9.1 Cellular Respiration: An Overview

Lesson Objectives
- Explain where organisms get the energy they need for life processes.
- Define cellular respiration.
- Compare photosynthesis and cellular respiration.

Lesson Summary

Chemical Energy and Food
Chemical energy is stored in food molecules.
- Energy is released when chemical bonds in food molecules are broken.
- Energy is measured in a unit called a calorie, the amount of energy needed to raise the temperature of 1 gram of water 1 degree Celsius.
- Fats store more energy per gram than do carbohydrates and proteins.

Overview of Cellular Respiration
Cellular respiration is the process that releases energy from food in the presence of oxygen.
- Cellular respiration captures the energy from food in three main stages:
  - glycolysis
  - the Krebs cycle
  - the electron transport chain
- Glycolysis does not require oxygen. The Krebs cycle and electron transport chain both require oxygen.
  - Aerobic pathways are processes that require oxygen.
  - Anaerobic pathways are processes that occur without oxygen.

Comparing Photosynthesis and Cellular Respiration
The energy in photosynthesis and cellular respiration flows in opposite directions. Their equations are the reverse of each other.
- Photosynthesis removes carbon dioxide from the atmosphere, and cellular respiration puts it back.
- Photosynthesis releases oxygen into the atmosphere, and cellular respiration uses oxygen to release energy from food.

Chemical Energy and Food

For Questions 1–4, complete each statement by writing the correct word or words.
1. A calorie is a unit of ___________.
2. The Calorie used on food labels is equal to ____________ calories.
3. A Calorie is also referred to as a ____________.
4. Cells use the energy stored in chemical bonds of foods to produce compounds that directly power the cell’s activities, such as ____________.
Overview of Cellular Respiration

For Questions 5–10, complete each statement by writing the correct word or words.

5. The equation that summarizes cellular respiration, using chemical formulas, is ____________________________.

6. If cellular respiration took place in just one step, most of the ____________ would be lost in the form of light and ____________.

7. Cellular respiration begins with a pathway called ____________, which takes place in the __________ of the cell.

8. At the end of glycolysis, about ____________ percent of the chemical energy is locked in the bonds of the __________ molecule.

9. Cellular respiration continues in the ____________ of the cell with the ____________ and electron transport chain.

10. The pathways of cellular respiration that require oxygen are said to be ____________.

   Pathways that do not require oxygen are said to be ____________.

11. **THINK VISUALLY** Complete the illustration by adding labels for the three main stages of cellular respiration.
Comparing Photosynthesis and Cellular Respiration

For Questions 12–15, write True if the statement is true. If the statement is false, change the underlined word or words to make the statement true.

12. The energy flow in photosynthesis and cellular respiration occurs in the **same** direction.

13. Photosynthesis **deposits** energy in Earth’s “savings account” for living organisms.

14. Cellular respiration removes carbon dioxide from the air.

15. Photosynthesis takes place in nearly all life.

16. Complete the table comparing photosynthesis and cellular respiration.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Photosynthesis</th>
<th>Cellular Respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>energy capture</td>
<td></td>
</tr>
<tr>
<td><strong>Location of reactions</strong></td>
<td>chloroplasts</td>
<td></td>
</tr>
<tr>
<td>Reactants</td>
<td></td>
<td></td>
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<tr>
<td>Products</td>
<td></td>
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</tbody>
</table>

Apply the Big idea

17. How does an understanding of the process of cellular respiration support the theory that the cell is the basic functional unit of life?
9.2 The Process of Cellular Respiration

Lesson Objectives

- Describe what happens during glycolysis.
- Describe what happens during the Krebs cycle.
- Explain how high-energy electrons are used by the electron transport chain.
- Identify how much ATP cellular respiration generates.

Lesson Summary

**Glycolysis** The word *glycolysis* literally means “sugar-breaking.” The end result is 2 molecules of a 3-carbon molecule called pyruvic acid.

- 2 ATP molecules are used at the start of glycolysis to get the process started.
- High-energy electrons are passed to the electron carrier \( \text{NAD}^+ \), forming two molecules of NADH.
- 4 ATP are synthesized during glycolysis for a net gain of 2 ATP.

