# 4.3 Photosynthesis in Detail

**VOCABULARY**

photosystem
electron transport chain
ATP synthase
Calvin cycle

**KEY CONCEPT** **Photosynthesis requires a series of chemical reactions.**

**MAIN IDEAS**

- The first stage of photosynthesis captures and transfers energy.
- The second stage of photosynthesis uses energy from the first stage to make sugars.

### Connect to Your World

In a way, the sugar-producing cells in leaves are like tiny factories with assembly lines. In a factory, different workers with separate jobs have to work together to put together a finished product. Similarly, in photosynthesis many different chemical reactions, enzymes, and ions work together in a precise order to make the sugars that are the finished product.

**MAIN IDEA**

## The first stage of photosynthesis captures and transfers energy.

In Section 2 you read a summary of photosynthesis. However, the process is much more involved than that general description might suggest. For example, during the light-dependent reactions, energy is captured and transferred in the thylakoid membranes by two groups of molecules called **photosystems.** The two photosystems are called photosystem I and photosystem II.

### Overview of the Light-Dependent Reactions

The light-dependent reactions are the *photo-* part of photosynthesis. During the light-dependent reactions, chlorophyll and other light-absorbing molecules capture energy from sunlight. Water molecules are broken down into hydrogen ions, electrons, and oxygen gas. The oxygen is given off as a waste product. Sugars are not made during this part of photosynthesis.

**FIGURE 3.1** The light-dependent reactions capture energy from sunlight and transfer energy through electrons. The solar cells that power a solar car do the same thing.



The main functions of the light-dependent reactions are to capture and transfer energy. In these reactions, as in the solar car in **FIGURE 3.1,** energy is transferred to electrons. The electrons are only used for energy in a few specific processes. Recall a time when you went to an amusement park. To go on rides, you needed special tickets that could be used only there. Similarly, the electrons are used for energy during photosynthesis but not for the cell's general energy needs.

Energy from the electrons is used to make molecules that act as energy carriers. These energy carriers are ATP and another molecule called NADPH. The ATP from the light-dependent reactions is usually not used for a cell's general energy needs. In this case, ATP molecules, along with NADPH molecules, go on to later stages of photosynthesis.

## Photosystem II and Electron Transport

In photosystem II, chlorophyll and other light-absorbing molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons. As shown in **FIGURE 3.2**, photosystem II needs water to function.

1. **Energy absorbed from sunlight** Chlorophyll and other light-absorbing molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons ($e^-$). High-energy electrons leave the chlorophyll and enter an **electron transport chain,** which is a series of proteins in the membrane of the thylakoid.
2. **Water molecules split** Enzymes break down water molecules. Oxygen, hydrogen ions ($H^+$), and electrons are separated from each other. The oxygen is released as waste. The electrons from water replace those electrons that left chlorophyll when energy from sunlight was absorbed.
3. **Hydrogen ions transported** Electrons move from protein to protein in the electron transport chain. Their energy is used to pump $H^+$ ions from outside to inside the thylakoid against a concentration gradient. The $H^+$ ions build up inside the thylakoid. Electrons move on to photosystem I.

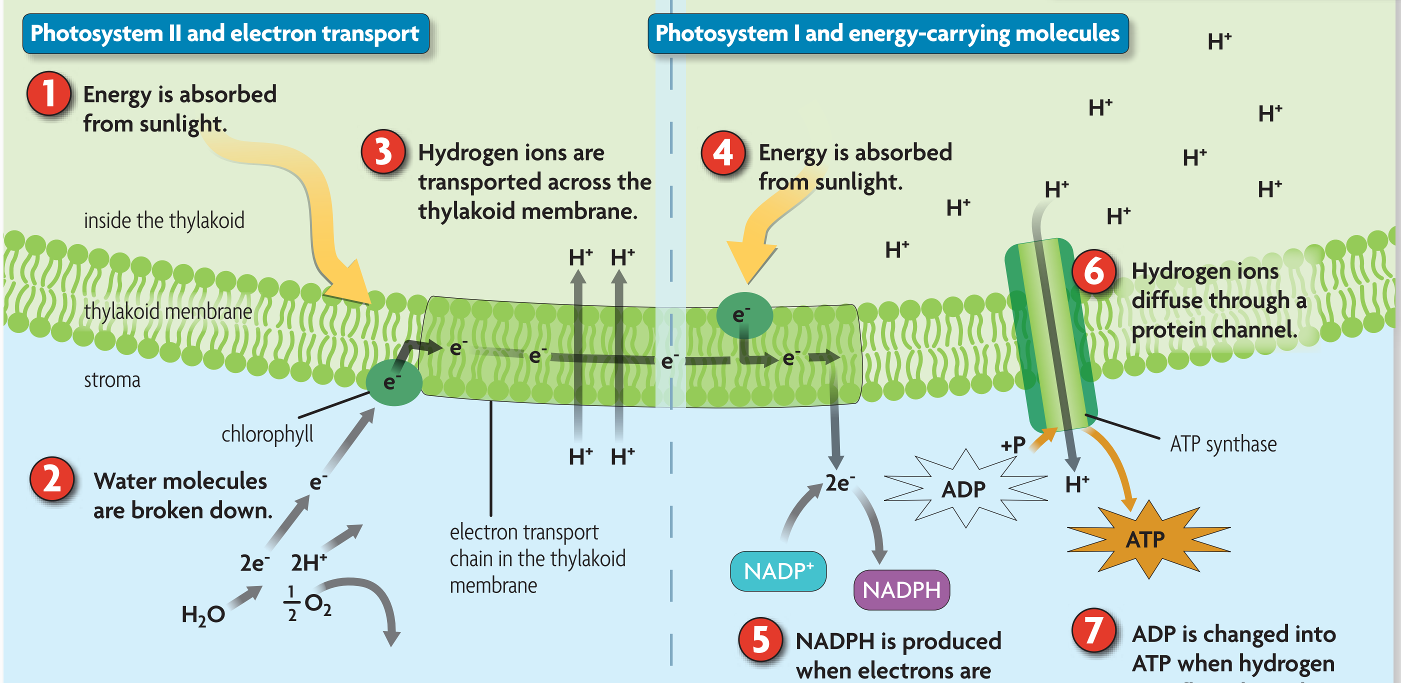
## Photosystem I and Energy-Carrying Molecules

