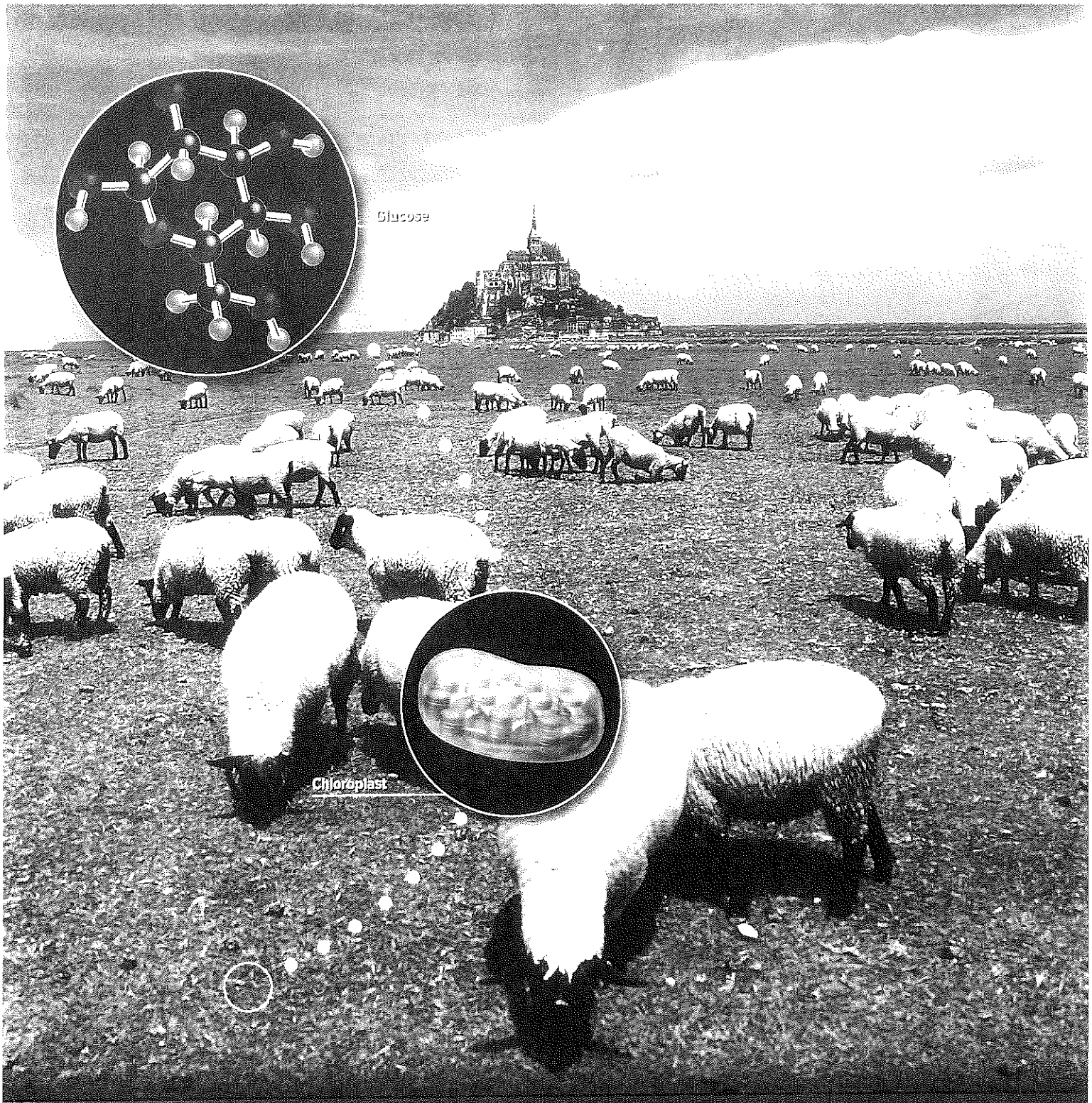


THEME FOCUS **Energy and Matter**
The Sun is the source of nearly all of the energy on Earth.

BIG Idea **Photosynthesis converts the Sun's energy into chemical energy, while cellular respiration uses chemical energy to carry out life functions.**

Reading Preview

Essential Questions

- What are the two laws of thermodynamics?
- What is the difference between an anabolic pathway and a catabolic pathway?
- How does ATP work in a cell?

Review Vocabulary

trophic level: each step in a food chain or a food web

New Vocabulary

energy
thermodynamics
metabolism
photosynthesis
cellular respiration
adenosine triphosphate (ATP)

Multilingual eGlossary

How Organisms Obtain Energy

MAIN Idea **All living organisms use energy to carry out all biological processes.**

Real-World Reading Link New York City is sometimes called "the city that never sleeps." Much like the nonstop movement of a big city, living cells are sites of constant activity.

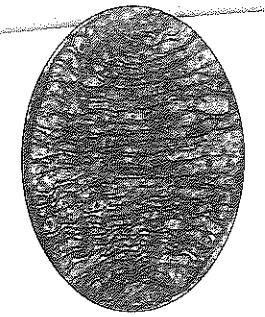
Transformation of Energy

Many chemical reactions and processes in your cells are ongoing, even when you might not think that you are using any energy. Macromolecules are assembled and broken down, substances are transported across cell membranes, and genetic instructions are transmitted. All of these cellular activities require **energy**–the ability to do work. **Figure 1** shows some of the major advancements in the study of cellular energy. **Thermodynamics** is the study of the flow and transformation of energy in the universe.

Laws of thermodynamics The first law of thermodynamics is the law of conservation of energy, which states that energy can be converted from one form to another, but it cannot be created nor destroyed. For example, the stored energy in food is converted to chemical energy when you eat and to mechanical energy when you run or kick a ball.

Figure 1
Understand Cellular Energy

Scientific discoveries have led to a greater understanding of photosynthesis and cellular respiration.

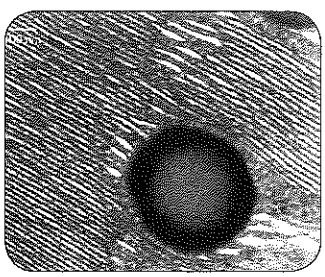


1844 Hugo von Mohl first observes chloroplasts in plant cells.

1948 Eugene Kennedy and Albert Lehninger discover that mitochondria are responsible for cellular respiration.

1800 1900 1940

1772 Joseph Priestley determines that plants take in carbon dioxide and emit oxygen.



1881–82 Chloroplasts are shown to be the organelles responsible for photosynthesis.

(t)Biophoto Associates/Science Source; (b)©Cail... Ages/Corbis

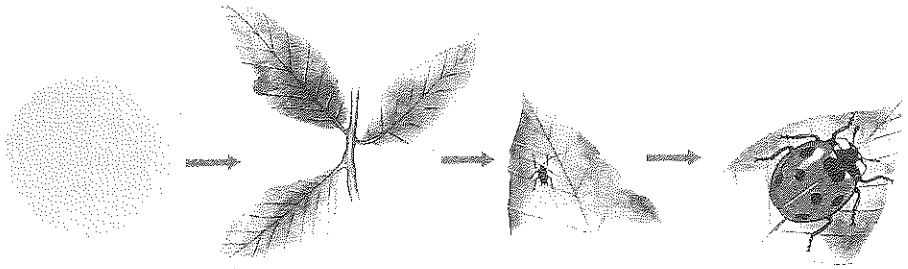


Figure 2 Almost all the energy in living organisms originates from the Sun, and energy flows from autotrophs to heterotrophs. *Relate the laws of thermodynamics to the organisms in the figure.*

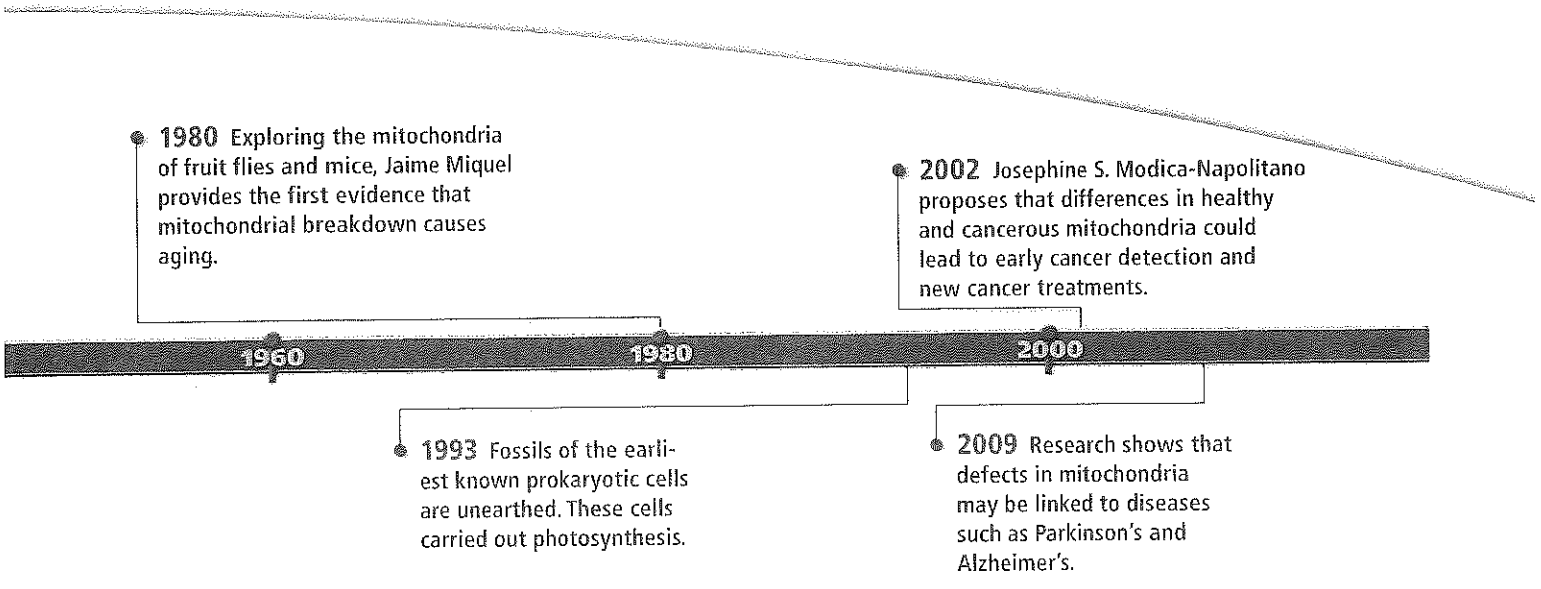
The second law of thermodynamics states that energy cannot be converted without the loss of usable energy. The energy that is "lost" is generally converted to thermal energy. Entropy (EN truh pee) is the measure of disorder, or unusable energy, in a system. Therefore, the second law of thermodynamics can also be stated as "entropy increases." One example of the second law of thermodynamics is evident in food chains. Recall that in a food chain, the amount of usable energy that is available to the next trophic level decreases.

