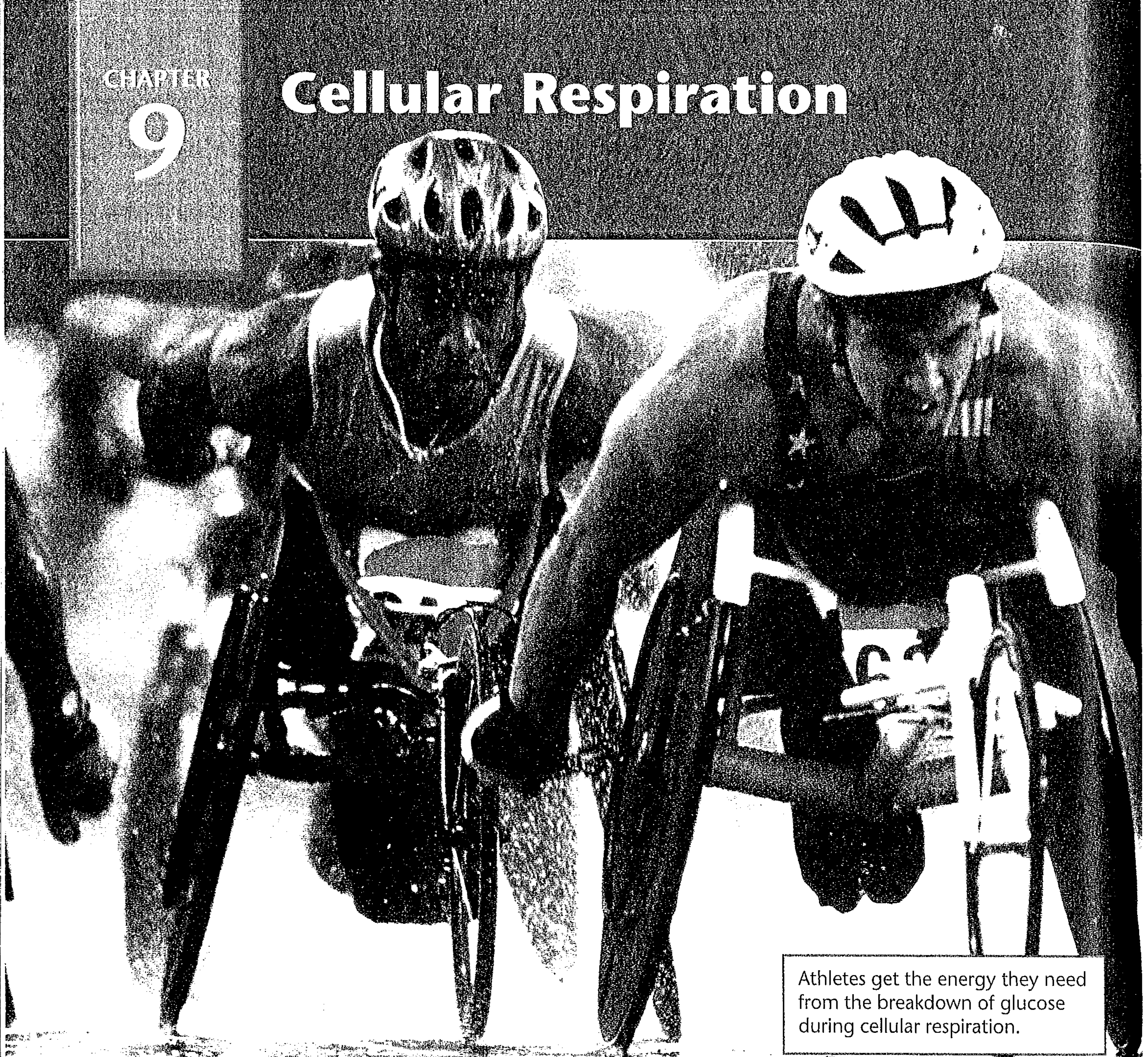
CHAPTER 9

Cellular Respiration



Athletes get the energy they need from the breakdown of glucose during cellular respiration.

Inquiry Activity

How do living things release energy?

Procedure

1. Draw a table with 5 rows and 4 columns. Label the columns from left to right: Item, Activities, Energy Source, and How Energy Is Released.
2. Fill in each row of your table for every item your teacher provides. List yourself as the last item and complete that row.

Think About It

1. **Using Tables and Graphs** Was it easier to describe how living things use energy or how nonliving things use energy?
2. **Using Tables and Graphs** What is the most common energy source for living things?
3. **Formulating Hypotheses** How do you think living things release the energy they need?

9–1 Chemical Pathways

When you are hungry, how do you feel? If you are like most people, your stomach may seem empty, you might feel a little dizzy, and above all, you feel weak. The sensations produced by hunger may vary, but the bottom line is always the same. Our bodies have a way of telling us when we need food.

Food provides living things with the chemical building blocks they need to grow and reproduce. Food serves as a source of raw materials for the cells of the body. Most of all, food serves as a source of energy.

Chemical Energy and Food

How much energy is actually present in food? Quite a lot, although it varies with the type of food, since our cells can use all sorts of molecules as food, including fats, sugars, and proteins. One gram of the sugar glucose ($C_6H_{12}O_6$), when burned in the presence of oxygen, releases 3811 calories of heat energy. 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 a kilocalorie, or 1000 calories. Cells, of course, don't "burn" glucose. Instead, they gradually release the energy from glucose and other food compounds.

This process begins with a pathway called **glycolysis** (gly-KAHL-ih-sis). Glycolysis releases only a small amount of energy. If oxygen is present, glycolysis leads to two other pathways that release a great deal of energy. If oxygen is not present, however, glycolysis is followed by a different pathway.

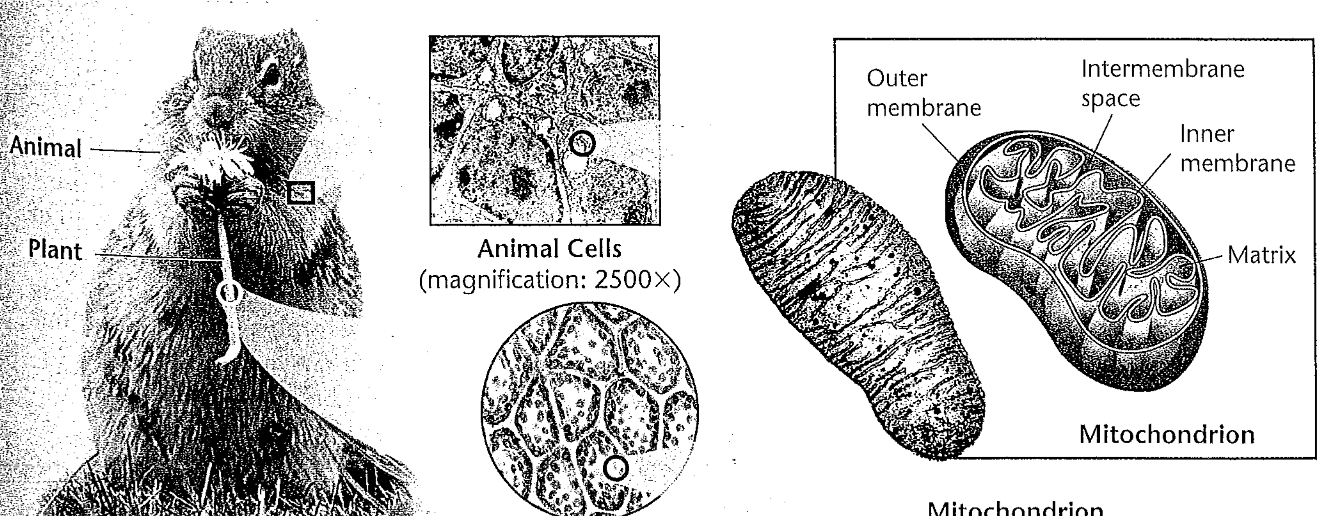
Guide for Reading

Key Concepts
- What is cellular respiration?
- What happens during the process of glycolysis?
- What are the two main types of fermentation?

