

4.2

Overview of Photosynthesis

KEY CONCEPT The overall process of photosynthesis produces sugars that store chemical energy.

MAIN IDEAS

- Photosynthetic organisms are producers.
- Photosynthesis in plants occurs in chloroplasts.

VOCABULARY

photosynthesis, p. 103

chlorophyll, p. 103

thylakoid, p. 104

light-dependent reactions, p. 105

light-independent reactions, p. 105

Review

chemical reaction, carbohydrate, enzyme, chloroplast



1.1 Students know usable energy is captured from sunlight by chloroplasts and is stored through the synthesis of sugar from carbon dioxide.

Review Life Science

7.1.d Students know that mitochondria liberate energy for the work that cells do and that chloroplasts capture sunlight energy for photosynthesis.

Connect Solar-powered calculators, homes, and cars are just a few things that use energy from sunlight. In a way, you are also solar-powered. Of course, sunlight does not directly give you the energy you need to play a sport or read this page. That energy comes from ATP. Molecules of ATP are often made from the breakdown of sugars, but how are sugars made? Plants capture some of the energy in sunlight and change it into chemical energy stored in sugars.

MAIN IDEA

Photosynthetic organisms are producers.

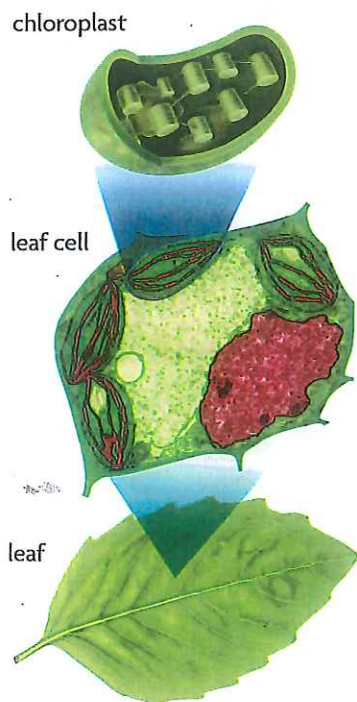
Some organisms are called producers because they produce the source of chemical energy for themselves and for other organisms. Plants, as well as some bacteria and protists, are the producers that are the main sources of chemical energy for most organisms on Earth. Certainly, animals that eat only plants obtain their chemical energy directly from plants. Animals that eat other animals, and bacteria and fungi that decompose other organisms, get their chemical energy indirectly from plants. When a wolf eats a rabbit, the tissues of the rabbit provide the wolf with a source of chemical energy. The rabbit's tissues are built from its food source—the sugars and other carbon-based molecules in plants. These sugars are made through photosynthesis.

Photosynthesis is a process that captures energy from sunlight to make sugars that store chemical energy. Therefore, directly or indirectly, the energy for almost all organisms begins as sunlight. Sunlight has several types of radiant energy, such as ultraviolet radiation, microwaves, and the visible light that lets you see. Plants absorb visible light for photosynthesis. Visible light appears white, but it is made up of several colors, or wavelengths, of light.

Chlorophyll (KLAWR-uh-fihl) is a molecule in chloroplasts, shown in **FIGURE 4.4**, that absorbs some of the energy in visible light. Plants have two main types of chlorophyll, called chlorophyll *a* and chlorophyll *b*. Together, these two types of chlorophyll absorb mostly red and blue wavelengths of visible light. Neither type absorbs much green light. Plants have other light-absorbing molecules that absorb green light, but there are fewer of these molecules. As a result, the green color of plants comes from the reflection of light's green wavelengths by chlorophyll.

Apply Describe the importance of producers and photosynthesis.

FIGURE 4.4 Chloroplasts in plant cells contain a light-absorbing molecule called chlorophyll. (leaf cell: colored TEM; magnification 4000×)



MAIN IDEA

Photosynthesis in plants occurs in chloroplasts.