In photosystem I, chlorophyll and other light-absorbing molecules in the thylakoid membrane also absorb energy from sunlight. The energy is added to electrons, some of which enter photosystem I from photosystem II.

Light-dependent reactions take place in and across the thylakoid membrane.

### FIGURE 3.2 Light-Dependent Reactions

**Photosystems II and I absorb energy from sunlight and transfer energy to the Calvin cycle.**




**Identify** **At what two points in the process are electrons used in the transfer of energy?**

**4** **Energy absorbed from sunlight** As in photosystem II, chlorophyll and other light-absorbing molecules inside the thylakoid membrane absorb energy from sunlight. Electrons are energized and leave the molecules.

**5** **NADPH produced** The energized electrons are added to a molecule called $NADP^+$, forming a molecule called NADPH. In photosynthesis, $NADP^+$ functions like ADP, and NADPH functions like ATP. The molecules of NADPH go to the light-independent reactions.

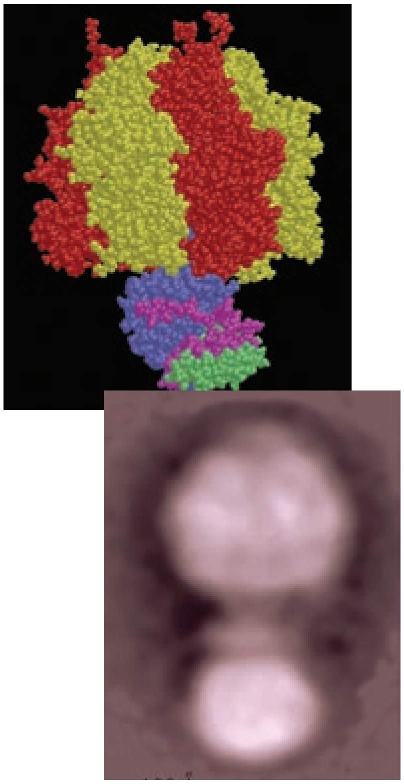


**FIGURE 3.3** Scientists have made detailed computer models of ATP synthase (top). Scientists are still working on viewing the actual molecule (bottom). (colored TEM; magnification 1,800,000×)

### ATP Production

The final part of the light-dependent reactions makes ATP. The production of ATP depends on the $H^+$ ions that build up inside the thylakoid from photosystem II, and on a complex enzyme in the thylakoid membrane.

**6** **Hydrogen ion diffusion** Hydrogen ions flow through a protein channel in the thylakoid membrane. Recall that the concentration of $H^+$ ions is higher inside the thylakoid than it is outside. This difference in $H^+$ ion concentration is called a chemiosmotic gradient, which stores potential energy. Therefore, the ions flow through the channel by diffusion.

**7** **ATP produced** The protein channel in step 6 is part of a complex enzyme called **ATP synthase,** shown in **FIGURE 3.3.** As the ions flow through the channel, ATP synthase makes ATP by adding phosphate groups to ADP.

