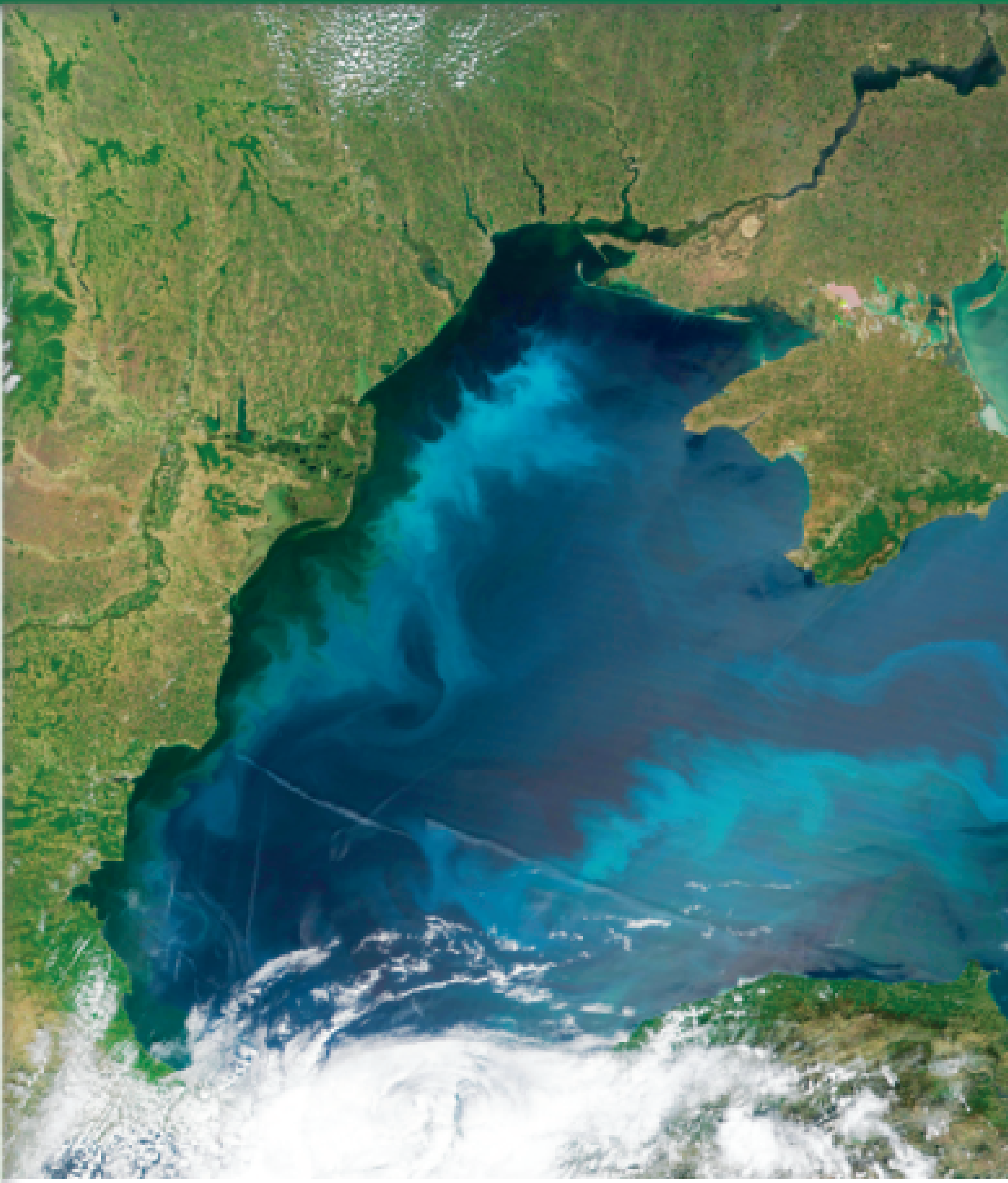
CHAPTER

5

Photosynthesis and Cellular Respiration



Chapter Concepts

5.1 Matter and Energy Pathways in Living Systems

- Photosynthesis, the process in which certain organisms trap solar energy, occurs in chloroplasts.
- Cellular respiration, the process in which energy-rich compounds are broken down to generate ATP, occurs in mitochondria.
- ATP is the source of energy for many of the chemical reactions that occur in cells.

5.2 Photosynthesis Stores Energy in Organic Compounds

- In light-dependent reactions, chloroplasts trap solar energy and transform the energy to the reducing power of NADPH and the chemical energy of ATP.
- Chemiosmosis is the mechanism by which energy stored in a concentration gradient is used to generate ATP.
- In light-independent reactions, the energy of ATP and NADPH is used to reduce carbon dioxide to synthesize glucose.

5.3 Cellular Respiration Releases Energy from Organic Compounds

- Aerobic cellular respiration involves three metabolic pathways: glycolysis, the Krebs cycle, and an electron transport system.
- Aerobic cellular respiration is the complete oxidation of glucose to release energy.
- Fermentation is the incomplete oxidation of glucose to release energy.

More than half of all oxygen generated on Earth is produced by phytoplankton—photosynthetic producers—in the oceans. When conditions of water temperature and nutrients are just right, the phytoplankton grow rapidly, or "bloom," producing large amounts of chlorophyll, which are visible to orbiting satellites (light blue in this photograph). Scientists have discovered that these "blooms" might do more than provide oxygen. They might also serve as an early warning of earthquakes along coastal regions. Prior to an earthquake, the ocean floor begins to shift. This causes an upwelling of nutrient-rich water from the ocean bottom. As the nutrients near the surface, they contribute to conditions that stimulate a bloom. When unexpected blooms appear near regions where tectonic plates meet, they may indicate that an earthquake and possibly a tsunami are imminent.

Only plants, algae, and some species of bacteria can convert the Sun's light energy into chemical energy. Is the way that plants use energy different from the way that your body uses energy?

Launch Lab

Seeing Green

In a functioning green plant, light energy is trapped by light-absorbing molecules called pigments and used to synthesize carbohydrates from carbon dioxide and water. The main photosynthetic pigment is chlorophyll. What effect does light have on chlorophyll if it is removed from a living plant?

Materials

- beaker of prepared chlorophyll solution (provided by your teacher)
- strong light source (such as a slide projector)

Procedure

1. In a darkened room, shine a strong beam of light at a sample of chlorophyll solution.
2. Observe the colour of the chlorophyll by viewing the sample at a slight angle.
3. Observe the colour of the chlorophyll by viewing the sample at a right angle to the beam of light.
4. Describe the colour you see in steps 2 and 3.

Analysis

1. Recall, from previous studies, that visible light is a mixture of different colours (wavelengths). Which colours of light do you think chlorophyll absorbs? Explain your reasoning.
2. Chlorophyll has a property called fluorescence. When a pigment molecule absorbs a specific colour (wavelength) of light, its electrons become "excited"—that is, they move to a higher energy state. Almost immediately, the excited electrons return to their original, lower-energy state as they emit (give off) the energy they absorbed. The emitted energy is visible as light of a longer, lower-energy wavelength. In which step did you observe fluorescence? Suggest a possible explanation for what you observed.

SECTION 5.1

Matter and Energy Pathways in Living Systems

Section Outcomes

In this section, you will
- **compare** and **summarize** the essential features of chloroplasts and mitochondria in relation to the role of photosynthesis in storing energy and the role of cellular respiration in releasing energy
- **summarize** and **explain** the role of ATP in cellular metabolism

Key Terms

photosynthesis
cellular respiration
chloroplast
thylakoids
mitochondria
metabolism
reducing power

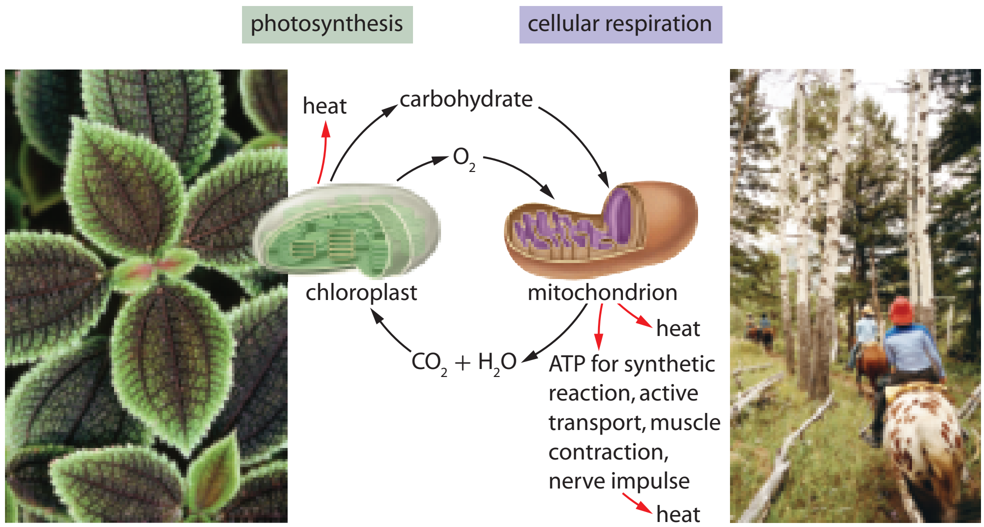


Figure 5.1 Chloroplasts trap the Sun's energy and use it to synthesize energy-rich compounds. Animals either eat the plants or other plant-eating animals. These consumers then use the stored, energy-rich compounds to generate ATP to fuel all life functions.

In Unit 1, you examined the processes of photosynthesis and cellular respiration as they relate to the connections between organisms and the biosphere. In this chapter you will look more closely at these energy-capturing and energy-releasing processes as they relate to the needs of individual organisms.

Photosynthesis: Capturing and Converting Light Energy from the Sun

Life on Earth is possible only because the Sun provides a constant input of energy in the form of light. Living organisms trap, store, and use energy to maintain and sustain cells. An overview of these general life processes is shown in Figure 5.1. All organisms need some form of energy to survive. Green plants and most other photosynthesizing organisms (autotrophs) have chloroplasts that contain the molecules that trap the Sun's energy and convert it to chemical energy. Non-photosynthesizing organisms (heterotrophs) must consume photosynthetic organisms or other heterotrophs to obtain the chemical energy they need.

In the process of **photosynthesis**, chloroplasts in autotrophs convert solar energy into chemical energy and store this in sugars and other carbohydrates. The by-products of photosynthesis are oxygen, molecules of ATP (which you will learn about shortly), and some heat. Some of the energy-rich compounds that result from photosynthesis are used immediately, and some are stored (as starch or converted to fat) for future use.

Cellular Respiration: Releasing Stored Energy

The chemical energy of compounds such as glucose is stored in their chemical bonds. All organisms must break down the energy-rich compounds—break down the chemical bonds—to release and use the energy.

In the process of **cellular respiration**, mitochondria in the cells of plants, animals, and other multicellular organisms break down carbohydrates (and other energy-rich products derived from them such as fats) to generate molecules of ATP. ATP is short for adenosine triphosphate, and it is the source of energy that all organisms use

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FYI
Some species of bacteria can perform photosynthesis. They do not have any membrane-bound organelles such as chloroplasts. However, the folds of membranes connected to their plasma membrane contain molecules that capture the Sun's energy for photosynthesis.

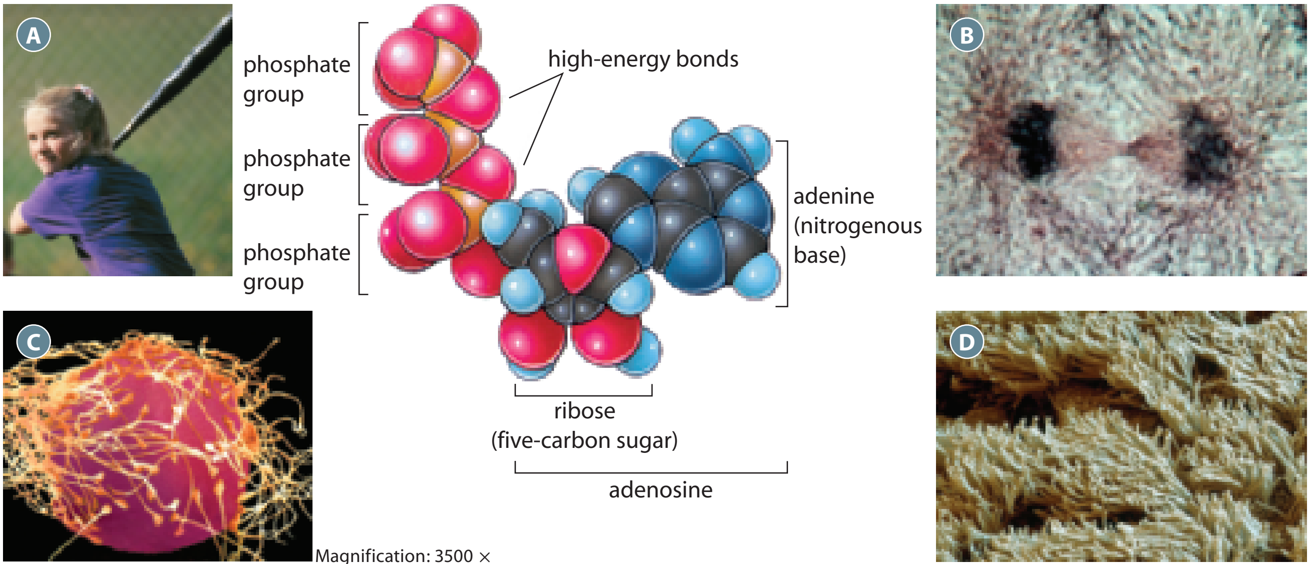

Figure 5.2 ATP is the source of energy for activities such as muscle contraction **(A)**, cell division **(B)**, flagella movement **(C)**, and cilia movement **(D)**. The adenosine part of ATP is composed of a molecule called adenine, which is bonded to a five-carbon sugar called ribose. Our bodies use about 40 kg of ATP daily. The amount of ATP available at any moment is enough to meet only immediate cellular needs. Thus, ATP must be synthesized constantly.

for nearly all cellular activities (Figure 5.2). This molecule is sometimes referred to as "the energy currency" of cells because when cells need energy they "spend" ATP.

ATP and Cellular Activity

ATP supplies the energy for cellular activities that include those listed below. Although ATP is always being used, sometimes quite rapidly, cells maintain an amazingly constant supply of ATP.

- active transport of ions and molecules across cell membranes
- moving chromosomes during cell division
- causing cilia and flagella to move
- causing muscles to contract
- synthesizing compounds such as carbohydrates, proteins, fats, and nucleic acids

How does ATP supply energy for cellular activity? As you can see in Figure 5.3, when the bond to the third phosphate group in ATP breaks, the energy from ATP is released. The reaction produces ADP or adenosine diphosphate—adenosine plus *two* phosphate groups—and a free phosphate group Ⓟ. ATP is then regenerated by the addition of a free phosphate group Ⓟ to ADP—a process that requires an input of energy. Molecules of ATP are broken down and regenerated thousands of times each day. The chemical energy that is released when the bond to the third phosphate group is broken enables most life-sustaining cellular activities to take place.

1. What is accomplished by the process of photosynthesis?
2. What is the function of cellular respiration?
3. What is ATP?
4. In terms of energy consumed and energy released, how is ATP related to ADP?

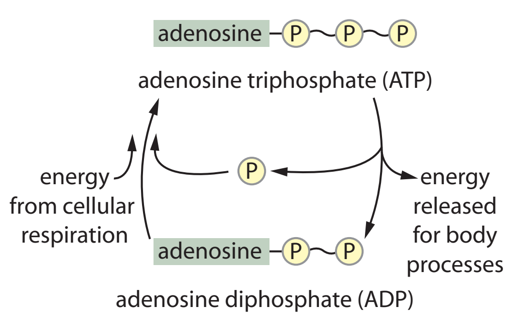

Figure 5.3 The release of a phosphate group from ATP and the subsequent regeneration of ATP from ADP creates a continuous cycle.

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Web Link
What if heart pacemakers, which are powered by batteries that require replacement every five to ten years, could be fueled by ATP? This is one of the questions guiding the investigation of ATP as a possible source of energy for implanted devices. What is the current state of this research?

www.albertabiology.ca
WWW

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FYI

In June 2005, a team of researchers, led by J. Thomas Beatty from the University of British Columbia, discovered evidence of green sulfur bacteria—a type of bacteria that lives in anoxic (non-oxygen) environments—living *photosynthetically* more than 2000 m deeper than sunlight can penetrate. The researchers hypothesize that the bacteria are adapted to capture energy from the extremely low-level radiation emitted from deep sea thermal vents.

Chloroplasts: Site of Photosynthesis

Parts of plants and many species of algae are green in colour because they contain chlorophyll, the green-coloured molecules that trap solar energy. Chlorophyll is the pigment you used in the Launch Lab on page 161 and is contained within cell organelles called **chloroplasts**. Most photosynthetic cells contain anywhere from 40 to 200 chloroplasts. A typical leaf may have 500 000 chloroplasts per square millimeter!

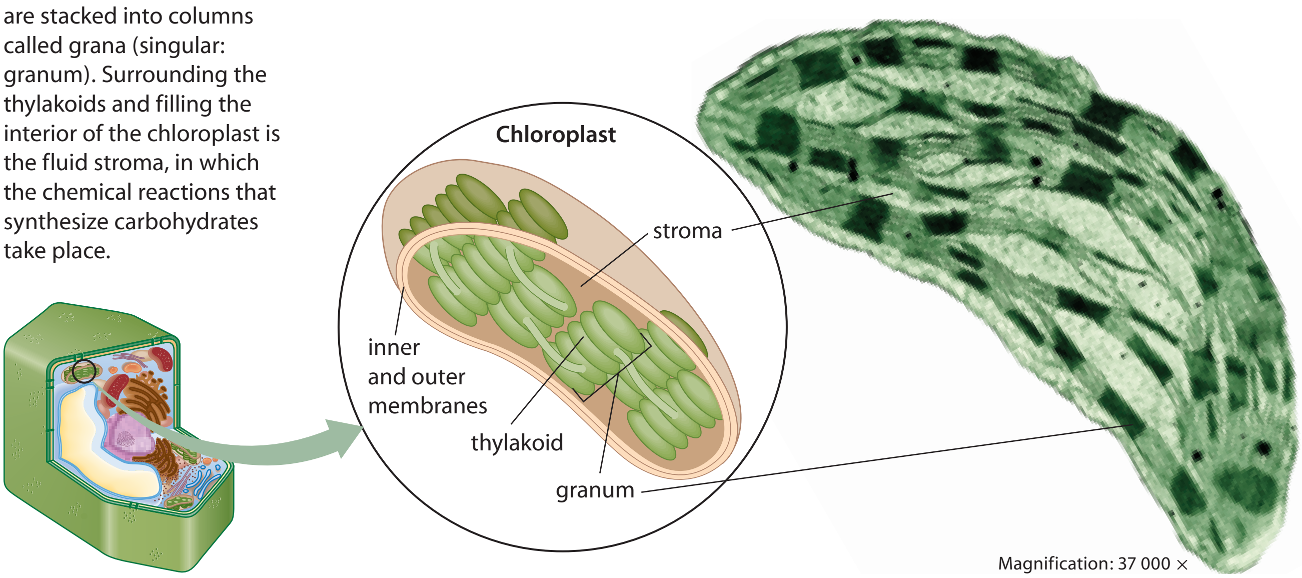
Chloroplasts are about 4 μm–6 μm in diameter and 1 μm–5 μm thick. They are bound by two membranes: an outer membrane and an inner one. The fluid in the inner space of a chloroplast, called the *stroma*, contains a concentrated mixture of proteins and other chemicals that are used in the synthesis (making) of carbohydrates. A third membrane system within the stroma is organized into interconnected flattened sacs called **thylakoids**. In some regions of the stroma, thylakoids are stacked up in structures called *grana*. Chlorophyll molecules are located in the thylakoid membranes of the chloroplast (Figure 5.4).

