7 Photosynthesis: Using Light to Make Food

COVER UP! PROTECTING YOURSELF FROM SHORT WAVELENGTHS OF LIGHT CAN BE LIFESAVING.

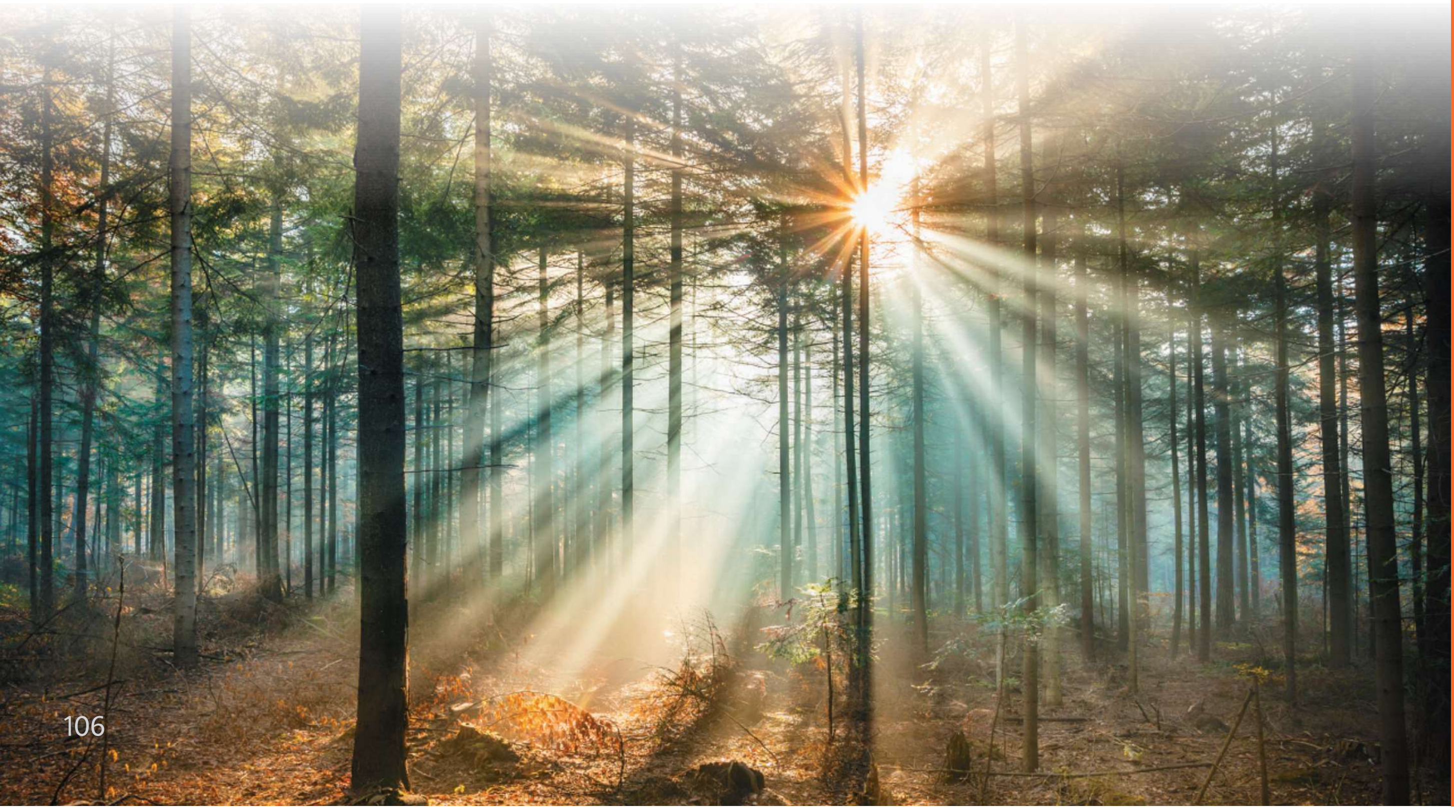
CHAPTER CONTENTS

Why Photosynthesis Matters

Do you like to eat? We humans can trace every morsel of our food back to plants. By capturing the energy of sunlight and using it to create organic materials, plants performing photosynthesis feed the world.

WANT TO DO SOMETHING SIMPLE TO COMBAT GLOBAL CLIMATE CHANGE? PLANT A TREE—YOU'LL BE GLAD YOU DID!

NEARLY ALL LIFE ON EARTH—INCLUDING YOU—CAN TRACE ITS SOURCE OF ENERGY BACK TO THE SUN.



CHAPTER THREAD

Solar Energy

Tapping into the sun. Rooftop solar panels are becoming a common sight.

BIOLOGY AND SOCIETY Solar Energy

A Solar Revolution

When you hear the term *solar power*, you may think of rooftop rows of solar panels. Indeed, the electricity that photovoltaic (PV) solar panels produce from sunlight can be used directly, stored in batteries, or transferred to the national electric grid. The advantages of solar panels are many: Sunlight is free, plentiful, and abundant across the whole planet; the technology is quite reliable because it uses no moving parts; and no pollution is created. It's not surprising, then, that residential photovoltaic systems are becoming more popular.

Photovoltaic panels are just one of many ways that humans can harness the sun to produce energy. Living organisms that capture sunlight through the process of photosynthesis can also serve as energy sources. For example, plant matter can be burned directly, as with stoves or boilers that burn wood or wood pellets. Plant material can also be used to produce biofuels such as bioethanol and biodiesel. You may have noticed a sticker on a gas pump declaring the percentage of ethanol in that gasoline; most cars today run on a blend of 85% gasoline and 15% ethanol. Many car manufacturers are producing "flexible-fuel" vehicles that can run on any combination of gasoline and bioethanol.

All of these methods of capturing the energy in sunlight share an important trait: They are all renewable—that is, they are derived from sources that are naturally replenished on a human time scale. In addition to solar energy, renewable energy (also called green energy) can be derived from wind through turbines, water through hydroelectric dams, and geothermal sources through heat pumps. In fact, the majority of new electricity-generating capacity installed in 2015 was renewable, accounting for nearly $300 billion in investment. About one-quarter of all electricity is now generated from renewable sources, and this percentage is rising steadily. One nation that is leading this effort is Iceland, which generates 99.8% of its electricity from renewable sources.

How do you benefit from the solar revolution? Society's ever-increasing demand for fossil fuels (oil, gasoline, diesel, and other products derived from petroleum) has serious consequences. Burning fossil fuels releases pollution, which can cause respiratory diseases and acid precipitation, and carbon dioxide (CO_2), which contributes to global climate change. Additionally, a barrel of oil removed from the ground can never be replaced. Therefore, your health and the health of the planet benefit from using green energy instead of fossil fuels.

Nearly all life on Earth taps into the energy of the sun. Photosynthesis is the process by which plants, algae, and other organisms use light to make sugars from carbon dioxide—sugars that are food for these organisms and the starting point for most of our own food. In this chapter, we'll first examine some basic concepts of photosynthesis; then we'll look at the specific mechanisms involved in this process.