### Summary of the Light-Dependent Reactions

- Energy is captured from sunlight by light-absorbing molecules. The energy is transferred to electrons that enter an electron transport chain.
- Water molecules are broken down into $H^+$ ions, electrons, and oxygen molecules. The water molecules provide the $H^+$ ions and electrons that are used in the light-dependent reactions.
- Energized electrons have two functions. They provide energy for $H^+$ ion transport, and they are added to $NADP^+$ to form NADPH.
- The flow of $H^+$ ions through ATP synthase makes ATP.
- The products are oxygen, NADPH, and ATP. Oxygen is given off as a waste product. Energy from ATP and NADPH is used later to make sugars.

**Summarize** **Describe how energy from sunlight is transferred to ATP and NADPH.**

MAIN IDEA

## The second stage of photosynthesis uses energy from the first stage to make sugars.

The light-independent reactions, like the light-dependent reactions, take place inside chloroplasts. But as the name implies, the light-independent reactions do not need sunlight. These reactions can take place anytime that energy is available. The energy sources for the light-independent reactions are the molecules of ATP and NADPH formed during the light-dependent reactions. The energy is needed for a series of chemical reactions called the Calvin cycle, which is named for the scientist who discovered the process.

## The Calvin Cycle

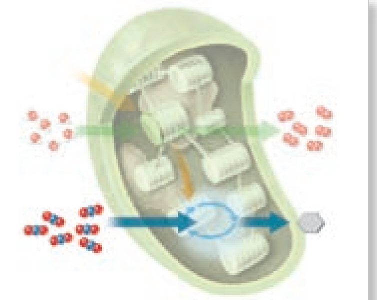
The Calvin cycle cannot take place without the ATP from the light-dependent reactions. The chemical reactions of the **Calvin cycle** use carbon dioxide ($CO_2$) gas from the atmosphere and the energy carried by ATP and NADPH to make simple sugars. Because the light-independent reactions build sugar molecules, they are the *synthesis* part of photosynthesis. Only one molecule of $CO_2$ is actually added to the Calvin cycle at a time. The simplified cycle in **FIGURE 3.4** shows three $CO_2$ molecules added at once.

1. **Carbon dioxide added** $CO_2$ molecules are added to five-carbon molecules already in the Calvin cycle. Six-carbon molecules are formed.
2. **Three-carbon molecules formed** Energy—ATP and NADPH—from the light-dependent reactions is used by enzymes to split the six-carbon molecules. Three-carbon molecules are formed and rearranged.
3. **Three-carbon molecules exit** Most of the three-carbon molecules stay in the Calvin cycle, but one high-energy three-carbon molecule leaves the cycle. After two three-carbon molecules have left the cycle, they are bonded together to build a six-carbon sugar molecule such as glucose.
4. **Three-carbon molecules recycled** Energy from ATP molecules is used to change the three-carbon molecules back into five-carbon molecules. The five-carbon molecules stay in the Calvin cycle. These molecules are added to new $CO_2$ molecules that enter the cycle.

