4.1 Chemical Energy and ATP

TEKS 4B, 9A

KEY CONCEPT All cells need chemical energy.

MAIN IDEAS
- The chemical energy used for most cell processes is carried by ATP.
- Organisms break down carbon-based molecules to produce ATP.
- A few types of organisms do not need sunlight and photosynthesis as a source of energy.

VOCABULARY

ATP
ADP
chemosynthesis

TEKS **4B** investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules and **9A** compare the structures and functions of different types of biomolecules, including carbohydrates, lipids, proteins, and nucleic acids.

Connect to Your World

The cells of all organisms—from algae to whales to people—need chemical energy for all of their processes. Some organisms, such as diatoms and plants, absorb energy from sunlight. Some of that energy is stored in sugars. Cells break down sugars to produce usable chemical energy for their functions. Without organisms that make sugars, living things on Earth could not survive.

MAIN IDEA **TEKS** 4B

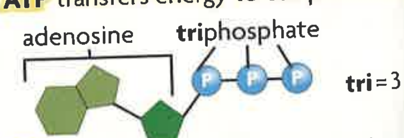
The chemical energy used for most cell processes is carried by ATP.

Sometimes you may feel that you need energy, so you eat food that contains sugar. Does food, which contains sugar and other carbon-based molecules, give you energy? The answer to this question is yes and no. All of the carbon-based molecules in food store chemical energy in their bonds. Carbohydrates and lipids are the most important energy sources in foods you eat. However, this energy is only usable after these molecules are broken down by a series of chemical reactions. Your energy does come from food, but not directly.

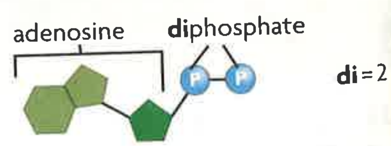
All cells, like that in **FIGURE 1.1**, use chemical energy carried by ATP—adenosine triphosphate. **ATP** is a molecule that transfers energy from the breakdown of food molecules to cell processes. You can think of ATP as a wallet filled with money. Just as a wallet carries money that you can spend, ATP carries chemical energy that cells can use. Cells use ATP for functions such as building molecules and moving materials by active transport.

VISUAL VOCAB

ATP transfers energy to cell processes.



ADP is a lower-energy molecule that can be converted into ATP.



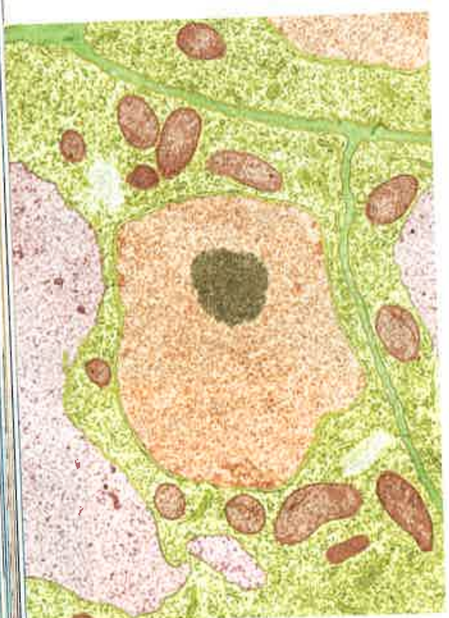
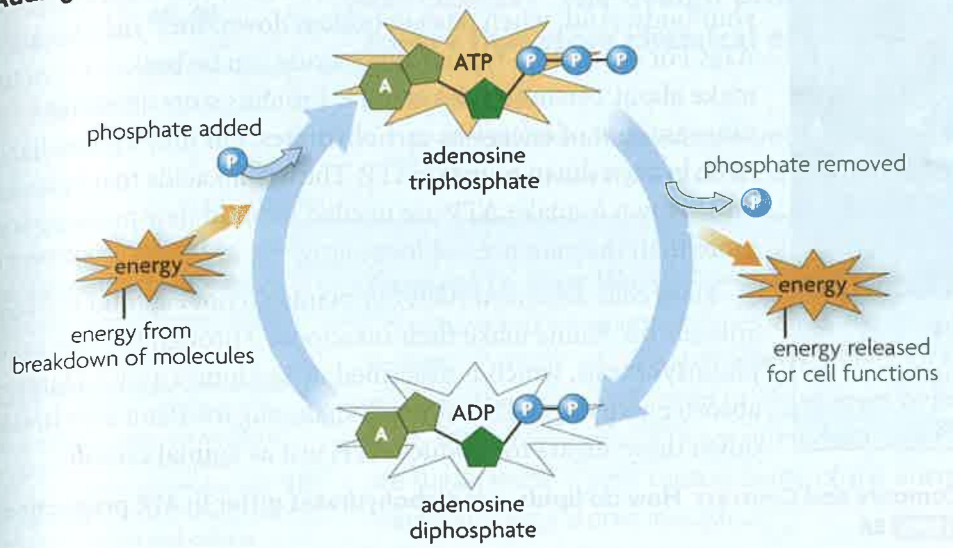


FIGURE 1.1 All cells, including plant cells, use ATP for energy. (colored TEM; magnification 9000×)

The energy carried by ATP is released when a phosphate group is removed from the molecule. ATP has three phosphate groups, but the bond holding the third phosphate group is unstable and is very easily broken. The removal of the third phosphate group usually involves a reaction that releases energy.

FIGURE 1.2 ATP and ADP

Adding a phosphate group to ADP forms ATP.



Infer **Where are molecules from food involved in the cycle?**

When the phosphate is removed, energy is released and ATP becomes ADP—adenosine diphosphate. **ADP** is a lower-energy molecule that can be converted into ATP by the addition of a phosphate group. If ATP is a wallet filled with money, ADP is a nearly empty wallet. The breakdown of ATP to ADP and the production of ATP from ADP can be represented by the cycle shown in **FIGURE 1.2.** However, adding a phosphate group to ADP to make ATP is not a simple process. A large, complex group of proteins is needed to do it. In fact, if just one of these proteins is faulty, ATP is not produced.

Synthesize **Describe the relationship between energy stored in food and ATP.**
TEKS 4B

> **CONNECT TO**
> **BIOCHEMISTRY**
> As you learned in the chapter **Chemistry of Life,** carbon-based molecules in living things—carbohydrates, lipids, proteins, and nucleic acids—have different structures and functions.

MAIN IDEA **TEKS 4B, 9A**

Organisms break down carbon-based molecules to produce ATP.

Foods that you eat do not contain ATP that your cells can use. First, the food must be digested. One function of digestion is to break down food into smaller molecules that can be used to make ATP. You probably know that different foods have different amounts of calories, which are measures of energy. Different foods also provide different amounts of ATP. The number of ATP molecules that are made from the breakdown of food is related to the number of calories in food, but not directly.

The number of ATP molecules produced depends on the type of molecule that is broken down—carbohydrate, lipid, or protein. Carbohydrates are not stored in large amounts in your body, but they are the molecules most commonly broken down to make ATP. The breakdown of the simple sugar glucose yields about 36 molecules of ATP.

> **READING TOOLBOX**
> **TAKING NOTES**
> Use a supporting main ideas chart to organize concepts related to chemical energy.
>
> All cells need chemical energy.
> → ATP carries energy.
> →
> →

FIGURE 1.3 FOOD AND ENERGY

MOLECULE	ENERGY
Carbohydrate	4 calories per mg
Lipid	9 calories per mg
Protein	4 calories per mg

You might be surprised to learn that carbohydrates do not provide the largest amount of ATP. Lipids store the most energy, as **FIGURE 1.3** shows. In fact, fats store about 80% of the energy in your body. And, when fats are broken down, they yield the most ATP. For example, a typical triglyceride can be broken down to make about 146 molecules of ATP. Proteins store about the same amount of energy as carbohydrates, but they are less likely to be broken down to make ATP. The amino acids that cells can break down to make ATP are needed to build new proteins more than they are needed for energy.

Plant cells also need ATP, but plants do not eat food the way animals do. Plants make their own food. Through the process of photosynthesis, which is described in Sections 2 and 3, plants absorb energy from sunlight and make sugars. Plant cells break down these sugars to produce ATP, just as animal cells do.

Compare and Contrast **How do lipids and carbohydrates differ in ATP production?** TEKS 9A

MAIN IDEA TEKS 4B

A few types of organisms do not need sunlight and photosynthesis as a source of energy.

Most, but not all, organisms rely directly or indirectly on sunlight and photosynthesis as their source of chemical energy. In places that never get sunlight, such as in the deep ocean, there are areas with living things. Some organisms live in very hot water near cracks in the ocean floor called hydrothermal vents. These vents release chemical compounds, such as sulfides, that can serve as an energy source. **Chemosynthesis** (KEE-mo-SIHN-thih-sihs) is a process by which some organisms use chemical energy to make energy-storing carbon-based molecules. These organisms still need ATP for energy. The processes that make their ATP are very similar to those in other organisms. Like plants, chemosynthetic organisms make their own food, but the raw materials differ.

Compare **How are chemosynthetic organisms and plants similar as energy sources?**

4.1 Formative Assessment

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REVIEWING MAIN IDEAS

1. How are **ATP** and **ADP** related? TEKS 4B
2. What types of molecules are broken down to make ATP? TEKS 4B, 9A
3. How are some organisms able to survive without sunlight and photosynthesis? TEKS 4B

CRITICAL THINKING

4. **Apply** Describe how you get energy indirectly from the food that you eat. TEKS 4B
5. **Compare and Contrast** How are the energy needs of plant cells similar to those of animal cells? How are they different?

CONNECT TO CHEMICAL REACTIONS

6. A water molecule is added to an ATP molecule to break ATP down into ADP and a phosphate group. Write the chemical equation for this reaction. TEKS 4B

4.2 Overview of Photosynthesis

TEKS 4B, 9B

KEY CONCEPT **The overall process of photosynthesis produces sugars that store chemical energy.**

MAIN IDEAS

- Photosynthetic organisms are producers.
- Photosynthesis in plants occurs in chloroplasts.

