CHAPTER 9

Photosynthesis

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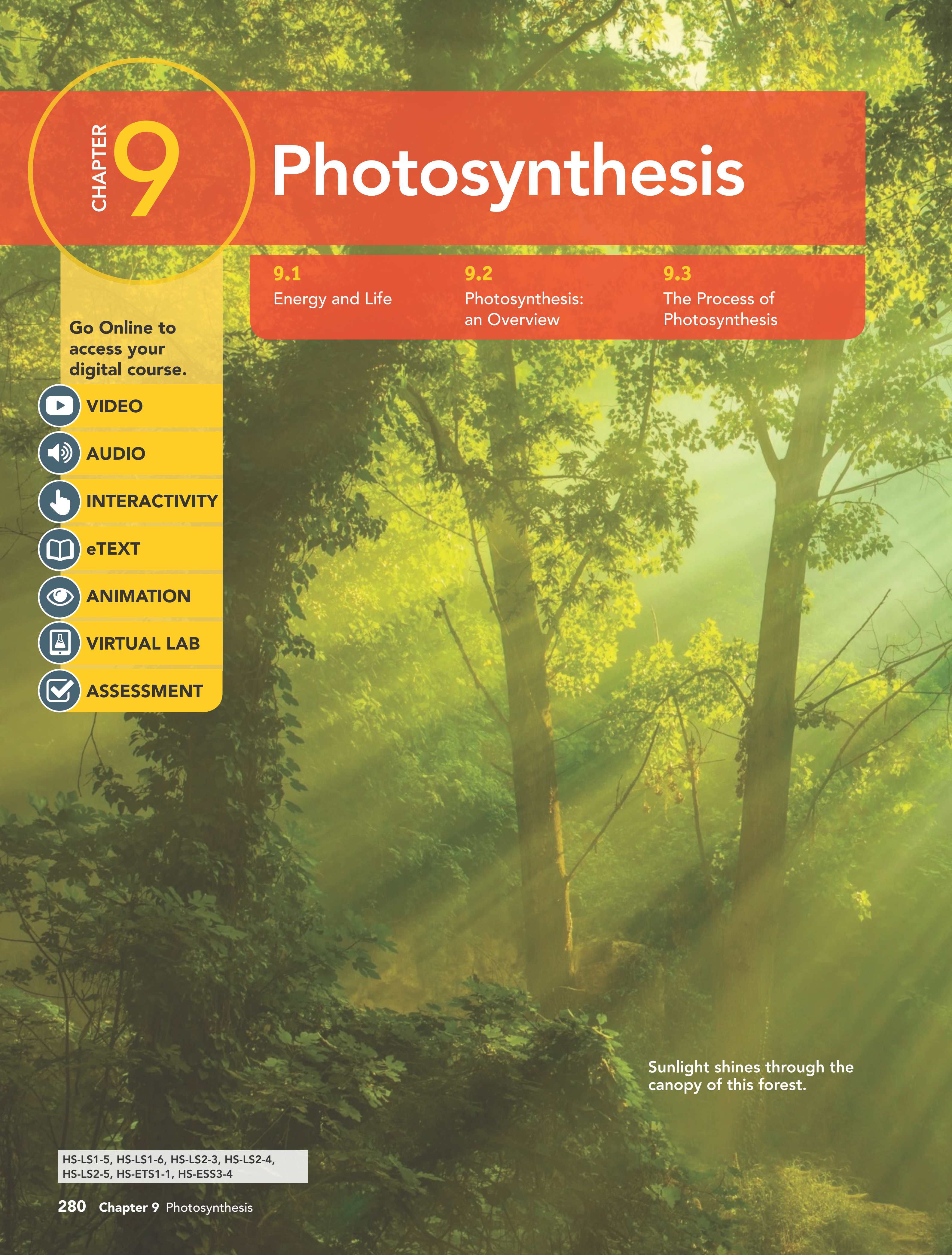


Sunlight shines through the canopy of this forest.

HS-LS1-5, HS-LS1-6, HS-LS2-3, HS-LS2-4, HS-LS2-5, HS-ETS1-1, HS-ESS3-4

CASE STUDY

What would it take to make an artificial leaf?

Have you seen solar panels around your city or town? Conventional solar panels use the energy from sunlight to produce an electric current, which can then be used to power a home or factory. The electricity can also feed into the wires of the electrical grid. But storing that electricity is difficult and expensive. Most panels capture only a fraction of the energy in the sunlight that hits them.

Solar panels are wonderful for converting sunlight to electricity. However, they're not so great in places that are not sunny. Even in places where solar panels can supply the electrical needs of an entire building during the summer, energy-independence is lost during the winter, when the days are shorter and snow periodically covers the panels.

What if solar panels could capture energy from the sun and convert it into stable, energy-containing substances that could be used as fuel? In other words, what if a solar panel acted more like, well . . . a leaf?

Green plants don't produce an electric current that can be run through a wire. However, they do harness the energy from sunlight very efficiently. The process is called photosynthesis. Plants store that energy in chemical form as sugars, oils, and complex carbohydrates. Might it be possible to design and build an artificial leaf, a device that captures sunlight like a plant and uses that energy to build stable, energy-containing substances that can be used for fuel?

For decades, researchers around the world have been trying to learn from nature and mimic the way in which plants carry out photosynthesis. As you will see in this chapter, the energy plants absorb from sunlight is used to raise the energy level of electrons taken from water to a point where these high-energy electrons can do useful chemical work.

An artificial photosynthetic system would do much the same thing. If energy from the sun could be used to make a chemical fuel that was easy to store and transport, this would solve many of the problems associated with solar energy.

But what sort of fuel should an artificial leaf produce? Sugars, like plants do? Or something else? The possibilities are intriguing. Perhaps we can make a fuel that burns more cleanly than fossil fuels. Or a fuel that is carbon-neutral. A carbon-neutral fuel does not produce carbon-based waste products like carbon dioxide when it is broken down to release energy. Hydrogen gas (H_2) is one example of a carbon-neutral fuel. It burns with oxygen gas (O_2) in the air to produce only one product, water vapor (H_2O). Carbon-neutral fuels do not produce greenhouse gases and therefore do not contribute to climate change.

Is it possible to build a cost-effective artificial leaf? What are the other constraints on designing this solution to an urgent real-world problem? What criteria should be used when evaluating competing solutions?

Throughout this chapter, look for connections to the CASE STUDY to help you answer these questions.

LESSON 9.1

Energy and Life

KEY QUESTIONS

- *Why is ATP useful to cells?*
- *What happens during the process of photosynthesis?*

HS-LS1-5: Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.

HS-LS2-3: Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions.

VOCABULARY

ATP
photosynthesis

READING TOOL

As you read the lesson, complete the main idea table for each heading. Fill out the table in your **Biology Foundations Workbook.**

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, to be sure, but where does it come from?

Chemical Energy and ATP

Energy is the ability to do work. Without energy, lights, appliances, and computers stop working. Living things depend on energy, too. Even when you are sleeping, your cells are busy using energy to synthesize new molecules, contract muscles, and carry out active transport. Simply put, without the ability to obtain and use energy by converting from one form to another, 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.

Storing Energy Whether they get energy from food or from sunlight, all living cells store energy in the chemical bonds of certain compounds. One of the most important compounds is adenosine triphosphate (uh DEN us seen try FAHS fayt), abbreviated **ATP**. As shown in **Figure 9-1**, ATP consists of adenine, a 5-carbon sugar called ribose, and three phosphate groups. Those phosphate groups are the key to ATP's ability to store and release energy.

BUILD VOCABULARY

Apply Prior Knowledge Your previous experience of the prefix *tri-* (three) in words like *triangle* and *tricycle* can help you remember that there are three phosphate groups in ATP.

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 to produce ATP.

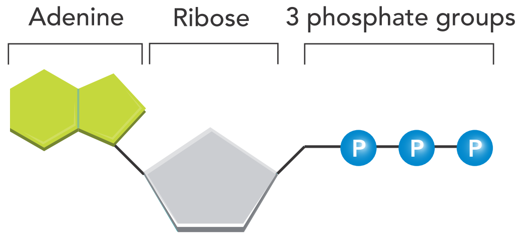


Figure 9-1

Adenosine Triphosphate (ATP)

All cells use a small molecule called ATP to store and release energy.

Releasing Energy Cells can release the energy stored in ATP by the controlled breaking of the chemical bonds between atoms in the second and third phosphate groups. As **Figure 9-2** shows, this means that ATP functions a little bit like a rechargeable battery.

