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.

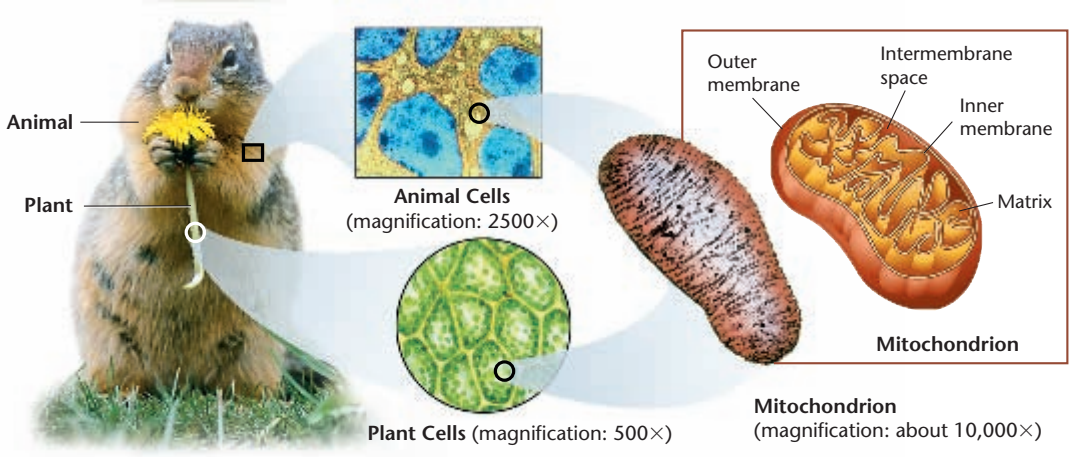
Guide for Reading

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.



SECTION RESOURCES

Print:
- ***Teaching Resources,*** Lesson Plan 9–1, Adapted Section Summary 9–1, Adapted Worksheets 9–1, Section Summary 9–1, Worksheets 9–1, Section Review 9–1, Enrichment
- ***Reading and Study Workbook A,*** Section 9–1
- ***Adapted Reading and Study Workbook B,*** Section 9–1
- ***Biotechnology Manual,*** Lab 1
- ***Probeware Lab Manual,*** Investigating Fermentation by Making Kimchi
- ***Lab Worksheets,*** Chapter 9 Real-World Lab

Technology:
- ***iText,*** Section 9–1
- ***Animated Biological Concepts DVD,*** 13 Glycolysis
- ***Transparencies Plus,*** Section 9–1
- ***Lab Simulations CD-ROM,*** Cell Respiration

Section 9–1

1 FOCUS

Objectives
9.1.1 ***Explain*** what cellular respiration is.
9.1.2 ***Describe*** what happens during the process of glycolysis.
9.1.3 ***Name*** the two main types of fermentation.

Guide for Reading

Vocabulary Preview
Call on volunteers to pronounce the section's Vocabulary words. Correct any mispronunciations, and then have all students pronounce each word together.

Reading Strategy
Students should write a question for each head and subhead. For example, they might write, "How are chemical energy and food related?" Encourage students to write an answer to each question as they read the section.

2 INSTRUCT

Chemical Energy and Food

Use Visuals
Figure 9–1 Ask: **Would it be correct to say that only animal cells contain mitochondria?** *(No; both plant and animal cells contain mitochondria.)* Help students recall from Chapter 7 that all eukaryotic cells contain mitochondria, including plant and algal cells. Ask: **How is this cell organelle separated from the cytoplasm of the cell?** *(By an outer membrane)* **How would you describe the inner mitochondrial membrane?** *(It is convoluted, with many turns and folds.)* **What is the space between the inner and outer membranes called?** *(Intermembrane space)* L1 L2

Overview of Cellular Respiration

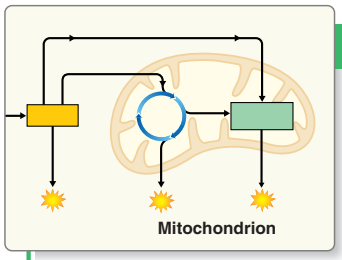
Build Science Skills

Applying Concepts To reinforce where important reactions take place within cells, draw a large cell on the board. Within the cell, draw a nucleus, a chloroplast, and a mitochondrion. Then, ask students to point to and identify where in the cell photosynthesis occurs *(chloroplast)*, glycolysis occurs *(cytoplasm)*, and cellular respiration occurs *(mitochondrion)*. L1 L2

