

Cell respiration

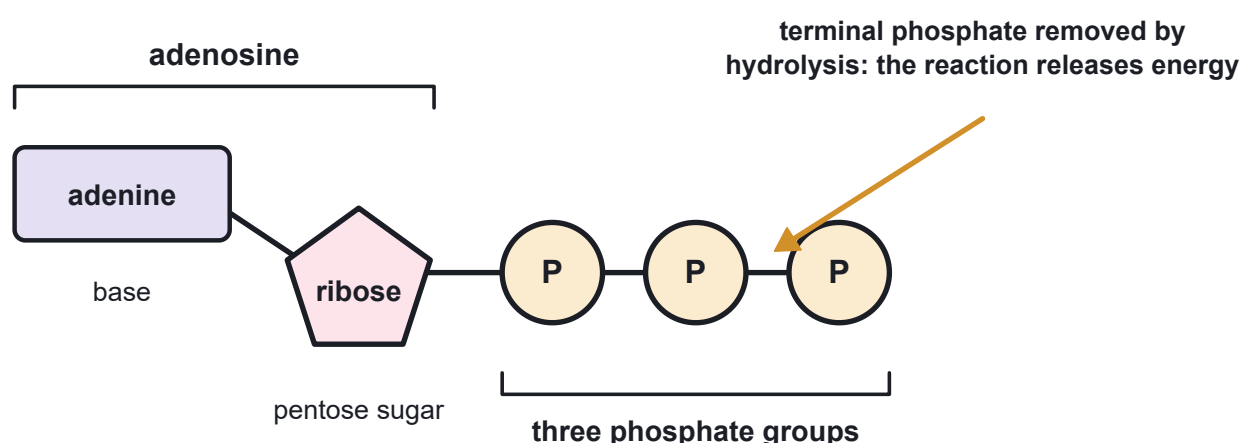
Revision notes • IB Biology C1.2: ATP, aerobic and anaerobic respiration, measuring respiration rate, and HL glycolysis, Krebs cycle, electron transport and chemiosmosis.

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

Cell respiration Spec C1.2

ATP: the molecule that distributes energy Spec C1.2.1, C1.2.2, C1.2.3

ATP (adenosine triphosphate) is the molecule that distributes energy within cells. It is a **nucleotide**, made of the base adenine, the pentose sugar ribose and a chain of three phosphate groups.



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ATP is a nucleotide: adenine, ribose and three phosphates. Hydrolysis of the **terminal phosphate** releases energy.

Why ATP suits its role as energy currency

- It is **soluble** in water, so it moves easily to wherever energy is needed in the cell.
- It is **stable** at the pH of a cell and does not break down unless an enzyme catalyses it, so energy is not wasted.
- It **cannot pass freely through membranes**, so it stays inside the cell where it was made.
- Hydrolysis of one phosphate group releases an amount of energy that is **sufficient for many tasks** in the cell, without releasing so much that most is wasted as heat.
- It is **rapidly regenerated** from ADP and phosphate, so a small pool of ATP can be recycled many times.

Life processes that ATP supplies with energy

- **Active transport** across membranes, for example pumping ions against their concentration gradient.

- **Synthesis of macromolecules** (anabolism), such as proteins, DNA and glycogen.
- **Movement:** of the whole cell (for example muscle contraction, cilia and flagella) or of cell components such as chromosomes during cell division.

Interconversion of ATP and ADP



Energy is released by **hydrolysis of ATP** to ADP (adenosine diphosphate) and phosphate. Energy is **required to synthesise ATP** from ADP and phosphate. In cells this energy comes from cell respiration (and in photosynthetic cells also from light). Often the phosphate removed from ATP is transferred to another molecule, making it more reactive.

Common mistake: ATP does not store large amounts of energy long term; it distributes energy. Fats and carbohydrates are the energy stores.

