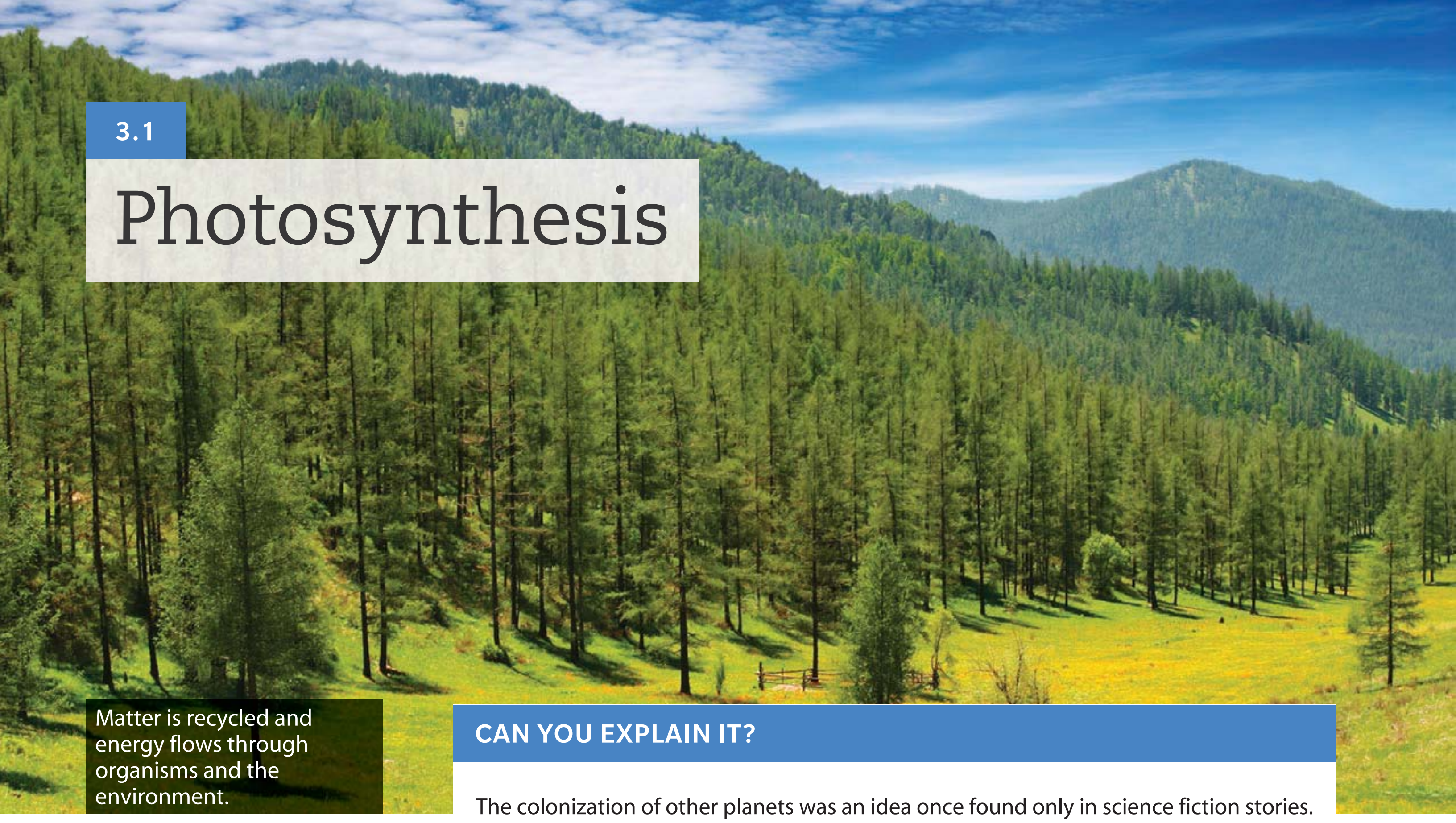


3.1

Photosynthesis

Matter is recycled and energy flows through organisms and the environment.

CAN YOU EXPLAIN IT?

The colonization of other planets was an idea once found only in science fiction stories. Today, this idea is closer to becoming a realistic pursuit. One of the problems that must be solved before the colonists leave Earth is this—where will the colonists get food? One line of inquiry involves figuring out what it takes to grow plants in an environment different from Earth.

Gather Evidence As you explore the lesson, gather evidence to describe the inputs and outputs of matter and the transfer and transformation of energy in photosynthesis.

FIGURE 1: Astronauts from NASA and around the world have been growing plants in space to learn how to someday grow them on other planets, such as Mars.

Explore Online

Predict Imagine you are colonizing another planet, and you want to grow plants there as a food source. What do you need to bring, and what questions would you ask about the planet in order to refine your list?

