

# Cells and Energy

## KEY CONCEPTS

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### 4.1 Chemical Energy and ATP

All cells need chemical energy.

### 4.2 Overview of Photosynthesis

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

### 4.3 Photosynthesis in Detail

Photosynthesis requires a series of chemical reactions.

### 4.4 Overview of Cellular Respiration

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

### 4.5 Cellular Respiration in Detail

Cellular respiration is an aerobic process with two main stages.

### 4.6 Fermentation

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

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colored SEM; magnification 1000×

## What makes these cells so important to many other organisms?

### Connecting CONCEPTS

**T**hese diatoms are single-celled algae that use the process of photosynthesis to store chemical energy in sugars. Animals eat photosynthetic organisms such as plants and algae to get this chemical energy. Photosynthetic organisms also produce the oxygen that is required to release much of the chemical energy in sugars.



**Ecology** Microscopic diatoms are absolutely necessary for the survival of other marine organisms, including the humpback whale. Why? Diatoms are eaten by small, shrimplike animals called krill. In turn, humpbacks and several other species of whales feed mainly on krill. In fact, a blue whale's stomach can hold more than a ton of krill.

# 4.1

# Chemical Energy and ATP

**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**, p. 100

**ADP**, p. 101

**chemosynthesis**, p. 102

## Review

carbohydrate, lipid, protein



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**Connect** 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

### 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 4.1**, 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.

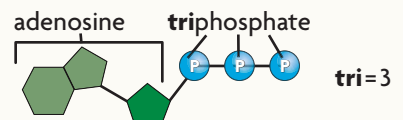
The energy carried by ATP is released when a phosphate group is removed from the molecule. ATP has three phosphate groups, but the bond holding the third phosphate group is unstable and is very easily broken. The removal of the third phosphate group usually involves a reaction that releases energy.



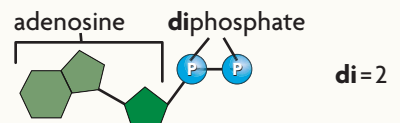
**FIGURE 4.1** All cells, including plant cells, use ATP for energy. (colored TEM; magnification 2500×)

## VISUAL VOCAB

**ATP** transfers energy to cell processes.

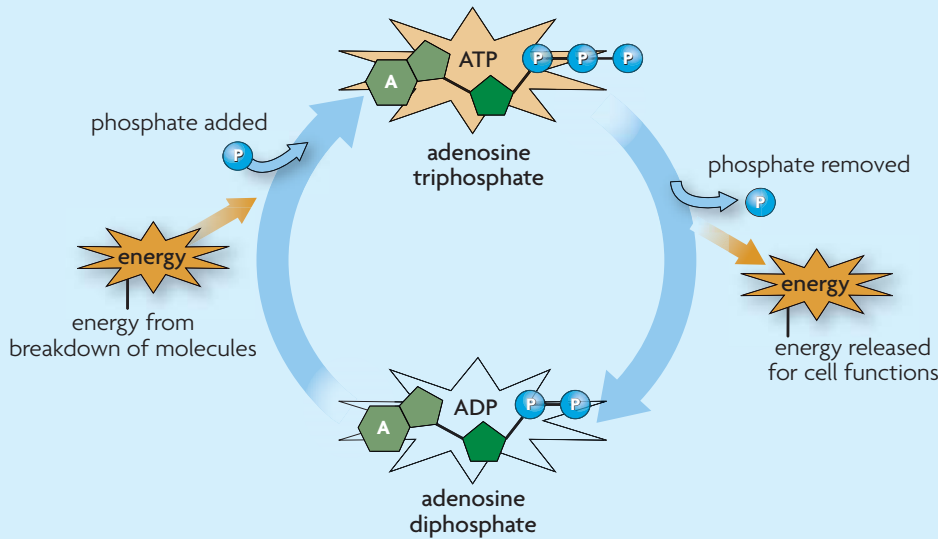


**ADP** is a lower-energy molecule that can be converted into ATP.



## FIGURE 4.2 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 4.2**. 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.

### ▶ MAIN IDEA

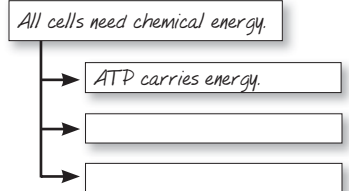
## Organisms break down carbon-based molecules to produce ATP.

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.

### TAKING NOTES

Use a supporting main ideas chart to organize concepts related to chemical energy.



### Connecting CONCEPTS

**Biochemistry** As you learned in **Chapter 2**, carbon-based molecules in living things—carbohydrates, lipids, proteins, and nucleic acids—have different structures and functions.



**FIGURE 4.3 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 4.3** shows. In fact, fats store about 80 percent 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 must. Plants make their own food. Through the process of photosynthesis, which is described in Sections 4.2 and 4.3, 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?

**▶ MAIN IDEA**

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

Most organisms rely directly or indirectly on sunlight and photosynthesis as their source of chemical energy. But some organisms do not need sunlight. 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 instead of light energy to make energy-storing carbon-based molecules. However, 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. It is the raw materials that differ.

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

## 4.1 ASSESSMENT



### REVIEWING ▶ MAIN IDEAS

1. How are **ATP** and **ADP** related?
2. What types of molecules are broken down to make ATP? Which are most often broken down to make ATP?
3. How are some organisms able to survive without sunlight and photosynthesis?

### CRITICAL THINKING

4. **Apply** Describe how you do not get energy directly from the food that you eat.
5. **Compare and Contrast** How are the energy needs of plant cells similar to those of animal cells? How are they different?

### Connecting CONCEPTS

6. **Chemical Reactions** A water molecule is added to an ATP molecule to break down ATP into ADP and a phosphate group. Write the chemical equation that represents this reaction.

# 4.2

## Overview of Photosynthesis

**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**, p. 103

**chlorophyll**, p. 103

**thylakoid**, p. 104

**light-dependent reactions**, p. 105

**light-independent reactions**, p. 105

### Review

chemical reaction, carbohydrate, enzyme, chloroplast



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**Connect** 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

## Photosynthetic organisms are producers.

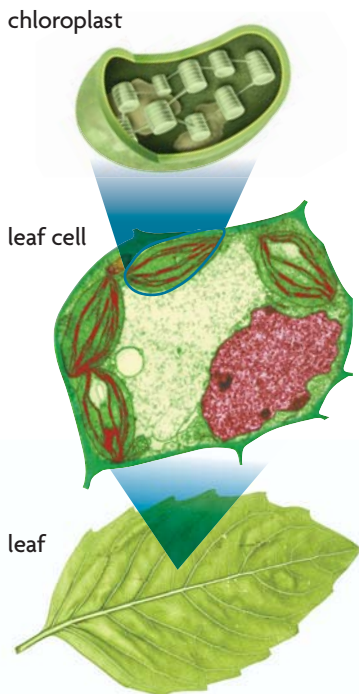
Some organisms are called producers because they produce the source of chemical energy for themselves and for other organisms. Plants, as well as some bacteria and protists, are the producers that are the main sources of chemical energy for most organisms on Earth. Certainly, animals that eat only plants 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 has several types 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 4.4**, 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 4.4** Chloroplasts in plant cells contain a light-absorbing molecule called chlorophyll. (leaf cell: colored TEM; magnification 4000×)



**▶ MAIN IDEA**

## Photosynthesis in plants occurs in chloroplasts.

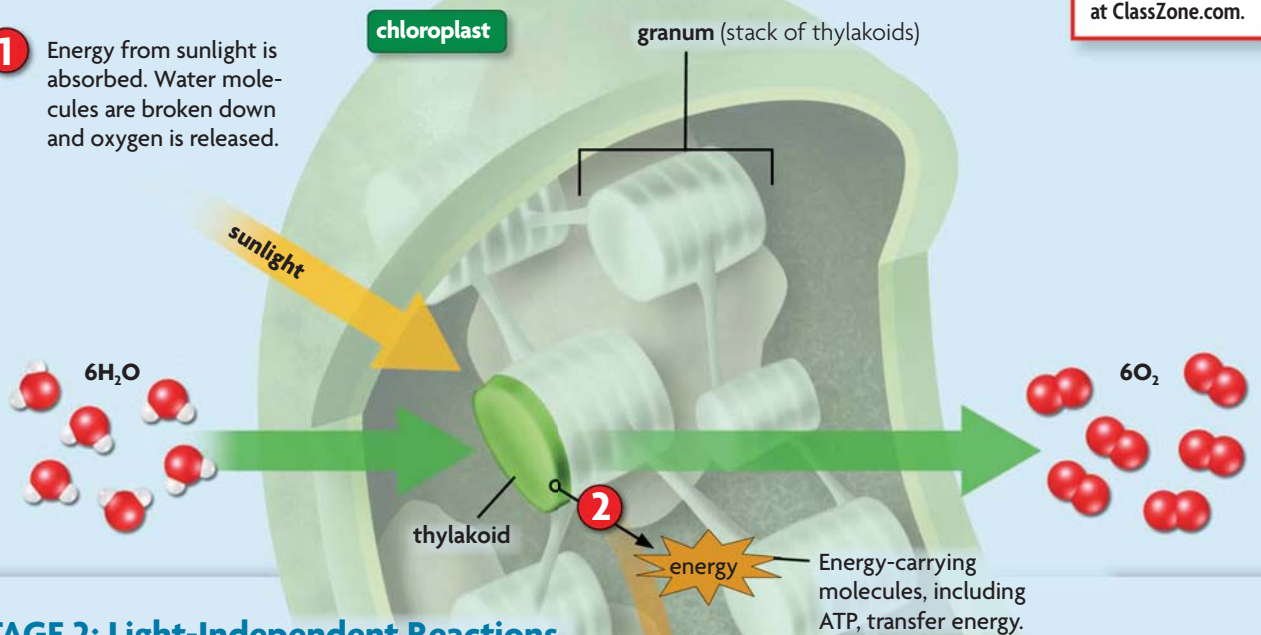
Chloroplasts are the membrane-bound organelles where photosynthesis takes place in plants. Most of the chloroplasts are in leaf cells that are specialized for photosynthesis, which has two main stages as shown in **FIGURE 4.5**. The two main parts of chloroplasts needed for photosynthesis are the grana 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 4.5 Photosynthesis Overview

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

#### STAGE 1: Light-Dependent Reactions

- 1** Energy from sunlight is absorbed. Water molecules are broken down and oxygen is released.