**The Krebs Cycle** The second stage of cellular respiration is the *Krebs cycle*, which operates only when oxygen is available. The Krebs cycle is a series of energy-extracting reactions.

- Pyruvic acid produced by glycolysis enters mitochondria. In the innermost compartment of a mitochondrion, or the *matrix*, pyruvic acid molecules are broken down into carbon dioxide and acetyl-CoA molecules.
- Acetyl-CoA combines with a 4-carbon compound, producing a 6-carbon molecule—citric acid. Energy released by the breaking and rearranging of carbon bonds is captured in ATP, NADH, and FADH\(_2\).
- The Krebs cycle produces four types of products:
  - high-energy electron carriers (NADH and FADH\(_2\))
  - carbon dioxide
  - 2 ATP molecules (per glucose molecule)
  - the 4-carbon molecule needed to start the cycle again

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

- The electron carriers produced during glycolysis and the Krebs cycle bring high-energy electrons to the electron transport chain. Oxygen is the final electron acceptor.
- The passing of electrons through the electron transport chain causes H\(^+\) ions to build up in the intermembrane space, making it positively charged relative to the matrix.
- The charge difference across the membrane forces H\(^+\) ions through channels in enzymes known as ATP synthases. As the ATP synthases spin, a phosphate group is added to ADP, generating ATP.

**The Totals** Together, glycolysis, the Krebs cycle, and the electron transport chain generate about 36 molecules of ATP per molecule of glucose.
Glycolysis

1. **THINK** Complete the diagram by writing on the lines provided the names and numbers of molecules used and produced during glycolysis.

   ![Diagram of glycolysis](image)

   - Glucose
   - ATP
   - NAD+

2. Why is it an investment for the cell to use two ATP at the beginning of glycolysis?

   - ATP is used to activate glucose.
   - ATP is not directly recovered at the end of glycolysis.
   - ATP is required for other cellular processes.

3. What are two advantages of glycolysis?

   - Energy production without oxygen.
   - It is a versatile energy source for various organisms.
   - It is the initial step in anaerobic respiration.
   - It provides building blocks for other metabolic pathways.
The Krebs Cycle

For Questions 4–7, write True if the statement is true. If the statement is false, change the underlined word or words to make the statement true.

4. The pyruvic acid produced in glycolysis enters the chloroplasts if oxygen is present in a cell.

5. In the matrix, pyruvic acid is converted to lactic acid before the Krebs cycle begins.

6. The compound that joins with a 4-carbon molecule in the Krebs cycle is called acetyl-CoA.

7. Carbon dioxide is the only product of the Krebs cycle that is not re-used or used in other stages of cellular respiration.

8. Complete the flowchart to show which of the Krebs cycle’s many products go on to the third stage of cellular respiration.

Electron Transport and ATP Synthesis

For Questions 9–14, complete each statement by writing the correct word or words.

9. In eukaryotes, the electron transport chain is composed of a series of electron carriers located in the ______________ of the mitochondrion.

10. In prokaryotes, the electron transport chain is in the ______________.

11. ______________ serves as the final electron acceptor of the electron transport chain.

12. ______________ and ______________ pass high-energy electrons to the electron transport chain.

13. The transfer of high-energy electrons down the electron transport chain causes ______________ to be transported across the mitochondrial membrane.

14. ATP synthases produce the force needed to add one ______________ to each ADP molecule by spinning when hydrogen ions flow through them.
The Totals

15. How many ATP molecules per glucose molecule does a cell gain from each of the three stages of cellular respiration?

16. Besides glucose, what other kinds of molecules can be used to produce ATP in cellular respiration?

17. Why is cellular respiration considered an efficient process?

Apply the Big idea

18. Where does the heat that warms your body come from? Explain your answer.
9.3 Fermentation

Lesson Objectives
- Explain how organisms get energy in the absence of oxygen.
- Identify the pathways the body uses to release energy during exercise.

Lesson Summary

**Fermentation**

Fermentation releases energy from food molecules by producing ATP without oxygen. Cells convert NADH to the electron carrier NAD⁺. This allows glycolysis to produce a steady stream of ATP. There are two forms of fermentation. Both start with the reactants pyruvic acid and NADH.

