CELL BIOLOGY

Cellular Respiration

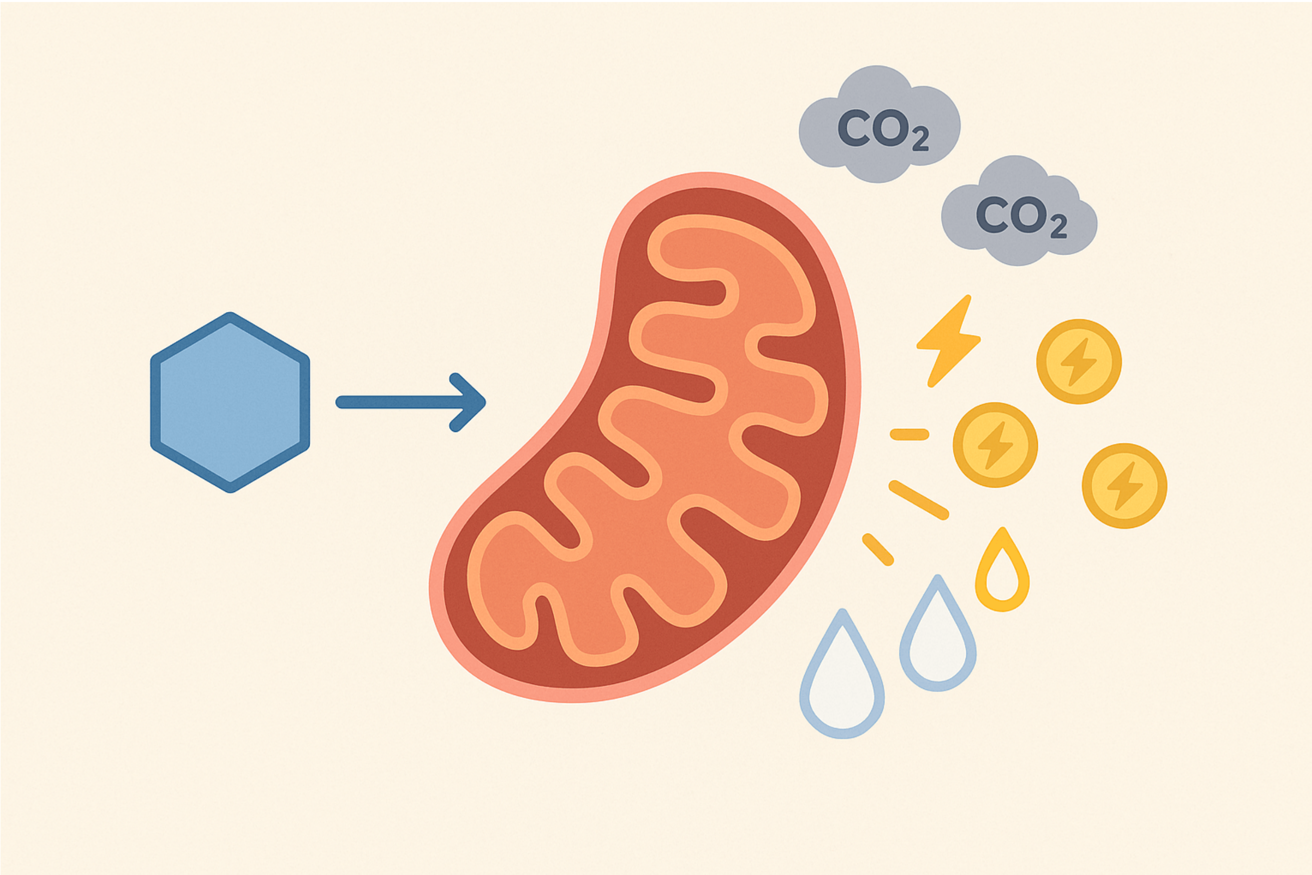
How cells cash glucose into ATP through glycolysis, the Krebs cycle, and the electron transport chain, with a 10-question practice set and full solutions.