The Basics of Photosynthesis

The process of photosynthesis is the ultimate source of energy for nearly every ecosystem on Earth. **Photosynthesis** is a process whereby plants, algae (which are protists), and certain bacteria transform light energy into chemical energy, using carbon dioxide and water as starting materials and releasing oxygen gas as a by-product. The chemical energy produced through photosynthesis is stored in the bonds of sugar molecules. Organisms that generate their own food are called autotrophs (see Chapter 6). Plants and other organisms that do this by photosynthesis—photoautotrophs—are the producers for most ecosystems (**Figure 7.1**). Photoautotrophs not only feed us but also clothe us (as the source of cotton fibers), house us (wood), and provide energy for warmth, light, and transportation (biofuels). **The fact that nearly all organisms—including you—can trace their source of energy back to the sun clearly illustrates that the ability to transform energy and matter is vital to the existence of life on Earth.**

NEARLY ALL LIFE ON EARTH CAN TRACE ITS SOURCE OF ENERGY BACK TO THE SUN.

Chloroplasts: Sites of Photosynthesis

Photosynthesis in plants and algae occurs within light-absorbing organelles called **chloroplasts** (see Figure 4.18). All green parts of a plant have chloroplasts and thus can carry out photosynthesis. In most plants, however, the leaves have the most chloroplasts (about 300 million chloroplasts in a piece of leaf the size of a nickel). Their green color is from **chlorophyll**, a pigment (light-absorbing molecule) in the chloroplasts that plays a central role in converting solar energy to chemical energy.

Chloroplasts are concentrated in the interior cells of leaves (**Figure 7.2**), with a typical cell containing 30–40 chloroplasts. Carbon dioxide (CO_2) enters a leaf, and oxygen (O_2) exits, by way of tiny pores called **stomata** (singular, *stoma*, meaning "mouth"). The carbon dioxide that enters the leaf is the source of carbon for much of the body of the plant, including the sugars and starches that we eat. So the bulk of the body of a plant derives from the air, not the soil. As proof of this idea, consider hydroponics, a means of growing plants using only air and water; no soil whatsoever is involved. In addition to carbon dioxide, photosynthesis requires water, which is absorbed by the plant's roots and transported to the leaves, where veins carry it to the photosynthetic cells.

Membranes within the chloroplast form the framework where many of the reactions of photosynthesis occur. Like a mitochondrion, a chloroplast has a double-membrane envelope. The chloroplast's inner membrane encloses a compartment filled with **stroma**, a thick fluid. (It's easy to confuse two terms associated with photosynthesis: *Stomata* are pores through which gases are exchanged,

▼ **Figure 7.1 A diversity of photoautotrophs.**

PHOTOSYNTHETIC AUTOTROPHS

Plants
(mostly on land)

Forest plants

Photosynthetic Protists
(aquatic)

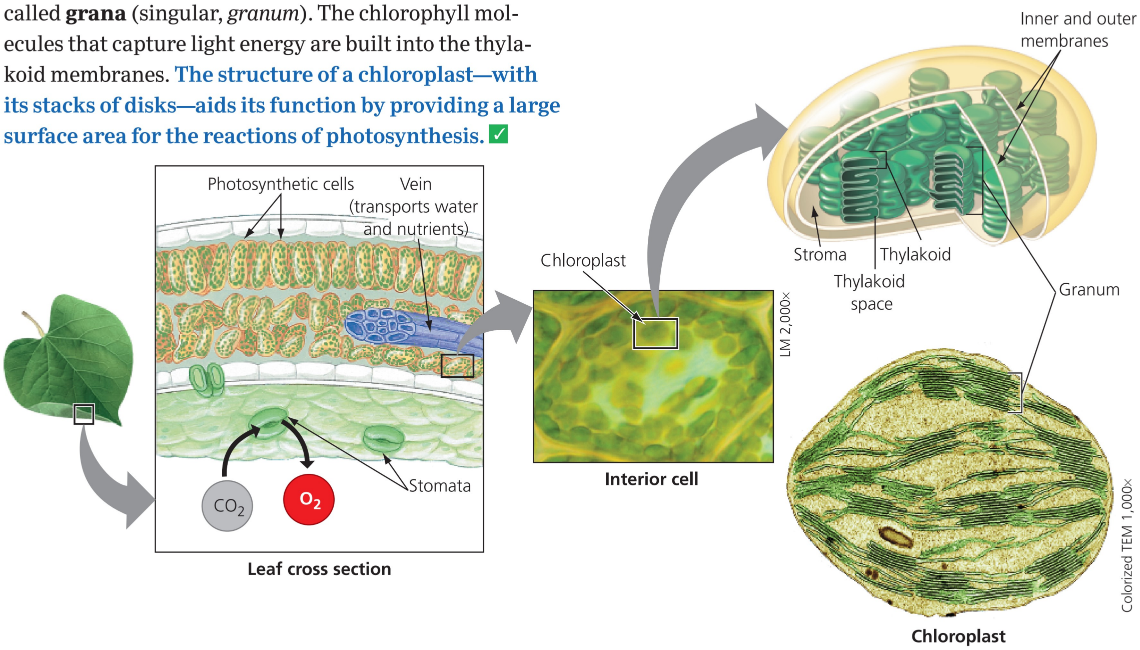
Kelp, a large, multicellular alga

Photosynthetic Bacteria
(aquatic)

Micrograph of cyanobacteria

and *stroma* is the fluid within the chloroplast.) Suspended in the stroma are interconnected membranous sacs called **thylakoids**. The thylakoids are concentrated in stacks called **grana** (singular, *granum*). The chlorophyll molecules that capture light energy are built into the thylakoid membranes. **The structure of a chloroplast—with its stacks of disks—aids its function by providing a large surface area for the reactions of photosynthesis.** ✓

▼ Figure 7.2 Journey into a leaf. This series of blowups takes you into a leaf's interior, then into a plant cell, and finally into a chloroplast, the site of photosynthesis.



✓ **CHECKPOINT**

Photosynthesis takes place within organelles called _____ using gases that are exchanged through pores called _____.

■ Answer: *chloroplasts; stomata*

An Overview of Photosynthesis

The following chemical equation, simplified to highlight the relationship between photosynthesis and cellular respiration, provides a summary of the reactants and products of photosynthesis:

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

Notice that the reactants of photosynthesis—carbon dioxide (CO_2) and water (H_2O)—are the same as the waste products of cellular respiration (see Figure 6.2). Also notice that photosynthesis produces what respiration uses—glucose ($C_6H_{12}O_6$) and oxygen (O_2). In other words, photosynthesis recycles the "exhaust" of cellular respiration and rearranges its atoms to produce food and oxygen. Photosynthesis is a chemical transformation that requires a lot of energy, and sunlight absorbed by chlorophyll provides that energy.

