

C1.2 CELL RESPIRATION

Guiding Questions

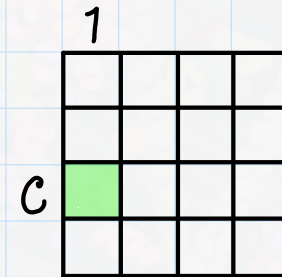
What are the roles of hydrogen and oxygen in the release of energy in cells?

How is energy distributed and used inside cells?

Linking Questions

In what forms is energy stored in living organisms?

What are the consequences of respiration for ecosystems?



Theme: Interactions + Interdependence

Level of Organization: Molecules

Written and drawn by:

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SL LEARNING OUTCOMES

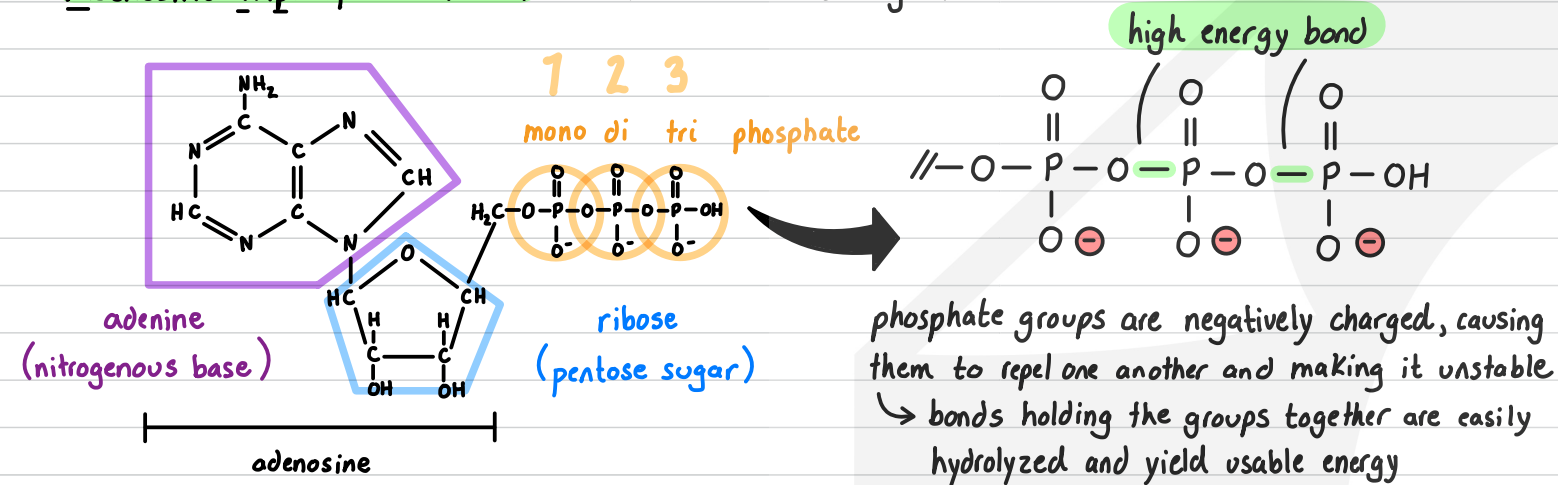
C1.2.1	ATP as the molecule that distributes energy within cells	Include the full name of ATP (adenosine triphosphate) and that it is a nucleotide. Students should appreciate the properties of ATP that make it suitable for use as the energy currency within cells.
C1.2.2	Life processes within cells that ATP supplies with energy	Include active transport across membranes, synthesis of macromolecules (anabolism), movement of the whole cell or cell components such as chromosomes.
C1.2.3	Energy transfers during interconversions between ATP and ADP	Students should know that energy is released by hydrolysis of ATP (adenosine triphosphate) to ADP (adenosine diphosphate) and phosphate, but energy is required to synthesize ATP from ADP and phosphate. Students are not required to know the quantity of energy in kilojoules, but students should appreciate that it is sufficient for many tasks in the cell.
C1.2.4	Cell respiration as a system for producing ATP within the cell using energy released from carbon compounds	Students should appreciate that glucose and fatty acids are the principal substrates for cell respiration but that a wide range of carbon/organic compounds can be used. Students should be able to distinguish between the processes of cell respiration and gas exchange.
C1.2.5	Differences between anaerobic and aerobic cell respiration in humans	Include which respiratory substrates can be used, whether oxygen is required, relative yields of ATP, types of waste product and where the reactions occur in a cell. Students should be able to write simple word equations for both types of respiration, with glucose as the substrate. Students should appreciate that mitochondria are required for aerobic, but not anaerobic, respiration.
C1.2.6	Variables affecting the rate of cell respiration	Application of skills: Students should make measurements allowing for the determination of the rate of cell respiration. Students should also be able to calculate the rate of cellular respiration from raw data that they have generated experimentally or from secondary data.

HL LEARNING OUTCOMES

C1.2.7	Role of NAD as a carrier of hydrogen and oxidation by removal of hydrogen during cell respiration	Students should understand that oxidation is a process of electron loss, so when hydrogen with an electron is removed from a substrate (dehydrogenation) the substrate has been oxidized. They should appreciate that redox reactions involve both oxidation and reduction, and that NAD is reduced when it accepts hydrogen.
C1.2.8	Conversion of glucose to pyruvate by stepwise reactions in glycolysis with a net yield of ATP and reduced NAD	Include phosphorylation, lysis, oxidation and ATP formation. Students are not required to know the names of the intermediates, but students should know that each step in the pathway is catalysed by a different enzyme.
C1.2.9	Conversion of pyruvate to lactate as a means of regenerating NAD in anaerobic cell respiration	Regeneration of NAD allows glycolysis to continue, with a net yield of two ATP molecules per molecule of glucose.
C1.2.10	Anaerobic cell respiration in yeast and its use in brewing and baking	Students should understand that 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.
C1.2.11	Oxidation and decarboxylation of pyruvate as a link reaction in aerobic cell respiration	Students should understand that lipids and carbohydrates are metabolized to form acetyl groups (2C), which are transferred by coenzyme A to the Krebs cycle.
C1.2.12	Oxidation and decarboxylation of acetyl groups in the Krebs cycle with a yield of ATP and reduced NAD	Students are required to name only the intermediates citrate (6C) and oxaloacetate (4C). Students should appreciate that citrate is produced by transfer of an acetyl group to oxaloacetate and that oxaloacetate is regenerated by the reactions of the Krebs cycle, including four oxidations and two decarboxylations. They should also appreciate that the oxidations are dehydrogenation reactions. <pre> graph TD A[3C (pyruvate)] --> B[link reaction] B --> C[2C (acetyl-CoA)] C --> D[6C (citrate)] D --> E[5C] E --> F[2 CO2] F --> G[4C (oxaloacetate)] G --> D </pre>
C1.2.13	Transfer of energy by reduced NAD to the electron transport chain in the mitochondrion	Energy is transferred when a pair of electrons is passed to the first carrier in the chain, converting reduced NAD back to NAD. Students should understand that reduced NAD comes from glycolysis, the link reaction and the Krebs cycle.
C1.2.14	Generation of a proton gradient by flow of electrons along the electron transport chain	Students are not required to know the names of protein complexes.
C1.2.15	Chemiosmosis and the synthesis of ATP in the mitochondrion	Students should understand how ATP synthase couples release of energy from the proton gradient with phosphorylation of ADP.
C1.2.16	Role of oxygen as terminal electron acceptor in aerobic cell respiration	Oxygen accepts electrons from the electron transport chain and protons from the matrix of the mitochondrion, producing metabolic water and allowing continued flow of electrons along the chain.
C1.2.17	Differences between lipids and carbohydrates as respiratory substrates	Include the higher yield of energy per gram of lipids, due to less oxygen and more oxidizable hydrogen and carbon. Also include glycolysis and anaerobic respiration occurring only if carbohydrate is the substrate, with 2C acetyl groups from the breakdown of fatty acids entering the pathway via acetyl-CoA (acetyl coenzyme A).

