell into a more dilute surrounding), which cannot happen passively — it needs ATP, so it is active, not osmosis. **Q15.** By osmosis: the root hair cytosol has a higher solute concentration than the soil water, so the soil water is hypotonic and water moves into the cell down its gradient. **Q16.** Water is small enough to slip between the phospholipids and mostly crosses through water-channel proteins (aquaporins); it moves down its own concentration gradient, so no ATP is used — the movement is passive. **Q17.** (a) IV = concentration of the salt solution; DV = change in mass of the cylinders. (b) e.g. time in solution / temperature / cylinder size — kept constant so it does not also affect the mass change. (c) Surface water left on a cylinder would add to its measured mass, making the mass gain look larger (or the loss smaller) — a systematic error. **Q18.** (a) P — its cells are isotonic at a higher concentration (0.30 mol L^{-1}), so they contain more solute. (b) The cylinders of Q would lose mass, because 0.30 mol L^{-1} is hypertonic to Q's cells (isotonic at only 0.15), so water leaves by osmosis. **Q19.** (a) Distilled water is hypotonic → water in → cells turgid → longer/firmer; the concentrated solution is hypertonic → water out → cells flaccid/plasmolysed → shorter/floppy. (b) The solution was isotonic to the carrot cells (same solute concentration, no net movement). (c) Firmness by hand is subjective — different people would rate the same cylinder differently, so it is less reliable; and it gives no number, whereas change in mass measures the water gained or lost directly (more valid) and can be compared and plotted. (d) Its isotonic point would be at a higher concentration than fresh carrot, because the cells now hold more solute, so they match a more concentrated external solution.

Fully-worked solutions

Q1. (a) **Osmosis** is the **net movement of water molecules across a selectively permeable membrane from a region of higher water concentration (a dilute solution) to a region of lower water concentration (a concentrated solution)**, down the water concentration gradient. (b) A **selectively permeable membrane** is one that **lets some substances cross while holding others back** — for example, letting water through but not a dissolved solute. (c) An

isotonic solution has the **same solute concentration as the cell**, so there is **no net movement of water** into or out of the cell.

Q2. (a) **No** — osmosis does not require the cell to use any ATP. (b) Net water moves **from the more dilute solution (lower solute concentration) to the more concentrated solution (higher solute concentration)**. (c) Osmosis is **passive** because it is driven by the **random motion of the water molecules themselves**, moving **down their own concentration gradient**; the cell supplies no energy, so no ATP is used.

Q3. (a) A **hypotonic** solution has a **lower solute concentration than the cell**. (b) A **hypertonic** solution has a **higher solute concentration than the cell**. (c) The cell's mass shows **no change**, because an isotonic solution has the **same solute concentration as the cell**; water still crosses the membrane both ways, but at **equal rates**, so there is **no net movement** of water and no mass change.

Q4. (a) In a **hypotonic** solution water moves **into** the cell, which **swells and bursts** — this outcome is called **lysis**. (b) In a **hypertonic** solution water moves **out** of the cell, which **shrinks and shrivels** — this outcome is called **crenation**. (c) In an **isotonic** solution the outside solution has the **same solute concentration** as the cell, so although water molecules keep crossing the membrane in both directions, they do so at **equal rates** — there is **no net movement** of water.

Q5. (a) **Turgid.** (b) **Plasmolysed** (plasmolysis). (c) When water enters, the plant cell swells, but its **strong, rigid cell wall resists the swelling** and builds up **turgor pressure** that pushes back on the entering water. This pressure **stops any more water entering and prevents the cell bursting**, so the cell becomes firm (turgid) rather than lysing as an animal cell would.

Q6. (a) A percentage change of **zero** means the solution is **isotonic** to the cells — it has the **same solute concentration** as the cells, so there was **no net movement of water** and therefore no change in mass. (b) The **percentage change in mass** is used so that cylinders that began at **slightly different starting masses** can be **compared fairly** (each change is expressed relative to its own starting mass). (c) Several cylinders are tested at each concentration to make the results **more reliable/repeatable** — repeating allows an anomalous cylinder to be spotted and reduces the effect of random variation.

Q7. Osmosis is the **net movement of water across a selectively permeable membrane from a higher water concentration (dilute) to a lower water concentration (concentrated)**. It **differs from simple diffusion** in two ways: osmosis involves **only water** (whereas simple diffusion can spread any dissolved or gaseous substance), and osmosis **requires a selectively permeable membrane** separating the two solutions (whereas simple diffusion is just particles spreading down their gradient and needs no membrane). *(1 mark: correct definition of osmosis; 1 mark: osmosis is specific to water; 1 mark: osmosis needs a selectively permeable membrane / diffusion does not.)*

Q8. In **osmosis**, **water** moves **down its own concentration gradient** (towards the more concentrated solution) and **no ATP** is used, because it is a passive process. In **active transport**, a **solute** is moved **against its concentration gradient** (from a low to a high concentration) and this **requires ATP** to power a carrier protein. *(1 mark: osmosis = water, down the gradient, no ATP; 1 mark: active transport = solute, against the gradient, uses ATP; 1 mark: a clear two-sided contrast covering what moves / direction / energy.)*

Q9. For the **red blood cell**: the salt solution is **hypertonic**, so water leaves the cell by osmosis and the cell **shrinks and shrivels — crenation**. For the **plant cell**: water also leaves by osmosis, but the membrane and contents shrink and **pull away from the rigid cell wall — plasmolysis**. The outcomes look different because the **plant cell has a strong cell wall** that keeps its outer shape while the membrane pulls inwards, whereas the **animal cell has no wall**, so the whole cell simply shrivels. *(1 mark: red blood cell shrivels — crenation; 1 mark: plant cell membrane pulls off the wall — plasmolysis; 1 mark: both lose water by osmosis because the solution is hypertonic; 1 mark: the difference is due to the plant cell wall / the animal cell having none.)*

Q10. (a) The over-fertilised soil water is now **hypertonic** to the root cells (more solute outside than inside), so water moves **out of the root cells by osmosis**, down the water concentration gradient. As the cells lose water they **lose turgor** and become flaccid, so the plant can no longer hold up its soft tissues and it **wilts**. (b) If a large amount of water is lost, the cells become **plasmolysed** (the membrane pulls away from the cell wall). *(a: 3 marks — soil is hypertonic; water leaves the root cells by osmosis; the cells lose turgor so the plant wilts; b: 1 mark — plasmolysed.)*

Q11. The floppy leaves show the cells have **lost turgor** (they are flaccid). When the plant is watered, the soil water becomes **hypotonic** to the cells (more dilute than the cells' contents), so water moves **into the cells by osmosis**. The contents swell and press the membrane against the cell wall, so the cells regain **turgor pressure** and become **turgid** again; the firm, turgid cells support the soft leaves, which become firm and upright. *(1 mark: watered soil is hypotonic, water enters by osmosis; 1 mark: cells regain turgor / become turgid; 1 mark: turgor supports the leaves so they become firm.)*

Q12. (a) Net water moves **from the beaker (distilled water) into the bag**. (b) The **mass of the bag increases**. The distilled water is **hypotonic** to the concentrated sugar solution inside the bag, so water moves **into the bag by osmosis**; because the sugar molecules are too large to cross the membrane, they stay inside, and the extra water raises the bag's mass. (c) The rate of net water movement **slows down** over time: as water enters the bag, the sugar solution inside becomes **more dilute**, while the beaker outside stays distilled water because the sugar cannot leave the bag — so the **difference in water concentration** between the two sides shrinks and the net movement gradually falls (approaching zero). *(1 mark: water moves into the bag; 1 mark: bag gains mass; 1 mark: because water enters by osmosis while sugar cannot leave; 1 mark: the rate slows as the concentrations become closer.)*

Q13. (a) In **0.0 and 0.2 mol** L^{-1} the solution is **hypotonic** to the cells (less solute than the cells), so water moved **into** the cells by osmosis and the cylinders **gained mass**; in **0.4 and 0.6 mol** L^{-1} the solution is **hypertonic** (more solute than the cells), so water moved **out** and the cylinders **lost mass**. (b) The isotonic concentration is about **0.3 mol** L^{-1}, because at 0.3 mol L^{-1} the change in mass is **zero** — no net movement of water, which means the external solute concentration equals that of the cells. (c) A cylinder in **1.0 mol** L^{-1} would **lose mass**, and lose **more** than the cylinder in 0.6 mol L^{-1}, because 1.0 mol L^{-1} is **even more hypertonic**, so even more water leaves the cells by osmosis. *(1 mark: gain = hypotonic/water in; 1 mark: loss = hypertonic/water out; 1 mark: isotonic ≈ 0.3 mol L^{-1} justified by the zero change; 1 mark: predicts a larger mass loss at 1.0 mol L^{-1} with reason.)*

Q14. (a) Water moves **into the organism** from the pond water, because the pond water is **hypotonic** to the organism's cytosol (the cytosol has the higher solute concentration), so water moves in by osmosis down its gradient. (b) If this were not controlled, water would **keep entering** the cell, which would **swell and could burst** (lyse). (c) Expelling water with the contractile vacuole moves water **out of the cell into the more dilute pond water** — that is, **against the direction osmosis pushes it** (osmosis would drive water in, not out). Movement against the natural gradient cannot happen passively; it needs an input of **ATP**, so it is an **active (ATP-requiring) process, not osmosis** (osmosis is always passive and down the gradient). *(1 mark: water enters because surroundings are hypotonic; 1 mark: the cell could swell and burst; 1 mark: the vacuole moves water against the osmotic gradient; 1 mark: this needs ATP, so it is active and not osmosis.)*

Q15. Water enters a **root hair cell** by **osmosis**. The cytosol of the root hair cell contains a **higher solute concentration** than the surrounding **soil water**, so the soil water is **hypotonic** to the cell. Water therefore moves **down its concentration gradient, from the soil water into the cell**, across the selectively permeable membrane. *(1 mark: names osmosis; 1 mark: soil water is more dilute / cell cytosol has more solute; 1 mark: so water moves from soil into the cell down the gradient.)*

Q16. Although water is a **polar** molecule, it is **small** enough for some to **slip directly between the phospholipids** of the membrane, and most water crosses through **water-channel proteins (aquaporins)** that provide an easy route across. The movement is classed as **passive** because water moves **down its own concentration gradient** (from higher to lower water concentration), driven by the random motion of the molecules — the cell supplies **no ATP**. *(1 mark: water is small / crosses between phospholipids; 1 mark: crosses through water-channel proteins/aquaporins; 1 mark: passive because it moves down the gradient with no ATP.)*

Q17. (a) The **independent variable** is the **concentration of the salt solution**; the **dependent variable** is the **change in mass of the potato cylinders**. (b) Any one suitable variable — for example the **time left in solution**, the **temperature**, or the **size/starting mass of the cylinders** — must be **kept constant** so that it does not **also affect the change in mass**, which would make it impossible to tell whether the concentration alone caused the result. (c) Any **surface water** left on a cylinder would **add to its measured mass**, making the recorded mass **larger than the true tissue mass** — so a gain would look bigger, or a loss smaller, than it really is. Because this shifts every affected reading in the same direction, it is a **systematic error**; blotting each cylinder dry removes it. *(1 mark: IV =*

concentration and DV = change in mass; 1 mark: names a valid controlled variable; 1 mark: explains it must be constant so it does not also affect the DV; 1 mark: surface water adds to the measured mass / a systematic error.)