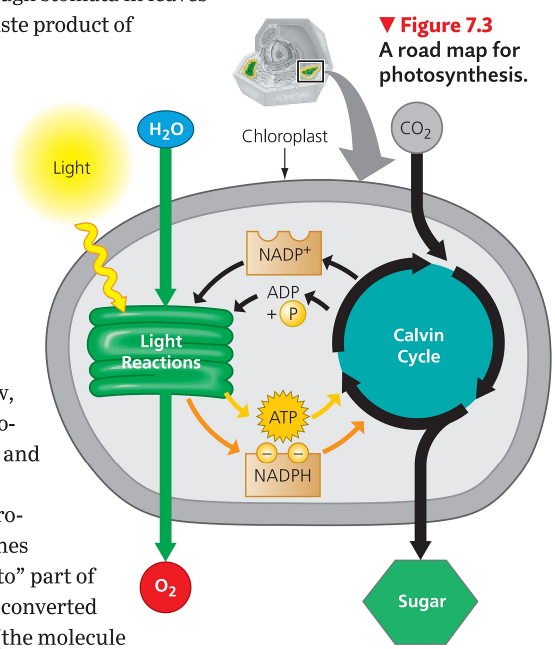
Recall that cellular respiration is a process of electron transfer (see Chapter 6). A "fall" of electrons from food molecules to oxygen to form water releases the energy that mitochondria can use to make ATP (see Figure 6.9). The opposite occurs in photosynthesis: Electrons are boosted "uphill" and added to carbon dioxide to produce sugar. Hydrogen is moved along with the electrons being transferred from water to carbon dioxide. This transfer of hydrogen requires the chloroplast to split water molecules into hydrogen and oxygen. The hydrogen is transferred along with electrons to carbon dioxide to form sugar. The oxygen escapes through stomata in leaves into the atmosphere as O_2, a waste product of photosynthesis.

The overall equation for photosynthesis is a simple summary of a complex process. Like many energy-producing processes within cells, photosynthesis is a multistep chemical pathway, with each step in the path producing products that are used as reactants in the next step. For a better overview, let's look at the two stages of photosynthesis: the light reactions and the Calvin cycle (**Figure 7.3**).

In the **light reactions**, chlorophyll in the thylakoid membranes absorbs solar energy (the "photo" part of photosynthesis), which is then converted to the chemical energy of ATP (the molecule

Figure Walkthrough
Mastering Biology
goo.gl/3rETcw

▼ Figure 7.3 A road map for photosynthesis.



that drives most cellular work) and **NADPH** (an electron carrier). During the light reactions, water is split, providing a source of electrons and giving off O_2 gas as a by-product.

The **Calvin cycle** uses the products of the light reactions to power the production of sugar from carbon dioxide (the "synthesis" part of photosynthesis). The enzymes that drive the Calvin cycle are dissolved in the stroma. ATP generated by the light reactions provides the energy for sugar synthesis. And the NADPH produced by the light reactions provides the high-energy electrons that drive the synthesis of glucose from carbon dioxide. Thus, the Calvin cycle indirectly depends on light to produce sugar because it requires the supply of ATP and NADPH produced by the light reactions.

WANT TO DO SOMETHING SIMPLE TO COMBAT GLOBAL CLIMATE CHANGE? PLANT A TREE—YOU'LL BE GLAD YOU DID!

The initial incorporation of carbon from CO_2 into organic compounds is called **carbon fixation**. This process has important implications for global climate, because the removal of carbon from the air and its incorporation into plant material can help reduce the concentration of carbon dioxide in the atmosphere. Deforestation, which removes a lot of photosynthetic plant life, thereby reduces the ability of the biosphere to absorb carbon. Planting new forests can have the opposite effect of fixing carbon from the atmosphere, potentially reducing the effect of the gases that contribute to global climate change. **The relationship between photosynthesis, carbon fixation, and global climate is a good example of how interactions between biological components at many different levels affect all life on Earth.** ✓

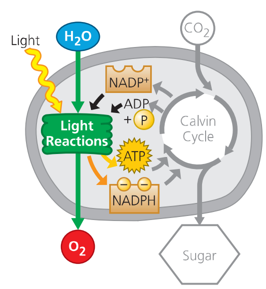
✓ CHECKPOINT

1. What molecules are the inputs of photosynthesis? What molecules are the outputs?
2. Name the two stages of photosynthesis in their proper order.

■ Answers: **1.** CO_2 and H_2O; glucose and O_2 **2.** light reactions, Calvin cycle

The Light Reactions: Converting Solar Energy to Chemical Energy

Chloroplasts are solar-powered sugar factories. Let's look at how they use the energy in sunlight to store chemical energy.

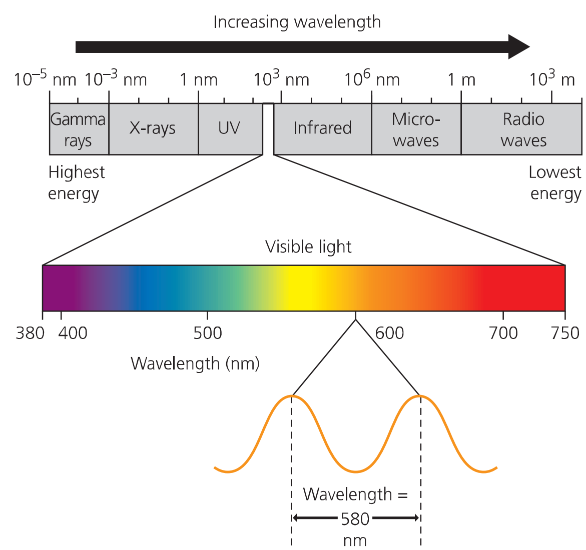


The Nature of Sunlight

Sunlight, like other forms of radiation, travels through space as rhythmic waves, like the ripples made by a pebble dropped into a pond. The distance between the crests of two adjacent waves is called a **wavelength**. The full range of radiation, from the very short wavelengths of gamma rays to the very long wavelengths of radio signals, is called the **electromagnetic spectrum (Figure 7.4)**. Visible light is the small fraction of the spectrum that our eyes see as different colors.

When sunlight shines on a pigmented material, certain wavelengths (colors) of the visible light are absorbed. The colors that are not absorbed are reflected by the material. For example, we see a pair of jeans as blue because pigments in the fabric absorb the other colors, leaving only blue light to be reflected to our eyes. In the 1800s, plant biologists discovered that only certain wavelengths of light are used by plants, as we'll see next.

▼ **Figure 7.4 The electromagnetic spectrum.** The middle of the figure expands the thin slice of the spectrum that is visible to us as different colors of light, from about 380 nanometers (nm) to about 750 nm in wavelength. The bottom of the figure shows waves of one particular wavelength of visible light.



THE PROCESS OF SCIENCE | Solar Energy

What Colors of Light Drive Photosynthesis?

BACKGROUND

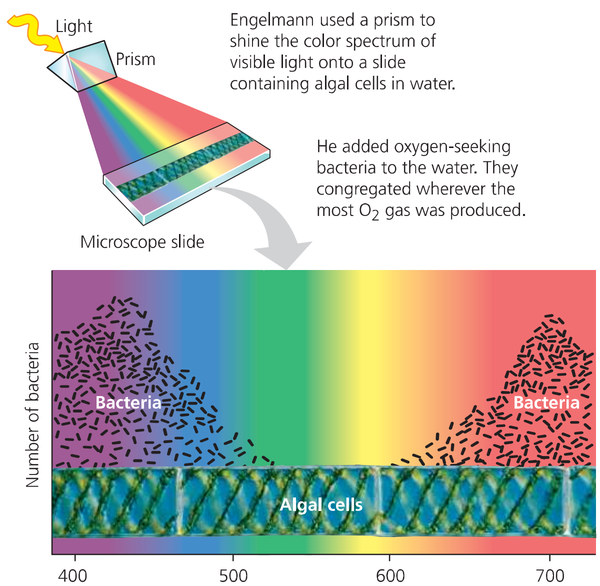
Scientific breakthroughs often occur after careful observations of natural phenomena. In 1883, German biologist Theodor Engelmann noticed that certain aquatic bacteria tend to cluster in areas with higher oxygen concentrations. He formed a hypothesis that oxygen-seeking bacteria would congregate near algae that were performing the most photosynthesis and therefore producing the most oxygen. He conducted a simple but elegant experiment to determine which wavelengths (colors) of light are used during photosynthesis.