C1.2.1—ATP as the molecule that distributes energy within cells. C1.2.2—Life processes within cells that ATP supplies with energy. C1.2.3—Energy transfers during interconversions between ATP and ADP

Adenosine Triphosphate (ATP) : a nucleotide consisting of :



- ATP's function is often described as the "energy currency" of the cell as like money, it is used in many different contexts and constantly recycled
- Specifically, it is used as temporary storage of energy and for energy transfer between metabolic reactions and components of the cell



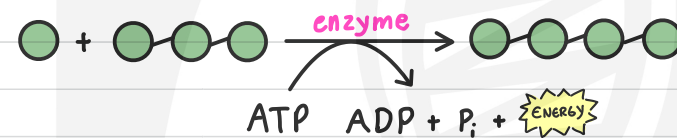
- Its properties make this function suitable:
 - ✓ ATP is water-soluble : moves freely throughout cell cytoplasm and aqueous solutions
 - ✓ ATP cannot simply diffuse across membranes: allows its movement to be controlled via carriers
 - ✓ ATP is chemically stable at ~ neutral pH (similar to cytoplasm): does not hydrolyze prematurely
 - ✓ $\text{ATP} + \text{H}_2\text{O} \rightleftharpoons \text{ADP} + \text{P}_i + \text{Energy}$ is easily reversible: facilitating use and re-use
 - ✓ energy released from hydrolysis is 'just right': sufficient for cellular processes with minimal waste

Cellular life processes that require ATP :

Anabolic reactions metabolism C1.1

- synthesizing larger, more complex macromolecules from smaller simpler monomers is endergonic, i.e. products have more energy than reactants and thus require energy
- each condensation reaction that links a monomer to polymer is coupled to the conversion of ATP to ADP in order to provide the necessary energy required

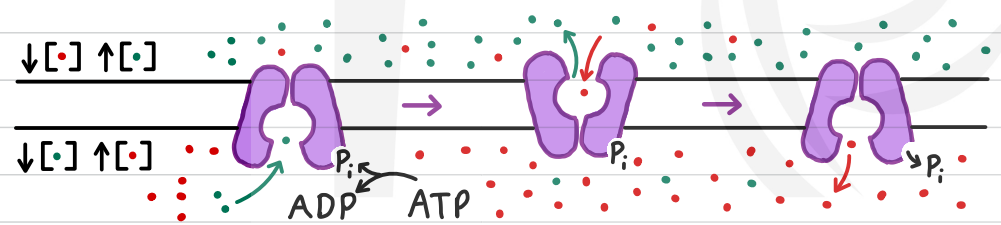
ex: DNA replication DNA replication D1.1
 mRNA and protein synthesis protein synthesis D1.2
 photosynthesis photosynthesis C1.3



Active transport membrane transport B2.1

- pumping substances across a membrane against their concentration gradient (low concentration to high concentration) is not passive and requires additional energy
- the energy supplied from ATP hydrolysis causes a reversible change to a protein pump, from a more stable configuration (open to one side of membrane) to less stable configuration (open to other side)

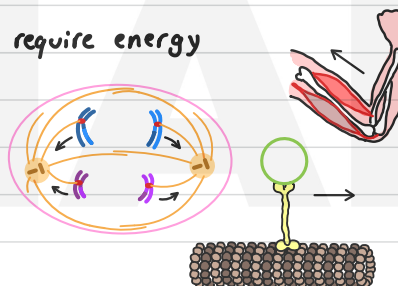
ex: Na^+/K^+ pump
 exocytosis and endocytosis



Movement

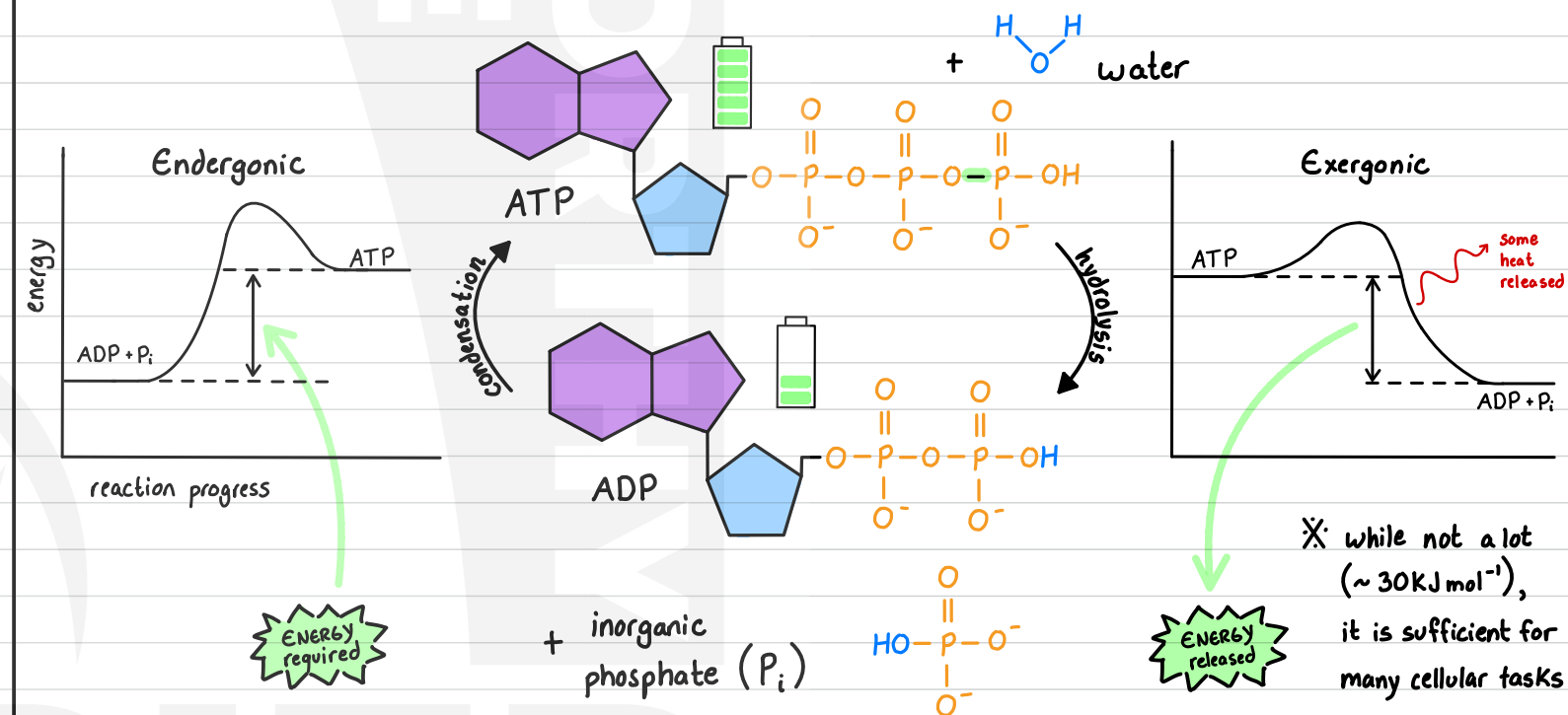
- movement of cell components and of the cell itself to another location require energy

ex: Chromosome movement during mitosis and meiosis cell + nuclear division D2.1
 vesicles moving and transporting substances within cell
 cells moving using flagella reproduction D3.1
 muscle cell contraction using myosin and actin muscle + motility B3.3



Interconversion of Adenosine Triphosphate (ATP) $\rightleftharpoons$ Adenosine Diphosphate (ADP)

- ATP contains more chemical potential energy than ADP
 $\therefore$ energy is released when it is converted to $\text{ADP} + \text{P}_i$ and required when converted to ATP



Energy is supplied by :

- oxidation of biomolecules via cellular respiration
- conversion of light to chemical energy in photosynthesis
- oxidation of inorganic substances via chemosynthesis

