

Unit 3: Cellular Energetics

Unit 3 covers how enzymes speed up the chemical reactions of life and how cells capture, store, and spend energy through photosynthesis and cellular respiration. CED topics 3.1 through 3.5.

AP Biology

Cellular Energetics

About 15 minutes to read

How to use this guide

Read the enzyme sections first because enzymes run every pathway in this unit. Then read the energy section, which states the laws that govern all of it. Photosynthesis and cellular respiration come last, and each one is presented as a sequence of locations with inputs and outputs. Exam questions usually give a scenario, such as a poisoned electron transport chain or a leaf in dim light, and ask what changes.

After the first read, use the trap boxes and the tables to review the distinctions the exam tests most often. Do not memorize the step-by-step details of the Calvin cycle or the electron transport chain. The CED excludes that memorization. Finish with the practice questions, then complete the recall check on the last page out loud and note any items you cannot explain yet.

What this unit is worth. The energy story told here returns later in the course. Photosynthesis and respiration reappear in Unit 8 when energy moves through ecosystems, and conserved metabolic pathways support the common-ancestry arguments of Unit 7. Learn the locations, inputs, and outputs now and you will recognize them when those units arrive.

3.1 Enzymes

An **enzyme** is a protein that acts as a biological catalyst. It speeds up a chemical reaction by lowering the **activation energy**, the minimum energy needed to start the reaction. The enzyme is not used up in the process. It can catalyze the same reaction again after each one finishes.

The molecule an enzyme acts on is the **substrate**. The substrate binds at the **active site**, a region of the enzyme whose shape and charge must be compatible with the substrate. When they bind, they form the **enzyme-substrate complex**. That fit is what makes each enzyme specific to its reaction. A substrate with the wrong shape or charge does not bind, and the reaction does not get the speed boost.

Trap. Lowering activation energy does not change the starting or ending energy of the reaction. The reactants and products hold the same energy with or without the enzyme. The enzyme only changes how much energy it takes to get started.

3.2 Environmental Impacts on Enzyme Function

Enzymes work best under **optimal enzyme conditions**, the temperature and pH at which a given enzyme is most efficient. Move outside that range and the reaction slows. The reason is structural. Conditions outside the optimal range disrupt hydrogen bonds, changing the enzyme shape and reducing how well it catalyzes.

Push temperature or pH far enough and the enzyme undergoes **denaturation**. The protein structure breaks down and the enzyme can no longer catalyze its reaction. Some denaturation is reversible, so the enzyme can regain activity when conditions return. Some is permanent.

The **relative concentrations of substrates and products** also matter. Raising the substrate concentration increases the rate because more substrate molecules collide with active sites. Letting product accumulate can slow the forward reaction, since the reverse reaction becomes more likely.

INHIBITOR	WHERE IT BINDS	WHAT HAPPENS
Competitive inhibitor	The active site, reversibly	Blocks the substrate from binding. Because the binding is reversible, a high substrate concentration can reduce the inhibitor effect.
Noncompetitive inhibitor	An allosteric site , separate from the active site	Changes the enzyme activity by binding elsewhere. Adding more substrate does not fix it, because the substrate binding site was never the problem.

Trap. Competitive and noncompetitive inhibitors both slow the enzyme, but they bind in different places. If a question says the inhibitor binds the active site, it is competitive. If it binds anywhere else, it is noncompetitive.

3.3 Cellular Energy

Two laws govern every energy story in biology. The **first law of thermodynamics** says energy cannot be created or destroyed, only transformed. Cells do not make energy. They convert it from one form to another. Living systems stay ordered because energy input exceeds energy loss.

The **second law of thermodynamics** says every energy transformation increases disorder, or entropy. Cells fight that disorder constantly by spending energy to maintain order. When a living system loses too much order, or when its energy flow stops, it dies.

Cells pay for expensive reactions with cheap ones through **energy coupling**. A process that releases energy is coupled to a process that requires energy, so the released energy drives the costly one. This is how cells do work without violating either law.

Reactions are organized into **metabolic pathways**, sequential series of reactions in which the product of one reaction is typically the reactant for the next. Breaking a large transformation into small steps lets the cell transfer energy in a controlled way instead of releasing it all at once.

Some of these pathways are ancient. **Conserved metabolic pathways** such as glycolysis and oxidative phosphorylation appear in all currently recognized domains of life: Archaea, Bacteria, and Eukarya. Their presence in every domain is evidence that all organisms share common ancestry.

Trap. The first law is about conservation. Energy is never created or destroyed. The second law is about disorder. Every transformation increases entropy. Questions that ask which law a scenario shows are testing whether you keep those two ideas separate.