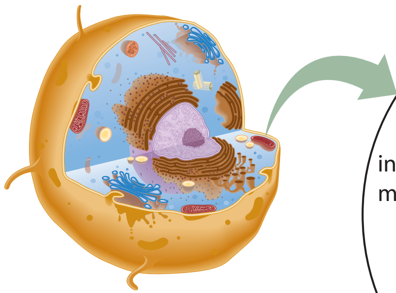
Mitochondria: Site of Cellular Respiration

The cells of eurkaryotic organisms (plants, animals, fungi, and protists) contain **mitochondria**. These are the organelles that enable cells to efficiently extract energy from their food (Figure 5.5). Mitochondria are smaller than chloroplasts, ranging from 0.5 μm–1.0 μm in diameter and 2 μm–5 μm in length. Like chloroplasts, mitochondria are bounded by two membranes. The fluid-filled space of the inner membrane is called the *matrix*. It contains proteins and other chemicals needed to break down carbohydrates and other high-energy molecules. The inner membrane has numerous folds, called *cristae*, which provide a large surface area for the production of ATP.

5. What is chlorophyll?
6. Where, in a typical plant cell, are the green parts located? Name the organelle, where it is often located in the cell, and the part of the organelle to which the green material is attached.
7. What is the function of mitochondria?
8. Name the life forms that contain mitochondria in their cells.

Figure 5.4 The flattened thylakoids in the chloroplasts of plant cells are stacked into columns called grana (singular: granum). Surrounding the thylakoids and filling the interior of the chloroplast is the fluid stroma, in which the chemical reactions that synthesize carbohydrates take place.





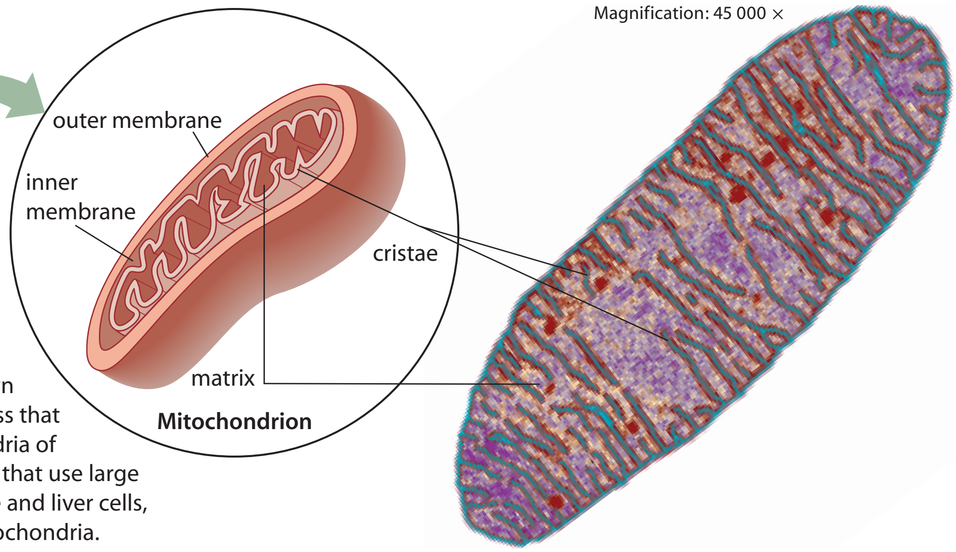


Figure 5.5 Glucose is broken down during cellular respiration, a process that is completed within the mitochondria of plant cells and animal cells. In cells that use large amounts of energy, such as muscle and liver cells, there may be as many as 1000 mitochondria.

Metabolic Pathways and Energy for Cellular Reactions

As you have seen in Unit 1, the chemical reaction for photosynthesis can be summarized as:

$$6CO_2(g) + 6H_2O(\ell) + \text{energy} \rightarrow C_6H_{12}O_6(s) + O_2(g)$$

The chemical reaction of cellular respiration can be summarized as:

$$C_6H_{12}O_6(s) + O_2(g) \rightarrow 6CO_2(g) + 6H_2O(\ell) + \text{energy}$$

Photosynthesis in chloroplasts and cellular respiration in mitochondria are intimately related. Photosynthesis uses the products of respiration as its starting reactants, and cellular respiration uses the products of photosynthesis as its starting reactants.

The reactions appear to be exact opposites of each other. However, these are *overall* reactions. They represent a *summary* of a series of reactions that, in combination, result in the reactions shown here. By analyzing the cellular respiration reaction, you will see why the summary equation represents a series of reactions.

The reaction that releases energy during cellular respiration is essentially the same as the combustion reaction that releases energy during the burning of wood, as shown in Figure 5.6. The cellulose in wood that burns in air is made of thousands of units of glucose ($C_6H_{12}O_6(s)$). A very high temperature is needed to start and maintain the burning of wood. The cells in living systems could not survive the high temperatures and large energy output of a combustion reaction. Instead, the reactions that occur in living cells take place in a very large number of controlled reactions. They occur in step-by-step sequences called *metabolic pathways*. In a metabolic pathway, the product of one reaction becomes the starting reactant for another.

Enzymes Catalyze Cellular Metabolism and Energy Production

The term **metabolism** refers to all the chemical reactions that occur within a cell to support and sustain its life functions. Two broad categories of reactions make up metabolism. *Anabolic* metabolic pathways synthesize larger molecules from smaller ones and require energy. *Catabolic* metabolic pathways break down larger molecules into smaller ones and release energy.

These chemical reactions do not occur unless they are activated in some way. Often, the energy for activating a reaction comes from heating the reactants. (Think of using a match to start those logs burning.) However, heating would destroy living cells, so another method is needed to activate metabolic reactions. All metabolic reactions are catalyzed by enzymes—specialized proteins that lower the energy needed to activate

Figure 5.6 An initial input of energy is necessary to start logs burning. The burning of each bit of wood almost immediately starts the combustion reaction in adjacent bits of wood. A very high temperature is necessary to keep the logs burning.

INVESTIGATION 5.A

Target Skills

Collecting and **interpreting** experimental data to identify the gases released as a result of metabolic processes

Gases Released During Photosynthesis and Cellular Respiration

Photosynthesis and cellular respiration are chemical reactions that produce by-products in the form of gases. How can you detect and identify the gas that plants release? How can you determine what gases you are exhaling?

Question

How can you identify the gases released by plants and animals?

Safety Precautions

- NaOH(aq) is caustic and will burn skin. If contact occurs, inform your teacher immediately and wash your skin under cold running cold water for 10 min.
- When you blow into any solution, *do not inhale* at any time.

Materials

- 600 mL beaker
- $NaHCO_3$(s)
- *Cabomba* (or other aquatic plant)
- bright lamp (or grow light)
- test tube and stopper
- short stemmed funnel
- wooden splint
- matches
- 0.1 mol/L NaOH(aq) in dropping bottle
- 50 mL Erlenmeyer flask and stopper
- bromothymol blue
- straw

Procedure

Part 1: Gas Released by Plants

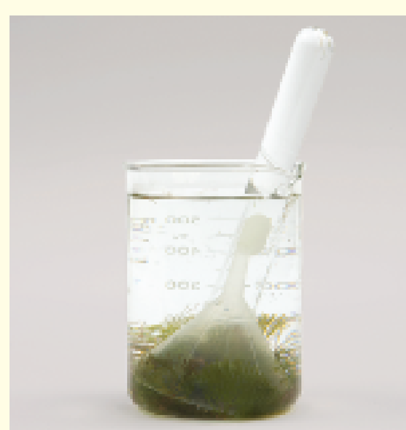
The first 5 steps must be completed the day before the remainder of the investigation is completed.

1. Fill a 600 mL beaker with aquarium water or tap water. Add 2 g of sodium hydrogen carbonate to the water.
2. Hold the small branches of *Cabomba* (or other aquatic plant) under water and clip off the ends of the stems so that air bubbles do not block the vessels.
3. Place a short-stemmed funnel over the branches.
4. Fill a test tube with water and cover the top while you invert it. Hold it under water and position it over the stem of the funnel as shown. Be sure there is no air in the test tube.
5. Place the apparatus in bright light and leave it until the next class period.
6. After about 24 h, carefully remove the test tube, keeping it inverted, put your thumb over the mouth of the test tube, and stopper it. Follow the directions below to test for the type of gas in the tube. Record your results.

Testing for Gases

Note: For safety purposes, your teacher may conduct some or all of these steps.

1. Wear goggles.
2. Keep the stoppered test tube containing a collected gas inverted and clamp it to a ring stand.
3. Ensure that there are no flammable materials, other than those with which you are working, in the room.
4. Light the wooden splint. Let it burn briefly then blow out the flame. The splint should still be glowing.
5. Gradually insert the glowing splint up into the inverted test tube. Observe the reaction.
   - If the gas is hydrogen, you will hear a loud pop when the splint reaches the gas.
   - If the gas is carbon dioxide, the splint will go out.
   - If the gas is oxygen, the splint will burn faster and you will see a flame.



Part 2: Gas Exhaled by Animals

1. Add about 35 mL of water to a 50 mL Erlenmeyer flask. Add a few drops of bromothymol blue to the water and swirl. (Place the flask on a piece of white paper to see the colour more clearly.)
2. Add sodium hydroxide one drop at a time and gently swirl the flask. Stop adding the sodium hydroxide when the water turns a deep greenish-blue colour.
3. Obtain a straw and blow gently into the flask. *Do not suck on the straw*. Continue to blow into the solution until you can no longer see any colour change.
4. Add a piece of *Cabomba* to the water and stopper the flask. Place it in a brightly lighted place. Leave it in place until you see a change. Record any changes over the next 24 h.

Analysis

1. What happened when you inserted the glowing splint into the test tube that had been collecting gas from the *Cabomba* plant? What is the identity of the gas?
2. Bromothymol blue is called a pH indicator because it changes colour with changes in pH (acidity) of a solution. It is a dark greenish-blue colour in a basic solution and a pale yellow colour in an acidic solution. What happened when you blew into the flask?
3. Read the following points then identify the gas in your exhaled breath.
   - Oxygen gas has very low solubility in water and does not react chemically with water.
   - Hydrogen gas is nearly insoluble in water and does not react with water.
   - Carbon dioxide is relatively soluble in water and reacts with water to produce carbonic acid.

Conclusion

4. Explain the source of the gas that you collected in the test tube over the *Cabomba* plant.
5. Explain the source of the gas that you exhaled.
6. Explain any changes in the appearance of the solution after Step 4 of Part 2.

biological reactions. Each of the thousands of reactions that occur in living cells has a specific enzyme that enables the reaction to proceed rapidly.

Q 9 Which releases energy: metabolic pathways that synthesize larger molecules from smaller ones or metabolic pathways that break down larger molecules into smaller ones?

Linking Reactions through Oxidation and Reduction

When an atom or molecule loses an electron, it is said to be oxidized, and the process by which this occurs is called *oxidation*. Conversely, when an atom or molecule gains an electron, it is said to be reduced, and the process is called *reduction*.

The electrons that are lost by one atom or molecule cannot exist on their own. They must combine with another atom or molecule. Thus, when one compound is oxidized (loses electrons), another compound must be reduced (gain electrons). This link between oxidation and reduction reactions is shown in Figure 5.7.

All compounds or atoms contain more energy in their reduced form than they do in their oxidized form. Energy-rich compounds (such as glucose) are in their reduced form. Molecules that, in their reduced form, contain a large amount of available energy are said to have **reducing power**.

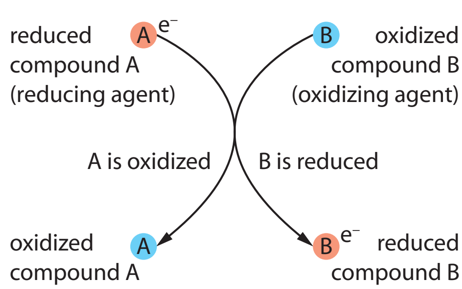


Figure 5.7 Oxidation and reduction reactions take place at the same time. If one compound is oxidized, another compound must be reduced. (That is, when one compound loses electrons, another compound gains those electrons.) Oxidation-reduction reactions are often called redox reactions for short.

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FYI

A simple way to help you remember what happens to electrons in an oxidation reaction and a reduction reaction is to remember the phrase, "LEO the lion says GER." LEO stands for "**L**oss of **E**lectrons is **O**xidation" and GER stands for "**G**ain of **E**lectrons is **R**eduction." In Alberta, it might be more appropriate to use the acronym, OIL RIG. **O**xidation **I**s **L**oss. **R**eduction **I**s **G**ain.

Q 10 What happens to the electrons that are lost by a compound that is undergoing an oxidation reaction?

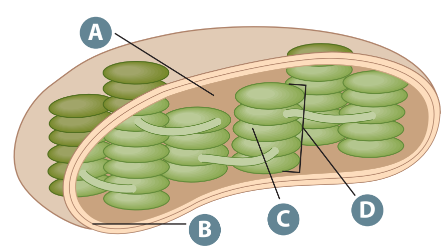
Q 11 Which contains more energy: a compound in its oxidized form or a compound in its reduced form?

Section 5.1 Summary

- Photosynthesis is the process by which plants and other photosynthetic organisms trap the Sun's energy and transform it into energy-rich chemical compounds.
- Cellular respiration is the process by which cells break down high-energy compounds and generate ATP.
- ATP is the direct source of energy for nearly all types of energy-requiring activities of living organisms.
- Chloroplasts have two outer membranes, an inner solution called the stroma, and a membrane system consisting of flattened sacs called thylakoids. Stacks of thylakoids are called grana.
- Chlorophyll molecules, the molecules that trap solar energy, are bound to the thylakoid membranes in chloroplasts.
- Chlorophyll gives plants their green colour.
- Mitochondria have outer and inner membranes that surround a fluid-filled region called the matrix. The inner membrane has many deep infoldings called cristae.
- The chemical reactions of photosynthesis and cellular respiration take place in a series of many step-by-step reactions called metabolic pathways.
- Enzymes are biological catalysts that reduce the amount of startup energy needed for the reactions in the metabolic pathways. In the absence of enzymes, the reactions could not occur at temperatures at which living organisms thrive.
- When a compound is oxidized in a chemical reaction, it loses electrons.
- When a compound is reduced in a chemical reaction, it gains electrons.
- Compounds contain more chemical energy in their reduced form than they do in their oxidized form.

Section 5.1 Review

1. Trace, in general terms, the path of energy from the sun to the contraction of a muscle in a predator such as a mountain lion (*Puma concolor*).
2. An autotroph is defined as an organism that makes its own food. Explain how this term describes photosynthetic organisms.
3. Use word processing or spreadsheet software to create a chart that compares and contrasts the process of photosynthesis and cellular respiration. ICT
4. Explain why it is appropriate to call ATP the "energy currency" of cells.
5. Use graphics software to draw a sketch or model of a molecule of ATP. Label the different groups that make up this molecule. ICT
6. Use graphics or word processing software to sketch the ATP energy cycle. Use the sketch to explain how this cycle enables life-sustaining cellular activities. ICT
7. Identify the regions of the chloroplast indicated on this diagram. Describe what happens in B and C.



8. Identify the part of a mitochondrion that performs a function related to the processes that occur in the stroma of chloroplasts. Explain your reasoning.
9. Define the term "metabolism," and explain the meaning of the term "metabolic pathway."
10. Explain the meaning of the term "reducing power."

SECTION
5.2

Photosynthesis Stores Energy in Organic Compounds

Section Outcomes

In this section, you will
- **describe** how pigments absorb light energy and transfer it as reducing power in NADPH
- **explain** how absorbed light energy is transferred to the chemical potential energy of ATP by chemiosmosis
- **describe** where the energy transfer processes take place in chloroplasts
- **explain** how scientific knowledge may lead to the development of new technologies
- **collect** and **interpret** data and calculate R_f values from chromatography experiments
- **conduct** investigations in print and electronic resources on C_3 and C_4 photosynthetic mechanisms

Key Terms

light-dependent reactions
light-independent reactions
electron transport system
photosystems
chemiosmosis
carbon dioxide fixation
Calvin-Benson cycle

Photosynthesis transforms the energy of sunlight into the chemical energy of glucose. As you know from Chapter 1, only a small portion of the Sun's total energy output reaches Earth's surface. An even smaller portion of this is used for photosynthesis. Even so, photosynthesizing organisms use that tiny fraction of the Sun's energy to synthesize about 1.4×10^{15} kg of energy-storing glucose and other sugars each year. That's enough sugar to fill a chain of railway boxcars reaching to the Moon and back 50 times.

Much of the glucose produced by plants is converted to cellulose (fibre) and other structural tissues. Glucose may also be converted to other sugars as well as storage forms of carbohydrates such as starch. In addition, sugars produced by photosynthesis are involved in the synthesis of other essential cellular substances such as amino acids, which are needed to make proteins. In fact, the products of photosynthesis account for nearly 95 percent of the dry weight of green plants. Other organisms—including humans—depend on the molecules, tissues, and substances that plants synthesize for their own use (Figure 5.8).