Chloroplasts are the membrane-bound organelles where photosynthesis takes place in plants. Most of the chloroplasts are in leaf cells that are specialized for photosynthesis, which has two main stages as shown in FIGURE 4.5. The two main parts of chloroplasts needed for photosynthesis are the grana and the stroma. Grana (singular, *granum*) are stacks of coin-shaped, membrane-enclosed compartments called **thylakoids** (THY-luh-KOYDZ). The membranes of the thylakoids contain chlorophyll, other light-absorbing molecules, and proteins. The stroma is the fluid that surrounds the grana inside a chloroplast.

FIGURE 4.5 Photosynthesis Overview

Chloroplasts absorb energy from sunlight and produce sugars through the process of photosynthesis.

STAGE 1: Light-Dependent Reactions

- 1 Energy from sunlight is absorbed. Water molecules are broken down and oxygen is released.

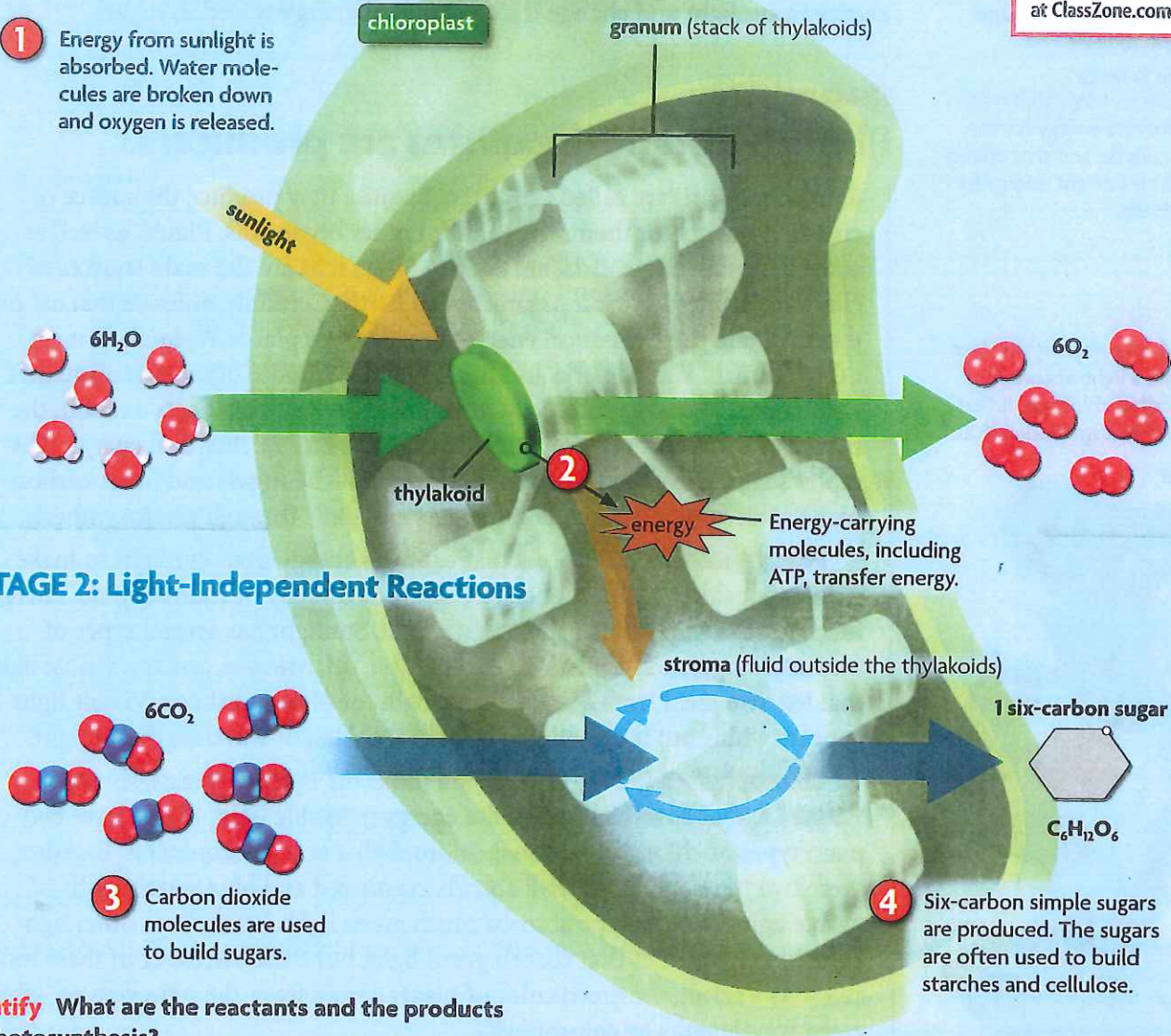
Animated BIOLOGY
View an animation of photosynthesis at ClassZone.com.