Vocabulary
calorie
glycolysis
cellular respiration
NAD$^+$
fermentation
anaerobic

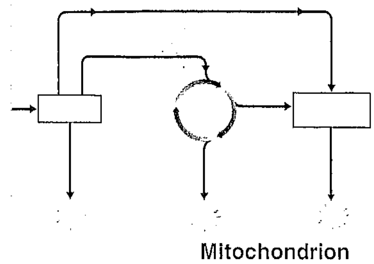
Reading Strategy: Asking Questions Before you read this section, rewrite the headings as *how, why,* or *what* questions about releasing energy. Then, as you read, write brief answers to your questions.

Figure 9–1 Living things get the energy they need from food. Both plant and animal cells carry out the final stages of cellular respiration in the mitochondria.



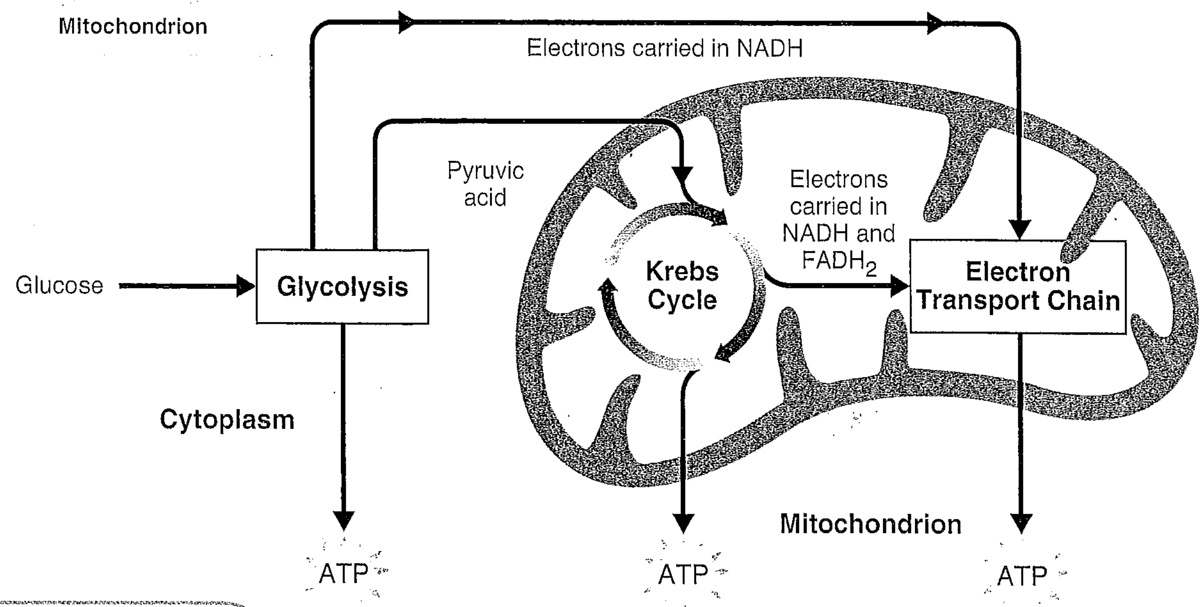
Plant Cells (magnification: 500×)

Mitochondrion
(magnification: about 10,000×)



CELLULAR RESPIRATION: AN OVERVIEW

Figure 9–2 Cellular respiration is the process that releases energy by breaking down food molecules in the presence of oxygen. Glycolysis takes place in the cytoplasm. The Krebs cycle and electron transport take place inside the mitochondria.



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Overview of Cellular Respiration

In the presence of oxygen, glycolysis is followed by the Krebs cycle and the electron transport chain. Glycolysis, the Krebs cycle, and the electron transport chain make up a process called **cellular respiration. Cellular respiration is the process that releases energy by breaking down glucose and other food molecules in the presence of oxygen.** The equation for cellular respiration is:

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

$$\text{oxygen} + \text{glucose} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

As you can see, cellular respiration requires oxygen, a food molecule such as glucose, and 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—it has to release the explosive chemical energy in food molecules a little bit at a time. The cell needs to find a way to trap those little bits of energy by using them to make ATP.

The three main stages of cellular respiration are shown in **Figure 9–2.** Each of the three stages captures some of the chemical energy available in food molecules and uses it to produce ATP.

Glycolysis

The first set of reactions in cellular respiration is glycolysis. **Glycolysis is the process in which one molecule of glucose is broken in half, producing two molecules of pyruvic acid, a 3-carbon compound.** The process of glycolysis is shown in **Figure 9–3.**

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 molecules of ATP are used up. In a way, those 2 ATP molecules are like an investment that pays back interest. In order to earn interest from a bank, first you have to put money into an account. Although the cell puts 2 ATP molecules into its "account" to get glycolysis going, when glycolysis is complete, 4 ATP molecules have been produced. This gives the cell a net gain of 2 ATP molecules.

NADH Production One of the reactions of glycolysis removes 4 high-energy electrons and passes them to an electron carrier called **NAD^+,** or nicotinamide adenine dinucleotide. Like $NADP^+$ in photosynthesis, each NAD^+ accepts a pair of high-energy electrons. This molecule, known as NADH, holds the electrons until they can be transferred to other molecules. By doing this, NAD^+ helps to pass energy from glucose to other pathways in the cell.

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. Besides speed, another advantage is that glycolysis itself does not require oxygen. This means that glycolysis can supply chemical energy to cells when oxygen is not available.

However, when a cell generates large amounts of ATP from glycolysis, it runs into a problem. In just a few seconds, all of the cell's available NAD^+ molecules are filled up with electrons. Without NAD^+, the cell cannot keep glycolysis going, and ATP production stops.

✓CHECKPOINT *What does glycolysis break down?*

Word Origins

Glycolysis comes from the Greek word *glukus,* meaning "sweet," and the Latin word *lysis,* which indicates a process of loosening or decomposing. Thus, *glycolysis* means "breaking glucose." **If *hydro* means "water," what do you think the term *hydrolysis* means?**

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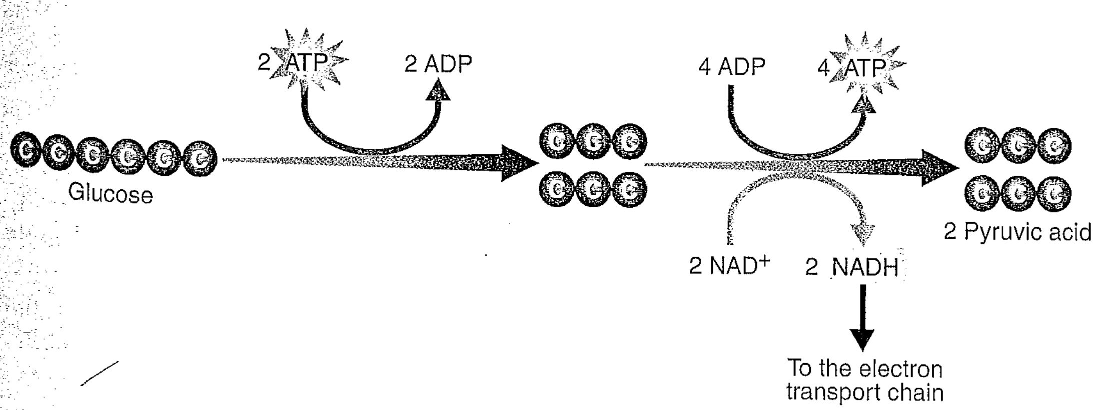
▼ **Figure 9–3** Glycolysis is the first stage in cellular respiration. **During glycolysis, glucose is broken down into 2 molecules of pyruvic acid.**



Fermentation

When oxygen is not present, glycolysis is followed by a different pathway. The combined process of this pathway and glycolysis is called fermentation. **Fermentation** releases energy from food molecules by producing ATP in the absence of oxygen.

