9 Cellular Respiration and Fermentation

Big idea Cellular Basis of Life

Q: How do organisms obtain energy?

9.1 Cellular Respiration: An Overview

Key Questions

Where do organisms get energy?

What is cellular respiration?

What is the relationship between photosynthesis and cellular respiration?

Vocabulary

calorie • cellular respiration • aerobic • anaerobic

Taking Notes

Preview Visuals Before you read, study **Figure 9–2** on page 252. Make a list of questions that you have about the diagram. As you read, write down the answers to the questions.

BUILD Vocabulary

PREFIXES The prefix *macro-* means "large" or "elongated." Macromolecules are made up of many smaller molecular subunits. Carbohydrates, proteins, and lipids are important macromolecules found in living things.

THINK ABOUT IT When you are hungry, how do you feel? If you are like most people, you might feel sluggish, a little dizzy, and—above all—weak. Weakness is a feeling triggered by a lack of energy. You feel weak when you are hungry because food serves as a source of energy. Weakness is your body's way of telling you that your energy supplies are low. But how does food get converted into a usable form of energy? Car engines have to burn gasoline in order to release its energy. Do our bodies burn food the way a car burns gasoline, or is there something more to it?

Chemical Energy and Food

Where do organisms get energy?

Food provides living things with the chemical building blocks they need to grow and reproduce. Recall that some organisms, such as plants, are autotrophs, meaning that they make their own food through photosynthesis. Other organisms are heterotrophs, meaning that they rely on other organisms for food. For all organisms, 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 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 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 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 triglyceride fats found in beef releases 8893 calories of heat energy when its bonds are broken. In general, carbohydrates and proteins contain approximately 4000 calories (4 Calories) of energy per gram, while fats contain approximately 9000 calories (9 Calories) per gram.

Cells, of course, don't simply burn food and release energy as heat. Instead, they break down food molecules gradually, capturing a little bit of chemical energy at key steps. This enables cells to use the energy stored in the chemical bonds of foods like glucose to produce compounds such as ATP that directly power the activities of the cell.

Analyzing Data

MATH

You Are What You Eat

Organisms get energy from the food they eat, but the energy contained in foods varies greatly. Most foods contain a combination of proteins, carbohydrates, and fats. One gram of protein or a carbohydrate such as glucose contains roughly 4 Calories. One gram of fat, however, contains about 9 Calories. The accompanying table shows the approximate composition of one serving of some common 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
Skinless roasted turkey, 3 slices	11	3	1

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. **Calculate** 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. **Calculate** Walking at a moderate pace consumes around 300 Calories per hour. At that rate, how many minutes would you have to walk to burn the Calories in one chocolate bar? (*Hint:* Start by calculating the number of Calories consumed per minute by walking.)

Overview of Cellular Respiration

What is cellular respiration?

If oxygen is available, organisms can obtain energy from food by a process called **cellular respiration.** **Cellular respiration is the process 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:

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

In Words:

Oxygen + Glucose ⟶ Carbon dioxide + Water + Energy

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. The cell needs to find a way to trap those little bits of energy by using them to make ATP.

FIGURE 9–1 A Controlled Release Cellular respiration involves a series of controlled reactions that slowly release the energy stored in food. If the energy were to be released too suddenly, most of it would be lost in the forms of light and heat—just as it is when a marshmallow catches fire.

In Your Notebook *Do plants undergo cellular respiration? What organelle(s) do they have that helps you determine the answer?*

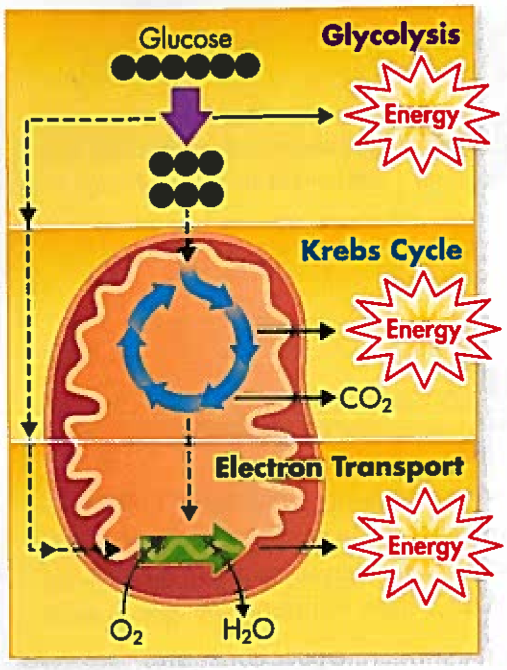

FIGURE 9–2 The Stages of Cellular Respiration There are three stages to cellular respiration: glycolysis, the Krebs cycle, and the electron transport chain. **Interpret Visuals** ***Which stage(s) of cellular respiration occur in the mitochondrion?***

Stages of Cellular Respiration

Cellular respiration captures the energy from food in three main stages—glycolysis, the Krebs cycle, and the electron transport chain. 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 (gly KAHL ih sis). Only a small amount of 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 chemical bonds of a molecule called pyruvic (py ROO vik) 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 generated. 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 9–2.** 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. 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: Most of the energy-releasing pathways within cells require oxygen, and that is the reason we need to breathe, to respire.

