3.2

Cellular Respiration

Cars need energy to move. A mixture of oxygen and gasoline, when ignited by a spark, produces a small, controlled explosion in the engine's cylinder that moves the axle.

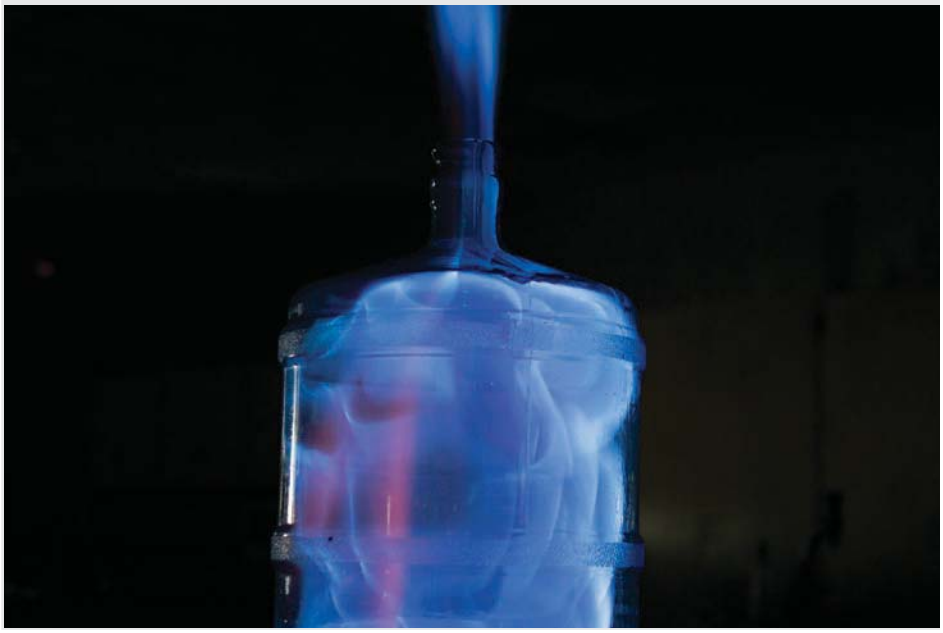
CAN YOU EXPLAIN IT?

Both cars and your body need fuel. Most cars use gasoline as a fuel, which often includes ethanol in addition to gasoline. For a car or a human body to use fuel, the energy in the chemical bonds of the fuel must be released. A combustion reaction in a car's engine releases this energy. Your body uses a similar reaction in which it releases the energy contained in the chemical bonds of the food you eat.

Gather Evidence
As you explore the lesson, gather evidence that bonds are broken and new bonds are formed in the process of cellular respiration.

FIGURE 1: The ignition of a mixture of ethanol and oxygen in the air produces a combustion reaction, which releases energy in the forms of heat and light.

Explore Online



Predict How is the process of fuel combustion in a car engine similar to the way the cells in your body release energy stored in fuel?

Matter and Energy in Cellular Respiration

Fuel is any material that reacts to release energy to be used for work. Not all fuels are alike. They have many different chemical structures.

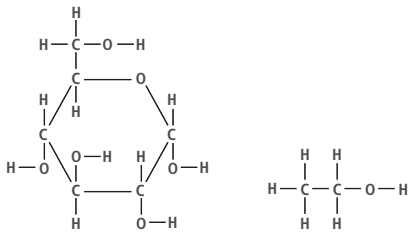


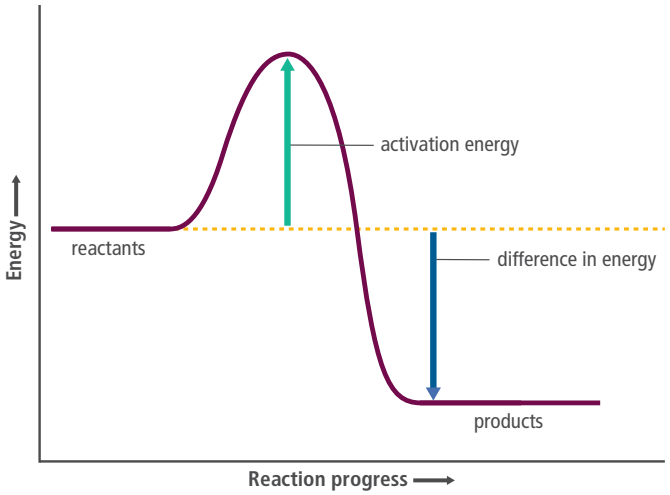
FIGURE 2: Ethanol is a fuel made from plant material, such as corn. As a renewable energy source, it helps reduce petroleum use. Glucose is a simple sugar that living things use for energy.

