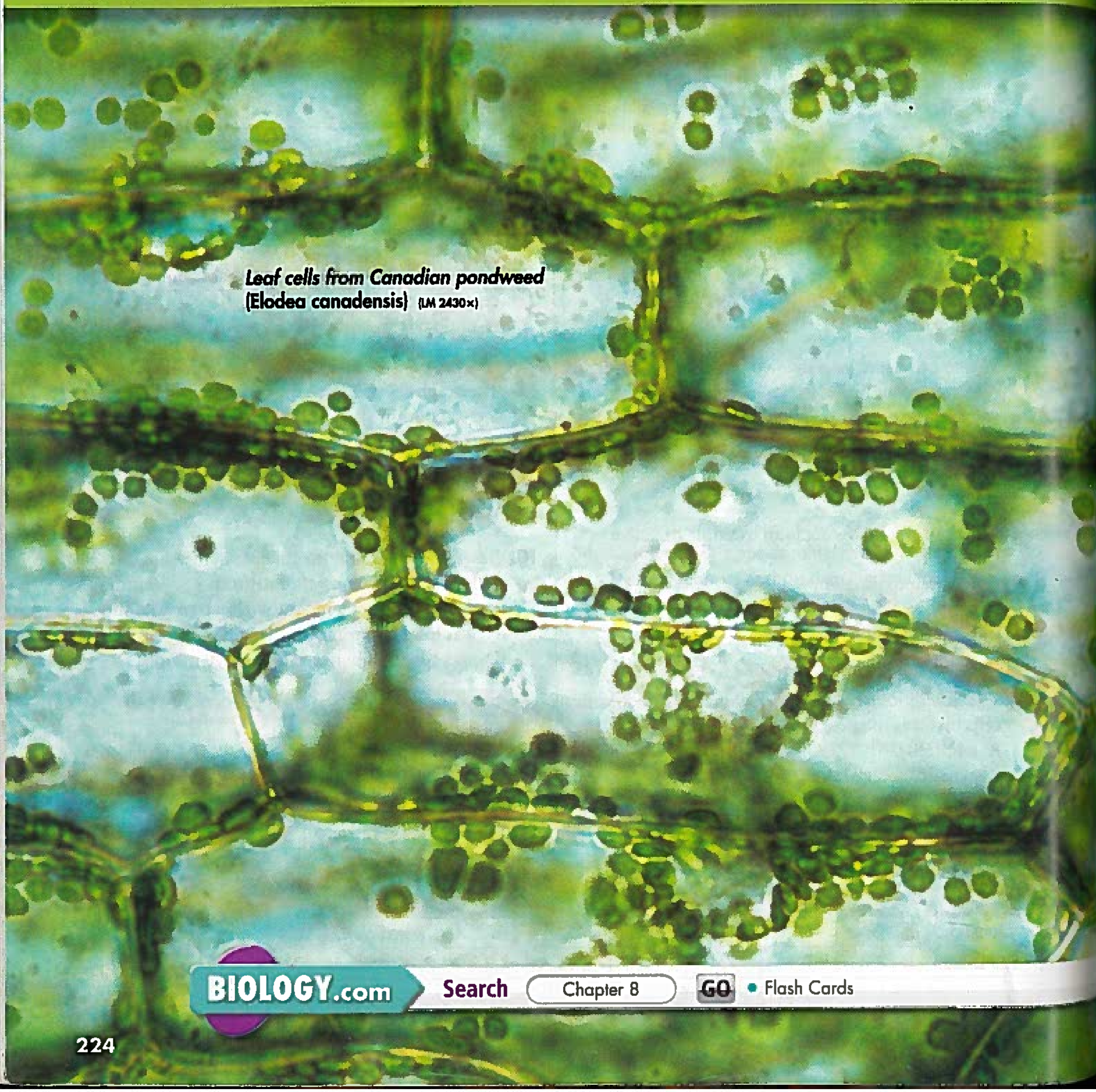
8 Photosynthesis

Big idea: Cellular Basis of Life

Q: How do plants and other organisms capture energy from the sun?



Leaf cells from Canadian pondweed (Elodea canadensis) (LM 2430×)

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8.1 Energy and Life

Key Questions

Why is ATP useful to cells?

What happens during the process of photosynthesis?

Vocabulary

adenosine triphosphate (ATP) • heterotroph • autotroph • photosynthesis

Taking Notes

Compare/Contrast Table As you read, create a table that compares autotrophs and heterotrophs. Think about how they obtain energy, and include a few examples of each.

BUILD Vocabulary

ACADEMIC WORDS The verb **obtain** means "to get" or "to gain." Organisms must obtain energy in order to carry out life functions.

THINK ABOUT IT Homeostasis is hard work. Just to stay alive, organisms and the cells within them have to grow and develop, move materials around, build new molecules, and respond to environmental changes. Plenty of energy is needed to accomplish all this work. What powers so much activity, and where does that power come from?

Chemical Energy and ATP

Why is ATP useful to cells?

Energy is the ability to do work. Nearly every activity in modern society depends upon energy. 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 takes plenty of energy to play soccer or other sports. However, there are times when that need is less obvious. Even when you are sleeping, your cells are quietly busy using energy to build new molecules, contract muscles, and carry out active transport. Simply put, without the ability to obtain and use energy, life would cease to exist.

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. As the candle burns, chemical bonds between carbon and hydrogen atoms in the wax are broken. New bonds then form between these atoms and oxygen, producing CO_2 and H_2O (carbon dioxide and water). These new bonds are at a lower energy state than the original chemical bonds in the wax. The energy lost is released as heat and light in the glow of the candle's flame.

Living things use chemical fuels as well. One of the most important compounds that cells use to store and release energy is **adenosine triphosphate** (uh DEN uh seen try FAHS fayt), abbreviated **ATP.** As shown in **Figure 8–1,** ATP consists of adenine, a 5-carbon sugar called ribose, and three phosphate groups. As you'll see, those phosphate groups are the key to ATP's ability to store and release energy.

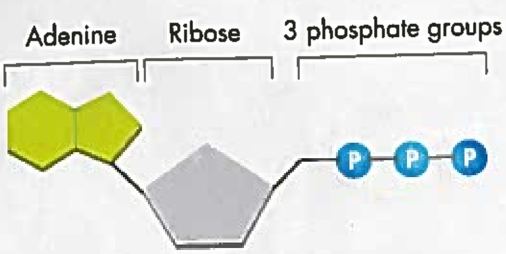


FIGURE 8–1 ATP ATP is the basic energy source used by all types of cells.

Storing Energy Adenosine diphosphate (ADP) is a compound 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 phosphate groups to ADP molecules, producing ATP. As seen in **Figure 8–2**, ADP is like a rechargeable battery that powers the machinery of the cell.

Releasing Energy Cells can release the energy stored in ATP by the controlled breaking of the chemical bonds between the second and third phosphate groups. Because a cell can add or subtract these phosphate groups, it has an efficient way of storing and releasing energy as needed. **ATP can easily release and store energy by breaking and re-forming the bonds between its phosphate groups. This characteristic of ATP makes it exceptionally useful as a basic energy source for all cells.**

Using Biochemical Energy One way cells use the energy provided by ATP is to carry out active transport. Many cell membranes contain sodium-potassium pumps, membrane proteins that pump 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. In addition, ATP powers movement, providing the energy for motor proteins that contract muscle and power the wavelike movement of cilia and flagella.