Because energy is used to add a phosphate group to ADP to generate ATP, and energy is released when a phosphate group on ATP is split off and released, ATP serves the cell as a way of storing and releasing energy as needed. ***ATP can 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.***

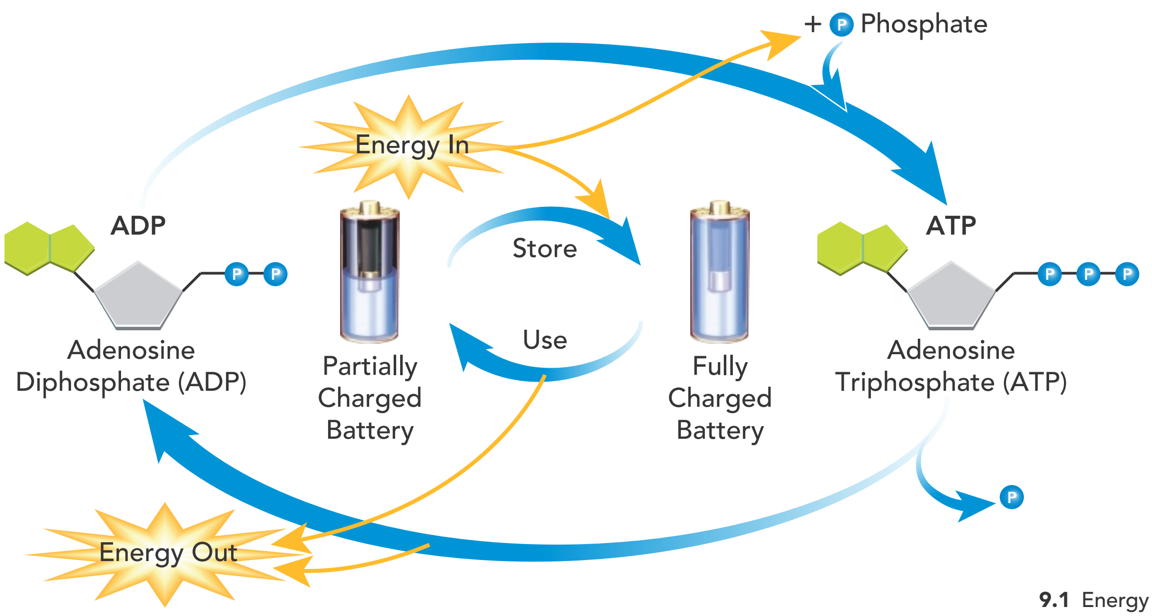
INTERACTIVITY

Visual Analogy

Figure 9-2

ATP and Batteries

ATP is like a fully-charged battery, and ADP is like a partially-charged battery. When a phosphate group combines with ADP, they form energy-rich ATP. When ATP loses the phosphate group, it releases energy and becomes ADP again.



Quick Lab — Guided Inquiry

How Do Organisms Capture and Use Energy?

1. Your teacher will provide you with two test tubes wrapped in foil. The test tubes contain colonies of *Euglena*, which are photosynthetic microorganisms. Find the hole in the foil around one of the test tubes.

2. Where do you predict *Euglena* will be found in each test tube? Record your prediction.
3. Carefully remove the foil from each test tube. Make sure not to shake or disturb their contents. Observe the locations of *Euglena* in the test tubes, and record your observations.

ANALYZE AND CONCLUDE

1. **Identify Patterns** What pattern do you observe in the distribution of *Euglena* in the two test tubes?
2. **Construct an Explanation** How could the pattern you observed in *Euglena* behavior be useful or beneficial to the organism? Propose a logical explanation.
3. **Apply Scientific Reasoning** *Euglena* can also live heterotrophically. If you repeated the experiment with test tubes of *Euglena* that also contained a food source, do you think the results of your experiment would be the same? Explain your reasoning.

READING TOOL

Write down the main idea of this section of text. As you read, list details about how cells use ATP to store and release energy.

How Cells Use ATP What do cells use ATP for? One way cells use the energy provided by ATP is for carrying 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. The energy stored in ATP also enables cells to move, providing power for motor proteins that contract muscle and power the wavelike movement of cilia and flagella.

Energy from ATP can be transferred to other molecules in the cell to power processes such as protein synthesis and responses to chemical signals at the cell surface. The chemical energy from ATP can even be converted to light. In fact, the blink of a firefly on a summer night comes from an enzyme that is powered by ATP!

INTERACTIVITY

Investigate how ATP powers the chemical reactions within a cell.

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 sugar. As you will see, that's exactly what they do.

READING CHECK Describe How does ATP provide the energy cells need?

Heterotrophs and Autotrophs

Cells have to produce ATP constantly because it gets used up quickly in an active cell. So, where do living things get the energy they use to produce ATP? There are several ways. Most animals obtain the chemical energy they need from 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 heron in **Figure 9-3**, obtain food from plants indirectly by feeding on other animals. Still other heterotrophs obtain food by absorbing nutrients from decomposing organisms in the environment. Mushrooms obtain food this way.

Originally, however, the energy in food comes from the sun. Plants, algae, and some bacteria are able to use energy from sunlight to synthesize food molecules. Organisms that make their own food are called autotrophs. Ultimately, nearly all life on Earth depends on the ability of autotrophs to capture and convert the energy from sunlight to synthesize high-energy carbohydrates—sugars and starches—that can be used as food. This process is known as **photosynthesis**. The word *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 9-3
The Lives of Heterotrophs

Herons are heterotrophs that get their energy by eating other organisms, such as fish.
Compare and Contrast How are heterotrophs and autotrophs similar? How are they different?

VIDEO
Learn how autotrophs use photosynthesis to their advantage.

HS-LS1-5, HS-LS2-3

LESSON 9.1 Review

KEY IDEAS

1. How do molecules of ATP store and provide energy for the cell?
2. Describe the transformation of energy that occurs during photosynthesis.

CRITICAL THINKING

3. **Use Models** Explain how a rechargeable battery can be used as a model of ADP and ATP.
4. **Develop Models** Develop a model to illustrate the role of photosynthesis in transforming energy. Include the terms *photosynthesis*, *sun*, *light energy*, *chemical energy*, *carbohydrates*, and *bonds*.
5. **CASE STUDY** Solar cells can provide the energy to run calculators, outdoor lights, and other devices. How does the conversion of light energy into stored chemical energy by solar cells compare to the process of photosynthesis?

LESSON 9.2

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?*

HS-LS1-5: Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.

HS-LS2-5: Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

VOCABULARY

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

READING TOOL

Fill in the concept map in your **Biology Foundations Workbook** to show the organization of a chloroplast.

BUILD VOCABULARY

Prefixes The prefix *chloro-* refers to the color green. Chlorophyll and chloroplasts are green in color.

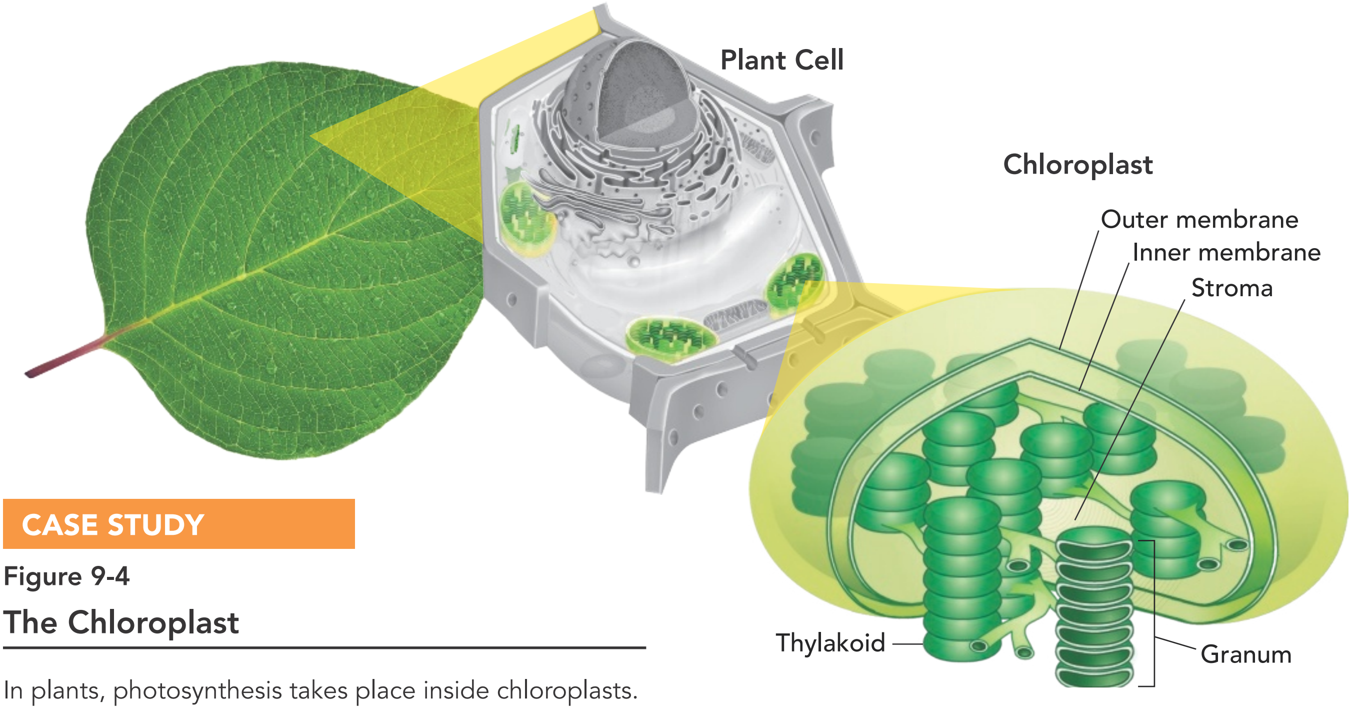
How would you design a system to capture the energy of sunlight? How could you convert the energy into a stable, useful, chemical form? Solving such problems may well be the key to making solar power a more useful energy alternative. Plants, however, have already solved all these issues on their own terms—and maybe we can learn a trick or two from them.

