Chapter 9

Photosynthesis and Cellular Respiration

Preview

1 Energy in Living Systems
- Chemical Energy
- Metabolism and the Carbon Cycle
- Transferring Energy

2 Photosynthesis
- Harvesting Light Energy
- Two Electron Transport Chains
- Producing Sugar
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3 Cellular Respiration
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Why It Matters

Everything you do—from moving, to breathing, to thinking—requires energy. The energy your body uses is mostly derived from the processes of photosynthesis and cellular respiration.

A saturniid caterpillar feeds on a leaf. The leaf provides the energy the caterpillar needs to grow and undergo metamorphosis.

The caterpillar gets the organic compounds it needs for cellular respiration from the leaf. Caterpillars, like other animals, are *heterotrophs.*

Carbohydrates and oxygen are produced in leaves by photosynthesis. A green pigment called *chlorophyll* gives plants their characteristic green color.

Section 1

Energy in Living Systems

Key Ideas	Key Terms	Why It Matters
› What type of energy is used in cells, and what is the ultimate source of this energy? › How is an organism's metabolism related to the carbon cycle? › How is energy released in a cell?	**photosynthesis** **cellular respiration** **ATP** **ATP synthase** **electron transport chain**	Plants convert sunlight into chemical energy. This chemical energy can be used for biological processes in nearly all living things.

Imagine an abandoned house that is falling apart. The house, like almost everything else in the universe, breaks down over time. Restoring order to the house would require an input of energy, such as the energy needed to apply a fresh coat of paint. Living things also need energy in order to stay in good repair, or maintain their *homeostasis.* Remember that homeostasis is the process of maintaining internal order and balance even when the environment changes. Every organism must maintain homeostasis as long as it lives. Therefore, organisms require a constant source of energy.

Chemical Energy

› **Organisms use and store energy in the chemical bonds of organic compounds. Almost all of the energy in organic compounds comes from the sun.** Solar energy enters living systems when plants, algae, and certain prokaryotes use sunlight to make organic compounds from carbon dioxide and water through the process of **photosynthesis.** Organisms that are able to perform photosynthesis, such as the wheat plants shown in **Figure 1,** are *autotrophs.* Autotrophs make organic compounds that serve as food for them and for almost all of the other organisms on Earth.

photosynthesis the process by which plants, algae, and some bacteria use sunlight, carbon dioxide, and water to produce carbohydrates and oxygen

Most autotrophs have a supply of food as long as sunlight is available. But how do other organisms get food molecules? To survive, organisms that cannot make their own food must absorb food molecules made by autotrophs, eat autotrophs, or eat organisms that consume autotrophs. Food molecules that are made or consumed by an organism are the fuel for its cells. Cells use these molecules to release the energy stored in the molecules' bonds. The energy is used to carry out life processes.

› **Reading Check** ***Why do organisms need a constant supply of energy? (See the Appendix for answers to Reading Checks.)***

Figure 1 Food crops such as wheat supply humans and other animals with the chemical energy needed to carry out life processes.

Hands-On

QuickLab

MULTI-DAY 15 min

Product of Photosynthesis

Plants use photosynthesis to produce food. One product of photosynthesis is oxygen. In this activity, you will observe the process of photosynthesis in elodea.

Procedure

1. Add **450 mL of baking-soda-and-water solution** to a **beaker.**
2. Put **two or three sprigs of elodea** into the beaker. The baking soda will provide the elodea with the carbon dioxide it needs for photosynthesis.
3. Place the wide end of a **glass funnel** over the elodea. The elodea and the funnel should be completely submerged in the solution.
4. Fill a **test tube** with the remaining solution. Place your thumb over the end of the test tube. Turn the test tube upside down, taking care that no air enters. Hold the opening of the test tube under the solution, and place the test tube over the small end of the funnel.
5. Place the beaker setup in a well-lit area near a lamp or in direct sunlight, and leave it overnight.

Analysis

1. **Describe** what happened to the solution in the test tube.
2. CRITICAL THINKING **Predicting Patterns** Explain what may happen if an animal, such as a snail, were put into the beaker with the elodea sprig.

Metabolism and the Carbon Cycle

Metabolism involves either using energy to build organic molecules or breaking down organic molecules in which energy is stored. Organic molecules contain carbon. Therefore, an organism's metabolism is part of Earth's carbon cycle. The carbon cycle not only makes carbon compounds continuously available in an ecosystem but also delivers chemical energy to organisms living within that ecosystem.

Photosynthesis Energy enters an ecosystem when organisms use sunlight during photosynthesis to convert stable carbon dioxide molecules into glucose, a less stable carbon compound. In plant cells and algae, photosynthesis takes place in chloroplasts. **Figure 2** summarizes the process by which energy from the sun is converted to chemical energy in chloroplasts.

Cellular Respiration Organisms extract energy stored in glucose molecules. Through the process of **cellular respiration,** cells make the carbon in glucose into stable carbon dioxide molecules and produce energy. Thus, stable and less stable compounds alternate during the carbon cycle and provide a continuous supply of energy for life processes in an ecosystem.

The breakdown of glucose during cellular respiration is summarized in **Figure 2.** The inputs are a glucose molecule and six oxygen molecules. The final products are six carbon dioxide molecules and six water molecules. Energy is also released and used to make **ATP** (adenosine triphosphate), an organic molecule that is the main energy source for cell processes.

cellular respiration the process by which cells produce energy from carbohydrates

ATP adenosine triphosphate, an organic molecule that acts as the main energy source for cell processes; composed of a nitrogenous base, a sugar, and three phosphate groups

Reading Check *How is solar energy related to the carbon cycle?*

Photosynthesis and Cellular Respiration

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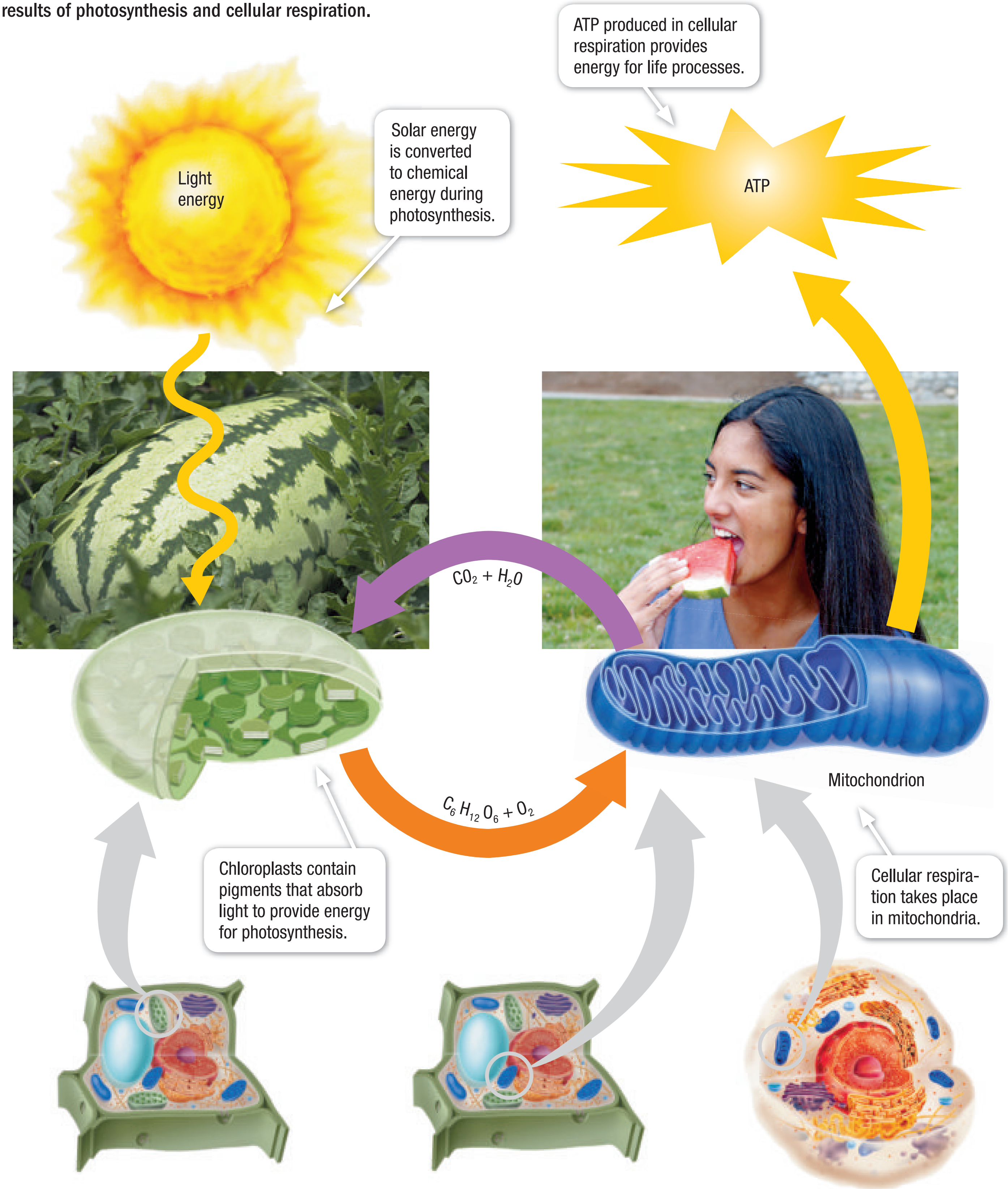


