Cell respiration

C1.2 · SL and HL

A seed respires without breathing through lungs

Follow energy, matter and electrons as separate quantities

Common C1.2 content: ATP use/recycling, respiration, human aerobic/anaerobic pathways and respiration-rate measurements.

Numerical examples and experimental datasets are invented for teaching.

Ventilation moves air, gas exchange transfers gases, and cellular respiration consists of enzyme-controlled reactions.

AHL follows carriers and the mitochondrial gradient

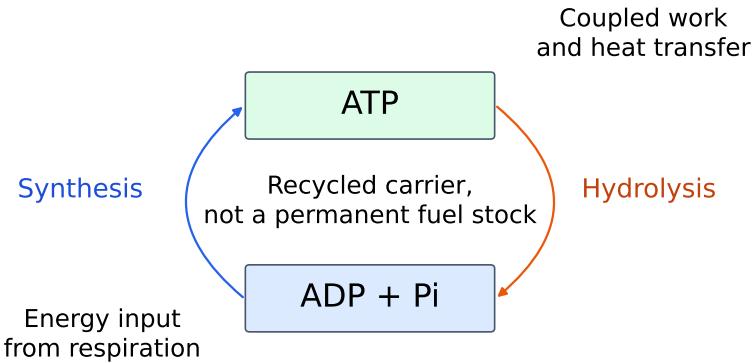
Different pathway stages need different accounting

AHL content: NAD, glycolysis, lactate, yeast fermentation, link reaction, Krebs cycle, electron transport, chemiosmosis and fuel entry.

Count carbon and carriers per original glucose, distinguishing gross from net ATP.

A gas flux does not directly measure ATP yield or coupling efficiency.

Use a recycled carrier to connect different processes



Respiration supports ATP synthesis; coupled hydrolysis supports cellular work.

ATP is a nucleotide with three phosphate groups

Feature	Meaning
Adenosine triphosphate	Adenine + ribose + three phosphates; adenosine is adenine plus ribose
Hydrolysis	ATP $\rightarrow$ ADP + inorganic phosphate releases energy overall under cellular conditions
Synthesis	Phosphorylation of ADP requires an energy supply
Caution	Isolated bond breaking needs energy. Overall hydrolysis and coupling explain useful energy transfer.

Different cellular processes couple to ATP use

Name the work and explain why it needs an energy supply

Active transport moves substances against electrochemical gradients through suitable proteins.

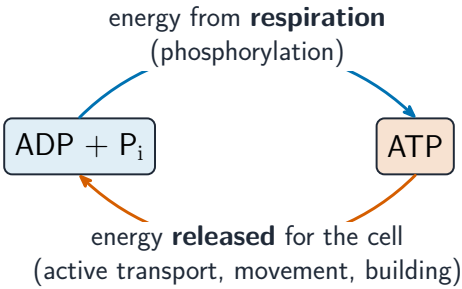
Anabolism builds macromolecules; motor systems support muscle contraction and chromosome movement.

ATP is a rapid short-term carrier, not a permanent long-term fuel stock or an energy packet acting at a distance.

A constant pool can hide rapid turnover

1. **Invented steady state.** ATP pool 120 molecules; synthesis and use each 600 molecules/second.
2. **Compare.** 600/120 = five pool-equivalents per second.
3. **Inference.** Equal synthesis and use keep concentration steady. A stable pool does not imply no reactions; reduced synthesis can limit ATP-dependent work.

The ATP cycle



> ATP is a currency, not a store

Distinguish movement of air, gas and chemical energy

Process	Explanation
Ventilation	Air moves into/out of an organ such as lungs
Gas exchange	Gases cross an exchange surface
Cellular respiration	Organic-substrate reactions support ATP production and release heat
Substrates	Glucose and fatty acids are principal fuels; other organic compounds can enter after suitable conversion

An overall equation summarizes many controlled steps

1. **Glucose model.** Glucose + oxygen → carbon dioxide + water.
2. **Balanced matter.** One glucose + six oxygen → six carbon dioxide + six water molecules.
3. **Energy.** Chemical energy is transferred, not created. Some supports ATP formation; some becomes heat. Seeds and plant cells in darkness can respire.