Chlorophyll and Chloroplasts

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.

Pigments Light-absorbing compounds, whether they are found on a painter's brush or in a living cell, are known as **pigments**. ***Photosynthetic organisms use pigments to capture the energy in sunlight.*** The principal pigment of green plants is known as **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, but instead reflects it. That's why most leaves are green.



CASE STUDY

Figure 9-4

The Chloroplast

In plants, photosynthesis takes place inside chloroplasts. Each chloroplast is filled with grana, which are stacks of thylakoid membranes.

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 these 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 8 that in plants and other photosynthetic eukaryotes, photosynthesis takes place inside organelles called chloroplasts. Chloroplasts are surrounded by two envelope membranes, and they are filled with saclike chlorophyll-containing membranes called **thylakoids** (THY luh koydz). These thylakoids are interconnected and arranged in stacks known as grana (singular: granum). 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 9-4**.

Energy Collection What's so special about chlorophyll that makes it essential for photosynthesis? Chlorophyll absorbs light very efficiently, transferring light energy to its own electrons. These high-energy electrons are then available to do chemical work, such as the building of sugar molecules from low-energy compounds like carbon dioxide and water. This is what makes photosynthesis work.

READING CHECK **Cause and Effect** How does photosynthesis depend on chlorophyll?

INTERACTIVITY

Learn more about the inputs and outputs of matter and energy in photosynthesis with an interactive model.

High-Energy Electrons

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 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, as shown in **Figure 9-5**.

Plant cells treat these high-energy electrons in much the same way. Instead of a pan, 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 $NADP^+$ does is simple. $NADP^+$ accepts and holds two 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 carry the high-energy electrons that were produced by light absorption in chlorophyll to chemical reactions elsewhere in the chloroplast. Those high-energy electrons can then be used to help build sugars like glucose from nothing more than carbon dioxide and water.

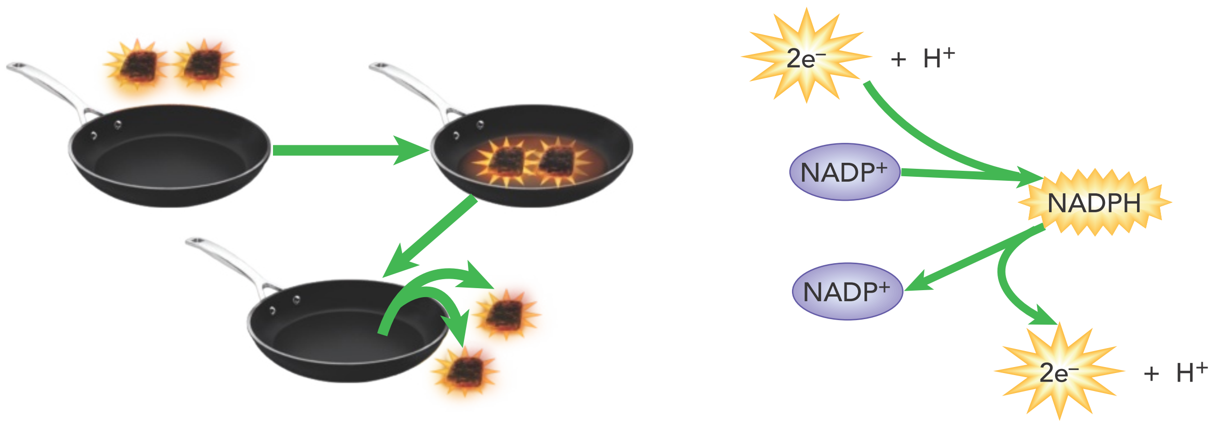
READING CHECK **Define** What is $NADP^+$?

Visual Analogy

Figure 9-5

Carrying Electrons

Like a pan being used to carry hot coals, $NADP^+$ carries pairs of electrons and an H^+ ion from place to place.



CASE STUDY **Develop a Solution Lab** **Open-ended Inquiry**

Plant Pigments and Photosynthesis

Problem Which wavelengths of light support plant growth?

In this lab, you will investigate the wavelengths of light that are used in photosynthesis, and construct an explanation for how light wavelength affects plant growth. You will use *Elodea*, a type of aquatic vegetation, as a test subject.

You can find this lab in your digital course.

An Overview 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 (low-energy reactants) into high-energy sugars and oxygen (products).*** Plants use these 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:

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

READING TOOL

Create a two-column table to describe and compare the light-dependent and light-independent reactions of photosynthesis.

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 take place in thylakoid membranes and use energy from sunlight to add a third phosphate to ADP to make ATP.

The light-dependent reactions also do something truly remarkable, which is to take low-energy electrons from water molecules, and use solar energy to raise them to a much higher energy level. These high-energy electrons are then transferred to the electron carrier, $NADP^+$, which is converted to NADPH as shown in **Figure 9-5**. NADPH is used in other chemical reactions. What happens to water after a pair of electrons is taken away from it? That's pretty remarkable, too. The oxygen atoms left over are released to the atmosphere as the oxygen gas we and all other animals breathe.

INTERACTIVITY

Conduct a virtual experiment to examine how the distance from a light source can affect the rate of photosynthesis.

INTERACTIVITY

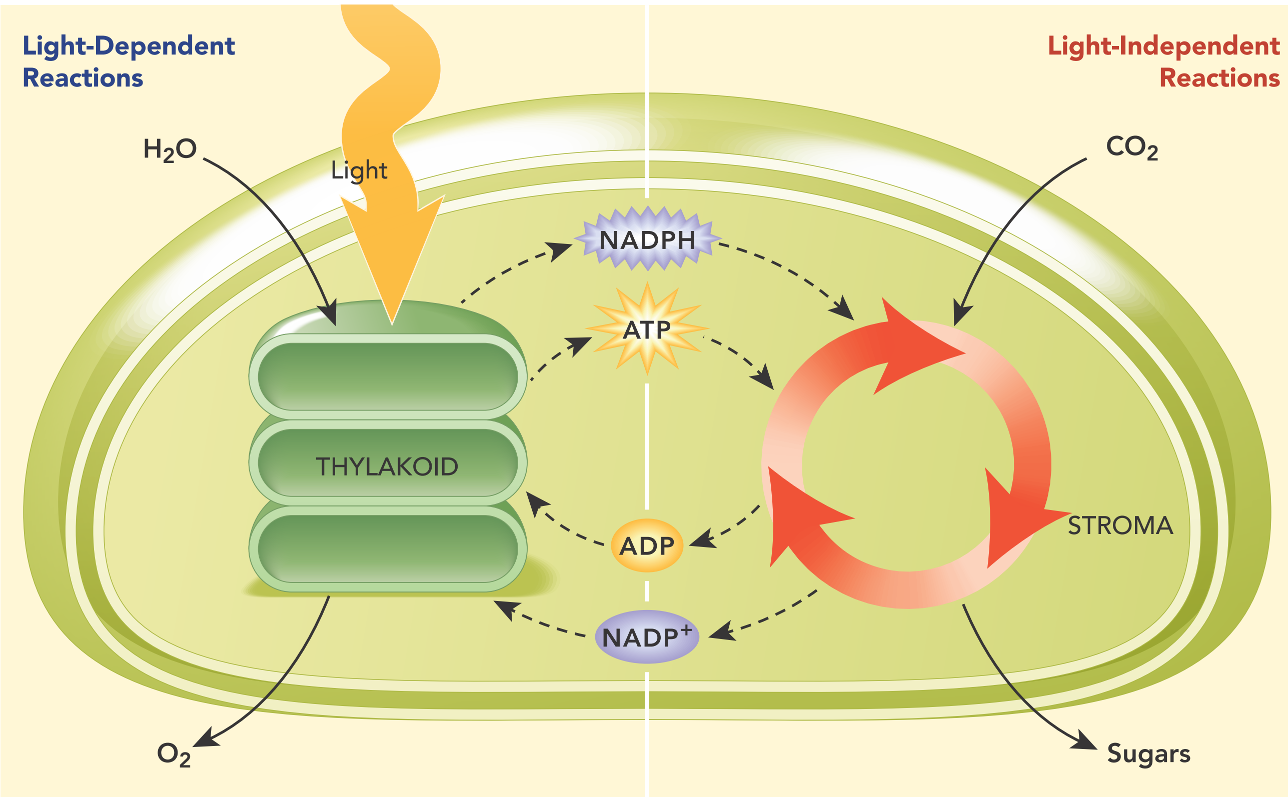
Figure 9-6

Stages of Photosynthesis

There are two stages of photosynthesis: the light-dependent reactions and the light-independent reactions. Light-dependent reactions depend on sunlight, while light-independent reactions may occur in the dark.

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**, the ATP and NADPH molecules produced in the light-dependent reactions are used to build high-energy sugars from carbon dioxide. As the name implies, no light is required to power the light-independent reactions, which take place outside the thylakoids, in the stroma of the chloroplast.

The interdependent relationship between the light-dependent and light-independent reactions is shown in **Figure 9-6**. 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.



