CHAPTER 6

Biochemical Pathways—Cellular Respiration

There are over 100 species of the fungus *Penicillium*, and each characteristically produces reproductive spores that line up and look like a hairbrush. The Latin word *penicillus* means little brush. These fungi do more than just produce the antibiotic penicillin. Many people are familiar with the blue, cottony growth on citrus fruits. It appears to be blue because of the pigment produced in the mold's spores. The blue cheeses, such as Cambozola, Stilton, Gorgonzola, and the original Roquefort, all have that color. Each of these cheeses is "aged" with *Penicillium roquefortii* to produce the characteristic color, texture, and flavor. The differences in the blue cheeses are determined by the kinds of milk used and the conditions under which the aging occurs. True Roquefort cheese is made from sheep's milk and aged in caves at Roquefort, France. American blue cheese is made from cow's milk and aged at various places in the United States. The blue color has become a very important feature of those cheeses. However, a team of researchers found a mutant species of *P. roquefortii* that produces spores having no blue color. The cheese made from that mold is "white" blue cheese. The flavor is exactly the same as blue cheese, but the cheese is commercially worthless, because people want the blue color.

How cheeses become different from one another in texture, flavor, and aroma is only one example of a vital metabolic process known as cellular respiration. Whether *Penicillium* or a person, all organisms must carry out cellular respiration; should they stop, they would die. Although the exact details of how each organism goes about performing this kind of metabolism differ, the basic concepts are the same. This chapter will present the basics of this process.

CHAPTER OUTLINE

6.1 Energy and Organisms

There are hundreds of different chemical reactions taking place within the cells of organisms. Many of these reactions are involved in providing energy for the cells. Organisms are classified into groups based on the kind of energy they use. Organisms that are able to use basic energy sources, such as sunlight, to make energy-containing organic molecules from inorganic raw materials are called **autotrophs** (*auto* = self; *troph* = feeding). There are also prokaryotic organisms that use inorganic chemical reactions as a source of energy to make larger, organic molecules. This process is known as **chemosynthesis.** Therefore, there are at least two kinds of autotrophs: Those that use light are called *photosynthetic* autotrophs and those that use inorganic chemical reactions are called *chemosynthetic* autotrophs. All other organisms require organic molecules as food and are called **heterotrophs** (*hetero* = other; *troph* = feeding). Heterotrophs get their energy from the chemical bonds of food molecules, such as carbohydrates, fats, and proteins, which they must obtain from their surroundings.

Within eukaryotic cells, certain biochemical processes are carried out in specific organelles. Chloroplasts are the sites of photosynthesis, and mitochondria are the sites of most of the reactions of cellular respiration (figure 6.1). Because prokaryotic cells lack mitochondria and chloroplasts, they carry out photosynthesis and cellular respiration within the cytoplasm or on the inner surfaces of the cell membrane or on other special membranes. Table 6.1 provides a summary of the concepts just discussed and how they are related to one another. **organelles, p. 73**

This chapter will focus on the reactions involved in the processes of cellular respiration. In **cellular respiration,** organisms control the release of chemical-bond energy from large, organic molecules and use the energy for the many activities necessary to sustain life. All organisms, whether autotrophic or heterotrophic, must carry out cellular respiration if they are to survive. Because nearly all organisms use organic molecules as a source of energy, they must obtain these molecules from their environment or manufacture these organic molecules, which they will later break down. Thus, photosynthetic organisms produce food molecules, such as carbohydrates, for themselves as well as for all the other organisms that feed on them. There are many variations of cellular respiration. Some organisms require the presence of oxygen for these processes, called *aerobic* processes. Other organisms carry out a form of respiration that does not require oxygen; these processes are called *anaerobic*.

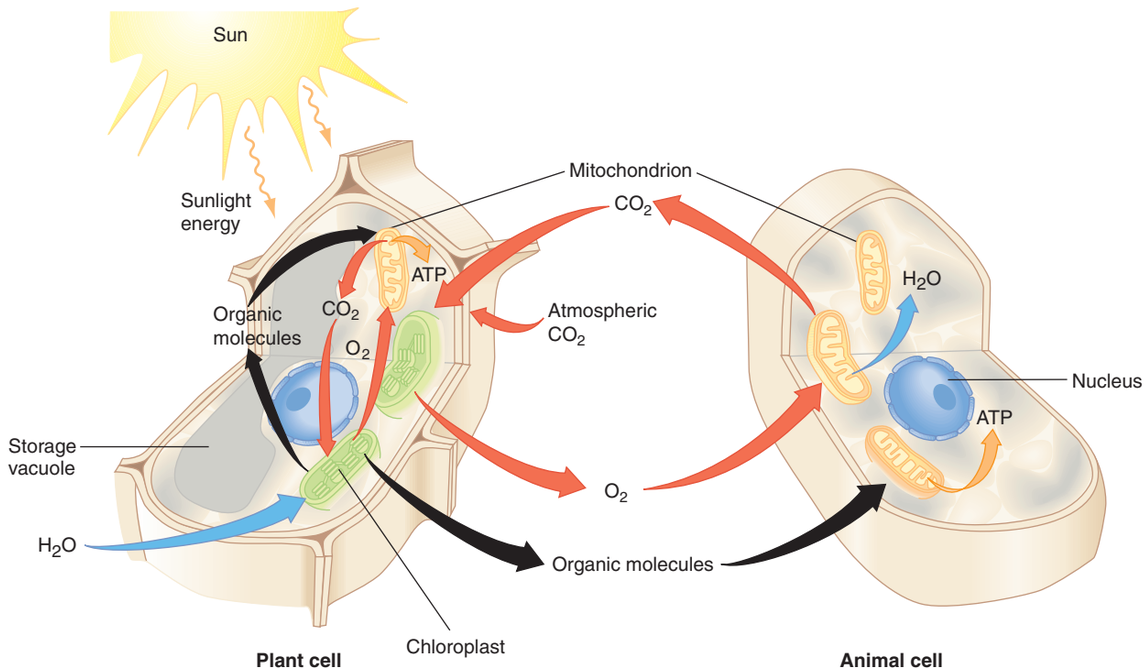


FIGURE 6.1 Biochemical Pathways That Involve Energy Transformation
Photosynthesis and cellular respiration both involve a series of chemical reactions that control the flow of energy. Organisms that contain photosynthetic machinery are capable of using light, water, and carbon dioxide to produce organic molecules, such as sugars, proteins, lipids, and nucleic acids. Oxygen is also released as a result of photosynthesis. In aerobic cellular respiration, organic molecules and oxygen are used to provide the energy to sustain life. Carbon dioxide and water are also released during aerobic respiration.

TABLE 6.1

Summary of Biochemical Pathways, Energy Sources, and Kinds of Organisms

Autotroph or Heterotroph	Biochemical Pathways	Energy Source	Kinds of Organisms	Notes
Autotroph	Photosynthesis	Light	Prokaryotic—certain bacteria	Prokaryotic photosynthesis is somewhat different from eukaryotic photosynthesis and does not take place in chloroplasts.
			Eukaryotic—plants and algae	Eukaryotic photosynthesis takes place in chloroplasts.
Autotroph	Chemosynthesis	Inorganic chemical reactions	Prokaryotic—certain bacteria and archaea	There are many types of chemosynthesis.
Autotroph and heterotroph	Cellular respiration	Oxidation of large organic molecules	Prokaryotic—bacteria and archaea	There are many forms of respiration. Some organisms use aerobic cellular respiration; others use anaerobic cellular respiration.
			Eukaryotic—plants, animals, fungi, algae, protozoa	Most respiration in eukaryotic organisms takes place in mitochondria and is aerobic.

6.2 An Overview of Aerobic Cellular Respiration

Aerobic cellular respiration is a specific series of enzyme-controlled chemical reactions in which oxygen is involved in the breakdown of glucose into carbon dioxide and water and the chemical-bond energy from glucose is released to the cell in the form of ATP. Although the actual process of aerobic cellular respiration involves many enzyme-controlled steps, the net result is that a reaction between sugar and oxygen results in the formation of carbon dioxide and water with the release of energy. The following equation summarizes this process:

$$\begin{array}{lcl} & & \text{carbon} \\ \text{glucose} + \text{oxygen} & \rightarrow & \text{dioxide} + \text{water} + \text{energy} \\ C_6H_{12}O_6 + 6\ O_2 & \rightarrow & 6\ CO_2 + 6\ H_2O + \text{energy} \\ & & \qquad\qquad\qquad\qquad\quad (\text{ATP} + \text{heat}) \end{array}$$

Covalent bonds are formed by atoms sharing pairs of fast-moving, energetic electrons. Therefore, the covalent bonds in the sugar glucose contain chemical potential energy. Of all the covalent bonds in glucose (O—H, C—H, C—C), those easiest to get at are the C—H and O—H bonds on the outside of the molecule. When these bonds are broken, two things happen:

1. The energy of the electrons can be used to phosphorylate ADP molecules to produce higher-energy ATP molecules.
2. Hydrogen ions (protons) are released. The ATP is used to power the metabolic activities of the cell. The chemical activities that remove electrons from glucose result in the glucose being *oxidized*.

These high-energy electrons must be controlled. If they were allowed to fly about at random, they would quickly combine with other molecules, causing cell death. Electron-transfer molecules, such as NAD^+ and FAD, temporarily hold the electrons and transfer them to other electron-transfer molecules. ATP is formed when these transfers take place (see chapter 5). Once energy has been removed from electrons for ATP production, the electrons must be placed in a safe location. In *aerobic* cellular respiration, these electrons are ultimately attached to oxygen. Oxygen serves as the final resting place of the less energetic electrons. When the electrons are added to oxygen, it becomes a negatively charged ion, $O^=$.