#### STAGE 2: Light-Independent Reactions

- 3** Carbon dioxide molecules are used to build sugars.

- 4** Six-carbon simple sugars are produced. The sugars are often used to build starches and cellulose.



**Identify** What are the reactants and the products in photosynthesis?

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at [ClassZone.com](http://ClassZone.com).

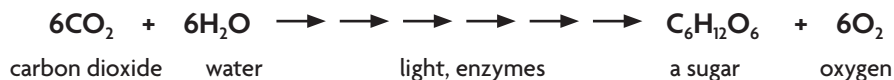
The **light-dependent reactions** capture energy from sunlight. These reactions take place within and across the membrane of the thylakoids. Water (H<sub>2</sub>O) and sunlight are needed for this stage of photosynthesis.

- 1 Chlorophyll absorbs energy from sunlight. The energy is transferred along the thylakoid membrane. H<sub>2</sub>O molecules are broken down. Oxygen molecules (O<sub>2</sub>) 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<sub>2</sub>) are needed during this stage of photosynthesis.

- 3 CO<sub>2</sub> 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<sub>6</sub>H<sub>12</sub>O<sub>6</sub>), 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<sub>2</sub> and H<sub>2</sub>O—and the products—a six-carbon sugar and O<sub>2</sub>. Those arrows tell you that photosynthesis has many steps. For example, the light-independent reactions need only one molecule of CO<sub>2</sub> 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.



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 4.4 and 4.5.

**Summarize** How is energy from sunlight used to make sugar molecules?

### Connecting CONCEPTS

**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 4.3.

## 4.2 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.

### 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.

### Connecting CONCEPTS

5. **Chemical Reactions** Overall, do you think photosynthesis is endothermic or exothermic? Explain your answer.



**MATERIALS**

- young ivy leaves
- hole punch
- 2 100-mL beakers
- 5 mL sodium bicarbonate/detergent solution
- water
- plastic 10-cc syringe
- forceps
- strong light source
- other light sources
- stopwatch

**PROCESS SKILLS**

- **Designing Experiments**
- **Analyzing**
- **Calculating**
- **Graphing**
- **Inferring**

## Rates of Photosynthesis

Photosynthesis converts some of the energy absorbed from sunlight into the chemical energy of sugars. The process is also the major source of oxygen in Earth's atmosphere. In this lab you will design an experiment to determine the effect of different light sources on the rate of photosynthesis in leaves.

**PROBLEM** How does a light source affect the rate of photosynthesis?

**PROCEDURE**

1. Use the hole punch to make five disks from an ivy leaf.
2. Fill one beaker halfway with the sodium bicarbonate/detergent solution. Fill a second beaker with water.
3. Remove the plunger from the syringe and place the ivy leaf disks into the syringe. Insert the plunger and draw 5 cc (5 mL) of the sodium bicarbonate/detergent solution into the syringe as shown in the photograph below (left).
4. Hold the syringe so that the tip is pointing upwards. Push on the plunger to squirt out any air in the syringe.
5. Place your finger on the tip of the syringe, as shown in the photograph below (right). Withdraw the plunger to form a vacuum, but be careful to not pull the plunger all the way out of the syringe. When the vacuum is formed, the gases in the air spaces in the leaf disks move into the syringe and the solution diffuses into the air spaces. Shake the syringe several times while your finger is on the tip.
6. Take your finger off of the tip of the syringe. This causes the leaf disks to sink to the bottom of the syringe because they become more dense from the diffusion of solution into the air spaces.
7. Open the syringe by pulling the plunger almost all the way out. Place your finger over the tip of the syringe and turn it so the tip is pointing down. Carefully remove the plunger and pour the contents of the syringe into the beaker of water. Use the forceps to remove the leaf disks if they stick to the walls of the syringe.
8. Place the beaker with the leaf disks under the light source and immediately start the stopwatch. Record the time it takes for each leaf disk to float to the top of the water. Use the rate at which the disks float as an indirect measurement of the rate of photosynthesis.



## DESIGN

1. Decide how to test different light sources on the rate of photosynthesis. Identify your independent variable. Have your teacher approve your choice.
2. Identify your control condition and the constants in the experiment. Examples of constants are the distance between the light and the beaker, and the temperature of the water.
3. Write the procedure for your experiment.
4. Design a data table, such as the one shown below, to record and organize your results.

**TABLE 1. THE EFFECT OF LIGHT SOURCES ON THE RATE OF PHOTOSYNTHESIS**

Time (sec)	Type of light _____ (# of disks)	Type of light _____ (# of disks)	Type of light _____ (# of disks)
0	0	0	0

5. Gather the additional materials you need for your experiment.
6. Test the rate of photosynthesis using the procedure on page 106. Be sure not to get any water on the light sources. Record your results. Continue collecting data until all five disks float in each experimental condition. (**Note:** If you test more than one condition at once, record a time and disk count for all of the beakers every time a disk floats in any of the beakers.)
7. If time allows, conduct three trials of your experiment.

## ANALYZE AND CONCLUDE

1. **Identify** What are the independent and dependent variables in your experiment?
2. **Calculate** Determine the mean rate of photosynthesis in each condition of your experiment. To calculate the rate of photosynthesis, use the formula below:  
$$\frac{5 \text{ (# disks floating)}}{\text{total time (sec)}} = \text{_____ disks/sec}$$
3. **Analyze** Determine the best type of graph to use to represent your data. Explain your choice and construct the graph. Be sure to carefully label the axes of the graph.
4. **Conclude** Based on your data, what can you conclude about how your independent variable affects the rate of photosynthesis?
5. **Infer** Why do you think sodium bicarbonate was used in this investigation? (Hint: Think about the equation for the overall process of photosynthesis.)
6. **Experimental Design** What are possible sources of unavoidable error in your design? Explain why they were present.
7. **Experimental Design** Identify possible reasons for inconsistent results.

# 4.3

## Photosynthesis in Detail

**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.

### VOCABULARY

**photosystem**, p. 108

**electron transport chain**, p. 109

**ATP synthase**, p. 110

**Calvin cycle**, p. 111

### Review

chlorophyll, thylakoid, light-dependent reactions, light-independent reactions



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**Connect** 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

## The first stage of photosynthesis captures and transfers energy.

In Section 4.2 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, 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.

The main functions of the light-dependent reactions are to capture and transfer energy. In these reactions, as in the solar car in **FIGURE 4.6**, energy is transferred to electrons. The electrons are only used for energy in a few specific processes. Recall a time you have gone to an amusement park. To go on rides, you needed special tickets that could only be used 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.

**FIGURE 4.6** 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.



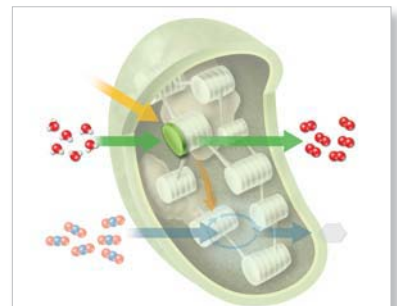
## Photosystem II and Electron Transport

In photosystem II, chlorophyll and other light-absorbing molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons. Photosystem II, shown in **FIGURE 4.7**, 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