Autotrophs and heterotrophs All organisms need energy to live. Directly or indirectly, nearly all the energy for life comes from the Sun. Some organisms make their own food, while others must obtain it from other organisms. Autotrophs are organisms that make their own food. Some autotrophs, called chemoautotrophs, use inorganic substances such as hydrogen sulfide as a source of energy. Other autotrophs, such as the plant in **Figure 2**, convert light energy from the Sun into chemical energy. Autotrophs that convert energy from the Sun are called photoautotrophs. Heterotrophs, such as the aphid and the ladybug in **Figure 2**, are organisms that need to ingest food to obtain energy.

VOCABULARY

Word origin

Autotroph
comes from the Greek word *autotrophos*, meaning *supplying one's own food*



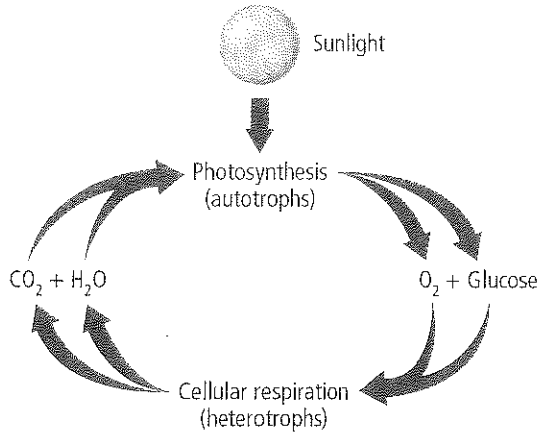


Figure 3 In an ecosystem, photosynthesis and cellular respiration form a cycle.
Identify *the anabolic and catabolic pathways in the figure.*

Launch Lab

Review **Based on what you have read about energy transformations, how would you now answer the analysis questions?**

Metabolism

All of the chemical reactions in a cell are referred to as the cell's **metabolism.** A series of chemical reactions in which the product of one reaction is the substrate for the next reaction is called a metabolic pathway. Metabolic pathways include two broad types: catabolic (ka tuh BAH lik) pathways and anabolic (a nuh BAH lik) pathways. Catabolic pathways release energy by breaking down larger molecules into smaller molecules. Anabolic pathways use the energy released by catabolic pathways to build larger molecules from smaller molecules. The relationship of anabolic and catabolic pathways results in the continual flow of energy within an organism.

Energy continually flows between the metabolic reactions of organisms in an ecosystem. **Photosynthesis** is the anabolic pathway in which light energy from the Sun is converted to chemical energy for use by the cell. In this reaction, autotrophs use light energy, carbon dioxide, and water to form glucose and oxygen. The energy stored in the glucose produced by photosynthesis can be transferred to other organisms when the molecules are consumed as food.

Cellular respiration is the catabolic pathway in which organic molecules are broken down to release energy for use by a cell. In cellular respiration, oxygen is used to break down organic molecules, resulting in the production of carbon dioxide and water. Notice the cyclical nature of these processes in **Figure 3,** where the products of one reaction are the reactants for the other reaction.

MiniLab 1

Relate Photosynthesis to Cellular Respiration

MiniLab

How do photosynthesis and cellular respiration work together in an ecosystem? Use a chemical indicator to examine how carbon dioxide is transferred in photosynthesis and cellular respiration.

Procedure

1. Read and complete the lab safety form.
2. Prepare a data table to record the contents, treatment, initial color, and final color for two experimental test tubes.
3. Pour 100 mL of **bromothymol blue (BTB) solution** into a **beaker.** Using a **straw,** exhale gently into the solution until it just turns yellow. **WARNING:** ***Do not exhale so much that the solution bubbles over or that you get a headache. Do not suck on the straw.***
4. Fill two large **test tubes** three-quarters full with the yellow BTB solution.
5. Cover one test tube entirely with **aluminum foil.** Place a 6-cm sprig of an **aquatic plant** into both of the tubes, tightly insert the **stoppers into** the tubes, and place them in a **rack** in bright light overnight.
6. Record your observations in your data table.

Analysis

1. **Describe** the purpose of the tube covered with aluminum foil.
2. **Explain** how your results demonstrate that photosynthesis and cellular respiration depend on one another.

ATP: The Unit of Cellular Energy

Connection to Chemistry Energy exists in many forms, including light energy, mechanical energy, thermal energy, and chemical energy. In living organisms, chemical energy is stored in biological molecules and can be converted to other forms of energy when needed. For example, the chemical energy in biological molecules is converted to mechanical energy when muscles contract. **Adenosine triphosphate** (uh DEN uh seen • tri FAHS fayt)–ATP–is the most important biological molecule that provides chemical energy.

ATP structure ATP is a multipurpose storehouse of chemical energy that can be used by cells in a variety of reactions. Although other carrier molecules transport energy within cells, ATP is the most abundant energy-carrier molecule in cells and is found in all types of organisms. As shown in **Figure 4,** ATP is a nucleotide made of an adenine base, a ribose sugar, and three phosphate groups.

ATP function ATP releases energy when the bond between the second and third phosphate groups is broken, forming a molecule called adenosine diphosphate (ADP) and a free phosphate group, as shown in **Figure 4.** Energy is stored in the phosphate bond formed when ADP receives a phosphate group and becomes ATP. As shown in **Figure 4,** ATP and ADP can be interchanged by the addition or removal of a phosphate group. Sometimes ADP becomes adenosine monophosphate (AMP) by losing an additional phosphate group. There is less energy released in this reaction, so most of the energy reactions in the cell involve ATP and ADP.

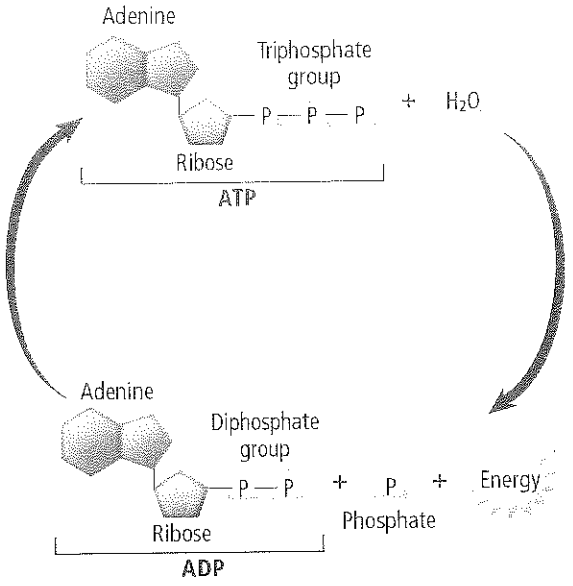


Figure 4 The breakdown of ATP releases energy for powering cellular activities in organisms.

Animation

Section 1 Assessment

Section Summary

- The laws of thermodynamics control the flow and transformation of energy in organisms.
- Some organisms produce their own food, whereas others obtain energy from the food they ingest.
- Cells store and release energy through coupled anabolic and catabolic reactions.
- The energy released from the breakdown of ATP drives cellular activities.

Understand Main Ideas

1. **Identify** the major source of energy for living organisms.
2. **Describe** an example of the first law of thermodynamics.
3. **Compare and contrast** anabolic and catabolic pathways.
4. **Explain** how ATP stores and releases energy by making a model.

Think Critically

Writing in Biology

5. Write an essay describing the laws of thermodynamics. Use examples related to biology to support your ideas.
6. **Create** an analogy to describe the relationship between photosynthesis and cellular respiration.

Online Quiz

Reading Preview

Essential Questions

- What are the two phases of photosynthesis?
- What is the function of a chloroplast during the light reactions?
- How can electron transport be described and diagramed?

Review Vocabulary

carbohydrate: an organic compound containing only carbon, hydrogen, and oxygen, usually in a 1:2:1 ratio

New Vocabulary

thylakoid
granum
stroma
pigment
$NADP^+$
Calvin cycle
rubisco

Multilingual eGlossary

Photosynthesis

MAIN Idea **Light energy is trapped and converted into chemical energy during photosynthesis.**

Real-World Reading Link Energy is transformed all around us every day. Batteries convert chemical energy into electric energy, and radios convert electric energy into the energy carried by sound waves. Similarly, some autotrophs convert light energy into chemical energy through photosynthesis.

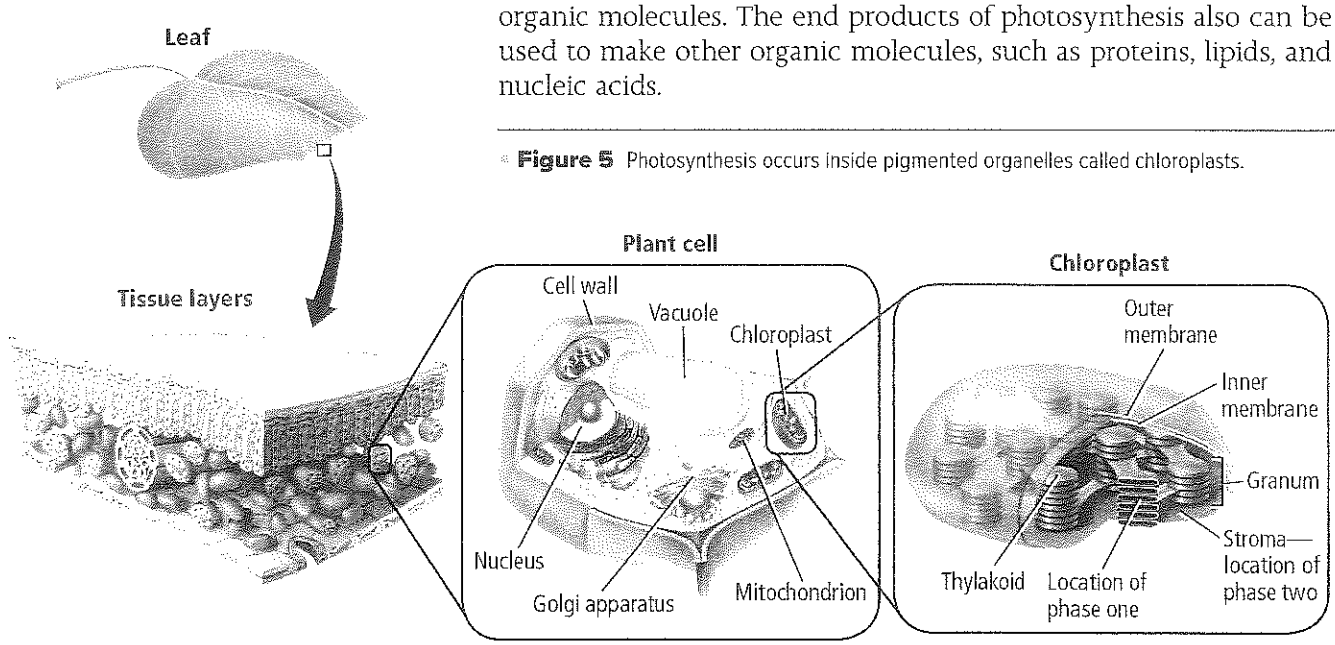
Overview of Photosynthesis

Most autotrophs, including plants, make organic compounds, such as sugars, by a process called photosynthesis. Recall that photosynthesis is a process in which light energy is converted into chemical energy. The overall chemical equation for photosynthesis is shown below.