Cell respiration: aerobic and anaerobic Spec C1.2.4, C1.2.5

Cell respiration is a system for producing ATP within the cell using energy released from carbon compounds. Glucose and fatty acids are the principal substrates, but a wide range of carbon (organic) compounds can be used, including amino acids.

Do not confuse it with **gas exchange**. Gas exchange is the diffusion of oxygen and carbon dioxide between an organism and its environment, for example across the alveoli. Cell respiration is a set of enzyme-catalysed reactions inside every living cell. Gas exchange supplies the oxygen that aerobic respiration uses and removes the carbon dioxide it produces.

Word equations (glucose as substrate)

Aerobic: glucose + oxygen → carbon dioxide + water

Anaerobic (humans): glucose → lactate

Differences between anaerobic and aerobic cell respiration in humans

	Aerobic	Anaerobic
Respiratory substrates	Carbohydrates, lipids (fatty acids) and amino acids	Glucose (carbohydrate) only
Oxygen required	Yes	No
Relative ATP yield per glucose	Large (about 30 ATP; older textbooks give 36–38)	Small (2 ATP)
Waste products	Carbon dioxide and water	Lactate
Where in the cell	Starts in the cytoplasm, mostly in mitochondria	Cytoplasm only
Mitochondria needed	Yes	No

Humans use anaerobic respiration when oxygen cannot be supplied fast enough, for example in muscles during very intense exercise. It gives ATP quickly but in small amounts, and the lactate must be removed later.

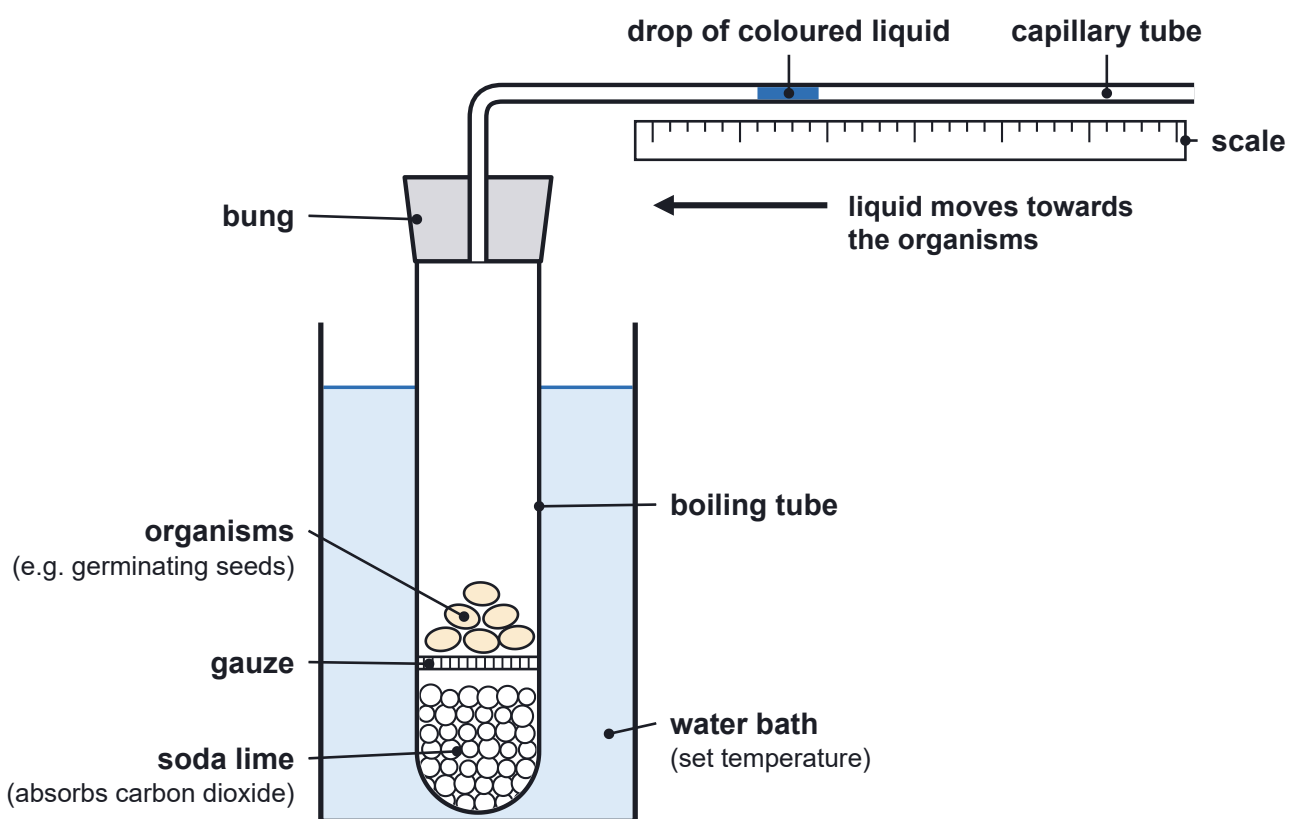
Exam tip: In 'compare' questions, write paired statements: 'aerobic respiration needs oxygen whereas anaerobic does not'. Lactate is the IB term; do not write lactic acid unless the question does.