VOCABULARY

photosynthesis
chlorophyll
thylakoid
light-dependent reactions
light-independent reactions

TEKS **4B** investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules and **9B** compare the reactants and products of photosynthesis and cellular respiration in terms of energy and matter

Connect to Your World

Solar-powered calculators, homes, and cars are just a few things that use energy from sunlight. In a way, you are also solar-powered. Of course, sunlight does not directly give you the energy you need to play a sport or read this page. That energy comes from ATP. Molecules of ATP are often made from the breakdown of sugars, but how are sugars made? Plants capture some of the energy in sunlight and change it into chemical energy stored in sugars.

MAIN IDEA **TEKS** 4B, 9B

Photosynthetic organisms are producers.

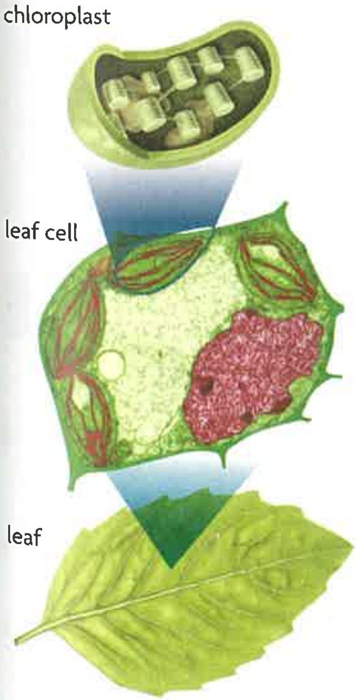
Some organisms are called producers because they produce the source of chemical energy for themselves and for other organisms. Plants, as well as some bacteria and protists, are the producers that are the main sources of chemical energy for most organisms on Earth. Certainly, animals that eat only plants obtain their chemical energy directly from plants. Animals that eat other animals, and bacteria and fungi that decompose other organisms, get their chemical energy indirectly from plants. When a wolf eats a rabbit, the tissues of the rabbit provide the wolf with a source of chemical energy. The rabbit's tissues are built from its food source—the sugars and other carbon-based molecules in plants. These sugars are made through photosynthesis.

Photosynthesis is a process that captures energy from sunlight to make sugars that store chemical energy. Therefore, directly or indirectly, the energy for almost all organisms begins as sunlight. Sunlight includes a wide range of radiant energy, such as ultraviolet radiation, microwaves, and the visible light that lets you see. Plants absorb visible light for photosynthesis. Visible light appears white, but it is made up of several colors, or wavelengths, of light.

Chlorophyll (KLAWR-uh-fihl) is a molecule in chloroplasts, shown in **FIGURE 2.1**, that absorbs some of the energy in visible light. Plants have two main types of chlorophyll, called chlorophyll *a* and chlorophyll *b*. Together, these two types of chlorophyll absorb mostly red and blue wavelengths of visible light. Neither type absorbs much green light. Plants have other light-absorbing molecules that absorb green light, but there are fewer of these molecules. As a result, the green color of plants comes from the reflection of light's green wavelengths by chlorophyll.

Apply **Describe the importance of producers and photosynthesis.**

FIGURE 2.1 Chloroplasts in plant cells contain a light-absorbing molecule called chlorophyll. (leaf cell: colored TEM; magnification 4000×)



MAIN IDEA TEKS 4B, 9B

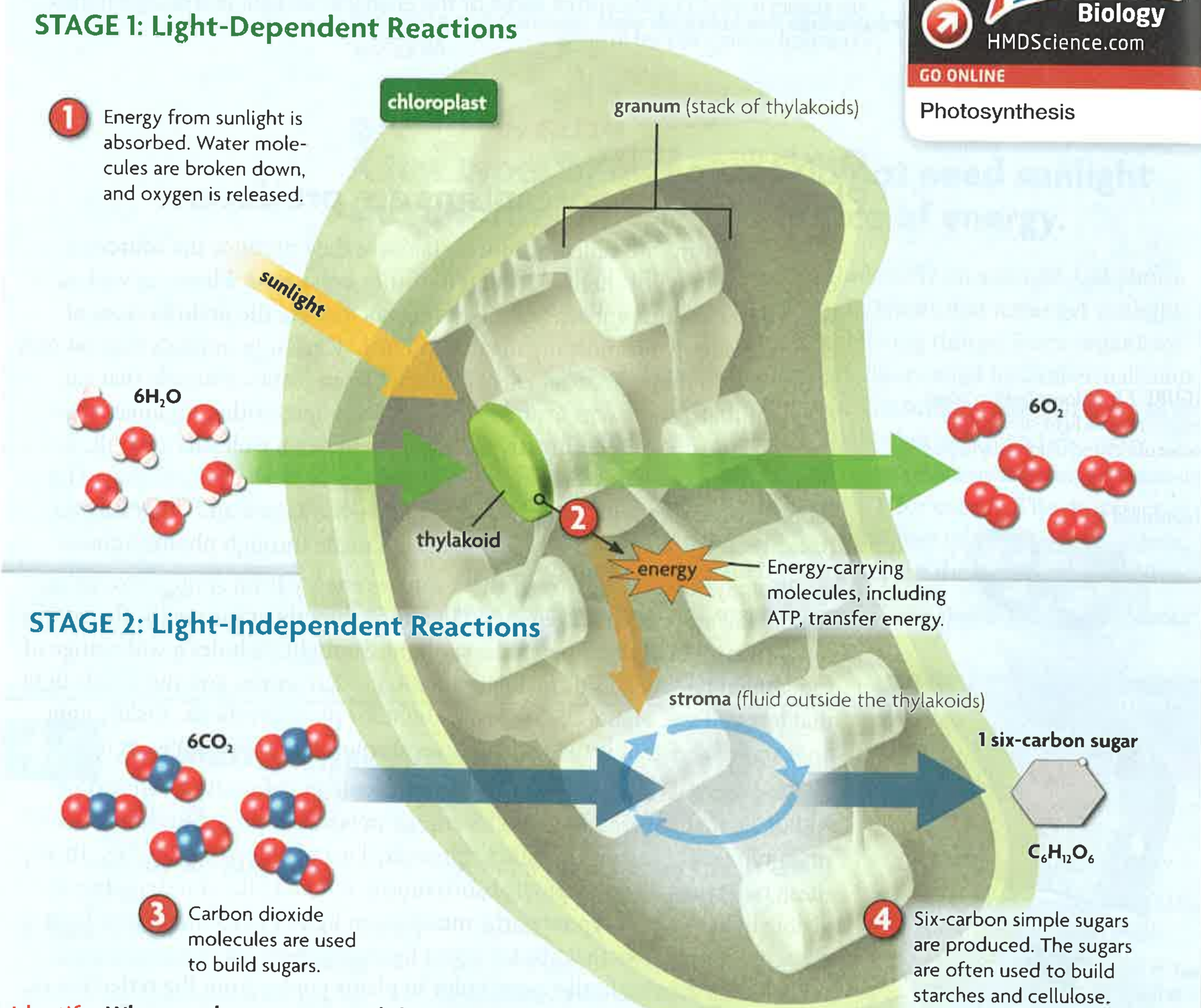
Photosynthesis in plants occurs in chloroplasts.

Chloroplasts are the membrane-bound organelles where photosynthesis takes place in plants. Most of the chloroplasts are in leaf cells that are specialized for photosynthesis, which has two main stages as shown in **FIGURE 2.2.** The two main parts of chloroplasts needed for photosynthesis are the grana and the stroma. Grana (singular, *granum*) are stacks of coin-shaped, membrane-enclosed compartments called **thylakoids** (THY-luh-KOYDZ). The membranes of the thylakoids contain chlorophyll, other light-absorbing molecules, and proteins. The stroma is the fluid that surrounds the grana inside a chloroplast.

FIGURE 2.2 Photosynthesis Overview

Chloroplasts absorb energy from sunlight and produce sugars through the process of photosynthesis.

Animated Biology HMDScience.com GO ONLINE Photosynthesis



Identify **What are the reactants and the products in photosynthesis?** TEKS 4B, 9B

The **light-dependent reactions** capture energy from sunlight. These reactions take place within and across the membrane of the thylakoids. Water (H_2O) and sunlight are needed for this stage of photosynthesis.

1. Chlorophyll absorbs energy from sunlight. The energy is transferred along the thylakoid membrane. Water molecules (H_2O) are broken down. Oxygen molecules (O_2) are released.
2. Energy carried along the thylakoid membrane is transferred to molecules that carry energy, such as ATP.

The **light-independent reactions** use energy from the light-dependent reactions to make sugars. These reactions occur in the stroma of chloroplasts. Carbon dioxide molecules (CO_2) are needed during this stage of photosynthesis.

3. CO_2 is added to a cycle of chemical reactions to build larger molecules. Energy from the light-dependent reactions is used in the reactions.
4. A molecule of a simple sugar is formed. The sugar, usually glucose ($C_6H_{12}O_6$), stores some of the energy that was captured from sunlight.

The equation for the whole photosynthesis process is shown below. As you can see, there are many arrows between the reactants—CO_2 and H_2O—and the products—a six-carbon sugar and O_2. Those arrows tell you that photosynthesis has many steps. For example, the light-independent reactions need only one molecule of CO_2 at a time, and the six-carbon sugar comes from a reaction that combines two three-carbon sugars. Also, enzymes and other chemicals are needed, not just light, carbon dioxide, and water.

$$\underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} \xrightarrow{} \xrightarrow{} \xrightarrow{} \underset{\text{light, enzymes}}{\xrightarrow{}} \xrightarrow{} \xrightarrow{} \underset{\text{a sugar}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2}$$

Glucose and other simple sugars, such as fructose, are not the only carbohydrates that come from photosynthesis. Plants need the simple sugars to build starch and cellulose molecules. In effect, plants need photosynthesis for their growth and development. You will learn more about the importance of another product of photosynthesis—oxygen—in Sections 4 and 5.

