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Cell Respiration

IB Biology - Revision Notes

Adenosine Triphosphate (ATP)

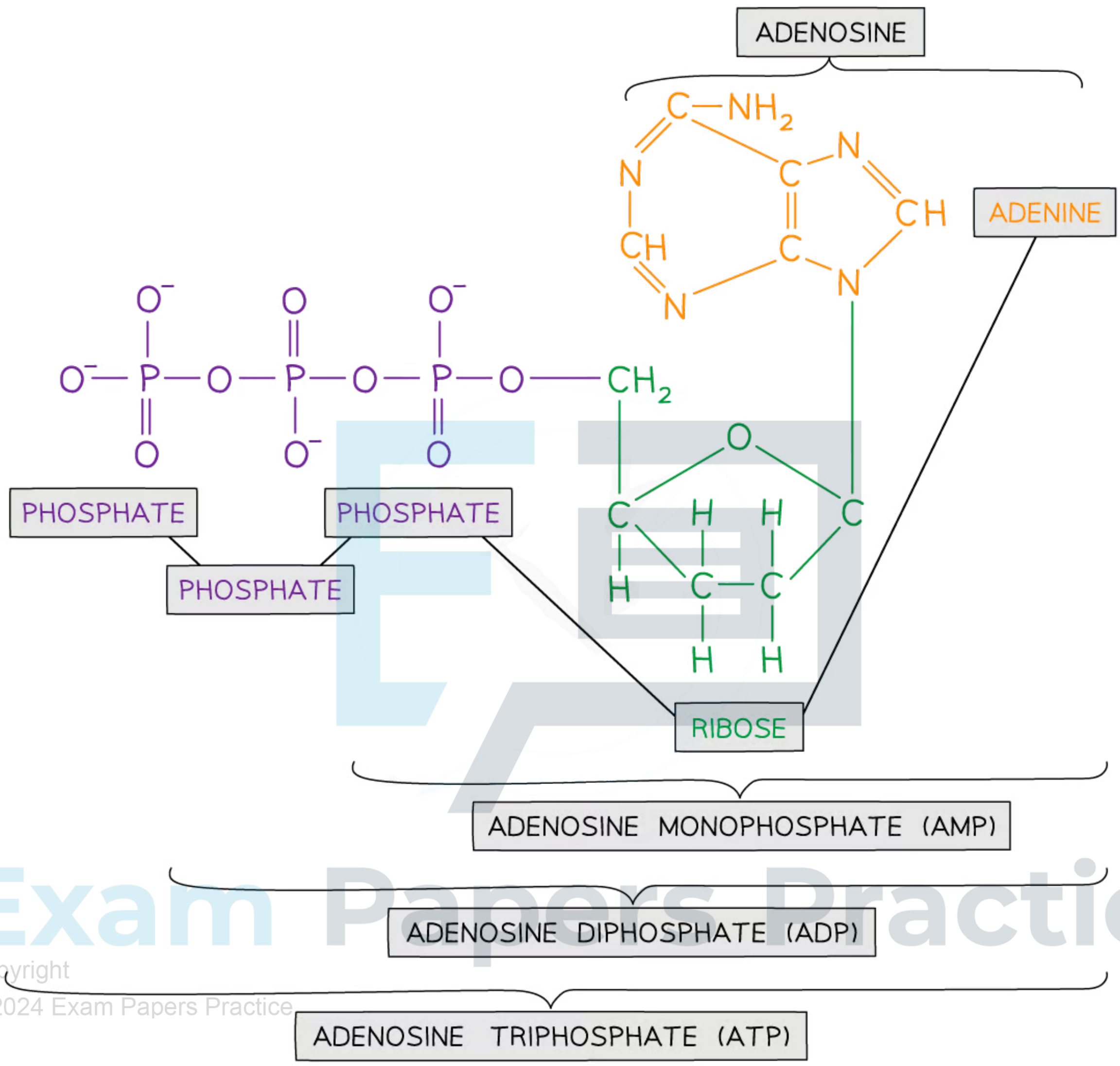
Adenosine Triphosphate (ATP)

- Living organisms require energy to perform and maintain life processes such as movement, nutrition and excretion
- This **energy is released by the process of cell respiration**
- Energy released during the reactions of respiration is transferred to the molecule **adenosine triphosphate** (ATP)
  - The energy is transferred in a series of small steps
  - Heat is lost at each step, which is used to regulate body temperature in endotherms
- ATP is a small and soluble molecule that provides a **short-term store** of chemical energy that cells can use to do work
  - Its solubility and size enables it to move easily in cells and living organisms by **facilitated diffusion**
- It is vital in linking energy requiring and energy yielding reactions
- ATP is described as a **universal energy currency**
  - Universal: It is used in all organisms
  - Currency: Like money, it can be used for different purposes (reactions) and is reused countless times
- The use of ATP as an 'energy-currency' is beneficial for many reasons:
  - The **hydrolysis of ATP** can be carried out **quickly and easily** wherever energy is required within the cell by the action of just one enzyme, ATPase
  - A **useful** (not too small, not too large) **quantity of energy is released** from the hydrolysis of one ATP molecule - this is beneficial as it reduces waste but also gives the cell control over what processes occur
  - ATP is **relatively stable** at cellular pH levels

Structure of ATP

- ATP is a phosphorylated nucleotide
- It is made up of:
  - Ribose sugar
  - Adenine base
  - Three phosphate groups

ATP Diagram



Structure of ATP contains ribose sugar, an adenine base and three phosphate groups

Features of ATP Table

Feature	Benefit
Releases a small but sufficient quantity of energy	This is enough energy to drive important metabolic reactions while keeping energy wastage low

Exists as a stable molecule	It doesn't break down unless a catalyst (ATPase) is present so energy won't be wasted
Can be recycled	The breakdown of ATP is a reversible reaction, ATP can be reformed from ADP and P_i. This means the same molecule can be reused elsewhere in the cell for different reactions
Hydrolysis is quick and easy	Allows cells to respond to a sudden increase in energy demand
Soluble and moves easily within cells	Can transport energy to different areas of the cell
Forms phosphorylated intermediates	This can make metabolites more reactive and lower the activation energy required for a reaction

Exam Tip

Be careful not to use the terms energy and ATP interchangeably. Energy is the capacity or power to do work while ATP is a molecule which carries energy to places in the cell that need it in order to do work.

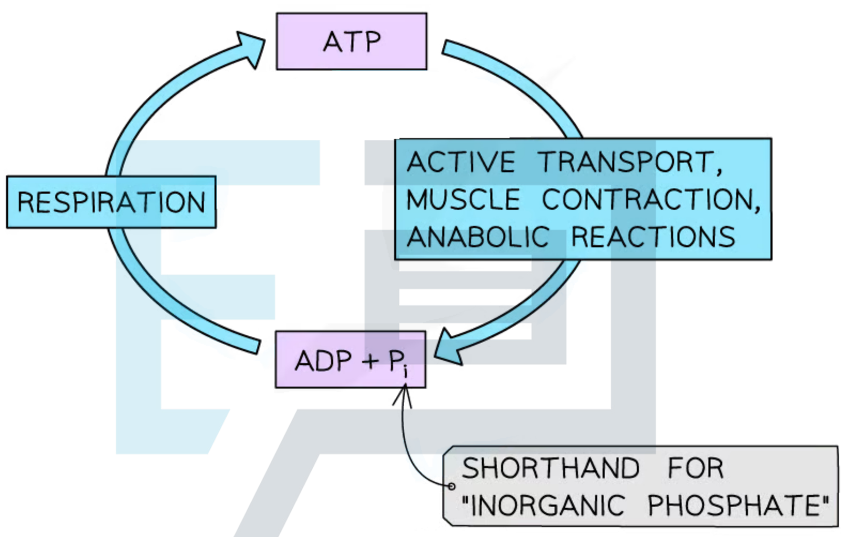
Life Processes Reliant On ATP

- Some of the life processes that are reliant on ATP as a source of energy include:
  - In **anabolic reactions** to synthesise larger molecules (macromolecules) from smaller ones
  - To move molecules across the cell membrane against their concentration gradient during **active transport**
  - Enabling **movement of the entire cell**
  - The **move cell components**, such as chromosomes, within the cell
- ATP is readily converted to **adenosine diphosphate** (ADP) and a **phosphate ion** (P_i), during which energy is released
  - Since ATP is a very **reactive molecule**, it is not stored in living organisms
- Molecules such as **glucose and fatty acids** are used as short-term stores of energy, while **glycogen**, **starch and triglycerides** act as long-term storage molecules of energy

Interconversions Between ATP & ADP

- ATP is a very reactive molecule and is readily converted to **ADP** and **phosphate** when releasing its energy
  - ADP and phosphate can then be **re-converted to ATP** during respiration
- Organisms require a **constant supply of ATP** because much of the energy is lost to the surroundings as **heat**