Because the oxygen has gained electrons, it has been *reduced. Thus, in the aerobic cellular respiration of glucose, glucose is oxidized and oxygen is reduced.* If something is oxidized (loses electrons), something else must be reduced (gains electrons). A molecule cannot simply lose its electrons—they have to go someplace! Eventually, the positively charged hydrogen ions that were released from the glucose molecule combine with the negatively charged oxygen ion to form water.

Once all the hydrogens have been stripped off the glucose molecule, the remaining carbon and oxygen atoms are

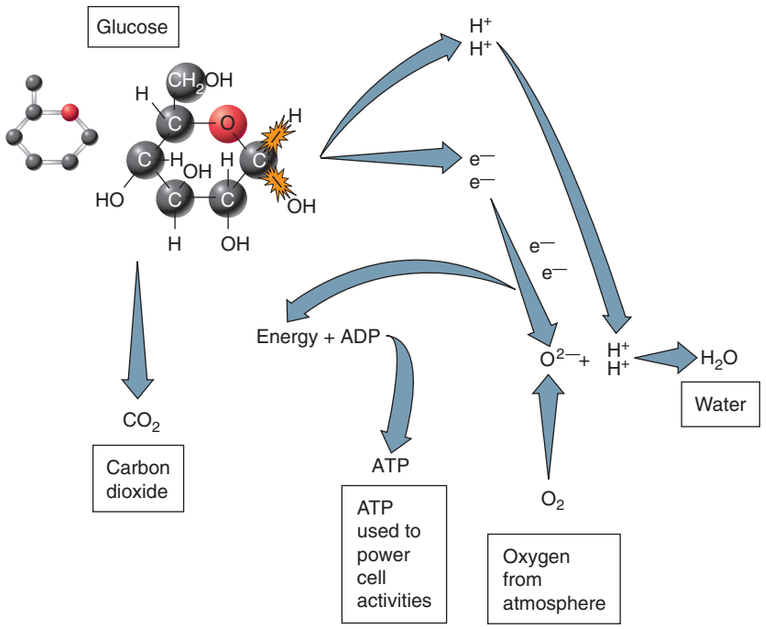


FIGURE 6.2 Aerobic Cellular Respiration and Oxidation-Reduction Reaction
During aerobic cellular respiration, a series of oxidation-reduction reactions takes place. When the electrons are removed (oxidation) from sugar, it is unable to stay together and breaks into smaller units. The reduction part of the reaction occurs when these electrons are attached to another molecule. In aerobic cellular respiration, the electrons are eventually picked up by oxygen and the negatively charged oxygen attracts two positively charged hydrogen ions (H^+) to form water.

rearranged to form individual molecules of CO_2. All the hydrogen originally a part of the glucose has been moved to the oxygen to form water. All the remaining carbon and oxygen atoms of the original glucose are now in the form of CO_2. The energy released from this process is used to generate ATP (figure 6.2).

In cells, these reactions take place in a particular order and in particular places within the cell. In eukaryotic cells, the process of releasing energy from food molecules begins in the cytoplasm and is completed in the mitochondrion. There are three distinct enzymatic pathways involved (figure 6.3): glycolysis, the Krebs cycle, and the electron-transport system.

Glycolysis

Glycolysis (*glyco* = sugar; *lysis* = to split) is a series of enzyme-controlled reactions that takes place in the cytoplasm of cells, which results in the breakdown of glucose with the release of electrons and the formation of ATP. During glycolysis, the 6-carbon sugar glucose is split into two smaller, 3-carbon molecules, which undergo further modification to form pyruvic acid or pyruvate.[1] Enough energy is released to produce two ATP molecules. Some of the bonds holding hydrogen atoms to the glucose molecule are broken, and the electrons are picked up by electron carrier molecules (NAD^+) and transferred to a series of electron-transfer reactions known as the electron-transport system (ETS).

The Krebs Cycle

The **Krebs cycle** is a series of enzyme-controlled reactions that takes place inside the mitochondrion, which completes the breakdown of pyruvic acid with the release of carbon dioxide, electrons, and ATP. During the Krebs cycle, the pyruvic acid molecules produced from glycolysis are further broken down. During these reactions, the remaining hydrogens are removed from the pyruvic acid, and their electrons are picked up by the electron carriers NAD^+ and FAD. These electrons are sent to the electron-transport system. A small amount of ATP is also formed during the Krebs cycle. The carbon and oxygen atoms that are the remains of the pyruvic acid molecules are released as carbon dioxide (CO_2).

[1]Several different ways of naming organic compounds have been used over the years. For our purposes, pyruvic acid and pyruvate are really the same basic molecule although technically, pyruvate is what is left when pyruvic acid has lost its hydrogen ion: pyruvic acid → H^+ + pyruvate. You also will see terms such as lactic acid and lactate and citric acid and citrate and many others used in a similar way.

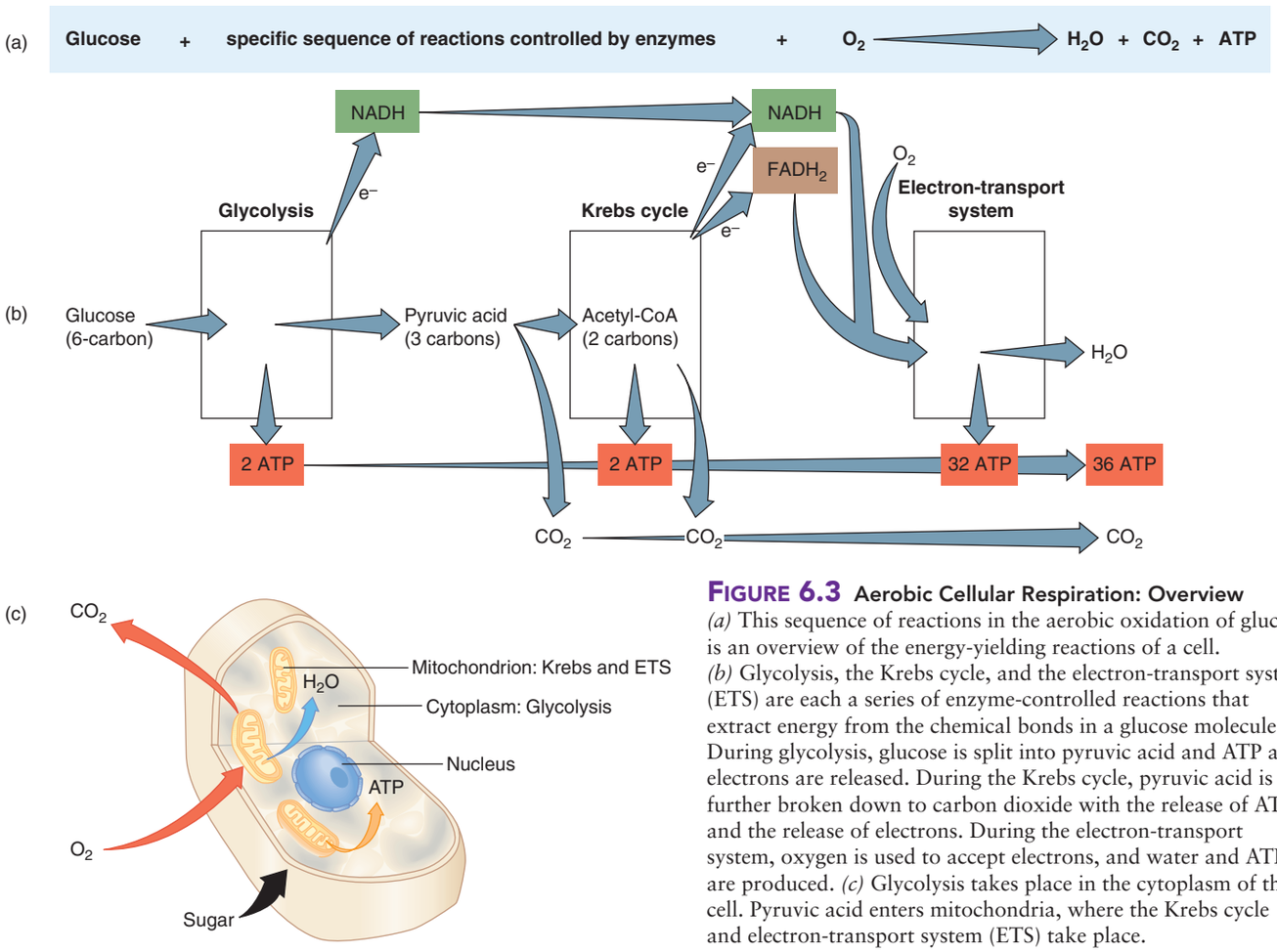


FIGURE 6.3 **Aerobic Cellular Respiration: Overview**
(a) This sequence of reactions in the aerobic oxidation of glucose is an overview of the energy-yielding reactions of a cell. *(b)* Glycolysis, the Krebs cycle, and the electron-transport system (ETS) are each a series of enzyme-controlled reactions that extract energy from the chemical bonds in a glucose molecule. During glycolysis, glucose is split into pyruvic acid and ATP and electrons are released. During the Krebs cycle, pyruvic acid is further broken down to carbon dioxide with the release of ATP and the release of electrons. During the electron-transport system, oxygen is used to accept electrons, and water and ATP are produced. *(c)* Glycolysis takes place in the cytoplasm of the cell. Pyruvic acid enters mitochondria, where the Krebs cycle and electron-transport system (ETS) take place.