METHOD

Engelmann placed a string of freshwater algal cells within a drop of water on a microscope slide and used a prism to expose the cells to the color spectrum. He then added oxygen-seeking bacteria to the water **(Figure 7.5)**.

RESULTS

The experiment showed that most bacteria congregated around algae exposed to blue-violet and red-orange light. Other experiments have since verified that those wavelengths are mainly responsible for photosynthesis. Variations of this classic experiment are still performed. For example, biofuel researchers test different species of algae to determine which wavelengths result in optimal fuel production. Biofuel facilities of the future may use a variety of species that take advantage of the full spectrum of light that shines down on them.



◀ **Figure 7.5 Investigating how light wavelength affects photosynthesis.**

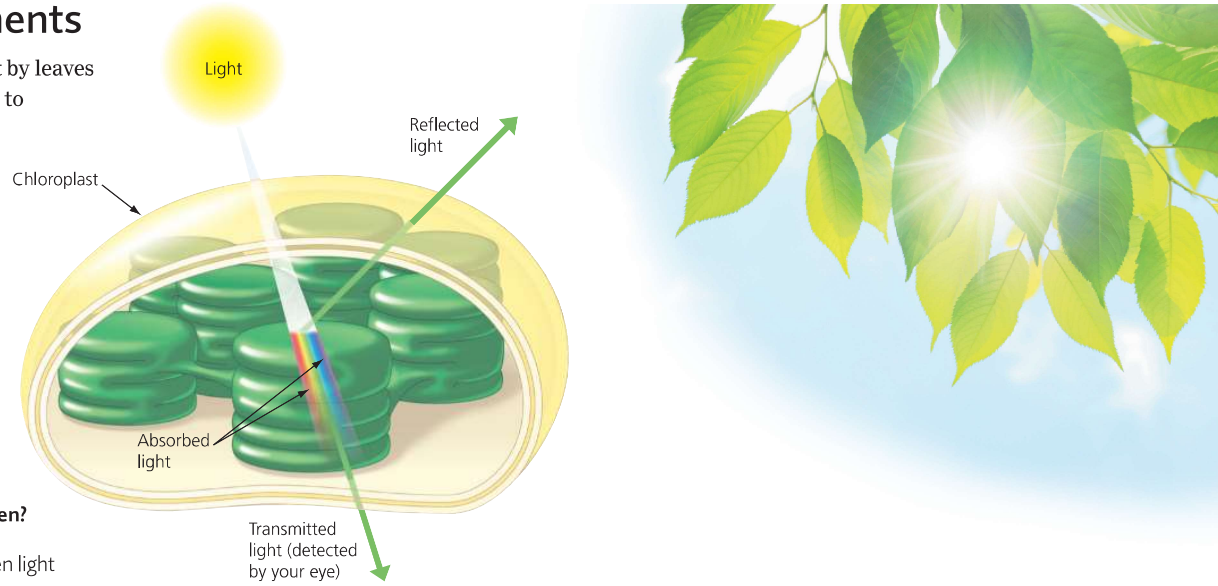
Thinking Like a Scientist

Why was Engelmann's use of a prism with natural sunlight a key to his discovery?

For the answer, see Appendix D.

Chloroplast Pigments

The selective absorption of light by leaves explains why they appear green to us; light of that color is poorly absorbed by chloroplasts and is thus reflected or transmitted toward the observer **(Figure 7.6)**. Energy cannot be destroyed, so the absorbed energy must be converted to other forms. Chloroplasts contain several different pigments that absorb light of different wavelengths. Chlorophyll *a*,



▶ **Figure 7.6 Why are leaves green?** Chlorophyll and other pigments in chloroplasts reflect or transmit green light while absorbing other colors.

the pigment that participates directly in the light reactions, absorbs mainly blue-violet and red light. A very similar molecule, chlorophyll *b*, absorbs mainly blue and orange light. Chlorophyll *b* does not participate directly in the light reactions, but it conveys absorbed energy to chlorophyll *a*, which then puts the energy to work in the light reactions.

Chloroplasts also contain a family of yellow-orange pigments called carotenoids, which absorb mainly blue-green light. Some carotenoids have a protective function: They dissipate excess light energy that would otherwise damage chlorophyll. Some carotenoids are human nutrients: beta-carotene (a bright orange/red pigment found in pumpkins, sweet potatoes, and carrots) is converted to vitamin A in the body, and lycopene (a bright red pigment found in tomatoes, watermelon, and red peppers) is an antioxidant that is being studied for potential anticancer properties. Additionally, the spectacular colors of fall foliage in some parts of the world are due partly to the yellow-orange light reflected from carotenoids **(Figure 7.7)**. The decreasing temperatures in autumn cause a decrease in the levels of chlorophyll, allowing the colors of the longer-lasting carotenoids to be seen in all their fall glory.

All of these chloroplast pigments are built into the thylakoid membranes (see Figure 7.2). There the pigments are organized into light-harvesting complexes called photosystems, our next topic. ✓

▲ **Figure 7.7 Photosynthetic pigments.** Falling autumn temperatures cause a decrease in the levels of green chlorophyll within the foliage of leaf-bearing trees. This decrease allows the colors of the carotenoids to be seen.

✓ CHECKPOINT

What is the specific name of the pigment that absorbs energy during the light reactions?

■ Answer: chlorophyll *a*

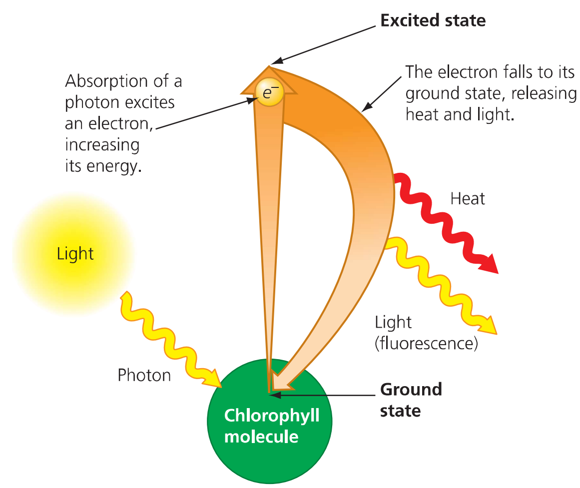
How Photosystems Harvest Light Energy

Thinking about light as waves explains most of light's properties. However, light also behaves as discrete packets of energy called photons. A **photon** is a fixed quantity of light energy. The shorter the wavelength of light, the greater the energy of a photon. A photon of violet light, for example, packs nearly twice as much energy as a photon of red light. This is why short-wavelength light—such as ultraviolet light and X-rays—can be damaging; photons at these wavelengths carry enough energy to damage proteins and DNA, potentially leading to cancerous mutations.