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

Photosynthesis occurs in two phases. The locations of these phases are shown in **Figure 5.** In phase one, the light-dependent reactions, light energy is absorbed and then converted into chemical energy in the form of ATP and NADPH. In phase two, the light-independent reactions, the ATP and NADPH that were formed in phase one are used to make glucose. Once glucose is produced, it can be joined to other simple sugars to form larger molecules. These larger molecules are complex carbohydrates, such as starch. Recall that carbohydrates are composed of repeating units of small organic molecules. The end products of photosynthesis also can be used to make other organic molecules, such as proteins, lipids, and nucleic acids.

Figure 5 Photosynthesis occurs inside pigmented organelles called chloroplasts.



Phase One: Light Reactions

The absorption of light is the first step in photosynthesis. Plants have special organelles to capture light energy. Once the energy is captured, two energy storage molecules, NADPH and ATP, are produced to be used in the light-independent reactions.

Chloroplasts Large organelles, called chloroplasts, capture light energy in photosynthetic organisms. In plants, chloroplasts are found mainly in the cells of leaves. As shown in **Figure 5**, chloroplasts are disk-shaped organelles that contain two main compartments essential to photosynthesis. The first compartment is called the thylakoid (THI la koyd). **Thylakoids** are flattened, saclike membranes that are arranged in stacks. These stacks are called **grana** (singular, granum). Light-dependent reactions take place within the thylakoids. The second important compartment is called the **stroma**, the fluid-filled space that is outside the grana. This is the location of the light-independent reactions in phase two of photosynthesis.

Pigments Light-absorbing colored molecules called **pigments** are found in the thylakoid membranes of chloroplasts. Different pigments absorb specific wavelengths of light, as illustrated in **Figure 6.**

The major light-absorbing pigments in plants are chlorophylls. There are several types of chlorophylls, but the most common two are chlorophyll *a* and chlorophyll *b*. The structure of chlorophyll can differ from one molecule to another, enabling distinct chlorophyll molecules to absorb light at unique areas of the visible spectrum. In general, chlorophylls absorb most strongly in the violet-blue region of the visible light spectrum and reflect light in the green region of the spectrum. This is why plant parts that contain chlorophyll appear green to the human eye.

Reading Check **Distinguish** between thylakoids and stroma.

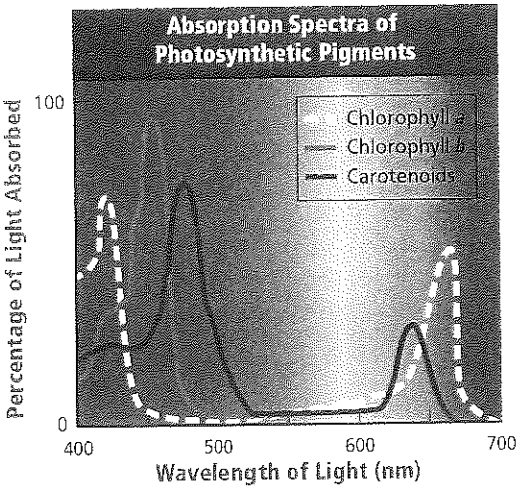


Figure 6 Colorful pigments found in the leaves of trees differ in their ability to absorb specific wavelengths of light.
Hypothesize *the effect on light absorption if a plant did not have chlorophyll* b.

MiniLab 2

MiniLab

Observe Chloroplasts

What do chloroplasts look like? Most ecosystems and organisms in the world depend on tiny organelles called chloroplasts. Discover what chloroplasts look like in this investigation.

Procedure

1. Read and complete the lab safety form.
2. Observe the **slides of plant and algae cells** with a **microscope.**
3. Identify the chloroplasts in the cells that you observe.
4. Make a data table to record your observations, and sketch the chloroplasts in the cells.

Analysis

1. **Compare and contrast** the physical features of the chloroplasts that you observed in the different cells.
2. **Hypothesize** why plant leaves vary in color.

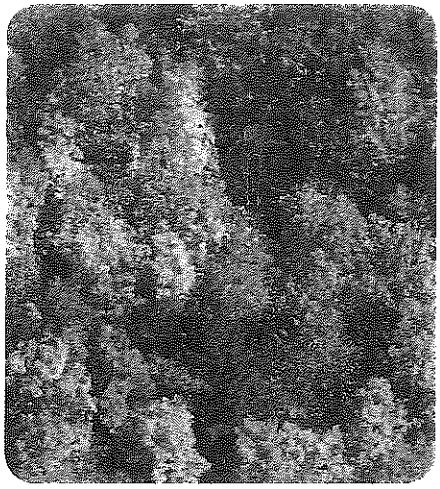


Figure 7 When chlorophyll breaks down in the leaves of some trees, the other pigments become visible.

VOCABULARY

Transport
to carry something from one place to another
$NADP^+$ molecules transport electrons during photosynthesis.

In addition to chlorophylls, most photosynthetic organisms contain accessory pigments that allow plants to trap additional light energy from other areas of the visible spectrum. One such group of accessory pigments is the carotenoids (kuh ROH tuh noydz). Carotenoids, such as ß-carotene (beta-carotene), absorb light mainly in the blue and green regions of the spectrum, while reflecting most light in the yellow, orange, and red regions. Carotenoids produce the colors of carrots and sweet potatoes.

Chlorophylls are more abundant than other pigments in leaves, and thus hide the colors of the other pigments. However, autumn in certain parts of the United States can bring out shades of yellow, red, and orange as the leaves turn colors, as shown in **Figure 7.** As trees prepare to lose their leaves before winter, the chlorophyll molecules break down, revealing the colors of the other pigments.

Electron transport The structure of the thylakoid membrane is the key to efficient energy transfer during electron transport. Thylakoid membranes have a large surface area, which provides the space needed to hold large numbers of electron-transporting molecules and two types of protein complexes called photosystems. Photosystem I and photosystem II contain light-absorbing pigments and proteins that play important roles in the light reactions. Follow along in **Figure 8** as you continue to read about electron transport.

- First, the light energy excites electrons in photosystem II. The light energy also causes a water molecule to split, releasing an electron into the electron transport system, a hydrogen ion (H^+)—also called a proton—into the thylakoid space, and oxygen (O_2) as a waste product. This breakdown of water is essential for photosynthesis to occur.
- The excited electrons move from photosystem II to an electron-acceptor molecule in the thylakoid membrane.
- Next, the electron-acceptor molecule transfers the electrons along a series of electron-carriers to photosystem I.
- In the presence of light, photosystem I transfers the electrons to a protein called ferrodoxin. The electrons lost by photosystem I are replaced by electrons shuttled from photosystem II.
- Finally, ferrodoxin transfers the electrons to the electron carrier **$NADP^+$**, forming the energy-storage molecule NADPH.

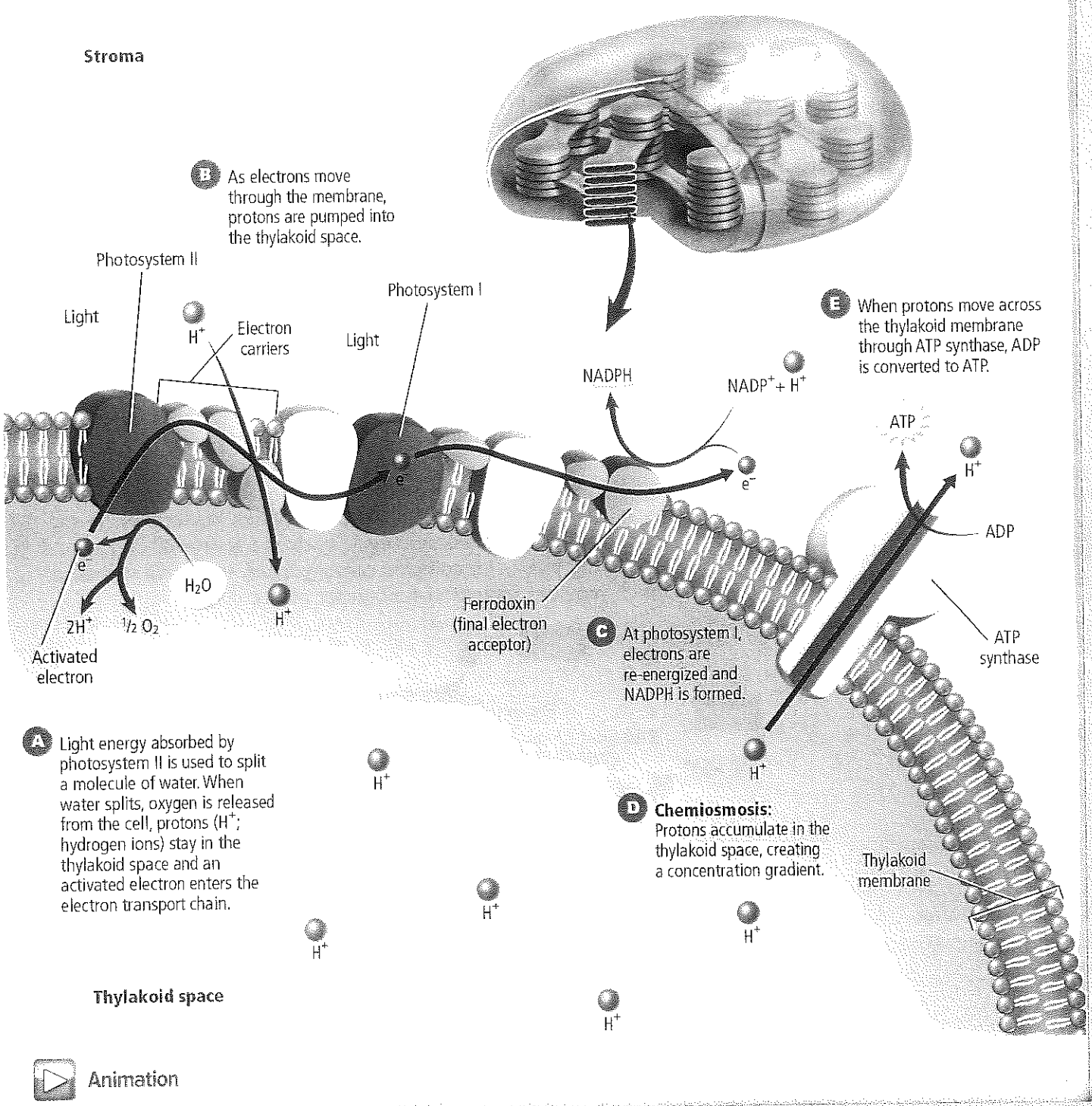
Chemiosmosis ATP is produced in conjunction with electron transport by the process of chemiosmosis—the mechanism by which ATP is produced as a result of the flow of electrons down a concentration gradient. The breakdown of water is essential not only for providing the electrons that initiate the electron transport chain, but also for providing the protons (H^+) necessary to drive ATP synthesis during chemiosmosis. The H^+ released during electron transport accumulate in the interior of the thylakoid. As a result of a high concentration of H^+ in the thylakoid interior and a low concentration of H^+ in the stroma, H^+ protons diffuse down their concentration gradient out of the thylakoid interior into the stroma through ion channels spanning the membrane, as shown in **Figure 8.** These channels are enzymes called ATP synthases. As H^+ moves through ATP synthases, ATP is formed in the stroma.