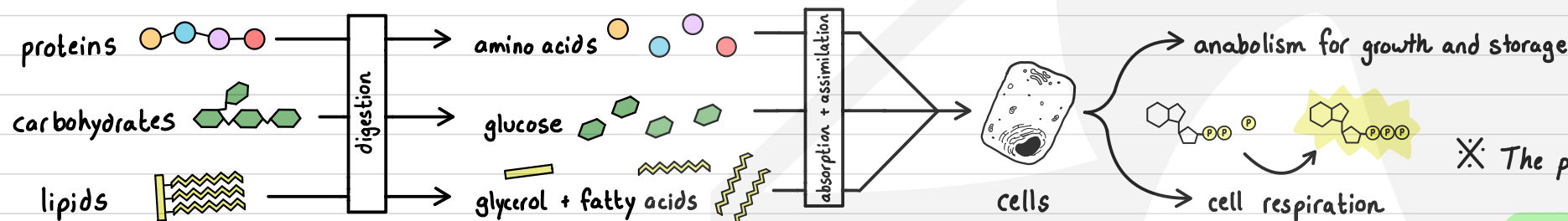
✗ ATP is sometimes directly hydrolyzed by water (like above) but it can also react directly with another molecule (phosphorylation) making it reactive where P_i is released later to be re-used

C1.2.4—Cell respiration as a system for producing ATP within the cell using energy released from carbon compounds. C1.2.5—Differences between anaerobic and aerobic cell respiration in humans

Cell respiration: the controlled release of energy from carbon compounds in cells to produce ATP

by specific enzymes in step-by-step pathways

carbohydrates, lipids, proteins (main substrates are glucose and fatty acids)



energy is released from carbon compounds by **oxidation** which is coupled to reduction → 'redox' reactions

reduction: the gain of electrons / Hydrogen

* extended in HL *

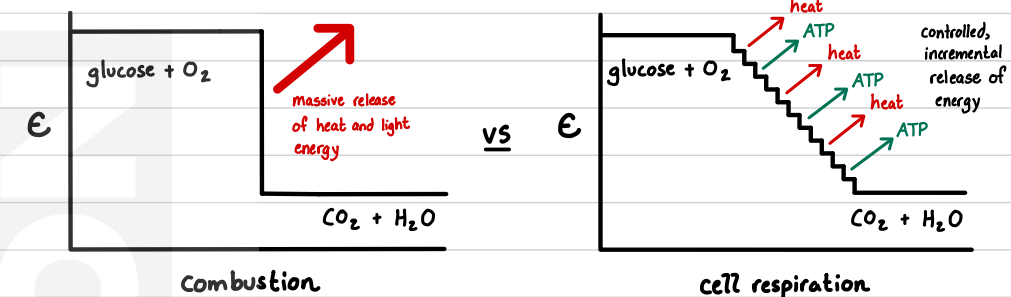
reduction



oxidation: the loss of electrons / Hydrogen

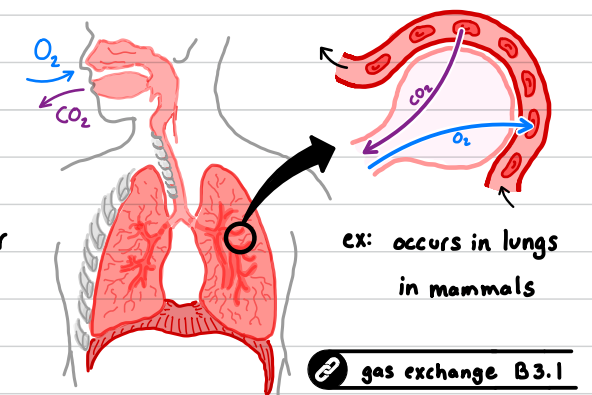


oxidation



✗ The processes of respiration is often confused with gas exchange → they're **NOT** the same!

gas exchange: the exchange of O_2 and CO_2 between an organism and its surroundings

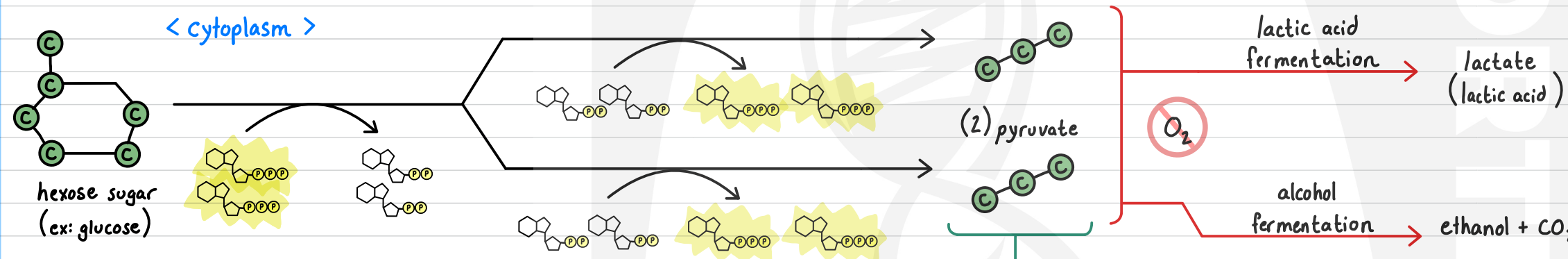


aerobic cell respiration requires O_2 and produces CO_2 as waste in order to produce ATP for cellular activities, creating a gradient. Gas exchanges is the diffusion of these gases.

∴ both processes are different but interdependent

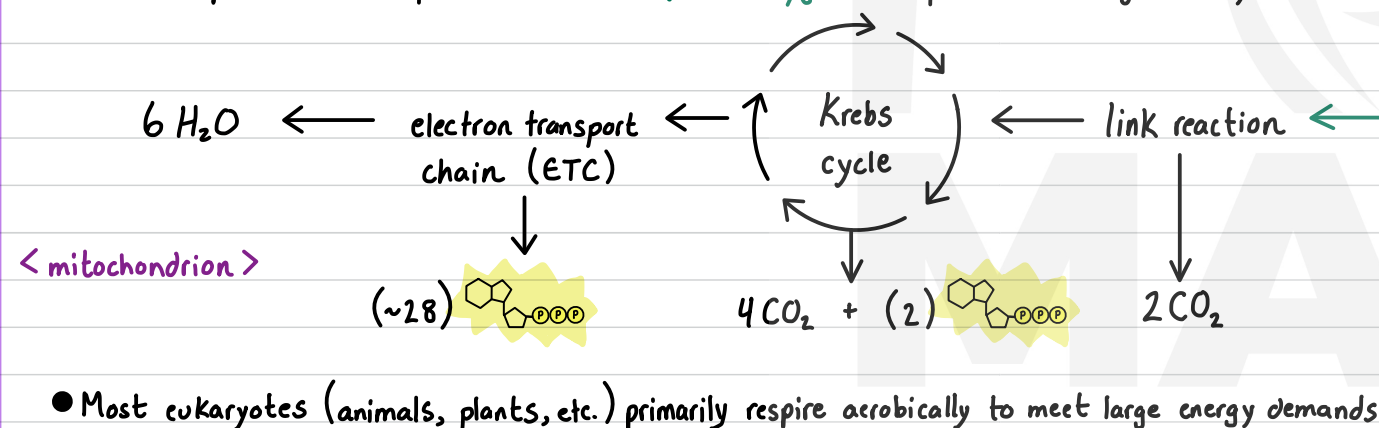
First step in cell respiration is **glycolysis**: breakdown of glucose into two pyruvate molecules, producing a net 2 ATP

anaerobic respiration: respiration in the **absence of oxygen**. No further ATP produced



- occurs in humans when energy demand is very high and there is not enough O_2 for aerobic respiration. Limit to how much lactate can be stored due to increasing acidic conditions, affecting contractions - O_2 required to break it down later. Some bacteria respire like this (lactobacillus)
- occurs in plants, yeast, fungi, bacteria. Used commercially to make alcoholic beverages, bake bread, and biofuel

aerobic respiration: respiration which **requires oxygen** and produces a large ATP yield

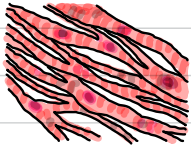


	(in humans)	aerobic respiration	anaerobic respiration
chemical reaction		glucose + oxygen → water + carbon dioxide reactants → waste products	glucose → lactate reactant → waste product
respiratory substrates		carbohydrates, lipids and amino acids (after deamination)	only carbohydrates
cellular location		begins in cytoplasm and ends in mitochondria	occurs in cytoplasm only
ATP yield		large ATP yield (>30 per glucose)	small ATP yield (2 per glucose)
reaction pathway		glycolysis → link reaction → Krebs cycle → ETC	glycolysis → fermentation