Matter and Energy in Photosynthesis

Living systems take in energy and matter and convert them to forms they can use. Plants, for example, are producers that capture light energy and convert it to chemical energy to carry out cell processes within the plant. The chemical energy takes the form of chemical bonds in sugar molecules. When a consumer, such as a panda, eats plant matter, it obtains this energy and other nutrients it needs for cell processes and growth through the process of digestion. Any matter that cannot be digested is excreted as waste.

FIGURE 2: This panda is a consumer that gets its energy and nutrients from eating leaves.

Explain Describe the transformation of energy as it is transferred from the sun to the panda.

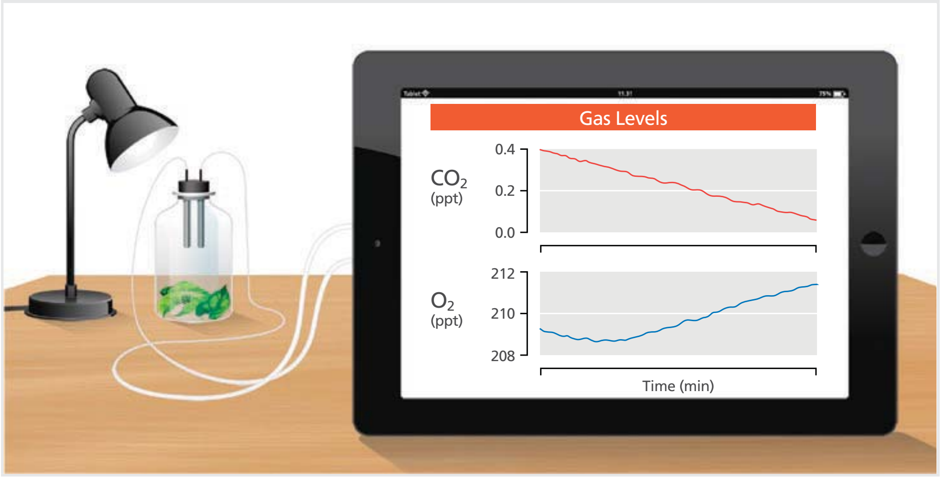
Modeling Photosynthesis

Plants, algae, and some bacteria use a process called photosynthesis to capture and transform light energy from the sun and store it in high-energy sugar molecules. Both plant cells and animal cells use sugars made by photosynthesis as an energy source. However, photosynthesis is not just important to organisms—it also helps regulate Earth's environment. Photosynthesis produces the oxygen we breathe, and it removes carbon dioxide from Earth's atmosphere.

Organisms are complex living systems. Organisms live and interact in ecosystems, which are systems within the biosphere. All organisms play different roles in the cycling of matter and the transfer of energy in their ecosystem. To better understand the relationship between organisms and the environment, scientists collect many different types of data.

Collaborate Discuss with a partner why it would be beneficial to human survival to have plants on a planet where oxygen levels are low and carbon dioxide levels are high.

FIGURE 3: This setup shows a plant in a closed system. Sensors are measuring carbon dioxide and oxygen concentrations in the chamber. The gas concentrations are shown in parts per thousand.



Gather Evidence Identify inputs and outputs for this system. How can the data help scientists understand the relationship between plants and the environment?

Photosynthesis is important to life on Earth. Nearly all organisms on Earth depend on this process. So understanding the relationship between organisms and photosynthesis is critical. Using equipment to measure the rate of photosynthesis, for example, is one way to study the impact that organisms have on the process. Using models is another way to understand processes like photosynthesis. Scientists can study the relationship between the inputs and outputs.

Energy and Matter

Model Draw a plant and label the inputs and outputs of photosynthesis. Where should the labels for enzymes and light be placed?

The process of photosynthesis can be modeled in various ways. For example, a chemical equation is one way to represent photosynthesis.

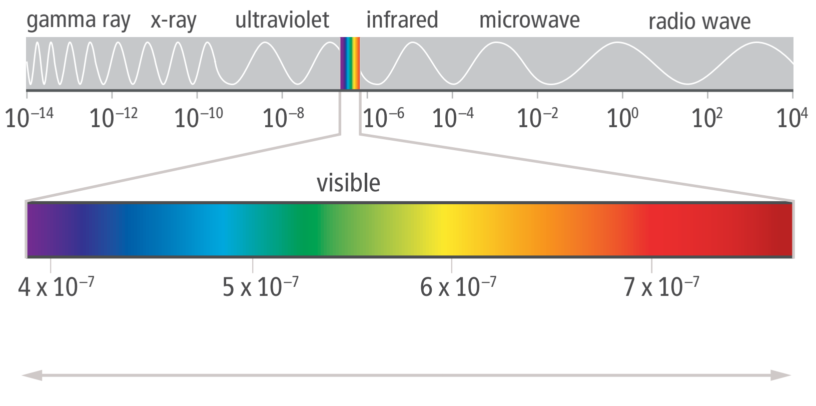
$$6CO_2 + 6H_2O \xrightarrow[\text{light}]{\text{enzymes}} \rightarrow \rightarrow 6O_2 + C_6H_{12}O_6$$