Q18. (a) **Vegetable P** has cells with the **higher internal solute concentration**. A tissue's isotonic point is the external concentration that **matches its cells' own solute concentration** (zero net water movement); P is isotonic at **0.30 mol** L^{-1} while Q is isotonic at only **0.15 mol** L^{-1}, so P's cells must contain **more solute**. (b) Cylinders of **Q** placed in **0.30 mol** L^{-1} would **lose mass**, because 0.30 mol L^{-1} is **hypertonic** to Q's cells (which are isotonic at only 0.15 mol L^{-1}) — so water would move **out** of Q's cells by osmosis. *(a: 1 mark — P; 1 mark — because its higher isotonic point matches a higher internal solute concentration; b: 1 mark — Q loses mass; 1 mark — because 0.30 mol* L^{-1} *is hypertonic to Q so water leaves.)*

Q19. (a) **Distilled water** is **hypotonic** to the carrot cells, so water moves **into** the cells by osmosis; the cells swell and press against their walls, becoming **turgid**, so the cylinders become **longer and firmer**. The **most concentrated solution** is **hypertonic**, so water moves **out** of the cells by osmosis; the cells lose turgor (and may plasmolyse), becoming **flaccid**, so the cylinders become **shorter and floppy**. (b) The solution that produced **no change** was **isotonic** to the carrot cells — it had the **same solute concentration** as the cells, so there was **no net movement of water**. (c) First, judging **firmness by hand** is **subjective** — different people (or the same person on a later cylinder) would rate the same cylinder differently, so the judgement cannot be checked or repeated, whereas a **balance gives the same objective reading** whoever takes it, making the results more **reliable**. Second, firmness gives **no number**, so the cylinders cannot be ranked or plotted against concentration, whereas the **change in mass** directly **measures how much water the tissue has gained or lost** — the very thing osmosis changes — so it is the more **valid** measure, and it can be graphed (as a percentage change) to read off the **isotonic point** where the change is zero. (d) The carrot stored in salty water now has **more solute inside its cells**, so its cells would only reach **no net water movement** in a **more concentrated** external solution. Its **isotonic point would therefore be at a higher salt concentration** than fresh carrot's, because the isotonic point matches the cells' internal solute concentration, which is now higher. *(a: 3 marks — distilled water hypotonic → water in → turgid → longer/firmer; concentrated solution hypertonic → water out → flaccid → shorter/floppy; correct link between osmosis direction and turgor/firmness outcome; b: 1 mark — isotonic, no net movement; c: 1 mark — firmness by hand is subjective, so different people rate it differently / it is not repeatable (less reliable); 1 mark — change in mass is quantitative and measures the water gained or lost directly (more valid), so results can be compared and plotted; d: 1 mark — isotonic point at a higher concentration; 1 mark — because the cells now hold more solute.)*

Chapter 2 Cell function and membrane transport — 2C Surface area to volume ratio, cell size and internal compartments

Theory

Every cell must constantly **exchange materials with its surroundings**: it takes in the oxygen and nutrients it needs (such as glucose and mineral ions) and removes the wastes it makes (such as carbon dioxide). All of this exchange happens **across the plasma membrane**, by the processes already covered in this chapter — **diffusion, facilitated diffusion and active transport** (2A) and, for water, **osmosis** (2B). This subtopic is not about *how* substances cross the membrane; it is about a problem set by the **size and shape** of a cell — whether the membrane has enough **area** to serve the whole **volume** of the cell, and what this means for how large a cell can be.

Two measurements that matter — surface area and volume. Two things about a cell decide whether it can keep itself supplied:

- the **surface area (SA)** is the total area of the **plasma membrane** — the surface **across which exchange happens**. A larger surface area lets a cell take in and remove substances faster, so surface area sets the cell's **supply**;
- the **volume (V)** is the amount of living material (cytoplasm) inside the cell. The more cytoplasm there is, the more oxygen and nutrients the cell uses and the more waste it makes, so volume sets the cell's **demand**.

For a cell to stay alive, its surface must be able to keep up with its volume: the **rate of exchange across the surface must match the rate at which the volume uses materials and makes wastes**.

The surface area to volume ratio. These two quantities are compared using the **surface area to volume ratio (SA:V)** — the surface area divided by the volume, that is, **how much exchange surface the cell has for each unit of its volume**. A **high** SA:V means there is plenty of membrane for the amount of cytoplasm, so exchange easily keeps up with demand; a **low** SA:V means there is too little membrane to serve the volume.

Because real cells are irregular, we use a simple **cube** as a model of a cell. A cube has **six square faces**, each of area side × side, so its **surface area = 6 × side^2**; its **volume = side × side × side = side^3**. The SA:V ratio is the surface area divided by the volume. For a cube-shaped cell of side 2 μm:

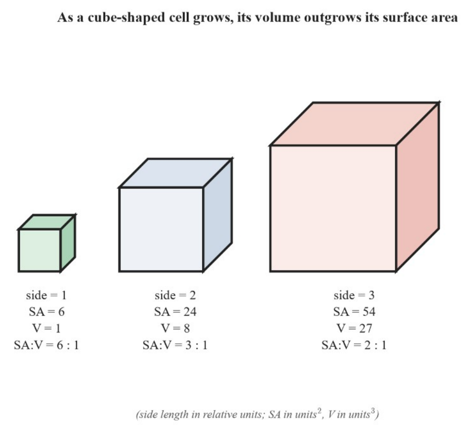
- SA = 6 × side^2 = 6 × $(2)^2$ = 6 × 4 = **24 μm^2**
- V = side^3 = $(2)^3$ = **8 μm^3**
- SA:V = 24 : 8 = **3 : 1**

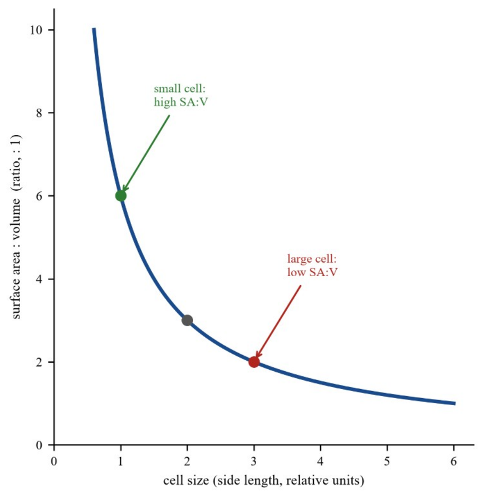
So this model cell has 3 units of membrane for every 1 unit of volume.

Why volume outgrows surface area. As a cube-shaped cell grows, its **surface area increases with the square of the side length (side^2), but its volume increases with the cube (side^3)**. Because the cube grows faster than the square, **volume increases faster than surface area**, so the **SA:V ratio falls as a cell gets larger**:

Side length	Surface area (6 × side^2)	Volume (side^3)	SA:V
1	6	1	6 : 1
2	24	8	3 : 1
3	54	27	2 : 1
4	96	64	1.5 : 1

Doubling the side length (say from 2 to 4) multiplies the surface area by 4 but the volume by 8, so the SA:V is **halved**.





Surface area to volume ratio limits cell size. A **small** cell has a **high** SA:V — a large membrane area for its small volume — so materials are exchanged fast enough for every part of the cell, and the short distance from the membrane to the centre is quickly crossed. A **large** cell has a **low** SA:V, which creates two problems:

1. **Not enough surface for the volume.** The demand of the large volume outstrips what the relatively small surface can supply, so materials cannot enter, and wastes cannot leave, **fast enough**.
2. **The distance to the centre is too great.** Substances move through the cytoplasm largely by diffusion, which is only fast over very short distances; in a large cell the centre is so far from the membrane that it would be **starved** of oxygen and nutrients and would build up waste.

For both reasons, a cell that grew too large could no longer keep itself supplied. This is why **cells are limited in size and stay microscopic**, and why organisms grow by **making more cells** rather than by making their existing cells much larger — many small cells keep a high total SA:V, whereas one huge cell would not.

Increasing the surface area — cells specialised for exchange. A cell whose job is **exchange** is often shaped to raise its SA:V, gaining extra surface area without much extra volume so that exchange is faster. Common ways to do this are:

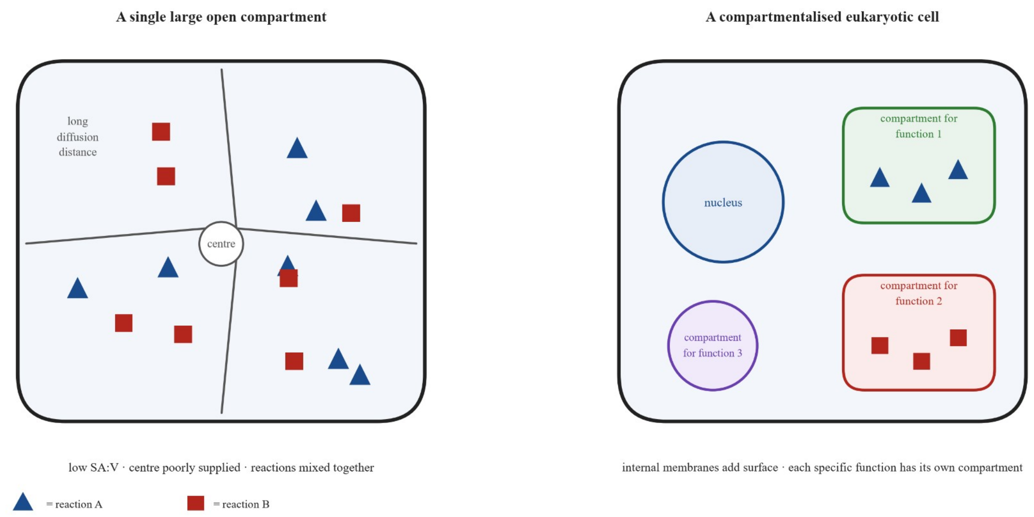
- being **flattened and thin**, giving a large surface for a small volume and only a short distance for substances to cross;
- being **long and thin** (elongated), which also raises the surface relative to the volume;
- folding the membrane into **many small projections** — for example the **microvilli** on a cell lining the small intestine greatly increase the surface for absorbing nutrients. (You met the **root hair cell**'s uptake of water and minerals in 2A and 2B; here the point is simply that its long, narrow shape gives it a large surface area for that uptake.)

In each case, a larger surface area for the same volume means a **higher SA:V** and therefore faster exchange across the membrane.