Compare human glucose pathways using the same features

Feature	Aerobic / anaerobic comparison
Oxygen	Required for sustained aerobic operation / not required for the lactate pathway
Location	Cytosol then mitochondrial stages / cytosol
Final products	Carbon dioxide and water / lactate
ATP and fuel	Much larger yield / net two ATP per glucose; fatty acids cannot replace glucose in the lactate route

Different routes can operate at the same time

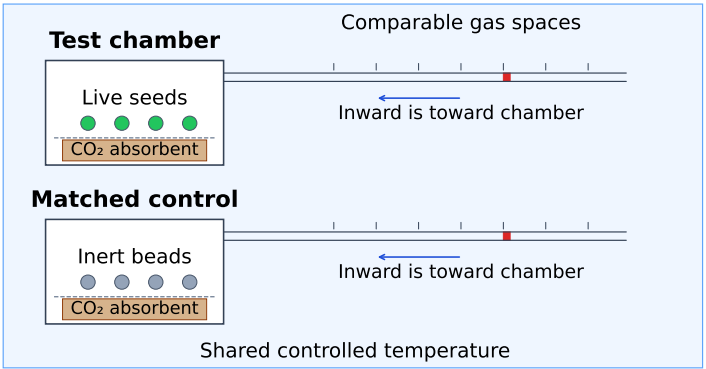
Mitochondrial participation and oxygen delivery both matter

Human anaerobic carbohydrate metabolism can support some ATP production when oxygen delivery cannot sustain the required aerobic rate.

A cell can combine routes; lactate can be transported and used in later metabolism rather than being permanently useless.

A cell without working aerobic machinery cannot perform all aerobic stages simply because oxygen is present.

A matched control tests movement unrelated to respiration



Absorb carbon dioxide, control temperature and compare matched gas spaces.

A moving marker is an oxygen-uptake estimate under conditions

Do not treat all displacement as a metabolic signal

Carbon dioxide absorbent removes respiratory carbon dioxide; oxygen uptake then reduces the gas-phase amount and can move the capillary marker.

Temperature/pressure drift, leaks and incomplete equilibration can distort the movement. A matched non-respiring control estimates shared drift.

Match occupied volume/gas space and absorbent arrangement; equal masses of glass beads and seeds do not automatically give equal gas spaces.

Normalize a measured volume by time and sample mass

1. **Invented supplied uptake.** 0.80 cubic centimetres in 4.0 minutes for 2.0 g tissue.
2. **Calculate.** $0.80/(4.0 \times 2.0) = 0.10$ cubic centimetres per minute per gram.
3. **Qualify.** Normalization does not remove species, germination stage, water content or tissue-condition differences; oxygen uptake does not count ATP directly.

Correct drift before applying capillary geometry

1. **Invented apparatus.** Radius 1.0 mm; test inward 30.0 mm; matched control inward 6.0 mm.
2. **Volume.** Corrected distance 24.0 mm; $\pi \times 1.0^2 \times 24.0 \approx 75.4$ cubic millimetres $= 0.0754$ cubic centimetres.
3. **Mass-specific rate.** Over 4.0 minutes and 1.5 g: $0.0754/(4.0 \times 1.5) \approx 0.0126$; about 0.013 to two significant figures.

The sign of drift is part of the correction

1. **Convention.** Take inward motion as positive. A control moving outward has negative displacement.
2. **Practice example.** Test $+10$ mm; control -2 mm; corrected $= 10 - (-2) = 12$ mm.
3. **Limits.** The control must estimate shared background. Large erratic drift or leaks can invalidate the estimate even after subtraction. Radius/diameter confusion multiplies area by four.

A temperature comparison needs independent comparable samples

Equilibrate before resetting the marker and measuring

Use approved germinating seeds or supplied data. Match species/stage, mass basis, gas space, oxygen availability and measurement interval.

Use a common controlled bath and matched controls; repeat with independent samples and show variation. Repeated readings on one group are not independent seed groups.

Keep corrosive absorbent physically separated by a suitable barrier under the school protocol. High temperatures can damage samples; two treatments do not locate an exact optimum.

A carrier must be recycled to keep the pathway operating

Oxidation and reduction occur together

Oxidation loses electrons; reduction gains electrons. Removing hydrogen with its electrons oxidizes an organic substrate.

Oxidized NAD accepts a pair of electrons and a proton, forming reduced NAD, NADH. Later electron transfer regenerates oxidized NAD.