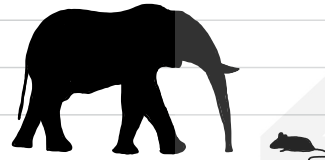
C1.2.6—Variables affecting the rate of cell respiration

The rate of cell respiration is impacted by several factors (each of which could be an IV in an investigation):

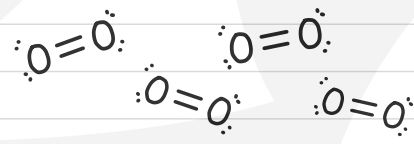
metabolic rate of the cell
→ cells vary in their energy demand ∴ rate will reflect this and vary



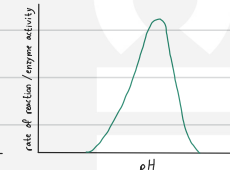
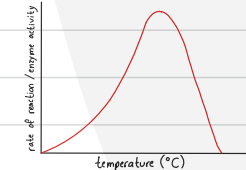
Size of the organism
→ smaller organisms have higher SA:vol ∴ higher rate to account for heat loss



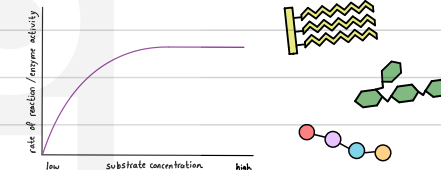
O₂ concentration
→ lower conc. of O₂ results in lower rates and absence results in anaerobic respiration



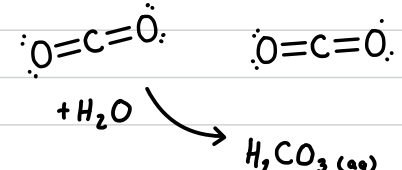
temperature and pH
→ respiration is enzyme-controlled
∴ temp/pH closer to optimal increases rate and beyond may denature enzymes



respiratory substrates
→ as substrate conc. increases, so does rate until enzyme saturation. type of substrate also matters



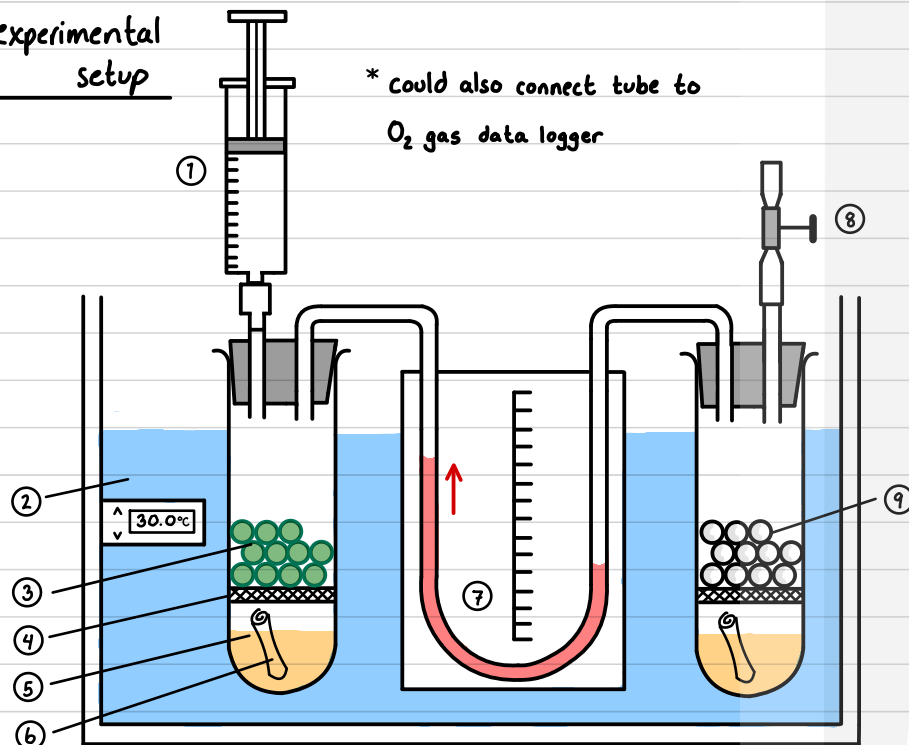
CO₂ concentration
→ as CO₂ is produced it can form carbonic acid and lower pH



The rate of aerobic respiration can be measured and determined using a **respirometer** - measures the rate of O₂ consumption

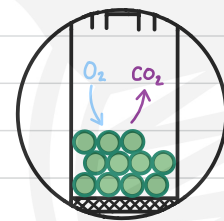
experimental setup

* could also connect tube to O₂ gas data logger

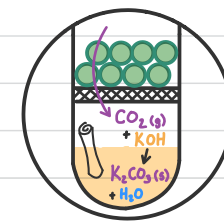


How it works

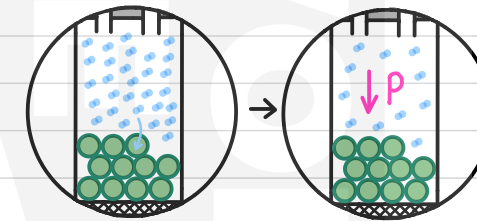
1 Study species respire aerobically, absorbing O₂ and releasing CO₂



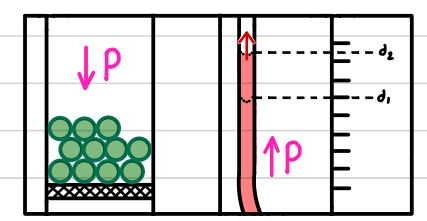
2 CO₂ is absorbed by alkali solution and converted to solid - removing it from air



3 As O₂ (g) is removed and CO₂ is absorbed, gas particles within tube decreases - decreasing pressure within



4 The pressure within manometer tube is higher than test tube, causing liquid within to move toward respiring organism (↑P to ↓P)
→ distance liquid moved over time is measured



- ① syringe - adds air to reset manometer
- ② electronic water bath - regulates temperature
- ③ aerobically respiring organism(s) (study species)
ex: germinating seeds, meal worms, insects
- ④ cage partition - allows gases through but prevents contact of organism with hazardous alkali solution
- ⑤ alkali solution (potassium hydroxide) - absorbs CO₂
 $\text{KOH} + \text{CO}_2(\text{g}) \rightarrow \text{K}_2\text{CO}_3(\text{s}) + \text{H}_2\text{O}$
* could also use soda lime pellets
- ⑥ rolled filter paper - increases absorption efficiency
- ⑦ manometer - capillary U-tube filled with coloured oil
- ⑧ Hoffman clip - seals respirometer and used to reset pressure
- ⑨ glass beads - control (same total volume as study species)

- the impact of CO₂ absorbent should be determined, i.e. how much does manometer move due to CO₂ absorption alone:
→ if setup is like one on the left, ensure glass beads are the same volume as study species and this is controlled
→ if setup is a single test tube, run experiment with and without organism (using beads) and subtract difference

- photosynthetic organisms both absorb and release O₂ - how to account for this:
→ run experiment in the dark to prevent photosynthesis and only measure respiration
- seal respirometer only after temperature has stabilized, otherwise expansion can cause explosion

Data

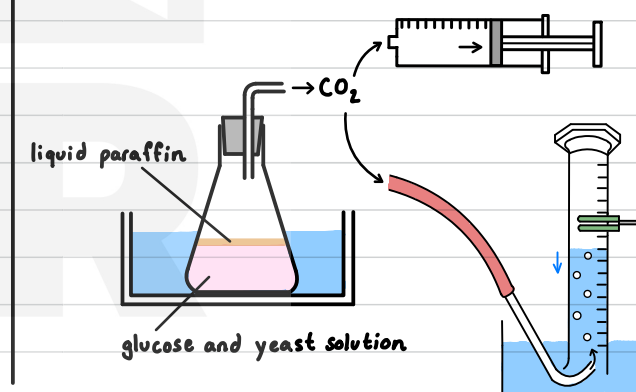
IV groups	movement of fluid in manometer (mm min ⁻¹)				
	T1	T2	T3	T4	T5

Determining rate of respiration

- rate of respiration = volume of O₂ per unit time (mm³ min⁻¹)
→ determine mean distance liquid moved in manometer after a set amount of time (longer the better)
→ volume O₂ consumed in tube can be calculated: $\pi r^2 d$ where r is radius of manometer tube (mm) and d is distance travelled (mm)
→ divide by length of time in chosen unit (min or s)
ex: liquid moved 10mm in 5min through 4mm diameter manometer tube
$$= \frac{\pi (2\text{mm})^2 10\text{mm}}{5\text{min}} = 25\text{mm}^3\text{min}^{-1}$$



measuring anaerobic respiration



- To prevent aerobic respiration the solution of glucose is boiled (to remove gases) and paraffin placed on top to stop O₂ from dissolving in
- CO₂ production can be measured via data logger, syringe or inverted cylinder

HL C1.2.7—Role of NAD as a carrier of hydrogen and oxidation by removal of hydrogen during cell respiration.