Figure 2 Photosynthesis and cellular respiration are major steps in the carbon cycle. **Compare the end results of photosynthesis and cellular respiration.**

Transferring Energy

In chemical reactions, energy can be absorbed and released during the breaking and forming of bonds. For example, when a log burns, the energy stored in wood molecules is released in a burst of heat and light. **In cells, chemical energy is gradually released in a series of chemical reactions that are assisted by enzymes.** Recall that enzymes are proteins that act as catalysts in biochemical reactions.

ATP When cells break down food molecules, some of the energy in the molecules is released as heat. Cells use much of the remaining energy to make ATP. When glucose is broken down during cellular respiration, energy is stored temporarily in molecules of ATP. ATP can be used to power chemical reactions, such as those that build molecules. Paper money is portable and can be earned in one place and spent in another. Like money, ATP is a portable form of energy "currency" inside cells. ATP can be "earned," or made, in one place and "spent," or used, in another place. For example, ATP can be used to contract a muscle cell, to actively transport protein, or to help make more ATP.

ATP is a nucleotide made up of a chain of three phosphate groups. This chain is unstable because the phosphate groups are negatively charged and thus repel each other. When the bond of the third phosphate group is broken, energy is released. This produces adenosine diphosphate, or ADP. The equation below summarizes the process.

$$\text{ATP} \longrightarrow \text{ADP} + \text{P} + \text{energy}$$

The reaction in which ATP is converted to ADP requires a small input of energy. But much more energy is released than is used during the reaction.

Reading Check ***How is ATP used inside a cell?***

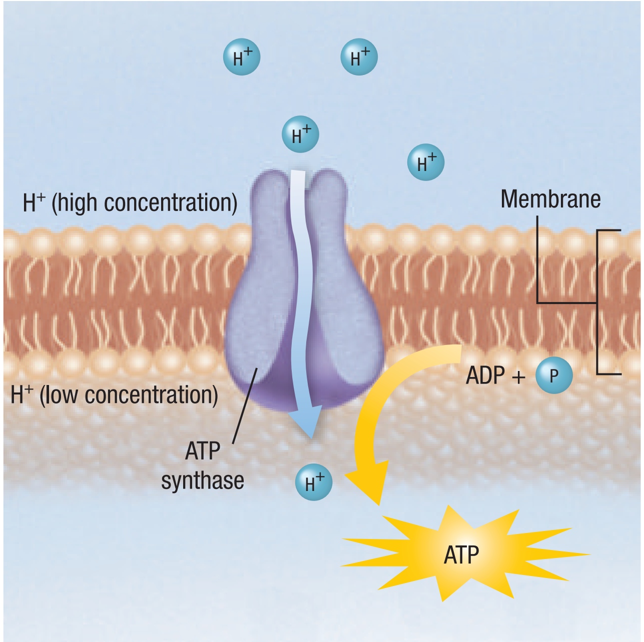
READING TOOLBOX

Key-Term Fold On the back of your key-term fold, write a definition in your own words for each key term in this section.

ACADEMIC VOCABULARY

process a set of steps, events, or changes

Figure 3 The energy of falling water can turn a water wheel, which provides energy to do work. In ATP synthase, the movement of hydrogen ions provides energy to convert ADP to ATP.



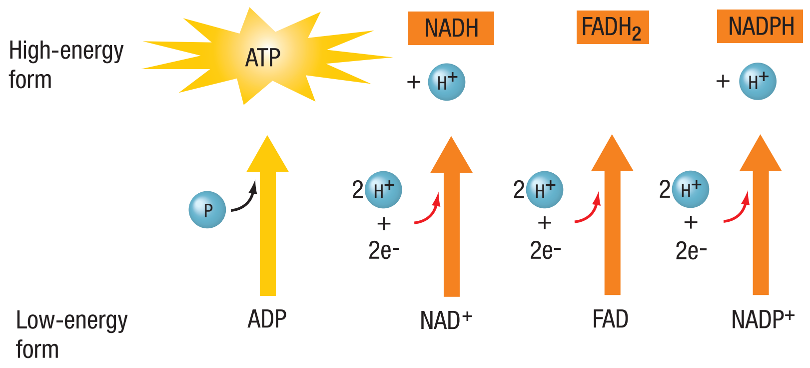


Figure 4 Electron carriers store energy by bonding with hydrogen, just as ATP stores energy by bonding a third phosphate group. **❯ Where is the electron transport chain found in animal cells?**

ATP Synthase In many cells, **ATP synthase,** an enzyme that catalyzes the synthesis of ATP, recycles ADP by bonding a third phosphate group to the molecule. As **Figure 3** shows, ATP synthase acts as both an enzyme and a carrier protein for hydrogen (H^+) ions. The flow of H^+ ions through ATP synthase powers the production of ATP. You can think of the H^+ ions moving through ATP synthase to produce ATP as falling water turning a water wheel to produce power. As H^+ ions flow, ATP synthase catalyzes a reaction in which a phosphate group is added to a molecule of ADP to make ATP.

Hydrogen Ion Pumps Recall how diffusion across cell membranes works. Particles of a substance diffuse through a membrane from a region of higher concentration to a region of lower concentration. The inner mitochondrial membrane allows H^+ ions to diffuse through only ATP synthase. When glucose is broken down during cellular respiration, NAD^+ (nicotinamide adenine dinucleotide) accepts electrons and hydrogen ions, which changes NAD^+ to NADH. As **Figure 4** shows, NADH enters an **electron transport chain,** a series of molecules in the inner membrane of a mitochondrion. The electron transport chain allows electrons to drop in energy as they are passed along and uses the energy released to pump H^+ ions out of a mitochondrion's inner compartment. This action increases the concentration of H^+ ions in the outer compartment. The ions then diffuse back into the inner compartment through ATP synthase.

ATP synthase an enzyme that catalyzes the synthesis of ATP

electron transport chain a series of molecules, found in the inner membranes of mitochondria and chloroplasts, through which electrons pass in a process that causes protons to build up on one side of the membrane

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Section 1 Review

❯ KEY IDEAS

1. **Identify** the primary source of energy that flows through most living systems.
2. **Explain** how an organism's metabolism is related to Earth's carbon cycle.
3. **Describe** how energy is released from ATP.

CRITICAL THINKING

4. **Analyzing Patterns** Explain how life involves a continuous flow of energy.
5. **Inferring Relationships** How can the energy in the food that a fox eats be traced back to the sun?
6. **Summarizing Information** What is the difference between cellular respiration and the process by which energy is released from a burning log?

WRITING FOR SCIENCE

7. **Career Connection** Research the educational background that a person needs to become an enzymologist. List the courses required, and describe additional degrees or training that are recommended for this career. Write a report on your findings.