Variables affecting the rate of cell respiration Spec C1.2.6

The rate of cell respiration is the amount of oxygen used, carbon dioxide produced or substrate used **per unit time**. To compare organisms of different sizes, divide by mass, for example mm³ of oxygen per gram per minute.

Variables that affect the rate

- **Temperature:** respiration is enzyme-catalysed, so rate rises to an optimum, then falls as enzymes denature.
- **Oxygen concentration:** low oxygen limits aerobic respiration.
- **Substrate availability:** for example glucose concentration for yeast, or stored food in germinating seeds.
- Others: type and activity of the organism, pH, and stage of development (germinating seeds respire faster than dry seeds).



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A simple respirometer. Soda lime absorbs carbon dioxide, so the **drop moves towards the organisms** as they use oxygen.

Measuring the rate

1. Place a known mass of organisms (for example germinating seeds or invertebrates) in a sealed tube with an alkali such as soda lime to absorb carbon dioxide.
2. Keep the tube in a water bath at a set temperature and let it equilibrate.
3. Record the distance the liquid drop moves in a fixed time.
4. Set up a control tube with glass beads of the same volume instead of organisms, to correct for temperature and pressure changes.
5. Repeat at different values of the independent variable (for example temperature) and calculate rates.

Rates can also be measured with oxygen or carbon dioxide sensors and a data logger, or for yeast by measuring the volume of carbon dioxide released.

Rate of respiration from a respirometer

2.5 g of germinating seeds were placed in a respirometer. The drop in the capillary tube (radius 0.50 mm) moved 30 mm in 10 minutes. Calculate the rate of oxygen uptake per gram.

1. Volume of oxygen = $\pi r^2 h = 3.14 \times 0.50^2 \times 30 = 23.6 \text{ mm}^3$.
2. Rate = $23.6 \text{ mm}^3 \div 10 \text{ min} = 2.36 \text{ mm}^3 \text{ min}^{-1}$.
3. Per gram: $2.36 \div 2.5 = 0.94 \text{ mm}^3 \text{ g}^{-1} \text{ min}^{-1}$.

Answer: $0.94 \text{ mm}^3 \text{ g}^{-1} \text{ min}^{-1}$ (to 2 significant figures).

Maths skill: Rate = amount $\div$ time. Always state units, and divide by mass when organisms or samples differ in size.

Practical skill: Use living organisms ethically: handle invertebrates gently, use gauze to keep them away from the corrosive soda lime, and return them to their habitat afterwards.

NAD, oxidation and glycolysis Spec C1.2.7, C1.2.8 HL only

Oxidation, reduction and NAD

Oxidation is a process of electron loss; **reduction** is electron gain. When hydrogen (with its electron) is removed from a substrate, a reaction called **dehydrogenation**, the substrate has been oxidised. Redox reactions involve both: whenever one molecule is oxidised, another is reduced.