Summarize **How is energy from sunlight used to make sugar molecules?** TEKS **4B, 9B**

CONNECT TO

CALVIN CYCLE

The light-independent reactions include a series of chemical reactions called the Calvin cycle. You can read more about the Calvin cycle in **Section 3.**

4.2 Formative Assessment

REVIEWING MAIN IDEAS

1. What are the roles of chloroplasts and **chlorophyll** in **photosynthesis**?
2. Describe the stages of photosynthesis. Use the terms **thylakoid, light-dependent reactions,** and **light-independent reactions** in your answer. TEKS **4B, 9B**

CRITICAL THINKING

3. **Apply** Suppose you wanted to develop a light to help increase plant growth. What characteristics should the light have? Why?
4. **Analyze** Explain why photosynthesis is important for building the structure of plant cells. TEKS **4B**

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CONNECT TO

CHEMICAL REACTIONS

5. Overall, do you think photosynthesis is endothermic or exothermic? Explain your answer. TEKS **4B**

4.3 Photosynthesis in Detail

TEKS 4B, 9B

VOCABULARY

photosystem
electron transport chain
ATP synthase
Calvin cycle

KEY CONCEPT **Photosynthesis requires a series of chemical reactions.**

MAIN IDEAS

- The first stage of photosynthesis captures and transfers energy.
- The second stage of photosynthesis uses energy from the first stage to make sugars.

TEKS 4B investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules and **9B** compare the reactants and products of photosynthesis and cellular respiration in terms of energy and matter

Connect to Your World

In a way, the sugar-producing cells in leaves are like tiny factories with assembly lines. In a factory, different workers with separate jobs have to work together to put together a finished product. Similarly, in photosynthesis many different chemical reactions, enzymes, and ions work together in a precise order to make the sugars that are the finished product.

MAIN IDEA **TEKS** 4B, 9B

The first stage of photosynthesis captures and transfers energy.

In Section 2, you read a summary of photosynthesis. However, the process is much more involved than that general description might suggest. For example, during the light-dependent reactions, light energy is captured and transferred in the thylakoid membranes by two groups of molecules called **photosystems.** The two photosystems are called photosystem I and photosystem II.

Overview of the Light-Dependent Reactions

The light-dependent reactions are the *photo-* part of photosynthesis. During the light-dependent reactions, chlorophyll and other light-absorbing molecules capture energy from sunlight. Water molecules are broken down into hydrogen ions, electrons, and oxygen gas. The oxygen is given off as a waste product. Sugars are not made during this part of photosynthesis.

FIGURE 3.1 The light-dependent reactions capture energy from sunlight and transfer energy through electrons. The solar cells that power a solar car do the same thing.

The main functions of the light-dependent reactions are to capture and transfer energy. In these reactions, as in the solar car in **FIGURE 3.1,** energy is transferred to electrons. The electrons are only used for energy in a few specific processes. Recall a time when you went to an amusement park. To go on rides, you needed special tickets that could be used only there. Similarly, the electrons are used for energy during photosynthesis but not for the cell's general energy needs.

Energy from the electrons is used to make molecules that act as energy carriers. These energy carriers are ATP and another molecule called NADPH. The ATP from the light-dependent reactions is usually not used for a cell's general energy needs. In this case, ATP molecules, along with NADPH molecules, go on to later stages of photosynthesis.

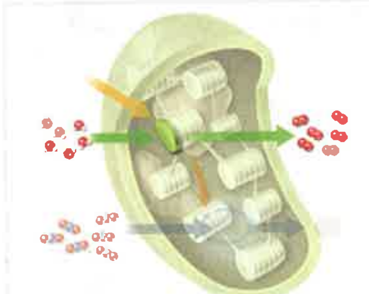
Photosystem II and Electron Transport

In photosystem II, chlorophyll and other light-absorbing molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons. As shown in **FIGURE 3.2**, photosystem II needs water to function.

1. **Energy absorbed from sunlight** Chlorophyll and other light-absorbing molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons (e^-). High-energy electrons leave the chlorophyll and enter an **electron transport chain**, which is a series of proteins in the membrane of the thylakoid.
2. **Water molecules split** Enzymes break down water molecules. Oxygen, hydrogen ions (H^+), and electrons are separated from each other. The oxygen is released as waste. The electrons from water replace those electrons that left chlorophyll when energy from sunlight was absorbed.
3. **Hydrogen ions transported** Electrons move from protein to protein in the electron transport chain. Their energy is used to pump H^+ ions from outside to inside the thylakoid against a concentration gradient. The H^+ ions build up inside the thylakoid. Electrons move on to photosystem I.

Photosystem I and Energy-Carrying Molecules

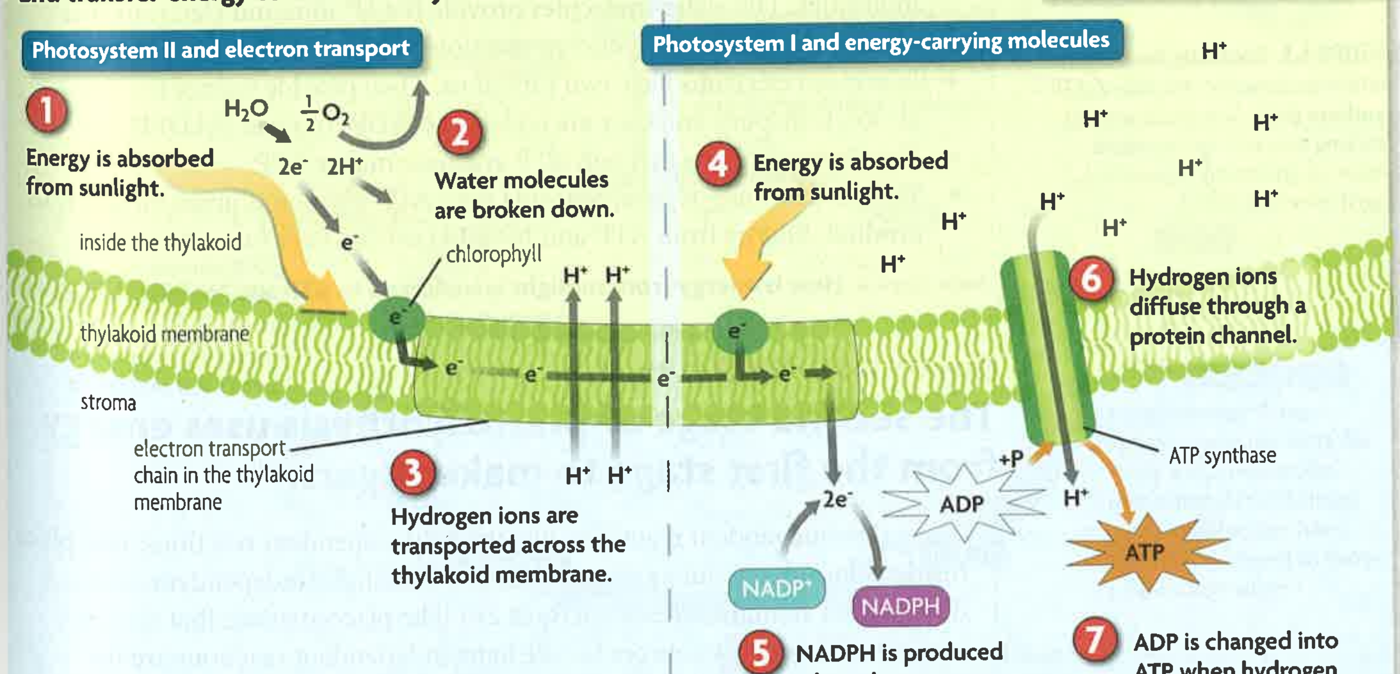
In photosystem I, chlorophyll and other light-absorbing molecules in the thylakoid membrane also absorb energy from sunlight. The energy is added to electrons, some of which enter photosystem I from photosystem II.



Light-dependent reactions take place in and across the thylakoid membrane.

FIGURE 3.2 Light-Dependent Reactions

Photosystems II and I absorb energy from sunlight and transfer energy to the Calvin cycle.



Identify **At what two points in the process are electrons used in the transfer of energy?** TEKS 4B

4 **Energy absorbed from sunlight** As in photosystem II, chlorophyll and other light-absorbing molecules inside the thylakoid membrane absorb energy from sunlight. Electrons are energized and leave the molecules.

5 **NADPH produced** The energized electrons are added to a molecule called $NADP^+$, forming a molecule called NADPH. In photosynthesis, $NADP^+$ functions like ADP, and NADPH functions like ATP. The molecules of NADPH go to the light-independent reactions.

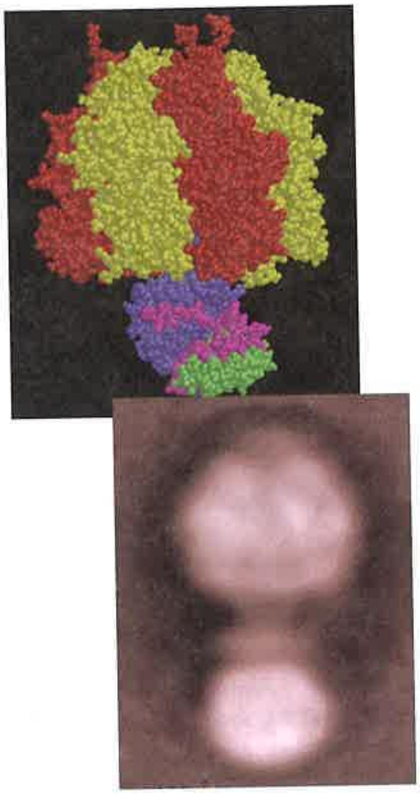


FIGURE 3.3 Scientists have made detailed computer models of ATP synthase (top). Scientists are still working on viewing the actual molecule (bottom). (colored TEM; magnification 1,800,000×)

ATP Production

The final part of the light-dependent reactions makes ATP. The production of ATP depends on the H^+ ions that build up inside the thylakoid from photosystem II, and on a complex enzyme in the thylakoid membrane.

6 **Hydrogen ion diffusion** Hydrogen ions flow through a protein channel in the thylakoid membrane. Recall that the concentration of H^+ ions is higher inside the thylakoid than it is outside. This difference in H^+ ion concentration is called a chemiosmotic gradient, which stores potential energy. Therefore, the ions flow through the channel by diffusion.

7 **ATP produced** The protein channel in Step 6 is part of a complex enzyme called **ATP synthase,** shown in **FIGURE 3.3.** As the ions flow through the channel, ATP synthase makes ATP by adding phosphate groups to ADP.