PROTECTING YOURSELF FROM SHORT WAVELENGTHS OF LIGHT CAN BE LIFESAVING.

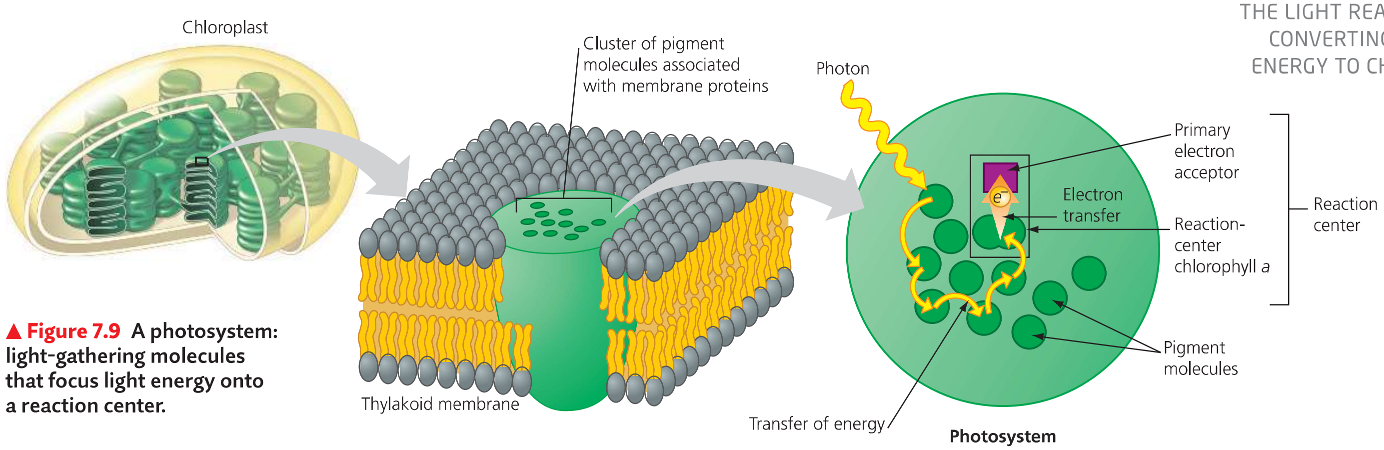
When a pigment molecule absorbs a photon, one of the pigment's electrons gains energy. This electron (e^-) is now said to be "excited"; that is, the electron has been raised from its starting state (called the ground state) to an excited state. The excited state is highly unstable, so an excited electron usually gives off its excess energy and falls back to its ground state almost immediately **(Figure 7.8a)**. Most pigments release heat energy as their light-excited electrons fall back to their ground state. (That's why a surface with a lot of pigment, such as a black driveway, gets so hot on a sunny day.) But some pigments emit light as well as heat after absorbing photons.

▼ **Figure 7.8 Excited electrons in pigments.**



(a) Absorption of a photon

(b) Fluorescence of a glow stick. Breaking a vial within a glow stick starts a chemical reaction that excites electrons within a fluorescent dye. As the electrons fall from their excited state to the ground state, the excess energy is emitted as light.



▲ **Figure 7.9 A photosystem: light-gathering molecules that focus light energy onto a reaction center.**

The fluorescent light emitted by a glow stick is caused by a chemical reaction that excites electrons of a fluorescent dye **(Figure 7.8b)**. The excited electrons quickly fall back down to their ground state, releasing energy in the form of fluorescent light.

In the thylakoid membrane, chlorophyll molecules are organized with other molecules into photosystems. Each **photosystem** has a cluster of a few hundred pigment molecules **(Figure 7.9)**. This cluster of pigment molecules functions as a light-gathering antenna. When a photon strikes one of the pigment molecules, the energy jumps from molecule to molecule until it arrives at the reaction center of the photosystem. The reaction center consists of chlorophyll *a* molecules that sit next to another molecule called a primary electron acceptor. This primary electron acceptor traps the light-excited electron from the chlorophyll *a* in the reaction center. As you'll see next, another team of molecules built into the thylakoid membrane then uses that trapped energy to make ATP and NADPH. ✅

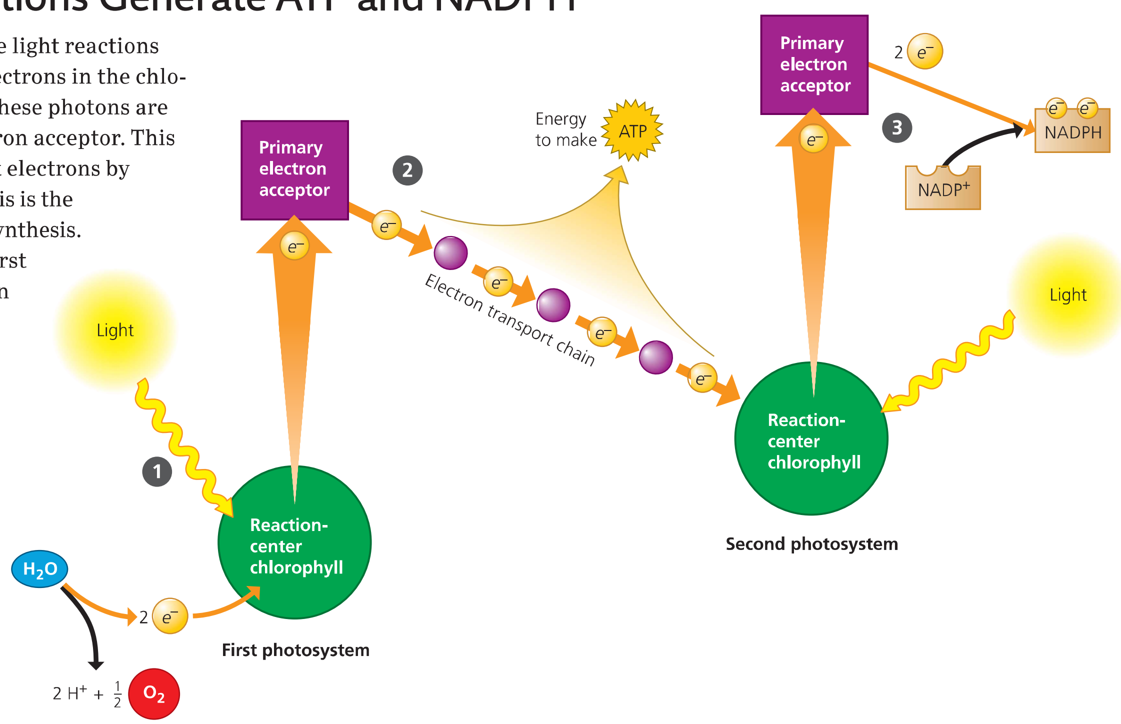
✅ CHECKPOINT

What is the role of a reaction center during photosynthesis?