HS-LS1-5, HS-LS2-5

LESSON 9.2 Review

KEY IDEAS

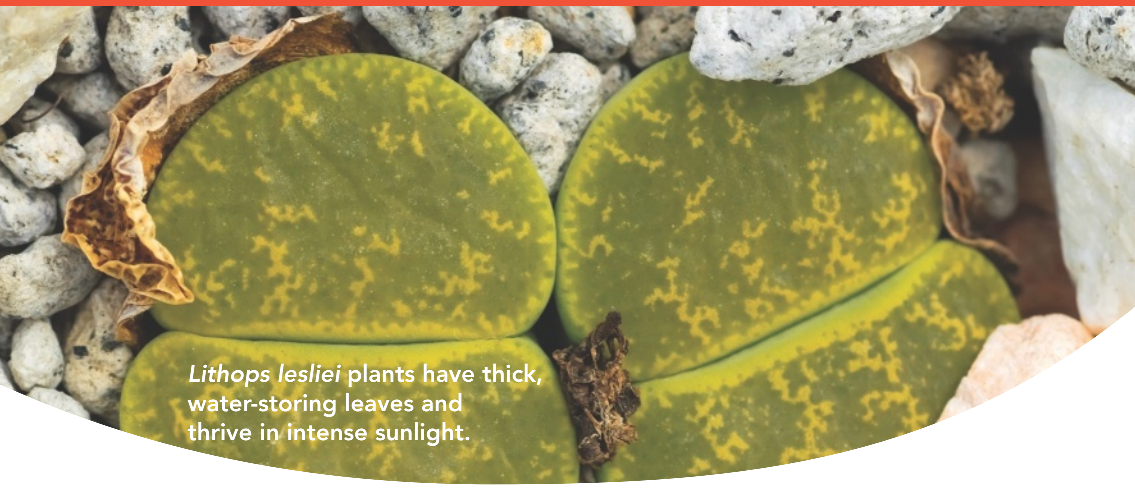
1. What is chlorophyll? What is its role in photosynthesis?
2. $NADP^+$ is an example of an electron carrier. Describe its function in photosynthesis.
3. Identify the reactants, products, and basic functions of photosynthesis.

CRITICAL THINKING

4. **Develop Models** Draw a model to show how the process of photosynthesis impacts both the flow of energy and the cycling of carbon through the atmosphere and biosphere.
5. **Summarize** What roles do ADP and ATP play in the light-dependent and light-independent reactions?
6. **Use Models** Use **Figure 9-6** as a model to describe how the light-dependent and light-independent reactions transform light energy into stored chemical energy.

The Process of Photosynthesis

LESSON 9.3



Lithops lesliei plants have thick, water-storing leaves and thrive in intense sunlight.

KEY QUESTIONS

- *What happens during the light-dependent reactions?*
- *What happens during the light-independent reactions?*
- *What factors affect photosynthesis?*

HS-LS1-5: Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.
HS-LS1-6: Construct and revise an explanation based on evidence for how carbon, hydrogen, and oxygen from sugar molecules may combine with other elements to form amino acids and/or other large carbon-based molecules.
HS-LS2-5: Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

VOCABULARY
photosystem
electron transport chain
ATP synthase
Calvin cycle

READING TOOL

As you read the lesson, complete the main idea table for the primary headings in your **Biology Foundations Workbook.**

Why are chloroplasts so full of membranes? Is there something about the thylakoid membranes in chloroplasts that makes them absolutely essential for the process of photosynthesis? As you'll see, there is. Membranes are barriers, and the thylakoids of chloroplasts keep positive and negative charges generated by light absorption on opposite sides of the membrane. This is the key to how the light-dependent reactions trap the energy of sunlight in chemical form.

The Light-Dependent Reactions: Generating ATP and NADPH

Recall that the process of photosynthesis involves two primary sets of reactions: the light-dependent and the light-independent reactions. The light-dependent reactions include 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 convert ADP and $NADP^+$ into the energy and electron carriers ATP and NADPH. These reactions also produce oxygen (O_2) as a by-product.***

The light-dependent reactions occur in the thylakoids of chloroplasts. Recall that thylakoids are saclike membranes. They contain most of the machinery needed to carry out photosynthesis, including clusters of chlorophyll and proteins known as **photosystems**. These photosystems are surrounded by accessory pigments and 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 membrane. Light absorption by chlorophyll molecules in the photosystems is the beginning of this important process.

Figure 9-7

Changing Colors

The green color of most leaves is caused by the reflection of green light by the pigment chlorophyll. Other pigments are revealed in autumn, when the chlorophyll breaks down.

Photosystem II The light-dependent reactions begin in photosystem II. This first photosystem is called photosystem II simply because it was discovered after photosystem I. As shown in **Figure 9-8,** chlorophyll molecules in photosystem II absorb light. This absorption of light raises electrons in chlorophyll to a higher energy level, and these high-energy electrons (e^-) are passed from chlorophyll 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 pull apart each water molecule into two electrons, two hydrogen ions H^+, and one oxygen atom (O). Because the negatively-charged electrons move to the outside of the membrane while the positively-charged H^+ ions are released inside, a charge separation is built up across the membrane.

These two electrons from water replace the high-energy electrons that chlorophyll lost to the electron transport chain. As electrons are taken from water, oxygen gas (O_2) is left behind and is released into the air. This 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.

BUILD VOCABULARY

Prefixes The words **photosynthesis** and **photosystem**, both contain the prefix *photo-*, which means "light." Light is needed for photosynthesis and the reactions that occur in photosystem II and photosystem I.

Electron Transport Chain What happens to the electrons as they move along the electron transport chain? Energy from the electrons is used by the proteins in the chain to pump still more H^+ ions from the stroma inside the thylakoid sac. 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 these electrons and pass them to other carriers and eventually to the electron carrier $NADP^+$. At the end of a short second electron transport chain, $NADP^+$ in the stroma picks 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.

READING CHECK **Explain** Why do organisms that perform photosynthesis require water and sunlight?

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 space within the thylakoids strongly positive with respect to the stroma on the other surface of the membrane. This gradient, the difference in both charge and H^+ ion concentration across the membrane, provides the energy to make ATP.

H^+ ions cannot cross the membrane directly. However, the thylakoid membrane contains a protein complex called **ATP synthase** that spans the membrane and allows H^+ ions to pass through it. Powered by the H^+ concentration difference, 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 enables light-dependent electron transport to synthesize not only NADPH (at the end of the electron transport chain), but ATP as well.