The Electron-Transport System (ETS)

The **electron-transport system** (ETS) is a series of enzyme-controlled reactions that converts the kinetic energy of hydrogen electrons to ATP. The electrons are carried to the electron-transport system from glycolysis and the Krebs cycle by NADH and $FADH_2$. The electrons are transferred through a series of oxidation-reduction reactions involving enzymes until eventually the electrons are accepted by oxygen atoms to form oxygen ions ($O^{=}$). During this process, a great deal of ATP is produced. The ATP is formed as a result of a proton gradient established when the energy of electrons is used to pump protons across a membrane. The subsequent movement of protons back across the membrane results in ATP formation. The negatively charged oxygen atoms attract two positively charged hydrogen ions to form water (H_2O).

Aerobic respiration can be summarized as follows. *Glucose* enters glycolysis and is broken down to pyruvic acid, which enters the Krebs cycle, where the pyruvic acid molecules are further dismantled. The remains of the pyruvic acid molecules are released as *carbon dioxide*. The electrons and hydrogen ions released from glycolysis and the Krebs cycle are transferred by NADH and $FADH_2$ to the electron-transport system, where the electrons are transferred to *oxygen* available from the atmosphere. When hydrogen ions attach to oxygen ions, *water* is formed. *ATP* is formed during all three stages of aerobic cellular respiration, but most comes from the electron-transfer system.

6.3 The Metabolic Pathways of Aerobic Cellular Respiration

This discussion of aerobic cellular respiration is divided into two levels: a fundamental description and a detailed description. It is a good idea to begin with the simplest description and add layers of understanding as you go to additional levels. Ask your instructor which level is required for your course of study.

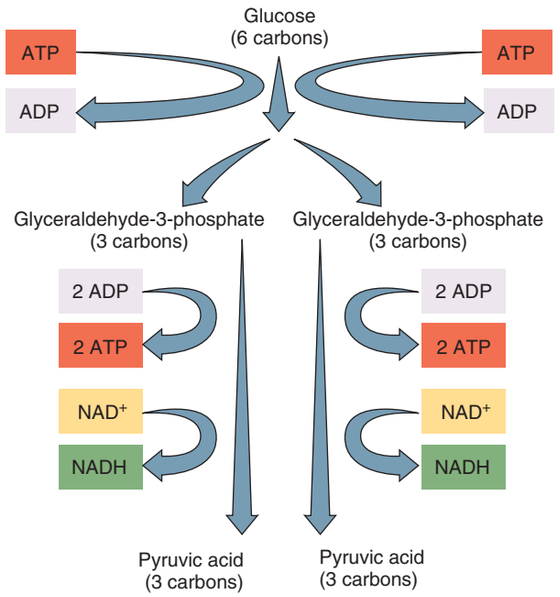


FIGURE 6.4 Glycolysis: Fundamental Description
Glycolysis is the biochemical pathway many organisms use to oxidize glucose. During this sequence of chemical reactions, the 6-carbon molecule of glucose is oxidized. As a result, pyruvic acid is produced, electrons are picked up by NAD^+, and ATP is produced.

Fundamental Description

Glycolysis

Glycolysis is a series of enzyme-controlled reactions that takes place in the cytoplasm. During glycolysis, a 6-carbon sugar molecule (glucose) has energy added to it from two ATP molecules. Adding this energy makes some of the bonds of the glucose molecule unstable, and the glucose molecule is more easily broken down. After passing through several more enzyme-controlled reactions, the 6-carbon glucose is broken down to two 3-carbon molecules known as glyceraldehyde-3-phosphate (also known as phosphoglyceraldehyde[2]), which undergo additional reactions to form pyruvic acid ($CH_3COCOOH$).

Enough energy is released by this series of reactions to produce four ATP molecules. Because two ATP molecules were used to start the reaction and four were produced, there is a *net gain* of two ATPs from the glycolytic pathway (figure 6.4). During the process of glycolysis, some hydrogens and their electrons are removed from the organic molecules being processed and picked up by the electron-transfer molecule NAD^+ to form NADH. Enough hydrogens are released during glycolysis to form 2 NADHs. The NADH with its extra electrons contains a large amount of potential energy, which can be used to make ATP in the electron-transport system. The job of the coenzyme NAD^+ is to transport these energy-containing electrons and protons safely to the electron-transport system. Once they have dropped off their electrons, the oxidized NAD^+s are available to pick up more electrons and repeat the job. The following is a generalized reaction that summarizes the events of glycolysis:

$$\text{glucose} + 2\ \text{ATP} + 2\ NAD^+ \rightarrow 4\ \text{ATP} + 2\ \text{NADH} + 2\ \text{pyruvic acid}$$

The Krebs Cycle

The series of reactions known as the Krebs cycle takes place within the mitochondria of cells. It gets its name from its discoverer, Hans Krebs, and the fact that the series of reactions

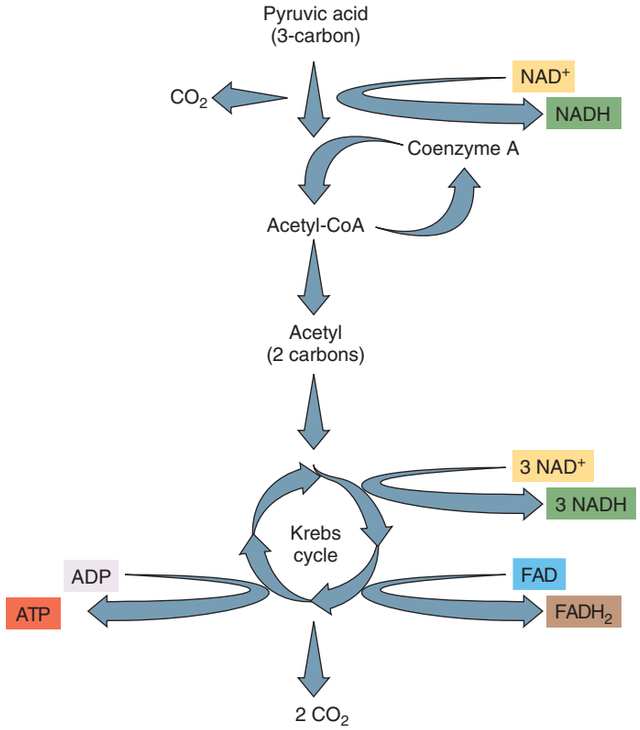


FIGURE 6.5 Krebs Cycle: Fundamental Description
The Krebs cycle takes place in the mitochondria of cells to complete the oxidation of glucose. During this sequence of chemical reactions, a pyruvic acid molecule produced from glycolysis is stripped of its hydrogens. The hydrogens are picked up by NAD^+ and FAD for transport to the ETS. The remaining atoms are reorganized into molecules of carbon dioxide. Enough energy is released during the Krebs cycle to form 2 ATPs. Because 2 pyruvic acid molecules were produced from glycolysis, the Krebs cycle must be run twice in order to complete their oxidation (once for each pyruvic acid).

[2]As with many things in science, the system for naming organic chemical compounds has changed. In the past, the term *phosphoglyceraldehyde* was commonly used for this compound and was used in previous editions of this text. However, today the most commonly used term is *glyceraldehyde-3-phosphate*. In order to reflect current usage more accurately, the term *glyceraldehyde-3-phosphate* is used in this edition.

begins and ends with the same molecule. The Krebs cycle is also known as the citric acid cycle and the TriCarboxylic Acid cycle (TCA). The 3-carbon pyruvic acid molecules released from glycolysis enter the mitochondria, are acted upon by specific enzymes, and are converted to 2-carbon **acetyl** molecules. At the time the acetyl is produced, 2 hydrogens are attached to NAD^+ to form NADH. The carbon atom that was removed is released as carbon dioxide. The acetyl molecule is attached to *coenzyme A (CoA)* and proceeds through the Krebs cycle. During the Krebs cycle (figure 6.5), the acetyl is completely oxidized.

The remaining hydrogens and their electrons are removed. Most of the electrons are picked up by NAD^+ to form NADH, but at one point in the process FAD picks up electrons to form $FADH_2$. Regardless of which electron carrier is being used, the electrons are sent to the electron-transport system. The remaining carbon and oxygen atoms are combined to form CO_2. As in glycolysis, enough energy is released to generate 2 ATP molecules. At the end of the Krebs cycle, the acetyl has been completely broken down (oxidized) to CO_2. The energy in the molecule has been transferred to ATP, NADH, or $FADH_2$. Also, some of the energy has been released as heat. For each of the acetyl molecules that enters the Krebs cycle, 1 ATP, 3 NADHs, and 1 $FADH_2$. If we count the NADH produced during glycolysis, when acetyl was formed, there are a total of 4 NADHs for each pyruvic acid that enters a mitochondrion. The following is a generalized equation that summarizes those reactions:

$$\text{pyruvic acid} + \text{ADP} + 4\ NAD^+ + \text{FAD} \longrightarrow 3\ CO_2 + 4\ \text{NADH} + FADH_2 + \text{ATP}$$

The Electron-Transport System

Of the three steps of aerobic cellular respiration, (glycolysis, Krebs cycle, and electron-transport system) cells generate the greatest amount of ATP from the electron-transport system (figure 6.6). During this stepwise sequence of oxidation-reduction reactions, the energy from the NADH and $FADH_2$ molecules generated in glycolysis and the Krebs cycle is used to produce ATP. Iron-containing *cytochrome* (*cyto* = cell; *chrom* = color) enzyme molecules are located on the membranes of the mitochondrion. The energy-rich electrons are passed (*transported*) from one cytochrome to another, and the energy is used to pump protons (hydrogen ions) from one side of the membrane to the other. The result of this is a higher concentration of hydrogen ions on one side of the membrane. As the concentration of hydrogen ions increases on one side, a proton gradient builds up. Because of this concentration gradient, when a membrane channel is opened, the protons flow back to the side from which they were pumped. As they pass through the channels, a phosphorylase enzyme (ATPase) speeds the formation of an ATP molecule by bonding a phosphate to an ADP molecule (phosphorylation). When all the electrons and hydrogen ions are accounted for, a total of 32 ATPs are formed from the electrons and hydrogens removed from the original glucose molecule. The hydrogens are then bonded to oxygen to form water. The following is a generalized reaction that summarizes the events of the electron-transport system:

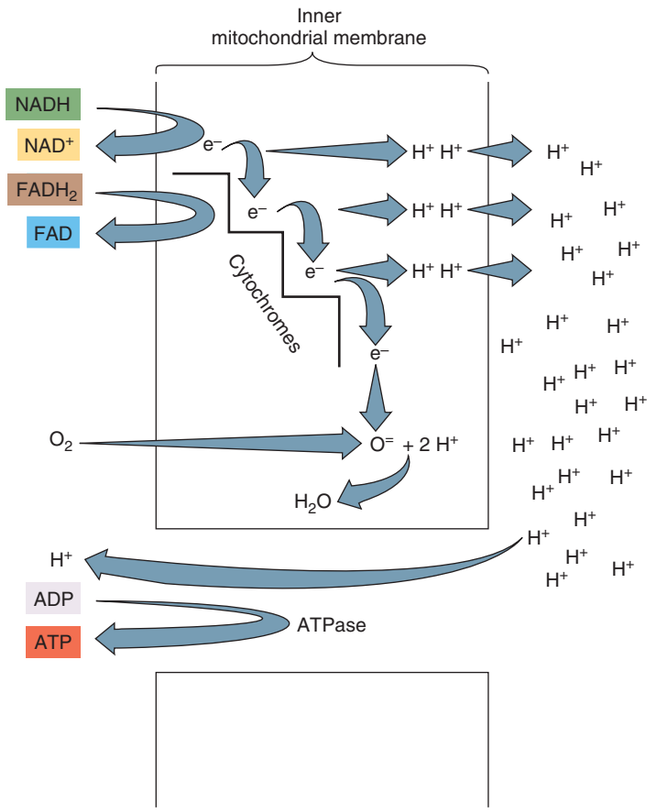


FIGURE 6.6 The Electron-Transport System: Fundamental Description
The electron-transport system (ETS) is also known as the cytochrome system. With the help of enzymes, the electrons are passed through a series of oxidation-reduction reactions. The energy the electrons give up is used to pump protons (H^+) across a membrane in the mitochondrion. When protons flow back through the membrane, enzymes in the membrane cause the formation of ATP. The protons eventually combine with the oxygen that has gained electrons, and water is produced.

$$6\ O_2 + 8\ \text{NADH} + 4\ FADH_2 + 32\ \text{ADP} \longrightarrow 8\ NAD^+ + 4\ \text{FAD} + 32\ \text{ATP} + 12\ H_2O$$

Detailed Description

Glycolysis

The first stage of the cellular respiration process takes place in the cytoplasm. This first step, known as glycolysis, consists of the enzymatic breakdown of a glucose molecule without the use of molecular oxygen. Because no oxygen is required, glycolysis is called an anaerobic process. The glycolysis

pathway can be divided into two general sets of reactions. The first reactions make the glucose molecule unstable, and later oxidation-reduction reactions are used to synthesize ATP and capture hydrogens.

Some energy must be added to the glucose molecule in order to start glycolysis, because glucose is a very stable molecule and will not automatically break down to release energy. In glycolysis, the initial glucose molecule gains a phosphate to become glucose-6-phosphate, which is converted to fructose-6-phosphate. When a second phosphate is added, fructose-1,6-bisphosphate (P—C_6—P) is formed. This 6-carbon molecule is unstable and breaks apart to form two 3-carbon, glyceraldehyde-3-phosphate molecules.

Each of the two glyceraldehyde-3-phosphate molecules acquires a second phosphate from a phosphate supply normally found in the cytoplasm. Each molecule now has 2 phosphates attached, 1, 3 isphosphoglycerate (P—C_3—P). A series of reactions follows, in which energy is released by breaking chemical bonds that hold the phosphates to 1,3 bisphosphoglycerate. The energy and the phosphates are used to produce ATP. Since there are 2 1,3 bisphosphoglycerate each with 2 phosphates, a total of 4 ATPs are produced. Because 2 ATPs were used to start the process, a net yield of 2 ATPs results. In addition, 4 hydrogen atoms detach from the carbon skeleton and their electrons are transferred to NAD^+ to form NADH, which transfers the electrons to the electron-transport system. The 3-carbon pyruvic acid molecules that remain are the raw material for the Krebs cycle. Because glycolysis occurs in the cytoplasm and the Krebs cycle takes place inside mitochondria, the pyruvic acid must enter the mitochondrion before it can be broken down further.

In summary, the process of glycolysis takes place in the cytoplasm of a cell, where glucose ($C_6H_{12}O_6$) enters a series of reactions that

1. Requires the use of 2 ATPs
2. Ultimately results in the formation of 4 ATPs
3. Results in the formation of 2 NADHs
4. Results in the formation of 2 molecules of pyruvic acid $CH_3COCOOH$)

Because 2 molecules of ATP are used to start the process and a total of 4 ATPs are generated, each glucose molecule that undergoes glycolysis produces a net yield of 2 ATPs (Figure 6.7).

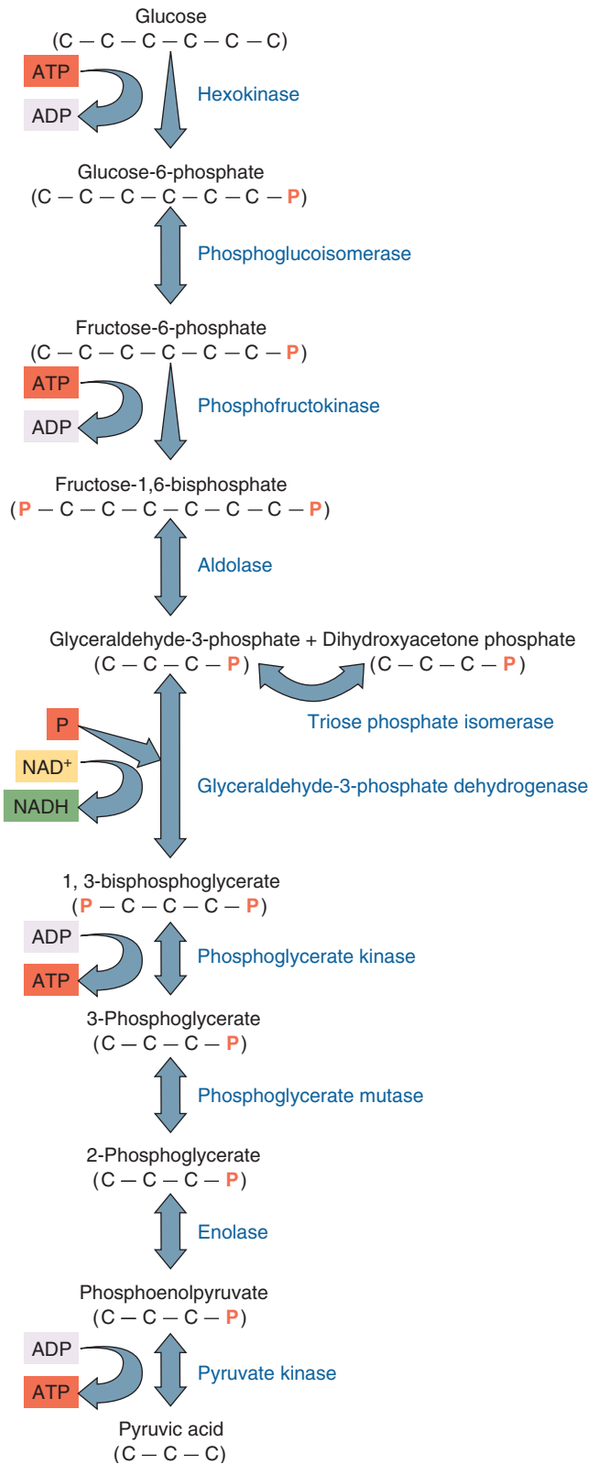


FIGURE 6.7 Glycolysis: Detailed Description
Glycolysis is a process that takes place in the cytoplasm of cells. It does not require the use of oxygen, so it is an anaerobic process. During the first few steps, phosphates are added from ATP and ultimately the 6-carbon sugar is split into two 3-carbon compounds. During the final steps in the process, NAD^+ accepts electrons and hydrogen to form NADH and ATP is produced. Two ATPs form for each of the 3-carbon molecules that are processed in glycolysis. Because there are two 3-carbon compounds, a total of 4 ATPs are formed. However, because 2 ATPs were used to start the process, there is a net gain of 2 ATPs. Pyruvic acid (pyruvate) is left at the end of glycolysis.