Answer: A reaction center transfers a light-excited photon from pigment molecules to molecules that can use this trapped energy to drive chemical reactions.

How the Light Reactions Generate ATP and NADPH

Two photosystems cooperate in the light reactions **(Figure 7.10)**. **1** Photons excite electrons in the chlorophyll of the first photosystem. These photons are then trapped by the primary electron acceptor. This photosystem then replaces the lost electrons by extracting new ones from water. This is the step that releases O_2 during photosynthesis. **2** Energized electrons from the first photosystem pass down an electron transport chain to the second photosystem. The chloroplast uses the energy released by this electron "fall" to make ATP. **3** The second photosystem transfers its light-excited electrons to $NADP^+$, converting it to NADPH.



▶ **Figure 7.10 The light reactions of photosynthesis.** The orange arrows trace a light-driven flow of electrons from H_2O to NADPH. These electrons also produce ATP.

Figure 7.11 shows the location of the light reactions in the thylakoid membrane. The two photosystems and the electron transport chain that connects them transfer electrons from H_2O to $NADP^+$, producing NADPH. Notice that the mechanism of ATP production during the light reactions is very similar to the mechanism we saw in cellular respiration (see Figure 6.10). In both cases, an electron transport chain pumps hydrogen ions (H^+) across a membrane—the inner mitochondrial membrane in the case of respiration and the thylakoid membrane in photosynthesis. And in both cases, ATP synthases use the energy stored by the H^+ gradient to make ATP. The main difference is that food provides the high-energy electrons in cellular respiration, whereas light-excited electrons flow down the transport chain during photosynthesis. The traffic of electrons shown in Figures 7.10 and 7.11 is analogous to the cartoon in **Figure 7.12**.

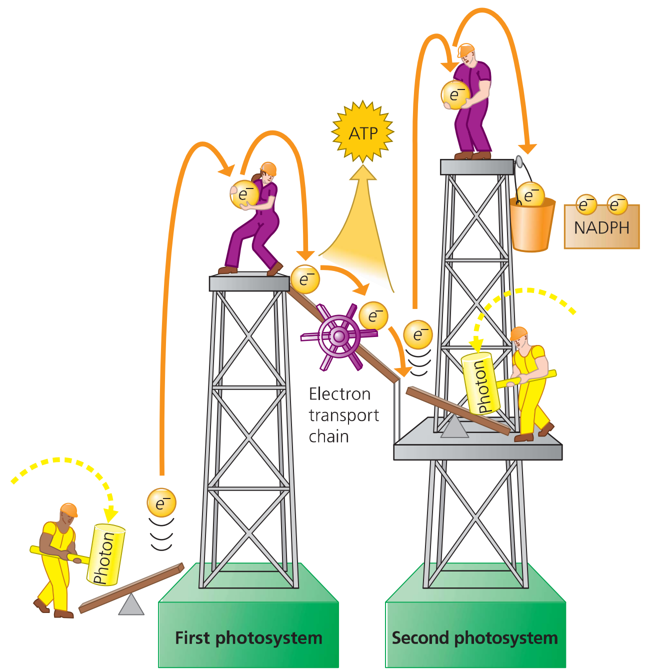
We have seen how the light reactions absorb solar energy and convert it to the chemical energy of ATP and NADPH. Notice again, however, that the light reactions did not produce any sugar. That's the job of the Calvin cycle, as we'll see next. ✓

✓ CHECKPOINT

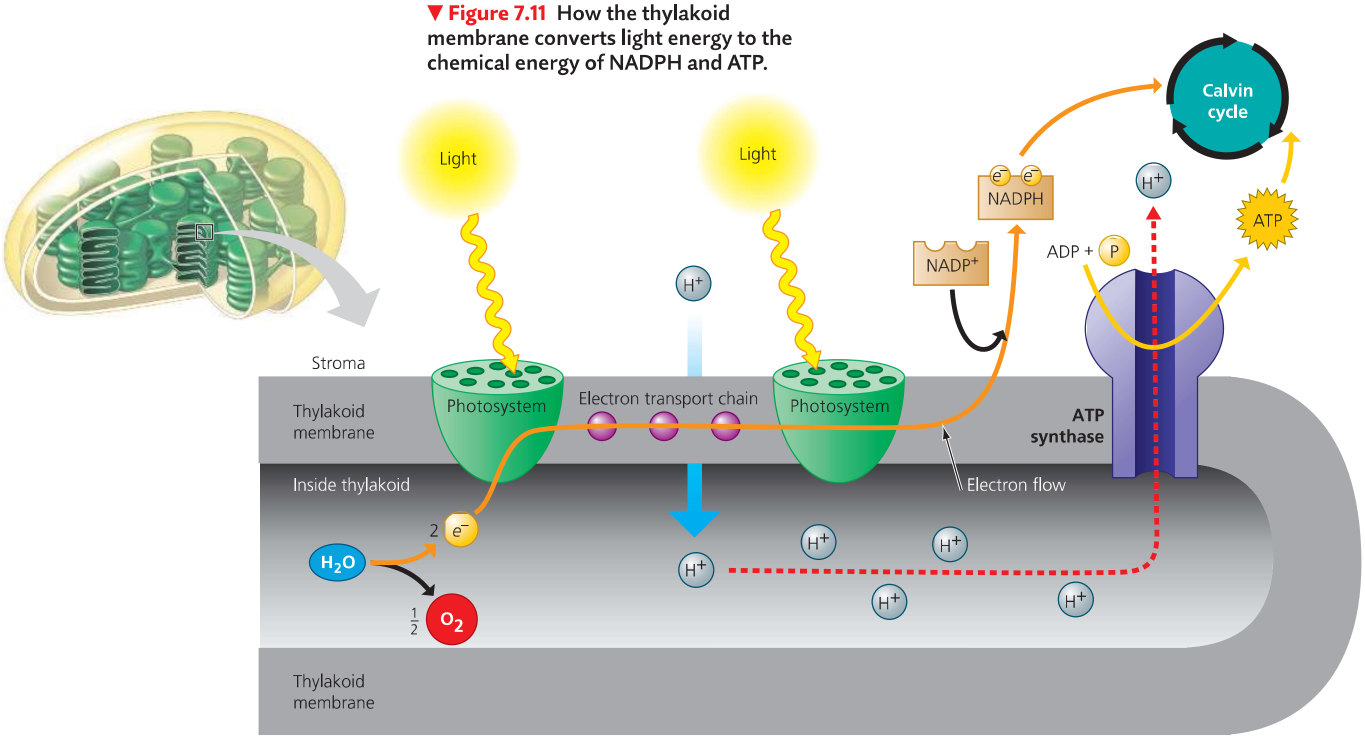
1. Why is water required as a reactant in photosynthesis? (*Hint*: Review Figures 7.10 and 7.11.)
2. In addition to conveying electrons between photosystems, the electron transport chains of chloroplasts provide the energy for the synthesis of _____.

