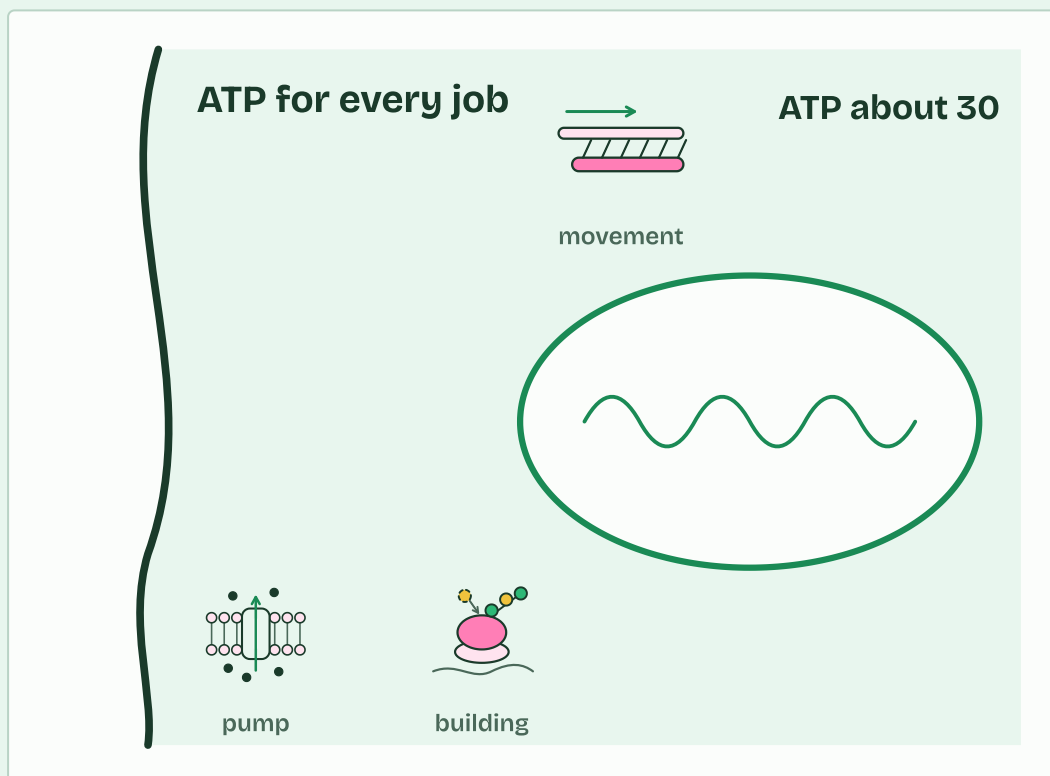


REVISION GUIDE

How a cell turns food into *ATP*

Cell respiration

Right now every cell in your body is pumping, building and moving, and every one of those jobs is paid for in ATP. Respiration remakes the ATP, releasing energy from glucose and fat a step at a time. Here is how it works with oxygen and without, and how to measure it in a tube of seeds.



12 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-c1-2-cell-respiration



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By the end you can

- ☐ Describe ATP as a nucleotide and explain what makes it suit the job of moving energy around a cell C1.2.1
- ☐ Explain how hydrolysis of ATP releases energy for active transport, building molecules and movement, and why remaking it takes energy C1.2.2, C1.2.3
- ☐ Explain respiration as the cell's way of making ATP from carbon compounds, and tell it apart from gas exchange C1.2.4
- ☐ Compare aerobic and anaerobic respiration in humans, with word equations for both C1.2.5
- ☐ Measure the rate of respiration with a respirometer and work it out from raw or secondary data C1.2.6
- ☐ Explain oxidation as the removal of hydrogen, and NAD as the carrier that is reduced when it accepts it C1.2.7
- ☐ Outline glycolysis: phosphorylation, lysis, oxidation and ATP formation, with its net yield C1.2.8
- ☐ Explain how making lactate, or ethanol and carbon dioxide in yeast, gives NAD back so glycolysis can go on, and how bakers and brewers use yeast C1.2.9, C1.2.10
- ☐ Outline the link reaction and the Krebs cycle: where the carbon dioxide and the reduced NAD come from C1.2.11, C1.2.12
- ☐ Explain how electrons passed along the chain build a proton gradient across the inner membrane C1.2.13, C1.2.14
- ☐ Explain how ATP synthase uses the proton gradient to make ATP, and why oxygen is needed at the end of the chain C1.2.15, C1.2.16
- ☐ Compare lipids and carbohydrates as fuels: energy per gram, and which routes each can take C1.2.17

Tick each one when you can do it without the book.

01

C1.2.1

ATP AS THE MOLECULE THAT DISTRIBUTES ENERGY WITHIN CELLS

The cell's *small change*

Every cell is busy all the time: pumping ions across its membrane, building molecules, moving things about. Each of those jobs needs energy, and in every living cell the energy arrives in the same form. It is carried by one molecule, **ATP**.

ATP stands for adenosine triphosphate. Take the base **adenine**, join it to the sugar **ribose** and add one **phosphate group**, and you have a **nucleotide**, the same kind of unit that RNA is built from (A1.2). ATP is that nucleotide with two more phosphate groups added in a chain.

Why is this the molecule that does the job? Because of a short list of properties, each with its reason.

KEY POINTS

- It dissolves in water, so it moves freely through the cytoplasm to wherever it is needed.
- It is stable in the watery cytoplasm until an enzyme acts on it, so its energy is not wasted on the way.
- Taking off one phosphate releases a modest amount of energy, enough for one step of a pump or one step in building a molecule, so little is lost as heat.
- The phosphate can be passed on to another molecule, making that molecule more reactive.
- Its charged phosphate groups keep it from leaking out through the membrane.
- It is remade from ADP and phosphate quickly and endlessly, so a cell needs only a small stock.

That is why ATP is called the cell's **energy currency**. Like coins, it is one kind of token that every job accepts. The savings are the food molecules: glycogen, starch and fat. ATP is the small change that is actually spent, and a cell holds only enough for seconds to a minute or two of work before it has to make more (chapter 3).

KEY TERMS

ATP

Adenosine triphosphate: the molecule that carries energy to jobs all over a cell. Adenine and ribose with a chain of three phosphate groups.

adenine

One of the four bases of nucleic acids. In ATP it is the part joined to the sugar.

ribose

A five-carbon sugar. It is the sugar in RNA and in ATP.

phosphate group

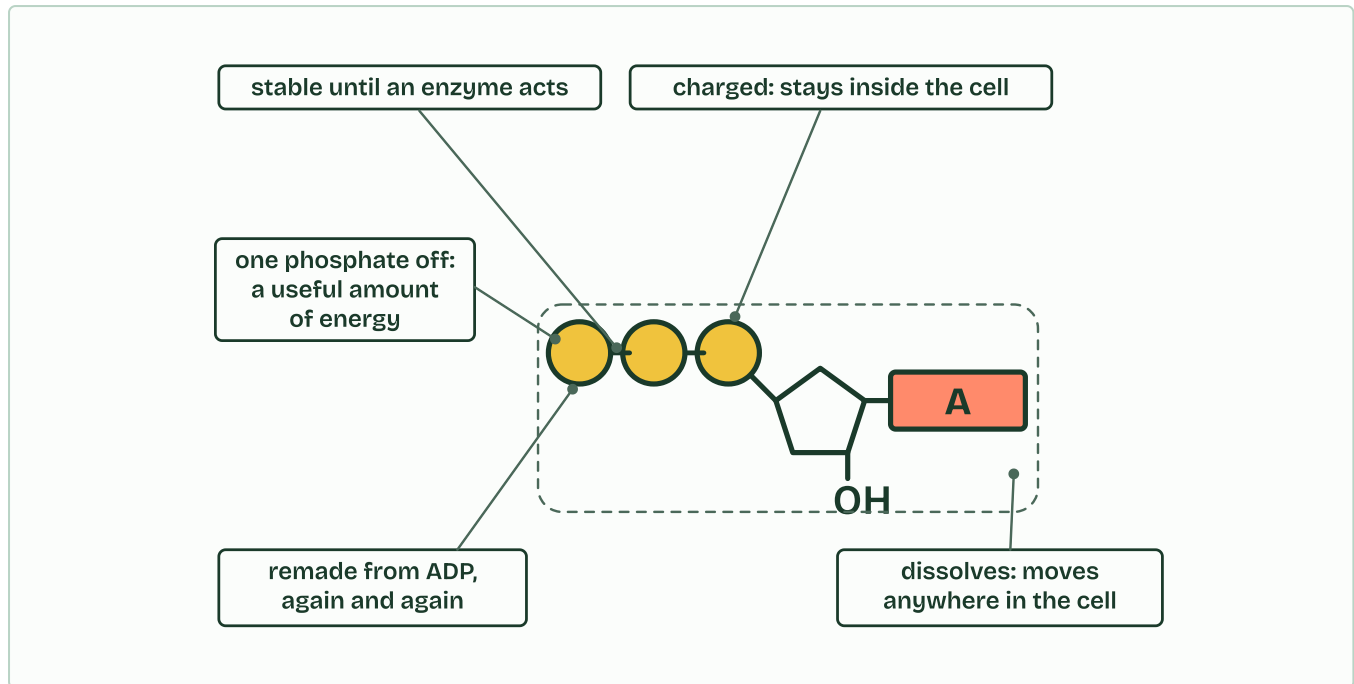
A phosphorus atom bonded to four oxygens. It is the unit that is added to ADP to make ATP, and removed from ATP to release energy.

nucleotide

A monomer of nucleic acids: a base, a sugar and a phosphate group.

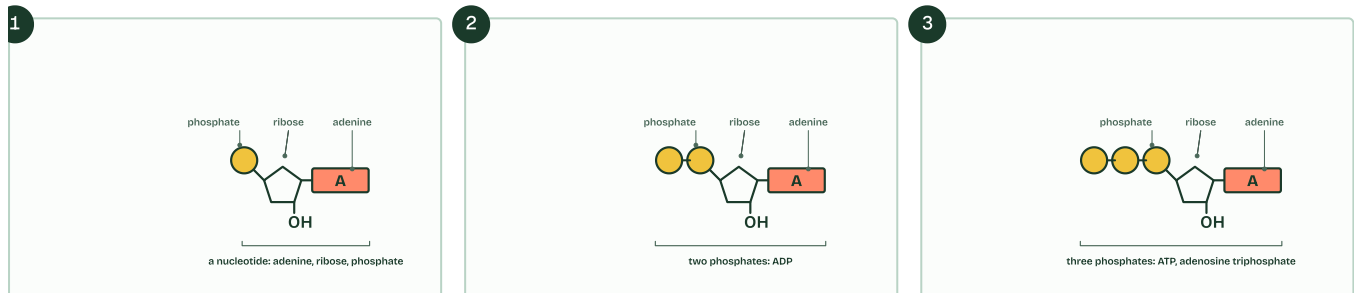
energy currency

A molecule that every job in a cell accepts as payment for its energy, so that energy from many different sources can be spent in the same way. ATP is the cell's energy currency.



STEP BY STEP

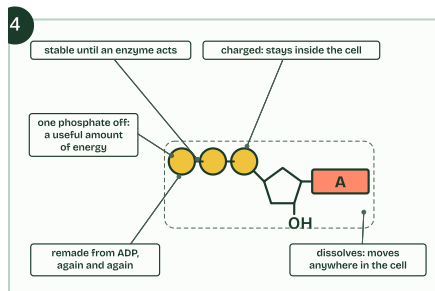
4 STEPS



A **nucleotide**: adenine, ribose and one phosphate.

Add a phosphate: **ADP**.

Add another: **ATP**, adenosine triphosphate.



What makes it the cell's **energy currency**.

WATCH OUT

ATP is not the cell's energy store. A cell keeps only a little and remakes it constantly; the stores are glycogen, starch and fat.

PREDICT

Removing one phosphate from ATP releases only a modest amount of energy. Why does that suit a cell?

- (A) Small amounts of energy can be stored for weeks
- (B) A job can take what it needs, with little wasted
- (C) Small amounts of energy can never heat up the cell at all
- (D) It means the ATP never has to be remade

Decide before you look. Answer on page 48.

02

C1.2.2

C1.2.3

WHAT ATP PAYS FOR, AND THE ENERGY IT MOVES

Spend it, *remake it*

A cell gets energy out of ATP by splitting it with water. In **hydrolysis**, a water molecule is used to take the last phosphate group off, and ATP becomes **ADP** (adenosine diphosphate) and a free phosphate. Energy is released, and the cell spends it.

Where does that energy come from? Not from “breaking a high-energy bond”: breaking any bond takes energy (C1.1). ADP and phosphate together are more stable than ATP and water were, and hold less energy, so the reaction releases the difference. It is the same rule as every other reaction.

Going the other way takes energy. To remake ATP, a phosphate is joined back on to ADP and water is released. In almost every cell the energy comes from respiration (this guide), and in the chloroplasts of a plant it comes from light (C1.3). So the ATP, the ADP and the phosphate go round and round, in the **ATP and ADP cycle**. Only the energy flows through. No transfer of energy is perfectly efficient, so some of it spreads out as heat each time ATP is spent and each time it is remade, which is part of why you are warm.

The energy pays for three kinds of job.

KEY POINTS

- **Active transport:** a pump in the membrane moves ions against their concentration gradient (B2.1).
- Building macromolecules, **anabolism:** a ribosome joins amino acids into a protein, and nucleotides are joined into DNA (C1.1).
- Movement: of the whole cell, as a sperm's tail or a muscle fibre moves, or of parts of it, as chromosomes are pulled apart in mitosis.

The guide asks for no number of kilojoules. What matters is that the energy from one ATP is enough for one step of many different tasks, and the cell uses a great many of them every second.

KEY TERMS

hydrolysis

A reaction in which a molecule is split by the addition of water. Hydrolysis of ATP removes its last phosphate group and releases energy.

ADP

Adenosine diphosphate: ATP with one phosphate group fewer. It is what ATP becomes when it is hydrolysed, and what is remade into ATP in respiration.

ATP and ADP cycle

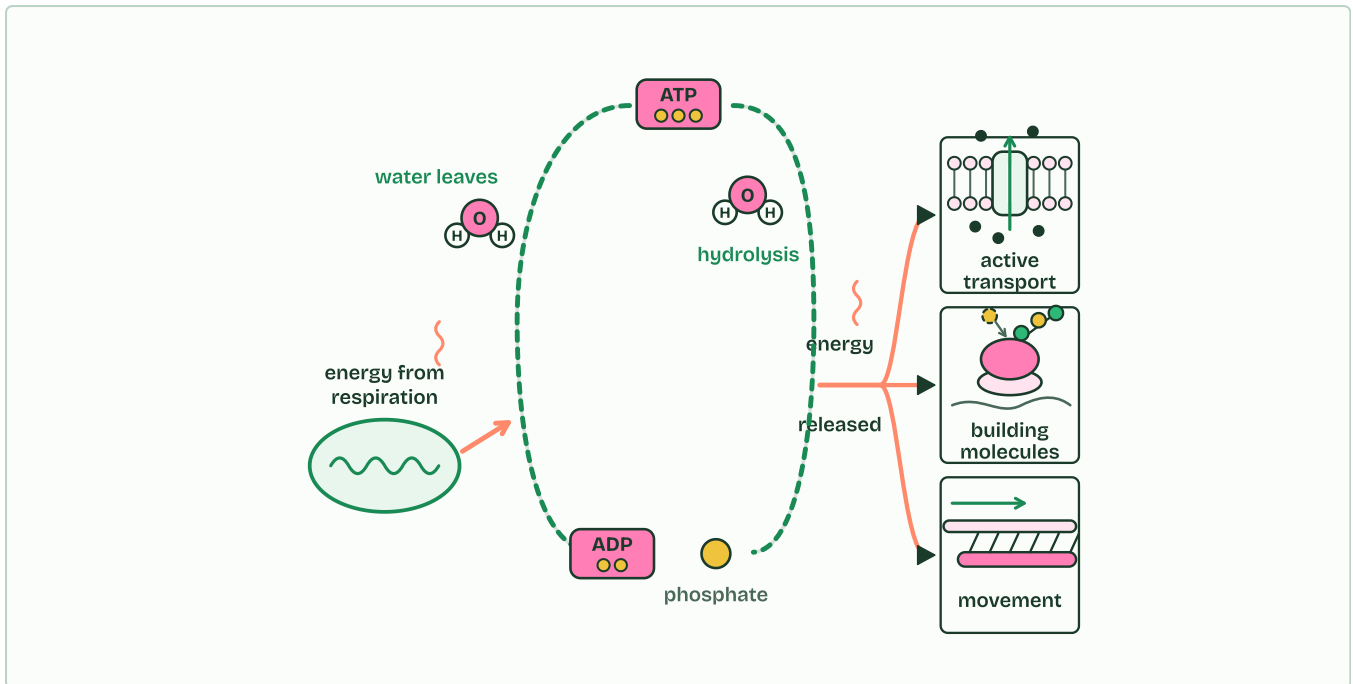
ATP is hydrolysed to ADP and phosphate, releasing energy, and ADP and phosphate are joined back into ATP using energy from respiration or light. The molecules go round; the energy flows through.

active transport

Moving a substance across a membrane against its concentration gradient, using a pump protein and energy from ATP.

