CHAPTER 10

Cellular Respiration

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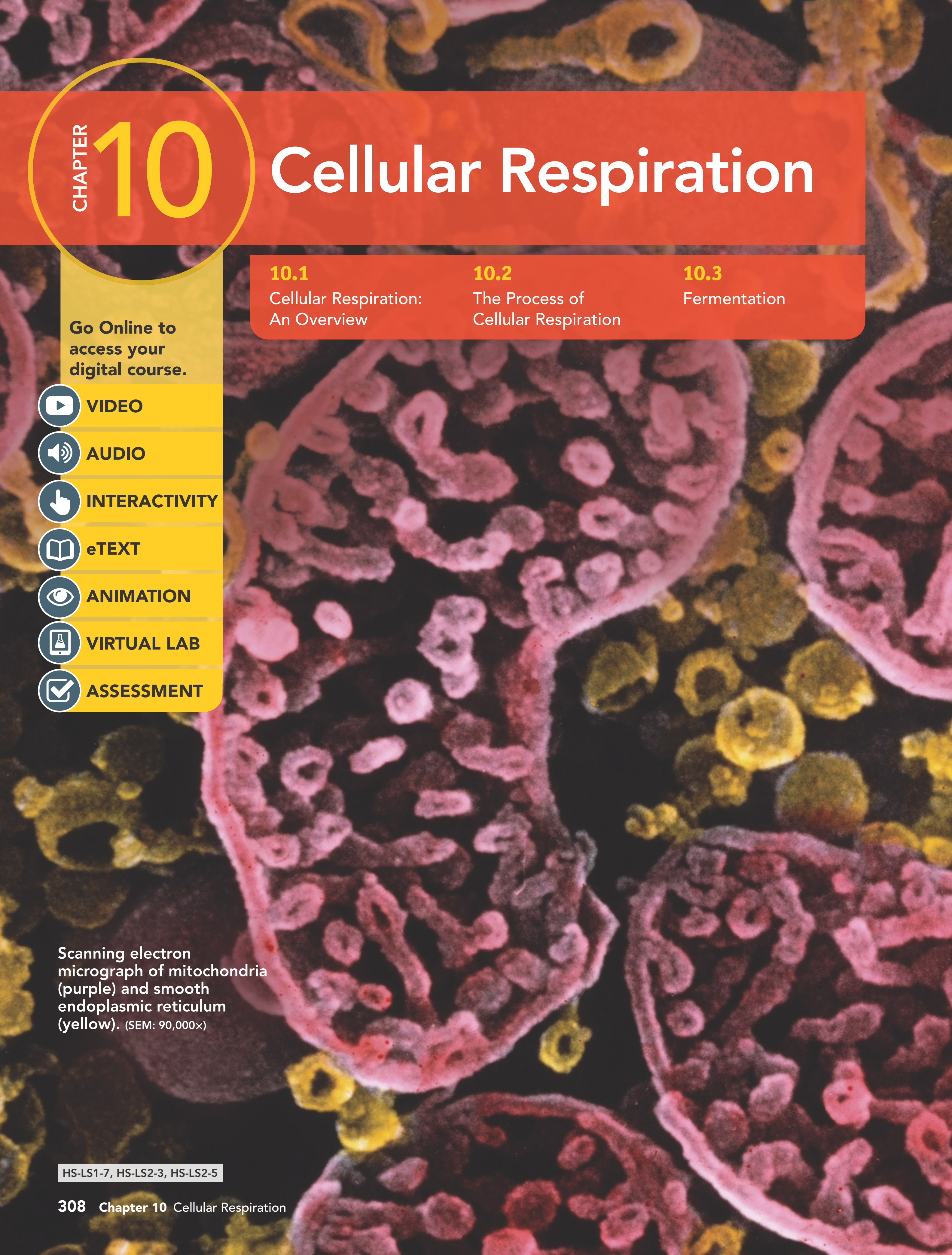


Scanning electron micrograph of mitochondria (purple) and smooth endoplasmic reticulum (yellow). (SEM: 90,000×)

HS-LS1-7, HS-LS2-3, HS-LS2-5

CASE STUDY

Can San Francisco sourdough be copied?

The city of San Francisco is famous for many things, including its sourdough bread. The bread has a distinctive chewy texture and tangy acidic taste, making it one of the city's favorite treats.

Breads that are not sourdough are made by combining flour with a mixture of water, baker's yeast, and sometimes a little sugar. After the ingredients are thoroughly mixed, the moist dough is left to rise as the yeast does its work. Then the dough is formed into a loaf and baked. Sourdough is different in several ways. Instead of baker's yeast, sourdough relies on "wild" yeast from the environment. Bacteria also contribute to the bread-making process. The yeast and bacteria are captured and then kept alive in a sourdough starter.

Making sourdough starter from scratch is a mysterious and hotly debated process. Many people use nothing but flour and water. Some people say all-purpose white flour is fine, but others insist on using rye or whole wheat flour or a mixture of different flours. Some starter recipes call for additional ingredients, such as active dry yeast, milk, buttermilk, yogurt, whey, or even crushed grapes.

The ingredients, whatever they may be, are mixed together and allowed to remain at room temperature. Within a day or so, the mixture begins to bubble. More flour and water are stirred in, and some of the mixture is discarded. Feeding the starter with fresh water and flour is done every day. After a few days, if all goes well, the would-be baker has a beige, bubbly lump that smells sour but is not spoiled. Some of this starter can be baked into bread, and some of it can be saved to make more starter.

In San Francisco, most of the bakeries captured their yeast and bacteria many years ago. One bakery claims that their sourdough starter was established in 1849 and has been growing ever since! The bakers maintain the starter by adding fresh flour and water, which keeps their microscopic friends alive and healthy. Then, for every batch of bread, they mix some of that starter with fresh dough. The yeast and bacteria grow rapidly, and they produce tiny bubbles that cause the dough to rise. The bacteria also produce compounds such as lactic acid and acetic acid, which provide the bread with its distinctive taste.

Bakeries in other cities have tried to duplicate San Francisco sourdough. Some have taken samples of the best sourdough starters and tried to maintain them. These bakeries have made some very good bread. However, try as they might, they have not been able to match the best loaves from San Francisco.

Why is the San Francisco sourdough so distinctive? Why has it been so hard to match this taste in other places around the country?

Throughout this chapter, look for connections to the CASE STUDY to help you answer these questions.

LESSON 10.1

Cellular Respiration: An Overview

KEY QUESTIONS

- *Where do organisms get energy?*
- *What is cellular respiration?*
- *What is the relationship between photosynthesis and cellular respiration?*

HS-LS1-7: Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy.
HS-LS2-3: Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions.
HS-LS2-5: Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

VOCABULARY
calorie
cellular respiration
aerobic
anaerobic

READING TOOL

As you read, record the key ideas from each heading in your **Biology Foundations Workbook.**

When you are hungry, how do you feel? If you are like most of us, you might feel sluggish, a little dizzy, and—above all—weak. You feel weak when you are hungry because food serves as a source of energy. This is your body's way of telling you that your energy supplies are low. How does food get converted into a usable form of energy? Do our bodies burn food the way a car burns gasoline, or is there something more to it?

Chemical Energy and Food

Food provides living things with the chemical building blocks needed to grow and reproduce. Food molecules contain chemical energy that is released when their chemical bonds are broken. ***Organisms get the energy they need from food.***

How much energy is actually present in food? Quite a lot, although it varies with the type of food. Energy that is stored in food is expressed in units of calories. A **calorie** is the amount of energy needed to raise the temperature of 1 gram of water 1 degree Celsius. The Calorie (capital *C*) that is used on food labels is actually a kilocalorie, or 1000 calories. Cells can use all sorts of molecules for food, including fats, proteins, and carbohydrates. The energy stored in each of these macromolecules (also called biomolecules) varies because their chemical structures, and therefore their energy-storing bonds, differ. For example, 1 gram of the sugar glucose releases 3811 calories of heat energy when it is burned. By contrast, 1 gram of the fat found in beef releases 8893 calories of heat energy. In general, carbohydrates and proteins contain approximately 4000 calories (4 Calories) of energy per gram, whereas fats contain approximately 9000 calories (9 Calories) per gram.

Of course, cells don't simply burn food and release energy as heat. Instead, they break down food molecules gradually, capturing a little bit of chemical energy every step along the way. This enables cells to use the energy stored in foods like glucose to synthesize compounds such as ATP that directly power the activities of the cell.

READING CHECK **Compare** What is the difference between the calorie (lowercase *c*) and the Calorie (capital *C*)?

Overview of Cellular Respiration

If oxygen is available, organisms can obtain energy from food by **cellular respiration**. ***Cellular respiration is a process of energy conversion that releases energy from food in the presence of oxygen.*** Although cellular respiration involves dozens of separate reactions, an overall chemical summary of the process is remarkably simple:

In Symbols:

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

In Words:

Oxygen + Glucose → Carbon dioxide + Water + Energy

INTERACTIVITY

Explore what happens during the different stages of cellular respiration.

As you can see, cellular respiration requires oxygen and a food molecule such as glucose, and it gives off carbon dioxide, water, and energy. Do not be misled, however, by the simplicity of this equation. If cellular respiration took place in just one step, all of the energy from glucose would be released at once, and most of it would be lost in the form of light and heat. Clearly, a living cell has to control that energy. It can't simply start a fire—the cell has to release the explosive chemical energy in food molecules a little bit at a time, trapping the energy in the form of ATP.

CASE STUDY **Analyzing Data**

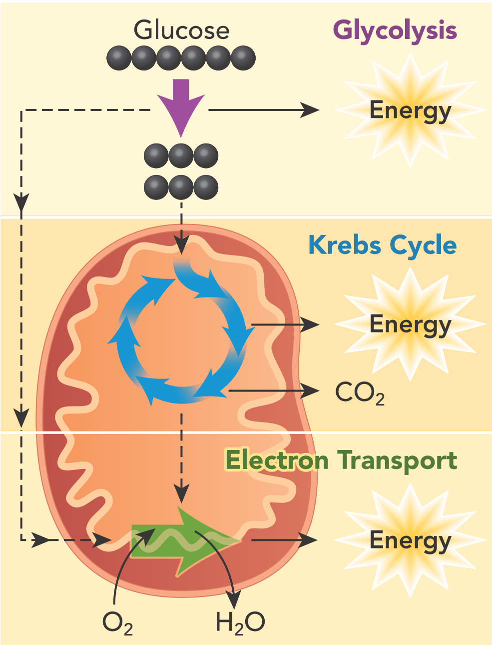
You Are What You Eat

The table shows the amount of proteins, carbohydrates, and fats for several different foods.

