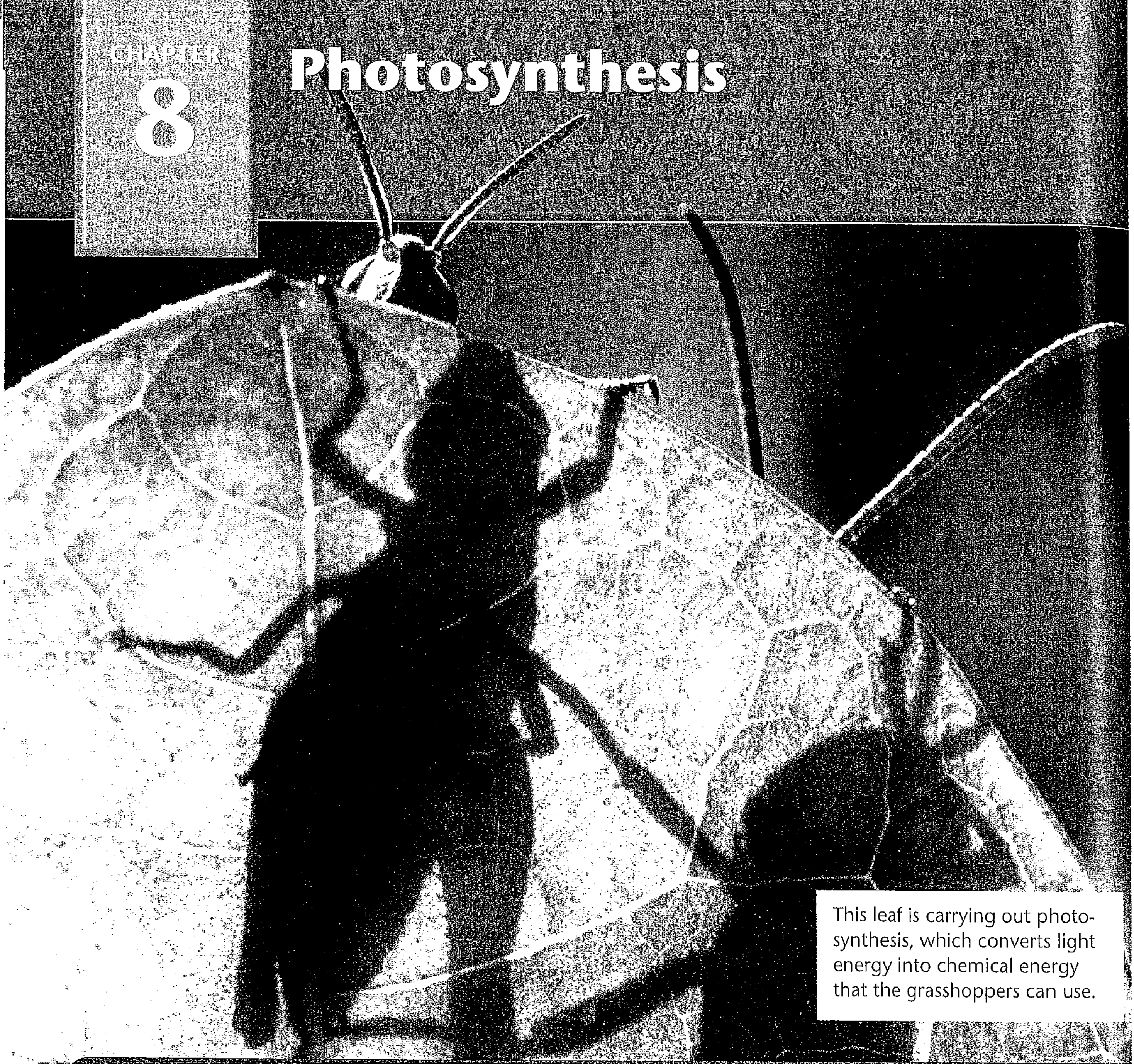
CHAPTER 8

Photosynthesis



This leaf is carrying out photosynthesis, which converts light energy into chemical energy that the grasshoppers can use.

Inquiry Activity

How do organisms capture and use energy?

Procedure

1. Obtain two test tubes wrapped in foil. Note the hole in the foil surrounding one test tube.
2. **Predicting** The test tubes contain *Euglena*, photosynthetic microorganisms that have chloroplasts and can move. Record your prediction of where in each test tube you will find *Euglena*.
3. Without shaking or disturbing the contents of the test tubes, carefully remove the foil. Record where *Euglena* are located in each test tube.

Think About It

1. **Observing** What pattern did you observe in the distribution of the *Euglena*? Why do you think they behave this way?
2. **Inferring** What is the source of energy that powers the *Euglena*'s swimming?

8–1 Energy and Life

Energy is the ability to do work. Nearly every activity in modern society depends on one kind of energy or another. When a car runs out of fuel—more precisely, out of the chemical energy in gasoline—it comes to a sputtering halt. Without electrical energy, lights, appliances, and computers stop working.

Living things depend on energy, too. Sometimes, the need for energy is easy to see. It is obvious that energy is needed to play soccer or other sports. However, there are times when that need is less obvious. For example, when you are sleeping, your cells are busy using energy to build new proteins and amino acids. Clearly, without the ability to obtain and use energy, life would cease to exist.

Guide for Reading

Key Concepts
- Where do plants get the energy they need to produce food?
- What is the role of ATP in cellular activities?

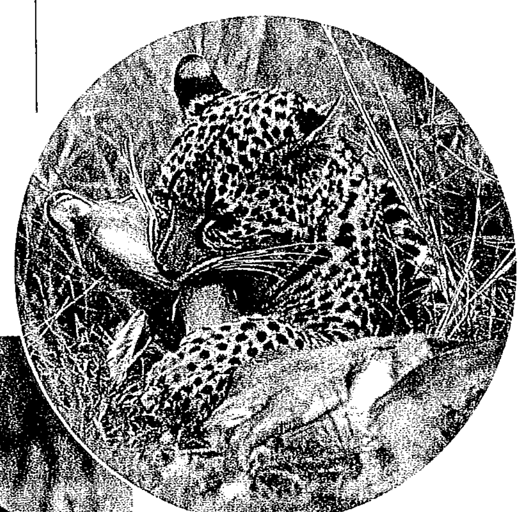
Vocabulary
autotroph
heterotroph
adenosine triphosphate (ATP)

Reading Strategy: Asking Questions Before you read, study the diagram in **Figure 8–3.** Make a list of questions that you have about the diagram. As you read, write down the answers to your questions.

Autotrophs and Heterotrophs

Where does the energy that living things need come from? The simple answer is that it comes from food. Originally, though, the energy in most food comes from the sun. **Plants and some other types of organisms are able to use light energy from the sun to produce food.** Organisms such as plants, which make their own food, are called **autotrophs** (AW-toh-trohfs).

Other organisms, such as animals, cannot use the sun's energy directly. These organisms, known as **heterotrophs** (HET-uh-roh-trohfs), obtain energy from the foods they consume. Impalas, for example, eat grasses, which are autotrophs. Other heterotrophs, such as the leopard shown in **Figure 8–1,** obtain the energy stored in autotrophs indirectly by feeding on animals that eat autotrophs. Still other heterotrophs—mushrooms, for example—obtain food by decomposing other organisms. To live, all organisms, including plants, must release the energy in sugars and other compounds.



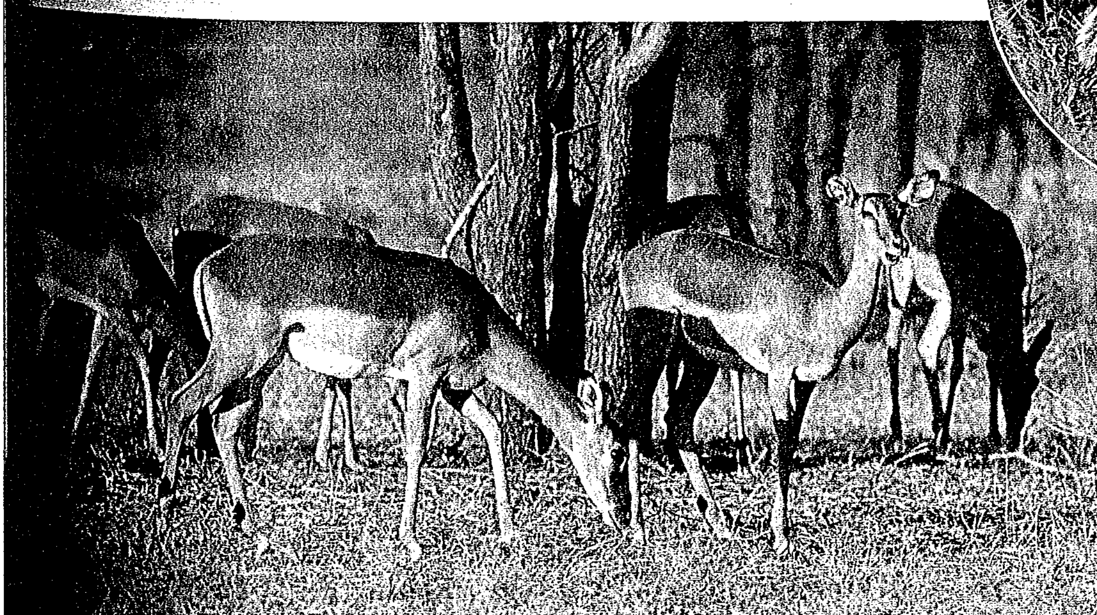
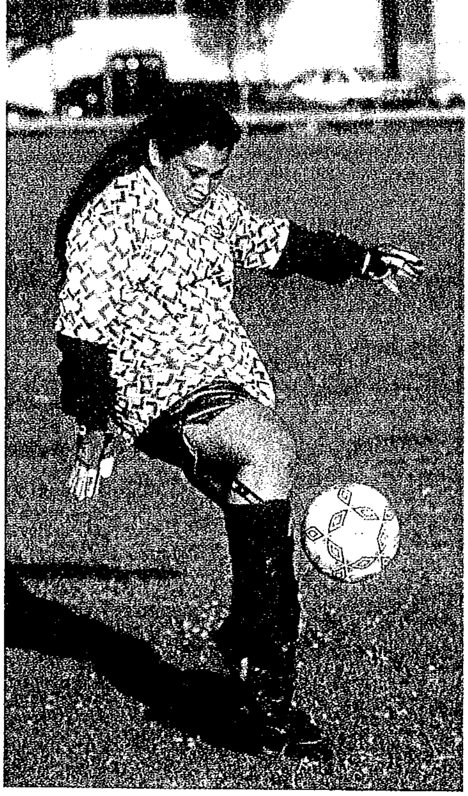
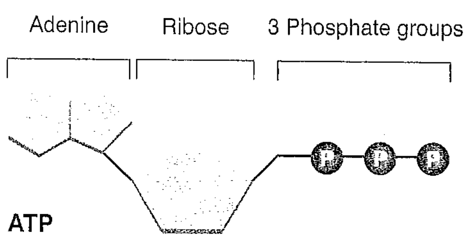


Figure 8–1 **Autotrophs use light energy from the sun to produce food.** These impalas get their energy by eating grass, while this leopard gets its energy by eating impalas and other animals. Impalas and leopards are both heterotrophs.