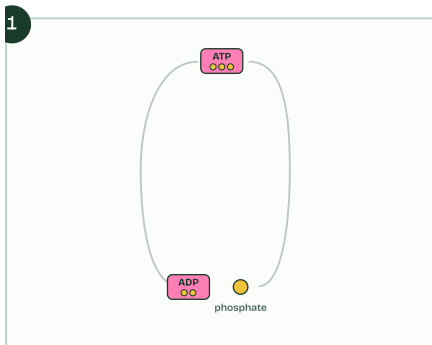
anabolism

The building up of large molecules from small ones, using energy. Making a protein from amino acids is anabolism.

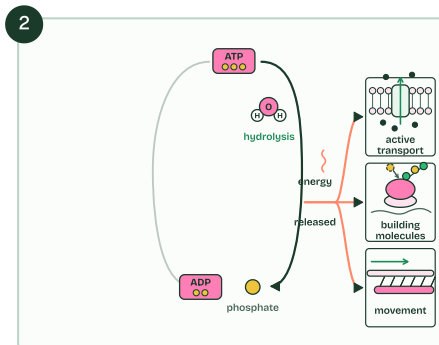


STEP BY STEP

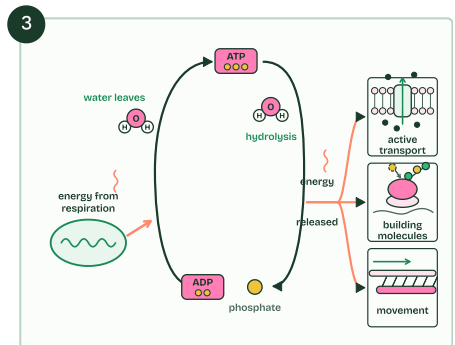
4 STEPS



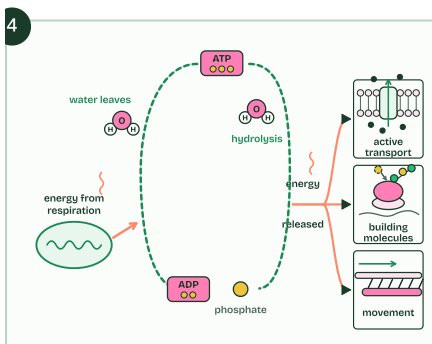
ATP, ADP and phosphate: the same molecules, used again and again.



Hydrolysis: water splits off the last phosphate. Energy is **released** for pumps, building and movement.



Remaking ATP **needs energy:** from respiration.



Spent and remade, over and over: the energy flows through, and some is lost as heat.

REMEMBER IT

What ATP pays for

B B	A A	M M
Building joining small molecules into large ones (anabolism)	Active transport pumping against the gradient	Movement of the whole cell or of its parts

WATCH OUT

Energy is not “stored in the bond” between phosphates, and breaking that bond does not release energy. Breaking a bond always takes energy; the energy released by hydrolysis is the difference between ATP and water before, and ADP and phosphate after.

PREDICT

Remaking ATP from ADP and phosphate needs energy.
Where does a muscle cell get it?

- Ⓐ From respiring glucose or fat
- Ⓑ From the warmth of the blood around it
- Ⓒ From sunlight falling on the skin
- Ⓓ From breaking ADP down further

Decide before you look. Answer on page 48.

C1.2.4 CELL RESPIRATION AS A SYSTEM FOR PRODUCING ATP USING ENERGY FROM CARBON COMPOUNDS

03 Fuel in, *ATP* out

Cell respiration is how a cell makes ATP, using energy released from carbon compounds. It happens in every living cell, all the time, because ATP is used all the time and only a little is kept (chapter 1). That includes plants: a leaf cell respire by day and by night.

The fuels are called **respiratory substrates**. The main two are **glucose** and **fatty acids**, but a cell can use a wide range of carbon compounds, amino acids among them when food is short. Glycogen in liver and muscle, and starch in a plant, are broken down to glucose first.

Respiration releases the energy a step at a time, each step helped by its own enzyme at body temperature. Burning glucose is **combustion**. It starts with glucose and oxygen and ends with carbon dioxide and water, as respiration does, and it releases the same total energy. But combustion releases it all at once, as heat and light, and makes no ATP. One is controlled and useful to a cell, the other is not.

Respiration is not **gas exchange**. Respiration is chemistry inside cells. Gas exchange is oxygen and carbon dioxide diffusing across a surface, in the lungs, the gills or a leaf, with no reaction and no energy released. The carbon dioxide you breathe out was made in the mitochondria of your cells, and it only leaves through your lungs. Breathing moves the air; that is not respiration either.

At higher level, chapters 6 to 12 open up each step.

Follow one carbon atom from the air, into a leaf and back out of a mitochondrion: the carbon trail, in C1.3.

KEY TERMS

cell respiration

The release of energy from carbon compounds in a cell, step by step, and its transfer to ATP.

respiratory substrates

The carbon compounds a cell breaks down in respiration. Glucose and fatty acids are the main ones.

glucose

A six-carbon sugar, $C_6H_{12}O_6$. It is the main fuel of respiration in most cells.

fatty acids

The long chains of carbon and hydrogen that make up most of a fat. They are respired for a large share of a cell's ATP.

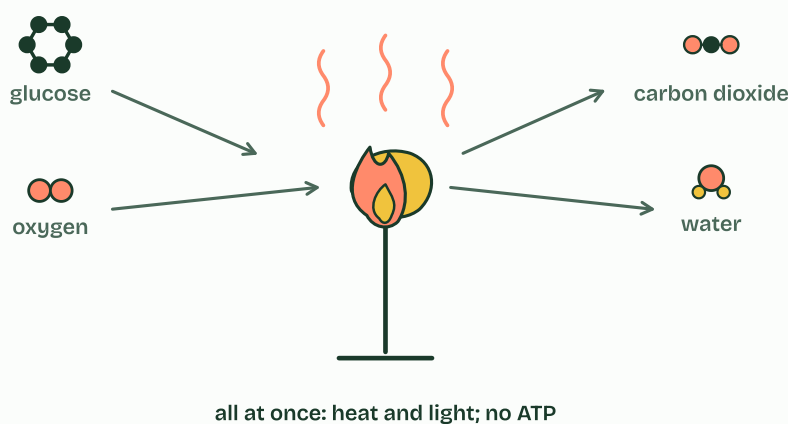
combustion

Burning: a fuel reacting quickly with oxygen and releasing its energy as heat and light.

gas exchange

The movement of oxygen into, and carbon dioxide out of, an organism or its cells by diffusion across a surface such as the lungs, gills or a leaf.

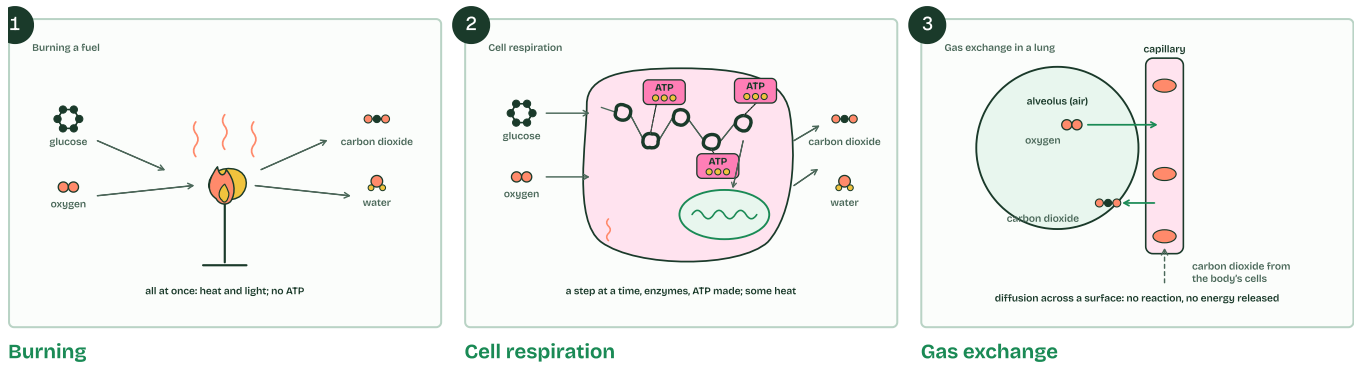
Burning a fuel



Three different things. What goes in, what comes out, and what is released?

SWITCH IT

3 SETTINGS

**WATCH OUT**

"Respiration" in everyday English means breathing. In biology it is the chemistry that makes ATP in every cell. Breathing moves air; gas exchange moves gases across a surface; neither releases energy.

WATCH OUT

Respiration does not "make energy". Energy is released from the fuel and transferred to ATP; none is created.

PREDICT

A leaf in bright light takes in carbon dioxide and gives out oxygen. Is it respiring?

- (A) No: a leaf photosynthesises instead of respiring
- (B) No: plants respire only at night
- (C) Yes: all its living cells respire all the time
- (D) Only its roots respire, below ground

Decide before you look. Answer on page 48.

04

C1.2.5 DIFFERENCES BETWEEN ANAEROBIC AND AEROBIC CELL RESPIRATION IN HUMANS

With oxygen and *without*

Both kinds of respiration start the same way, in the cytoplasm. A glucose molecule is split into two molecules of **pyruvate** in a process called **glycolysis**, which releases enough energy to make a small amount of ATP. After that the routes divide, according to whether there is oxygen, and they differ most in their **yield** of ATP for each glucose.

Aerobic respiration goes on with oxygen. The pyruvate goes into a **mitochondrion** and is broken down completely, to carbon dioxide and water, and a large amount of ATP is made. The word equation is **glucose + oxygen → carbon dioxide + water**. It needs mitochondria and oxygen, and it can use fatty acids and other compounds as well as glucose.

Anaerobic respiration in humans stops early. When there is not enough oxygen, the pyruvate stays in the cytoplasm and is turned into **lactate**. The word equation is **glucose → lactate**. It needs no mitochondria, no oxygen, and makes no carbon dioxide, but only glucose can be used: fatty acids cannot be respired without oxygen.

When does a human cell respire anaerobically? When muscles work so hard that the blood cannot bring oxygen fast enough: a short sprint, a heavy lift. Anaerobic respiration gives ATP at once, without waiting for oxygen, but only for a short time. Muscles do not switch from one route to the other. Aerobic respiration goes on, and anaerobic respiration adds to it.

Why make lactate at all, rather than stopping at pyruvate? Chapter 8 explains.

KEY TERMS

pyruvate

A three-carbon molecule. Glycolysis makes two of them from each glucose.

glycolysis

The splitting of glucose into two pyruvate in the cytoplasm. It releases enough energy to make a small amount of ATP, and it does not need oxygen.

yield

How much of a product a process makes from a set amount of starting material: here, the number of ATP made from each glucose.

aerobic respiration

Respiration that needs oxygen. Glucose is broken down completely to carbon dioxide and water in the mitochondria, making a large amount of ATP.

mitochondrion

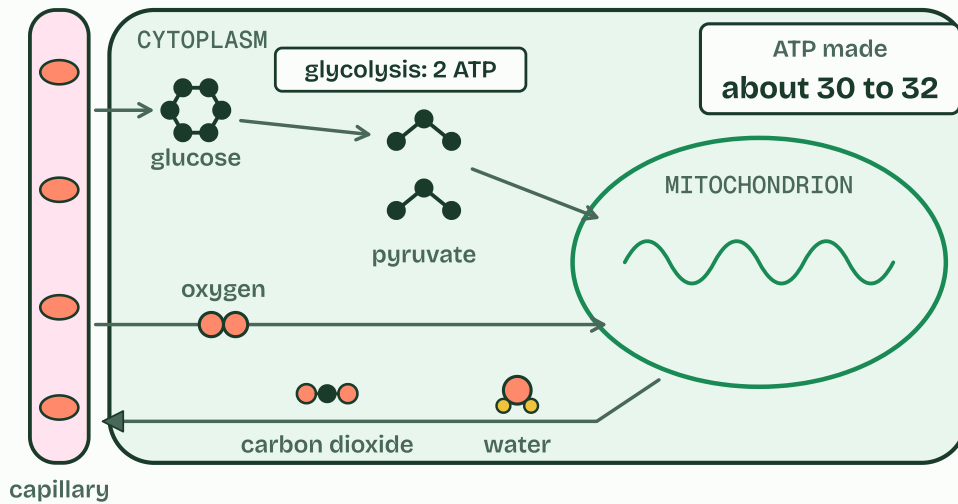
The organelle where aerobic respiration is completed. It makes most of a cell's ATP.

anaerobic respiration

Respiration without oxygen. In humans pyruvate is turned into lactate in the cytoplasm, and only a small amount of ATP is made.

lactate

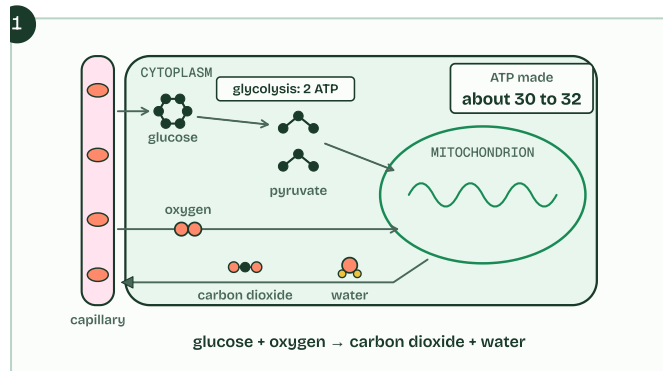
The waste product of anaerobic respiration in humans. It is made from pyruvate in the cytoplasm.



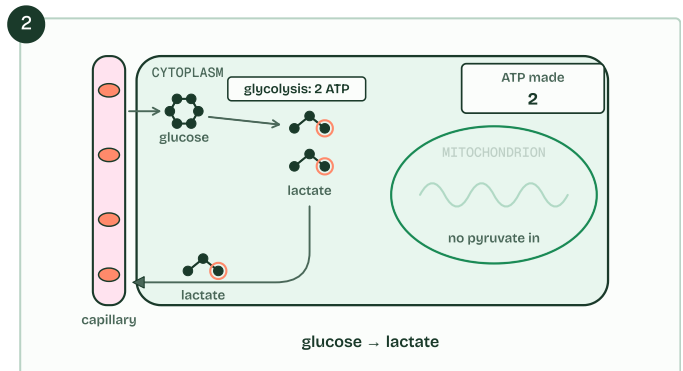
One glucose in a muscle cell. Switch the oxygen supply and follow the pyruvate.

