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.

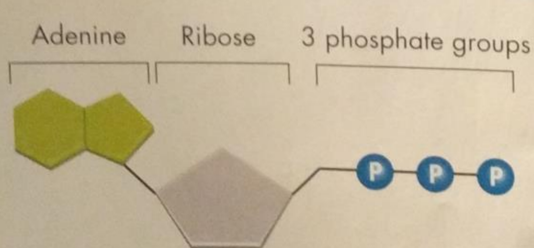


FIGURE 8–1 ATP ATP is the basic energy source used by all types of cells.

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!

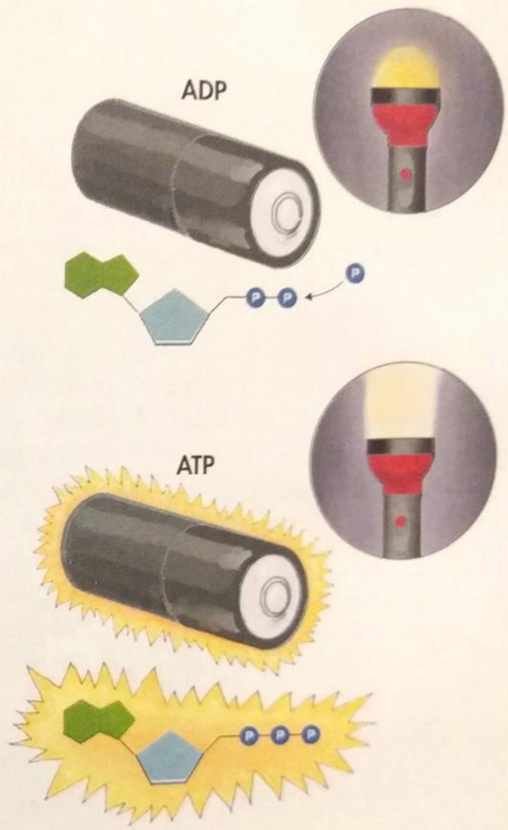
ATP is such a useful source of energy that you might think cells would be packed with ATP to get them through the day—but this is not the case. In fact, most cells have only a small amount of ATP—enough to last for a few seconds of activity. Why? Even though ATP is a great molecule for transferring energy, 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 absorbing nutrients from decomposing organisms in the environment.

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. Cheetahs, in turn, get their energy by eating other organisms that eat the grass.

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.

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.

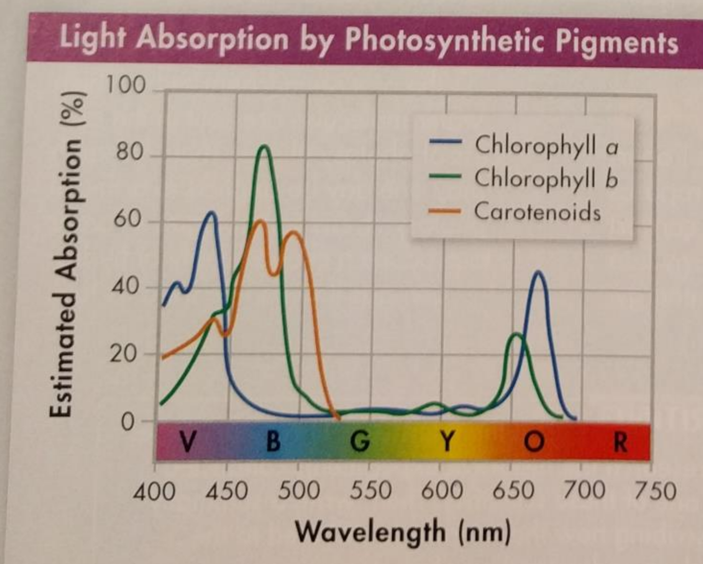
Chlorophyll and Chloroplasts

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.**

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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.**

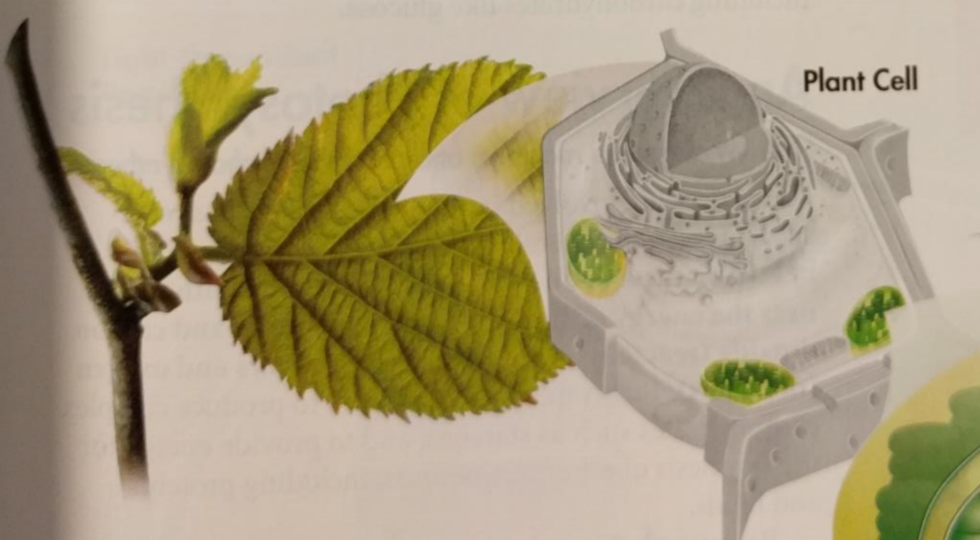
Energy Collection What's so special about chlorophyll that makes it important for photosynthesis? Because light is a form of energy, any compound that absorbs light absorbs energy. Chlorophyll absorbs visible light especially well. In addition, when chlorophyll absorbs light, a large fraction of that 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.