Reading Check **Summarize** the function of water during chemiosmosis in photosynthesis.

Visualizing Electron Transport

Figure 8

Activated electrons are passed from one molecule to another along the thylakoid membrane in a chloroplast. The energy from electrons is used to form a proton gradient. As protons move down the gradient, a phosphate is added to ADP, forming ATP.



Animation

Phase Two: The Calvin Cycle

Although NADPH and ATP provide cells with large amounts of energy, these molecules are not stable enough to store chemical energy for long periods of time. Thus, there is a second phase of photosynthesis called the **Calvin cycle**, in which energy is stored in organic molecules such as glucose. The reactions of the Calvin cycle are also referred to as the light-independent reactions. Follow along in **Figure 9** as you learn the steps of the Calvin cycle.

- In the first step of the Calvin cycle, called carbon fixation, six carbon dioxide (CO_2) molecules combine with six 5-carbon compounds to form twelve 3-carbon molecules called 3-phosphoglycerate (fahs foh GLI suh rayt) (3-PGA). The joining of carbon dioxide with other organic molecules is called carbon fixation.
- In the second step, the chemical energy stored in ATP and NADPH is transferred to the 3-PGA molecules to form high-energy molecules called glyceraldehyde 3-phosphates (G3P). ATP supplies the phosphate groups for forming G3P molecules, while NADPH supplies hydrogen ions and electrons.
- In the third step, two G3P molecules leave the cycle to be used for the production of glucose and other organic compounds.
- In the final step of the Calvin cycle, an enzyme called **rubisco** converts the remaining ten G3P molecules into 5-carbon molecules called ribulose 1, 5-bisphosphates (RuBP). These molecules combine with new carbon dioxide molecules to continue the cycle.

Because rubisco converts inorganic carbon dioxide molecules into organic molecules that can be used by the cell, it is considered one of the most important biological enzymes. Plants use the sugars formed during the Calvin cycle both as a source of energy and as building blocks for complex carbohydrates, including cellulose, which provides structural support for plants.

CAREERS IN BIOLOGY

Phytochemist A biologist who studies the chemical products of plants is a phytochemist. Phytochemists might work in medical research to find new treatments for diseases.

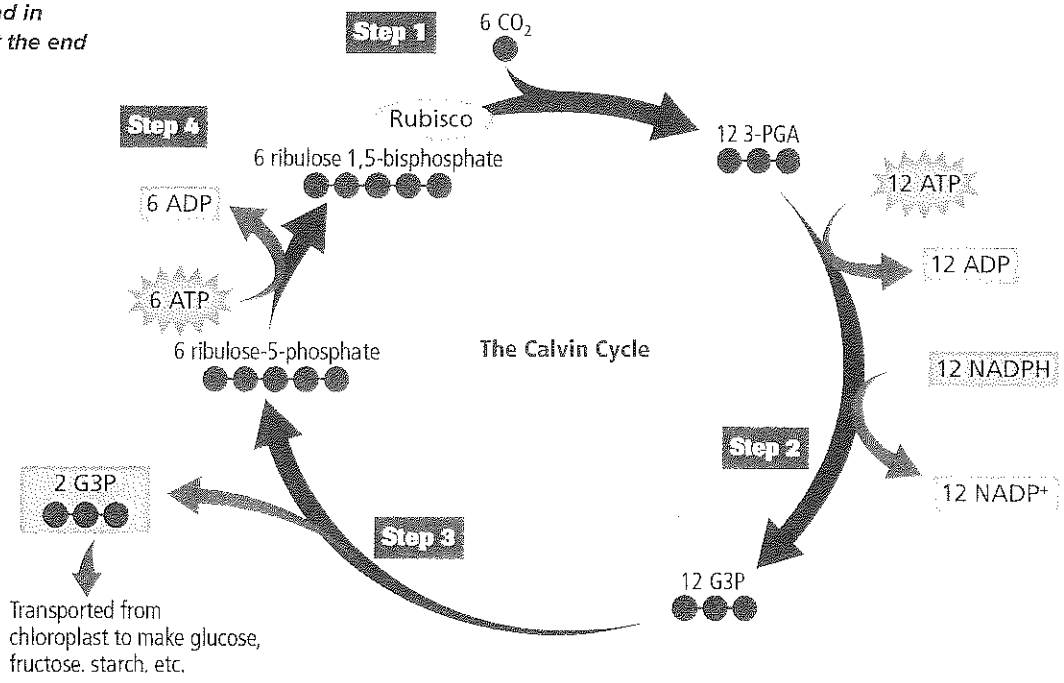


Figure 9 The Calvin cycle joins carbon dioxide with organic molecules inside the stroma of the chloroplast.

Determine the compound in which energy is stored at the end of the Calvin cycle.

Animation

Alternative Pathways

The environment in which an organism lives can impact the organism's ability to carry out photosynthesis. Environments in which the amount of water or carbon dioxide available is insufficient can decrease the ability of a photosynthetic organism to convert light energy into chemical energy. For example, plants in hot, dry environments are subject to excessive water loss that can lead to decreased photosynthesis. Many plants in extreme climates have alternative photosynthesis pathways to maximize energy conversion.

C_4 plants One adaptive pathway that helps plants maintain photosynthesis while minimizing water loss is called the C_4 pathway. The C_4 pathway occurs in plants such as sugarcane and corn. These plants are called C_4 plants because they fix carbon dioxide into four-carbon compounds instead of three-carbon molecules during the Calvin cycle. C_4 plants also have significant structural modifications in the arrangement of cells in the leaves. In general, C_4 plants keep their stomata (plant cell pores) closed during hot days, while the four carbon compounds are transferred to special cells where CO_2 enters the Calvin cycle. This allows for sufficient carbon dioxide uptake, while simultaneously minimizing water loss.

CAM plants Another adaptive pathway used by some plants to maximize photosynthetic activity is called crassulacean (KRAH soo lay shun) acid metabolism (CAM photosynthesis). The CAM pathway occurs in water-conserving plants that live in deserts, salt marshes, and other environments where access to water is limited. CAM plants, such as cacti, orchids, and the pineapple in **Figure 10**, allow carbon dioxide to enter the leaves only at night, when the atmosphere is cooler and more humid. At night, these plants fix carbon dioxide into organic compounds. During the day, carbon dioxide is released from these compounds and enters the Calvin cycle. This pathway also allows for sufficient carbon dioxide uptake while minimizing water loss.

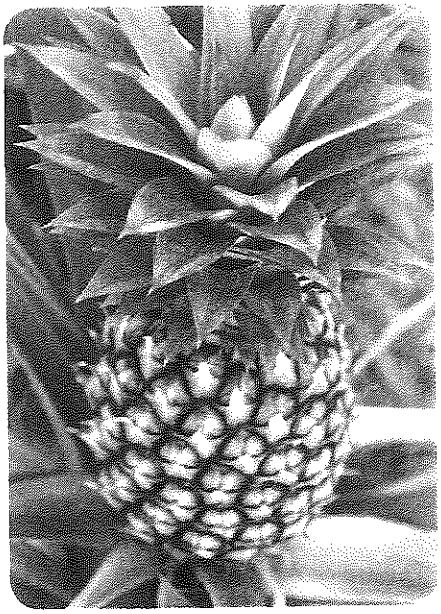


Figure 10 This pineapple plant is an example of a CAM plant.

APPLYING PRACTICES

Develop and Use Models Go to the resources tab in ConnectED to find the Applying Practices worksheet *Modeling Photosynthesis.*

Section 2 Assessment

Section Summary

- Plants contain chloroplasts with light-absorbing pigments that convert light energy into chemical energy.
- Photosynthesis is a two-phase process that consists of light reactions and the Calvin cycle.
- In the light reactions, autotrophs trap and convert light energy into chemical energy in the form of NADPH and ATP.
- In the Calvin cycle, chemical energy in ATP and NADPH is used to synthesize carbohydrates such as glucose.

Understand Main Ideas

1. MAIN Idea **Summarize** how chemical energy is formed from light energy during photosynthesis.
2. **Relate** the structure of a chloroplast to the phases of photosynthesis.
3. **Explain** why water is essential for the light reactions.
4. **Summarize** the steps in the Calvin cycle.
5. **Diagram** and explain electron transport.

Think Critically

6. **Predict** how environmental factors such as light intensity and carbon dioxide levels can affect rates of photosynthesis.

WRITING in Biology

7. Research the effects of global warming on photosynthesis. Write an article summarizing your findings.

Online Quiz

Reading Preview

Essential Questions

- What are the stages of cellular respiration?
- What is the role of electron carriers in each stage of cellular respiration?
- What are the similarities between alcoholic fermentation and lactic acid fermentation?

Review Vocabulary

cyanobacterium: a type of bacterium that is a photosynthetic autotroph

New Vocabulary

anaerobic process
aerobic respiration
aerobic process
glycolysis
Krebs cycle
fermentation

Multilingual eGlossary

Cellular Respiration

MAIN IDEA **Living organisms obtain energy by breaking down organic molecules during cellular respiration.**

Real-World Reading Link Monarch butterflies must constantly feed on nectar from flowers to provide energy to sustain themselves during their winter migration to parts of Mexico and California each year. Similarly, humans and other living organisms need reliable food sources to supply energy to survive and grow.