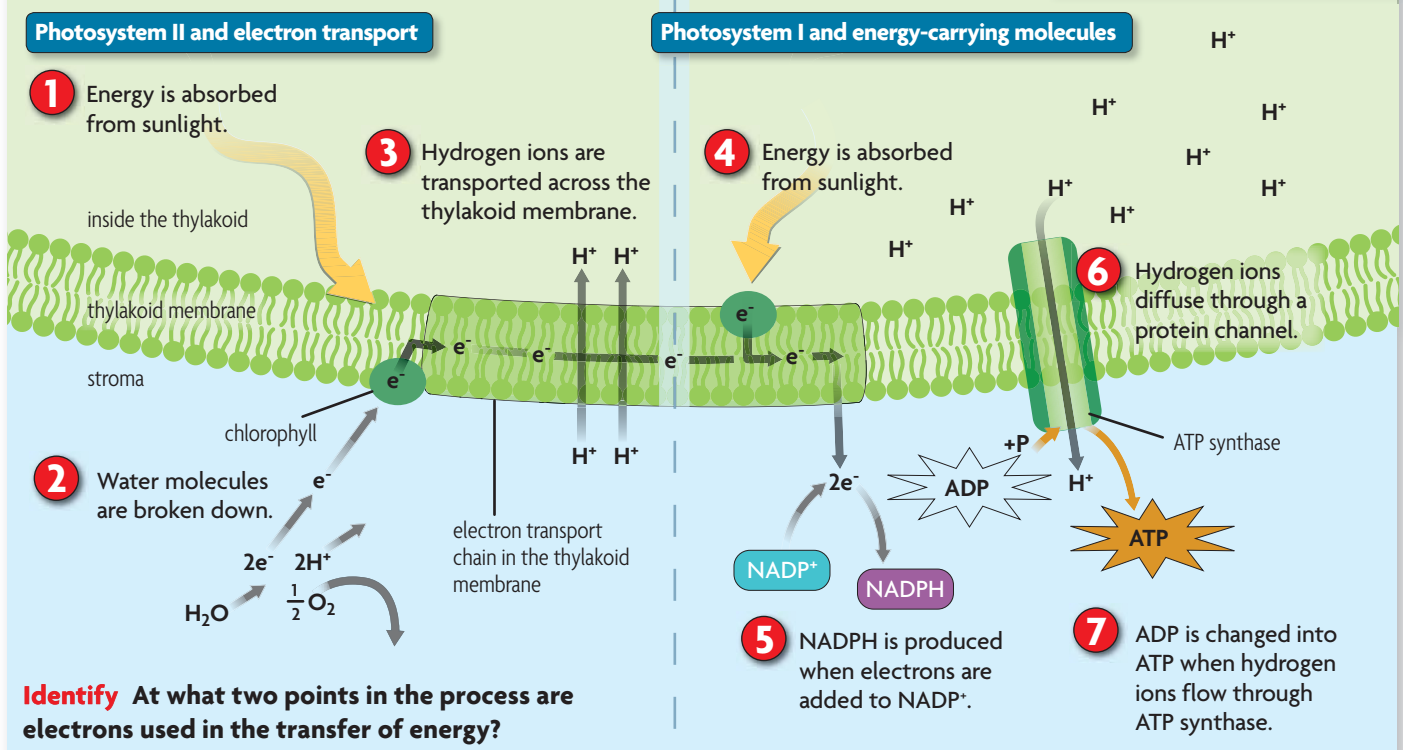
In photosystem I, chlorophyll and other light-absorbing molecules in the thylakoid membrane also absorb energy from sunlight. The energy is added to electrons, some of which enter photosystem I from photosystem II.

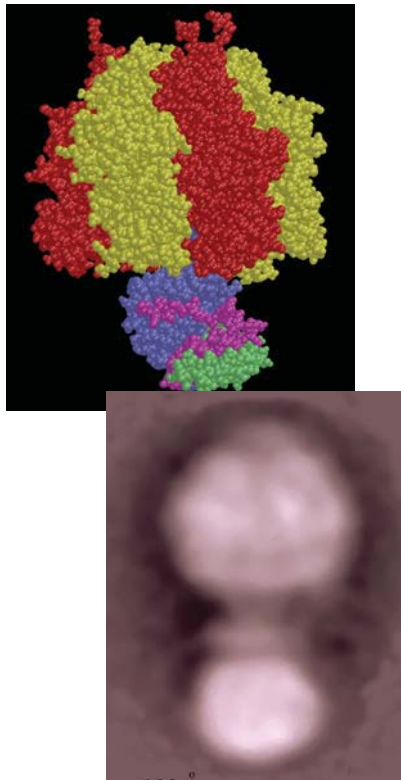


Light-dependent reactions take place in and across the thylakoid membrane.

### FIGURE 4.7 Light-Dependent Reactions

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





**FIGURE 4.8** 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 $\times$ )

- 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  $\text{NADP}^+$ , which functions like ADP. A molecule called NADPH is made. In photosynthesis, NADPH functions like ATP. The molecules of NADPH go to the light-independent reactions.

### ATP Production

The final part of the light-dependent reactions makes ATP. The production of ATP depends on the  $\text{H}^+$  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  $\text{H}^+$  ions is higher inside the thylakoid than it is outside. This difference in  $\text{H}^+$  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 4.8**. 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  $\text{H}^+$  ions, electrons, and oxygen molecules. The water molecules provide the  $\text{H}^+$  ions and electrons that are used in the light-dependent reactions.
- Energized electrons have two functions. They provide energy for  $\text{H}^+$  ion transport, and they are added to  $\text{NADP}^+$  to form NADPH.
- The flow of  $\text{H}^+$  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** Describe how energy from sunlight is transferred to ATP and NADPH.

### ▶ MAIN IDEA

## 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 from the light-dependent reactions. The chemical reactions of the **Calvin cycle** use carbon dioxide ( $\text{CO}_2$ ) 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  $\text{CO}_2$  is actually added to the Calvin cycle at a time. The simplified cycle in **FIGURE 4.9** shows three  $\text{CO}_2$  molecules added at once.

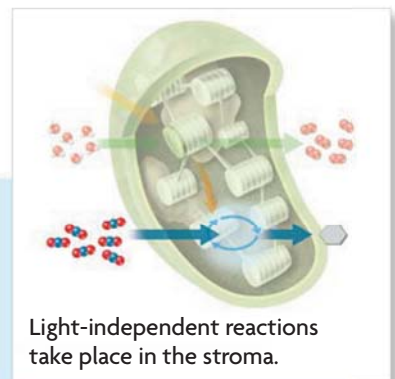
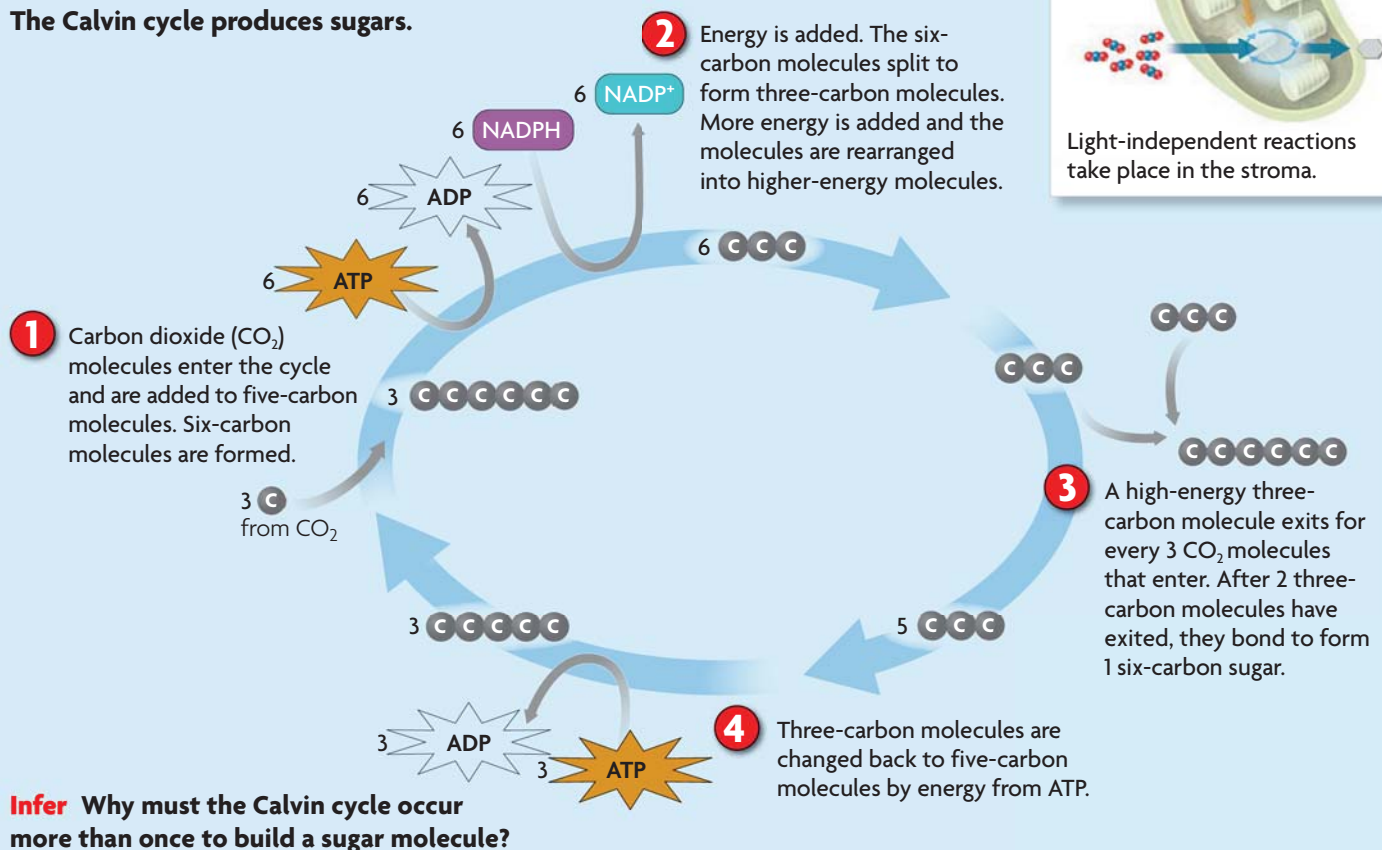
- 1 Carbon dioxide added**  $\text{CO}_2$  molecules are added to five-carbon molecules already in the Calvin cycle. Six-carbon molecules are formed.
- 2 Three-carbon molecules formed** Energy—ATP and NADPH—from the light-dependent reactions is used by enzymes to split the six-carbon molecules. Three-carbon 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  $\text{CO}_2$  molecules that enter the cycle.