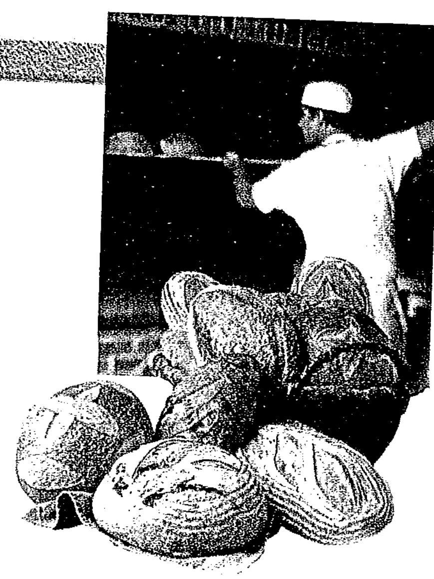
During fermentation, cells convert NADH to NAD^+ by passing high-energy electrons back to pyruvic acid. This action converts NADH back into the electron carrier NAD^+, allowing glycolysis to continue producing a steady supply of ATP. Because fermentation does not require oxygen, it is said to be **anaerobic.** The term *anaerobic* means "not in air." **The two main types of fermentation are alcoholic fermentation and lactic acid fermentation.**

Alcoholic Fermentation Yeasts and a few other microorganisms use alcoholic fermentation, forming ethyl alcohol and carbon dioxide as wastes. The equation for alcoholic fermentation after glycolysis is:

$$\textbf{pyruvic acid} + \textbf{NADH} \longrightarrow \textbf{alcohol} + \textbf{CO}_2 + \textbf{NAD}^+$$

Alcoholic fermentation produces carbon dioxide as well as alcohol. Alcoholic fermentation causes bread dough to rise. When yeast in the dough runs out of oxygen, it begins to ferment, giving off bubbles of carbon dioxide that 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.

Problem Solving



A Family Recipe

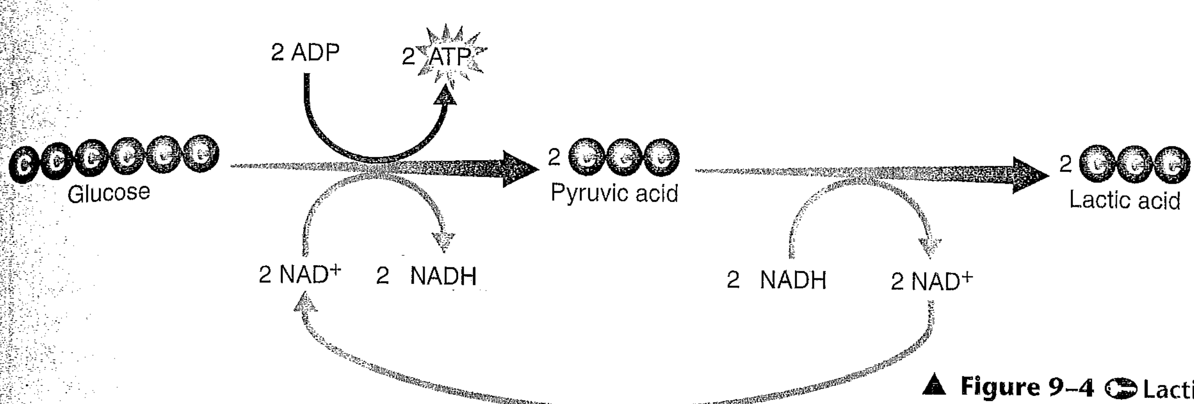
You have opened a bakery, selling bread made according to your family's favorite recipe. Unfortunately, most of your customers find your bread too heavy. You need to make your bread more appealing to your customers. Before bread is baked, yeast cells in the dough ferment some of the carbohydrate in the flour, producing bubbles of carbon dioxide. These bubbles cause the dough to rise and give bread its light, spongy structure. How can you make your bread lighter?

Defining the Problem In your own words, write down what problem you are trying to solve.

Organizing Information The process of fermentation is a series of chemical reactions catalyzed by enzymes. Review what you've learned about such reactions. Make a list of factors, such as temperature and the amounts of yeast and flour in the dough, that might affect the process of fermentation. Predict how each factor will affect the rate of fermentation.

Creating a Solution Write a detailed description of an experiment that could determine if changing the process of fermentation would make the bread lighter. Identify each of your variables. What controls and experimental treatments will you use?

Presenting Your Plan Make a poster showing the procedures in your proposed experiment and explain it to your classmates.



▲ **Figure 9–4** **Lactic acid fermentation converts glucose into lactic acid.** The first part of the equation is glycolysis. The second part shows the conversion of pyruvic acid to lactic acid.

Lactic Acid Fermentation In many cells, the pyruvic acid that accumulates as a result of glycolysis can be converted to lactic acid. Because this type of fermentation produces lactic acid, it is called lactic acid fermentation. This process regenerates NAD^+ so that glycolysis can continue, as shown in **Figure 9–4.** The equation for lactic acid fermentation after glycolysis is:

$$\text{pyruvic acid} + \text{NADH} \longrightarrow \text{lactic acid} + NAD^+$$

Lactic acid is produced in your muscles during rapid exercise when the body cannot supply enough oxygen to the tissues. Without enough oxygen, the body is not able to produce all of the ATP that is required. When you exercise vigorously by running, swimming, or riding a bicycle as fast as you can, the large muscles of your arms and legs quickly run out of oxygen. Your muscle cells rapidly begin to produce ATP by lactic acid fermentation. The buildup of lactic acid causes a painful, burning sensation. This is why muscles may feel sore after only a few seconds of intense activity.

Unicellular organisms also produce lactic acid as a waste product during fermentation. For example, prokaryotes are used in the production of a wide variety of foods and beverages, such as cheese, yogurt, buttermilk, and sour cream. Pickles, sauerkraut, and kimchi are also produced using lactic acid fermentation.

9–1 Section Assessment

1. **Key Concept** Describe the process of cellular respiration.
2. **Key Concept** What are the products of glycolysis?
3. **Key Concept** Name the two main types of fermentation.
4. What is a calorie? A Calorie?
5. How is the function of NAD^+ similar to that of $NADP^+$?
6. **Critical Thinking Comparing and Contrasting** How are lactic acid fermentation and alcoholic fermentation similar? How are they different?

Focus on the BIG Idea

Matter and Energy
Write the conversion of ADP to ATP as a chemical equation. What are the reactants and the product? You may wish to refer back to Chapter 2 to review chemical equations.

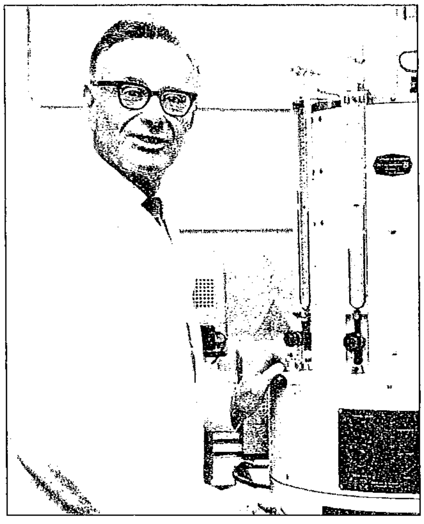
9–2 The Krebs Cycle and Electron Transport

Guide for Reading

Key Concepts
- What happens during the Krebs cycle?
- How are high-energy electrons used by the electron transport chain?

Vocabulary
aerobic
Krebs cycle
electron transport chain

Reading Strategy: Using Visuals Before you read, review **Figure 9–2** on page 222. Then, preview **Figures 9–6** and **9–7.** As you read, notice where the Krebs cycle and electron transport take place.



▲ **Figure 9–5** Hans Krebs won the Nobel Prize in 1953 for his discovery of the citric acid cycle, or Krebs cycle.

At the end of glycolysis, about 90 percent of the chemical energy that was available in glucose is still unused, locked in the high-energy electrons of pyruvic acid. To extract the rest of that energy, the cell turns to one of the world's most powerful electron acceptors—oxygen. Oxygen is required for the final steps of cellular respiration. Because the pathways of cellular respiration require oxygen, they are said to be **aerobic.**

As you know, the word *respiration* is often used as a synonym for breathing. This is why we have used the term *cellular respiration* to refer to energy-releasing pathways within the cell. The double meaning of respiration points out a crucial connection between cells and organisms: The energy-releasing pathways within cells require oxygen, and that is the reason we need to breathe, to respire.

The Krebs Cycle

In the presence of oxygen, pyruvic acid produced in glycolysis passes to the second stage of cellular respiration, the **Krebs cycle.** The Krebs cycle is named after 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.