STAGE 2: Light-Independent Reactions

- 3 Carbon dioxide molecules are used to build sugars.

- 4 Six-carbon simple sugars are produced. The sugars are often used to build starches and cellulose.

Identify What are the reactants and the products in photosynthesis?



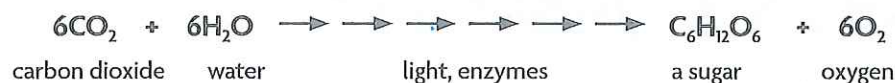
The **light-dependent reactions** capture energy from sunlight. These reactions take place within and across the membrane of the thylakoids. Water (H_2O) and sunlight are needed for this stage of photosynthesis.

- 1 Chlorophyll absorbs energy from sunlight. The energy is transferred along the thylakoid membrane. H_2O molecules are broken down. Oxygen molecules (O_2) are released.
- 2 Energy carried along the thylakoid membrane is transferred to molecules that carry energy, such as ATP.

The **light-independent reactions** use energy from the light-dependent reactions to make sugars. These reactions occur in the stroma of chloroplasts. Carbon dioxide molecules (CO_2) are needed during this stage of photosynthesis.

- 3 CO_2 is added to a cycle of chemical reactions to build larger molecules. Energy from the light-dependent reactions is used in the reactions.
- 4 A molecule of a simple sugar is formed. The sugar, usually glucose ($\text{C}_6\text{H}_{12}\text{O}_6$), stores some of the energy that was captured from sunlight.

The equation for the whole photosynthesis process is shown below. As you can see, there are many arrows between the reactants— CO_2 and H_2O —and the products—a six-carbon sugar and O_2 . Those arrows tell you that photosynthesis has many steps. For example, the light-independent reactions need only one molecule of CO_2 at a time, and the six-carbon sugar comes from a reaction that combines two three-carbon sugars. Also, enzymes and other chemicals are needed, not just light, carbon dioxide, and water.



Glucose and other simple sugars, such as fructose, are not the only carbohydrates that come from photosynthesis. Plants need the simple sugars to build starch and cellulose molecules. In effect, plants need photosynthesis for their growth and development. You will learn more about the importance of another product of photosynthesis—oxygen—in Sections 4.4 and 4.5.

Summarize How is energy from sunlight used to make sugar molecules?

Connecting CONCEPTS

Calvin Cycle The light-independent reactions include a series of chemical reactions called the Calvin cycle. You can read more about the Calvin cycle in Section 4.3.

4.2 ASSESSMENT



REVIEWING MAIN IDEAS

1. What are the roles of chloroplasts and **chlorophyll** in **photosynthesis**? 1.f, 7.1.d
2. Describe the stages of photosynthesis. Use the terms **thylakoid**, **light-dependent reactions**, and **light-independent reactions** in your answer. 1.f