Energy from ATP powers other important events in the cell, including the synthesis of proteins 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 that is powered by ATP!

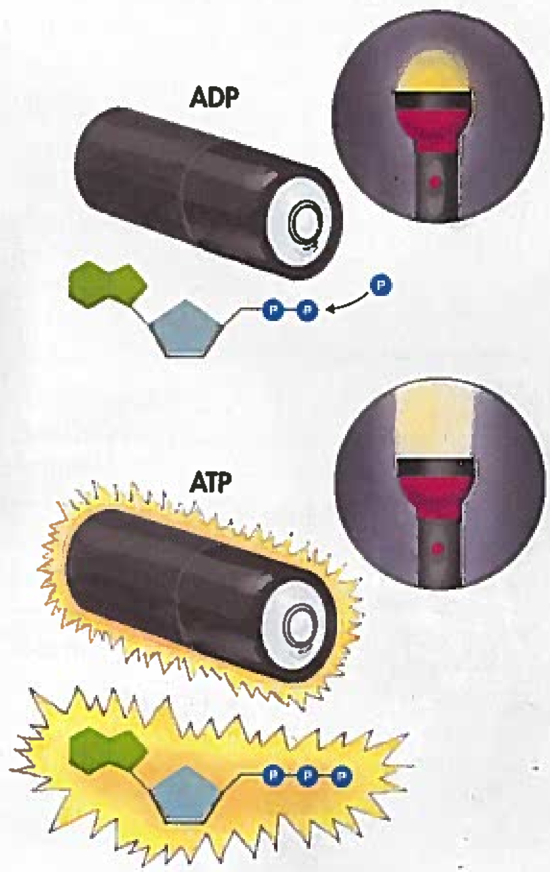
ATP is such a useful source of energy that you might think cells would be packed with ATP to get them through the day—but this is not the case. In fact, most cells have only a small amount of ATP—enough to last for a few seconds of activity. Why? Even though ATP is a great molecule for transferring energy, it is not a good one for storing large amounts of energy over the long term. A single molecule of the sugar glucose, for example, stores more than 90 times the energy required to add a phosphate group to ADP to produce ATP. Therefore, it is more efficient for cells to keep only a small supply of ATP on hand. Instead, 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.

In Your Notebook *With respect to energy, how are ATP and glucose similar? How are they different?*

VISUAL ANALOGY

ATP AS A CHARGED BATTERY

FIGURE 8–2 When a phosphate group is added to an ADP molecule, ATP is produced. ADP contains some energy, but not as much as ATP. In this way, ADP is like a partially charged battery that can be fully charged by the addition of a phosphate group.
Use Analogies ***Explain the difference between the beams of light produced by the flashlight "powered" by ADP and the flashlight "powered" by ATP.***



MYSTERY **CLUE**

Like all plants, the willow tree van Helmont planted was an autotroph. What might its ability to harness the sun's energy and store it in food have to do with the tree's gain in mass?

Heterotrophs and Autotrophs

What happens during the process of photosynthesis?

Cells are not "born" with a supply of ATP—they must somehow produce it. So, where do living things get the energy they use to produce ATP? The simple answer is that it comes from the chemical compounds that we call food. Organisms that obtain food by consuming other living things are known as **heterotrophs.** Some heterotrophs get their food by eating plants such as grasses. Other heterotrophs, such as the cheetah in **Figure 8–3,** obtain food from plants indirectly by feeding on plant-eating animals. Still other heterotrophs—mushrooms, for example—obtain food by decomposing other organisms.

Originally, however, the energy in nearly all food molecules comes from the sun. Plants, algae, and some bacteria are able to use light energy from the sun to produce food. Organisms that make their own food are called **autotrophs.** Ultimately, nearly all life on Earth, including ourselves, depends on the ability of autotrophs to capture the energy of sunlight and store it in the molecules that make up food. The process by which autotrophs use the energy of sunlight to produce high-energy carbohydrates—sugars and starches—that can be used as food is known as **photosynthesis.** *Photosynthesis* comes from the Greek words *photo*, meaning "light," and *synthesis*, meaning "putting together." Therefore, photosynthesis means "using light to put something together." **In the process of photosynthesis, plants convert the energy of sunlight into chemical energy stored in the bonds of carbohydrates.** In the rest of this chapter, you will learn how this process works.

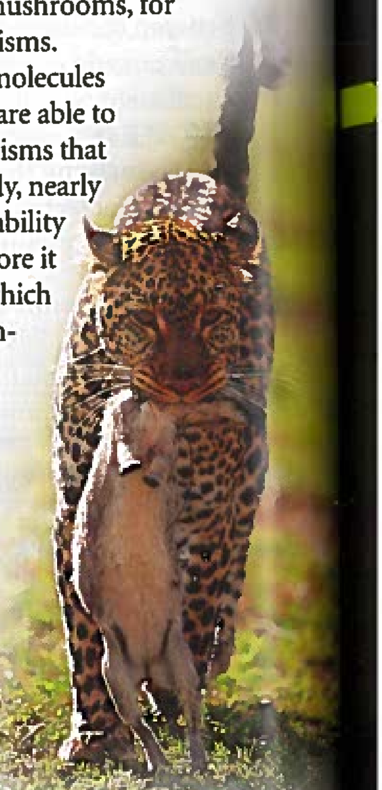


FIGURE 8–3 Autotrophs and Heterotrophs Grass, an autotroph, uses energy from the sun to produce food. African hares get their energy by eating grass. Cheetahs, in turn, get their energy by eating other organisms, like the hare.

8.1 Assessment

Review Key Concepts

1. **a. Review** What is ATP and what is its role in the cell?
   b. Explain How does the structure of ATP make it an ideal source of energy for the cell?
   c. Use Analogies Explain how ADP and ATP are each like a battery. Which one is "partially charged" and which one is "fully charged?" Why?
2. **a. Review** What is the ultimate source of energy for plants?
   b. Explain How do heterotrophs obtain energy? How is this different from how autotrophs obtain energy?
   c. Infer Why are decomposers, such as mushrooms, considered heterotrophs and not autotrophs?

Apply the Big idea

Interdependence in Nature

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

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Biology & 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.

1650 1700 1750 1800 1850 1900 1950 2000

1643

▲ After analyzing his measurements of a willow tree's water intake and mass increase, Jan van Helmont concludes that trees gain most of their mass from water.

1771

Joseph Priestley experiments with a bell jar, a candle, and a plant and concludes that the plant releases oxygen. ▼

1779

Jan 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. ▼

1845

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

1948

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

1992

Rudolph 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.

2004

▲ So Iwata and Jim Barber identify the precise mechanism by which water molecules are split in the process of photosynthesis. Their research may one day be applied to artificial photosynthesis technologies in order to produce a cheap supply of hydrogen gas that can be used as fuel.

WRITING 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.