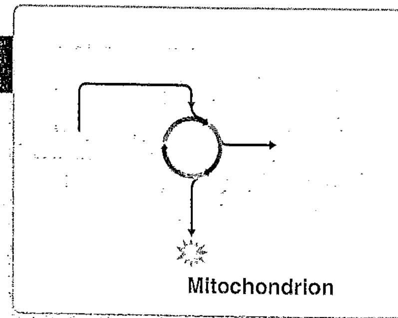
A The Krebs cycle begins when pyruvic acid produced by glycolysis enters the mitochondrion. One carbon atom from pyruvic acid becomes part of a molecule of carbon dioxide, which is eventually released into the air. The other two carbon atoms from pyruvic acid are joined to a compound called coenzyme A to form acetyl-CoA. (The acetyl part of acetyl-CoA is made up of 2 carbon atoms, 1 oxygen atom, and 3 hydrogen atoms.) Acetyl-CoA then adds the 2-carbon acetyl group to a 4-carbon molecule, producing a 6-carbon molecule called citric acid.

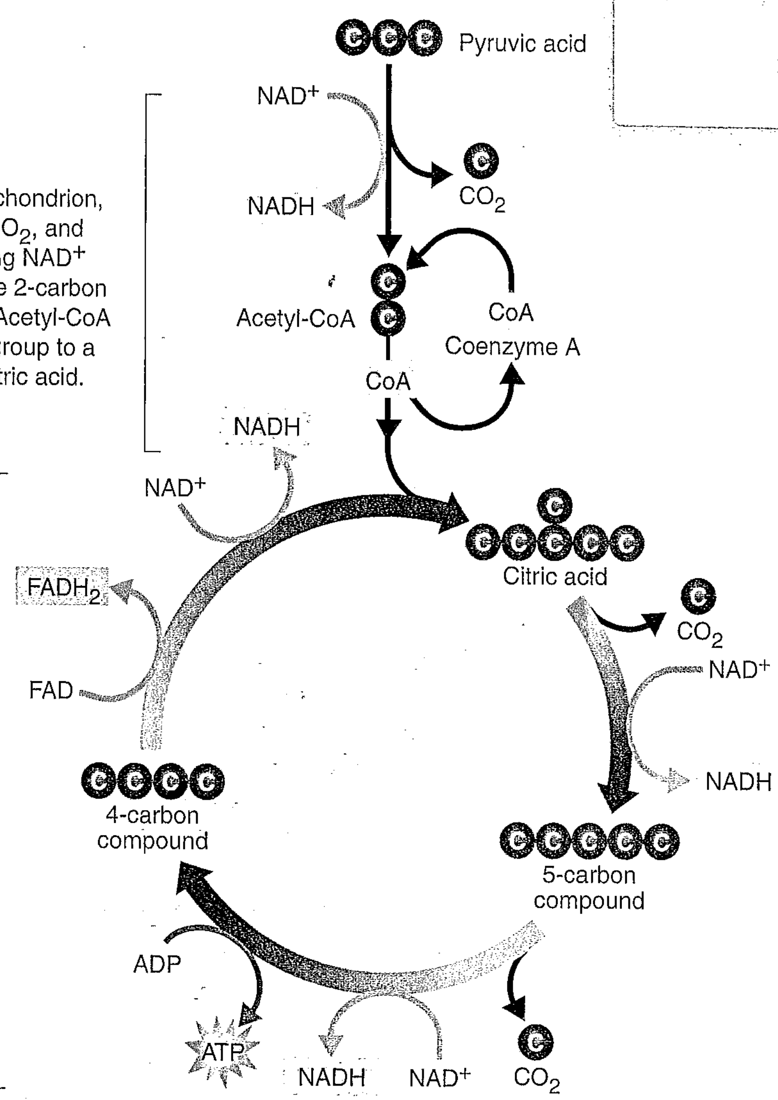
B As the cycle continues, citric acid is broken down into a 4-carbon molecule, more carbon dioxide is released, and electrons are transferred to energy carriers. Follow the reactions in **Figure 9–6,** and you will see how this happens. First, look at the 6 carbon atoms in citric acid. One is removed, and then another, releasing 2 molecules of carbon dioxide and leaving a 4-carbon molecule. This 4-carbon molecule is then ready to accept another 2-carbon acetyl group, which starts the cycle all over again.

Next, look for ATP. For each turn of the cycle, a molecule similar to ADP is converted to a molecule that is similar to ATP. Finally, look at the electron carriers, NAD^+ and FAD.

FIGURE 9–6 THE KREBS CYCLE

During the Krebs cycle, pyruvic acid from glycolysis is used to make carbon dioxide, NADH, ATP, and $FADH_2$.





A Citric Acid Production
As pyruvic acid enters the mitochondrion, a carbon is removed, forming CO_2, and electrons are removed, changing NAD^+ to NADH. Coenzyme A joins the 2-carbon molecule, forming acetyl-CoA. Acetyl-CoA then adds the 2-carbon acetyl group to a 4-carbon compound, forming citric acid.

B Energy Extraction
Citric acid is broken down into a 5-carbon compound, then into a 4-carbon compound. Along the way, two more molecules of CO_2 are released, and electrons join NAD^+ and FAD, forming NADH and $FADH_2$. In addition, one molecule of ATP is generated. The energy tally from one molecule of pyruvic acid is 4 NADH, 1 $FADH_2$, and 1 molecule of ATP.

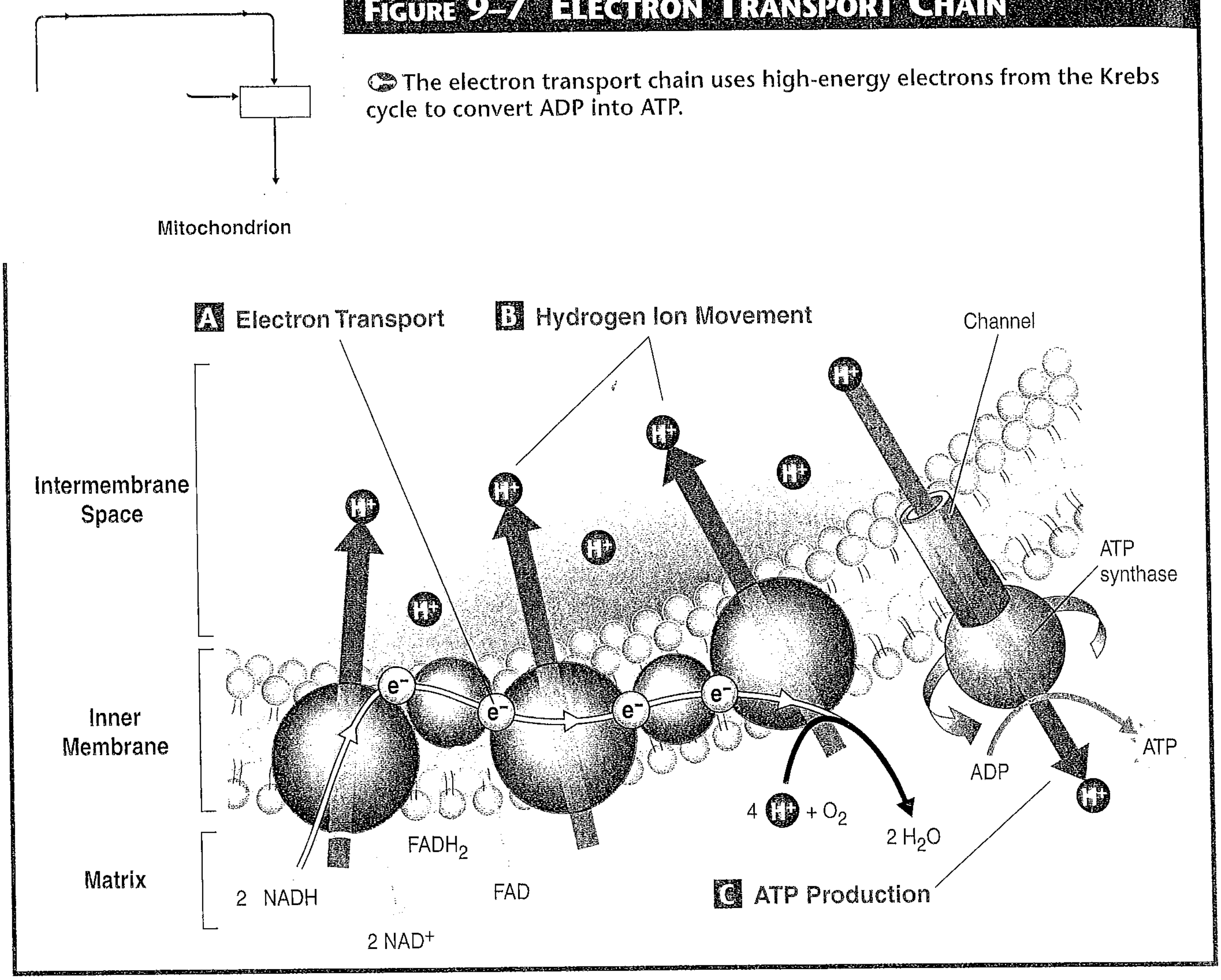
At five places in the cycle, a pair of high-energy electrons is accepted by electron carriers, changing NAD^+ to NADH and FAD to $FADH_2$. FAD (flavine adenine dinucleotide) and $FADH_2$ are molecules similar to NAD^+ and NADH, respectively.