Section 2

Photosynthesis

Key Ideas	Key Terms	Why It Matters
❯ What is the role of pigments in photosynthesis? ❯ What are the roles of the electron transport chains? ❯ How do plants make sugars and store extra unused energy? ❯ What are three environmental factors that affect photosynthesis?	thylakoid pigment chlorophyll Calvin cycle	Nearly all of the energy for life processes comes from the sun and is stored in organic molecules during the process of photosynthesis.

Plants, algae, and certain prokaryotes capture about 1% of the energy in the sunlight that reaches Earth and convert it to chemical energy through photosynthesis. Photosynthesis is the process that provides energy for almost all life.

Harvesting Light Energy

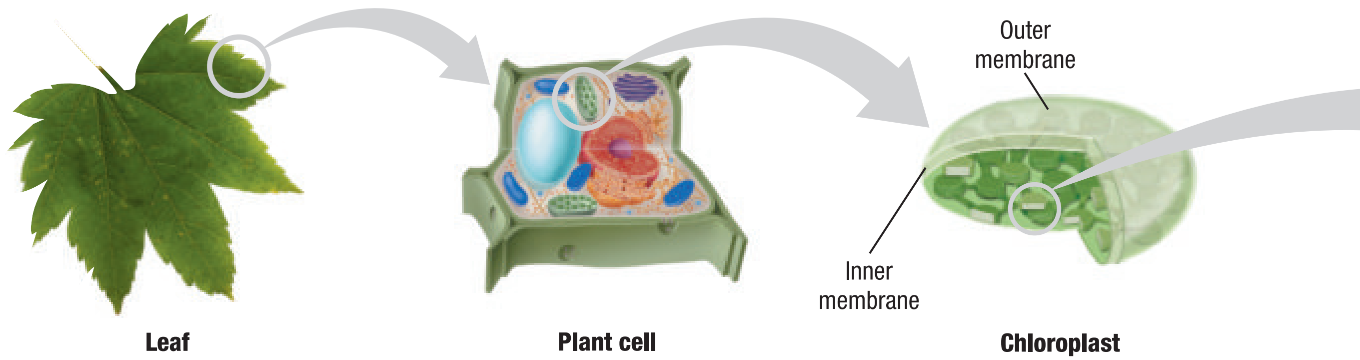
The cells of many photosynthetic organisms have chloroplasts, organelles that convert light energy into chemical energy. Study the diagram of a chloroplast in **Figure 5.**

A chloroplast has an outer membrane and an inner membrane. Molecules diffuse easily through the outer membrane. The inner membrane is much more selective about what substances enter and leave. Both membranes allow light to pass through.

The space inside the inner membrane is the stroma. Within the stroma is a membrane called the *thylakoid membrane*. This membrane is folded in a way that produces flat, disc-like sacs called **thylakoids.** These sacs, which contain molecules that absorb light energy for photosynthesis, are arranged in stacks. The first stage of photosynthesis begins when light waves hit these stacks.

❯ **Reading Check** ***Describe the structure of a chloroplast.***

Figure 5 Pigments, as well as other molecules that participate in photosynthesis, are embedded in thylakoids. ❯ **Where are thylakoids located?**



Electromagnetic Radiation Light is a form of electromagnetic radiation, energy that can travel through empty space in the form of waves. Radio waves, X-rays, and microwaves are also forms of electromagnetic radiation. The difference between these forms of radiation is that they have different wavelengths. Each wavelength corresponds to a certain amount of energy. The wavelength is the distance between consecutive wave peaks. Sunlight contains all of the wavelengths of visible light. You see these wavelengths as different colors.

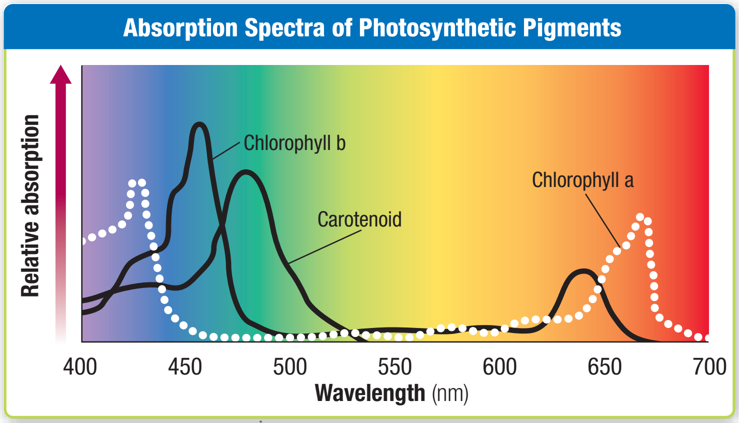


Figure 6 This graph show the colors of light that three different pigments absorb. Where a curve peaks, much of the light at that wavelength is absorbed. Where a curve dips, much of the light at that wavelength is reflected or transmitted.

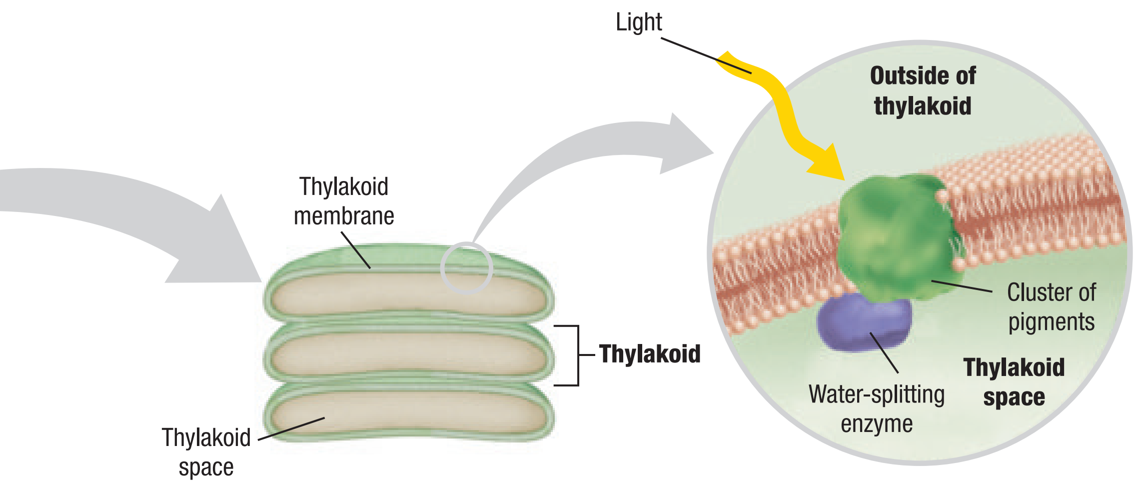
Pigments What makes the human eye sensitive to light? Cells in the back of the eye contain pigments. A **pigment** is a substance that absorbs certain wavelengths (colors) of light and reflects all of the others. **In plants, light energy is harvested by pigments that are located in the thylakoid membrane of chloroplasts.** **Chlorophyll** is a green pigment in chloroplasts that absorbs light energy to start photosynthesis. It absorbs mostly blue and red light and reflects green and yellow light, which makes plants appear green. Plants have two types of chlorophyll: chlorophyll *a* and chlorophyll *b*. Plants also have pigments called *carotenoids*. Carotenoids absorb blue and green light, and they reflect yellow, orange, and red light. When chlorophyll fades away in the fall, the colors of carotenoids are exposed. Carotenoids aid photosynthesis by allowing plants to absorb additional light energy. **Figure 6** shows the wavelengths of light that are absorbed by chlorophyll *a,* chlorophyll *b,* and carotenoids—the pigments found in thylakoid membranes.

Electron Carriers When light hits a thylakoid, energy is absorbed by many pigment molecules. They all funnel the energy to a special chlorophyll molecule in a region called the *reaction center,* where the energy causes the electrons to become "excited" and to move to a higher energy level. These electrons are transferred quickly to other nearby molecules and then to an electron carrier.

thylakoid (THIE luh KOYD) a membrane system found within chloroplasts that contains the components for photosynthesis

pigment a substance that gives another substance or a mixture its color

chlorophyll (KLAWR uh FIL) a green pigment that is present in most plant and algae cells and some bacteria, that gives plants their characteristic green color, and that absorbs light to provide energy for photosynthesis



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Two Electron Transport Chains

Electrons from the electron carrier are used to produce new molecules, including ATP, that temporarily store chemical energy. The carrier transfers the electrons to the first of two electron transport chains in the thylakoid membrane. Trace the path taken by the electrons in the electron transport chains shown in **Figure 7.** **› During photosynthesis, one electron transport chain provides energy to make ATP, while the other provides energy to make NADPH.** Both chains use energy from electrons excited by light.