The Process of Photosynthesis

$$6CO_2(g) + 6H_2O(\ell) + \text{energy} \rightarrow C_6H_{12}O_6(s) + O_2(g)$$

The summary equation for photosynthesis tells you that the starting reactants are carbon dioxide and water, and the end products are glucose and oxygen. There is, however, much that takes place between what appears on the left side of the equation and the result on the right side of the equation.

The arrow in the photosynthesis equation represents over 100 distinct

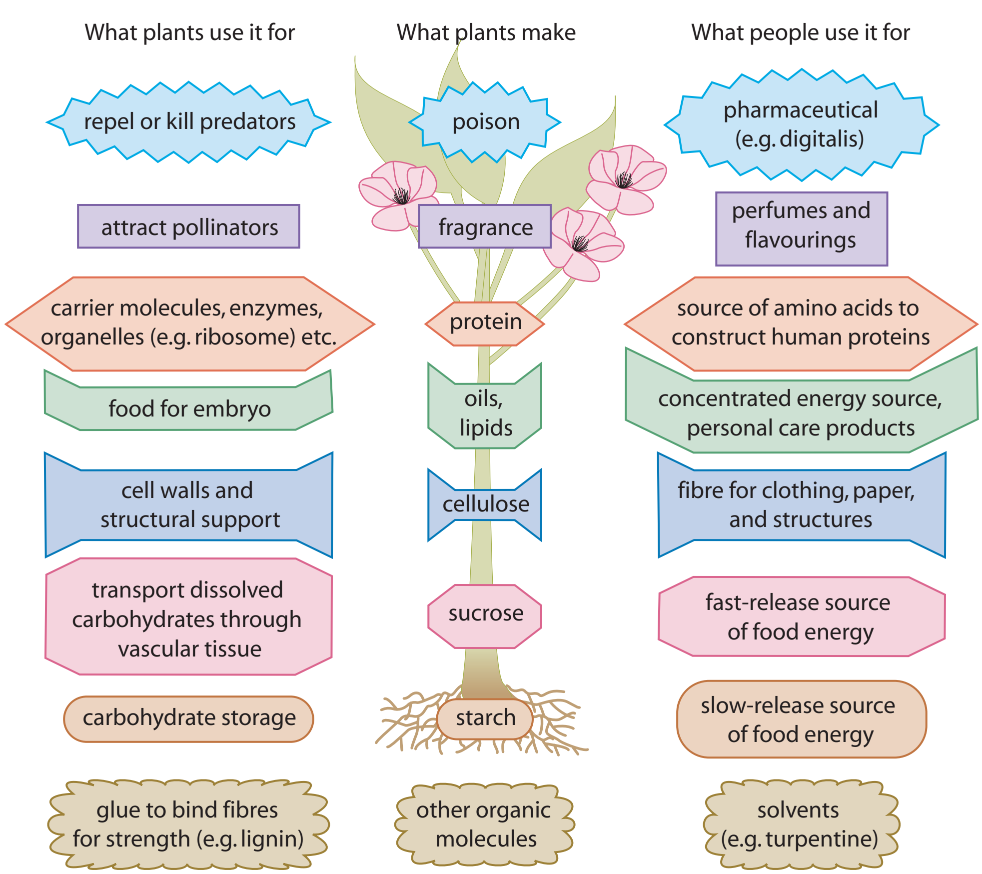


Figure 5.8 Plants produce structural and metabolic substances for their own use. Humans have developed numerous technologies to take advantage of the properties of these plant substances.

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FYI
In the past, the light-independent reactions were called the "dark reactions" because these reactions do not require light. They can, however, take place in the dark or in the light. Therefore, they are now more commonly referred to as light-independent reactions.

chemical reactions that lead to the end products. The term photosynthesis suggests that the process involves two sets of reactions. *Photo*, meaning light, refers to the reactions that capture light energy; *synthesis* refers to the reactions that produce a carbohydrate. The two sets of reactions that make up photosynthesis are called the light-dependent reactions and the light-independent reactions.

In the **light-dependent reactions**, solar energy is trapped and used to generate two high-energy compounds: ATP and NADPH (reduced nicotinamide adenine dinucleotide phosphate), which has a large amount of reducing power. In the **light-independent reactions**, the energy of ATP and the reducing power of NADPH are used to reduce carbon dioxide to make glucose. Glucose can then be converted into starch for storage.

Q 12 What are the two sets of reactions that are involved in photosynthesis?

The Light-Dependent Reactions of Photosynthesis

During the light-dependent reactions, the pigments within the thylakoid membranes absorb light energy. A *pigment* is a compound that absorbs certain wavelengths of visible light, while reflecting others that give the pigment its specific colour. A photosynthetic pigment is a compound that traps light energy and passes it on to other chemicals, which use the energy to synthesize high-energy compounds. Photosynthetic organisms have a variety of photosynthetic pigments, although chlorophyll, which is green, is the main type of photosynthetic pigments in plants.

Chlorophyll does not absorb green light. To understand why chlorophyll is green, examine Figure 5.9A.

When you shine white light through a prism, the prism separates the colours (wavelengths) of light into a spectrum. As you can see in Figure 5.9A, a chlorophyll solution absorbs red and blue light while it transmits or reflects green light. Therefore, the light that reaches your eyes is green.

An *absorbance spectrum* is a graph that shows the relative amounts of light of different colours that a compound absorbs. Figure 5.9B shows the absorbance spectra of two chlorophylls—chlorophyll *a* and chlorophyll *b*. Figure 5.9B also includes the absorbance spectrum of another pigment called beta-carotene. Beta-carotene is a member of a very large class of pigments called carotenoids. The carotenoids absorb blue and green light, so they are yellow, orange, and red in colour (see Figure 5.9C). Beta-carotene is responsible for the orange colour of carrots. It can be converted into vitamin A, which can then be converted into retinal, which is the visual pigment in your eyes.

Each photosynthetic pigment absorbs light of different colours. Having a variety of pigments enables a plant to use a greater percentage of the Sun's light.

Figure 5.9D shows another type of spectrum, called an action spectrum. An action spectrum shows the relative effectiveness of different wavelengths of light for promoting photosynthesis. This is reflected by a response in the rate at which oxygen is released. Observe that the action spectrum parallels the absorbance spectra of the three pigments together. This observation links the production of oxygen in photosynthesis with selected wavelengths of light, as well as with the specific pigments that absorb these wavelengths.

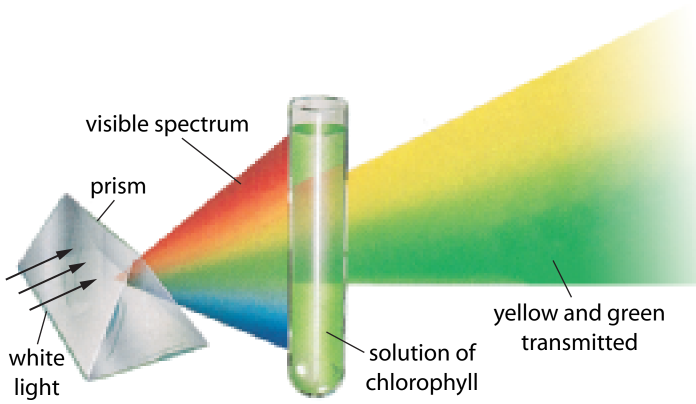
Q 13 What is a pigment?

Q 14 In reference to the properties of light, what makes chlorophyll green?

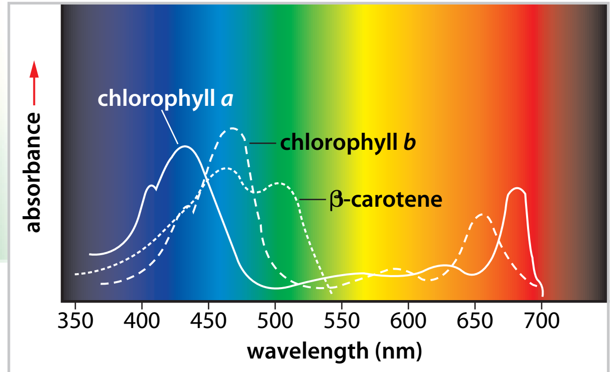
Q 15 What is the advantage to a plant of having more than one pigment?

BiologyFile

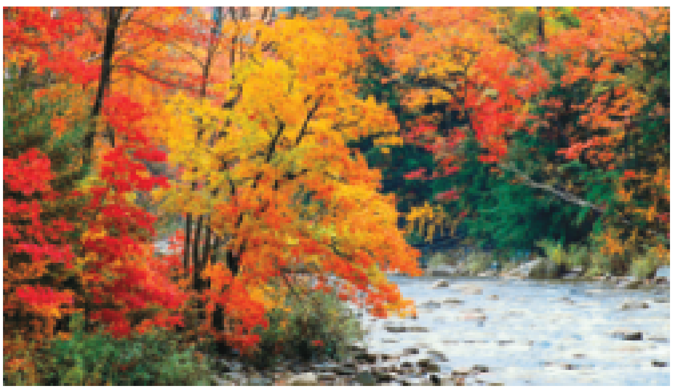
FYI
In addition to absorbing light energy, the carotenoids have another important function: they protect chlorophyll molecules from chemical damage. During the formation of the oxygen molecules that are released by plants, some very reactive chemicals are produced. Without carotenoids, these chemicals would destroy the chlorophyll. Biologists used this fact to develop a type of herbicide that inhibits the synthesis of the careteniods. Without the carotenoids, the chlorophyll is destroyed and the plants die.



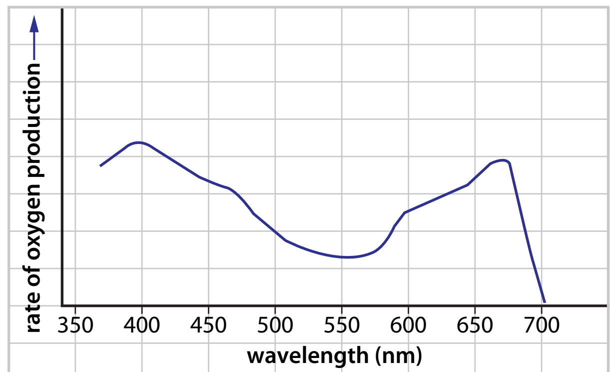
A When you look at an object, you see the colours that were *not* absorbed by the object. Leaves appear green because chlorophyll molecules in leaf cells reflect green and yellow wavelengths of light and absorb the other wavelengths (red and blue).



B This absorbance spectrum for three photosynthetic pigments shows that each pigment absorbs a different combination of colours of light.



C During spring and summer months, chlorophyll masks the presence of carotenoids and other plant pigments in leaves. Cooler temperatures in autumn cause leaves to stop making chlorophyll. With the green pigment no longer present to reflect green light to our eyes, the colours reflected by carotenoids and other plant pigments become visible.



D This action spectrum for photosynthesis shows the rate at which oxygen is produced during photosynthesis. Notice that the shape of the graph line generally mirrors the shape of the graph lines in Figure 5.9B.

Figure 5.9 Light-reflecting and light absorbing characteristics of pigments.

The Path of Electrons in the Light-Dependent Reactions

In Section 5.1, you read that chlorophyll is bound to the membranes of the thylakoids inside the chloroplast. Chlorophyll and other pigments are arranged in the thylakoid membranes in clusters called **photosystems**. The chloroplasts of plants and algae have two photosystems, called photosystem I (abbreviated to PSI) and photosystem II (abbreviated to PSII). The photosystems are named for the order in which scientists discovered them, not for their sequence in the process of photosynthesis.

Each photosystem is made up of pigment molecules that include one dozen or more chlorophyll molecules, as well as a few carotenoid molecules. Also present in the photosystem is a molecule that accepts electrons. All the pigment molecules in each photosystem can absorb light energy of various wavelengths. However, they always pass the energy along to one specialized, electron-accepting chlorophyll *a* molecule called the *reaction centre*. (Some biologists refer to pigment molecules in a photosystem as antennas because they collect light energy just as radio and television antennas collect electromagnetic energy.)

16 What is a photosystem?

17 Identify the types of molecules that are present in a photosystem.

BiologyFile

FYI

When chlorophyll is free in a solution and it absorbs light, it fluoresces. When a molecule fluoresces, it re-emits the energy it absorbed in the form of light that has a longer wavelength than the absorbed light. You observed fluorescence when you performed the Launch Lab at the start of this chapter.

INVESTIGATION 5.B

Target Skills

Collecting and **interpreting** data from a chromatography experiment

Calculating reference flow values from data

Using Chromatography to Separate Plant Pigments

Chromatography is a technique that is used to separate and analyze complex mixtures, such as plant pigments. You will use this technique to examine the pigments in a green leaf.

Question

Which pigments can you identify in a green leaf?

Prediction

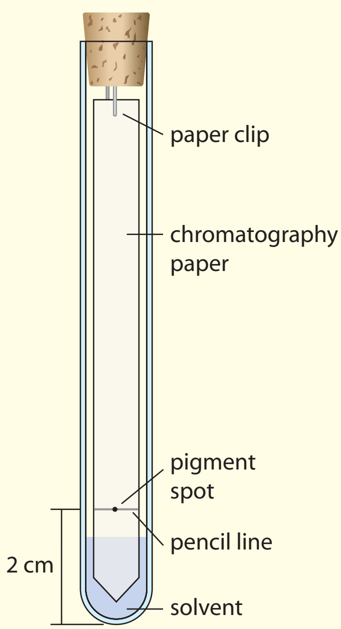
Predict at least three pigments that you will observe.

Safety Precautions

The solvent is volatile. Ensure that there are no flames in the classroom, and avoid breathing the vapours from the solvent. The classroom must be well-ventilated.

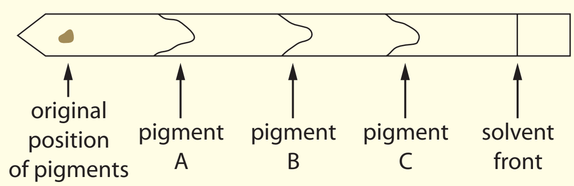
Materials

- coleus or spinach leaves (or pigment mixture supplied by your teacher)
- isopropanol (solvent)
- chromatography paper
- paper clip
- retort stand
- test-tube clamp
- cork stopper
- watch glass
- large test tube



Procedure

1. Attach the large test tube to a retort stand.
2. Set up the cork stopper and the paper clip as shown.
3. Measure a piece of chromatography paper so that it is long enough to hang from the paper clip but not so long that it touches the bottom of the test tube. (Refer to the diagram.) Cut the paper to a point at one end.
4. Place a coleus or spinach leaf over the pointed end of the chromatography paper. Run the edge of a watch glass over the leaf, about 2 cm up from the tip of the paper. Use the watch glass to squeeze out the pigment mixture. Repeat this at least 10 times in the same spot to ensure that enough pigment mixture has been deposited onto the paper.
5. Place 5 mL to 10 mL of solvent in the test tube.
6. Hang the chromatography paper from the stopper in the test tube so that the tip of the paper is in the solvent but the pigment mixture is not.
7. Wait until the solvent has travelled up to about 2 cm from the top of the paper.
8. Remove the paper from the test tube. Immediately, before the solvent evaporates, mark the location of the solvent front with a pencil. Also mark the edges of each pigment, as shown in this diagram.



9. Measure and record the distance that each pigment travelled, starting from where you applied the pigment mixture to where each pigment stopped moving up the paper strip.
10. Measure and record the distance that the solvent front travelled.
11. Prepare a data table with the following headings, and record your observations and measurements in the first three columns.

Observations and Data for Chromatography of Plant Pigments

Pigment colour	Distance travelled by pigment (cm)	Distance travelled by solvent (cm)	R_f (reference flow) value	Name of pigment

12. Calculate the R_f (reference flow) value of each pigment, using the following formula:

$$R_f \text{ value} = \frac{\text{distance travelled by pigment (solute)}}{\text{distance travelled by solvent}}$$

Analysis

1. Sketch your paper strip, using different colours to show the different pigments and their positions. Your sketch is called a chromatogram.

2. Which pigment is (a) most soluble and (b) least soluble in the solvent you used? Explain how you decided.

3. Compare your observations and R_f values with those of your classmates. Identify sources of error in this investigation that might account for any differences.

4. Use the following chart as a guide to help you complete the last column in your data table. (You may not have observed all the pigments in this chart, or you may have observed other pigments.)

Examples of Plant Pigments and Their Colours

Pigment or pigment group	Colour
chlorophyll *a*	bluish-green
chlorophyll *b*	yellowish-green
carotenoids	orange
pheophytin	olive-green
xanthophylls	yellow
phycocyanin	blue
phycoerythrin	red

Conclusion

5. a) Which pigments did you identify in your leaf?

b) Do you think additional pigments could still be present? Hypothesize how you could find out.

When a reaction centre has received the energy passed on to it, an electron in the reaction centre is "excited." This means that the electron is raised to a higher energy level. The electron is then passed to an electron-accepting molecule. Since this electron-acceptor has received an electron, it becomes reduced so it is at a high energy level. Figure 5.10 outlines four steps that occur after the energized electron reaches the electron-acceptor.

Step 1 When the electron leaves the reaction centre in photosystem II and goes to the electron-acceptor, the reaction centre is missing an electron. This electron must be replaced before photosystem II can absorb more light energy to excite an electron. The source of the new electron is a water molecule. A water molecule is split in a series of reactions that release electrons, hydrogen ions, and oxygen atoms. The oxygen that is released by plants comes from these water-splitting reactions.

Step 2 From the electron-acceptor, the energized electron is transferred along a series of electron-carrying molecules. Together, these molecules are referred to as an **electron transport system**. With each transfer along the electron transport system, the electron releases a small amount of energy (Figure 5.11). This released energy is used to push hydrogen ions from the stroma, across the thylakoid membrane, and into the *thylakoid space*—the area inside the thylakoid.