- **Alcoholic fermentation** produces ethyl alcohol and carbon dioxide
  - occurs in yeast and a few other microorganisms
  - produces alcoholic beverages and causes bread dough to rise

- **Lactic acid fermentation** produces lactic acid
  - occurs in most organisms, including humans
  - used to produce beverages such as buttermilk and foods such as cheese, yogurt, and pickles

**Energy and Exercise**

The body uses different pathways to release energy.

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

**For Questions 1–6, write True if the statement is true. If the statement is false, change the underlined word or words to make the statement true.**

1. Glycolysis provides the pyruvic acid molecules used in fermentation.
2. Fermentation allows glycolysis to continue by providing the NADPH needed to accept high-energy electrons.
3. Fermentation is an aerobic process.
4. Fermentation occurs in the mitochondria of cells.
5. Alcoholic fermentation gives off carbon dioxide and is used in making bread.
6. Most organisms perform fermentation using a chemical reaction that converts pyruvic acid to lactic acid.
7. Compare and contrast fermentation and cellular respiration by completing the compare/contrast table. Write your answers in the empty table cells.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Fermentation</th>
<th>Cellular Respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td></td>
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</tr>
<tr>
<td>Reactants</td>
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<tr>
<td>Products</td>
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</tbody>
</table>

8. Compare and contrast alcoholic fermentation and lactic acid fermentation by completing the compare/contrast table. Write your answers in the empty table cells.

<table>
<thead>
<tr>
<th>Type of Fermentation</th>
<th>Summary Equation</th>
<th>Use in Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcoholic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactic acid</td>
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</tbody>
</table>

9. What causes humans to become lactic acid fermenters?

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Energy and Exercise

10. What are three main sources of ATP available for human muscle cells?

11. During a race, how do your muscle cells produce ATP after the store of ATP in muscles is used?

12. Why does a sprinter have an oxygen debt to repay after the race is over?

13. A runner needs more energy for a longer race. How does the body generate the necessary ATP?

14. Why are aerobic forms of exercise so beneficial for weight control?

Apply the Big idea

15. Compare and contrast the role of fermentation and cellular respiration in the actual production of ATP. In your response, consider which process produces ATP and which process contributes to its production.
Multiple Choice

Write the letter that best answers the question or completes the statement on the line provided.

1. How do organisms get the energy they need?
   a. by burning food molecules and releasing their energy as heat
   b. by breathing oxygen into the lungs and combining it with carbon dioxide
   c. by breaking down food molecules gradually and capturing their chemical energy
   d. by using the sun’s energy to break down food molecules and form chemicals

2. Which of the following is NOT a stage of cellular respiration?
   a. fermentation
   b. electron transport
   c. glycolysis
   d. Krebs cycle

3. Cellular respiration is called an aerobic process because it requires
   a. light.
   b. exercise.
   c. oxygen.
   d. glucose.

4. Photosynthesis is to chloroplasts as cellular respiration is to
   a. chloroplasts.
   b. cytoplasm.
   c. mitochondria.
   d. nuclei.

5. The products of photosynthesis are the
   a. products of cellular respiration.
   b. reactants of cellular respiration.
   c. products of glycolysis.
   d. reactants of fermentation.

6. Glycolysis provides a cell with a net gain of
   a. 2 ATP molecules.
   b. 4 ATP molecules.
   c. 18 ATP molecules.
   d. 36 ATP molecules.

7. Glycolysis requires
   a. ATP.
   b. oxygen.
   c. sunlight.
   d. NADP⁺.

8. The Krebs cycle starts with
   a. lactic acid and yields carbon dioxide.
   b. glucose and yields ATP.
   c. pyruvic acid and yields lactic acid.
   d. pyruvic acid and yields carbon dioxide.