▲ **Figure 8–2** **ATP is used by all types of cells as their basic energy source.** The energy needed by the cells of this soccer player comes from ATP.

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Chemical Energy and ATP

Energy comes in many forms, including light, heat, and electricity. Energy can be stored in chemical compounds, too. For example, when you light a candle, the wax melts, soaks into the wick, and is burned, releasing energy in the form of light and heat. As the candle burns, high-energy chemical bonds between carbon and hydrogen atoms in the wax are broken. The high-energy bonds are replaced by low-energy bonds between these atoms and oxygen. The energy of a candle flame is released from electrons. When the electrons in those bonds are shifted from highe energy levels to lower energy levels, the extra energy is released as heat and light.

Living things use chemical fuels as well. One of the princip chemical compounds that cells use to store and release energy i **adenosine triphosphate** (uh-DEN-uh-seen try-FAHS-fayt), abbreviated **ATP.** As **Figure 8–2** shows, ATP consists of adenin a 5-carbon sugar called ribose, and three phosphate groups. Those three phosphate groups are the key to ATP's ability to store and release energy.

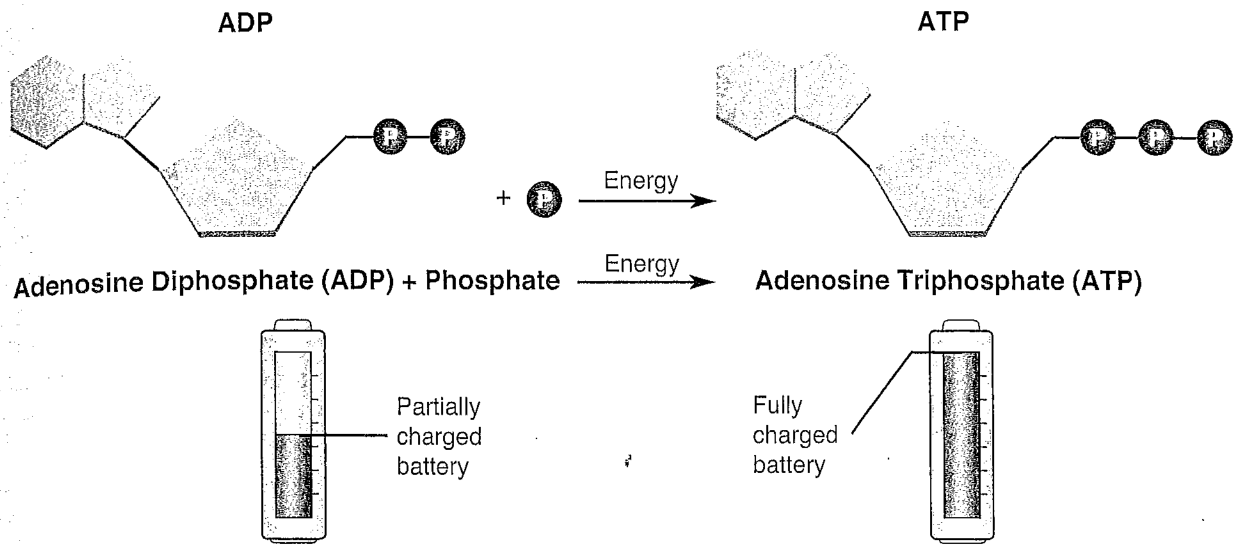
Storing Energy Adenosine diphosphate (ADP) is a compoun that looks almost like ATP, except that it has two phosphate groups instead of three. This difference is the key to the way in which living things store energy. When a cell has energy available, it can store small amounts of it by adding a phosphate group to ADP molecules, producing ATP, as shown in **Figure 8–3.** In a way, ATP is like a fully charged battery, ready to power the machinery of the cell.

Releasing Energy How is the energy that is stored in ATP released? Simply by breaking the chemical bond between the second and third phosphates, energy is released. Because a cell can subtract that third phosphate group, it can release energy as needed. ATP has enough energy to power a variety of cellula activities, including active transport across cell membranes, protein synthesis, and muscle contraction. **The characteristics of ATP make it exceptionally useful as the basic energy source of all cells.**

CHECKPOINT *What is the difference between ATP and ADP?*

Using Biochemical Energy

One way cells use the energy provided by ATP is to carry out activ transport. Many cell membranes contain a sodium-potassium pump, a membrane protein that pumps sodium ions (Na^+) out of the cell and potassium ions (K^+) into it. ATP provides the energy that keeps this pump working, maintaining a carefully regulated balance of ions on both sides of the cell membrane. ATP produces movement, too, providing the energy for motor proteins that mov organelles throughout the cell.



▲ **Figure 8–3** ATP can be compared to a fully charged battery because both contain stored energy, whereas ADP resembles a partially charged battery. **Predicting** *What happens when a phosphate group is removed from ATP?*

Energy from ATP powers other important events in the cell, including the synthesis of proteins and nucleic acids and responses to chemical signals at the cell surface. The energy from ATP can even be used to produce light. In fact, the blink of a firefly on a summer night comes from an enzyme powered by ATP!

ATP is such a useful source of energy that you might think the cells would be packed with ATP to get them through the day, but this is not the case. In fact, most cells have only a small amount of ATP, enough to last them for a few seconds of activity. Why? Even though ATP is a great molecule for transferring energy, it is not a good one for storing large amounts of energy over the long term. A single molecule of the sugar glucose stores more than 90 times the chemical energy of a molecule of ATP. Therefore, it is more efficient for cells to keep only a small supply of ATP on hand. Cells can regenerate ATP from ADP as needed by using the energy in foods like glucose. As you will see, that's exactly what they do.

8–1 Section Assessment

1. **Key Concept** What is the ultimate source of energy for plants?
2. **Key Concept** What is ATP and what is its role in the cell?
3. Describe one cellular activity that uses the energy released by ATP.
4. How do autotrophs obtain energy? How do heterotrophs obtain energy?
5. **Critical Thinking Comparing and Contrasting** With respect to energy, how are ATP and glucose similar? How are they different?

Focus on the BIG Idea

Interdependence in Nature Recall that energy flows and that nutrients cycle through the biosphere. How does the process of photosynthesis impact the flow of energy and the cycling of nutrients? You may wish to refer to Chapter 3 to help you answer this question.

8–2 Photosynthesis: An Overview

Guide for Reading

Key Concepts
- What did the experiments of van Helmont, Priestley, and Ingenhousz reveal about how plants grow?
- What is the overall equation for photosynthesis?
- What is the role of light and chlorophyll in photosynthesis?

Vocabulary
photosynthesis
pigment
chlorophyll

Reading Strategy: Summarizing As you read, find the key ideas under each blue head. Write down a few key words from each key idea. Then, use the key words in your summary.

The key cellular process identified with energy production : photosynthesis. In the process of **photosynthesis,** plant: use the energy of sunlight to convert water and carbon dioxid into high-energy carbohydrates—sugars and starches—and oxygen, a waste product. The investigations of many scientists have contributed to the current understanding of the process (photosynthesis.

Investigating Photosynthesis

Research into photosynthesis began centuries ago with a simp question: When a tiny seedling grows into a tall tree with a mass of several tons, where does the tree's increase in mass come from? From the soil? From the water? From the air?

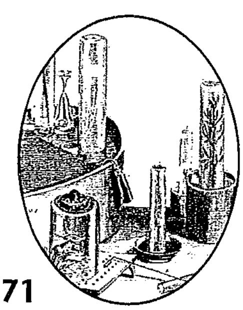
Van Helmont's Experiment In the 1600s, the Belgian physician Jan van Helmont devised an experiment to find out if plants grew by taking material out of the soil. Van Helmont determined the mass of a pot of dry soil and a small seedling. Then, he planted the seedling in the pot of soil. He watered it regularly. At the end of five years, the seedling, which by then had grown into a small tree, had gained about 75 kg.

Biology and History

Understanding Photosynthesis

Many scientists have contributed to understanding how plants carry out photosynthesis. Early research focused on the overall process. Later researchers investigated the detailed chemical pathways.

1643
Jan van Helmont
After careful measurements of a plant's water intake and mass increase, van Helmont concludes that trees gain most of their mass from water.



1771
Joseph Priestley
Using a bell jar, a candle, and a plant, Priestley finds that the plant releases oxygen.

1779
Jan Ingenhousz
Ingenhousz finds that aquatic plants produce oxygen bubbles in the light but not in the dark. He concludes that plants need sunlight to produce oxygen.

1600 1700 1800

The mass of the soil, however, was almost unchanged. He concluded that most of the gain in mass had come from water, because that was the only thing that he had added.

Van Helmont's experiment accounts for the "hydrate," or water, portion of the carbohydrate produced by photosynthesis. But where does the carbon of the "carbo-" portion come from? Although van Helmont did not realize it, carbon dioxide in the air made a major contribution to the mass of his tree. The carbon in carbon dioxide is used to make sugars and other carbohydrates in photosynthesis. Van Helmont had only part of the story, but he had made a major contribution to science.