8.2 Photosynthesis: An Overview

Key Questions

🔑 *What role do pigments play in the process of photosynthesis?*

🔑 *What are electron carrier molecules?*

🔑 *What are the reactants and products of photosynthesis?*

Vocabulary

pigment • chlorophyll • thylakoid • stroma • $NADP^+$ • light-dependent reactions • light-independent reactions

Taking Notes

Outline Make an outline using the green and blue headings in this lesson. Fill in details as you read to help you organize the information.

THINK ABOUT IT How would you design a system to capture the energy of sunlight and convert it into a useful form? First, you'd have to collect that energy. Maybe you'd spread out lots of flat panels to catch the light. You might then coat the panels with light-absorbing compounds, but what then? How could you take the energy, trapped ever so briefly in these chemical compounds, and get it into a stable, useful, chemical form? Solving such problems may well be the key to making solar power a practical energy alternative. But plants have already solved all these issues on their own terms—and maybe we can learn a trick or two from them.

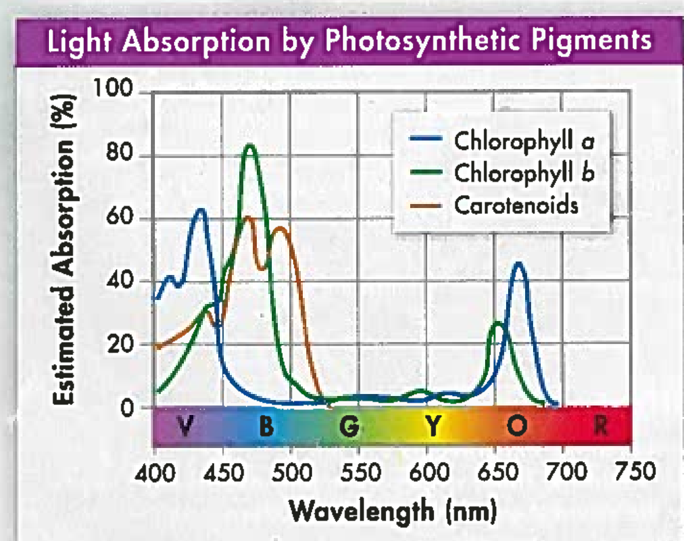
Chlorophyll and Chloroplasts

🔑 ***What role do pigments play in the process of photosynthesis?***

Our lives, and the lives of nearly every living thing on the surface of Earth, are made possible by the sun and the process of photosynthesis. In order for photosynthesis to occur, light energy from the sun must somehow be captured.

Light Energy from the sun travels to Earth in the form of light. Sunlight, which our eyes perceive as "white" light, is actually a mixture of different wavelengths. Many of these wavelengths are visible to our eyes and make up what is known as the visible spectrum. Our eyes see the different wavelengths of the visible spectrum as different colors: shades of red, orange, yellow, green, blue, indigo, and violet.

FIGURE 8–4 Light Absorption



Pigments Plants gather the sun's energy with light-absorbing molecules called **pigments.** 🔑 **Photosynthetic organisms capture energy from sunlight with pigments.** The plants' principal pigment is **chlorophyll** (KLAWR uh fil). The two types of chlorophyll found in plants, chlorophyll *a* and chlorophyll *b*, absorb 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, as shown in **Figure 8–4.**

Leaves reflect green light, 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. Most of the time, the intense green color of chlorophyll overwhelms the accessory pigments, so we don't notice them. As temperatures drop late in the year, however, chlorophyll molecules break down first, leaving the reds and oranges of the accessory pigments for all to see. The beautiful colors of fall in some parts of the country are the result of this process.

Chloroplasts Recall from Chapter 7 that in plants and other photosynthetic eukaryotes, photosynthesis takes place inside organelles called chloroplasts. Chloroplasts contain an abundance of saclike photosynthetic membranes called **thylakoids** (THY luh koydz). Thylakoids are interconnected and arranged in stacks known as grana (singular: granum). Pigments such as chlorophyll are located in the thylakoid membranes. The fluid portion of the chloroplast, outside of the thylakoids, is known as the **stroma.** The structure of a typical chloroplast is shown in **Figure 8–5.**

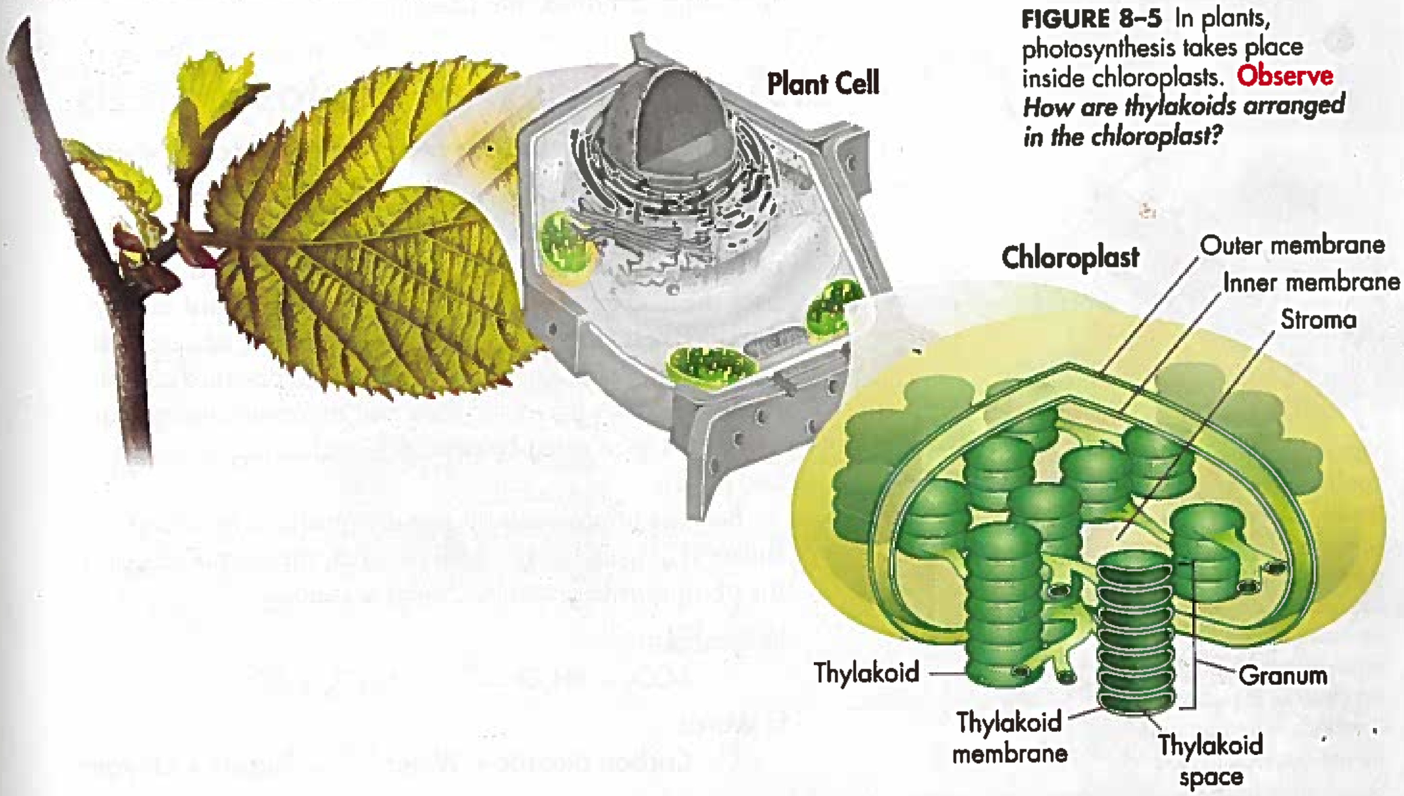
Energy Collection What's so special about chlorophyll that makes it important for photosynthesis? Because light is a form of energy, any compound that absorbs light absorbs energy. Chlorophyll absorbs visible light especially well. In addition, when chlorophyll absorbs light, a large fraction of that light energy is transferred directly to electrons in the chlorophyll molecule itself. By raising the energy levels of these electrons, light energy can produce a steady supply of high-energy electrons, which is what makes photosynthesis work.