Producing ATP In mitochondria, electron transport chains pump H^+ ions through a membrane, which produces a concentration gradient. This process also happens in chloroplasts.

Step 1 Water Splitting The excited electrons that leave chlorophyll molecules must be replaced by other electrons. Plants get these replacement electrons from water molecules, H_2O. During photosynthesis, an enzyme splits water molecules inside the thylakoid. When water molecules are split, chlorophyll molecules take the electrons from the hydrogen atoms, H, which leaves H^+ ions. The remaining oxygen atoms, O, from the split water molecules combine to form oxygen gas, O_2. This oxygen gas is not used for any later steps of photosynthesis, so it is released into the atmosphere.

Figure 7 Photosynthesis converts light energy to chemical energy. This figure shows key molecules involved in the capture of light, electron transport, and synthesis of ATP and NADPH. **› What causes H^+ ions to move through the carrier protein that produces ATP?**

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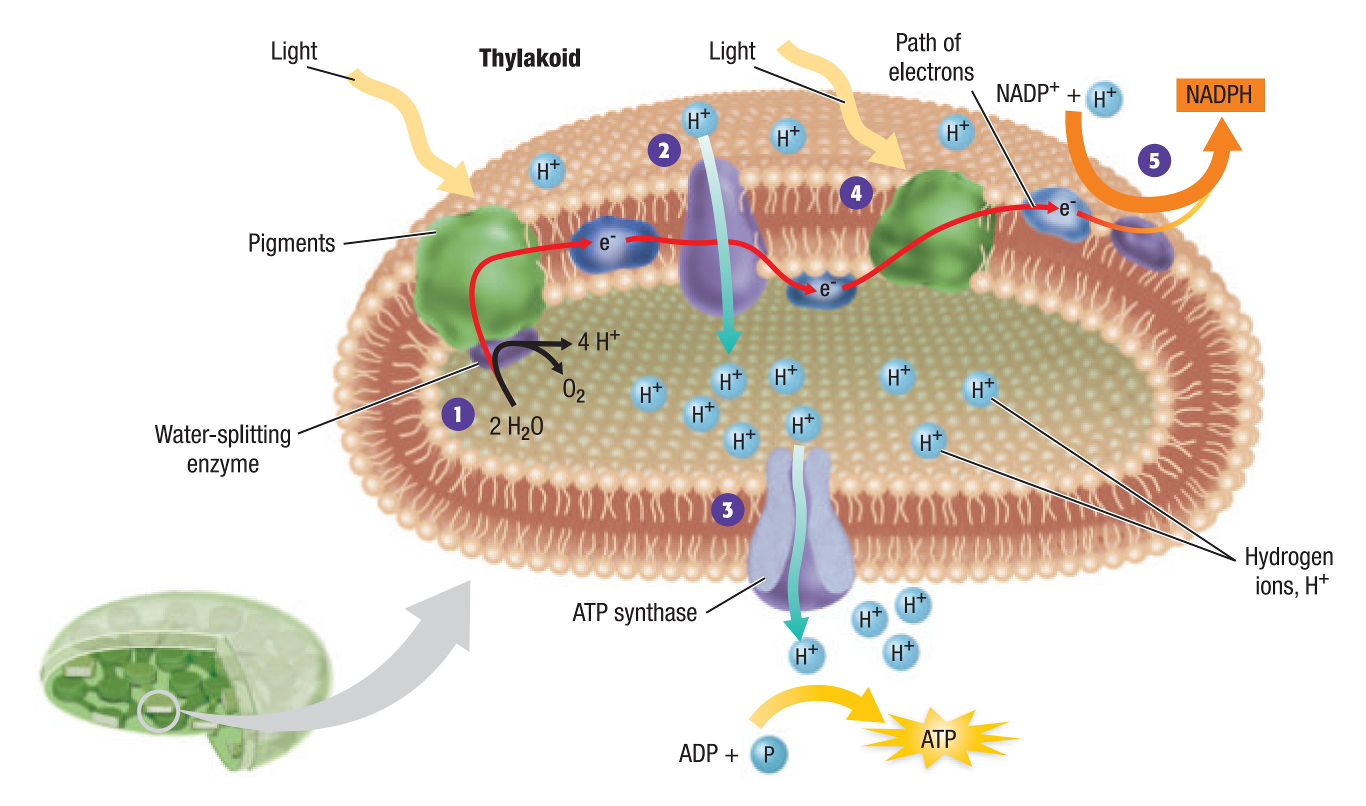
Electron Transport Chains of Photosynthesis



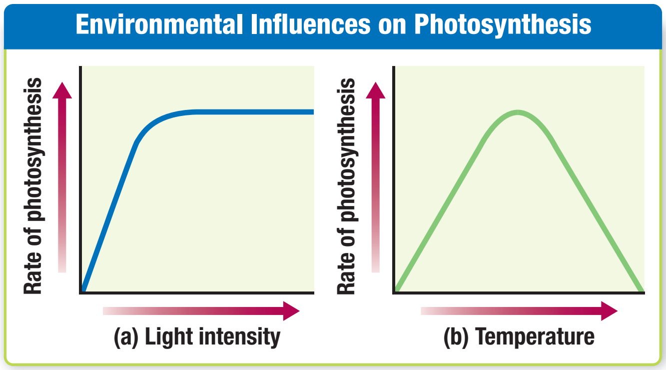
Data

QuickLab

15 min

Photosynthetic Rate

Changes in a plant's surroundings influence photosynthetic rate. The two graphs illustrate how photosynthetic rate responds to changes in light intensity and temperature. Use the graphs to answer the following questions.



Analysis

1. **Describe** how increasing light intensity affects the rate of photosynthesis.
2. **Explain** whether continuing to increase light intensity will increase the rate of photosynthesis.
3. **Describe** how increasing temperature affects the rate of photosynthesis.
4. CRITICAL THINKING **Inferring Relationships** Explain how a global temperature increase could affect plants.

Step 2 Hydrogen Ion Pump A protein acts as a membrane pump. Excited electrons transfer some of their energy to pump H^+ ions into the thylakoid. This process creates a concentration gradient across the thylakoid membrane.

Step 3 ATP Synthase The energy from the diffusion of H^+ ions through the carrier protein is used to make ATP. These carrier proteins are unusual because they function both as an ion channel and as the enzyme ATP synthase. As hydrogen ions pass through the channel portion of the protein, ATP synthase catalyzes a reaction in which a phosphate group is added to a molecule of ADP. The result of the reaction is ATP, which is used to power the final stage of photosynthesis.

Producing NADPH While one electron transport chain provides energy used to make ATP, a second electron transport chain receives excited electrons from a chlorophyll molecule and uses them to make NADPH. The second electron transport chain is to the right of the second cluster of pigment molecules in **Figure 7.**

Step 4 Reenergizing In this second chain, light excites electrons in the chlorophyll molecule. The excited electrons are passed on to the second chain. They are replaced by the de-energized electrons from the first transport chain.

Step 5 Making NADPH Excited electrons combine with H^+ ions and an electron acceptor called $NADP^+$ to form NADPH. NADPH is an electron carrier that provides the high-energy electrons needed to store energy in organic molecules. Both NADPH and the ATP made during the first stage of photosynthesis will be used to provide the energy to carry out the final stage of photosynthesis.

› **Reading Check** ***Summarize how ATP and NADPH are formed during photosynthesis.***

READING TOOLBOX

Describing Space Use spatial language to describe production of ATP and NADPH during photosynthesis.