Priestley's Experiment More than 100 years after van Helmont's experiment, the English minister Joseph Priestley performed an experiment that would give another insight into the process of photosynthesis. Priestley took a candle, placed a glass jar over it, and watched as the flame gradually died out. Something in the air, Priestley reasoned, was necessary to keep a candle flame burning. When that substance was used up, the candle went out. That substance was oxygen.

Priestley then found that if he placed a live sprig of mint under the jar and allowed a few days to pass, the candle could be relighted and would remain lighted for a while. The mint plant had produced the substance required for burning. In other words, it released oxygen.

CHECKPOINT *What did Priestley discover about photosynthesis?*

Word Origins

Photosynthesis comes from the Greek words *photo,* meaning "light," and *synthesis,* meaning "putting together." Therefore, *photosynthesis* means "using light to put something together," specifically, carbohydrates. *Chemo* means "having to do with chemicals or chemical reactions." **What do you think *chemosynthesis* means?**

Writing in Science

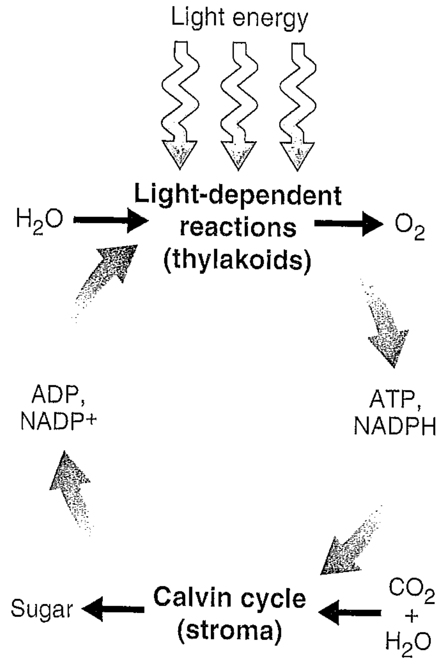
Use the Internet or library resources to research the experiments conducted by one of these scientists. Then, write a summary describing how the scientist contributed to the modern understanding of photosynthesis.

1845
Julius Robert Mayer
Mayer proposes that plants convert light energy into chemical energy.

1948
Melvin Calvin
Calvin traces the chemical path that carbon follows to form glucose. These reactions are also known as the Calvin cycle.

1992
Rudolph Marcus
Marcus wins the Nobel Prize in chemistry for describing the process by which electrons are transferred from one molecule to another in the electron transport chain.

1800 1900 2000



▲ **Figure 8–4** Photosynthesis is a series of reactions that uses light energy from the sun to convert water and carbon dioxide into sugars and oxygen.

Jan Ingenhousz Later, the Dutch scientist Jan Ingenhousz showed that the effect observed by Priestley occurred only when the plant was exposed to light. The results of both Priestley's and Ingenhousz's experiments showed that light is necessary for plants to produce oxygen. **The experiments performed by van Helmont, Priestley, and Ingenhousz led to work by other scientists who finally discovered that in the presence of light, plants transform carbon dioxide and water into carbohydrates, and they also release oxygen.**

The Photosynthesis Equation

Because photosynthesis usually produces 6-carbon sugars ($C_6H_{12}O_6$) as the final product, the overall equation for photosynthesis can be shown as follows:

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

$$\text{carbon dioxide} + \text{water} \xrightarrow{\text{light}} \text{sugars} + \text{oxygen}$$

Photosynthesis uses the energy of sunlight to convert water and carbon dioxide into high-energy sugars and oxygen. Plants then use the sugars to produce complex carbohydrates such as starches. Plants obtain carbon dioxide from the air or water in which they grow. The process of photosynthesis is shown in **Figure 8–4.**

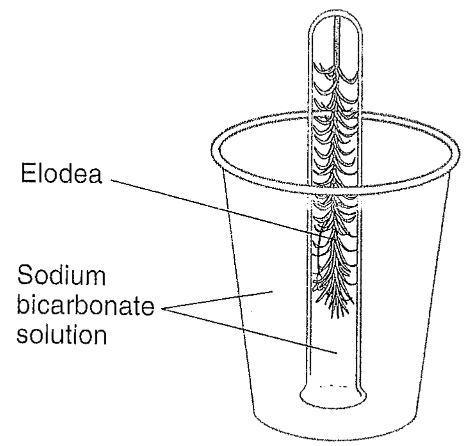
Quick Lab

What waste material is produced during photosynthesis?

Materials large clear plastic cup, sodium bicarbonate solution, elodea plant, large test tube

Procedure

1. Fill a large clear plastic cup about half full with sodium bicarbonate solution. The sodium bicarbonate solution is a source of carbon dioxide.
2. Place an elodea plant in a large test tube with the cut stem at the bottom. Fill the tube with sodium bicarbonate solution. **CAUTION:** *Handle the test tube carefully.*
3. Hold your thumb over the mouth of the tube. Turn the tube over, and lower it to the bottom of the cup. Make sure there is no air trapped in the tube.
4. Place the cup in bright light.
5. After at least 20 minutes, look closely at the elodea leaves. Record your observations.



Analyze and Conclude

1. **Observing** What did you observe on the elodea leaves?
2. **Inferring** What substance accumulated in the leaves? Should that substance be considered a waste product? Explain.
3. **Applying Concepts** What plant organelle carries out photosynthesis and produces the gas?

Light and Pigments

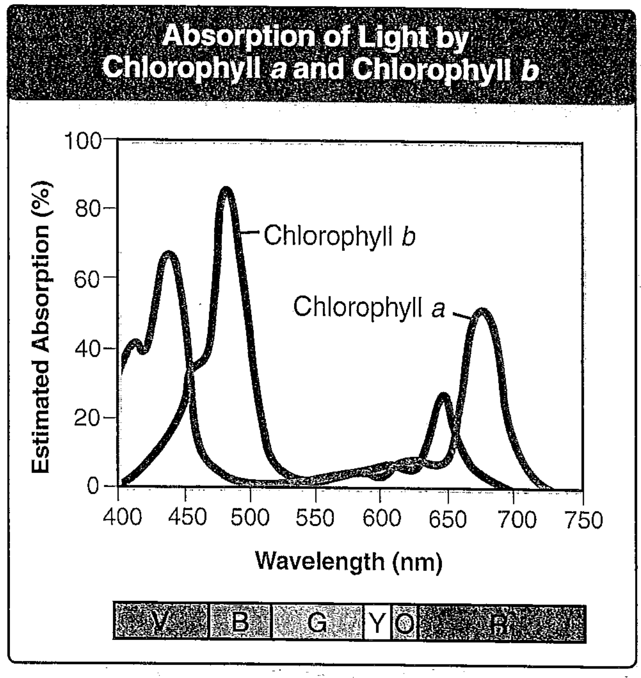
Although the equation tells you that water and carbon dioxide are required for photosynthesis, it does not tell you how plants use these low-energy raw materials to produce high-energy sugars. To answer that question, you have to know how plants capture the energy of sunlight. **In addition to water and carbon dioxide, photosynthesis requires light and chlorophyll, a molecule in chloroplasts.**

Energy from the sun travels to Earth in the form of light. Sunlight, which your eyes perceive as "white" light, is actually a mixture of different wavelengths of light. Many of these wavelengths are visible to your eyes and make up what is known as the visible spectrum. Your eyes see the different wavelengths of the visible spectrum as different colors.

Plants gather the sun's energy with light-absorbing molecules called **pigments.** The plants' principal pigment is **chlorophyll** (KLAWR-uh-fil). There are two main types of chlorophyll: chlorophyll *a* and chlorophyll *b*.

As **Figure 8–5** shows, chlorophyll absorbs light very well in the blue-violet and red regions of the visible spectrum. However, chlorophyll does not absorb light well in the green region of the spectrum. Green light is reflected by leaves, which is why plants look green. Plants also contain red and orange pigments such as carotene that absorb light in other regions of the spectrum.

Because light is a form of energy, any compound that absorbs light also absorbs the energy from that light. When chlorophyll absorbs light, much of the energy is transferred directly to electrons in the chlorophyll molecule, raising the energy levels of these electrons. These high-energy electrons make photosynthesis work.



▲ Figure 8–5 Photosynthesis requires light and chlorophyll. In the graph above, notice how chlorophyll *a* absorbs light mostly in the blue-violet and red regions of the visible spectrum, whereas chlorophyll *b* absorbs light in the blue and red regions of the visible spectrum.

8–2 Section Assessment

1. **Key Concept** What did van Helmont, Priestley, and Ingenhousz discover about plants?
2. **Key Concept** Describe the process of photosynthesis, including the reactants and products.
3. **Key Concept** Why are light and chlorophyll needed for photosynthesis?
4. Describe the relationship between chlorophyll and the color of plants.
5. **Critical Thinking Predicting** How well would a plant grow under pure yellow light? Explain your answer.

Writing in Science

Descriptive Writing

Write a summary paragraph describing either van Helmont's, Priestley's, or Ingenhousz's experiments with plants and light. *Hint:* Use the first boldface key sentence on page 206 to give you an idea for the topic sentence.

8–3 The Reactions of Photosynthesis

Guide for Reading

Key Concepts
- What happens in the light-dependent reactions?
- What is the Calvin cycle?

Vocabulary
thylakoid
photosystem
stroma
NADP+
light-dependent reactions
ATP synthase
Calvin cycle

Reading Strategy: Using Visuals Before you read, preview **Figures 8–7, 8–10,** and **8–11.** As you read, notice where in the chloroplast each stage of photosynthesis takes place.

The requirements of photosynthesis were discovered in the 1800s. It was not until the second half of the 1900s, however, that biologists understood the complex reactions that make this important cellular process possible.