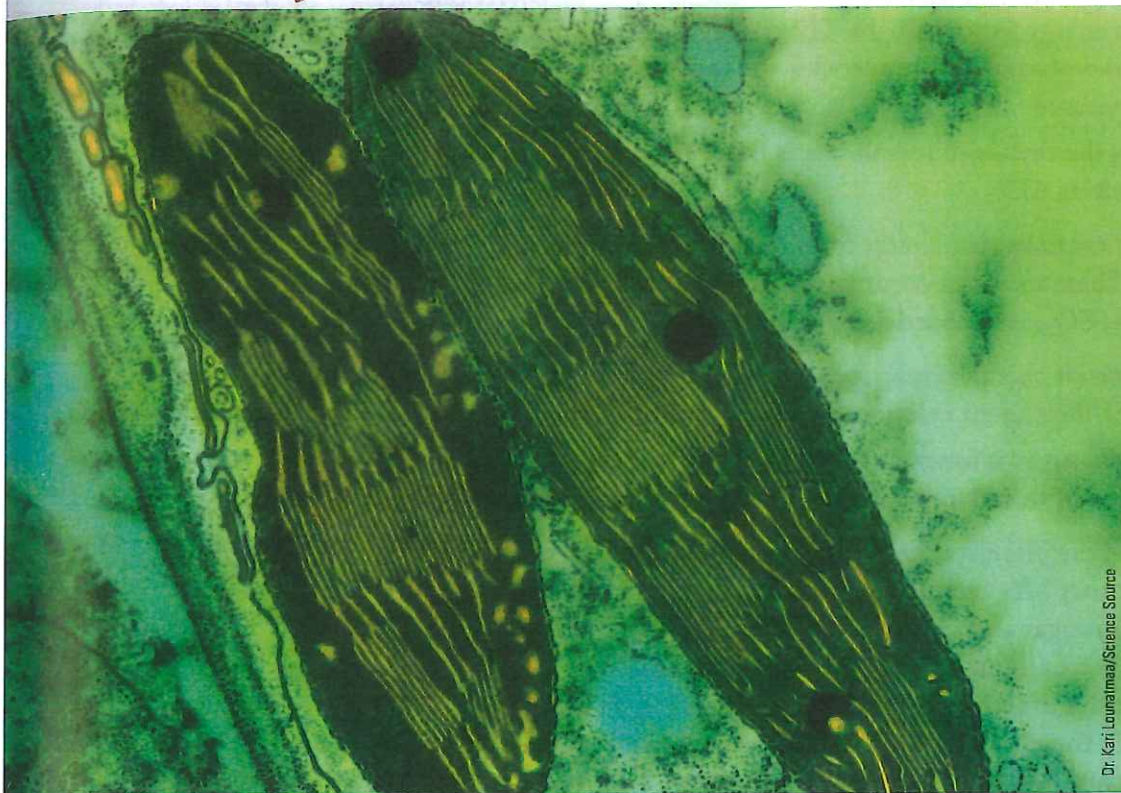
CRITICAL THINKING

3. **Apply** Suppose you wanted to develop a light to help increase plant growth. What characteristics should the light have? Why?
4. **Analyze** Explain why photosynthesis is important for building the structure of plant cells.

Connecting CONCEPTS

5. **Chemical Reactions** Overall, do you think photosynthesis is endothermic or exothermic? Explain your answer.

Photosynthesis



Chloroplasts in the leaf of the pea plant *Pisum sativum* (color-enhanced TEM). The light-dependent reactions of photosynthesis take place within the thylakoids of the chloroplasts (thylakoid membranes are shown in yellow).

Dr. Keri Lounasmaa/Science Source

STUDY OUTLINE

- 8.1 Photosynthesis: An Overview
- 8.2 The Light-Dependent Reactions of Photosynthesis
- 8.3 The Light-Independent Reactions of Photosynthesis
- 8.4 Photorespiration and Alternative Processes of Carbon Fixation
- 8.5 Photosynthesis and Cellular Respiration Compared

Why it matters . . . Plants, some protists (the algae), and some archaeans and bacteria, absorb the radiant energy of sunlight and convert it into chemical energy. These organisms use the chemical energy to convert simple inorganic raw materials—water, carbon dioxide (CO_2) from the air, and inorganic minerals from the soil—into organic molecules. The conversion of light energy to chemical energy in the form of sugar and other organic molecules is called **photosynthesis**. As part of their photosynthetic reactions, these organisms release oxygen.