Analyze How are glucose and ethanol similar in structure and function? How do they differ?

Energy in Living Systems

Whether food for organisms or fuel for cars, almost all the energy on Earth has its origins in the sun. In the process of photosynthesis, plants transform light energy from the sun into chemical energy in the form of glucose. When an organism eats a plant, any energy the plant has not used can be used by the consumer.

Ancient plants and animals that died decomposed and were buried under soil, rock, and sometimes sea water. These organisms decomposed into organic materials that contain unused stored energy. Over millions of years, heat and pressure transformed these remains into the fossil fuels we use today. Chemical bonds must be broken for the stored energy to be released. In cars, a combustion reaction provides the energy needed to break these bonds and release energy. In cells, a similar process called cellular respiration releases chemical energy from sugars and other carbon-based molecules to make ATP when oxygen is present.



Exothermic Reaction

FIGURE 3: Activation energy is the energy needed to start a chemical reaction. An exothermic reaction releases more energy than it absorbs. Cellular respiration is an exothermic reaction.

Gather Evidence Explain why cellular respiration is an exothermic reaction. Cite evidence from the graph shown in Figure 3 to support your explanation.

Hands-On Lab

Cellular Respiration and Exercise

Burning fuel through either combustion or cellular respiration requires oxygen. In each process, bonds break and new bonds form. In this lab, you will use an indicator called bromothymol blue to gather evidence to support a claim about the inputs and outputs of cellular respiration. Bromothymol blue changes color in the presence of an acid.

Predict What evidence could there be to support the claim that during cellular respiration, chemical bonds are broken and new bonds are formed?

SAFETY

Do not consume any of the materials used in this lab. Be careful not to breathe in through the straw.

MATERIALS

- bromothymol blue solution
- cups or beakers (2)
- straw
- timer

PROCEDURE

1. Place the amount of bromothymol blue solution specified by your teacher in a cup or beaker.
2. Get the timer ready. Slowly blow through the straw into the bromothymol blue solution, and record how long it takes for the solution to change from blue to yellow. Be sure not to inhale when the straw is in the solution.
3. Place the amount of bromothymol blue solution specified by your teacher in a second cup or beaker.
4. Run in place for approximately one minute.
5. Get the timer ready again. Slowly blow through the straw into the bromothymol blue solution, and record how long it takes for the solution to turn yellow.

ANALYZE

The water turned acidic when you blew into it because carbon dioxide in your breath reacted with water to form carbonic acid.

1. How do your findings support the claim that bonds were broken and new bonds were formed to produce the gas you breathed out?
2. When you exercised, what was different about the time it took the solution to change color? Explain why this happened.

FIGURE 4: Bromothymol blue is an indicator that changes color in the presence of an acid.

The Process of Cellular Respiration

During cellular respiration, the breakdown of glucose and other carbon-based molecules releases energy stored in their chemical bonds. The stored energy is transferred to ATP, which we can think of as the cell's "energy currency." Energy in the form of heat is also released in the process. The release of heat accounts for why the body temperatures of mammals range from 36 to 39°C (97–103°F).

Cellular respiration is an aerobic process, which means that it requires oxygen to take place. Some organisms can produce small amounts of ATP through anaerobic processes, or processes that do not require oxygen. However, the presence of oxygen allows cellular respiration to produce far more ATP from each glucose molecule. The inputs and outputs of cellular respiration are shown in Figure 5.