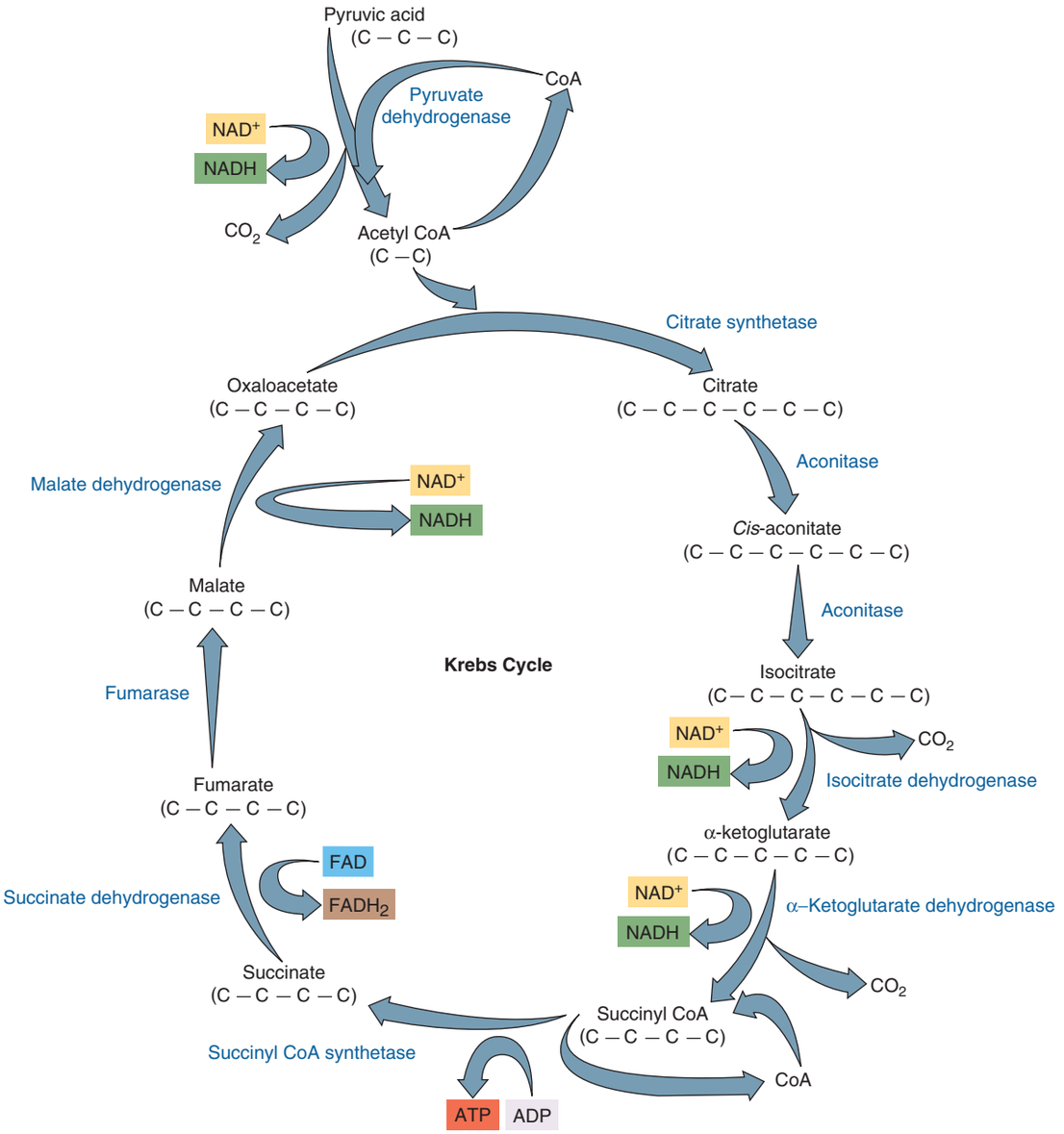


FIGURE 6.8 Krebs Cycle: Detailed Descriptions
The Krebs cycle occurs within the mitochondrion. Pyruvate enters the mitochondrion from glycolysis and is converted to a 2-carbon compound, acetyl. With the help CoA, the 2-carbon acetyl combines with 4-carbon oxaloacetate to form a 6-carbon citrate molecule. Through a series of reactions in the Krebs cycle, electrons are removed and picked up by NAD^+ and FAD to form NADH and $FADH_2$, which will be shuttled to the electron-transport system. Carbons are removed as carbon dioxide. Enough energy is released that 1 ATP is formed for each acetyl that enters the cycle.

The Krebs Cycle

After pyruvate (pyruvic acid) enters the mitochondrion, it is first acted upon by an enzyme, along with a molecule known as *coenzyme* A (*CoA*) (figure 6.8). This results in three significant products. Hydrogen atoms are removed and NADH is formed, a carbon is removed and carbon dioxide is formed, and a 2-carbon acetyl molecule is formed, which temporarily attaches to coenzyme A to produce acetyl-coenzyme A. (These and subsequent reactions of the Krebs cycle take place in the fluid between the membranes of the mitochondrion.) The acetyl coenzyme A enters the series of reactions known as the Krebs cycle. During the Krebs cycle, the acetyl is systematically dismantled. Its hydrogen atoms are removed and the remaining carbons are released as carbon dioxide.

The first step in this process involves the acetyl coenzyme A. The acetyl portion of the complex is transferred to a 4-carbon

compound called *oxaloacetate* (*oxaloacetic acid*) and a new 6-carbon citrate molecule (citric acid) is formed. The coenzyme A is released to participate in another reaction with pyruvic acid. This newly formed citrate is broken down in a series of reactions, which ultimately produces oxaloacetate, which was used in the first step of the cycle (hence, the names Krebs cycle, citric acid cycle, and tricarboxylic acid cycle). The compounds formed during this cycle are called *keto acids*.

In the process, electrons are removed and, along with protons, become attached to the coenzymes NAD^+ and FAD. Most become attached to NAD^+ but some become attached to FAD. As the molecules move through the Krebs cycle, enough energy is released to allow the synthesis of 1 ATP molecule for each acetyl that enters the cycle. The ATP is formed from ADP and a phosphate already present in the mitochondria. For each pyruvate molecule that enters a mitochondrion and is processed through the Krebs cycle, 3 carbons are released as 3 carbon dioxide molecules, 5 pairs of hydrogen atoms are removed and become attached to NAD^+ or FAD, and 1 ATP molecule is generated. When both pyruvate molecules have been processed through the Krebs cycle, (1) all the original carbons from the glucose have been released into the atmosphere as 6 carbon dioxide molecules; (2) all the hydrogen originally found on the glucose has been transferred to either NAD^+ or FAD to form NADH or $FADH_2$; and (3) 2 ATPs have been formed from the addition of phosphates to ADPs (review figure 6.8).

In summary, the Krebs cycle takes place within the mitochondria. For each pyruvate molecule that enters the Krebs cycle:

1. The three carbons of the pyruvate are released as carbon dioxide (CO_2).
2. Five pairs of hydrogens become attached to hydrogen carriers to become 4 NADHs and 1 $FADH_2$.
3. One ATP is generated.

The Electron-Transport System

The series of reactions in which energy is transferred from the electrons and protons carried by NADH and $FADH_2$ is known as the electron-transport system (ETS) (figure 6.9). This is the final stage of aerobic cellular respiration and is dedicated to generating ATP. The reactions that make up the electron-transport system are a series of oxidation-reduction reactions in which the electrons are passed from one electron carrier molecule to another until ultimately they are accepted by oxygen atoms. The negatively charged oxygen combines with the hydrogen ions to form water. It is this step that makes the process aerobic. Keep in mind that potential energy increases whenever things experiencing a repelling force are pushed together, such as adding the third phosphate to an ADP molecule. Potential energy also increases whenever things that attract each other are pulled apart, as in the separation of the protons from the electrons.

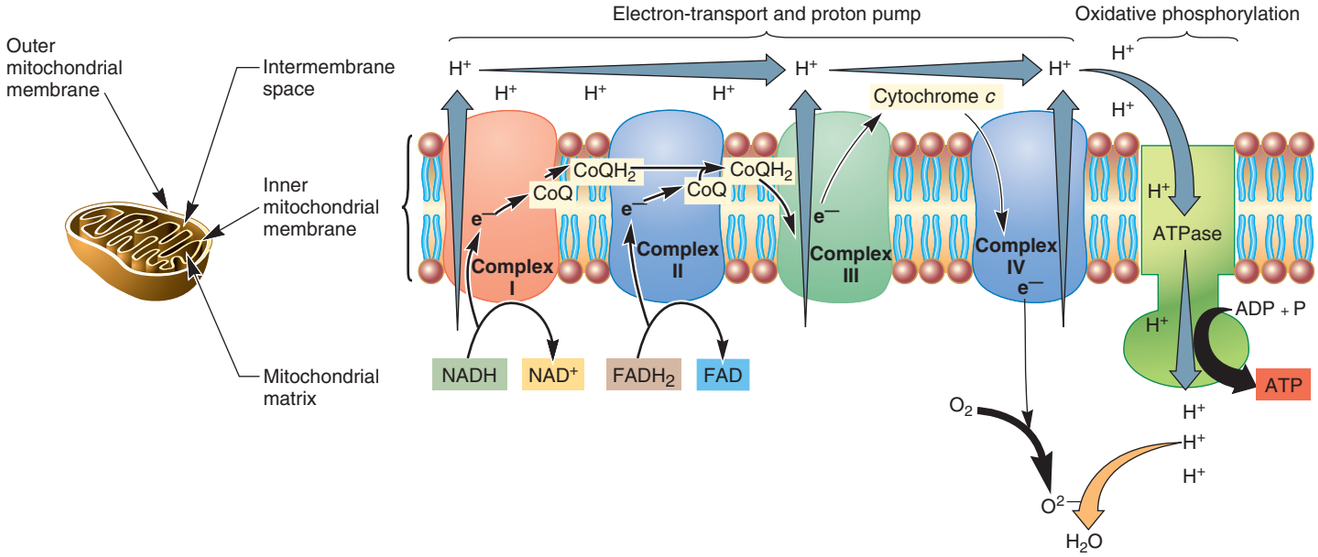


FIGURE 6.9 The Electron-Transport System: Detailed Description
Most of the ATP produced by aerobic cellular respiration comes from the ETS. NADH and $FADH_2$ deliver electrons to the enzymes responsible for the ETS. There are several protein complexes in the inner membrane of the mitochondrion, each of which is responsible for a portion of the reactions that yield ATP. The energy of electrons is given up in small amounts and used to pump protons into the intermembrane space. When these protons flow back through pores in the membrane, ATPase produces ATP. The electrons eventually are transferred to oxygen and the negatively charged oxygen ions accept protons to form water.