Inside a Chloroplast

In plants and other photosynthetic eukaryotes, photosynthesis takes place inside chloroplasts. The chloroplasts, shown in **Figure 8–6,** contain saclike photosynthetic membranes called **thylakoids** (THY-luh-koydz). Thylakoids are arranged in stacks known as grana (singular: granum). Proteins in the thylakoid membrane organize chlorophyll and other pigments into clusters known as **photosystems.** These photosystems are the light-collecting units of the chloroplast.

Scientists describe the reactions of photosystems in two parts: the light-dependent reactions and the light-independent reactions, or Calvin cycle. The relationship between these two sets of reactions is shown in **Figure 8–7.** The light-dependent reactions take place within the thylakoid membranes. The Calvin cycle takes place in the **stroma,** the region outside the thylakoid membranes.

Figure 8–6 In plants, photosynthesis takes place inside chloroplasts. **Observing** *What are thylakoids?*

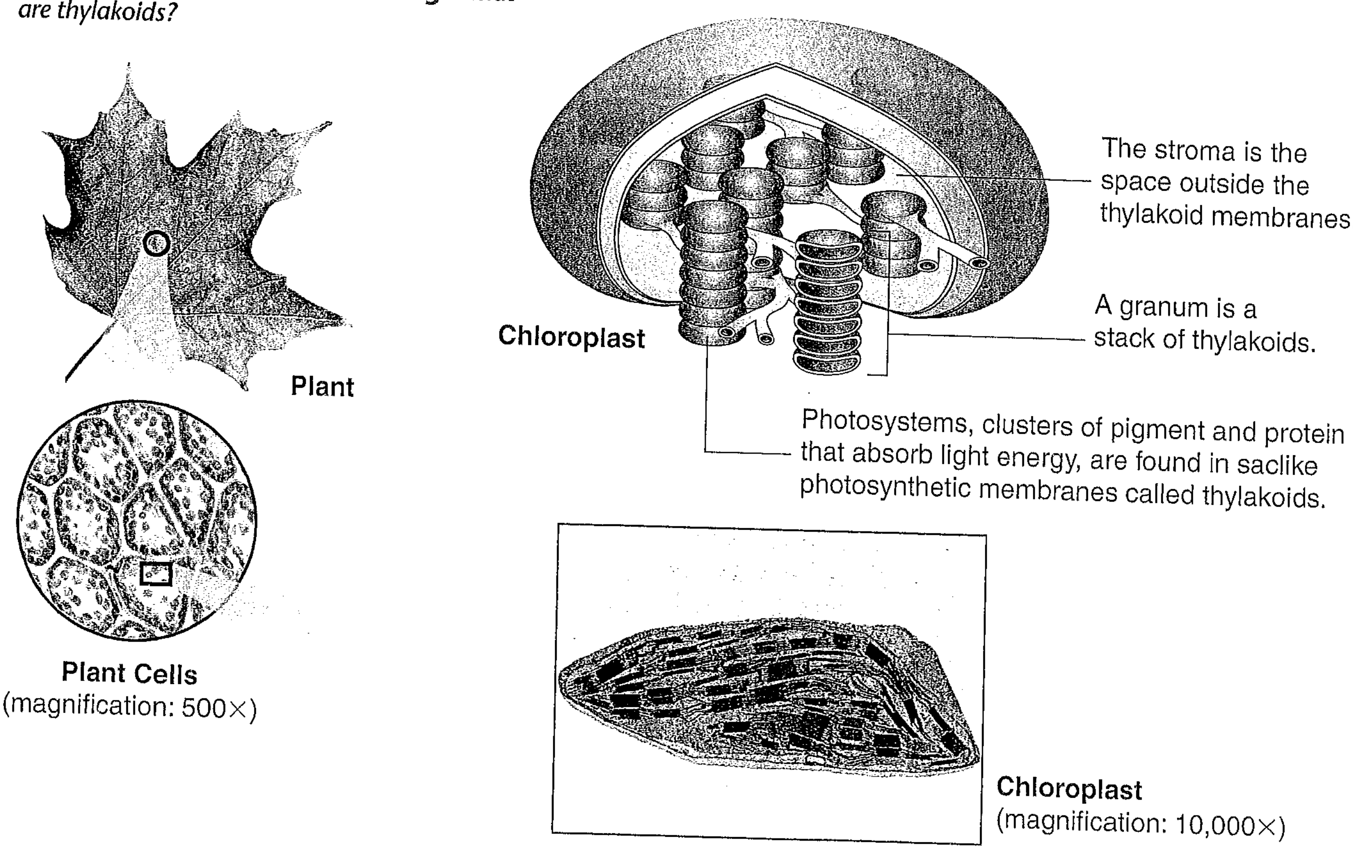
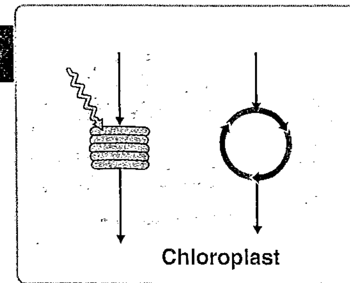
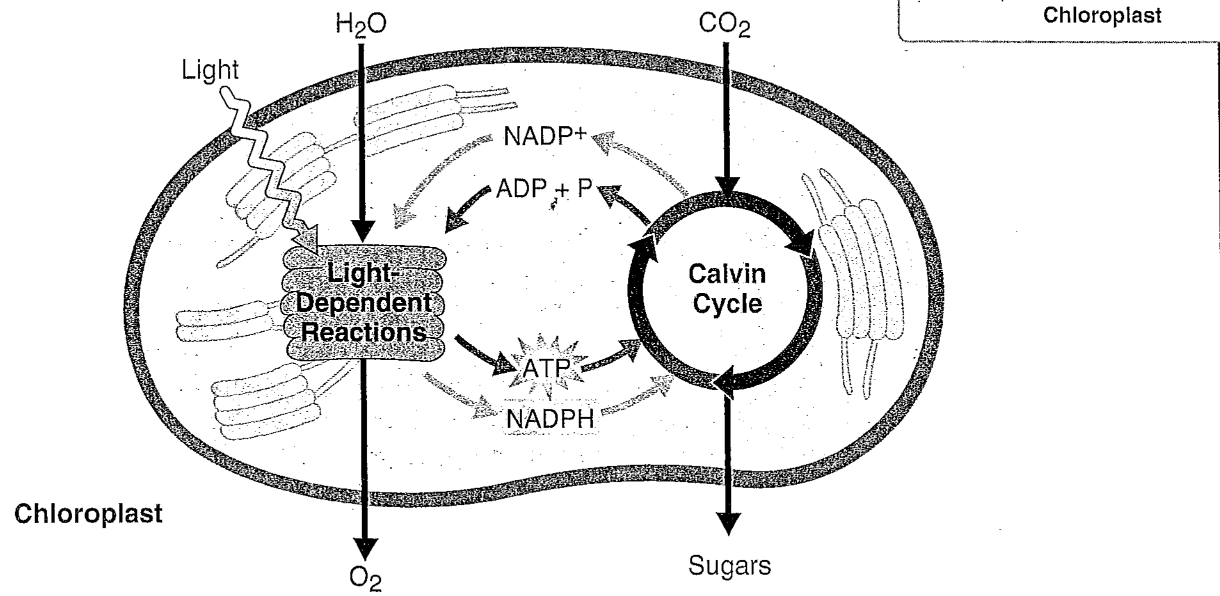


FIGURE 8–7 PHOTOSYNTHESIS: AN OVERVIEW



The process of photosynthesis includes the light-dependent reactions as well as the Calvin cycle. **Interpreting Graphics** *What are the products of the light-dependent reactions?*

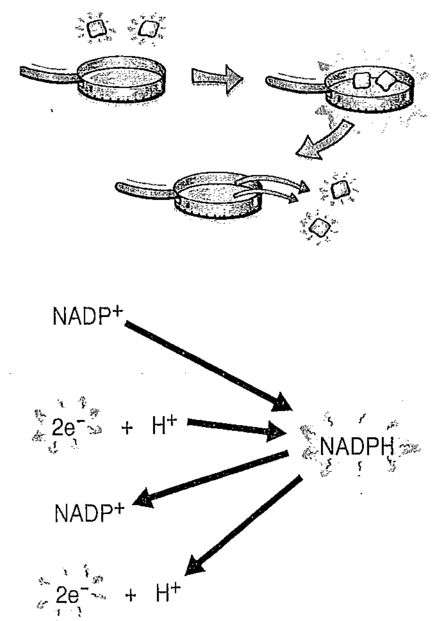


Electron Carriers

When sunlight excites electrons in chlorophyll, the electrons gain a great deal of energy. These high-energy electrons require a special carrier. Think of a high-energy electron as being similar to a red-hot coal from a fireplace or campfire. If you wanted to move the coal from one place to another, you wouldn't pick it up in your hands. You would use a pan or bucket—a carrier—to transport it. Cells treat high-energy electrons in the same way. Instead of a pan or bucket, they use electron carriers to transport high-energy electrons from chlorophyll to other molecules, as shown in **Figure 8–8.** A carrier molecule is a compound that can accept a pair of high-energy electrons and transfer them along with most of their energy to another molecule. This process is called electron transport, and the electron carriers themselves are known as the electron transport chain.

One of these carrier molecules is a compound known as **$NADP^+$** (nicotinamide adenine dinucleotide phosphate). The name is complicated, but the job that $NADP^+$ has is simple. $NADP^+$ accepts and holds 2 high-energy electrons along with a hydrogen ion (H^+). This converts the $NADP^+$ into NADPH. The conversion of $NADP^+$ into NADPH is one way in which some of the energy of sunlight can be trapped in chemical form.