This model shows the inputs and outputs as reactants and products. The multiple arrows indicate that the process of photosynthesis has many steps. Light and enzymes are placed over the arrows to indicate that they must be present for this reaction to take place. In this equation, carbon dioxide and water are reactants, and oxygen and glucose are products. Plant cells use glucose to form complex carbohydrates such as starch and cellulose, which the plant uses for growth and maintenance.

Light and Photosynthesis

Light is a form of energy known as electromagnetic radiation. Electromagnetic radiation travels in waves of various wavelengths, as shown in Figure 4. Plants absorb only visible light to use for photosynthesis. Even in the visible portion of the electromagnetic spectrum, not all wavelengths are absorbed by plants. Visible light consists of different wavelengths that correspond to different colors of light.

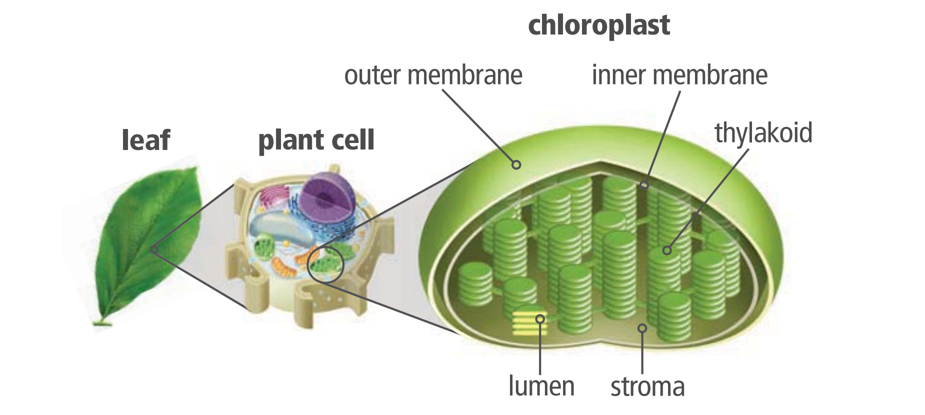
FIGURE 4: The Electromagnetic Spectrum



Analyze Think about light as a form of energy and answer the following questions: What are microwaves used for? What are radio waves used for? What do you think might happen if visible light were blocked from Earth? How would photosynthesis be impacted?

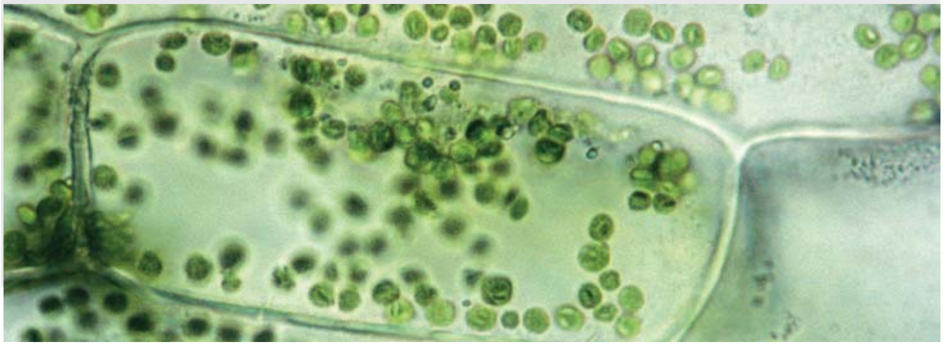
In plant cells, light absorption and photosynthesis take place inside an organelle called a chloroplast. Inside the inner membrane of the chloroplast are stacks of disc-shaped sacs called thylakoids, which contain pigment molecules called chlorophyll.

FIGURE 5: The area inside the chloroplast is the stroma. The area inside the thylakoid sac is called the lumen. The stages of photosynthesis occur across the thylakoid membrane that separates the stroma and the lumen.



Different types of chlorophyll absorb different wavelengths of light, transforming the light energy into chemical energy through photosynthesis. Unabsorbed wavelengths get reflected by the plant's pigments, and our eyes detect these as the plant's color.

FIGURE 6: Chlorophyll is a pigment molecule in chloroplasts. Plants have two main types of chlorophyll, called chlorophyll *a* and chlorophyll *b*.