ATP Cycle Diagram

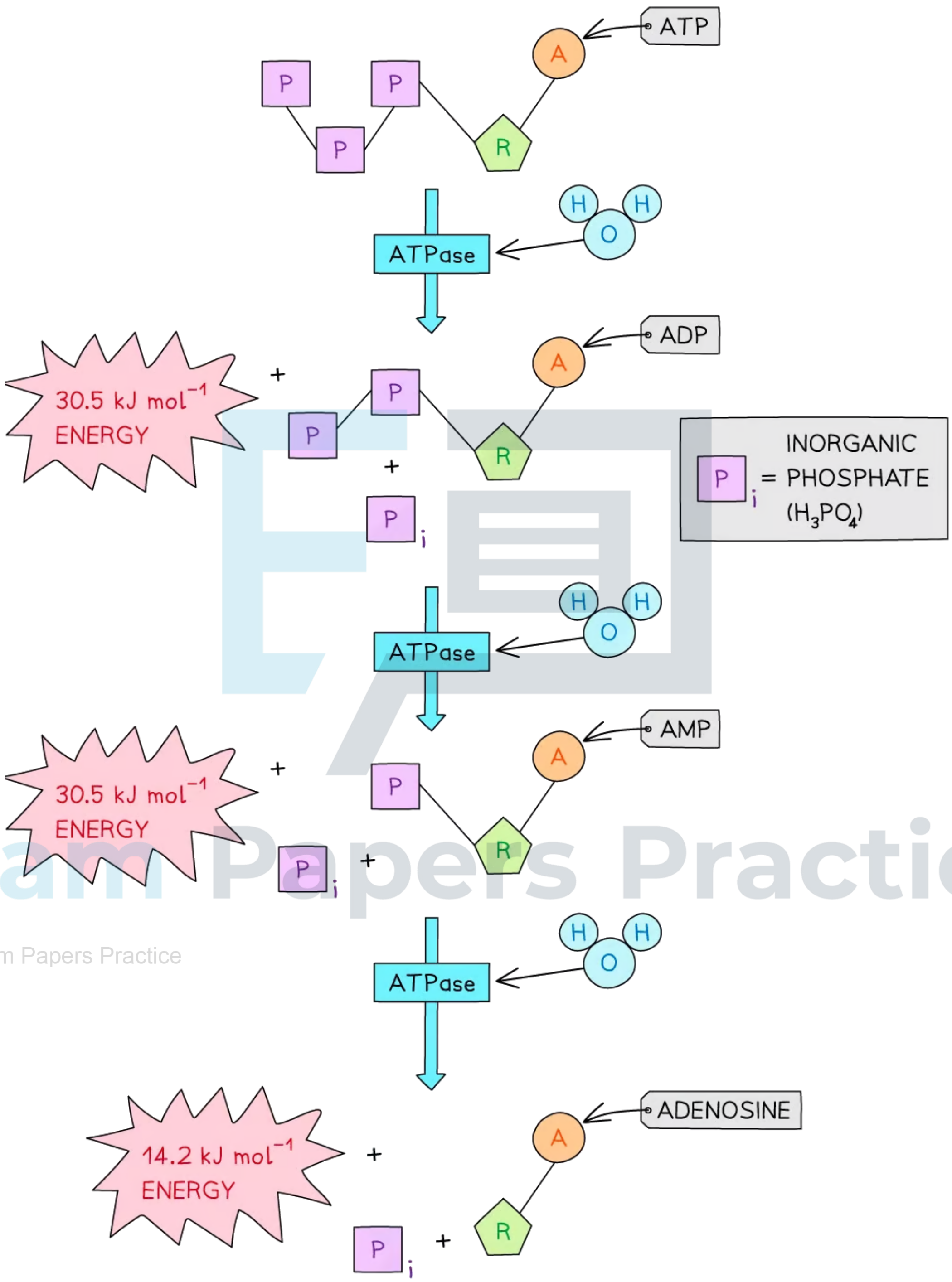


The constant cycling of ATP and ADP + P_i within a cell

Hydrolysis of ATP

- When ATP is hydrolysed (broken down), ADP and phosphate are produced
- As ADP forms, **free energy** is released that can be used for processes within a cell e.g. DNA synthesis
  - Removal of one phosphate group from ATP releases approximately 30.5 kJ mol $^{-1}$ of energy, forming ADP
  - Removal of a second phosphate group from ADP also releases approximately 30.5 kJ mol^{-1} of energy, forming AMP
  - Removal of the third and final phosphate group from AMP releases 14.2 kJ mol^{-1} of energy, forming adenosine

Hydrolysis of ATP Diagram

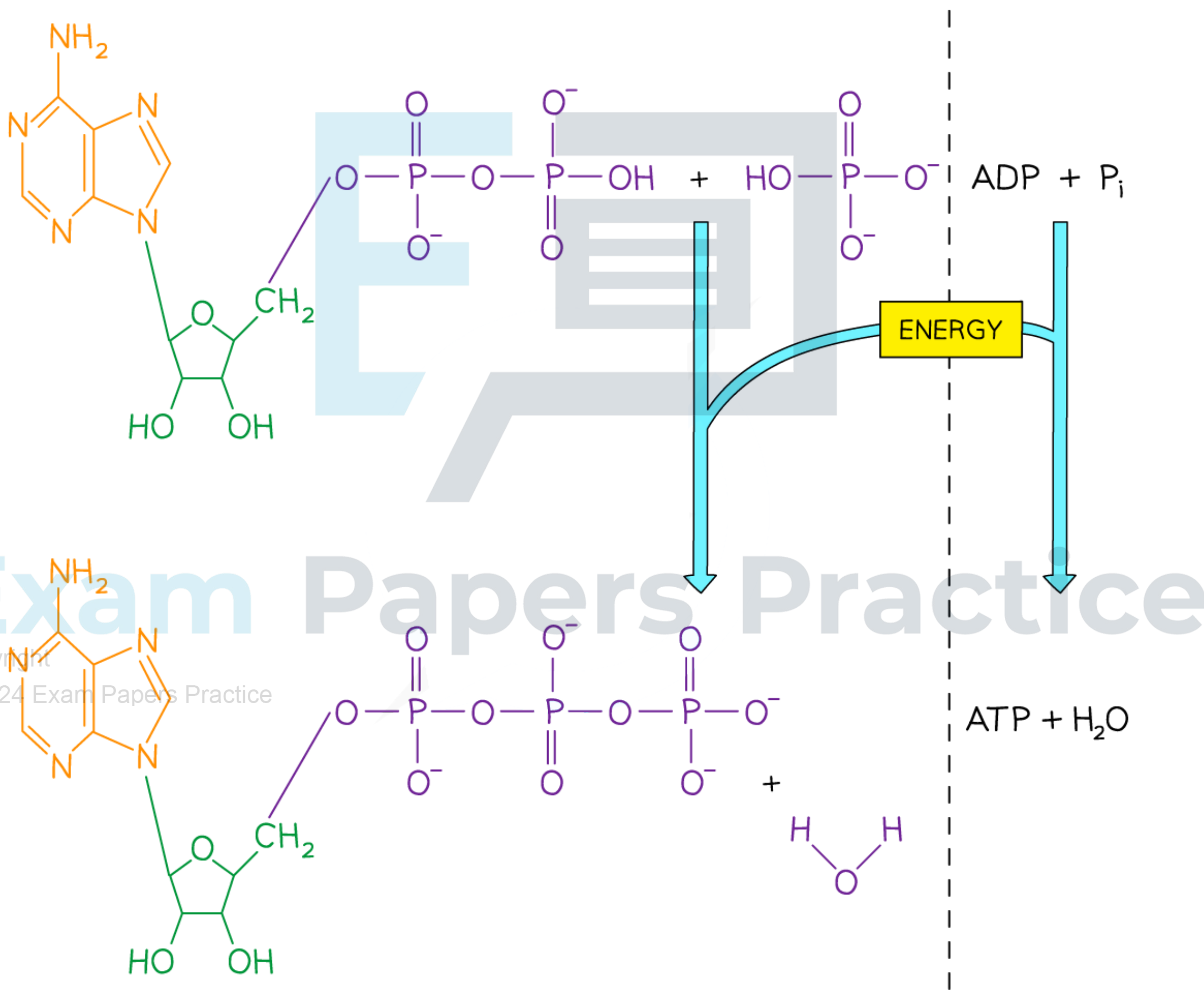


The hydrolysis of ATP

ATP synthesis

- On average humans use more than 50 kg of ATP in a day but only have a maximum of ~ 200g of ATP in their body at any given time
- Organisms **cannot build up large stores of ATP** and it rarely passes through the cell surface membrane
- This means the cells must make ATP as and when they need it
- ATP is formed when ADP is combined with an inorganic phosphate (Pi) group
  - This is an **energy-requiring reaction**
  - **Water is released** as a waste product (therefore ATP synthesis is a **condensation reaction**)

Synthesis of ATP Diagram



Energy-requiring synthesis of ATP from ADP and Phosphate

Exam Tip

Note that you are not required to know the exact quantity of energy in kilojoules that are involved with the interconversions between ATP and ADP, but you should appreciate that it is sufficient for performing tasks within the cell.