Pathways of cellular respiration that require oxygen are said to be **aerobic** ("in air"). The Krebs cycle and 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.

Recall that mitochondria are structures in the cell that convert chemical energy stored in food to usable energy for the cell. Glycolysis actually occurs in the cytoplasm of a cell, but 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.

MYSTERY CLUE

If whales remain underwater for 45 minutes or more, do you think they rely primarily on aerobic or anaerobic pathways?

In Your Notebook *Make a flowchart that shows the different steps of cellular respiration.*

Comparing Photosynthesis and Cellular Respiration

What is the relationship between 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? Where does all of the carbon dioxide waste product go? How does the chemical energy stored in food get replaced? As it happens, cellular respiration is balanced by another process: photosynthesis. The energy in photosynthesis and cellular respiration flows in opposite directions. Look at **Figure 9–3** and think of the chemical energy in carbohydrates as money in the 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.

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 nearly all life: plants, animals, fungi, protists, and most bacteria. Energy capture by photosynthesis, however, occurs only in plants, algae, and some bacteria.

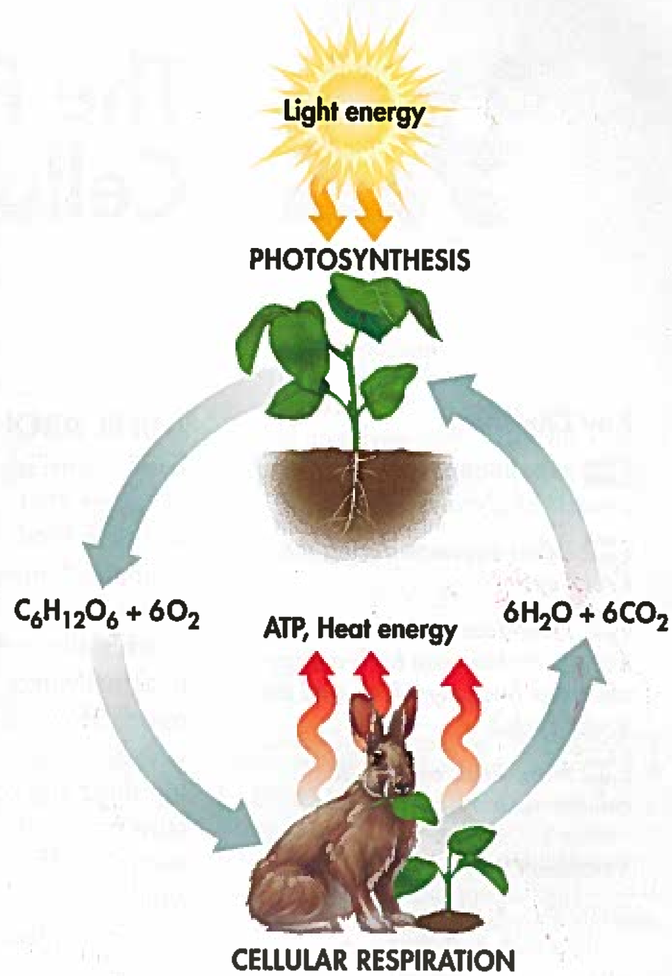

FIGURE 9–3 Opposite Processes Photosynthesis and cellular respiration can be thought of as opposite processes. **Compare and Contrast** ***Exactly how is the equation for photosynthesis different from the equation for cellular respiration?***

9.1 Assessment

Review Key Concepts

1. a. **Review** Why do all organisms need food?
   b. **Relate Cause and Effect** Why do macromolecules differ in the amount of energy they contain?
2. a. **Review** Write the overall reaction for cellular respiration.
   b. **Apply Concepts** How does the process of cellular respiration maintain homeostasis at the cellular level?
3. a. **Review** In what ways are cellular respiration and photosynthesis considered opposite processes?
   b. **Use Analogies** How is the chemical energy in glucose similar to money in a savings account?

BUILD VOCABULARY

4. The Greek word *glukus* means "sweet," and the Latin word *lysis* refers to a process of loosening or decomposing. Based on this information, write a definition for the word *glycolysis*.

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9.2 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 energy does cellular respiration generate?***

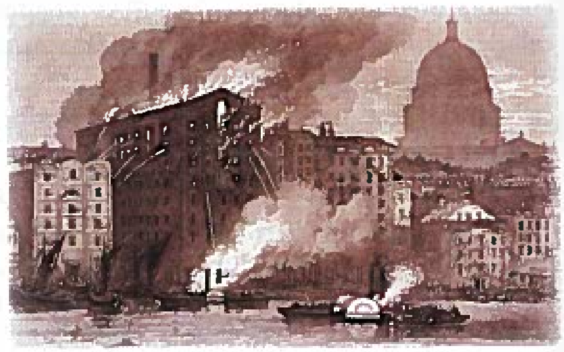
Vocabulary

glycolysis • NAD⁺ •
Krebs cycle • matrix

Taking Notes

Compare/Contrast Table As you read, make a compare/contrast table showing the location, starting reactants, and end products of glycolysis, the Krebs cycle, and the electron transport chain. Also include how many molecules of ATP are produced in each step of the process.

