6 Pathways that Harvest and Store Chemical Energy

Chapter Outline

Plants use sunlight-driven photosynthesis to synthesize carbohydrates. The energy released from taking apart (catabolizing) these carbohydrates is a primary source of chemical energy for both plants and animals. A sequence of controlled enzyme-catalyzed pathways allows these catabolic chemical reactions to operate without causing excessive damage.

Some of the energy made available from the catabolism of carbohydrates and other fuel molecules drives the synthesis of adenosine triphosphate (ATP). Inside the cells, ATP molecules function as a form of energy currency; the hydrolysis of ATP, an exergonic reaction that yields adenosine diphosphate (ADP) and a phosphate ion, liberates a small amount of chemical energy, some of which activates the biochemical reactions needed in cells. This small energy transfer "nudges" biochemical reactions that support life.

The two primary means of maintaining ATP supplies are substrate-level phosphorylation and oxidative phosphorylation. In substrate phosphorylation, a phosphate group on an organic molecule is transferred to ADP, restoring it to ATP. This pathway makes ATP quickly, but phosphorylated organic molecules are present in only limited quantity in cells, so it is only a short-term solution to increased ATP demand. Oxidative phosphorylation, which bonds ADP to free phosphate ions in a process linked to the activity of the respiratory chain in mitochondria, makes a lot of ATP, but it requires continual access to oxygen and reduced coenzymes. The reduced coenzymes are NADH and $FADH_2$. The reduced coenzymes are continuously supplied by the ongoing catabolism of glucose and its metabolites via glycolysis and the citric-acid cycle, while oxygen molecules come from the environment.

Big Idea 1 recognizes that evolution ties together all parts of biology. Chapter 6 reviews energy transfers that are conserved across all categories of animals and plants. It also briefly considers the ways that agriculture and fermented beverages developed among early humans. The specific parts of the AP Biology curriculum that are covered in Chapter 6 include:

- **1.D.1:** There are several hypotheses about the natural origin of life on Earth, each with supporting scientific evidence.

Big Idea 2 focuses on free energy and the use of molecular building blocks that are fundamental to life processes. Specific parts of the AP Biology curriculum that are covered in Chapter 6 include:

- **2.A.1:** All living systems require constant input of free energy (e.g., the Calvin cycle, glycolysis, the Krebs cycle, and fermentation).
- **2.A.2:** Organisms capture and store free energy for use in biological processes (e.g., NADP in the reactions of photosynthesis and the importance of oxygen in cellular respiration).

Big Idea 4 states that biological systems interact in complex ways. Specific parts of the AP Biology curriculum that are covered in Chapter 6 include:

- **4.A.2:** The structure and function of subcellular components, and their interactions, provide essential cellular processes.
- **4.C.1:** Variation in molecular units provides cells with a wider range of functions (e.g.,the role of chlorophyll in photosynthesis).

Chapter Review

Concept 6.1 *introduces how ATP, reduced coenzymes, and chemiosmosis play important roles in biological energy metabolism. The energy needed for many biochemical reactions in cells is provided by the hydrolysis of ATP, yielding ADP and either phosphorylated proteins or inorganic phosphate (hydrogen phospahate; commonly abbreviated as* P_i*). As ATP is "used" in this way, it is also being continuously produced by two processes, substrate phosphorylation and oxidative phosphorylation.*

In substrate phosphorylation, phosphate groups on proteins and other molecules are transferred to ADP to quickly restore ATP supplies. Although substrate phosphorylation rapidly delivers ATP, the supply of phosphorylated substrates that can "give up" phosphate groups in this manner is limited.

In contrast, ATP production resulting from oxidative phosphorylation yields much more ATP, although oxidative phosphorylation requires more ingredients: oxygen, reduced coenzymes (NADH and $FADH_2$), and, of course, ADP and P_i. The mitochondrion is the intracellular organelle where most of the components of oxidative phosphorylation are found.