3.4 Photosynthesis

Photosynthesis is the series of reactions that uses carbon dioxide, water, and light energy to make carbohydrates and oxygen. It first evolved in prokaryotic organisms. In eukaryotes it happens in the chloroplast, and each part of the chloroplast has its job.

STRUCTURE	WHAT HAPPENS THERE
Thylakoid	Internal membrane system holding chlorophyll and electron transport proteins. The light reactions happen here.
Granum	Stacks of thylakoids. The light reactions occur in the grana.
Stroma	The fluid inside the chloroplast but outside the thylakoid. The Calvin cycle runs here.

Chlorophyll pigments sit in the thylakoid membranes and absorb light energy, boosting electrons to a higher energy level. That happens inside **photosystems I and II**, pigment-protein complexes connected by electron transfer through an electron transport chain. Water splits to replace the electrons lost from photosystem II. In photosystem I, electrons are ultimately transferred to NADP⁺, reducing it to **NADPH**.

The **light reactions** are the light-powered half of photosynthesis. They run in the thylakoid membranes and grana and produce ATP and NADPH, which then power the production of organic molecules.

Trap. The light reactions need light. The Calvin cycle does not need light directly, but it needs the ATP and NADPH the light reactions make. In darkness the Calvin cycle stops because its supplies run out, not because light touches it directly.

The **electron transport chain** is a series of oxidation and reduction reactions that moves electrons and builds an electrochemical gradient of protons, hydrogen ions, across a membrane. In photosynthesis that membrane is the thylakoid membrane. The protons then flow back through **ATP synthase**, a membrane-bound enzyme. That flow is **chemiosmosis**, and it drives the formation of ATP from ADP and inorganic phosphate. When light powers this process, it is called **photophosphorylation**.

The **Calvin cycle** is the carbon fixation half of photosynthesis. It runs in the stroma and uses the ATP and NADPH from the light reactions to build carbohydrates from carbon dioxide. The CED is explicit about what you must memorize here. Memorizing the steps, structures, and enzyme names of the Calvin cycle beyond ATP synthase is beyond AP scope. Know the inputs, the outputs, and the location.

STAGE	LOCATION	INPUTS	OUTPUTS
Light reactions	Thylakoid membranes and grana	Light energy, water, NADP+, ADP	ATP, NADPH, oxygen
Calvin cycle	Stroma	Carbon dioxide, ATP, NADPH	Carbohydrates

3.5 Cellular Respiration

Cellular respiration is the process that uses energy from biological macromolecules to synthesize ATP. Respiration and fermentation are characteristic of all forms of life. **Aerobic cellular respiration** in eukaryotes is a series of coordinated enzyme-catalyzed reactions that capture energy from those macromolecules, using oxygen as the **terminal electron acceptor**.

It starts with **glycolysis** in the cytosol. Glycolysis releases the energy in glucose to form ATP from ADP and inorganic phosphate, plus NADH and **pyruvate**. Pyruvate is then transported from the cytosol into the mitochondrion, where oxidation continues.

Inside the **mitochondrial matrix**, the **Krebs cycle** takes over. It releases carbon dioxide from organic intermediates, synthesizes ATP, and transfers electrons to the coenzymes NAD⁺ and FAD, forming **NADH and FADH₂**. Those carriers deliver their electrons to the electron transport chain in the inner mitochondrial membrane.

The electron transport chain builds a proton gradient across the inner mitochondrial membrane, the same chemiosmosis principle as in the chloroplast. Protons flow back through ATP synthase, and that flow drives **oxidative phosphorylation**, the formation of ATP from ADP and inorganic phosphate during aerobic respiration. Oxygen waits at the end of the chain as the terminal electron acceptor. Anaerobic prokaryotes use other molecules in that role. The **folding of the inner mitochondrial membrane** into cristae increases its surface area, fitting in more electron transport chains and ATP synthase molecules so more ATP can be synthesized.

Trap. Oxygen does not directly make ATP. It accepts electrons at the end of the transport chain, which keeps the chain moving. Without oxygen the chain backs up, the gradient collapses, and oxidative phosphorylation stops.

When oxygen is absent, cells use **fermentation**. Fermentation lets glycolysis keep running without oxygen and produces organic molecules such as alcohol and lactic acid. It produces far less ATP than aerobic respiration because it skips the Krebs cycle and oxidative phosphorylation, but it keeps the cell alive when oxygen is missing.

One detail the CED keeps out of memorization range: **decoupling oxidative phosphorylation** from electron transport generates heat, which endothermic organisms can use to regulate body temperature. Know that it exists. Do not memorize its mechanism.

Confusions That Cost Points

Most missed questions in this unit come from a short list of pairs that look alike under time pressure. Review each pair carefully so you can tell them apart when you see them in a question.