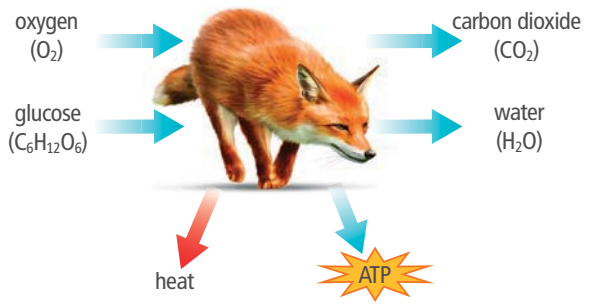


FIGURE 5: Inputs and Outputs of Cellular Respiration

Explain What is the role of the organism in this model of cellular respiration? Explain your answer.

Energy and Matter The balanced chemical equation for cellular respiration is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow \rightarrow \rightarrow 6CO_2 + 6H_2O + \text{heat} + \text{ATP}$$

1. How does this equation represent the law of conservation of matter—that matter cannot be created or destroyed?
2. How does this equation represent the law of conservation of energy—that energy cannot be created or destroyed? Consider the role of photosynthesis in your answer.

Mitochondria

Cellular respiration takes place inside an organelle called the mitochondrion (plural *mitochondria*), shown in Figure 6. Mitochondria release the chemical energy required to make ATP. Both plant and animal cells contain mitochondria, because both plants and animals carry out cellular respiration.

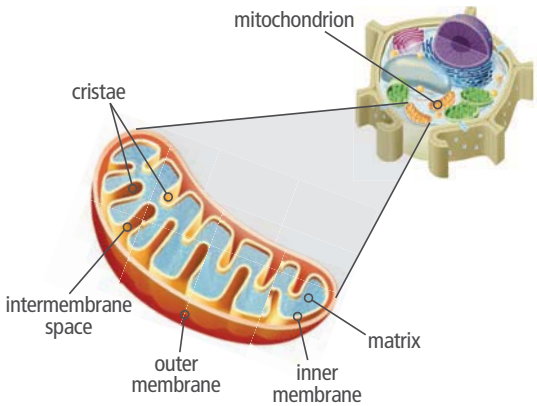


FIGURE 6: The mitochondrion has an inner membrane with many folds, called cristae. The outer membrane separates the mitochondrion from the rest of the cell. The space between the two membranes is called the intermembrane space.

Collaborate With a partner, cite evidence that supports the claim that mitochondria are the "powerhouses of the cell."