**READING TOOLBOX**

**VOCABULARY**

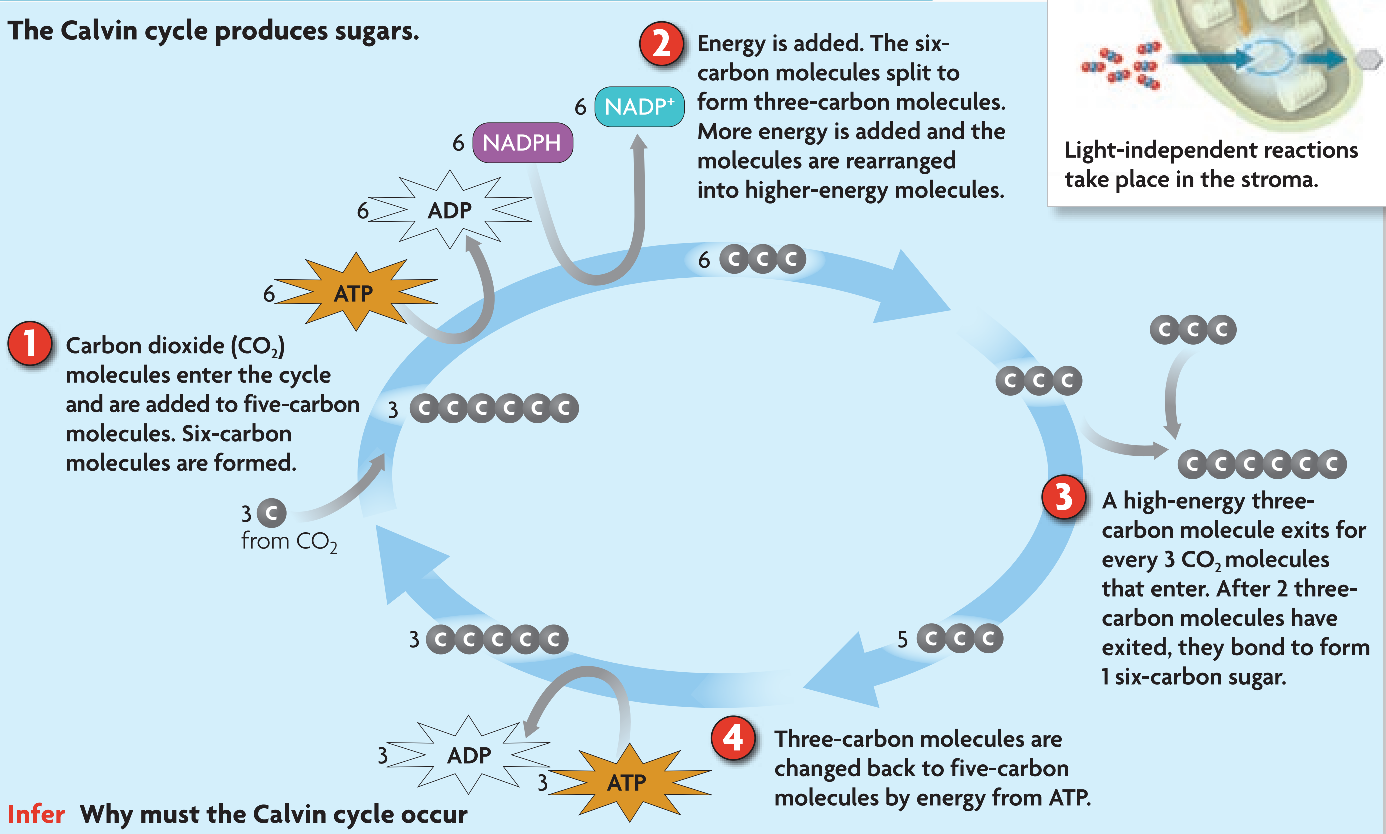
The light-dependent reactions are the *photo-* part of photosynthesis. The light-independent reactions are the *synthesis* part of photosynthesis.



Light-independent reactions take place in the stroma.

### FIGURE 3.4 Light-Independent Reactions (Calvin Cycle)

**The Calvin cycle produces sugars.**




**Infer** Why must the Calvin cycle occur more than once to build a sugar molecule?

## Summary of the Light-Independent Reactions

- Carbon dioxide enters the Calvin cycle.
- ATP and NADPH from the light-dependent reactions transfer energy to the Calvin cycle and keep the cycle going.
- One high-energy three-carbon molecule is made for every three molecules of carbon dioxide that enter the cycle.
- Two high-energy three-carbon molecules are bonded together to make a sugar. Therefore, six molecules of carbon dioxide must be added to the Calvin cycle to make one six-carbon sugar.
- The products are a six-carbon sugar such as glucose, $NADP^+$, and ADP. The $NADP^+$ and ADP molecules return to the light-dependent reactions.

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## Functions of Photosynthesis

Photosynthesis is much more than just a biochemical process. Photosynthesis is important to most organisms on Earth, as well as to Earth's environment. Recall that plants produce food for themselves and for other organisms through photosynthesis. Both plant cells and animal cells release the energy stored in sugars through cellular respiration. Cellular respiration, which uses the oxygen that is a waste product of photosynthesis, is the process that makes most of the ATP used by plant and animal cells.

Photosynthesis does more than make sugars. It also provides materials for plant growth and development. The simple sugars from photosynthesis are bonded together to form complex carbohydrates such as starch and cellulose. Starches store sugars until they are needed for energy. Cellulose is a major part of plant structure—it is the building block of plant cell walls. Photosynthesis also helps to regulate Earth's environment. The carbon atoms used to make sugar molecules come from carbon dioxide gas in the air, so photosynthesis removes carbon dioxide from Earth's atmosphere.

CONNECT TO
**ECOLOGY**
Photosynthesis is a major part of the carbon cycle. You will learn more about the carbon cycle in **Principles of Ecology.**

**Summarize** **How does the Calvin cycle build sugar molecules?**

## 4.3 Formative Assessment

### REVIEWING ▶ MAIN IDEAS

1. How do the two **photosystems** work together to capture energy from sunlight?
2. Explain the relationship between the light-dependent and the light-independent reactions.

### CRITICAL THINKING

3. **Connect** Explain how the **Calvin cycle** is a bridge between carbon in the atmosphere and carbon-based molecules in the food you eat.
4. **Evaluate** Explain why the chemical equation for photosynthesis (below) is a highly simplified representation of the process. How is the equation accurate? How is it inaccurate?

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

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PREMIUM CONTENT

CONNECT TO
**CELL FUNCTIONS**

5. Explain how both passive transport and active transport are necessary for photosynthesis to occur.