In Your Notebook *In your own words, explain why most plants will not grow well if kept under green light.*

ZOOMING IN

THE CHLOROPLAST

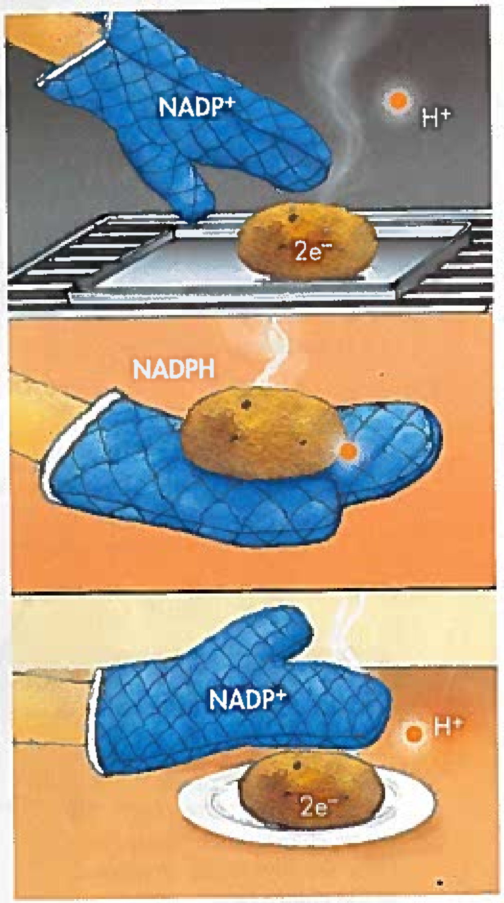
FIGURE 8–5 In plants, photosynthesis takes place inside chloroplasts. **Observe** ***How are thylakoids arranged in the chloroplast?***



VISUAL ANALOGY

CARRYING ELECTRONS

FIGURE 8–6 $NADP^+$ is a carrier molecule that transports pairs of electrons (and an H^+ ion) in photosynthetic organisms, similar to how an oven mitt is used to transport a hot object such as a baked potato.



High-Energy Electrons

What are electron carrier molecules?

In a chemical sense, the high-energy electrons produced by chlorophyll are highly reactive and require a special "carrier." Think of a high-energy electron as being similar to a hot potato straight from the oven. If you wanted to move the potato from one place to another, you wouldn't pick it up in your hands. You would use an oven mitt—a carrier—to transport it, as shown in **Figure 8–6.** Plant cells treat high-energy electrons in the same way. Instead of an oven mitt, however, they use electron carriers to transport high-energy electrons from chlorophyll to other molecules. **An electron carrier is a compound that can accept a pair of high-energy electrons and transfer them, along with most of their energy, to another molecule.**

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 the high-energy electrons that were produced by light absorption in chlorophyll to chemical reactions elsewhere in the cell. These high-energy electron carriers are used to help build a variety of molecules the cell needs, including carbohydrates like glucose.

An Overview of Photosynthesis

What are the reactants and products of photosynthesis?

Many steps are involved in the process of photosynthesis. However, the overall process of photosynthesis can be summarized in one sentence. **Photosynthesis uses the energy of sunlight to convert water and carbon dioxide (reactants) into high-energy sugars and oxygen (products).** Plants then use the sugars to produce complex carbohydrates such as starches, and to provide energy for the synthesis of other compounds, including proteins and lipids.

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

In Symbols:

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

In Words:

$$\text{Carbon dioxide} + \text{Water} \xrightarrow{\text{light}} \text{Sugars} + \text{Oxygen}$$

MYSTERY CLUE

Van Helmont concluded that water must have provided the extra mass gained by the tree. Further studies would prove that he had only half of the answer. What reactant involved in the photosynthesis equation was he not accounting for?

Light-Dependent Reactions Although the equation for photosynthesis looks simple, there are many steps to get from the reactants to the final products. In fact, photosynthesis actually involves two sets of reactions. The first set of reactions is known as the **light-dependent reactions** because they require the direct involvement of light and light-absorbing pigments. The light-dependent reactions use energy from sunlight to produce energy-rich compounds such as ATP. These reactions take place within the thylakoids—specifically, in the thylakoid membranes—of the chloroplast. Water is required in these reactions as a source of electrons and hydrogen ions. Oxygen is released as a byproduct.

Light-Independent Reactions Plants absorb carbon dioxide from the atmosphere and complete the process of photosynthesis by producing carbon-containing sugars and other carbohydrates. During the **light-independent reactions,** ATP and NADPH molecules produced in the light-dependent reactions are used to produce high-energy sugars from carbon dioxide. As the name implies, no light is required to power the light-independent reactions. The light-independent reactions take place outside the thylakoids, in the stroma.