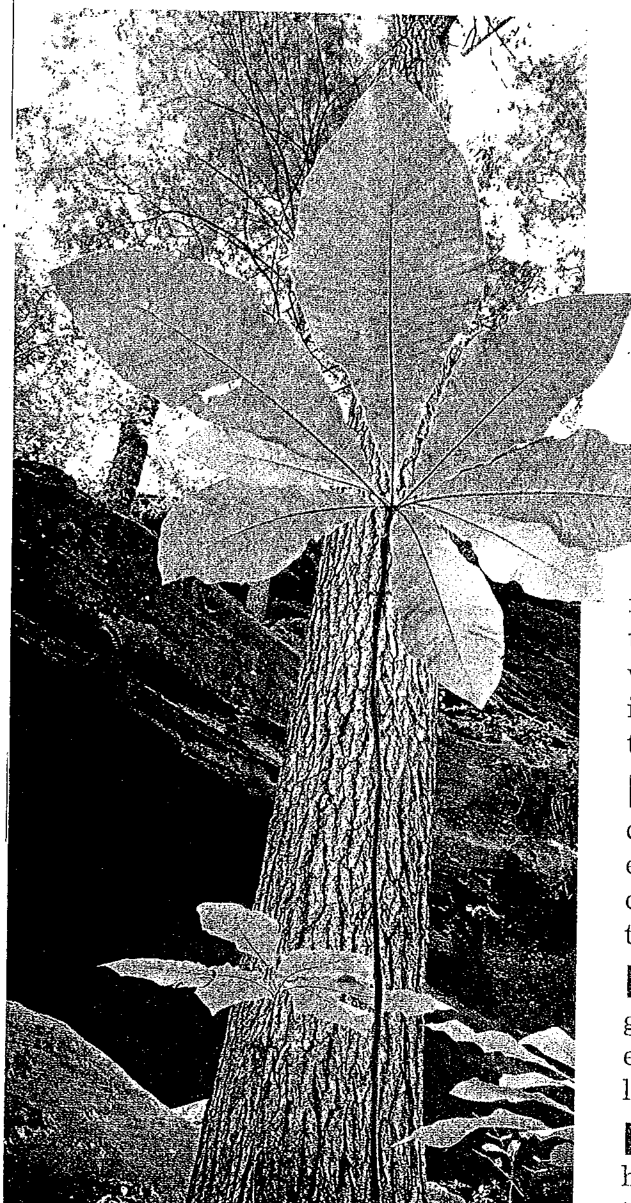
The NADPH can then carry high-energy electrons produced by light absorption in chlorophyll to chemical reactions elsewhere in the cell. These high-energy electrons are used to help build a variety of molecules the cell needs, including carbohydrates like glucose.



▲ **Figure 8–8** Like a pan being used to carry hot coals, electron carriers such as $NADP^+$ transport electrons. **Interpreting Graphics** *What eventually happens to those electrons?*

Light-Dependent Reactions

As you might expect from their name, the **light-dependent reactions** require light. That is why plants like the one in **Figure 8–9** need light to grow. The light-dependent reactions use energy from light to produce ATP and NADPH. **The light-dependent reactions produce oxygen gas and convert ADP and $NADP^+$ into the energy carriers ATP and NADPH.** Look at **Figure 8–10** to see what happens at each step of the process.



▲ **Figure 8–9** Like all plants, this seedling needs light to grow. **Applying Concepts** *What stage of photosynthesis requires light?*

A Photosynthesis begins when pigments in photosystem II absorb light. That first photosystem is called photosystem II because it was discovered after photosystem I. The light energy is absorbed by electrons, increasing their energy level. These high-energy electrons are passed on to the electron transport chain.

As light continues to shine, does the chlorophyll run out of electrons? No, it does not. The thylakoid membrane contains a system that provides new electrons to chlorophyll to replace the ones it has lost. These new electrons come from water molecules (H_2O). Enzymes on the inner surface of the thylakoid membrane break up each water molecule into 2 electrons, 2 H^+ ions, and 1 oxygen atom. The 2 electrons replace the high-energy electrons that chlorophyll has lost to the electron transport chain. As plants remove electrons from water, oxygen is left behind and is released into the air. This reaction is the source of nearly all of the oxygen in Earth's atmosphere, and it is another way in which photosynthesis makes our lives possible. The hydrogen ions left behind when water is broken apart are released inside the thylakoid membrane.

B High-energy electrons move through the electron transport chain from photosystem II to photosystem I. Energy from the electrons is used by the molecules in the electron transport chain to transport H^+ ions from the stroma into the inner thylakoid space.

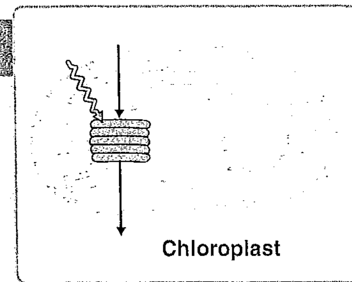
C Pigments in photosystem I use energy from light to reenergize the electrons. $NADP^+$ then picks up these high-energy electrons, along with H^+ ions, at the outer surface of the thylakoid membrane, plus an H^+ ion, and becomes NADPH.

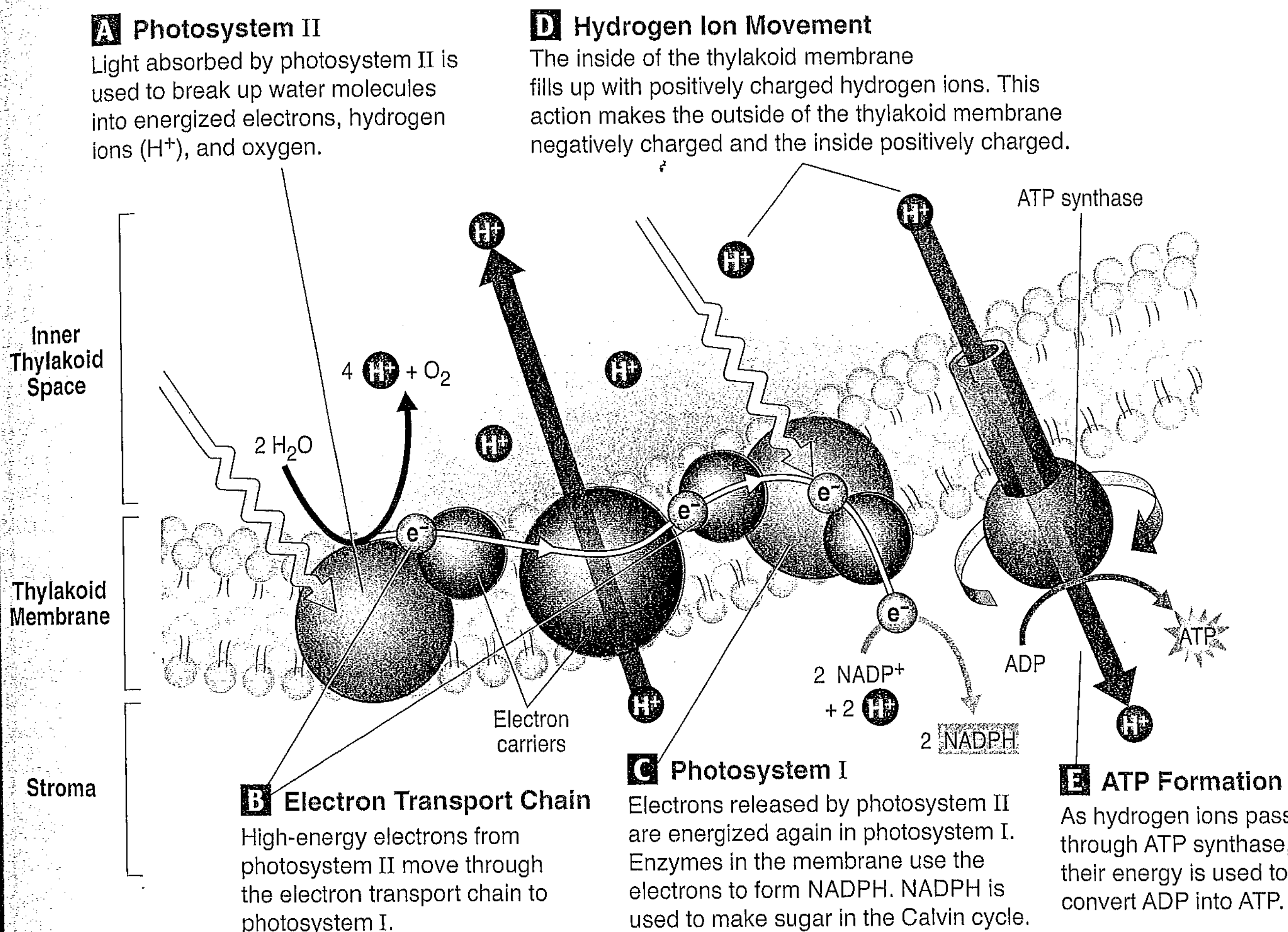
D As electrons are passed from chlorophyll to $NADP^+$, more hydrogen ions are pumped across the membrane. After a while, the inside of the membrane fills up with positively charged hydrogen ions. This makes the outside of the thylakoid membrane negatively charged and the inside positively charged. The difference in charges across the membrane provides the energy to make ATP. This is why the H^+ ions are so important.

E H^+ ions cannot cross the membrane directly. However, the cell membrane contains a protein called **ATP synthase** (SIN-thays) that spans the membrane and allows H^+ ions to pass through it. As H^+ ions pass through ATP synthase, the protein rotates like a turbine being spun by water in a hydroelectric power plant.

Light-Dependent Reactions

Figure 8–10 **The light-dependent reactions use energy from sunlight to produce ATP, NADPH, and oxygen.** The light-dependent reactions take place within the thylakoid membranes of chloroplasts.





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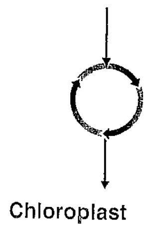
As it rotates, ATP synthase binds ADP and a phosphate group together to produce ATP. Because of this system, light-dependent electron transport produces not only high-energy electrons but ATP as well.