Calvin cycle a biochemical pathway of photosynthesis in which carbon dioxide is converted into glucose using ATP and NADPH

ACADEMIC VOCABULARY

method a way of doing something

Producing Sugar

The first two stages of photosynthesis depend directly on light because light energy is used to make ATP and NADPH. **In the final stage of photosynthesis, ATP and NADPH are used to produce energy-storing sugar molecules from the carbon in carbon dioxide.** The use of carbon dioxide to make organic compounds is called *carbon dioxide fixation,* or *carbon fixation.* The reactions that fix carbon dioxide are light-independent reactions, sometimes called *dark reactions*. Among photosynthetic organisms, there are several ways in which carbon dioxide is fixed. The most common method of carbon dioxide fixation is the **Calvin cycle,** which is described in the following steps:

Step 1 Carbon Fixation In carbon dioxide fixation, an enzyme adds a molecule of carbon dioxide, CO_2, to a five-carbon compound. This process occurs three times to yield three six-carbon molecules.

Step 2 Absorbing Energy Each six-carbon compound splits into two three-carbon compounds. Phosphate groups from ATP and electrons from NADPH are added to the three-carbon compounds to form three-carbon sugars.

Step 3 Making Sugar One of the resulting three-carbon sugars leaves the cycle and is used to make organic compounds—including glucose, sucrose, and starch—in which energy is stored for later use by the organism.

Figure 8 The Calvin cycle is the most common method of carbon dioxide fixation. **What is formed when the three six-carbon molecules split during step 2 of the Calvin cycle?**

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Calvin Cycle

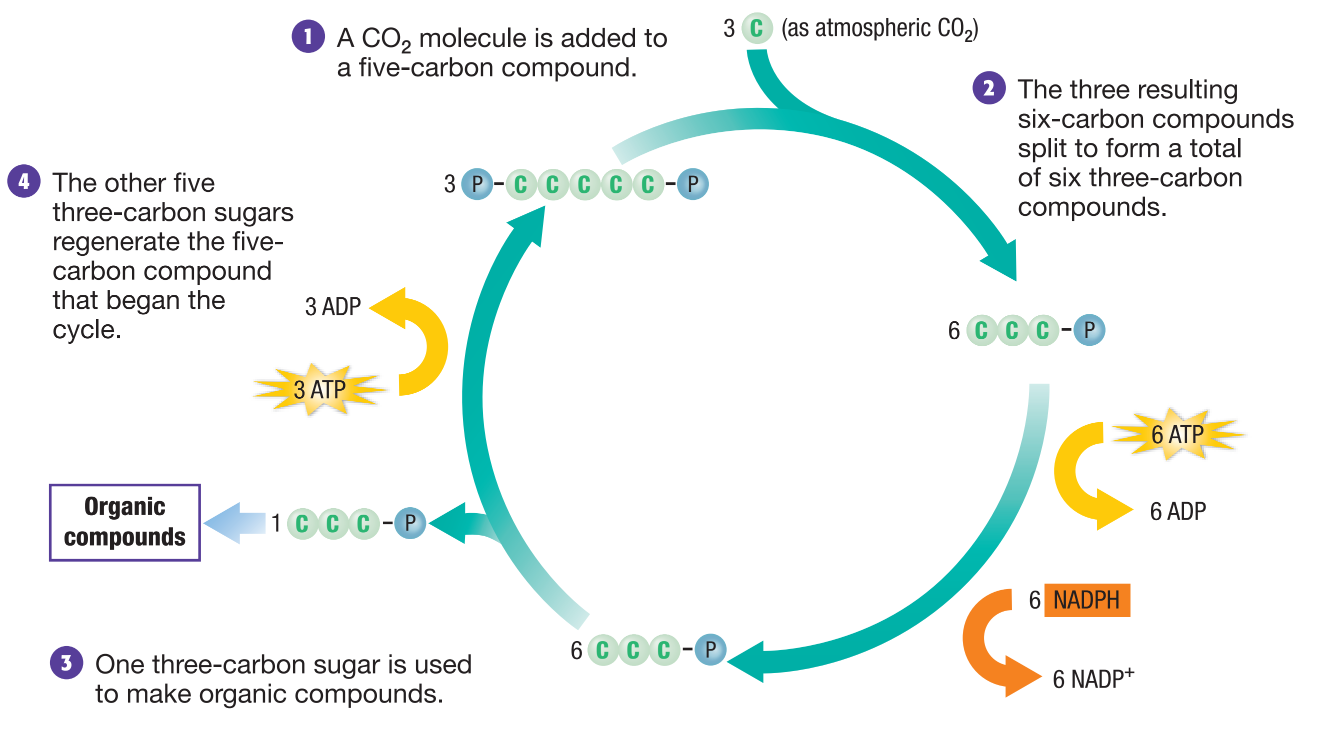


Figure 9 Some plants, such as a cactus (left), grow in extremely sunny, dry environments. Others, such as the bromeliad (right), are able to grow in shady areas.

Step 4 Recycling The remaining five three-carbon sugars are rearranged. Using energy from ATP, enzymes reform three molecules of the initial five-carbon compound. This process completes the cycle. The reformed compounds are used to begin the cycle again.

Factors that Affect Photosynthesis

Light intensity, carbon dioxide concentration, and temperature are three environmental factors that affect photosynthesis. The most obvious of these factors is light. **Figure 9** shows plants that are adapted to different levels of light. In general, the rate of photosynthesis increases as light intensity increases until all of the pigments in a chloroplast are being used. At this saturation point, the rate of photosynthesis levels off because the pigments cannot absorb more light.

The concentration of carbon dioxide affects the rate of photosynthesis in a way similar to light. Once a certain concentration of carbon dioxide is present, photosynthesis cannot proceed any faster.

Photosynthesis is most efficient in a certain range of temperatures. Like all metabolic processes, photosynthesis involves many enzyme-assisted chemical reactions. Unfavorable temperatures may inactivate certain enzymes so that reactions cannot take place.

Reading Check *How does temperature affect photosynthesis?*

Section 2 Review

KEY IDEAS

1. **Summarize** how autotrophs capture the energy in sunlight.
2. **Compare** the roles of water molecules and H^+ ions in electron transport chains.
3. **Describe** the role of the Calvin cycle in photosynthesis.
4. **Name** the three main environmental factors that affect the rate of photosynthesis in plants.

CRITICAL THINKING

5. **Organizing Information** Make a table in which you identify the role of each of the following in photosynthesis: light, water, pigments, ATP, NADPH, and carbon dioxide.

METHODS OF SCIENCE

6. **Inferring Relationships** How do you think photosynthesis will be affected if the sun's rays are blocked by clouds or by smoke from a large fire? How might the levels of atmospheric carbon dioxide and oxygen be affected? What experiments could scientists conduct in the laboratory to test your predictions?

Section 3
Cellular Respiration

Key Ideas	Key Terms	Why It Matters
❯ How does glycolysis produce ATP? ❯ How is ATP produced in aerobic respiration? ❯ Why is fermentation important?	glycolysis anaerobic aerobic Krebs cycle fermentation	Cellular respiration is the process used by humans and most other organisms to release the energy stored in the food they consume.

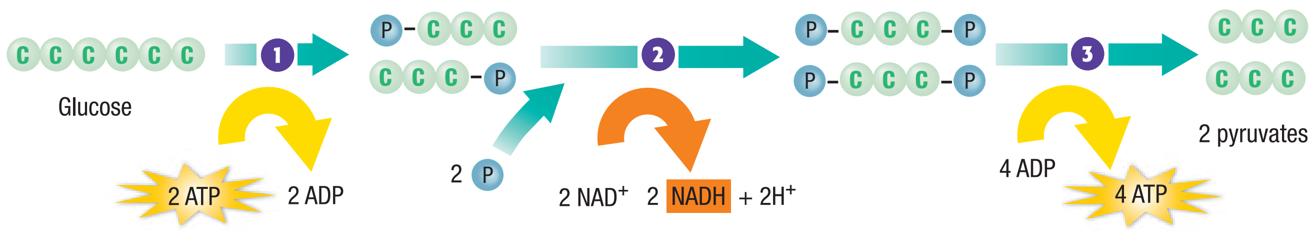
Where do the students shown in **Figure 10** get energy? Most of the foods we eat contain energy. Much of the energy in a hamburger, for example, is stored in proteins, carbohydrates, and fats. But before you can use that energy, it must be released and transferred to ATP. Like cells of most organisms, your cells transfer the energy in organic compounds, especially the glucose made during photosynthesis, to ATP through cellular respiration, which begins with glycolysis.