Summary of the Light-Dependent Reactions

- Energy is captured from sunlight by light-absorbing molecules. The energy is transferred to electrons that enter an electron transport chain.
- Water molecules are broken down into H^+ ions, electrons, and oxygen molecules. The water molecules provide the H^+ ions and electrons that are used in the light-dependent reactions.
- Energized electrons have two functions. They provide energy for H^+ ion transport, and they are added to $NADP^+$ to form NADPH.
- The flow of H^+ ions through ATP synthase makes ATP.
- The products are oxygen, NADPH, and ATP. Oxygen is given off as a waste product. Energy from ATP and NADPH is used later to make sugars.

Summarize How is energy from sunlight transferred to ATP and NADPH? TEKS 4B

MAIN IDEA TEKS 4B, 9B

The second stage of photosynthesis uses energy from the first stage to make sugars.

The light-independent reactions, like the light-dependent reactions, take place inside chloroplasts. But as the name implies, the light-independent reactions do not need sunlight. These reactions can take place anytime that energy is available. The energy sources for the light-independent reactions are the molecules of ATP and NADPH formed during the light-dependent reactions. The energy is needed for a series of chemical reactions called the Calvin cycle, which is named for the scientist who discovered the process.

The Calvin Cycle

The Calvin cycle cannot take place without the ATP and NADPH from the light-dependent reactions. The chemical reactions of the **Calvin cycle** use carbon dioxide (CO_2) gas from the atmosphere and the energy carried by ATP and NADPH to make simple sugars. Because the light-independent reactions build sugar molecules, they are the *synthesis* part of photosynthesis. Only one molecule of CO_2 is actually added to the Calvin cycle at a time. The simplified cycle in **FIGURE 3.4** shows three CO_2 molecules added at once.

1. **Carbon dioxide added** CO_2 molecules are added to five-carbon molecules already in the Calvin cycle. Six-carbon molecules are formed.
2. **Three-carbon molecules formed** Energy—ATP and NADPH—from the light-dependent reactions is used by enzymes to split the six-carbon molecules. Three-carbon molecules are formed and rearranged.
3. **Three-carbon molecules exit** Most of the three-carbon molecules stay in the Calvin cycle, but one high-energy three-carbon molecule leaves the cycle. After two three-carbon molecules have left the cycle, they are bonded together to build a six-carbon sugar molecule such as glucose.
4. **Three-carbon molecules recycled** Energy from ATP molecules is used to change the three-carbon molecules back into five-carbon molecules. The five-carbon molecules stay in the Calvin cycle. These molecules are added to new CO_2 molecules that enter the cycle.

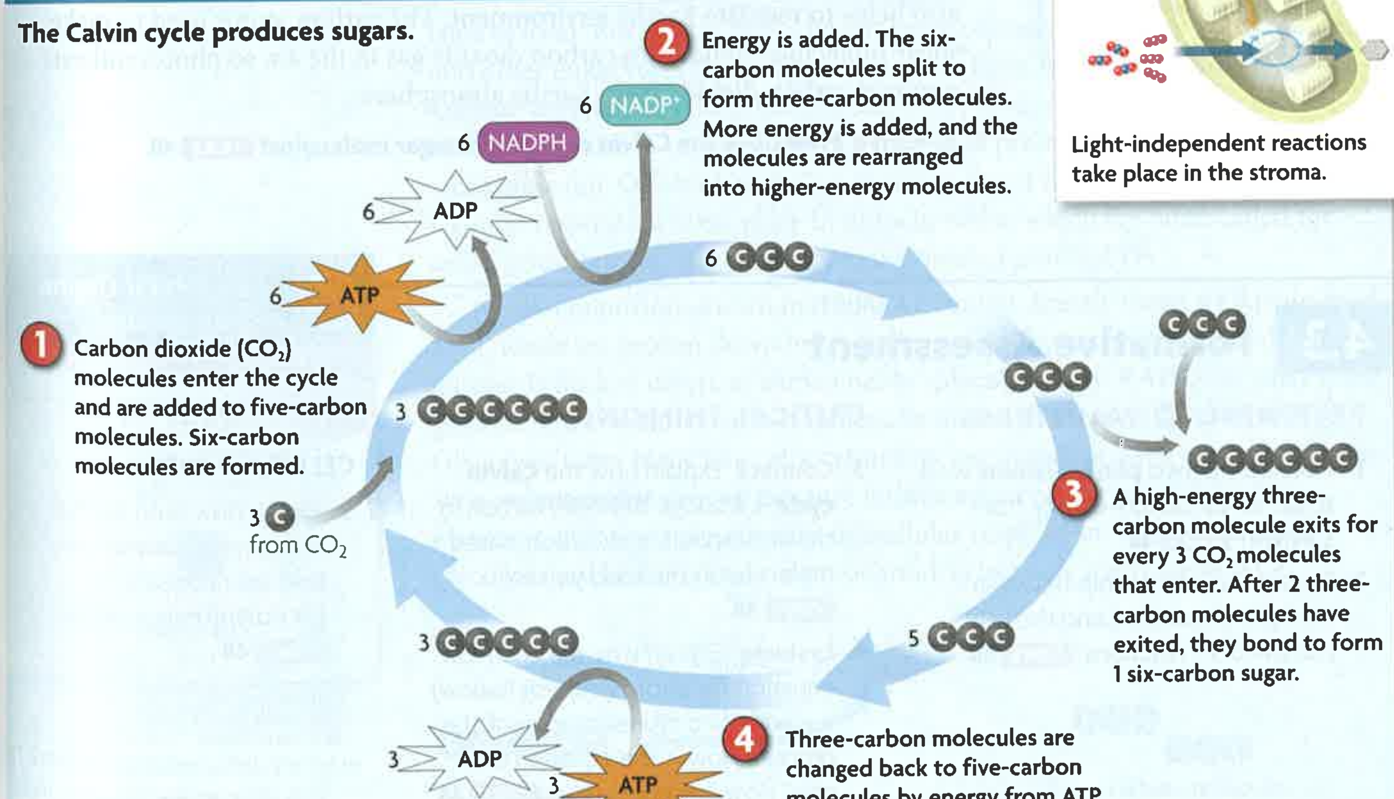
READING TOOLBOX

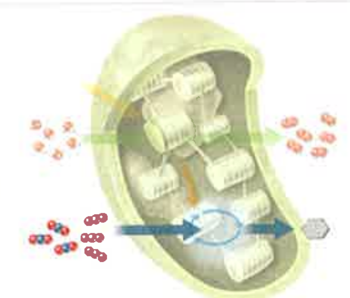
VOCABULARY

The light-dependent reactions are the *photo-* part of photosynthesis. The light-independent reactions are the *synthesis* part of photosynthesis.

FIGURE 3.4 Light-Independent Reactions (Calvin Cycle)

The Calvin cycle produces sugars.





Light-independent reactions take place in the stroma.

Infer Why must the Calvin cycle occur more than once to build a sugar molecule?

READING TOOLBOX

LARY
pendent reactions
part of
e light-
s are the

mary of the Light-Independent Reactions

arbon dioxide enters the Calvin cycle.
TP and NADPH from the light-dependent reactions transfer energy to
ie Calvin cycle and keep the cycle going.
ne high-energy three-carbon molecule is made for every three molecules
f carbon dioxide that enter the cycle.
wo high-energy three-carbon molecules are bonded together to make a
ugar. Therefore, six molecules of carbon dioxide must be added to the
alvin cycle to make one six-carbon sugar.
he products are a six-carbon sugar such as glucose, $NADP^+$, and ADP.
he $NADP^+$ and ADP molecules return to the light-dependent reactions.

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CONNECT TO
ECOLOGY
Photosynthesis is a major part of the carbon cycle. You will learn more about the carbon cycle in the chapter **Principles of Ecology.**

Functions of Photosynthesis

Photosynthesis is much more than just a biochemical process. Photosynthesis is important to most organisms on Earth, as well as to Earth's environment. Recall that plants produce food for themselves and for other organisms through photosynthesis. Both plant cells and animal cells release the energy stored in sugars through cellular respiration. Cellular respiration, which uses the oxygen that is a waste product of photosynthesis, is the process that makes most of the ATP used by plant and animal cells.

Photosynthesis does more than make sugars. It also provides materials for plant growth and development. The simple sugars from photosynthesis are bonded together to form complex carbohydrates such as starch and cellulose. Starches store sugars until they are needed for energy. Cellulose is a major part of plant structure—it is the building block of plant cell walls. Photosynthesis also helps to regulate Earth's environment. The carbon atoms used to make sugar molecules come from carbon dioxide gas in the air, so photosynthesis removes carbon dioxide from Earth's atmosphere.

Summarize **How does the Calvin cycle build sugar molecules?** TEKS 4B

4.3 Formative Assessment

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REVIEWING MAIN IDEAS

1. How do the two **photosystems** work together to capture energy from sunlight? TEKS 4B
2. Explain the relationship between the light-dependent and the light-independent reactions. TEKS 4B

CRITICAL THINKING

3. **Connect** Explain how the **Calvin cycle** is a bridge between carbon in the atmosphere and carbon-based molecules in the food you eat. TEKS 4B
4. **Evaluate** Explain why the chemical equation for photosynthesis (below) is a simplified representation of the process. How is the equation accurate? How is it inaccurate? TEKS 4B
$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$

CONNECT TO
CELL FUNCTIONS

5. Explain how both passive transport and active transport are necessary for photosynthesis to occur. TEKS 4B

4.4 Overview of Cellular Respiration

TEKS 4B, 9B

KEY CONCEPT **The overall process of cellular respiration converts sugar into ATP using oxygen.**

MAIN IDEAS
- Cellular respiration makes ATP by breaking down sugars.
- Cellular respiration is like a mirror image of photosynthesis.

VOCABULARY
- cellular respiration
- aerobic
- glycolysis
- anaerobic
- Krebs cycle

TEKS **4B** investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules and **9B** compare the reactants and products of photosynthesis and cellular respiration in terms of energy and matter

Connect to Your World

The term *cellular respiration* may lead you to form a mental picture of cells breathing. This image is not correct, but it is useful to remember. Your cells need the oxygen that you take in when you breathe. That oxygen helps your body release the energy in sugars and other carbon-based molecules. Indirectly, your breathing is connected to the ATP that your cells need for everything you do.

MAIN IDEA TEKS 4B

Cellular respiration makes ATP by breaking down sugars.