The catabolism of fuel molecules, such as glucose, supports both pathways of ATP production, yielding energy transfers that result in substrate phosphorylation and that produce the reduced coenzymes needed for oxidative phosphorylation. As NADH and $FADH_2$ are oxidized, this energy transfer develops a gradient of hydrogen ions (H^+) inside the mitochondrion. The gradient provides energy transfer to an enzyme, ATP synthase, accelerating its rate of binding ADP and P_i, thereby making ATP.

1. Discuss this statement: The hydrolysis of ATP to support an anabolic process includes both endergonic and exergonic reactions, depending on which perspective one takes: the hydrolysis of ATP or the formation of anabolic products.

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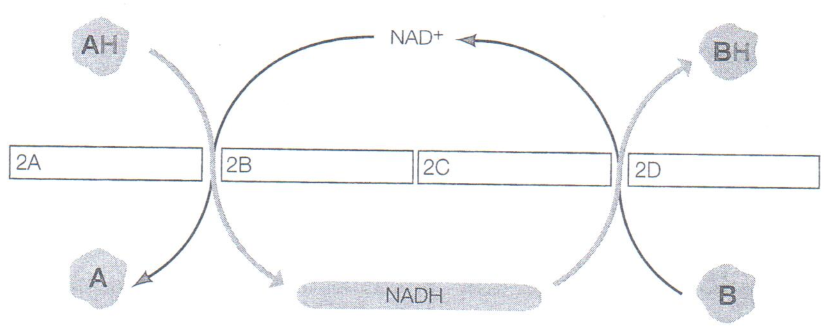
2. The diagram at the right shows the conversion of compound AH to compound A and the conversion of compound B to compound BH, with interconversions of NAD+ and NADH. To each of the four boxes, add either "oxidation" or "reduction." Explain your label choices.



a. Box 2A: ____

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b. Box 2B: ____

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c. Box 2C: ____

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d. Box 2D: ____

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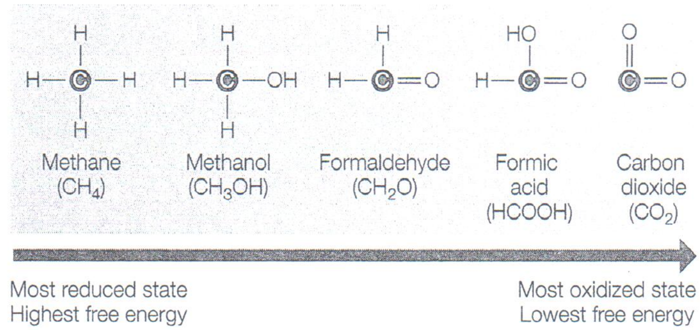
3. Use the figure to the right as a guide to answering the following questions regarding these molecules:

propanoic acid	propanol	propane
C_2H_5COOH	C_3H_7OH	C_3H_8



a. Which compound is in the most reduced state? ______________________

b. Which compound has the lowest free energy? ______________________

c. Which compound is in the most oxidized state? ______________________

d. Which compound has the highest free energy? ______________________

Concept 6.2 *describes how carbohydrate catabolism in the presence of oxygen releases a large amount of energy. In cellular respiration, the fuel molecule under consideration is usually glucose, a monosaccharide carbohydrate. The catabolic pathways are well studied:*

Glycolysis → Pyruvate oxidation → Citric acid (Krebs) cycle

Along the catabolic pathways, ATP is made directly by substrate phosphorylation. Reduced coenzymes are also produced, thus supporting oxidative phosphorylation, a process that generates considerably more ATP synthesis than does substrate phosphorylation.

4. Explain how the following two membrane-embedded proteins in mitochondria simultaneously influence the gradient of hydrogen ions and ATP synthesis.

a. Proton pump ______________________

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b. ATP synthase ______________________

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5. The complete catabolism of glucose can yield an energy transfer up to 686 kcal/mol. Indicate whether each of the following statements is true or false, then explain your answer.

a. All 686 kcal/mol is directly transferred to ATP synthesis.
TRUE FALSE [*choose one, then explain*]