Explain Place these systems in order from largest to smallest, beginning with Earth, and explain your reasoning: tree, biosphere, plant cell, chloroplast, leaf

Analyze Which colors of light are absorbed, and which colors are reflected by most plants?

Engineering

Choosing a Light Source

Scientists and engineers may study the inputs and outputs of a system as part of optimizing the system. For example, different light sources can affect the rate of photosynthesis in a plant system. Different light sources emit light with a variety of wavelengths. Light emitting diodes, or LEDs, can be designed to only give off certain colors, such as red, blue, or green, which correspond to different wavelengths of visible light. Applying specific light sources to plants is one way to optimize the rate of photosynthesis.

Explore Online

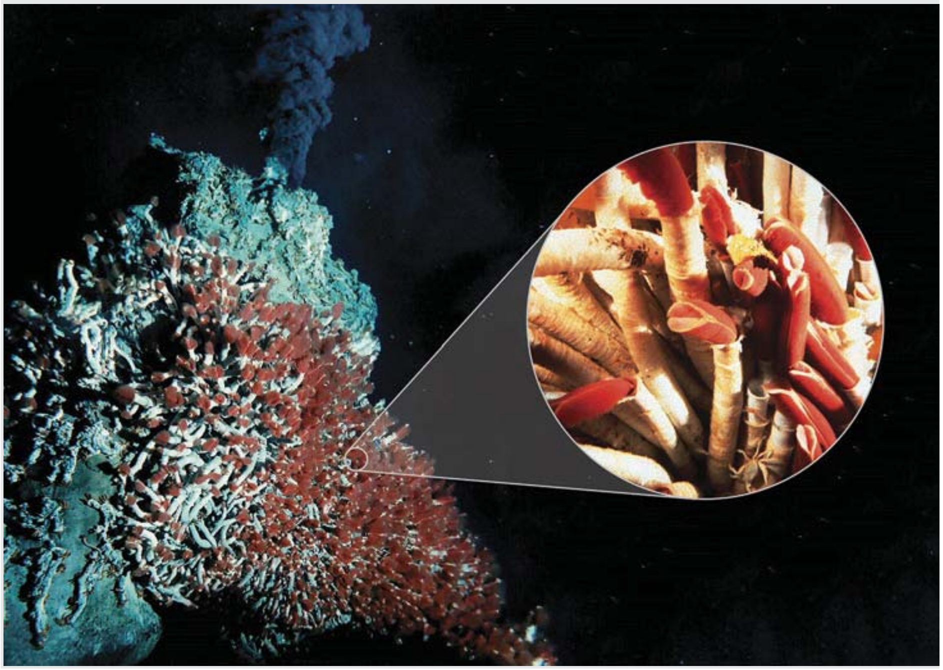
Hands-On Lab

Investigating Light Sources and Photosynthesis Design an experiment to investigate the effect of different light sources on the rate of photosynthesis.

Comparing Producers

Most, but not all, organisms rely directly or indirectly on sunlight and photosynthesis. Places such as deep oceans and dark caves have thriving populations despite never receiving any sunlight. The very hot water found near cracks in the ocean floor, called hydrothermal vents, is one such environment. These vents release chemical compounds such as hydrogen sulfide (H_2S) that serve as an energy source. Hydrothermal vents support a dense ecosystem made up of organisms completely dependent on the chemicals coming out of the sea floor.

FIGURE 7: Chemosynthetic microbes live on or below the sea floor, and inside the bodies of other vent animals. Tubeworms grow in clumps around the vents.



Chemosynthesis is the process of using chemical energy to make sugars from carbon dioxide for energy storage. Like plants that rely on photosynthesis, chemosynthetic organisms make their own food, but the raw materials differ.

The producers that live around hydrothermal vents carry out a process represented by the following chemical equation. The process produces the carbohydrates these producers need for energy.

$$6CO_2 + 24H_2S + 6O_2 \rightarrow C_6H_{12}O_6 + 24S + 18H_2O$$

Model Make a graphic organizer to compare the inputs and outputs for chemosynthesis and for photosynthesis.

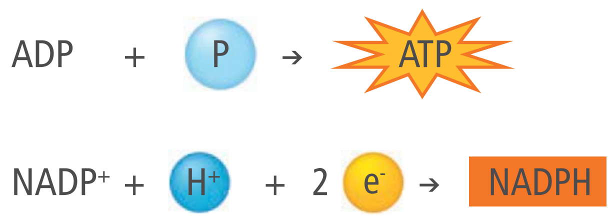
Analyze Think back to the question about growing plants on another planet and answer the following questions:

1. What inputs would you need to provide in order for plants to carry out photosynthesis?
2. What are the outputs from plants that are needed for human survival?
3. How would producers that carry out chemosynthesis differ from photosynthetic producers as a possible food source?