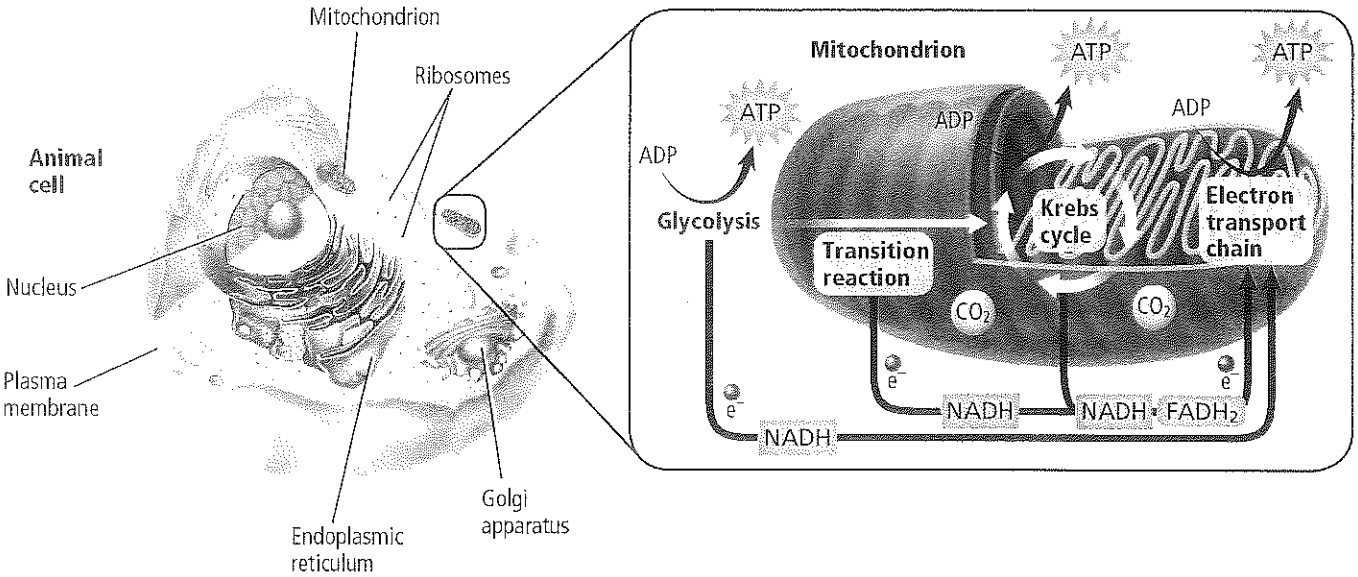
Overview of Cellular Respiration

Recall that organisms obtain energy in a process called cellular respiration. The function of cellular respiration is to harvest electrons from carbon compounds, such as glucose, and use that energy to make ATP. ATP is used to provide energy for cells to do work. The overall chemical equation for cellular respiration is shown below. Notice the equation for cellular respiration is the opposite of the equation for photosynthesis.

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

Cellular respiration occurs in two main parts: glycolysis and aerobic respiration. The first stage, glycolysis, is an anaerobic process. **Anaerobic processes** do not require oxygen. **Aerobic respiration** includes the Krebs cycle and electron transport and is an aerobic process. **Aerobic processes** require oxygen. Cellular respiration with aerobic respiration is summarized in **Figure 11.**

Figure 11 Cellular respiration occurs in the mitochondria, the energy powerhouse organelles of a cell.



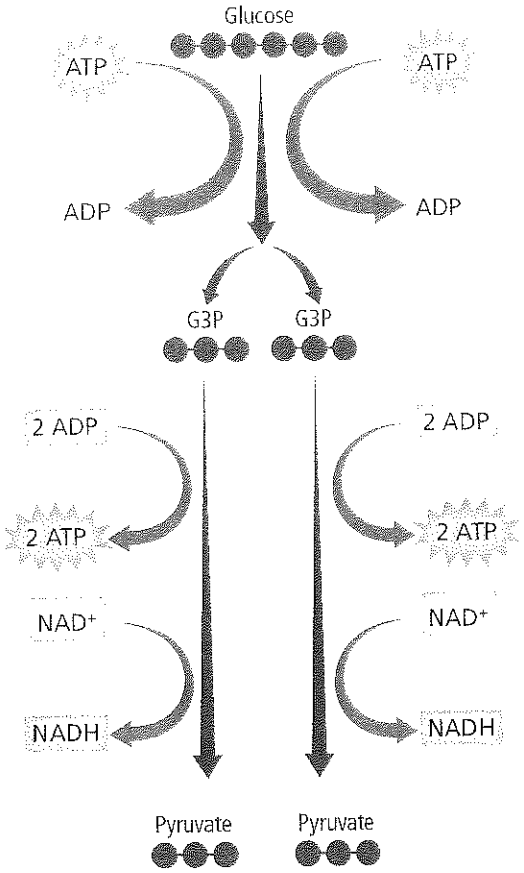


Figure 12 Glucose is broken down during glycolysis inside the cytoplasm of cells. *Summarize the reactants and products of glycolysis.*

Personal Tutor

Glycolysis

Glucose is broken down in the cytoplasm through the process of **glycolysis.** Two molecules of ATP and two molecules of NADH are formed for each molecule of glucose that is broken down. Follow along with **Figure 12** as you read about the steps of glycolysis.

First, two phosphate groups, derived from two molecules of ATP, are joined to glucose. Notice that some energy, two ATP, is required to start the reactions that will produce energy for the cell. The 6-carbon molecule is then broken down into two 3-carbon compounds. Next, two phosphates are added and electrons and hydrogen ions (H^+) combine with two NAD^+ molecules to form two NADH molecules. NAD^+ is similar to NADP, an electron carrier used during photosynthesis. Last, the two 3-carbon compounds are converted into two molecules of pyruvate. At the same time, four molecules of ATP are produced.

Reading Check **Explain** why there is a net yield of two, not four, ATP molecules in glycolysis.

Krebs Cycle

Glycolysis has a net result of two ATP and two pyruvate molecules. Most of the energy from the glucose is still contained in the pyruvate. In the presence of oxygen, pyruvate is transported into the mitochondrial matrix, where it is eventually converted to carbon dioxide. The series of reactions in which pyruvate is broken down into carbon dioxide is called the **Krebs cycle**, or the tricarboxylic acid (TCA) cycle. This cycle also is referred to as the citric acid cycle.

VOCABULARY

WORD ORIGIN

Glycolysis comes from the Greek words *glykys*, meaning *sweet* and *lysis*, meaning *to rupture or break*

FOLDABLES

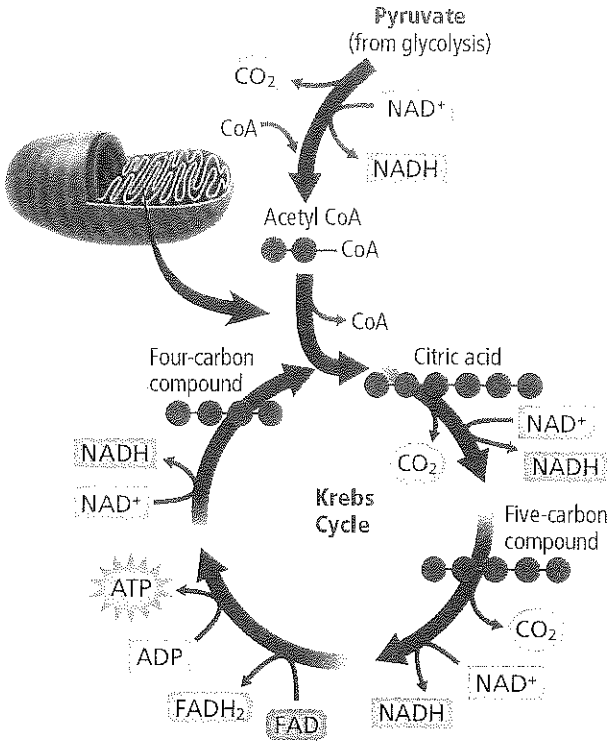
Incorporate information from this section into your Foldable.

APPLYING PRACTICES

Develop and Use Models Go to the resources tab in ConnectED to find the Applying Practices worksheet *Modeling Cellular Respiration.*

Figure 13 Pyruvate is broken down into carbon dioxide during the Krebs cycle inside the mitochondria of cells.
Trace *Follow the path of carbon molecules that enter and leave the Krebs cycle.*

Animation



Study Tip

Clarifying Statement Work with a partner to read the text and discuss unfamiliar words and difficult concepts. Write a clarifying statement to summarize the Krebs cycle.

Steps of the Krebs cycle Prior to the Krebs cycle, pyruvate first reacts with coenzyme A (CoA) to form a 2-carbon intermediate called acetyl CoA. At the same time, carbon dioxide is released and NAD^+ is converted to NADH. Acetyl CoA then moves to the mitochondrial matrix. The reaction results in the production of two carbon dioxide molecules and two NADH molecules. Follow along in **Figure 13** as you continue reading about the steps of the Krebs cycle.

- The Krebs cycle begins with acetyl CoA combining with a 4-carbon compound to form a 6-carbon compound known as citric acid.
- Citric acid is then broken down in the next series of steps, releasing two molecules of carbon dioxide and generating one ATP, three NADH, and one $FADH_2$. FAD is another electron carrier similar to NAD^+ and $NADP^+$.
- Finally, acetyl CoA and citric acid are generated and the cycle continues.

Recall that two molecules of pyruvate are formed during glycolysis, resulting in two "turns" of the Krebs cycle for each glucose molecule. The net yield from the Krebs cycle is six carbon dioxide molecules, two ATP, eight NADH, and two $FADH_2$. Ten NADH and two $FADH_2$ move on to play a significant role in the next stage of aerobic respiration.

CAREERS IN BIOLOGY

Bioenergeticist A researcher who studies energy transfers in cells is a bioenergeticist. Some bioenergeticists study mitochondria and their relationship to aging and disease.

Electron Transport

In aerobic respiration, electron transport is the final step in the breakdown of glucose. It also is the point at which most of the ATP is produced. High-energy electrons and hydrogen ions from NADH and $FADH_2$ produced in the Krebs cycle are used to convert ADP to ATP.

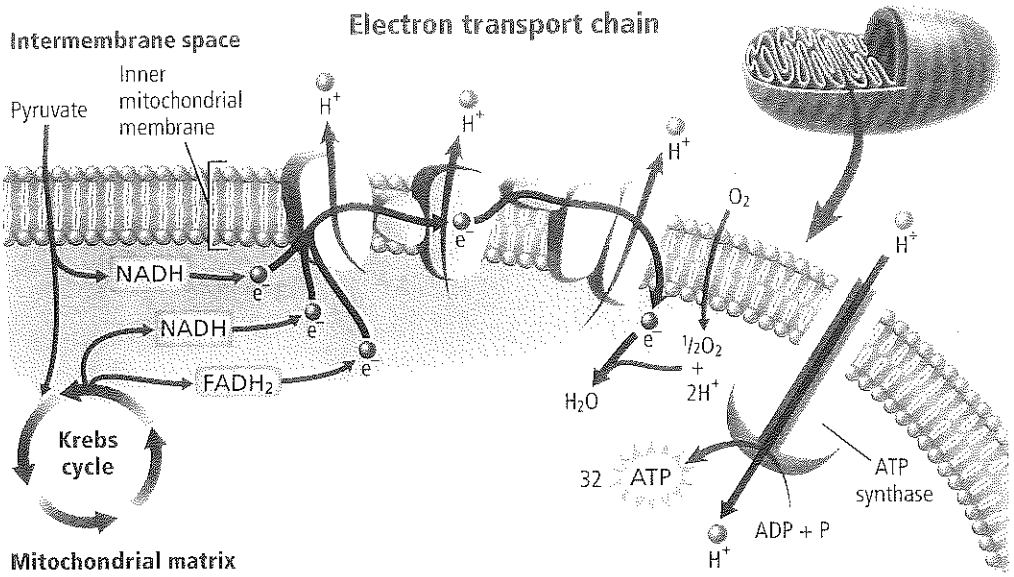


Figure 14 Electron transport occurs along the mitochondrial membrane.
Compare and contrast ***electron transport in cellular respiration and photosynthesis.***

As shown in **Figure 14,** electrons move along the mitochondrial membrane from one protein to another. As NADH and $FADH_2$ release electrons, the energy carriers are converted to NAD^+ and FAD, and H^+ ions are released into the mitochondrial matrix. The H^+ ions are pumped into the mitochondrial matrix across the inner mitochondrial membrane. H^+ ions then diffuse down their concentration gradient back across the membrane and into the matrix through ATP synthase molecules in chemiosmosis. Electron transport and chemiosmosis in cellular respiration are similar to these processes in photosynthesis. Oxygen is the final electron acceptor in the electron transport system in cellular respiration. Protons and electrons are transferred to oxygen to form water.