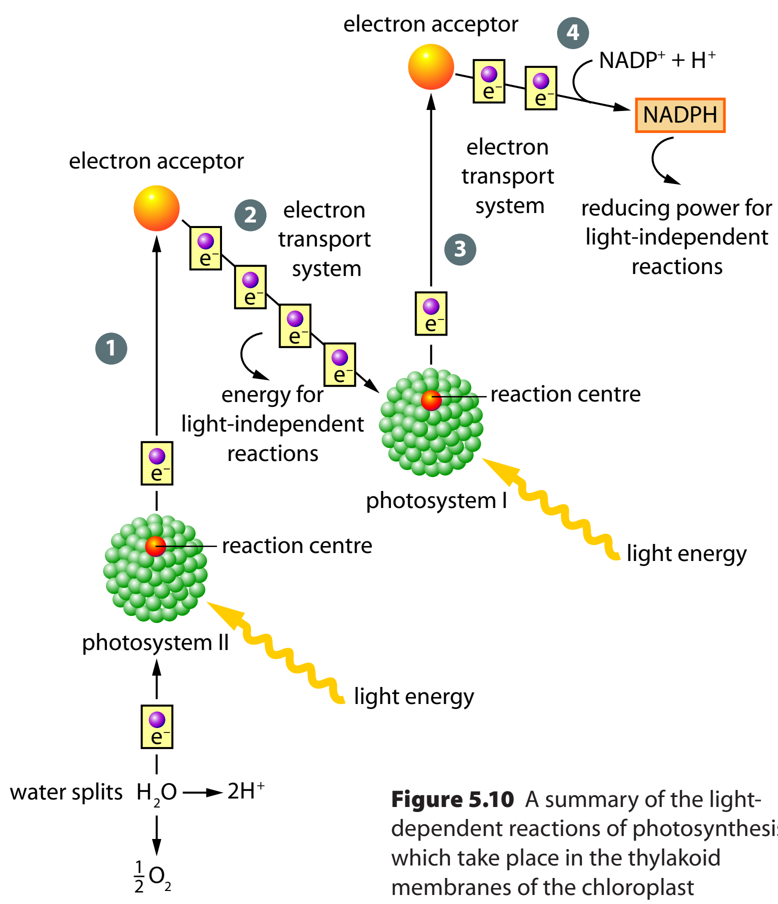


Figure 5.10 A summary of the light-dependent reactions of photosynthesis, which take place in the thylakoid membranes of the chloroplast

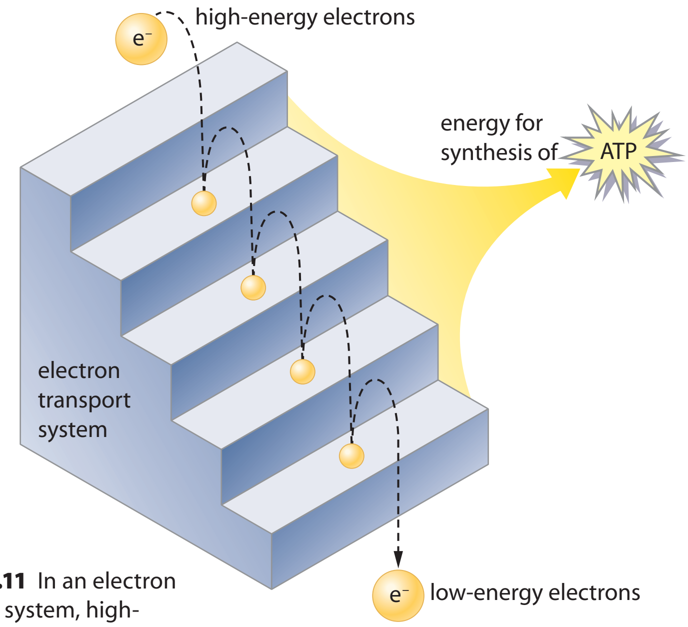


Figure 5.11 In an electron transport system, high-energy electrons give off a small amount of energy with each step as they pass from one electron-carrying molecule to another. (These molecules, called cytochromes, are a class of proteins specialized for transferring electrons.) The energy given off from these energy transfers is used to synthesize ATP.

The energy that is released as an electron is passed through the electron transport system is stored temporarily in a hydrogen ion concentration gradient across the thylakoid membrane. There are many more hydrogen ions in the thylakoid space than there are in the stroma. You can compare this concentration gradient to water behind a dam. Energy is stored in the potential energy of the water. In a dam, the energy is used by allowing the water to flow down and turn turbines that will generate electric energy. In the hydrogen ion gradient, the energy will be used to generate ATP from ADP and free phosphate groups.

Step 3 When the events of steps 1 and 2 are taking place, light energy is absorbed by photosystem I. This energy is transferred to a reaction centre, where an electron becomes excited. Once again, the excited electron is passed to a high-energy electron-acceptor. In photosystem I, the lost electron is replaced by an electron that has reached the end of the electron transport system from photosystem II.

Step 4 The electron that was received by the electron-acceptor from photosystem I is used to reduce $NADP^+$ to form NADPH. The reducing power of NADPH will be used in the light-independent reactions.

18 Describe or sketch what happens to electrons in the electron transport system.

19 How does $NADP^+$ become converted to NADPH?

20 How are electrons replaced in photosystem I, and what is the source of the replacement electrons?

21 What is the effect of having a greater concentration of hydrogen ions in the thylakoid space than in the stroma?

Making ATP: Chemiosmosis

When the hydrogen ions are forced from the stroma to the thylakoid space, they cannot diffuse back across the membrane because the membrane is impermeable to these charged particles. A special structure called ATP synthase, embedded in the thylakoid membrane, provides the only pathway for the hydrogen ions to move down their concentration gradient (Figure 5.12). This pathway is linked to a mechanism that bonds a free phosphate group to an ADP molecule to form ATP. As the hydrogen ions move down their concentration gradient through the ATP synthase, the energy of the gradient is used to generate ATP molecules. This linking of the movement of hydrogen ions to the production of ATP is called **chemiosmosis**. You will encounter this process again in Section 5.3 when you consider the making of ATP in the mitochondria during cellular respiration.

22 Explain why hydrogen ions cannot diffuse out of the thylakoid space.

23 What is ATP synthase, and what is its significance?

24 What two events are linked in chemiosmosis?

Mimicking Nature

Scientists and engineers are fascinated by the ability of plants to use chlorophyll to trap solar energy and convert it into chemical energy. Engineers have been able to design and construct technology that traps solar energy and converts it into electrical energy (see Figure 5.13 on page 176). The technology is practical for the space station with its large solar receptors and small devices such as your calculator. However, the amount of electrical energy that can be produced by solar cells at Earth's surface is not enough to supply much of the energy that society needs. As a result, a large percentage of the energy that is used every day comes from the burning of fossil fuels, which add large amounts of carbon dioxide to the atmosphere. Since carbon dioxide is a greenhouse gas, it contributes to global warming.

In the search for an alternative source of energy, many scientists have been looking closely at hydrogen. Hydrogen is a totally clean fuel. When hydrogen burns in oxygen, the only product is pure, clean water. So why not use hydrogen as a fuel? There is very little hydrogen found free, as a gas, in nature. To split water into hydrogen and oxygen gases requires the input of more energy than can be produced when the hydrogen is burned. Obtaining hydrogen from

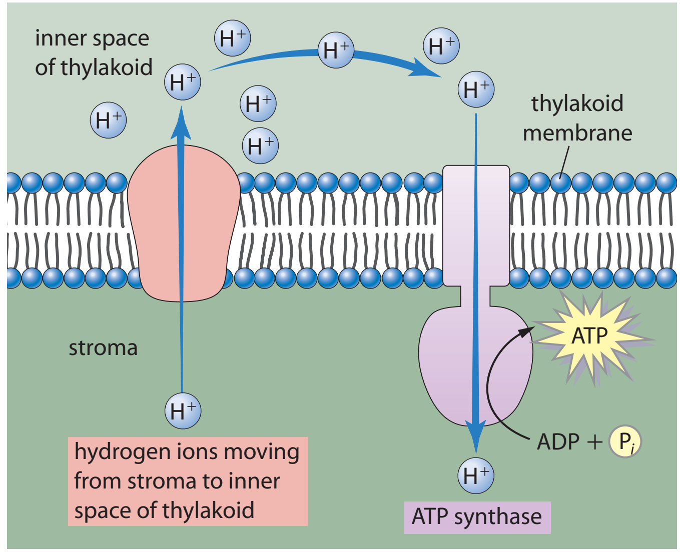


Figure 5.12 You can think of the hydrogen ions passing through the ATP synthase as being like water passing through a dam. The water turns a turbine that generates electrical energy. The movement of hydrogen ions through ATP synthase "turns a molecular turbine" that generates ATP.

Thought Lab 5.1 Modelling the Source of Oxygen in the Light-Dependent Reactions

Target Skills

Using a model to predict and trace the source of oxygen atoms in photosynthesis

In the 1930s, a graduate student at Stanford University in California, C.B. van Niel, demonstrated that the source of the oxygen given off during photosynthesis was water molecules, not carbon dioxide as was commonly hypothesized. When radioactive isotopes came into widespread use in biology laboratories in the early 1950s, it became possible to test and verify van Niel's findings. (Isotopes are atoms of an element that are chemically similar but differ in the number of neutrons in their nucleus.) A radioactive isotope of oxygen was used as a tracer. Tracers are used to follow a particular molecule through a chemical reaction.

Procedure

1. Examine the following general equation that resulted from the van Niel experiment:

   $CO_2(g) + 2H_2O^*(\ell) \rightarrow CH_2O(s) + H_2O(\ell) + O_2^*(g)$

2. Radioactive water tagged with an isotope of oxygen as a tracer (shown by the *) was used. Note where the tagged oxygen ends up on the right side of the equation.
3. Assume that the experiment was repeated, but this time a radioactive tag was put on the oxygen in CO_2.
4. Using materials provided by your teacher, model what you predict the appearance of the results would be. Your model must include a "tag" to indicate the oxygen isotope on the left side of the arrow as well as where it ends up on the right side of the arrow.
5. Use labels or different colours in your model to indicate what happens to the carbon and hydrogen in this reaction.

Analysis

1. Explain how an isotope can be used as a tracer.
2. Using your model, predict what happens to:
   a) all oxygen molecules that originated from carbon dioxide
   b) all carbon molecules that originated from carbon dioxide
   c) all hydrogen molecules that originated from water

Figure 5.13 Like chloroplasts, solar collectors can absorb light energy from the Sun and convert this energy to other forms. In plants, solar energy is converted to chemical energy. In solar collectors, the solar energy is usually converted to heat or to electrical energy. The electrical energy may be stored for later use by using it to charge storage batteries. (A car battery is an example of a storage battery.)

other compounds usually results in the release of carbon dioxide.

As you know, photosystem II uses the energy of light to split water. Plants release oxygen gas but not hydrogen gas. The hydrogen from the water becomes part of the concentration gradient or is added to $NADP^+$ to reduce it to NADPH. Teams of scientists are now looking for a way to produce an artificial system similar to photosystem II that will use solar energy to split water but convert the released ions and electrons into hydrogen gas instead of using them for reducing power. Should the scientists succeed with their research, hydrogen, a completely clean fuel, will become available in the future.

Biology File

FYI

Certain types of partial blindness occur when cells in the retina lose the ability to trap light and send signals to the brain. Some research scientists are studying a protein from photosystem I as a potential replacement for these missing functions in the retina. The scientists are looking for a way to attach these proteins to the retina and replace cells that have stopped functioning. Much more research is needed before the system will be feasible.

25. State two reasons why hydrogen is not easily used as a fuel.

26. Explain why scientists are investigating ways to produce hydrogen using an artificial system similar to photosystem II.

The Light-Independent Reactions of Photosynthesis

When there is a sufficient amount of NADPH and ATP in the stroma of the chloroplasts, the energy of these molecules can be used to synthesize glucose in the presence or absence of light. The series of reactions by which carbohydrates are synthesized is called the **Calvin-Benson cycle** in honour of Melvin Calvin and Andrew Benson, the researchers most responsible for the discovery of the process. They used a radioactive isotope of carbon as a tracer to discover the reactions that make up the cycle. Although many chemical reactions are involved, the reactions of the Calvin-Benson cycle can be summarized as shown in Figure 5.14 and as described below.

1. *Fixing Carbon Dioxide*: The first stage in the synthesis of carbohydrates is **carbon dioxide fixation**, which means that the carbon atom in carbon dioxide is chemically bonded to a pre-existing molecule in the stroma. This molecule is a five-carbon compound called **rib**u**l**ose **b**is**p**hosphate, or RuBP for short. The resulting six-carbon compound is unstable and immediately breaks down into two identical three-carbon compounds. Because these three-carbon compounds are the first stable products of the process, plants that demonstrate this process are called C_3 plants. You could summarize the reaction that leads to these three-carbon compounds as:
   $CO_2 + RuBP \rightarrow \text{unstable } C_6 \rightarrow 2\ C_3$
2. *Reduction*: In this stage, the newly formed three-carbon compounds are in a low-energy state. To convert them into a higher energy state, they are first activated by ATP and then reduced by NADPH. The result of these reactions is two molecules of PGAL. (PGAL is short for glyceraldehyde-3-phosphate.) In their reduced (higher-energy) state, some of the PGAL molecules leave the cycle and may be used to make glucose. The remaining PGAL molecules move on to the third stage of the cycle.

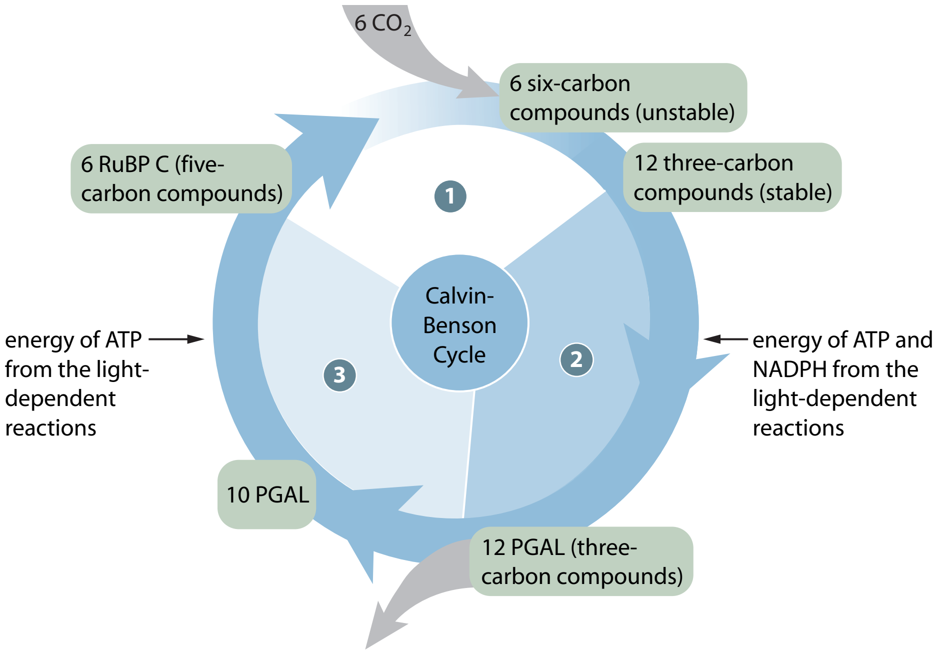


Figure 5.14 For every 12 PGAL molecules that are synthesized in the Calvin-Benson cycle, two leave the chloroplasts and go into the cytoplasm. There, they are used to make glucose and other high-energy compounds.

3. *Replacing RuBP*: Most of the reduced PGAL molecules are used to make more RuBP. Energy, supplied by ATP, is required to break and reform the chemical bonds to make the five-carbon RuBP from PGAL. As described in Figure 5.14, the Calvin-Benson cycle must be completed six times in order to synthesize one molecule of glucose. Of the 12 PGAL molecules that are produced in six cycles, 10 are used to regenerate RuBP, and 2 are used to make glucose.

27 Briefly outline the function and significance of the Calvin-Benson cycle.

28 What does the term "carbon dioxide fixation" mean?

Section 5.2 Summary

- Photosynthesis consists of two separate sets of chemical reactions: light-dependent reactions and light-independent reactions.
- Chlorophylls *a* and *b* and the carotenoids are photosynthetic pigments that absorb light.
- Light energy trapped by a pigment molecule energizes (excites) electrons.
- When an electron in photosystem II is excited, it is transferred to and then passed along an electron transport system.
- Energy released during electron transport is used to force hydrogen ions across the thylakoid membrane and create a concentration gradient.
- Energy from the concentration gradient is used to generate ATP from ADP and phosphate by means of chemiosmosis. As hydrogen ions move down their concentration gradient, they drive the reaction that generates ATP.
- An electron from water replaces the electron that was lost from photosystem II. The oxygen from the water molecule is converted to molecular oxygen.
- When an electron from photosystem I is excited, it is eventually used to reduce $NADP^+$ to NADPH.
- The series of reactions that synthesize carbohydrates is the Calvin-Benson cycle, which occurs in the stroma.
- In this cycle, carbon dioxide combines with RuBP to form a six-carbon

BiologyFile

FYI

The enzyme that catalyzes the reaction between carbon dioxide and RuBP at the start of the Calvin-Benson cycle is known as rubisco (**ribu**lose **bis**phosphate **carbo**xylase). All enzymes are proteins, and rubisco is probably the most abundant protein on Earth. Biologists estimate that photosynthetic organisms synthesize 1000 kg of rubisco every second.

Thought Lab 5.2 Adaptations and Applications of Photosynthesis

Target Skills

Investigating and **integrating** information from print and electronic sources to learn about photosynthesis and possible applications of our knowledge

Working cooperatively to investigate, synthesize, and present information about photosynthesis and its possible technological applications

Rubisco is essential for the fixing of carbon, and yet it is also the reason for the inefficiency of photosynthesis. Biologists estimate that the maximum efficiency of photosynthesis—assuming that each photosystem absorbs the maximum possible amount of light—is 30 percent. Some laboratory-grown plants, raised under tightly controlled conditions, have yielded efficiencies of up to 25 percent. In "the field," however, photosynthetic efficiency is actually much lower, ranging from as little as 0.1 percent to 3 percent. Sugar cane, one of the most efficient photosynthesizers in nature, has an efficiency of about 7 percent.

The Calvin-Benson cycle takes place in all plants, but different species of plants are adapted to use it in different ways, largely due to temperature conditions in different environments. At the heart of these adaptations, and the photosynthetic efficiency of plants, is a process called photorespiration. Photorespiration works against photosynthesis because rubisco can catalyze reactions involving oxygen as easily as it does reactions involving carbon dioxide. Thus, rubisco can *remove* carbon from carbon-related reactions. This means that plants can fix carbon and release carbon dioxide at nearly equal rates, which basically counteracts the fixation process.

Procedure

1. Working in a small group, use print and electronic resources to investigate the following topics and their relationship to one another. Use the Analysis questions to help you focus your research.
   - photorespiration
   - CAM photosynthesis
   - C_4 photosynthesis
2. Decide how group members can share the tasks of researching information and presenting your findings, ideas, and decisions.