Explore Online

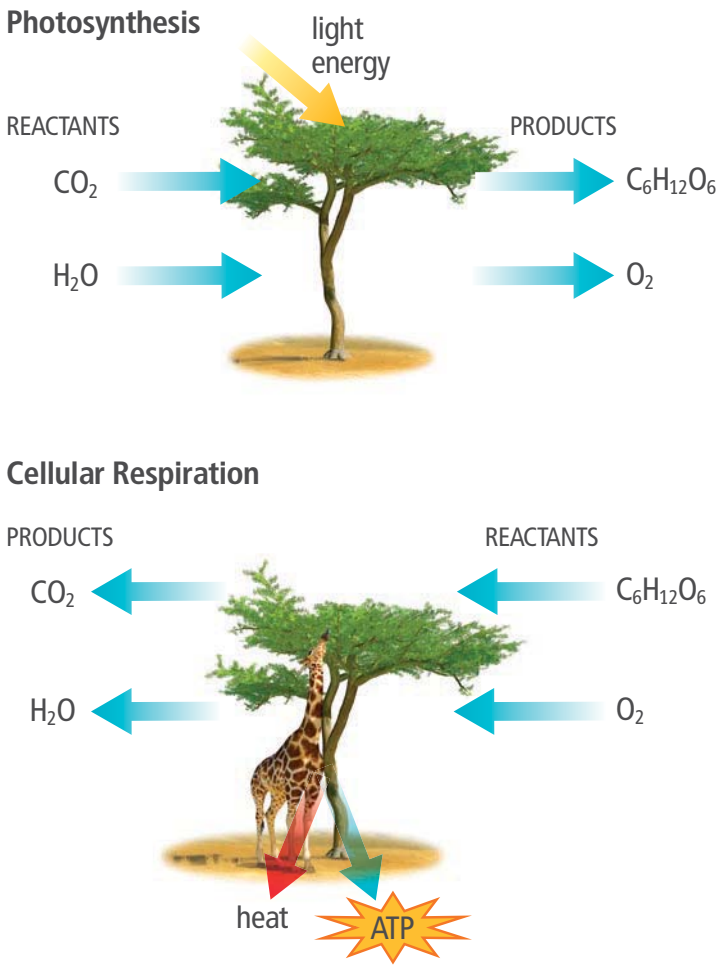
Hands-On Lab

Investigating Photosynthesis and Cellular Respiration Design an experiment to determine which organisms (pond snails or *Elodea*) produce carbon dioxide and which use carbon dioxide.

Cellular Respiration and Photosynthesis

Almost all energy for living things comes from photosynthesis, either directly or indirectly. Producers absorb light energy from the sun and transform it using photosynthesis to a usable form of energy, or food. This energy is then passed from producers to consumers. Although only producers carry out photosynthesis, both producers and consumers carry out cellular respiration. Photosynthesis stores energy from sunlight as chemical energy. In contrast, cellular respiration releases stored energy as ATP and heat.

FIGURE 7: A Comparison of Photosynthesis and Cellular Respiration



Analyze What is the relationship between the inputs and outputs of photosynthesis and cellular respiration?

Model Sort the following terms into those that occur during photosynthesis and those that occur during cellular respiration. Then place the terms in the correct order.

- absorption of sunlight
- ATP production
- production of sugars
- breakdown of sugars

Using Chemical Energy

One way that organisms maintain homeostasis is through cellular respiration, which releases energy to carry out cell processes and helps maintain body temperature. Bonds in food molecules and oxygen molecules are broken and new molecules are formed that transfer energy in forms that the organism can use. Cellular respiration transfers chemical energy stored in the bonds of glucose and other molecules to ATP.

Analyze Identify the inputs and outputs of glycolysis and the two stages of cellular respiration.

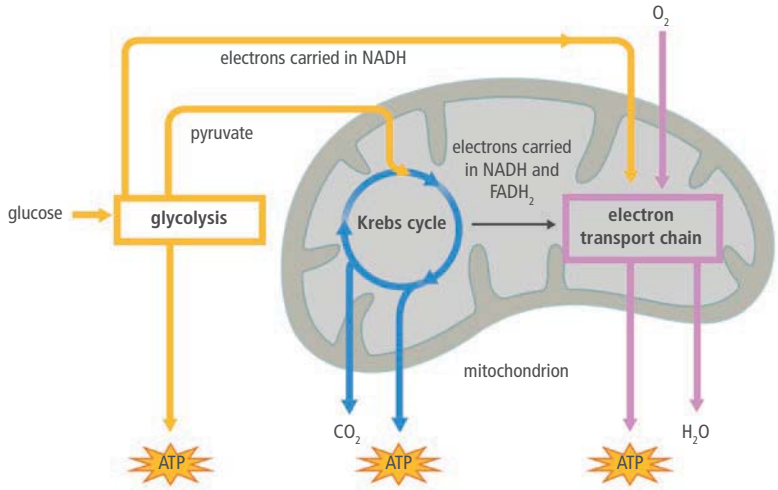
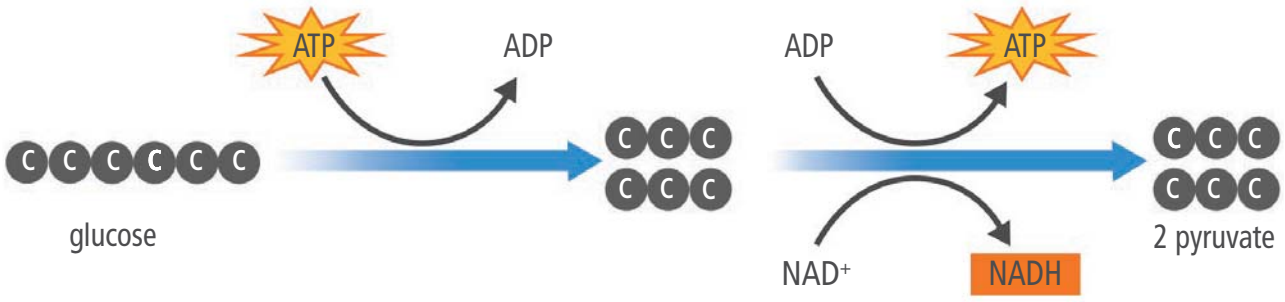


FIGURE 8: The process of glycolysis occurs before the two main stages of cellular respiration: the Krebs cycle and the electron transport chain.