Overall, electron transport produces 32 ATP. Each NADH molecule produces three ATP and each group of three $FADH_2$ produces two ATP. In eukaryotes, one molecule of glucose yields 36 ATP under ideal conditions.

Prokaryotic cellular respiration Some prokaryotes also undergo aerobic respiration. Because prokaryotes do not have mitochondria, there are differences in the process. The main difference involves the use of the prokaryotic cellular membrane as the location of electron transport. In eukaryotic cells, pyruvate is transported to the mitochondria. In prokaryotes, this movement is unnecessary, saving the prokaryotic cell two ATP, and increasing the net total of ATP produced to 38.

Anaerobic Respiration

Some cells can function for a short time when oxygen levels are low. Some prokaryotes are anaerobic organisms—they grow and reproduce without oxygen. In some cases these cells continue to produce ATP through glycolysis. However, there are problems with solely relying on glycolysis for energy. Glycolysis provides only two net ATP for each molecule of glucose, and a cell has a limited amount of NAD^+. Glycolysis will stop when all the NAD^+ is used up if there is not a process to replenish NAD^+. The anaerobic pathway that follows glycolysis is anaerobic respiration, or fermentation. **Fermentation** occurs in the cytoplasm and regenerates the cell's supply of NAD^+ while producing a small amount of ATP. The two main types of fermentation are lactic acid fermentation and alcohol fermentation.

VOCABULARY

WORD USAGE

Concentration
Science usage: the relative amount of a substance dissolved in another substance
The concentration of hydrogen ions is greater on one side of the membrane than on the other.

Common usage: the directing of close, undivided attention
The student's concentration was focused on the exam.

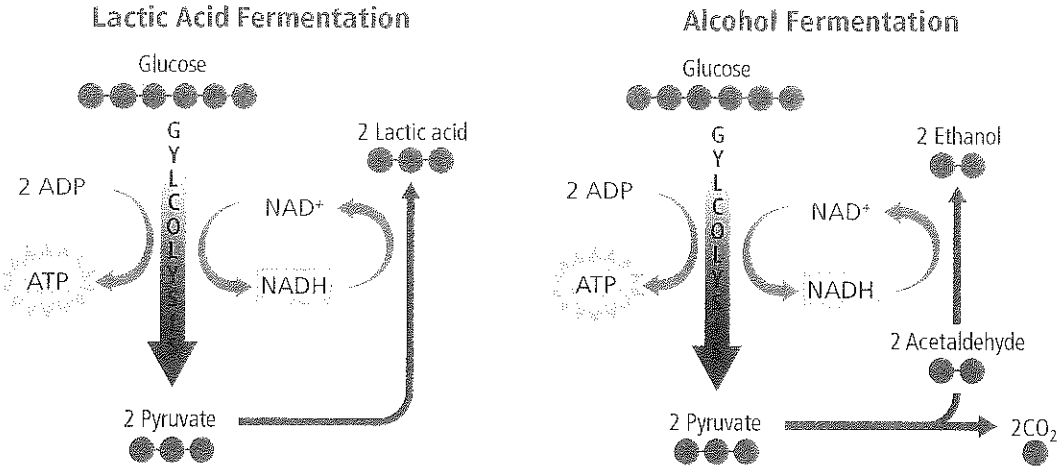


Figure 15 When oxygen is absent or in limited supply, fermentation can occur. **Compare and contrast** *lactic acid fermentation and alcohol fermentation.*

Virtual Lab

Connection to **Lactic acid fermentation** In lactic acid fermentation, enzymes convert the pyruvate made during glycolysis to lactic acid, as shown in **Figure 15.** This involves the transfer of high-energy electrons and protons from NADH. Skeletal muscles produce lactic acid when the body cannot supply enough oxygen, such as during periods of strenuous exercise. When lactic acid builds up in muscle cells, muscles become fatigued and might feel sore. Lactic acid also is produced by several microorganisms that often are used to produce many foods, including cheese, yogurt, and sour cream.

Alcohol fermentation Alcohol fermentation occurs in yeast and some bacteria. **Figure 15** shows the chemical reaction that occurs during alcohol fermentation when pyruvate is converted to ethyl alcohol and carbon dioxide. Similar to lactic acid fermentation, NADH donates electrons during this reaction and NAD^+ is regenerated.

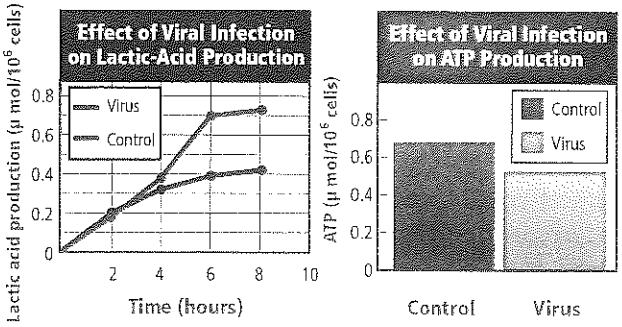
DATA ANALYSIS LAB 1

Based On Real Data*

Interpret the Data

How does viral infection affect cellular respiration? Infection by viruses can significantly affect cellular respiration and the ability of cells to produce ATP. To test the effect of viral infection on the stages of cellular respiration, cells were infected with a virus, and the amount of lactic acid and ATP produced were measured.

Data and Observations



Think Critically

1. **Analyze** how the virus affected lactic acid production in the cells.
2. **Calculate** After 8 hours, by what percentage was the lactic acid higher in the virus group than in the control group? By what percentage was ATP production decreased?
3. **Infer** why having a virus such as the flu might make a person feel tired.

Data obtained from: El-Bacha, T., et al. 2004. Mayaro virus infection alters glucose metabolism in cultured cells through activation of the enzyme 6-phosphofructo 1-kinase. *Molecular and Cellular Biochemistry* 266: 191–198.

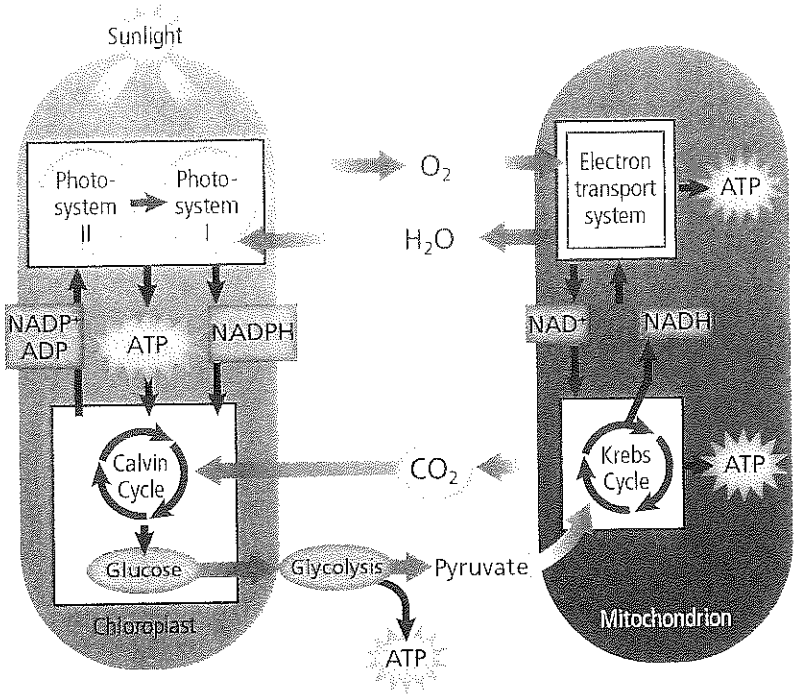


Figure 16 Photosynthesis and cellular respiration form a cycle in which the products of one metabolic pathway form the reactants of the other metabolic pathway.

Photosynthesis and Cellular Respiration

As you have learned, photosynthesis and cellular respiration are two important processes that cells use to obtain energy. They are metabolic pathways that produce and break down simple carbohydrates. **Figure 16** shows how these two processes are related. Recall that the products of photosynthesis are oxygen and glucose, the reactants needed for cellular respiration. The products of cellular respiration, which are carbon dioxide and water, are the reactants for photosynthesis.

BrainPOP

Section 3 Assessment

Section Summary

- Many living organisms use cellular respiration to break down glucose.
- NADH and $FADH_2$ are important electron carriers for cellular respiration.
- In the absence of oxygen, cells can sustain glycolysis by fermentation.

Understand Main Ideas

1. **Summarize** the stages of cellular respiration.
2. **Identify** how many carbons from one glucose molecule enter one round of the Krebs cycle.
3. **Explain** how high-energy electrons are used in electron transport.
4. **Describe** the role of fermentation in maintaining ATP and NAD^+ levels.

Think Critically

MATH in Biology

5. How many ATP, NADH, and $FADH_2$ are produced in each step of cellular respiration? How is the number of ATP produced different from the net ATP available?
6. **Compare and contrast** the two types of fermentation.

Online Quiz

CUTTING-EDGE BIOLOGY

Tracking Human Evolution

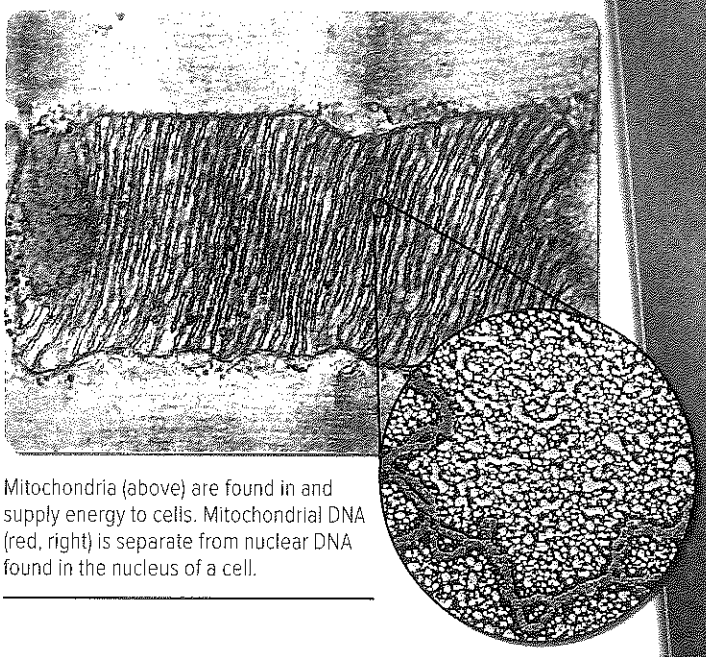
DNA evidence has been used to solve mysteries that were decades, or even centuries old—but imagine trying to unravel a mystery that is millions of years old. This is exactly what scientists are doing when they use DNA analysis to track human evolution.