■ Answers: **1.** The splitting of water provides electrons for converting NAD^+ to NADPH. **2.** ATP

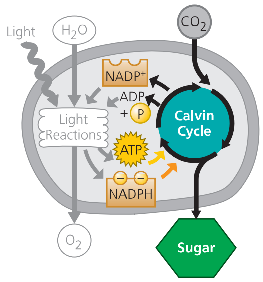
▼ **Figure 7.12 The light reactions illustrated using a hard-hat analogy.** The energy of sunlight is used to boost an electron from a low-energy state to a high-energy state.



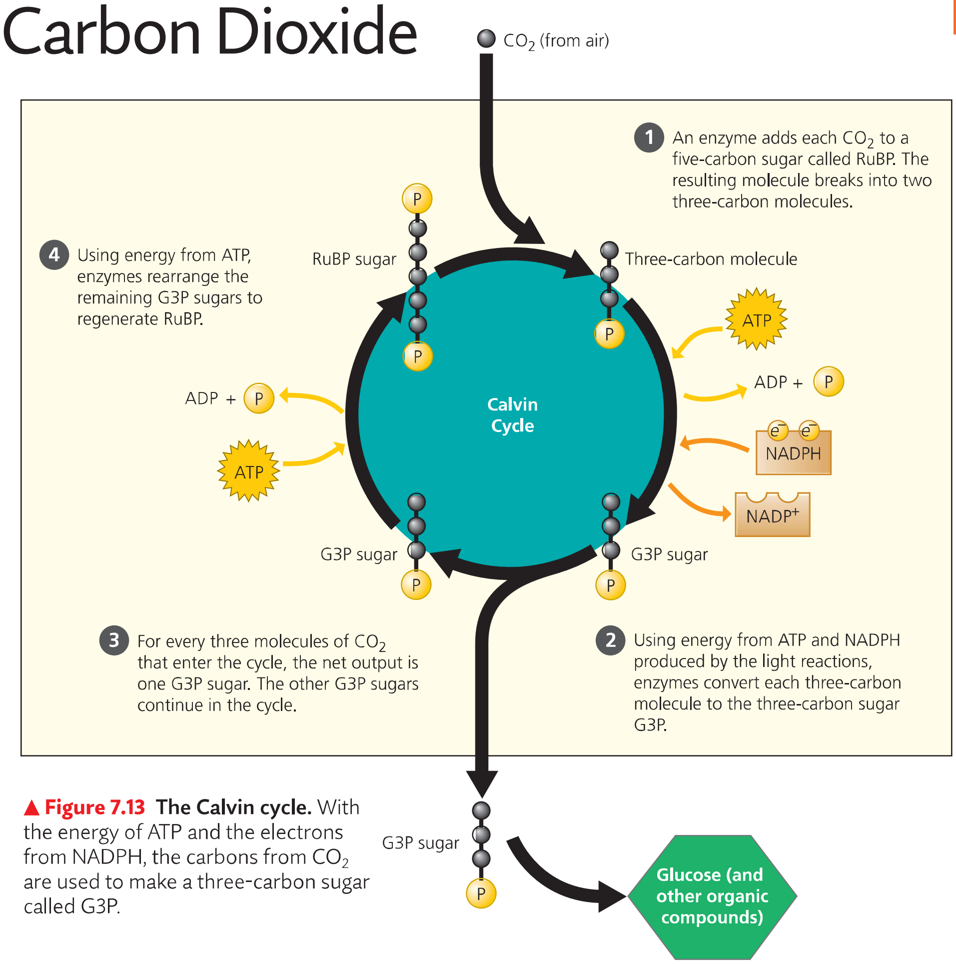
▼ **Figure 7.11 How the thylakoid membrane converts light energy to the chemical energy of NADPH and ATP.**



The Calvin Cycle: Making Sugar from Carbon Dioxide



If chloroplasts are solar-powered sugar factories, then the Calvin cycle is the actual sugar-manufacturing machinery. This process is called a cycle because its starting material is regenerated. With each turn of the cycle, there are chemical inputs and outputs. The inputs are CO_2 from the air as well as two products of the light reactions: ATP (which provides energy) and NADPH (which provides electrons). Using carbon from CO_2, energy from ATP, and high-energy electrons from NADPH, the Calvin cycle constructs an energy-rich sugar molecule called glyceraldehyde 3-phosphate (G3P). The plant cell can then use G3P as the raw material to make the glucose and other organic compounds (such as cellulose and starch) that it needs. **Figure 7.13** presents the basics of the Calvin cycle, emphasizing inputs and outputs. Each ● symbol represents a carbon atom, and each Ⓟ symbol represents a phosphate group. ✅



▲ **Figure 7.13 The Calvin cycle.** With the energy of ATP and the electrons from NADPH, the carbons from CO_2 are used to make a three-carbon sugar called G3P.

EVOLUTION CONNECTION Solar Energy

Creating a Better Biofuel Factory

Throughout this chapter, we've studied how plants convert solar energy to chemical energy by photosynthesis. Such transformations are vital to our welfare and to Earth's ecosystems. As discussed in the Biology and Society section, scientists are attempting to tap into the energy of photosynthesis to produce biofuels. But the production of biofuels is highly inefficient. In fact, it is usually far more costly to produce biofuels than to extract the equivalent amount of fossil fuels.

Biomechanical engineers are working to solve this dilemma by turning to an obvious example: evolution by natural selection. In nature, organisms with genes that make them better suited to their local environment will, on average, more often survive and pass those genes on to the next generation. Repeated over many generations, genes that enhance survival within that environment will become more common, and the species evolves.

When trying to solve an engineering problem, scientists can impose their own desired outcomes using a process called directed evolution (see the Process of Science section in Chapter 5 for another example).

✅ **CHECKPOINT**

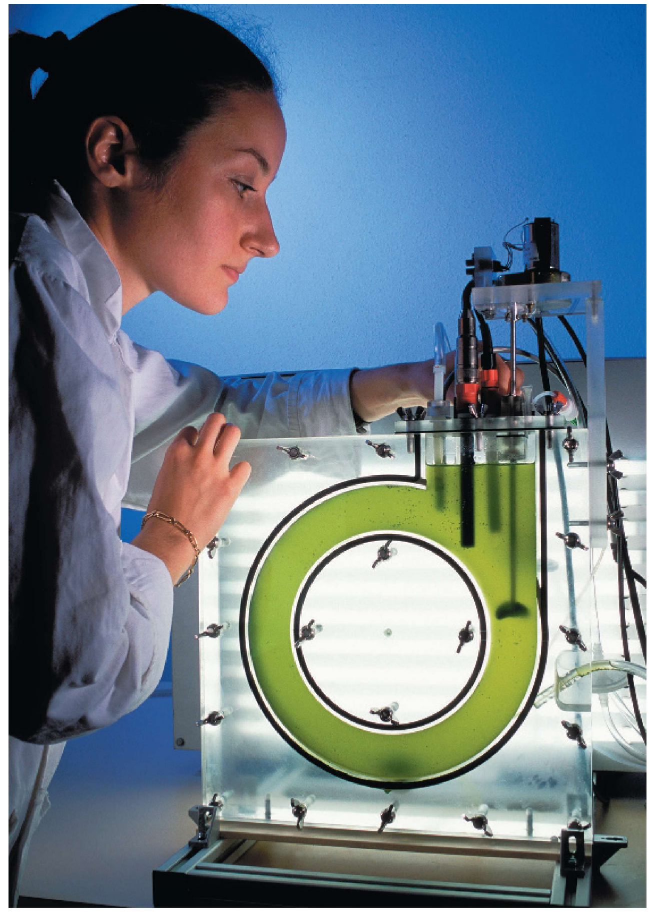
What is the function of NADPH in the Calvin cycle?

