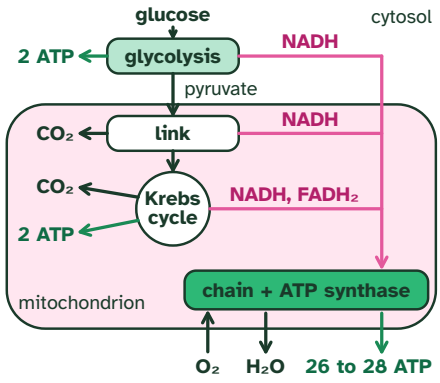
Fuel into *ATP*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Respiration takes hydrogen off the fuel a step at a time. Its electrons build a proton gradient, and the gradient makes ATP.



Draw it like this. Glycolysis in the cytosol; everything after it in the mitochondrion.

3.5.A START HERE

Four stages, *one map*

- **Cellular respiration** makes ATP with energy released from carbon compounds, in every living cell, all the time. Energy is transferred to ATP: none is made.
- **Aerobic:** glucose + oxygen → carbon dioxide + water. The energy comes out a step at a time, each step with its own enzyme. Burning releases it all at once, and makes no ATP.
- Energy is released by taking hydrogen off the fuel. **NAD^+** accepts the hydrogen and is reduced to **NADH**, a hydrogen carrier that takes it to the chain.
- A cell has only a little NAD^+, so NADH must keep being turned back into it.

THEY ALWAYS HAPPEN TOGETHER: REDOX — *OIL RIG*

O **Oxidation** Is Loss of electrons: hydrogen removed

R **Reduction** Is Gain of electrons: hydrogen accepted

3.5.A LEARN THE LEDGER

What goes in, what comes out, *and where*

STAGE	WHERE	IN	OUT, FOR ONE GLUCOSE
1 **Glycolysis** needs no oxygen	Cytosol	Glucose (6 carbons). 2 ATP are spent to start it.	**2 pyruvate, net 2 ATP, 2 NADH** 4 ATP are made, so 2 are gained.
2 **Pyruvate oxidation** the link	Matrix of the mitochondrion	2 pyruvate (3 carbons each)	**2 acetyl groups, 2 CO_2, 2 NADH** A carbon leaves each pyruvate as carbon dioxide.
3 **Krebs cycle** two turns	Matrix	2 acetyl groups (2 carbons each)	**4 CO_2, 6 NADH, 2 $FADH_2$, 2 ATP** Its main product is the carriers, not ATP.
4 **Oxidative phosphorylation** chain and ATP synthase	Inner membrane	NADH, $FADH_2$ and oxygen	**Water, about 26 to 28 ATP** NAD^+ and FAD go back for more hydrogen.

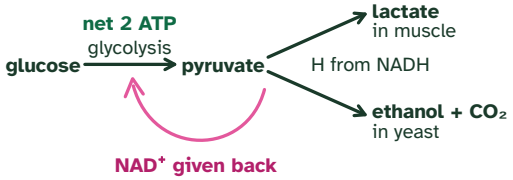
All six carbons of glucose leave as carbon dioxide: two in the link, four in the Krebs cycle.

In all: about **30 to 32 ATP** for one glucose

3.5.A WITHOUT OXYGEN

Fermentation gives NAD^+ back

- Glycolysis turns two NAD^+ into NADH for every glucose. Without the **regeneration of NAD^+**, glycolysis stops very quickly.
- Without oxygen, NADH cannot be unloaded at the chain. **In muscle**, pyruvate takes the hydrogen from NADH and becomes **lactate**.
- **In yeast**, each pyruvate loses a carbon as carbon dioxide, and what is left takes the hydrogen to become **ethanol**.
- Glycolysis goes on, at a net **2 ATP per glucose**. The last step makes no ATP: its whole point is the NAD^+.



3.5.A COMPARE

With oxygen and *without*

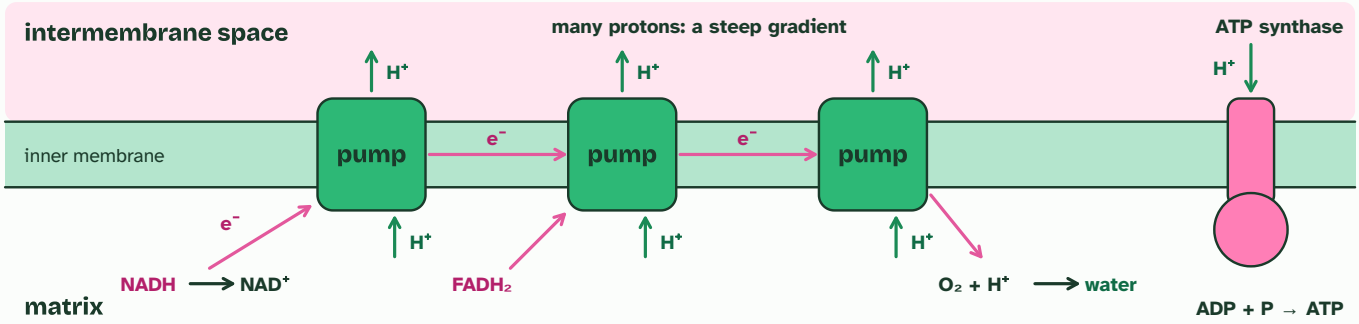
- Both routes start with glycolysis. Muscles ferment when the blood cannot bring oxygen fast enough, as in a sprint: fermentation adds to aerobic respiration, it does not replace it.