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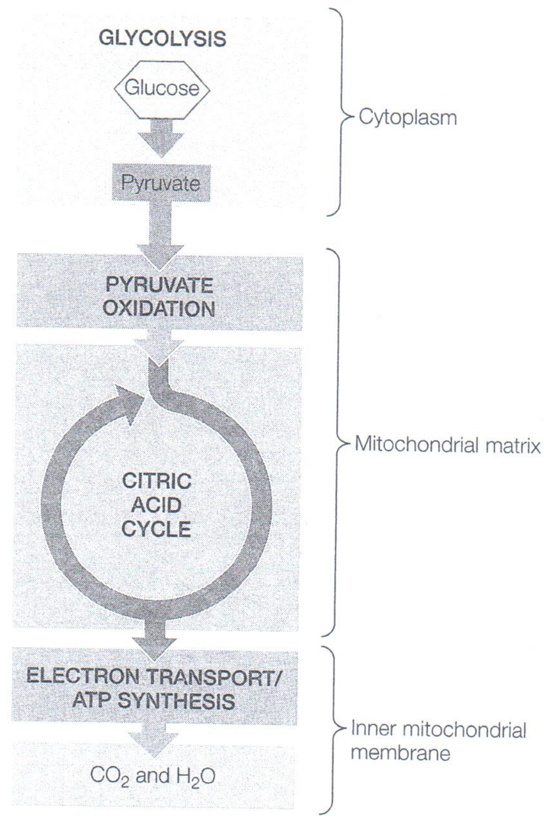
b. Less than half of the 686 kcal/mol is directly transferred to ATP synthesis.
TRUE FALSE [*choose one, then explain*]

c. Only 10% of the 686 kcal/mol is directly transferred to ATP synthesis, in accordance with the principles of thermodynamics.
TRUE FALSE [*choose one, then explain*]

6. Assume that the diagram at the right refers to the catabolism of one glucose molecule.

Draw arrows to show where NADH and $FADH_2$ are generated. Include the number of each produced. Then, add arrows to show where the reduced coenzymes participate in energy-transfer reactions.



7. Starting with *three* molecules of glucose, insert the appropriate numbers in the blanks below, assuming complete catabolism with oxygen available.

a. ________ molecules of ATP must be hydrolyzed to start the process.

b. ________ molecules of NADH are produced.

c. ________ molecules of $FADH_2$ are produced.

d. ________ molecules of ATP are produced via substrate phosphorylation.

e. ________ molecules of water are produced in the electron transport chain.

f. ________ molecules of carbon dioxide are released from the process.

Concept 6.3 *examines how carbohydrate catabolism in the absence of oxygen releases a small amount of energy. Organisms that live in conditions in which molecular oxygen is periodically unavailable or is never available use the process called fermentation to reoxidize NADH to NAD^+. Without NAD^+, glycolysis and all subsequent steps of catabolism come to a halt, and ATP production stops. Complex organisms like ourselves, as well as some microbes, produce lactic acid or lactate as a byproduct of fermentation, whereas yeasts and some plants produce an alcohol known as ethanol as a byproduct of fermentation.*

8. Lactic acid fermentation and alcoholic fermentation both result in alterations to three-carbon pyruvate molecules. Which of these two fermentation pathways converts pyruvate to the smaller catabolites? Provide specific details.

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Concept 6.4 *explains how catabolic and anabolic pathways are integrated. Changes in cellular activity and in the availability of fuel molecules occur frequently in nature. During lean times or under high metabolic activity, energy transfers occur by breaking down a variety of fuel molecules, allowing for the catabolism of proteins, fats, and carbohydrates. By contrast, in times of plenty, cellular reserves are restored through anabolism. For example, many types of smaller molecules can be converted to lipids. In addition, the storage-polymer of glucose, called glycogen, is synthesized in muscle and liver.*

9. Carbohydrates are not the only source of fuel molecules. Identify two additional pools of fuel molecules whose catabolism can yield energy transfers that result in ATP synthesis. For each of the two categories of fuel molecules you've identified, briefly describe how the molecules are utilized, and comment on any similarities to glucose catabolism.

a. Fuel-molecule pool 1: ______________________________

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b. Fuel-molecule pool 2: ______________________________

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10. Catabolism and anabolism are intrinsically linked together in your body. Describe what happens to quantities of each of the molecules below during times with plenty of access to food *and* during times with limited access to food.

a. Glucose ______________________________

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b. Lipids ______________________________

c. Proteins ______________________________

11. Cells of the brain and the heart are highly specialized to carry out specific functions in the body, and their metabolic needs must be met, or death will soon follow. Part of this specialization includes reliance on glucose as a key fuel molecule. Explain how glucose is made available to the brain and heart during times when carbohydrates are not readily available.