The need for internal compartments. Staying small solves the exchange problem for the tiniest cells, such as **bacteria (prokaryotic cells)**: with a high SA:V they can exchange materials, and carry out most of their chemical reactions, across or just inside the plasma membrane. But the larger **eukaryotic cells** of plants, animals, fungi and protists carry out many different jobs at once and cannot rely on the plasma membrane alone. They meet the problem a second way: the inside of the cell is divided up by **internal membranes** into many separate compartments — the **membrane-bound organelles** (whose structures are covered in 1D). Dividing the cell into compartments helps in three linked ways:

- **it adds a large amount of extra membrane surface *inside* the cell** — because many reactions take place on membranes, these internal membranes give the cell far more working surface than its outer membrane alone could, partly making up for the low SA:V of the whole cell;
- **it gives each process its own space with its own conditions** — an organelle can hold its own set of enzymes and keep the conditions a particular reaction needs, so that reaction runs efficiently in its own compartment, and reactions that would interfere with one another are kept apart;

- **it lets one cell carry out many functions at the same time** — a **division of labour** in which each compartment has a **specific cellular function** (for example the nucleus, or the organelles in which the cell's energy transformations take place — the roles of those energy organelles are the subject of 2D).



So the surface area to volume ratio explains both why **cells must stay small** and why the larger eukaryotic cell is **divided into compartments** — two responses to the same geometric problem, that a cell's volume grows faster than the surface across which it must exchange everything it needs.

Worked examples

Example 1 — scaffolded

A cube-shaped model cell has a side length of 4 µm. Calculate its surface area, its volume, and its surface area to volume ratio.

Working	Comment
A cube has **6 square faces**, each of area side × side, so **SA = 6 × side²** = 6 × (4)² = 6 × 16 = **96 µm²**.	A cube has six faces — find one face's area, then multiply by 6.
V = side³ = (4)³ = 4 × 4 × 4 = **64 µm³**.	The volume of a cube is the side length cubed.
SA:V = 96 : 64. Dividing both numbers by 64 gives 96 ÷ 64 = 1.5, so **SA:V = 1.5 : 1** (the same as 3 : 2).	Simplify the ratio; writing it "to 1" makes ratios easy to compare.
The cell has **1.5 units of membrane for every 1 unit of volume** (SA:V = 1.5 : 1).	State the final ratio and what it means.

Example 2 — scaffolded

Explain, in terms of the surface area to volume ratio, why cells cannot grow larger than a certain size.

Working	Comment
As a cell grows, its **volume increases faster than its surface area** (volume grows with side³, surface area only with side²), so its **SA:V falls**.	Start from how the two quantities scale with size.
A large cell therefore has a **low SA:V**: its membrane is too small to supply the demands of its large volume, so materials cannot be taken in, and wastes removed, **fast enough**.	Link the low SA:V to a shortfall of supply against demand.
The **distance from the membrane to the centre** is also greater in a large cell, and diffusion is only fast over short distances, so the **centre would be starved** of oxygen and nutrients.	Add the second consequence — the diffusion distance.

Working	Comment
Because a cell that grew too big could not keep itself supplied, **cells are limited in size and stay small**.	State the conclusion the question asks for.

Example 3 — unscaffolded

Two cube-shaped model cells are compared: cell P has a side length of 2 μm and cell Q has a side length of 5 μm. Calculate the surface area to volume ratio of each, and state which cell exchanges materials with its surroundings more efficiently, justifying your answer.

For cell **P** (side 2 μm): SA = $6 \times (2)^2 = 6 \times 4 =$ **24 μm²**, V = $(2)^3 =$ **8 μm³**, so **SA:V = 24 : 8 = 3 : 1**. For cell **Q** (side 5 μm): SA = $6 \times (5)^2 = 6 \times 25 =$ **150 μm²**, V = $(5)^3 =$ **125 μm³**, so **SA:V = 150 : 125 = 1.2 : 1**. Cell **P** has the **higher SA:V** (3 : 1 compared with 1.2 : 1), so it has **more membrane surface for each unit of its volume** and can exchange materials with its surroundings **more efficiently** — every part of the smaller cell is kept supplied, whereas Q's larger volume is served by proportionally less membrane. ∴ the smaller cell P, with the higher surface area to volume ratio, exchanges materials more efficiently.

Example 4 — unscaffolded

A cell lining the small intestine has its surface folded into thousands of tiny finger-like projections called microvilli. Explain how the microvilli give the cell a high surface area to volume ratio, and why this helps the cell carry out its function.

The cell's job is to **absorb** the products of digestion from the gut, and that absorption happens **across its membrane**. Folding the surface into thousands of **microvilli greatly increases the membrane surface area without adding much to the cell's volume**, so the cell has a **high surface area to volume ratio**. Because a larger surface area allows **more to be absorbed per unit time**, the folded surface makes the cell far more effective at absorption than a smooth-surfaced cell of the same volume would be. ∴ the microvilli raise the cell's SA:V, and the extra surface area speeds up the absorption of nutrients across the membrane.

Practice questions

Scaffolded

Q1. Define each of the following terms: (a) surface area to volume ratio; (b) the surface area of a cell, and state what it determines for the cell; (c) the volume of a cell, and state what it determines for the cell.

Q2. A cell must exchange materials with its surroundings. (a) Name the structure across which a cell exchanges materials with its surroundings. (b) State whether the surface area of a cell represents its supply of, or its demand for, materials. (c) Explain why, for a cell to survive, its surface area must be large enough for its volume.

Q3. The surface area to volume ratio changes as a cell changes size. (a) State what happens to the SA:V ratio as a cell gets larger. (b) State whether surface area or volume increases faster as a cell gets larger. (c) Explain why doubling the side length of a cube-shaped cell does not double its SA:V ratio.

Q4. A cube-shaped model cell has a side length of 3 μm. (a) Calculate its surface area. (b) Calculate its volume. (c) Calculate its surface area to volume ratio, expressed as a ratio to 1.

Q5. Cells are limited in how large they can be. (a) State one reason a cell with a low SA:V cannot supply its whole volume. (b) State why the centre of a very large cell would be poorly supplied, even if enough materials could cross the membrane. (c) Explain why wastes build up inside a very large cell, even though a large cell has a bigger surface area than a small one.

Q6. Large eukaryotic cells contain internal membrane-bound compartments. (a) State what these internal compartments are called. (b) State one way that having internal compartments helps a large cell, in terms of surface area. (c) Explain how keeping different reactions in separate compartments helps a cell carry out many processes at once.

Unscaffolded

Q7. Define the surface area to volume ratio, and explain why a high SA:V is an advantage for the exchange of materials. *(3 marks)*

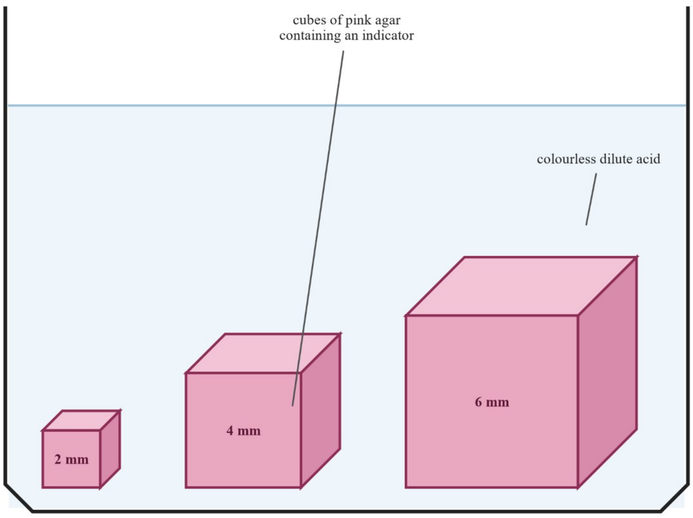
Q8. For a cell exchanging materials with its surroundings, distinguish between what its surface area represents and what its volume represents. *(3 marks)*

Q9. Cell X has a surface area of 800 μm^2 and a volume of 2000 μm^3. Cell Y has a surface area of 50 μm^2 and a volume of 20 μm^3. (a) Calculate the surface area to volume ratio of each cell, expressed as a ratio to 1. (b) Cell X has sixteen times the surface area of cell Y, yet it is far less able to keep the whole of its volume supplied. Explain why. *(4 marks)*

Q10. Explain why the innermost region of a very large cell would not be adequately supplied with oxygen, even though oxygen is able to cross the plasma membrane. *(3 marks)*

Q11. A cell in the wall of an air sac in the lungs, where gases are exchanged with the air, is extremely flat and thin. (a) Explain how being flat and thin gives the cell a high surface area to volume ratio. (b) Explain how this shape helps the cell carry out gas exchange. *(3 marks)*

Q12. *(Stimulus.)* Cubes of pink agar containing an indicator are placed in a beaker of colourless dilute acid, as shown below. As the acid diffuses into a cube, it turns the agar colourless. The set-up is shown at the start.



cubes drawn to scale; shown at the start, before the acid has begun to diffuse into them

(a) Calculate the surface area to volume ratio of the 2 mm cube and of the 6 mm cube.
(b) Predict which cube will become colourless all the way to its centre first, and justify your answer using the surface area to volume ratio.
(c) All three cubes are placed in the same beaker of acid at the same time. State one other variable that must be kept the same for all three cubes if any difference in the time they take to decolourise is to be due to their size alone. *(5 marks)*

Q13. *(Data interpretation.)* Four cube-shaped model cells of different sizes were studied. For each, the table shows the side length, the surface area to volume ratio, and the percentage of the cell's volume that received an adequate supply of oxygen by diffusion in a fixed time.