SWITCH IT

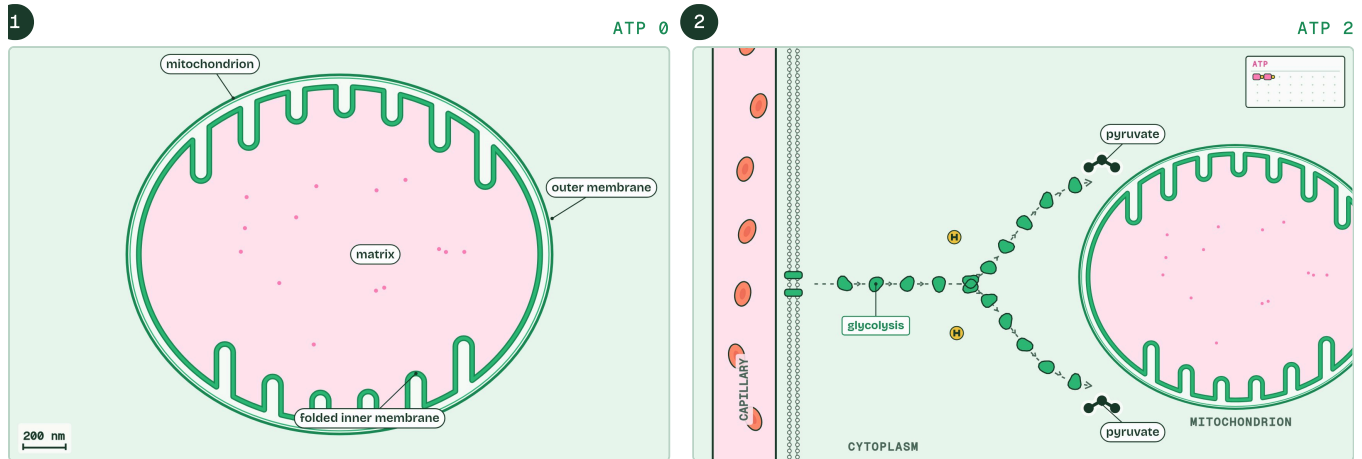
2 SETTINGS



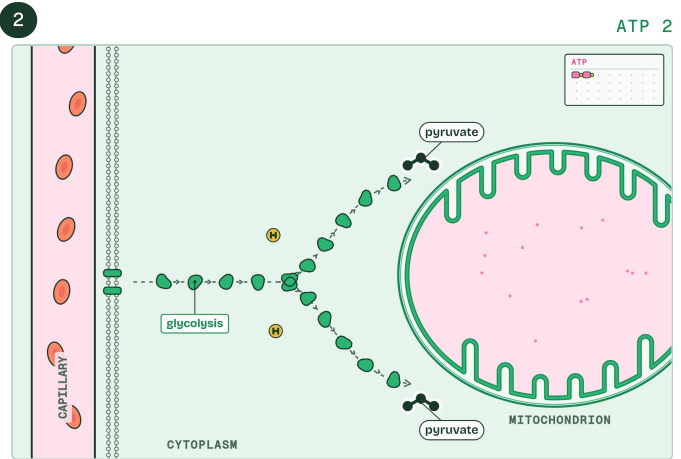
Plenty of oxygen



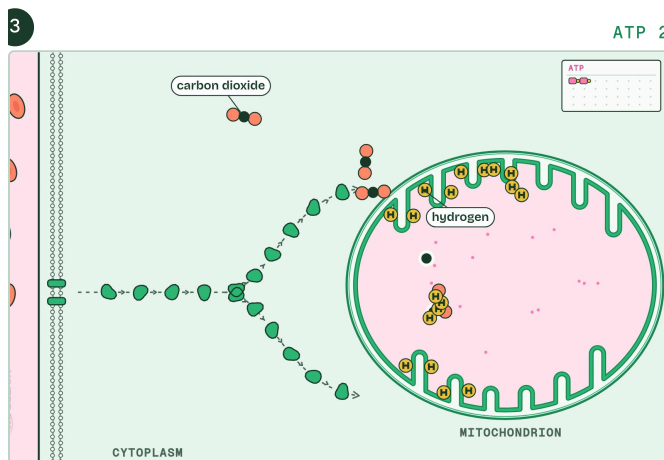
Not enough oxygen



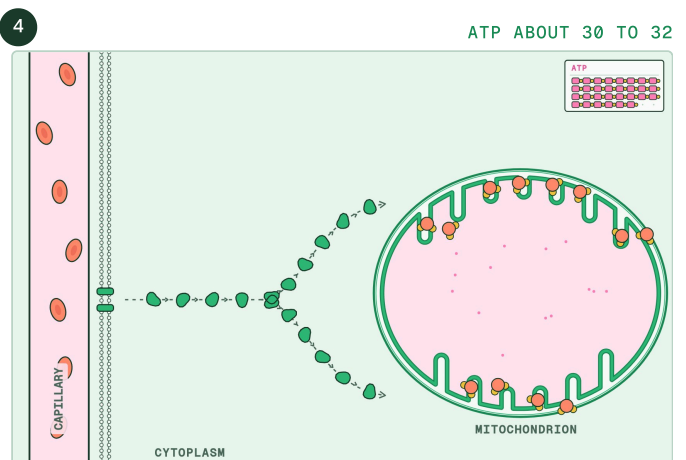
One **mitochondrion**. Its inner membrane is deeply folded.



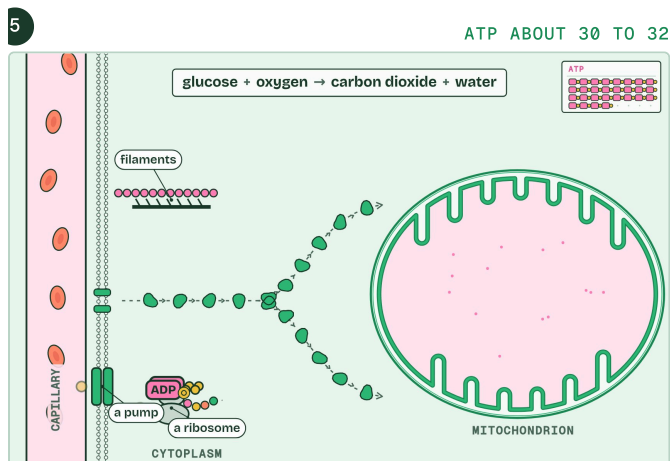
Splitting glucose into two pyruvate in the **cytoplasm** gives a little ATP: 2.



With oxygen, pyruvate goes into a **mitochondrion**. Its carbon leaves as **carbon dioxide**; its hydrogen goes to the folds of the inner membrane.



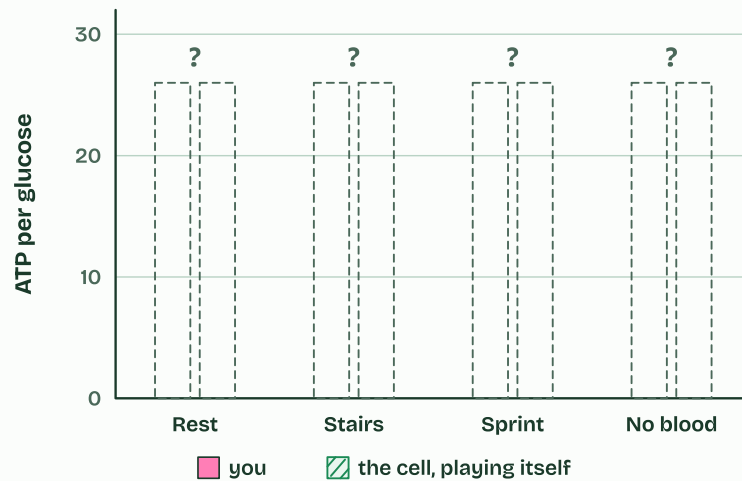
Oxygen joins the hydrogen to make **water**. Here, at the folds, most of the ATP is made: about 30 to 32 from one glucose.



Aerobic respiration: $\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water}$. The energy released remakes ATP for the cell's work.

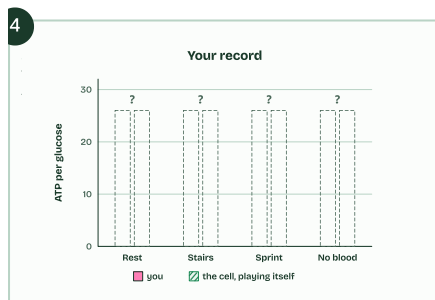
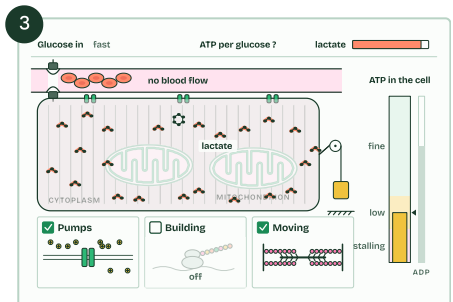
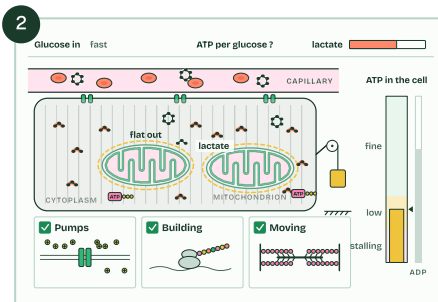
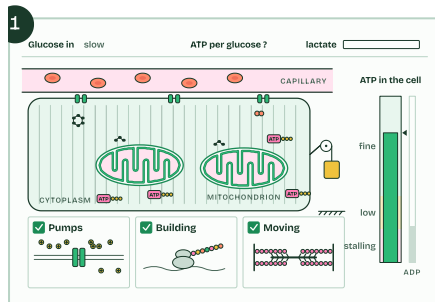
Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-2-cell-respiration#two-routes

Your record



STEP BY STEP

4 STEPS



Play the rounds to fill in the record.

PREDICT

A sprinter's leg muscles run short of oxygen. Per glucose, how much ATP does anaerobic respiration make compared with aerobic?

- (A) About the same, just faster
- (B) About half as much
- (C) About one fifteenth as much
- (D) None at all: it only makes lactate

Decide before you look. Answer on page 48.

REMEMBER IT

Anaerobic in humans is LOW

L L	O O	W W
Lactate the waste product	Only 2 ATP per glucose	Without oxygen in the cytoplasm

WATCH OUT

Glycolysis happens in the cytoplasm in both routes; only what follows it happens in the mitochondria.

WATCH OUT

The waste product in human muscle is lactate, not carbon dioxide. People often call it lactic acid. Lactate is not what makes muscles ache the next day.

05

C1.2.6

VARIABLES AFFECTING THE RATE OF CELL RESPIRATION

A rate you *cannot* see

Respiration happens inside cells, so you cannot watch it. You measure it from what goes in or comes out: oxygen taken up, carbon dioxide given out, or fuel used. The **rate of respiration** is the amount changed divided by the time taken, and for living material it is given **per gram per minute** as well, so that samples of different mass can be compared.

A class can do it three ways.

KEY POINTS

- **Oxygen uptake** in a **respirometer**: germinating seeds in a sealed tube, with **potassium hydroxide** to absorb the carbon dioxide they give out, and a drop of coloured liquid in a **capillary** whose movement shows the change in gas volume.
- **Carbon dioxide output**: a gas sensor or data logger in a sealed chamber, or hydrogencarbonate indicator changing colour. With yeast, the rise of a dough or the gas collected over a sugar solution works too (the dry lab's dough mode).
- **Fuel used**: the fall in the glucose in a yeast culture, measured with test strips.

The capillary is a long thin cylinder, so the volume of gas is $\pi r^2 \times$ the distance the drop moved, where r is half the bore. A bore of 1 mm holds 0.785 mm³ for every mm.

A second tube, the same in every way but with glass beads in place of the seeds, is the **control**. Anything that moves its drop, such as the gas warming or cooling or the air pressure changing, is not respiration, so its movement is taken off the seeds'.

What changes the rate? Temperature: respiration is enzymes at work, so it speeds up as it warms until they begin to denature (C1.1). How far germination has gone: dry seeds hardly respire, and soaked ones respire more each day. The mass of the seeds, and the kind of seed. With yeast: the sugar it is given, the temperature, and how much oxygen there is. The seeds are kept in the dark so that they cannot photosynthesise and hide the gas changes.

In an experiment on any of these, the one thing you change on purpose is the independent variable (the temperature, say), the rate you measure is the dependent variable, and everything else you hold the same is a controlled variable: the mass and age of the seeds, the volume of the tube, the time. You may also be asked to work out a rate from someone else's numbers: the steps are the same (figure 5.2).

KEY TERMS

rate of respiration

The amount of oxygen taken up, carbon dioxide given out or fuel used, in each unit of time.

per gram per minute

A way of giving a rate that allows for the mass of living material, so that samples of different mass can be compared. Written g⁻¹ min⁻¹.

respirometer

An apparatus that measures the rate of respiration from the change in the volume of gas in a sealed tube of living material.

potassium hydroxide

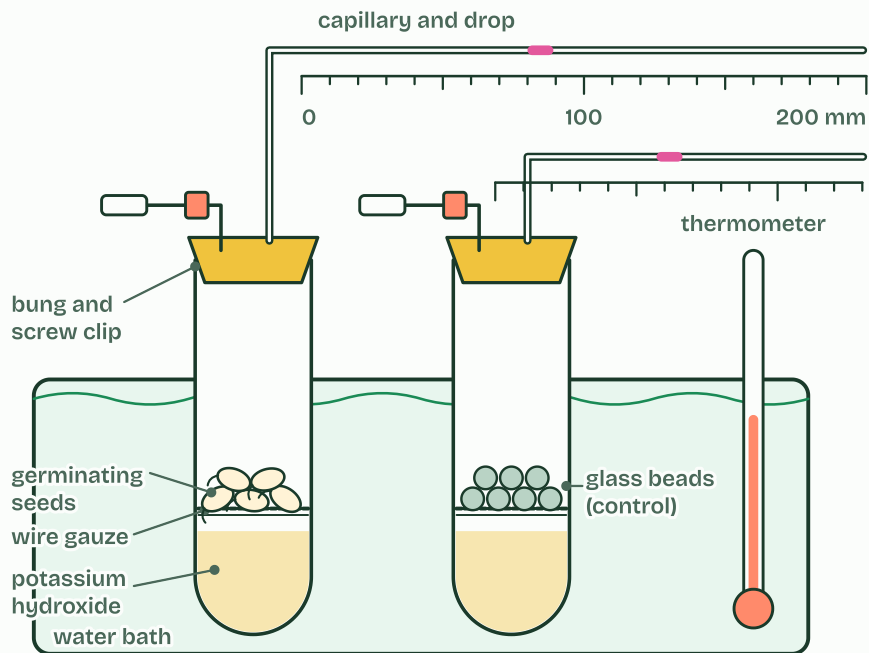
An alkali that absorbs carbon dioxide. It is used in a respirometer so that the carbon dioxide given out does not hide the oxygen taken up.

capillary

A very thin tube. In a respirometer the drop moves along it as the volume of gas changes.

control

A set-up kept the same as the experiment in every way except the one thing being tested. The bead tube shows what moves the drop that is not respiration.



Water bath and thermometer Keep the temperature steady, because gas expands as it warms.

Wire gauze Holds the seeds above the potassium hydroxide, so they never touch it.

Glass bead tube The control: the same volume of glass beads, the same everything else. Anything that moves its drop is not respiration.

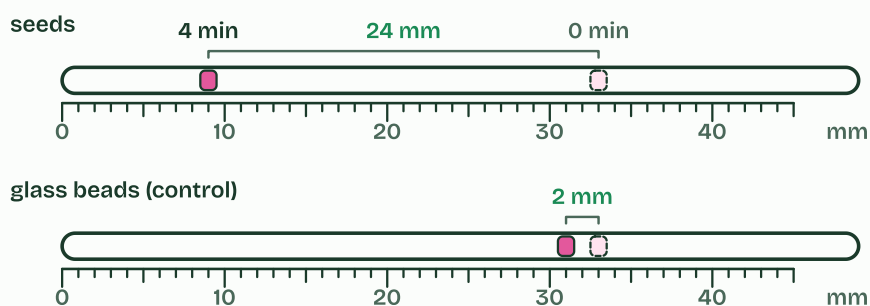
Capillary and coloured drop The drop moves as the gas inside shrinks. The bore sets how far it moves for each mm^3 .

Potassium hydroxide An alkali that absorbs carbon dioxide. Without it, the carbon dioxide given out would make up for the oxygen taken in.

Germinating seeds Soaked a few days ago, respiring hard, and kept in the dark. Weighed first, so the rate can be given per gram.

Bung and screw clip Seal the tube. Left open while the tube warms to the bath, then closed to start.