Let's now look in just a bit more detail at what happens to the electrons and protons that are carried to the electron-transport systems by NADH and $FADH_2$ and how these activities are used to produce ATP. The mitochondrion consists of two membranes—an outer, enclosing membrane and an inner, folded membrane. The reactions of the ETS are associated with this inner membrane. Within the structure of the membrane are several *enzyme complexes,* which perform particular parts of the ETS reactions (review figure 6.9). The production of ATPs involves two separate but connected processes. Electrons carried by NADH enter reactions in enzyme complex I, where they lose some energy and are eventually picked up by a coenzyme (coenzyme Q). Electrons from $FADH_2$ enter enzyme complex II and also are eventually transferred to coenzyme Q. Coenzyme Q transfers the electrons to enzyme complex III. In complex III, the electrons lose additional energy and are transferred to cytochrome c, which transfers electrons to enzyme complex IV. In complex IV, the electrons are eventually transferred to oxygen. As the electrons lose energy in complex I, complex III, and complex IV, additional protons are pumped into the intermembrane space. When these protons flow down the concentration gradient through channels in the membrane, phosphorylase enzymes (ATPase) in the membrane are able to use the energy to generate ATP.

A total of 12 pairs of electrons and hydrogens are transported to the ETS from glycolysis and the Krebs cycle for each glucose that enters the process. In eukaryotic organisms, the pairs of electrons can be accounted for as follows: 4 pairs are carried by NADH and were generated during glycolysis outside the mitochondrion, 8 pairs are carried as NADH and were generated within the mitochondrion, and 2 pairs are carried by $FADH_2$ and were generated within the mitochondrion.

- For each of the 8 NADHs generated within the mitochondrion, enough energy is released to produce 3 ATP molecules. Therefore, 24 ATPs are released from these electrons carried by NADH.
- In eukaryotic cells, the electrons released during glycolysis are carried as NADH and converted to $FADH_2$ in order to shuttle them into the mitochondria. Once they are inside the mitochondria, they follow the same pathway as the other $FADH_2$s.

The electrons carried by $FADH_2$ are lower in energy. When these electrons go through the series of oxidation-reduction reactions, they release enough energy to produce a total of 8 ATPs. Therefore, a total of 32 ATPs are produced from the hydrogen electrons that enter the ETS.

Finally, a complete accounting of all the ATPs produced during all three parts of aerobic cellular respiration results in a total of 36 ATPs: 32 from the ETS, 2 from glycolysis, and 2 from the Krebs cycle.

In summary, the electron-transport system takes place within the mitochondrion, where

1. Oxygen is used up as the oxygen atoms receive the hydrogens from NADH and $FADH_2$ to form water (H_2O).
2. NAD^+ and FAD are released, to be used over again.
3. Thirty-two ATPs are produced.

6.4 Aerobic Cellular Respiration in Prokaryotes

The discussion so far in this chapter has dealt with the process of aerobic cellular respiration in eukaryotic organisms. However, some prokaryotes also use aerobic cellular respiration. Because prokaryotes do not have mitochondria, there are some differences between what they do and what eukaryotes do. The primary difference involves the electrons carried from glycolysis to the electron-transport system. In eukaryotes, the electrons released during glycolysis are carried by NADH and transferred to FAD to form $FADH_2$ in order to get the electrons across the outer membrane of the mitochondrion. Because $FADH_2$ results in the production of fewer ATPs than NADH, there is a cost to the eukaryotic cell of getting the electrons into the mitochondrion. This transfer is not necessary in prokaryotes, so they are able to produce a theoretical 38 ATPs for each glucose metabolized, rather than the 36 ATPs produced by eukaryotes (table 6.2).

TABLE 6.2

Aerobic ATP Production: Prokaryotic vs. Eukaryotic Cells

Cellular Respiration Stage	Prokaryotic Cells ATP Theoretically Generated	Eukaryotic Cells ATP Theoretically Generated
Glycolysis	Net gain 2 ATP	Net gain 2 ATP
Krebs cycle	2 ATP	2 ATP
ETS	34 ATP	32 ATP
Total	38 ATP	36 ATP

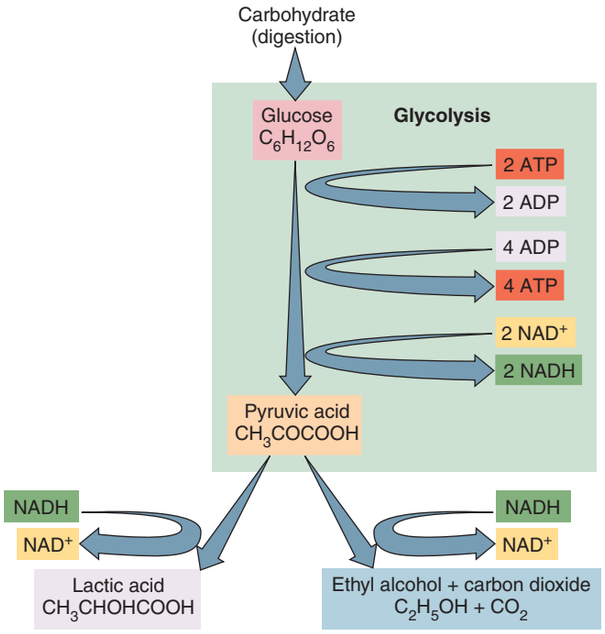
6.5 Anaerobic Cellular Respiration

Although aerobic cellular respiration is the fundamental process by which most organisms generate ATP, some organisms do not have the necessary enzymes to carry out the Krebs cycle and ETS. Most of these are prokaryotic organisms, but there are certain eukaryotic organisms, such as yeasts, that can live in the absence of oxygen and do not use the Krebs cycle and ETS. Even within organisms, there are differences in the metabolic activities of cells. Some of their cells are unable to perform aerobic respiration, whereas others are able to survive for periods of time without it. However, all of these cells still need a constant supply of ATP. An organism that does not require O_2 as its final electron acceptor is called *anaerobic* (*an* = without; *aerob* = air) and performs anaerobic cellular respiration. Although they do not use oxygen, some anaerobic organisms are capable of using other inorganic or organic molecules as their final electron acceptors. The acceptor molecule might be sulfur, nitrogen, or other inorganic atoms or ions. It might also be an organic molecule, such as pyruvic acid ($CH_3COCOOH$).

Fermentation is the word used to describe anaerobic pathways that oxidize glucose to generate ATP energy by using an organic molecule as the ultimate hydrogen acceptor. Anaerobic respiration is the incomplete oxidation of glucose and results in the production of smaller hydrogen-containing organic molecules and energy in the form of ATP and heat. Many organisms that perform anaerobic cellular respiration use the glycolysis pathway to obtain energy from sugar molecules. Typically, glucose proceeds through the glycolysis pathway, producing pyruvic acid. The pyruvic acid then undergoes one of several alternative changes, depending on the kind of organism and the specific enzymes it possesses. Some organisms are capable of returning the electrons removed from sugar in the earlier stages of glycolysis to the pyruvic acid formed at the end of glycolysis. When this occurs, the pyruvic acid is converted into lactic acid, ethyl alcohol, acetone, or other organic molecules (figure 6.10). The organisms that produce ethyl alcohol have the enzymes necessary to convert pyruvic acid to ethyl alcohol (ethanol) and carbon dioxide. The formation of molecules such as alcohol and lactic acid is necessary to regenerate the NAD^+ needed for use in glycolysis. It must be done here, because it is not being regenerated by an ETS, as happens in aerobic respiration. Although many products can be formed from pyruvic acid, we will look at only two anaerobic pathways in detail.

Alcoholic Fermentation

Alcoholic fermentation is the anaerobic respiration pathway that yeast cells follow when oxygen is lacking in their environment. In this pathway, the pyruvic acid is converted to ethanol (a 2-carbon alcohol, C_2H_5OH) and carbon dioxide. Yeast cells then are able to generate only 4 ATPs from glycolysis. The cost for glycolysis is still 2 ATPs; thus, for each glucose a yeast cell oxidizes, it profits by 2 ATPs.



Fermentation Product	Possible Source	Importance
Lactic acid	Bacteria: *Lactobacillus bulgaricus*	Aids in changing milk to yogurt
	Homo sapiens Muscle cells	Produced when O_2 is limited; results in pain and muscle inaction
Ethyl alcohol +CO_2	Yeast: *Saccharomyces cerevisiae*	Brewing and baking

FIGURE 6.10 Fermentations
The upper portion of this figure is a simplified version of glycolysis. Many organisms can carry out the process of glycolysis and derive energy from it. The ultimate end product is determined by the kinds of enzymes the specific organism can produce. The synthesis of these various molecules is the organism's way of oxidizing NADH to regenerate NAD^+ and reducing pyruvic acid to a new end product.