Side length (µm)	SA:V (: 1)	Volume adequately supplied (%)
10	0.6	100
20	0.3	78
30	0.2	55
40	0.15	40

(a) Describe the relationship between the SA:V ratio and the percentage of the volume adequately supplied.
(b) Explain this relationship in terms of surface area to volume ratio and diffusion distance.
(c) Identify the independent variable and the dependent variable in this investigation, and predict the percentage adequately supplied for a model cell of side length 50 μm. *(5 marks)*

Q14. Explain two ways in which dividing a large eukaryotic cell into internal membrane-bound compartments helps it to function. *(4 marks)*

Q15. A bacterium is about 2 μm across, while a typical human cell is about 20 μm across. Explain, in terms of the surface area to volume ratio, why the bacterium can carry out most of its chemical reactions and exchange at its plasma membrane, whereas the larger human cell relies on internal organelles. *(4 marks)*

Q16. Two cells have the same volume, but one is shaped like a sphere and the other is flattened and disc-shaped. (a) State which cell has the greater surface area to volume ratio. (b) Explain your answer, and state how this affects the rate at which the cell can exchange materials. *(3 marks)*

Q17. *(Suggest.)* An engineer proposes building an artificial cell shaped like a cube with a side length ten times that of a normal cell. (a) Explain two problems that the cell's surface area to volume ratio would cause. (b) Suggest one change to the cell's structure that would help overcome these problems, and explain how it would help. *(4 marks)*

Q18. *(Model evaluation.)* In a school investigation, cubes of agar are used as a model of living cells to study how size affects the exchange of substances. State one strength and two limitations of using agar cubes as a model of cells, and give an overall judgement of how useful the model is. *(4 marks)*

Q19. *(Synthesis.)* A student compares one large cube-shaped cell of side length 6 μm with eight small cube-shaped cells, each of side length 3 μm. Together the eight small cells have the same total volume as the one large cell ($8 \times 27 = 216$, and $6^3 = 216$). The large cell has a surface area of 216 μm^2 and a volume of 216 μm^3, so its surface area to volume ratio is 1 : 1; each small cell has a surface area of 54 μm^2 and a volume of 27 μm^3. (a) Calculate the total surface area of the eight small cells, and use it to state the surface area to volume ratio of the eight-cell arrangement as a whole. (b) Explain which arrangement — the one large cell or the eight small cells — can exchange materials with its surroundings more efficiently, and why. (c) Using surface area to volume ratio and diffusion distance, explain why large organisms are built from very many small cells rather than a few very large ones. (d) A real cell cannot solve its exchange problem by splitting into eight separate cells. Explain how a large eukaryotic cell instead deals with its low surface area to volume ratio from the inside. *(8 marks)*

Answers

Q1. (a) The surface area of a cell divided by its volume — how much exchange surface it has for each unit of volume. (b) The total area of the plasma membrane; it determines how fast the cell can exchange materials (its supply). (c) The amount of living material (cytoplasm); it determines how much material the cell uses and how much waste it makes (its demand). **Q2.** (a) The plasma (cell) membrane. (b) Its supply. (c) The surface must be able to exchange materials fast enough to meet the demands of the whole volume; if the surface is too small for the volume, supply cannot keep up and the cell cannot survive. **Q3.** (a) It decreases (falls). (b) Volume increases faster. (c) Volume grows with side^3 while surface area grows only with side^2, so doubling the side multiplies surface area by 4 but volume by 8, halving the SA:V rather than keeping it the same. **Q4.** (a) 54 μm^2. (b) 27 μm^3. (c) 54 : 27 = 2 : 1. **Q5.** (a) The volume's demand for materials is greater than the small surface can supply. (b) The centre is too far from the membrane for diffusion, which is only fast over short distances, to supply it. (c) Volume grows faster than surface area, so a large cell has less membrane for each unit of volume; its greater volume of cytoplasm makes more waste than the relatively smaller membrane can remove, so waste builds up. **Q6.** (a) Organelles. (b) The internal membranes add extra membrane surface inside the cell for reactions to happen on. (c) Each reaction has its own compartment with its own conditions, so reactions do not interfere and many can run at once. **Q7.** The surface area divided by the volume (the exchange surface per unit of volume); a high SA:V means a large membrane area for the volume, so materials are exchanged fast enough to supply the whole cell. **Q8.** Surface area is the membrane area available for exchange and sets the cell's supply; volume is the amount of cytoplasm and sets the cell's demand for materials and its waste production. **Q9.** (a) Cell X: 800 : 2000 = 0.4 : 1; cell Y: 50 : 20 = 2.5 : 1. (b) What counts is the surface available for each unit of volume, not the total surface: X's volume is 100 times Y's while its surface area is only 16 times, so X has the far lower SA:V (0.4 : 1 against 2.5 : 1) and its membrane cannot meet the demands of its large volume. **Q10.** The cell's low SA:V means too little membrane for the volume, and the centre is too far from the membrane for diffusion (fast only over short distances) to supply it, so oxygen is used up before it reaches the middle. **Q11.** (a) A flat, thin shape gives a large surface area for a very small volume, so a high SA:V. (b) The large surface and short distance across the thin cell let gases diffuse in and out quickly. **Q12.** (a) 2 mm cube: 24 : 8 = 3 : 1; 6 mm cube: 216 : 216 = 1 : 1. (b) The 2 mm cube, because its higher SA:V and shorter distance to the centre let the acid diffuse throughout it fastest. (c) e.g. the agar itself — every cube must be made from the same agar with the same concentration of indicator (or: each cube must be completely surrounded by the acid), so that only size differs. **Q13.** (a) As the SA:V ratio decreases (cells get larger), the percentage of the volume adequately supplied decreases. (b) A lower SA:V means less membrane per unit volume, so exchange cannot keep up, and the greater diffusion distance to the centre leaves the interior under-supplied. (c) IV = side length (size) of the cell; DV = percentage of the volume adequately supplied; a 50 µm cell (SA:V 0.12 : 1) would be supplied to well under 40% (e.g. about 25–30%). **Q14.** Any two of: the internal membranes add extra surface area for reactions; each process gets its own compartment and conditions; reactions that would interfere are kept apart; many processes can run at once (division of labour). **Q15.** The bacterium is small with a high SA:V, so its plasma membrane provides enough surface for exchange and reactions; the larger human cell has a low SA:V, so it needs internal membranes/organelles to add surface and localise its functions. **Q16.** (a) The flattened, disc-shaped cell. (b) A sphere has the smallest surface area for a given volume, so flattening it increases surface area without changing volume, raising the SA:V; a higher SA:V means faster exchange. **Q17.** (a) Its low SA:V means the surface is too small to supply the huge volume, and the centre is too far from the membrane for diffusion. (b) e.g. fold/flatten the surface to increase surface area, or divide the interior into compartments — this raises the working surface and shortens diffusion distances. **Q18.** Strength: size can be changed and diffusion measured easily and safely, showing the SA:V effect clearly. Limitations: agar is not alive (no metabolism), cells are not cube-shaped, and there is no membrane/transport proteins/organelles. Judgement: useful for showing the geometric SA:V effect but not a full model of a living cell. **Q19.** (a) Total SA of the eight small cells = 8 × 54 = 432 μm^2; their total volume is 216 μm^3, so the arrangement's SA:V = 432 : 216 = 2 : 1 — twice the large cell's 1 : 1. (b) The eight small cells, because for the same total volume they have a higher total SA:V, so they exchange materials more efficiently. (c) Small cells have a high SA:V and a short diffusion distance, so every cell is supplied; a few huge cells would have a low SA:V and long diffusion distances, starving their interiors. (d) It divides its interior into membrane-bound compartments (organelles), whose internal membranes add a great deal of extra working surface inside the cell and give each function its own space.

Fully-worked solutions

Q1. (a) The **surface area to volume ratio** is the **surface area of a cell divided by its volume** — that is, **how much exchange surface the cell has for each unit of its volume**. (b) The **surface area** is the **total area of the plasma membrane**; it determines **how fast the cell can exchange materials** with its surroundings — the cell's **supply**. (c) The **volume** is the **amount of living material (cytoplasm)** in the cell; it determines **how much material the cell uses and how much waste it makes** — the cell's **demand**.

Q2. (a) The **plasma (cell) membrane**. (b) Its **supply** — a larger surface area lets the cell take in and remove materials faster. (c) The surface is the only place exchange can happen, so it must be able to **take in materials, and remove wastes, fast enough to meet the demands of the whole volume**. If the surface is **too small for the volume**, supply cannot keep up with demand and the cell cannot survive.

Q3. (a) The SA:V ratio **decreases (falls)** as a cell gets larger. (b) **Volume** increases faster. (c) The **volume grows with side^3** but the **surface area only with side^2**, so doubling the side length multiplies the **surface area by 4** but the **volume by 8**. Because volume grows twice as much, the SA:V is **halved**, not kept the same — so it certainly does not double.

Q4. (a) **SA = 6 × side^2** = $6 \times (3)^2 = 6 \times 9$ = **54 µm^2**. (b) **V = side^3** = $(3)^3$ = **27 µm^3**. (c) **SA:V = 54 : 27**; dividing both by 27 gives **2 : 1**.

Q5. (a) The **demand of the large volume is greater than the small surface can supply**, so materials cannot be taken in (and wastes removed) fast enough. (b) The **centre is too far from the membrane**, and diffusion is **only fast over short distances**, so materials are used up before they reach the middle — the centre stays poorly supplied even if the surface could admit enough. (c) A large cell does have a **bigger surface area** than a small one, but its **volume has grown faster still** (volume with side^3, surface area only with side^2), so it has **less membrane for each unit of its volume** — a **low SA:V**. Its **larger volume of cytoplasm makes more waste**, while the relatively **smaller membrane can remove that waste only so fast**, so waste is produced faster than it can leave and **builds up inside the cell**.

Q6. (a) **Organelles** (membrane-bound compartments). (b) The **internal membranes add extra membrane surface area inside the cell** for reactions to take place on. (c) Each reaction is carried out in its **own compartment**, which can hold its **own enzymes and conditions**; this keeps reactions that would **interfere with one another apart**, so the cell can run **many different processes at the same time**.

Q7. The **surface area to volume ratio** is the **surface area divided by the volume** — the amount of **exchange surface per unit of volume**. A **high SA:V** is an advantage because it means the cell has a **large membrane area for the amount of cytoplasm it must supply**, so materials can be taken in and wastes removed **fast enough to keep the whole cell supplied**. *(1 mark: SA:V defined as surface area ÷ volume; 1 mark: high SA:V = large surface for the volume; 1 mark: so exchange keeps up with the cell's needs.)*

Q8. A cell's **surface area** is the **area of plasma membrane available for exchange**, and it represents the cell's **supply** — the rate at which it can take in and remove materials. Its **volume** is the **amount of cytoplasm**, and it represents the cell's **demand** — how much material the volume uses and how much waste it produces. So surface area is about **supply across the membrane** while volume is about **demand within the cell**. *(1 mark: surface area = membrane area / supply; 1 mark: volume = cytoplasm / demand; 1 mark: a clear two-sided contrast of supply against demand.)*

Q9. (a) **Cell X:** SA:V = **800 : 2000**; dividing both numbers by 2000 gives **0.4 : 1**. **Cell Y:** SA:V = **50 : 20**; dividing both by 20 gives **2.5 : 1**. (b) What decides whether a cell can keep itself supplied is **not its total surface area but the surface it has for each unit of its volume**. Cell X's **volume is 100 times** cell Y's (2000 µm^3 against 20 µm^3) while its **surface area is only 16 times** greater, so **each unit of X's cytoplasm is served by far less membrane** — X's SA:V (**0.4 : 1**) is much lower than Y's (**2.5 : 1**). The **demand of X's large volume therefore outstrips what its surface can supply**, and materials must also travel much further to reach its interior, so X is the less well supplied cell despite its far larger surface area. *(a: 1 mark — cell X = 0.4 : 1; 1 mark — cell Y = 2.5 : 1; b: 1 mark — it is surface per unit volume that matters: X's volume is 100× but its surface only 16×, so X has the lower SA:V; 1 mark — so its surface cannot meet the demand of its large volume / its interior is further from the membrane.)*