1. **Interpret Data** Per serving, which of the foods included in the table has the most protein? Which has the most carbohydrates? Which has the most fat?
2. **Reason Quantitatively** Approximately how many more Calories are there in 2 slices of bacon than there are in 3 slices of roasted turkey? Why is there a difference?
3. **Compare** Use the table to compare nutrients in a slice of sourdough bread with other foods.

Composition of Some Common Foods

Food	Protein (g)	Carbohydrate (g)	Fat (g)
Apple, 1 medium	0	22	0
Bacon, 2 slices	5	0	6
Chocolate, 1 bar	3	23	13
Eggs, 2 whole	12	0	9
2% milk, 1 cup	8	12	5
Potato chips, 15 chips	2	14	10
Sourdough bread, 2 slices	8	36	1
Skinless roasted turkey, 3 slices	11	3	1



INTERACTIVITY

Figure 10-1

The Stages of Cellular Respiration

There are three stages to cellular respiration: glycolysis, the Krebs cycle, and the electron transport chain.

Stages of Cellular Respiration Cellular respiration captures the energy from food in three main stages—glycolysis, the Krebs cycle, and electron transport. Although cells can use just about any food molecule for energy, we will concentrate on just one as an example—the simple sugar glucose.

Glucose first enters a chemical pathway known as glycolysis. Only about 10 percent of its energy is captured to produce ATP during this stage. In fact, at the end of glycolysis, about 90 percent of the chemical energy that was available in glucose is still unused, locked in the chemical bonds of a molecule called pyruvic acid.

How does the cell extract the rest of that energy? First, pyruvic acid enters the second stage of cellular respiration, the Krebs cycle, where a little more energy is captured. The bulk of the energy, however, comes from the final stage of cellular respiration, the electron transport chain. This stage requires reactants from the other two stages of the process, as shown by dashed lines in **Figure 10-1**. How does the electron transport chain extract so much energy from these reactants? It uses one of the world's most powerful electron acceptors—oxygen.

Oxygen and Energy Oxygen is required at the very end of the electron transport chain. Any time a cell's demand for energy increases, its use of oxygen increases, too. The double meaning of respiration points out a crucial connection between cells and organisms: Most of the energy-releasing pathways within cells require oxygen, and that is the reason we need to breathe, or respire.

Pathways of cellular respiration that require oxygen are said to be **aerobic** ("in air"). The Krebs cycle and the electron transport chain are both aerobic processes. Even though the Krebs cycle does not *directly* require oxygen, it is classified as an aerobic process because it cannot run without the oxygen-requiring electron transport chain. Glycolysis, however, does not directly require oxygen, nor does it rely on an oxygen-requiring process to run. Glycolysis is therefore said to be **anaerobic** ("without air"). Even though glycolysis is anaerobic, it is considered part of cellular respiration because its final products are key reactants for the aerobic stages.

Glycolysis occurs in the cytoplasm. In contrast, the Krebs cycle and electron transport chain, which generate the majority of ATP during cellular respiration, take place inside the mitochondria. If oxygen is not present, another anaerobic pathway, known as fermentation, makes it possible for the cell to keep glycolysis running, generating ATP to power cellular activity. You will learn more about fermentation later in this chapter.

BUILD VOCABULARY

Using Prefixes The prefix *an-* in *anaerobic* means "not" or "without." Anaerobic processes do not use oxygen, so they are not aerobic.

READING CHECK **Summarize** What stages of cellular respiration are considered aerobic?

Comparing Photosynthesis and Cellular Respiration

If nearly all organisms break down food by the process of cellular respiration, why doesn't Earth run out of oxygen? As it happens, cellular respiration is balanced by another process: photosynthesis. The energy flows in photosynthesis and cellular respiration take place in completely opposite directions. Look at **Figure 10-2**, and then think of the chemical energy as part of Earth's savings account. Photosynthesis is the process that "deposits" energy. Cellular respiration is the process that "withdraws" energy. As you might expect, the equations for photosynthesis and cellular respiration are the reverse of each other.

Chemically, the process of photosynthesis uses water and carbon dioxide as the raw materials to synthesize carbohydrates. Cellular respiration does the opposite, using carbohydrates as sources of chemical energy while releasing water and carbon dioxide. ***Photosynthesis removes carbon dioxide from the atmosphere, and cellular respiration puts it back. Photosynthesis releases oxygen into the atmosphere, and cellular respiration uses that oxygen to release energy from food.***

The global balance between cellular respiration and photosynthesis is essential to maintain Earth as a living planet. Another necessity is a constant input of energy into the system. This input comes from the sun. You can trace the flow of energy from the sun to organisms that perform photosynthesis and then to a series of organisms that perform cellular respiration.

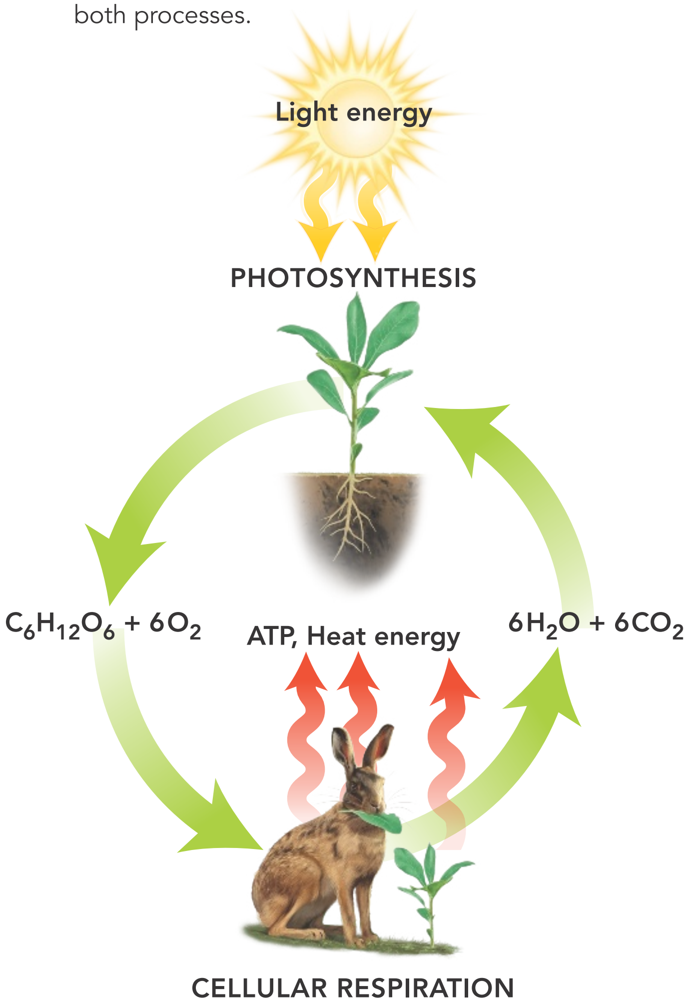
INTERACTIVITY

Investigate how algae can be used to create biofuels by conducting a virtual experiment.

Figure 10-2

A Global Balance

Photosynthesis and respiration can be thought of as opposite processes because the products of one are the reactants of the other. Note that plants perform both processes.



HS-LS1-7, HS-LS2-3, HS-LS2-5

LESSON 10.1 Review

KEY QUESTIONS

1. Why do all organisms need food?
2. Write the overall reaction for cellular respiration.
3. "Photosynthesis and cellular respiration have opposite effects on gases in the atmosphere." Explain this statement.

CRITICAL THINKING

4. **Identify** Breathing is required for cellular respiration. Use the reactants, products, and stages of cellular respiration to explain why breathing is required.
5. **Construct an Explanation** Compare the chemical equations for photosynthesis and cellular respiration. Explain how the two processes are interrelated.

LESSON 10.2

The Process of Cellular Respiration

KEY QUESTIONS

- *What happens during the process of glycolysis?*
- *What happens during the Krebs cycle?*
- *How does the electron transport chain use high-energy electrons from glycolysis and the Krebs cycle?*
- *How much ATP does cellular respiration generate?*

HS-LS1-7: Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy.

HS-LS2-3: Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions.

HS-LS2-5: Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

VOCABULARY

glycolysis
NAD^+
Krebs cycle
matrix

READING TOOL

As you read, take note of the sequence of events in cellular respiration. Fill in the graphic organizer in your **Biology Foundations Workbook.**

Food burns! It's true that many common foods (think of apples, bananas, and ground beef) have too much water in them to actually light with a match, but foods with little water (think of sugar, flour, and cooking oil) will burn. In fact, wheat grain, which contains both carbohydrates and protein, is so flammable that it has caused many fires, including the one seen here at a grain elevator in North Dakota. So, plenty of energy is available in food, but how does a living cell extract that energy without catching fire or blowing itself up? The trick is to release and capture that energy a little bit at a time.

Glycolysis

The first set of reactions in cellular respiration is known as **glycolysis**, which literally means "sugar-breaking." ***During glycolysis, 1 molecule of glucose, a 6-carbon compound, is transformed into 2 molecules of the 3-carbon compound pyruvic acid.*** As the bonds in glucose are broken and rearranged, small amounts of energy are released and captured in other molecules. The process of glycolysis is shown in **Figure 10-3**.