Cell Respiration

Cell Respiration

Cell respiration as a system for producing ATP

- Cell respiration is the **controlled release of energy from organic compounds to produce ATP**
- Respiration is a **series of chemical reactions** that happens in **every cell**
- Its purpose is to **release energy** in usable forms from chemical energy stored in food e.g. glucose
- Respiration is a catabolic process
- **Glucose** is the main respiratory fuel used in cells
  - **Lipids** and **proteins** can also be used but they must undergo several changes before they can enter the respiratory pathway
  - Glucose can **enter glycolysis directly** which makes it easier to oxidise than lipids and proteins
  - Since proteins are primarily structural molecules, they will only be used as a respiratory fuel in conditions where glucose and lipids are not available
- **Organic** food substances contain **a lot of chemical energy**
- This **energy cannot be released in one, uncontrolled step** in cells, which would cause cell damage and tissue death
- Enzymes **control the release of energy** through a series of chemical reactions called a **pathway**
- This ends in the production of **ATP** (adenosine triphosphate)
  - To make ATP, a **phosphate group** is linked to adenosine diphosphate (**ADP**)
  - This process **requires energy** which comes from the breakdown of organic molecules
- The energy that is released is used for
  - Fuelling anabolic processes
  - Muscle contraction
  - Fuelling **active transport**
  - Moving molecules around the cell
  - **Generating heat** to maintain body temperature in warm-blooded animals

Exam Tip

Respiration is **often confused with gas exchange**, but remember that respiration is a **chemical process** while gas exchange involves the exchange of carbon dioxide and oxygen at the alveoli or cells

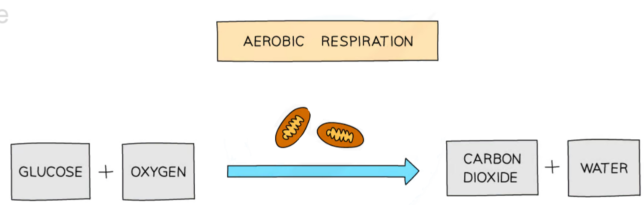
Comparing Anaerobic & Aerobic Cell Respiration

Differences between anaerobic and aerobic respiration in humans

- Respiration involves the transfer of **chemical potential energy** from nutrient molecules (such as carbohydrates, fats and proteins) into a usable energy form (through the synthesis of ATP) that can be used for work within an organism
- It is a vital process that takes place in the cells of all living organisms
- There are two forms of respiration depending on the oxygen availability of the cell:
  - **Aerobic** respiration
  - **Anaerobic** respiration
- **Aerobic** respiration is the process of breaking down a **respiratory substrate** in order to produce ATP **using oxygen**
  - The substrate is completely oxidised, thereby releasing a large amount of energy
- **Anaerobic** respiration takes place **in the absence of oxygen** and also breaks down a respiratory substrate but produces **less ATP** for the cell
- The main **respiratory substrate** involved in respiration is **glucose**

Aerobic respiration

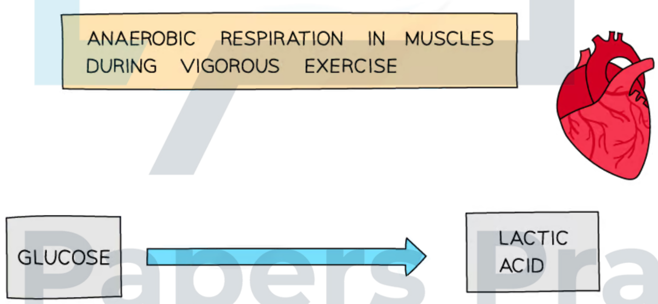
- Aerobic cell respiration requires oxygen and gives a **large yield of ATP from glucose**
- The presence of oxygen allows **glucose to be broken down fully** into carbon dioxide and water
- This yields far more energy (approx. 36 ATP molecules) than anaerobic respiration (2 ATP molecules) per molecule of glucose
- CO_2 is a **waste product** and has to be excreted
  - Except in plants where it is used for photosynthesis
- Water is a **by-product** and contributes to the organism's water needs
  - Some animals that live in deserts **drink very little** but survive on this water
- Most of the reactions of aerobic respiration, in eukaryotes, take place in the **mitochondria**



Aerobic respiration releases energy during the reaction between glucose and oxygen

Anaerobic respiration

- In cells, there is a much **lower energy yield** from respiration in **anaerobic conditions** than in aerobic conditions
- The reactions of anaerobic respiration will occur in the **cytoplasm** of cells and does not involve the mitochondria
- There can be different ways in which oxygen becomes unavailable
  - When **oxygen supply can't keep up with demand** in heavily respiring cells
    - But a short supply of ATP is still required e.g. **vigorous exercise** requiring a lot of muscle contraction
  - In conditions where oxygen **cannot reach the organisms** e.g. in waterlogged soil
- In anaerobic respiration, **glucose is only partially oxidised** meaning only **a small part of its chemical energy is released** and transferred to ATP
  - The only ATP-producing reaction that continues is the first stage of respiration (around 2 ATP molecules per molecule of glucose)
- As there is no oxygen, **none of the remaining reactions** (of aerobic respiration) can take place
  - This means that around **36 ATP molecules are not produced anaerobically** that would otherwise have been produced in the presence of oxygen
  - 2 ATP molecules are better than zero ATP molecules, so anaerobic respiration can give **a short discharge of energy** when oxygen runs out
- Different types of organisms produce **different products** when respiring anaerobically
  - **Plants and yeasts** produce **ethanol** and CO_2
  - **Animals** produce **lactate**



Anaerobic respiration in humans (and other animal cells) will partially oxidise glucose to form lactic acid

Comparison of Aerobic & Anaerobic Respiration in Humans Table

	Aerobic respiration	Anaerobic respiration
Oxidation of glucose	Complete	Incomplete
Oxygen required	Yes	No

Relative ATP yield	High (~36 molecules)	Low (2 molecules)
Products	CO_2 and H_2O	Lactate
Location of reactions	Cytoplasm and mitochondria	Cytoplasm

Exam Tip

You should be able to write simple word equations for both types of respiration, with glucose as the substrate. Remember that ATP is produced during both aerobic and anaerobic respiration

Cell Respiration: Skills

The Rate of Cell Respiration

Variables affecting the rate of cell respiration

- The rate of cell respiration may vary depending on the following:
  - How **metabolically active** the cell is
    - e.g. muscle cells will have a higher rate of cell respiration than adipose cells because of their higher energy needs
  - **Size** of the organism
    - e.g. smaller organisms will have a higher surface area : volume ratio than larger organisms, so they will have a higher rate of respiration to compensate for higher heat loss
  - The **oxygen supply**
    - When oxygen availability is low, cells will respire anaerobically
  - Supply of **respiratory substrates**
    - e.g. glucose availability is of particular importance, since it is the main respiratory substrate
    - The lower the supply of these substrates, the lower the rate of respiration will be
  - **Temperature**
    - The rate of respiration will **increase up to the optimum temperature** of the enzymes catalysing the reactions, whereafter the rate will drop as the enzymes denature
  - **pH**
    - Carbon dioxide released during respiration will **decrease the pH** of cells and tissues, which may also denature enzymes involved with respiration

Determining the rate of respiration

- Respirometers are used to measure and investigate the **rate of oxygen consumption** during respiration in organisms
- The experiments usually **require live organisms** such as seeds or invertebrates
  - **Use of animals should be minimised** when seeds can provide excellent data
- There are **many different designs of respirometers**, though they all have certain features in common
  - A **sealed container** containing **live organisms** and **air**
  - An alkaline solution (e.g. potassium hydroxide) to absorb CO_2
  - A **capillary tube** connected to the container and set **against a graduated scale** (a **manometer**)
- The organisms **respire aerobically** and **absorb oxygen** from the air
- The **CO_2** they release is **absorbed by the alkali**
- This **reduces the air pressure** inside the sealed chamber

- The manometer fluid (shown in red below) **moves towards the organisms** because of the pressure drop inside the chamber
- The respirometer must be kept in **very temperature-controlled conditions** because slight fluctuations in temperature can affect the air pressure
  - A **thermostatically controlled water bath** is the best way to maintain a constant temperature
- **Repeat readings** should be carried out for each set of experimental conditions, in order to **identify** and **eliminate anomalies**
  - **Repeat** readings give a **reliable** mean