SUBJECT	LEVEL	INCLUDES
Biology	High school and early college	Practice set, answer key, revision sheet

Read this note online, with updates: gauravtiwari.org/study-notes/cellular-respiration

INSIDE

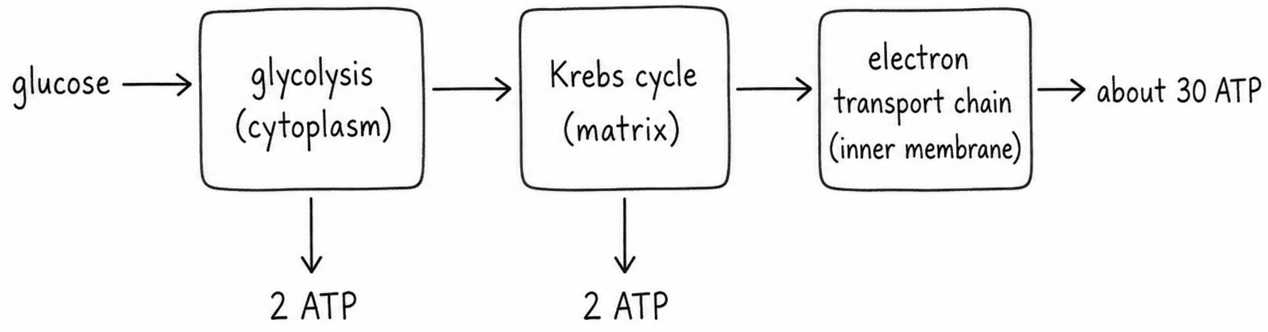
Cellular respiration is how cells extract energy from glucose. The process unfolds in three linked stages, glycolysis in the cytoplasm, the Krebs cycle in the mitochondrial matrix, and oxidative phosphorylation on the inner mitochondrial membrane, and yields roughly 30 to 32 ATP per glucose molecule. This note walks through each stage with stoichiometry, the electron transport chain, the difference between aerobic and anaerobic respiration, and how the whole sequence mirrors photosynthesis in reverse.



Cellular respiration, glucose plus oxygen enters the mitochondrion, ATP, water, and CO2 come out.

The Net Equation of Cellular Respiration

The summary fits in one line and is the exact reverse of photosynthesis:



The 3-stage assembly line: a little ATP up front, most of it at the end from the electron transport chain.

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{ATP}$$

Glucose plus oxygen yields carbon dioxide, water, and energy in the form of ATP. The energy is not released as heat in a single explosion; it is harvested step by step through controlled enzyme reactions so the cell can capture as much of it as possible in usable form.

Stage 1: Glycolysis

Glycolysis happens in the cytoplasm, not the mitochondrion. One glucose molecule (6 carbons) is broken into two molecules of pyruvate (3 carbons each). The cell invests 2 ATP to get the reaction started and then produces 4 ATP plus 2 NADH along the way. Net yield: 2 ATP and 2 NADH per glucose.

Glycolysis is anaerobic, it does not require oxygen. This matters because cells that lack mitochondria (red blood cells) or are temporarily oxygen-starved (muscle during a sprint) can still produce ATP this way, just less efficiently.

Stage 2: The Krebs Cycle

Each pyruvate enters the mitochondrial matrix and is converted to acetyl-CoA, releasing one CO_2 and producing one NADH. Acetyl-CoA then enters the Krebs cycle (also called the citric acid cycle or TCA cycle), where it joins oxaloacetate and runs through eight enzymatic steps that ultimately regenerate oxaloacetate while releasing more CO_2.

Per glucose (two pyruvates), the Krebs cycle produces 6 NADH, 2 $FADH_2$, 2 GTP/ATP, and releases 6 CO_2. Every breath of carbon dioxide you exhale came from the Krebs cycle running in your mitochondria right now.

Stage 3: Oxidative Phosphorylation

This is where the bulk of the ATP comes from. NADH and $FADH_2$ from stages 1 and 2 deliver electrons to the electron transport chain on the inner mitochondrial membrane. Electrons hop through four complexes (I, II, III, IV). At each hop, complexes I, III, and IV pump protons from the matrix into the intermembrane space, building a proton gradient.