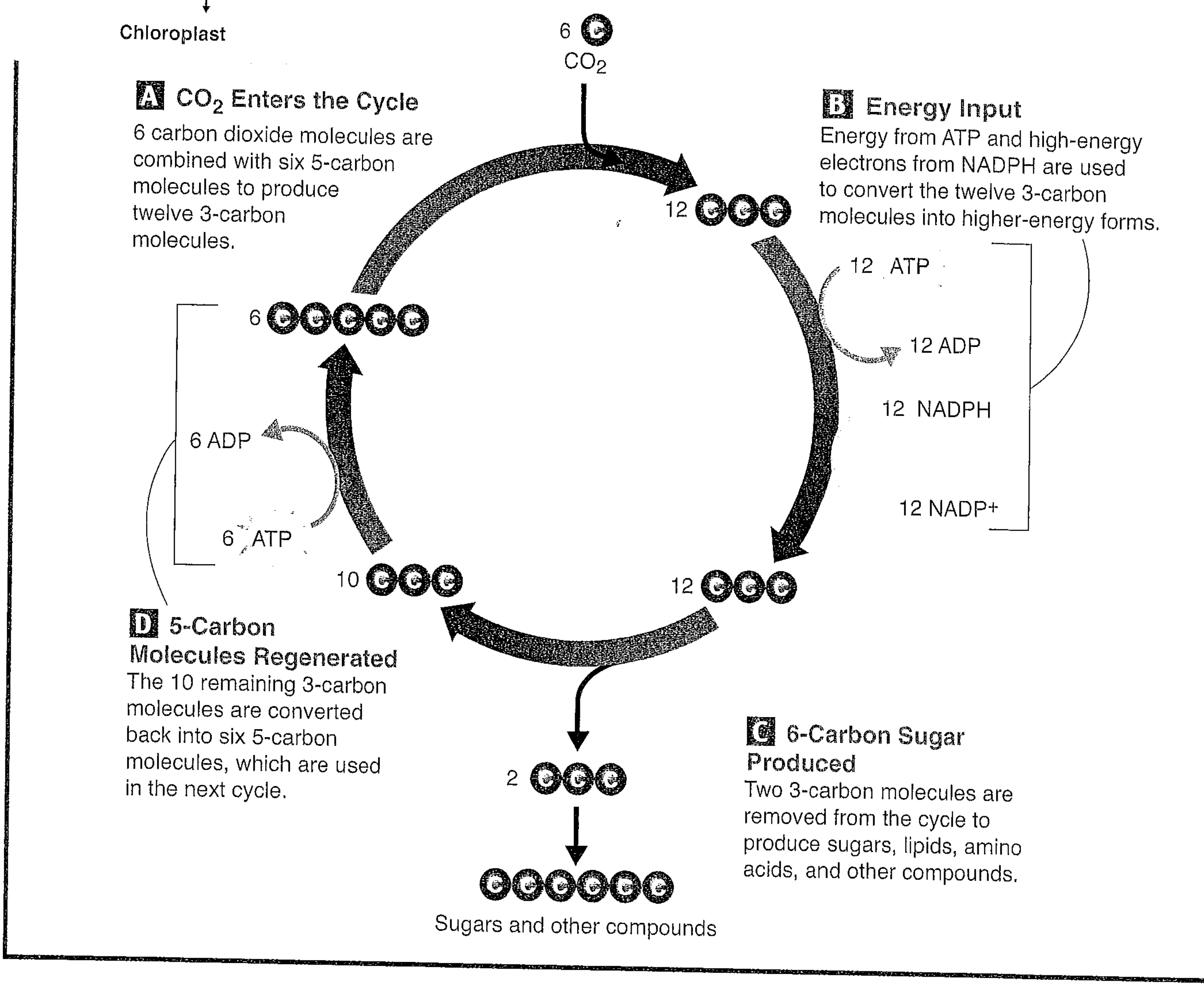
As we have seen, the light-dependent reactions use water, ADP, and $NADP^+$, and they produce oxygen and two high-energy compounds: ATP and NADPH. What good are these compounds? As we will see, they have an important role to play in the cell: They provide the energy to build energy-containing sugars from low-energy compounds.

CHECKPOINT *What is the role of photosystem II? How does that role compare with the role of photosystem I?*

Figure 8–11 Calvin Cycle

The Calvin cycle uses ATP and NADPH to produce high-energy sugars. The Calvin cycle takes place in the stroma of chloroplasts and does not require light.





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The Calvin Cycle

The ATP and NADPH formed by the light-dependent reactions contain an abundance of chemical energy, but they are not stable enough to store that energy for more than a few minutes. During the **Calvin cycle,** plants use the energy that ATP and NADPH contain to build high-energy compounds that can be stored for a long time. **The Calvin cycle uses ATP and NADPH from the light-dependent reactions to produce high-energy sugars.** The Calvin cycle is named after the American scientist Melvin Calvin, who worked out the details of this remarkable cycle. Because the Calvin cycle does not require light, these reactions are also called the light-independent reactions. Follow **Figure 8–11** to see how the Calvin cycle works.

A Six carbon dioxide molecules enter the cycle from the atmosphere. The carbon dioxide molecules combine with six 5-carbon molecules. The result is twelve 3-carbon molecules.

B The twelve 3-carbon molecules are then converted into higher-energy forms. The energy for this conversion comes from ATP and high-energy electrons from NADPH.

C Two of the twelve 3-carbon molecules are removed from the cycle. The plant cell uses these molecules to produce sugars, lipids, amino acids, and other compounds needed for plant metabolism and growth.

D The remaining ten 3-carbon molecules are converted back into six 5-carbon molecules. These molecules combine with six new carbon dioxide molecules to begin the next cycle.

The Calvin cycle uses six molecules of carbon dioxide to produce a single 6-carbon sugar molecule. As photosynthesis proceeds, the Calvin cycle works steadily removing carbon dioxide from the atmosphere and turning out energy-rich sugars. The plant uses the sugars to meet its energy needs and to build more complex macromolecules such as cellulose that it needs for growth and development. When other organisms eat plants, they can also use the energy stored in carbohydrates.

✓CHECKPOINT *What are the main products of the Calvin cycle?*

Go Online NSTA SCILINKS
For: Links on photosynthesis
Visit: www.SciLinks.org
Web Code: cbn-3083

Analyzing Data

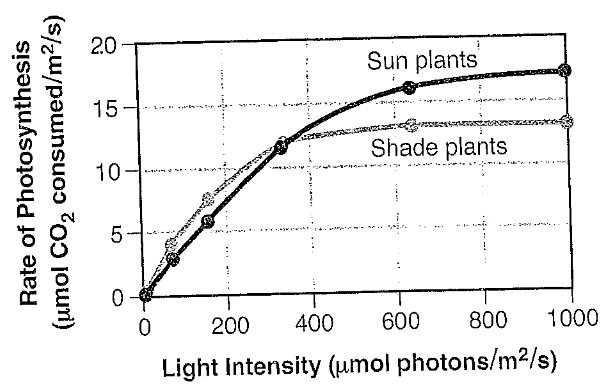
Rates of Photosynthesis

The rate at which a plant carries out photosynthesis depends in part on its environment. Plants that grow in the shade, for example, carry out photosynthesis at low levels of light. Plants that grow in the sun, such as desert plants, typically carry out photosynthesis at much higher levels of light.

The graph compares the rates of photosynthesis between plants that grow in the shade and plants that grow in the sun. It shows how the rate of photosynthesis changes with the number of micromoles of photons per square meter per second (μmol photons/m^2/s), a standard unit of light intensity.

1. **Using Tables and Graphs** When light intensity is below 200 μmol photons/m^2/s, do sun plants or shade plants have a higher rate of photosynthesis?
2. **Drawing Conclusions** Does the relationship in question 1 change when light intensity increases above 400 μmol photons/m^2/s? Explain your answer.

Rates of Photosynthesis



3. **Inferring** The average light intensity in the Sonoran Desert is about 400 μmol photons/m^2/s. According to the graph, what would be the approximate rate of photosynthesis for sun plants that grow in this environment?
4. **Going Further** Suppose you transplant a sun plant to a shaded forest floor that receives about 100 μmol photons/m^2/s. Do you think this plant will grow and thrive? Why or why not? How does the graph help you answer this question?

The two sets of photosynthetic reactions work together—the light-dependent reactions trap the energy of sunlight in chemical form, and the light-independent reactions use that chemical energy to produce stable, high-energy sugars from carbon dioxide and water. And, in the process, we animals get an atmosphere filled with oxygen. Not a bad deal at all.

Factors Affecting Photosynthesis

Many factors affect the rate at which photosynthesis occurs. Because water is one of the raw materials of photosynthesis, a shortage of water can slow or even stop photosynthesis. Plants that live in dry conditions, such as desert plants and conifers, have a waxy coating on their leaves that reduces water loss.

Temperature is also a factor. Photosynthesis depends on enzymes that function best between 0°C and 35°C. Temperatures above or below this range may damage the enzymes, slowing down the rate of photosynthesis. At very low temperatures, photosynthesis may stop entirely.

The intensity of light also affects the rate at which photosynthesis occurs. As you might expect, increasing light intensity increases the rate of photosynthesis. After the light intensity reaches a certain level, however, the plant reaches its maximum rate of photosynthesis. The level at which light intensity no longer affects photosynthesis varies from plant type to plant type. The conifers shown in **Figure 8–12** can carry out photosynthesis only on warm, sunny days.