Q10. The innermost region is poorly supplied for two linked reasons. First, a very large cell has a **low surface area to volume ratio**, so the membrane is **too small to supply the demands of the large volume**. Second, and more importantly here, the **centre is a long way from the membrane**, and oxygen moves through the cytoplasm by **diffusion, which is only fast over very short distances**; oxygen is **used up by the cell before it can diffuse all the way to the centre**, so the innermost region is left short of oxygen even though oxygen can cross the membrane at the surface. *(1 mark: large cell has a low SA:V / too little surface for the volume; 1 mark: the centre is far from the membrane; 1 mark: diffusion is slow over that distance, so oxygen is used up before reaching the centre.)*

Q11. (a) A **flat, thin** cell has a **large surface area** (its broad flat faces) for a **very small volume**, so it has a **high surface area to volume ratio**. (b) The **large surface area** provides plenty of membrane for gases to cross, and because the cell is **thin the distance the gases must diffuse is very short**; together these let **oxygen and carbon dioxide be exchanged quickly** between the air and the cell, which suits its role in gas exchange. *(a: 1 mark — flat/thin = large surface for a small volume, so high SA:V; b: 1 mark — large surface area allows rapid exchange; 1 mark — short diffusion distance across the thin cell speeds exchange.)*

Q12. (a) **2 mm cube:** SA = 6 × $(2)^2$ = **24 mm²**, V = $(2)^3$ = **8 mm³**, so SA:V = 24 : 8 = **3 : 1**. **6 mm cube:** SA = 6 × $(6)^2$ = **216 mm²**, V = $(6)^3$ = **216 mm³**, so SA:V = 216 : 216 = **1 : 1**. (b) The **2 mm cube** will become colourless all the way to its centre **first**. It has the **higher SA:V (3 : 1 versus 1 : 1)**, so it has more surface for the acid to enter through relative to its volume, and its **centre is a much shorter distance from the surface**, so the acid diffuses throughout it fastest. (c) Because all three cubes sit in the **same beaker for the same time**, the **concentration, volume and temperature of the acid are already the same** for each of them. What must still be kept the same is the **agar itself** — every cube must be made from the **same agar, with the same concentration of indicator** — and each cube must be **completely surrounded by the acid**. Only then can a difference in the time taken to decolourise be put down to the cubes' **size (their SA:V)** rather than to some other difference between them. *(a: 1 mark — 2 mm cube = 3 : 1; 1 mark — 6 mm cube = 1 : 1; b: 1 mark — predicts the 2 mm cube; 1 mark — justified by its higher SA:V / shorter diffusion distance; c: 1 mark — one valid controlled variable.)*

Q13. (a) As the **SA:V ratio decreases** (the cells get larger), the **percentage of the volume adequately supplied decreases —** the two fall together. (b) A **lower SA:V** means there is **less membrane for each unit of volume**, so materials cannot be exchanged fast enough to supply all of the cytoplasm; at the same time the **greater distance from the surface to the centre** means diffusion cannot reach the deep interior quickly, so a **smaller percentage of the volume is adequately supplied**. (c) The **independent variable is the side length (size) of the model cell**; the **dependent variable is the percentage of the volume adequately supplied**. A 50 µm cell would have an even lower SA:V (0.12 : 1), so it would be adequately supplied to **well under 40%** — for example about **25–30%**. *(a: 1 mark — lower SA:V goes with a lower percentage supplied; b: 1 mark — lower SA:V = less surface per volume, so exchange cannot keep up; 1 mark — longer diffusion distance leaves the interior under-supplied; c: 1 mark — IV = side length/size and DV = percentage adequately supplied; 1 mark — a prediction below 40%.)*

Q14. Any **two** of the following, each explained: (i) the **internal membranes add a large amount of extra membrane surface inside the cell**, giving more working surface for reactions than the outer membrane alone could provide, which helps make up for the cell's low SA:V; (ii) **each process is given its own compartment with its own enzymes and conditions**, so a reaction runs efficiently in its own space and **reactions that would interfere with one another are kept apart**; (iii) because the work is shared out among compartments (a **division of labour**), the cell can **carry out many different processes at the same time**. *(1 mark: state the first way; 1 mark: explain the first way; 1 mark: state the second way; 1 mark: explain the second way.)*

Q15. The bacterium is **small (about 2 µm)**, so it has a **high surface area to volume ratio**: its **plasma membrane provides enough surface**, relative to its small volume, for it to **exchange materials and carry out most of its chemical reactions at or just inside the membrane**. The human cell is **much larger (about 20 µm)**, so it has a **low surface area to volume ratio**: its plasma membrane alone **cannot provide enough surface** for its large volume, so it relies on **internal membrane-bound organelles** to **add working surface inside the cell and to localise its many functions** in separate compartments. *(1 mark: bacterium is small = high SA:V; 1 mark: so its plasma membrane suffices for exchange/reactions; 1 mark: human cell is larger = low SA:V; 1 mark: so it needs internal organelles to add surface / localise functions.)*

Q16. (a) The **flattened, disc-shaped cell** has the greater surface area to volume ratio. (b) A **sphere has the smallest possible surface area for a given volume**, so a spherical cell has the lowest SA:V; **flattening the cell into a disc increases its surface area while its volume stays the same**, which **raises the SA:V**. A **higher SA:V means more membrane surface for the same volume**, so the flattened cell can **exchange materials faster** than the spherical one.

(a: 1 mark — the flattened disc-shaped cell; b: 1 mark — a sphere has the least surface area for a given volume, so flattening adds surface without adding volume, raising SA:V; 1 mark — higher SA:V means faster exchange.)

Q17. (a) Because the cell's side length is ten times normal, its **volume (side^3) is far larger relative to its surface area (side^2)**, giving it a **very low SA:V**, which causes two problems: its **surface is too small to supply the demands of its huge volume**, so materials cannot be exchanged fast enough; and its **centre is far too distant from the membrane** for diffusion, which is only fast over short distances, to supply it. (b) Any one suitable change, explained — for example **folding or flattening the surface to greatly increase the surface area** (raising the SA:V so more can be exchanged), or **dividing the interior into membrane-bound compartments** (adding internal working surface and shortening the distances substances must travel). *(a: 1 mark — surface too small for the volume (low SA:V); 1 mark — centre too far for diffusion; b: 1 mark — a valid structural change; 1 mark — explains how it raises surface area / shortens diffusion distance.)*

Q18. A **strength** of the model is that the **size of the "cell" can be changed easily and the diffusion of the acid measured directly and safely**, so it **clearly demonstrates how SA:V affects the rate of exchange**. Two **limitations**: agar cubes are **not alive** — they do **not respire or use up the diffusing substance** the way a real cell does; and they are **not realistic cells** — real cells are **not cube-shaped** and, unlike solid agar, have a **selectively permeable membrane with transport proteins and internal organelles**, so substances enter a real cell by more than simple diffusion. **Overall judgement:** the model is **useful for showing the geometric surface-area-to-volume effect**, but it should **not be taken as a complete picture of a living cell**. *(1 mark: one valid strength; 2 marks: two valid limitations; 1 mark: a reasoned overall judgement.)*

Q19. (a) Each small cell has a surface area of 54 µm^2, so the **eight small cells together have $8 \times 54 = 432$ µm^2 of membrane**, while their **total volume is still 216 µm^3** — the same volume of living material as the single large cell. The arrangement's ratio is therefore **432 : 216 = 2 : 1**, which is **twice the large cell's 1 : 1**: dividing the same volume into eight cells serves it with **twice as much membrane**. (b) The **eight small cells** can exchange materials more efficiently. Although the eight together have the **same total volume** as the one large cell, each small cell has a **higher SA:V**, so the eight cells provide a **greater total membrane surface for that same volume**, letting materials be exchanged fast enough throughout. (c) Building an organism from **many small cells** keeps each cell's **SA:V high and its diffusion distances short**, so **every cell can be kept supplied** with materials and cleared of wastes. A few **very large cells** would each have a **low SA:V** and a **long distance from surface to centre**, so their interiors would be **starved** — which is why large organisms are made of very many small cells. (d) A real cell cannot divide itself into eight and still be one cell, so a large eukaryotic cell deals with its low SA:V **from the inside**: it divides its interior into **membrane-bound compartments (organelles)**. Their **internal membranes add a great deal of extra working surface within the cell**, far more than the plasma membrane alone provides, and each compartment **holds one function with its own enzymes and conditions**, so the cell's reactions are no longer confined to the surface of a single open space. *(a: 1 mark — total surface area of the eight small cells = $8 \times 54 = 432$ µm^2; 1 mark — 432 : 216 = 2 : 1, twice the large cell's 1 : 1; b: 1 mark — the eight small cells are more efficient; 1 mark — because they give a higher total SA:V for the same volume; c: 1 mark — small cells keep a high SA:V and short diffusion distance so all are supplied; 1 mark — a huge cell would have a low SA:V and long diffusion distance, starving its centre; d: 1 mark — divides its interior into membrane-bound compartments (organelles); 1 mark — the internal membranes add working surface inside the cell / localise each function.)*

Chapter 2 Cell function and membrane transport — 2D Photosynthesis and cellular respiration

Theory

A cell is a busy chemical factory. To stay alive it must constantly do **work** — pumping substances across its membrane by active transport (2A), building large molecules such as proteins, and, in many cells, moving. All of this work needs a supply of **energy**. Energy is never made from nothing; it is **transformed** from one form into another. Two organelles are specialised for the cell's energy transformations, and you met their **structure** in 1D: the **chloroplast** and the **mitochondrion**. This subtopic is about their **function** — exactly **what goes into and what comes out of** each one.

ATP — the cell's usable energy. The energy a cell can actually use to do work is carried by a molecule called **ATP** (adenosine triphosphate). ATP acts like a rechargeable energy "currency": when the cell needs energy for a task, energy is released from ATP; the cell then remakes its ATP using energy from food. At this level you do not need the chemical detail of ATP — only that **ATP is the form of energy the cell can use**, and that the job of cellular respiration is to keep the cell supplied with it.

Photosynthesis — the function of the chloroplast. Photosynthesis is the process that **captures light energy and uses it to build glucose**. It takes place in the **chloroplasts**, which are found **only in plant cells and algae**. Its energy transformation is:

light energy → chemical energy stored in glucose.

The **inputs** (raw materials) of photosynthesis are **carbon dioxide** and **water**, together with the **light energy** that the green pigment **chlorophyll** (held in the thylakoid membranes of the chloroplast — see 1D) absorbs. The **outputs** (products) are **glucose**, in which the captured energy is now stored, and **oxygen**, which is released. In words:

carbon dioxide + water → glucose + oxygen (using **light energy**)

The overall reaction can be summarised as:

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ (light energy absorbed, in the chloroplast)

Photosynthesis **builds up** (makes) glucose, so it **stores** energy. It can only happen **when light is available**, and only in cells that contain chloroplasts.

Cellular respiration — the function of the mitochondrion. Cellular respiration does, in effect, the opposite job: it **breaks down glucose to release the chemical energy stored in it** and transfers that energy to **ATP**, which the cell can then use. The form studied here is **aerobic** cellular respiration — "aerobic" means it **requires oxygen** — and it takes place in the **mitochondria**. Crucially, mitochondria are found in **both plant and animal cells**, so **all these cells respire**. Its energy transformation is:

chemical energy stored in glucose → ATP (the cell's usable energy).