Glycolysis and the Stages of Cellular Respiration

Cellular respiration occurs in mitochondria. Before it can take place, however, glucose must be broken down into compounds the mitochondria can use. This process occurs in the cytoplasm of the cell. Glycolysis, shown in Figure 9, is an anaerobic process that uses a series of enzyme-catalyzed reactions to break glucose into two three-carbon molecules, called pyruvate. Mitochondria use the pyruvate molecules to fuel cellular respiration.

FIGURE 9: Glycolysis

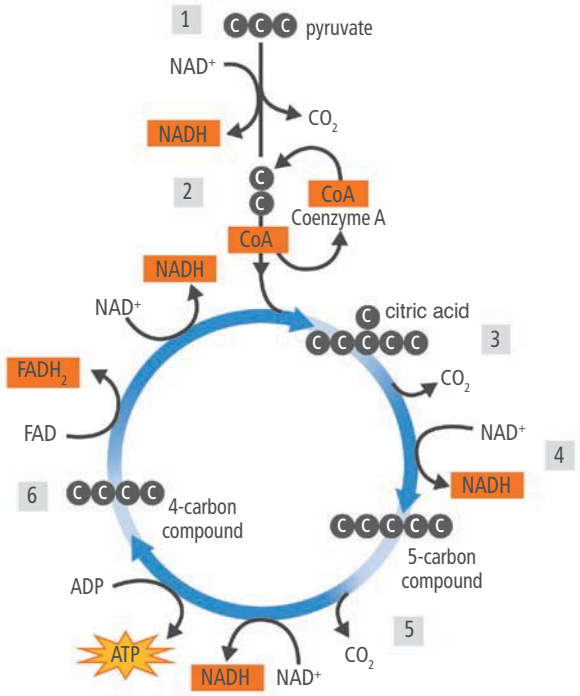


Gather Evidence Summarize evidence that bonds are broken and new bonds are formed in glycolysis.

Krebs Cycle

The Krebs cycle, sometimes called the citric acid cycle, is the first set of reactions in cellular respiration. The function of the Krebs cycle is to complete the breakdown of glucose started in glycolysis and fuel the production of ATP. This is done by transferring high-energy electrons to the electron transport chain.

FIGURE 10: The Krebs Cycle



The Krebs cycle is summarized in the steps below.

1. **Pyruvate is broken down** A 3-carbon pyruvate molecule is split into a 2-carbon molecule and a carbon dioxide molecule, which is given off as waste. High-energy electrons are transferred to NAD^+, forming a molecule of NADH. The NADH moves to the second stage of cellular respiration, the electron transport chain.
2. **Coenzyme A is added** A molecule called coenzyme A bonds to the 2-carbon molecule, forming an intermediate molecule.
3. **Citric acid is formed** The 2-carbon part of the intermediate molecule is added to a 4-carbon molecule to form the 6-carbon molecule called citric acid.
4. **Citric acid is broken down** The citric acid molecule is broken down by an enzyme, and a 5-carbon molecule is formed. A molecule of NADH is made, which moves out of the Krebs cycle. A molecule of carbon dioxide is given off as a waste product.
5. **Five-carbon molecule is broken down** The 5-carbon molecule is broken down by an enzyme. A 4-carbon molecule, a molecule of NADH, and one ATP are formed. Carbon dioxide is given off as a waste product.
6. **Four-carbon molecule is rearranged** Enzymes rearrange the 4-carbon molecule, releasing high-energy electrons. Molecules of NADH and $FADH_2$, another electron carrier, are made. They leave the Krebs cycle, and the 4-carbon molecule remains.