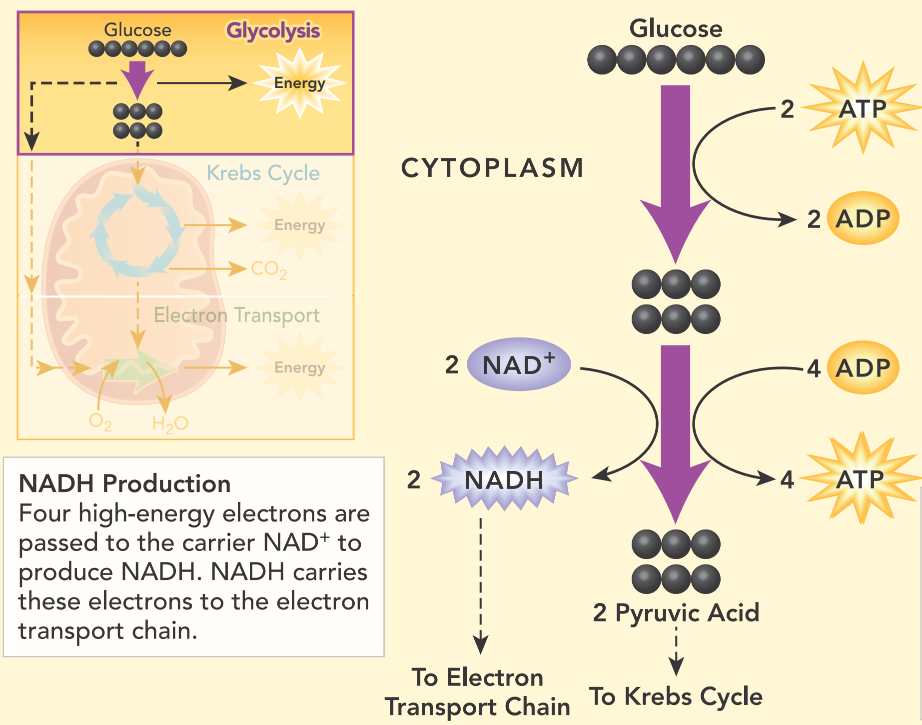
ATP Production Even though glycolysis is an energy-releasing process, the cell needs to put in a little energy to get things going. At the pathway's beginning, 2 ATP molecules are used up. Earlier in this chapter, photosynthesis and cellular respiration were compared, respectively, to a deposit to and a withdrawal from a savings account. Similarly, the 2 ATP molecules used at the onset of glycolysis are like an investment that pays back interest. Although the cell puts 2 ATP molecules into its "account" to get glycolysis going, glycolysis produces 4 ATP molecules. This gives the cell a net gain of 2 ATP molecules for each molecule of glucose that enters glycolysis.

NADH Production One of the reactions of glycolysis removes 4 electrons, now in a high-energy state, and passes them to an electron carrier called **NAD+**, or nicotinamide adenine dinucleotide. Like NADP+ in photosynthesis, each NAD+ molecule accepts a pair of high-energy electrons and a hydrogen ion. This molecule, now known as NADH, holds the electrons until they can be transferred to other molecules. As you will see, in the presence of oxygen, these high-energy electrons can be used to produce even more ATP molecules.

The Advantages of Glycolysis In the process of glycolysis, 4 ATP molecules are synthesized from 4 ADP molecules. Given that 2 ATP molecules are used to start the process, there is a net gain of just 2 ATP molecules. Although the energy yield from glycolysis is small, the process is so fast that cells can produce thousands of ATP molecules in just a few milliseconds. The speed of glycolysis can be a big advantage when the energy demands of a cell suddenly increase.

Besides speed, another advantage of glycolysis is that the process itself does not require oxygen. This means that glycolysis can quickly supply chemical energy to cells when oxygen is not available. When oxygen is available, however, the pyruvic acid and NADH "outputs" generated during glycolysis become the "inputs" for the other processes of cellular respiration.

READING CHECK **Use Analogies** How is the ATP produced in glycolysis like earning a return on an investment?



Up Close

Figure 10-3

Glycolysis

Glycolysis is the first stage of cellular respiration. During glycolysis, glucose is broken down into 2 molecules of pyruvic acid. ATP and NADH are produced as part of the process.

NADH Production
Four high-energy electrons are passed to the carrier NAD+ to produce NADH. NADH carries these electrons to the electron transport chain.

ATP Production
Two ATP molecules are "invested" to get the process of glycolysis going. Overall, 4 ATP molecules are produced, for a net gain of 2 ATP per molecule of glucose.

READING TOOL

Make a T-chart for the three stages of cellular respiration. Write down the inputs in one column and the outputs in the other.

The Krebs Cycle

In the presence of oxygen, the pyruvic acid produced in glycolysis passes to the second stage of cellular respiration, the **Krebs cycle**. The Krebs cycle is named for Hans Krebs, the British biochemist who demonstrated its existence in 1937. ***During the Krebs cycle, pyruvic acid is broken down into carbon dioxide in a series of energy-extracting reactions.*** Because citric acid is the first compound formed in this series of reactions, the Krebs cycle is also known as the citric acid cycle.

Citric Acid Production The Krebs cycle begins when pyruvic acid produced by glycolysis passes through the two membranes of the mitochondrion and into the matrix. The **matrix** is the innermost compartment of the mitochondrion and the site of the Krebs cycle reactions. Once inside the matrix, 1 carbon atom from pyruvic acid is split off to produce carbon dioxide, which is eventually released into the air. The other 2 carbon atoms from pyruvic acid rearrange to form acetic acid, which is joined to a compound called coenzyme A. The resulting molecule is called acetyl-CoA. As the Krebs cycle begins, acetyl-CoA hands off that 2-carbon acetyl group to a 4-carbon molecule already present in the cycle, producing a 6-carbon molecule called citric acid.

Energy Extraction Follow the reactions in **Figure 10-4** to see how the cycle continues. First, look at the 6 carbon atoms in citric acid. One is removed, and then another is removed, releasing 2 molecules of carbon dioxide and leaving a 4-carbon molecule. Why is the Krebs cycle a "cycle"? Because the 4-carbon molecule produced in the last step is the same molecule that accepts the acetyl-CoA in the first step. The molecule needed to start the reactions of the cycle is remade with every "turn."

Next, look for ATP. For each turn of the cycle, a molecule of ADP is converted to a molecule of ATP. Recall that glycolysis produces 2 molecules of pyruvic acid from 1 molecule of glucose. So, each starting molecule of glucose results in two complete turns of the Krebs cycle and, therefore, 2 ATP molecules. Finally, look at the electron carriers, NAD^+ and FAD (flavine adenine dinucleotide). At five places in each cycle, electron carriers accept a pair of high-energy electrons and a hydrogen ion, changing NAD^+ to NADH and FAD to $FADH_2$. FAD and $FADH_2$ are molecules similar to NAD^+ and NADH, respectively.

What happens to these Krebs cycle products—carbon dioxide, ATP, and electron carriers? Carbon dioxide diffuses out of the mitochondria, out of the cell, and into the bloodstream, and then is exhaled. The ATP molecules are *very* useful, becoming immediately available to power cellular activities. As for the carrier molecules like NADH, in the presence of oxygen, the electrons they hold are used to generate huge amounts of ATP.

READING CHECK **List** Make a list of the energy carriers involved in the Krebs cycle. Include their names before and after they accept the electrons.

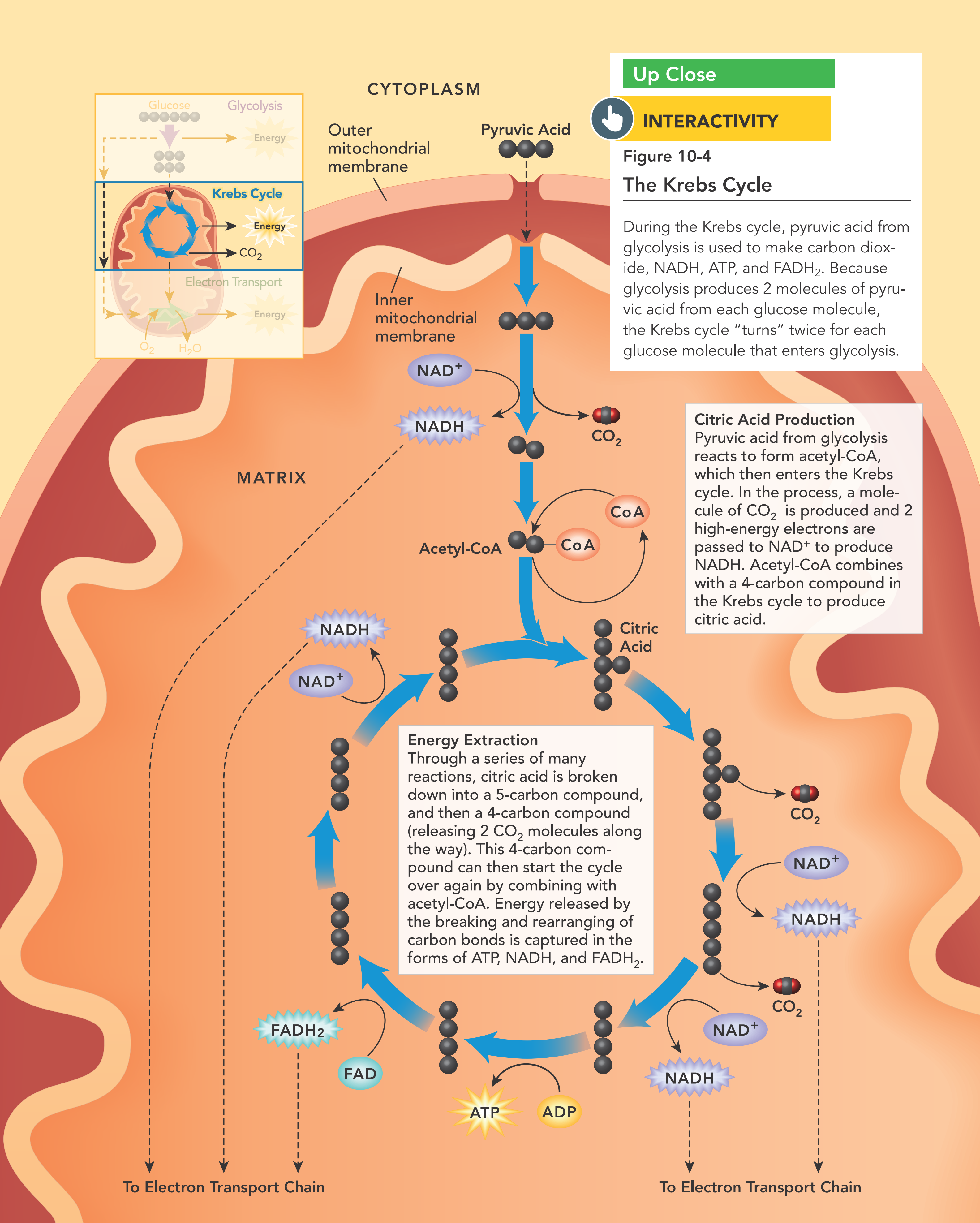
Up Close

INTERACTIVITY

Figure 10-4

The Krebs Cycle

During the Krebs cycle, pyruvic acid from glycolysis is used to make carbon dioxide, NADH, ATP, and $FADH_2$. Because glycolysis produces 2 molecules of pyruvic acid from each glucose molecule, the Krebs cycle "turns" twice for each glucose molecule that enters glycolysis.