Although during alcoholic fermentation yeasts get ATP and discard the waste products ethanol and carbon dioxide, these waste products are useful to humans. In making bread, the carbon dioxide is the important end product; it becomes trapped in the bread dough and makes it rise—the bread is *leavened*. Dough that has not undergone this process is called *unleavened*. The alcohol produced by the yeast evaporates

OUTLOOKS 6.1

Souring vs. Spoilage

The fermentation of carbohydrates to organic acid products, such as lactic acid, is commonly called *souring.* Cultured sour cream, cheese, and yogurt are produced by the action of fermenting bacteria. Lactic-acid bacteria of the genus *Lactobacillus* are used in the fermentation process. While growing in the milk, the bacteria convert lactose to lactic acid, which causes the milk to change from a liquid to a solid curd. The higher acid level also inhibits the growth of spoilage microorganisms.

Spoilage, or putrefaction, is the anaerobic respiration of proteins with the release of nitrogen and sulfur-containing organic compounds as products. Protein fermentation by the bacterium *Clostridium* produces foul-smelling chemicals such as putrescine, cadaverine, hydrogen sulfide, and methyl mercaptan. *Clostridium perfringens* and *C. sporogenes* are the two anaerobic bacteria associated with the disease gas gangrene. A gangrenous wound is a foul-smelling infection resulting from the fermentation activities of those two bacteria.

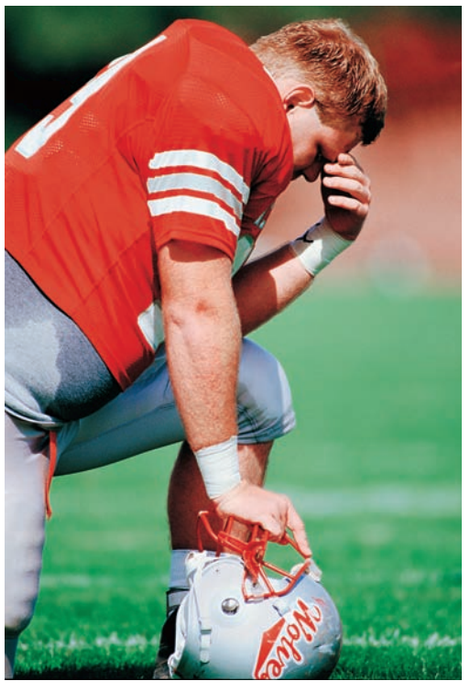
during the baking process. In the brewing industry, ethanol is the desirable product produced by yeast cells. Champagne, other sparkling wines, and beer are products that contain both carbon dioxide and alcohol. The alcohol accumulates, and the carbon dioxide in the bottle makes them sparkling (bubbly) beverages. In the manufacture of many wines, the carbon dioxide is allowed to escape, so these wines are not sparkling; they are called "still" wines.

Lactic Acid Fermentation

In **lactic acid fermentation,** the pyruvic acid ($CH_3COCOOH$) that results from glycolysis is converted to lactic acid ($CH_3CHOHCOOH$) by the transfer of electrons that had been removed from the original glucose. In this case, the net profit is again only 2 ATPs per glucose. The buildup of the waste product, lactic acid, eventually interferes with normal metabolic functions and the bacteria die. The lactic acid waste product from these types of anaerobic bacteria are used to make yogurt, cultured sour cream, cheeses, and other fermented dairy products. The lactic acid makes the milk protein coagulate and become puddinglike or solid. It also gives the products their tart flavor, texture, and aroma (Outlooks 6.1).

In the human body, different cells have different metabolic capabilities. Nerve cells must have a constant supply of oxygen to conduct aerobic cellular respiration. Red blood cells lack mitochondria and must rely on the anaerobic process of lactic acid fermentation to provide themselves with energy. Muscle cells can do either. As long as oxygen is available to skeletal muscle cells, they function aerobically. However, when oxygen is unavailable—because of long periods of exercise or heart or lung problems that prevent oxygen from getting to the skeletal muscle cells—the cells make a valiant effort to meet energy demands by functioning anaerobically.

While skeletal muscle cells are functioning anaerobically, they accumulate lactic acid. This lactic acid must ultimately be metabolized, which requires oxygen. Therefore, the accumulation of lactic acid represents an *oxygen debt,* which must be repaid in the future. It is the lactic acid buildup that makes muscles tired when we exercise. When the lactic acid concentration becomes great enough, lactic acid fatigue results. As a person cools down after a period of exercise, breathing and heart rate stay high until the oxygen debt is repaid and the level of oxygen in the muscle cells returns to normal. During



this period, the lactic acid that has accumulated is converted back into pyruvic acid. The pyruvic acid can then continue through the Krebs cycle and the ETS as oxygen becomes available. In addition to what is happening in the muscles, much of the lactic acid is transported by the bloodstream to the liver, where about 20% is metabolized through the Krebs cycle and 80% is resynthesized into glucose.

6.6 Metabolic Processing of Molecules Other Than Carbohydrates

Up to this point, we have discussed only the methods and pathways that allow organisms to release the energy tied up in carbohydrates (sugars). Frequently, cells lack sufficient carbohydrates for their energetic needs but have other materials from which energy can be removed. Fats and proteins, in addition to carbohydrates, make up the diet of many organisms. These three foods provide the building blocks for the cells, and all can provide energy. Carbohydrates can be digested to simple sugars, proteins can be digested to amino acids, and fats can be digested to glycerol and fatty acids. The basic pathways organisms use to extract energy from fat and protein are the same as for carbohydrates: glycolysis, the Krebs cycle, and the electron-transport system. However, there are some additional steps necessary to get fats and proteins ready to enter these pathways and several points in glycolysis and the Krebs cycle where fats and proteins enter to be respired.

Fat Respiration

A triglyceride (also known as a neutral fat) is a large molecule that consists of a molecule of glycerol with 3 fatty acids attached to it. Before these fats can be broken down to release energy, they must be converted to smaller units by digestive processes. Several enzymes are involved in these steps. The first step is to break the bonds between the glycerol and the fatty acids. Glycerol is a 3-carbon molecule that is converted into glyceraldehyde-3-phosphate. Because glyceraldehyde-3-phosphate is involved in one of the steps in glycolysis, it can enter the glycolysis pathway (figure 6.11). The remaining fatty acids are often long molecules (typically 14 to 20 carbons long), which also must be processed before they can be further metabolized. First, they need to enter the mitochondrion, where subsequent reactions take place. Once inside the mitochondrion, each long chain of carbons that makes up the carbon skeleton is hydrolyzed (split by the addition of a water molecule) into 2-carbon fragments. Next, each of the 2-carbon fragments is converted into acetyl. The acetyl molecules are carried into the Krebs cycle by coenzyme A molecules. Once in the Krebs cycle, they proceed through the Krebs cycle just like the acetyls from glucose (Outlooks 6.2).

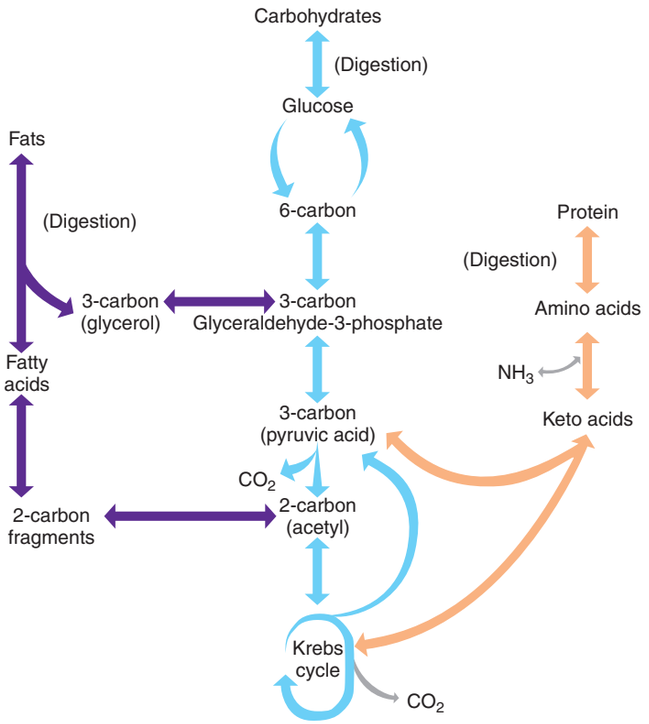


FIGURE 6.11 The Interconversion of Fats, Carbohydrates, and Proteins
Cells do not necessarily use all food as energy. One type of food can be changed into another type to be used as raw materials for the construction of needed molecules or for storage. Notice that many of the reaction arrows have two heads (i.e., these reactions can go in either direction). For example, glycerol can be converted into glyceraldehyde-3-phosphate and glyceraldehyde-3-phosphate can become glycerol.

By following the glycerol and each 2-carbon fragment through the cycle, you can see that each molecule of fat has the potential to release several times as much ATP as does a molecule of glucose. Each glucose molecule has 6 pairs of hydrogen, whereas a typical molecule of fat has up to 10 times that number. This is why fat makes such a good long-term energy storage material. It is also why it takes so long for people on a weight-reducing diet to remove fat. It takes time to use all the energy contained in the fatty acids. On a weight basis, there are twice as many calories in a gram of fat as there are in a gram of carbohydrate.