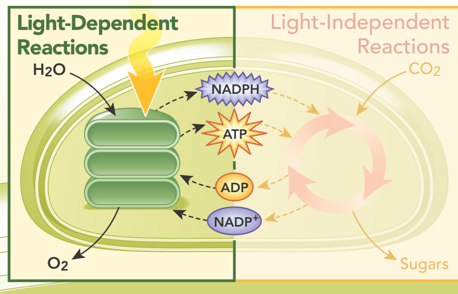
ANIMATION

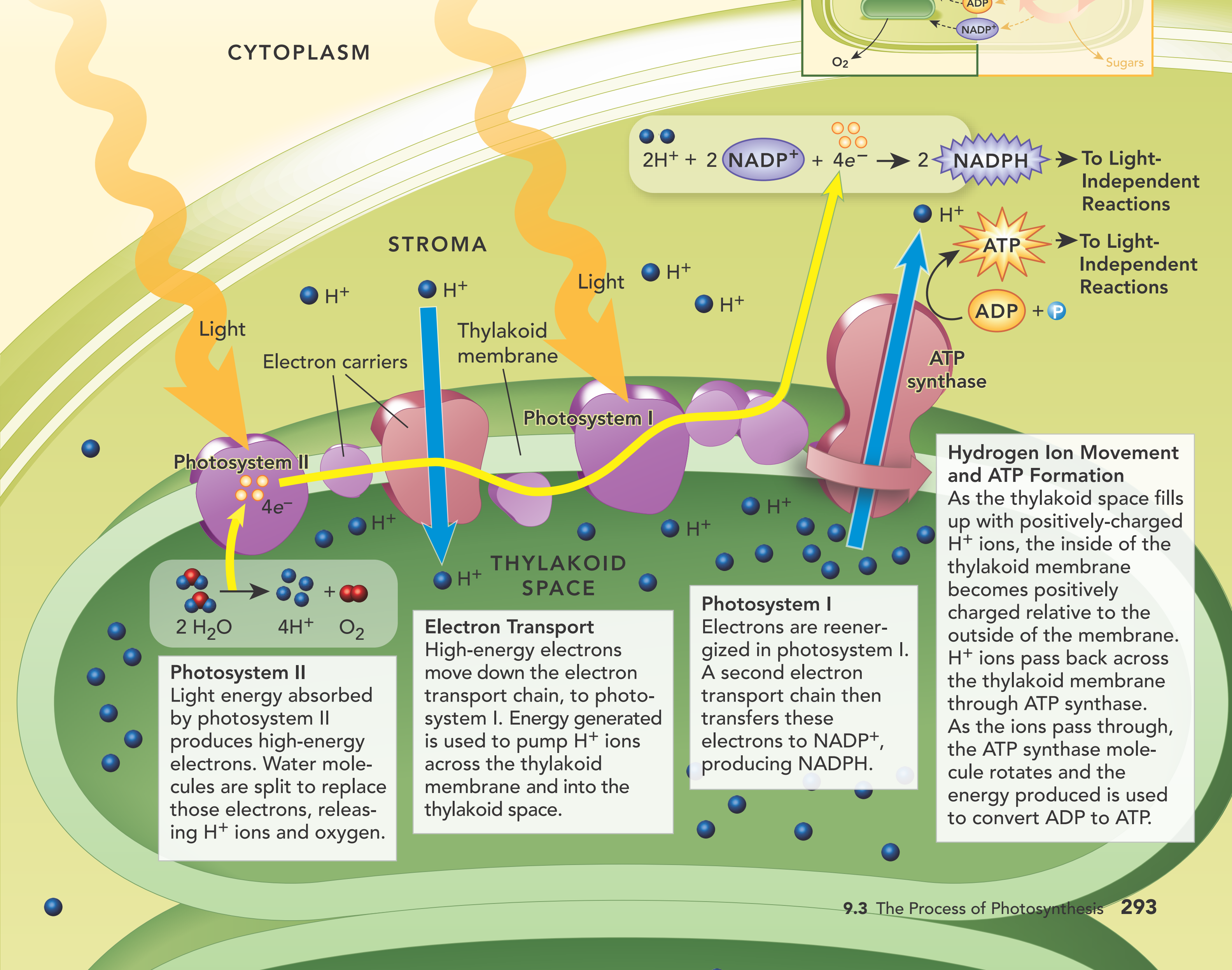
Up Close

Figure 9-8

The Light-Dependent Reactions

The light-dependent reactions occur inside the thylakoids of a chloroplast. They use energy from sunlight to produce ATP and NADPH. Oxygen is released in the process.





Summary of Light-Dependent Reactions The light-dependent reactions of photosythesis use light energy and water to produce oxygen gas and convert ADP and $NADP^+$ into the energy carriers ATP and NADPH. What good are these compounds? As you 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.

READING CHECK **Describe** What is the role of ATP synthase in photosynthesis?

READING TOOL

Draw a flowchart to show the sequence of events in the Calvin cycle. Be sure to include the inputs and outputs into the cycle.

The Light-Independent Reactions: Producing Sugars

The ATP and NADPH formed by the light-dependent reactions contain plenty of chemical energy, but they are not stable enough to store that energy for more than a few minutes. ***During the light-independent reactions, ATP and NADPH from the light-dependent reactions are used to synthesize high-energy sugars.*** The light-independent reactions are commonly referred to as the **Calvin Cycle**. The Calvin cycle is named after the American scientist Melvin Calvin, who worked out the details of this remarkable cycle. Follow **Figure 9-9** to see each step in this set of reactions.

Carbon Dioxide Enters the Cycle Carbon dioxide molecules (CO_2) enter the Calvin cycle from the atmosphere. An enzyme in the stroma of the chloroplast combines these carbon dioxide molecules with 5-carbon compounds already present in the organelle, producing 3-carbon compounds that continue into the cycle. For every six 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.

INTERACTIVITY

Explore more details of the light-dependent and light-independent reactions to gain a deeper understanding of photosynthesis.

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 synthesize 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. As the cycle continues, more and more carbon dioxide is removed from the air and converted into the compounds the plant needs for growth and development.

Summary of the Calvin Cycle The Calvin cycle uses six molecules of carbon dioxide to produce a single 6-carbon sugar molecule. The energy for the reactions is supplied by compounds produced in the light-dependent reactions. As photosynthesis proceeds, the Calvin cycle removes carbon dioxide from the atmosphere and turns out energy-rich sugars. The plant uses the sugars to meet its energy needs and to synthesize 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.

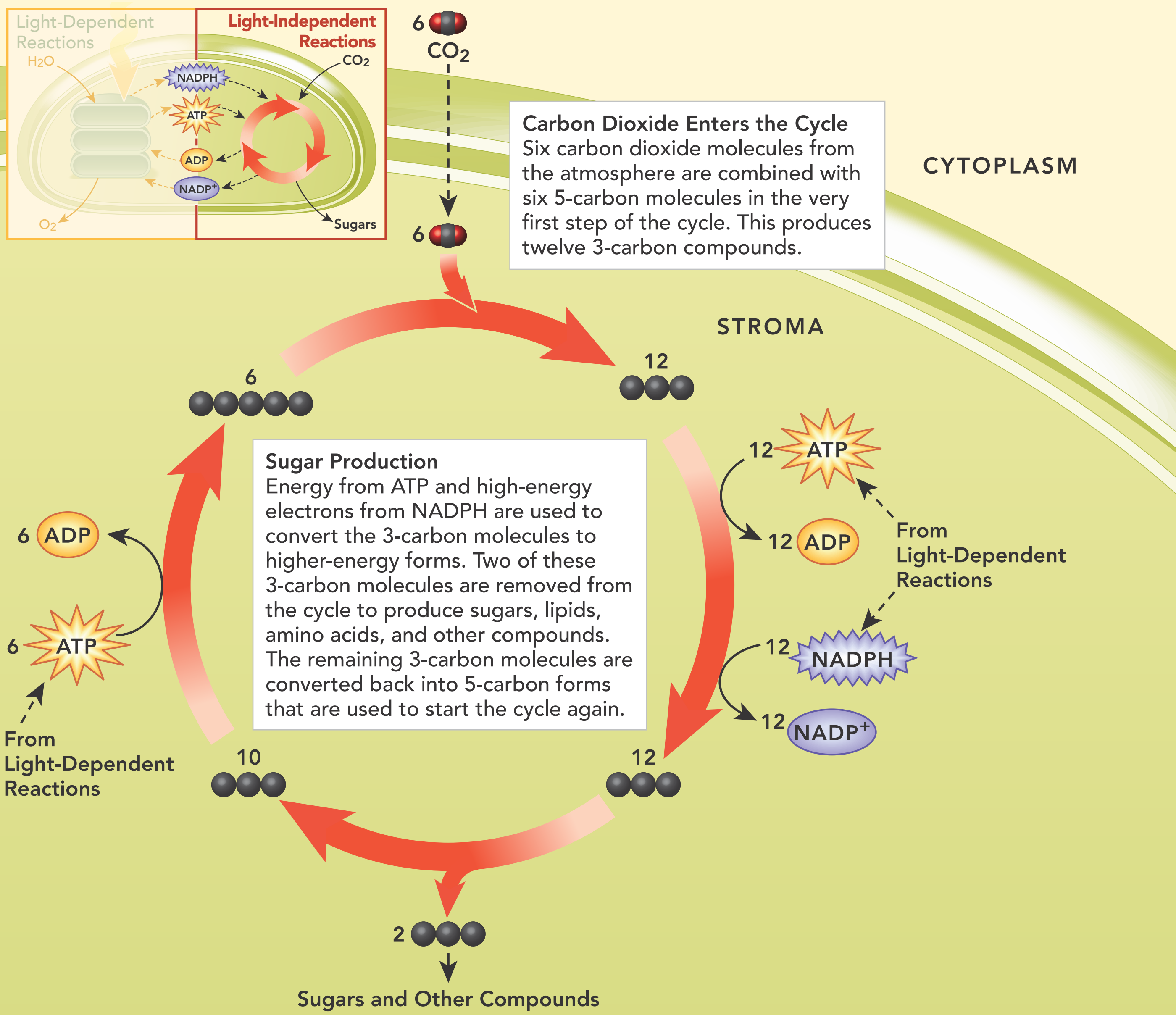
The End Results The two sets of photosynthetic reactions work together—the light-dependent reactions trap the energy of sunlight in chemical form, and the light-independent reactions use that chemical energy to synthesize stable, high-energy sugars from carbon dioxide and water. In the process, animals, including ourselves, get plenty of food and an atmosphere filled with oxygen. Not a bad deal at all!

Up Close

Figure 9-9

The Light-Independent Reactions

The light-independent reactions occur in the stroma of the chloroplast, which is the region outside the thylakoids. ATP and NADPH from the light-dependent reactions provide the energy for glucose to be assembled. **Interpret Visuals** How many molecules of ATP are needed for each "turn" of the Calvin cycle?



Carbon Dioxide Enters the Cycle
Six carbon dioxide molecules from the atmosphere are combined with six 5-carbon molecules in the very first step of the cycle. This produces twelve 3-carbon compounds.

Sugar Production
Energy from ATP and high-energy electrons from NADPH are used to convert the 3-carbon molecules to higher-energy forms. Two of these 3-carbon molecules are removed from the cycle to produce sugars, lipids, amino acids, and other compounds. The remaining 3-carbon molecules are converted back into 5-carbon forms that are used to start the cycle again.

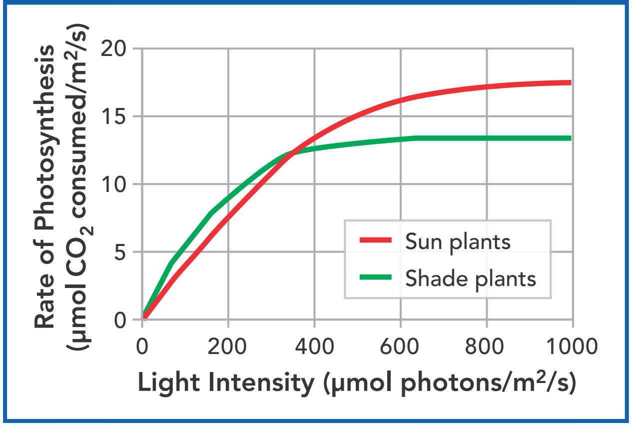
Analyzing Data

Rates of Photosynthesis

Different plants perform photosynthesis at different rates. The rates may change in response to several factors, including temperature, available water, and light intensity. The graph shows how the rates of photosynthesis vary with light intensity for two groups of plants: plants that thrive in direct sunlight, and plants that thrive in the shade.