Citric Acid Production
Pyruvic acid from glycolysis reacts to form acetyl-CoA, which then enters the Krebs cycle. In the process, a molecule of CO_2 is produced and 2 high-energy electrons are passed to NAD^+ to produce NADH. Acetyl-CoA combines with a 4-carbon compound in the Krebs cycle to produce citric acid.

Energy Extraction
Through a series of many reactions, citric acid is broken down into a 5-carbon compound, and then a 4-carbon compound (releasing 2 CO_2 molecules along the way). This 4-carbon compound can then start the cycle over again by combining with acetyl-CoA. Energy released by the breaking and rearranging of carbon bonds is captured in the forms of ATP, NADH, and $FADH_2$.

BUILD VOCABULARY

Multiple Meanings The verb *transport* means to move from one place to another. *Transport* can also be used as a noun to refer to a method of moving something.

Electron Transport and ATP Synthesis

Products from both the Krebs cycle and glycolysis feed into the last stage of cellular respiration, the electron transport chain, as seen in **Figure 10-5**. Recall that glycolysis generates high-energy electrons that are passed to NAD^+, forming NADH. Those NADH molecules can enter the mitochondrion, where they join the NADH and $FADH_2$ molecules generated by the Krebs cycle. The electrons are then passed from all those carriers to the electron transport chain. ***The electron transport chain uses the high-energy electrons from glycolysis and the Krebs cycle to synthesize ATP from ADP.***

INTERACTIVITY

Develop and use a model of the three stages of cellular respiration.

Electron Transport

NADH and $FADH_2$ pass their high-energy electrons to the electron transport chain. In eukaryotes, the electron transport chain is composed of a series of electron carriers located in the inner membrane of the mitochondrion. In prokaryotes, the same chain is in the cell membrane. High-energy electrons are passed from one carrier to the next. At the end of the electron transport chain is an enzyme that combines these electrons with hydrogen ions and oxygen to form water. Oxygen is the final electron acceptor of the chain, which is why electron transport is aerobic, or oxygen-requiring. Oxygen accepts low energy electrons at the end of the chain, and without it, the electron transport chain cannot function.

Every time 2 high-energy electrons pass down the electron transport chain, their energy is used to transport hydrogen ions (H^+) across the membrane. During electron transport, H^+ ions build up in the intermembrane space, making it positively charged relative to the matrix. In turn, the other side becomes negatively charged so that the membrane itself becomes a sort of biological "battery" that can power the synthesis of ATP.

ATP Production

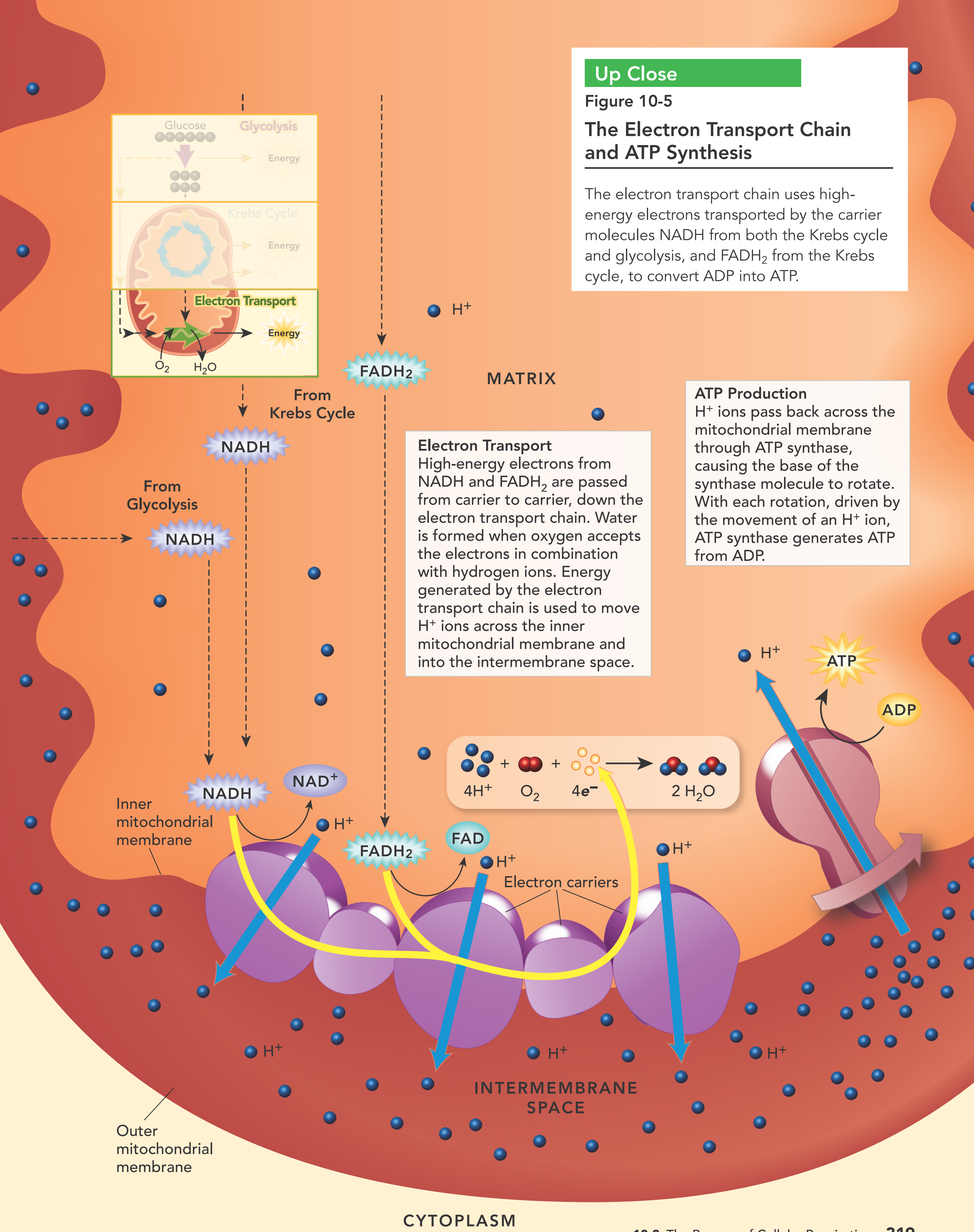
How does the cell use the potential energy from charge differences built up as a result of electron transport? As in photosynthesis, the cell uses a process known as chemiosmosis to produce ATP. The inner mitochondrial membrane contains enzymes known as ATP synthases. The charge difference across the membrane forces H^+ ions through channels in these enzymes, actually causing the ATP synthases to spin. With each rotation, the enzyme grabs an ADP molecule and attaches a phosphate group, producing ATP.

INTERACTIVITY

Discover how exercise affects mitochondria.

The beauty of this system is the way in which it couples the movement of high-energy electrons with the production of ATP. Every time a pair of high-energy electrons moves down the electron transport chain, the energy is used to move H^+ ions across the membrane. These ions then rush back across the membrane with enough force to spin the ATP synthase and generate enormous amounts of ATP. On average, each pair of high-energy electrons that moves down the full length of the electron transport chain provides enough energy to produce 3 molecules of ATP that can be used to power cellular activities.

READING CHECK **Identify** What role does oxygen play in the electron transport chain?



Up Close

Figure 10-5

The Electron Transport Chain and ATP Synthesis

The electron transport chain uses high-energy electrons transported by the carrier molecules NADH from both the Krebs cycle and glycolysis, and $FADH_2$ from the Krebs cycle, to convert ADP into ATP.

Electron Transport
High-energy electrons from NADH and $FADH_2$ are passed from carrier to carrier, down the electron transport chain. Water is formed when oxygen accepts the electrons in combination with hydrogen ions. Energy generated by the electron transport chain is used to move H^+ ions across the inner mitochondrial membrane and into the intermembrane space.

ATP Production
H^+ ions pass back across the mitochondrial membrane through ATP synthase, causing the base of the synthase molecule to rotate. With each rotation, driven by the movement of an H^+ ion, ATP synthase generates ATP from ADP.

HS-LS1-7

Modeling Lab Open-ended Inquiry

Making a Model of Cellular Respiration

Problem How can you create a model of cellular respiration?

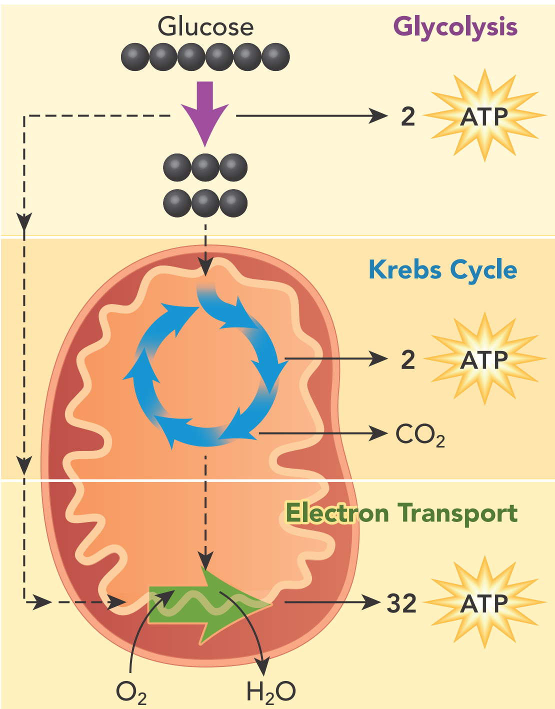
In this lab, you will plan and construct a model of cellular respiration. You will use the model to demonstrate how matter and energy flow in and out of the cell. Then you will evaluate the model and the models made by classmates.

You can find this lab in your digital course.

Figure 10-6

Energy Totals

The complete breakdown of glucose through cellular respiration results in the production of 36 molecules of ATP.



The Totals

Glycolysis nets just 2 ATP molecules per molecule of glucose. In the presence of oxygen, everything changes. ***Together, glycolysis, the Krebs cycle, and the electron transport chain release about 36 molecules of ATP per molecule of glucose.*** Notice in **Figure 10-6** that under aerobic conditions, these pathways enable the cell to produce 18 times as much energy as can be generated by anaerobic glycolysis alone. This is roughly 36 ATP molecules per glucose molecule versus just 2 ATP molecules in glycolysis.

Our diets contain much more than just glucose, of course, but that's no problem for the cell. Complex carbohydrates are broken down to simple sugars like glucose. Lipids and proteins can be broken down into molecules that enter the Krebs cycle or glycolysis at one of several places. Like a furnace that can burn oil, gas, or wood, the cell can generate chemical energy in the form of ATP from just about any source.