The **inputs** of aerobic respiration are **glucose** and **oxygen**; the **outputs** are **carbon dioxide** and **water**, plus the **energy transferred to ATP**. In words:

glucose + oxygen → carbon dioxide + water (+ energy released as **ATP**)

The overall reaction can be summarised as:

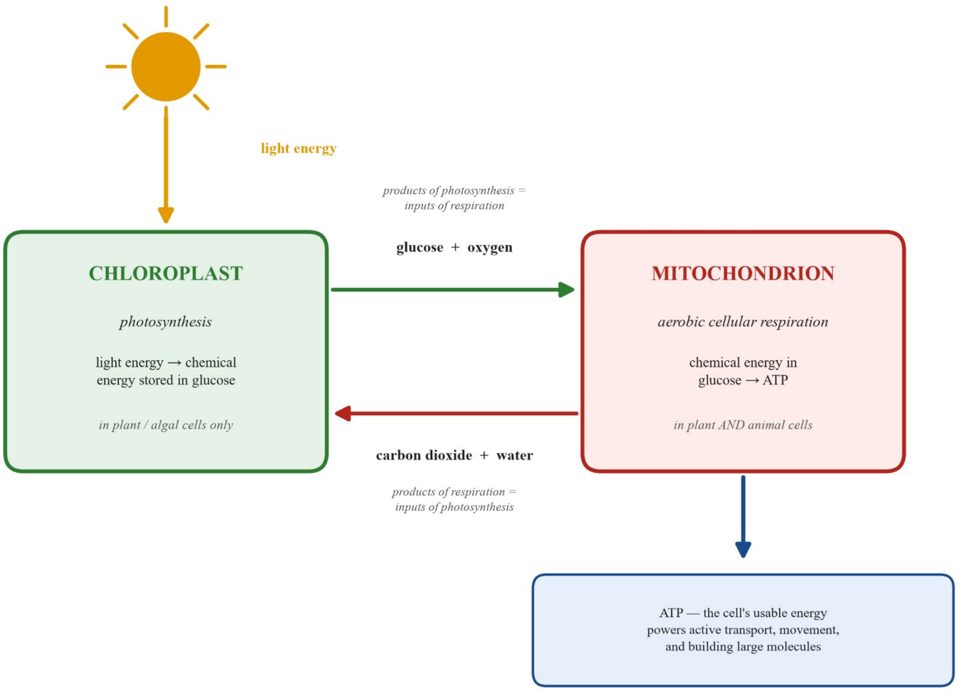
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ (+ energy for making ATP, in the mitochondrion)

The many folds (**cristae**) of the mitochondrion's inner membrane (see 1D) give a large surface area on which these reactions can take place, which is why cells with a high energy demand contain many mitochondria. Cellular respiration **breaks down** glucose, so it **releases** energy, and it happens **continuously — day and night — in both plant and animal cells**, because a cell always needs ATP.

Comparing the two processes. The chloroplast and the mitochondrion carry out almost opposite jobs:

Feature	Chloroplast — photosynthesis	Mitochondrion — aerobic respiration
Energy transformation	light energy → chemical energy in glucose	chemical energy in glucose → ATP
Effect on glucose	**builds up** (makes) glucose — stores energy	**breaks down** glucose — releases energy
Inputs (raw materials)	carbon dioxide + water (+ light energy)	glucose + oxygen
Outputs (products)	glucose + oxygen	carbon dioxide + water (+ ATP)
Found in which cells	plant and algal cells only (need chloroplasts)	all respiring cells — plant **and** animal
When it occurs	only when light is available	continuously, day and night

How the two processes fit together. Look carefully at the two rows of inputs and outputs and you will see that **the outputs of one process are the inputs of the other**. The glucose and oxygen made by photosynthesis are exactly what respiration needs; the carbon dioxide and water made by respiration are exactly what photosynthesis needs. The two processes are therefore described as **complementary**, and the matter (the carbon, hydrogen and oxygen atoms) is **cycled** between them:



Two ideas are worth separating here. **Matter is recycled** — the same atoms pass back and forth between the processes. But **energy flows one way**: light energy is captured and stored in glucose, then released and transferred to ATP, and is finally lost from the cell as **heat** when ATP is used. Because that heat cannot be recaptured, living things need a **continuous input of light energy** (from the Sun) to keep going.

Plant cells versus animal cells. A **plant cell** contains **both** chloroplasts and mitochondria, so in the light it can make glucose by photosynthesis **and** break glucose down by respiration to supply its ATP. An **animal cell** has **mitochondria but no chloroplasts**, so it **cannot make its own glucose** — it must **obtain glucose from food** (ultimately from plants) and then respire it. This is why, in the end, almost all life depends on photosynthesis: it is the process that captures the Sun's energy and stores it in the glucose that respiration later releases.

> **Common misconception.** Because a plant releases oxygen in the light, students often think plants "only respire at night" or "photosynthesise instead of respiring". In fact plant cells **respire all the time**; in the

light they simply photosynthesise *as well*, and usually make oxygen faster than they use it, which hides the respiration going on underneath.

Worked examples

Example 1 — scaffolded

A cell in the green leaf of a plant is brightly lit. Name the process that captures the light energy, state the organelle in which it occurs, list its inputs and outputs, and describe the energy transformation involved.

Working	Comment
The process is **photosynthesis**, which occurs in the **chloroplast** (present in this leaf cell).	Name the process and the specialised organelle first.
Its **inputs** are **carbon dioxide** and **water**, together with the **light energy** absorbed by chlorophyll.	Inputs = the raw materials taken in (plus the energy source).
Its **outputs** are **glucose** and **oxygen**.	Outputs = the products made.
In words: **carbon dioxide + water → glucose + oxygen** (using light energy).	A word equation shows the inputs and outputs together.
The energy transformation is **light energy → chemical energy stored in glucose** — the process **builds up** glucose, storing energy.	Describe the change in the *form* of energy, not just “energy is used”.

Example 2 — scaffolded

A muscle cell is contracting hard and needs a large, steady supply of usable energy. Name the process that supplies this energy, state the organelle involved, give its inputs and outputs, and explain the energy transformation.

Working	Comment
The process is **aerobic cellular respiration**, which occurs in the **mitochondria**.	Name the process and organelle.
Its **inputs** are **glucose** and **oxygen**; “aerobic” tells you **oxygen is required**.	Two inputs — remember oxygen, not just glucose.
Its **outputs** are **carbon dioxide** and **water**, and the **energy transferred to ATP**.	Outputs include the waste products *and* the useful ATP.
The energy transformation is **chemical energy stored in glucose → ATP**; respiration **breaks down** glucose to release its energy.	State the change in energy form; respiration releases (does not store) energy.
The muscle cell has a **high energy demand**, so it needs a steady supply of **ATP** from respiration to keep contracting.	Link the ATP back to the cell’s need for energy.

Example 3 — unscaffolded

Explain why photosynthesis and aerobic cellular respiration are described as **complementary** processes. In your answer, refer to the inputs and outputs of each.

The two processes are complementary because **the outputs of one are the inputs of the other**. The **outputs of photosynthesis are glucose and oxygen** — and these are exactly the **inputs of aerobic respiration**. The **outputs of respiration are carbon dioxide and water** — and these are exactly the **inputs of photosynthesis**. So the matter (the carbon, hydrogen and oxygen atoms) is passed back and forth, or **cycled**, between the two processes: what one process releases, the other takes in. ∴ photosynthesis and respiration are complementary because each supplies the raw materials that the other uses, so matter cycles between them.

Example 4 — unscaffolded

A student argues: "Plant cells make their own glucose by photosynthesis, so they have no need for mitochondria." Explain why this reasoning is wrong.

The reasoning is wrong because **photosynthesis and respiration do different jobs**. Photosynthesis **stores** energy by building glucose, but it does **not** supply the cell with **ATP**, the form of energy the cell actually uses for its work; and it only runs **when there is light**. To get usable energy, a plant cell must **break the glucose back down by cellular respiration**, which happens in its **mitochondria** and supplies **ATP continuously, day and night**. So a plant cell needs **both** organelles: **chloroplasts** to capture light and make glucose, and **mitochondria** to release that glucose's energy as ATP. ∴ plant cells do need mitochondria, because photosynthesis makes food but only respiration provides the ATP the cell uses.

Practice questions

Scaffolded

Q1. Define each of the following terms: (a) photosynthesis; (b) cellular respiration; (c) ATP.

Q2. Photosynthesis is one of the two key energy processes in cells. (a) Name the organelle in which photosynthesis occurs. (b) State the two raw-material inputs of photosynthesis (other than light energy). (c) State the two outputs (products) of photosynthesis.

Q3. Aerobic cellular respiration supplies a cell with usable energy. (a) Name the organelle in which aerobic cellular respiration occurs. (b) State the two inputs of aerobic cellular respiration. (c) State the two waste products of aerobic cellular respiration, and name the useful form of energy it supplies to the cell.

Q4. Both processes involve a transformation of energy. (a) Describe the energy transformation that takes place in photosynthesis. (b) Describe the energy transformation that takes place in cellular respiration. (c) State why a cell must carry out cellular respiration.

Q5. The two organelles are not found in every cell. (a) State which type(s) of cell can carry out photosynthesis. (b) State which type(s) of cell carry out cellular respiration. (c) Name the organelle an animal cell uses to release energy from glucose, and state whether animal cells contain chloroplasts.

Q6. The two processes can be written as word equations. (a) Write the word equation for photosynthesis. (b) Write the word equation for aerobic cellular respiration. (c) State the relationship you notice between the two word equations.