■ *Answer: It provides the high-energy electrons that are added to CO_2 to form G3P (a sugar).*

During this process, scientists in the laboratory (instead of the natural environment) determine which organisms are the fittest. Directed evolution of biofuel production often involves microscopic algae **(Figure 7.14)** rather than plants because algae are easier to manipulate and maintain within the laboratory. Furthermore, some algae produce nearly half their own body weight in hydrocarbons that are only a few chemical steps away from useful biofuels.

In a typical directed evolution experiment, the researcher starts with a large collection of individual alga—sometimes naturally occurring species and sometimes transgenic algae that have been engineered to carry useful genes, such as fungal genes for enzymes that break down cellulose. The algae are exposed to mutation-promoting chemicals. This produces a highly varied collection of algae that can be screened for the desired outcome: the ability to produce the most useful biofuel in the largest quantity. The tiny fraction of total algae that can best perform this task is grown and subjected to another round of mutation and selection. After many repetitions, the algae may slowly improve their ability to efficiently produce biofuels. Many research laboratories—some within major petroleum companies—are using such methods and may someday produce an alga that can provide the ultimate source of green energy, an achievement that would highlight how lessons from evolution can be applied to improve our lives.

▼ **Figure 7.14** **Microscopic biofuel factories.** This researcher is monitoring a reaction chamber in which microscopic algae are using light to produce biofuels.



Chapter Review

SUMMARY OF KEY CONCEPTS

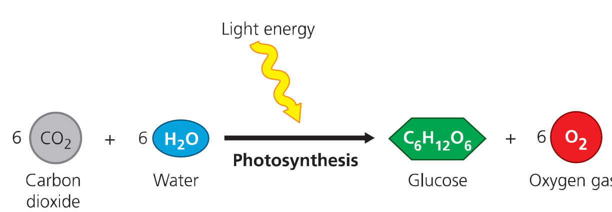
The Basics of Photosynthesis

Photosynthesis is a process whereby light energy is transformed into chemical energy. During the process, carbon dioxide and water are used to make sugar molecules.

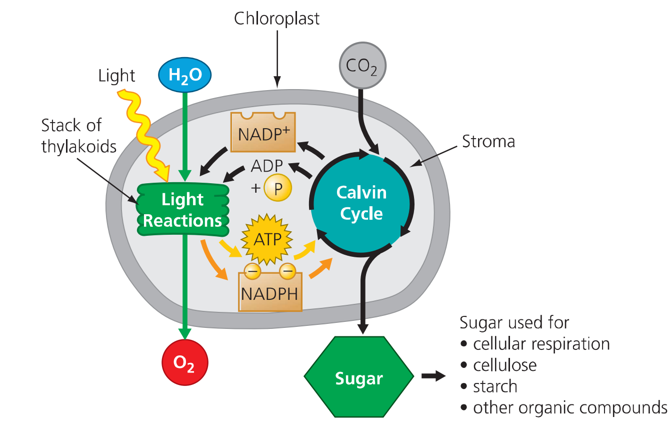
Chloroplasts: Sites of Photosynthesis

Chloroplasts contain a thick fluid called stroma surrounding a network of membranes called thylakoids.

An Overview of Photosynthesis



The overall process of photosynthesis can be divided into two stages connected by energy-carrying and electron-carrying molecules:



The Light Reactions: Converting Solar Energy to Chemical Energy

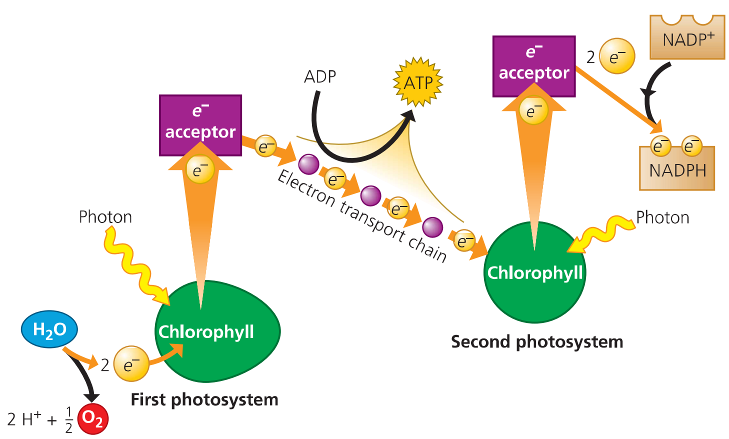
The Nature of Sunlight

Visible light is part of the electromagnetic spectrum. It travels through space as waves. Different wavelengths of light appear as different colors. Shorter wavelengths carry more energy.

Chloroplast Pigments

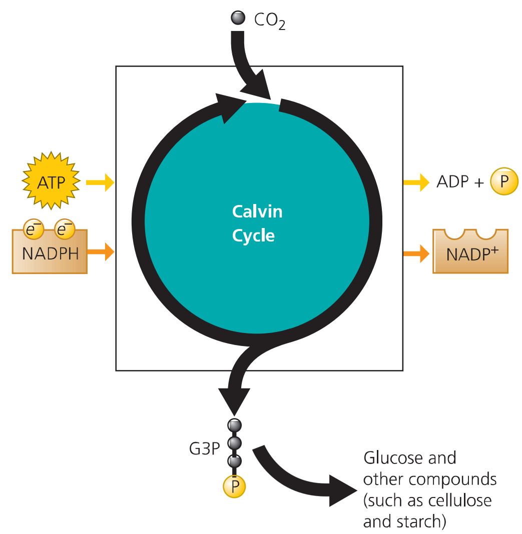
Pigment molecules absorb light energy of certain wavelengths and reflect other wavelengths. We see the reflected wavelengths as the color of the pigment. Several chloroplast pigments absorb light of various wavelengths and convey it to other pigments, but it is the green pigment chlorophyll *a* that participates directly in the light reactions.

How Photosystems Harvest Light Energy and How the Light Reactions Generate ATP and NADPH



The Calvin Cycle: Making Sugar from Carbon Dioxide

Within the stroma (fluid) of the chloroplast, carbon dioxide from the air and ATP and NADPH produced during the light reactions are used to produce G3P, an energy-rich sugar molecule that can be used to make glucose and other organic molecules.



SELF-QUIZ

1. The light reactions take place in the structures of the chloroplast called the ______, while the Calvin cycle takes place in the ______.
2. In terms of the spatial organization of photosynthesis within the chloroplast, what is the advantage of the light reactions producing NADPH and ATP on the stroma side of the thylakoid membrane?
3. Which of the following are inputs to photosynthesis? Choose all that apply. Which are outputs? Choose all that apply.
   a. CO_2
   b. O_2
   c. sugar
   d. H_2O
   e. light
4. Explain how the name "photosynthesis" describes what this process accomplishes.
5. What color of light is the least effective in driving photosynthesis? Why?