### VOCABULARY

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

**FIGURE 4.9 Light-Independent Reactions (Calvin Cycle)**

The Calvin cycle produces sugars.



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

### Connecting CONCEPTS

**Ecology** Photosynthesis is a major part of the carbon cycle. You will learn more about the carbon cycle in Chapter 13.

## Summary of the Light-Independent Reactions

- Carbon dioxide enters the Calvin cycle.
- ATP and NADPH from the light-dependent reactions transfer energy to the Calvin cycle and keep the cycle going.
- One high-energy three-carbon molecule is made for every three molecules of carbon dioxide that enter the cycle.
- Two high-energy three-carbon molecules are bonded together to make a sugar. Therefore, six molecules of carbon dioxide must be added to the Calvin cycle to make one six-carbon sugar.
- The products are a six-carbon sugar such as glucose, NADP<sup>+</sup>, and ADP. The NADP<sup>+</sup> and ADP molecules return to the light-dependent reactions.

## 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?

## 4.3 ASSESSMENT



### REVIEWING MAIN IDEAS

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

### 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.
4. **Evaluate** Explain why the chemical equation for photosynthesis (below) is a highly simplified representation of the process. How is the equation accurate? How is it inaccurate?



### Connecting CONCEPTS

5. **Cell Functions** Explain how both passive transport and active transport are necessary for photosynthesis to occur.

# 4.4

## Overview of Cellular Respiration

**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**, p. 113  
**aerobic**, p. 113  
**glycolysis**, p. 113  
**anaerobic**, p. 113  
**Krebs cycle**, p. 115

**Review**  
 mitochondria, ATP,  
 electron transport chain



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**Connect** 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.

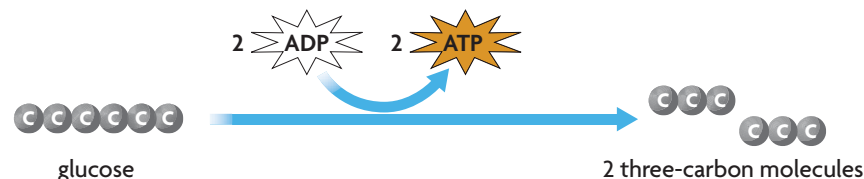
### ▶ MAIN IDEA

## Cellular respiration makes ATP by breaking down sugars.

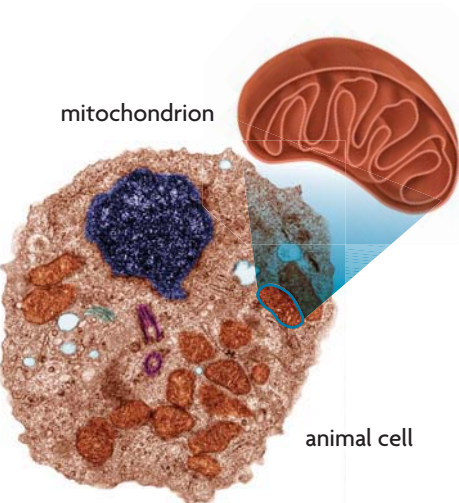
Plants use photosynthesis to make their own food. Animals eat other organisms as food. But food is not a direct source of energy. Instead, plants, animals, and other eukaryotes break down molecules from food to produce ATP.

**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, which means 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 4.10**, 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.



**Explain** What is the function of cellular respiration?



**FIGURE 4.10** Mitochondria, found in both plant and animal cells, produce ATP through cellular respiration. (colored TEM; magnification 4500×)



**▶ MAIN IDEA**

## Cellular respiration is like a mirror image of photosynthesis.

### Connecting CONCEPTS

**Photosynthesis** Review the overall process of photosynthesis in Section 4.2 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 4.11**.

**FIGURE 4.11 Cellular Respiration Overview**

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

**Animated**  
**BIOLOGY**  
View an animation of cellular respiration at [ClassZone.com](http://ClassZone.com).

### STAGE 1: Krebs Cycle

- 1 Three-carbon molecules from glycolysis enter cellular respiration in mitochondria.



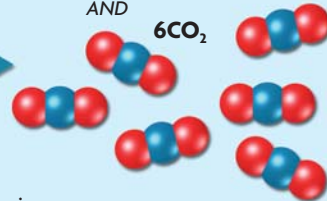
matrix (area enclosed by inner membrane)

mitochondrion



AND

6CO<sub>2</sub>



- 2 Energy-carrying molecules transfer energy to Stage 2.



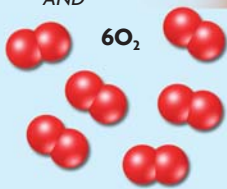
### STAGE 2: Electron Transport

- 3 Energy-carrying molecules from glycolysis and the Krebs cycle enter Stage 2 of cellular respiration.

energy from glycolysis

AND

6O<sub>2</sub>

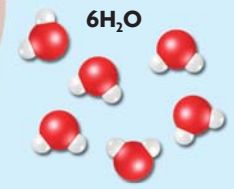


inner membrane



AND

6H<sub>2</sub>O



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

- 4 ATP molecules are produced. Heat and water are released as waste products.



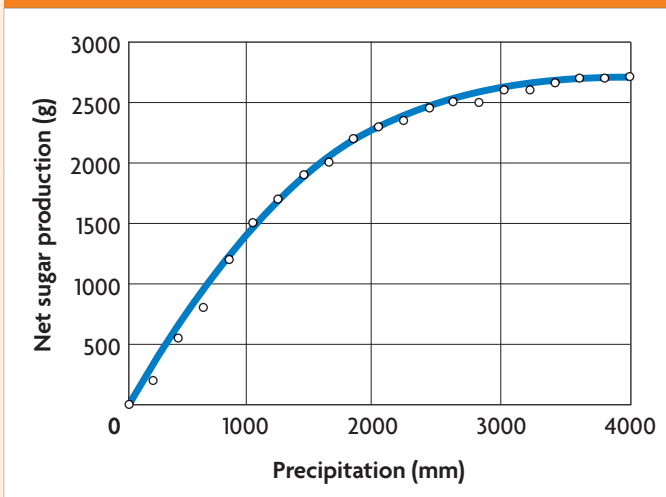
# Photosynthesis and Plants

After scientists record their data in tables, they usually make graphs to display it for analysis. Graphs show the relationship between two variables. The pattern of curve or line that is drawn will help you to form conclusions about your data.

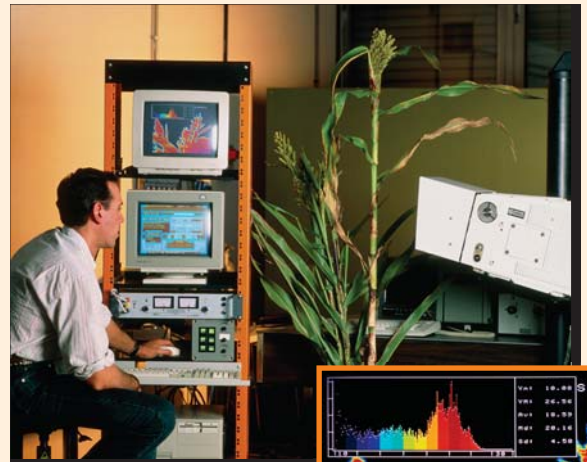
### EXAMPLE

Scientists study the net amount of sugar production per meter squared per year in forest plants. Look at graph below. Notice that the amount of net sugar production increases rapidly at first, then levels off after about 2500 mm of precipitation. Scientists can conclude that forests need about 2500 mm of rain annually for maximum net sugar production.

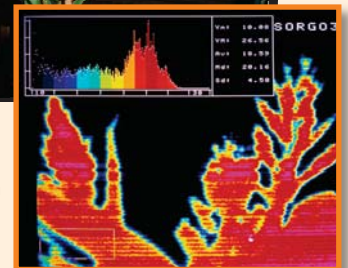
**GRAPH 1. NET SUGAR PRODUCTION**



Source: H. Leith, *Human Ecology 1*



Infrared imaging techniques can be used to study sugar production and plant growth conditions.