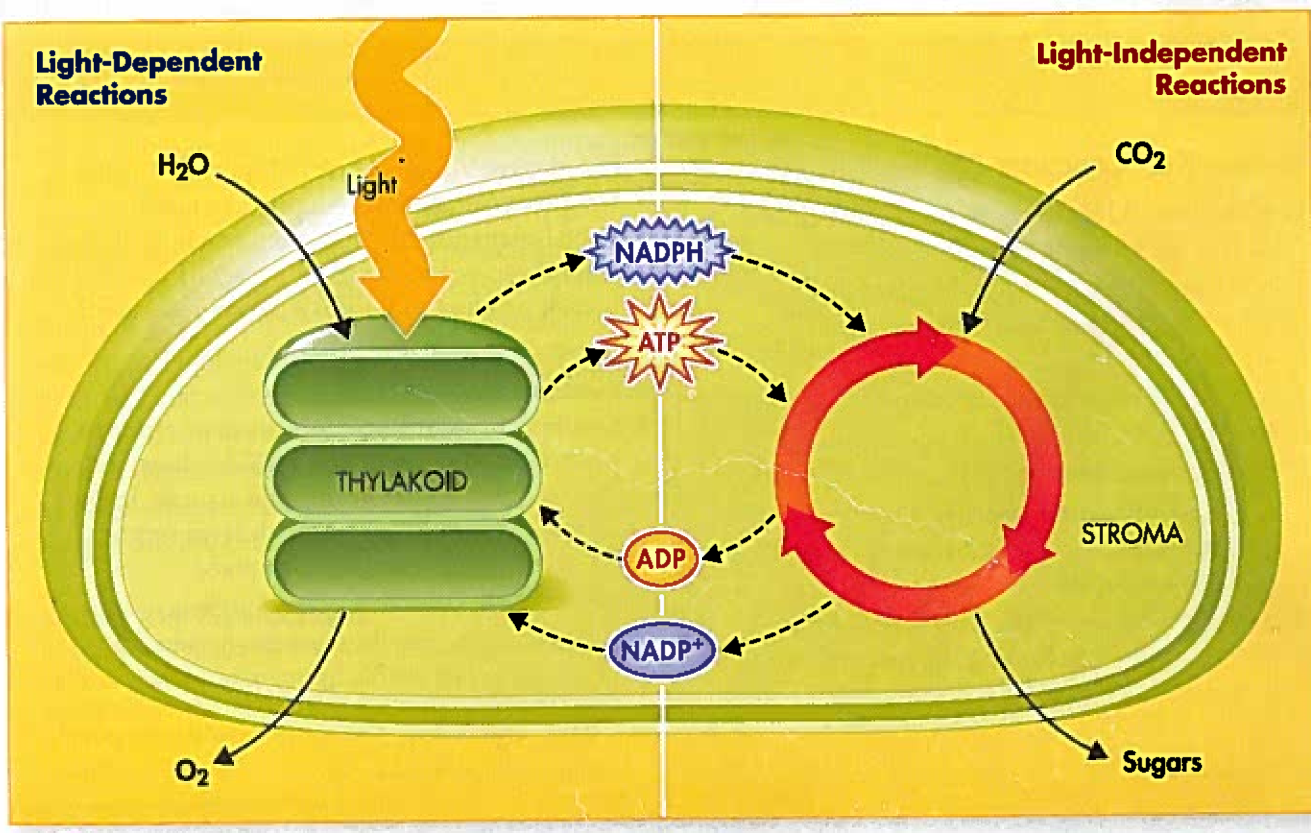
The interdependent relationship between the light-dependent and light-independent reactions is shown in **Figure 8–7.** As you can see, the two sets of reactions work together to capture the energy of sunlight and transform it into energy-rich compounds such as carbohydrates.

In Your Notebook *Create a two-column compare/contrast table that shows the similarities and differences between the light-dependent and light-independent reactions of photosynthesis.*

BUILD Vocabulary

ACADEMIC WORDS The noun **byproduct** means "anything produced in the course of making another thing." Oxygen is considered a byproduct of the light-dependent reactions of photosynthesis because it is produced as a result of extracting electrons from water. Also, unlike ATP and NADPH, oxygen is not used in the second stage of the process, the light-independent reactions.

FIGURE 8–7 The Stages of Photosynthesis There are two stages of photosynthesis: light-dependent reactions and light-independent reactions. **Interpret Diagrams** *What happens to the ATP and NADPH produced in the light-dependent reactions?*



8.3 The Process of Photosynthesis

THINK ABOUT IT Why membranes? Why do chloroplasts contain so many membranes? Is there something about biological membranes that makes them absolutely essential for the process of photosynthesis? As you'll see, there is. When most pigments absorb light, they eventually lose most of that energy as heat. In a sense, the "trade secret" of the chloroplast is how it avoids such losses, capturing light energy in the form of high-energy electrons—and membranes are the key. Without them, photosynthesis simply wouldn't work.

Key Questions

What happens during the light-dependent reactions?

What happens during the light-independent reactions?

What factors affect photosynthesis?

Vocabulary

photosystem • electron transport chain • ATP synthase • Calvin cycle

Taking Notes

Flowchart As you read, create a flowchart that clearly shows the steps involved in the light-dependent reactions.

The Light-Dependent Reactions: Generating ATP and NADPH

What happens during the light-dependent reactions?

Recall that the process of photosynthesis involves two primary sets of reactions: the light-dependent and the light-independent reactions. The light-dependent reactions encompass the steps of photosynthesis that directly involve sunlight. These reactions explain why plants need light to grow. **The light-dependent reactions use energy from sunlight to produce oxygen and convert ADP and $NADP^+$ into the energy carriers ATP and NADPH.**

The light-dependent reactions occur in the thylakoids of chloroplasts. Thylakoids are saclike membranes containing most of the machinery needed to carry out these reactions. Thylakoids contain clusters of chlorophyll and proteins known as **photosystems.** The photosystems, which are surrounded by accessory pigments, are essential to the light-dependent reactions. Photosystems absorb sunlight and generate high-energy electrons that are then passed to a series of electron carriers embedded in the thylakoid membrane. Light absorption by the photosystems is just the beginning of this important process.

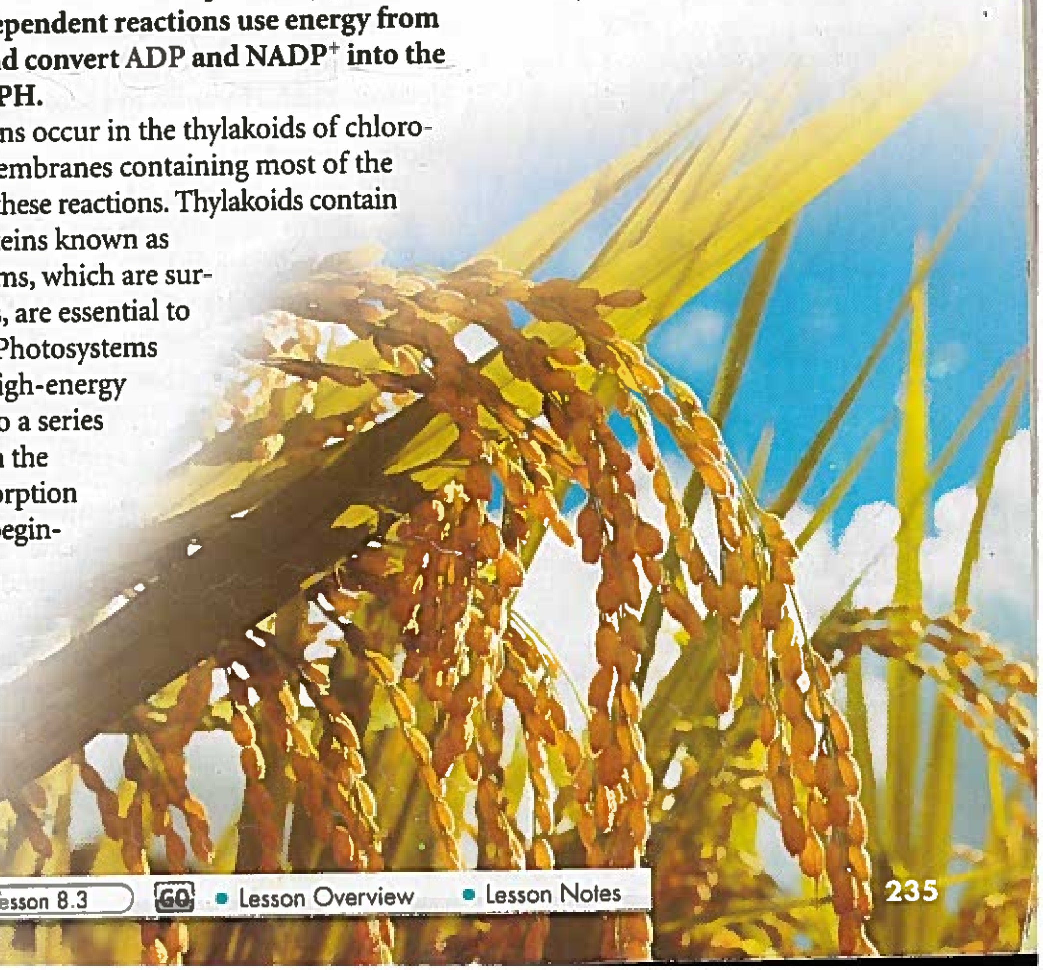


FIGURE 8–8 The Importance of Light Like all plants, this rice plant needs light to grow.
Apply Concepts ***Which stage of photosynthesis requires light?***