Unscaffolded

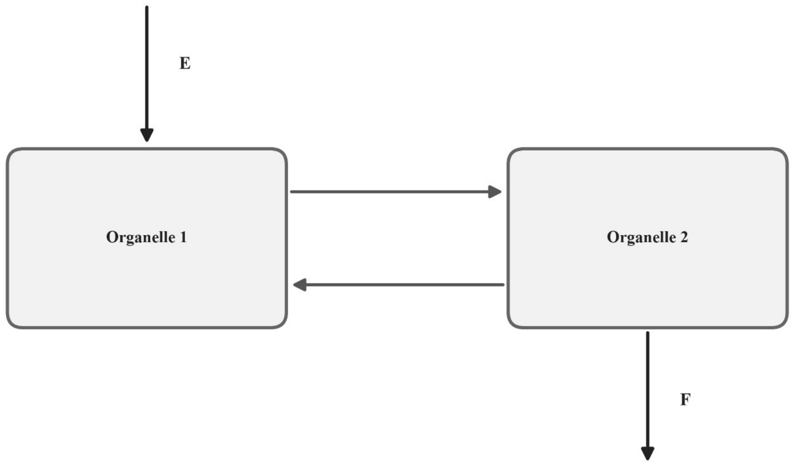
Q7. Distinguish between photosynthesis and cellular respiration, with reference to the energy transformation each carries out and whether it builds up or breaks down glucose. *(3 marks)*

Q8. A carbon atom is part of a carbon dioxide molecule in the air around a plant. Describe how, through photosynthesis and then cellular respiration in that plant, the carbon atom could end up in a carbon dioxide molecule once again. *(3 marks)*

Q9. Animal cells cannot photosynthesise, yet they still need glucose in order to respire. Explain where an animal obtains this glucose, and explain why an animal ultimately depends on photosynthesis in plants. *(3 marks)*

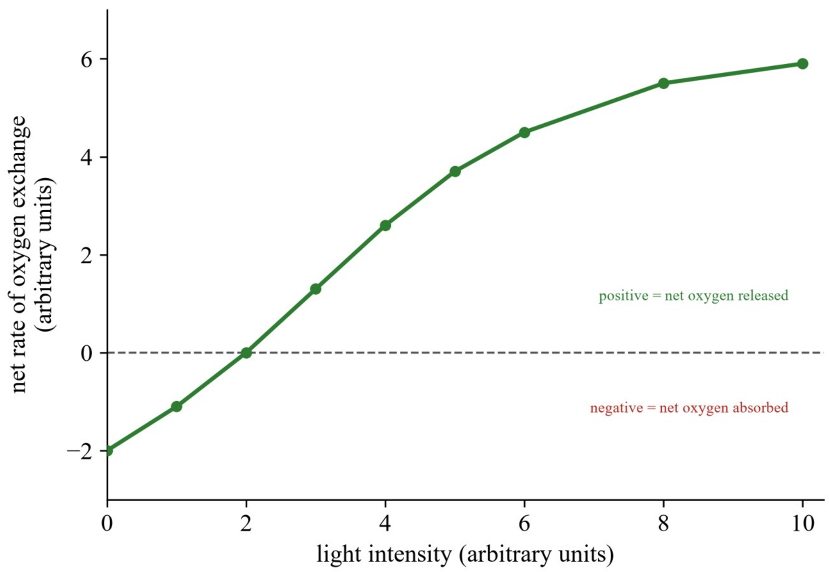
Q10. A student states that plants respire only at night, when they are not photosynthesising. Explain why this statement is incorrect. *(3 marks)*

Q11. *(Stimulus.)* The diagram shows two organelles in a plant cell and the movement of substances and energy between them and the rest of the cell. The organelles are labelled Organelle 1 and Organelle 2; E is an energy input and F is a useful energy output.



(a) Name the process carried out in Organelle 1 and the process carried out in Organelle 2.
(b) State what form of energy the input labelled E is.
(c) Name the useful output labelled F, and state one use the cell makes of it. *(5 marks)*

Q12. *(Data interpretation.)* A green water plant was kept at different light intensities and the **net** rate of oxygen exchange with the water was measured. The results are shown below.



(a) Explain why the plant showed a net **absorption** of oxygen at a light intensity of zero (in the dark).
(b) Explain why the plant showed a net **release** of oxygen at high light intensity.
(c) At one light intensity the net exchange of oxygen was zero. Use the graph to state this light intensity, and state what a net exchange of zero tells you about the rates of the two processes occurring in the plant. *(4 marks)*

Q13. Active transport across the plasma membrane (subtopic 2A) requires a supply of ATP. Explain how cellular respiration provides this ATP, and name the organelle responsible. *(2 marks)*

Q14. Cellular respiration in the mitochondria is described as aerobic. (a) State what the term “aerobic” means. (b) The oxygen supply to a group of cells is reduced. Predict and explain the effect this has on the amount of ATP the cells’ mitochondria can produce. *(3 marks)*

Q15. *(Investigation design.)* A student investigates how light intensity affects the rate of photosynthesis in pondweed. She places a piece of pondweed in water and counts the number of oxygen bubbles it releases each minute while a lamp is held at different distances from it. (a) Identify the independent variable and the dependent variable in this investigation. (b) State one variable that must be kept constant, and explain why it must be controlled. (c) Explain one reason why counting bubbles is only an approximate measure of the rate of photosynthesis. *(5 marks)*

Q16. *(Model evaluation.)* The relationship between the two processes is often modelled, as it is in this subtopic, by two boxes — one for the chloroplast and one for the mitochondrion — joined by a pair of equal arrows, with the products of each process becoming the raw materials of the other. State one strength of this model, two of its limitations, and give an overall judgement of how useful it is. *(4 marks)*

Q17. A palisade cell from a leaf and a cell from deep inside a root come from the same plant. The leaf palisade cell contains many chloroplasts; the root cell contains none. (a) State which of the two cells can carry out photosynthesis and which can carry out only respiration, and justify your answer. (b) State where the root cell obtains the glucose that it respires. *(3 marks)*

Q18. Biologists say that in living systems "energy flows through, but matter is recycled". Using photosynthesis and cellular respiration, explain this statement. *(3 marks)*

Q19. *(Synthesis.)* A researcher seals a small green water plant in a transparent, airtight tube of water. The water contains an indicator that changes colour with the amount of dissolved **carbon dioxide**. The tube is kept in bright light for several hours and then moved into darkness. (a) In bright light, the amount of dissolved carbon dioxide in the tube **falls**. Name the process responsible and explain, in terms of its inputs and outputs, why the carbon dioxide level falls. (b) In the dark, the amount of dissolved carbon dioxide **rises**. Name the process now responsible and explain why the carbon dioxide level rises. (c) The researcher also sets up a second, identical tube of water and indicator containing **no plant**, and keeps it beside the first tube throughout. Explain why this second tube is included, and state the result expected in it. (d) The researcher repeats the experiment with a small water **animal** (a snail) in place of the plant, kept in bright light. Predict how the dissolved carbon dioxide would change, and explain your prediction. *(8 marks)*

Answers

Q1. (a) The process, in chloroplasts, that uses light energy to build glucose from carbon dioxide and water (releasing oxygen). (b) The process, in mitochondria, that breaks down glucose using oxygen to release its energy as ATP (producing carbon dioxide and water). (c) The molecule that stores and supplies energy in a form the cell can use for its activities. **Q2.** (a) The chloroplast. (b) Carbon dioxide and water. (c) Glucose and oxygen. **Q3.** (a) The mitochondrion. (b) Glucose and oxygen. (c) Carbon dioxide and water; the useful energy form is ATP. **Q4.** (a) Light energy → chemical energy stored in glucose. (b) Chemical energy in glucose → ATP. (c) To release the energy stored in glucose as ATP, the usable energy the cell needs for its activities. **Q5.** (a) Cells that contain chloroplasts — plant and algal cells. (b) Both plant and animal cells — both contain mitochondria. (c) The mitochondrion; no, animal cells do not contain chloroplasts. **Q6.** (a) Carbon dioxide + water → glucose + oxygen (using light energy). (b) Glucose + oxygen → carbon dioxide + water (+ energy as ATP). (c) They are the reverse of each other — the inputs of one are the outputs of the other. **Q7.** Photosynthesis transforms light energy into chemical energy, building up glucose (stores energy); respiration breaks glucose down, transferring its chemical energy to ATP (releases energy). **Q8.** The carbon dioxide is used in photosynthesis and the carbon atom is built into glucose; the plant then respires that glucose, breaking it down, and the carbon atom is released as carbon dioxide again (CO_2 → glucose → CO_2). **Q9.** Animals obtain glucose by eating food (plants, or animals that ate plants); that glucose was originally made by photosynthesis in plants, so animals ultimately depend on plant photosynthesis (for glucose and oxygen). **Q10.** Incorrect — plant cells respire continuously, day and night; in the light they also photosynthesise, and usually release oxygen faster than they use it, which hides the respiration. **Q11.** (a) Organelle 1 = photosynthesis; Organelle 2 = (aerobic cellular) respiration. (b) Light energy. (c) F is ATP; used for e.g. active transport, movement, or building large molecules. **Q12.** (a) In the dark there is no photosynthesis, so only respiration occurs, using up oxygen → net absorption. (b) In bright light photosynthesis exceeds respiration, producing more oxygen than is used → net release. (c) At a light intensity of 2 arbitrary units; the rate of photosynthesis exactly equals the rate of respiration. **Q13.** Respiration releases the energy in glucose as ATP, which powers active transport; this occurs in the mitochondrion. **Q14.** (a) Requires oxygen. (b) Less oxygen (a required input) means the rate of aerobic respiration falls, so the mitochondria produce less ATP. **Q15.** (a) IV = light intensity (lamp distance); DV = number of oxygen bubbles per minute (rate of photosynthesis). (b) e.g. temperature / carbon-dioxide concentration / the same pondweed — so it does not also affect the rate. (c) e.g. bubbles vary in size, or not all oxygen forms bubbles, so the count is only an estimate. **Q16.** Strength: it shows at a glance that the outputs of one process are the inputs of the other, so matter is cycled between them. Limitations: the equal arrows imply the two processes always run at the same rate; it is static, so it does not show that photosynthesis stops without light while respiration continues; it shows no amounts or scale; it does not show that the energy is finally lost as heat. Judgement: useful for showing the complementary input–output relationship, but not a complete picture. **Q17.** (a) The leaf palisade cell can photosynthesise (it has chloroplasts and light) as well as respire; the root cell can only respire (no chloroplasts, no light). (b) From the leaf cells — glucose made by photosynthesis is transported to the roots. **Q18.** Matter (the atoms in carbon dioxide, water, glucose and oxygen) cycles between the two processes; energy flows one way — light → chemical energy in glucose → ATP → lost as heat — so a continuous input of light energy is needed. **Q19.** (a) Photosynthesis; carbon dioxide is an input that is used up (built into glucose), so its level falls. (b) Respiration; carbon dioxide is an output, so it is released and its level rises. (c) It is the control: with no plant present, any colour change in the first tube can be attributed to the plant rather than to the light, the temperature or the water itself; no change would be expected in it. (d) Carbon dioxide would rise, because the animal has no chloroplasts and can only respire (releasing carbon dioxide), even in the light.

Fully-worked solutions

Q1. (a) **Photosynthesis** is the process, occurring in **chloroplasts**, that **uses light energy to build glucose from carbon dioxide and water**, releasing oxygen; its energy transformation is light energy → chemical energy stored in glucose. (b) **Cellular respiration** is the process, occurring in **mitochondria**, that **breaks down glucose (using oxygen) to release the chemical energy stored in it and transfer it to ATP**, producing carbon dioxide and water. (c) **ATP** is the molecule that **stores and supplies energy in a form the cell can use** for its activities (its usable energy "currency").

Q2. (a) The **chloroplast**. (b) **Carbon dioxide** and **water**. (c) **Glucose** and **oxygen**.

Q3. (a) The **mitochondrion**. (b) **Glucose** and **oxygen**. (c) The waste products are **carbon dioxide** and **water**; the useful form of energy it supplies is **ATP**.