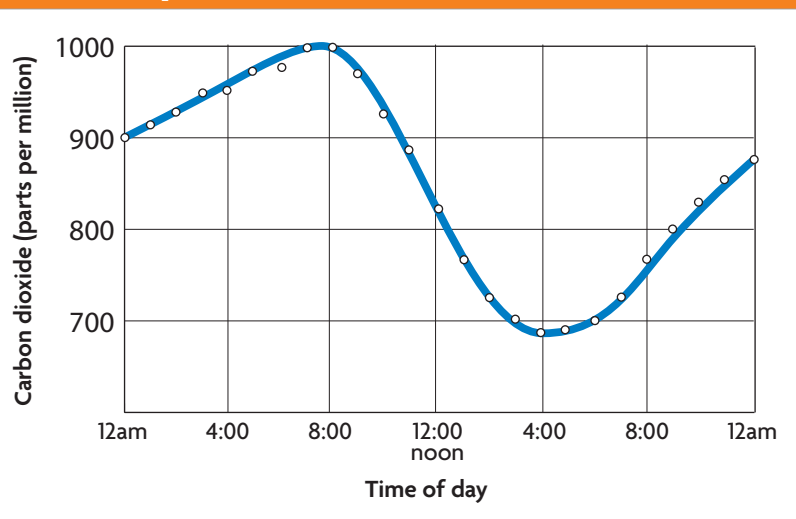


### INTERPRET A GRAPH

Look at the graph to the right. It shows the amount of carbon dioxide in the air during different times of the day in Biosphere 2, an enclosed research and education center in Arizona.

- Interpret** What is the relationship between the time of day and the amount of carbon dioxide in the research facility?
- Infer** Using your knowledge of the process of photosynthesis, draw a conclusion about the pattern of the data.

**GRAPH 2. CO<sub>2</sub> LEVELS OVER TIME**



# 4.5

## Cellular Respiration in Detail

**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.

### Review

glycolysis, Krebs cycle, electron transport chain, cellular respiration, aerobic respiration



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**Connect** 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.

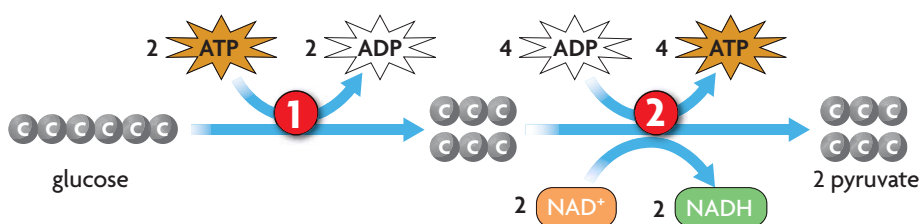
### ▶ MAIN IDEA

## Glycolysis is needed for cellular respiration.

In Section 4.4 you read a summary of how 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 one another, 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  $\text{NAD}^+$ . Molecules of NADH are formed. A series of reactions converts the three-carbon molecules to pyruvate (py-ROO-vayt), which enters cellular respiration. Four ATP molecules are made.



## Connecting CONCEPTS

**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 4.6.

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?

### ▶ MAIN IDEA

## 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 4.14**. 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.

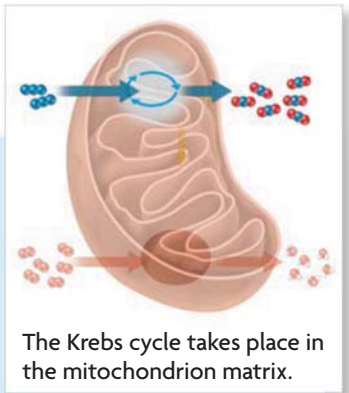
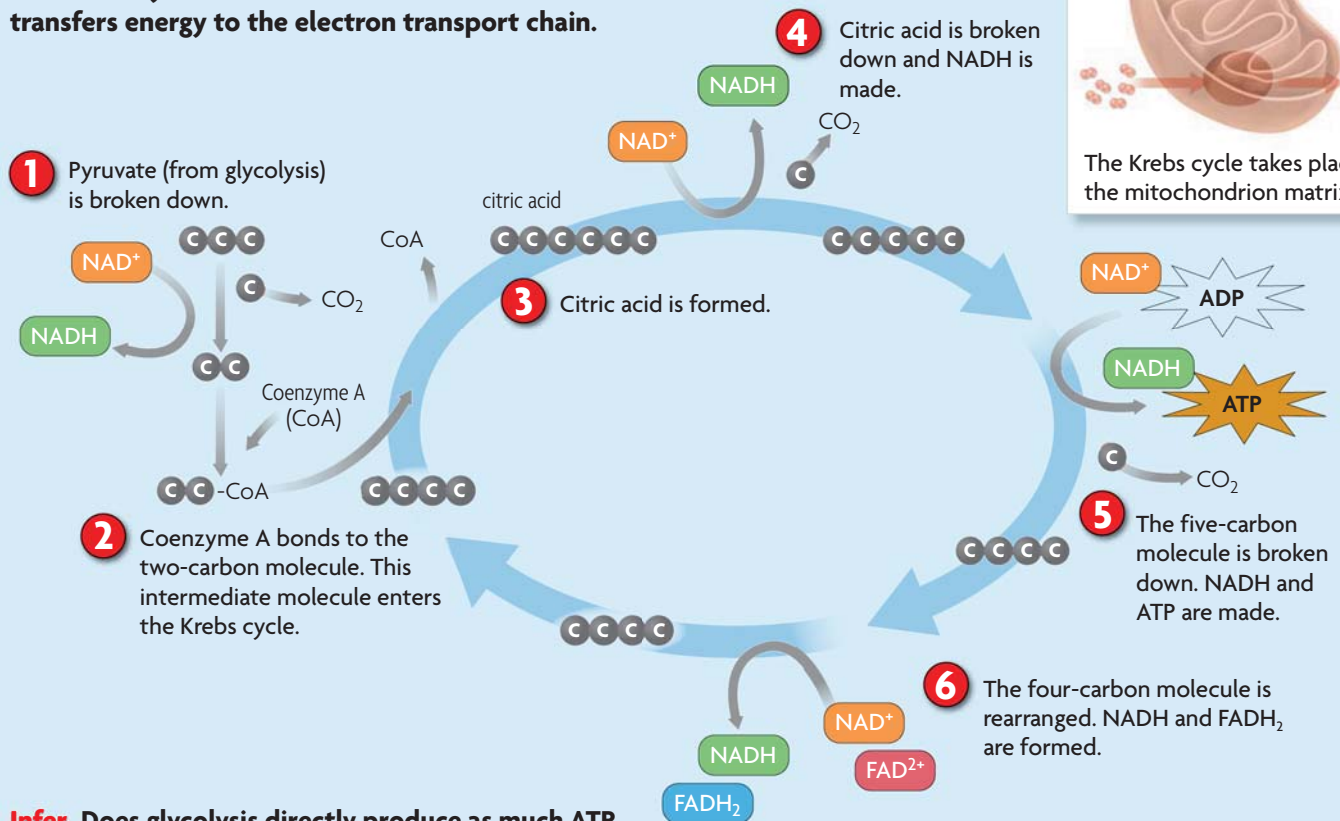


**FIGURE 4.13** Gasoline engines burn carbon-based molecules in the presence of oxygen, and they release water, carbon dioxide, and energy. The overall process of cellular respiration is similar.

- 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  $\text{NAD}^+$ , 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  $\text{FADH}_2$ , which is another electron carrier, are made. They leave the Krebs cycle and the four-carbon molecule remains.

## FIGURE 4.14 The Krebs Cycle

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



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

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<sub>2</sub> 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<sub>2</sub> molecules.

**Analyze** In what two ways is the Krebs cycle important for making ATP?

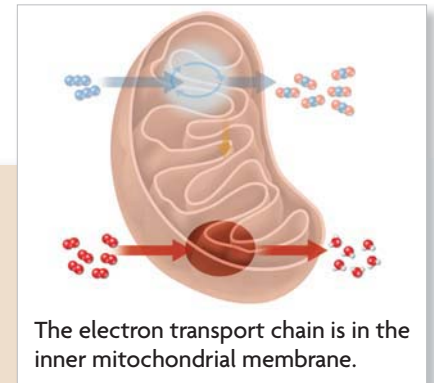
### MAIN IDEA

## 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<sub>2</sub> to pump hydrogen ions against a concentration gradient, and across the inner mitochondrial membrane.