THINK ABOUT IT



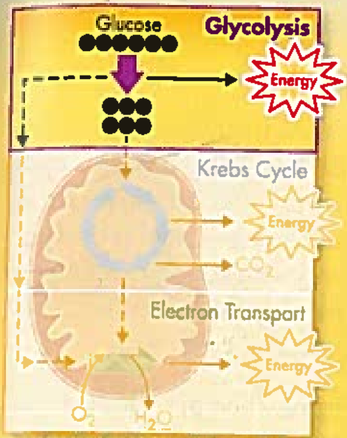
Food burns! It's true, of course, that many common foods (think of apples, bananas, and ground beef) have too much water in them to actually light with a match. However, foods with little water, including sugar and cooking oil, will indeed burn. In fact, flour, which contains both carbohydrates and protein, is so flammable that it has caused several explosions, including the one seen here at London's City Flour Mills in 1872 (which is why you're not supposed to store flour above a stove). So, plenty of energy is available in food, but how does a living cell extract that energy without setting a fire or blowing things up?

Glycolysis

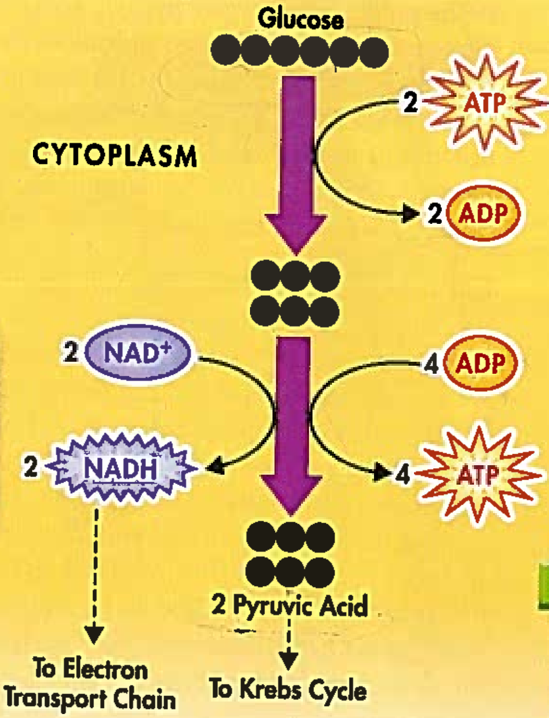
🔑 ***What happens during the process of glycolysis?***

The first set of reactions in cellular respiration is known as **glycolysis**, a word that literally means "sugar-breaking." Glycolysis involves many chemical steps that transform glucose. The end result is 2 molecules of a 3-carbon molecule called pyruvic acid. 🔑 **During glycolysis, 1 molecule of glucose, a 6-carbon compound, is transformed into 2 molecules of pyruvic acid, a 3-carbon compound.** As the bonds in glucose are broken and rearranged, energy is released. The process of glycolysis can be seen in **Figure 9–4.**

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 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. 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, 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
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.

ZOOMING IN

GLYCOLYSIS

FIGURE 9–4 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. **Interpret Visuals** ***How many carbon atoms are there in glucose? How many carbon atoms are in each molecule of pyruvic acid?***

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. 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.

In Your Notebook *In your own words, describe the advantages of glycolysis to the cell in terms of energy production.*

BUILD Vocabulary

ACADEMIC WORDS The verb **synthesize** means "to bring together as a whole." Therefore, a molecule of ATP is synthesized when a phosphate group combines with the molecule ADP, forming a high-energy bond.

MYSTERY CLUE

The urge to surface and gasp for breath when underwater is a response to CO_2 buildup in the blood. The average human can hold his or her breath for only about a minute. Whales stay underwater for much longer. What does this suggest about a whale's tolerance of CO_2?

The Krebs Cycle

What happens during 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.