What happens to each of these Krebs cycle products? First, the carbon dioxide released is the source of all the carbon dioxide in your breath. Every time you exhale, you expel the carbon dioxide produced by the Krebs cycle. Next, the ATP produced directly in the Krebs cycle can be used for cellular activities. However, what does the cell do with all those high-energy electrons in carriers like NADH? In the presence of oxygen, those high-energy electrons can be used to generate huge amounts of ATP.

CHECKPOINT *Why is the Krebs cycle also known as the citric acid cycle?*

Figure 9–7 Electron Transport Chain

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



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Electron Transport

The Krebs cycle generates high-energy electrons that are passed to NADH and $FADH_2$. The electrons are then passed from those carriers to the **electron transport chain.** **The electron transport chain uses the high-energy electrons from the Krebs cycle to convert ADP into ATP.** Look at **Figure 9–7** to see how this happens.

A High-energy electrons from NADH and $FADH_2$ are passed along the electron transport chain. In eukaryotes, the electron transport chain is composed of a series of carrier proteins 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 protein 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 serves as the final electron acceptor of the electron transport chain. Thus, oxygen is essential for getting rid of low-energy electrons and hydrogen ions, the wastes of cellular respiration.

B Every time 2 high-energy electrons transport 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. The other side of the membrane, from which those H^+ ions have been taken, is now negatively charged.

C How does the cell use the charge differences that build up as a result of electron transport? The inner membranes of the mitochondria contain protein spheres called ATP synthases. As H^+ ions escape through channels into these proteins, the ATP synthases spin. Each time it rotates, the enzyme grabs a low-energy ADP and attaches a phosphate, forming high-energy ATP.

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, producing 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 electron transport chain provides enough energy to produce three molecules of ATP from ADP.

✓CHECKPOINT *What is the role of ATP synthase in cellular respiration?*

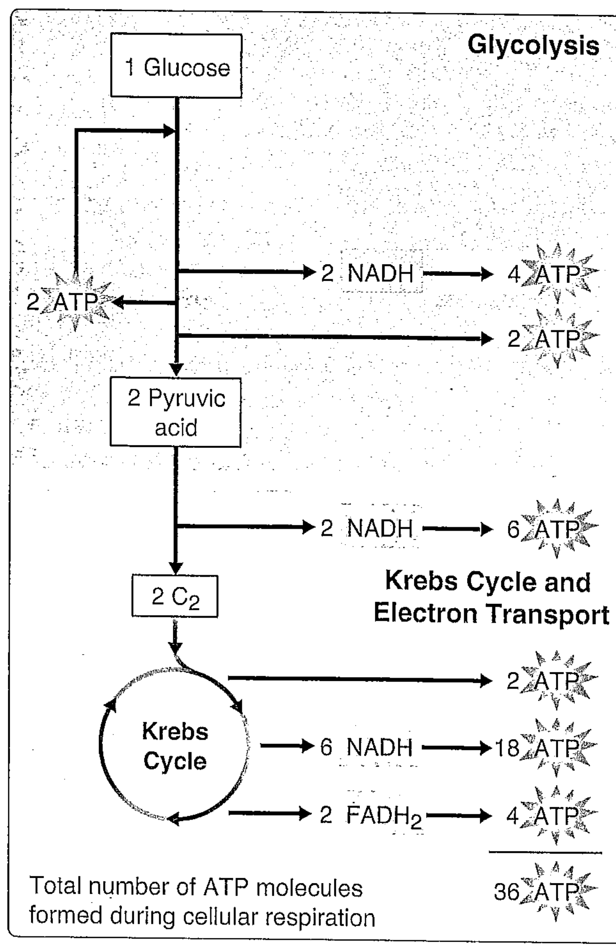
The Totals

Although glycolysis produces just 2 ATP molecules per molecule of glucose, in the presence of oxygen, everything changes. As **Figure 9–8** shows, the Krebs cycle and electron transport enable the cell to produce roughly 36 ATP molecules per glucose molecule, 18 times as much as can be generated in the absence of oxygen.

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 represent about 38 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 62 percent? It is released as heat, which is one of the reasons your body feels warmer after vigorous exercise.

▼ **Figure 9–8** The complete breakdown of glucose through cellular respiration, including glycolysis, results in the production of 36 molecules of ATP. **Interpreting Graphics** *How many molecules of ATP are produced during glycolysis?*



▲ **Figure 9–9** During a race, runners rely on the energy supplied by ATP to make it to the finish line. **Applying Concepts** *When runners begin a race, how do their bodies obtain energy?*

Energy and Exercise

Bang! The starter's pistol goes off, and the runners push off their starting blocks and sprint down the track. The initial burst of energy soon fades, and the runners settle down to a steady pace. After the runners hit the finish line, they walk around slowly and breathe deeply to catch their breath.

Let's look at what happens at each stage of the race in terms of the pathways the body uses to release energy. To obtain energy, the body uses ATP already in muscles and new ATP made by lactic acid fermentation and cellular respiration. At the beginning of a race, the body uses all three ATP sources, but stored ATP and lactic acid fermentation can only supply energy for a limited time.

Quick Energy What happens when your body needs lots of energy in a hurry? In response to sudden danger, quick actions might make the difference between life and death. To an athlete, a sudden burst of speed might win a race.

Cells normally contain small amounts of ATP produced during glycolysis and cellular respiration. When the starting gun goes off in a footrace, the muscles of the runners contain only enough of this ATP for a few seconds of intense activity. Before most of the runners have passed the 50-meter mark, that store of ATP is nearly gone. At this point, their muscle cells are producing most of their ATP by lactic acid fermentation. These sources can usually supply enough ATP to last about 90 seconds. In a 200- or 300-meter sprint, such as in **Figure 9–9**, this may be just enough to reach the finish line.

Fermentation produces lactic acid as a byproduct. When the race is over, the only way to get rid of lactic acid is in a chemical pathway that requires extra oxygen. For that reason, you can think of a quick sprint building up an oxygen debt that a runner has to repay after the race with plenty of heavy breathing.

Long-Term Energy What happens if a race is longer? How does your body generate the ATP it needs to run 2 kilometers or more, or to play in a soccer game that lasts more than an hour? For exercise longer than about 90 seconds, cellular respiration is the only way to generate a continuing supply of ATP. Cellular respiration releases energy more slowly than fermentation, which is why even well-conditioned athletes have to pace themselves during a long race or over the course of a game. Your body stores energy in muscle 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 why aerobic forms of exercise such as running, dancing, and swimming are so beneficial for weight control.

CHECKPOINT *Why do runners breathe heavily after a race?*

Quick Lab

How does exercise affect disposal of wastes from cellular respiration?