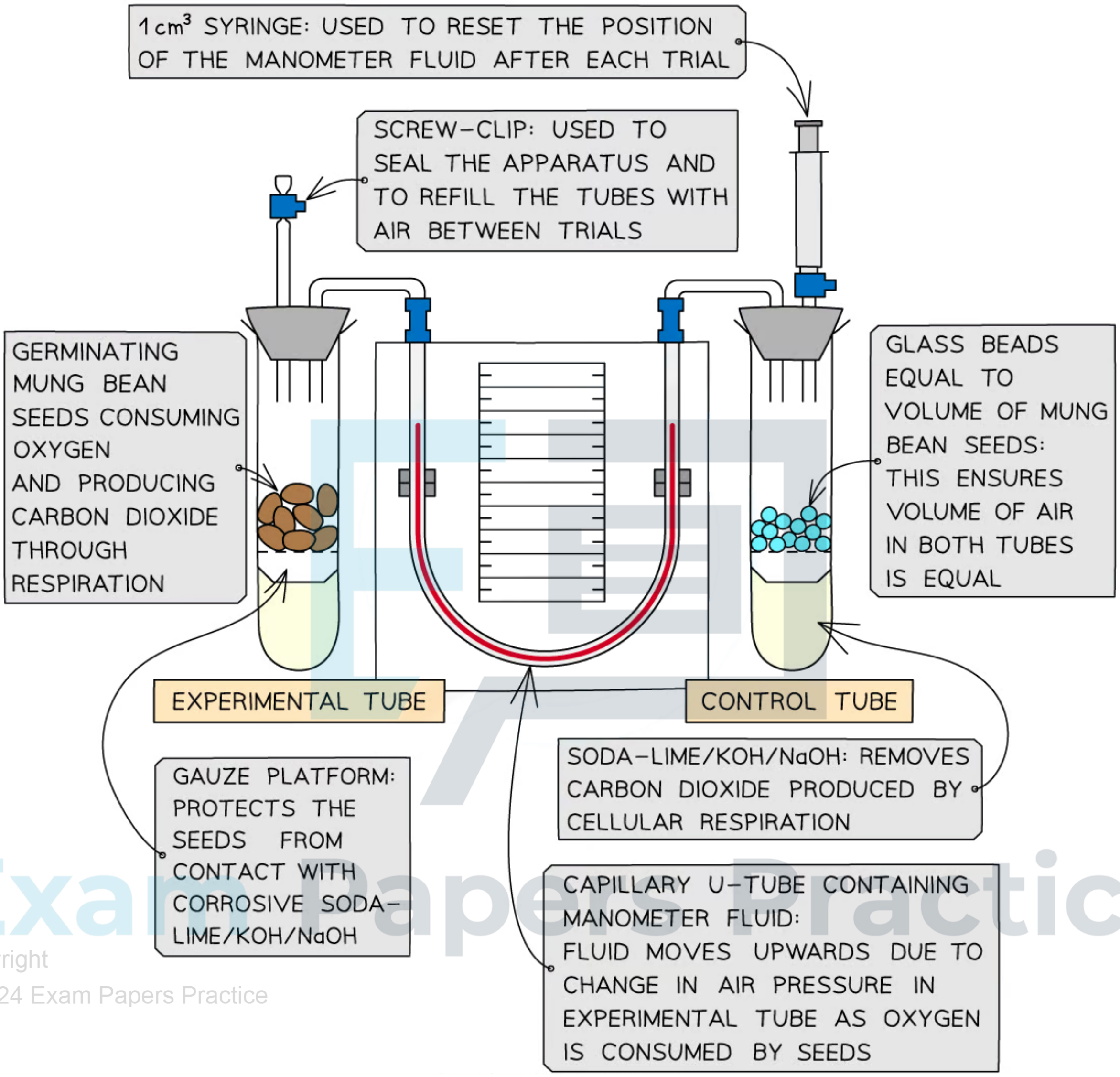
Analysis

  - Respirometers can be used in experiments **to investigate how different factors affect the rate of respiration** of organisms over time
    - E.g. temperature – using a series of water baths

Use of technology to measure rate of respiration

- **Technological devices** can automate and make the measurement of respiration rate easier
  - Not to be confused with **breathing rate**
- **Oxygen sensors** and **CO_2 monitors** can measure oxygen and CO_2 concentration in real-time
  - Without the need to expose the subject to hazards such as strong alkalis
- **Dataloggers** can record data over a period of time for analysis later

Respirometer Diagram



The typical set-up of a respirometer

The equation for calculating a change in gas volume

- The volume of oxygen consumed ($mm^3 min^{-1}$) during respiration can be worked out using the radius of the lumen of the capillary tube *r* (mm) and the distance moved by the manometer fluid *h* (mm) in a minute using the formula:

$$\pi r^2 h$$

- The volume of oxygen consumed can then be used to determine the average rate of respiration per unit time

Worked example

A respirometer was set up with germinating mung beans in the experimental tube. After a period of equilibration, the liquid in the capillary was measured to move by 2.3 cm in 25 minutes. The capillary tube had an internal diameter of 0.30 mm. Calculate the average rate of respiration of the mung beans, measured as the rate oxygen uptake, in mm^3 min^{-1}Use the value of pi (π) = 3.141.

Answer:

Step 1: Calculate the cross-sectional area of the capillary tube

$$\text{Diameter} = 0.30\text{mm, so radius} = 0.30 \div 2 = 0.15 \text{ mm}$$

$$\text{Cross sectional area} = \pi r^2 = 3.141 \times 0.15^2 = 0.0707 \text{ mm}^2$$

Step 2: Calculate the volume of oxygen that had been taken up

The liquid moved 2.3 cm, which is 23mm

Volume of liquid moved in 25 minutes =

$\pi r^2 h$, where h = 23 mm

$$= 0.0707 \times 23 = 1.625 \text{ mm}^3$$

Step 3: Calculate the average rate of oxygen consumption per minute

$$\text{Rate per minute} = 1.625 \div 25$$

$$= \mathbf{0.065\ mm^3\ min^{-1}}$$

Exam Tip

There are several ways you can manage variables and increase the reliability of results in respirometer experiments:

- Use a controlled water bath to keep the **temperature** constant
- Have a control tube with an equal volume of inert material to the volume of the organisms to compensate for changes in atmospheric **pressure**
- Repeat the experiment multiple times for reliability and calculate a **mean**

Oxidation & Reduction (HL)

Oxidation & Reduction in Cell Respiration

- Oxidation and reduction are commonly known as **redox reactions**
- These reactions occur at the same time and involve the transfer of electrons between molecules
  - **Oxidation** is the **loss of electrons**
  - **Reduction** is the **gain of electrons**
- Redox reactions also involve hydrogen, oxygen and energy transfer
  - **Oxidation** is also the **loss of hydrogen**, **gain of oxygen** and **releases energy** to the surroundings (exergonic)
  - **Reduction** is also the **gain of hydrogen**, **loss of oxygen** and **absorbs energy** from the surroundings (endergonic)
- Molecules that have a strong tendency to lose/donate their electrons, are known as **reducing agents**
- Molecules that that have a strong tendency to gain electrons, are known as **oxidising agents**
- Oxidation and reduction reactions feature in **cellular respiration** and **photosynthesis**

Comparison of Oxidation and Reduction Table

Oxidation	Reduction
Loss of electrons	Gain of electrons
Loss of hydrogen	Gain of hydrogen
Gain of oxygen	Loss of oxygen
Exergonic (releases energy)	Endergonic (absorbs energy)

Oxidation and reduction in cell respiration

- Respiration involves a group of molecules called **electron carriers** which accept or donate their electrons

- **NAD^+** (nicotinamide adenine dinucleotide) is the primary electron carrier involved in respiration
- **FAD** (flavin adenine dinucleotide) is another electron carrier used in respiration
- NAD and FAD are both coenzymes which serve as links between redox reactions
- Both NAD and FAD serve as **oxidising agents**:
  - NAD^+ and FAD gain electrons and also gain one or more hydrogen ions (from molecules involved in respiration), switching to a slightly different form called **reduced NAD (NADH)** and **reduced FAD ($FADH_2$)**
  - $NAD^+ + 2e^- + 2H^+ \rightarrow NADH + H^+$
  - $FAD + 2e^- + 2H^+ \rightarrow FADH_2$
- These electron carriers are used to transport the electrons they have gained to other reactions in respiration
- When they lose these electrons they return to their original form releasing their electrons in the process
  - $NADH \rightarrow NAD^+ + 2e^- + 2H^+$
  - $FADH_2 \rightarrow FAD + 2e^- + 2H^+$
- This is an example of a **redox reaction**

Exam Tip

To help you remember which way around loss and gain of electrons is from redox reactions, think OILRIG:

- **O**xidation **I**s **L**oss
- **R**eduction **I**s **G**ain

NAD is a collective term for the different forms NAD takes; NAD exists in an oxidised and a reduced form:

- NAD^+ is the oxidised form and acts as an oxidising agent
- NADH is the reduced form and acts a reducing agent

Glycolysis (HL)