Transforming Light Energy into Chemical Energy

So far you have seen that plants transform energy from sunlight into chemical energy stored in the chemical bonds of sugar molecules. But, how does this transformation of energy happen? Chloroplasts in cells are like solar-powered chemical factories. They transfer light energy to energy-carrying molecules called ATP and NADPH. Cells use these molecules as energy currency for cell processes. In plant cells, they are used to convert carbon dioxide into sugars.

FIGURE 8: Two energy-carrying molecules are used in photosynthesis. ATP stores energy in a phosphate-phosphate bond, and NADPH carries high-energy electrons.

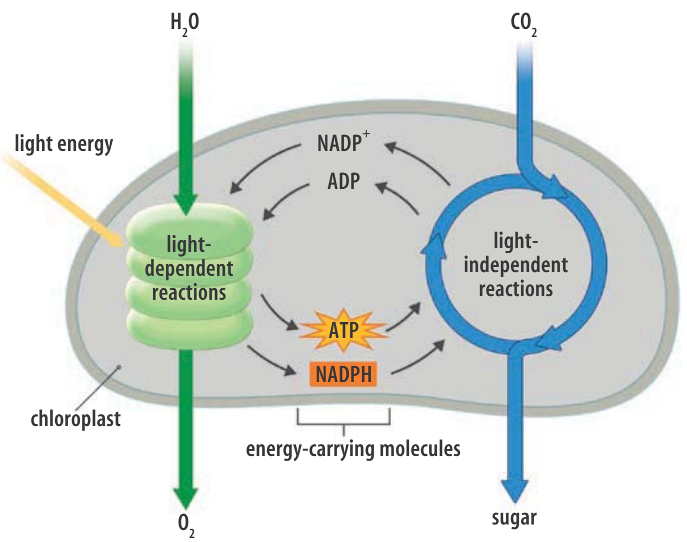


Predict How do you think plant cells transfer energy from sunlight to the energy-carrying molecules ATP and NADPH?

Stages of Photosynthesis

Photosynthesis can be broken into two stages – the light-dependent reactions and the light-independent reactions. The light-dependent reactions take place within and across the membrane of the thylakoids, which are stacked inside the chloroplast. The light-independent reactions take place in the stroma, the area outside the thylakoids.

FIGURE 9: The two stages of photosynthesis, light-dependent reactions and light-independent reactions, occur in the chloroplast.



Gather Evidence Examine the diagram of the chloroplast. How does alternating between light-dependent and light-independent reactions help the cell conserve energy and matter? Cite evidence from the diagram to support your answer.

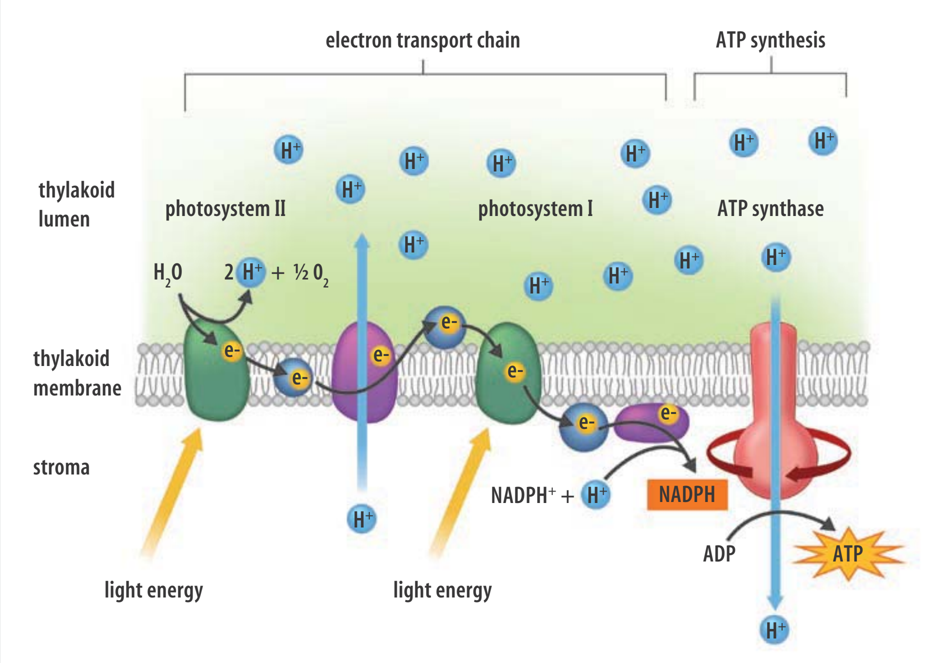
Analyze Identify the inputs and outputs for both stages of photosynthesis. Specify for both energy and matter.