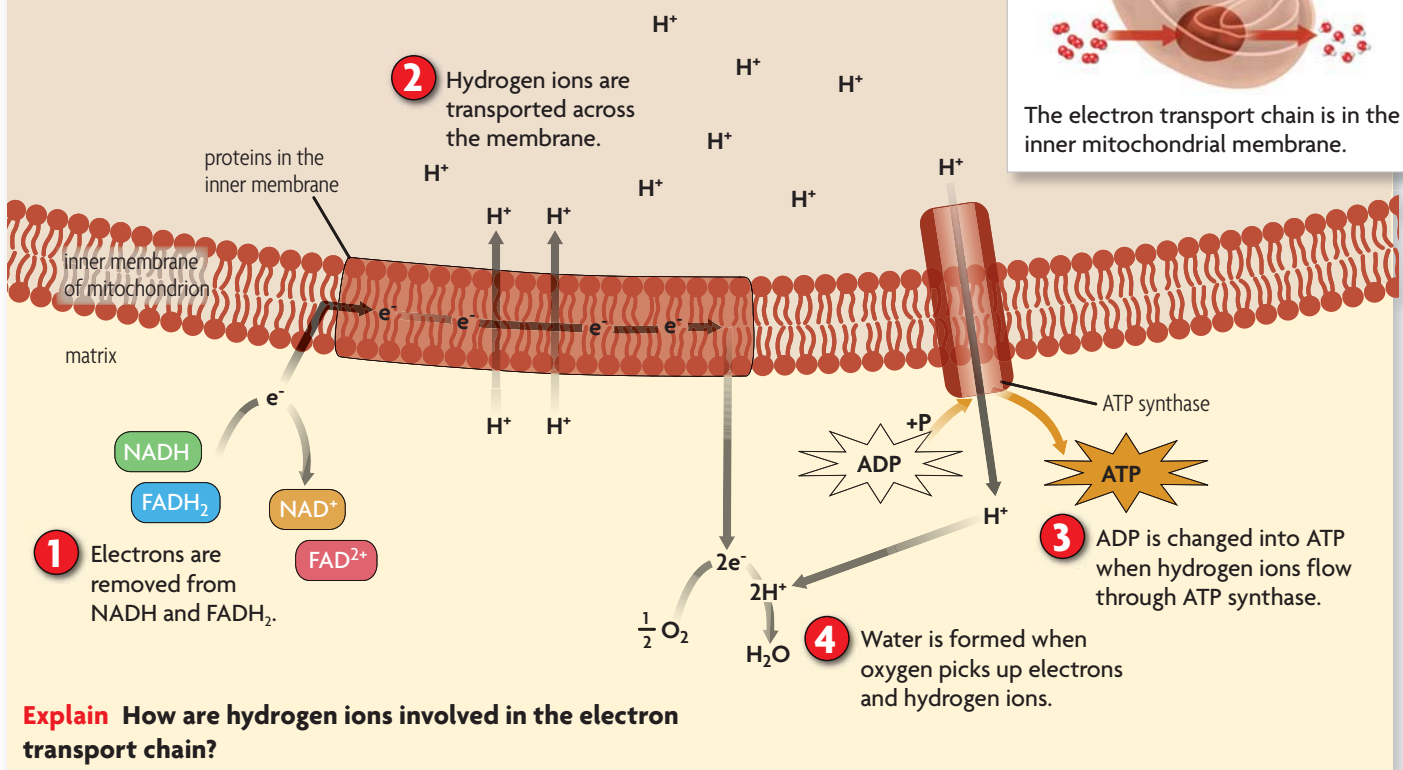
The ions later flow back through the membrane to produce ATP. Oxygen is needed at the end of the process to pick up electrons that have gone through the chain. The electron transport chain is shown in **FIGURE 4.15**.

- 1 Electrons removed** Proteins inside the inner membrane of the mitochondrion take high-energy electrons from NADH and FADH<sub>2</sub>. Two molecules of NADH and one molecule of FADH<sub>2</sub> 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 on the inside 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. The oxygen picks up electrons and hydrogen ions to form water. The water molecules are given off as a waste product.



**FIGURE 4.15 The Electron Transport Chain**

Energy from the Krebs cycle is used to produce ATP.



- 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

### 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 4.17**, and think about other similarities and differences between the processes.

FIGURE 4.17 PHOTOSYNTHESIS AND CELLULAR RESPIRATION		
	PHOTOSYNTHESIS	CELLULAR RESPIRATION
Organelle for process	chloroplast	mitochondrion
Reactants	CO <sub>2</sub> and H <sub>2</sub> O	sugars (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) and O <sub>2</sub>
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 <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) and O <sub>2</sub>	CO <sub>2</sub> and H <sub>2</sub> O

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?



**FIGURE 4.16** Like sandbags passed down a line of people, high-energy electrons are passed along a chain of proteins in the inner mitochondrial membrane.

## 4.5 ASSESSMENT



### REVIEWING MAIN IDEAS

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

### CRITICAL THINKING

4. **Compare and Contrast** Describe the similarities and differences between the Krebs cycle and the Calvin cycle.
5. **Evaluate** Is oxygen necessary for the production of all ATP in your cells? Why or why not?

### Connecting CONCEPTS

6. **Common Ancestry** 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?



# 4.6

## Fermentation

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

### ▶ MAIN IDEAS

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

### VOCABULARY

**fermentation**, p. 122

**lactic acid**, p. 123

### Review

ATP, glycolysis, cellular respiration, aerobic, anaerobic



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**Connect** Think about a time that 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

## Fermentation allows glycolysis to continue.

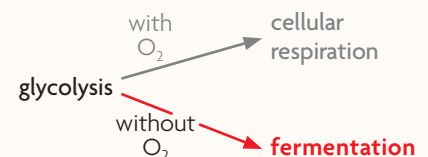
The cells in your body cannot store large amounts of oxygen for cellular respiration. The amount of oxygen that is provided by breathing is enough for your cells during normal activities. When you are reading or talking to friends, your body can maintain its oxygen levels. When you are doing high levels of activity, as the sprinter is in **FIGURE 4.18**, 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.

**Fermentation** does not make ATP, but it allows glycolysis to continue. Fermentation removes electrons from NADH molecules and recycles NAD<sup>+</sup> 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<sup>+</sup>.

### VISUAL VOCAB

**Fermentation** is an anaerobic process that allows glycolysis to continue.

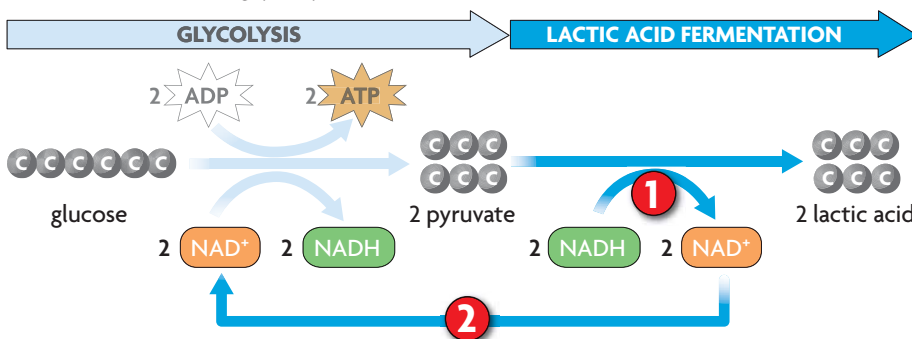


**FIGURE 4.18** Muscle cells use anaerobic processes during hard exercise.

Without  $\text{NAD}^+$  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**,  $\text{C}_3\text{H}_6\text{O}_3$ , is what causes your muscles to “burn” during hard exercise.

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



As you can see, the role of fermentation is simply to provide glycolysis with a steady supply of  $\text{NAD}^+$ . 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.

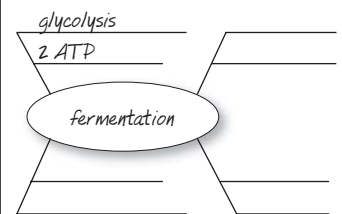
### ▶ MAIN IDEA

## 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.

### TAKING NOTES

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

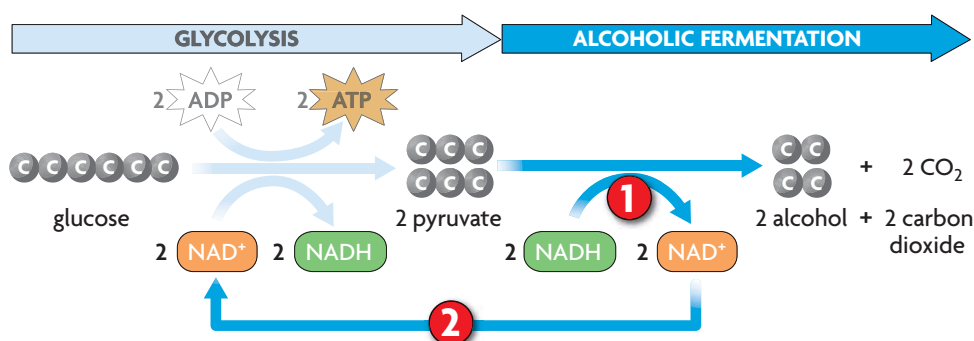


### Connecting CONCEPTS

**Human Biology** Muscle cells need ATP to contract. You will learn how muscles produce your movements in Chapter 33.

Lactic acid fermentation is not the only anaerobic process. Alcoholic fermentation is used by many yeasts and by 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  $\text{NAD}^+$ .
- 2 The molecules of  $\text{NAD}^+$  are recycled back to glycolysis. The recycling of  $\text{NAD}^+$  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  $\text{NAD}^+$ . Just like lactic acid fermentation, alcoholic fermentation recycles  $\text{NAD}^+$  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





**FIGURE 4.19** Fermentation by molds and bacteria produces the different flavors and textures of various cheeses.

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.

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

## 4.6 ASSESSMENT



### REVIEWING MAIN IDEAS

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

### CRITICAL THINKING

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

### Connecting CONCEPTS

5. **Aerobic Respiration** How is the role of oxygen in cellular respiration similar to the role of  $\text{NAD}^+$  in fermentation?

Use these inquiry-based labs and online activities to deepen your understanding of photosynthesis and cellular respiration.

## INVESTIGATION

### Cellular Respiration

Plant cells use cellular respiration to make ATP from the sugars they produce during photosynthesis. In this experiment, you will compare cellular respiration rates in dormant and germinated seeds.