Scale Read in mm. Each reading is $\pm 0.5 \text{ mm}$.



$$\text{Corrected distance} = 24 - 2 = 22 \text{ mm}$$

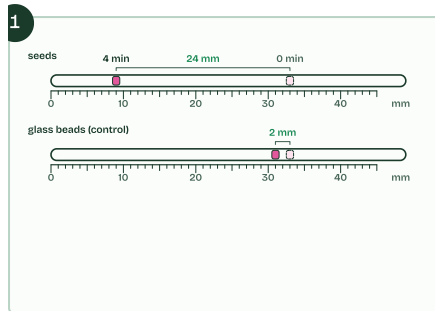
$$\text{Volume} = \pi r^2 \times \text{distance} = 3.14 \times 0.5^2 \times 22 = 17.3 \text{ mm}^3$$

(a bore of 1 mm, so $r = 0.5 \text{ mm}$)

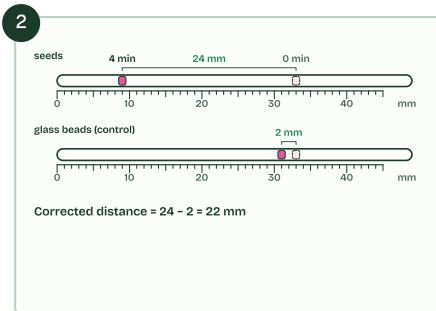
$$\text{Rate} = 17.3 \text{ mm}^3 \div 4 \text{ min} \div 3.0 \text{ g} = 1.44 \text{ mm}^3 \text{ g}^{-1} \text{ min}^{-1}$$

STEP BY STEP

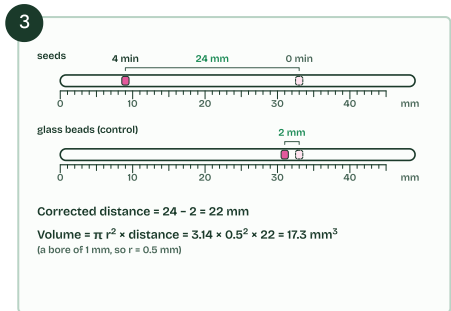
4 STEPS



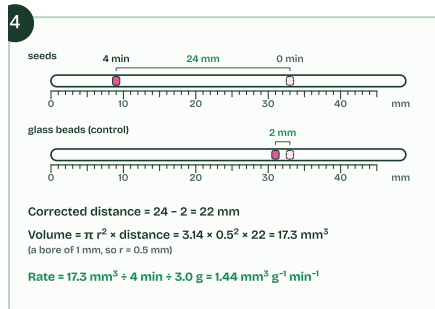
Read both drops at the start and the end.



Take off the control's movement.



Turn distance into volume with the bore.



Divide by time and by mass.

WATCH OUT

The drop does not move because the seeds give out carbon dioxide: that is removed. It moves because of what the seeds take up.

WATCH OUT

Germinating seeds are not "breathing". They have no lungs; their cells respire, and the gases cross their surfaces by diffusion.

PREDICT

In the respirometer the seeds respire and the potassium hydroxide absorbs their carbon dioxide. Which way does the drop move?

- (A) Away from the seeds, pushed by the carbon dioxide they give out
- (B) Towards the seeds, as they take in oxygen
- (C) Towards the seeds, as they give out water vapour
- (D) It stays still: the gases in and out balance

Decide before you look. Answer on page 48.

06

C1.2.7 HL

ROLE OF NAD AS A CARRIER OF HYDROGEN, AND OXIDATION BY REMOVAL OF HYDROGEN

Taking *hydrogen* away

In respiration, energy is released from fuel molecules by taking hydrogen off them. To see why, you need two words. **Oxidation** is the loss of electrons, and **reduction** is the gain of electrons. They always happen together: what one molecule loses, another gains. A reaction that does both is a **redox reaction**.

A hydrogen atom is a proton and an electron. So when hydrogen is removed from a molecule, which is called **dehydrogenation**, it loses electrons too, and has been oxidised. The enzymes that do it are dehydrogenases.

The hydrogen has to go somewhere. It is accepted by **NAD**, a molecule built from nucleotides, like ATP. When NAD accepts hydrogen it is reduced, and is then called **reduced NAD**. Reduced NAD carries the hydrogen, and the energy that comes with it, to where it is used (the electron transport chain, chapters 10 and 11), and is turned back into NAD there. So NAD is a **hydrogen carrier**.

A cell has only a little NAD, so it must be unloaded and used again and again, as ATP is. Every stage of respiration that follows either loads NAD or depends on NAD being given back (chapter 8).

Why does it matter? A large part of the energy in a fuel is in its hydrogen and the electrons that go with it. Respiration is, step by step, taking hydrogen off the fuel and passing it to oxygen: that is the role of hydrogen, and of oxygen, in the release of energy.

KEY TERMS

oxidation

The loss of electrons. In respiration it is mostly the removal of hydrogen from a molecule, because each hydrogen takes an electron with it.

reduction

The gain of electrons.

redox reaction

A reaction in which one substance is oxidised and another is reduced.

dehydrogenation

The removal of hydrogen (a proton and an electron) from a molecule. It oxidises the molecule. Enzymes that do it are dehydrogenases.

NAD

A hydrogen carrier built from nucleotides. It accepts hydrogen and is reduced, becoming reduced NAD, and gives it up again where the hydrogen is used.

reduced NAD

NAD that has accepted hydrogen. It carries the hydrogen, and the energy that comes with it, to the electron transport chain.

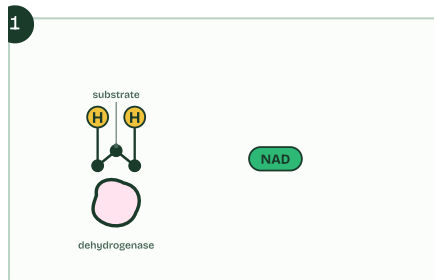
hydrogen carrier

A molecule that picks up hydrogen in one place and delivers it in another. NAD is the hydrogen carrier of respiration.

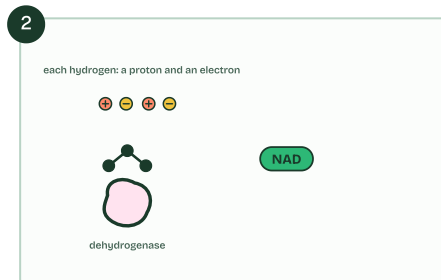


STEP BY STEP

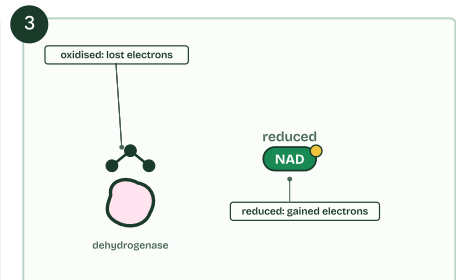
4 STEPS



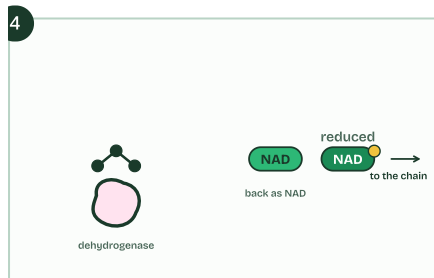
A substrate, an enzyme, and NAD.



Hydrogen is removed: **dehydrogenation**.
Each hydrogen is a proton and an electron.



The substrate is **oxidised**; NAD is **reduced**. A **redox** reaction.



Reduced NAD carries the hydrogen away and comes back as NAD.

REMEMBER IT

Oxidation and reduction

O
Oil

Oxidation Is Loss
of electrons

R
Rig

Reduction Is Gain
of electrons

WATCH OUT

Reduced NAD carries hydrogen, protons and electrons together, and the energy that comes with them. It is not ATP and it is not “energy” itself.

PREDICT

A dehydrogenase takes two hydrogens off a molecule of fuel. What has happened to that molecule?

- ☐ (A) It is reduced, because it has gained a charge
- ☐ (B) It is phosphorylated by the hydrogen
- ☐ (C) Nothing; only the NAD changes
- ☐ (D) It is oxidised: it has lost electrons

Decide before you look. Answer on page 48.

C1.2.8 HL CONVERSION OF GLUCOSE TO PYRUVATE IN GLYCOLYSIS, WITH A NET YIELD OF ATP AND REDUCED NAD

07 Two ATP in, *four* out

Glycolysis turns one glucose into two pyruvate, in the cytoplasm, in about ten steps. Each step has its own enzyme, and the product of one step is the substrate of the next: it is a metabolic pathway (C1.1). The guide groups the steps into four stages, and you do not need to name the molecules in between.

KEY POINTS

- **Phosphorylation:** two ATP each give a phosphate group to the glucose. That costs 2 ATP, but a sugar carrying two charged phosphates is made reactive and ready to split.
- **Lysis:** the 6-carbon sugar with its two phosphates splits into two 3-carbon sugars, each with one phosphate.
- **Oxidation:** hydrogen is taken off each 3-carbon sugar and accepted by NAD, so two reduced NAD are made for the glucose. The energy released lets each 3-carbon sugar take on a second phosphate, a free one from the cytoplasm, not one from ATP.
- **ATP formation:** each 3-carbon sugar passes its two phosphates to ADP, making ATP directly, and ends as pyruvate.

KEY TERMS

phosphorylation

The addition of a phosphate group to a molecule. In glycolysis two ATP each give a phosphate group to the sugar, which makes it reactive.

lysis

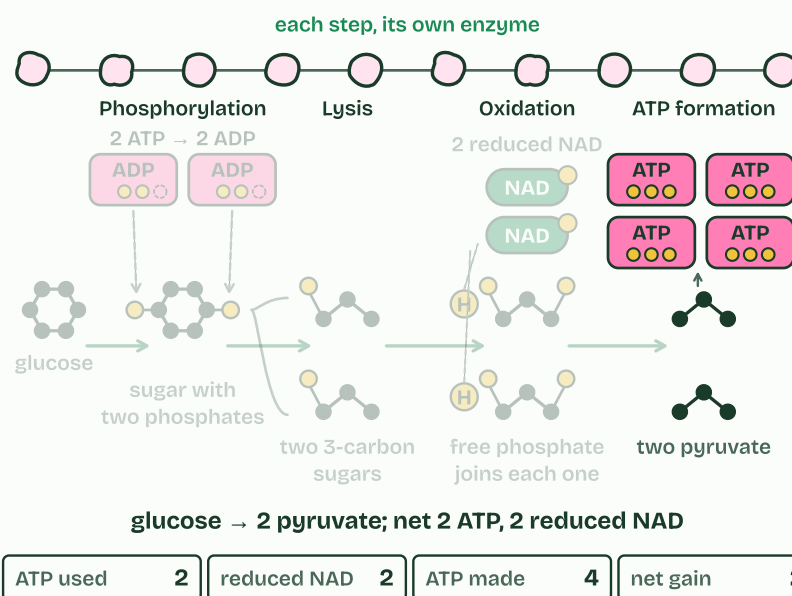
Splitting. In glycolysis the 6-carbon sugar with two phosphates is split into two 3-carbon sugars.

oxidation

In glycolysis, the removal of hydrogen from each 3-carbon sugar by a dehydrogenase, with NAD accepting it.

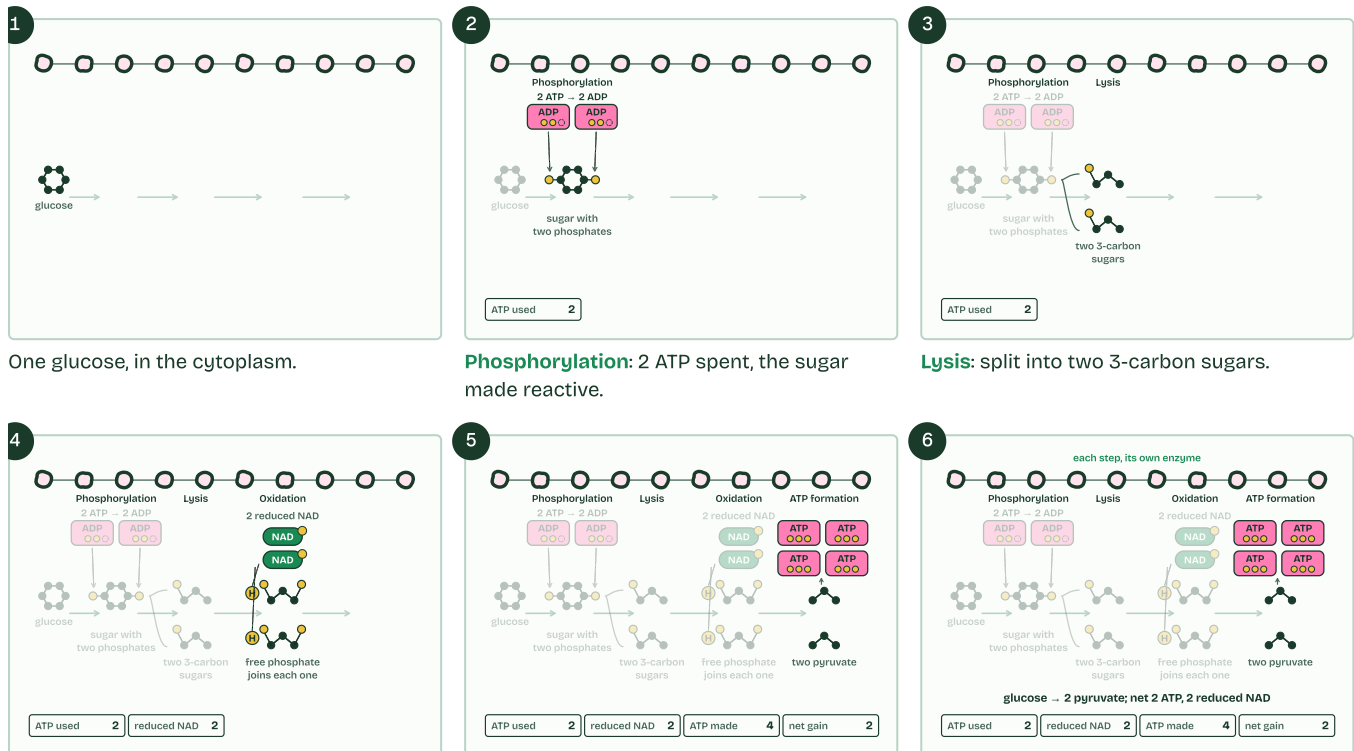
ATP formation

The making of ATP from ADP and a phosphate group. In glycolysis each 3-carbon sugar passes its phosphates to ADP, and ends as pyruvate.



STEP BY STEP

6 STEPS



PREDICT

Glycolysis spends 2 ATP at the start. How many does it make by the end, from one glucose?

- (A) 4, so the cell gains 2
- (B) 2, so it only breaks even
- (C) 6, one for each carbon in glucose
- (D) 30, from the hydrogen it removes

Decide before you look. Answer on page 48.

REMEMBER IT

The four stages of glycolysis, in order

P Penguins	L Love	O Orange	A Anchovies
Phosphorylation 2 ATP spent	Lysis 6 carbons split into 3 and 3	Oxidation hydrogen to NAD	ATP formation 4 ATP made

WATCH OUT

Glycolysis does not need oxygen, and it does not happen in the mitochondrion.

C1.2.9 HL
AND BAKING

C1.2.10 HL

LACTATE AND ETHANOL AS WAYS OF REGENERATING NAD, AND BREWING

08

Giving *NAD* back

Glycolysis needs NAD. Every glucose that goes through it turns two NAD into reduced NAD. A cell has only a little NAD, so if reduced NAD is not turned back into NAD, glycolysis stops very quickly. Giving NAD back is called the **regeneration of NAD**.

With oxygen, reduced NAD is unloaded at the electron transport chain in the mitochondrion (chapters 10 and 11). Without oxygen it cannot be, so a cell needs another way to give NAD back.

In human muscle, pyruvate takes the hydrogen from reduced NAD and becomes lactate. NAD is given back, so glycolysis can go on, with a net yield of 2 ATP per glucose. Making lactate releases no extra energy: its whole point is to give NAD back.

Yeast follow the same pathway as far as pyruvate. Without oxygen, each pyruvate loses a carbon as carbon dioxide, and what is left takes the hydrogen from reduced NAD to become **ethanol**. NAD is given back, and the yield is again 2 ATP per glucose. Only the last step differs from humans, and so the final products do.

Bakers and brewers use what yeast make. In **baking**, yeast respire the sugars in the dough and the carbon dioxide forms bubbles that stretch it, so the dough rises; the ethanol evaporates in the oven. In **brewing**, yeast in a sugary liquid made from barley or grapes, with little air, make ethanol, which is kept, while the carbon dioxide escapes or is kept in for fizz. Early in a dough or a brew there is oxygen and the yeast respire aerobically, so carbon dioxide is given off from the start; as the oxygen runs out, anaerobic respiration takes over. Anaerobic respiration in yeast is often called **fermentation**.