Use Visuals

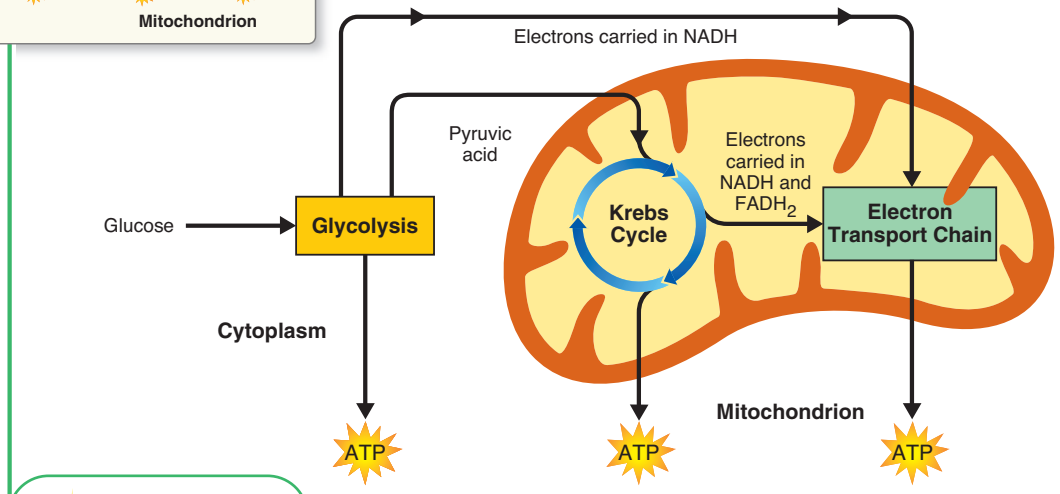
Figure 9–2 Have students study the figure. Then, ask: **Where does the glucose used in respiration come from?** *(Cells obtain glucose mainly by breaking down carbohydrates such as starch.)* **How do you know that this series of reactions occurs in the presence of oxygen?** *(If there were no oxygen present, then fermentation would occur, not cellular respiration.)* **What does glycolysis supply to the Krebs cycle and to the electron transport chain?** *(It supplies pyruvic acid to the Krebs cycle and high-energy electrons via NADH to the electron transport chain.)* **What stages of cellular respiration occur in mitochondria?** *(The Krebs cycle and the electron transport chain)* L1 L2

Go Online
active art
For: Cellular Respiration activity
Visit: PHSchool.com
Web Code: cbe-3091
Students interact with the process of cellular respiration.



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:

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

oxygen + glucose ⟶ carbon dioxide + water + 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.

ESL Support for English Language Learners

Comprehension: Ask Questions

Beginning Write the chemical equation for cellular respiration on the board. Place labels under each of the molecules in the reaction, as shown on page 222. Read the equation aloud, pointing to the chemical symbols and the corresponding words as you do so. Explain the equation. Then, ask the students questions that can be answered orally or by pointing at the correct answer. For example, "What is one product of cellular respiration?" When students answer correctly, reinforce their comprehension by repeating the word they said or, if they pointed, saying the word aloud yourself. L1

Intermediate After students complete the beginning-level activity, ask questions that cannot be answered directly from the information on the board, for example, "What part of the equation represents the food you ate (will eat) at lunch today?" L2

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.