**SKILLS** Measuring, Collecting Data, Graphing, Analyzing Data

**PROBLEM** How do respiration rates compare in dormant and germinated seeds?

#### PROCEDURE

1. Label the three test tubes as follows:

Tube 1: pre-soaked seeds; Tube 2: dry seeds;

Tube 3: no seeds

2. Layer into the test tubes the following materials. Be sure that the layers of materials are compact, but not too tight.

Tube 1: pre-soaked seeds, cotton plug, 1/2 tsp. potassium hydroxide, cotton plug

Tube 2: dry seeds, cotton plug, 1/2 tsp. potassium hydroxide, cotton plug

Tube 3: cotton plug, 1/2 tsp. potassium hydroxide, cotton plug

**Caution:** Potassium hydroxide is a strong base; avoid contact with eyes, skin, and clothing.

3. Use the rubber band to hold the three test tubes together.

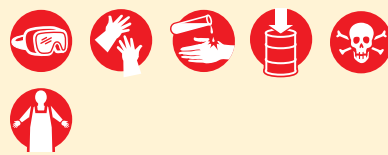
4. Pour the 25 mL of colored water into the beaker.

5. Invert the test tubes and place them in the beaker.

6. Construct a data table and record the distance that the colored water travels up each of the three test tubes.

#### MATERIALS

- 3 test tubes
- marking pen
- 6 pre-soaked seeds
- 6 dry seeds
- 6 cotton plugs
- 1.5 teaspoons potassium hydroxide (KOH) powder
- rubber band
- 100-mL beaker
- 25 mL colored water
- metric ruler



#### ANALYZE AND CONCLUDE

1. **Analyze** Choose the type of graph that best represents the data. Construct your graph.

2. **Analyze** Describe your observations and measurements of test tubes 1 and 2. What do the data show? Explain why differences between the two tubes might exist.

3. **Evaluate** What is the function of test tube 3 in the experiment? What do the measurements from this test tube demonstrate?

4. **Infer** Potassium hydroxide reacts with, and removes, carbon dioxide from the air. Why might cellular respiration be responsible for water rising into some of the test tubes?

5. **Predict** Suppose this experiment were allowed to run an additional day. What might you expect to encounter? What about after a week?



## INVESTIGATION

### Investigate Fermentation in Foods

Carbon dioxide gas is released as a waste product of fermentation in yeasts. In this experiment you will change an independent variable to change the rate of fermentation.

#### SKILL Designing Experiments

#### MATERIALS

- plastic bottles
- yeast
- foods or beverages containing sugar
- warm water
- round balloons
- balance
- spatula
- graduated cylinders
- paper towels
- string
- metric ruler



**PROBLEM** What conditions affect fermentation?

#### DESIGN

1. Choose a variable, such as temperature or concentration, to test in the experiment. Use at least two experimental conditions.
2. Design your procedure and get your teacher's approval. List the experimental constants.
3. Design a data table that includes both the independent variable and the dependent variable.
4. Conduct your experiment. Measure carbon dioxide production for 15 minutes during each experimental trial.

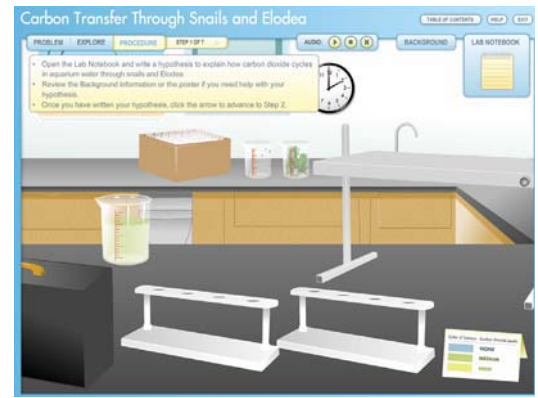
#### ANALYZE AND CONCLUDE

1. **Identify** What is your independent variable? What is the dependent variable? How did you operationally define the dependent variable?
2. **Analyze** Choose the best way to graph your data. Construct your graph.
3. **Analyze** How did your manipulation of the independent variable affect fermentation rate?
4. **Experimental Design** What are possible sources of unavoidable error in your design? Explain why they were present.

### VIRTUAL LAB

#### Carbon Dioxide Transfer Through Snails and Elodea

How does CO<sub>2</sub> cycle through a simple biological system? In this interactive lab, you will place snails and elodea in varying conditions and test for the presence of CO<sub>2</sub>.



### ANIMATED BIOLOGY

#### Mirror Processes

Are the light-dependent reactions of photosynthesis really a “mirror image” of the electron transport chain in cellular respiration? Build a diagram of each to compare how electrons move through the system.



### WEBQUEST

An athletic challenge, such as weightlifting, requires a lot of energy and can stress muscles to their limits. Complete this WebQuest to learn how athletes cope with the burn. Review how cells process energy and explore how athletes train.

## KEY CONCEPTS

Vocabulary Games

Concept Maps

Animated Biology

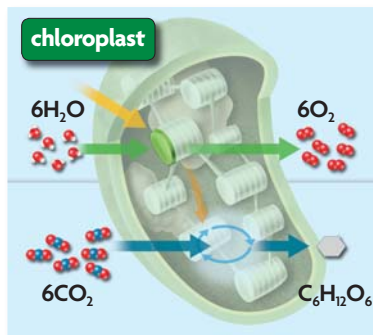
Online Quiz

### 4.1 Chemical Energy and ATP

**All cells need chemical energy.** Adenosine triphosphate (ATP) is the primary source of energy in all cells. ATP transfers energy for cell processes such as building new molecules and transporting materials.

### 4.2 Overview of Photosynthesis

**The overall process of photosynthesis produces sugars that store chemical energy.** Photosynthesis uses energy captured from sunlight to change carbon dioxide and water into oxygen and sugars. Sunlight is absorbed during the light-dependent reactions, and sugars are made during the light-independent reactions.

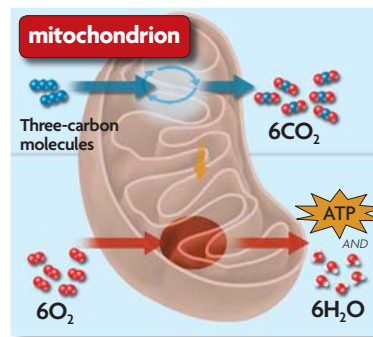


### 4.3 Photosynthesis in Detail

**Photosynthesis requires a series of chemical reactions.** Energy from sunlight is absorbed in the thylakoid membrane by photosystems II and I in the light-dependent reactions. The energy is transferred to the Calvin cycle, which builds sugar molecules from carbon dioxide.

### 4.4 Overview of Cellular Respiration

**The overall process of cellular respiration converts sugar into ATP using oxygen.** Glycolysis splits glucose and when oxygen is present the products of glycolysis are used in cellular respiration. The Krebs cycle transfers energy to the electron transport chain, which produces most of the ATP in eukaryotic cells.



### 4.5 Cellular Respiration in Detail

**Cellular respiration is an aerobic process with two main stages.** The Krebs cycle breaks down carbon-based molecules and transfers energy to electron carriers. The electron carriers provide energy to the electron transport chain. ATP is produced by the electron transport chain when hydrogen ions flow through ATP synthase.

### 4.6 Fermentation

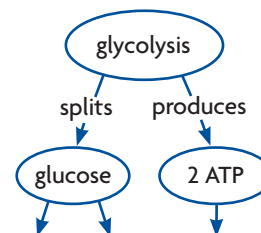
**Fermentation allows the production of a small amount of ATP without oxygen.** Fermentation allows glycolysis to continue producing ATP when oxygen is unavailable. Lactic acid fermentation occurs in many cells, including human muscle cells.

## Synthesize Your Notes

**Two-Column Chart** Compare and contrast photosynthesis and cellular respiration. Use your notes to make detailed charts that include details about both processes. Highlight important vocabulary and processes.

Photosynthesis	Cellular Respiration
absorbs sunlight	produces ATP
occurs in chloroplasts	occurs in mitochondria
$6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$	$\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$

**Concept Map** Use a concept map like the one below to summarize and organize the processes of photosynthesis, cellular respiration, and fermentation.



# Chapter Assessment

## Chapter Vocabulary

**4.1** ATP, p. 100  
ADP, p. 101  
chemosynthesis, p. 102

**4.2** photosynthesis, p. 103  
chlorophyll, p. 103  
thylakoid, p. 104  
light-dependent reactions, p. 105  
light-independent reactions,  
p. 105

**4.3** photosystem, p. 108  
electron transport chain, p. 109  
ATP synthase, p. 110  
Calvin cycle, p. 111

**4.4** cellular respiration, p. 113  
aerobic, p. 113  
glycolysis, p. 113  
anaerobic, p. 113  
Krebs cycle, p. 115

**4.6** fermentation, p. 122  
lactic acid, p. 123

## Reviewing Vocabulary

### Keep It Short

For each vocabulary term below, write a short, precise phrase that describes its meaning. For example, a short phrase to describe *ATP* could be “energy for cells.”

1. photosynthesis
2. light-dependent reactions
3. cellular respiration
4. aerobic
5. Krebs cycle
6. fermentation

### Greek and Latin Word Parts

Use the definitions of the word parts to answer the next three questions.