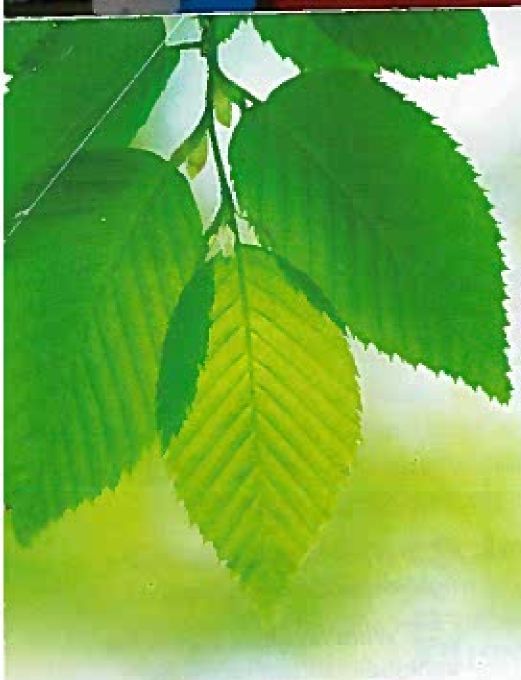


FIGURE 8–9 Why Green? The green color of most plants is caused by the reflection of green light by the pigment chlorophyll. Pigments capture light energy during the light-dependent reactions of photosynthesis.

Photosystem II The light-dependent reactions, shown in **Figure 8–10,** begin when pigments in photosystem II absorb light. (This first photosystem is called photosystem II simply because it was discovered after photosystem I.) Light energy is absorbed by electrons in the pigments found within photosystem II, increasing the electrons' energy level. These high-energy electrons (e^-) are passed to the electron transport chain. An **electron transport chain** is a series of electron carrier proteins that shuttle high-energy electrons during ATP-generating reactions.

As light continues to shine, more and more high-energy electrons are passed to the electron transport chain. Does this mean that chlorophyll eventually runs out of electrons? No, 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 break up each water molecule into 2 electrons, 2 H^+ ions, and 1 oxygen atom. The 2 electrons replace the high-energy electrons that have been 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.

In Your Notebook *Explain in your own words why photosynthetic organisms need water and sunlight.*

Electron Transport Chain What happens to the electrons as they move down the electron transport chain? Energy from the electrons is used by the proteins in the chain to pump H^+ ions from the stroma into the thylakoid space. At the end of the electron transport chain, the electrons themselves pass to a second photosystem called photosystem I.

Photosystem I Because some energy has been used to pump H^+ ions across the thylakoid membrane, electrons do not contain as much energy as they used to when they reach photosystem I. Pigments in photosystem I use energy from light to reenergize the electrons. At the end of a short second electron transport chain, $NADP^+$ molecules in the stroma pick up the high-energy electrons, along with H^+ ions, at the outer surface of the thylakoid membrane, to become NADPH. This NADPH becomes very important, as you will see, in the light-independent reactions of photosynthesis.

Hydrogen Ion Movement and ATP Formation Recall that in photosystem II, hydrogen ions began to accumulate within the thylakoid space. Some were left behind from the splitting of water at the end of the electron transport chain. Other hydrogen ions were "pumped" in from the stroma. The buildup of hydrogen ions makes the stroma negatively charged relative to the space within the thylakoids. This gradient, the difference in both charge and H^+ ion concentration across the membrane, provides the energy to make ATP.

BUILD Vocabulary

ACADEMIC WORDS The noun **gradient** refers to "an area over which something changes." There is a charge gradient across the thylakoid membrane because there is a positive charge on one side and a negative charge on the other.

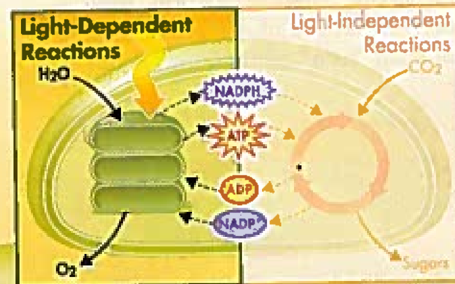
H^+ ions cannot cross the membrane directly. However, the thylakoid membrane contains a protein called **ATP synthase** that spans the membrane and allows H^+ ions to pass through it. Powered by the gradient, H^+ ions pass through ATP synthase and force it to rotate, almost like a turbine being spun by water in a hydroelectric power plant. As it rotates, ATP synthase binds ADP and a phosphate group together to produce ATP. This process, which is known as chemiosmosis (kem ee ahz MOH sis), enables light-dependent electron transport to produce not only NADPH (at the end of the electron transport chain), but ATP as well.