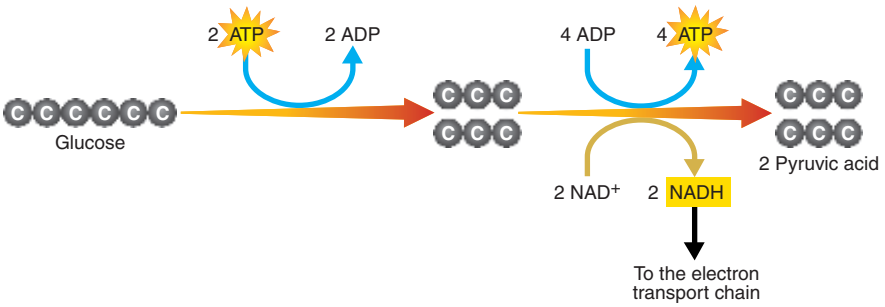
However, when a cell generates large amounts of ATP from glycolysis, it runs into a problem. In just a few seconds, all of the cell's available NAD^+ molecules are filled up with electrons. Without NAD^+, the cell cannot keep glycolysis going, and ATP production stops.

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?**

Go Online NSTA SCILINKS
For: Links on cellular respiration
Visit: www.SciLinks.org
Web Code: cbn-3091



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

TEACHER TO TEACHER

When I introduce cellular respiration to students, I take a novel approach that sounds "off the wall," but it works. We first look at the overall equation for cellular respiration. I have the students take note of the products, and then we work backward. With this approach, I find that my students come away with a greater understanding of the total process and also have greater retention of the basic concepts. I also do a fermentation lab with my students using a variety of juices, including orange, grape, prune, apple, pineapple, and even diet cola. In addition, we make breads using different sugars and compare the weights of the resulting doughs. (CO_2 is a heavy gas.)

—Greg McCurdy
Biology Teacher
Salem High School
Salem, IN

Glycolysis

Word Origins

Hydrolysis means "breaking down water." L2

Build Science Skills

Using Analogies Some students may not be familiar with interest-bearing bank savings accounts. To clarify the analogy used in the text, show students a bank statement of a savings account. Point out that a person has to deposit money into the account in order to earn interest, just as a cell must put 2 ATPs into the "account" to earn the interest of additional ATPs. L2 L3

Use Visuals

Figure 9–3 Have students study the process of glycolysis. Remind students that the cell must expend energy to get the process going. Ask: **Where in the figure does it show that the cell is using energy to start glycolysis?** *(During the breakdown of glucose, 2 molecules of ATP change to 2 molecules of ADP.)* Have a volunteer point out where in the process 2 NAD^+ molecules accept electrons. Then, ask: **NAD^+ is an electron carrier in this process. What is an electron carrier?** *(An electron carrier is a compound that can accept a pair of high-energy electrons and transfer them along with most of their energy to another molecule.)* **Glycolysis is an energy-releasing process. Where in this figure does it show energy being released?** *(On the right side of the figure, 4 ATP molecules are produced from 4 ADP molecules using the energy released from the breakdown of the glucose molecule.)* L1

Go Online NSTA SCILINKS
Download a worksheet on cellular respiration for students to complete, and find additional teacher support from NSTA SciLinks.

Answer to . . .

CHECKPOINT *Glycolysis breaks down a molecule of glucose into 2 molecules of pyruvic acid.*

Fermentation

Build Science Skills

Comparing and Contrasting Display to students a piece of leavened bread and a piece of unleavened bread. Ask: **What is the difference between the two breads?** *(The unleavened bread is thinner than the leavened bread and has no holes, while the leavened bread is thicker than the unleavened bread and has little holes in it.)* Explain that *leaven* means "to raise," and so *unleavened* bread is bread that didn't rise when baked. Ask: **What was added to the leavened bread that made it rise?** *(Yeast)* **What process did the yeast carry out that caused the bread to rise?** *(Alcoholic fermentation)* L1 L2

Problem Solving

Bread recipes are often precise about ingredients, though where and how to allow the dough to rise is often left up to the cook. Students may focus on the amount of yeast or flour, or they may want to focus on the conditions of the place where the dough is left to rise. This activity might be more appropriate for small groups than for individual students. L2 L3

Defining the Problem A typical definition of the problem: How can the production of bubbles of carbon dioxide be increased during the making of bread?

Organizing Information Students should know that temperature affects the action of enzymes and that temperature affects the processes of living things such as yeast. They should also understand that the amount of food available for a living thing to use will affect the outcome. Students should write a prediction for each factor listed.

Creating a Solution A typical experiment might identify temperature as the manipulated variable.