NAD (nicotinamide adenine dinucleotide) is the main carrier of hydrogen in cell respiration. It accepts hydrogen removed from substrates and is reduced, forming reduced NAD. Reduced NAD carries the hydrogen (and its energy) to the electron transport chain.



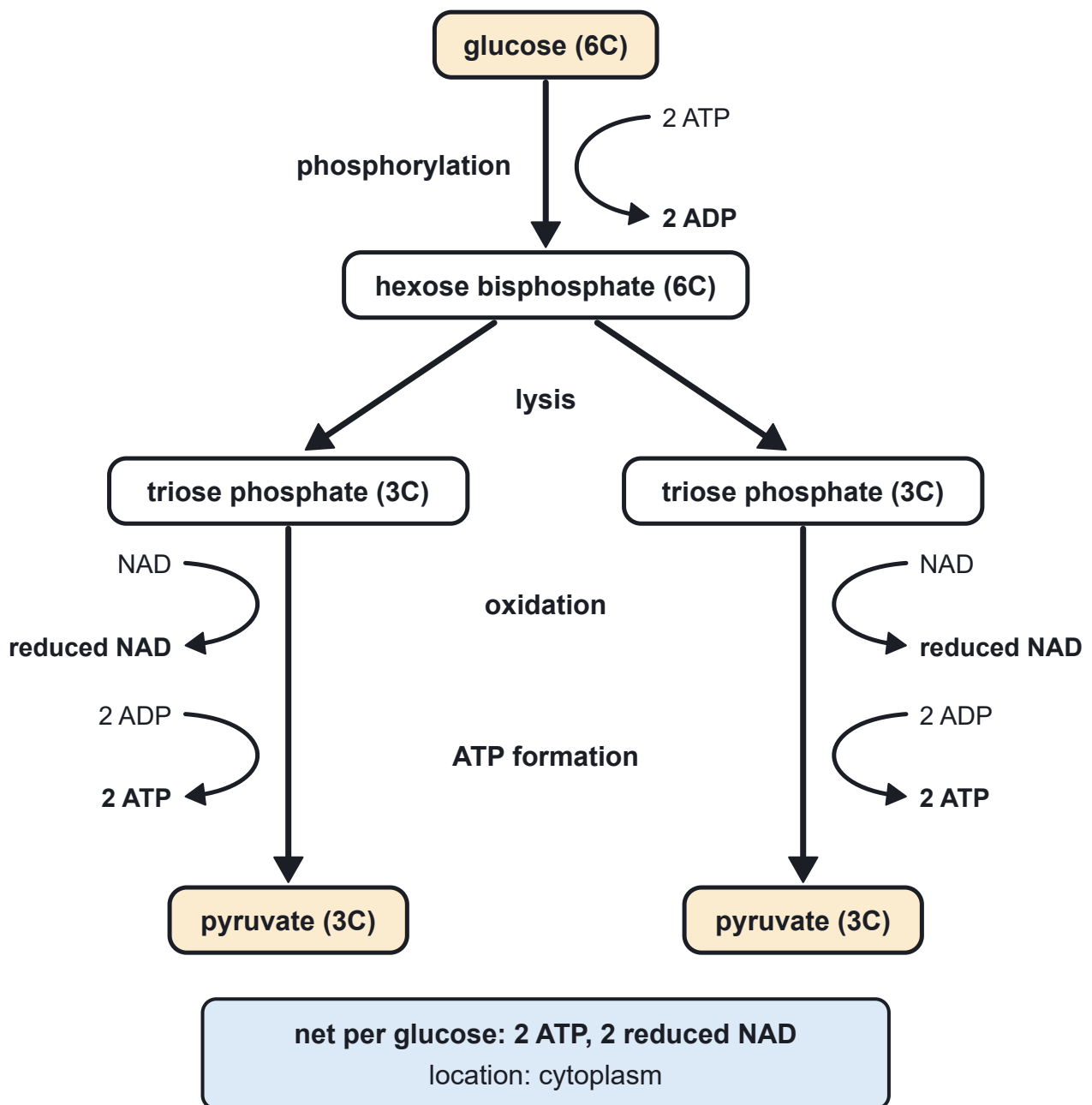
Glycolysis

Glycolysis is the conversion of glucose (6C) to two molecules of pyruvate (3C). It takes place in the cytoplasm, does not need oxygen and is a linear pathway in which each step is catalysed by a different enzyme. It has four key stages:

1. **Phosphorylation:** two phosphate groups are added to glucose, using 2 ATP. This makes the sugar less stable and ready to split.
2. **Lysis:** the 6C sugar bisphosphate splits into two 3C triose phosphate molecules.
3. **Oxidation:** hydrogen is removed from each triose phosphate and accepted by NAD, giving 2 reduced NAD per glucose.
4. **ATP formation:** phosphate groups are transferred to ADP, forming 4 ATP per glucose, and two pyruvate are produced.

Yield of glycolysis per molecule of glucose

Product	Number
ATP used	2
ATP produced	4
Net ATP	2
Reduced NAD	2
Pyruvate	2



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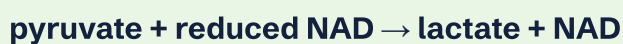
Glycolysis: phosphorylation, lysis, oxidation and ATP formation give a net yield of **2 ATP and 2 reduced NAD** per glucose.

Exam tip: You do not need the names of the intermediates, but you must say that each step is catalysed by a different enzyme and give the net yield: 2 ATP and 2 reduced NAD.

Anaerobic respiration: lactate and yeast Spec C1.2.9, C1.2.10 HL only

Glycolysis needs a supply of NAD to accept hydrogen. Without oxygen, reduced NAD cannot be oxidised by the electron transport chain, so the cell's NAD would soon all be reduced and glycolysis would stop. Anaerobic respiration solves this by using pyruvate as the hydrogen acceptor.

Humans: pyruvate to lactate



Regeneration of NAD allows glycolysis to continue, with a **net yield of two ATP** molecules per molecule of glucose. No carbon dioxide is produced. The reaction happens in the cytoplasm.

Yeast

The pathways of anaerobic respiration are the **same in humans and yeasts** apart from the regeneration of NAD using pyruvate, and therefore the final products. In yeast, pyruvate is decarboxylated (CO₂ removed) to ethanal, which is then reduced by reduced NAD to **ethanol**, regenerating NAD.

Yeast: glucose → ethanol + carbon dioxide

Uses of anaerobic respiration in yeast

Process	Useful product	What happens to the other product
Brewing (beer, wine)	Ethanol	CO ₂ escapes, or is kept to make the drink fizzy
Baking (bread)	Carbon dioxide, which makes the dough rise	Ethanol evaporates during baking

Common mistake: Lactate formation does not produce extra ATP. Its purpose is to regenerate NAD so glycolysis can keep making its 2 ATP.

The link reaction and the Krebs cycle Spec C1.2.11, C1.2.12 HL only

The link reaction

In aerobic respiration, pyruvate from glycolysis is transported into the **mitochondrial matrix**. There it undergoes **oxidation** (hydrogen removed, NAD reduced) and **decarboxylation** (carbon removed as CO₂). The remaining 2C acetyl group is attached to coenzyme A, forming **acetyl CoA**, which transfers the acetyl group to the Krebs cycle.

pyruvate (3C) + NAD + CoA → acetyl CoA (2C) + CO₂ + reduced NAD

Lipids and carbohydrates are both metabolised to form acetyl groups (2C), so this is where the pathways for different respiratory substrates join. Per glucose the link reaction happens twice.