NAD neither creates electrons nor provides a permanent electron sink. If the pool stays reduced, reactions needing oxidized NAD are limited.

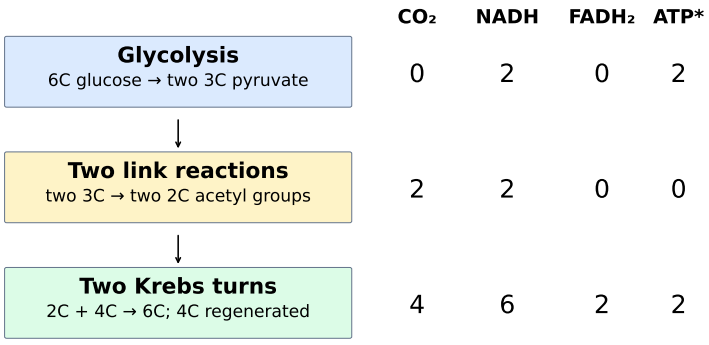
Count duplicated reactions after a six-carbon molecule splits

1. **Investment.** One glucose is phosphorylated using two ATP, then a six-carbon intermediate splits into two three-carbon phosphorylated molecules.
2. **Pay-off.** Oxidation forms two NADH; four ATP are formed in total by substrate-level phosphorylation; two pyruvate remain.
3. **Net.** Four produced minus two invested = two net ATP/glucose. Glycolysis directly uses no oxygen and releases no carbon dioxide.

Regenerate NAD without claiming another ATP gain

Human / yeast pathway	**Carbon and carrier accounting**
Human lactate formation	Pyruvate is reduced using NADH; oxidized NAD is regenerated. Two 3C lactates per glucose
Yeast fermentation	Pyruvate loses carbon dioxide to form ethanal, then ethanol formation uses NADH and regenerates NAD
Yeast products / uses	Two ethanol + two carbon dioxide per glucose; brewing uses ethanol, baking uses carbon dioxide
ATP	Net two ATP comes from glycolysis; regeneration adds none.

Count each stage per original glucose



Per glucose; *net substrate-level ATP-equivalents only

The carbon and carrier ledger differs from a final ATP-yield calculation.

Two pyruvate molecules undergo two link reactions

1. **Per pyruvate.** Three carbons → one carbon dioxide + a two-carbon acetyl group; NAD is reduced.
2. **Coenzyme A.** Carries the acetyl group toward the Krebs cycle; the link step directly produces no ATP.
3. **Per glucose.** Two acetyl groups, two carbon dioxide and two NADH. Count both pyruvate molecules.

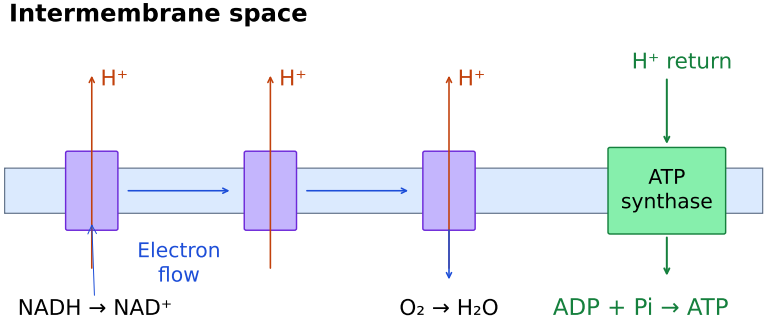
A regenerated acceptor is not a fresh net carbon input

1. **Entry.** Acetyl 2C + oxaloacetate 4C → citrate 6C.
2. **Per turn.** Two decarboxylations, four oxidations: two carbon dioxide, three NADH, one reduced FAD and one substrate-level ATP-equivalent.
3. **Regeneration.** Oxaloacetate is restored. Two turns per glucose give four carbon dioxide, six NADH, two reduced FAD and two ATP-equivalents.

Four oxidations do not imply four reduced NAD per turn

1. **Carrier identity.** One of the four oxidations reduces FAD rather than NAD.
2. **Combined glucose ledger.** Glycolysis + link + two Krebs turns: six carbon dioxide, ten NADH, two reduced FAD, four net substrate-level ATP-equivalents.
3. **Limit.** Those carriers are not already counted as ATP. Do not infer which acetyl carbon leaves first from a simple carbon-number diagram.

Separate electron flow from proton movement



Electrons drive proton pumping; oxygen accepts electrons and forms water.