Analyze How is the Krebs cycle a bridge between the energy in sugars and energy-carrying molecules?

Explain During the hands-on lab, which product of the Krebs cycle caused the bromothymol blue solution to change color?

The Krebs cycle is a continual series of reactions. All the carbon atoms in glucose eventually end up as carbon dioxide, a waste product expelled from the cell. The role of the electron carriers NADH and $FADH_2$ is to transfer electrons to the electron transport chain in the next stage of respiration. The transferred electrons will fuel the formation of ATP.

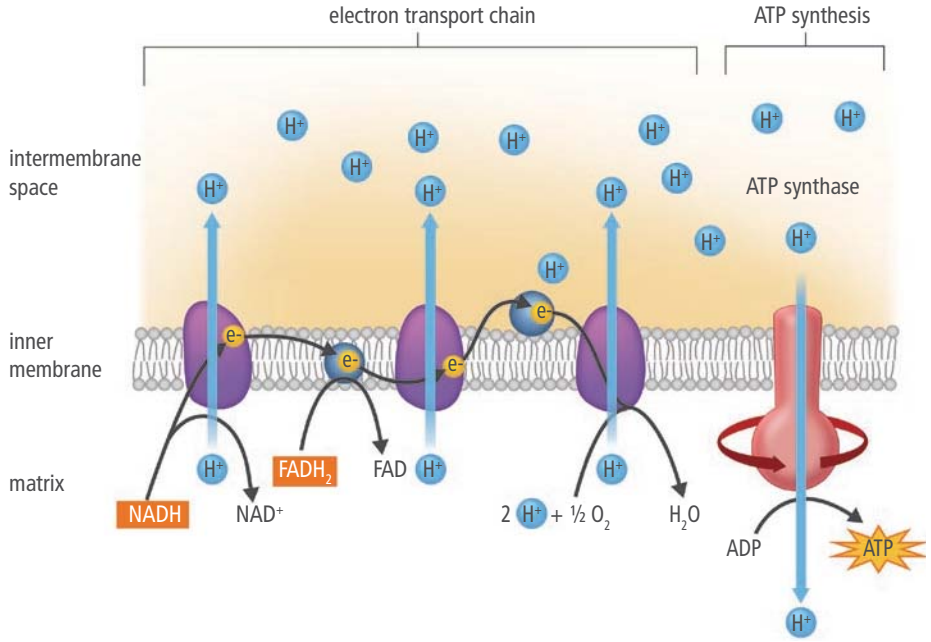
The Electron Transport Chain

The second stage of cellular respiration, the electron transport chain, uses proteins embedded in the inner membrane of the mitochondrion. It is similar to the electron transport chain stage of photosynthesis. The energy carried by the NADH and $FADH_2$ molecules produced in the Krebs cycle is used to make ATP. A number of enzymes are involved in this process.

Model Make a simple flow chart to summarize the energy transfer from energy-carrying molecules to ATP.

FIGURE 11: The Electron Transport Chain

Explore Online



The electron transport chain is summarized in the steps below.

1. **Electrons are transferred** Proteins inside the inner membrane of the mitochondrion take high-energy electrons from NADH and $FADH_2$.
2. **Hydrogen ions are transported** High-energy electrons travel from protein to protein in the electron transport chain. The proteins use energy from the electrons to pump hydrogen ions across the inner membrane to produce a gradient, just as in photosynthesis. The hydrogen ions build up in the intermembrane space.
3. **ATP is produced** Like in photosynthesis, the flow of hydrogen ions is used to make ATP. Hydrogen ions diffuse through a protein channel in the inner membrane of the mitochondrion. The channel is part of the ATP synthase enzyme. ATP synthase adds phosphate groups to ADP to make ATP molecules.
4. **Water is formed** Oxygen picks up electrons and hydrogen ions to form water. The water molecules are given off as a waste product.

Together, glycolysis and cellular respiration produce up to 38 ATP molecules for every glucose molecule.

Collaborate With a partner, discuss how the electron transport chain depends on the Krebs cycle. Consider the role of energy in your discussion.