How efficient is cellular respiration? The 36 ATP molecules generated represent about 36 percent of the total energy of glucose. That might not seem like much, but it means that the cell is actually more efficient at using food than the engine of a typical automobile is at burning gasoline. What happens to the remaining 64 percent? It is released as heat, which is one of the reasons your body feels warmer after vigorous exercise and why your body temperature remains a steady 37°C day and night.

HS-LS1-7, HS-LS2-3, HS-LS2-5

LESSON 10.2 Review

KEY QUESTIONS

1. What are the products of glycolysis?
2. What happens to pyruvic acid in the Krebs cycle?
3. How does the electron transport chain use the high-energy electrons from glycolysis and the Krebs cycle?
4. How many molecules of ATP may be produced from glucose?

CRITICAL THINKING

5. **Integrate Information** How does the presence of oxygen affect the chemical pathways used to extract energy from glucose?
6. **Construct an Explanation** How are hydrogen ions (H^+) essential for the production of ATP?
7. **Use Models** Create a model to show the bonds that are broken and formed in cellular respiration.

Fermentation

LESSON 10.3

KEY QUESTIONS

- *How do organisms generate energy when oxygen is not available?*
- *How does the body produce ATP during different stages of exercise?*

HS-LS1-7: Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy.
HS-LS2-3: Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions.

We are air-breathing organisms who use oxygen to release chemical energy from the foods we eat. What happens if oxygen is not available? What happens when you hold your breath and dive underwater like a dolphin, or use up oxygen so quickly that you cannot replace it fast enough? Do your cells simply stop working? Microorganisms in places where oxygen is not available, like the middle of a mound of moist bread dough, face the same problem. Is there a pathway that allows cells to extract energy from food in the absence of oxygen?

VOCABULARY
fermentation

READING TOOL
As you read the text, compare and contrast cellular respiration and fermentation. Fill in the Venn Diagram in your **Biology Foundations Workbook.**

Fermentation

Recall from earlier in this chapter that two benefits of glycolysis are that it can produce ATP quickly and that it does not require oxygen. This means that in the absence of oxygen, many cells can use glycolysis alone to generate all the ATP they need. However, when a cell begins to generate large amounts of ATP this way, it runs into a problem. In just a few seconds, all of the cell's available NAD^+ molecules are filled up with electrons. Without oxygen, the electron transport chain does not run, so there is nowhere for the NADH molecules to deposit their electrons. Thus, NADH does not get converted back to NAD^+. Without NAD^+, the cell cannot keep glycolysis going, and ATP production stops. That's where a process called fermentation comes in.

When oxygen is not present, glycolysis is kept going by a pathway that makes it possible to continue to produce ATP without oxygen. The combined process of this pathway and glycolysis is called **fermentation**. ***In the absence of oxygen, fermentation releases energy from food molecules by producing ATP.***

BUILD VOCABULARY

Word Origins The word **fermentation** comes from the Latin word *fermentum*, which means "yeast".

During fermentation, cells convert NADH to NAD^+ by passing high-energy electrons back to pyruvic acid. This action converts NADH back into the electron carrier NAD^+, allowing glycolysis to keep going and to produce a steady supply of ATP. Fermentation is an anaerobic process that occurs in the cytoplasm of cells. Sometimes, glycolysis and fermentation are together referred to as anaerobic respiration. There are two slightly different forms of the process—alcoholic fermentation and lactic acid fermentation, which are summarized in **Figure 10-7**.

Alcoholic Fermentation Alcoholic fermentation is carried out by yeast, producing ethyl alcohol and carbon dioxide. A summary of alcoholic fermentation after glycolysis is written below.

$$\text{Pyruvic acid} + \text{NADH} \rightarrow \text{Alcohol} + CO_2 + NAD^+$$

Alcoholic fermentation is used to produce beer, wine, and other alcoholic beverages. It is also the process that causes bread dough to rise. Since the yeast very quickly use up any oxygen dissolved in the dough, they switch over to fermentation, giving off tiny bubbles of carbon dioxide. These bubbles form the air spaces you see in a slice of bread. The small amount of alcohol produced in the dough evaporates when the bread is baked.

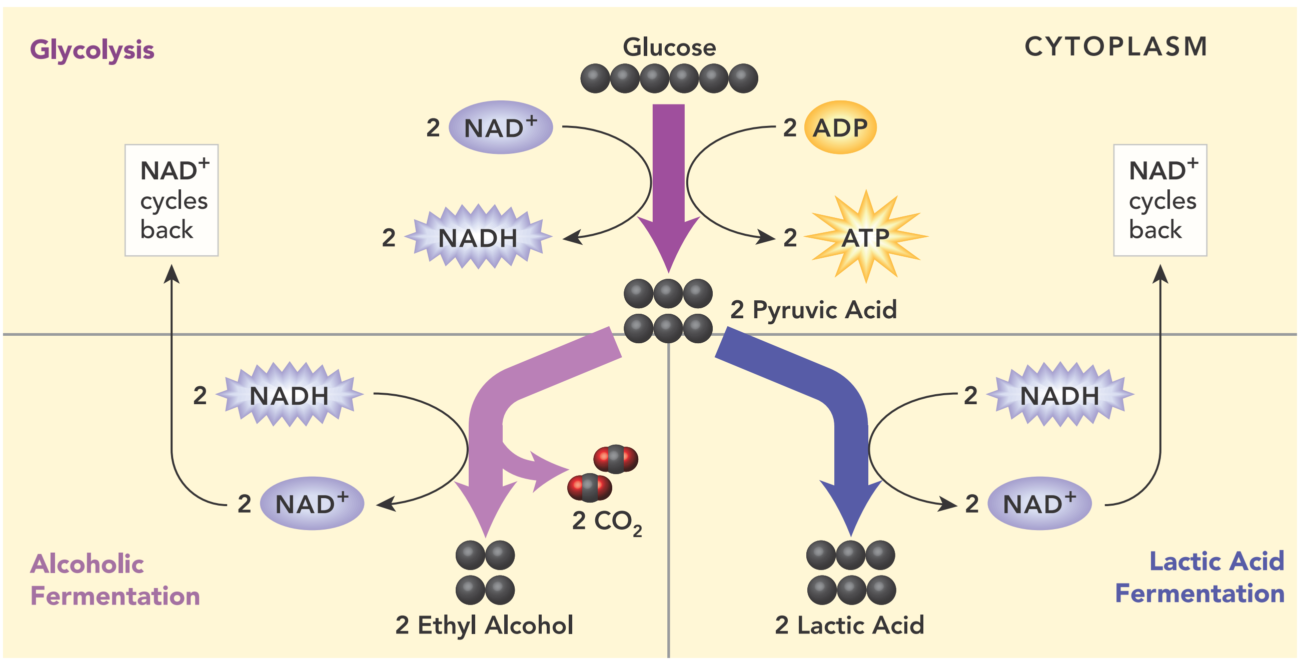
Lactic Acid Fermentation Other organisms carry out fermentation using a chemical reaction that converts pyruvic acid to lactic acid. Unlike alcoholic fermentation, lactic acid fermentation does not give off carbon dioxide. However, like alcoholic fermentation, lactic acid fermentation also regenerates NAD^+ so that glycolysis can continue. Lactic acid fermentation after glycolysis is summarized here.

$$\text{Pyruvic acid} + \text{NADH} \rightarrow \text{Lactic acid} + NAD^+$$

Figure 10-7

Fermentation

In alcoholic fermentation, pyruvic acid produced by glycolysis is converted into alcohol and carbon dioxide. Lactic acid fermentation converts the pyruvic acid to lactic acid.



INTERACTIVITY

Figure 10-8

Evidence of Fermentation

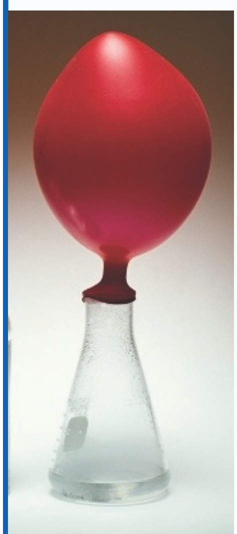
The foods in this photograph are all produced using lactic acid fermentation.

Certain bacteria that produce lactic acid as a waste product during fermentation are important to the food industry. Fermentation by these bacteria help to produce cheese, yogurt, buttermilk, and sour cream—to which the acid contributes the familiar sour taste. Pickles, sauerkraut, and kimchi, which are shown in **Figure 10-8**, are also produced using lactic acid fermentation. Lactic acid fermenting bacteria are also found in sourdough starters, and the acids they produce contribute to the taste and texture of sourdough bread.

Humans are also lactic acid fermenters. During brief periods without enough oxygen, many of the cells in our bodies produce ATP by lactic acid fermentation. The cells best adapted to doing that are muscle cells, which often need very large supplies of ATP for rapid bursts of activity.

READING CHECK **Identify** In what part of the cell does fermentation occur?

CASE STUDY **Quick Lab** **Guided Inquiry**



Rise Up

1. Obtain three balloons and three plastic bottles or flasks. Stretch the balloons by pulling on them and then blowing them up once or twice. Label the bottles #1, #2, and #3. Fill each plastic bottle about half full with very warm water.
2. To each bottle, add the following, and then gently swirl to dissolve the contents.

   Bottle #1: packet of yeast (7 g)
   Bottle #2: 60 mL of sugar
   Bottle #3: packet of yeast and 30 mL of sugar
3. Record your observations, and then carefully stretch a balloon over the mouth of each bottle.
4. Every 5 minutes for 30 minutes, use string to measure the widest circumference of each balloon. Record your measurements.

ANALYZE AND CONCLUDE

1. **Communicate Information** How did the results for the three bottles differ?
2. **Draw Conclusions** What caused this difference? Explain.
3. **Design an Experiment** Write a procedure for testing another factor that could affect the rate of fermentation in yeast.

READING TOOL

Create a cause-and-effect diagram to summarize what happens in cells during a sprint and a long-distance race.

VIDEO

Discover how athletes can use lactic acid fermentation to their advantage.

Energy and Exercise

Bang! The starter's pistol goes off. The swimmers dive from their blocks and sprint furiously through the water toward the other end of the pool, 50 meters away. The race takes a little more than 20 seconds, and many of the swimmers don't even take a single breath once they hit the water. When they reach the wall, some of the swimmers are thrilled and others are disappointed, but all of them are out of breath. For nearly a minute, much longer than the race itself, they huff and puff to recover from the effort. Most of them aren't breathing normally until several minutes afterward. What's going on? How did they manage to swim such a fast race without breathing? Why does it take so long to recover, even for the best athletes in the world?