1. **Analyze 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. **Analyze Data** Light intensity in the Sonoran Desert averages about 400 μmol photons/m^2/s. What is the approximate rate of photosynthesis for sun plants that grow in this environment?

Rates of Photosynthesis



3. **Draw Conclusions** As the rate of photosynthesis increases, what do you think happens to the rate at which sugars are produced by the plant?

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.

CASE STUDY

INTERACTIVITY

Investigate how photosynthesis could be used to generate electricity.

Factors Affecting Photosynthesis

Many factors affect the rate of chemical reactions, including those that occur during photosynthesis.

Temperature, Light, and Water

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.

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 closure keeps the plants from drying out, it also 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 Plants C4 plants have a specialized chemical pathway that allows them to capture 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 four carbon atoms instead of three. 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 in which carbon dioxide becomes incorporated into organic acids during photosynthesis. The process is called Crassulacean Acid Metabolism (CAM) because it was first observed in members of the family Crassulacaea. 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 inside the leaf, enabling carbohydrate production. CAM plants include pineapple, many desert cacti, and the fleshy "ice plant" shown in **Figure 9-10**. Ice plants are often planted near freeways along the California coast to lessen brush fires and prevent erosion.

Figure 9-10
CAM Plants

This ice plant is an example of a CAM plant. It survives in very dry conditions because air enters its leaves only at night, minimizing water loss.

HS-LS1-5, HS-LS1-6, HS-LS2-5

LESSON 9.3 Review

KEY IDEAS

1. Describe three chemical changes that occur during the light-dependent reactions.
2. What do plants do with the high-energy sugar molecules they produce during the Calvin cycle?
3. Assuming there is enough light and water for photosynthesis to occur, explain why a temperature between 0°C and 35°C is still important.

CRITICAL THINKING

4. **Develop Models** Draw a model that shows how the six carbon atoms that enter the Calvin cycle as carbon dioxide flow through the cycle.
5. **Construct an Explanation** In a laboratory experiment, a plant receives sunlight and water, but not carbon dioxide. Predict what happens to the plant and construct an explanation for your prediction using what you know about the light-dependent and light-independent reactions.
6. **Plan an Investigation** How would you investigate the effect of temperature on photosynthesis? Outline the steps of a practical investigation.
7. **Develop Models** Draw a model to illustrate how high-energy sugar molecules produced during the Calvin cycle move through the carbon cycle.

CASE STUDY WRAP-UP

What would it take to make an artificial leaf?

Scientists have used their knowledge of photosynthesis to make an artificial leaf. The next step is to improve artificial leaves and develop practical, cost-efficient ways of using the technology.

HS-LS1-5, HS-ETS1-1, HS-ESS3-4

Make Your Case

Scientists are developing a variety of new technologies for artificial leaves. None of them involve duplicating all of the steps and reactions of photosynthesis. However, these artificial leaves are able to use sunlight to assemble energy-rich molecules, such as hydrogen (H_2) and methane (CH_4). Research the latest developments in this technology, as well as the potential benefits and drawbacks.

Evaluate a Solution

1. **Define the Problem** What problems could an artificial leaf help solve?
2. **Identify Constraints** How well do you think an artificial leaf could solve one or more of the problems you identified? Describe the costs, constraints, and reliability of the solution, as well as its impact on the environment.

Daniel Nocera

Technology on the Case

Chemistry and the Leaf

A leaf is like a miniature chemistry factory. The raw materials are water, carbon dioxide, and sunlight, and the products are glucose and oxygen. To develop a useful artificial leaf, chemist Daniel Nocera adapted a well-known chemical process that also involves an energy input. The process is called electrolysis. Two electrodes are placed in water, and a strong electric current is passed through them. The electricity pulls the water molecules apart. Oxygen gas (O_2) bubbles out at the positive electrode, and hydrogen gas (H_2) bubbles out at the negative electrode.

In Nocera's artificial leaf, light energy powers electrolysis inside a thin wafer. The device uses the energy to distribute positive and negative charges to opposite sides of the wafer. On each surface, catalysts make use of the charge separation to split water molecules. This releases a stream of tiny bubbles, some of which contain hydrogen gas and some oxygen. Hydrogen gas can be compressed and used as a fuel to power engines and other devices.

More recently, Nocera and other researchers have taken their invention a step further. They have paired their original artificial leaves with bacteria that absorb the hydrogen molecules. The bacteria combine the hydrogen with carbon dioxide from the atmosphere. The products are alcohols that can be burned as fuels.

Careers on the Case

Work Toward a Solution

Applying chemical processes in nature to develop new technologies requires efforts from many professionals, including chemical engineers.

Chemical Engineer

After a new chemical process has been developed in the laboratory, chemical engineers research ways to adapt the process for large-scale production. The result of their efforts may be a new medicine, or food, or a new kind of plastic or some other material. Sometimes, their work allows an existing product to be produced much more easily—and at a lower cost.

VIDEO

Watch this video to learn about other careers in biology.

Lesson Review

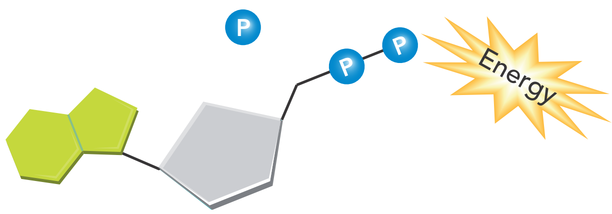
Go to your Biology Foundations Workbook for longer versions of these lesson summaries.

9.1 Energy and Life

All living things need energy to stay alive and carry out their life processes. Cells can store energy in the bonds of chemical compounds. One of the most important of these compounds is ATP (adenosine triphosphate). A cell can store a small amount of energy by adding a phosphate group to ADP to make ATP. When a cell needs energy, it can release it by breaking the chemical bond between the second and third phosphate groups of ATP.

Most life on Earth depends on the ability of autotrophs (plants and algae) to capture the energy from sunlight and convert it into the chemical energy stored in carbohydrates. This process is known as photosynthesis.

- ATP
- photosynthesis



Use An Analogy Describe how ADP and ATP act like a rechargeable battery to store and release energy.

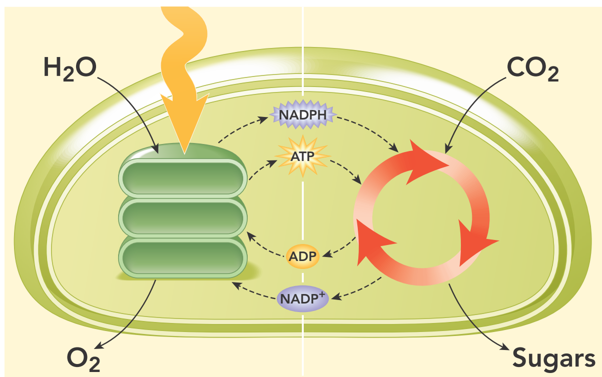
9.2 Photosynthesis: An Overview

Nearly every living thing on Earth depends on photosynthesis. Photosynthetic organisms capture energy from sunlight with pigments.

Plant cells use compounds called electron carriers to accept and transfer pairs of high-energy electrons from the chlorophyll to other molecules. One of these carrier compounds is $NADP^+$ (nicotinamide adenine dinucleotide phosphate).

Photosynthesis uses light energy to convert water and carbon dioxide into high-energy sugars and oxygen. Photosynthesis involves two sets of reactions: light-dependent and light-independent. The light-dependent reactions take place in the thylakoid membranes. The light-independent reactions take place in the stroma.

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



Interpret Diagrams Label each side of the diagram. Then, write a caption to describe each process.

9.3 The Process of Photosynthesis

The light-dependent reactions of photosynthesis use light energy to produce oxygen and convert ADP and $NADP^+$ into ATP and NADPH.

The light-independent reactions of photosynthesis are also known as the Calvin cycle. The Calvin cycle uses the ATP and NADPH synthesized during the light-dependent reactions and carbon dioxide to make high-energy sugars.

Although many factors affect the rate of photosynthesis, the most important are temperature, light intensity, and the availability of water.