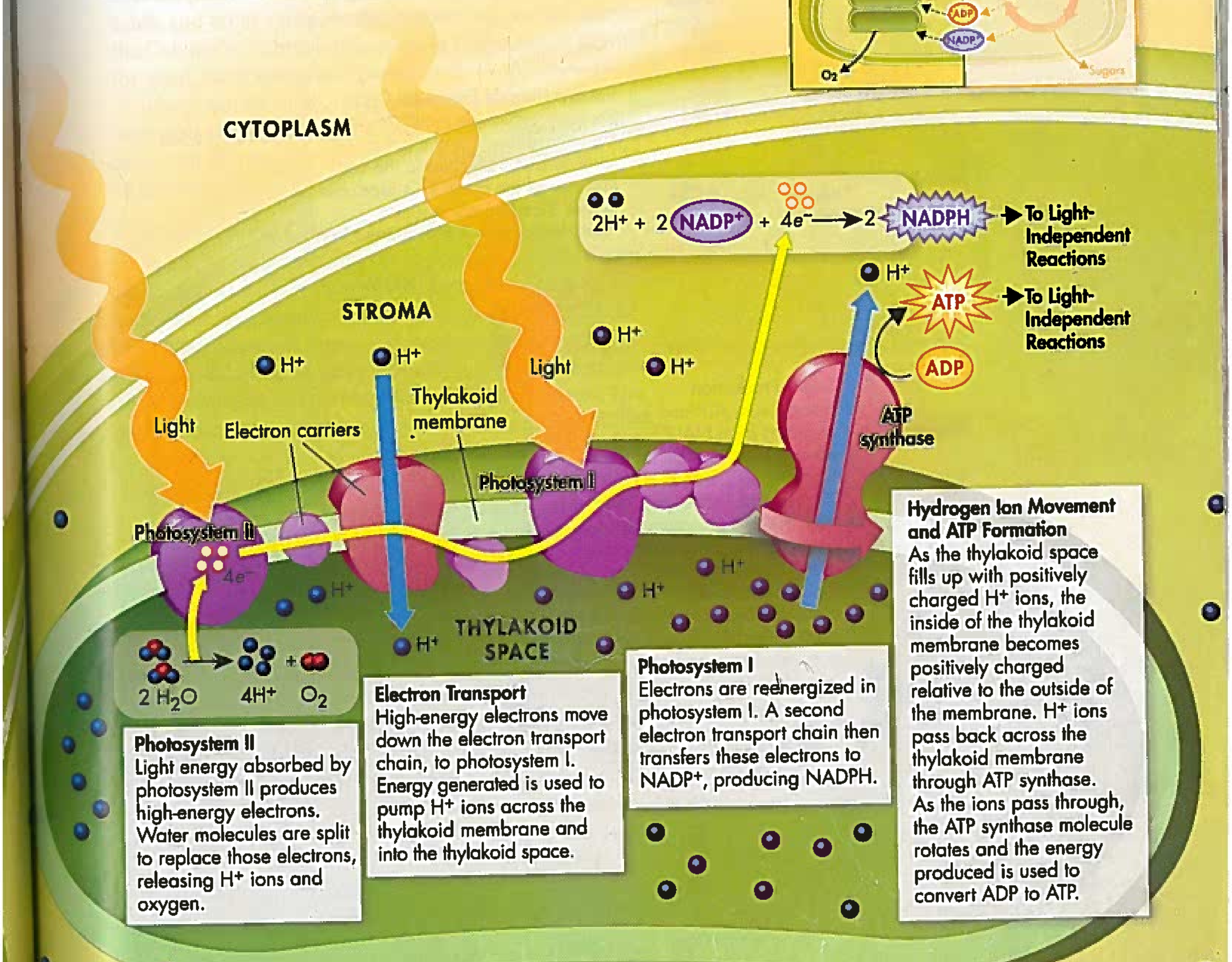
Summary of Light-Dependent Reactions The light-dependent reactions produce oxygen gas and convert ADP and $NADP^+$ into the energy carriers ATP and NADPH. What good are these compounds? As we will see, they have an important role to play in the cell: They provide the energy needed to build high-energy sugars from low-energy carbon dioxide.

ZOOMING IN

LIGHT-DEPENDENT REACTIONS

FIGURE 8–10 The light-dependent reactions of photosynthesis take place in the thylakoids of the chloroplast. They use energy from sunlight to produce ATP, NADPH, and oxygen. **Interpret Visuals** ***How many molecules of NADPH are produced per water molecule used in photosynthetic electron transport?***





ZOOMING IN

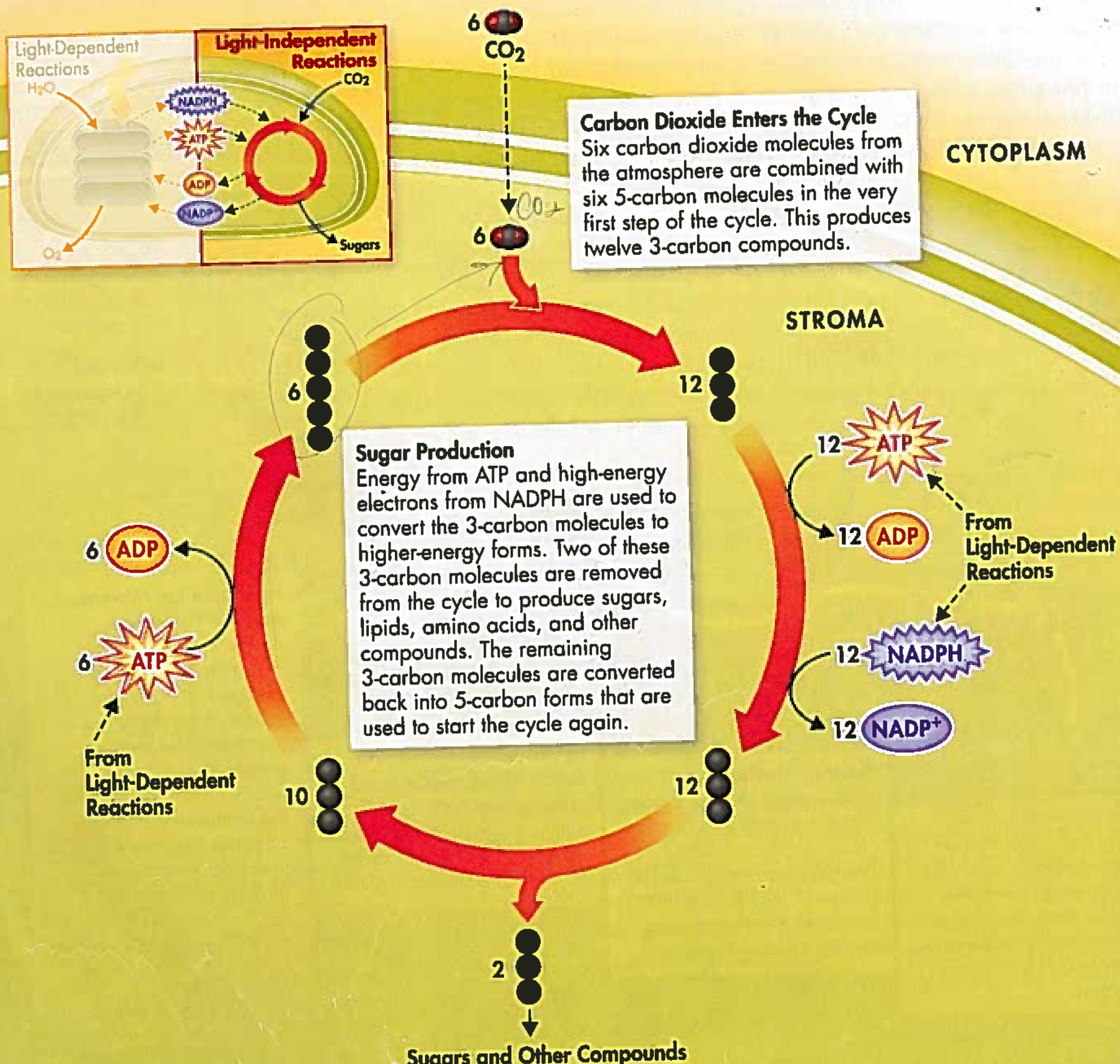
LIGHT-INDEPENDENT REACTIONS

FIGURE 8–11 The light-independent reactions of photosynthesis take place in the stroma of the chloroplast. The reactions use ATP and NADPH from the light-dependent reactions to produce high-energy sugars such as glucose. **Interpret Visuals** ***How many molecules of ATP are needed for each "turn" of the Calvin cycle?***

The Light-Independent Reactions: Producing Sugars

What happens during the light-independent reactions?

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 light-independent reactions, commonly referred to as the **Calvin cycle,** plants use the energy that ATP and NADPH contain to build stable high-energy carbohydrate compounds that can be stored for a long time. **During the light-independent reactions, ATP and NADPH from the light-dependent reactions are used 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. Follow **Figure 8–11** to see each step in this set of reactions.