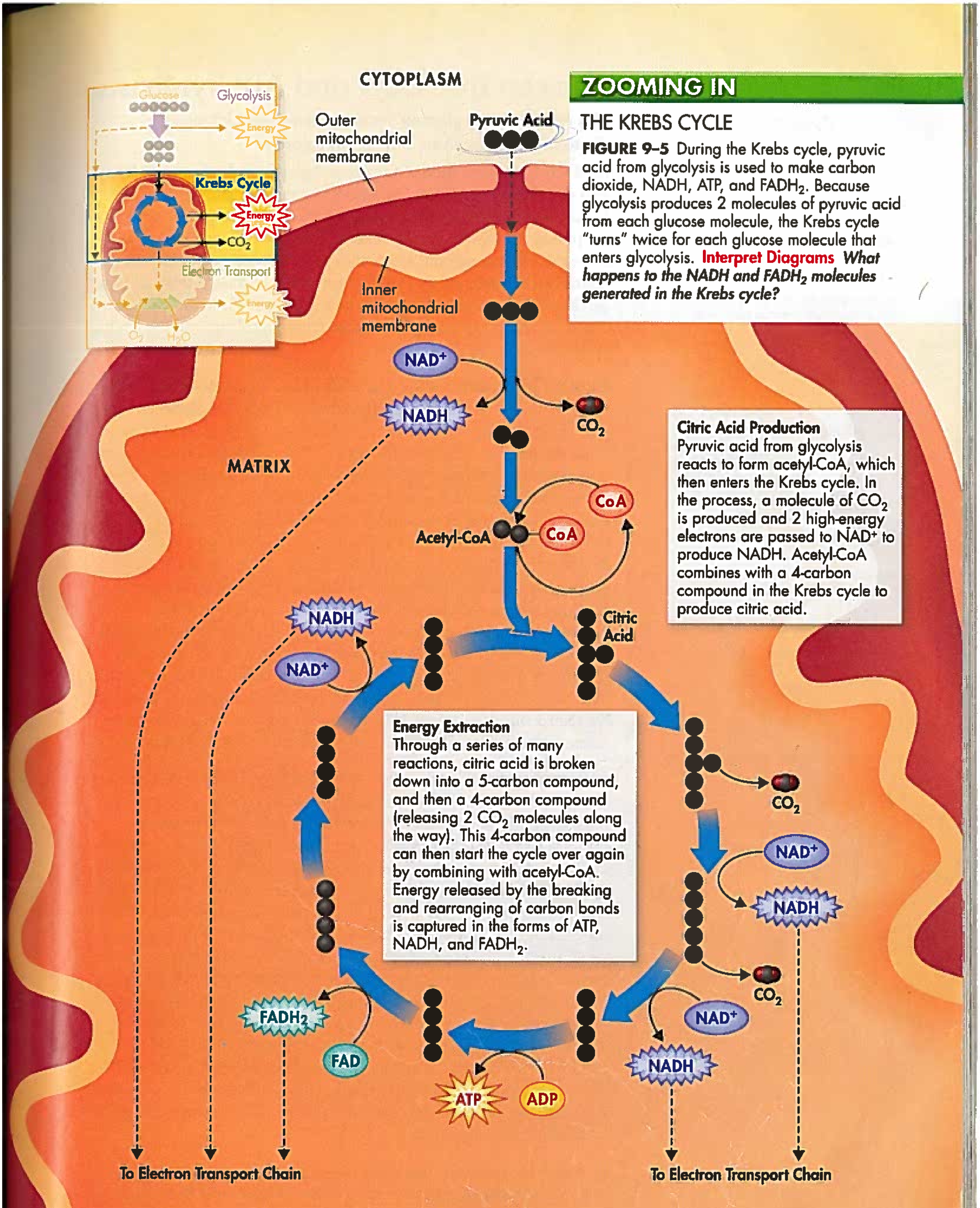
Citric Acid Production The Krebs cycle begins when pyruvic acid produced by glycolysis passes through the two membranes of the mitochondrion and into the matrix. The **matrix** is the innermost compartment of the mitochondrion and the site of the Krebs cycle reactions. Once inside the matrix, 1 carbon atom from pyruvic acid becomes part of a molecule of carbon dioxide, which is eventually released into the air. The other 2 carbon atoms from pyruvic acid rearrange and form acetic acid, which is joined to a compound called coenzyme A. The resulting molecule is called acetyl-CoA. (The acetyl part of acetyl-CoA is made up of 2 carbon atoms, 1 oxygen atom, and 3 hydrogen atoms.) As the Krebs cycle begins, acetyl-CoA adds the 2-carbon acetyl group to a 4-carbon molecule already present in the cycle, producing a 6-carbon molecule called citric acid.

Energy Extraction 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 9–5** 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. 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, electron carriers accept a pair of high-energy electrons, changing NAD^+ to NADH and FAD to $FADH_2$. FAD and $FADH_2$ are molecules similar to NAD^+ and NADH, respectively.

What happens to each of these Krebs cycle products—carbon dioxide, ATP, and electron carriers? Carbon dioxide is not useful to the cell and is expelled every time you exhale. The ATP molecules are *very* useful and become 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.

In Your Notebook *List the electron carriers involved in the Krebs cycle. Include their names before and after they accept the electrons.*



ZOOMING IN

THE KREBS CYCLE

FIGURE 9–5 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. **Interpret Diagrams** ***What happens to the NADH and $FADH_2$ molecules generated in the Krebs cycle?***

Electron Transport and ATP Synthesis

How does the electron transport chain use high-energy electrons from glycolysis and the Krebs cycle?