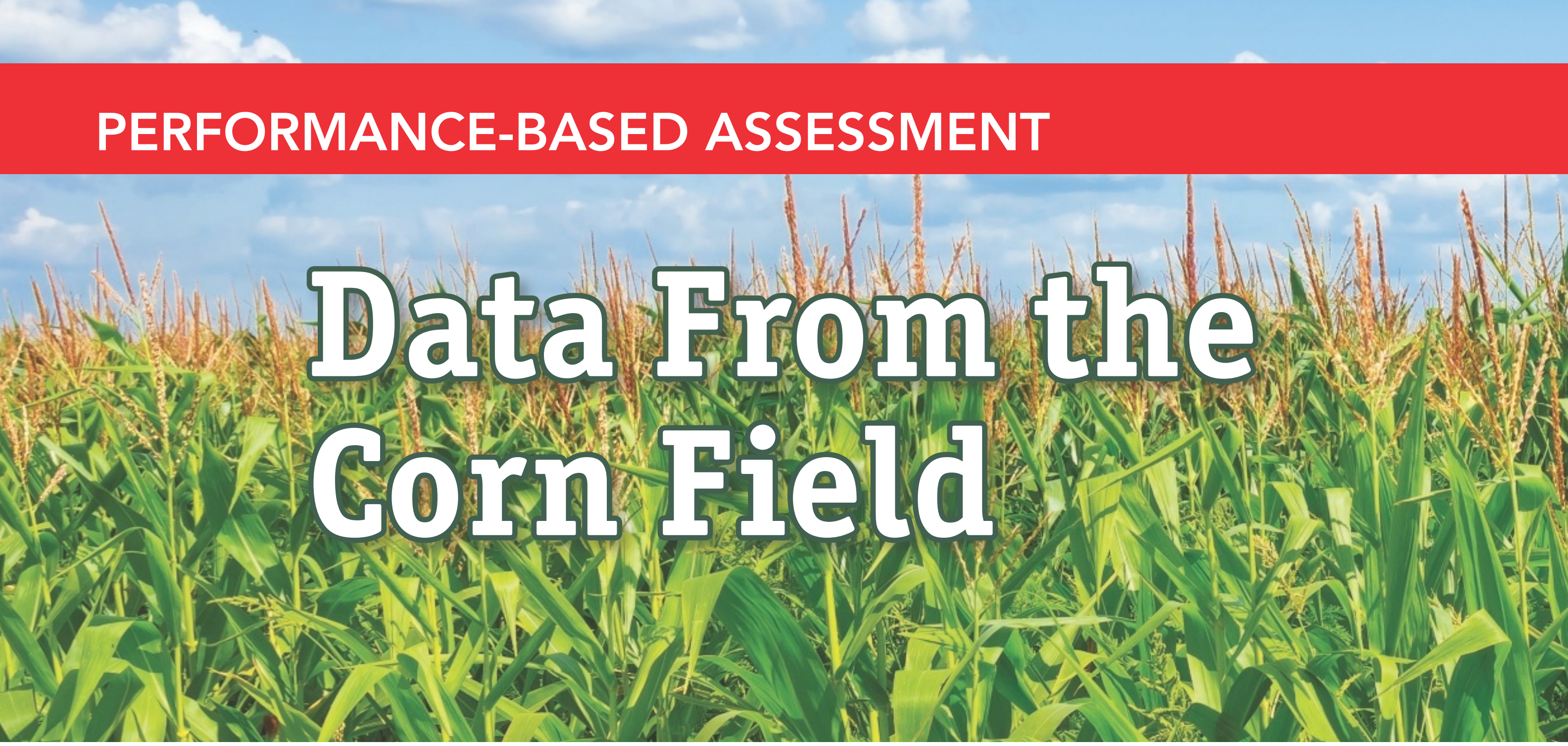
- photosystem
- electron transport chain
- ATP synthase
- Calvin cycle

Apply Concepts Explain why temperature, light intensity, and water availability affect the rate of photosynthesis.

Organize Information

Complete the table to summarize the processes described in this chapter.

Process	Occurs in	Inputs	Outputs
1.	2.	CO_2, H_2O, sunlight	O_2, high-energy sugars
Calvin cycle	3.	NADPH, ATP, CO_2	6-carbon sugar, ADP, $NADP^+$
4.	thylakoids	5.	NADPH, ATP, O_2
Electron transport chain	6.	7.	low-energy electrons, energy to pump H^+ ions from the stroma inside the thylakoid sac
	Photosystem II	8.	9.
	Photosystem I	10.	11.
	ATP synthase	12.	13.



PERFORMANCE-BASED ASSESSMENT

Data From the Corn Field

Design a Solution

HS-LS1-5, HS-LS1-6, HS-LS2-4, HS-LS2-5, CCSS.ELA-LITERACY.RST.9-10.1, CCSS.ELA-LITERACY.WHST.9-10.1, CCSS.ELA-LITERACY.WHST.9-10.7, CCSS.MATH.CONTENT.HSN.Q.A.1, CCSS.MATH.CONTENT.HSS.IC.B.6

Matter is constantly moving in and out of the biosphere, which is the part of Earth in which all life exists. For example, consider the gain in mass that might be shown by a typical field of corn in the American Midwest.

On a warm morning in late spring, a farmer plants his fields with row after row of corn seeds. After a week or so, tiny seedlings begin poking out of the ground. Then the seedlings grow taller. Over the next few weeks they develop new roots and leaves, and then corn ears. After only three or four months, the fields are covered in tall, green corn plants, the ears ready to harvest. This process and these changes are repeated year after year across the United States, especially in a band of land that stretches from Ohio to Nebraska.

A typical acre can yield more than 3800 kilograms of corn. This yield includes only the corn itself. More than half the mass of the corn plant is not harvested, but is plowed under to enrich the soil for the next growing season. What is the source of the mass of these plants? It cannot be the soil. The soil remains thick and fertile year after year. Water is part of the source of the mass, but not all of it. Only about one fourth of the mass of a corn plant is water. A corn plant is about 40 percent carbon by mass. Where does all that carbon come from?

SCIENCE PROJECT

The table describes the significant inputs and outputs of a one-acre corn field. The inputs are things that are added to the field, either by the farmer or naturally. The outputs are the products that the field produces.

Typical Inputs and Outputs of a One-Acre Corn Field

Component	Role	Weight
Corn	Output	3800 kg (8400 lb)
Seeds	Input	5 kg (11 lb)
Fertilizer	Input	23 kg (50 lb)
Water (56 cm of rain)	Input	2.3 million kg (5 million lb)

1. **Construct an Explanation** What are the sources of the mass of corn plants? How does photosynthesis contribute to the mass of corn plants?
2. **Calculate** Use the data provided to calculate, as precisely as you can, the amount of carbon dioxide removed from the atmosphere by one acre of corn.
3. **Design a Solution** Is it reasonable to expect that Earth's plants can take up the extra carbon that human activities are adding to the atmosphere? Would some plants be better than others?
   - Research the productivity of different types of plants, including agricultural crops as well as forests. Include plants from different climates. You also may wish to research carbon sequestration in soil.
   - Identify other criteria that should be considered—for example, uses of the plants, water consumption, and cold hardiness.
   - Choose 2–3 plants that could be the most effective at removing carbon from the atmosphere. Write a proposal, citing evidence from your research. Include a model of how your solution depends on plants, photosynthesis, and the carbon cycle.

ASSESSMENT

KEY QUESTIONS AND TERMS

9.1 Energy and Life

HS-LS1-5, HS-LS2-3

1. Energy is defined as the ability to
a. communicate.
b. reproduce.
c. grow.
d. do work.

2. Which of the following is NOT a form of energy?
a. light
b. oxygen
c. heat
d. electricity

3. Which of the following is used by cells to store and release the energy needed to power cellular processes?
a. ATP.
b. RNA.
c. DNA.
d. $NADP^+$.

4. How do heterotrophs and autotrophs differ in the way they obtain energy?

5. Compare the amounts of energy stored by ATP and glucose. Which compound is used by a cell as an immediate source of energy?

6. Describe how ATP can release and store energy for the cell.

7. How do plants synthesize high-energy carbohydrates?

9.2 Photosynthesis: An Overview

HS-LS1-5, HS-LS2-5

8. Plants use the green pigment chlorophyll to
a. absorb sunlight.
b. store sunlight.
c. reflect sunlight.
d. change light to heat.

9. High-energy electrons are transported from chlorophyll to other molecules in the chloroplast by
a. the thylakoid membranes.
b. pigments such as carotene.
c. electron carriers such as $NADP^+$.
d. the protein ATP synthase.

10. Identify and describe the two main parts of a chloroplast where photosynthesis occurs.

11. Write the basic equation for photosynthesis using the names of the starting and final substances of the process.

9.3 The Process of Photosynthesis

HS-LS1-5, HS-LS1-6, HS-LS2-5

12. The clusters of chlorophyll and proteins that absorb sunlight and generate high-energy electrons in the chloroplasts are called
a. carrier proteins.
b. transport chains.
c. photosystems.
d. synthase proteins.

13. In photosystem II, as high-energy electrons are passed to the electron transport chain, the chlorophyll gains new electrons from
a. oxygen atoms.
b. water molecules.
c. hydrogen ions.
d. carbon dioxide.

14. The light-independent reactions of photosynthesis are also known as the
a. Calvin cycle.
b. sugar cycle.
c. carbon cycle.
d. ATP cycle.

15. What is the function of the electrons as they move along the electron transport chain?

16. What occurs as H^+ ions pass through ATP synthase in the thylakoid membrane, and what is this process called?

17. Why is it important that carbon dioxide molecules from the atmosphere enter the Calvin cycle?

18. Name three important factors that can affect the rate of photosynthesis.

19. Crabgrass is an example of a C4 plant. In addition to biochemical adaptations seen in C4 and CAM plants, what is another way that plants can protect themselves from dry, hot conditions?

20. How does a cow use the sugar molecules stored in the grass it eats?

21. Discuss three factors that affect the rate at which photosynthesis occurs.

CRITICAL THINKING

HS-LS1-5, HS-LS1-6, HS-LS2-5

22. **Use Models** Photosynthesis usually produces glucose ($C_6H_{12}O_6$) as a final product. What are the sources of the carbon atoms and hydrogen atoms in glucose? Use a symbolic equation as a model to support your explanation.