Plants use photosynthesis to make their own food. Animals eat other organisms as food. But food is not a direct source of energy. Instead, plants, animals, and other eukaryotes break down molecules from food to produce ATP. **Cellular respiration** releases chemical energy from sugars and other carbon-based molecules to make ATP when oxygen is present. Cellular respiration is an **aerobic** (air-OH-bihk) process, meaning that it needs oxygen to take place. Cellular respiration takes place in mitochondria, which are often called the cell's "powerhouses" because they make most of a cell's ATP.

A mitochondrion, shown in **FIGURE 4.1**, cannot directly make ATP from food. First, foods are broken down into smaller molecules such as glucose. Then, glucose is broken down, as shown below. **Glycolysis** (gly-KAHL-uh-sihs) splits glucose into two three-carbon molecules and makes two molecules of ATP. Glycolysis takes place in a cell's cytoplasm and does not need oxygen. Glycolysis is an **anaerobic** process because it does not need oxygen to take place. However, glycolysis is necessary for cellular respiration. The products of glycolysis are broken down in mitochondria to make many more ATP.

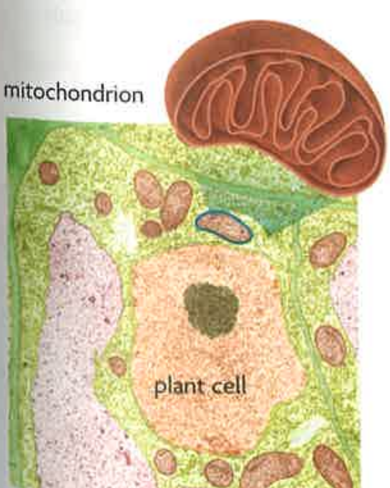

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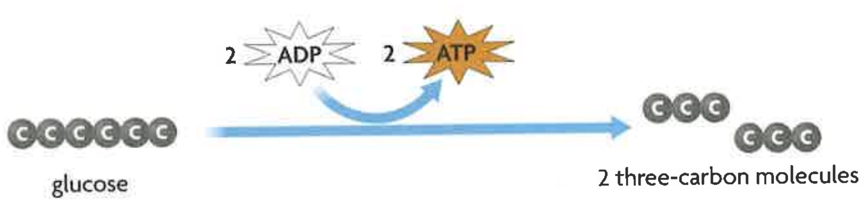
FIGURE 4.1 Mitochondria, found in both plant and animal cells, produce ATP through cellular respiration. (colored TEM; magnification 7000×)



Explain What is the function of cellular respiration? TEKS 4B

MAIN IDEA TEKS 4B, 9B

Cellular respiration is like a mirror image of photosynthesis.

CONNECT TO

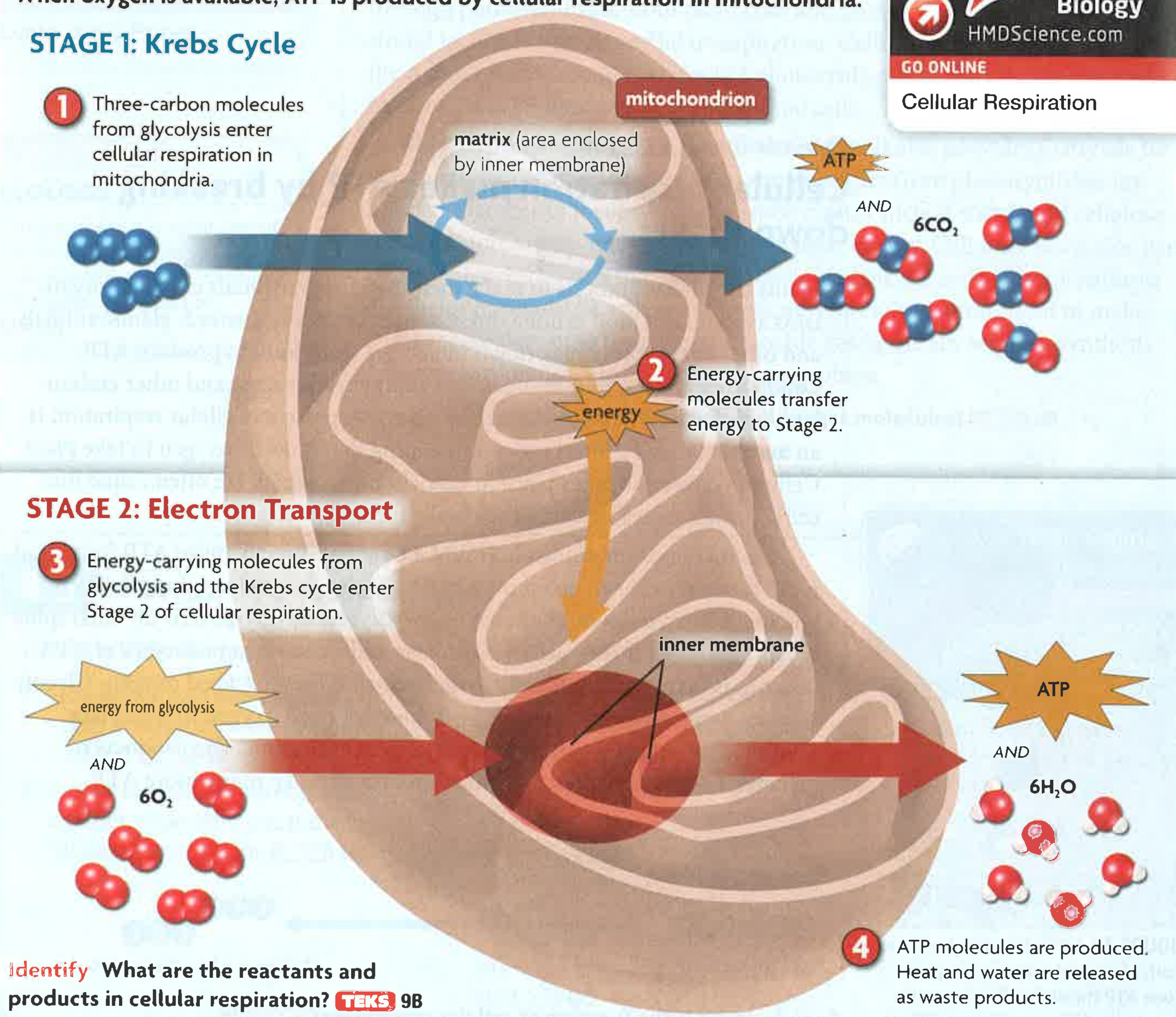
PHOTOSYNTHESIS

Review the overall process of photosynthesis in **Section 2**, and compare photosynthesis to cellular respiration.

Photosynthesis and cellular respiration are not true opposites, but you can think about them in that way. For example, chloroplasts absorb energy from sunlight and build sugars. Mitochondria release chemical energy to make ATP. The chemical equation of cellular respiration is also basically the reverse of photosynthesis. But the structures of chloroplasts and mitochondria are similar. A mitochondrion is surrounded by a membrane. It has two parts that are involved in cellular respiration: the matrix and the inner mitochondrial membrane. In mitochondria, cellular respiration takes place in two main stages, as shown in **FIGURE 4.2.**

FIGURE 4.2 Cellular Respiration Overview

When oxygen is available, ATP is produced by cellular respiration in mitochondria.



Identify **What are the reactants and products in cellular respiration?** TEKS 9B

The **Krebs cycle** produces molecules that carry energy to the second part of cellular respiration. The Krebs cycle, named for the scientist who discovered the process, takes place in the interior space, or matrix, of the mitochondrion.

1 Three-carbon molecules from glycolysis are broken down in a cycle of chemical reactions. A small number of ATP molecules are made. Other types of energy-carrying molecules are also made. Carbon dioxide is given off as a waste product.

2 Energy is transferred to the second stage of cellular respiration.

An electron transport chain made of proteins needs energy-carrying molecules from the Krebs cycle and oxygen to make ATP. This part of the process takes place in and across the inner mitochondrial membrane.

3 Energy is transferred to a chain of proteins in the inner membrane of the mitochondrion.

4 A large number of ATP molecules are made. Oxygen enters the process and is used to make water molecules. Water and heat are given off as waste products.

Up to 38 ATP molecules are made from the breakdown of 1 glucose molecule—2 from glycolysis and 34 or 36 from cellular respiration. The equation for cellular respiration is shown below, but it actually has many more steps. For example, the cellular respiration equation includes glycolysis. And many enzymes are also part of the process.

$$\underset{\text{a sugar}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2} \rightarrow \rightarrow \rightarrow \rightarrow \underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O}$$

Use **FIGURE 4.3** to compare cellular respiration with photosynthesis. As you can see, photosynthesis uses the products of cellular respiration. It converts energy from sunlight into sugars. Cellular respiration needs the products of photosynthesis. It releases stored energy from sugars to make ATP that can be used by cells.

Apply Does glucose actually react with oxygen during cellular respiration? Explain. TEKS 9B

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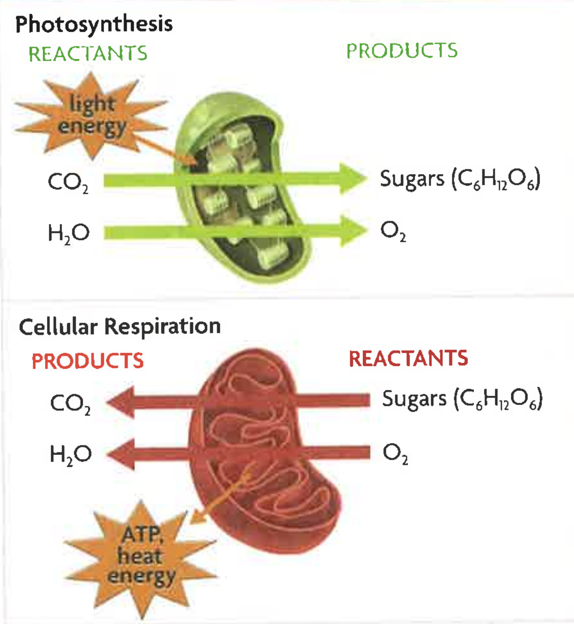
Carbon Dioxide Transfer Through Snails and *Elodea*

FIGURE 4.3 COMPARING PROCESSES



The products of photosynthesis—sugars and O_2—are the reactants in cellular respiration.