The purpose of cell respiration is to transfer the chemical energy in biomolecules (like glucose) into ATP for easier, later use through a series of reactions in a metabolic pathway

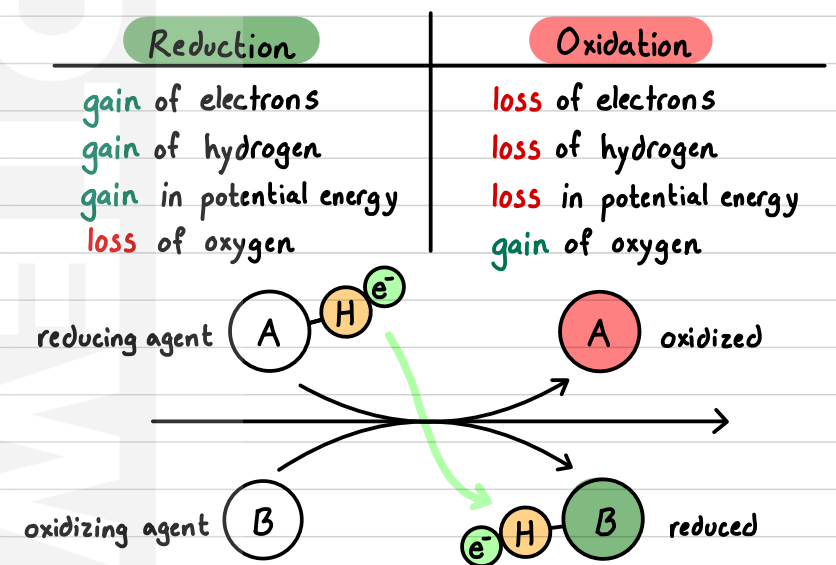
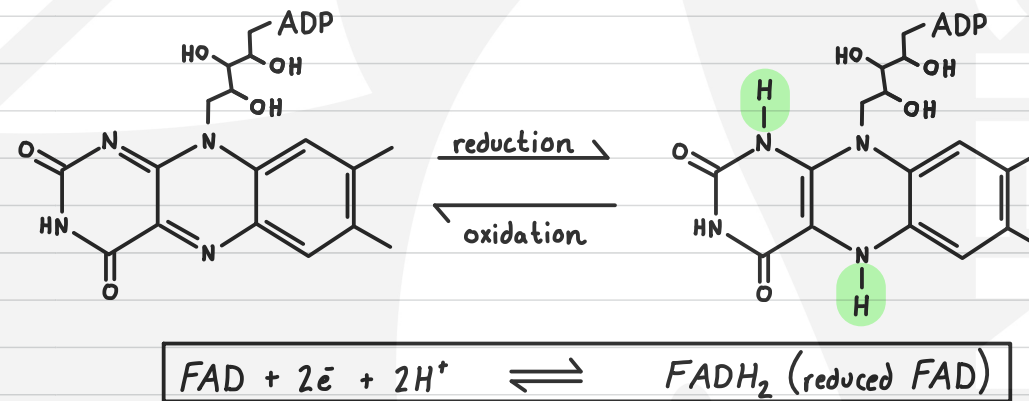
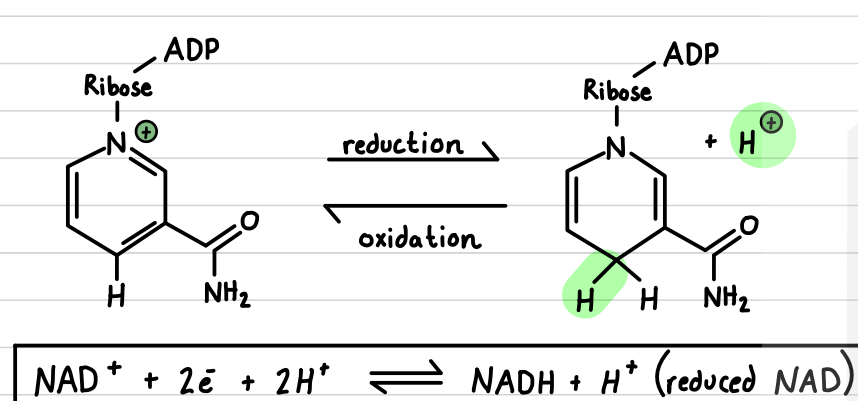
✗ note: you do not need to know the structures of NAD⁺ and FAD

How is energy incrementally taken, transferred, and used?

→ electron/hydrogen carriers carry energy-rich electrons (e⁻) in order to ultimately produce ATP

→ organic, non-protein molecule which aid an enzyme in its catalysis functions

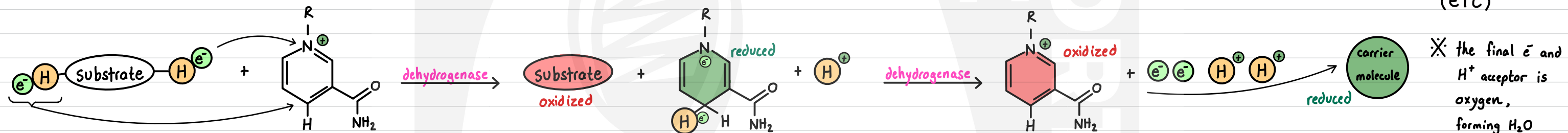
→ **Nicotinamide Adenine Dinucleotide (NAD)** and **Flavin Adenine Dinucleotide (FAD)** are **coenzymes** which accept and donate hydrogen atoms (and electrons) reversibly in redox reactions



→ NAD⁺ accepts 2 electrons and a proton from hydrogen atoms, becoming reduced NAD (NADH), the other proton is released (H⁺)

→ FAD accepts 2 electrons and 2 protons from hydrogen atoms, becoming reduced FAD (FADH₂)

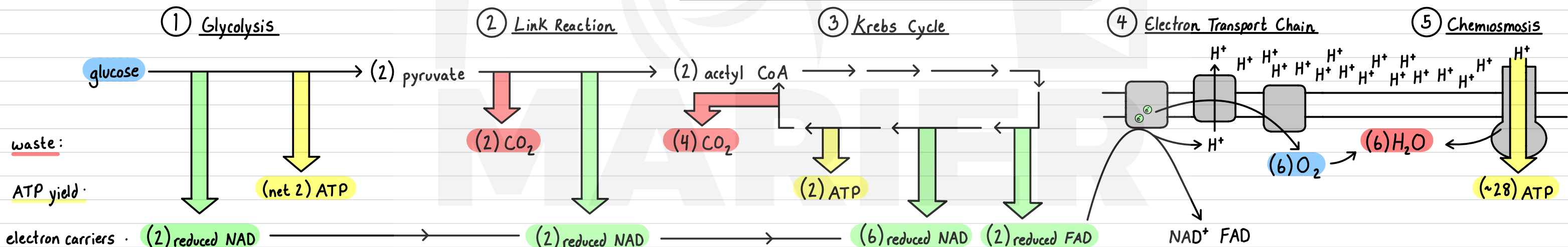
→ **Dehydrogenase enzymes** remove 2 Hydrogen (2e⁻, 2H⁺) from a substrate and transfers them to NAD⁺ and FAD, reducing them. Later, they are oxidized, donating the protons and electrons to the electron transport chain (ETC)



✗ NAD⁺ is reduced in glycolysis, link reaction, and Krebs cycle. FAD is reduced in the Krebs cycle

✗ Both NADH and FADH₂ are oxidized by protein complexes in the ETC and can be reused