KEY TERMS

regeneration of NAD

Turning reduced NAD back into NAD, so that it can accept hydrogen again. It lets glycolysis go on.

yeast

A single-celled fungus. Baker's and brewer's yeast respire sugars, with or without oxygen.

ethanol

A two-carbon alcohol. It is the product of anaerobic respiration in yeast, with carbon dioxide.

baking

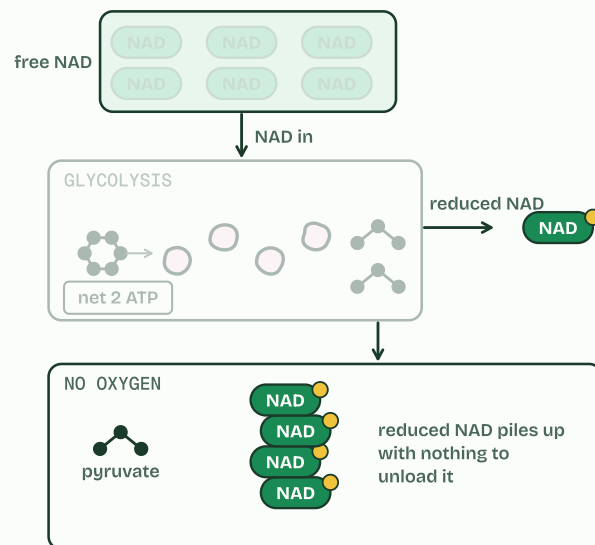
Making bread. Yeast in the dough respire its sugars, and the carbon dioxide they give out makes the dough rise.

brewing

Making drinks such as beer and wine. Yeast in a sugary liquid, with little air, make ethanol, which is kept.

fermentation

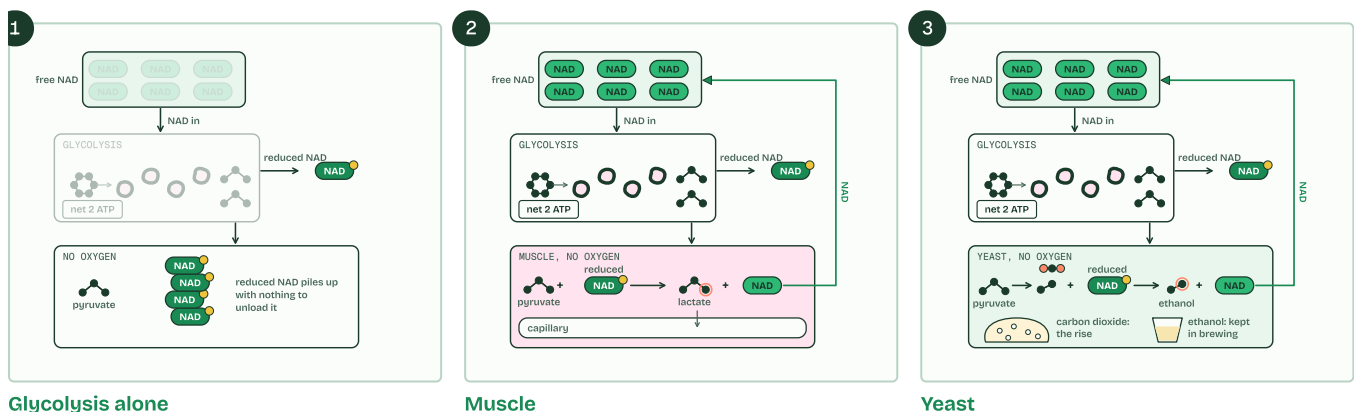
Anaerobic respiration in yeast (making ethanol and carbon dioxide) or in muscle (making lactate), especially when it is put to use, as in brewing and baking.



Glycolysis with no oxygen. Watch the NAD in the tray, then see what each cell does about it.

SWITCH IT

3 SETTINGS



Glycolysis alone

Muscle

Yeast

PREDICT

Without oxygen, why does a muscle cell turn pyruvate into lactate instead of leaving it as pyruvate?

- (A) Lactate stores more energy for later
- (B) Pyruvate is poisonous to muscle cells, so it must be changed
- (C) Lactate can be turned straight into ATP
- (D) It gives NAD back, so glycolysis can go on

Decide before you look. Answer on page 49.

WATCH OUT

Yeast without oxygen make ethanol and carbon dioxide, not lactate; humans make lactate, not ethanol or carbon dioxide.

WATCH OUT

Lactate is not a poison that must be got rid of straight away. It is carried in the blood and later used as a fuel, or made back into glucose in the liver.

09

C1.2.11 HL

C1.2.12 HL

THE LINK REACTION, AND THE KREBS CYCLE

The carbon leaves as *carbon dioxide*

With oxygen, pyruvate is carried from the cytoplasm into the **matrix**, the fluid inside the inner membrane of the mitochondrion. Two sets of reactions follow, one after the other.

The **link reaction** links glycolysis to the Krebs cycle. Each pyruvate (3C) is **decarboxylated**, which takes a carbon off as carbon dioxide, and oxidised: hydrogen is removed and accepted by NAD. The 2-carbon **acetyl group** that is left is picked up by **coenzyme A** and carried to the cycle. Fatty acids and other carbohydrates are also broken down to acetyl groups, which join the same route (chapter 12). All of this happens twice for each glucose, once for each pyruvate.

In the **Krebs cycle**, the acetyl group is transferred to **oxaloacetate** (4C) to make **citrate** (6C). Round the cycle the compound is oxidised four times, each a dehydrogenation: three load NAD, and one loads another carrier. One ATP is made. Then oxaloacetate is remade, ready for the next acetyl group, and the cycle turns twice for each glucose.

Glycolysis and the Krebs cycle sit beside the Calvin cycle on one map in C1.3.

KEY TERMS

matrix

The fluid inside the inner membrane of a mitochondrion. The link reaction and the Krebs cycle happen in it.

link reaction

The step between glycolysis and the Krebs cycle. Pyruvate is decarboxylated and oxidised, and the acetyl group left over is carried on by coenzyme A.

decarboxylated

Having a carbon removed as carbon dioxide. Decarboxylation takes place in the link reaction and in the Krebs cycle.

acetyl group

A group of two carbon atoms, left when pyruvate loses a carbon. Fatty acids are also broken down to acetyl groups.

coenzyme A

A carrier of acetyl groups. It carries the acetyl group to the Krebs cycle and goes back for more.

Krebs cycle

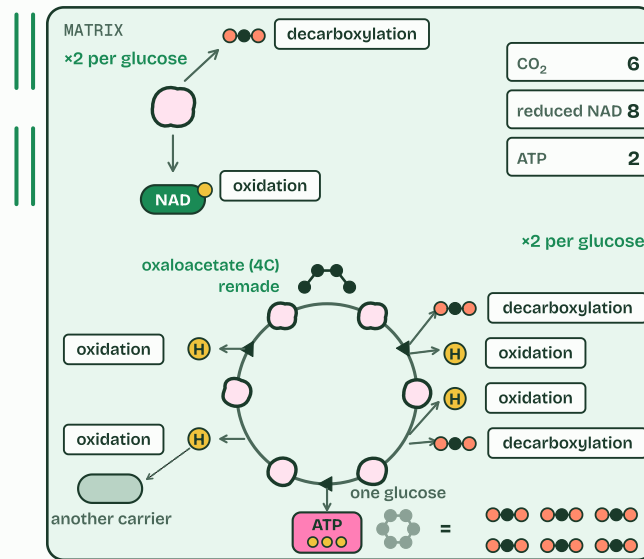
A cycle of reactions in the matrix. An acetyl group joins oxaloacetate to make citrate, and the cycle gives off carbon dioxide, loads hydrogen carriers and makes a little ATP.

oxaloacetate

A 4-carbon compound. It joins an acetyl group to make citrate, and is remade at the end of each turn of the Krebs cycle.

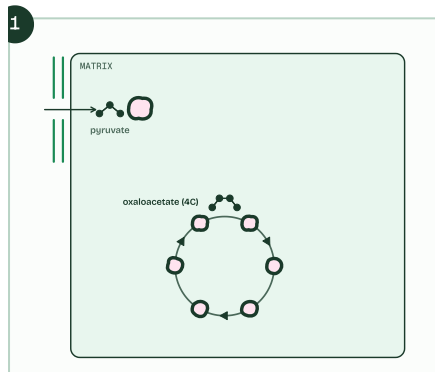
citrate

A 6-carbon compound, the first made in the Krebs cycle from an acetyl group and oxaloacetate.

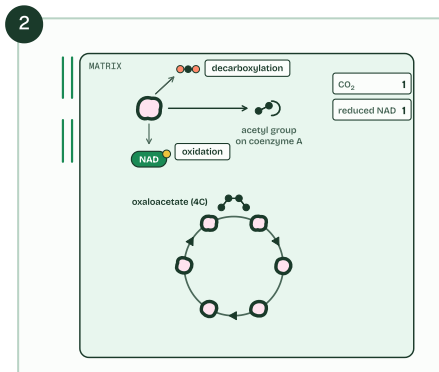


STEP BY STEP

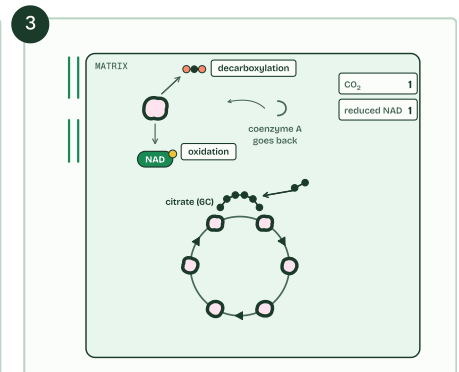
6 STEPS



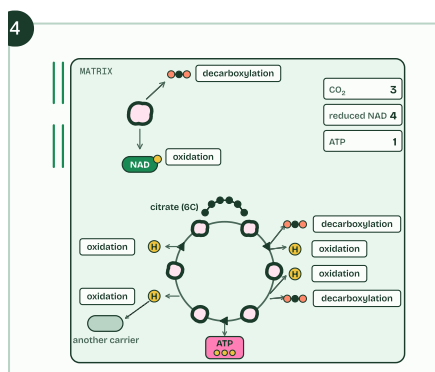
Pyruvate goes into the **matrix**.



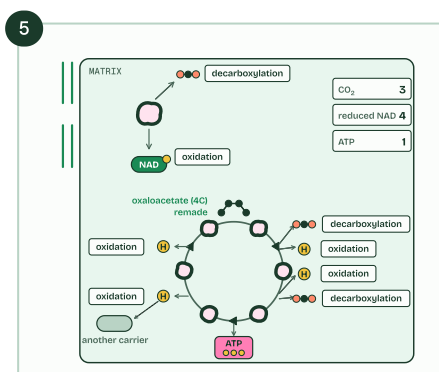
Link reaction: a carbon off as CO₂ (**decarboxylation**), hydrogen to NAD (**oxidation**). The **acetyl group** goes on with **coenzyme A**.



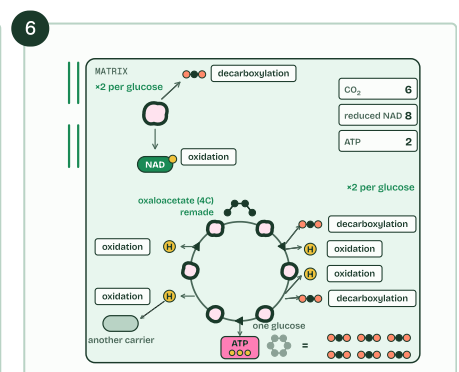
Acetyl (2C) + oxaloacetate (4C) → **citrate** (6C).



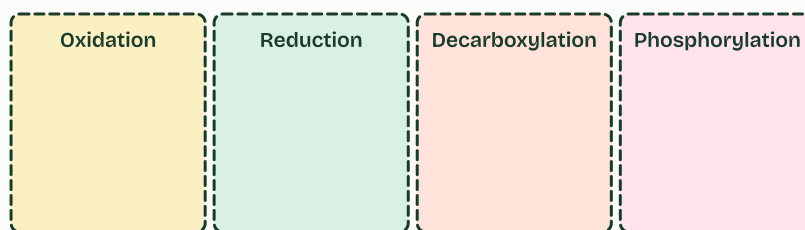
Two decarboxylations, four oxidations, one ATP.



Oxaloacetate is **remade**: a cycle.



Two turns per glucose: all six carbons gone as CO₂.



Eight steps to sort

Hydrogen removed from a 3-carbon sugar in glycolysis	NAD accepts hydrogen and becomes reduced NAD
A carbon leaves pyruvate as carbon dioxide	Glucose gains a phosphate from ATP
Hydrogen removed from a compound in the Krebs cycle	Oxygen accepts electrons at the end of the chain
Citrate loses a carbon as carbon dioxide, on the way round the cycle	ADP gains a phosphate, making ATP

Name the reaction: eight steps of respiration and four kinds of reaction. Which bin does each belong in, and what tells you?

PREDICT

Each turn of the Krebs cycle takes in a 2-carbon acetyl group. Why does the cycle not fill up with carbon?

- (A) The carbons are kept, stored in the matrix as citrate
- (B) Two carbons leave as carbon dioxide each turn
- (C) The acetyl carbons are turned into ATP
- (D) Oxaloacetate takes the carbons out of the mitochondrion

Decide before you look. Answer on page 49.

WATCH OUT

The Krebs cycle makes little ATP directly, only one a turn. Its main product is reduced NAD, which the chain turns into most of the ATP.

WATCH OUT

Citrate is made from oxaloacetate and the acetyl group, not from glucose, and the cycle's carbon dioxide comes from the fuel's carbon, not from the oxygen breathed in.

10

Down the *chain*

C1.2.13 HL

C1.2.14 HL

REDUCED NAD AND THE ELECTRON TRANSPORT CHAIN; THE PROTON GRADIENT

Reduced NAD is made in three places: glycolysis, the link reaction and the Krebs cycle. The electrons they carry all end up at the **inner membrane** of the mitochondrion, which is folded into **cristae** to give room for many copies of what happens there.

In that membrane sits the **electron transport chain**: a series of **electron carriers**, some of them proton pumps. A pair of electrons is passed from reduced NAD to the first carrier, and the reduced NAD is turned back into NAD, which goes back for more hydrogen. That is the transfer of energy.

The electrons are passed from carrier to carrier, each holding them a little more tightly than the one before, so they always move on and never go back. A little energy is released at each step, like a ball dropping down a staircase. Oxygen, at the very end, holds them most tightly of all (chapter 11). You do not need to name the carriers: “the chain” and “proton pumps” are enough.

The pumps use that energy to move **protons** (hydrogen ions) from the matrix, across the inner membrane, into the narrow **intermembrane space**. They pile up there, so there are far more protons in the space than in the matrix: a **proton gradient**. The membrane does not let them leak back, so the gradient is a store of energy, like water held behind a dam. Chapter 11 lets it out.

KEY TERMS

inner membrane

The inner of the two membranes of a mitochondrion. It is folded into cristae and holds the electron transport chain and ATP synthase.

cristae

The folds of the inner mitochondrial membrane. They give a large area for the electron transport chain and ATP synthase.

electron transport chain

A series of electron carriers in the inner mitochondrial membrane. Electrons are passed along it, and the energy released is used to pump protons.

electron carriers

Molecules that pass electrons on, one to the next. In the chain, some of them are proton pumps.

protons

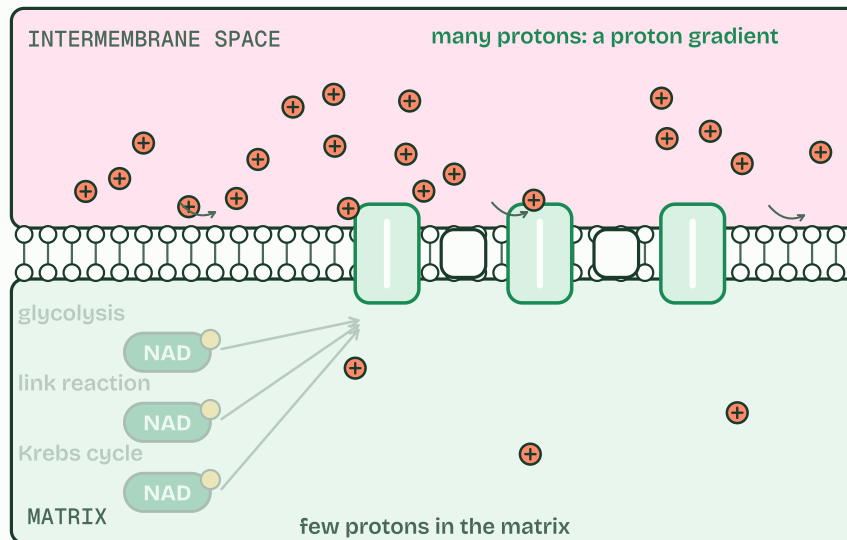
Hydrogen ions, H^+ : a hydrogen atom that has lost its electron.

intermembrane space

The narrow gap between the inner and outer membranes of a mitochondrion. Protons are pumped into it.