Glycolysis

The primary fuel for cellular respiration is glucose, which is formed when carbohydrates, such as starch and sucrose, are broken down. If too few carbohydrates are available to meet an organism's energy needs, other molecules, such as fats, can be broken down to make ATP. In fact, one gram of fat releases more energy than two grams of carbohydrates do. Proteins and nucleic acids can also be used to make ATP, but they are usually used for building important cell parts.

Figure 10 These students get their energy by eating carbohydrates, fats, proteins, and other organic molecules. ❯ **What is the origin of the energy-containing organic molecules in these students' food?**

Glycolysis



1 Two ATP molecules are used to break glucose into two smaller units. A phosphate group is added to the 6-carbon compound.

2 Each 3-carbon compound reacts with a phosphate group. Hydrogen atoms are transferred to NAD^+, producing NADH.

3 Each 3-carbon sugar is converted to a 3-carbon molecule of pyruvate. Four ATP molecules are produced.

Figure 11 Glycolysis uses two ATP molecules but produces four ATP molecules. The process results in a net gain of ATP. **› What is the starting material in glycolysis?**

Steps of Glycolysis In the first stage of cellular respiration, glucose is broken down in the cytoplasm by glycolysis. In **glycolysis,** enzymes break down one six-carbon molecule of glucose into two three-carbon pyruvate molecules, as **Figure 11** shows. Most of the energy that was stored in the glucose molecule is stored in the pyruvate.

Step 1 Breaking Down Glucose In the first stage of glycolysis, two ATP molecules are used to break glucose into two smaller units. This stage has four steps with four different enzymes. A phosphate group from ATP is added to the six-carbon compound. This makes the molecule reactive so that an enzyme can break it into two three-carbon sugars, each with a phosphate group. ATP is produced in the next two stages.

Step 2 NADH Production In the second stage, each three-carbon compound reacts with another phosphate group (not from ATP). As the two three-carbon sugars react further, hydrogen atoms, including their electrons, are transferred to two molecules of NAD^+, which produces two molecules of the electron carrier NADH. NADH is used later in other cell processes, where it is recycled to NAD^+.

Step 3 Pyruvate Production In a series of four reactions, each three-carbon sugar is converted into a three-carbon molecule of pyruvate. This process produces four ATP molecules. **› Thus, the breaking of a sugar molecule by glycolysis results in a net gain of two ATP molecules.**

Glycolysis is the only source of energy for some prokaryotes. This process is **anaerobic,** so it takes place without oxygen. Other organisms use oxygen to release even more energy from a glucose molecule. Metabolic processes that require oxygen are **aerobic.** In aerobic respiration, the pyruvate product of glycolysis undergoes another series of reactions to produce more ATP molecules.

› Reading Check *What are the three products of glycolysis?*

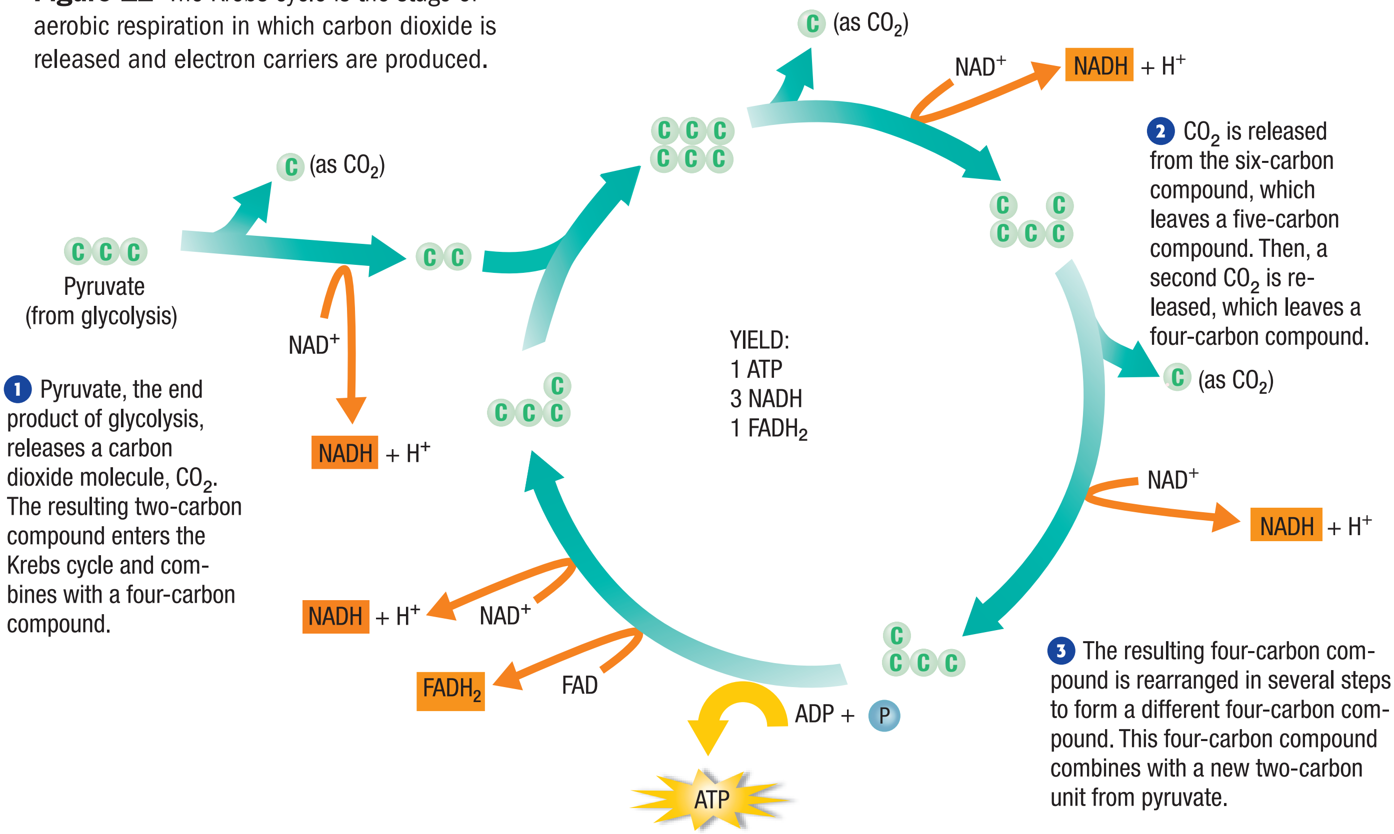
glycolysis (glie KAHL i sis) the anaerobic breakdown of glucose to pyruvate, which makes a small amount of energy available to cells in the form of ATP

anaerobic (AN uhr OH bik) describes a process that does not require oxygen

aerobic (er OH bik) describes a process that requires oxygen

Krebs Cycle

Figure 12 The Krebs cycle is the stage of aerobic respiration in which carbon dioxide is released and electron carriers are produced.



Krebs cycle a series of biochemical reactions that convert pyruvate into carbon dioxide and water

Aerobic Respiration

Organisms such as humans can use oxygen to produce ATP efficiently through aerobic respiration. Pyruvate is broken down in the **Krebs cycle,** a series of reactions that produce electron carriers. The electron carriers enter an electron transport chain, which powers ATP synthase. Up to 34 ATP molecules can be produced from one glucose molecule in aerobic respiration.

Krebs Cycle The first stage of aerobic respiration, the Krebs cycle, is named for Hans Krebs, a German biochemist. He was awarded the Nobel Prize in 1953 for discovering it. As **Figure 12** shows, the Krebs cycle begins with pyruvate, which is produced during glycolysis. Pyruvate releases a carbon dioxide molecule to form a two-carbon compound. An enzyme attaches this two-carbon compound to a four-carbon compound and forms a six-carbon compound.

The six-carbon compound releases one carbon dioxide molecule and then another. Energy is released each time, which forms an electron carrier, NADH. The remaining four-carbon compound is converted to the four-carbon compound that began the cycle. This conversion takes place in a series of steps that produce ATP, then FADH$_2$, and another NADH. The four-carbon compound combines with a new two-carbon unit from pyruvate to continue the cycle.