Products from both the Krebs cycle and glycolysis feed into the last step of cellular respiration, the electron transport chain, as seen in **Figure 9–6.** 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 $FADH_2$ 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 convert ADP into ATP.**

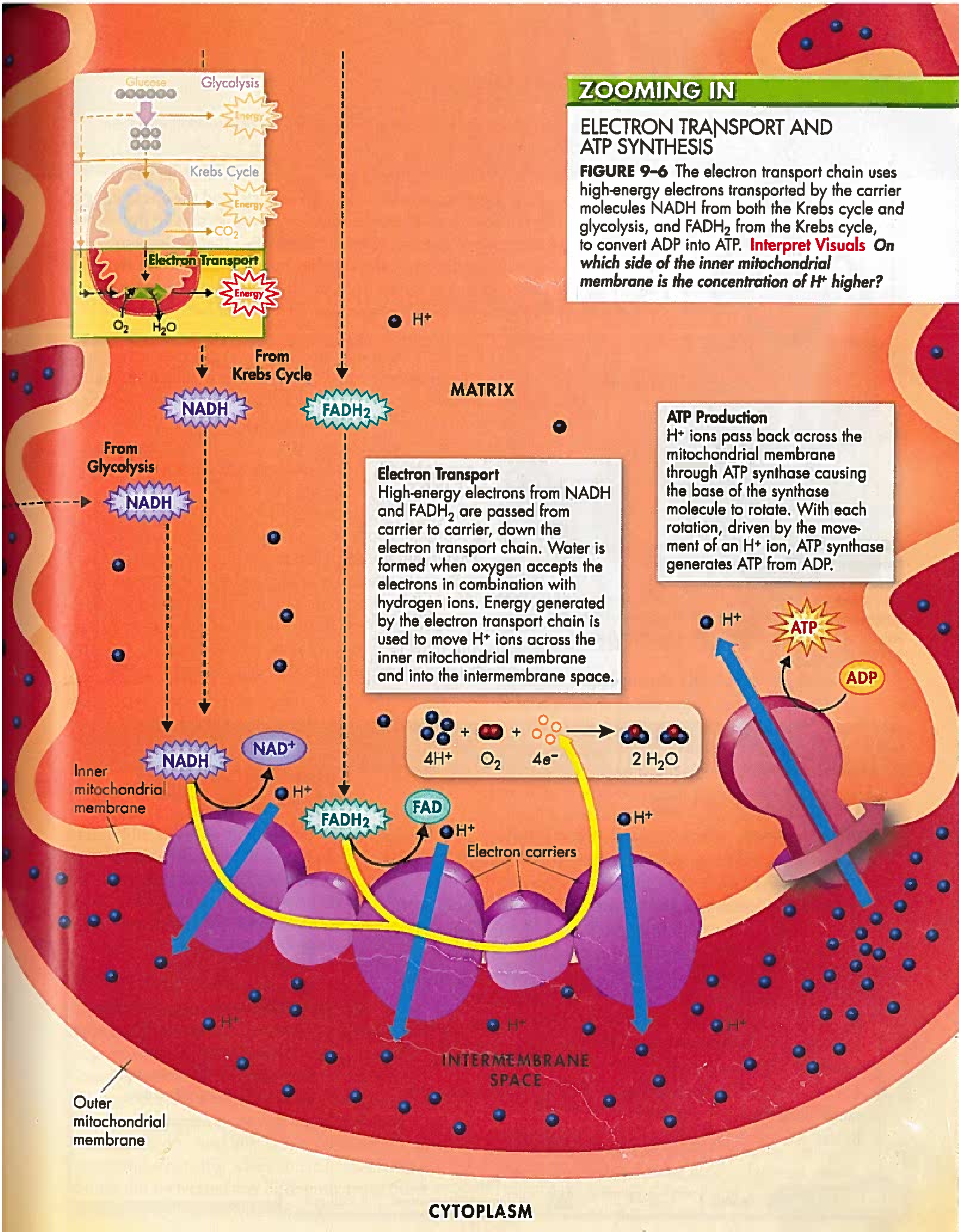
Electron Transport NADH and $FADH_2$ pass their high-energy electrons to the electron transport chain. In eukaryotes, the electron transport chain is composed of a series of electron carriers located in the inner membrane of the mitochondrion. In prokaryotes, the same chain is in the cell membrane. High-energy 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 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. Without oxygen, 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. Similarly, the matrix side of the membrane, from which those H^+ ions have been taken, is now negatively charged compared to the intermembrane space.

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.

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.

In Your Notebook *Relate the importance of oxygen in cellular respiration to the reason you breathe faster during intense exercise.*



ZOOMING IN

ELECTRON TRANSPORT AND ATP SYNTHESIS

FIGURE 9–6 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. **Interpret Visuals** ***On which side of the inner mitochondrial membrane is the concentration of H^+ higher?***