The aerobic cell respiration metabolic pathway consists of 5 major phases
Overview of entire process:



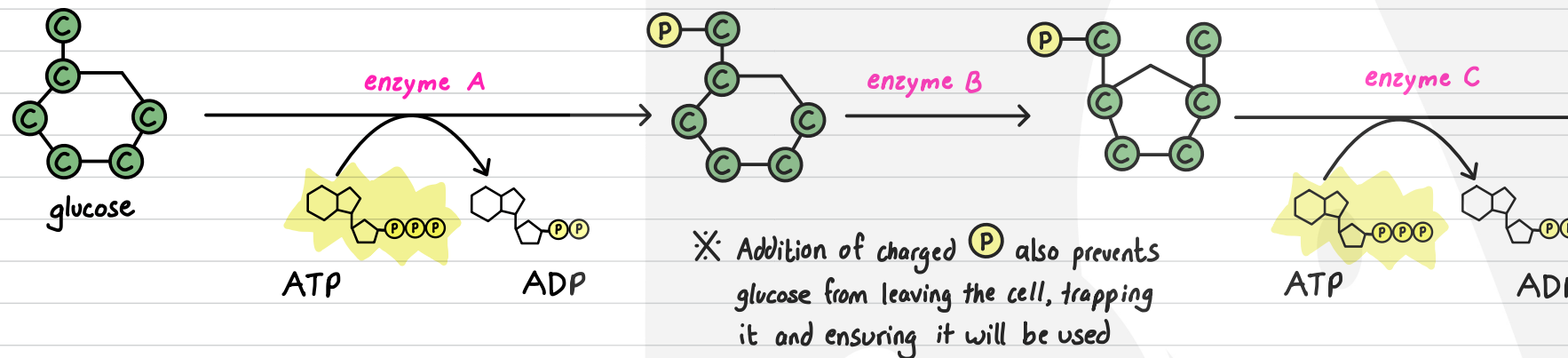
① **Glycolysis**: the first stage of respiration where a 6 carbon molecule (glucose) is broken down into two molecules of pyruvate in a stepwise linear metabolic pathway ✖ means "sugar splitting"

- takes place in the cytoplasm of cells and does not require oxygen
- Consists of first 'investing' energy [1, 2] to receive back a 'payoff' with interest' (ATP and reduced NAD) [3, 4]

Note: It is not required to know the exact structures and names of respiratory intermediates and enzymes. Understand that each step in the pathway is catalyzed by a different enzyme

1 Phosphorylation

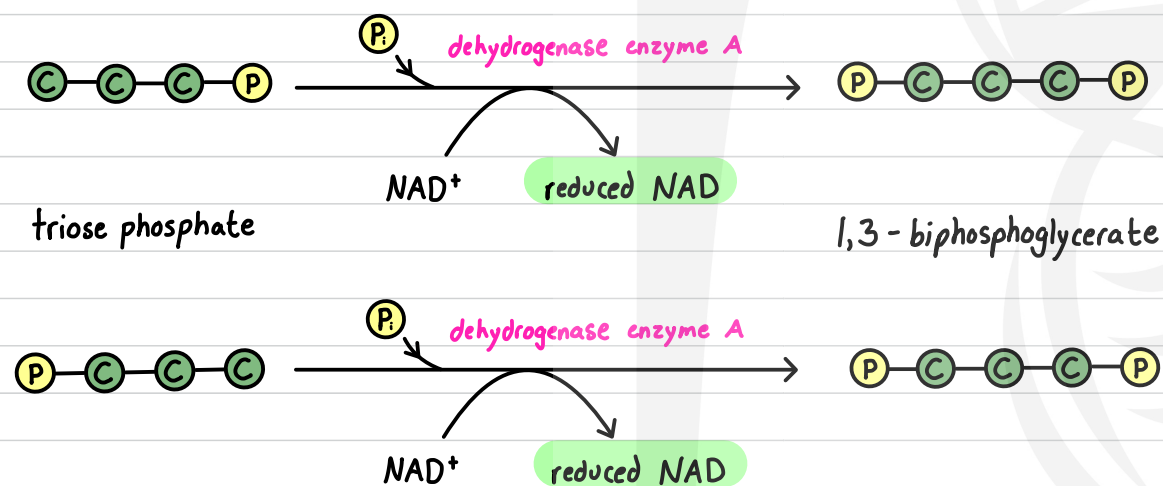
Glucose is **phosphorylated** twice through the **dephosphorylation** of 2 ATP molecules
 → this makes fructose 1,6-biphosphate energetically unstable and more reactive



2 **Lysis** Due to the attached phosphates, fructose 1,6-biphosphate is unstable and lyses (splits) into 2 triose phosphate (G3P) molecules

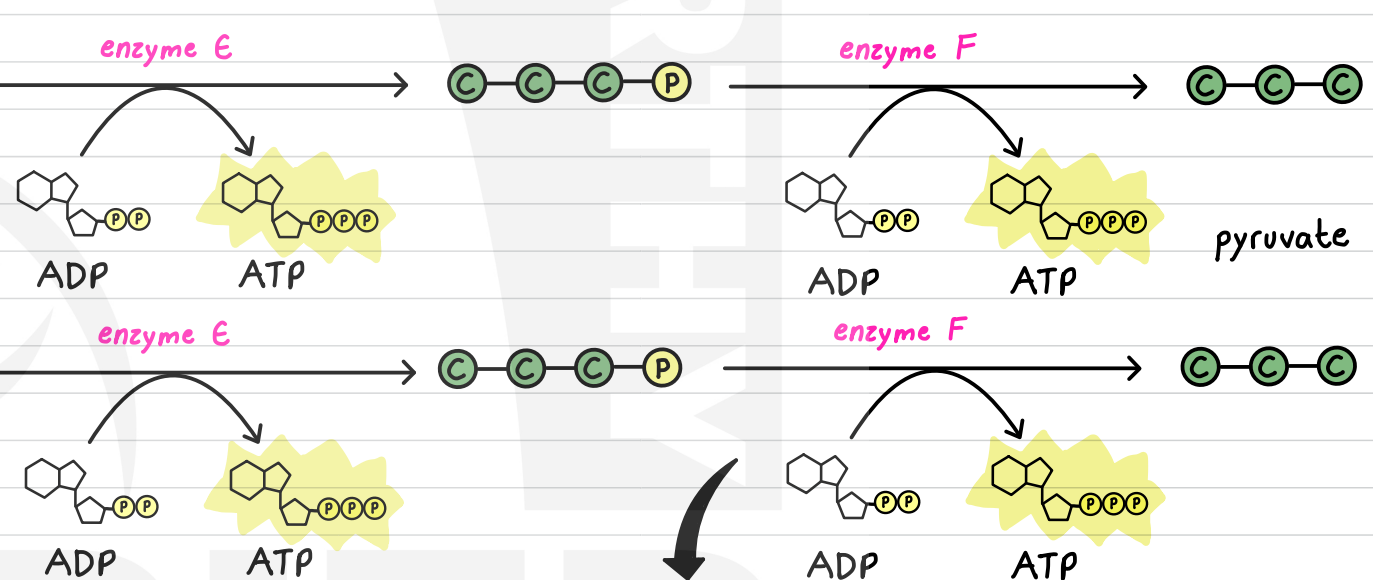
3 Oxidation

Each triose phosphate is oxidized through the removal of hydrogen and $2e^-$ (dehydrogenation). NAD^+ accepts the hydrogen and electrons, becoming reduced NAD
 → energy released from oxidation allows phosphorylation by an inorganic phosphate (P_i) to the oxidized substrate, forming a high energy product



4 ATP formation

Each molecule of 1,3-biphosphoglycerate is dephosphorylated twice, transferring the phosphate to ADP via **substrate-level phosphorylation (SLP)** forming 4 ATP total (a net of 2)
 → the end products are two 3-carbon molecules of pyruvate



Summary

location: cytoplasm
 products per glucose: (2) pyruvate, (2) reduced NAD, (net 2) ATP via SLP

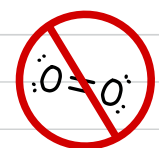
Enzyme (specific to the phosphorylated substrate) binds to it and ADP at **active site** to catalyze the reaction.
 ✖ as each substrate is different, a different enzyme is used