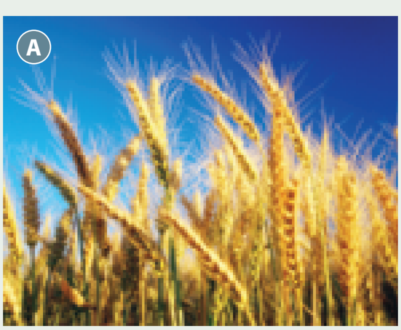
Analysis

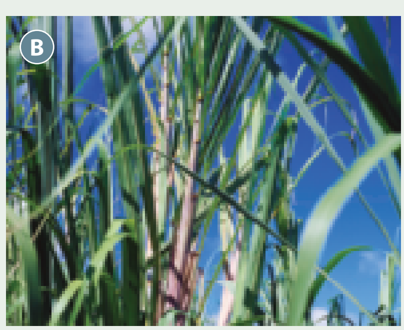
1. **a)** Identify at least three examples each of the following groups of plants: C_3, C_4, and CAM.

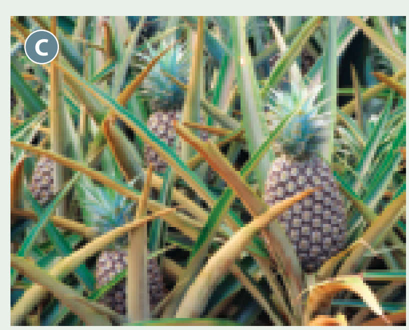
   b) Select one plant from each group. Explain the environmental limiting factors affecting the plant, and describe the adaptations that enable the plant to survive in its typical environment.
2. Illustrate, using pathway diagrams, the essential similarities and differences in the light-independent stage of C_3, C_4, and CAM photosynthesis.
3. In what ways can our understanding of photosynthesis enhance practices in the following areas:
   - growing desired crops
   - protecting desired crops from disease and disease-causing organisms

Extension

4. Biologists and plant technologists have long viewed photorespiration as a wasteful leftover from the evolutionary past of photosynthetic organisms. Thus, biotechnology research into improving efficiency of photosynthesis in crop plants has tended to work from the assumption that photorespiration must be engineered out of the genetic makeup of the plants. However, researchers at the University of California-Davis published a study, in 2004, that suggests the desire to minimize or remove photorespiration may be wrong-headed. Plants, they discovered, may need photorespiration to absorb and process inorganic nitrogen (as nitrate) from the soil. This discovery, if satisfactorily confirmed, has implications for global warming and our assumptions about how plants will, and won't, respond to elevated temperatures and rising concentrations of atmospheric carbon dioxide. Investigate the findings of the UC-Davis researchers as well as the implications of these findings for global warming scenarios. Write a paragraph outlining your opinion of the following statement: "Despite our good intentions, where biotechnology is concerned, our ignorance may lead to unhealthy, harmful consequences to the biosphere and, thus, to ourselves."







Wheat **(A)** is a C_3 plant. Sugar cane **(B)** is a C_4 plant. A pineapple **(C)** is a CAM plant. Why do these three types of plants have different adaptations for synthesizing sugars?

compound that immediately splits into two three-carbon compounds.
- ATP and NADPH from the light-dependent reactions provide energy and reducing power to form PGAL from the newly formed three-carbon compounds.
- Six cycles produce 12 PGAL molecules, 10 of which regenerate RuBP and 2 of which are used to make glucose.

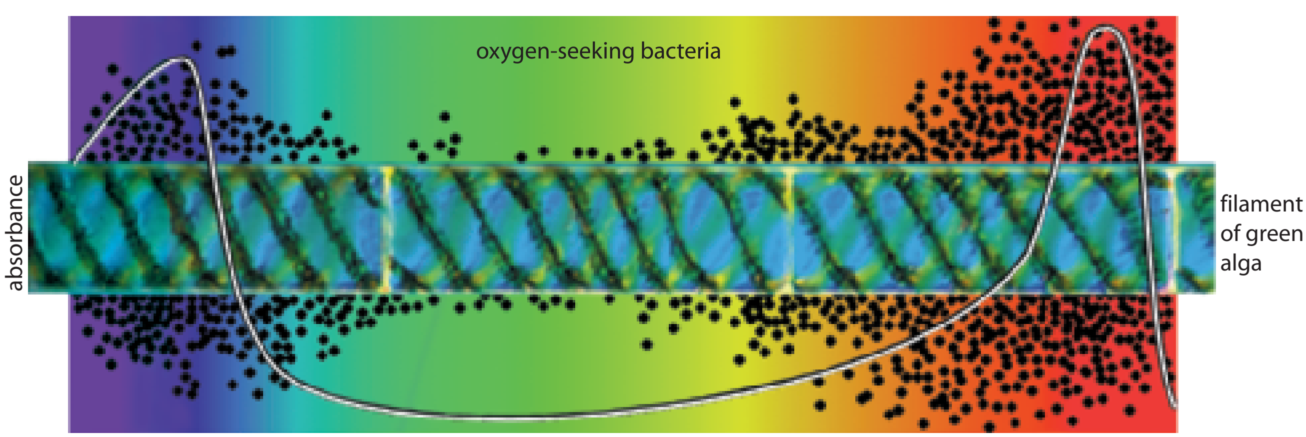
Section 5.2 Review

1. List four ways that a plant uses the glucose it produces.
2. Compare, in general terms, the light-dependent and light-independent reactions that make up photosynthesis.
3. Use graphics or spreadsheet software to sketch the absorbance spectrum for chlorophyll *a*, chlorophyll *b*, and beta-carotene. ICT
4. Compare the absorbance spectrum to the action spectrum in a green plant.
5. Predict why most green plants contain more than one photosynthetic pigment.
6. Describe or define the term "photosystem."
7. Summarize, in point form, the events that take place in the light-dependent reactions of photosynthesis.
8. Describe or define the term, electron transport system. Explain what happens to electrons in this system.
9. Is NADPH an oxidized or a reduced molecule? Explain.
10. Explain how the electrons "lost" from chlorophyll molecules when light is absorbed at the beginning of photosynthesis are replaced.
11. Explain, in general terms, the process of chemiosmosis.
12. Identify the source of ATP and NADPH required to synthesize glucose.
13. Use graphics or word processing software to summarize the main events in the Calvin-Benson cycle. ICT

Use the following information to answer the next question.

In 1882, a British biologist named T.W. Englemann used the rate of oxygen production to measure the rate of photosynthesis in a green alga. He chose aerobic bacteria as an indicator for oxygen production. To produce the view shown below, Englemann projected a visible spectrum onto a slide under a light microscope. Then he arranged a filament of algal cells parallel to the spectrum. The dark spots represent the bacteria.

14. a) Interpret the pattern of bacteria and the graph line in figure below.
    b) Englemann's purpose in designing this experiment was to describe the action spectrum of photosynthesis. State a hypothesis he might have used for the experiment. Explain how the results he obtained supported or refuted this hypothesis.



INVESTIGATION 5.C

Target Skills

Identifying a testable variable that would affect the rate of photosynthesis

Hypothesizing and **predicting** the effect of this variable on the rate of photosynthesis

Explaining how data supports or refutes the hypothesis

The Rate of Photosynthesis

Oxygen is one of the products of the light-dependent reactions of photosynthesis. The volume of oxygen that is produced by the plant can therefore be used to measure the rate of photosynthesis taking place. However, it is often difficult to accurately measure the volume of gas produced. In this activity, you will use small disks cut from the leaf of a plant to perform a basic floating leaf disk assay. (An assay is a procedure that is used to analyze or determine the amount of substance in a sample.) Once you have mastered this technique, you will use the floating leaf disk assay to design your own investigation of variables that affect the rate of photosynthesis. In preparation for the investigation, review the structure of leaves and the chambers through which gases move as shown in the diagram.

Question

What variables affect the rate of photosynthesis?

Part 1: Floating Leaf Disk Assay

Materials

- plant leaf
- single-hole punch
- 10 mL plastic syringe (without the needle)
- liquid dish soap
- 0.25% sodium bicarbonate
- medicine dropper
- 200 mL beaker
- lamp with a reflector and 150 W bulb
- timer

Procedure

1. Obtain 100 mL of the 0.25% sodium bicarbonate solution and place it in the beaker.

2. Use the medicine dropper to add 5 drops of liquid dish soap to the bicarbonate solution.

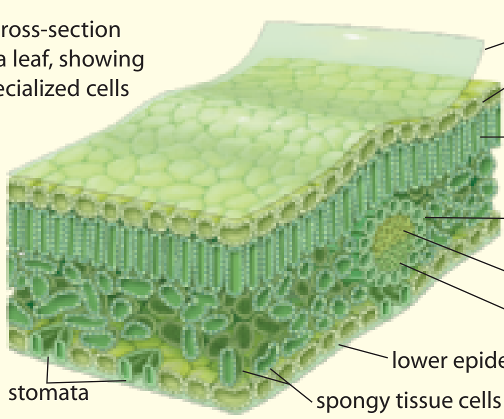
3. Use the single-hole punch to cut 10 uniform leaf disks. Avoid cutting through major leaf veins. Remove the plunger and place the leaf disks in the barrel of a plastic syringe. Tap the syringe gently until the leaf disks are near the bottom of the barrel.

4. Replace the plunger in the syringe. Push the plunger down until only a small volume of air remains in the barrel. Be careful, however, not to crush any of the leaf disks.

5. You are going to infiltrate the leaf disks with sodium bicarbonate solution by removing most of the air from the leaf tissue and replacing it with the sodium bicarbonate solution. To do this:

- Use the plunger to draw 5 mL of solution into the barrel of the syringe.
- Tap on the syringe to suspend the leaf disks in the solution.

A cross-section of a leaf, showing specialized cells



A Palisade tissue cells: long, narrow cells packed with chloroplasts. These cells lie under the upper surface of the leaf and are the sites where most photosynthesis occurs in the leaf.

B Vascular tissue cells: cells that form bundled arrangements of tubes that transport fluids throughout the plant. Xylem tubes carry water and minerals from the roots to the leaves. Phloem tubes carry sugars to various parts of the plant.

C Spongy tissue cells: round and more loosely packed than palisade cells, with many air spaces between them. These cells have chloroplasts, so they perform some photosynthesis. Their structure helps the cells to exchange gases and water with the environment.

D Stomata: small openings in the outer (epidermal) layer that allow carbon dioxide into the leaf and oxygen out of the leaf. Water also diffuses out of the leaf through stomata.

- Hold a finger over the open end of the syringe and draw back on the plunger. This creates a vacuum inside the syringe.
- Hold this vacuum for 10 to 15 seconds and then remove your finger from the open end of the syringe. The sodium bicarbonate solution will gradually infiltrate the air spaces inside the leaf disks.
- Hold the open end of the syringe over the beaker of solution and slowly push the plunger back down, again taking care not to crush the leaf disks.
- Repeat the infiltration procedure at least 5 times; otherwise your leaf disks may not sink to the bottom of the solution in the beaker.

6. Pour the disks and solution from the syringe back into the beaker of sodium bicarbonate and dish soap.
7. If your leaf disks are still floating, carefully add more dish soap—1 drop at a time. You may have to remove the leaf disks and repeat the infiltration procedure if you can't get the disks to sink to the bottom of the beaker.
8. Once all of the leaf disks are resting on the bottom, direct white light onto the beaker. Start the timer.
9. At the end of each minute, record the number of disks that have floated to the surface of the solution. Swirl the beaker gently if some disks get stuck to the side, but keep the beaker in the light.
10. Record your results in a suitable data table.

Analysis

1. Use a computer and spreadsheet software to construct a graph of your data. ICT
2. Using the graph, estimate the time at which 50 percent of the leaf disks were floating on the surface. The point at which 50 percent of the leaf disks are floating will be your point of reference for future investigations.
3. Normally the extracellular spaces within the mesophyll layer of a plant leaf are filled with air for purposes of gas exchange. As a result, leaf disks float on the water. Explain how you removed most of the air from these extracellular spaces. What was the result of the removal of most of the air from the air spaces in the leaf disks?

Conclusions

4. What variable were you testing in this experiment?
5. Based on your current understanding of photosynthesis, explain why the leaf disks started to float after being exposed to white light.

Part 2: Design your Own Investigation

There are a number of variables that affect the rate of photosynthesis in a plant leaf. The variables include the amount of carbon dioxide in the water, different wavelengths of light, and the intensity of light, to name only a few. Your challenge is to design an investigation to test the effects of one of these variables on the rate of photosynthesis. Be sure to:

- state your own question
- make a hypothesis based on this question
- identify the materials that you will require
- write out the experimental procedure you will use
- conduct your investigation
- collect and graph your data
- determine if your results support or disprove your hypothesis
- communicate the results of your investigation in the form of a formal lab report.

SECTION
5.3

Cellular Respiration Releases Energy from Organic Compounds

Section Outcomes

In this section, you will
- **distinguish**, in general terms, among aerobic respiration, anaerobic respiration, and fermentation
- **explain** how carbohydrates are oxidized by glycolysis and the Krebs cycle to produce reducing power in NADH and $FADH_2$ and chemical potential in ATP
- **explain** how chemiosmosis converts the reducing power of NADH and $FADH_2$ to the chemical potential of ATP
- **design** an experiment to demonstrate that oxygen is consumed during aerobic cellular respiration and that heat is produced
- **explain** that science and technology are developed to meet societal needs such as the production of foods and fuels
- **investigating** and **integrating**, from print and electronic sources, information on the action of metabolic toxins such as hydrogen sulfide and cyanide

Key Terms

aerobic cellular respiration
anaerobic cellular respiration
glycolysis
Krebs cycle
electron transport system
chemiosmosis
fermentation

Figure 5.15 Running and other forms of strenuous activity require large amounts of energy. Even when you are still and resting, however, the cells of your body still need energy to continue functioning.

The runner in Figure 5.15 is clearly exhausted. Have you ever been playing a sport or running so hard that you thought you could not take another step? Even after you stopped, you probably kept breathing deeply and felt the heat within your body. What caused your muscles to heat up so much? Why does your breathing rate stay high for a long time after you stop exerting yourself? The answers to these questions are related to the process that provides energy in individual cells: cellular respiration.

The Process of Cellular Respiration

You know that photosynthesis reduces carbon dioxide to glucose. That is, electrons (and hydrogen ions) are chemically added to carbon dioxide to produce high-energy glucose molecules. The summary equation for cellular respiration is shown below:

$$C_6H_{12}O_6(s) + O_2(g) \rightarrow$$
$$6CO_2(g) + 6H_2O(\ell) + \text{energy (ATP)}$$

Cellular respiration releases the energy of these molecules by oxidizing glucose to carbon dioxide. That is, electrons (and hydrogen ions) are removed from glucose, releasing energy and producing carbon dioxide and water. You can see the reduction-oxidation relationship in photosynthesis and cellular respiration more clearly in Figure 5.16.

reduction (gain of hydrogen and electrons)

$$CO_2 + H_2O \rightarrow (CH_2O) + O_2$$

oxidation (loss of hydrogen and electrons)

oxidation

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O$$

reduction

Figure 5.16 The summary equations for photosynthesis and cellular respiration are sometimes written as shown here. Notice that if you multiply all the chemical formulas on both sides of the equation by six, you get the summary equations for these processes.

Three Pathways for Energy Release

Different species of organisms are adapted to release energy from their food sources in different ways. Organisms that live in *oxic* (oxygen-containing) conditions carry out **aerobic cellular**

respiration. The term "aerobic" means that the process requires oxygen to produce ATP. Animals, plants, and many types of fungi, protists, and bacteria use aerobic cellular respiration for energy.

Organisms that live in *anoxic* (no-oxygen) conditions carry out **anaerobic cellular respiration**. The term "anaerobic" means that the process does not require oxygen to produce ATP. In fact, for some organisms, oxygen may be lethal.

Some types of bacteria carry out anaerobic cellular respiration, as do members of archaea. The deep-ocean producers (chemosynthetic organisms) that you read about on page 12 are examples of organisms that depend on anaerobic cellular respiration. Some nitrogen-fixing bacteria and some other types of soil bacteria (see page 49) are also examples of organisms that carry out anaerobic cellular respiration.

A third pathway for releasing energy from food sources is **fermentation**. Fermentation is an anaerobic process, but it is not technically classified as anaerobic cellular respiration. Yeasts and the bacteria that cause milk to sour (*Lactobacillus bulgaricus*) are examples of organisms that carry out fermentation. Fermentation also occurs in the muscle cells of mammals.

Q 29 Explain the difference between oxic conditions and anoxic conditions.

Q 30 Describe how aerobic cellular respiration is different from anaerobic respiration.

Examining Aerobic Cellular Respiration

Aerobic cellular respiration is an oxidation reaction in which a series of enzyme-catalyzed reactions transfer electrons from high-energy molecules—mainly glucose—to oxygen. This process is the main means for releasing energy, in the form of ATP, in plants, animals, and most other eukaryotic cells.

Figure 5.17 on page 186 outlines the key events in cellular respiration. You will learn about each of these events in the pages that follow. Note that cellular respiration begins with **glycolysis**, which occurs in the cytoplasm of all cells. *Glycolysis is an anaerobic process*, which means that it can proceed without oxygen. Glycolysis generates a small amount of ATP. However, the product of glycolysis, a molecule called pyruvate, still contains a large amount of chemical energy. If oxygen is not available to eukaryotic cells, pyruvate proceeds to the process of fermentation.

When sufficient oxygen is present, pyruvate is transported from the cytoplasm into the mitochondrion. In the mitochondrion, pyruvate undergoes a reaction that prepares it for entry into the Krebs cycle. The major function of the **Krebs cycle** is to transform the energy of glucose into reducing power of molecules called NADH and $FADH_2$. These molecules supply high-energy electrons to an **electron transport system** that produces a large amount of ATP. Water is the final end-product of this process.

Outside the Mitochondria: Glycolysis

Glycolysis occurs in all living cells. For some types of cells, it is the only source of energy because it can proceed anaerobically. For example, yeast can live indefinitely without oxygen. However, yeast also can use oxygen when it is available. Your muscles can function anaerobically for awhile but must obtain oxygen eventually.

As shown in Figure 5.18, the role of glycolysis is to split glucose (a six-carbon molecule) into two molecules of pyruvate (a three-carbon molecule). You might be surprised to see that ATP molecules are *used* at the start of glycolysis. Although glucose is a high-energy molecule, more energy must be added to start the series of reactions. After energy has been added

INVESTIGATION 5.D

Oxygen Consumption and Heat Production in Germinating Seeds*

Target Skills

Demonstrating quantitatively the consumption of oxygen by germinating seeds

Designing an experiment to demonstrate quantitatively that cellular respiration produces heat

Measuring temperature changes over a period of time in germinating and non-germinating seeds

When seeds germinate (begin to grow and develop), they cannot trap energy from the Sun because they have not yet developed any chlorophyll. As well, they often germinate under a layer of soil. Therefore, seeds must have enough stored energy to germinate—developing roots and shoots as well as the chloroplasts and chlorophyll they will need as they mature and are exposed to sunlight.