Glycolysis

- **Glycolysis** is the first stage of respiration
- It takes place in the **cytoplasm** of the cell and involves:
  - **Trapping glucose** in the cell by phosphorylating the molecule
  - **Splitting the glucose molecule in two**
- It results in the production of
  - Two **pyruvate** (3 carbon/3C) molecules
  - Net gain two **ATP** (Four ATP are produced in total but two are used during the reactions of glycolysis)
  - Two reduced NAD

Steps of glycolysis

- **Phosphorylation**: glucose (6C) is activated by phosphorylation from two ATP to form fructose-1,6-bisphosphate (6C)
  - This makes the 6C molecule less stable and therefore more **reactive**

Glucose + 2ATP → Fructose-1,6-bisphosphate

- **Lysis**
  - Fructose-1,6-bisphosphate (6C) splits into two molecules of triose phosphate (3C)

Fructose-1,6-bisphosphate → 2 Triose phosphate

- **Oxidation**:
  - Hydrogen is removed from each molecule of triose phosphate by dehydrogenase enzyme and transferred to coenzyme NAD to form two reduced NAD
  - Triose phosphate is oxidised to for another 3C molecule glycerate-3-phosphate

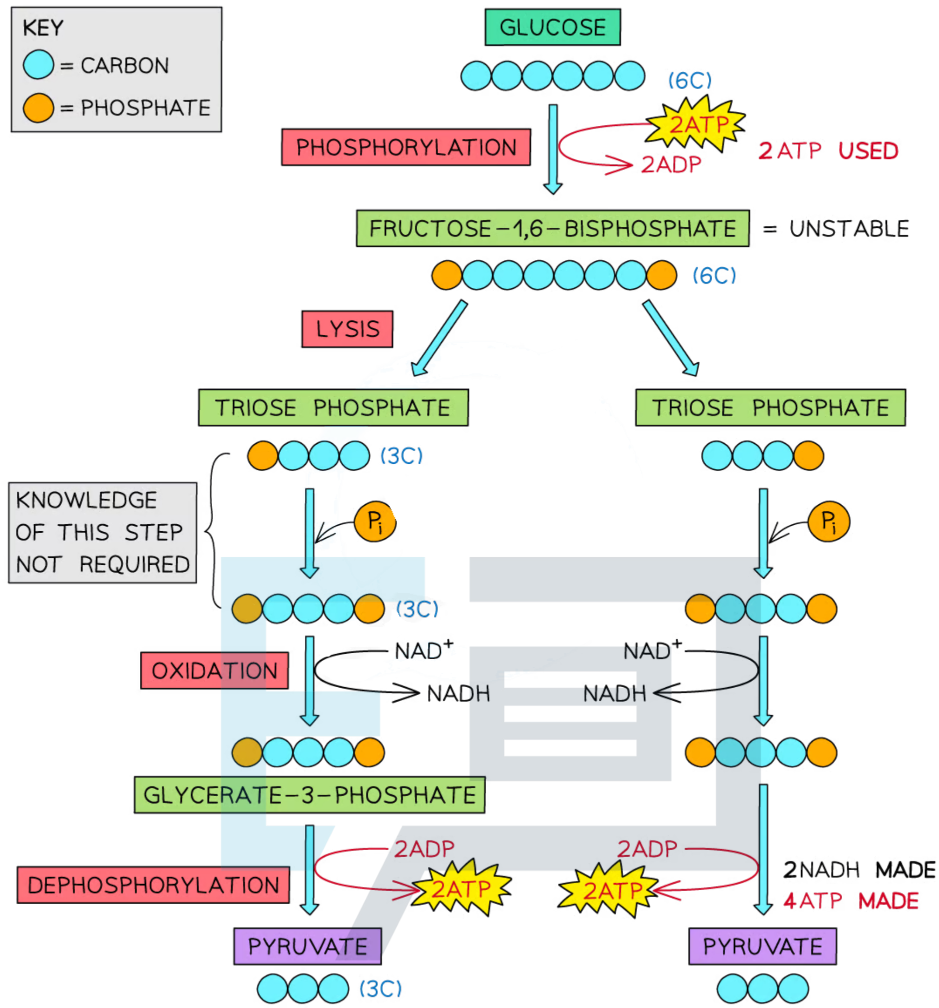
2 Triose phosphate → 2 Glycerate-3-phosphate

$4H + 2NAD \rightarrow 2NADH + 2H^+$

- **ATP formation**
  - Phosphates are transferred from the intermediate substrate molecules to form four ATP through **substrate-linked phosphorylation**

$4P_i + 4ADP \rightarrow 4ATP$

- Two molecules of **pyruvate** are produced as the end product of glycolysis which can be used in the next stage of respiration
- Each step in the pathway is catalysed by a **different enzyme**



Glycolysis, the formation of two pyruvate molecules from one glucose sugar molecule

Exam Tip

It may seem strange that ATP is used and also produced during glycolysis. At the start ATP is used to **make glucose more reactive** (it is usually very stable) and to **lower the activation energy** of the reaction.

You may see 4H (four hydrogens) also written as $2H^+ + 2e^-$

You do not need to know the **intermediate** compounds of glycolysis but do take note that each step in the pathway is catalysed by a different enzyme.

Anaerobic Respiration (HL)

Anaerobic Cell Respiration: Lactate Production

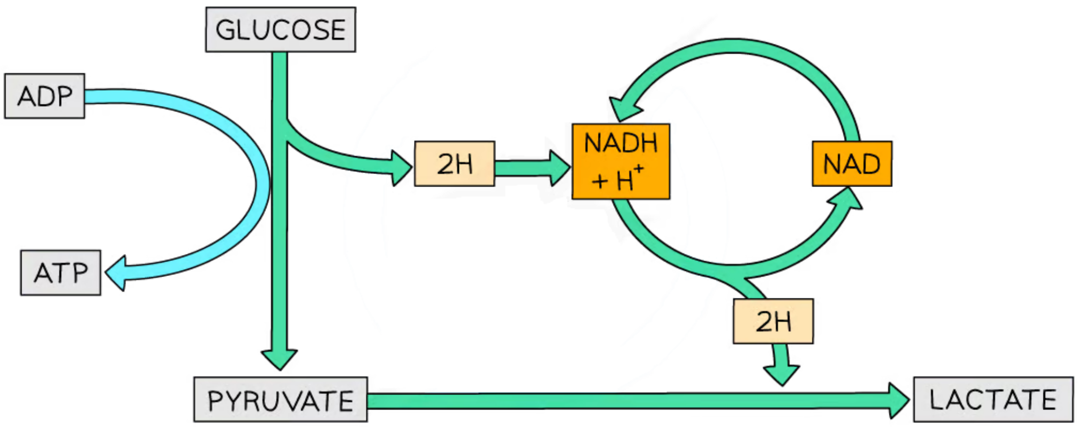
Anaerobic pathways

- Sometimes cells experience conditions with **little or no oxygen**, which prevents respiratory substrates such as glucose from being completely oxidised
  - This prevents most of the reactions that produce ATP from occurring
- However, there is still a way for **cells to produce some ATP in low oxygen conditions through anaerobic respiration**
- Some cells are able to **oxidise the reduced NAD** produced during glycolysis so it can be used for further hydrogen transport
- This means that **glycolysis can continue** and **small amounts of ATP** are still produced
  - There is a net yield of about **two ATP molecules** per glucose molecule
- Different cells use different pathways to achieve this
  - Yeast and microorganisms **convert pyruvate to ethanol**
  - Other microorganisms and mammalian muscle cells **convert pyruvate to lactate**

Converting pyruvate to lactate

- In this pathway reduced NAD transfers its hydrogens to pyruvate to form lactate
  - This allows NAD to be reoxidised in the absence of oxygen and pyruvate formation can continue
- **Pyruvate is reduced** to lactate by enzyme lactate dehydrogenase
- Pyruvate is the hydrogen acceptor
- The final product lactate can be further metabolised