Plants and other photosynthetic organisms are the most abundant and important *primary producers* of Earth. A **primary producer** is an organism that uses light energy or chemical energy to convert simple inorganic molecules into organic molecules. Plants and other photosynthetic organisms use some of the organic molecules they make as an energy source for their own activities, but they also serve—directly or indirectly—as a food source for *consumers*, the animals that live by eating plants or other animals. Eventually, the bodies of both primary producers and consumers provide chemical energy for bacteria, fungi, and other *decomposers*. In short, the entire food chain on the planet depends on photosynthetic organisms, and because photosynthesis releases oxygen as a product, animals rely on continuing photosynthetic activity to continue to breathe.

This chapter begins with an overview of the photosynthetic reactions. We then examine light and light absorption and the reactions that use absorbed energy to make organic molecules from inorganic substances. In this discussion, we focus on *oxygenic* (oxygen-generating) *photosynthesis* in plants and green algae; other eukaryotic photosynthesizers have individual variations on the process (see Chapter 27). Prokaryotic photosynthesis is described in Chapter 26.

8.1 Photosynthesis: An Overview

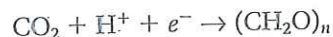
Photosynthesizers and other organisms that make all of their required organic molecules from CO_2 and other inorganic sources such as water are called **autotrophs** (*autos* = self; *trophos* = feeding). Autotrophs that use light as the energy source to make organic molecules by photosynthesis are called **photoautotrophs**. Consumers and decomposers, which need a source of organic molecules to survive, are called **heterotrophs** (*hetero* = different).

As the pathway of energy flows from the Sun through plants (primary producers) and animals to decomposers, the organic molecules made by photosynthesis are broken down into inorganic molecules again, and the chemical energy captured in photosynthesis is released as heat energy. Because the reactions capturing light energy are the first step in this pathway, photosynthesis is the vital link between the energy of sunlight and the vast majority of living organisms.

Electrons Play a Primary Role in Photosynthesis

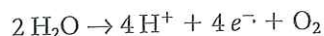
Photosynthesis proceeds in two stages, each involving multiple reactions (**Figure 8.1**). In the first stage, the **light-dependent reactions**, the energy of sunlight is absorbed and converted into chemical energy in the form of ATP and NADPH. ATP is the main energy source for plant cells (as it is for all types of living cells), and NADPH (nicotinamide adenine dinucleotide phosphate) carries electrons that are pushed to high energy levels by absorbed light. In the second stage of photosynthesis, the **light-independent reactions** (also called the *Calvin cycle*), these electrons are used as a

source of energy to convert inorganic CO_2 to an organic form. The conversion process, called **CO_2 fixation**, is a reduction reaction, in which electrons are added to CO_2 . As part of the reduction, protons are also added to CO_2 (reduction and oxidation are discussed in Section 7.1). With the added electrons and protons (H^+), CO_2 is converted to a carbohydrate that contains carbon, hydrogen, and oxygen atoms in the ratio 1 C:2 H:1 O.



Carbohydrate units are often symbolized as $(\text{CH}_2\text{O})_n$, with the “ n ” indicating that different carbohydrates are formed from different multiples of the carbohydrate unit.

In plants, algae, and one group of photosynthetic bacteria (the cyanobacteria), the source of electrons and protons for CO_2 fixation is water (H_2O), the most abundant substance on Earth. Oxygen (O_2) generated from the splitting of the water molecule is released into the environment as a by-product of photosynthesis:



Thus, plants, algae, and cyanobacteria use three resources that are readily available—sunlight, water, and CO_2 —to produce almost all the organic matter on Earth, and to supply the oxygen of our atmosphere.

In organisms that are able to split water, the two reactions shown above are combined and multiplied by 6 to produce a six-carbon carbohydrate such as glucose:



Note that water appears on both sides of the equation; it is both consumed as a reactant and generated as a product in photosynthesis.

Although glucose is the major product of photosynthesis, other monosaccharides, disaccharides, polysaccharides, lipids, and amino acids are also produced indirectly. In fact, all the organic molecules of plants are assembled as direct or indirect products of photosynthesis.