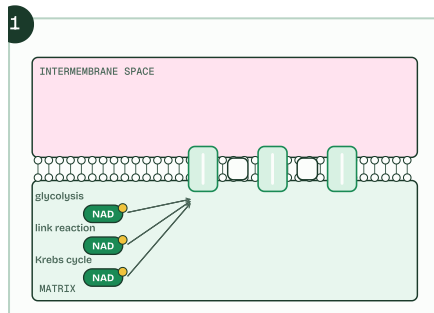
proton gradient

A difference in the concentration of protons across a membrane. In a mitochondrion it is high in the intermembrane space and low in the matrix, and it stores energy.

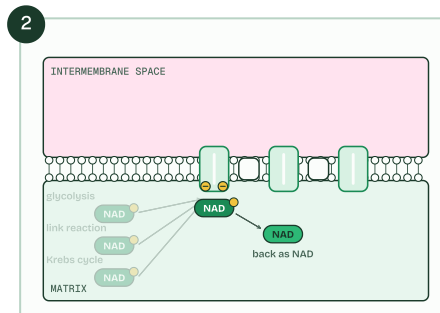


STEP BY STEP

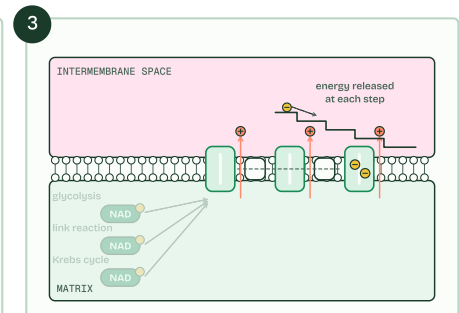
4 STEPS



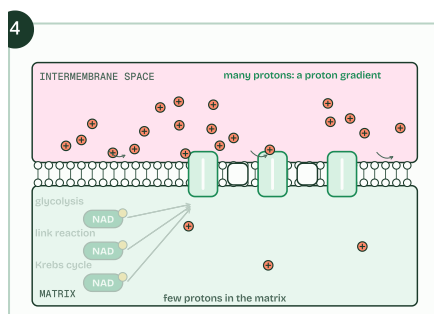
Reduced NAD from all three stages arrives at the inner membrane.



It hands a **pair of electrons** to the first carrier, and becomes NAD again.



Each step down releases a little energy, used to **pump protons**.



Protons pile up in the intermembrane space: a **proton gradient**.

WATCH OUT

The chain does not make ATP; it makes a proton gradient. And “proton” here means a hydrogen ion, not a hydrogen atom.

PREDICT

Electrons pass along the chain of carriers, releasing a little energy at each step. What is that energy used for?

- (A) Making ATP directly at each carrier
- (B) Splitting water into hydrogen and oxygen
- (C) Heating the matrix to the right temperature
- (D) Pumping protons across the inner membrane

Decide before you look. Answer on page 49.

C1.2.15 HL

C1.2.16 HL

CHEMIOSMOSIS AND ATP SYNTHESIS; OXYGEN AS THE TERMINAL ELECTRON ACCEPTOR

11

Protons through the *turbine*

Protons can return to the matrix through one protein only: **ATP synthase**. It spans the inner membrane, with a channel through it, a part that turns, and a head in the matrix where ATP is made.

As protons flow down their gradient through the channel, they turn the rotor. The turning changes the shape of the head, which joins ADP and phosphate into ATP. ATP synthase couples the energy released by the flow of protons to the phosphorylation of ADP. Making ATP with the energy of a proton gradient across a membrane is called **chemiosmosis**. (Biochemists call the chain and the synthase together oxidative phosphorylation.)

The chain needs one more thing at its end. Oxygen is the **terminal electron acceptor**: it takes the electrons from the last carrier, and protons from the matrix, and becomes water, called **metabolic water**. That empties the chain so that electrons keep flowing, and taking protons from the matrix helps to keep the gradient steep. Most of the ATP from one glucose, about 30 to 32 in all, is made here.

KEY TERMS

ATP synthase

The enzyme that makes ATP using the flow of protons down their gradient through it. It spans the inner mitochondrial membrane, with a part that turns and a head in the matrix.

chemiosmosis

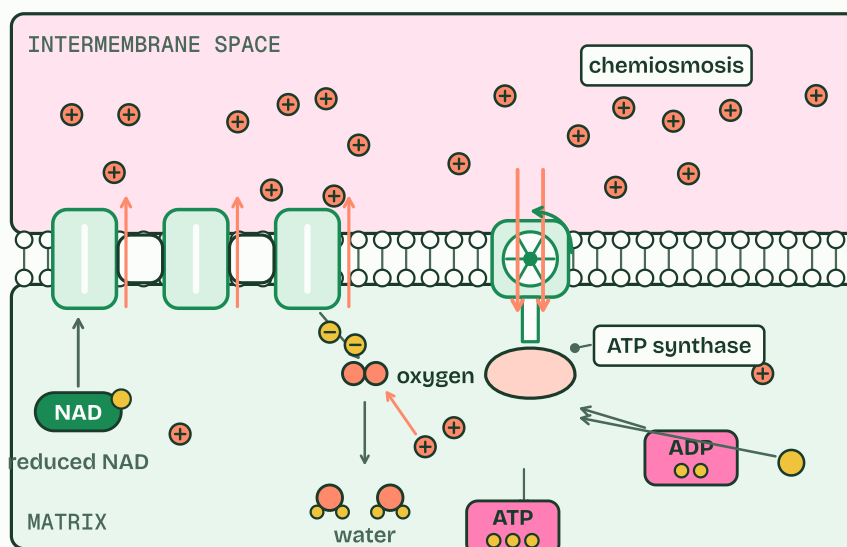
The making of ATP using the energy released as protons flow down their gradient through ATP synthase.

terminal electron acceptor

The last molecule to receive electrons from the electron transport chain. In aerobic respiration it is oxygen.

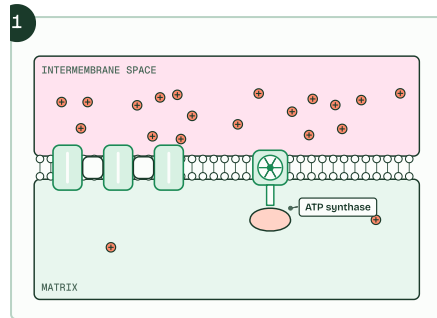
metabolic water

Water made in respiration, when oxygen accepts electrons and protons at the end of the chain.

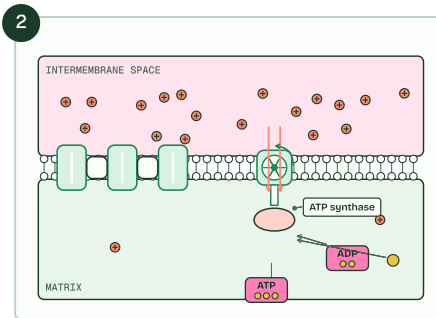


STEP BY STEP

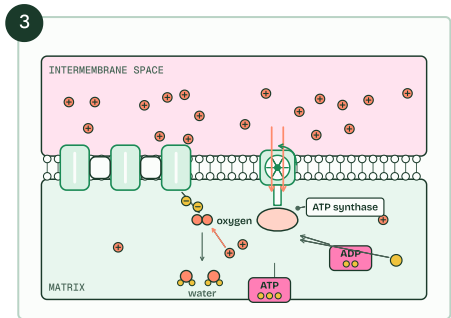
4 STEPS



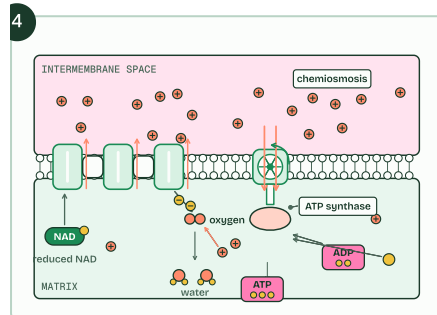
One way back for the protons: **ATP synthase**.



Protons flowing down the gradient turn it, and their energy joins **ADP and phosphate**: ATP.

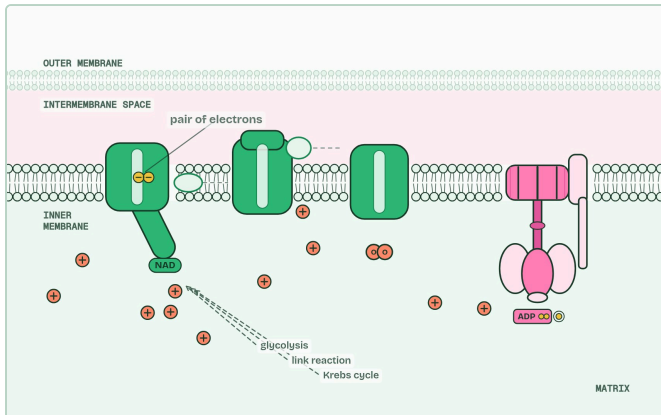


Oxygen takes the electrons and protons at the end, making **water**.

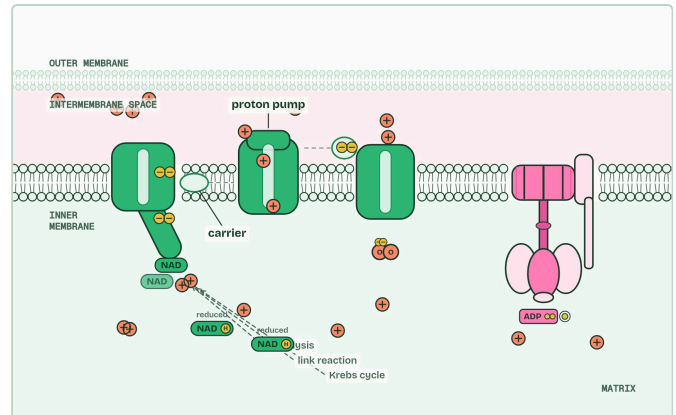


Chemiosmosis: the gradient makes ATP, and oxygen keeps the chain flowing.

1 H⁺ IN THE SPACE 0 · ATP 0 2 H⁺ IN THE SPACE 8 · ATP 0

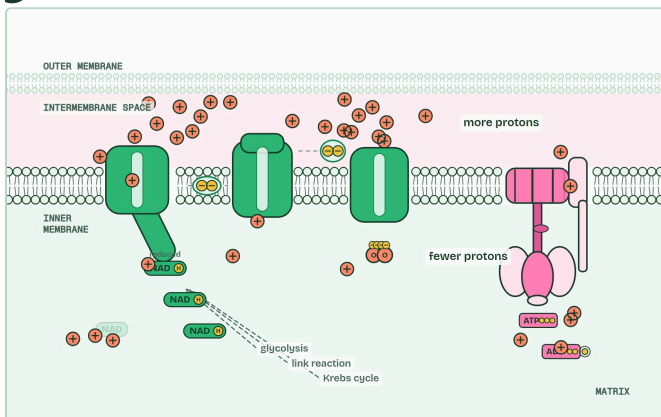


Reduced NAD from glycolysis, the link reaction and the Krebs cycle hands a **pair of electrons** to the first carrier, and becomes NAD again.

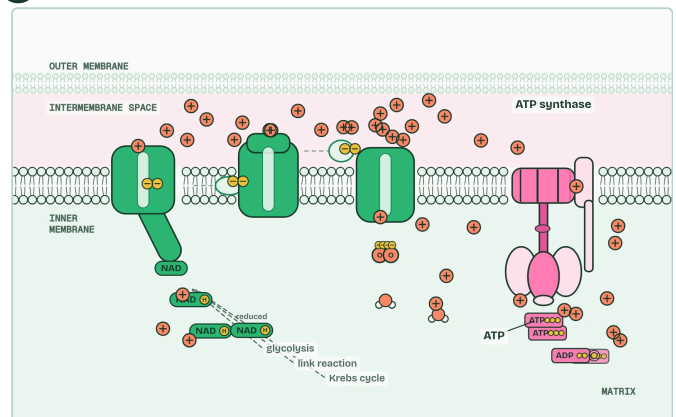


As the electrons pass along the chain they give up energy, which the carriers use to **pump protons** into the intermembrane space.

3 H⁺ IN THE SPACE 23 · ATP 1 4 H⁺ IN THE SPACE 24 · ATP 8

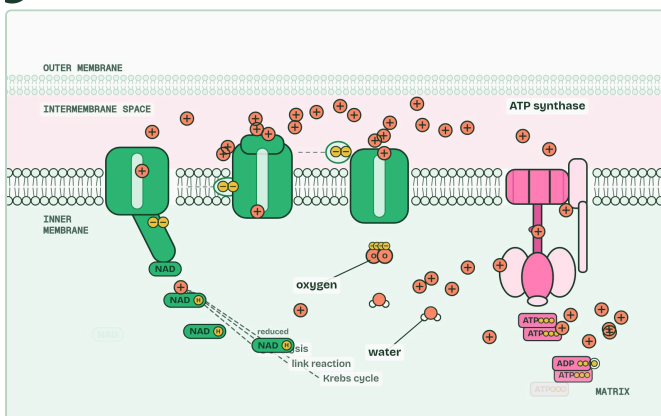


Protons pile up in the narrow space: a **proton gradient**. The membrane will not let them back through, except at one place.



Protons flow back down their gradient through **ATP synthase**, turning it. The energy joins **ADP** and **phosphate**: **ATP**.

5 H⁺ IN THE SPACE 22 · ATP 16



Oxygen takes the electrons at the end of the chain, with protons from the matrix, making **water**. That keeps the electrons flowing.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-2-cell-respiration#synthase

HOW WE KNOW (BEYOND THE GUIDE)

In 1961 Peter Mitchell suggested that the chain and the making of ATP were linked by a gradient of protons, not by some unknown high-energy chemical. Most biochemists doubted it for years. Experiments in the 1960s and 1970s, in which membranes given an artificial proton gradient made ATP, won them over, and he received the Nobel Prize in Chemistry in 1978.

WATCH OUT

Oxygen does not become carbon dioxide. It ends up in water. The carbon dioxide came from the fuel's carbon, in the link reaction and the Krebs cycle.

WATCH OUT

ATP synthase is not a pump: protons flow through it, down their gradient, and that flow drives it. The pumps are in the chain.

PREDICT

A cell's mitochondria run out of oxygen. What happens to the electron transport chain?

- (A) Electrons back up and the pumping stops
- (B) It runs faster to make up for it
- (C) It keeps pumping, but makes no water
- (D) ATP synthase runs backwards and starts to make oxygen

Decide before you look. Answer on page 49.

12

Fat or *sugar*?

C1.2.17 HL DIFFERENCES BETWEEN LIPIDS AND CARBOHYDRATES AS RESPIRATORY SUBSTRATES

Glucose and fatty acids are the two main fuels, and they are not equal. **Lipids** release about twice as much energy per gram as **carbohydrates** when they are respired: about 37 kJ in each gram against about 17.

They also take different routes. Carbohydrate goes through glycolysis, so it can be respired with oxygen or without. A fatty acid is cut into 2-carbon acetyl groups, which enter the Krebs cycle at once as **acetyl CoA** (acetyl coenzyme A). Glycolysis is the one stage that works without oxygen, and a fatty acid never goes through it: no oxygen, no use for fat.

In practice, muscles use fat for long, steady work, such as walking, a gentle jog or a migrating bird in flight, and carbohydrate for hard, fast work, when oxygen is short. That is why fat is the long-term store and glycogen the quick one (B1.1).

KEY TERMS

lipids

A group of molecules that includes fats and oils. They are respired for much of the energy in long, steady work.

carbohydrates

Sugars, starch and glycogen. Glucose, the main fuel of respiration, is a carbohydrate.

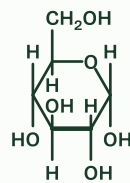
acetyl CoA

Acetyl coenzyme A: an acetyl group carried by coenzyme A. Fatty acids and carbohydrates both supply it to the Krebs cycle.

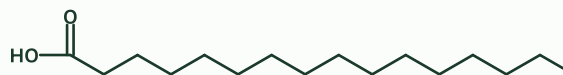
oxidisable hydrogen

Hydrogen in a molecule that can be removed in respiration and passed on, carrying energy. Fats have much more of it per gram than carbohydrates.