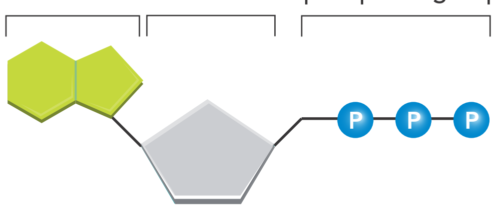
23. **Develop Models** Draw a diagram to use as a model of photosynthesis. The model should show the flow of matter and the transformation of light energy into chemical energy.

24. **Summarize** Explain the role of $NADP^+$ as an energy carrier in photosynthesis.

25. **Analyze Text Structure** Using the text from this chapter, analyze the relationships among the key terms *ATP, NADP+*, and *ATP synthase*.

26. **Construct an Explanation** How does photosynthesis benefit both the organism that undergoes it and many other organisms? Include in your explanation how carbon, hydrogen, and oxygen atoms from the reactants of photosynthesis recombine to form compounds that are useful to the organisms.

27. **Use Models** The diagram shows a model of ATP. How would you revise the diagram to illustrate how ATP provides energy for the cell?



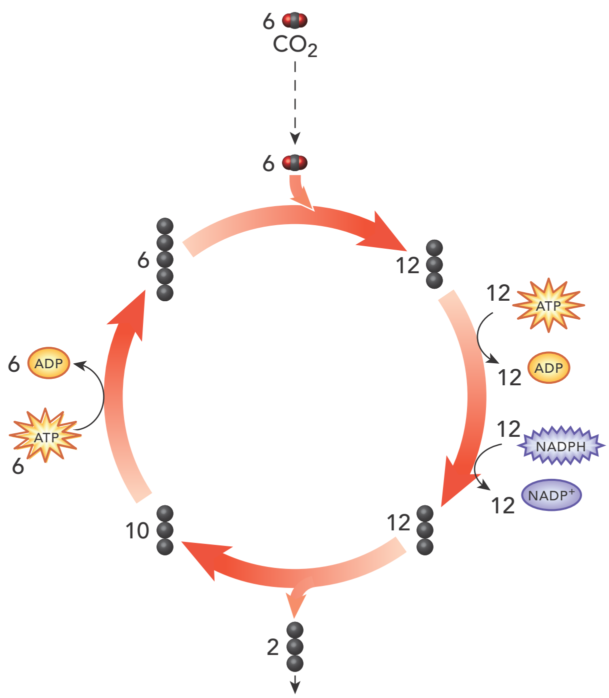
28. **Defend Your Claim** Could heterotrophs survive without autotrophs? Could autotrophs survive without heterotrophs? Make a claim, and then cite evidence from the text and use logical reasoning to defend it.

29. **Ask Questions** You are observing a species of single-celled algae in a well-lit aquarium. What questions could you ask, and then investigate, to help explain the role of photosynthesis in the algae?

30. **Evaluate** A student plans to isolate chlorophyll, mix it in a solution of carbon dioxide and water, and then shine light on the mixture. Do you predict glucose will be produced inside the mixture? Evaluate this investigation and explain your reasoning.

31. **Construct an Explanation** During photosynthesis, water molecules (H_2O) split to produce H^+ ions. Use this information, and what you know about the reactions involved in photosynthesis, to explain why water is necessary for photosynthesis to occur.

32. **Energy and Matter** Review the diagram that summarizes the light-independent reactions (Calvin cycle) shown.
    - **a.** Why are the light-independent reactions shown as a cycle? What are the inputs and outputs of the cycle?
    - **b.** How many carbon atoms enter the Calvin cycle to produce one molecule of glucose? What is the source of these carbon atoms?
    - **c.** Why do the light-independent reactions depend on the light-dependent reactions?



ASSESSMENT

CROSSCUTTING CONCEPTS

33. **Systems and System Models** A student uses a marble track, like the one shown below, as a model to demonstrate part of the process of photosynthesis. The marbles represent electrons. What process of photosynthesis does the model demonstrate? Describe a way that the model could be improved.

34. **Energy and Matter** Explain how the process of photosynthesis can be used as evidence that energy flows through an ecosystem while matter cycles through an ecosystem.

MATH CONNECTIONS

Analyze and Interpret Data

CCSS.MATH.CONTENT.MP2, CCSS.MATH.CONTENT.HSF.BF.A.1, CCSS.MATH.CONTENT.HSS.ID.A.1

Consider the chemical equation that describes the flow of matter in the process of photosynthesis. Use the equation to answer questions 35–37.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

35. **Draw Conclusions** What is the source of the hydrogen atoms in glucose ($C_6H_{12}O_6$), one of the products of the reaction?

36. **Infer** When a carbon dioxide molecule (CO_2) enters the reaction, do all three of its atoms become part of a glucose molecule ($C_6H_{12}O_6$)? Explain your reasoning.

37. **Reason Quantitatively** Over time, a leaf converts 264 grams of carbon dioxide into 180 grams of glucose. How do you account for the difference in mass of 84 grams?

An aquatic plant emits bubbles of oxygen when placed under a bright light. The table shows the results of an experiment to show the effect of light intensity on bubble production. Use the data in the table to answer questions 38–40.

Oxygen Production

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

38. **Create an Equation** Write a linear equation that fits the data approximately. To determine the equation, plot the points and draw a line that passes near the points.

39. **Interpret Graphs** Describe the trend in the data. Use the linear equation you constructed to predict the number of bubbles that would appear when the light source is 5, 25, and 50 cm away.

40. **Draw Conclusions** What conclusion about photosynthesis is supported by the evidence from this experiment? Explain your reasoning.

LANGUAGE ARTS CONNECTIONS

Write About Science

HS-LS1-5, CCSS.ELA-LITERACY.WHST.9-10.2

41. **Write Informative Texts** Write a paragraph that describes how the light-dependent and light-independent reactions work together to perform photosynthesis.

42. **Write Explanatory Texts** Write a paragraph that explains how the flow of matter and energy into a cell results in the transfer from light energy to stored chemical energy in photosynthesis.

Read About Science

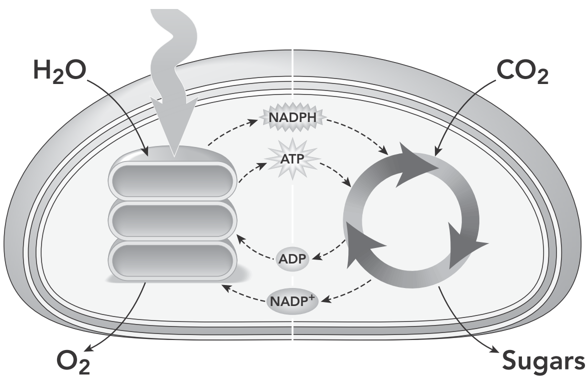
CCSS.ELA-LITERACY.RST.9-10.5

43. **Analyze Text Structure** Explain the relationship among these parts or systems of photosynthesis: photosystem I, photosystem II, ATP, $NADP^+$, light-dependent reactions, and light-independent reactions. Use the organization and headings of Lesson 9.2 to help you construct your response.

END-OF-COURSE TEST PRACTICE

1. A student is making a model to illustrate the functions of ADP and ATP in photosynthesis. Which model best illustrates the role of ATP in photosynthesis?
A. A power plant that generates energy
B. A rechargeable battery that stores and releases energy
C. A pigment that receives the energy of sunlight
D. A pan that carries coal
E. A hammer that helps break apart water molecules

Questions 2 and 3.
The diagram is a model of the process of photosynthesis.



2. During photosynthesis, how is the light energy that strikes the cell transformed into the chemical energy stored in sugars?
A. Energy is transferred directly to sugars, with no intermediates.
B. Energy is transferred to sugars through intermediates such as H_2O, O_2, and CO_2.
C. Energy is transferred to sugars through intermediates, such as ATP and NADPH.
D. Energy is transferred to sugars through intermediates, such as chloroplasts.
E. Energy is transferred to sugars through light-dependent reactions.

3. Which statement accurately describes the role of the light-independent reactions?
A. Transforming light energy into chemical energy
B. Transferring chemical energy to high-energy sugars
C. Returning chemical energy to light energy
D. Transferring light energy among different compounds
E. Performing chemical reactions without an energy source

4. Which of the following describe the role of photosynthesis in the carbon cycle?
A. Storage of carbon in the atmosphere
B. Storage of carbon in the geosphere
C. Transfer of carbon from the hydrosphere to the atmosphere
D. Transfer of carbon from the atmosphere to the hydrosphere
E. Transfer of carbon from the atmosphere to the biosphere

5. Plants use the sugars produced by photosynthesis to synthesize which of the following types of macromolecules?
I. complex carbohydrates
II. amino acids
III. lipids
A. I only
B. II only
C. III only
D. I and II only
E. I, II, and III

ASSESSMENT

For additional assessment practice, go online to access your digital course.

If You Have Trouble With...					
Question	1	2	3	4	5
See Lesson	9.1	9.2	9.3	9.2	9.3
Performance Expectation	HS-LS1-5	HS-LS1-5	HS-LS1-5	HS-LS2-5	HS-LS1-6