The Light-Dependent Reactions

The light-dependent reactions are the *photo* part of photosynthesis. The main functions of the light-dependent reactions are to capture and transfer energy. Light energy is captured and transferred in the thylakoid membrane by two groups of molecules called photosystem II and photosystem I. They are named for the order in which they were discovered, not the order in which they occur.

FIGURE 10: The Light-Dependent Reactions

Explore Online



The light-dependent reactions are summarized in the steps below.

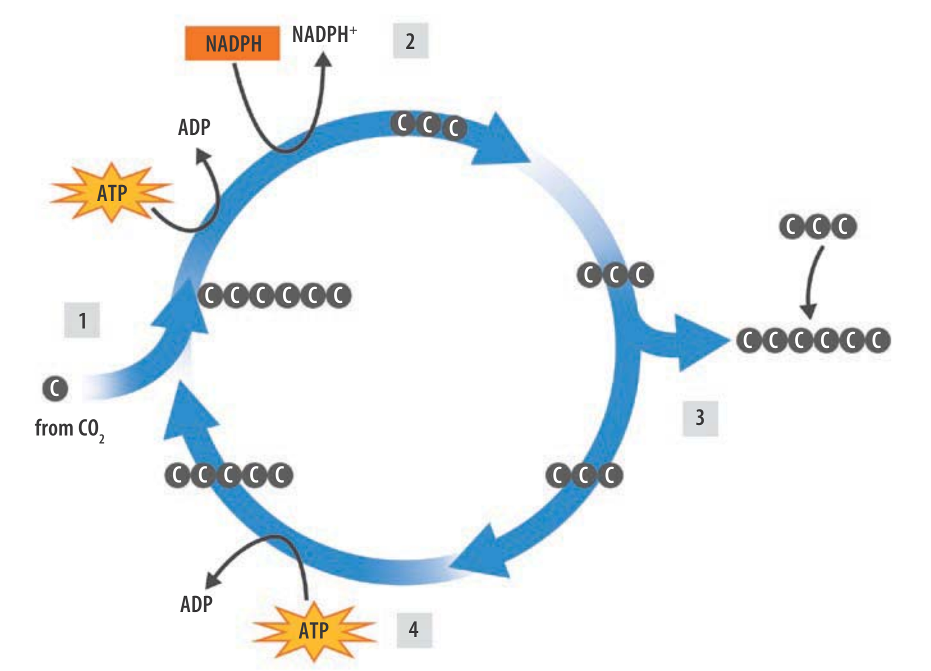
1. **Energy absorbed from sunlight**—In photosystem II, chlorophyll and other pigment molecules in the thylakoid membrane absorb energy from sunlight. The energy is transferred to electrons (e^-). These high-energy electrons leave the chlorophyll and enter the electron transport chain, a series of proteins in the thylakoid membrane.
2. **Water molecules split**—Enzymes break down water molecules. Electrons from water molecules replace the electrons that left the chlorophyll. Hydrogen ions (H^+) remain inside the thylakoid, and oxygen is released as a waste product.
3. **Hydrogen ions transported**—Energized electrons move from protein to protein in the electron transport chain. Their energy is used to pump hydrogen ions across the thylakoid membrane. The result is a buildup of hydrogen ions inside the thylakoid, establishing a concentration gradient, which is a form of stored energy. The electrons move on to photosystem I.
4. **Energy absorbed from sunlight**—In photosystem I, chlorophyll and other pigment molecules in the thylakoid membrane absorb energy from sunlight. Energized electrons leave the pigment molecules.
5. **NADPH produced**—The energized electrons from photosystem I are added to $NADP^+$ to form NADPH, an energy-carrying molecule, by an enzyme.
6. **Hydrogen ion diffusion**—Hydrogen ions diffuse out of the thylakoid through the ATP synthase protein channel. Diffusion of the hydrogen ions is powered by the concentration gradient. ATP synthase uses energy from the concentration gradient to make ATP by adding a phosphate group to ADP.

Model Make a simple flow chart to show how energy is transferred from light to ATP in the light-dependent stage of photosynthesis.

The Light-Independent Reactions

The second stage of photosynthesis uses energy from the light-dependent reactions to make sugars. As the name for this stage implies, the light-independent reactions do not need sunlight. These reactions can take place any time energy is available. The energy sources for the light-independent reactions are the molecules ATP and NADPH formed during the light-dependent reactions. This energy is needed for a series of chemical reactions called the Calvin cycle, named for the scientist Melvin Calvin, who discovered the process. The Calvin cycle is the *synthesis* part of photosynthesis. Its chemical reactions use the energy carried by the ATP and NADPH produced by the light-dependent reactions to make simple sugars.