Lactate Fermentation Diagram



The pathway of lactate fermentation

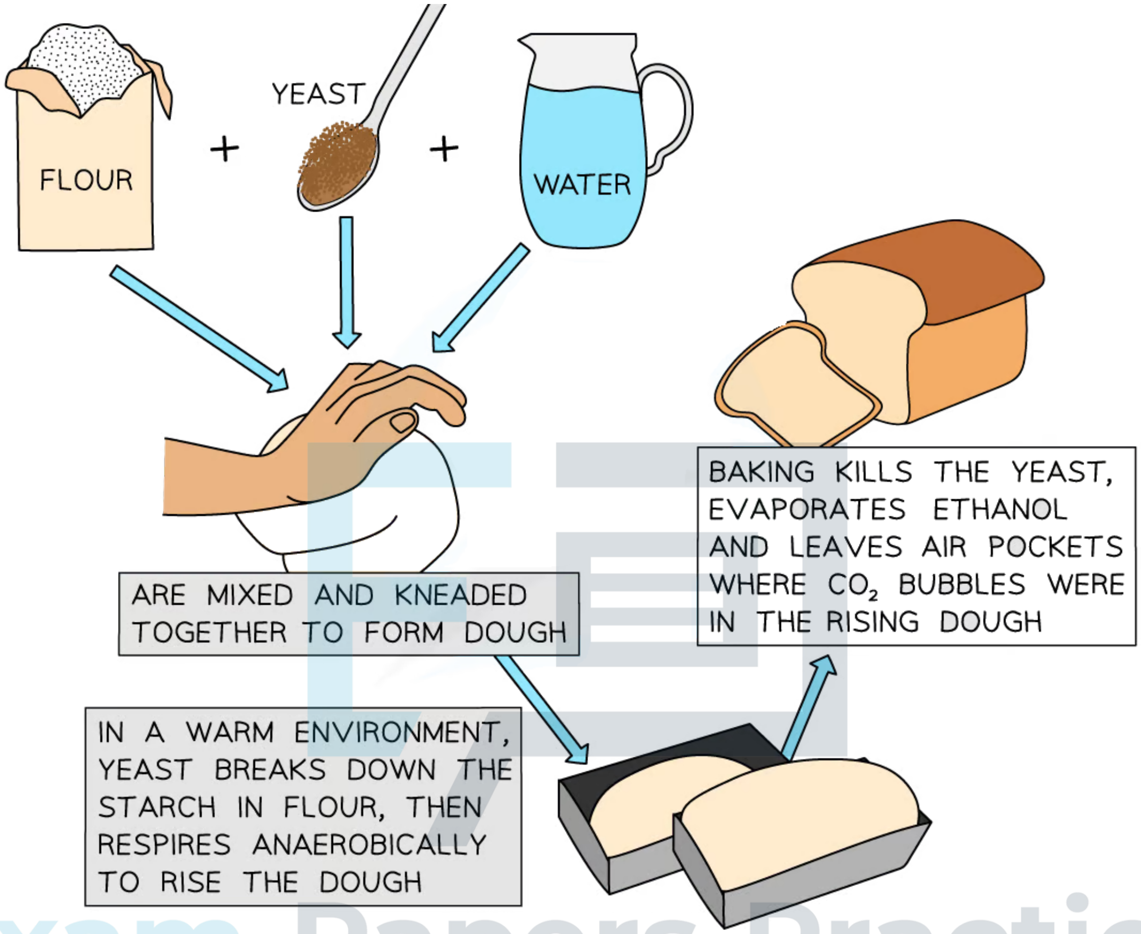
Metabolisation of lactate

- After lactate is produced two things can happen:
  1. It can be **oxidised back to pyruvate** which is then channelled into the Krebs cycle for ATP production
  2. It can be **converted into glycogen** for storage in the liver
- The **oxidation of lactate back to pyruvate needs extra oxygen**
  - This extra oxygen is referred to as an **oxygen debt**
  - It explains why animals **breathe deeper and faster after exercise**

Anaerobic Cell Respiration: Yeast

- Alcoholic fermentation occurring in yeast cells have been useful to humans for thousands of years
  - Carbon dioxide causes bread dough to rise in **bread making**
  - Ethanol is the main ingredient in **alcoholic beverages**, such as beer and wine
- Bakers can make use of anaerobic cell respiration in yeasts to produce ethanol and carbon dioxide in baking
- Yeasts are **single-celled fungi** that live in areas where sugars are present e.g. on fruit or on leaves
  - They can respire **aerobically** or **anaerobically**
- **Flour** contains starch, and when mixed with **water** and **yeast** can form a bread dough
- The dough is **kneaded** to mix everything together
- The dough is then **left in a warm place** to encourage the yeast to respire
- Yeast cells **grow rapidly in number** while oxygen is still present in the dough
  - The yeast **hydrolyses the starch** into maltose and glucose and respires the sugars, **aerobically at first**
- The dough soon **becomes anaerobic** (all the oxygen within it is used up aerobically by the yeast)
- **Anaerobic respiration takes over** and **CO_2 bubbles** begin to form in the dough
- These bubbles allow the dough to **rise** (swell up)
- Baking the dough **kills the yeast** and the bubbles form the fluffy texture of the finished bread
- **Ethanol**, the other product of anaerobic respiration of yeast, is produced but **evaporates** during the final baking stage

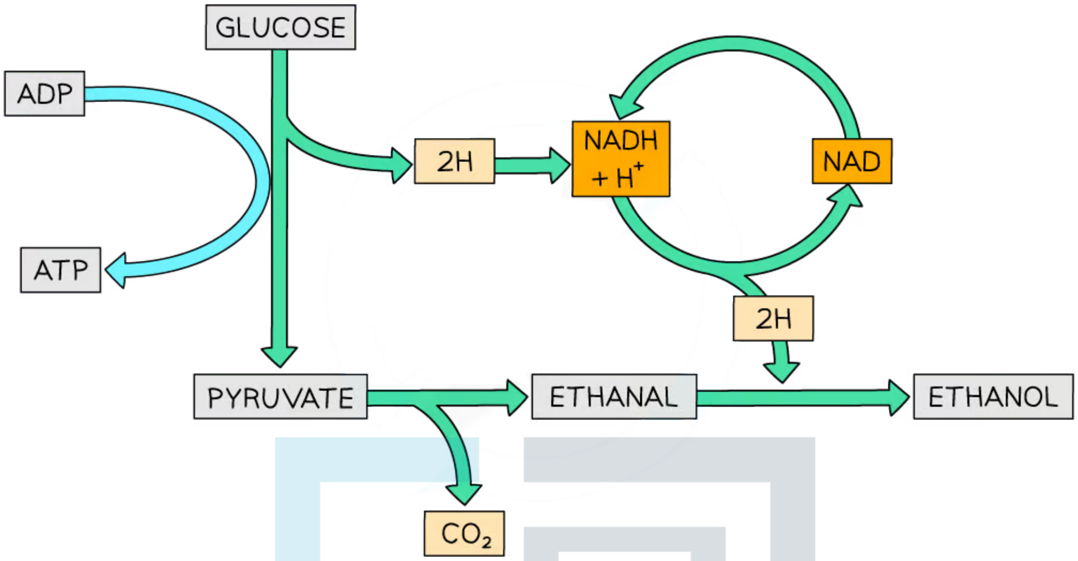
Role of Yeast in Bread Making Diagram



The role of anaerobic respiration of yeast in bread making to cause bread dough to rise

- In the alcoholic fermentation pathway reduced NAD transfers its hydrogens to ethanal to form ethanol
- In the first step of the pathway **pyruvate is decarboxylated** to ethanal producing **CO_2**
- Then **ethanal is reduced to ethanol** by the enzyme alcohol dehydrogenase
- Ethanal is the hydrogen acceptor
- Ethanol cannot be further metabolised; it is a waste product

Alcohol Fermentation Diagram



The pathway of alcoholic fermentation

Exam Tip

Remember that carbon dioxide is also produced as a product of alcoholic fermentation, which is not the case when pyruvate is converted to lactate in animal cells.

It is easy to confuse the words ethanal and ethanol so be clear in your mind which one you are referring to in exam answers.

The Link Reaction & The Krebs Cycle (HL)

The Link Reaction

Entering the link reaction

- The end product of glycolysis is **pyruvate** (3C)
- Pyruvate contains a substantial amount of chemical energy that can be further utilised in respiration to produce more ATP
- When **oxygen is available** pyruvate will **enter the mitochondrial** matrix and **aerobic** respiration will continue
- Once in the matrix pyruvate takes part in the link reaction