4.4 Formative Assessment

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REVIEWING ● MAIN IDEAS

1. How are **cellular respiration** and **glycolysis** related? **TEKS 4B**
2. Summarize the **aerobic** stages of cellular respiration. Be sure to discuss the **Krebs cycle** and the electron transport chain in your answer. **TEKS 4B**

CRITICAL THINKING

3. **Analyze** Describe the relationship between cellular respiration and photosynthesis. Discuss the functions of chloroplasts and mitochondria. **TEKS 4B, 9B**
4. **Apply** Is glucose a reactant in the aerobic stages of cellular respiration? Explain. **TEKS 4B**

CONNECT TO CHEMICAL REACTIONS

5. Is the process of cellular respiration exothermic or endothermic? Explain your answer. **TEKS 4B**

4.5 Cellular Respiration in Detail

TEKS 4B, 9B

KEY CONCEPT **Cellular respiration is an aerobic process with two main stages.**

MAIN IDEAS

- Glycolysis is needed for cellular respiration.
- The Krebs cycle is the first main part of cellular respiration.
- The electron transport chain is the second main part of cellular respiration.

TEKS **4B** investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules and **9B** compare the reactants and products of photosynthesis and cellular respiration in terms of energy and matter

Connect to Your World

If chloroplasts are like tiny factories that make products, mitochondria are like power plants that burn fuel to produce electricity. In a power plant, a processed fuel is burned in the presence of oxygen, and energy is released as useful electricity. During cellular respiration, oxygen and digested molecules from food are used to produce useful energy in the form of ATP.

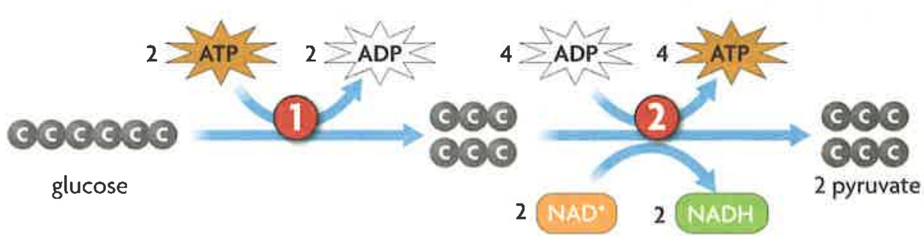
MAIN IDEA **TEKS** 4B

Glycolysis is needed for cellular respiration.

In Section 4, you read a summary of the way cellular respiration produces ATP molecules. But cellular respiration, like photosynthesis, is a very complex process. For example, glucose and oxygen do not react directly with each other, and many chemical reactions, such as glycolysis, must take place.

Glycolysis is an ongoing process in all cells, including yours. It takes place in the cytoplasm before cellular respiration, and it does not require oxygen. Glycolysis makes a small number of ATP molecules, but its other products are much more important. If oxygen is available, the products of glycolysis are used to produce many more ATP molecules through cellular respiration. The process of glycolysis can be summarized as follows.

1. Two ATP molecules are used to energize a glucose molecule. The glucose molecule is split into two three-carbon molecules. A series of enzymes and chemical reactions rearranges the three-carbon molecules.
2. Energized electrons from the three-carbon molecules are transferred to molecules of NAD^+, forming NADH molecules. A series of reactions converts the three-carbon molecules to pyruvate (py-ROO-vayt), which enters cellular respiration. This process also forms four ATP molecules.



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Glycolysis

CONNECT TO

FERMENTATION

When cells do not have a supply of oxygen for the aerobic processes of cellular respiration, the anaerobic processes of fermentation take place. You will learn about fermentation in **Section 6.**

Although glycolysis makes four ATP molecules, recall that two ATP molecules are used to first split the glucose molecule. So the breakdown of one glucose molecule by glycolysis gives a net gain of two ATP molecules. The pyruvate and NADH produced by glycolysis are used for cellular respiration when oxygen is present. NADH is an electron carrier like NADPH, the electron carrier in photosynthesis.

Summarize How does glycolysis result in a net gain of two ATP molecules? **TEKS 4B**

MAIN IDEA **TEKS 4B**

The Krebs cycle is the first main part of cellular respiration.

Cellular respiration makes many more ATP molecules than does glycolysis. It begins with the breakdown of pyruvate in Steps 1 and 2 below. The process continues with the Krebs cycle, shown in **FIGURE 5.2.** Notice that Steps 1, 4, and 5 below are very similar. In those steps, a carbon-based molecule is split, a molecule of carbon dioxide is formed, and energy-carrying NADH molecules are made. In fact, the main function of the Krebs cycle is to transfer high-energy electrons to molecules that carry them to the electron transport chain. The Krebs cycle is also sometimes called the citric acid cycle because citric acid is the first molecule formed, as you can see in Step 3 below.

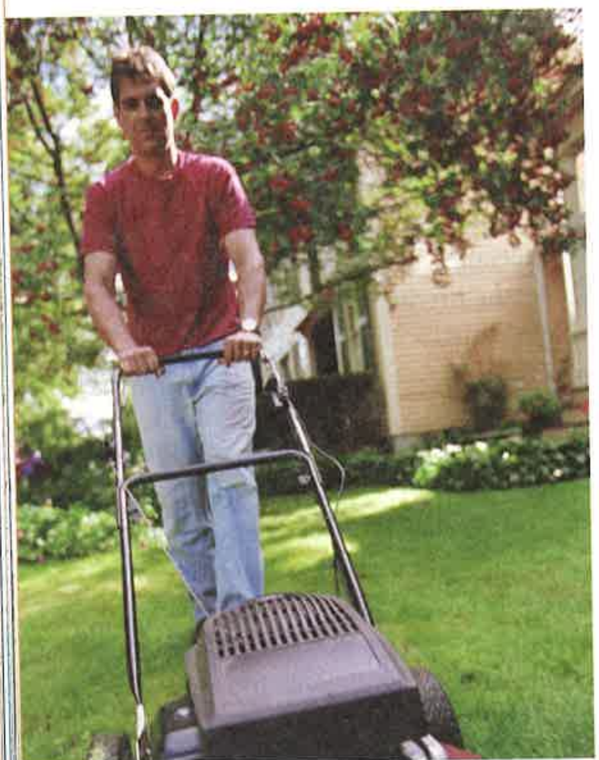
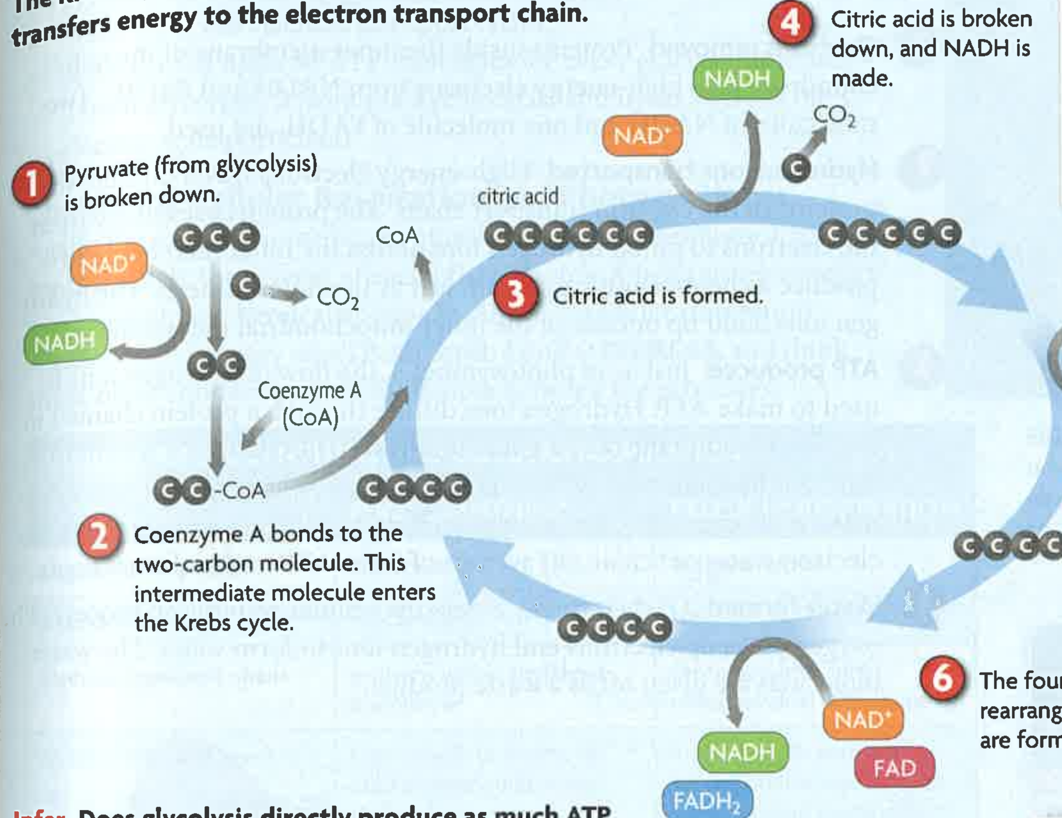


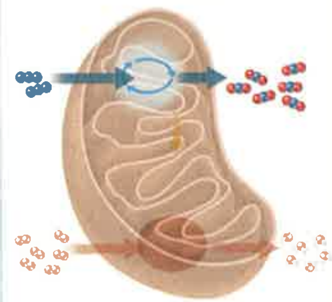
FIGURE 5.1 Gasoline engines burn carbon-based molecules in the presence of oxygen, and they release water, carbon dioxide, and energy. The overall process of cellular respiration is similar.