HL

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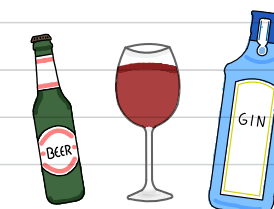


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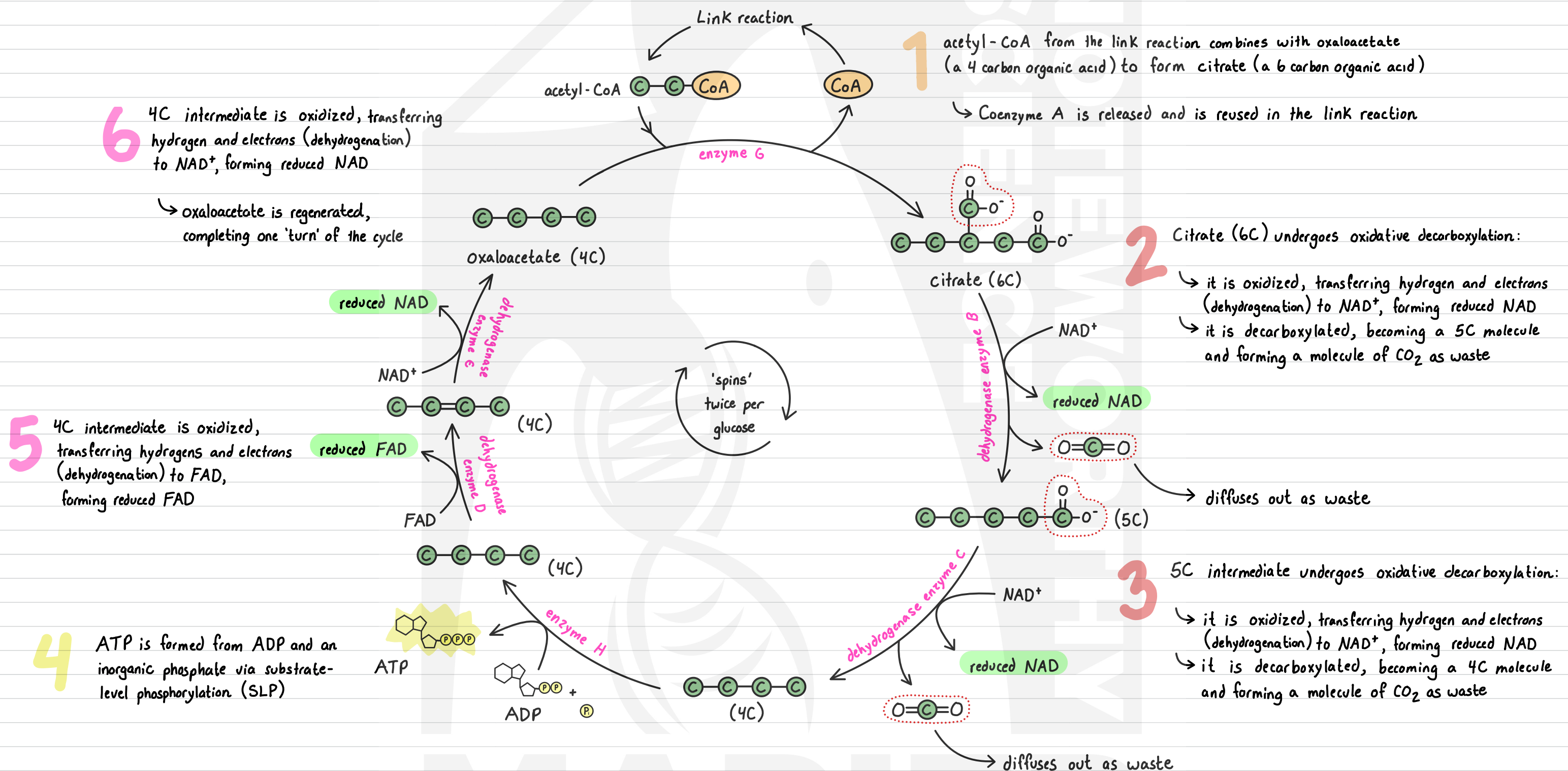
HL

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✕ named after its discoverer, Hans Krebs. Also known as Citric Acid Cycle, after the first intermediate formed

③ **Krebs Cycle**: cyclical metabolic pathway where acetyl groups are decarboxylated and oxidized resulting in the reduction of NAD^+ and FAD and the production of ATP and CO_2



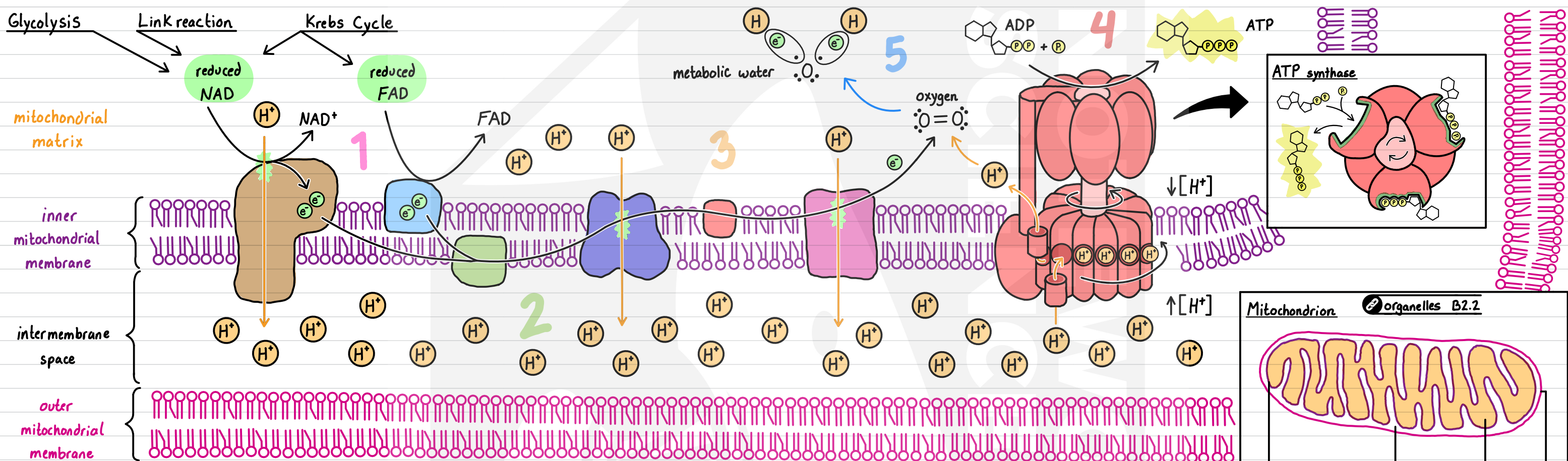
✕ reactions where substrates are oxidized in order to reduce electron carriers are **dehydrogenation reactions** (removing hydrogen) and are catalyzed by **dehydrogenase enzymes**

Summary

location: mitochondrial matrix

products per cycle: (3) reduced NAD, (1) reduced FAD, (1) ATP via SLP, (2) CO_2

products per glucose: (6) reduced NAD, (2) reduced FAD, (2) ATP via SLP, (4) CO_2



④ **Electron Transport Chain (ETC)**: Series of carriers in the inner mitochondrial membrane that accept electrons from reduced coenzymes allowing the generation of a proton gradient in the intermembrane space.

1 Reduced NAD (from glycolysis, link reaction, and Krebs cycle) is oxidized to NAD^+ , donating electrons and protons. Reduced FAD (from Krebs cycle) is oxidized to FAD by another protein complex, donating electrons and protons. $\rightarrow \text{NAD}^+$ and FAD can now be reused in previous metabolic pathways.