FIGURE 11: The Light-Independent Reactions



Collaborate A common misconception is that the bulk of a plant's material comes from soil or water. Explain where the carbon in sugars actually comes from, citing evidence from the Calvin cycle to support your answer.

The light-independent reactions are summarized in the steps below.

1. **Carbon dioxide added**—A CO_2 molecule is added to a 5-carbon molecule already in the cycle, yielding a 6-carbon molecule.
2. **Three-carbon molecules formed**—The 6-carbon molecule splits, forming two 3-carbon molecules. ATP and NADPH provide the energy to rearrange these 3-carbon molecules into higher-energy molecules that also have 3 carbons each.
3. **Three-carbon molecules exit**—One high-energy 3-carbon molecule leaves the cycle while the rest remain. One 6-carbon sugar molecule is formed from every two 3-carbon molecules that exit the cycle.
4. **Three-carbon molecules recycled**—Energy from ATP is used to change five 3-carbon molecules into three 5-carbon molecules, which stay in the Calvin cycle to accept new CO_2 molecules that enter the cycle.

Explain How does the Calvin cycle act as a bridge between carbon in the atmosphere and carbon-based molecules in the food you eat?

Model Develop a model to illustrate how photosynthesis transforms light energy into chemical energy. In your model, show how energy from sunlight is transformed to energy stored in sugars, and identify the inputs and outputs for each stage of the process.

Guided Research

Variation in Photosynthesis

Not all plants carry out photosynthesis in exactly the same way. There are three different pathways of photosynthesis that depend on the carbon-based compound first produced when CO_2 enters the light-independent reactions. Recall the light-independent reactions, or Calvin cycle, use energy from ATP and NADPH to build sugars from smaller molecules. Carbon enters the Calvin cycle as CO_2 molecules, which are rearranged during chemical reactions to form sugar. Early in the process, 3-carbon molecules are formed and exit the cycle to form 6-carbon sugars. The formation of 3-carbon molecules occurs in most plants, resulting in the name C3 plants. This is one pathway in which carbon is rearranged in plants. A second pathway results in 4-carbon molecules being formed early in the Calvin cycle. These plants are called C4 plants. Finally, a third pathway takes in CO_2 and incorporates the carbon in organic acids called crassulacean acids, named after the plant types in which this process occurs. Crassulacean plants include the succulent, or water-storing plants, such as cacti.

Explain How are the three pathways of photosynthesis similar in terms of carbon and the formation of carbon-based molecules?

Nearly all land plants exchange gases through openings called stomata. Carbon dioxide enters and oxygen exits through these openings. At the same time, water that has been absorbed through the plant roots transpires, or is given off as water vapor through the open stomata. So the stomata play an important role in regulating the input of CO_2 and the output of oxygen as part of photosynthesis, as well as overall water loss.

FIGURE 12: Stomata are found on above-ground parts of plants, including the petals of flowers, stems, and leaves.

The stomata do not stay open all the time. Instead, the stomata open and close in response to homeostatic mechanisms in the plant. This helps the plant conserve water when water availability is limited. In general, plants lose water fastest during intense sunlight, especially when the temperature is warm, or when the air is dry, or in windy conditions. The variations among C3, C4, and CAM plants are mainly based on plant adaptations to different climates.

Plants can be classified by the way their photosynthetic pathways are adapted to environmental conditions. Most plants are C3 and C4 plants, which open their stomata during the day, losing most of the water taken up by their roots. But CAM plants are adapted for life in extremely hot and arid climates. These plants generally keep their stomata closed during the day to reduce the amount of water that is lost in transpiration. The stomata often are open through the night, when it is cooler and more humid. CAM plants fix CO_2 at night, avoiding water loss by not opening their stomata during the day. The CO_2 is released during the day to be used in photosynthetic reactions.

Predict How would you expect the abundance of C3 plants to change as regions around the world become warmer and drier?

FIGURE 13: Three Pathways of Photosynthesis

C3 Plants	C4 Plants	CAM Plants
		
rice, wheat, oat, soybean, cotton, most trees and lawn grasses	corn, nutgrass, and tumbleweed	succulents, cacti, bromeliads, and orchids
stomata open in daytime	stomata open in daytime	stomata open at night

Language Arts Connection Carry out further research to learn more about these variations in photosynthesis. Prepare a presentation to explain the differences between C3, C4, and CAM plants. In your presentation, include information about how each type of plant carries out photosynthesis, and how the differences help plants survive in different environments. Use text, visuals, and interactive components to make the concepts in your presentation engaging and easy to understand.