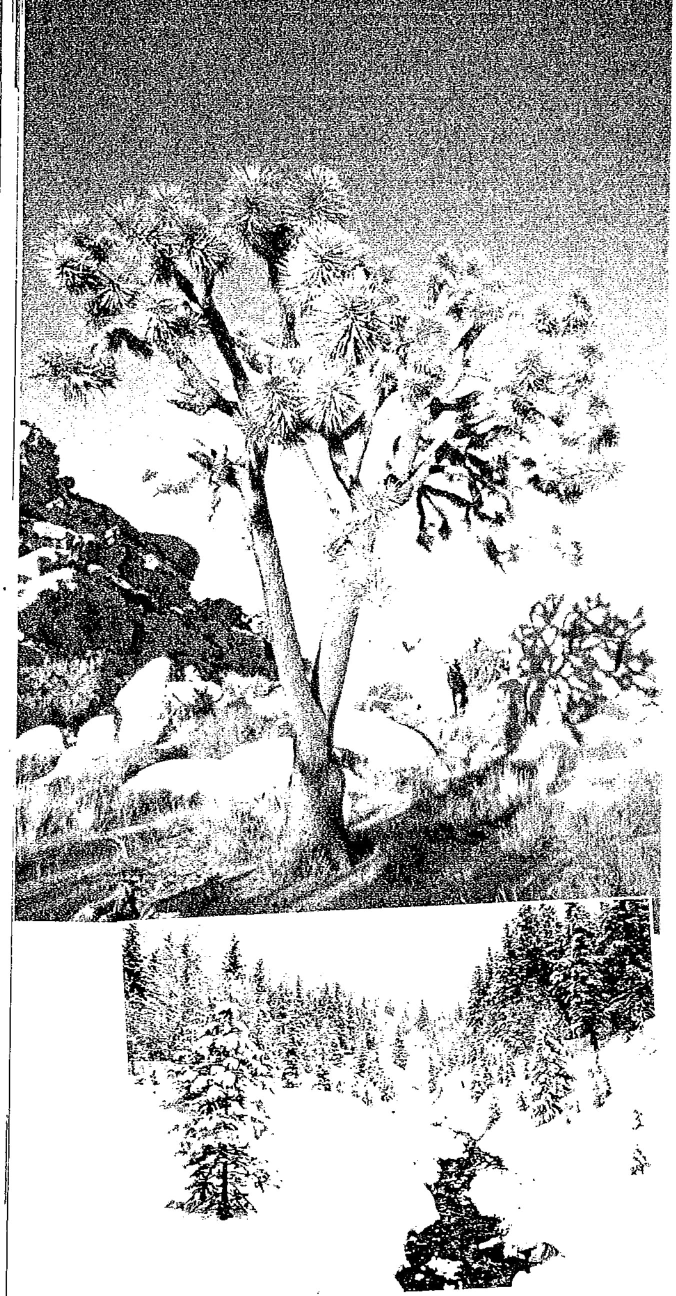


Figure 8–12 Both temperature and the availability of water can affect rates of photosynthesis. Desert plants such as this Joshua tree (above) are adapted to survive with little water. During the cold winter months these conifers (below) may only occasionally carry out photosynthesis. **Comparing and Contrasting** *What do both plants shown have that helps them conserve water?*

8–3 Section Assessment

1. **Key Concept** Summarize the light-dependent reactions.
2. **Key Concept** What reactions make up the Calvin cycle?
3. How is light energy converted into chemical energy during photosynthesis?
4. What is the function of NADPH?
5. **Critical Thinking Applying Concepts** Why are the light-dependent reactions important to the Calvin cycle?

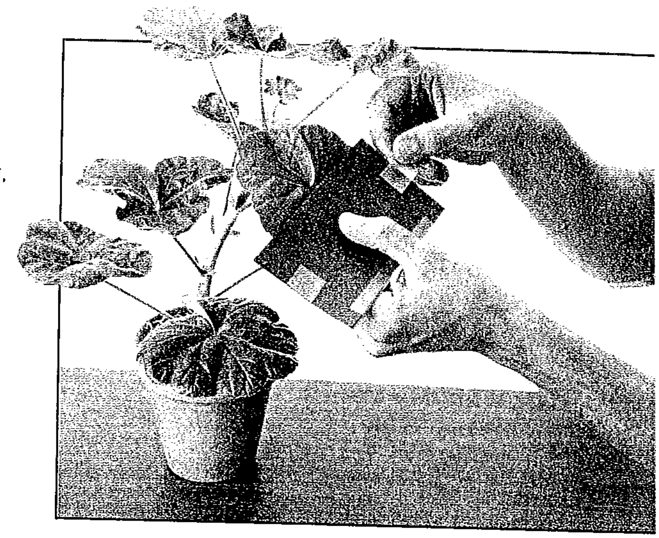
Thinking Visually

Making a Flowchart

Construct a flowchart that illustrates the steps of photosynthesis. Begin with the energy of sunlight and end with the production of sugars. Include as much detail as possible in the numerous steps.

Investigating Photosynthesis

If only part of a leaf receives light, does the whole leaf perform photosynthesis? What if a leaf receives only light of one color? You are going to design an experiment to test the effects of colored light on photosynthesis.



Problem How do different colors of light affect starch synthesis during photosynthesis?

Materials

- scissors
- black construction paper
- potted plant
- tape
- blue, red, and green cellophane
- 5 large test tubes
- glass-marking pencil
- forceps
- 400-mL beaker
- 5 petri dishes
- iodine solution
- paper towels

Skills Predicting, Formulating Hypotheses

Design Your Experiment

1. **Predicting** As a result of photosynthesis, new starch molecules are synthesized and accumulate in leaves. Record your prediction of how keeping part of a leaf in darkness will affect starch synthesis.
2. Cut two pieces of black construction paper large enough to cover half of one leaf of the plant.
3. Sandwich half of the leaf between the pieces of black paper and tape the paper in place.
4. **Formulating Hypotheses** Develop a hypothesis that predicts how the color of light will affect photosynthesis. Record your hypothesis.
5. Design an experiment to test your hypothesis. Refer to the Lab Tips box on page 55. Have your teacher check your plan. Set up your experiment using whole leaves from the same plant as in step 3.
6. Leave your plant in a sunlit area for 2 days.
7. Cut off one leaf that was not treated as well as each of the experimental leaves, including the half-covered leaf. Roll up each leaf and put it in a large test tube. Label each tube and petri dish with the treatment the leaf received.
8. Put on your goggles and lab apron. Before you test the leaves for starch, the chlorophyll must be removed from the leaves. Your teacher will add alcohol to your test tubes and heat them in hot water. **CAUTION:** *Alcohol is toxic and flammable, and its fumes are irritating.* When the color has disappeared from each leaf, use forceps to swirl each leaf in a beaker of water. Place it in a labeled petri dish.
9. Put on your plastic gloves. Cover each leaf with iodine solution. Iodine solution stains starch blue or black. **CAUTION:** *Iodine is corrosive and irritating to the skin and can stain clothes and skin. Be careful not to spill it.*
10. After 1 minute, use forceps to gently swirl each leaf in the beaker of water and lay the leaf flat on a paper towel.
11. Observe each leaf and record your observations. Wash your hands before leaving the lab.

Analyze and Conclude

1. **Observing** Was your prediction about starch synthesis in the part of the first leaf covered in black paper correct? Explain your answer.
2. **Observing** What effect did each color of light have on starch synthesis in the leaves? Was your hypothesis correct?
3. **Communicating Results** Use your knowledge of chlorophyll to explain your results.

Go Further

Designing Experiments Where is starch found in the multicolored leaves of a coleus plant? Use your observations to propose a hypothesis. With your teacher's approval, perform an experiment to test your hypothesis. Explain your results.

Chapter 8 Study Guide

8–1 Energy and Life

Key Concepts

- Plants and some other types of organisms are able to use light energy from the sun to produce food.
- The characteristics of ATP make it exceptionally useful as the basic energy source of all cells.

Vocabulary

autotroph, p. 201
heterotroph, p. 201
adenosine triphosphate (ATP), p. 202

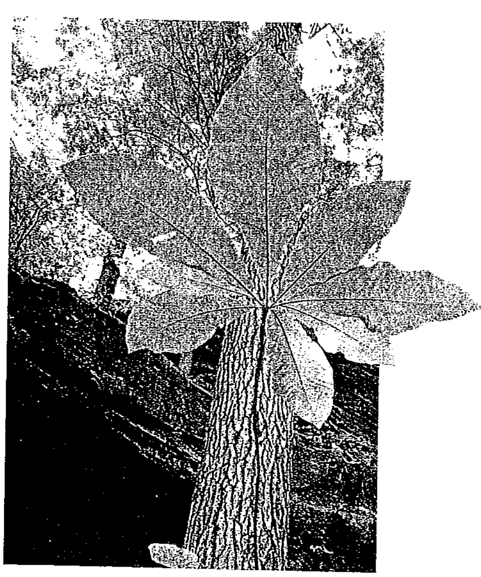
8–2 Photosynthesis: An Overview

Key Concepts

- The experiments performed by van Helmont, Priestley, and Ingenhousz led to work by other scientists who finally discovered that in the presence of light, plants transform carbon dioxide and water into carbohydrates, and they also release oxygen.
- Photosynthesis uses the energy of sunlight to convert water and carbon dioxide into high-energy sugars and oxygen.
- In addition to water and carbon dioxide, photosynthesis requires light and chlorophyll, a molecule found in chloroplasts.

Vocabulary

photosynthesis, p. 204
pigment, p. 207
chlorophyll, p. 207



8–3 The Reactions of Photosynthesis

Key Concepts

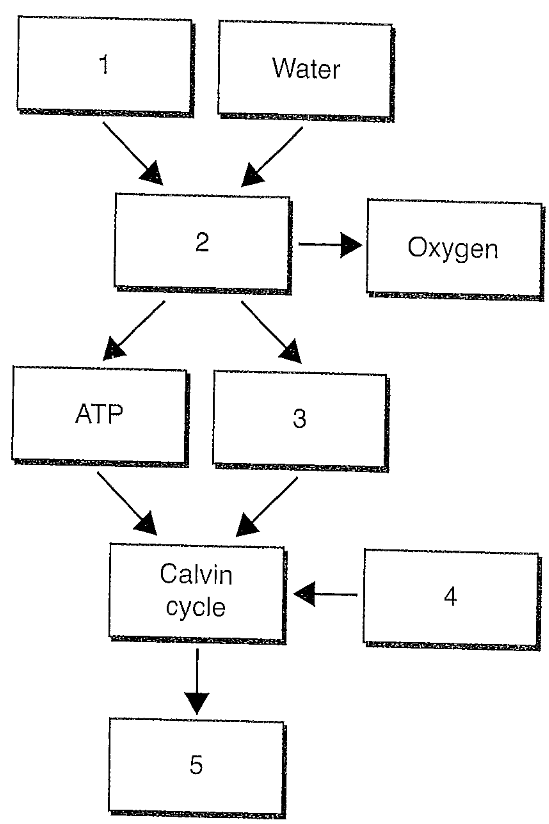
- The process of photosynthesis includes the light-dependent reactions as well as the Calvin cycle.
- The light-dependent reactions produce oxygen gas and convert ADP and $NADP^+$ into ATP and NADPH. The light-dependent reactions occur in the thylakoid.
- The Calvin cycle uses ATP and NADPH from the light-dependent reactions to produce high-energy sugars. The Calvin cycle is also known as the light-independent reactions.