What each is made of

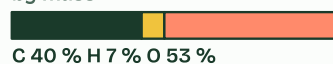


glucose



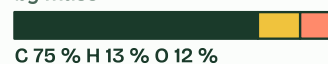
palmitic acid, a fatty acid

by mass



C 40 % H 7 % O 53 %

by mass



C 75 % H 13 % O 12 %

■ carbon ■ hydrogen ■ oxygen

Energy released per gram

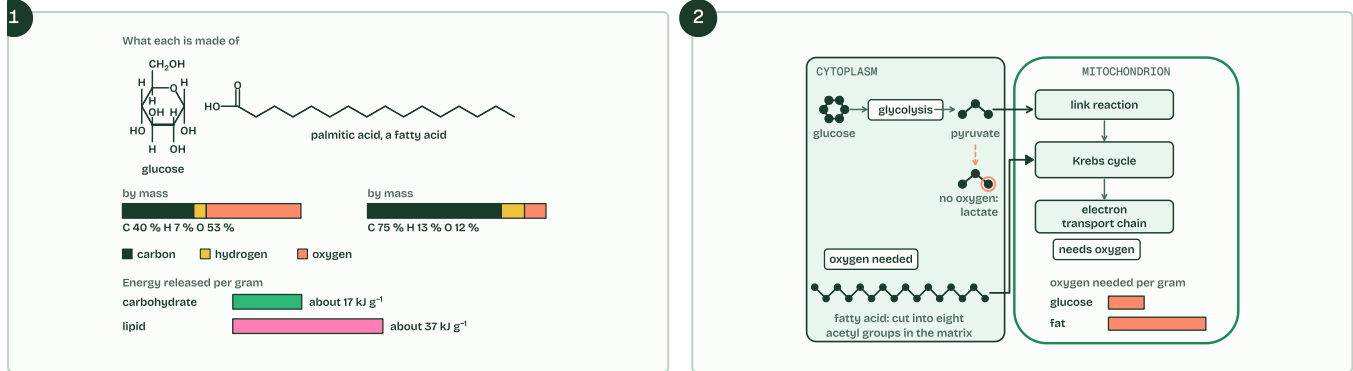
carbohydrate about 17 kJ g⁻¹

lipid about 37 kJ g⁻¹

Glucose and a fatty acid, side by side: what they are made of, and how each is respired.

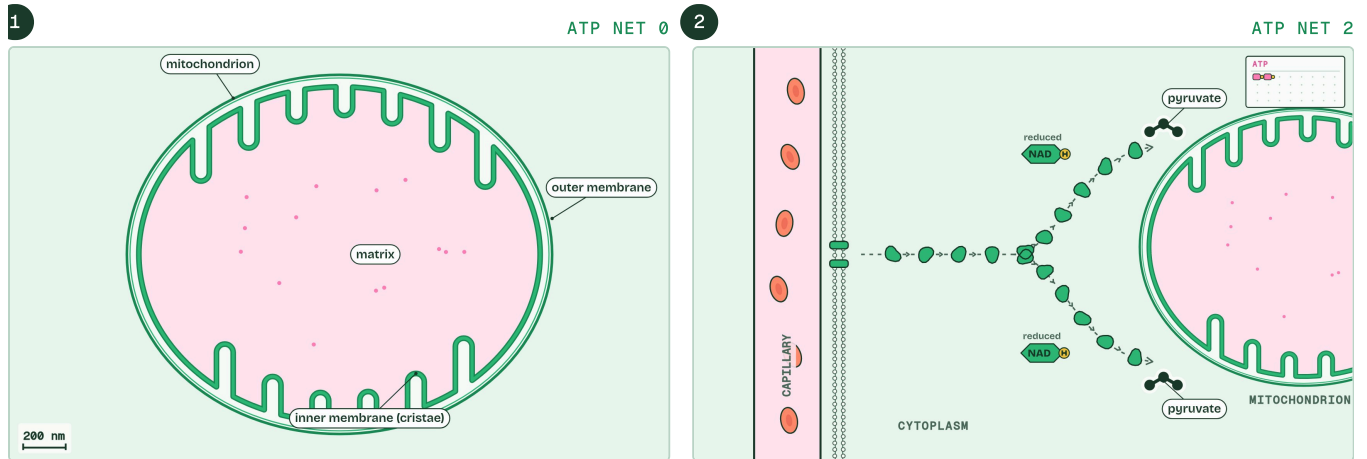
SWITCH IT

2 SETTINGS



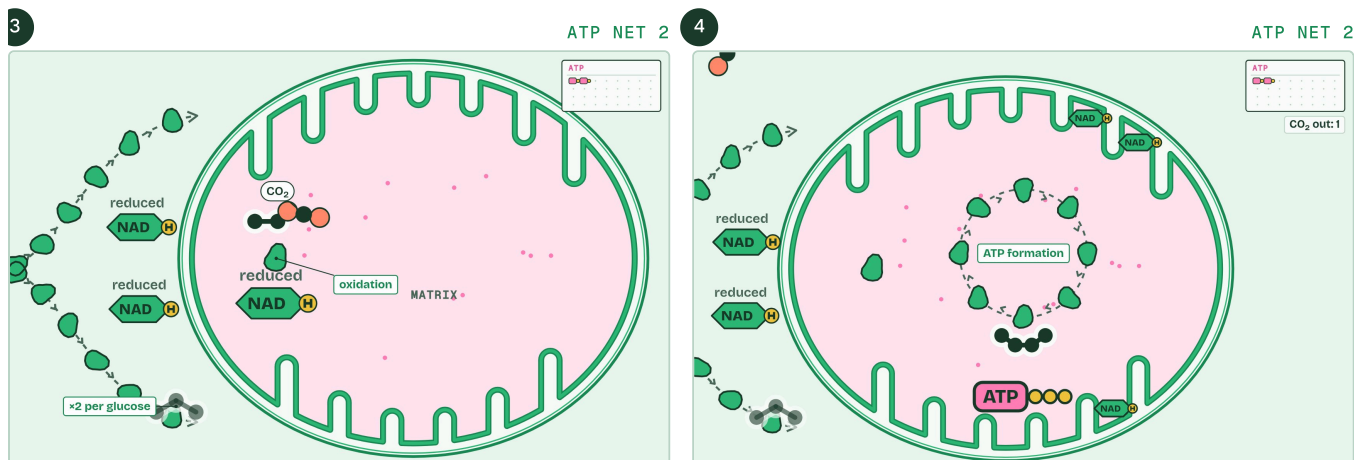
What is in them

How they are respired



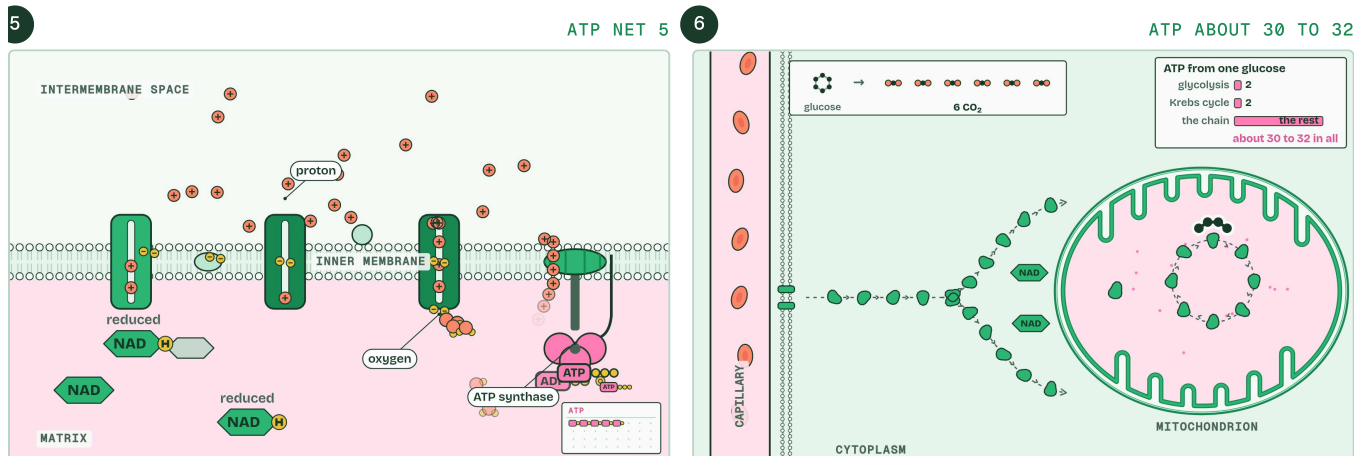
Inside a muscle fibre, one **mitochondrion**: the folded inner membrane (**cristae**), the **matrix** inside it.

Net from one glucose: **2 ATP**, **2 reduced NAD** and **2 pyruvate**.



The **link reaction**, in the **matrix**: pyruvate loses a carbon as CO₂ (**decarboxylation**) and hydrogen to NAD (**oxidation**).

One **ATP** is made, and a fourth oxidation passes hydrogen to another carrier.



Protons flow back through **ATP synthase**, turning it: most of the ATP is made here. **Oxygen** takes the electrons at the end, making water.

From one glucose: **6 CO₂**, water, and **about 30 to 32 ATP**, nearly all of it from the chain.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-2-cell-respiration#fuels

PREDICT

Gram for gram, fat releases about twice the energy of carbohydrate when respired. Why?

- ☐ (A) Fat molecules are much bigger, so they hold more bonds
- ☐ (B) Fat is respired anaerobically, which is faster
- ☐ (C) Fat holds less oxygen and more hydrogen to oxidise
- ☐ (D) Fat skips glycolysis, so no ATP is spent

Decide before you look. Answer on page 49.

WATCH OUT

Fat cannot be used anaerobically: fatty acids enter at the Krebs cycle, which needs the chain, which needs oxygen. A sprint runs on carbohydrate.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

acetyl CoA 12

Acetyl coenzyme A: an acetyl group carried by coenzyme A. Fatty acids and carbohydrates both supply it to the Krebs cycle.

acetyl group 09

A group of two carbon atoms, left when pyruvate loses a carbon. Fatty acids are also broken down to acetyl groups.

active transport 02

Moving a substance across a membrane against its concentration gradient, using a pump protein and energy from ATP.

adenine 01

One of the four bases of nucleic acids. In ATP it is the part joined to the sugar.

ADP 02

Adenosine diphosphate: ATP with one phosphate group fewer. It is what ATP becomes when it is hydrolysed, and what is remade into ATP in respiration.

aerobic respiration 04

Respiration that needs oxygen. Glucose is broken down completely to carbon dioxide and water in the mitochondria, making a large amount of ATP.

anabolism 02

The building up of large molecules from small ones, using energy. Making a protein from amino acids is anabolism.

anaerobic respiration 04

Respiration without oxygen. In humans pyruvate is turned into lactate in the cytoplasm, and only a small amount of ATP is made.

ATP 01

Adenosine triphosphate: the molecule that carries energy to jobs all over a cell. Adenine and ribose with a chain of three phosphate groups.

ATP and ADP cycle 02

ATP is hydrolysed to ADP and phosphate, releasing energy, and ADP and phosphate are joined back into ATP using energy from respiration or light. The molecules go round; the energy flows through.

ATP formation 07

The making of ATP from ADP and a phosphate group. In glycolysis each 3-carbon sugar passes its phosphates to ADP, and ends as pyruvate.

ATP synthase 11

The enzyme that makes ATP using the flow of protons down their gradient through it. It spans the inner mitochondrial membrane, with a part that turns and a head in the matrix.

baking 08

Making bread. Yeast in the dough respire its sugars, and the carbon dioxide they give out makes the dough rise.

brewing 08

Making drinks such as beer and wine. Yeast in a sugary liquid, with little air, make ethanol, which is kept.

capillary 05

A very thin tube. In a respirometer the drop moves along it as the volume of gas changes.

carbohydrates 12

Sugars, starch and glycogen. Glucose, the main fuel of respiration, is a carbohydrate.

cell respiration 03

The release of energy from carbon compounds in a cell, step by step, and its transfer to ATP.

chemiosmosis 11

The making of ATP using the energy released as protons flow down their gradient through ATP synthase.

citrate 09

A 6-carbon compound, the first made in the Krebs cycle from an acetyl group and oxaloacetate.

coenzyme A 09

A carrier of acetyl groups. It carries the acetyl group to the Krebs cycle and goes back for more.

combustion 03

Burning: a fuel reacting quickly with oxygen and releasing its energy as heat and light.

control 05

A set-up kept the same as the experiment in every way except the one thing being tested. The bead tube shows what moves the drop that is not respiration.

cristae 10

The folds of the inner mitochondrial membrane. They give a large area for the electron transport chain and ATP synthase.

decarboxylated 09

Having a carbon removed as carbon dioxide. Decarboxylation takes place in the link reaction and in the Krebs cycle.

dehydrogenation 06

The removal of hydrogen (a proton and an electron) from a molecule. It oxidises the molecule. Enzymes that do it are dehydrogenases.

electron carriers 10

Molecules that pass electrons on, one to the next. In the chain, some of them are proton pumps.

electron transport chain 10

A series of electron carriers in the inner mitochondrial membrane. Electrons are passed along it, and the energy released is used to pump protons.

energy currency 01

A molecule that every job in a cell accepts as payment for its energy, so that energy from many different sources can be spent in the same way. ATP is the cell's energy currency.

ethanol 08

A two-carbon alcohol. It is the product of anaerobic respiration in yeast, with carbon dioxide.

fatty acids 03

The long chains of carbon and hydrogen that make up most of a fat. They are respired for a large share of a cell's ATP.

fermentation 08

Anaerobic respiration in yeast (making ethanol and carbon dioxide) or in muscle (making lactate), especially when it is put to use, as in brewing and baking.

gas exchange 03

The movement of oxygen into, and carbon dioxide out of, an organism or its cells by diffusion across a surface such as the lungs, gills or a leaf.

glucose 03

A six-carbon sugar, C₆H₁₂O₆. It is the main fuel of respiration in most cells.

glycolysis 04

The splitting of glucose into two pyruvate in the cytoplasm. It releases enough energy to make a small amount of ATP, and it does not need oxygen.

hydrogen carrier 06

A molecule that picks up hydrogen in one place and delivers it in another. NAD is the hydrogen carrier of respiration.

hydrolysis 02

A reaction in which a molecule is split by the addition of water. Hydrolysis of ATP removes its last phosphate group and releases energy.

inner membrane 10

The inner of the two membranes of a mitochondrion. It is folded into cristae and holds the electron transport chain and ATP synthase.

intermembrane space 10

The narrow gap between the inner and outer membranes of a mitochondrion. Protons are pumped into it.

Krebs cycle 09

A cycle of reactions in the matrix. An acetyl group joins oxaloacetate to make citrate, and the cycle gives off carbon dioxide, loads hydrogen carriers and makes a little ATP.

lactate 04

The waste product of anaerobic respiration in humans. It is made from pyruvate in the cytoplasm.

link reaction 09

The step between glycolysis and the Krebs cycle. Pyruvate is decarboxylated and oxidised, and the acetyl group left over is carried on by coenzyme A.

lipids 12

A group of molecules that includes fats and oils. They are respired for much of the energy in long, steady work.

lysis 07

Splitting. In glycolysis the 6-carbon sugar with two phosphates is split into two 3-carbon sugars.

matrix 09

The fluid inside the inner membrane of a mitochondrion. The link reaction and the Krebs cycle happen in it.

metabolic water 11

Water made in respiration, when oxygen accepts electrons and protons at the end of the chain.

mitochondrion 04

The organelle where aerobic respiration is completed. It makes most of a cell's ATP.

NAD 06

A hydrogen carrier built from nucleotides. It accepts hydrogen and is reduced, becoming reduced NAD, and gives it up again where the hydrogen is used.

nucleotide 01

A monomer of nucleic acids: a base, a sugar and a phosphate group.

oxaloacetate 09

A 4-carbon compound. It joins an acetyl group to make citrate, and is remade at the end of each turn of the Krebs cycle.

oxidation 06

The loss of electrons. In respiration it is mostly the removal of hydrogen from a molecule, because each hydrogen takes an electron with it.

oxidisable hydrogen 12

Hydrogen in a molecule that can be removed in respiration and passed on, carrying energy. Fats have much more of it per gram than carbohydrates.

per gram per minute 05

A way of giving a rate that allows for the mass of living material, so that samples of different mass can be compared. Written $\text{g}^{-1} \text{min}^{-1}$.

phosphate group 01

A phosphorus atom bonded to four oxygens. It is the unit that is added to ADP to make ATP, and removed from ATP to release energy.

phosphorylation 07

The addition of a phosphate group to a molecule. In glycolysis two ATP each give a phosphate group to the sugar, which makes it reactive.

potassium hydroxide 05

An alkali that absorbs carbon dioxide. It is used in a respirometer so that the carbon dioxide given out does not hide the oxygen taken up.

proton gradient 10

A difference in the concentration of protons across a membrane. In a mitochondrion it is high in the intermembrane space and low in the matrix, and it stores energy.

protons 10

Hydrogen ions, H^+ : a hydrogen atom that has lost its electron.

pyruvate 04

A three-carbon molecule. Glycolysis makes two of them from each glucose.

rate of respiration 05

The amount of oxygen taken up, carbon dioxide given out or fuel used, in each unit of time.

redox reaction 06

A reaction in which one substance is oxidised and another is reduced.

reduced NAD 06

NAD that has accepted hydrogen. It carries the hydrogen, and the energy that comes with it, to the electron transport chain.

reduction 06

The gain of electrons.

regeneration of NAD 08

Turning reduced NAD back into NAD, so that it can accept hydrogen again. It lets glycolysis go on.

respiratory substrates 03

The carbon compounds a cell breaks down in respiration. Glucose and fatty acids are the main ones.

respirometer 05

An apparatus that measures the rate of respiration from the change in the volume of gas in a sealed tube of living material.

ribose 01

A five-carbon sugar. It is the sugar in RNA and in ATP.

terminal electron acceptor 11

The last molecule to receive electrons from the electron transport chain. In aerobic respiration it is oxygen.

yeast 08

A single-celled fungus. Baker's and brewer's yeast respire sugars, with or without oxygen.

yield 04

How much of a product a process makes from a set amount of starting material: here, the number of ATP made from each glucose.