Materials 2 small test tubes, glass-marking pencil, 10-mL graduated cylinder, bromthymol blue solution, 2 straws, clock or watch with second hand

Procedure

1. **Predicting** Record your prediction of how exercise will affect your body's production of carbon dioxide.
2. If you are using a carbon dioxide probe, see your teacher for instructions.
3. Label two test tubes A and B. Put 10 mL of water and a few drops of bromthymol blue solution in each test tube. Carbon dioxide causes bromthymol blue to turn yellow or green.
4. Your partner will time you during this step. When your partner says "go," slowly blow air through a straw into the bottom of test tube A.
   CAUTION: *Do not inhale through the straw.*
5. When the solution changes color, your partner should say "stop," and then record how long the color change took.
6. Jog in place for 1 minute.
   CAUTION: *Do not do this if you have a medical condition that interferes with exercise. If you feel faint or dizzy, stop immediately and sit down.*
7. Repeat steps 4 and 5 using test tube B.
8. Trade roles with your partner. Repeat steps 3 through 7.

Analyze and Conclude

1. **Analyzing Data** How did exercise affect the time for the solution to change color? Did these results support your prediction?
2. **Inferring** What process in your body produces carbon dioxide? How does exercise affect this process?
3. **SAFETY** What safety procedures did you follow? Why were these procedures important?

Figure 9–10 Photosynthesis and cellular respiration can be thought of as opposite processes. **Comparing and Contrasting** *Exactly how is the equation for photosynthesis different from the equation for cellular respiration?*

Comparing Photosynthesis and Cellular Respiration

	Photosynthesis	Cellular Respiration
Function	Energy capture	Energy release
Location	Chloroplasts	Mitochondria
Reactants	CO_2 and H_2O	$C_6H_{12}O_6$ and O_2
Products	$C_6H_{12}O_6$ and O_2	CO_2 and H_2O
Equation	$6CO_2 + 6H_2O \xrightarrow{\text{Energy}} C_6H_{12}O_6 + 6O_2$	$6O_2 + C_6H_{12}O_6 \xrightarrow{\text{Energy}} 6CO_2 + 6H_2O$

Comparing Photosynthesis and Cellular Respiration

The energy flows in photosynthesis and cellular respiration take place in opposite directions. Earlier in this chapter, the chemical energy in carbohydrates was compared to money in a 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, shown in **Figure 9–10**, are the reverse of each other.

On a global level, photosynthesis and cellular respiration are also opposites. 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 release of energy by cellular respiration takes place in all eukaryotes and some prokaryotes. Energy capture by photosynthesis, however, occurs only in plants, algae, and some bacteria.

9–2 Section Assessment

1. **Key Concept** What happens to pyruvic acid during the Krebs cycle?
2. **Key Concept** How does the electron transport chain use the high-energy electrons from the Krebs cycle?
3. Why is cellular respiration considered to be much more efficient than glycolysis alone?
4. How many molecules of ATP are produced in the entire breakdown of glucose?
5. **Critical Thinking Comparing and Contrasting** Compare the energy flow in photosynthesis to the energy flow in cellular respiration.
6. **Critical Thinking Using Analogies** How is the chemical energy in glucose similar to money in a savings account?

Thinking Visually

Organizing Information
Using **Figure 9–6** and **Figure 9–7** as guides, prepare a poster showing the main events of the process of cellular respiration. For each event, show the reactant and products and where in the mitochondrion the event occurs. Use your poster to explain cellular respiration to a classmate.

ISSUES in Biology

Should Creatine Supplements Be Banned?

Many athletes now use a dietary supplement called creatine to enhance their performance. Creatine may improve athletic performance, but critics point to potentially serious side effects as a reason to control its use.

Although muscle cells contain only enough ATP for a few seconds of intense activity, most have a reserve nearly twice as large in the form of a molecule called creatine phosphate. When the muscle goes to work and starts to use up its available ATP, phosphates are transferred from creatine phosphate directly to ADP, regenerating ATP in a matter of milliseconds. The more creatine phosphate a muscle contains, the longer it can sustain intense activity. Hoping to increase their capacity for strong, short-term muscle contractions, many athletes have added creatine to their diets. Should athletes be allowed to use creatine supplements?

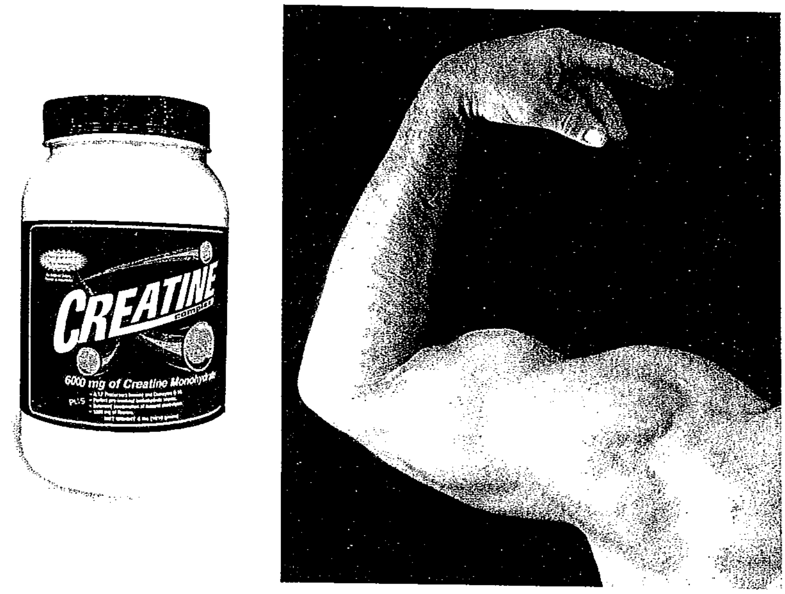
The Viewpoints

Creatine Supplements Should Be Allowed

Creatine is a natural substance found in human cells and in foods such as meat. Taken in recommended doses, creatine helps build muscle strength and performance, which can mean the difference between winning and losing. When athletes have followed instructions on container labels, no serious side effects have been reported. The risks are small and the rewards of winning are large enough to justify its use.

Creatine Supplements Should Be Banned

Like any natural substance, creatine can be abused. Creatine is known to cause water loss, putting the athletes who use it at risk for dehydration, muscle injury, diarrhea, kidney failure, and perhaps even death. Because creatine is considered a dietary supplement and not a drug, the Food and Drug Administration (FDA) has never determined its safety. Until a truly safe dose has been determined by careful scientific studies, athletes should not be allowed to use creatine.



Research and Decide

1. **Analyzing the Viewpoints** To make an informed decision, learn more about this issue by consulting library or Internet resources. Then, list the key arguments expressed by the proponents and critics of using creatine as a dietary supplement. What is known? What is not known? What are the benefits? What are the risks?
2. **Forming Your Opinion** Should athletes be allowed to take creatine to enhance performance? Weigh the pro and con arguments. Research to find out if some professional sports have banned the use of creatine by athletes. What were the reasons for this decision? Do some arguments outweigh others? Which arguments? Explain your answer.
3. **Writing an Editorial** Write an editorial for a sports magazine that takes a stand on creatine. Your editorial should persuade your readers that your opinion is justified.

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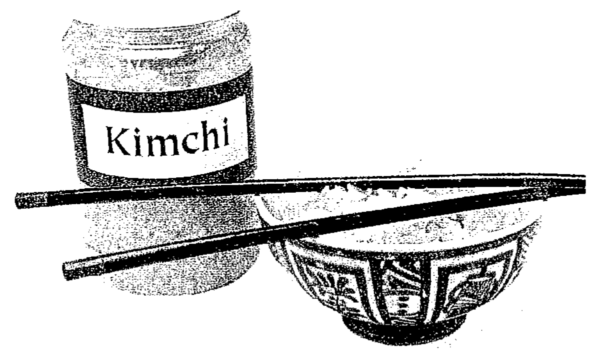
Real-World Lab

Investigating Fermentation by Making Kimchi

In this investigation, you will make a popular Korean side dish known as kimchi. Kimchi is made by allowing microorganisms to ferment Chinese cabbage. The main microorganism involved is a bacterium called Lactobacillus. *This bacterium mainly carries out lactic acid fermentation. Some species of* Lactobacillus *and other microorganisms on the cabbage carry out alcoholic fermentation. All of these microorganisms occur naturally on the surface of the Chinese cabbage. As these microorganisms ferment the Chinese cabbage, you will measure the chemical changes that occur during this process. You will use your knowledge of fermentation to explain the observations that you make.*



Problem
How does fermentation affect pH?