9. In eukaryotes, electron transport occurs in the
   a. inner mitochondrial membrane.
   b. nucleus.
   c. cell membrane.
   d. cytoplasm.
10. Which of the following pass high-energy electrons to the electron transport chain?
   a. NADH and FADH₂
   b. ATP and ADP
   c. citric acid
   d. acetyl-CoA

11. Cellular respiration uses 1 molecule of glucose to produce approximately
   a. 2 ATP molecules.
   b. 4 ATP molecules.
   c. 32 ATP molecules.
   d. 36 ATP molecules.

12. Lactic acid fermentation occurs in
   a. bread dough.
   b. any environment containing oxygen.
   c. muscle cells.
   d. mitochondria.

13. During fermentation,
   a. NAD⁺ is regenerated, allowing glycolysis to continue.
   b. glucose is split into 3 pyruvic acid molecules.
   c. oxygen is required.
   d. carbon dioxide is produced.

14. Breathing heavily after running a race is your body’s way of
   a. making more citric acid.
   b. repaying an oxygen debt.
   c. restarting glycolysis.
   d. stopping the electron transport chain.

15. The energy needed to win a 1-minute footrace is produced mostly by
   a. lactic acid fermentation.
   b. cellular respiration.
   c. using up stores of ATP
   d. breaking down fats.

Completion

Complete each statement on the line provided.

16. Photosynthesis occurs only in plants, algae, and some bacteria. In contrast, ______________ occurs in all eukaryotic cells.

17. Glycolysis rearranges a 6-carbon glucose molecule into two 3-carbon molecules of ______________.

18. When ______________ pass through ATP synthase, ATP molecules are produced from ADP molecules.

19. Glycolysis alone nets only ______________ molecules of ATP from each glucose molecule.

20. The body gets rid of lactic acid in a chemical pathway that requires ______________.
Short Answer

In complete sentences, write the answers to the questions on the lines provided.

21. Figure 9–1 shows how energy flows among the sun, plants, animals, and fossil fuels. Which arrow represents cellular respiration? Explain your reasoning.

22. What roles does oxygen play in photosynthesis and in cellular respiration?

23. The electron transport chain uses the energy stored in high-energy electrons to pump $H^+$ ions across the inner mitochondrial membrane. Why?

24. What role does oxygen play in the electron transport chain?

25. Given the inefficiency of two of the pathways shown in Figure 9–2, what advantage could there be to using these pathways to produce energy?
Using Science Skills

*Use the diagram below to answer the following questions on the lines provided.*

A student poured a solution of bromthymol blue indicator into three test tubes. Then, he placed an aquatic plant in two of the test tubes, as shown. He placed a stopper on each test tube and placed them all in the dark for 24 hours. Bromthymol blue turns from blue to yellow in the presence of CO₂.

26. **Apply Concepts** Look at Figure 9–3. Which process or processes would you expect the organisms in the test tubes to carry out—cellular respiration, photosynthesis, or both? When would you expect each process to occur?

27. **Infer** What is the purpose of the bromthymol blue in Figure 9–3? How can the student use this indicator to draw conclusions about the processes that the aquatic plants are carrying out? Explain your answer.

28. **Predict** Predict what will happen to the test tubes in Figure 9–3 after 24 hours in the dark.

29. **Predict** Assume that after 24 hours in the dark, the bromthymol blue in test tubes 2 and 3 in Figure 9–3 had turned yellow. The student then placed test tube 3 in a sunny window. He left test tube 2 in the dark. Predict what color the solution in each test tube will be after the next 24 hours.

30. **Apply Concepts** Explain your prediction in question 29 in terms of cellular respiration and/or photosynthesis.
**Essay**

*Write the answer to each question in the space provided.*

31. What would happen if all the energy in glucose were released in just one step instead of gradually as it is in cellular respiration? How is the gradual process of cellular respiration advantageous to the cell?

32. Describe the main steps and the results of the Krebs cycle.

33. Identify the electron carriers of cellular respiration. Discuss the relationship between the electron carriers and the electron transport chain.
34. People who suffer from a heart attack often have an increased ratio of lactic acid to pyruvic acid in their hearts. What does this observation say about the availability of oxygen in the heart muscle cells of someone who has had a heart attack? How could you use this information to screen people who might be at risk for a heart attack?

35. Why does lactic acid fermentation “kick in” during a sprint race?