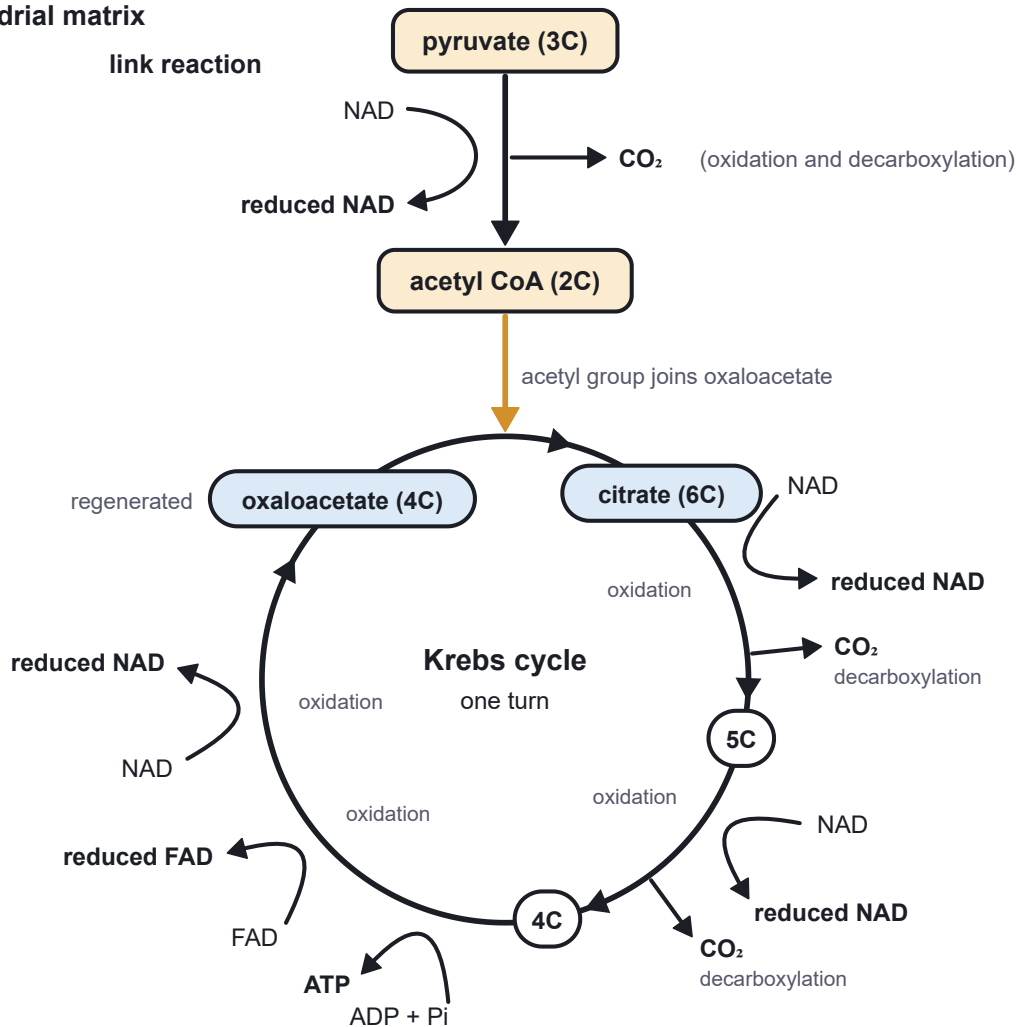
The Krebs cycle

1. The acetyl group (2C) is transferred from coenzyme A to **oxaloacetate (4C)**, forming **citrate (6C)**. Coenzyme A is released to collect another acetyl group.
2. Citrate is converted back to oxaloacetate by a series of reactions that include **two decarboxylations**, releasing 2 CO₂.
3. The cycle includes **four oxidations**, which are dehydrogenation reactions. Three of them reduce NAD; the fourth reduces another hydrogen carrier, FAD. Reduced FAD also passes its electrons to the electron transport chain, but IB questions focus on NAD.
4. One ATP is produced directly in each turn.
5. Oxaloacetate is regenerated, so the cycle can accept another acetyl group.