Vocabulary

thylakoid, p. 208
photosystem, p. 208
stroma, p. 208
$NADP^+$, p. 209
light-dependent reactions, p. 210
ATP synthase, p. 210
Calvin cycle, p. 212

Thinking Visually

Using the information in this chapter, complete the following flowchart about photosynthesis:



Chapter 8 Assessment

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. Which of the following are autotrophs?
   a. impalas
   b. plants
   c. leopards
   d. mushrooms

2. One of the principal chemical compounds that living things use to store energy is
   a. DNA.
   b. ATP.
   c. H_2O.
   d. CO_2.

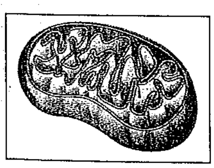
3. Which scientist concluded that most of a growing plant's mass comes from water?
   a. Priestley
   b. van Helmont
   c. Ingenhousz
   d. Calvin

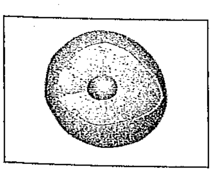
4. In addition to light and chlorophyll, photosynthesis requires
   a. water and oxygen.
   b. water and sugars.
   c. oxygen and carbon dioxide.
   d. water and carbon dioxide.

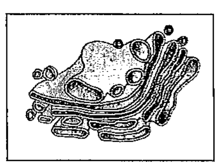
5. The leaves of a plant appear green because chlorophyll
   a. reflects blue light.
   b. absorbs blue light.
   c. reflects green light.
   d. absorbs green light.

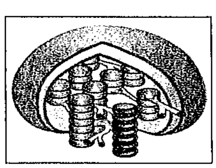
6. The products of photosynthesis are
   a. sugars and oxygen.
   b. sugars and carbon dioxide.
   c. water and carbon dioxide.
   d. hydrogen and oxygen.

7. Which organelle contains chlorophyll?

a. 

b. 

c. 

d. 

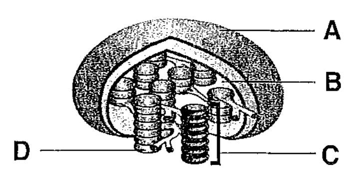
8. The first process in the light-dependent reactions of photosynthesis is
   a. light absorption.
   b. electron transport.
   c. oxygen production.
   d. ATP formation.

9. Which substance from the light-dependent reactions of photosynthesis is a source of energy for the Calvin cycle?
   a. ADP
   b. NADPH
   c. H_2O
   d. pyruvic acid

10. The light-independent reactions of photosynthesis are also known as the
    a. Calvin cycle.
    b. Priestley cycle.
    c. Ingenhousz cycle.
    d. van Helmont cycle.

Understanding Concepts

11. How do heterotrophs and autotrophs differ in the way they obtain energy?
12. Describe the three parts of an ATP molecule.
13. Use the analogy of a battery to explain how energy is stored in and released from ATP.
14. Compare the amounts of energy stored by ATP and glucose. Which compound is used by the cell as an immediate source of energy?
15. How were Priestley's and Ingenhousz's discoveries about photosynthesis related?
16. Write the basic equation for photosynthesis using the names of the starting and final substances of the process.
17. What role do plant pigments play in the process of photosynthesis?
18. Identify the structures labeled A, B, C, and D. In which structure(s) do the light-dependent reactions occur? In which structure(s) does the Calvin cycle take place?



19. Explain the role of $NADP^+$ as an energy carrier in photosynthesis.
20. What is the role of ATP synthase? How does it work?
21. Summarize what happens during the Calvin cycle.
22. How do the events in the Calvin cycle depend on the light-dependent reactions?
23. Describe three factors that affect the rate at which photosynthesis occurs.

Critical Thinking

24. **Formulating Hypotheses** Some plant leaves contain yellow and red pigments as well as chlorophyll. In the fall, those leaves may become red or yellow. Suggest an explanation for those color changes.
25. **Using Analogies** Develop an analogy to explain ATP and energy transfer to a classmate who does not understand the concept.
26. **Interpreting Graphics** The Calvin cycle is sometimes described as the light-independent reactions. Study **Figure 8–11** on page 212 and give evidence to support the idea that the Calvin cycle does not depend on light.
27. **Designing Experiments** Design an experiment that uses pond water and algae to demonstrate the importance of light energy to pond life. Be sure to identify the variables you will control and the variable you will change.
28. **Using Tables and Graphs** A water plant placed in a bright light gives off bubbles of oxygen. In the laboratory, you notice that if the light is placed at different distances from the plant, the rate at which the plant produces bubbles changes. Your data are shown in the following table.

Oxygen Production

Distance From Light (cm)	Bubbles Produced per Minute
10	39
20	22
30	8
40	5

   a. On graph paper, plot the data on a line graph. Describe the trend. When the light was farther from the plant, did the number of bubbles produced increase or decrease? Explain.
   b. At what distance is gas production at its highest?
   c. What relationship exists between the distance from the plant to the light and the number of bubbles produced? Explain your answer.
29. **Predicting** Suppose you water a potted plant and place it by a window in an airtight jar. Predict when photosynthesis might occur over the next few days. Would you expect the pattern to change if the plant were left there for several weeks? Explain.
30. **Inferring** Examine the photograph of the Indian pipe plant shown below. What can you conclude about the ability of the Indian pipe plant to make its own food? Explain your answer.

Focus on the BIG Idea

Matter and Energy Recall what you learned about the flow of energy through an ecosystem. Explain how photosynthesis relates to that flow.

Writing in Science

Imagine that you are an oxygen atom and two of your friends are hydrogen atoms. Together, you make up a water molecule. Describe the events and changes that happen to you and your friends as you journey through the light-dependent reactions and Calvin cycle of photosynthesis. Include illustrations with your description.

Performance-Based Assessment

Making Models Construct a two- or three-dimensional model of an ATP molecule. Label the various parts of the molecule. Use the model to explain how ATP is broken down into ADP and AMP. (AMP contains one phosphate group.) How does your model change?

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Standardized Test Prep

Test-Taking Tip

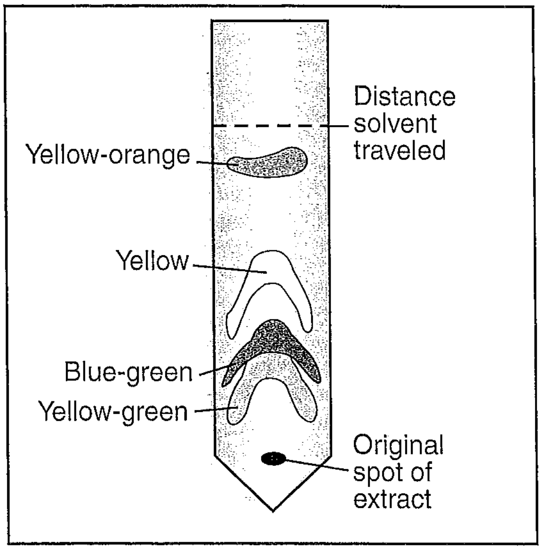
When a paragraph and some related questions accompany a diagram, read the paragraph and all of the labels carefully. For example, in questions 7–9, the paragraph tells you that the drops of pigment were placed at the bottom of the strip. This information helps you interpret the events represented by the diagram.

Directions: Choose the letter that best answers the question or completes the statement.

1. The principal pigment in plants that captures sunlight energy is
   (A) chlorophyll.
   (B) oxygen.
   (C) ADP.
   (D) ATP.
   (E) NADPH.
2. Which of the following is NOT produced in the light-dependent reactions of photosynthesis?
   (A) NADPH
   (B) sugars
   (C) hydrogen ions
   (D) ATP
   (E) oxygen
3. Which equation best summarizes the process of photosynthesis?
   (A) water + carbon dioxide $\xrightarrow{\text{light}}$ sugars + oxygen
   (B) sugars + oxygen $\xrightarrow{\text{light}}$ water + carbon
   (C) water + oxygen $\xrightarrow{\text{light}}$ sugars + carbon dioxide
   (D) oxygen + carbon dioxide $\xrightarrow{\text{light}}$ sugars + oxygen
   (E) sugars + carbon dioxide $\xrightarrow{\text{light}}$ water + oxygen
4. The color of light that is LEAST useful to a plant during photosynthesis is
   (A) red.
   (B) blue.
   (C) green.
   (D) orange.
   (E) violet.
5. The first step in photosynthesis is the
   (A) synthesis of water.
   (B) production of oxygen.
   (C) formation of ATP.
   (D) breakdown of carbon dioxide.
   (E) absorption of light energy.
6. In a typical plant, all of the following factors are necessary for photosynthesis EXCEPT
   (A) chlorophyll.
   (B) light.
   (C) oxygen.
   (D) carbon dioxide.
   (E) water.

Questions 7–9

Several drops of concentrated pigment were extracted from spinach leaves. These drops were placed at the bottom of a strip of highly absorbent paper. After the extract dried, the paper was suspended in a test tube containing alcohol so that only the tip of the paper was in the alcohol. As the alcohol was absorbed and moved up the paper, the various pigments contained in the extract separated as shown in the diagram below.



7. Which pigment traveled the shortest distance?
   (A) yellow-orange
   (B) yellow
   (C) blue-green
   (D) yellow-green
   (E) black
8. A valid conclusion that can be drawn from this information is that spinach leaves
   (A) use only chlorophyll during photosynthesis.
   (B) contain several pigments.
   (C) contain more orange pigment than yellow pigment.
   (D) are yellow-orange rather than green.
   (E) have only one color of pigment.
9. In which organelles would most of these pigments be found?
   (A) vacuoles
   (B) centrioles
   (C) mitochondria
   (D) chloroplasts
   (E) ATP