To figure out why it takes so long for the swimmers to recover, think of the pathways the body uses to provide the chemical energy needed to power these swimmers through 50 meters of water. As they begin the race, the competitors have only enough ATP in their muscle cells to power them for a few seconds. To keep going, they must immediately generate new ATPs by cellular respiration or by lactic acid fermentation.

Quick Energy If the swimmers in **Figure 10-9** had entered the pool for a leisurely swim, they'd be able to produce all the ATP they needed using the process of cellular respiration. The oxygen they breathed in and passed along to their muscles via the bloodstream would be more than enough to keep aerobic respiration going. But this is not a leisurely swim or a walk in the park. These athletes are depending on their muscles to produce their absolute maximum effort and to sustain it for the length of the pool. The oxidative pathways of aerobic respiration simply cannot supply the ATP they need quickly enough to keep them going at top speed. They need to flood their muscles with ATP, and they need to do it quickly.

The solution is lactic acid fermentation. As we've seen, the fermentation pathway doesn't involve the Krebs cycle, the electron transport chain, or oxygen. As a result, it works much more rapidly, supplying all the ATP a well-trained athlete needs to support maximum effort for 30 to 40 seconds. Sprinters, whether swimming or running, rely on this pathway for bursts of quick energy that make the difference between winning or losing a race.

Figure 10-9

Exercise and Energy

During a 50-meter race, swimmers rely on the energy supplied by ATP to make it to the finish line.

This process, of course, produces lactic acid as a byproduct, which quickly builds up in the muscles and bloodstream of the athletes. When the race is over, the only way to get rid of this lactic acid is by means of another chemical pathway that requires extra oxygen. For that reason, you can think of a quick sprint as building up an "oxygen debt" that the swimmers have to repay with plenty of heavy breathing after the race. That's why just 20 seconds of swimming may produce an oxygen debt that requires several minutes of huffing and puffing to clear. ***For short, quick bursts of energy, the body uses ATP already in muscles as well as ATP made by lactic acid fermentation.***

INTERACTIVITY

Explore the differences between cellular respiration and fermentation.

Long-Term Energy What happens if the race is longer? How does your body generate the ATP it needs to swim or run for thousands of meters or to engage in a soccer game that lasts more than an hour? ***For exercise longer than about 90 seconds, cellular respiration is the only way to continue generating a supply of ATP.*** Cellular respiration releases energy more slowly than fermentation does, which is why even well-conditioned athletes have to pace themselves during a long race or over the course of a game.

Figure 10-10

Marathon Runners

Runners need well-conditioned circulatory and respiratory systems to maintain aerobic respiration in their muscles to go the distance.

Your body stores energy in muscle cells and other tissues in the form of the carbohydrate glycogen. These stores of glycogen are usually enough to last for 15 or 20 minutes of activity. After that, your body begins to break down other stored molecules, including fats, for energy. This is one reason that aerobic forms of exercise—such as running, dancing, and swimming—are so beneficial for weight control. Athletes competing in long-distance events, like the marathon in **Figure 10-10**, depend upon the efficiency of their respiratory and circulatory systems to supply oxygen to their muscles to support aerobic respiration for long periods of time.

HS-LS1-7, HS-LS2-3

LESSON 10.3 Review

KEY QUESTIONS

1. Name the two main types of fermentation.
2. Why do runners breathe heavily after a sprint race?

CRITICAL THINKING

3. **Infer** Why is lactic acid fermentation useful for short bursts of energy but not for meeting a long-term energy demand, such as running a marathon?
4. **Construct an Explanation** Pyruvic acid is the final product of glycolysis, which is the first stage of cellular respiration. Why is pyruvic acid never the end product of fermentation?
5. **Apply Scientific Reasoning** An Olympic sprinter has just broken the world record for the 100-meter dash. Which process will her body likely use to recover from her "oxygen debt"? Explain.

CASE STUDY WRAP-UP

Can San Francisco sourdough be copied?

San Francisco sourdough bread has a unique taste. To begin explaining this taste, scientists investigated the microorganisms that contribute to the sourdough.

HS-LS2-3

Make Your Case

Many years ago, San Francisco bakers realized that their sourdough starters contained two very special microorganisms: a useful "wild" yeast and a type of bacteria called *Lactobacillus*. After scientists studied the bacteria closely, they realized they had discovered a new species. The bacteria are now called *Lactobacillus sanfranciscensis* in honor of the city in which they were discovered.

Develop a Solution

1. **Conduct Research** Why is the taste of San Francisco sourdough so distinctive and difficult to match? Research facts and opinions to construct an answer.
2. **Design a Solution** Describe steps you could take to develop an effective method for copying San Francisco sourdough bread. Assume that you have access to sourdough starter and all the ingredients and equipment you need.

Technology on the Case

Like Bread Dough in a Vat?

The photo shows an example of a bioreactor. Like bread dough, a bioreactor holds growing colonies of bacteria or other organisms, generally in a liquid mixture. Over time, the products of biochemical reactions build up in the mixture. Bioreactors are used to produce ingredients for many drugs and medicines. Other bioreactors produce fermented beverages or foods like sour cream and yogurt. A Korean dish called kimchi is made from fermented vegetables. In one traditional method, the fermentation takes place in a sealed pot that is kept underground.

Modern bioreactors are designed so that conditions can be tightly controlled. Variables such as temperature, light, oxygen levels, and acidity of the solution can all affect the growth of microorganisms, which in turn affects the products they release. Bioreactors are also designed to prevent contamination. If unwanted bacteria or yeast cells enter the bioreactor, they could reduce the yield of the desired product or ruin the product completely.

Scientists and engineers have been investigating a new way to use bioreactors, by sending them into space! On Earth, the pull of gravity can make it difficult to produce a delicate drug or gather a cell culture. In space, the effects of gravity are minimal.

Whether in space or here on Earth, all bioreactors take advantage of the chemical reactions of living organisms. For that reason, they really are like bread dough in a vat!

Careers on the Case

Bread bakers and people in many other careers need to know about fermentation and its effects.

Baker

Bread depends on the products of fermentation, as do many beverages, cheeses, and other foods. In other cases, though, fermentation can ruin or spoil foods. Understanding fermentation and the actions of microorganisms is essential for bakers, chefs, and anyone who prepares food or helps keep food safe to eat.

VIDEO

Watch this video to learn about other careers in biology.

CHAPTER 10
STUDY GUIDE

Lesson Review

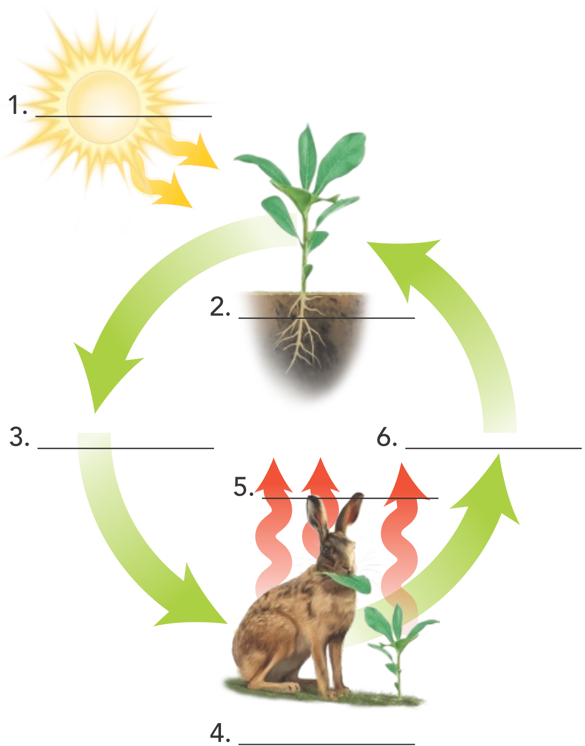
Go to your Biology Foundations Workbook for longer versions of these lesson summaries.

10.1 Cellular Respiration: An Overview

Organisms get the energy they need from food. Cellular respiration is the process that releases energy from food in the presence of oxygen. There are three stages of cellular respiration: glycolysis, the Krebs cycle, and the electron transport chain.

Photosynthesis removes carbon dioxide from the atmosphere, and cellular respiration puts it back. Photosynthesis releases oxygen into the atmosphere, and cellular respiration uses that oxygen to release energy from food.

- calorie
- cellular respiration
- aerobic
- anaerobic



Summarize Complete this diagram by filling in numbers 1 through 6.

10.2 The Process of Cellular Respiration

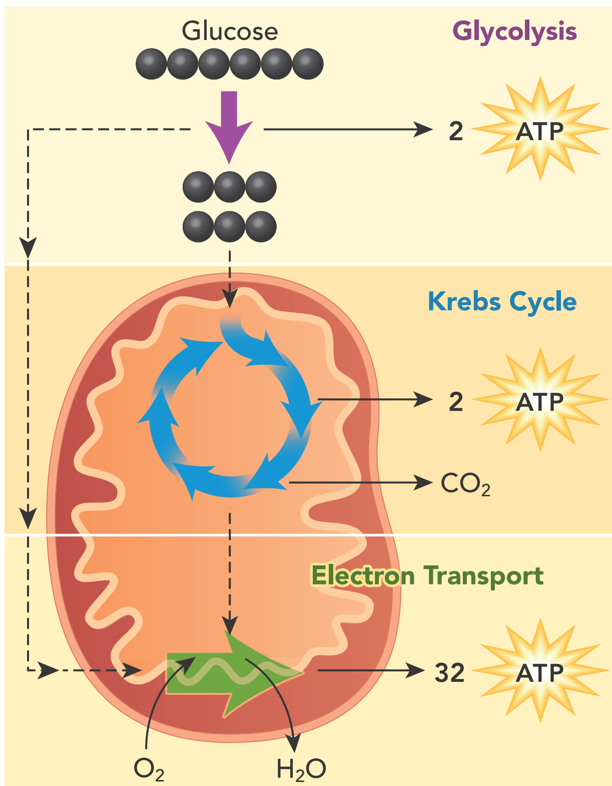
During glycolysis, 1 molecule of glucose is transformed into 2 molecules of pyruvic acid.

During the Krebs cycle, pyruvic acid is broken down into carbon dioxide in a series of energy-extracting reactions.

The electron transport chain uses the high-energy electrons from glycolysis and the Krebs cycle to convert ADP into ATP.