To germinate, seeds need suitable temperatures, water, and oxygen. Oxygen initiates cellular respiration. The amount of oxygen consumed by the seeds is approximately equal to the amount of carbon dioxide produced as the seeds respire. In Part 1 of this investigation, you will use an apparatus called a respirometer to measure the consumption of oxygen. The respirometer contains limewater and germinating seeds. As the seeds consume oxygen, they give off carbon dioxide. The carbon dioxide is then absorbed by the limewater, creating a slight vacuum in the respirometer. This vacuum will draw a drop of liquid detergent in the tubing inward. This movement will be measured using a ruler taped to the tubing. Note: If suitable probeware and interfaces are available, your teacher will explain how to modify the procedure for Part 1 with this equipment.

In Part 2, you will design your own investigation to demonstrate and measure the heat produced as germinating seeds respire.

Part 1: Oxygen Consumption in Cellular Respiration

Question

How can you demonstrate quantitatively that germinating seeds consume oxygen?

Prediction

Based on the experimental set-up, predict what will happen to indicate that oxygen is being consumed as the seeds respire.

Safety Precautions

If glass tubing is used instead of plastic tubing, handle the tubes very carefully to avoid breakage.

Materials

- large test tube
- ruler
- 1 g of seeds of any kind
- one-hole stopper
- limewater
- pipette
- wad of cotton
- marker
- liquid detergent
- balance
- paper towels
- spatula
- scotch tape
- support stand and clamp
- rigid plastic tubing, 20 cm long and bent at right angle

Procedure

1. Obtain some small plant seeds. If possible, have a different type of seeds from those used by your classmates. Germinate the seeds by spreading them on wet paper towel a day or two before the lab.
2. Start to make a respirometer by inserting the short end of the tube into the hole of the stopper. The long end of the tube should be sticking out at a right angle as shown in the photograph.
3. Draw a line 0.5 cm above the bottom of the test tube with the marker. Add limewater to the tube up to this mark.

4. Moisten a small wad of cotton and place it on top of the limewater. Now place one gram of germinating seeds on top of the moistened cotton.
5. Tape the ruler to the tubing as shown in the photograph. Use a pipette to add a drop of detergent to the tubing near the end.
6. Carefully insert the stopper and tubing into the test tube to form an airtight seal. Use a support stand and clamps to keep the respirometer apparatus in an upright position.
7. Wait five minutes to allow for the absorption of any carbon dioxide that was in the respirometer when it was assembled. Take an initial reading wherever the drop of detergent is with respect to the ruler. Always take the measurement from the same part of the detergent drop. Record the initial reading in a suitable data table.
8. Take readings every minute for 15 minutes and record them in the data table. Graph your data.

Analysis

1. How did the rate of oxygen consumption in different types of plant seeds compare?

Conclusions

2. Describe what you observed that indicated cellular respiration was occurring in the germinating seeds.
3. Name at least two sources of error that could have affected your observations and data. Explain how significant these sources of error are to the outcome of your investigation.

Part 2: Heat Production in Cellular Respiration

Question

How can you demonstrate that heat is a product of germinating (respiring) seeds?

Hypothesis

State a hypothesis that enables you to obtain quantitative data about the heat given off by germinating seeds.

Prediction

Make a prediction about the outcome of your investigation.

Safety Precautions

The buildup of gases in an enclosed container such as a test tube or flask could cause the container to rupture or shatter. Provide a means for venting gases out of any system you use.

Materials

- germinating seeds (e.g., chickpeas)
- other materials your group decides are needed

Note: Consider using probeware or similar data-logging equipment if it is available.

Experimental Plan

1. With your group, develop a written plan that outlines the procedure you will follow to test your hypothesis. Be sure to consider the following in your procedure:
   - safety
   - controlled variables
   - data collection and recording
2. In the course of your planning, you may wish to consult other investigations you have performed earlier this year (for example, Investigation 2.B in Chapter 2) or in previous science courses. These investigations may provide ideas or procedures that you can adopt or modify.
3. Review your hypothesis and procedure with your teacher before you perform it.

Data and Observations

4. Decide how you will measure the heat given off by germinating seeds.
5. Decide how you will record and display your data to assist you in analyzing and drawing conclusions about your results.

Analysis

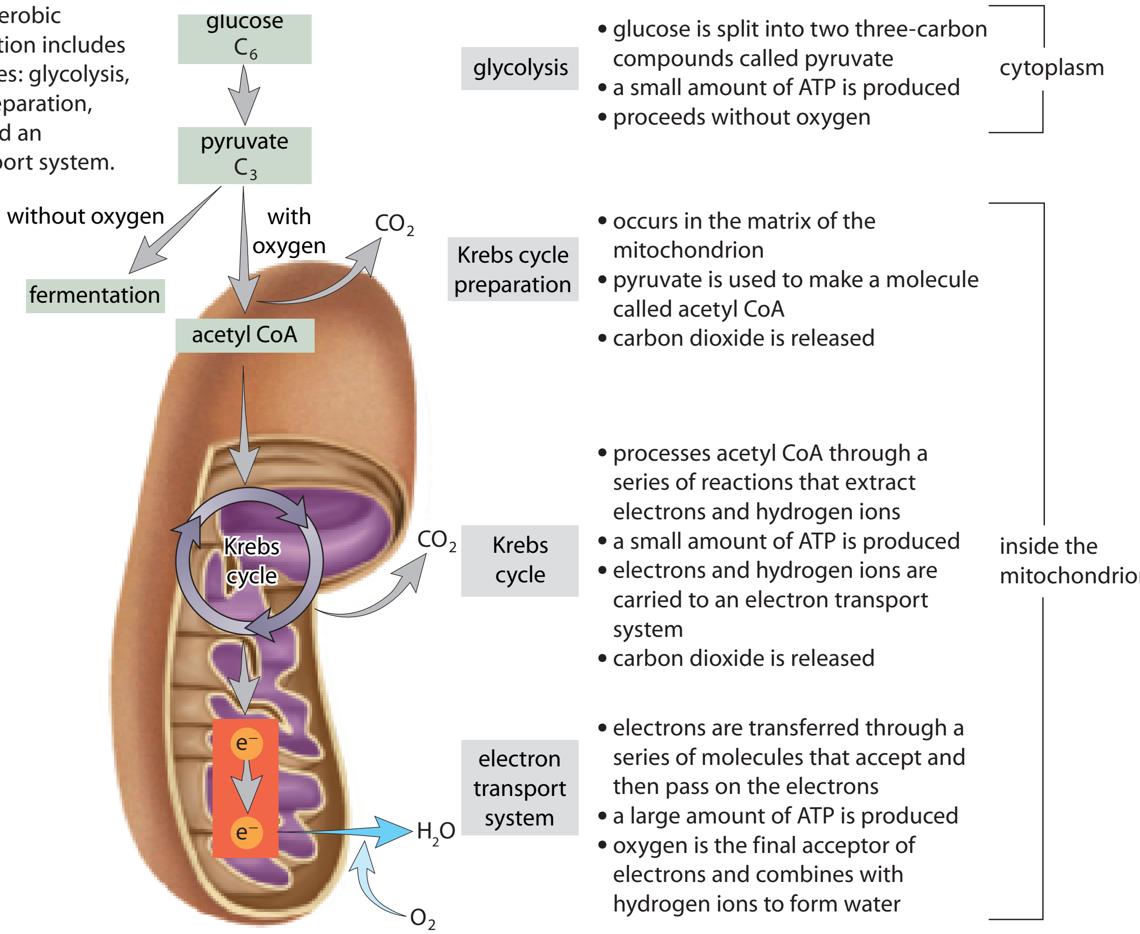
1. What variables did you manipulate and control?
2. Compare your results with those obtained by others in the class. Use the differences, if any, to identify possible sources of error in your procedure and/or data collection.

Conclusions

3. Explain why your results either supported or refuted your hypothesis.
4. Predict the results of your investigation if you let it run for a longer period of time, such as several days or a week. Justify your prediction by explaining your reasoning.

*Part 1 adapted from *Agri-science Resources for High School Sciences*, P.E.I. Agriculture Sector Council

Figure 5.17 Aerobic cellular respiration includes four main stages: glycolysis, Krebs cycle preparation, Krebs cycle, and an electron transport system.



to glucose, it splits and two intermediate three-carbon molecules are formed. Several more reactions occur in which some ATP is synthesized and a molecule called NAD^+ (nicotinamide adenine dinucleotide) is reduced to NADH. The amount of ATP that is synthesized (4 molecules) is greater than the amount of ATP that was used to start the process

Summary of Glycolysis

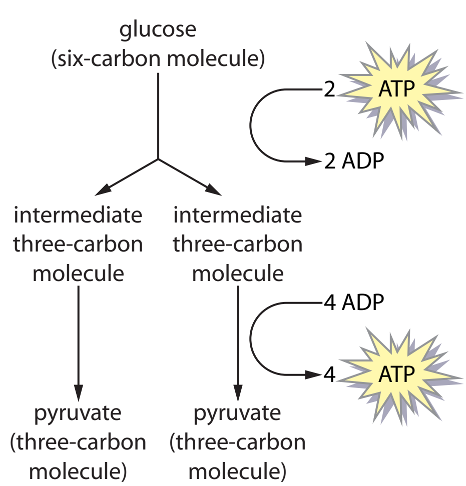


Figure 5.18 Glycolysis breaks down glucose to form two molecules of pyruvate. This process also generates a small amount of ATP and NADH.

(2 molecules). Thus, there is a net gain of two molecules of ATP in the cell. When glycolysis is complete, there are two identical three-carbon molecules of pyruvate.

When oxygen is not available, or for species that cannot utilize oxygen, glycolysis is the *only* pathway by which the cell can extract energy from glucose. However, the products of glycolysis, pyruvate, must be processed further through fermentation, as you will see later. When sufficient oxygen is present in the cell, pyruvate is transported into the matrix of the mitochondria in preparation for the Krebs cycle.

31 State where glycolysis occurs in a cell and whether or not oxygen is required.

32 Name three products that result from glycolysis.

Inside the Mitochondria: Krebs Cycle Preparation

Pyruvate must undergo one reaction before a portion of it can enter the Krebs cycle. As shown at right, pyruvate loses a carbon atom in the form of carbon dioxide, and the other two carbon atoms are bonded to a molecule called Coenzyme A (often shortened to CoA). During this reaction, another NAD^+ is reduced to NADH. You could think of CoA as being like a tow truck. It attaches to the two-carbon compound (called an acetyl group) and "tows" it to the Krebs cycle where the CoA releases the acetyl group.

The Krebs Cycle

The Krebs cycle is outlined in Figure 5.19. It is called a cycle because the last compound—a four-carbon compound that picks up a group of two carbons from acetyl-CoA—must be regenerated so it can pick up more two-carbon groups. During one complete cycle, a two-carbon group is added to the Krebs cycle and two carbon atoms are fully oxidized to carbon dioxide. (The carbon dioxide is a waste product—the gas that you exhale when you breathe.)

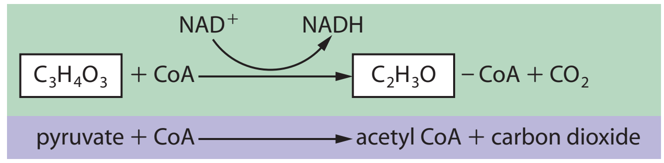
Most of the energy released when the carbon atoms are oxidized is transformed into reducing power in the form of reduced NADH and another molecule called $FADH_2$ (flavin adenine dinucleotide). $FADH_2$ is very similar to NADH and to NADPH. Also during the Krebs cycle, an ATP molecule is generated.

33 State where the reactions of the Krebs cycle occur in a cell.

34 What compound that is derived from glucose actually enters the Krebs cycle?

35 The carbon atoms that are derived from glucose are fully oxidized in the Krebs cycle. What becomes reduced during the Krebs cycle?

Forming Acetyl-CoA



Electron Transport

The vast majority of the ATP molecules in aerobic cellular respiration are produced during electron transport. The electron transport system in mitochondria is very similar to the electron transport system in chloroplasts. High-energy electrons are passed to a chain of electron-carrying molecules that are attached to the inner membrane of the mitochondrion. As electrons are passed from one carrier to another, energy is released in small, controlled amounts. The energy is used to pump hydrogen ions across the membrane from the matrix to the intermembrane space (the space between the inner and outer membranes of the mitochondrion).

The build-up of ions in the intermembrane space creates a hydrogen-

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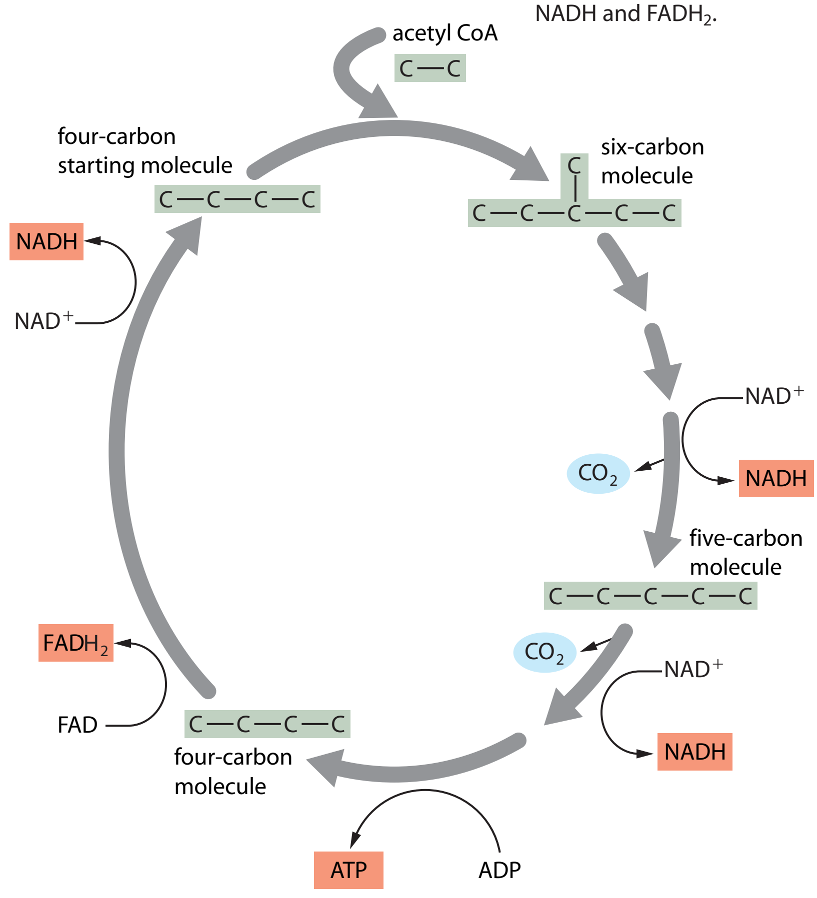
FYI
Glucose in not the only simple sugar that you consume in your diet. Common table sugar is sucrose. Milk contains the sugar lactose. Many foods contain starch. Your body can break down any of these sugars and convert them into glucose so they can enter glycolysis.

Figure 5.19 The role of the Krebs cycle is to transfer the energy that was originally stored in glucose to the reducing power of NADH and $FADH_2$.



Biology File

FYI
Some biologists and biochemists call the Krebs cycle the citric acid cycle because the cycle begins with citric acid (which contains the two carbon atoms from acetyl-CoA). Many biochemists call the Krebs cycle the TCA cycle because citric acid is a **t**ri**c**arboxylic **a**cid. If you encounter either of those terms when you are doing research, keep in mind that they are exactly the same as the Krebs cycle.

ion concentration gradient. The ions can diffuse back across the membrane but only through channels created by the enzyme ATP synthase. This enzyme uses the energy of the concentration gradient to bind a phosphate group to ADP, forming ATP. This process is chemiosmosis. As in the chloroplast, **chemiosmosis** in the mitochondrion couples the movement of hydrogen ions down their concentration gradient to the synthesis of ATP from ADP and phosphate.

Oxygen is the final electron-accepting molecule in the electron transport system. The oxygen accepts electrons and hydrogen ions. The resulting molecule is water.

The Role of Oxygen in Aerobic Cellular Respiration

You learned earlier that glycolysis does not require oxygen. Oxygen is not part of the Krebs cycle, either. In fact, oxygen does not play any role in aerobic cellular respiration until the very last set of reactions in electron transport. So why is this type of cellular respiration called *aerobic*?

The reason becomes clear if you trace the route of the reactions backwards from the end of the process. If oxygen were not present to receive electrons, the whole process would ultimately fail. The last electron carrier would not be able to release its electron. This means that the previous carrier would not be able to pass *its* electron, and so on up the line of electron transport. Soon, all of the carriers would have electrons and the reduced NADH and $FADH_2$ would be unable to lose *their* electrons. All of the compounds would remain in their reduced, energized state. There would be no oxidized NAD^+ or FAD to pick up electrons from the Krebs cycle. All reactions would cease.

The only part of aerobic cellular respiration that would be able to proceed without oxygen is glycolysis. However, glycolysis does not produce enough energy to sustain the needs of most eukaryotic cells.

Compare the amount of ATP produced by glycolysis with the yield of ATP harvested from glucose during all the stages of aerobic cellular respiration in a typical cell (Figure 5.20). Notice that the majority of the ATP in aerobic cellular respiration is generated by chemiosmosis, using the energy of a hydrogen ion concentration gradient that is formed by the electron transport system. All the energy, in the form of ATP, that your body uses to carry out every task is produced by the chemical reactions summarized here.