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Concept 6.5 *studies photosynthesis, and shows how light energy is converted to chemical energy. Most plants do not appear to eat, yet they grow. Until it became clear to scientists that plants take up carbon dioxide from the environment and use solar energy to fuel sugar synthesis, it was thought that most of their growth was fueled by things they take from the soil. During "light reactions" of photosynthesis, sunlight's energy activates chlorophyll molecules to capture light energy in the synthesis of ATP and NADPH. As these compounds accumulate, water molecules are catabolized, liberating hydrogen ions sufficient to build a chemiosmotic gradient similar to that in mitochondria. Molecular oxygen is a byproduct of photosynthesis. Energy released during ATP hydrolysis and the oxidation of NADPH drive the "Calvin cycle," in which carbohydrates such as glucose are made (see Concept 6.6).*

12. Photosystem I and photosystem II are directly activated by different wavelengths of photon energy. Describe each and discuss their interdependence.

a. Photosystem I: ______________________________

b. Photosystem II: ______________________________

Concept 6.6 *examines how photosynthetic organisms use chemical energy to convert CO_2 to carbohydrates. Carbon dioxide, ATP, and NADPH are the key requirements for the synthesis of sugars by plants. The light reactions of photosynthesis generate ATP and NADPH (Concept 6.5), and CO_2 is taken up from the environment, especially from the atmosphere, via the leaves of plants.*

13. Briefly describe each of the three major segments of the Calvin cycle, noting the key components needed in each segment.

14. Explain the claim that Rubisco (RuBP) is the most abundant protein on the planet, by describing its role in the Calvin cycle.

15. A student says that because plants can carry out photosynthesis, they do not need cellular respiration. His lab partner argues that photosynthesis without respiration is a wasted effort. Who is correct? Explain your answer.

Science Practices & Inquiry

In the AP Biology Curriculum Framework, there are seven **Science Practices**. In this chapter, we focus on **Science Practice 6:** The student can work with scientific explanations and theories. More specifically, we focus on **Practice 6.2:** The student can construct explanations of phenomena based on evidence produced through scientific practices.

Question 16 asks you to construct explanations of the mechanisms and structural features of cells that allow organisms to capture, store, or use free energy (**Learning Objective 2.5**) and to construct explanations based on scientific evidence as to how interactions of subcellular structures provide essential functions (**Learning Objective 4.5**).

16. In the absence of electron transport, an artificial H^+ gradient is sufficient for ATP synthesis in cellular organelles. In an experiment, chloroplasts were isolated from plant cells and incubated at pH 7. The chloroplasts were then subjected to six different conditions. They were incubated with ADP, phosphate (P_i), and magnesium ions (Mg^{2+}) at pH 7 and at pH 3.8. The chloroplasts were then incubated at pH 3.8 with one of the four components (ADP, P_i, Mg^{2+}, chloroplasts) missing.

ATP formation was measured using luciferase, which catalyzes the formation of a luminescent (light-emitting) molecule if ATP is present. Here are the data from the original paper:

a. Circle the control reaction in the table.

b. Use the control data to correct the raw data for the experimental reaction mixtures and complete the table.

Reaction #	Mixture Description	Luciferase activity (light emission)	
		Raw data	Corrected data
1	Complete, pH 3.8	141	
2	Complete, pH 7.0	12	
3	Complete, pH 3.8 – P_i	12	
4	Complete, pH 3.8 – ADP	4	
5	Complete, pH 3.8 – Mg^{2+}	60	
6	Complete, pH 3.8 – chloroplasts	7	

c. Summarize the results of the experiment. ____________________

d. Explain why ATP production dropped in the absence of P_i. ____________________

e. Explain why ATP production could be negative in this experiment. ____________________

f. Discuss where the free energy comes from to drive the production of ATP. ____________________