Products of the Krebs Cycle Each time the carbon-carbon bonds are rearranged or broken, energy is released. **The total yield of energy-storing products from one time through the Krebs cycle is one ATP, three NADH, and one $FADH_2$. Electron carriers transfer energy through the electron transport chain, which ultimately powers ATP synthase.**

Electron Transport Chain The second stage of aerobic respiration takes place in the inner membranes of mitochondria. Recall that electrons pass through a series of molecules called an *electron transport chain,* as **Figure 13** shows. **1** The electrons that are carried by NADH and $FADH_2$ pass through this chain. Energy is transferred into each molecule through which the electrons pass. Some of the molecules are hydrogen ion pumps. **2** Energy from the electrons is used to actively transport hydrogen ions, H^+, out of the inner mitochondrial compartment. As H^+ ions accumulate in the outer compartment, a concentration gradient across the inner membrane is created.

ATP Production The enzyme ATP synthase is also present on the inner membranes of mitochondria. **3** Hydrogen ions diffuse through a channel in this enzyme. This movement provides energy, which is used to produce several ATP molecules from ADP.

The Role of Oxygen At the end of the electron transport chain, the electrons have given up most of their energy. **4** An oxygen atom combines with these electrons and two H^+ ions to form two water molecules, H_2O. If oxygen is not present, the electron transport chain stops. The electron carriers cannot be recycled, so the Krebs cycle also stops. Without oxygen, a cell can produce ATP only by glycolysis.

Reading Check ***Why is glycolysis important to the Krebs cycle?***

READING TOOLBOX

Pattern Puzzles Make a pattern puzzle to help you remember the steps in aerobic respiration.

Figure 13 Along the inner mitochondrial membrane, an electron transport chain produces a hydrogen ion gradient. The diffusion of hydrogen ions provides energy for the production of ATP by ATP synthase.

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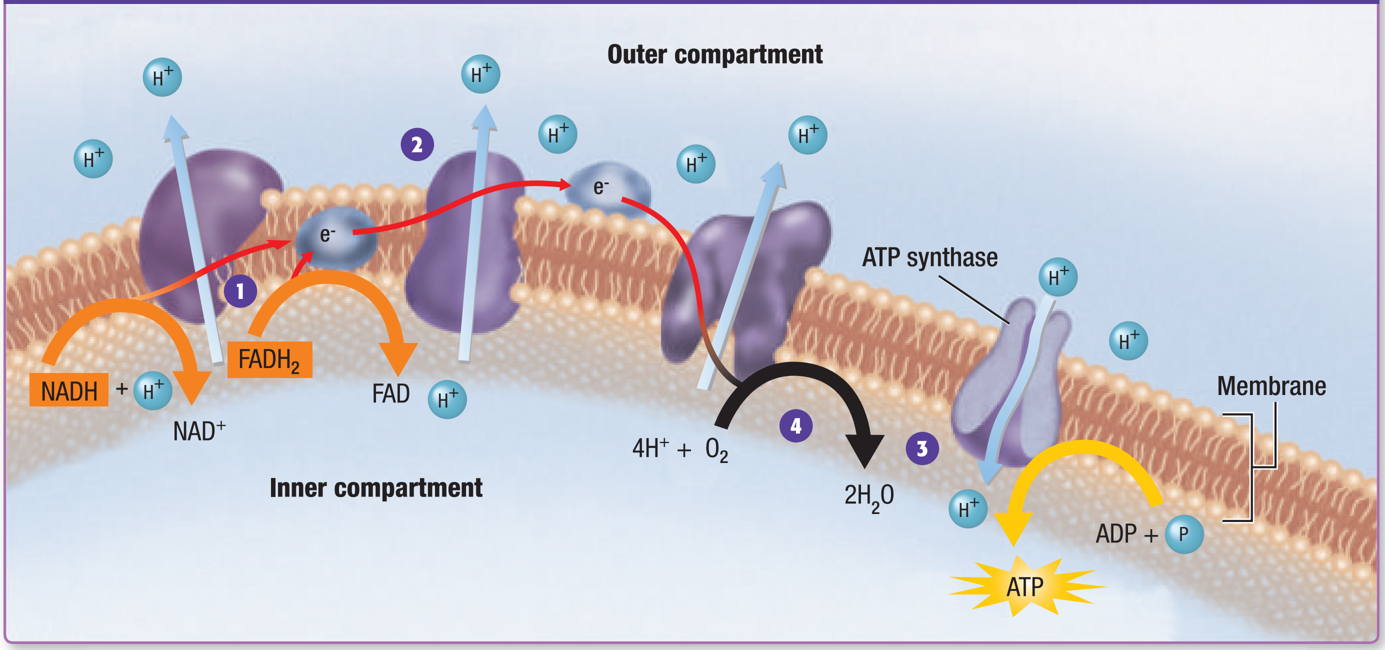
Electron Transport Chain



Fermentation

Many prokaryotes live entirely on the energy released in glycolysis. Recall that glycolysis produces two ATP molecules and one molecule of the electron carrier NADH. The NADH must be able to transfer its electrons to an acceptor so that NAD^+ is continuously available. Under anaerobic conditions, the electron transport chain, if present, does not work. Organisms must have another way to recycle NAD^+. So, electrons carried by NADH are transferred to pyruvate, which is produced during glycolysis. This process in which carbohydrates are broken down in the absence of oxygen, called **fermentation,** recycles the NAD^+ that is needed to continue making ATP through glycolysis. **Fermentation enables glycolysis to continue supplying a cell with ATP in anaerobic conditions.** Two types of fermentation are lactic acid fermentation and alcoholic fermentation.

ACADEMIC VOCABULARY

transfer to carry or remove something from one thing to another

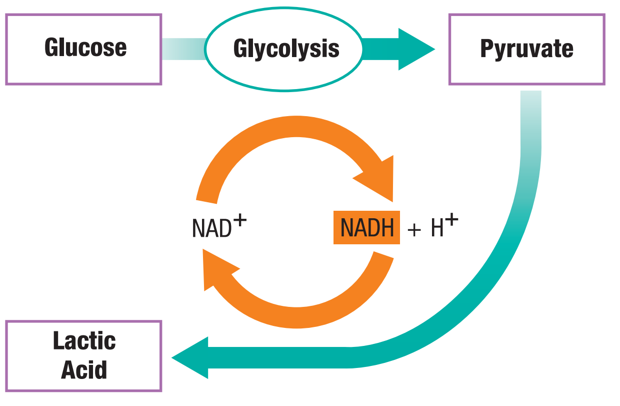
fermentation the breakdown of carbohydrates by enzymes, bacteria, yeasts, or mold in the absence of oxygen

Lactic Acid Fermentation Recall that the end products of glycolysis are three-carbon pyruvate molecules. In some organisms, pyruvate accepts electrons and hydrogen from NADH. Pyruvate is converted to lactic acid in a process called *lactic acid fermentation,* as **Figure 14** shows. Lactic acid fermentation also occurs in the muscles of animals, including humans. During vigorous exercise, muscle cells must operate without enough oxygen. So, glycolysis becomes the only source of ATP as long as the glucose supply lasts. For glycolysis to continue, NAD^+ is recycled by lactic acid fermentation.

Alcoholic Fermentation In other organisms, an enzyme removes carbon dioxide from the three-carbon pyruvate to form a two-carbon molecule. Then, a second enzyme adds electrons and hydrogen from NADH to the molecule to form ethanol (ethyl alcohol) in a process called *alcoholic fermentation.* In this process, NAD^+ is recycled and glycolysis can continue to produce ATP.