In summary, fats are an excellent source of energy and the storage of fat is an important process. Furthermore, other kinds of molecules can be converted to fat. You already know that people can get fat from eating sugar. Notice in figure 6.12 that both carbohydrates and fats can enter the Krebs cycle and release energy. Although people require both fats

OUTLOOKS 6.2

Lipid Metabolism and Ketoacidosis

In starvation and severe diabetes mellitus, the body does not metabolize sugars properly, and it shifts to using fats as its main source of energy. When this occurs, the Krebs cycle is unable to perform as efficiently and the acetyl CoA does not move into the mitochondria. It accumulates in the blood. To handle this problem, the liver converts the acetyl CoA to *ketone bodies.*

Ketone bodies include compounds such as acetoacetic acid, β-hydroxybutryic acid, and acetone. As ketone bodies accumulate in the blood, the pH decreases and the person experiences *ketosis,* or *ketoacidosis,* with symptoms such as an increased breathing rate; in untreated cases, it can lead to depression of the central nervous system, coma, and death.

and carbohydrates in their diets, they need not be in precise ratios; the body can make some interconversions. This means that people who eat excessive amounts of carbohydrates will deposit body fat. It also means that people who starve can generate glucose by breaking down fats and using the glycerol to synthesize glucose. **nutrition, p. 542**

Protein Respiration

Proteins can be catabolized and interconverted just as fats and carbohydrates are (review figure 6.12). The first step in using protein for energy is to digest the protein into individual amino acids. Each amino acid then needs to have the amino group (—NH_2) removed. The remaining carbon skeleton, a keto acid, enters the respiratory cycle as acetyl, pyruvic acid, or one of the other types of molecules found in the Krebs cycle. As the acids progress through the Krebs cycle, the electrons are removed and sent to the ETS, where their energy is converted into the chemical-bond energy of ATP. The amino group that was removed from the amino acid is converted into ammonia. Some organisms excrete ammonia directly; others convert ammonia into other nitrogen-containing compounds, such as urea or uric acid. All of these molecules are toxic and must be eliminated. They are transported in the blood to the kidneys, where they are eliminated. In the case of a high-protein diet, increasing fluid intake will allow the kidneys to remove the urea or uric acid efficiently. **kidneys, p. 535**

When proteins are eaten, they are digested into their component amino acids. These amino acids are then available to be used to construct other proteins. Proteins cannot be stored; if they or their component amino acids are not needed immediately, they will be converted into fat or carbohydrates or will be metabolized to provide energy. This presents a problem for individuals who do not have ready access to a continuous source of amino acids in their diet (e.g., individuals on a low-protein diet). If they do not have a source of dietary protein, they must dismantle proteins from important cellular components to supply the amino acids they need. This is why proteins and amino acids are considered an important daily food requirement.

One of the most important concepts is that carbohydrates, fats, and proteins can all be used to provide energy. The fate of any type of nutrient in a cell depends on the cell's momentary needs. An organism whose daily food-energy intake exceeds its daily energy expenditure will convert only the necessary amount of food into energy. The excess food will be interconverted according to the enzymes present and the organism's needs at that time. In fact, glycolysis and the Krebs cycle allow molecules of the three major food types (carbohydrates, fats, and proteins) to be interchanged.

As long as a person's diet has a certain minimum of each of the three major types of molecules, a cell's metabolic machinery can manipulate molecules to satisfy its needs. If a person is on a starvation diet, the cells will use stored carbohydrates first. Once the carbohydrates are gone (after about 2 days), the cells will begin to metabolize stored fat. When the fat is gone (after few days to weeks), the proteins will be used. A person in this condition is likely to die (How Science Works 6.1).

HOW SCIENCE WORKS 6.1

Applying Knowledge of Biochemical Pathways

As scientists have developed a better understanding of the processes of aerobic cellular respiration and anaerobic cellular respiration, several practical applications of this knowledge have developed:

- Although for centuries people have fermented beverages such as beer and wine, they were often plagued by sour products that were undrinkable. Once people understood that there were yeasts that produced alcohol under *anaerobic* conditions and bacteria that converted alcohol to acetic acid under *aerobic* conditions, it was a simple task to prevent acetic acid production by preventing oxygen from getting to the fermenting mixture.
- When it was discovered that the bacterium that causes gas gangrene is anaerobic and is, in fact, poisoned by the presence of oxygen, various oxygen therapies were developed to help cure patients with gangrene. Some persons with gangrene are placed in *hyperbaric chambers,* with high oxygen levels under pressure. In other patients, only the affected part of the body is enclosed. Under such conditions, the gangrene-causing bacteria die or are inhibited.
- Because many disease-causing organisms are prokaryotic and have somewhat different pathways and enzymes than do eukaryotic organisms, it is possible to develop molecules, antibiotics, that selectively interfere with the enzymes of prokaryotes without affecting eukaryotes, such as humans.
- When physicians recognized that the breakdown of fats releases ketone bodies, they were able to diagnose diseases such as diabetes and anorexia more easily, because people with these illnesses have bad breath.

High-Efficiency Anaerobic Bioreactors

Hyperbaric Chamber

Summary

In aerobic cellular respiration, organisms convert foods into energy (ATP) and waste materials (carbon dioxide and water). Three distinct metabolic pathways are involved in aerobic cellular respiration: glycolysis, the Krebs cycle, and the electron transport system. Glycolysis takes place in the cytoplasm of the cell, and the Krebs cycle and electron-transport system take place in mitochondria. Organisms that have oxygen can perform aerobic cellular respiration. Organisms and cells that do not use oxygen perform anaerobic cellular respiration (fermentation) and can use only the glycolysis pathway. Aerobic cellular respiration yields much more ATP than anaerobic cellular respiration. Glycolysis and the Krebs cycle serve as a molecular interconversion system: Fats, proteins, and carbohydrates are interconverted according to the cell's needs.

Key Terms

Use the interactive flash cards on the ***Concepts in Biology,*** *12/e website to help you learn the meaning of these terms.*

acetyl 116
alcoholic fermentation 122
aerobic cellular respiration 113
autotrophs 112
cellular respiration 112
chemosynthesis 112
electron-transport system (ETS) 115
fermentation 122
glycolysis 114
heterotrophs 112
Krebs cycle 114
lactic acid fermentation 123

Basic Review

1. Organisms that are able to use basic energy sources, such as sunlight, to make energy-containing organic molecules from inorganic raw materials are called
   a. autotrophs.
   b. heterotrophs.
   c. aerobic.
   d. anaerobic.
2. Cellular respiration processes that do not use molecular oxygen are called
   a. heterotrophic.
   b. anaerobic.
   c. aerobic.
   d. anabolic.
3. The chemical activities that remove electrons from glucose result in the glucose being
   a. reduced.
   b. oxidized.
   c. phosphorylated.
   d. hydrolysed.
4. The positively charged hydrogen ions that are released from the glucose during cellular respiration eventually combine with _____ ion to form _____.
   a. another hydrogen, a gas
   b. a carbon, carbon dioxide
   c. an oxygen, water
   d. a pyruvic acid, lactic acid
5. The Krebs cycle and ETS are biochemical pathways performed in which eukaryotic organelle?
   a. nucleus
   b. ribosome
   c. chloroplast
   d. mitochondria
6. In a complete accounting of all the ATPs produced in aerobic cellular respiration, there are a total of _____ ATPs: _____ from the ETS, _____ from glycolysis, and _____ from the Krebs cycle.
   a. 36, 32, 2, 2
   b. 38, 34, 2, 2
   c. 36, 30, 2, 4
   d. 38, 30, 4, 4
7. Anaerobic pathways that oxidize glucose to generate ATP energy by using an organic molecule as the ultimate hydrogen acceptor are called
   a. fermentation.
   b. reduction.
   c. Krebs.
   d. electron pumps.
8. When skeletal muscle cells function anaerobically, they accumulate the compound _____, which causes muscle soreness.
   a. pyruvic acid
   b. malic acid
   c. carbon dioxide
   d. lactic acid
9. Each molecule of fat can release _____ of ATP, compared with a molecule of glucose.
   a. smaller amounts
   b. the same amount
   c. larger amounts
   d. only twice the amount
10. Some organisms excrete ammonia directly; others convert ammonia into other nitrogen-containing compounds, such as
    a. urea or uric acid.
    b. carbon dioxide.
    c. sweat.
    d. fat.

Answers

1. a 2. b 3. b 4. c 5. d 6. a 7. a 8. d 9. c 10. a

Concept Review

*Answers to the Concept Review questions can be found on the **Concepts in Biology,** 12/e website.*

6.1 Energy and Organisms

1. How do autotrophs and heterotrophs differ?
2. What is chemosynthesis?
3. How are respiration and photosynthesis related to autotrophs and heterotrophs?

6.2 Aerobic Cellular Respiration—an Overview

4. Aerobic cellular respiration occurs in three stages. Name these and briefly describe what happens in each stage.
5. Which cellular organelle is involved in the process of respiration?

6.3 The Metabolic Pathways of Aerobic Cellular Respiration

6. For glycolysis, the Krebs cycle, and the electron-transport system, list two molecules that enter and two molecules that leave each pathway.

7. How is each of the following involved in aerobic cellular respiration: NAD^+, pyruvic acid, oxygen, and ATP?

6.4 Aerobic Cellular Respiration in Prokaryotes

8. How is aerobic cellular respiration different between prokaryotic and eukaryotic organisms?

6.5 Anaerobic Cellular Respiration

9. Describe how glycolysis and the Krebs cycle can be used to obtain energy from fats and proteins.

6.6 Metabolic Processing of Molecules Other Than Carbohydrates

10. What are the differences between fat and protein metabolism biochemical pathways?
11. Describe how carbohydrates, fats, and proteins can be interconverted from one to another.

Thinking Critically

For guidelines to answer this question, visit the ***Concepts in Biology,*** *12/e website.*

Picture yourself as an atom of hydrogen tied up in a molecule of fat. You are present in the stored fat of a person who is starving. Trace the biochemical pathways you would be part of as you moved through the process of aerobic cellular respiration. Be as specific as you can in describing your location and how you got there, as well as the molecules of which you are a part. Of what molecule would you be a part at the end of this process?