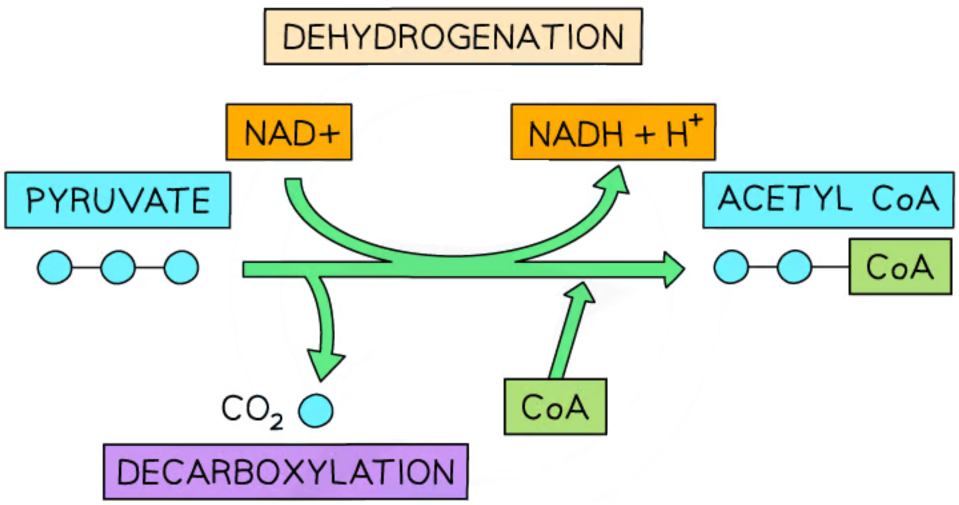
The link reaction

- The link reaction takes place in the matrix of the mitochondria
- It is referred to as the link reaction because it **links glycolysis** to the **Krebs cycle**
- The steps are:
  - **Oxidative decarboxylation** reaction in which:
    - **Carbon dioxide is removed** to produce a 2C molecule
    - **This 2C molecule is then oxidised** (loss of hydrogen and 2 high energy electrons) to produce an **acetyl compound** and thereby reducing NAD to NADH
  - **Combination of the acetyl compound with** coenzyme A to form acetyl coenzyme A (acetyl CoA)
- It produces:
  - Acetyl CoA
  - Carbon dioxide (CO_2)
  - Reduced NAD (NADH)

pyruvate + NAD + CoA → acetyl CoA + carbon dioxide + reduced NAD

- **Acetyl coenzyme A is supplied to the Krebs cycle** where aerobic respiration continues

Link Reaction Diagram



The link reaction occurs in the mitochondrial matrix. It dehydrogenates and decarboxylates the three-carbon pyruvate to produce the two-carbon acetyl CoA that can enter the Krebs Cycle.

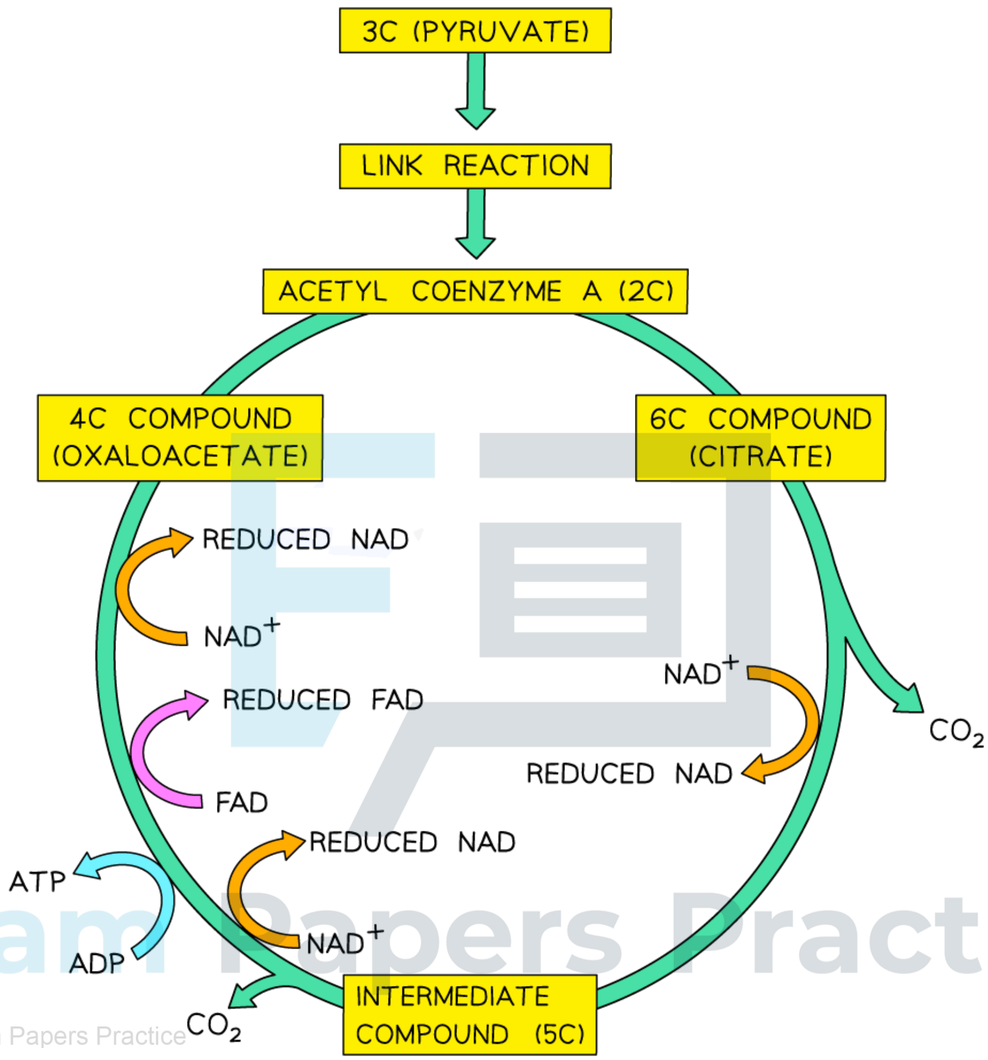
Exam Tip

Remember that there are two pyruvate molecules produced per glucose molecule so you need to **multiply everything by 2** when thinking about what happens to a single glucose molecule in aerobic respiration.

The Krebs Cycle

- The Krebs cycle (sometimes called the citric acid cycle) consists of a **series of enzyme-controlled reactions**
- The **Krebs cycle** takes place in the matrix of the mitochondria
- **Two carbon (2C) Acetyl CoA** enters the circular pathway from the **link reaction**
- A four carbon compound (4C) called **oxaloacetate** accepts the 2C acetyl fragment from acetyl CoA to form a six carbon compound (6C) called **citrate**
  - Coenzyme A is released in this reaction to be reused in the link reaction
- **Citrate (6C) is then converted back to oxaloacetate (4C)** through a series of **oxidation-reduction (redox) reactions**

The Krebs Cycle Diagram



The Krebs Cycle uses acetyl CoA from the link reaction to produce reduced carbon dioxide, reduced NAD, reduced FAD and ATP

The reactions involved in the Krebs cycle

- Oxaloacetate (4C) is regenerated in the Krebs cycle through a series of **redox reactions**
- Decarboxylation of citrate (6C)
  - Releasing **two CO_2** as waste gas
- **Oxidation** (dehydrogenation) of citrate (6C) releases hydrogen atoms
- **Reduction** of coenzymes NAD and FAD (by the released H atoms)

- 3 NAD^+ and 1 FAD → **3NADH + H^+ and 1 $FADH_2$**
- **Substrate-level phosphorylation**
  - A phosphate is transferred from one of the intermediates to ADP, forming one **ATP**

- As the link reaction produces two molecules of acetyl CoA (one per each pyruvate), the **Krebs cycle occurs twice**
- **Per glucose molecule**, the Krebs cycle produces:
  - 4 CO_2
  - 2 ATP
  - 6 NADH + H^+ (reduced NAD)
  - 2 $FADH_2$ (reduced FAD)

Exam Tip

The Krebs cycle is often referred to as cyclical or circular. This is because the 4C oxaloacetate is **regenerated** throughout the reaction so that it can start all over again by adding another acetyl CoA.

You are required to name only the intermediates citrate (6C) and oxaloacetate (4C) in the Krebs cycle.

Oxidative Phosphorylation (HL)

Transfer of Energy to the Electron Transport Chain

- The electron transport chain is made up of a **series of** redox **reactions** that occur via membrane proteins (also known as electron carriers) embedded into the inner mitochondrial membrane
- The chain is used to transport electrons and move protons (hydrogen ions) across the membrane
  - Electron carriers are positioned close together which allows the **electrons to pass from carrier to carrier**
  - The cristae of the mitochondria are **impermeable to protons** so the electron carriers are needed to pump them across the membrane to establish a **proton (or electrochemical) concentration gradient** that can be used to power **oxidative phosphorylation**
- **Energy is transferred** when a pair of electrons is passed to the first carrier in the chain
  - This converts reduced NAD back to **NAD**
    - The reduced NAD comes from glycolysis, the link reaction and the Krebs cycle
- H^+ (protons) are created when **electrons are removed** from hydrogen atoms
  - These protons play a role in **generating ATP** in the electron transport chain
- As electrons, that are received from reduced NAD (and FAD), are transported along the electron carriers, **energy is released** in a controlled manner
  - This energy is used to form ATP by adding P_i to ADP
    - **3 ATP molecules** are produced for every molecule of reduced NAD
  - This contributes to the total yield of **32 ATP molecules** per molecule of glucose oxidised during aerobic respiration
- **Oxygen** acts as the **final electron acceptor** in the chain and forms **water**