Prefix or Root	Meaning
<i>photo-</i>	light
<i>syn-</i>	together
<i>aero-</i>	air
<i>spirare</i>	to breathe

7. Describe how the meaning of the term *photosynthesis* is a combination of the meanings of the prefixes *photo-* and *syn-*.
8. Explain how the prefix *aero-* is related to the terms *aerobic* and *anaerobic*.
9. Why is the root *spirare* the basis of the term *cellular respiration*? Explain your answer.

## Reviewing MAIN IDEAS

10. Describe the roles of ADP and ATP in the transfer and use of energy in cells.
11. What types of carbon-based molecules are most often broken down to make ATP? Explain how ATP production differs depending on the type of carbon-based molecule that is broken down.
12. Describe how and where energy from light is absorbed during photosynthesis. What happens to the energy after it is absorbed?
13. Write the chemical equation for photosynthesis and explain what it represents.
14. What roles do electrons and hydrogen ions play in the light-dependent reactions of photosynthesis?
15. Describe how the light-independent reactions are the *synthesis* part of photosynthesis.
16. How does glycolysis contribute to the overall process of cellular respiration?
17. Write the chemical equation for cellular respiration and explain what it represents.
18. What is the function of the Krebs cycle? In your answer, describe the products of the Krebs cycle and what happens to them.
19. Explain the function of the electron transport chain in cellular respiration. Why is oxygen needed for the electron transport chain?
20. Fermentation does not produce ATP. Why is fermentation such an important process in cells?
21. How is alcoholic fermentation similar to lactic acid fermentation? How is it different?

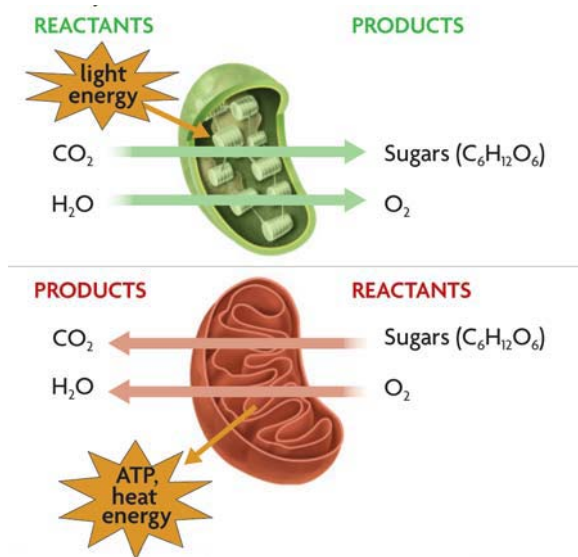


## Critical Thinking

- 22. Infer** Human brain cells do not use fermentation. Explain why a lack of oxygen for even a short period of time might result in the death of brain cells.
- 23. Apply** Energy is transferred in several different ways during photosynthesis and cellular respiration. Give two examples of how energy is transferred in the processes. Explain both examples.
- 24. Analyze** How do photosynthesis and cellular respiration form a cycle of energy storage and use?
- 25. Synthesize** How do cellular respiration and fermentation depend on glycolysis? How does glycolysis depend on aerobic and anaerobic processes?
- 26. Analyze** Consider the following two groups of processes:
- light-dependent reactions and electron transport chain
  - Calvin cycle and Krebs cycle
- Which pair is nearly identical? Which is nearly opposite? Explain.

## Interpreting Visuals

Use the diagram to answer the next three questions.



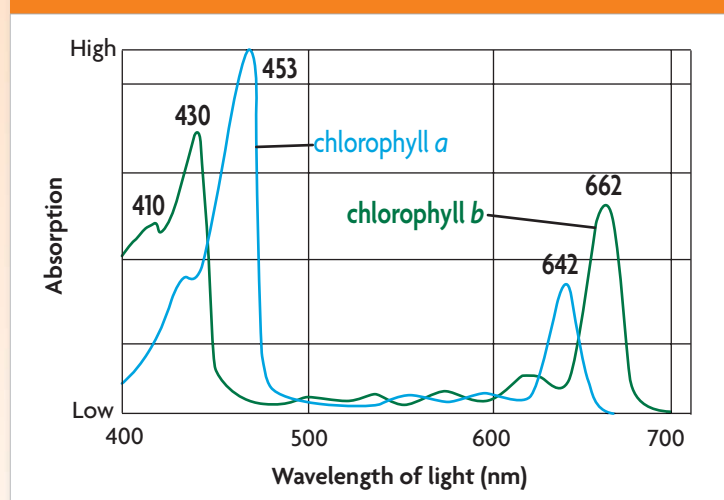
- 27. Apply** Which process stores energy? Which process releases energy? How do you know?
- 28. Infer** Use information in the visual to explain why a plant would be able to survive in a sealed transparent container.
- 29. Infer** Which of the processes in the diagram is necessary for most living things to survive? Explain.

## Analyzing Data

Use information in the text and the graph below to answer the next two questions.

Plants have several different molecules that together absorb all of the different wavelengths of visible light. Visible light ranges between the wavelengths of about 400 and 700 nanometers (nm).

### ABSORPTION OF LIGHT BY CHLOROPHYLL



- 30. Analyze Data** What range of wavelengths is absorbed by chlorophyll *a*? chlorophyll *b*?
- 31. Synthesize** Suppose a type of plant has only chlorophylls *a* and *b* and is exposed to different wavelengths of light. At which wavelengths would there be the greatest amounts of carbon dioxide in the air around the plants? The least? Explain your answers.

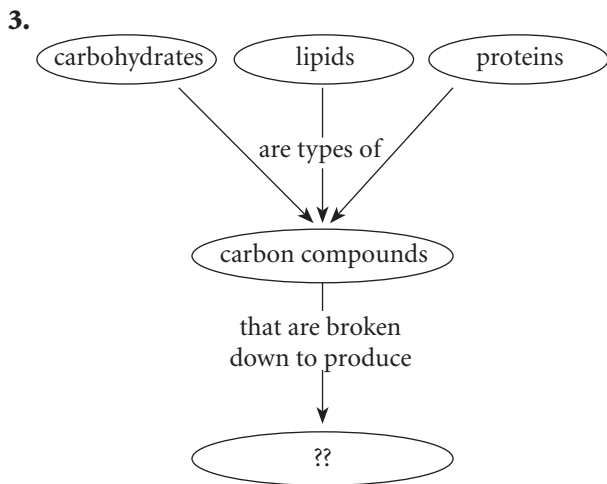
## Connecting CONCEPTS

- 32. Write an Analogy** Suppose that photosynthesis or cellular respiration takes place in a factory. You are a tour guide at the factory, explaining each step of the process to a group of visitors. Use analogies to describe what happens at each step. For example, you could describe the photosystems of photosynthesis as “the green machines next to windows to absorb light.” Be sure to include important details of the process you select.
- 33. Analyze** Look at the micrograph of diatoms and the photograph of the whale on pages 98–99. Write a paragraph that explains the two ways in which the whale depends on diatoms for the energy that its cells need.



1. A group of students wants to find out how much carbon dioxide is used by plants during the daytime. What control could be used in this experiment?
- A the amount of water used during the daytime
  - B the amount of oxygen released at night
  - C the amount of carbon dioxide used at night
  - D the amount of oxygen used during the daytime

2. Which of the following groups of organisms uses cellular respiration in mitochondria to produce ATP for their energy needs?
- A plants only
  - B eukaryotes
  - C animals only
  - D prokaryotes



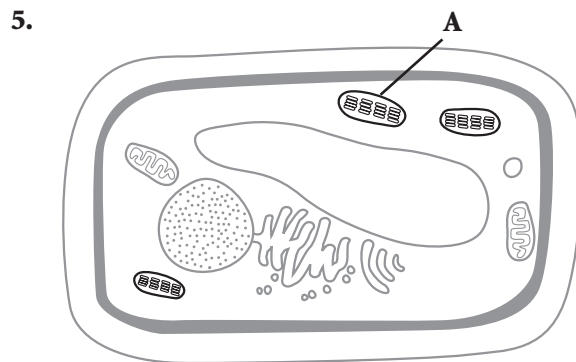
This concept map shows some of the carbon-based molecules in cells. Some of these molecules can be broken down to produce usable chemical energy. Which of the following terms *best* completes this concept map?

- A electrons
- B ATP
- C lactic acid
- D hydrogen ions

4. Photosynthesis is a part of various cycles that help to move oxygen and carbon through the environment. What form of abiotic carbon do plants remove from the environment?
- A glucose
  - B starch
  - C carbon dioxide
  - D ATP

### THINK THROUGH THE QUESTION

Some terms in questions, such as biotic or abiotic, may be unfamiliar to you. Often, terms like these are used to present an example but are not necessary to answer the question. Find the important pieces of information in the question and focus on those points.



Which of the following *best* represent the final products of the chemical reactions that take place inside the organelle labeled A in this diagram?

- A sugars, oxygen
- B ATP, electrons
- C ATP, sugars
- D carbon dioxide, water

6. Which process is represented by the following chemical equation?



- A photosynthesis
- B fermentation
- C glycolysis
- D cellular respiration