Materials
- 2 resealable plastic sandwich bags
- chopped Chinese cabbage
- noniodized salt
- 2.5-mL (1/2 teaspoon) measuring spoon
- pH-indicator paper
- thermometer

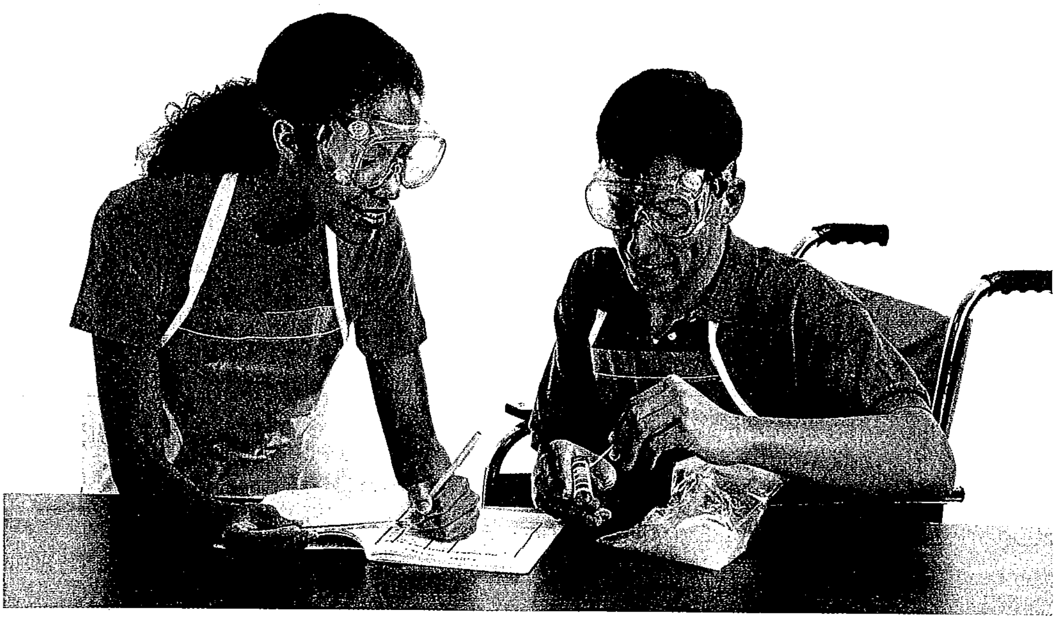
Skills
Predicting, Measuring, Drawing Conclusions

Procedure

1. **Formulating Hypotheses** Recall that pH is a measure of how acidic or basic a solution is. Bases have pH levels between 7 and 14, and acids have pH levels between 0 and 7. Formulate a hypothesis that explains how fermentation leads to changes in pH. Record your hypothesis and your prediction of how the pH of the kimchi will change over time as it ferments.
2. Put one resealable plastic bag inside the other. Half-fill the inner bag with chopped cabbage. Add 2.5 mL of salt. Seal both bags and turn them upside down several times to mix the ingredients.
3. Unseal the bags and press down on them to expel any air. Then, reseal the bags. Label the plastic bags containing the kimchi with your name and place them in a cool area where they will remain undisturbed. Copy the data table shown. Measure and record the air temperature in your copy of the data table. Wash your hands at the end of each lab period.
4. Each day, observe the kimchi in the bags. Record your observations of any changes in the appearance of the kimchi or the bags in your data table. When a small amount of liquid appears in the bottom of the inner bag, open the bags. **CAUTION:** *Do not eat the kimchi.*

Data Table

Day	pH	Temperature	Observations
1			
8			
15			
22			
29			



5 With your teacher's guidance, select the equipment and technology needed to measure pH—either pH-indicator paper or a pH probe. If you are using a pH probe, see your teacher for instructions.

6 Use pH-indicator paper to measure the pH of the liquid. Record the pH in your data table.

7 Press out any gas in the bags and reseal them. Return the bags to the cool area and leave them undisturbed for a week.

8 One week after you first measured the pH, repeat steps 6 and 7. Then, move the bags containing the kimchi to a refrigerator. Record the temperature of the refrigerator in your data table. Continue to observe the kimchi and record its pH every week for 4 weeks.

Analyze and Conclude

1. **Using Tables and Graphs** Use your data table to construct a graph showing the relationship between pH and time. With your teacher's guidance, select the appropriate equipment and technology—either graph paper or a graphing calculator. Describe how the pH of the kimchi changed over time.
2. **Inferring** What substance do you think was responsible for the change in pH? What process could have produced this substance?
3. **Evaluating and Revising** Was your prediction correct? What changes would you make in your hypothesis as a result of your observations?
4. **Inferring** Did you see any evidence that a gas was produced or consumed in the bags? If so, what was this gas? What process was responsible for this change? Explain the reasons for your answers.

Go Further

Designing Experiments Yogurt is made from milk using microorganisms that carry out lactic acid fermentation. Do research using scientific literature to form a hypothesis to determine how a factor, such as temperature or sugar concentration, affects the fermentation of yogurt. Your description should state your hypothesis, identify all variables, and explain how the outcome of the experiment could support or contradict your hypothesis.

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Share Your Data Online Enter your pH values in the data-sharing table online. Then, look at the data entered by other students. Based on the available data, how do you think a change in pH over time is related to fermentation? Why might your results differ from those of other students?

Chapter 9 Study Guide

9–1 Chemical Pathways

Key Concepts

- Cellular respiration is the process that releases energy by breaking down glucose and other food molecules in the presence of oxygen.
- Glycolysis is the process in which one molecule of glucose is broken in half, producing two molecules of pyruvic acid, a 3-carbon compound.
- Glycolysis captures two pairs of high-energy electrons with the carrier NAD^+. Because glycolysis does not require oxygen, it supplies chemical energy to cells when oxygen is not available.
- The two main types of fermentation are alcoholic fermentation and lactic acid fermentation.
- In the absence of oxygen, yeast and a few other microorganisms use alcoholic fermentation, forming ethyl alcohol and carbon dioxide as wastes.
- Animals cannot perform alcoholic fermentation, but some cells, such as human muscle cells, can convert glucose into lactic acid. This is called lactic acid fermentation.

Vocabulary
calorie, p. 221
glycolysis, p. 221
cellular respiration, p. 222
NAD^+, p. 223
fermentation, p. 224
anaerobic, p. 224

9–2 The Krebs Cycle and Electron Transport

Key Concepts

- 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 the Krebs cycle to convert ADP into ATP.
- The products of photosynthesis are similar to the reactants of cellular respiration. The products of cellular respiration are the reactants of photosynthesis.

Vocabulary
aerobic, p. 226
Krebs cycle, p. 226
electron transport chain, p. 228

Thinking Visually

Using the information in this chapter, complete the following compare-and-contrast table about fermentation and cellular respiration:

Comparing Fermentation and Cellular Respiration

Characteristic	Fermentation	Cellular Respiration
Starting reactants	1	2
Pathways involved	3	4
End products	5	6
Number of ATP molecules produced	7	8

Chapter 9 Assessment

Reviewing Content

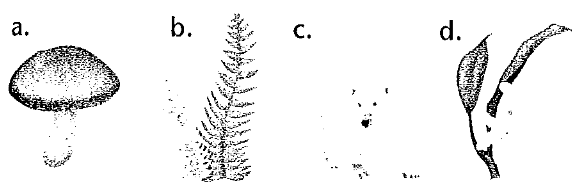
Choose the letter that best answers the question or completes the statement.

1. In cells, the energy available in food is used to make an energy-rich compound called
   a. water. c. ATP.
   b. glucose. d. ADP.

2. The first step in releasing the energy of glucose in the cell is known as
   a. alcoholic fermentation.
   b. glycolysis.
   c. the Krebs cycle.
   d. electron transport.

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. Which organisms perform cellular respiration?



   a. only c c. all of the above
   b. only a and c d. only a and b

5. The net gain of energy from glycolysis is
   a. 4 ATP molecules.
   b. 2 ATP molecules.
   c. 8 ADP molecules.
   d. 3 pyruvic acid molecules.

6. Because fermentation takes place in the absence of oxygen, it is said to be
   a. aerobic.
   b. anaerobic.
   c. cyclic.
   d. essential to oxygen production.