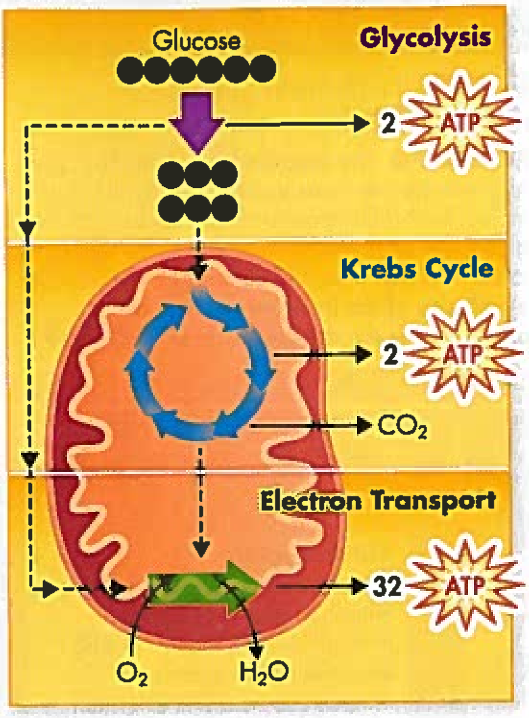


FIGURE 9–7 Energy Totals The complete breakdown of glucose through cellular respiration results in the production of 36 molecules of ATP. **Calculate** ***How many times more energy is produced by all three stages of cellular respiration than by glycolysis alone?*** MATH

The Totals

How much energy does cellular respiration generate?

Although 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 9–7** that under aerobic conditions these pathways enable the cell to produce 18 times as much energy as can be generated by anaerobic glycolysis alone (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 37°C day and night.

9.2 Assessment

Review Key Concepts

1. **a. Review** What are the products of glycolysis?
   b. Compare and Contrast How is the function of NAD^+ similar to that of $NADP^+$?
2. **a. Review** What happens to pyruvic acid in the Krebs cycle?
   b. Interpret Visuals Look at **Figure 9–5** and list the products of the Krebs cycle. What happens to each of these products?
3. **a. Review** How does the electron transport chain use the high-energy electrons from glycolysis and the Krebs cycle?
   b. Relate Cause and Effect How does the cell use the charge differences that build up across the inner mitochondrial membrane during cellular respiration?
4. **a. Review** How many molecules of ATP are produced in the entire breakdown of glucose?
   b. Use Analogies How is the cell like a furnace?

Apply the Big idea

Cellular Basis of Life

5. As you have learned, cellular respiration is a process by which cells transform energy stored in the bonds of food molecules into the bonds of ATP. What does the body do with all of the ATP this process generates? Review the characteristics of life in Chapter 1 and explain why ATP is necessary for each life process.

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Biology & Society

Should Creatine Supplements Be Regulated?

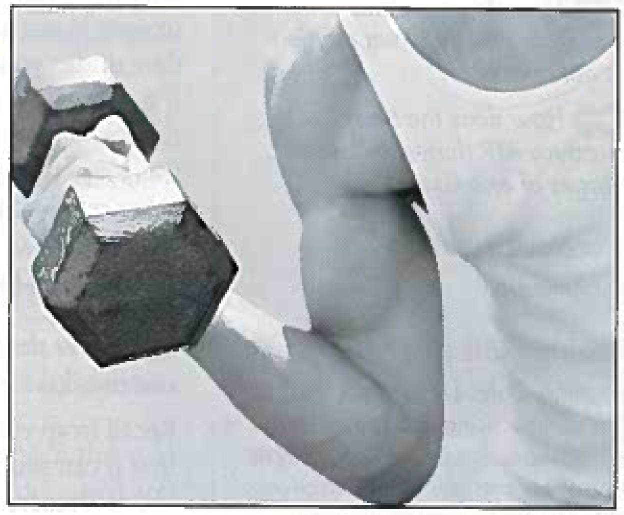
ATP is the chemical compound that gives muscles the energy to contract, but the amount of ATP in most muscle cells is only enough for a few seconds of activity. Muscle cells have a chemical trick, however, that enables them to sustain maximum effort for several more seconds. They attach phosphate groups to a compound called creatine. As they contract, the cells quickly transfer phosphate from creatine to ADP, producing enough ATP to keep working. The creatine phosphate in skeletal muscles effectively doubles or triples the amount of ATP available for intense exercise.

If a little creatine is good, then more creatine would be even better, right? That's what many athletes think and that's why they take creatine supplements. Some studies do suggest that creatine may increase the body's capacity for strong, short-term muscle contractions. As a reason to regulate the use of creatine, however, critics point to potentially serious side effects—such as liver and kidney damage—when creatine is overused.

Because creatine occurs naturally in the body and in foods, testing for creatine use is nearly impossible; so, creatine is *not* banned in major sports leagues. However, due to a lack of long-term studies, the NCAA prohibits coaches from giving creatine to college athletes. Some schools argue that creatine should be banned altogether.

The Viewpoints

Creatine Supplements Should Not Be Regulated Taken in recommended doses, creatine helps build muscle strength and performance. Creatine supplements may help athletes train longer and build strength. No serious side effects have been reported in people who follow the instructions on container labels. Of course, anything can be harmful when abused, but creatine should not be treated any differently from other substances such as caffeine or sugar.