Q4. (a) In photosynthesis, **light energy is transformed into chemical energy that is stored in glucose**. (b) In cellular respiration, the **chemical energy stored in glucose is transformed into ATP**, the cell's usable energy. (c) A cell must respire to **release the energy stored in glucose as ATP**, because ATP is the form of energy the cell needs to carry out its activities (such as active transport, movement and building molecules).

Q5. (a) Only cells that contain **chloroplasts** — that is, **plant and algal cells**. (b) **Both plant and animal cells** carry out aerobic cellular respiration, because **both types of cell contain mitochondria**. (c) An animal cell uses the **mitochondrion** to release energy from glucose; **no**, animal cells do **not** contain chloroplasts.

Q6. (a) **Carbon dioxide + water → glucose + oxygen** (using light energy). (b) **Glucose + oxygen → carbon dioxide + water** (+ energy released as ATP). (c) The two equations are the **reverse of each other**: the **inputs of one process are the outputs of the other**, which is why the processes are described as complementary.

Q7. In **photosynthesis**, **light energy is transformed into chemical energy stored in glucose**, and the process **builds up (makes) glucose** — so it **stores** energy. In **cellular respiration**, the **chemical energy stored in glucose is transferred to ATP**, and the process **breaks glucose down** — so it **releases** energy for the cell to use. The two are therefore opposite: one stores energy by building glucose, the other releases energy by breaking glucose down. *(1 mark: photosynthesis = light → chemical energy, builds up glucose; 1 mark: respiration = breaks down glucose, chemical energy → ATP; 1 mark: a clear two-sided contrast of stores vs releases / builds vs breaks.)*

Q8. First, the plant **takes in the carbon dioxide and uses it in photosynthesis**: carbon dioxide is an **input**, and the **carbon atom is built into a glucose molecule** (an output), where its energy is now stored. Later, the plant **respires that glucose in its mitochondria**, **breaking the glucose down**; carbon dioxide is an **output** of respiration, so the **carbon atom is released as carbon dioxide once again**. The same carbon atom has therefore passed **carbon dioxide → glucose → carbon dioxide**, showing how matter is cycled between the two processes. *(1 mark: carbon dioxide is used in photosynthesis and the carbon is built into glucose; 1 mark: the plant respires (breaks down) that glucose; 1 mark: the carbon is released as carbon dioxide again.)*

Q9. An animal cell has **no chloroplasts**, so it **cannot make its own glucose** by photosynthesis; instead it **obtains glucose from the food it eats** — from plants, or from other animals that ate plants — by digesting and absorbing it. That glucose **originally came from photosynthesis in plants**, and the oxygen the animal uses to respire it was also released by photosynthesis. So the animal **ultimately depends on plant photosynthesis** for both the glucose and the oxygen its respiration needs. *(1 mark: animals obtain glucose from food / by eating other organisms; 1 mark: that glucose was originally made by photosynthesis in plants; 1 mark: so the animal ultimately depends on photosynthesis for its glucose (and oxygen).)*

Q10. The statement is **incorrect**. **Plant cells respire continuously — day and night** — because they always need a supply of ATP for their activities. During the day, a plant cell **also photosynthesises** (while there is light), so **both processes occur at the same time**; because photosynthesis usually **produces oxygen faster than respiration uses it**, it can look as though the plant is only photosynthesising, but respiration is still going on underneath. At night there is no light, so **only respiration** occurs. Plants therefore respire **all the time**, not only at night. *(1 mark: plant cells respire continuously, day and night, because they always need ATP; 1 mark: in the light both photosynthesis and respiration occur together; 1 mark: photosynthesis in the light masks the respiration / at night only respiration occurs — correcting the misconception.)*

Q11. (a) **Organelle 1** carries out **photosynthesis** and **Organelle 2** carries out **aerobic cellular respiration**. (You can tell because the energy input E goes *into* Organelle 1, and only photosynthesis takes in energy from outside, while the useful energy output F comes *out of* Organelle 2, as respiration supplies the cell with usable energy.) (b) **E is light energy**. (c) **F is ATP**, the cell's usable energy; the cell uses it for **any energy-requiring activity — for example active transport, movement, or building large molecules** (any one). *(a: 1 mark for Organelle 1 = photosynthesis, 1 mark for Organelle 2 = respiration; b: 1 mark — light energy; c: 1 mark — ATP, 1 mark — a valid use of ATP.)*

Q12. (a) At a light intensity of **zero (in the dark) there is no photosynthesis**, so the plant is **only respiring**; respiration **takes in (uses up) oxygen**, so there is a **net absorption** of oxygen. (b) At **high light intensity the rate of photosynthesis is high and exceeds the rate of respiration**, so **more oxygen is produced (by photosynthesis) than is used (by respiration)**, giving a **net release** of oxygen. (c) Reading from the graph, the curve crosses the zero line at a **light intensity of 2 arbitrary units**. Where the **net exchange is zero**, the **rate of photosynthesis exactly equals the rate of respiration**, so the oxygen made by photosynthesis is used by respiration just as fast as it is produced. *(a: 1* *mark — no photosynthesis in the dark, only respiration uses oxygen; b: 1 mark — photosynthesis exceeds respiration so oxygen is released; c: 1 mark — light intensity = 2 arbitrary units, read from the graph; 1 mark — the rate of photosynthesis equals the rate of respiration.)*

Q13. Active transport needs **ATP** to power its carrier (pump) proteins. This ATP is supplied by **cellular respiration**, which **breaks down glucose to release its chemical energy and transfer it to ATP**; this occurs in the **mitochondrion**. So the mitochondria supply the ATP that the membrane pumps use for active transport. *(1 mark: respiration releases the energy in glucose as ATP, which active transport uses; 1 mark: this occurs in the mitochondrion.)*

Q14. (a) **"Aerobic" means the process requires (uses) oxygen** — oxygen is one of its inputs. (b) With a **reduced oxygen supply**, the mitochondria have **less of a required input**, so the **rate of aerobic respiration falls**; because less glucose is being broken down, the mitochondria **produce less ATP** (the cell's usable energy). *(a: 1 mark — aerobic = requires oxygen; b: 1 mark — less oxygen slows aerobic respiration (a required input is limited); 1 mark — so the mitochondria make less ATP.)*

Q15. (a) The **independent variable is the light intensity** (changed by moving the lamp closer or further away); the **dependent variable is the number of oxygen bubbles released per minute** (a measure of the rate of photosynthesis). (b) Any one suitable variable — for example the **temperature of the water**, the **carbon-dioxide concentration**, or using the **same piece of pondweed** — must be **kept constant** so that it does **not also affect the rate of photosynthesis**, which would make it impossible to be sure that light intensity alone caused any change. (c) Counting bubbles is only approximate because, for example, the **bubbles may not all be the same size**, or **not all of the oxygen produced forms bubbles** (some dissolves), so the number of bubbles does not measure the exact volume of oxygen made. *(a: 1 mark — IV = light intensity; 1 mark — DV = bubbles per minute / rate of photosynthesis; b: 1 mark — names a valid controlled variable; 1 mark — explains it must be kept constant so that it does not also affect the rate of photosynthesis; c: 1 mark — a valid reason bubble-counting is only an estimate.)*

Q16. A **strength** of the model is that it **shows at a glance that the outputs of one process are the inputs of the other** — glucose and oxygen passing one way, carbon dioxide and water the other — which makes the **cycling of matter** between the two organelles easy to picture. Two **limitations**: the two arrows are drawn the **same size**, so the model suggests the two processes always occur **at the same rate**, whereas in bright light photosynthesis is usually **faster** than respiration; and the model is **static**, so it does **not show that photosynthesis stops when there is no light while respiration continues day and night** (it also shows no amounts or scale, and does not show that the energy is finally **lost as heat**, so unlike matter it cannot be cycled). **Overall judgement:** the model is **useful for showing the complementary input–output relationship** between the chloroplast and the mitochondrion, but it should **not be read as meaning that the two processes always balance**. *(1 mark: one valid strength; 2 marks: two valid limitations; 1 mark: a reasoned overall judgement.)*

Q17. (a) The **leaf palisade cell can carry out photosynthesis** (as well as respiration), because it **contains chloroplasts and is exposed to light**; the **root cell can carry out only respiration**, because it has **no chloroplasts and receives no light**, so it cannot photosynthesise. (b) The root cell obtains the glucose it respires **from the leaf cells** — glucose made by **photosynthesis in the leaves is transported to the roots** (and other non-photosynthesising parts of the plant). *(a: 1 mark — leaf cell photosynthesises (has chloroplasts/light); 1 mark — root cell only respires (no chloroplasts/light); b: 1 mark — glucose is supplied from the leaves / made by photosynthesis elsewhere.)*

Q18. Matter is recycled because the **same atoms are passed back and forth** between the two processes: the carbon dioxide and water released by respiration are used again in photosynthesis, and the glucose and oxygen made by photosynthesis are used again in respiration. **Energy, however, flows one way**: **light energy is captured and stored as chemical energy in glucose**, then **released and transferred to ATP**, and is eventually **lost from the cell as heat** as the ATP is used. Because the heat **cannot be recaptured and reused**, living things need a **continuous input of light energy**, even though the matter can keep cycling. *(1 mark: matter (the atoms / molecules) cycles between the two processes; 1 mark: energy flows one way — light → chemical energy in glucose → ATP; 1 mark: energy is finally lost as heat and cannot be reused, so a continuous light input is needed.)*

Q19. (a) The process responsible is **photosynthesis**. Carbon dioxide is one of its **inputs (raw materials)**: in the light the plant uses up carbon dioxide, **building it into glucose**, so the amount of dissolved carbon dioxide in the tube **falls**. (b) The process responsible is **cellular respiration**. In the dark there is **no photosynthesis**, so the plant cells **only respire**, and carbon dioxide is an **output** of respiration; the plant therefore **releases carbon dioxide**, so its dissolved level **rises**. (c) The second tube is the **control**. It is kept under **exactly the same conditions** as the first but contains **no plant**, so it shows what happens to the indicator when the one thing being investigated is removed. If the first tube changes colour and the control does not, the change can confidently be **attributed to the plant** rather than to the light, the temperature, or the indicator reacting with the water on its own. The expected result is that the control shows **no change in colour**, because with no plant there is **no photosynthesis or respiration** to alter the amount of dissolved carbon dioxide. (d) The dissolved carbon dioxide would **rise**. The animal (snail) has **no chloroplasts**, so it **cannot photosynthesise** even in the light; it can **only respire**, which **releases carbon dioxide**, so the carbon dioxide level increases. *(a: 1 mark — photosynthesis; 1 mark — carbon dioxide is an input used up, so its level falls; b: 1 mark — respiration; 1 mark — carbon dioxide is an output released in the dark, so its level rises; c: 1 mark — it is a control, showing the change is caused by the plant and not by the light/temperature/water; 1 mark — no change of colour expected, as there is no plant to photosynthesise or respire; d: 1 mark — carbon dioxide rises; 1 mark — because the animal has no chloroplasts and can only respire.)*