Fermentation

The cells in your body cannot store large amounts of oxygen for cellular respiration. The amount of oxygen that is provided by breathing is enough for your cells during normal activities. When you are doing high levels of activity, such as playing a game of basketball as shown in Figure 12, your body cannot bring in enough oxygen for your cells, even though you breathe faster. How do your cells function without oxygen to keep cellular respiration going?

The production of ATP without oxygen continues through the anaerobic processes of glycolysis and fermentation. Fermentation does not make ATP, but it allows glycolysis to continue. Fermentation removes electrons from NADH molecules and recycles NAD^+ molecules for glycolysis. Why is this process important? Because glycolysis, just like cellular respiration, needs a molecule that picks up electrons. It needs molecules of NAD^+.

The role of fermentation is simply to provide the process of glycolysis with a steady supply of NAD^+. If you've ever felt your muscles "burn" during hard exercise, that is a result of fermentation. Lactic acid is a waste product of fermentation that builds up in muscle cells and causes that burning feeling. Once oxygen is available again, your cells return to using cellular respiration. The lactic acid is quickly broken down and removed from the cells.

Analyze What is the role of anaerobic respiration in organisms? What is the role in ecosystems?

FIGURE 12: During strenuous or prolonged activity, athletes may not be able to sustain the oxygen levels their bodies need. If not enough oxygen is supplied to the cells, anaerobic respiration takes over.

FIGURE 13: Bifidobacteria live in the digestive tracts of animals, including humans.

Not all organisms rely on oxygen for respiration. Organisms that use anaerobic respiration have an important role in an ecosystem, because they can live in places where most other organisms cannot. For example, microorganisms, such as the bifidobacteria shown in Figure 13, live in the digestive tracts of animals and help in the process of digestion. They must get their ATP from anaerobic processes because oxygen is not available.

Explain Summarize the evidence that you have gathered to explain how molecules are rearranged and energy is transferred in the process of cellular respiration.

1. Cite evidence to support the claim that bonds are broken and new bonds are formed in each stage of cellular respiration.
2. Explain how energy is transferred from the bonds of food molecules to cellular processes.

Hands-On Lab

Aerobic and Anaerobic Processes in Yeast

The species used in this investigation, *Saccharomyces cerevisiae,* like other species of yeast, is a facultative anaerobe. It can break down sugars using either aerobic or anaerobic processes, depending on the presence of oxygen. When oxygen is not present, yeast carry out ethanol fermentation. This process produces carbon dioxide and ethanol, a type of alcohol.

Predict How will you know whether aerobic or anaerobic processes are occurring in the bottle?

FIGURE 14: Yeast are single-celled organisms that belong to the group of organisms called fungi.

SAFETY

Obtain and wear goggles for this lab. Do not eat any materials used in this lab.

MATERIALS

- active dry yeast (1 package)
- balance (optional)
- balloon, round
- funnel
- graduated cylinder
- marker
- ruler, metric
- string, 30 cm
- sugar, granulated
- tablespoon (optional)
- timer
- water, very warm (40°C)
- water bottle, plastic, 500 mL
- weighing boat (optional)

PROCEDURE

1. Blow up the balloon a few times to stretch it.
2. Using the funnel, pour 150 mL of warm water into the bottle. Dry the funnel.
3. Using the dry funnel, add 1 packet of yeast to the water. Swirl the mixture gently.
4. Using the funnel, add 1 tablespoon (12 g) of sugar to the yeast solution, swirl, and quickly cover the bottle with the balloon. Allow the mixture to react for 5 minutes.
5. After 5 minutes have passed, use the string, marker, and ruler to measure the circumference of the balloon.
6. In a data table, record the circumference of the balloon, along with all of your observations of what is happening in the bottle. Continue making and recording observations every 5 minutes for the next 30 minutes.
7. Dispose of waste according to your teacher's instructions.

ANALYZE

1. Describe evidence, if any, that aerobic respiration took place in the bottle.
2. How does matter cycle during aerobic respiration? Explain how the reactants are rearranged to form the products. What is the source of energy, how is the energy transferred, and how is it used in the cell?
3. Describe evidence, if any, that fermentation took place in the bottle.
4. How does matter cycle during fermentation? Explain how the reactants are rearranged to form the products. What is the source of energy, how is the energy transferred, and how is it used in the cell?