Creatine Supplements Should Be Regulated
Scientists know that creatine can cause severe health problems when abused. But even when used properly, creatine is known to cause some problems, such as dehydration and stomach upset. There have been no studies on creatine use by people younger than 18, and there are no good studies of its long-term effects. For these reasons, creatine supplements should be regulated like cigarettes and alcohol—no one under the age of 18 should be allowed to buy them, and schools should have the right to regulate or prohibit their use by athletes.

Research and Decide

1. Analyze the Viewpoints Learn more about this issue by consulting library or Internet resources. Then, list the key arguments of the proponents and critics of creatine use.

2. Form an Opinion Should creatine be regulated? Research examples of high schools or colleges that have banned creatine use by athletes. What were the reasons for these decisions? Do you agree with them?

9.3 Fermentation

Key Questions

How do organisms generate energy when oxygen is not available?

How does the body produce ATP during different stages of exercise?

Vocabulary

fermentation

Taking Notes

Outline Before you read, make an outline using the green and blue headings in the text. As you read, fill in notes under each heading.

BUILD Vocabulary

RELATED WORD FORMS The noun **fermentation** and the verb *ferment* are related word forms. Dough that is beginning to ferment is just starting to undergo the process of fermentation.

THINK ABOUT IT We are air-breathing organisms, and we use oxygen to release chemical energy from the food we eat. But what if oxygen is not around? What happens when you hold your breath and dive under water, or use up oxygen so quickly that you cannot replace it fast enough? Do your cells simply stop working? And, what about microorganisms that live in places where oxygen is not available? Is there a pathway that allows cells to extract energy from food in the absence of oxygen?

Fermentation

How do organisms generate energy when oxygen is not available?

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. 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 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 followed 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.**

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 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, as seen in **Figure 9–8.**

In Your Notebook *Make a compare/contrast table in which you compare alcoholic fermentation to lactic acid fermentation.*

Alcoholic Fermentation Yeasts and a few other microorganisms use alcoholic fermentation, which produces ethyl alcohol and carbon dioxide. A summary of alcoholic fermentation after glycolysis is

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

Alcoholic fermentation is used to produce alcoholic beverages. It is also the process that causes bread dough to rise. When yeast cells in the dough run out of oxygen, the dough begins to ferment, 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.

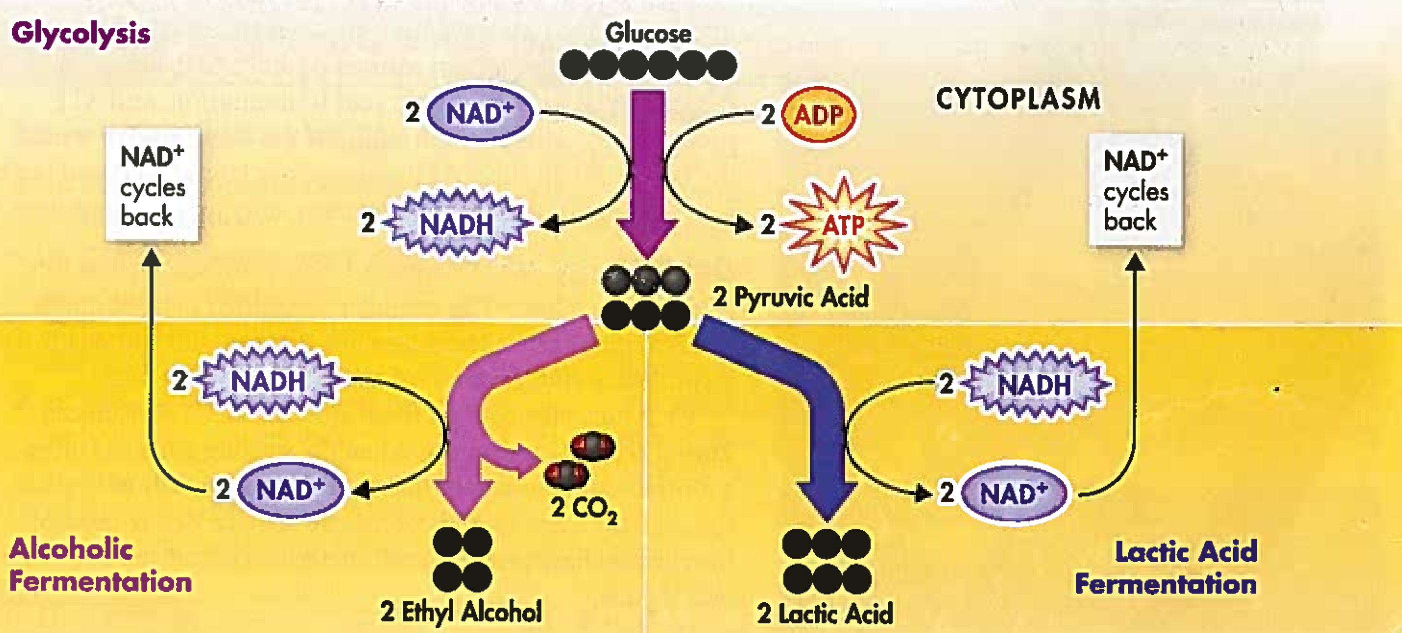
Lactic Acid Fermentation Most organisms carry out fermentation using a chemical reaction that converts pyruvic acid to lactic acid. Unlike alcoholic fermentation, lactic acid fermentation does not give off carbon dioxide. However, like alcoholic fermentation, lactic acid fermentation also regenerates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

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

Certain bacteria that produce lactic acid as a waste product during fermentation are important to industry. For example, prokaryotes are used in the production of a wide variety of foods and beverages—such as cheese, yogurt, buttermilk, and sour cream—to which the acid contributes the familiar sour taste. Pickles, sauerkraut, and kimchi are also produced using lactic acid fermentation.