Carbon Dioxide Enters the Cycle Carbon dioxide molecules enter the Calvin cycle from the atmosphere. An enzyme in the stroma of the chloroplast combines these carbon dioxide molecules with 5-carbon compounds that are already present in the organelle, producing 3-carbon compounds that continue into the cycle. For every 6 carbon dioxide molecules that enter the cycle, a total of twelve 3-carbon compounds are produced. Other enzymes in the chloroplast then convert these compounds into higher-energy forms in the rest of the cycle. The energy for these conversions comes from ATP and high-energy electrons from NADPH.

Sugar Production At midcycle, two of the twelve 3-carbon molecules are removed from the cycle. This is a very special step because these molecules become the building blocks that the plant cell uses to produce sugars, lipids, amino acids, and other compounds. In other words, this step in the Calvin cycle contributes to all of the products needed for plant metabolism and growth.

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.

Summary of the Calvin Cycle The Calvin cycle uses 6 molecules of carbon dioxide to produce a single 6-carbon sugar molecule. The energy for the reactions that make this possible is supplied by compounds produced in the light-dependent reactions. 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 macromolecules needed for growth and development, including lipids, proteins, and complex carbohydrates such as cellulose. When other organisms eat plants, they, too, can use the energy and raw materials stored in these compounds.

The End Results 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, animals, including ourselves, get plenty of food and an atmosphere filled with oxygen. Not a bad deal at all!

In Your Notebook *What happens to the $NADP^+$, ADP, and sugars produced by the Calvin cycle?*

MYSTERY CLUE

Melvin Calvin used radioactively labeled carbon atoms in carbon dioxide to show what happens to the carbon used in the light-independent reactions. Where does this carbon end up?

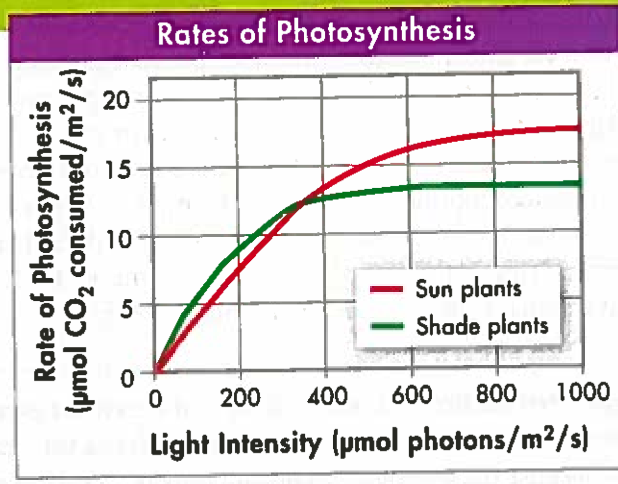
Analyzing Data

Rates of Photosynthesis

The rate at which a plant carries out photosynthesis depends in part on environmental factors such as temperature, amount of water available, and light intensity. The graph shows how the average rates of photosynthesis between sun plants and shade plants changes with light intensity.

1. Use 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. Infer Light intensity in the Sonoran Desert averages 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?



3. Form a Hypothesis 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?

Factors Affecting Photosynthesis

What factors affect photosynthesis?

Temperature, Light, and Water Many factors influence the rate of photosynthesis. **Among the most important factors that affect photosynthesis are temperature, light intensity, and the availability of water.** The reactions of photosynthesis are made possible by enzymes that function best between 0°C and 35°C. Temperatures above or below this range may affect those 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, high light intensity increases the rate of photosynthesis. After the light intensity reaches a certain level, however, the plant reaches its maximum rate of photosynthesis.

Because water is one of the raw materials of photosynthesis, a shortage of water can slow or even stop photosynthesis. Water loss can also damage plant tissues. To deal with these dangers, plants (such as desert plants and conifers) that live in dry conditions often have waxy coatings on their leaves that reduce water loss. They may also have biochemical adaptations that make photosynthesis more efficient under dry conditions.

BUILD Vocabulary

MULTIPLE MEANINGS The noun *intensity* is commonly used to refer to something or someone who is very emotional, focused, or active. In science, however, *intensity* refers to energy. Thus, light intensity is a measure of the amount of energy available in light. More intense light has more energy.

In Your Notebook *Explain in your own words what role enzymes play in chemical reactions such as photosynthesis.*

Photosynthesis Under Extreme Conditions In order to conserve water, most plants under bright, hot conditions (of the sorts often found in the tropics) close the small openings in their leaves that normally admit carbon dioxide. While this keeps the plants from drying out, it causes carbon dioxide within the leaves to fall to very low levels. When this happens to most plants, photosynthesis slows down or even stops. However, some plants have adapted to extremely bright, hot conditions. There are two major groups of these specialized plants: C4 plants and CAM plants. C4 and CAM plants have biochemical adaptations that minimize water loss while still allowing photosynthesis to take place in intense sunlight.

▶ ***C4 Photosynthesis*** C4 plants have a specialized chemical pathway that allows them to capture even very low levels of carbon dioxide and pass it to the Calvin cycle. The name "C4 plant" comes from the fact that the first compound formed in this pathway contains 4 carbon atoms. The C4 pathway enables photosynthesis to keep working under intense light and high temperatures, but it requires extra energy in the form of ATP to function. C4 organisms include important crop plants like corn, sugar cane, and sorghum.

▶ ***CAM Plants*** Other plants adapted to dry climates use a different strategy to obtain carbon dioxide while minimizing water loss. These include members of the family Crassulaceae. Because carbon dioxide becomes incorporated into organic acids during photosynthesis, the process is called Crassulacean Acid Metabolism (CAM). CAM plants admit air into their leaves only at night. In the cool darkness, carbon dioxide is combined with existing molecules to produce organic acids, "trapping" the carbon within the leaves. During the daytime, when leaves are tightly sealed to prevent the loss of water, these compounds release carbon dioxide, enabling carbohydrate production. CAM plants include pineapple trees, many desert cacti, and also the fleshy "ice plants" shown in **Figure 8–12**, which are frequently planted near freeways along the west coast to retard brush fires and prevent erosion.

FIGURE 8–12 CAM Plants Plants like this ice plant can survive in dry conditions due to their modified light-independent reactions. Air is allowed into the leaves only at night, minimizing water loss.

8.3 Assessment

Review Key Concepts

1. **a. Review** Summarize what happens during the light-dependent reactions of photosynthesis.
   b. Sequence Put the events of the light-dependent reactions in the order in which they occur and describe how each step is dependent on the step that comes before it.
2. **a. Review** What is the Calvin cycle?
   b. Compare and Contrast List at least three differences between the light-dependent and light-independent reactions of photosynthesis.
3. **a. Review** What are the three primary factors that affect the rate of photosynthesis?
   b. Interpret Graphs Look at the graph on page 240. What are the independent and dependent variables being tested?

BUILD VOCABULARY

4. The word *carbohydrate* comes from the prefix *carbo-*, meaning "carbon," and the word *hydrate*. Based on the reactants of the photosynthesis equation, what does *hydrate* mean?

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