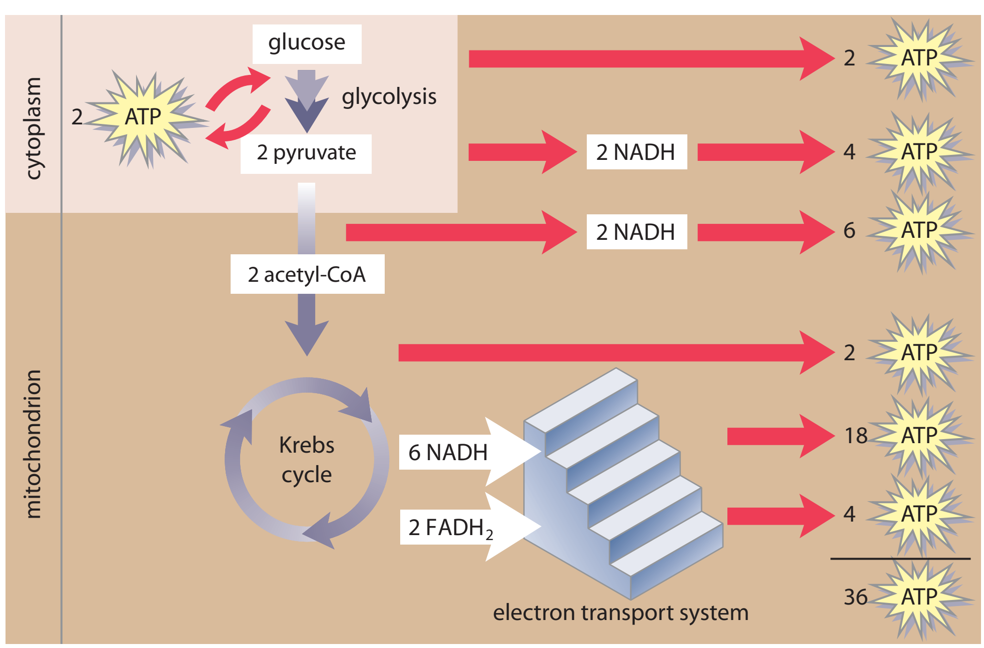


Figure 5.20 In aerobic cellular respiration, only a small amount of ATP is generated by glycolysis, and only a small amount of ATP is generated by the Krebs cycle. The majority of the ATP is generated by chemiosmosis using energy generated via the electron transport system.

Anaerobic Cellular Respiration Uses a Different Final Electron-Acceptor

In anoxic (no oxygen) environments such as swampy sediments and your colon (large intestine), some organisms use anaerobic cellular respiration for their energy needs. These organisms are prokaryotes—that is, various species belonging to the domains Bacteria and Archaea.

As is the case with aerobic respiration, anaerobic cellular respiration usually includes an electron transport system and a concentration gradient to generate molecules of ATP. Anaerobic cellular respiration is not as efficient as aerobic respiration, however, providing less energy (fewer ATPs).

Since oxygen is not available as the final electron-accepting molecule, a different chemical must serve as the final electron acceptor. For most anaerobic

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Web Link

Pyruvate dehydrogenase complex deficiency is a rare genetic disorder in which the enzyme that converts pyruvate to acetyl-CoA is missing or functions poorly. What are the symptoms of this disorder, what treatments are available, and how successful are they?

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WWW

Thought Lab 5.3 The Effects of Metabolic Toxins on Cellular Respiration

Target Skills

Investigating and **integrating**, from print and electronic sources, the action of metabolic toxins on cellular respiration

Evaluating the reliability, accuracy, and validity of information sources consulted

Working cooperatively to investigate metabolic toxins

In the 1930s, a chemical called dinitrophenol (DNP) was used in diet pills. DNP affects chemiosmosis by disrupting the hydrogen ion concentration gradient, thus interfering with the production of ATP. This leads to rapid oxidation of compounds in the Krebs cycle, and encourages the metabolizing of carbohydrates and fats. Since the production of ATP is severely impaired, energy production in the body is instead given off as significant amounts of heat. People lost a lot of weight quickly, but many people lost a lot more—their health and, in some cases, their lives. DNP was quickly banned from public consumption, but it is still used in industry to make products such as dyes, preservatives for wood, and pesticides. It is, unfortunately, also popular with bodybuilders who use it at great risk to their personal safety.

DNP is an example of a metabolic toxin—a chemical that impairs or disrupts metabolic pathways. In this activity, you will investigate and report on metabolic toxins that affect the function of mitochondria.

Procedure

1. Choose one of the following metabolic toxins to investigate:
   - antimycin
   - malonate
   - rotenone
   - cyanide
   - oligomycin
   - arsenic
   - hydrogen sulfide
2. Find four different sources of information about your chosen metabolic toxin. Include information from two print sources and two electronic sources. Search for and collect the following information:
   - What are its physical properties?
   - When and why was it first developed and used?
   - How does it work? (That is, what is its effect on metabolism?)
   - How dangerous is it?
   - What, if any, evidence is there to link it to human disorders?
   - What, if any, antidotes or treatments for exposure are there?
3. Create a "Metabolic Toxin Profile" for the toxin you investigate. Your profile should include an introductory paragraph that summarizes the results of your research findings. Use appropriate headings to organize the information in your profile. Also include the sources of information you have used to construct your profile.
4. Share your profile with your classmates. As a class, decide on a suitable format in which to collect and present profiles of all the metabolic toxins investigated. (For example, you could construct a comparison chart or an electronic database.)

Analysis

1. Classify the metabolic toxins you investigated on the basis of the metabolic pathway they affect.
2. Consider each of the information resources you used to construct your profile.
   a) How did you assess the accuracy of its information?
   b) How did you assess the validity (truth) of its information?
   c) Examine the profiles and information sources from other students who investigated the same metabolic toxin. Re-examine and assess the reliability of the information sources that you used to construct your profile.
   d) Which do you think provided information in which you have greater confidence: print sources or electronic sources? Give reasons to support your opinion.
   e) Are four sources of information sufficient for providing accurate and reliable information? Justify your answer.

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Web Link
The environment of your mouth supports a variety of aerobic and anaerobic bacteria. The numbers and diversity of these populations change over time, notably between birth and puberty. Around what time do anaerobic bacteria begin populating the mouth? Which diseases of the teeth and gums are associated with these bacteria?

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cells, this is an inorganic chemical such as sulfate, nitrate, or carbon dioxide. Depending on the inorganic chemical, common by-products are elemental sulfur, nitrite, elemental nitrogen, or methane.

36 Where, in the mitochondria, are the electron carriers located?

37 What is the source of the high-energy electrons for electron transport in mitochondria?

38 Describe the function of oxygen in cellular respiration.

Fermentation

Anaerobic organisms do not use oxygen, and some cells in aerobic organisms are sometimes without oxygen. These cells and organisms use metabolic pathways that do not require oxygen or an electron transport system to produce ATP from energy sources. These pathways, called fermentation, typically occur in the cytoplasm of the cell. **Fermentation** is a metabolic pathway that includes glycolysis and one or two reactions in which NADH is oxidized to NAD^+ by reducing pyruvate to other compounds. Fermentation is much less efficient at supplying energy than aerobic cellular respiration, because fermentation only produces the amount of ATP that is generated in glycolysis.

Many single-celled organisms such as yeasts and some bacteria, carry out fermentation. Fermentation also occurs in parts of an organism that are in an anaerobic environment such as in a plant that is partly submerged in a pond or in cells that are deep within a multicellular organism without direct access to oxygen. There are many types of fermentation pathways. Two common types are *lactate fermentation* and *ethanol fermentation*.

Lactate Fermentation

Some single-celled organisms and some animal cells that are temporarily without oxygen carry out lactate fermentation. They use NADH to convert pyruvate to a molecule called lactate (also called lactic acid) in a single step (Figure 5.21). The resulting NAD^+ is recycled to continue the process. This process occurs in your muscle cells when they are working strenuously. During such times, the demand for energy exceeds what can be produced aerobically. Glycolysis, then, is increased to a point where it exceeds the oxygen supply, creating a condition of "oxygen debt." In this condition, pyruvate starts to accumulate, since it cannot be broken down fast enough in the Krebs cycle and the electron transport system. To sustain glycolysis, the muscle must remove excess pyruvate by converting it to lactate, which is temporarily stored in the muscle cells. If enough lactate builds up, the muscle fatigues and cramps. When oxygen is present again (through heavy breathing after exercise), the lactate is converted back to pyruvate. The pyruvate may then be processed as usual through aerobic pathways.

Ethanol Fermentation

Some organisms are able to function aerobically as well as anaerobically. When they function anaerobically, they carry out ethanol fermentation. Yeasts and some kinds of bacteria convert pyruvate to ethanol and carbon dioxide through ethanol fermentation. The process involves two steps, as shown in Figure 5.22.

Fermentation by brewer's yeast (*Saccharomyces cerevisiae*) is used in industry to manufacture baked goods and alcoholic beverages (Figure 5.23). Depending on the substance being fermented, the variety of yeast used, and

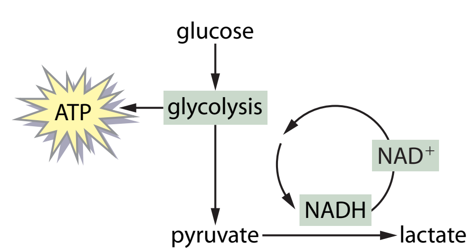


Figure 5.21 In lactate fermentation, pyruvate is converted to lactate in a single step that oxidizes NADH to NAD^+.

whether carbon dioxide is allowed to escape during the process, yeast fermentation may be used to produce wine or champagne from grapes, the syrupy drink called mead from honey, and cider from apples. Beer is brewed by fermenting sugars in grain such as barley, rice, or corn.

Depending on the organism, fermentation can yield other substances besides lactate and ethanol. Table 5.2 lists several examples. Two other examples, acetone and butanol, were essential during World War I. The British needed butanol to make artificial rubber for tires and machinery and acetone to make a smokeless gunpowder called cordite. Prior to the war, acetone was made by heating wood in the absence of oxygen (a technique called pyrolysis). Up to 100 tonnes of lumber were needed to produce 1 tonne of acetone. When war broke out in 1917, the demand for acetone was intense. A swift and efficient means for producing the chemical was needed. Two years earlier, Chaim Weizmann, a chemist working in Manchester, England, had developed a fermentation process using the anaerobic bacterium *Clostridium acetobutylicum*. Through this process, Weizmann converted 100 tonnes of molasses or grain into 12 tonnes of acetone and 24 tonnes of butanol. For the war effort, Weizmann modified the technique for large-scale production. (Today, both acetone and butanol are produced more economically from petrochemicals.)

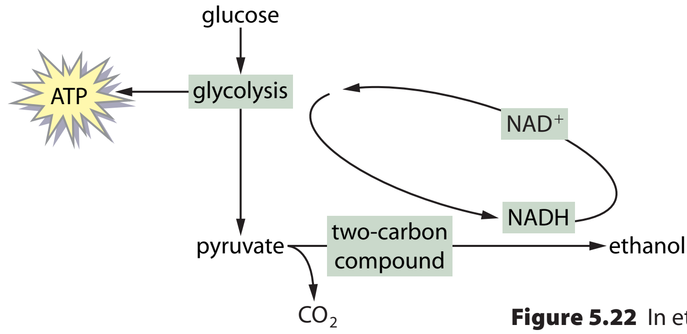


Figure 5.22 In ethanol fermentation, pyruvate is converted to a two-carbon molecule and then to ethanol. In the process, NADH oxidizes to NAD^+.

39 What does it mean to say that glycolysis is an anaerobic process?

40 Under what conditions does fermentation occur?

41 Describe how lactate fermentation is similar to and different from ethanol fermentation.

Ethanol Fermentation and Fuel Production

Glucose is the main fuel for many organisms. However, much of the chemical energy of glucose remains in the compounds that form after glycolysis

Table 5.2 Selected Fermentation Products and their Uses

Product of Fermentation	Possible Sources	Uses
acetic acid	Bacteria: *Leuconostoc* sp. *Acetobacter xylenam*	sours beer; produces vinegar
diacetyl	Bacteria: *Streptococcus diacetilactis*	provides fragrance and flavour to buttermilk
lactic acid (lactate)	Bacteria: *Lactobacillus bulgaricus*	aids in changing milk to yogurt
propionic acid + CO_2	Bacteria: *Proprionibacterium shermani*	produces the "eyes" (holes) and flavour of Swiss cheese

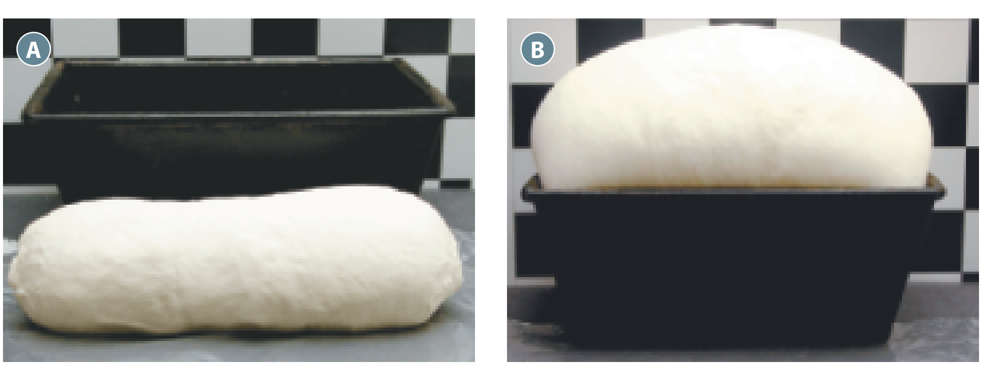


Figure 5.23 In **(A)**, bread dough with yeast is being left in a warm place so that yeast has time to ferment. After a few hours, the bread dough in **(B)** has doubled in size (risen) due to the carbon dioxide produced by fermentation. When the dough is baked, the carbon dioxide gas will be driven off, leaving small holes that help give the bread a light, chewy texture.

Energy from Manure

Alberta raises about 3.5 million pigs each year—about 15 percent of the Canadian total. Pork is a valuable resource. Canada exports over $2 billion worth of pork per year, making us one of the world's top exporters. But is what's good for the economy harming the environment? According to figures from Statistics Canada, pig manure is the largest source of greenhouse gas emissions from the hog-production system. Pig manure is also, however, a source of biogas (methane from animal wastes), which can be used as an alternative to traditional fuels. Around the world, especially in developing countries, biogas is used to heat homes, cook food, and power generators.

How Biogas Is Made

The process of anaerobic digestion is used to treat sewage, animal wastes, and municipal solid wastes. An anaerobic digester is an airtight tank with heating coils and sometimes a mechanical mixer. Oxygen is poisonous to anaerobic bacteria, so an oxygen-free environment is important.

Anaerobic digestion is a two-part process that works best at a temperature of 35 °C or higher. First, acid-forming bacteria break down the manure into simple organic compounds. Then a second group of anaerobic micro-organisms break down the acids into methane and carbon dioxide. Biogas consists of 60 to 80 percent methane gas, 20 to 40 percent carbon dioxide, and trace amounts of other compounds, such as hydrogen sulfide, ammonia, and water vapour. The set-up cost varies greatly, since there are different types and sizes of anaerobic digesters.

The Value of Biogas

Research and small-scale case studies indicate that about 1 kg of hog manure produces between 0.5 m^3 and 1 m^3 of biogas (with 60 to 65 percent methane). 1 m^3 of biogas is enough to cook three meals daily for a family of four to six people, replacing approximately 11 kg (one tank) of propane. To produce 1 m^3 of biogas, a family needs at least 5 L of pig manure per day, requiring about five mature pigs. Many variables, such as the pigs' diet, the type of digester used, and the digester temperature, influence these figures.

• • •

1. Manure digestion for the production of electricity is currently in use in Vegreville, Alberta, at Highmark Renewables. Find out more about this and other integrated manure utilization systems (IMUS).

2. Yuanhui Zhang, an agricultural engineering professor at the University of Illinois, has been able to convert small amounts of hog manure into crude oil. Subsequent experiments have yielded a refined product with the approximate heating value of diesel fuel. Investigate the current status of this ongoing work.

is complete. The process of fermentation does not remove much of this chemical energy. Therefore, the products of fermentation can still be used for fuel.

In organisms that carry out ethanol fermentation, the ethanol they produce is released as a waste product. In fact, the ethanol waste is toxic to yeast. As ethanol concentrations approach 12 percent, the yeast cells begin to die. However, humans learned long ago that this "waste" burns. Ethanol was a common lamp fuel during the 1800s, and it was used for early internal combustion engines and cars, also starting in the 1800s.

Historically, because gasoline costs less to produce than ethanol, its use was limited to small-scale, specialized applications. This situation changed in the late 1970s. At that time, rising oil prices, dwindling petroleum reserves, and environmental concerns caused some governments to invest in alternative energy resources such as ethanol fuels. Whenever gas prices rise, some of these alternative resources become commercially viable sources of fuel. In cars, the use of gasohol (a mixture of 10 percent ethanol and 90 percent gasoline) is becoming more common. Cars manufactured after 1980 can use gasohol without any engine modification. As well, auto companies are designing engines that can use fuels with ethanol percentages that are much higher than 10. Brazil is currently leading the world in the production of ethanol and its use as a fuel. Most cars designed and built is Brazil today can burn pure ethanol (Figure 5.24) or several combinations of gasoline and ethanol.

Ethanol Production

In Canada, the most common source of ethanol is the fermentation of corn and wheat. First the grain is ground into a meal. Then it is mixed with water to form a slurry called "mash." Enzymes added to the mash convert the starches into glucose. The mash is heated to destroy any bacteria, then cooled and placed in fermenters. In the fermenters, yeast is added to the mash. The yeast grows on the glucose under anaerobic conditions and releases the end products, ethanol, and carbon dioxide. When the fermentation is complete, the resulting product, called "beer," is approximately 10 percent ethanol and 90 percent water.

Distilling the beer to eliminate as much of the water as possible yields nearly pure ethanol. A small amount of gasoline is added to make the ethanol unfit for human consumption (called denaturing). The solid residues from the grain and yeast are dried to produce a vitamin- and protein-rich product called Distiller's Dried Grains and Solubles (DDGS). DDGS is used as feed for poultry and cattle.

The combustion of ethanol produces carbon dioxide, which is one of the greenhouse gases that contributes to global warming. However, unlike gasoline, the source of ethanol (grain) is a renewable resource. Ethanol is made by the fermentation of corn, grain, sugar cane, and many other crops that can be regrown quickly. In addition, these same crops also absorb carbon dioxide in order to produce more sugars and, through processing, more ethanol. Even so, the burning of ethanol is not "carbon-neutral." In other words, the production and burning of ethanol release more CO_2 into the atmosphere than is absorbed by growing plants. So why use it? As an additive to gasoline, ethanol increases the octane rating of the fuel; that is, it burns more slowly and prevents engine "ping." As well, ethanol-gasoline mixtures reduce the amount of carbon monoxide in the exhaust. Burning pure ethanol on its own also eliminates the release of partially burned hydrocarbons and volatile organic compounds (VOCs) that contribute to smog.