The relationships between the light-dependent and light-independent reactions are summarized in **Figure 8.1**. Notice that the ATP and NADPH produced by the light-dependent reactions, along with CO_2 , are the reactants of the light-independent reactions. The ADP, inorganic phosphate (P_i), and NADP^+ (the oxidized form of NADPH) produced by the light-independent reactions, along with H_2O , are the reactants for the light-dependent reactions. The light-dependent and light-independent reactions thus form a cycle in which the net inputs are H_2O and CO_2 , and the net outputs are organic molecules and O_2 .

Oxygen Released by Photosynthesis Derives from the Splitting of Water

Early investigators thought that the O_2 released by photosynthesis came from the CO_2 entering the process. The fact that it

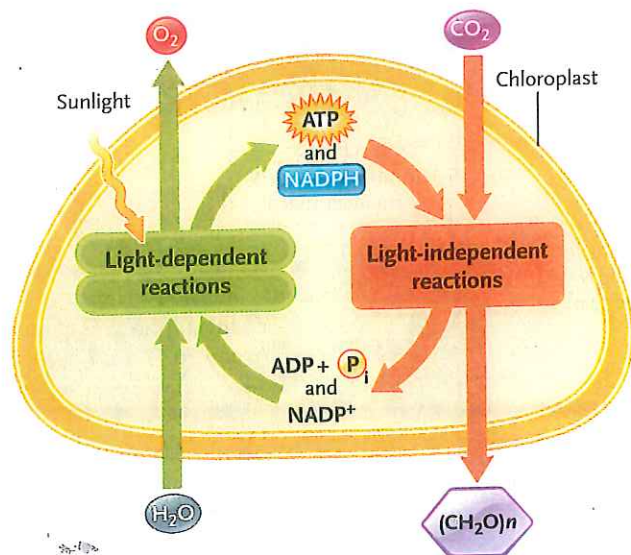
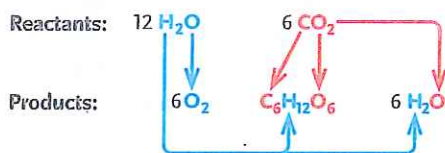


FIGURE 8.1 The light-dependent and light-independent reactions of photosynthesis, and their interlinking reactants and products. Both series of reactions occur in the chloroplasts of plants and algae.

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comes from the splitting of water was demonstrated experimentally in 1941 when Samuel Ruben and Martin Kamen of the University of California, Berkeley, used a heavy isotope of oxygen, ^{18}O , to trace the pathways of the atoms through photosynthesis. A substance containing heavy ^{18}O can be distinguished readily from the same substance containing the normal isotope, ^{16}O . When a photosynthetic organism was supplied with water containing ^{18}O , the heavy isotope showed up in the O_2 given off in photosynthesis. However, if the organisms were supplied with carbon dioxide containing ^{18}O , the heavy isotope showed up in the carbohydrate and water molecules assembled during the reactions—but not in the oxygen gas. This experiment, and similar experiments using different isotopes, revealed where each atom of the reactants end up in products:



The water-splitting reaction probably developed before oxygen-consuming organisms appeared, evolving first about 3 billion years ago in primitive photosynthetic bacteria that were ancestors to present-day cyanobacteria. The oxygen released by the reaction profoundly changed the atmosphere. It allowed for aerobic respiration in which oxygen serves as the final acceptor for electrons removed in cellular oxidations. The existence of all animals depends on the oxygen provided by the water-splitting reaction of photosynthesis.