1. **Pyruvate broken down** A pyruvate molecule is split into a two-carbon molecule and a molecule of carbon dioxide, which is given off as a waste product. High-energy electrons are transferred from the two-carbon molecule to NAD^+, forming a molecule of NADH. The NADH moves to the electron transport chain.
2. **Coenzyme A** A molecule called coenzyme A bonds to the two-carbon molecule made from the breakdown of pyruvate. This intermediate molecule goes to the Krebs cycle.
3. **Citric acid formed** The two-carbon part of the intermediate molecule is added to a four-carbon molecule to form a six-carbon molecule called citric acid. Coenzyme A goes back to Step 2.
4. **Citric acid broken down** The citric acid molecule is broken down by an enzyme, and a five-carbon molecule is formed. A molecule of NADH is made and moves out of the Krebs cycle. A molecule of carbon dioxide is given off as a waste product.
5. **Five-carbon molecule broken down** The five-carbon molecule is broken down by an enzyme. A four-carbon molecule, a molecule of NADH, and a molecule of ATP are formed. The NADH leaves the Krebs cycle. Carbon dioxide is given off as a waste product.
6. **Four-carbon molecule rearranged** Enzymes rearrange the four-carbon molecule. High-energy electrons are released. Molecules of NADH and $FADH_2$, which is another electron carrier, are made. They leave the Krebs cycle, and the four-carbon molecule remains.

FIGURE 5.2 The Krebs Cycle

The Krebs cycle breaks down citric acid and transfers energy to the electron transport chain.





The Krebs cycle takes place in the mitochondrion matrix.

Infer **Does glycolysis directly produce as much ATP as the Krebs cycle? Indirectly? Explain your answer.**

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Krebs Cycle

The products from the breakdown of one molecule of pyruvate are

- three molecules of carbon dioxide that are given off as a waste product
- one molecule of ATP
- four molecules of NADH to the electron transport chain
- one molecule of $FADH_2$ to the electron transport chain

Remember, glycolysis produces two pyruvate molecules. Therefore, the products above are half of what comes from one glucose molecule. The totals are six carbon dioxide, two ATP, eight NADH, and two $FADH_2$ molecules.

Analyze **How are the products of the Krebs cycle important for making ATP?** **TEKS 4B**

MAIN IDEA **TEKS 4B, 9B**

The electron transport chain is the second main part of cellular respiration.

The electron transport chain takes place in and across the inner membrane of a mitochondrion. As with electron transport in photosynthesis, proteins make up the electron transport chain in cellular respiration. The proteins use energy from the electrons supplied by NADH and $FADH_2$ to pump hydrogen ions against a concentration gradient and across the inner mitochondrial membrane.

The ions later flow back through the membrane to produce ATP. Oxygen is needed at the end of the process to pick up electrons that have gone through the chain. The electron transport chain is shown in **FIGURE 5.3.**

1. **Electrons removed** Proteins inside the inner membrane of the mitochondrion take high-energy electrons from NADH and $FADH_2$. Two molecules of NADH and one molecule of $FADH_2$ are used.
2. **Hydrogen ions transported** High-energy electrons travel through the proteins in the electron transport chain. The proteins use energy from the electrons to pump hydrogen ions across the inner membrane to produce a chemiosmotic gradient, just as in photosynthesis. The hydrogen ions build up outside of the inner mitochondrial membrane.
3. **ATP produced** Just as in photosynthesis, the flow of hydrogen ions is used to make ATP. Hydrogen ions diffuse through a protein channel in the inner membrane of the mitochondrion. The channel is part of the ATP synthase enzyme. ATP synthase adds phosphate groups to ADP to make ATP molecules. For each pair of electrons that passes through the electron transport chain, an average of three ATP molecules are made.
4. **Water formed** Oxygen finally enters the cellular respiration process. Th oxygen picks up electrons and hydrogen ions to form water. The water molecules are given off as a waste product.

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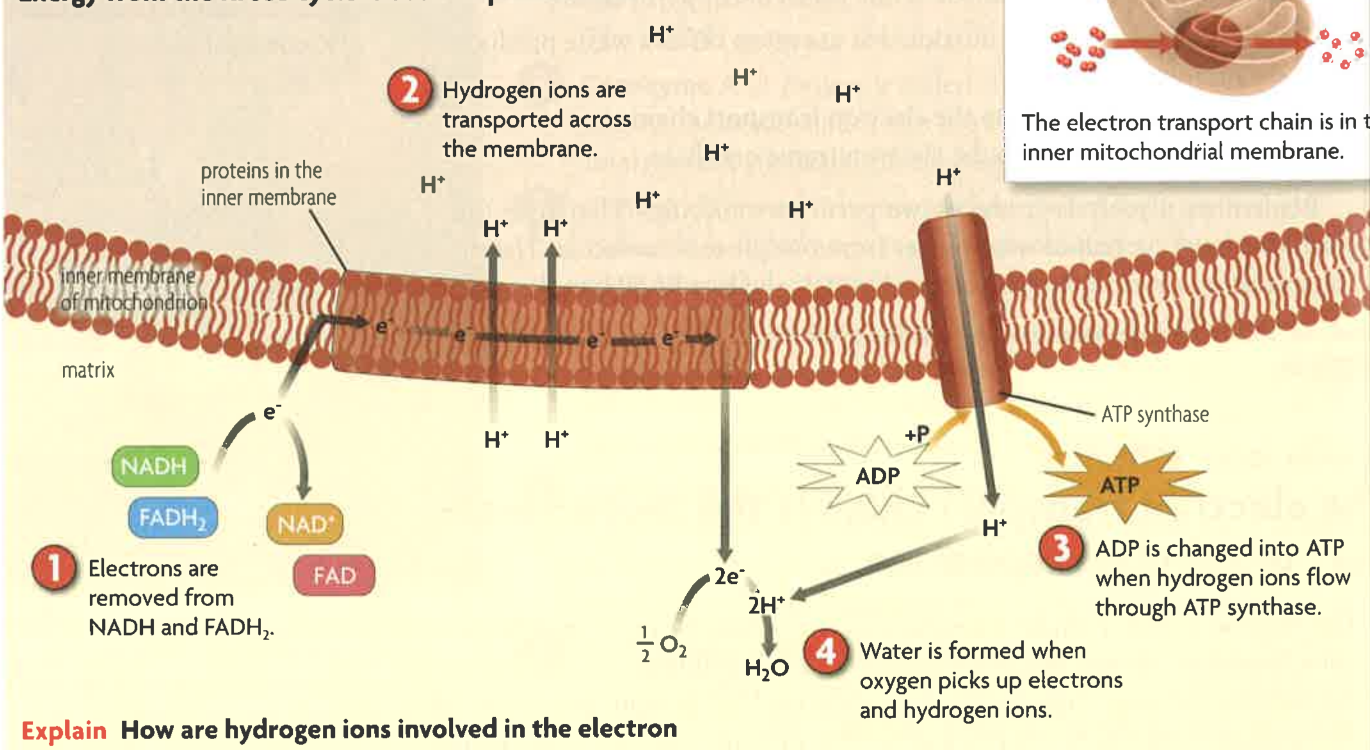
Electronic Transport Chain

FIGURE 5.3 The Electron Transport Chain

Energy from the Krebs cycle is used to produce ATP.


The electron transport chain is in t inner mitochondrial membrane.



Explain How are hydrogen ions involved in the electron transport chain?

The products of cellular respiration—including glycolysis—are

- Carbon dioxide from the Krebs cycle and from the breakdown of pyruvate before the Krebs cycle
- Water from the electron transport chain
- A net gain of up to 38 ATP molecules for every glucose molecule—2 from glycolysis, 2 from the Krebs cycle, and up to 34 from the electron transport chain

FIGURE 5.4 Like sandbags passed down a line of people, high-energy electrons are passed along a chain of proteins in the inner mitochondrial membrane.

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Comparing Cellular Respiration and Photosynthesis

Again, think about how photosynthesis and cellular respiration are approximately the reverse of each other. Photosynthesis stores energy from sunlight as chemical energy. In contrast, cellular respiration releases stored energy as ATP and heat. Look at **FIGURE 5.5**, and think about other similarities and differences between the processes.

FIGURE 5.5 PHOTOSYNTHESIS AND CELLULAR RESPIRATION

	PHOTOSYNTHESIS	CELLULAR RESPIRATION
Organelle for process	chloroplast	mitochondrion
Reactants	CO_2 and H_2O	sugars ($C_6H_{12}O_6$) and O_2
Electron transport chain	proteins within thylakoid membrane	proteins within inner mitochondrial membrane
Cycle of chemical reactions	Calvin cycle in stroma of chloroplasts builds sugar molecules	Krebs cycle in matrix of mitochondria breaks down carbon-based molecules
Products	sugars ($C_6H_{12}O_6$) and O_2	CO_2 and H_2O

Animated Biology HMDScience.com GO ONLINE Mirror Processes

Recall the roles of electrons, hydrogen ions, and ATP synthase. In both processes, high-energy electrons are transported through proteins. Their energy is used to pump hydrogen ions across a membrane. And the flow of hydrogen ions through ATP synthase produces ATP. As you can see, the parts of the processes are very similar, but their end points are very different.

Analyze **How does the electron transport chain depend on the Krebs cycle?** TEKS 4B

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4.5 Formative Assessment

REVIEWING ● MAIN IDEAS

1. What is the role of pyruvate in cellular respiration? TEKS 4B
2. Describe in your own words the function of the Krebs cycle. TEKS 4B
3. Explain the functions of electrons, hydrogen ions, and oxygen in the electron transport chain. TEKS 4B

CRITICAL THINKING

4. **Compare** Describe the relationship between cellular respiration and photosynthesis in terms of energy and matter. TEKS 4B, 9B
5. **Evaluate** Is oxygen necessary for the production of all ATP in your cells? Why or why not?

CONNECT TO COMMON ANCESTRY

6. Protein molecules called cytochromes are part of the electron transport chain. They are nearly identical in every known aerobic organism. How do these molecules show the unity of life on Earth? TEKS 7A

4.6 Fermentation

TEKS 4B

KEY CONCEPT **Fermentation allows the production of a small amount of ATP without oxygen.**

VOCABULARY

fermentation
lactic acid

MAIN IDEAS

- Fermentation allows glycolysis to continue.
- Fermentation and its products are important in several ways.

TEKS **4B** investigate and explain cellular processes, including homeostasis, energy conversions, transport of molecules, and synthesis of new molecules

Connect to Your World

Think about a time when you worked or exercised hard. Maybe you moved heavy boxes or furniture. Maybe, playing basketball, you found yourself repeatedly running up and down the court. Your arms and legs began to feel heavy, and they seemed to lose strength. Your muscles became sore, and even when you rested you kept breathing hard. Your muscles were using fermentation.

MAIN IDEA **TEKS** **4B**

Fermentation allows glycolysis to continue.