Together, glycolysis, the Krebs cycle, and the electron transport chain release about 36 molecules of ATP per molecule of glucose.

- glycolysis
- NAD+
- Krebs cycle
- matrix



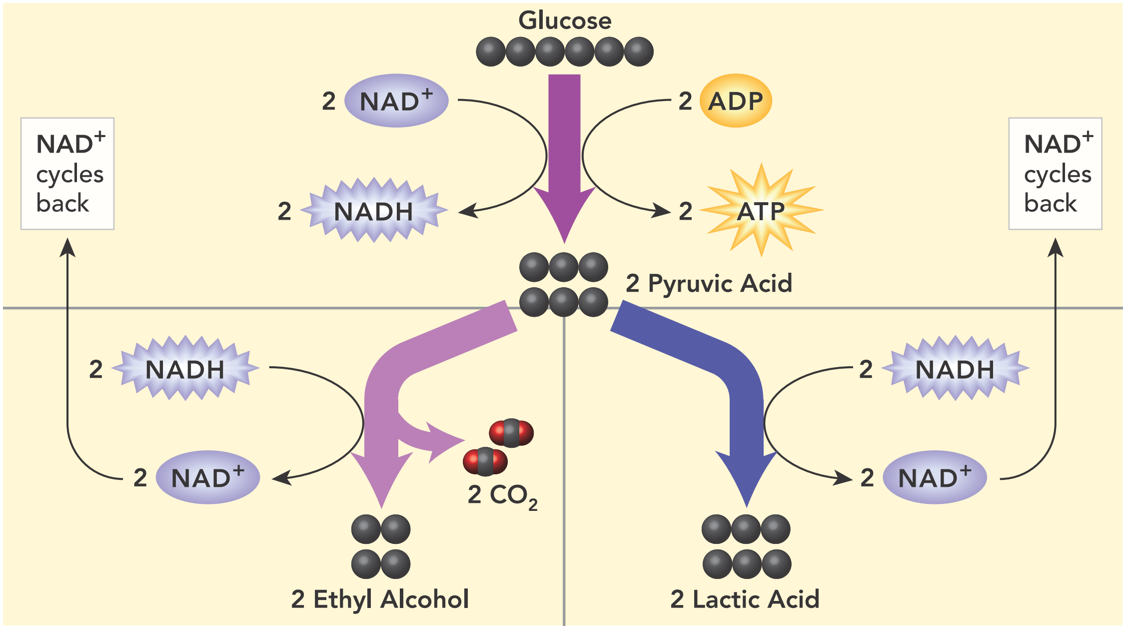
Use Visuals How many times more energy is produced by all three stages of cellular respiration than by glycolysis alone?

10.3 Fermentation

In the absence of oxygen, glycolysis is kept going by the pathway of fermentation, which releases energy from food molecules by producing ATP. There are two slightly different forms of the process: alcoholic fermentation and lactic acid fermentation.

For short, quick bursts of energy, the body uses ATP already in muscles as well as ATP made by lactic acid fermentation. For exercise longer than about 90 seconds, cellular respiration is the only way to continue generating a supply of ATP.

- fermentation

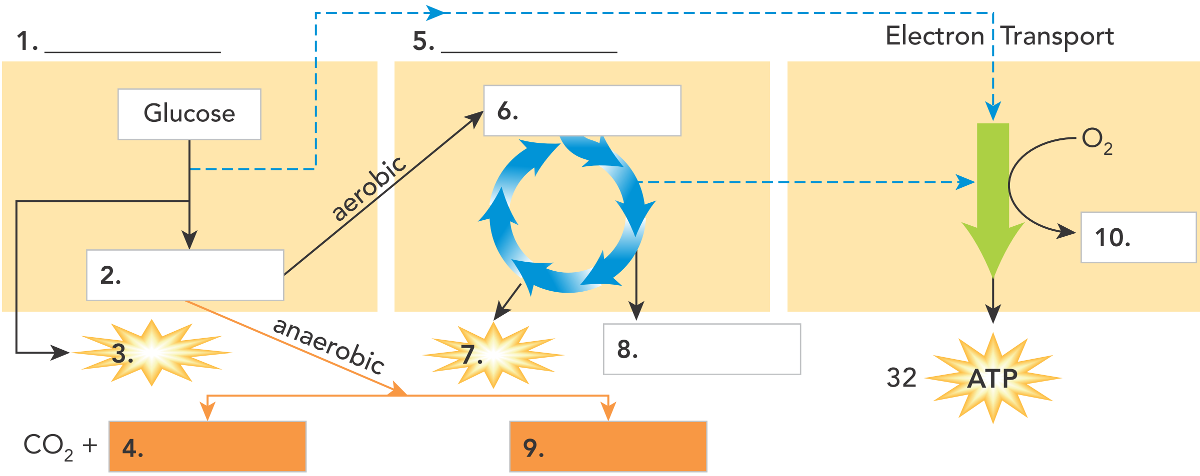


Compare and Contrast How are alcoholic fermentation and lactic acid fermentation similar? How are they different?

Organize Information

Complete the flowchart to show the stages of cellular respiration and fermentation.

Cellular Respiration and Fermentation



PERFORMANCE-BASED ASSESSMENT

Making a Better Bread

Mastering Fermentation

Communicating Information

CCSS.MATH.CONTENT.MP2, CCSS.ELA-LITERACY.RST.9-10.3

STEM Professional bakers and cooks often try to develop new recipes for their favorite foods or dishes. Amateurs enjoy this process, too. For example, when following a recipe for bread, an enterprising baker might change the amount of sugar or salt, add new ingredients like raisins or sesame seeds, or change the timing of the different steps.

In many ways, developing a new recipe is an example of the engineering process in action. Engineers often try out a variety of plans and ideas to develop a working model, or prototype, of their invention or process. Then, when they have settled on the prototype, they produce it full size or in large amounts.

Read the recipe for sourdough bread shown here, and then answer these questions.

Sourdough Bread

Ingredients: 4 cups bread flour, 3 tablespoons sugar, 2 tablespoons salt, 1/4 ounce dry yeast, 1 cup warm milk, 2 tablespoons margarine, 1 1/2 cups sourdough starter

Steps

1. In a large bowl, combine 1 cup flour and the sugar, salt, and dry yeast. Add milk and margarine. Stir in starter. Gradually mix in 3 cups flour.
2. Turn dough out onto a floured surface and knead for 8 to 10 minutes. Place in a greased bowl, turn once to oil surface, and cover. Let the dough rise at room temperature for 1 hour or until doubled in volume.
3. Punch down, and let rest 15 minutes. Shape into 2 or 3 small loaves. Place on a greased baking pan. Allow to rise for 1 hour or until doubled.
4. Bake at 375°F (190°C) for 30 minutes.

SCIENCE PROJECT

1. **Construct an Explanation** How is fermentation important in the baking of sourdough bread? During which step does fermentation occur? To construct your answer, apply your knowledge of fermentation and scientific reasoning.

2. **Conduct Research** A sourdough starter is essential to making sourdough bread. Research how to make and maintain your own sourdough starter.

3. **Predict** Consider the following changes to the recipe. Predict the result of each change, and explain your reasoning. Assume that each change occurs individually, without enacting any of the other changes.

   a. Step 2 is eliminated.

   b. Before step 3, the dough is rolled into very thin sheets.

   c. In step 3, the dough rises for only 30 minutes.

   d. In step 2, the dough rises inside a refrigerator.

4. **Conduct Research** Bakers might follow many recipes or procedures for baking bread or related products. Select a recipe from a cookbook or the Internet, and research how it relies on fermentation.

5. **Communicate Information** Write a brief report to share your research findings and conclusions. Be sure to address the following points:

   - Describe the steps that are followed to produce the food. Explain how fermentation is used.
   - Which organisms are used to perform the fermentation process? Why are the organisms useful for the food?
   - How does the food-making process compare with the processes used for other foods that depend on fermentation?

Swiss cheese gets its unique flavor from lactic acid fermentation and the effects of bacteria on lactic acid. The holes in the cheese come from pockets of carbon dioxide gas that fermentation releases.

CHAPTER 10

ASSESSMENT

KEY QUESTIONS AND TERMS

10.1 Cellular Respiration: An Overview

HS-LS1-7, HS-LS2-3, HS-LS2-5

1. Cells use the energy available in food to make a final energy-rich compound called
   a. water. c. ATP.
   b. glucose. d. ADP.
2. Each gram of glucose contains approximately how much energy?
   a. 9 calories c. 4 calories
   b. 9 Calories d. 4 Calories
3. The process that releases energy from food in the presence of oxygen is
   a. synthesis.
   b. cellular respiration.
   c. ATP synthase.
   d. photosynthesis.
4. The first step in releasing the energy of glucose in a cell is known as
   a. fermentation.
   b. glycolysis.
   c. the Krebs cycle.
   d. electron transport.
5. What is a calorie? Briefly explain how cells use a high-calorie molecule such as glucose.
6. Write a chemical equation for cellular respiration. Label the molecules involved.
7. What percentage of the energy contained in a molecule of glucose is captured in the bonds of ATP at the end of glycolysis?
8. What does it mean if a process is "anaerobic"? Which part of cellular respiration is anaerobic?

10.2 The Process of Cellular Respiration

HS-LS1-7, HS-LS2-3, HS-LS2-5

9. The net gain of energy in glycolysis from one molecule of glucose is
   a. 4 ATP molecules.
   b. 2 ATP molecules.
   c. 8 ADP molecules.
   d. 3 pyruvic acid molecules.
10. In eukaryotes, the Krebs cycle takes place within the
    a. chloroplast. c. mitochondrion.
    b. nucleus. d. cytoplasm.
11. The electron transport chain uses the high-energy electrons from the Krebs cycle to
    a. produce glucose.
    b. move H^+ ions across the inner mitochondrial membrane.
    c. convert acetyl-CoA to citric acid.
    d. convert glucose to pyruvic acid.
12. How is glucose changed during glycolysis?
13. What is NAD^+? Why is it important?
14. Summarize what happens during the Krebs cycle. What happens to high-energy electrons generated during the Krebs cycle?
15. How is ATP synthase involved in making energy available to the cell?