Products per turn of the Krebs cycle (two turns per glucose)

Product	Per turn	Per glucose
CO ₂	2	4
Reduced NAD	3	6
Reduced FAD	1	2
ATP	1	2

mitochondrial matrix



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Each turn of the Krebs cycle: **2 CO₂, 3 reduced NAD, 1 reduced FAD and 1 ATP**; oxaloacetate is regenerated.

Exam tip: Name only citrate and oxaloacetate. Remember the counts: two decarboxylations and four oxidations per turn, and two turns per glucose.

Electron transport chain, chemiosmosis and oxygen

Spec C1.2.13, C1.2.14, C1.2.15, C1.2.16

HL only

Reduced NAD delivers energy to the chain

Reduced NAD comes from **glycolysis**, the **link reaction** and the **Krebs cycle**. Energy is transferred when reduced NAD passes a pair of electrons to the first carrier in the **electron transport chain**, a series of carriers embedded in the inner mitochondrial membrane (on the cristae). This converts reduced NAD back to NAD, which can return to accept more hydrogen.

A proton gradient

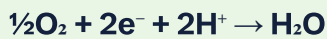
The electrons pass from carrier to carrier. At each step they lose energy, and some carriers use this energy to **pump protons** (H^+) from the matrix across the inner membrane into the **intermembrane space**. Because the inner membrane is impermeable to protons, a **proton gradient** builds up: a higher concentration of protons in the intermembrane space than in the matrix.

Chemiosmosis and ATP synthase

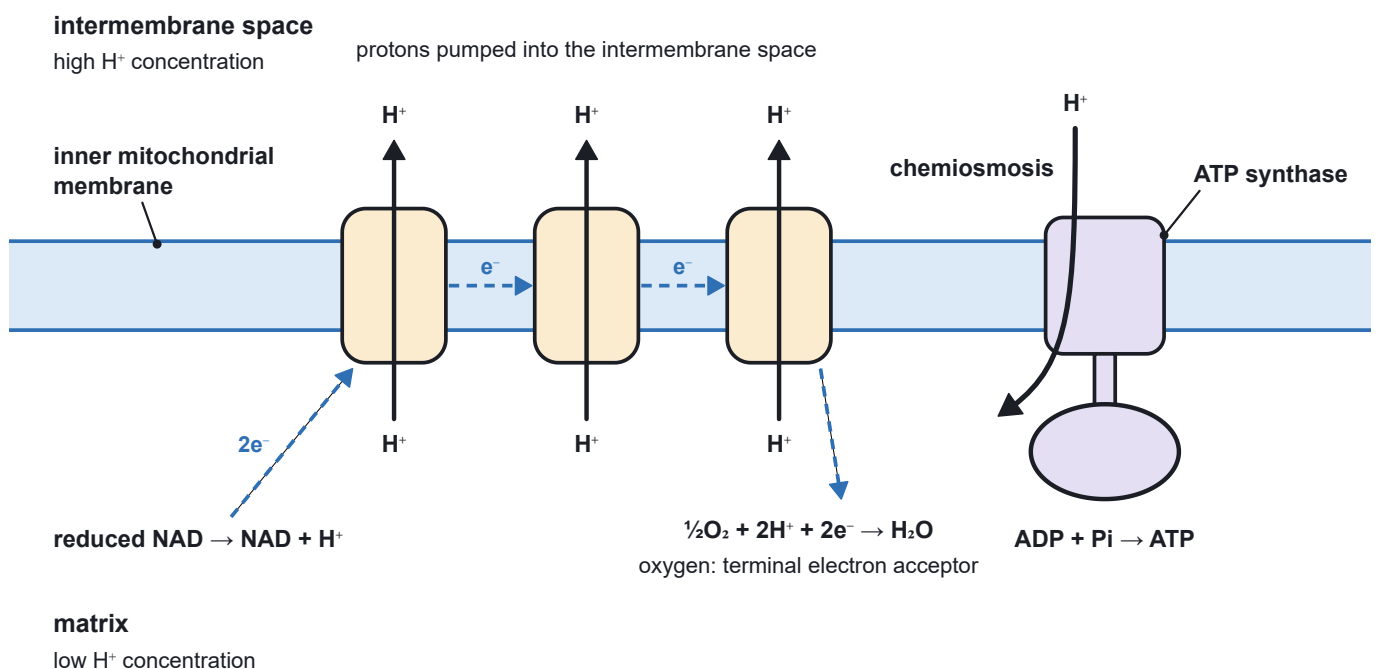
Chemiosmosis is the movement of protons down their concentration gradient through ATP synthase. Protons can only diffuse back into the matrix through channels in **ATP synthase**. As they flow through, part of the enzyme rotates, and ATP synthase couples the release of energy from the proton gradient with the **phosphorylation of ADP**, forming ATP. Most of the ATP from aerobic respiration is made this way.