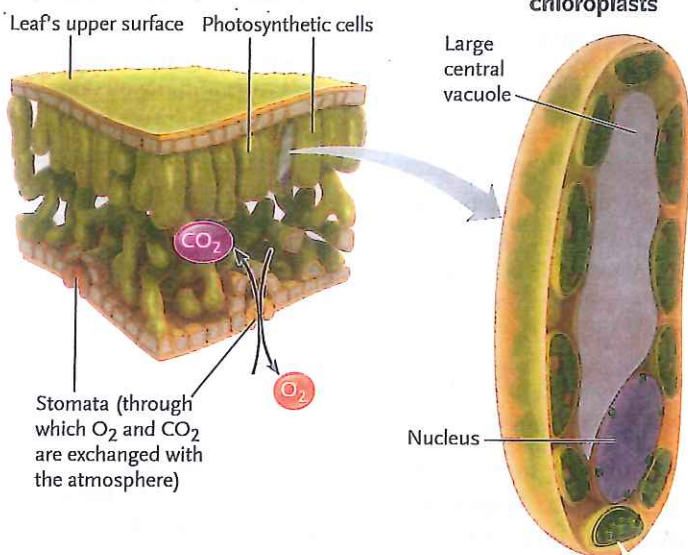
In Eukaryotes, Photosynthesis Takes Place in Chloroplasts

In eukaryotes, the photosynthetic reactions take place in the chloroplasts of plants and algae. In cyanobacteria, the reactions are distributed between the plasma membrane and the cytosol.

Chloroplasts from individual algal and plant groups differ in structural details. The chloroplasts of plants and green algae are formed from three membranes that enclose three compartments inside the organelles (**Figure 8.2**). (Chloroplast structure is also described in Section 4.4.) An *outer membrane* covers the entire surface of the organelle. An *inner membrane* lies just inside the outer membrane. Between the outer and inner membranes is an *intermembrane compartment*. The fluid within the compartment formed by the inner membrane is the **stroma**. Within the stroma is the third membrane system, the *thylakoid membranes*, which form flattened, closed sacs called **thylakoids**. The space enclosed by a thylakoid is called the *thylakoid lumen*.

In green algae and higher plants, thylakoids are arranged into stacks called **grana** (singular, *granum*; shown in Figure 8.2). The grana are interconnected by flattened, tubular membranes called *stromal lamellae*. The stromal lamellae probably link the thylakoid lumens into a single continuous space within the stroma.

Cutaway of a small section from the leaf



Cutaway view of a chloroplast

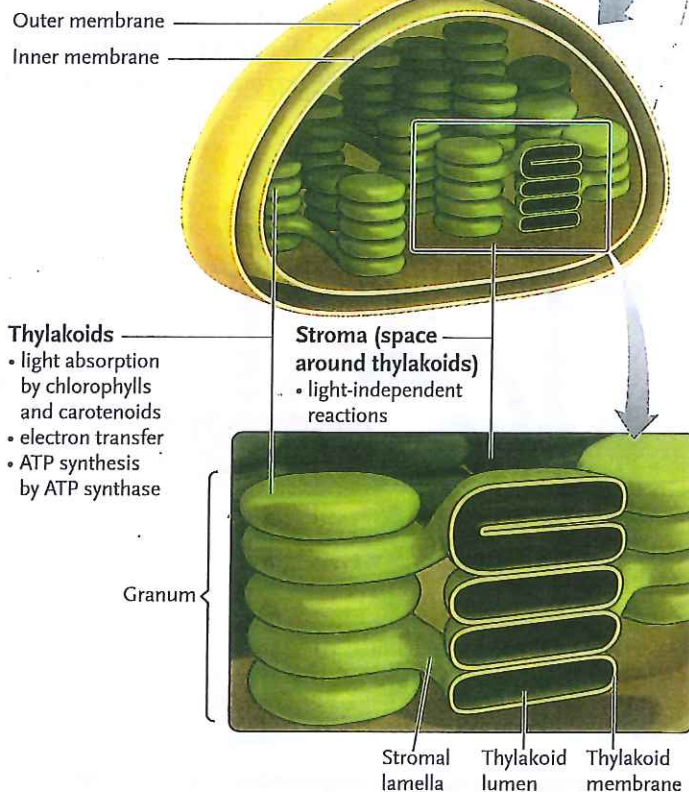


FIGURE 8.2 The membranes and compartments of chloroplasts.
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