Presenting Your Plan Encourage students to include as many details as possible on their posters. Allow time for students or groups to present their experiments to the class.

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:

$$\text{pyruvic acid} + \text{NADH} \longrightarrow \text{alcohol} + CO_2 + NAD^+$$

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.

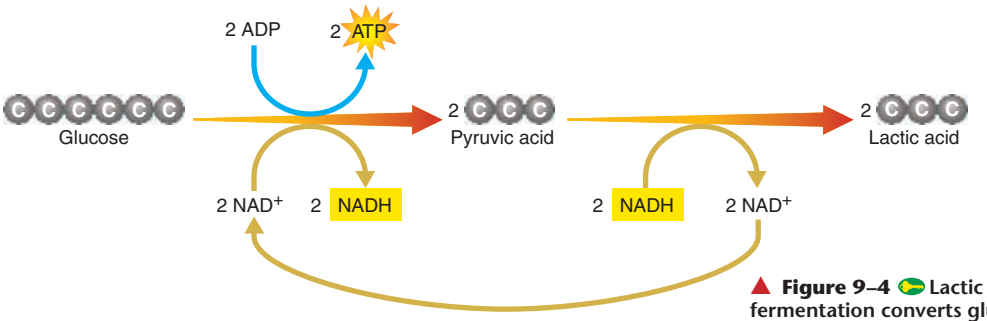
Creating a Solution Write a detailed description of an experiment that could determine if changing the process of fermentation would make the bread lighter. Identify each of your variables. What controls and experimental treatments will you use?

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

BIO INSIGHTS — FACTS AND FIGURES

Yeast leavens bread through fermentation Yeast and other organisms that can carry out both fermentation and cellular respiration, including many kinds of bacteria, are called facultative anaerobes. Human muscle cells also behave as facultative anaerobes. What happens to the end product of glycolysis—pyruvic acid—depends on whether oxygen is present. If there is no oxygen, then fermentation begins.

Baker's yeast, *Saccharomyces cerevisiae,* is the most common organism used to leaven bread. Sourdough bread is leavened by lactobacilli and other lactic-acid bacteria found in flour and milk. Chemicals can also be used to leaven bread. Yeast multiplies best between temperatures of about 27°C and 43°C. It is dormant below 10°C, and it dies at temperatures above 49°C.



▲ **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:

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

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.

9–1 Section Assessment

1. Cellular respiration is the process that releases energy by breaking down molecules in food in the presence of oxygen.
2. Glycolysis produces 2 molecules of pyruvic acid, 2 molecules of ATP, and 2 molecules of NADH.
3. Alcoholic fermentation and lactic acid fermentation
4. A calorie is the amount of energy required to raise the temperature of 1 gram of water 1 degree Celsius. A Calorie is 1000 calories.
5. Both are electron carriers.
6. Similar: Both provide energy to cells in the absence of oxygen. Different: Alcoholic fermentation produces alcohol, carbon dioxide, and NAD^+, while lactic acid fermentation produces lactic acid and NAD^+.

Use Visuals

Figure 9–4 Have students study the process shown in the figure. Point out that the process of glucose breaking down and giving off energy in the figure is similar to the process shown in Figure 9–3. Then, ask: **What is missing from this series of reactions that makes the process anaerobic?** *(There is no oxygen in the process.)* Point out that this pathway shows how an electron carrier behaves cyclically. In lactic acid fermentation, 2 NADH molecules become 2 NAD^+ molecules, resupplying the cell with the electron carriers needed in glycolysis. L2

3 ASSESS

Evaluate Understanding

Call on students at random to explain what occurs during glycolysis. Then, ask students to write the equations for alcoholic fermentation and lactic acid fermentation.

Reteach

Have students make three simple flowcharts, using words in each box that explain the processes of glycolysis, alcoholic fermentation, and lactic acid fermentation. Tell students that they can use Figures 9–3 and 9–4 for reference.

Focus on the BIG Idea

The chemical equation for the conversion of ADP to ATP is ADP + P → ATP. The reactants are ADP and P; the product is ATP.

Interactive Textbook

If your class subscribes to the iText, use it to review the Key Concepts in Section 9–1.