EVIDENCE FOR ENDOSYMBIOSIS | INVESTIGATING PHOTOSYNTHESIS AND CELLULAR RESPIRATION | Go online to choose one of these other paths.

Lesson Self-Check

CAN YOU EXPLAIN IT?

FIGURE 15: Because ethanol burns more cleanly than gasoline, it is added to gasoline to help reduce the emission of greenhouse gases produced by combustion engines in cars. Like gasoline, ethanol contains energy in its chemical bonds that can be released by the process of combustion.

Explore Online

Combustion and cellular respiration are both exothermic reactions that result in the release of energy. The energy is released when chemical bonds that store energy are broken. Combustion is a fast process that results in the production of energy in the forms of heat and light.

$$CH_3CH_2OH + O_2 \longrightarrow \longrightarrow \longrightarrow 2CO_2 + 3H_2O + \text{heat}$$

In contrast, cellular respiration is a slow process, with energy being released over a series of several steps. This makes energy available for use whenever cells of the body need it to carry out cellular activities.

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

Explain A scientist named Antoine Lavoisier demonstrated that cellular respiration is a combustion process. Recall that car engines use a combustion reaction to release energy. Construct an explanation for how the breakdown of fuel in a car engine compares to the breakdown of fuel in your body's cells. Answer the following questions:

1. Look carefully at the equations for both combustion and cellular respiration, and compare the inputs and outputs. How can the different inputs result in the same outputs based on what you know about chemical bonds and atoms?
2. What is missing from the process of combustion that makes it an imperfect model for cellular respiration? Explain your answer.

CHECKPOINTS

Check Your Understanding

1. How does carbon flow between photosynthesis and cellular respiration?

- **a.** Photosynthesis produces carbon dioxide from glucose generated by the process of cellular respiration.
- **b.** Cellular respiration produces carbon dioxide from glucose generated by the process of photosynthesis.
- **c.** Photosynthesis produces carbon dioxide from ATP generated by the process of cellular respiration.
- **d.** Cellular respiration produces carbon dioxide from ATP generated by the process of photosynthesis.

2. Which of the following are the main inputs, or reactants, in cellular respiration? Select all correct answers.

- **a.** pyruvate
- **b.** glucose
- **c.** carbon dioxide
- **d.** oxygen

3. Which of the following are the main outputs, or products, of cellular respiration? Select all correct answers.

- **a.** water
- **b.** energy
- **c.** oxygen
- **d.** carbon dioxide

4. Before cellular respiration, glucose must be broken down by the process of

- **a.** photosynthesis.
- **b.** glycolysis.
- **c.** electron transport.
- **d.** fermentation.

5. During which process is lactic acid formed when there is not enough oxygen present for cellular respiration to take place?

- **a.** fermentation
- **b.** glycolysis
- **c.** Calvin cycle
- **d.** Krebs cycle

6. Use the following terms to complete the statement: *ATP, cellular respiration, electron transport chain, glycolysis, Krebs cycle, photosynthesis*

Living things require energy to grow and reproduce and to carry out different cell processes. Certain cells can capture energy from the sun through the process of _____. Through a series of reactions, that energy is transferred to organisms. Through the process of _____, the energy currency of the cell, _____, is produced. This is a three-part process, beginning with _____ in the cell cytoplasm and proceeding within the mitochondrion with the _____ and, finally, the _____.

7. How do you know that energy and matter are conserved during the process of cellular respiration? Explain.

8. Energy is transferred in several different ways during the process of cellular respiration. Give two examples of ways that energy is transferred during this process.

9. Is oxygen necessary for the production of ATP in your cells? Why or why not?

10. How are photosynthesis and cellular respiration related?

MAKE YOUR OWN STUDY GUIDE

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

Cellular respiration is a process that breaks down food molecules to release energy to fuel cellular processes in organisms.

Remember to include the following information in your study guide:

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

Consider how molecules are rearranged and energy is transferred during the process of cellular respiration.