Section 5.3 Summary

- Three metabolic pathways make up aerobic cellular respiration.
- The first set of reactions in aerobic cellular respiration is called glycolysis.

BiologyFile

FYI

Red Deer, Alberta has one of only seven ethanol production plants in Canada. Seven more plants are in the planning stages.

Figure 5.24 Many modern Brazilian cars are called flex-cars because they can operate on gasoline or ethanol.

Biology File

Web Link

The First Nation Ethanol Development Corporation was established in 2004 with an initial focus on establishing an ethanol plant in southwestern Ontario. What other products are planned for this plant? And why is the use of corn, as the main fermentation feedstock, an appropriate choice for this venture?

www.albertabiology.ca

WWW

It is an anaerobic process that takes place in the cytoplasm of the cell.

- During glycolysis, a small amount of ATP is generated, and NAD^+ is reduced to NADH.
- The fate of pyruvate, the final product of glycolysis, depends on the availability of oxygen and on the type of organism.
- When oxygen is available, pyruvate enters the matrix of the mitochondrion. A series of reactions yield carbon dioxide and acetyl-CoA. NAD^+ is reduced to NADH.
- Acetyl-CoA enters the Krebs cycle by combining with a four-carbon compound.
- During the Krebs cycle, two carbon atoms are fully oxidized to carbon dioxide, NAD^+ and FAD are reduced to NADH and $FADH_2$, and a small amount of ATP is produced.
- The reduced NADH and $FADH_2$ that are formed during the Krebs cycle donate their electrons to the electron carriers in electron transport.
- As electrons are passed from one carrier to the next, the energy that is released is used to pump hydrogen ions across the mitochondrial inner membrane into the intermembrane space, creating a concentration gradient.
- The energy stored in the gradient is used to generate ATP by chemiosmosis.
- Organisms that carry out anaerobic cellular respiration use inorganic chemicals other than oxygen as the final electron-acceptor. This produces ATP for the cell, but not as much as in aerobic respiration.
- In muscle that is functioning anaerobically, pyruvate is converted to lactate and the reduced NADH is reoxidized so that glycolysis can continue.
- In yeast growing anaerobically, pyruvate is converted to carbon dioxide and ethanol.
- Fermentation is used on an industrial scale to produce ethanol.
- Ethanol is used as an additive to gasoline to reduce some environmental contaminants.

Section 5.3 Review

1. Summarize photosynthesis and cellular respiration in terms of reduction and oxidation of carbon-based molecules.
2. Compare, in general terms, aerobic cellular respiration, anaerobic cellular respiration, and fermentation.
3. Identify the three energy-releasing metabolic pathways associated with aerobic cellular respiration.
4. Use graphics or word processing software to summarize glycolysis, the first stage of aerobic cellular respiration. Include where this process takes place, whether or not oxygen is required for these reactions, the products that are formed as a result of glycolysis, and where these products go next. ICT
5. Use graphics or word processing software to summarize the Krebs cycle, the second stage of aerobic cellular respiration. Include where this process takes place, whether or not oxygen is required for these reactions, the products that are formed as a result of the Krebs cycle, and where these products go next. ICT
6. Use graphics or word processing software to summarize the electron transport system, the third stage of aerobic cellular respiration. Include where this process takes place, whether or not oxygen is required for these reactions, the products that are formed as a result of the electron transport system, and where these products go next. ICT
7. Explain the term "chemiosmosis."
8. Identify the final electron acceptor in aerobic cellular respiration, and explain what happens if this molecule is not present in the cell.
9. Explain why aerobic cellular respiration produces so much more ATP than does anaerobic cellular respiration.
10. Describe the term "fermentation," and explain why this process is considered to be anaerobic.
11. Compare lactate fermentation to ethanol fermentation in terms of starting and ending material and ATP production.

The summary equations for photosynthesis and cellular respiration represent dozens of different reactions. The central function of photosynthesis and cellular respiration is to produce energy-rich compounds and break them down to release their stored energy. The useful form of energy is ATP (adenosine triphosphate). The energy is contained in the bonds between the phosphate groups, leaving ADP (adenosine diphosphate) and a free phosphate group. When the bond to the last phosphate group is broken, the energy released is available to do cellular work. Energy stored in energy-rich compounds is used to add a phosphate group back to ADP to regenerate ATP.

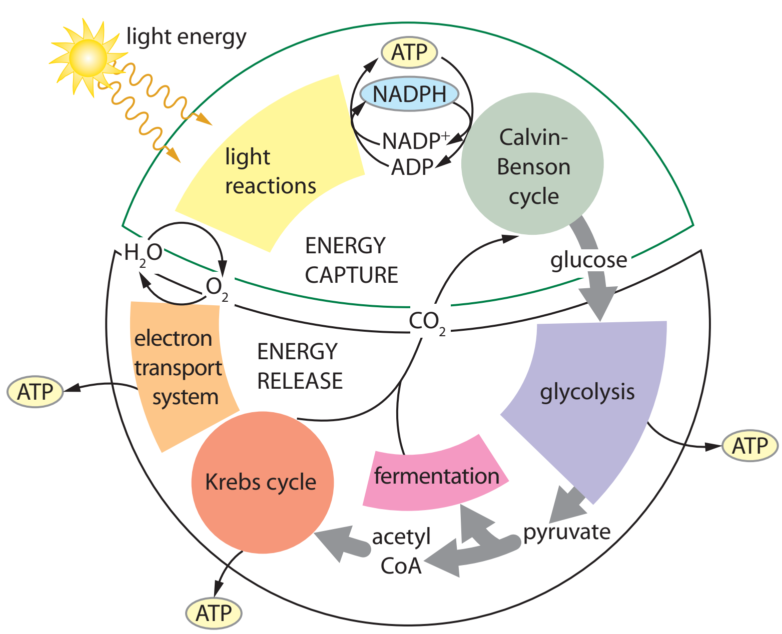
In photosynthesis, the carbon dioxide and water are involved in two separate sets of reactions. Water is split into hydrogen ions, electrons, and oxygen in the light-dependent reactions; carbon dioxide is incorporated into carbohydrates in the light-independent reactions.

In the light-dependent reactions, which take place in the thylakoid membranes of the chloroplasts, pigments capture light energy and use it to excite electrons that are channelled away to produce ATP and NADPH. During the light-independent reactions in the stroma of the chloroplasts, the chemical potential energy of ATP and the reducing power of NADPH are used to reduce carbon dioxide and form glucose and other carbohydrates via the Calvin-Benson cycle.

The glucose synthesized by plants and other photosynthesizing organisms (autotrophs) is the source of energy for virtually all living organisms. The glucose is processed to extract the energy in a series of three major sets of chemical reactions: glycolysis, the Krebs cycle, and electron transport. Glycolysis is an anaerobic process that occurs in the cytoplasm and breaks down glucose to form pyruvate. In most organisms, the pyruvate passes into the mitochondria where it is broken down into carbon dioxide and acetyl CoA in preparation for the Krebs cycle, which occurs in the matrix. Energy released from the breakdown of compounds in the Krebs cycle is used to reduce NAD^+ and FAD to NADH and $FADH_2$. These reduced compounds contribute their electrons to electron carriers embedded in the inner mitochondrial membranes. As the electrons are passed from one carrier to the next in electron transport, the energy that is released in a stepwise manner is used to pump hydrogen ions across the inner mitochondrial membrane, forming a concentration gradient that generates ATP through chemiosmosis.

In some organisms, glycolysis is their only source of energy. In these organisms, the pyruvate is broken down into carbon dioxide and alcohol (ethanol fermentation) or lactate (lactate fermentation). Humans have long been using the fermentation process to obtain ethanol, which is becoming popular as a fuel for transportation.

Chapter 5 Graphic Organizer



Career Focus: Ask a Research Scientist

Dr. Salim Abboud has always been interested in science as a way to solve problems. Today, he is a research scientist at the Alberta Research Council and an Adjunct Professor at the University of Alberta, where he applies scientific knowledge to solve some of the most urgent issues facing our society today. Dr. Abboud's current research focusses on improving waste management techniques and developing environmentally friendly and waste-free methods of composting organic materials and other wastes. This research is on the cutting edge of science, particularly as our society begins to move to a more sustainable way of life. Dr. Abboud's goal, like the goals of most research scientists, is to find ways of solving current problems and to develop technologies and solutions for issues that will be facing us in the future.

Q What are the main areas of your research?

I am working on finding the optimal conditions and technologies to maximize the process of composting and make it as clean and complete as possible. Using compost as a soil amendment gives us an alternative to using chemicals (such as fertilizers and pesticides) on land, thereby saving energy and natural resources. As well, I am interested in the biofiltration of gaseous emissions from municipal and industrial sites.

Q What is biofiltration?

If you take a material, such as a volatile organic compound (VOC), that causes air pollution, you may be able to oxidize it into non-harmful compounds, such as CO_2 and water. This also works on other noxious emissions, such as reduced sulfur compounds that have such a strong smell. They can be oxidized into SO_2 and water, which eliminates the negative effects of the sulfur compound.

Q Do you spend all your time in a laboratory, or do you get to go out and do field work?

I spend a significant amount of time out in the field. I set up pilot experiments and test new conditions in different locations, such as industrial sites. In addition, I am involved in work at the Edmonton Waste Management Centre of Excellence, which houses a leading edge composting facility.

Q What makes the Edmonton composter so special?

The Edmonton composter is the largest composter in North America, handling almost 1200 t of compost every day. All household solid waste in Edmonton goes to the composter, where it is treated. About 65 to 70 percent of the waste ends up as compost or recyclable commodities, and about 30 percent is a residual that is sent to the landfill.

Q So no household garbage in Edmonton goes directly to the landfill?

No, it doesn't. In fact, we are still working to reduce the 30 percent. We are aiming to keep about 95 percent of waste from landfills by gasification techniques (burning), which will extract energy that can be used to create electricity.

Q Why do you think these issues are so important?

At the moment, as a society, we produce an enormous amount of garbage and other pollutants. I believe that it is possible to use resources in environmentally and socially friendly ways. It is no longer appropriate to take a natural resource, use part of it, and then throw the rest away. My focus is industrial ecology, organizing industries in ways that are similar to nature. In nature, there is no waste—one process feeds into the next. My question is why throw out garbage? Compost it, and return it to where it came from. Close the loop, and eventually we won't have a pollution problem.

Q Can you give me an example of what you mean?

Sure. Let's talk about organic waste. It comes from food and fibre produced from plants. After we use plants, we can compost them and add the compost to the soil, which will produce more plants and complete the cycle.

Other Careers Related to Science

Conservation Biologist Researchers who focus on conservation biology have many opportunities to work on relevant and meaningful projects at local as well as global levels. Some areas of conservation biology include protecting endangered or threatened species and increasing their numbers, reclaiming polluted sites, developing barriers to protect ecosystems from the impact of nearby developments, and developing policies to ensure long-term protection of the natural environment.

Biophysicist As the name suggests, biophysicists combine knowledge and techniques from the disciplines of biology and physics in order to investigate the mechanisms by which organisms function at an environmental as well as a cellular level. Applications of biophysical research affect fields as diverse as biotechnology, agriculture, ecology, and medicine.

Agronomist Agronomists study food, food production, and the earth material, soil, that both anchors plants and supplies them with nutrients that are made available through biogeochemical cycles. Drawing upon their knowledge of chemistry as well as plant biology, agronomists investigate methods to enhance existing agricultural techniques as well as to supplement or replace them with alternative technologies. Some agronomists work with "high-tech" technologies such as genetic manipulation (for example, so that plants may be grown without pesticides or synthetic fertlizers). Other agronomists prefer to work from a more "natural" foundation by concentrating on organic farming techniques.

Environmental Microbiologist Researchers in this field combine interests in chemistry, ecology, molecular genetics, and the biology of microscopic life in order to examine the activity of cellular processes in soil, water, and the atmosphere. Practical applications of such research include wastewater treatment, bioremediation, environmental risk assessessment, and control techniques for water- and air-borne pathogens.

Go Further…

1. Research the methods of waste disposal that are used in your community. How much of your community waste goes to a landfill? How much is recycled or composted?
2. Why is waste disposal such an important issue? What can you do in your daily life to improve the situation?
3. Volatile organic compounds, or VOCs, are a significant pollution problem. Research and list some common sources of VOCs and what is being done to solve the problem.

UNIT 3 REVIEW

Understanding Concepts

1. Describe, in general terms, the role of autotrophic organisms in an ecosystem.

2. Describe, in general terms, how both autotrophs and heterotrophs release the energy stored in glucose.

3. List four cellular activities that rely on ATP as a source of energy.

4. Explain how the release of a phosphate group from ATP and the subsequent regeneration of ATP from ADP creates a continuous cycle.

5. Describe the function of the chloroplast.

6. Use graphics software to draw a sketch of a chloroplast and label the following structures. ICT
- **a)** outer membrane
- **b)** inner membrane
- **c)** stroma
- **d)** thylakoids
- **e)** grana

7. Explain the relationship between thylakoids and grana in a chloroplast.

8. Explain the significance of NADPH in photosynthesis and NADH in aerobic cellular respiration.

9. Use graphics software to draw a sketch of a mitochondrion and label the following features. ICT
- **a)** cristae
- **b)** inner membrane
- **c)** outer membrane
- **d)** matrix

10. Identify simple tests that you can do in a lab to detect the presence of the following.
- **a)** oxygen gas
- **b)** carbon dioxide dissolved in water

11. Compare a metabolic pathway that synthesizes larger molecules from smaller ones to a metabolic pathway that breaks down larger molecules to smaller ones.

12. Explain why many of the chemical reactions that occur in living organisms are linked to oxidation and reduction reactions.

13. Describe how matter and energy are linked through the reactions that take place in the chloroplasts and in the mitochondria.

14. Describe the major function of photosynthetic pigments.

15. Explain what happens when you shine white light through a glass prism. Describe how you can use this phenomenon to study the properties of photosynthetic pigments.

16. Explain how an action spectrum differs from an absorbance spectrum.

17. Describe, in general terms, the function of the photosystems and identify where you would find these systems in a chloroplast.

18. When electrons travel down the electron transport system between photosystem II and photosystem I, a small amount of energy is released at each step. Describe how this energy is temporarily stored in the chloroplast.

19. When an electron is emitted from photosystem II, it does not return. The photosystem cannot trap any more light energy until the "hole" in the photosystem is filled with another electron. Identify the source of the electron that fills the "hole" in photosystem II.

20. Identify the source of oxygen that is released from the chloroplast during photosynthesis. Explain the main function of the reaction in which oxygen is released.

21. Identify the source of the electrons that reduce $NADP^+$ during the light-dependent reactions of photosynthesis.

22. NADPH is said to have reducing power. Explain the meaning of reducing power in this context.

23. The membranes of the thylakoids are impermeable to hydrogen ions (H^+), meaning that these ions cannot diffuse across the membranes from the inner space of the thylakoid to the stroma.
- **a)** Identify the only path by which the hydrogen ions can move down their concentration gradient across the membrane to the stroma.
- **b)** Identify the process that is associated with the movement of hydrogen ions through this pathway and identify the end product of this process.

24. Identify the location in the chloroplast where the reactions that form glucose take place.

25. Outline the Calvin-Benson cycle in terms of carbon dioxide fixation, reduction, and regeneration.

26. Identify where the reactions of glycolysis take place.

27. Identify the products of glycolysis that contain useful energy.

28. Explain the cause of the burning sensation in muscles when they have been working anaerobically for awhile.

29. Identify the products of fermentation in yeast.

30. Explain what happens to lactate (lactic acid) in muscle cells when oxygen becomes available while resting after a strenuous workout.

31. List the end products of the following.
   a) glycolysis
   b) Kreb's cycle
   c) electron transport

32. Identify the stage of aerobic cellular respiration during which the greatest number of ATP molecules is produced.

Applying Concepts

33. Outline, in the form of a paragraph, a drawing, or both, the meaning and significance of chemiosmosis in the mitochondrion. ICT

34. The function of the Calvin-Benson cycle is to use six carbon dioxide molecules to produce one glucose molecule. Describe why this set of reactions is called a cycle.

35. Explain what is meant by the following statement: "The reactions of glycolysis occur anaerobically."

36. Four molecules of ATP are formed when one glucose molecule goes through the reactions of glycolysis. Is it correct to say that glycolysis yields two molecules of ATP? Explain your answer.

37. Describe what happens to the pyruvate produced during glycolysis in muscle cells when there is very little oxygen available.

38. Explain how a lack of oxygen stops the process of electron transport and the reactions of the Kreb's cycle.

39. What is "oxygen debt," and how is it "repaid?"

40. Identify the structure in a chloroplast that is analagous (has a similar structure and performs a similar function) to each of the following structures in a mitochondrion. How do the functions of these structures differ?
   a) matrix
   b) outer membrane
   c) inner membrane
   d) cristae

Making Connections

41. Explain the following statement in terms of what green plants make.
"As the rainforest species disappear, so do many possible cures for life-threatening diseases."

42. An analogy is a type of comparison in which you compare two similar systems or ideas by using something that is familiar to help describe or explain something that is less familiar.
   a) Use the idea of a rechargeable battery as an analogy for the cycle that "recharges" ATP from ADP and a free phosphate group.
   b) Outline, in the form of a paragraph or a diagram, an analogy to compare the structure and function of chloroplasts with an active solar system. (An active solar system uses a mechanical, chemical, or electrical device to transfer light energy from the Sun to another part of the system for the purpose of doing useful work.)

43. Pyruvate is available as a dietary supplement. Its reported benefits are controversial but include enhanced weight loss and increased endurance levels during physical exercise. Infer how taking pyruvate could lead to these effects.

44. Research scientists are investigating methods for getting photosynthesis to proceed outside a chloroplast. Identify three practical uses and societal benefits that would come from the successful achievement of this goal.

45. Dinitrophenol (DNP) is a chemical that interferes with the production of ATP in both chloroplasts and mitochondria. In an attempt to identify the minimal concentration of DNP required to inhibit ATP production, DNP was applied to separate suspensions of both organelles. Data are shown in the table below.
   a) Which data represent the chloroplast?
   b) Which organelle would be considered the most active? Explain your answer.
   c) Which organelle is more at risk to changing concentrations of DNP? Explain.

DNP Concentration and ATP Production

Organelle	Concentration of DNP			
	5%	15%	25%	35%
volume of $CO_2(g)$ released (mL)	0.50	0.11	0.05	0.01
volume of $O_2(g)$ released (mL)	0.88	0.04	0.01	n/a