A multimedia presentation combines text, sounds, and images. A successful multimedia presentation includes:

- a clear and consistent focus
- ideas that are presented clearly and logically
- graphics, text, music, video, and sounds that support key points
- an organization that is appropriate to its purpose and audience

INVESTIGATING LIGHT SOURCES AND PHOTOSYNTHESIS

THE COLOR OF PLANTS ON OTHER PLANETS

Go online to choose one of these other paths.

Lesson Self-Check

CAN YOU EXPLAIN IT?

As scientists and engineers plan for the next phase of space exploration—traveling to and colonizing other planets, they must devise ways of meeting the needs of humans. Today's astronauts are studying how plants grow in space. Their results will help scientists determine the best way to keep plants alive until they arrive at the new planet. The next step in this process will be to determine how plants might grow in the new planet's environment.

FIGURE 14: Growing plants in space is important not only as a long-term food source, but also as a connection to life on our home planet, Earth.

Explain Use what you have learned to further explain how plants could be grown on other planets. Address the following in your explanation:

1. What inputs do plants need to carry out photosynthesis, and how might you provide these on another planet?
2. What outputs do plants produce from photosynthesis, and how do these benefit humans?
3. How do plants transfer energy from light to sugar molecules?
4. What questions would you ask about the planet to refine your list of necessary materials?

CHECKPOINTS

Check Your Understanding

1. Which of these are the result of producers performing photosynthesis? Select all correct answers.
   - **a.** Makes oxygen available for cellular respiration
   - **b.** Tranfers carbon dioxide back to the atmosphere
   - **c.** Transfers energy from sunlight to consumers
   - **d.** Cycles carbon through the biosphere

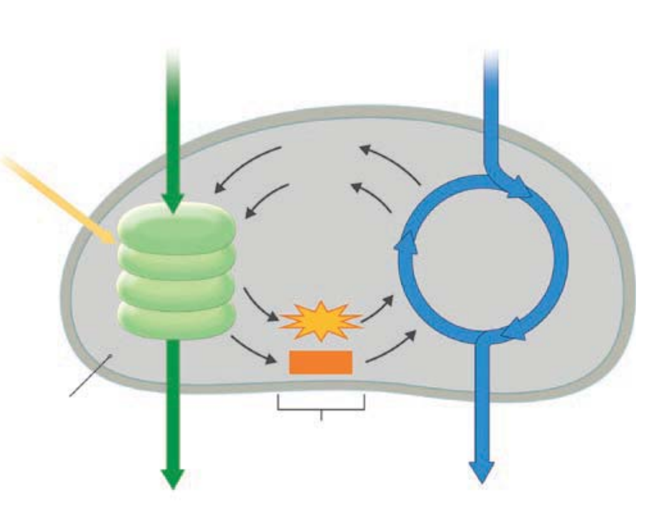
2. Write the overall chemical equation for photosynthesis. Be sure to show the relationship of light and enzymes to the reaction.

3. Use the terms below to complete this paragraph:
   NADPH, ATP, thylakoids, chlorophyll, chloroplasts, electrons

   Light energy is absorbed by __ found in the membranes of __, which are saclike structures inside __. The light energy dislodges __, which are used to make __. Energy from this process is used to make __. The electrons and energy are used to make sugars, which the plant stores or consumes for energy.

4. Draw a Venn diagram to compare chemosynthesis to photosynthesis.

FIGURE 15: The two stages of photosynthesis, light-dependent reactions and light-independent reactions, occur in the chloroplast.



5. Draw the diagram above, and add the following labels to illustrate the transfer of matter and energy in photosynthesis:
   NADPH, $NADP^+$, sugars, light, ADP, O_2, H_2O, ATP, CO_2

6. Draw a simple ecosystem made up of at least one producer and one consumer. Add arrows and labels to show how energy and matter flow from the sun to the producer and from the producer to the consumer.

7. Draw a diagram showing the interaction between light and chlorophyll. The diagram should show how this interaction results in the transfer of energy and electrons through photosystem I and photosystem II.

8. Is it true that all organisms on Earth depend on the sun as their energy source? Explain your answer.

MAKE YOUR OWN STUDY GUIDE

In your Evidence Notebook, design a study guide that supports the main idea from this lesson:

Photosynthesis is a process used by most producers to transform light energy into stored chemical energy.

Remember to include the following information in your study guide:

- Use examples that model main ideas.
- Record explanations for the phenomena you investigated.
- Use evidence to support your explanations. Your support can include drawings, data, graphs, laboratory conclusions, and other evidence recorded throughout the lesson.

Consider how the models for photosynthesis you have used in this lesson can be used to explain changes in energy and matter. Explain these changes in terms of energy flow and matter cycling within and between systems.