Oxygen as terminal electron acceptor

At the end of the chain, **oxygen** accepts electrons from the last carrier and protons from the matrix, producing **metabolic water**.



Removing electrons at the end allows continued flow of electrons along the chain. Without oxygen the carriers stay reduced, reduced NAD cannot be oxidised, the proton gradient is not maintained and no NAD is available for the link reaction and Krebs cycle, so aerobic respiration stops.



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Electron flow pumps protons into the intermembrane space; they return through **ATP synthase** (chemiosmosis). Oxygen is the terminal electron acceptor.

Exam tip: Give the direction precisely: protons are pumped into the intermembrane space and flow back into the matrix through ATP synthase. You do not need the names of the protein complexes.

Lipids and carbohydrates as respiratory substrates

Spec C1.2.17

HL only

Lipids compared with carbohydrates as respiratory substrates		
	Carbohydrate (e.g. glucose)	Lipid (fatty acids)
Energy yield per gram	Lower	Higher, roughly twice as much
Why	More oxygen in the molecule; less oxidisable hydrogen and carbon	Less oxygen; more oxidisable hydrogen and carbon
Entry into respiration	Glycolysis → pyruvate → link reaction	Broken into 2C acetyl groups, entering as acetyl CoA
Anaerobic respiration possible	Yes	No

Energy in respiration comes from oxidising carbon and hydrogen in the substrate. A fatty acid is mostly long hydrocarbon chain with very little oxygen, so more of its atoms can be oxidised than in glucose, where many carbons already carry oxygen. Each gram of lipid therefore yields more reduced NAD and more ATP.

Glycolysis and anaerobic respiration occur only if carbohydrate is the substrate. Fatty acids are broken down into 2C acetyl groups, which enter the pathway via acetyl CoA and are then oxidised in the Krebs cycle. As this needs oxygen to regenerate NAD through the electron transport chain, fatty acids cannot be used in anaerobic respiration. (Beyond the syllabus: the small glycerol part of a triglyceride can be converted to triose phosphate and enter glycolysis, but fatty acids supply nearly all the energy in a lipid.)

Exam tip: Linking question: in what forms is energy stored in living organisms? Fat stores more energy per gram than glycogen, but only glycogen can supply glucose for anaerobic respiration.

Quick check

1. What is the full name of ATP and what type of molecule is it?
2. Write the word equation for anaerobic respiration in humans.
3. Why is soda lime used in a respirometer?
4. **HL only** Name the two Krebs cycle intermediates you need to know and their number of carbons.
5. **HL only** What is the role of oxygen in aerobic respiration?

Quick check answers

Cell respiration

1. Adenosine triphosphate; a nucleotide.
2. glucose → lactate
3. It absorbs carbon dioxide, so the movement of the drop measures oxygen uptake.
4. Citrate (6C) and oxaloacetate (4C).
5. It is the terminal electron acceptor: it accepts electrons and protons, forming water, so electrons keep flowing along the chain.