Dry lab: *Respirometer: seeds and dough*

Germinating seeds in a sealed tube use oxygen, and a coloured drop creeps along a scale as they do. Change one thing, read the drop each minute, and work out how fast the seeds respire. Or switch to dough and race five sugars.

seeds

start

200 180 160 140 120 100 80 60 40 20 0

beads

200 180 160 140 120 100 80 60 40 20 0

scales in mm, counting up towards each tube

25 °C

KOH corrosive

seeds

glass beads

under a dark cover: the seeds are kept in the dark

Yeast dough: five tubes, one sugar in each, read against a ruler every 5 minutes.

Germinating seeds over potassium hydroxide, with a glass-bead tube beside them as the control. Both drops sit at the start mark: read each one every minute.

Run it on the page: set one variable, read the drops, and the table and graph fill in.

2.03 g

balance

0:00

min : s

clock



Run it online: change the variables, run the trials, and the table and graph fill in as you go. biologybybradford.com/guides/ib-biology-c1-2-cell-respiration#lab

Your question

How does one factor change the rate at which germinating seeds take up oxygen? Start with temperature. Then try the dough: which sugar makes yeast respire fastest?

What you can change

One independent variable at a time: the water bath's temperature, how long ago the seeds were soaked, the mass of seeds, or whether the potassium hydroxide is in. In dough mode, the sugar. Everything else stays fixed unless you change it on purpose.

What to record

The drop's position on the scale every minute, in mm, for the seeds and for the glass-bead tube beside them. Then the rate in mm^3 of oxygen per gram per minute, three or more trials at each value, a mean and a standard deviation, and a graph. The coach under the bench helps you plan, process and evaluate.

Find out

- **Temperature.** Run 5 to 40 °C in 5 °C steps, with 3-day seeds and 2.0 g, three trials at each. Then try 45 °C: what happens to the drop as the run goes on?
- **Waking up.** At 25 °C, run dry seeds, then 1 to 5 days since soaking, then boiled seeds.
- **Per gram.** At 25 °C, run 1 to 6 g of seeds. The table gives the rate for the whole tube: work out the rate per gram for each mass too, and plot both.
- **No potassium hydroxide.** Run 3-day mung beans with it in, then with water in its place.
- **HL Fat or starch?** Switch the seeds to sunflower, run them with the potassium hydroxide in and out, and work out the respiratory quotient: $1 - (\text{rate without} \div \text{rate with})$.
- **The clip.** At 25 °C, leave the clip open for 0, 5 and 10 minutes before starting. Watch the bead tube's drop.
- **Five sugars.** Switch to yeast dough at 30 °C and run the rack three times, so you have three tubes of each sugar, over 30 minutes.

Record

- Every run's settings: what you changed, and everything you kept the same.
- Both drops' positions every minute, in mm: the seeds' and the glass-bead tube's. For the dough, each top every 5 minutes.
- Change one thing at a time.
- Three or more trials at each value, then a mean and its standard deviation.
- Use **Graph your results** under the lab, or download the CSV and plot it yourself.
- The bench keeps each variable's results: choose it again to see them.
- When you are done, choose one investigation and write it up with the IA coach under the bench.

QUESTIONS ON THE LAB

QUESTION 1

With the potassium hydroxide taken out, the drop beside the mung beans hardly moves. Why?

- (A) The seeds stop respiring once the alkali is gone
- (B) Water vapour from the seeds fills the space in the tube
- (C) Their carbon dioxide out matches their oxygen in
- (D) The capillary blocks without potassium hydroxide in it

Answer on page 49.

QUESTION 2

In the first two minutes the drop beside the glass beads moved 10 mm away from its tube, then stopped. What does that tell you?

- (A) The gas in the tubes was still warming to the bath
- (B) The beads were respiring for a short time
- (C) The potassium hydroxide was giving off a gas
- (D) Somebody misread the scale on both tubes at the very start

Answer on page 49.

QUESTION 3

Sucrose dough rose almost as fast as glucose dough, but starch dough barely beat dough with no sugar. Why?

- (A) Sucrose is smaller than glucose, so it gets into the yeast cells faster
- (B) Starch dough is so sweet that the yeast slow down to protect themselves
- (C) Yeast split sucrose outside the cell; they have no enzyme for starch
- (D) Glucose and sucrose are really the same molecule

Answer on page 50.

QUESTION 4

With the potassium hydroxide out, the drop beside germinating sunflower seeds still creeps towards them. Why?

- (A) Sunflower seeds take in carbon dioxide from the air in the tube as they grow
- (B) Respiring fat uses more oxygen than the carbon dioxide it gives out
- (C) Sunflower seeds respire faster than mung beans do
- (D) Oil leaking from the seeds soaks up all of the carbon dioxide instead

Answer on page 50.

WRITE IT UP AS AN INVESTIGATION

Your results from this dry lab can be written up the way an IB scientific investigation is: four criteria, each worth 6 marks. Tick each line as your write-up does it. The coach on the page checks these as you go; it never gives a mark.

1 Research design

A focused question set in its biology; your choices of what to measure, how, over what range and how often, explained rather than listed; what you kept the same and how; safety, ethics and the environment; a method someone else could follow and repeat.

- ☐ My question names what I changed.
- ☐ It gives the range I used, with units.
- ☐ It names what I measured and how.
- ☐ It names the organism or system.
- ☐ My background explains, with the biology, why the two should be linked.
- ☐ I cite my sources, and each reference can be traced.
- ☐ If I give a hypothesis, it predicts and explains.
- ☐ Every variable has its How, Why and Units.
- ☐ For each thing kept the same, I say how I kept it so.
- ☐ I list at least three things I kept the same.
- ☐ I name the apparatus that set what I changed, and the instrument that measured.
- ☐ I test enough values.
- ☐ My values spread wide enough.
- ☐ I run at least three trials at every value.
- ☐ I run a control.
- ☐ I explain why these values, this many and this often.
- ☐ Someone else could repeat my method.
- ☐ I deal with safety, ethics and the environment.

3 Conclusion

Your question answered from the processed data, with numbers quoted and the spread taken into account; the biology that explains the pattern; a comparison with published work; no claim bigger than the data.

- ☐ I answer my question in a sentence, naming both variables.
- ☐ I quote my processed numbers.
- ☐ I say how sure the spread lets me be.
- ☐ I say whether my hypothesis is supported.
- ☐ I explain the pattern with biology.
- ☐ I compare my result with published work, and cite it.
- ☐ I claim no more than my data show.

2 Data analysis

Raw data recorded clearly, with titles, units, uncertainties and the same decimal places down a column; what you saw as well as what you measured; processing that suits the question, shown with a worked example; the spread shown; a graph a reader can trust.

- ☐ Each table has a numbered title that says what it shows.
- ☐ Every heading has its quantity and its unit.
- ☐ Every raw data heading has its uncertainty.
- ☐ Each uncertainty is realistic for the instrument.
- ☐ Each uncertainty has the same decimal places as its readings.
- ☐ I record what I saw as well as what I measured.
- ☐ I show one worked example of my processing, and it is right.
- ☐ I say why I left out any trial.
- ☐ My error bars show a spread my repeats can support.
- ☐ My graph has a numbered title and labelled axes with units.
- ☐ I say what the error bars show.
- ☐ A straight line, if I draw one, has its R^2 .
- ☐ A statistical test, if I run one, has its hypotheses and suits the data.

4 Evaluation

Weaknesses and limitations of this method (not slips in carrying it out), with evidence from your own data, the effect each had on the results, which mattered most and why, and a realistic improvement for each.

- ☐ I give at least three weaknesses or limitations.
- ☐ Every row is filled in.
- ☐ No slips in carrying it out: weaknesses of the method itself.
- ☐ Each improvement is specific: which instrument, how many, what changes.
- ☐ Each effect says what it did to my data.
- ☐ At least two rows point to evidence in my own data.
- ☐ At least one limitation: what this experiment cannot tell me.
- ☐ I say which mattered most, and why.
- ☐ I deal with what stands out in my data.
- ☐ My improvements improve this investigation, not a new one.

Variables

Variable	How?	Why?	Units
Independent: temperature			
Dependent: rate of oxygen uptake			
Kept the same: days since soaking			
Kept the same: mass of seeds			
Kept the same: capillary bore			
Kept the same: volume and strength of potassium hydroxide			
Kept the same: time with the clip open before starting			
Kept the same: volume of glass beads			
Kept the same: kind of seed			
Kept the same: length of the run			

Evaluation

Weakness or limitation	Which?	Evidence in my data	Effect on my results	Improvement

Data generated with the respirometer dry lab, biologybybradford.com (a simulation). These checks catch what is missing. They cannot judge how good it is: that is what your teacher does.

**Check yourself**

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on C1.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=C1.2&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 Removing one phosphate from ATP releases only a modest amount of energy. Why does that suit a cell?

B A job can take what it needs, with little wasted

Most jobs in a cell come in small steps: one stroke of a pump, one step in building a protein. A packet of energy close to the size of the job means little is wasted as heat, and a big job simply uses many ATP. A glucose molecule holds far more energy than any one job needs, which is why the cell turns it into ATP first.

02 Remaking ATP from ADP and phosphate needs energy. Where does a muscle cell get it?

A From respiring glucose or fat

From respiration. The energy released step by step as glucose or fat is broken down is used to join phosphate back onto ADP. Body warmth cannot do it: heat is energy that has already been lost from reactions, and it cannot be put back into a molecule.

03 A leaf in bright light takes in carbon dioxide and gives out oxygen. Is it respiring?

C Yes: all its living cells respire all the time

Yes. Every living cell respire all the time, because every cell needs ATP every second. In bright light the leaf photosynthesises faster than it respire, so overall it takes in carbon dioxide and gives out oxygen: the gas exchange you measure is the difference between the two (C1.3).

04 A sprinter's leg muscles run short of oxygen. Per glucose, how much ATP does anaerobic respiration make compared with aerobic?

C About one fifteenth as much

About one fifteenth: 2 ATP against about 30 to 32. Without oxygen the glucose is only split, not broken down completely, so most of its energy is still locked in the lactate. The sprinter's muscles burn through glucose far faster to keep up, which is one reason a sprint cannot last.

05 In the respirometer the seeds respire and the potassium hydroxide absorbs their carbon dioxide. Which way does the drop move?

B Towards the seeds, as they take in oxygen

Towards the seeds. They take oxygen out of the air in the tube; the carbon dioxide they give out is absorbed as fast as it is made, so the gas shrinks and the drop is pulled in. How far it moves each minute is how fast they take up oxygen. Take the potassium hydroxide away and the drop hardly moves (the dry lab lets you try).

06 A dehydrogenase takes two hydrogens off a molecule of fuel. What has happened to that molecule?

D It is oxidised: it has lost electrons

It is oxidised. Each hydrogen taken away carries an electron with it, and losing electrons is oxidation. The NAD that accepts them gains the electrons and is reduced. In respiration, oxidation almost always means hydrogen being taken off the fuel.

07 Glycolysis spends 2 ATP at the start. How many does it make by the end, from one glucose?

A 4, so the cell gains 2

Four, for a net gain of two. The two spent at the start make the sugar reactive enough to split; the four made later come from energy released as the 3-carbon sugars are oxidised and changed into pyruvate. So for one glucose the **net yield** is **2 ATP**, with **2 reduced NAD** and **2 pyruvate**. No oxygen is used anywhere in glycolysis, so it is the same in aerobic and anaerobic respiration. The big yield comes later, in the mitochondrion.

08 Without oxygen, why does a muscle cell turn pyruvate into lactate instead of leaving it as pyruvate?

D It gives NAD back, so glycolysis can go on

To give NAD back. Glycolysis turns NAD into reduced NAD, and without oxygen nothing else can unload it. Turning pyruvate into lactate takes the hydrogen off reduced NAD, so NAD is free to collect more, and glycolysis keeps making its 2 ATP per glucose.

09 Each turn of the Krebs cycle takes in a 2-carbon acetyl group. Why does the cycle not fill up with carbon?

B Two carbons leave as carbon dioxide each turn

Two carbons leave as carbon dioxide in every turn, in the two decarboxylations, and the cycle ends where it started, with the 4-carbon oxaloacetate. Two carbons in, two out: this is where most of the carbon dioxide you breathe out is made. Count the carbons: glucose has 6; two leave as carbon dioxide in the link reactions and four in the two turns of the cycle, so all six are gone. The carriers, not the ATP, are the main product so far: per glucose the cycle makes only 2 ATP, and the chain turns the reduced NAD into most of the ATP (chapters 10 and 11).

10 Electrons pass along the chain of carriers, releasing a little energy at each step. What is that energy used for?

D Pumping protons across the inner membrane

Pumping protons, from the matrix into the intermembrane space. No ATP is made at the carriers themselves; the energy is first stored as a gradient of protons, and the gradient is spent making ATP in chapter 11.

11 A cell's mitochondria run out of oxygen. What happens to the electron transport chain?

A Electrons back up and the pumping stops

The electrons back up. With nothing to take them at the end, the last carrier stays full, then the one before it, all the way back. No electrons flow, so no protons are pumped, the gradient runs down and ATP synthase stops. Reduced NAD cannot be unloaded either. Try it in the film below.

12 Gram for gram, fat releases about twice the energy of carbohydrate when respired. Why?

C Fat holds less oxygen and more hydrogen to oxidise

A fatty acid is mostly carbon and hydrogen, with very little oxygen: palmitic acid, a common fatty acid, is only about one eighth oxygen by mass, and glucose about a half. So a gram of fat has far more **oxidisable hydrogen** and carbon to oxidise, and respiring it takes about 2.7 times as much oxygen per gram: 23 oxygen molecules for one palmitic acid, against 6 for one glucose. Size does not matter (a gram is a gram), and fat cannot be respired anaerobically at all.

QUESTIONS ON THE DRY LAB

Q1 With the potassium hydroxide taken out, the drop beside the mung beans hardly moves. Why?

C Their carbon dioxide out matches their oxygen in

The seeds are still respiring. Respiring sugar and starch gives out one molecule of carbon dioxide for every molecule of oxygen taken up, so with nothing to absorb the carbon dioxide the gas in the tube hardly changes in volume. That is why the respirometer needs its absorbent to measure oxygen uptake.

Q2 In the first two minutes the drop beside the glass beads moved 10 mm away from its tube, then stopped. What does that tell you?

A The gas in the tubes was still warming to the bath

Glass beads do not respire, so anything that moves their drop is not respiration. Gas expands as it warms, and the tubes had not quite reached the bath's temperature. The seeds' tube warmed in the same way, so subtracting the bead tube's movement takes the drift out. Leaving the clip open longer before starting would have stopped it.

Q3 Sucrose dough rose almost as fast as glucose dough, but starch dough barely beat dough with no sugar. Why?

C Yeast split sucrose outside the cell; they have no enzyme for starch

Yeast put an enzyme, invertase, in their cell wall, which splits sucrose into glucose and fructose before it is taken in, so sucrose is nearly as quick as glucose. Yeast make no amylase, so starch is broken down only slowly by the flour's own enzymes, which is also where the "no sugar" dough's sugar comes from.

Q4 With the potassium hydroxide out, the drop beside germinating sunflower seeds still creeps towards them. Why?

B Respiring fat uses more oxygen than the carbon dioxide it gives out

Sunflower seeds store oil. Fat holds little oxygen, so respiring it takes up more oxygen than it gives out carbon dioxide (about 7 carbon dioxide for every 10 oxygen), and the gas still shrinks. Mung beans store starch, which gives one for one (chapter 12).

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.