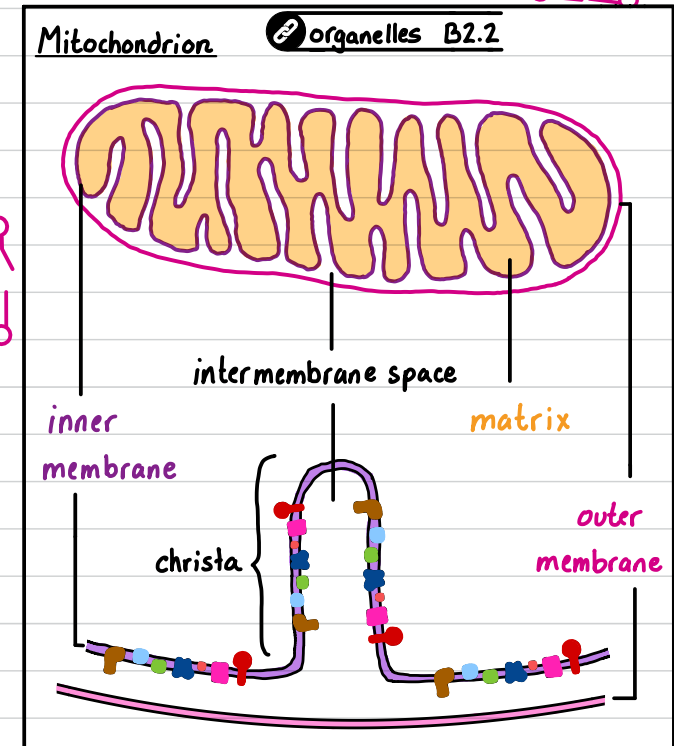
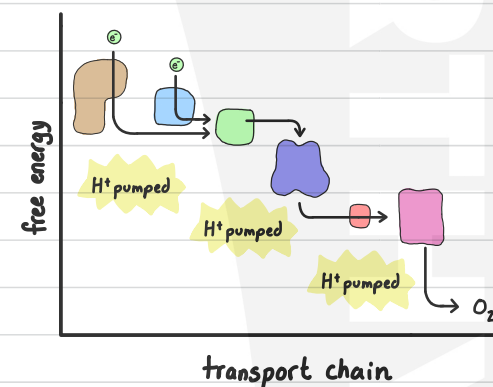
2 electrons released are donated to protein complexes embedded in the inner mitochondrial membrane, reducing them. As electrons move from one carrier to another, they move from a higher energy level to a lower one, releasing energy.

3 the energy released by electrons is used to pump H^+ from the mitochondrial matrix into the intermembrane space. $\rightarrow$ creates a large electrochemical proton gradient across the inner membrane (low in matrix, high in intermembrane space) aka **proton-motive force**.

⑤ **Chemiosmosis**: process by which the synthesis of ATP is driven by the diffusion of protons down their electrochemical gradient through ATP synthase.

4 large proton gradient in the intermembrane space diffuses down its concentration gradient through the enzyme **ATP synthase** back into the matrix. This causes the enzyme to spin (like a turbine), catalyzing the **oxidative phosphorylation** of ADP, capturing the potential energy from the H^+ gradient as **ATP**.

5 oxygen is the terminal acceptor of electrons in the ETC. It also accepts H^+ from the mitochondrial matrix, forming metabolic water ($4\text{e}^- + 4\text{H}^+ + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$). $\rightarrow$ this is why aerobic respiration requires O_2 : without it the electrons will stop flowing in the ETC and the H^+ gradient is no longer maintained, halting chemiosmosis.



Summary of ATP generation per glucose

ATP via SLP: 2 (glycolysis)
2 (Krebs cycle)

ATP via oxidative phosphorylation: 25 (10 reduced NAD $\times$ 2.5)
3 (2 reduced FAD $\times$ 1.5)

no O_2 required = 2 O_2 required = 30 grand total = 32

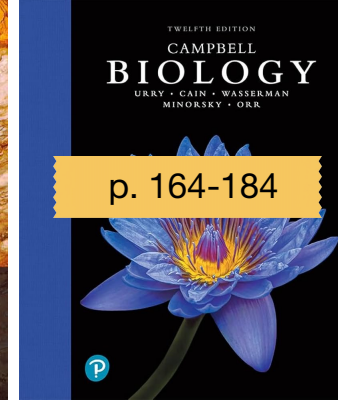
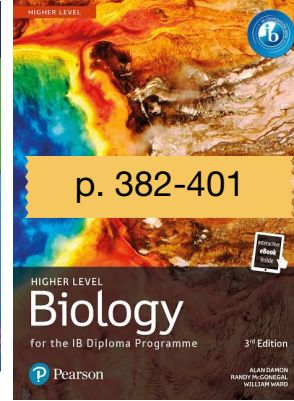
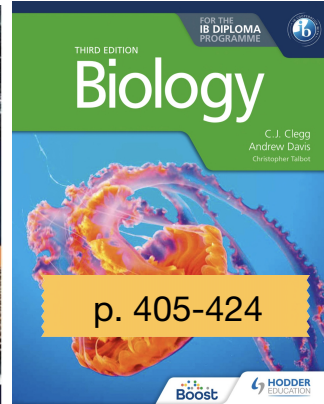
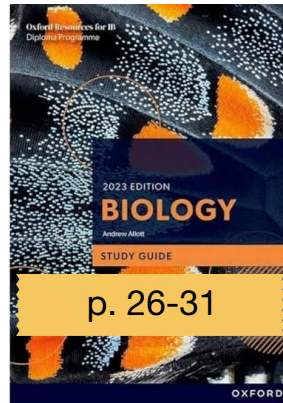
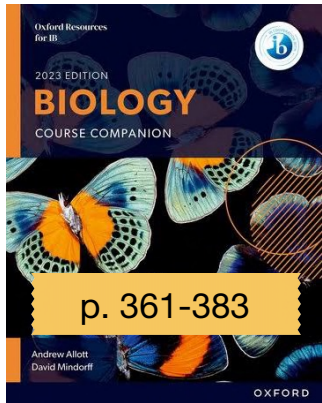
* values are estimates based on H^+ generated by the e^- donated. 10 H^+ generated/NADH, 6 H^+ /FADH₂ (4 H^+ needed per ATP)

Resource Links

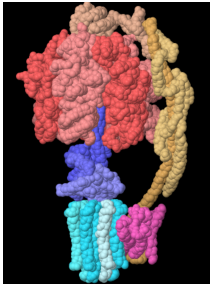
each resource is hyperlinked



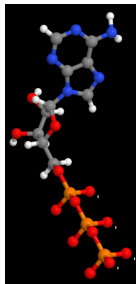
Textbooks



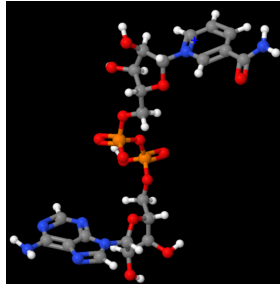
3D models



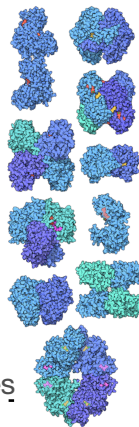
ATP synthase



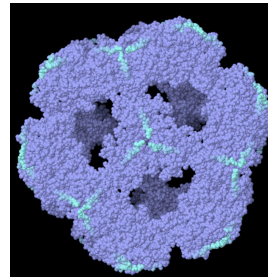
ATP



NAD



Glycolytic enzymes



Pyruvate dehydrogenase complex

Articles

Boyer P. D. (1999). What makes ATP synthase spin?. Nature, 402(6759), 247–249. <https://doi.org/10.1038/46193>

Boyer P. D. (2002). A research journey with ATP synthase. The Journal of biological chemistry, 277(42), 39045–39061. <https://doi.org/10.1074/jbc.X200001200>

Cross, R. L. (2004). Turning the ATP motor. Nature, 427(6973), 407–408. <https://doi.org/10.1038/427407b>

Dawson, J. (2021, January 4). ATP Synthase. BIOC*2580: Introduction to Biochemistry. <https://ecampusontario.pressbooks.pub/bioc2580/chapter/atp-synthase/>

Lactic Acid Does Not Cause Muscle Soreness - Track & Field News. (2019, January 2). Track & Field News. <https://trackandfieldnews.com/track-coach/lactic-acid-does-not-cause-muscle-soreness/>

Oxidation states. (n.d.). JCE Software, Published by the Division of Chemical Education of the American Chemical Society. <https://www2.chem.wisc.edu/deptfiles/genchem/netorial/modules/biomolecules/modules/lipids/lipid5.htm>

Simulators / Interactives