The proton gradient drives ATP synthase (Complex V), which spins like a rotary motor and produces ATP. Oxygen is the final electron acceptor at Complex IV, without oxygen, the chain backs up, NADH and $FADH_2$ cannot deliver their electrons, and the whole stage stalls. That is why aerobic respiration requires oxygen.

Per glucose, oxidative phosphorylation produces roughly 26-28 ATP, depending on how efficiently the proton gradient is converted.

Total ATP Yield

STAGE	LOCATION	ATP	NADH	$FADH_2$	CO_2
Glycolysis	Cytoplasm	2 net	2	0	0
Pyruvate oxidation	Mitochondrial matrix	0	2	0	2
Krebs cycle	Mitochondrial matrix	2 (as GTP)	6	2	4
Oxidative phosphorylation	Inner membrane	~26-28	(uses NADH)	(uses $FADH_2$)	0
TOTAL per glucose		**~30-32**	10	2	6

Aerobic vs Anaerobic Respiration

When oxygen is unavailable, glycolysis continues but the Krebs cycle and oxidative phosphorylation cannot. The cell must regenerate NAD^+ somehow so glycolysis can keep running.

- **Lactic acid fermentation** (animal muscle cells, some bacteria). Pyruvate is reduced to lactate, regenerating NAD^+. This is why your muscles burn during intense sprinting, lactate accumulates faster than oxygen can clear it.
- **Alcoholic fermentation** (yeast, some bacteria). Pyruvate is converted to ethanol and CO_2. This is the entire basis of bread, beer, and wine.

Both anaerobic pathways yield only 2 ATP per glucose (the glycolysis net), versus 30-32 with oxygen. The 15x efficiency gap is why large active animals depend on aerobic respiration.

Cellular Respiration vs Photosynthesis

The two processes are mirror images. Photosynthesis builds glucose from CO_2 and water using light energy; cellular respiration breaks glucose back down using oxygen and stores the energy as ATP. Plants run both, photosynthesis in chloroplasts to make food, respiration in mitochondria to use it.

Related study notes: Photosynthesis, Mitochondria, Enzyme, Protein.

Practice Questions

Work each question before reading its solution. The set runs from direct recall and substitution to the applied questions that exams actually use to separate grades.

Q1. Write the overall equation of aerobic respiration and compare it with photosynthesis.

SOLUTION

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy (ATP + heat). It is photosynthesis run in reverse direction, energy released instead of stored; plants run both, animals only this one. The symmetry is the carbon cycle at the cellular scale.

Q2. Summarize glycolysis: location, inputs, outputs, and its evolutionary significance.

SOLUTION

In the cytoplasm, glucose (6C) splits into 2 pyruvate (3C), netting 2 ATP and 2 NADH, no oxygen required. Every domain of life runs it, testifying to its origin before Earth's atmosphere held oxygen. It is the universal opening move of metabolism.

Q3. What happens to pyruvate when oxygen is present, before the Krebs cycle proper?

SOLUTION

It enters the mitochondrion and is oxidized by pyruvate dehydrogenase to acetyl-CoA, releasing 1 CO_2 and loading 1 NADH per pyruvate. This link step commits the carbon to full oxidation: 2 pyruvate yield 2 acetyl-CoA, 2 CO_2, 2 NADH.

Q4. Where does most of respiration's CO_2 actually come from, and where does the O_2 go?

SOLUTION

CO_2 exits during the link step and the Krebs cycle, not during the electron transport chain. O_2 serves only at the chain's very end, as the final electron acceptor, combining with electrons and protons into water. The gas you exhale and the gas you inhale are consumed and produced in different rooms of the factory.

Q5. Explain chemiosmosis: how does the electron transport chain make ATP without touching ATP directly?

SOLUTION

The chain's complexes use electron energy from NADH and $FADH_2$ to pump protons from the matrix into the intermembrane space, building an electrochemical gradient. Protons flow back through ATP synthase, spinning its rotor, and the rotation mechanically stitches ADP and phosphate into ATP. Electron energy becomes a proton dam; the dam turns a turbine. Mitchell's once-heretical idea earned the 1978 Nobel.