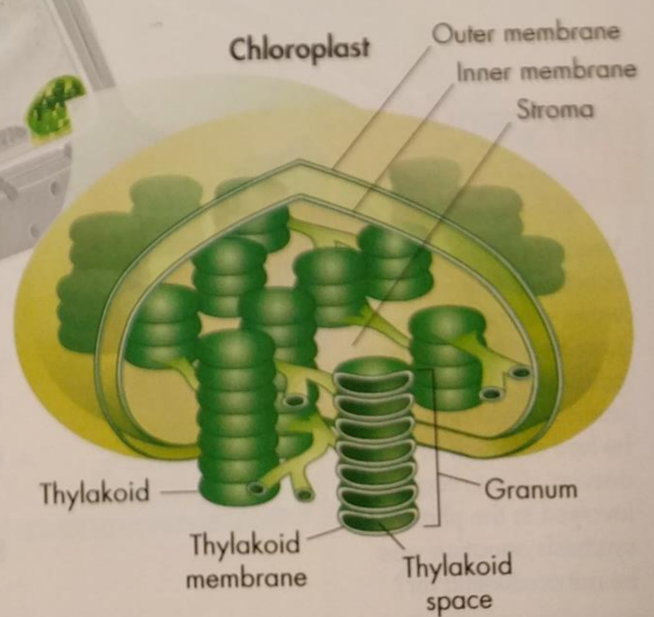
In Your Notebook *In your own words, explain why most plants will not grow well if kept under green light.*

ZOOMING IN

THE CHLOROPLAST

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

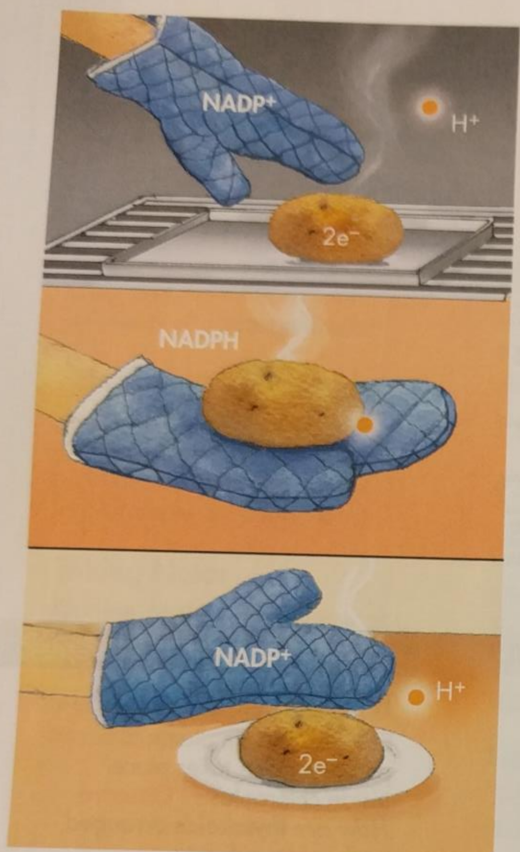




VISUAL ANALOGY

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.