10.3 Fermentation

HS-LS1-7, HS-LS2-3

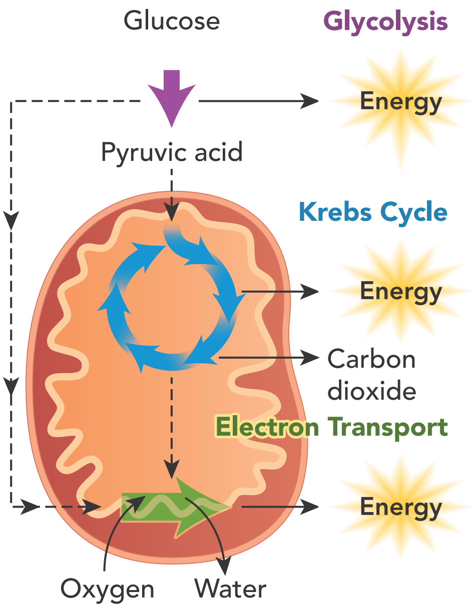
16. Because fermentation takes place in the absence of oxygen, it is said to be
    a. aerobic.
    b. anaerobic.
    c. cyclic.
    d. oxygen-rich.
17. Most of the time, the process carried out by yeast that causes bread dough to rise is
    a. alcoholic fermentation.
    b. lactic acid fermentation.
    c. cellular respiration.
    d. mitosis.
18. During heavy exercise, the buildup of lactic acid in muscle cells results in
    a. cellular respiration.
    b. oxygen debt.
    c. fermentation.
    d. the Krebs cycle.
19. How are fermentation and cellular respiration similar?
20. Write equations to show how lactic acid fermentation compares with alcoholic fermentation. Which reactant(s) do they have in common?

CRITICAL THINKING

HS-LS1-7, HS-LS2-5

21. **Construct an Explanation** Explain how cellular respiration and photosynthesis can be considered both opposite and interrelated processes.

The diagram shown is a model summarizing the stages of cellular respiration. Use the diagram to answer questions 22 and 23.



22. **Use Models** Suppose a chemical in a cell were to inhibit the function of mitochondria. Predict how the model would be affected, and explain why.

23. **Evaluate Models** The model shows the same image for energy during each stage. Explain how you could improve the model to better represent the energy released during each stage.

24. **Identify** What are the reactants of anaerobic cellular respiration? What are the products?

25. **Identify** What are the reactants of aerobic cellular respiration? What are the products?

26. **Compare and Contrast** How is the function of NAD^+ in cellular respiration similar to that of $NADP^+$ in photosynthesis?

27. **Use Analogies** Why is comparing cellular respiration to a burning fire a poor analogy?

28. **Compare and Contrast** Where is the electron transport chain found in a eukaryotic cell? Where is it found in a prokaryotic cell?

29. **Use Models** Explain how the products of glycolysis and the Krebs cycle are related to the electron transport chain. Draw a flowchart that shows the relationships between these products and the electron transport chain.

30. **Use Models** Draw and label a mitochondrion surrounded by cytoplasm. Indicate where glycolysis, the Krebs cycle, and the electron transport chain occur in a eukaryotic cell.

31. **Infer** Certain types of bacteria thrive in conditions that lack oxygen. What does that fact indicate about the way they obtain energy?

32. **Design an Investigation** Would individuals who carry out regular aerobic exercise suffer less muscle discomfort during intense exercise than other individuals? Outline an experiment that could answer this question.

33. **Apply Scientific Reasoning** To function properly, heart muscle cells require a steady supply of oxygen. After a heart attack, small amounts of lactic acid are present. What does this evidence suggest about the nature of a heart attack?

34. **Form a Hypothesis** In certain cases, regular exercise causes an increase in the number of mitochondria in muscle cells. How might that change improve an individual's ability to perform activities that require great amounts of energy?

35. **Predict** Yeast cells can carry out both fermentation and cellular respiration, depending on whether oxygen is present. In which case would you expect yeast cells to grow more rapidly? Explain.

36. **Explain** Explain how a sprinter gets energy during a 30-second race. Is the process aerobic or anaerobic? How does it compare to a long-distance runner getting energy during a 5-kilometer race?

CROSSCUTTING CONCEPTS

37. Energy and Matter Energy cannot be created or destroyed. Explain how energy is conserved in cellular respiration. Include in your explanation how energy is transferred and converted at the levels of a single cell and of an organism.

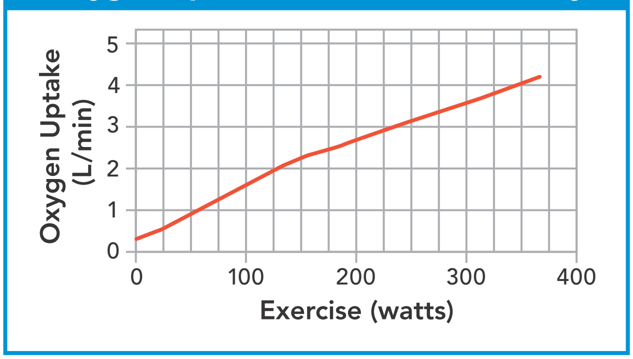
38. Systems and System Models Edie uses snap beads to model cellular respiration. She uses red beads for oxygen atoms, black beads for carbon atoms, and white beads for hydrogen atoms. How can she describe this reaction? What is one limitation of the model?

MATH CONNECTIONS

Analyze and Interpret Data

CCSS.MATH.CONTENT.MP2

Use the graph to answer questions 39 and 40. The graph shows data collected by a scientist who compared the volume of oxygen breathed per minute to the difficulty level of exercise, measured in watts.



Oxygen Uptake and Exercise Difficulty

39. Interpret Graphs Based on the graph, which increase in exercise difficulty level resulted in an increase in oxygen uptake of approximately 2 L/min?

40. Draw Conclusions Which of the following is a valid hypothesis for the trend shown on the graph? Evaluate the choices, and then explain why you selected the answer you did. Identify the criteria you used to select the answer, and describe how the other choices failed to meet your criteria.

a. As exercise becomes more difficult, the body relies more and more on lactic acid fermentation.
b. Exercise below a level of 100 watts does not require increased oxygen uptake.
c. Difficult exercise requires additional oxygen intake in order to generate extra ATP for muscle cells.
d. The human body cannot maintain exercise levels above 500 watts.

LANGUAGE ARTS CONNECTIONS

Write About Science

CCSS.ELA-LITERACY.WHST.9-10.2, CCSS.ELA-LITERACY.WHST.9-10.4

41. Write Explanatory Texts Expand the analogy of deposits and withdrawals of money that was used in the chapter to write a short paragraph to explain cellular respiration.

42. Produce Clear Writing Write a paragraph that explains the conditions under which fermentation occurs and differentiates between alcoholic and lactic acid fermentation.

Read About Science

CCSS.ELA-LITERACY.RST.9-10.1, CCSS.ELA-LITERACY.RST.9-10.10

43. Cite Textual Evidence Carbon monoxide (CO) molecules bring the electron transport chain in a mitochondrion to a stop by binding to an electron carrier. Use this information and cite additional information from the text to explain why carbon monoxide gas kills aerobic organisms.

44. Read and Comprehend Review **Figure 10-5** and the text that accompanies it. How does the diagram illustrate the process described in the passage? How does the diagram relate to the information presented about the other stages of cellular respiration?

CHAPTER 10

END-OF-COURSE TEST PRACTICE

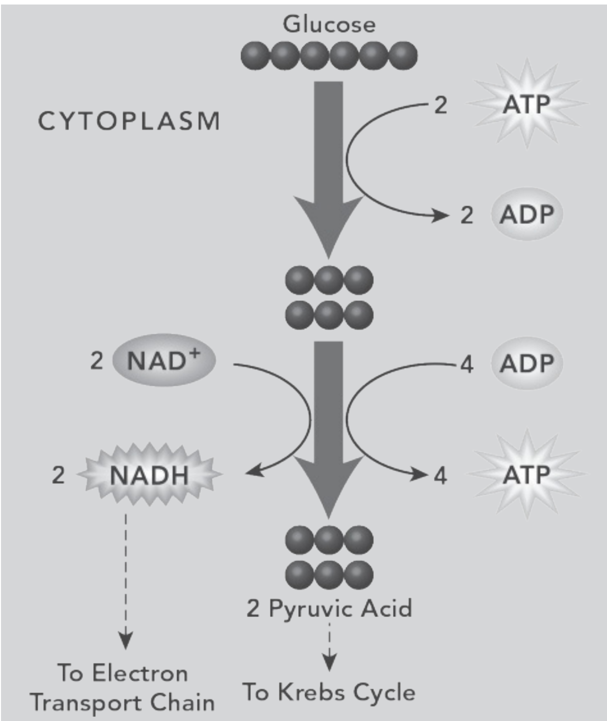
1. In a model summarizing cellular respiration, which of the following must be represented as raw materials, or the reactants of the process?

A. glucose and carbon dioxide
B. glucose and oxygen
C. carbon dioxide and oxygen
D. oxygen and lactic acid
E. water and oxygen

2. Which statement best describes an event represented in the model that contributes to the production of ATP?

A. A net gain of 6 ATP molecules is achieved.
B. Oxygen molecules are broken down and converted into pyruvic acid.
C. High-energy electrons are passed to NAD^+ forming NADH.
D. Carbon atoms in glucose are transformed into energy in the form of ATP.
E. Pyruvic acid is broken down to form carbon dioxide.

The diagram shows a model of glycolysis. Use the diagram to answer question 3.



3. During glycolysis, what is the source of the chemical energy that is captured in ATP?

A. the chemical bonds in pyruvic acid
B. the chemical bonds in glucose
C. the nuclei of atoms in glucose
D. high-energy electrons in the cytoplasm
E. high-energy electrons in mitochondria

4. What best describes the role of molecular oxygen (O_2) in cellular respiration?

A. It is accepts electrons when reacting to form water.
B. It combines with carbon and hydrogen to form glucose.
C. It is released when water breaks apart.
D. It is released when glucose breaks apart.
E. It reacts to form carbon dioxide and water.

5. Which is a role of cellular respiration in cycling materials between the atmosphere and biosphere?

A. It transfers carbon to the atmosphere as carbon dioxide.
B. It transfers carbon to the biosphere as glucose.
C. It transfers oxygen gas to the atmosphere.
D. It transfers water from the atmosphere to the biosphere.
E. It transfers carbon to the atmosphere as pyruvic acid.

ASSESSMENT

For additional assessment practice, go online to access your digital course.

If You Have Trouble With...					
Question	1	2	3	4	5
See Lesson	10.1	10.2	10.2	10.2	10.1
Performance Expectation	HS-LS1-7	HS-LS1-7	HS-LS1-7	HS-LS1-7	HS-LS2-5