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

FIGURE 9–8 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. **Compare and Contrast** ***What reactants and products do the two types of fermentation have in common?***



Quick Lab
GUIDED INQUIRY

How Does Exercise Affect Disposal of Wastes From Cellular Respiration?

❶ 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.

❷ 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.*

❸ When the solution changes color, your partner should say "stop" and then record how long the color change took.

❹ Jog in place for 2 minutes. **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.*

❺ Repeat steps 2–4 using test tube B.

❻ Trade roles with your partner. Repeat steps 1 through 5.

Analyze and Conclude

1. **Analyze Data** How did exercise affect the time it took the solution to change color?

2. **Infer** What process in your body produces carbon dioxide? How does exercise affect this process?

Energy and Exercise

How does the body produce ATP during different stages of exercise?

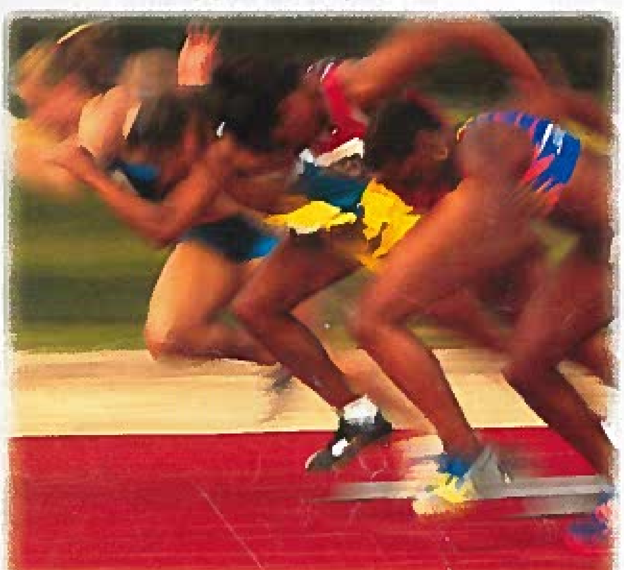
Bang! The starter's pistol goes off, and the runners push off their starting blocks and sprint down the track, as seen in **Figure 9–9.** The initial burst of energy soon fades, and the runners settle down to a steady pace. After the runners hit the finish line, they walk around slowly and breathe deeply 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. Humans have three main sources of ATP: ATP already in muscles, ATP made by lactic acid fermentation, and ATP produced by cellular respiration. At the beginning of a race, the body uses all three ATP sources, but stored ATP and lactic acid fermentation can supply energy only 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 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.

FIGURE 9–9 Exercise and Energy During a race, runners rely on the energy supplied by ATP to make it to the finish line. **Apply Concepts** *At the beginning of a race, what is the principal source of energy for the runners' muscles?*



At this point, the runners' muscle cells are producing most of their ATP by lactic acid fermentation, which can usually supply enough ATP to last about 90 seconds. In a 200- or 300-meter sprint, 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 as building up an oxygen debt that a runner has to repay with plenty of heavy breathing after the race. An intense effort that lasts just 10 or 20 seconds 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.**

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 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. 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. Some organisms, like the bear in **Figure 9–10**, count on energy stored in fat to get them through long periods without food.

MYSTERY CLUE

Whales rely on lactic acid fermentation for much of their energy requirements during a deep dive. If they can't inhale to repay their oxygen debt, what are they doing with all of the lactic acid produced by fermentation?

FIGURE 9–10 Energy Storage Hibernating animals like this brown bear in Alaska rely on stored fat for energy when they sleep through the winter. **Predict** ***How will this bear look different when it wakes up from hibernation?***

9.3 Assessment

Review Key Concepts

1. a. **Review** Name the two main types of fermentation.
   b. **Compare and Contrast** How are alcoholic fermentation and lactic acid fermentation similar? How are they different?
2. a. **Review** Why do runners breathe heavily after a sprint race?
   b. **Sequence** List the body's sources of energy in the order in which they are used during a long-distance race.

PRACTICE PROBLEM

3. You have opened a bakery, selling bread made according to your family's secret recipe. Unfortunately, most customers find the bread too heavy. Review what you have learned about chemical reactions in Chapter 2 and make a list of factors such as temperature that might affect the enzyme-catalyzed fermentation reaction involved in baking bread. Predict how each factor will affect the rate of fermentation and propose a solution for making the bread lighter by adding more bubbles to your family bread recipe.

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