The cells in your body cannot store large amounts of oxygen for cellular respiration. The amount of oxygen that is provided by breathing is enough for your cells during normal activities. When you are reading or talking to friends, your body can maintain its oxygen levels. When you are doing high levels of activity, as the sprinter is in **FIGURE 6.1**, your body cannot bring in enough oxygen for your cells, even though you breathe faster. How do your cells function without enough oxygen to keep cellular respiration going?

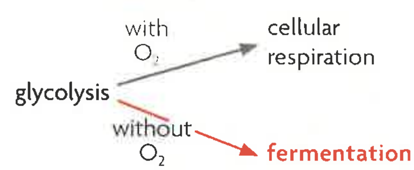
Recall that glycolysis yields two ATP molecules when it splits glucose into two molecules of pyruvate. Glycolysis is always occurring and does not require oxygen. If oxygen is available, the products of glycolysis—pyruvate and the electron carrier NADH—are used in cellular respiration. Then, oxygen picks up electrons at the end of the electron transport chain in cellular respiration. But what happens when oxygen is not there to pick up electrons? The production of ATP without oxygen continues through the anaerobic processes of glycolysis and fermentation.

FIGURE 6.1 Muscle cells use anaerobic processes during hard exercise.

Fermentation does not make ATP, but it allows glycolysis to continue. Fermentation removes electrons from NADH molecules and recycles NAD^+ molecules for glycolysis. Why is this process important? Because glycolysis, just like cellular respiration, needs a molecule that picks up electrons. It needs molecules of NAD^+.

VISUAL VOCAB

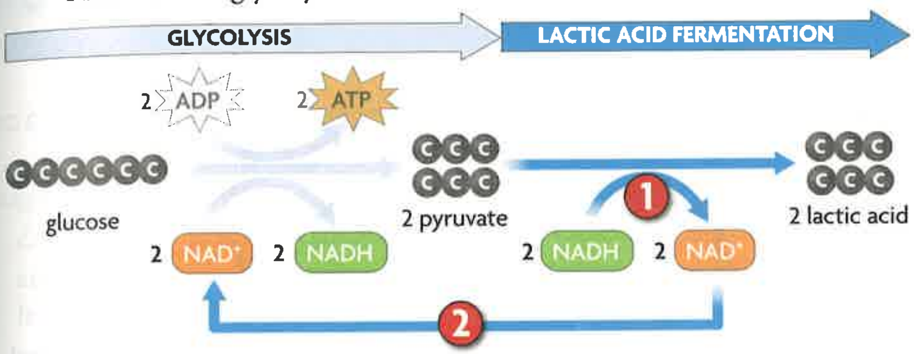
Fermentation is an anaerobic process that allows glycolysis to continue.



Without NAD^+ to pick up high-energy electrons from the splitting of glucose, glycolysis would stop. When the high-energy electrons are picked up, though, a eukaryotic cell can continue breaking down glucose and other simple sugars to make a small amount of ATP.

Suppose that a molecule of glucose has just been split by glycolysis in one of your muscle cells, but oxygen is unavailable. A process called lactic acid fermentation takes place. Lactic acid fermentation occurs in your muscle cells, the cells of other vertebrates, and in some microorganisms. **Lactic acid,** $C_3H_6O_3$, is what causes your muscles to "burn" during hard exercise.

1. Pyruvate and NADH from glycolysis enter the fermentation process. Two NADH molecules provide energy to convert pyruvate into lactic acid. As the NADH is used, it is converted back into NAD^+.
2. Two molecules of NAD^+ are recycled back to glycolysis. The recycling of NAD^+ allows glycolysis to continue.



As you can see, the role of fermentation is simply to provide glycolysis with a steady supply of NAD^+. By itself, fermentation does not produce ATP. Instead, it allows glycolysis to continue to produce ATP. However, fermentation does produce the lactic acid waste product that builds up in muscle cells and causes a burning feeling. Once oxygen is available again, your cells return to using cellular respiration. The lactic acid is quickly broken down and removed from the cells. This is why you continue to breathe hard for several minutes after you stop exercising. Your body is making up for the oxygen deficit in your cells, which allows the breakdown of lactic acid in your muscles.

Sequence **Which process must happen first, fermentation or glycolysis? Explain.**

MAIN IDEA TEKS 4B

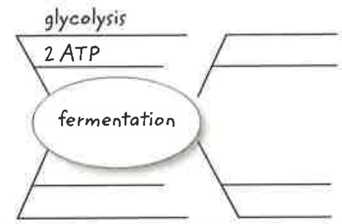
Fermentation and its products are important in several ways.

How would your diet change without cheese, bread, and yogurt? How would pizza exist without cheese and bread? Without fermentation, a pizza crust would not rise and there would be no mozzarella cheese as a pizza topping. Cheese, bread, and yogurt are just a few of the foods made by fermentation. Milk is changed into different cheeses by fermentation processes carried out by different types of bacteria and molds. Waste products of their fermentation processes give cheeses their different flavors and textures. Additionally, some types of bacteria that use lactic acid fermentation sour the milk in yogurt.

READING TOOLBOX

TAKING NOTES

Use a mind map to take notes on the processes involved in fermentation.



CONNECT TO

HUMAN BIOLOGY

Muscle cells need ATP to contract. You will learn how muscles produce your movements in the chapter **Protection, Support, and Movement.**

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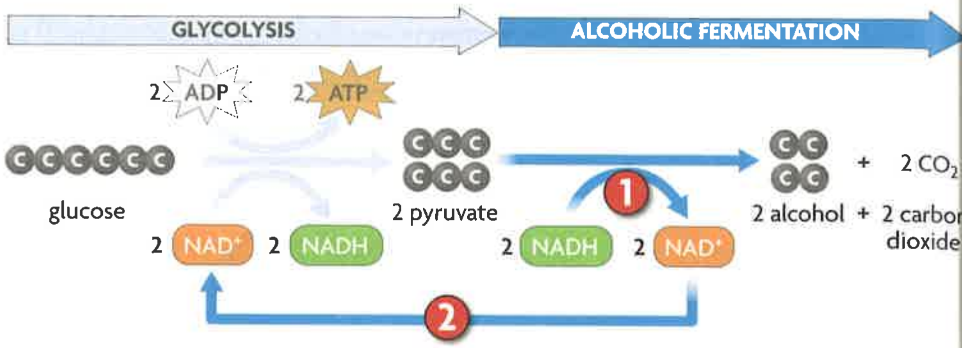
Energy and Athletic Training

Lactic acid fermentation is not the only anaerobic process. Alcoholic fermentation occurs in many yeasts and in some types of plants. Alcoholic fermentation begins at the same point as lactic acid fermentation. That is, glycolysis splits a molecule of glucose and produces two net ATP molecules, two pyruvate molecules, and two NADH molecules. Pyruvate and NADH enter alcoholic fermentation.

1. Pyruvate and NADH from glycolysis enter alcoholic fermentation. Two NADH molecules provide energy to break down pyruvate into an alcohol and carbon dioxide. As the NADH molecules are used, they are converted back into molecules of NAD^+.
2. The molecules of NAD^+ are recycled back to glycolysis. The recycling of NAD^+ allows glycolysis to continue.



The products of this process are two molecules of an alcohol, often ethyl alcohol, two molecules of carbon dioxide, and two molecules of NAD^+. Just like lactic acid fermentation, alcoholic fermentation recycles NAD^+ and so allows glycolysis to keep making ATP.

QUICK LAB **DESIGN YOUR OWN**

Fermentation

One waste product of alcoholic fermentation is carbon dioxide. In this lab, you will determine which beverage causes yeast to undergo a higher rate of fermentation.

PROBLEM What factors affect the rate of fermentation in yeast?

PROCEDURE

1. Write an operational definition for the dependent variable that you will use to measure the rate of fermentation.
2. Develop a technique using a balloon to measure fermentation rate.
3. Design your experiment. Have your teacher approve your experimental design. Write your experimental procedure and conduct your experiment.
4. Construct a data table to record your data. Construct a graph to display your data.

ANALYZE AND CONCLUDE

1. **Identify** What are the independent variable, dependent variable, and constants?
2. **Analyze** How did the independent variable affect the rate of fermentation? Why?
3. **Experimental Design** Identify possible reasons for any inconsistent results you observed.

MATERIALS

- 2 empty plastic bottles
- 1 package of yeast
- 2 100-mL graduated cylinders
- 2 250-mL beakers
- 2 beverages
- 2 round balloons
- 30 cm string
- metric ruler

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FIGURE 6.2 Fermentation by molds and bacteria produces the different flavors and textures of various cheeses.

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Fermentation and Food

Alcoholic fermentation in yeast is particularly useful. When bread or pizza crust is made, yeast is used to cause the dough to rise. The yeast breaks down sugars in the dough through glycolysis and alcohol fermentation. The carbon dioxide gas produced by alcoholic fermentation causes the dough to puff up and rise. When the dough is baked, the alcohol that is produced during fermentation evaporates into the air. The yeast in dough is killed by the heat of baking.

Bacteria that rely upon fermentation play a very important role in the digestive systems of animals. Microorganisms in the digestive tracts of animals, including humans, must obtain their ATP from anaerobic processes because oxygen is not available. Without them, neither you nor other animals would be able to fully digest food. Why? These bacteria continue the breakdown of molecules by taking in undigested material for their needs. The additional breakdown of materials by digestive bacteria allows the host animal to absorb more nutrients from food.

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Photosynthesis and Cellular Respiration

Apply **Explain the importance of alcoholic fermentation in the production of bread's light, fluffy texture.**

4.6 Formative Assessment

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REVIEWING ▶ MAIN IDEAS

1. What is the relationship between glycolysis and **fermentation**? TEKS 4B
2. Summarize the process of alcoholic fermentation in yeast. TEKS 4B

CRITICAL THINKING

3. **Compare and Contrast** How are **lactic acid** fermentation and alcoholic fermentation similar? How are they different? TEKS 4B
4. **Compare and Contrast** Describe the similarities and differences between cellular respiration and fermentation. TEKS 4B

CONNECT TO

CELLULAR RESPIRATION

5. How is the role of oxygen in cellular respiration similar to the role of NAD^+ in fermentation ? TEKS 4B