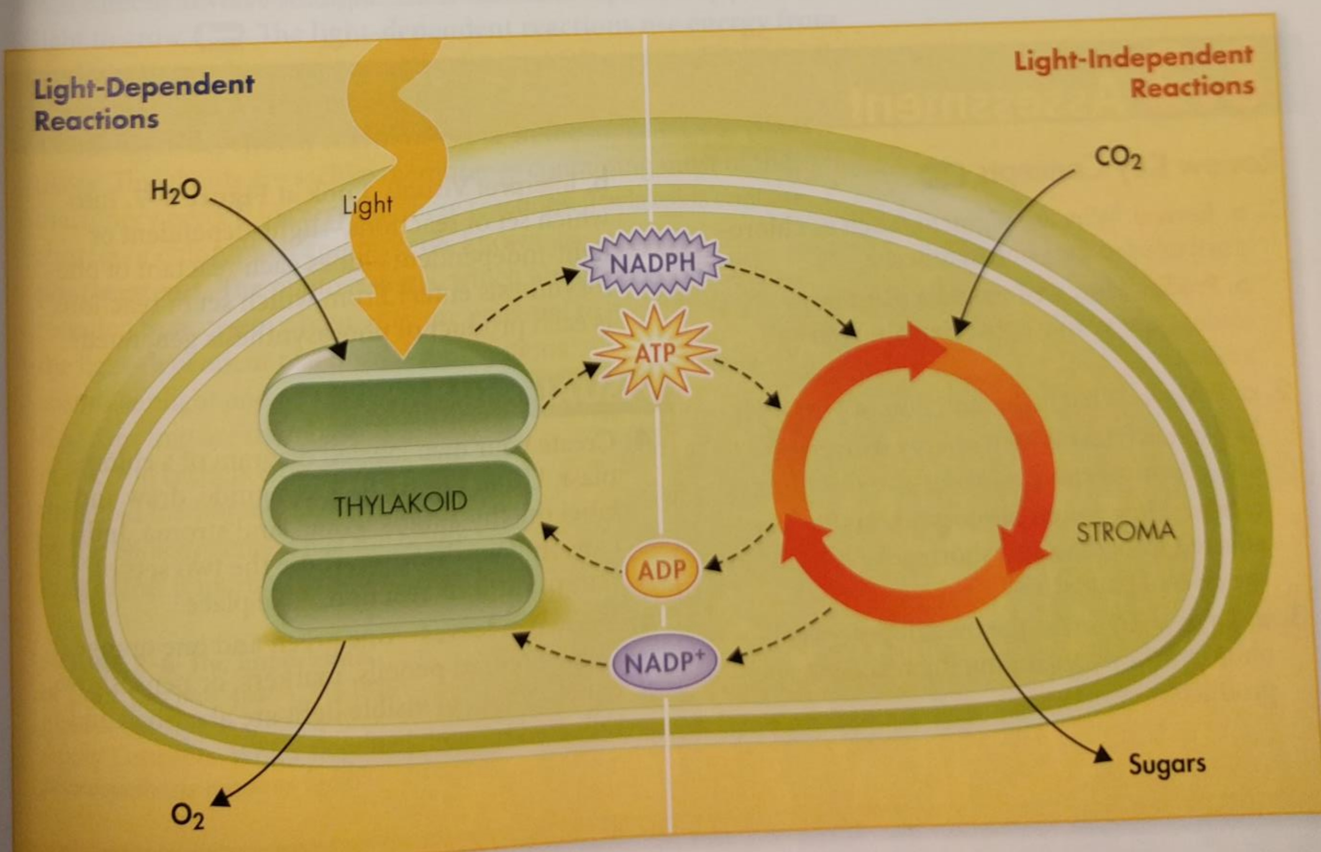
The interdependent relationship between the light-dependent and light-independent reactions is shown in **Figure 8–7.** As you can see, the two sets of reactions work together to capture the energy of sunlight and transform it into energy-rich compounds such as carbohydrates.

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?***



Quick Lab
GUIDED INQUIRY

What Waste Material Is Produced During Photosynthesis?

1. Fill a large, clear, plastic cup about halfway full with sodium bicarbonate solution. The sodium bicarbonate solution is a source of carbon dioxide.

2. Place a freshly cut *Elodea* plant (with the cut stem at the bottom) in a large test tube. Fill the tube with sodium bicarbonate solution. **CAUTION:** *Handle the test tube carefully.*

3. Hold your finger over the mouth of the test tube. Turn the test tube over, and lower it to the bottom of the cup. Make sure no air is trapped in the test tube.

4. Place the cup in bright light.

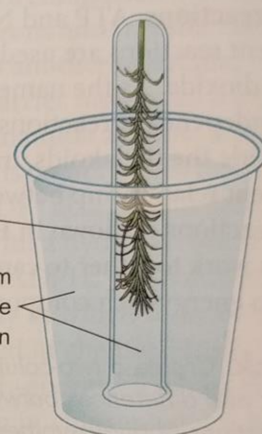
5. After no fewer than 20 minutes, look closely at the elodea leaves. Record your observations.

Analyze and Conclude

1. **Observe** What did you observe on the *Elodea* leaves?

2. **Infer** What substance accumulated on the leaves? Should that substance be considered a waste product? Explain.

3. **Apply Concepts** Which plant organelle carries out photosynthesis and produces the gas?



8.2 Assessment

Review Key Concepts

1. a. **Review** Why are pigments such as chlorophyll needed for photosynthesis?
   b. **Predict** How well would a plant grow under pure yellow light? Explain your answer.
2. a. **Review** What is the function of NADPH?
   b. **Explain** How is light energy converted into chemical energy during photosynthesis?
   c. **Infer** How would photosynthesis be affected if there were a shortage of $NADP^+$ in the cells of plants?
3. a. **Review** Describe the overall process of photosynthesis, including the reactants and products.
   b. **Interpret Visuals** Look at **Figure 8–7.** Into which set of reactions—light-dependent or light-independent—does each reactant of photosynthesis enter? From which set of reactions is each product of photosynthesis generated?

VISUAL THINKING

4. Create your own labeled diagram of a chloroplast. Using **Figure 8–5** as a guide, draw and label the thylakoids, grana, and stroma. Indicate on your drawing where the two sets of photosynthesis reactions take place.
5. Draw two leaves—one green and one orange. Using colored pencils, markers, or pens, show which colors of visible light are absorbed and reflected by each leaf.