The inner membrane separates the proton compartments

Pumping is from matrix to intermembrane space

NADH transfers electrons to the chain and is oxidized to NAD. Glycolysis supplies cytosolic reducing equivalents through shuttles; NADH does not freely diffuse through the inner membrane.

Energy from electron transfer drives proton pumping outward from matrix, establishing concentration and electrical differences across the inner membrane.

Oxygen is the terminal electron acceptor and forms water with electrons and protons. It does not directly make ATP or become the carbon dioxide of decarboxylation.

Return through ATP synthase is opposite to pumping

1. **Stored difference.** The inner membrane limits uncontrolled proton flow; the electrochemical gradient is a usable energy source.
2. **Coupling.** Protons return from intermembrane space to matrix through ATP synthase, supporting ADP + inorganic phosphate $\rightarrow$ ATP.
3. **Yield.** Oxidative phosphorylation adds to substrate-level contributions; transport, shuttles and leak prevent one universal ATP total for every cell.

Distinguish an electron-flow block from a proton leak

1. **Electron-flow block.** Pumping stops; the existing gradient dissipates. ATP production falls and NADH oxidation is impaired.
2. **Proton leak.** Return bypasses ATP synthase. Electron flow and oxygen uptake can continue while ATP yield falls.
3. **Interpretation.** Oxygen uptake alone does not demonstrate efficient ATP synthesis; a gradient and suitable coupling are both needed.

Higher energy per gram does not mean every pathway can use it

Substrate feature	Consequence
Fatty acids	Break down to acetyl groups entering via acetyl-CoA, downstream of glycolysis in the usual even-chain model
Composition	Less oxygen and more oxidizable carbon/hydrogen per gram than carbohydrate; greater complete-oxidation energy yield
Anaerobic limit	Fatty acids cannot sustain the human glycolytic lactate route; their carriers depend on aerobic reoxidation
Other components	Glycerol has its own entry route; distinguish fatty acids from all lipid-associated molecules

Use supplied energy values without turning them into ATP yields

1. **Invented comparison.** 8.0 g each; supplied values fat 39 kJ/g, carbohydrate 17 kJ/g.
2. **Calculate.** 312 kJ versus 136 kJ; ratio about 2.29.
3. **Limit.** Overall supplied energies do not equal energy retained in ATP; actual substrate, physiology and coupling matter.

Attempt all handout questions before checking

Keep units, compartments and correction signs explicit

Explain ATP turnover and human pathway comparisons, distinguishing cellular chemistry from ventilation.

Calculate mass-specific oxygen uptake and capillary-volume corrections; compare independent samples.

Evaluate equilibration, temperature, gas space, absorbent separation, pressure drift and apparatus leaks.

Check the common numerical answers

1. **ATP pool and supplied uptake.** $750/150$ = five pool-equivalents/second; $0.96/(4.0 \times 1.5) = 0.16$ cubic centimetres per minute per gram.
2. **Geometry.** Corrected 32.0 mm; $\pi \times 0.50^2 \times 32.0 = 25.13$ cubic millimetres = 0.02513 cubic centimetres. Divide by 5.0×0.80: about 0.0063 cubic centimetres per minute per gram.
3. **Variation.** Mean 0.10 and range 0.02 in supplied rate units; the observed range is not automatically a confidence interval.

AHL answers: follow carbon, carriers and the gradient

1. **Glucose ledger.** Six carbon dioxide, ten NADH, two reduced FAD and four net substrate-level ATP-equivalents; oxidative phosphorylation is additional.
2. **Direction.** Pumping: matrix $\rightarrow$ intermembrane space; ATP-synthase return: intermembrane space $\rightarrow$ matrix. Oxygen accepts electrons and forms water.
3. **Fuel.** $6.0 \times 39 = 234$ kJ versus $6.0 \times 17 = 102$ kJ, ratio about 2.29; greater fat energy does not enable the human anaerobic lactate route.

Check yourself

Name the measured quantity before drawing an energy conclusion

A seed respires without lungs. A constant ATP concentration can coexist with rapid turnover.

A marker distance needs calibration or area before it becomes a volume; a volume needs time and mass for a mass-specific rate.

An oxygen-uptake rate is not a direct ATP count, and isolated bond breaking is not the source of energy released by overall ATP hydrolysis.