Mitochondrial DNA You might wonder what mitochondria have to do with DNA analysis and human evolution. Mitochondria often are called the powerhouses of the cell. They are the organelles in which cells release the energy stored in food. Mitochondria have their own DNA, which is much smaller than nuclear DNA and more abundant due to its presence outside the nucleus and the number of mitochondria in most cells. Mitochondrial DNA (mtDNA) is easier to detect and extract than nuclear DNA, making it a useful tool for unlocking some of science's toughest mysteries.

One particular characteristic of mtDNA makes it especially useful for tracking human evolution. Mitochondria are inherited through maternal lineage. When a sperm and egg combine at fertilization, the nuclear DNA of the two gametes combine, but the mitochondria in the offspring are supplied solely by the egg. Therefore, mtDNA can be used as a marker to trace motherhood from generation to generation.

Tracing evolution Scientists use DNA analysis to trace the path of prehuman creatures, called hominids, as they spread around the world. The genomic DNA that is found in the nuclei of cells often is degraded or present in miniscule amounts in these ancient samples. However, scientists discovered that mtDNA is found abundantly and can be used for their analysis.

EM Magnification: 150,000×



Mitochondria (above) are found in and supply energy to cells. Mitochondrial DNA (red, right) is separate from nuclear DNA found in the nucleus of a cell.

Mutations in mtDNA occur in relatively predictable patterns, and those patterns are studied and compared by scientists. By comparing mutations in mtDNA, scientists can trace mtDNA inheritance. Based on these studies of mtDNA, scientists have determined that the most recent maternal common ancestor of people living on Earth today is "Mitochondrial Eve." Mitochondrial Eve is thought to be a woman who lived in Africa approximately 200,000 years ago.

Based on the theory of Mitochondrial Eve, an international study is being conducted to trace the migration and ancestry of early humans. The project uses mtDNA sequences in females, but uses sequences from the Y chromosome to trace ancestry in males.

WRITING in Biology

Research Paper Research mtDNA. Choose one aspect of the current research with mtDNA and write a research paper about it.

Don W. Fawcett/Photo Researchers, Inc.

WebQuest

BIOLAB

Design Your Own

DO DIFFERENT WAVELENGTHS OF LIGHT AFFECT THE RATE OF PHOTOSYNTHESIS?

Background: **Photosynthesizing organisms need light to complete photosynthesis. White light is composed of the different colors of light found in the visible light spectrum, and each color of light has a specific wavelength. During this lab, you will design an experiment to test the effect of different light wavelengths on the rate of photosynthesis.**

Question: *How do different wavelengths of light affect photosynthesis rates?*

Possible Materials

Choose materials that would be appropriate for this lab.

aquatic plant material
Erlenmeyer flasks
test tubes (15 mL)
graduated cylinder (10 mL)
metric ruler
colored cellophane (assorted colors)
aluminum foil
lamp with reflector and 150 W bulb
baking soda solution (0.25%)
watch with a second hand

Safety Precautions

Plan and Perform the Experiment

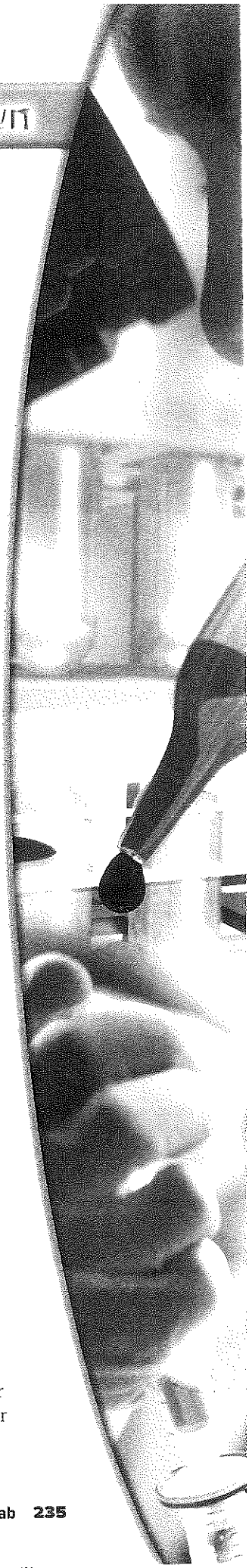
1. Read and complete the lab safety form.
2. Predict how different wavelengths of light will affect the rate of photosynthesis in your plant.
3. Design an experiment to test your prediction. Write a list of steps that you will follow, and identify the controls and variables that you will use.
4. Explain how you will generate light with different wavelengths, supply the plant with carbon dioxide, and measure the oxygen production of the plant.
5. Create a data table for recording your observations and measurements.
6. Make sure your teacher approves your plan before you begin.
7. Conduct your experiment as approved.
8. **Cleanup and Disposal** Clean up all equipment as instructed by your teacher, and return everything to its proper place. Dispose of plant material as instructed by your teacher. Wash your hands thoroughly with soap and water.

Analyze and Conclude

1. **Identify** the controls and variables in your experiment.
2. **Explain** how you measured the rate of photosynthesis.
3. **Graph** your data.
4. **Describe** how the rate of photosynthesis is affected by different wavelengths of light based on your data.
5. **Discuss** whether or not your data supported your prediction.
6. **Error Analysis** Identify possible sources of error in your experimental design, procedure, and data collection.
7. **Suggest** how you would reduce these sources of error if you repeated the experiment.

COMMUNICATE

Peer Review Post your data and graph at the front of the room. Review data posted by other students. Discuss and use comments from other students to improve your own methods.



Chapter 8 Study Guide

THEME FOCUS Energy and Matter The Sun is the source of nearly all of the energy on Earth, and it is converted to chemical energy at the cellular level through photosynthesis.

BIG Idea Photosynthesis converts the Sun's energy into chemical energy, while cellular respiration uses chemical energy to carry out life functions.

Section 1 How Organisms Obtain Energy

energy (p. 218)
thermodynamics (p. 218)
metabolism (p. 220)
photosynthesis (p. 220)
cellular respiration (p. 220)
adenosine triphosphate (ATP) (p. 221)

Key Idea All living organisms use energy to carry out all biological processes.

- The laws of thermodynamics control the flow and transformation of energy in organisms.
- Some organisms produce their own food, whereas others obtain energy from the food they ingest.
- Cells store and release energy through coupled anabolic and catabolic reactions.
- The energy released from the breakdown of ATP drives cellular activities.

Section 2 Photosynthesis

thylakoid (p. 223)
granum (p. 223)
stroma (p. 223)
pigment (p. 223)
$NADP^+$ (p. 224)
Calvin cycle (p. 226)
rubisco (p. 226)

Key Idea Light energy is trapped and converted into chemical energy during photosynthesis.

- Plants contain chloroplasts with light-absorbing pigments that convert light energy into chemical energy.
- Photosynthesis is a two-phase process that consists of light reactions and the Calvin cycle.
- In the light reactions, autotrophs trap and convert light energy into chemical energy in the form of NADPH and ATP.
- In the Calvin cycle, chemical energy in ATP and NADPH is used to synthesize carbohydrates such as glucose.

Section 3 Cellular Respiration

anaerobic process (p. 228)
aerobic respiration (p. 228)
aerobic process (p. 228)
glycolysis (p. 229)
Krebs cycle (p. 229)
fermentation (p. 231)

Key Idea Living organisms obtain energy by breaking down organic molecules during cellular respiration.

- Many living organisms use cellular respiration to break down glucose.
- The stages of cellular respiration are glycolysis, the Krebs cycle, and electron transport.
- NADH and $FADH_2$ are important electron carriers for cellular respiration.
- In the absence of oxygen, cells can sustain glycolysis by fermentation.

Chapter 8 Assessment

Section 1

Vocabulary Review

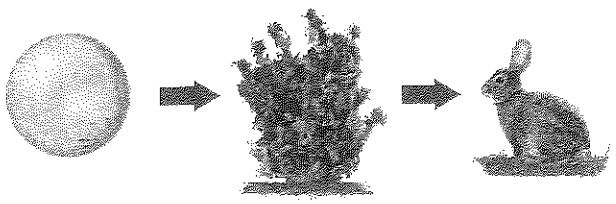
Each of the following sentences is false. Make each sentence true by replacing the italicized word with a vocabulary term from the Study Guide page.

1. *Metabolism* is the energy currency of the cell.
2. The study of the flow and transformation of energy is called *energy*.
3. *Bioenergetics* can exist in many forms.
4. Chemical reactions that convert energy within a cell are refered to as *autotrophs*.
5. Light energy is converted into chemical energy during the process of *sunlight*.

Understand Main Ideas

6. Which is not a characteristic of energy?
   A. cannot be created nor destroyed
   B. is the capacity to do work
   C. exists in forms such as chemical, light, and mechanical
   D. changes spontaneously from disorder to order
7. Which organism depends on an external source of organic compounds?
   A. autotroph
   B. heterotroph
   C. chemoautotroph
   D. photoautotroph

Use the figure below to answer question 8.



8. **THEME FOCUS Energy and Matter** Which part of this food chain provides energy to just one other part?
   A. the chemoautotroph
   B. the heterotroph
   C. the Sun
   D. the photoautotroph
9. What do cells store and release as the main source of chemical energy?
   A. ATP
   B. ADP
   C. $NADP^+$
   D. NADPH

Constructed Response

10. **THINK IDEA** How do autotrophs and heterotrophs differ in the way in which they obtain energy?
11. **Open Ended** Use an analogy to describe the role of ATP in living organisms.

Think Critically

12. **Describe** how energy is released from ATP.
13. **Relate** anabolic and catabolic reactions. Create an analogy for the relationship between photosynthesis and cellular respiration.

Section 2

Vocabulary Review

Write the vocabulary term from the Study Guide page for each definition.

14. the location of the light reactions
15. a stack of thylakoids
16. a colored molecule that absorbs light
17. a process in which energy is stored in organic molecules

Understand Main Ideas

Use the equation below to answer question 18.