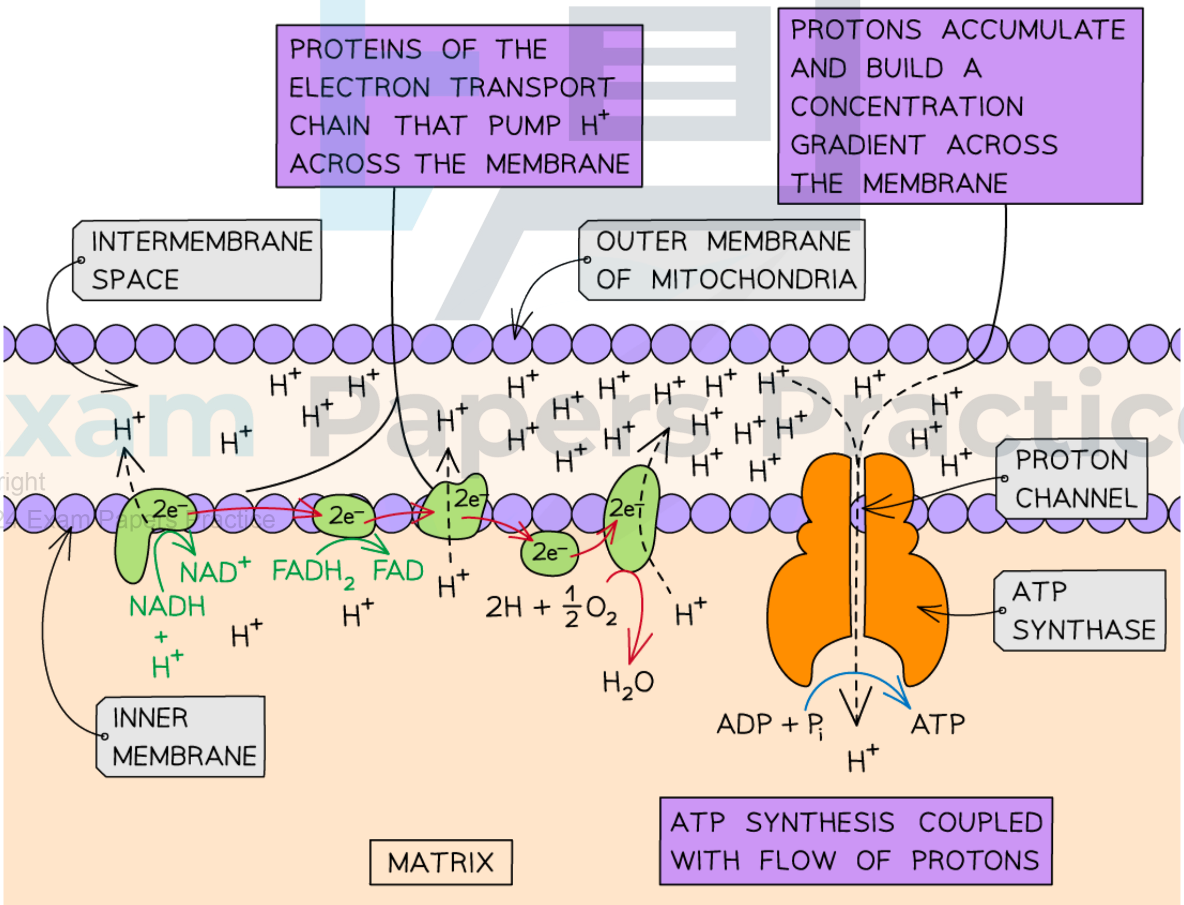
Electron Transport Chain: Flow of Electrons

- **Protons** and **electrons** are important in the electron transport chain as they play a role in the synthesis of ATP
  - **Electrons** are **given to the electron transport chain** (from reduced NAD and reduced FAD)
  - **Protons** (from reduced NAD and reduced FAD) are **released when the electrons are lost**
  - The carrier proteins pump these protons across the cristae into the intermembrane space, **creating a proton gradient** (more hydrogen ions in the matrix)
  - Returning the protons down the gradient, back into the mitochondrial matrix, **releases the energy required for ATP synthesis**

Chemiosmosis in Cell Respiration

- Movement of electrons through the electron transport chain causes a **proton or electrochemical gradient**
  - Positively charged protons accumulate in the **intermembrane space**
  - The **movement of protons back into the matrix is then used to power ATP synthesis**
- Protons that have built up in the intermembrane space can only pass through the phospholipid bilayer by facilitated diffusion through a membrane-embedded protein called **ATP synthase**
- ATP synthase acts a lot like a water wheel; it is turned by the flow of the protons moving through it, down their electrochemical gradient.
- As ATP synthase turns, it catalyses phosphorylation of ADP, **generating ATP**
- This process, in which energy from a proton gradient is used to make ATP, is called **chemiosmosis**.

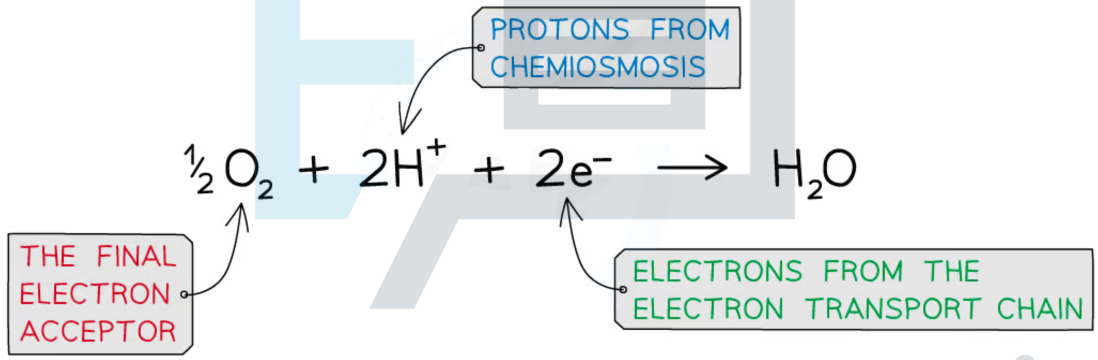
Chemiosmosis Diagram



Oxidative Phosphorylation, involving the electron transport chain and chemiosmosis, generates a large amount of ATP

Oxygen as the Final Electron Acceptor

- The final link in the electron transport chain is **oxygen** and is referred to as the final or **terminal electron acceptor**
  - This is the **last acceptor of the electrons** and allows for the continued flow of electrons along the chain
  - Oxygen is reduced by the **electrons**, and when combined with **protons** from the mitochondrial matrix, it forms **water**
- If oxygen is **not present** to accept electrons:
  - **Reduced NAD** and **reduced FAD** will not be oxidised to regenerate NAD+ and FAD, so there will be no further hydrogen transport
  - The **electron transport chain will stop**, and ATP will no longer be produced by chemiosmosis
  - Without enough **ATP,** cells can't **carry out the reactions** they need to function
- The electron transport chain is hugely efficient at generating energy in the cell but relies on an abundance of oxygen



Oxygen is the final electron acceptor and combines with protons to form metabolic water

Exam Tip

Examiners often ask why oxygen is so important for aerobic respiration, so remember the following:

- Oxygen acts as the final electron acceptor.
- Without oxygen, the electron transport chain cannot continue as the electrons have nowhere to go.
- Without oxygen accepting the electrons (and hydrogens) the reduced coenzymes NADH and $FADH_2$ cannot be oxidised to regenerate NAD and FAD, so they can't be used in further hydrogen transport.

Respiratory Substrates (HL)

Respiratory Substrates: Lipids & Carbohydrates

- Lipids are an excellent **source of energy**
  - When oxidised during respiration, they transfer **more than twice the amount of energy per gram as carbohydrates**
  - This is because lipids have **less oxygen atoms** per molecule than carbohydrates, which makes the hydrogen and carbon atoms in lipid molecules **more oxidisable**
- Lipids are also very good at their role as an **energy storage molecule**
  - This is mainly due to the fact that they are **insoluble** and will not cause a decrease in the water potential of a cell
    - A decrease in the water potential will cause water from nearby cells to move into the cell by osmosis
  - Fat stores will allow animals to **survive unfavourable conditions**, while plants may store oil reserves in seeds and fruits
- Lipids can also be used as a **source of metabolic water** for desert animals
  - This is because oxidation of lipids will produce much more water than the same amount of carbohydrates
- Glycolysis and anaerobic respiration can only occur if carbohydrate is the substrate
  - In order to enter respiratory pathways, lipids must first be broken down into **fatty acids**
    - The fatty acids are then further broken down into **2C acetyl groups**
    - These can then combine with coenzyme A to form **acetyl coenzyme A** which can enter the Krebs cycle

Comparing Lipids and Carbohydrates Table

Function	Lipids	Carbohydrates
Energy storage	Higher energy content per gram	Lower energy content per gram
Source of metabolic water	Oxidation produces higher volume of metabolic water	Oxidation produces lower volume of metabolic water
Solubility in cells	Insoluble thereby not affecting the osmotic properties of cells	Soluble thereby affecting the osmotic properties of cells
Ability to be broken down	Hydrolysed less easily so energy is transferred more slowly	Hydrolysed more easily with energy transferred more quickly