PAIR	HOW TO SEPARATE THEM
Competitive vs noncompetitive inhibition	Competitive binds the active site. Noncompetitive binds an allosteric site. Location is the whole distinction.
Light reactions vs Calvin cycle	Light reactions run in the thylakoid membranes and need light, making ATP and NADPH. The Calvin cycle runs in the stroma and uses those products to fix carbon dioxide into carbohydrates.
Photophosphorylation vs oxidative phosphorylation	Both make ATP through chemiosmosis at ATP synthase. Photophosphorylation is light-driven in the chloroplast. Oxidative phosphorylation is driven by the breakdown of macromolecules in the mitochondrion.
NADPH vs NADH	NADPH carries electrons in photosynthesis. It is made in photosystem I for the Calvin cycle. NADH carries electrons in respiration. It is made in glycolysis and the Krebs cycle for the mitochondrial electron transport chain.
Thylakoid vs stroma	The thylakoid is the membrane system where the light reactions happen. The stroma is the fluid around it where the Calvin cycle happens. Membrane versus fluid.
Fermentation vs aerobic respiration	Fermentation runs without oxygen and keeps glycolysis going. Aerobic respiration uses oxygen as the terminal electron acceptor and produces far more ATP.
First law vs second law	The first law is conservation. Energy only changes form. The second law is disorder. Every transformation increases entropy.
Denaturation vs suboptimal conditions	Suboptimal temperature or pH slows an enzyme by disrupting hydrogen bonds. Denaturation breaks the structure down and the enzyme stops working. Slowed versus stopped.

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next page, so complete the questions before checking them.

- 1.** A researcher adds a molecule shaped like the substrate of an enzyme. The reaction rate falls, but raising the substrate concentration restores it. The added molecule is most likely
 - A. a noncompetitive inhibitor binding to an allosteric site
 - B. a molecule that denatures the enzyme
 - C. a competitive inhibitor binding to the active site
 - D. a second substrate for the same reaction

- 2.** An enzyme that breaks down lactose has no effect on maltose, a similar sugar. This specificity is best explained by the fact that
 - A. maltose has a higher activation energy than lactose
 - B. the active site shape and charge fit lactose but not maltose
 - C. the enzyme is denatured by maltose
 - D. lactose lowers the activation energy more than maltose does

- 3.** An enzyme works fastest at pH 7. At pH 2 its activity drops to zero, and restoring pH 7 does not bring the activity back. The best explanation is that
 - A. the enzyme was denatured by the acidic conditions
 - B. the substrate was used up at pH 2
 - C. a competitive inhibitor blocked the active site
 - D. the optimal pH of the enzyme shifted permanently to 2

- 4.** A cell couples the breakdown of ATP to the transport of a molecule against its concentration gradient. This is an example of
 - A. a violation of the first law of thermodynamics
 - B. entropy decreasing with no energy input
 - C. a metabolic pathway running in reverse
 - D. energy coupling

- 5.** A poison blocks the Calvin cycle but leaves the thylakoid membranes undamaged. In the light, the chloroplast will still produce
- A. carbohydrates
 - B. ATP and NADPH
 - C. carbon dioxide
 - D. glucose, but only in the stroma
- 6.** A chemical destroys the proton gradient across the thylakoid membrane without damaging ATP synthase itself. The direct result is that
- A. ATP production by photophosphorylation stops
 - B. the Calvin cycle speeds up to compensate
 - C. chlorophyll stops absorbing light energy
 - D. NADPH production increases
- 7.** Muscle cells produce lactic acid during intense exercise. The main benefit of this fermentation pathway is that it
- A. produces as much ATP as aerobic respiration
 - B. replaces the Krebs cycle permanently
 - C. allows glycolysis to continue in the absence of oxygen
 - D. uses oxygen as the terminal electron acceptor
- 8.** A poison blocks the transfer of electrons to oxygen at the end of the mitochondrial electron transport chain. Which process stops as a direct result?
- A. glycolysis, immediately and completely
 - B. the Calvin cycle
 - C. ATP synthesis by the Krebs cycle
 - D. oxidative phosphorylation