Q6. Tally the ATP: how much does 1 glucose yield, and why do textbooks now say "about 30" instead of 38?

SOLUTION

Substrate-level: 2 (glycolysis) + 2 (Krebs). The 10 NADH and 2 $FADH_2$ feed the chain for roughly 25 more. Modern measured yields are ~2.5 ATP per NADH and 1.5 per $FADH_2$, minus the cost of shuttling cytoplasmic NADH into the mitochondrion, giving 30 to 32 overall. The gradient leaks and the exchange rates are not integers; the old 38 assumed perfect accounting.

Q7. Without oxygen, why does the whole system stall at glycolysis, and how does fermentation rescue it?

SOLUTION

No O_2 means the chain backs up, NADH cannot unload, and NAD^+, glycolysis's essential oxidizer, runs out. Fermentation regenerates NAD^+ by dumping electrons onto pyruvate: to lactate in muscle, or to ethanol and CO_2 in yeast. It buys continued glycolysis at 2 ATP per glucose, a 15-fold pay cut taken to keep the lights on.

Q8. Compare the energy yield of aerobic respiration and fermentation, and connect it to sprinting versus marathon pace.

SOLUTION

Aerobic: ~30 ATP per glucose, limited by oxygen delivery, sustainable. Fermentation: 2 ATP, fast, oxygen-free, but burns glucose 15 times faster for the same power and accumulates lactate. Sprints run on fast glycolysis and stored phosphates; distance running must stay near the oxygen-supplied aerobic ceiling. The burn of a 400 m race is the chemistry of the shortfall.

Q9. Cyanide blocks cytochrome c oxidase, the chain's final complex. Trace why this is lethal within minutes.

SOLUTION

With the terminal electron acceptor step blocked, the whole chain halts, the proton gradient dissipates, and ATP synthase stops; NADH piles up and the Krebs cycle strangles for lack of NAD^+. Cells fall back on fermentation's 2 ATP, hopelessly short for heart and brain. Death by cyanide is death by unplugged mitochondria, with oxygen abundant and unusable.

Q10. Brown fat is packed with mitochondria that make heat instead of ATP. What is being uncoupled, and why is that useful?

SOLUTION

Uncoupling protein 1 opens a proton leak across the inner membrane, letting the gradient discharge WITHOUT passing through ATP synthase: the dammed energy dissipates directly as heat. Hibernating mammals and human infants use it for non-shivering warmth. The same principle killed dieters who took the uncoupler DNP in the 1930s: unlimited fuel burn, uncontrolled fever.

Answer Key

QUICK ANSWERS

Q1 glucose + oxygen → CO_2 + water + ATP **Q2** cytoplasm; 2 pyruvate + 2 ATP + 2 NADH **Q3** pyruvate → acetyl-CoA + CO_2 + NADH **Q4** CO_2 from Krebs/link; O_2 accepts electrons into water **Q5** proton gradient drives the ATP synthase rotor

Q6 ≈30-32 ATP; leaky, non-integer stoichiometry **Q7** fermentation recycles NAD^+ so glycolysis continues **Q8** 30 vs 2 ATP: endurance vs burst **Q9** the chain stops; ATP output collapses **Q10** proton leak turns the gradient into heat

Revision Sheet

The ledger

Glycolysis 2 ATP + 2 NADH; link 2 NADH; Krebs 2 ATP + 6 NADH + 2 $FADH_2$; chain ~25 ATP.

Modern total

≈30-32 ATP per glucose (2.5/NADH, 1.5/$FADH_2$, shuttle costs).

Geography

Glycolysis: cytoplasm. Link + Krebs: matrix. Chain + synthase: inner membrane.

No oxygen

Fermentation recycles NAD^+: lactate (muscle) or ethanol + CO_2 (yeast); 2 ATP only.

Chemiosmosis

Electrons pump protons; the gradient spins ATP synthase. O_2 is the final acceptor.

Poisons and heat

Cyanide blocks the last complex; uncouplers (brown fat, DNP) vent the gradient as heat.

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