	AEROBIC	FERMENTATION
Oxygen	Needed	Not needed
Where	Cytosol, then mitochondria	Cytosol only
ATP	**About 30 to 32**	**2**
Waste	Carbon dioxide and water	Lactate; or ethanol and carbon dioxide
Fuels	Glucose, fatty acids and others	Glucose only

Fermentation in humans is LOW: Lactate, Only 2 ATP, Without oxygen.

3.5.B IN THE INNER MITOCHONDRIAL MEMBRANE

The *electron transport chain* and chemiosmosis



1
Carriers unload
NADH and $FADH_2$ pass electrons to the chain and become NAD^+ and FAD again.

2
Electrons step down
Each carrier holds them more tightly than the last, so a little energy is released at every step.

3
Protons are pumped
The pumps use that energy to move protons from the matrix into the intermembrane space.

4
Oxygen
The terminal electron acceptor: it takes the electrons, and protons from the matrix, and becomes water.

5
ATP synthase
Protons flow back through it, down their gradient. The flow joins ADP and phosphate: chemiosmosis.

3.5.B WHAT STOPS

No oxygen, or a *leak*

- The chain with ATP synthase is **oxidative phosphorylation**. The same machinery works in thylakoid membranes and in the plasma membrane of prokaryotes.

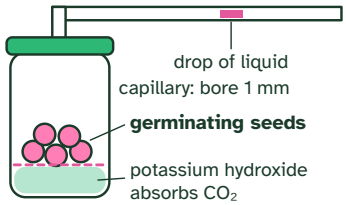
No oxygen the chain backs up
Nothing takes the electrons at the end, so every carrier stays full. Pumping stops, the gradient runs down, ATP synthase stops and NADH cannot be unloaded.

Uncoupling heat, not ATP
Protons leak back without passing through ATP synthase. The chain still runs, but the energy of the gradient is released as heat: brown fat in newborns and hibernating mammals.

3.5.A RESPIROMETER

Measuring the *rate*

- In a **respirometer**, potassium hydroxide absorbs the carbon dioxide, so the drop's movement shows **oxygen uptake**.
- Volume = πr^2 × distance moved. Rate = volume ÷ time, and per gram to compare samples.
- A **control** tube holds glass beads: its movement is not respiration, so subtract it.



3.5.A FUELS

Fat or *sugar*?

- Lipids release about **twice the energy per gram** of carbohydrates.
- Carbohydrate goes through glycolysis, so it can be respired with oxygen or without.
- A fatty acid is cut into 2-carbon acetyl groups that enter the Krebs cycle, so **fat needs oxygen**.
- Proteins can be used too: amino acids lose their nitrogen and join as pyruvate or acetyl groups.

37 kJ in a gram of lipid

17 kJ in a gram of carbohydrate

WATCH OUT

Five mistakes that *cost points*

- ✕ **Respiration is not breathing.** It is the chemistry that makes ATP in every cell: plants too, day and night.
- ✕ **Glycolysis is in the cytosol and needs no oxygen.** Only what follows it is in the mitochondrion.
- ✕ **The chain makes a proton gradient, not ATP.** ATP synthase makes the ATP, and it is not a pump.
- ✕ **Oxygen becomes water, not carbon dioxide.** The carbon dioxide comes from the carbons of the fuel.
- ✕ **Muscle makes lactate; yeast makes ethanol and carbon dioxide.** Never the other way around.

COVER THE SHEET

Can you *answer these?*

1. Describe what glycolysis takes in and gives out.
2. Identify where each stage of aerobic respiration happens.
3. Explain why a muscle cell turns pyruvate into lactate.
4. Calculate the oxygen used if the drop moves 20 mm.
5. Explain how the chain builds a proton gradient.
6. Predict what happens to the chain with no oxygen. Justify it.
7. Explain how uncoupling makes heat.
8. Explain why fat cannot be respired without oxygen.

IN THE EXAM

Follow the hydrogen: off the fuel, onto NAD^+, to the chain, onto oxygen. Say where each step happens, and write "proton gradient" before you write "ATP".

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.