Answer Key

- 1. C.** The molecule competes for the active site, and extra substrate outcompetes it, which is the signature of competitive inhibition. A binds an allosteric site, and extra substrate would not restore the rate. B is wrong because denaturation is not reversed by adding substrate. D invents a role the scenario does not support.
- 2. B.** Specificity comes from the fit between substrate and active site. Shape and charge must be compatible, so a similar sugar that does not fit is ignored. A sounds scientific but does not explain why one sugar reacts and the other does not. C would stop all activity, not just maltose activity. D confuses who lowers the activation energy. The enzyme does, not the substrate.
- 3. A.** Activity lost at extreme pH and not regained when conditions return is denaturation, the breakdown of protein structure. B is the trap of blaming the substrate when the enzyme is the part that broke. C is wrong because inhibition is reversible and pH does not create an inhibitor. D misreads the situation. The enzyme did not adapt. It was destroyed.
- 4. D.** A reaction that releases energy driving one that requires energy is energy coupling. A is the trap. Nothing is created or destroyed here, so the first law holds. B describes something the second law forbids without energy input. C names a direction change that the scenario never mentions.
- 5. B.** The light reactions run in the thylakoid membranes, which are undamaged, so ATP and NADPH production continues in the light. A is the trap. Carbohydrates are the product of the blocked Calvin cycle. C reverses the direction of the pathway. D combines two errors. Glucose is a Calvin cycle product, and the stroma is where that blocked cycle runs.
- 6. A.** ATP synthase makes ATP only when protons flow through it down their gradient. No gradient means no flow and no ATP, even with the enzyme intact. B is the trap. The Calvin cycle depends on the ATP that just stopped, so it slows, not speeds. C confuses light capture with the gradient. Chlorophyll still absorbs light. D gets the mechanism backwards. NADPH production also depends on the electron transport that built the gradient.
- 7. C.** Fermentation exists to keep glycolysis running when oxygen is absent, producing alcohol or lactic acid as byproducts. A is the main trap. Fermentation yields far less ATP than aerobic respiration. B overstates a temporary backup as a replacement. D contradicts the definition. Fermentation is the pathway used when oxygen is not available.
- 8. D.** Oxygen is the terminal electron acceptor, so blocking that step backs up the chain, collapses the proton gradient, and stops oxidative phosphorylation. A is the trap. Glycolysis happens in the cytosol and does not need oxygen directly. B is the wrong organelle entirely. The Calvin cycle is in the chloroplast. C is wrong because the Krebs cycle synthesizes some ATP directly and does not depend on the electron transport chain.

When you check your answers, note which distinction each miss came from. Make a flashcard for that distinction and drill it spaced out over the next few days instead of rereading the whole section. If you missed one of these questions, the same distinction is worth practicing again in Rycal, where the Cellular Energetics deck has flashcards for it and more practice questions use the same kinds of traps.

One-Page Recall Check

Say each answer out loud before you look back, and mark the ones you cannot finish. Anything you cannot say out loud yet belongs in your flashcard deck. In Rycal, add those items to the Cellular Energetics deck and let spaced review bring them back over the next few days.

- Explain why an enzyme is specific to its substrate, using shape and charge.
- State what lowering activation energy does and what it does not change.
- Distinguish competitive from noncompetitive inhibition by where each inhibitor binds.
- Explain what happens to enzyme structure outside its optimal temperature or pH.
- State the first and second laws of thermodynamics in one sentence each.
- Explain energy coupling using ATP and a cellular work example.
- Describe what a metabolic pathway is and why cells break reactions into steps.
- Explain what conserved metabolic pathways suggest about the history of life.
- Name the three chloroplast structures and state what happens in each.
- Trace an electron from water through the photosystems to NADPH.
- Explain chemiosmosis in one sentence for the chloroplast and one for the mitochondrion.
- List the inputs and outputs of the light reactions and the Calvin cycle from memory.
- Walk through cellular respiration in order, naming the location of glycolysis, the Krebs cycle, and oxidative phosphorylation.
- Explain the role of oxygen as the terminal electron acceptor.
- State what fermentation accomplishes and what it produces.
- State what the CED excludes from memorization in this unit.

Where to go next. Turn every missed item above into flashcards and drill them spaced out over several days rather than in one sitting. In Rycal, open the Cellular Energetics deck under AP Biology. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Enzyme, activation energy, substrate, active site, enzyme-substrate complex, denaturation, optimal enzyme conditions, competitive inhibitor, noncompetitive inhibitor, allosteric site, first law of thermodynamics, second law of thermodynamics, energy coupling, metabolic pathway, conserved metabolic pathways, photosynthesis, stroma, thylakoid, granum, chlorophyll, photosystems I and II, light reactions, electron transport chain, ATP synthase, chemiosmosis, photophosphorylation, NADPH, Calvin cycle, cellular respiration, aerobic cellular respiration, glycolysis, pyruvate, Krebs cycle, mitochondrial matrix, NADH and FADH₂, terminal electron acceptor, oxidative phosphorylation, fermentation, decoupling oxidative phosphorylation, folding of the inner mitochondrial membrane, relative concentrations of substrates and products.

About this guide. Written for Rycal and aligned to the College Board AP Biology course framework, Unit 3, topics 3.1-3.5. All questions and explanations are original Rycal writing. Rycal is independent and is not affiliated with or endorsed by the College Board.