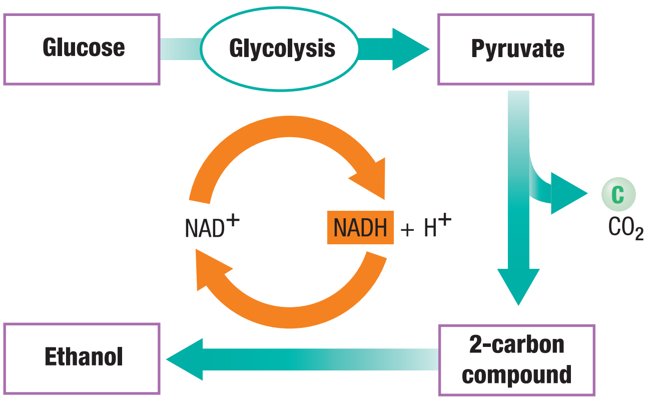
Reading Check ***Explain how fermentation recycles NAD^+.***

Figure 14 When oxygen is not present, cells recycle NAD^+ through fermentation. **Compare lactic acid fermentation with alcoholic fermentation.**



Lactic acid fermentation

In lactic acid fermentation, pyruvate is converted to lactic acid.



Alcoholic fermentation

In alcoholic fermentation, pyruvate is broken down to ethanol, releasing carbon dioxide.

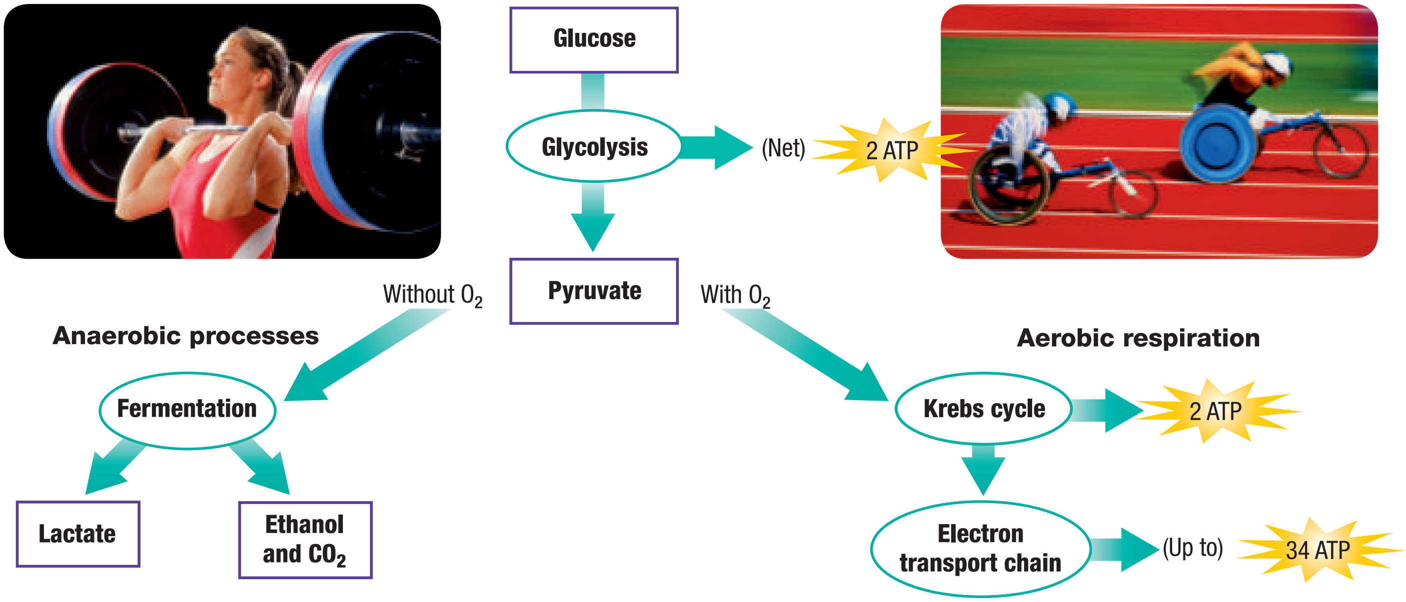


Figure 15 Most ATP is produced during aerobic respiration. **❯ Which cellular respiration process produces ATP molecules most efficiently?**

Efficiency of Cellular Respiration The total amount of ATP that a cell harvests from each glucose molecule depends on the presence or absence of oxygen. **Figure 15** compares the amount of ATP produced in both cases.

In the first stage of cellular respiration, glucose is broken down to pyruvate during glycolysis. Glycolysis is an anaerobic process, and it results in a net gain of two ATP molecules.

In the second stage of cellular respiration, pyruvate either passes through the Krebs cycle or undergoes fermentation. When oxygen is not present, fermentation occurs. The NAD^+ that is recycled during fermentation allows glycolysis to continue producing ATP.

Cells release energy most efficiently when oxygen is present because they make most of their ATP during aerobic respiration. For each molecule of glucose that is broken down, as many as two ATP molecules are made during the Krebs cycle. The Krebs cycle feeds NADH and $FADH_2$ to the electron transport chain. The electron transport chain can produce up to 34 ATP molecules.

Section 3 Review

❯ KEY IDEAS

1. **List** the products of glycolysis, and explain the role of each of these products in both aerobic respiration and anaerobic respiration.
2. **Summarize** the roles of the Krebs cycle and the electron transport chain during aerobic respiration.
3. **Describe** the role of fermentation in the second stage of cellular respiration.

CRITICAL THINKING

4. **Inferring Conclusions** Excess glucose in your blood is stored in your liver as glycogen. How might your body sense when to convert glucose to glycogen and glycogen back to glucose again?

ALTERNATIVE ASSESSMENT

5. **Analyzing Methods** Research ways that fermentation is used in food preparation. Find out what kinds of microorganisms are used in cultured dairy products, such as yogurt, sour cream, and some cheeses. Research the role of alcoholic fermentation by yeast in bread making. Prepare an oral report to summarize your findings.

Chapter 9 Summary

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SUPER SUMMARY
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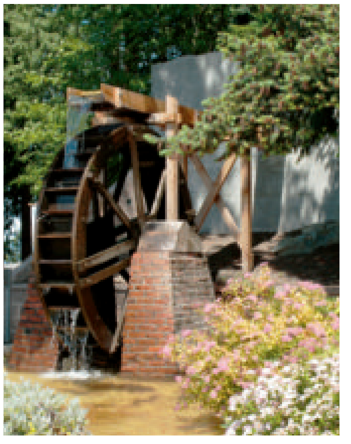
Key Ideas	Key Terms

1 Energy in Living Systems



- Organisms use and store energy in the chemical bonds of organic compounds.
- Metabolism involves either using energy to build organic molecules or breaking down organic molecules in which energy is stored. Organic molecules contain carbon. Therefore, an organism's metabolism is part of Earth's carbon cycle.
- In cells, chemical energy is gradually released in a series of chemical reactions that are assisted by enzymes.

Key Terms

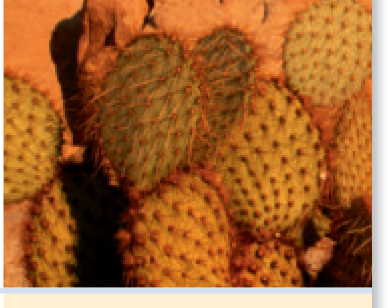
photosynthesis (197)
cellular respiration (198)
ATP (198)
ATP synthase (201)
electron transport chain (201)

2 Photosynthesis

- In plants, light energy is harvested by pigments located in the thylakoid membrane of chloroplasts.
- During photosynthesis, one electron transport chain provides energy used to make ATP, while the other provides energy to make NADPH.
- In the final stage of photosynthesis, chemical energy is stored by being used to produce sugar molecules from the carbon in the gas carbon dioxide.
- Light intensity, carbon dioxide concentration, and temperature are three environmental factors that affect photosynthesis.

Key Terms

thylakoid (202)
pigment (203)
chlorophyll (203)
Calvin cycle (206)



3 Cellular Respiration

- The breaking of a sugar molecule by glycolysis results in a net gain of two ATP molecules.
- The total yield of energy-storing products from one time through the Krebs cycle is one ATP, three NADH, and one $FADH_2$. Electron carriers transfer energy through the electron transport chain, which ultimately powers ATP synthase.
- Fermentation enables glycolysis to continue supplying a cell with ATP in anaerobic conditions.

Key Terms

glycolysis (209)
anaerobic (209)
aerobic (209)
Krebs cycle (210)
fermentation (212)