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

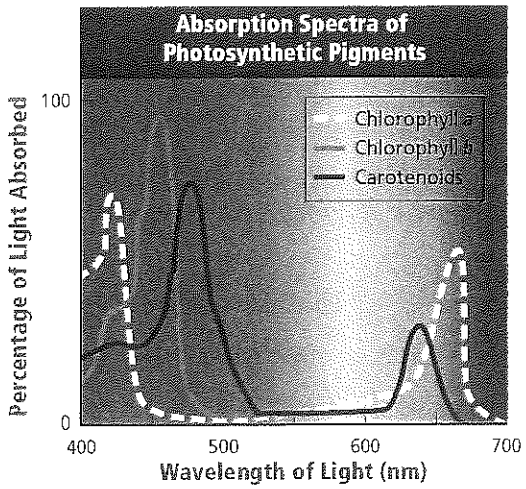
18. What waste product of photosynthesis is released to the environment?
   A. carbon dioxide
   B. water
   C. oxygen
   D. ammonia

Online Test Practice

Chapter 8 Assessment

19. Which is the internal membrane of the chloroplast that is organized into flattened membranous sacs?
   A. thylakoids
   B. mitochondria
   C. theca
   D. stroma

Use the figure below to answer question 20.



20. Of which wavelength of light do carotenoids absorb the greatest percentage?
   A. 400
   B. 500
   C. 600
   D. 700

21. Which supplies energy used to synthesize carbohydrates during the Calvin cycle?
   A. CO_2 and ATP
   B. ATP and NADPH
   C. NADPH and H_2O
   D. H_2O and O_2

Constructed Response

22. **Key Idea** Summarize the phases of photosynthesis. Describe where each phase occurs in the chloroplast.

23. **Short Answer** Why is hydrogen ion generation essential for ATP production during photosynthesis?

24. **Short Answer** Explain why the Calvin cycle depends on light reactions.

Think Critically

25. **Explain** the following statement: The oxygen generated by photosynthesis is simply a by-product formed during the production of ATP and carbohydrates.

26. **Predict** the effect of the loss of forests on cellular respiration in other organisms.

27. **Describe** two alternative photosynthesis pathways found in plants. Suggest how these adaptations might help plants.

Section 3

Vocabulary Review

Define each vocabulary term in a complete sentence.

28. Krebs cycle

29. anaerobic process

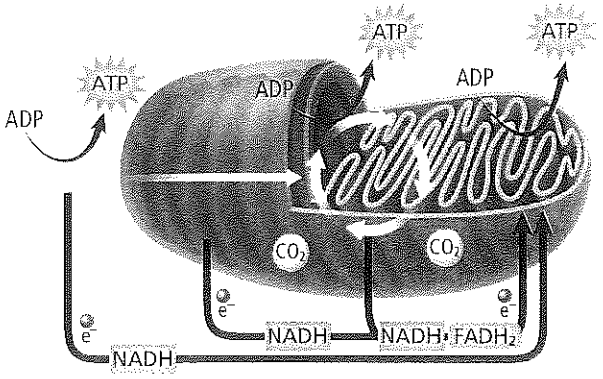
30. fermentation

31. aerobic

32. glycolysis

Understand Main Ideas

Use the figure below to answer questions 33 and 34.



33. Which organelle is illustrated in the figure?
   A. Golgi apparatus
   B. mitochondrion
   C. nucleus
   D. endoplasmic reticulum

34. Which process does not occur in the organelle illustrated above?
   A. glycolysis
   B. Krebs cycle
   C. conversion of pyruvate to acetyl CoA
   D. electron transport

Online Test Practice

35. Which is not a stage of cellular respiration?
   A. glycolysis
   B. Krebs cycle
   C. electron transport chain
   D. lactic acid fermentation

36. What is produced when the electrons leave the electron transport chain in cellular respiration and bind to the final electron acceptor for the chain?
   A. H_2O
   B. O_2
   C. CO_2
   D. CO

37. In which molecule is most of the energy of glucose stored at the end of glycolysis?
   A. pyruvate
   B. acetyl CoA
   C. ATP
   D. NADH

Constructed Response

38. **Short Answer** Discuss the roles of NADH and $FADH_2$ in cellular respiration.

39. **Short Answer** In cellular respiration, where do the electrons in the electron transport chain originate? What is the final destination of the electrons?

40. **Short Answer** Why do your muscles hurt for some time after a large amount of strenuous exercise?

Think Critically

41. **Explain** The end products of cellular respiration are CO_2 and H_2O. Where do the oxygen atoms in the CO_2 originate? Where does the oxygen atom in H_2O originate?

42. BIG Idea What is the advantage of aerobic metabolism over anaerobic metabolism in energy production in living organisms?

43. **Compare and contrast** electron transport in photosynthesis and cellular respiration.

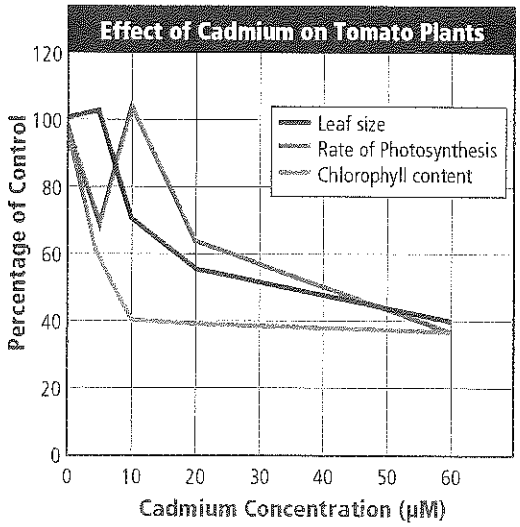
Summative Assessment

44. BIG Idea What are the chemical equations for photosynthesis and cellular respiration? Analyze the relationship between photosynthesis and cellular respiration using the equations for both processes.

45. WRITING in Biology Write an article using what you know about the relationship between photosynthesis and cellular respiration to explain the importance of plants in an ecosystem.

DBQ **Document-Based Questions** *Cadmium is a heavy metal that is toxic to humans, plants, and animals. It is often found as a contaminant in soil. Use the data below to answer questions about the effect of cadmium on photosynthesis in tomato plants.*

Data obtained from: Chaffei, C., et al. 2004. Cadmium toxicity induced changes in nitrogen management in *Lycopersicon esculentum* leading to a metabolic safeguard through an amino acid storage strategy. *Plant and Cell Physiology* 45(11): 1681–1693.



46. What was the effect of cadmium on leaf size, chlorophyll content, and photosynthesis rate?

47. At what concentration of cadmium was the largest effect on leaf size observed? On chlorophyll content? On photosynthesis rate?

48. Predict the effects on cellular respiration if an animal eats contaminated tomatoes.

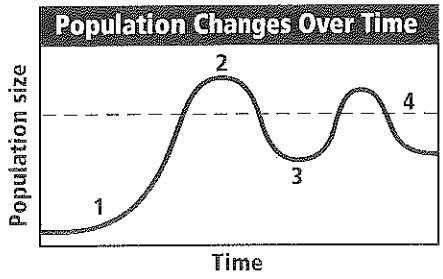
Standardized Test Practice

Cumulative

Multiple Choice

1. Suppose that the most common form of element X is X-97. The isotope X-99 has more of which?
   A. neutrons
   B. protons
   C. orbiting electrons
   D. overall charge

Use the graph below to answer question 2.



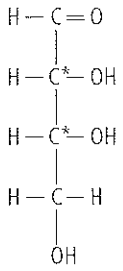
2. Which part of the graph indicates exponential growth?
   A. 1
   B. 2
   C. 3
   D. 4

3. Which type of transport does NOT require the input of additional energy?
   A. active transport
   B. diffusion
   C. endocytosis
   D. exocytosis

4. Which step occurs during the Calvin cycle?
   A. formation of ATP
   B. formation of six-carbon sugars
   C. release of oxygen gas
   D. transport of electrons by $NADP^+$

5. Which describes extinctions caused by deforestation in tropical rain forests?
   A. ecosystem pollution
   B. habitat destruction
   C. introduced species
   D. species overexploitation

Use the diagram below to answer question 6.



6. Based on the diagram, which is the correct molecular formula if the molecule shown above has six carbons?
   A. $C_6H_8O_4$
   B. $C_6H_{10}O_6$
   C. $C_6H_{12}O_4$
   D. $C_6H_{12}O_6$

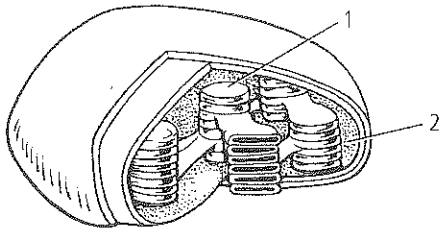
7. Which energy transformation can occur only in autotrophs?
   A. chemical energy into mechanical energy
   B. electrical energy into thermal energy
   C. light energy into chemical energy
   D. mechanical energy into thermal energy

8. Which statement does the cell theory support?
   A. Cells can form from proteins in the environment.
   B. Cells contain membrane-bound organelles.
   C. Life-forms are made of one or more cells.
   D. Organelles are the smallest form of life.

9. Which part of the scientific method evaluates the procedures used in an experiment?
   A. forming a hypothesis
   B. publishing results
   C. making an observation
   D. peer review

Short Answer

Use the illustration below to answer question 10.



10. The diagram above shows a chloroplast. Name the two parts shown in the diagram and state which phase of photosynthesis occurs in each part.

11. Compare and contrast the structure of a cell wall and the structure of a cell membrane.

12. Relate the bonds between phosphate groups in ATP to the release of energy when a molecule of ATP is changed to ADP.

13. Name three components of a cell's plasma membrane and explain why each component is important for the function of the cell.

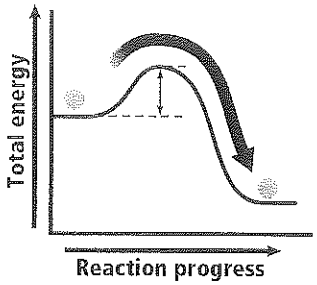
14. What kind of mixture is formed by stirring a small amount of table salt into water until the salt all dissolves? Identify the components of this mixture.

15. In which parts of a plant would you expect to find cells with the most chloroplasts? Explain your answer.

16. Long-distance runners often talk about training to raise their anaerobic threshold. The anaerobic threshold is the point at which certain muscles do not have enough oxygen to perform aerobic respiration and begin to perform anaerobic respiration. Hypothesize why you think it is important for competitive runners to raise their anaerobic threshold.

Extended Response

Use the graph below to answer question 17.



17. The graph shows the effect of an enzyme involved in the breakdown of proteins in the digestive system. Hypothesize how protein digestion would be different in a person who does not have this enzyme.

18. Which organelle would you expect to find in large numbers in cells that pump stomach acid out against a concentration gradient? Give a reason for your answer.

Essay Question

The human body constantly interacts with the environment, taking in some substances and releasing others. Many substances taken in by humans have a specific role in maintaining basic cellular processes such as respiration, ion transport, and synthesis of various macromolecules. Likewise, many of the substances released by the body are waste products of cellular processes.

Using the information in the paragraph above, answer the following question in essay format.

19. Write an essay that explains how humans take in substances that are important for cellular respiration, and how they release the waste products from this process.

NEED EXTRA HELP?

If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Review Section . . .	6.1	4.1	7.4	8.2	5.2	6.4	8.1	7.1	1.3	8.2	7.3	8.1	7.2	6.3	7.3	8.3	6.2	7.2, 7.4	8.3