7. The Krebs cycle takes place within the
   a. chloroplast.
   b. nucleus.
   c. mitochondrion.
   d. cytoplasm.

8. The electron transport chain uses the high-energy electrons from the Krebs cycle to
   a. produce glucose.
   b. convert ADP to ATP.
   c. produce acetyl-CoA.
   d. produce GTP.

9. A total of 36 molecules of ATP are produced from 1 molecule of glucose as a result of
   a. cellular respiration.
   b. glycolysis.
   c. alcoholic fermentation.
   d. lactic acid fermentation.

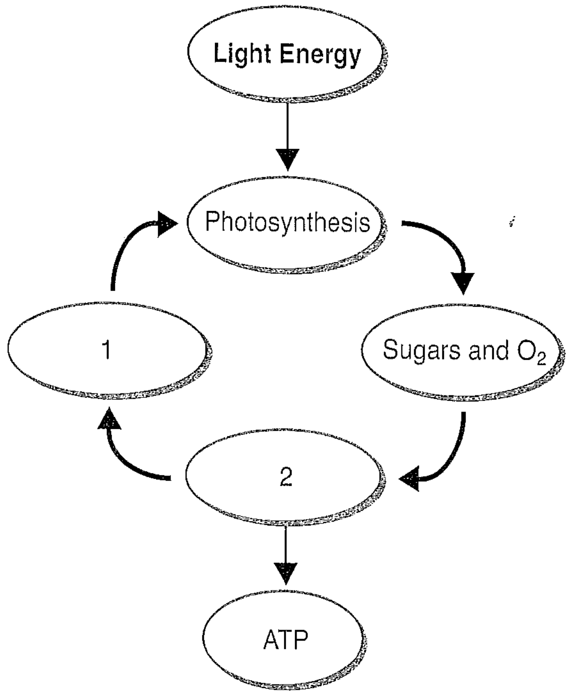
10. During heavy exercise, the buildup of lactic acid in muscle cells results in
    a. alcoholic fermentation.
    b. oxygen debt.
    c. the Calvin cycle.
    d. the Krebs cycle.

Understanding Concepts

11. What is a calorie? How do cells use a high-calorie molecule such as glucose?
12. How is glucose changed during glycolysis? What products are produced as a result of glycolysis?
13. What are the two pathways that might follow glycolysis? What factor can determine which of those pathways a cell might follow?
14. Use formulas to write a chemical equation for cellular respiration. Label the formulas with the names of the compounds.
15. Draw and label a mitochondrion surrounded by cytoplasm. Indicate where glycolysis, the Krebs cycle, and the electron transport chain occur.
16. How is NAD^+ involved in the products of glycolysis? What happens to a cell's NAD^+ when large numbers of high-energy electrons are produced in a short time?
17. Which two compounds react during fermentation? Which of these compounds passes high-energy electrons to the other?
18. Write equations to show how lactic acid fermentation compares with alcoholic fermentation. Which reactant(s) do they have in common?
19. How are fermentation and cellular respiration similar? What is the main difference between their starting compounds?
20. Summarize what happens during the Krebs cycle. What happens to the high-energy electrons generated during the Krebs cycle?
21. How is ATP synthase involved in making energy available to the cell?
22. When runners race for about 20 minutes, how do their bodies obtain energy?

Critical Thinking

23. **Interpreting Graphics** Complete the following concept map showing the flow of energy in photosynthesis and cellular respiration.



24. **Comparing and Contrasting** Where is the electron transport chain found in a eukaryotic cell? In a prokaryotic cell?
25. **Inferring** Certain types of bacteria thrive in conditions that lack oxygen. What does that fact indicate about the way they obtain energy?
26. **Predicting** In certain cases, regular exercise causes an increase in the number of mitochondria in muscle cells. How might that situation improve an individual's ability to perform energy-requiring activities?
27. **Formulating Hypotheses** 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.
28. **Designing Experiments** 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.
29. **Inferring** 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?
30. **Applying Concepts** Carbon monoxide (CO) molecules bring the electron transport chain in a mitochondrion to a stop by binding to an electron carrier. Use this information to explain why carbon monoxide gas kills organisms.

Focus on the BIG Idea

Matter and Energy In Chapter 3, you learned that certain substances are involved in chemical cycles. Draw a sketch that illustrates how cellular respiration fits into one of those cycles.

Writing in Science

Expand the analogy of deposits and withdrawals of money that was used in the chapter to write a short paragraph to explain cellular respiration. (*Hint:* You may wish to start out making a compare-and-contrast table that lists the similarities and differences between the two items.)

Performance-Based Assessment

Creating Diagrams Make one or more diagrams with labels or captions to show how two athletes get energy when the first athlete runs for 30 seconds and the second athlete runs for 20 minutes. How are the processes similar? How are they different? Be sure to show whether the energy is produced by an aerobic process or by an anaerobic process.

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Standardized Test Prep

Test-Taking Tip When you are asked to analyze a graph showing experimental data, first look at the shape of the curve. Identify the variables and try to determine how they are related. Then, read and answer the questions that relate to the graph.

Directions: Choose the letter that best answers the question or completes the statement.

1. What raw materials are needed for cellular respiration?
(A) glucose and carbon dioxide
(B) glucose and oxygen
(C) carbon dioxide and oxygen
(D) oxygen and lactic acid
(E) carbon dioxide and water

2. What happens during the Krebs cycle?
(A) Hydrogen ions and oxygen form water.
(B) The cell releases a small amount of energy through fermentation.
(C) Each glucose molecule is broken down into two molecules of pyruvic acid.
(D) Hydrogen ions build up on one side of the mitochondrial membrane.
(E) Pyruvic acid is broken down into carbon dioxide in a series of reactions.

3. Which substance is needed to begin the process of glycolysis?
(A) ATP
(B) NADP
(C) NADH
(D) pyruvic acid
(E) carbon dioxide

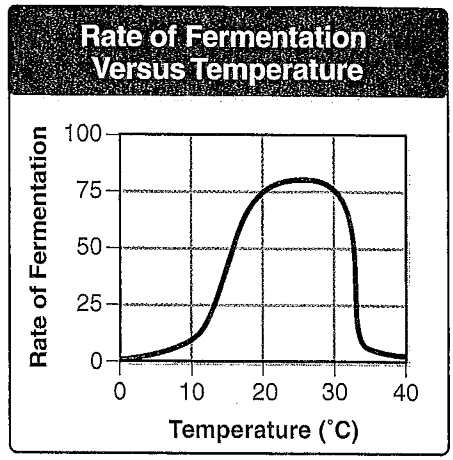
4. In eukaryotic cells, most of cellular respiration takes place in the
(A) nuclei.
(B) cytoplasm.
(C) mitochondria.
(D) cell walls.
(E) centrioles.

5. What substance produced by alcoholic fermentation makes bread dough rise?
(A) oxygen
(B) lactic acid
(C) carbon dioxide
(D) water
(E) alcohol

6. The human body can use all of the following as energy sources EXCEPT
(A) ATP in muscles.
(B) glycolysis.
(C) lactic acid fermentation.
(D) alcoholic fermentation.
(E) cellular respiration.

7. Which of the following best represents the waste products of cellular respiration?
(A) CO_2
(B) H_2O
(C) O_2
(D) CO_2 and H_2O
(E) CO_2 and O_2

Questions 8–9 The graph below shows the rate of alcoholic fermentation for yeast at different temperatures.



8. What is the relationship between the rate of fermentation and temperature?
(A) The rate of fermentation continually increases as temperature increases.
(B) The rate of fermentation continually decreases as temperature increases.
(C) The rate of fermentation increases with temperature, then it rapidly decreases.
(D) The rate of fermentation decreases with temperature, then it increases.
(E) There is no relationship between the rate of fermentation and temperature.

9. Which statement could explain the data shown in the graph?
(A) The molecules that regulate fermentation perform optimally at temperatures above 30°C.
(B) The yeast begins releasing carbon dioxide at 30°C.
(C) The yeast cannot survive at temperatures above 30°C.
(D) The molecules that regulate fermentation perform optimally below 10°C.
(E) The yeast cannot survive at temperatures below 30°C.