chapter 31

Energy and Enzymes:
Life's Driving and Controlling Forces

Outline

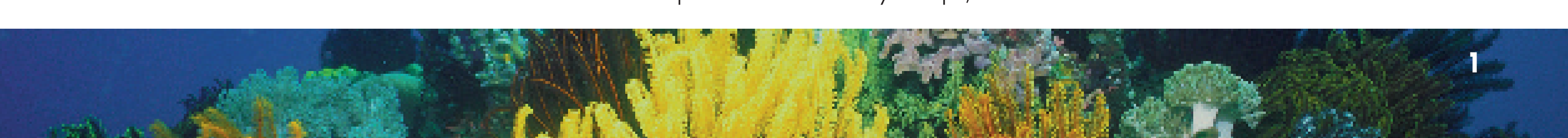
What Is Energy?
The Laws of Energy Transformations
Activation Energy
Enzymes: Biological Catalysts
- Enzyme Structure
- Enzyme Function
- Factors Affecting Enzyme Activity

Cofactors and Coenzymes
ATP: The Cell's Energy Currency
- How Cells Convert Energy: An Overview

Concepts

1. Energy drives all life processes in a cell. Energy is the capacity to do work. It can exist in two forms: Kinetic energy is actively involved in doing work, and potential energy is stored for future use.
2. The cell obtains energy by utilizing chemical fuel and by obeying the first and second laws of thermodynamics.
3. The speed of a chemical reaction depends on the activation energy necessary to initiate it. Catalysts reduce the amount of activation energy necessary to initiate a chemical reaction and, therefore, speed up the reaction. Cells use specialized proteins and nucleic acids (RNA) called enzymes as biological catalysts.
4. Any factor (e.g., temperature, pH, and other chemicals) that alters an enzyme's shape affects the enzyme's activity. Cofactors are metal ions or organic molecules that facilitate enzyme activity. Specific cofactors that are nonprotein organic molecules are called coenzymes.
5. ATP is the universal energy currency of all cells.

This chapter contains evolutionary concepts, which are set off in this font.



An animal's use of the sun's radiant energy begins with photosynthetic plants (and certain microorganisms) "capturing" that energy and converting it to chemical energy in the form of carbohydrates. Because plants capture the sun's energy, they are **primary producers.** A **primary consumer** is a plant-eating animal, or herbivore (L. *herba,* grass + *vorare,* to devour), that obtains organic molecules by eating producers or their products. Primary consumers use the energy in organic molecules to carry out all of their cellular activities, including the synthesis of complex organic molecules. Primary consumers are preyed on by other animals, the **secondary consumers,** and so on, in what is termed a **food chain.** As each organism dies, its constituents are broken down by digestion or by various **decomposers,** such as bacteria and fungi. This producer-consumer-decomposer sequence in a food chain represents a flow of both energy and matter in an ecosystem. An **ecosystem** is an array of organisms and their physical environment, all interacting through a one-way flow of energy and a cycling of materials.

Nutrients are continuously being broken down to provide the energy necessary for life. In fact, life is a constant flow of energy that an animal or plant channels to do the work of living. This "living chemistry" is called metabolism. **Metabolism** (Gr. *metaballein,* to change) is the total of all the chemical reactions occurring in a cell. It involves the acquisition and use of energy in stockpiling, breaking down, assembling, and eliminating substances to ensure the maintenance, growth, and reproduction of the organisms. Metabolism consists of synthetic processes called **anabolism** (Gr. *anabole,* building up) and degrading processes called **catabolism** (Gr. *katabole,* breaking down). This chapter focuses on what energy is, how an animal uses it, and how enzymes control metabolism.

What Is Energy?

Energy is the capacity to do work. **Work** is the transfer of energy. Energy can also be transformed. For example, a plant can transform solar (radiant) energy into chemical energy. The plant can then be burned in a steam generator and the energy transformed into the energy of motion (e.g., the turning of a wheel). Energy has many forms: the heat from a furnace, the sound of a jet plane, the electric current that lights a bulb, the radioactivity in a heart pacemaker, or the pull of a magnet.

Energy exists in two states: kinetic and potential. **Kinetic energy** is the energy of motion (e.g., a thundering waterfall). **Potential energy** is stored energy (e.g., a giant boulder poised on a pinnacle). In a living animal, energy in chemical bonds is a form of potential energy. Animals use the bond energy in organic molecules to accomplish biological work. Much of the work an animal performs involves the transformation of potential energy to kinetic energy in its cells.

The most convenient way to measure energy is in terms of heat production. This is why the study of energy is called **thermodynamics** (Gr. *therme,* heat + *dynamis,* power). The most commonly employed unit for measuring heat in an animal is the **kilocalorie (kcal)** or nutritional **Calorie** (notice the large "C"). A kilocalorie is the amount of heat necessary to raise 1 kg of water 1° C and is equal to 1,000 calories. A reasonable daily intake of energy for an average person is approximately 2,000 to 2,500 kcal. A **calorie** (notice the small "c") is the amount of heat it takes to raise the temperature of 1 g (1 cc) of water 1° C (usually from 14.5 to 15.5° C).

The Laws of Energy Transformations

Two laws of thermodynamics govern energy transformations. The **first law of thermodynamics,** sometimes called the law of energy conservation, states that energy can neither be created nor destroyed, only transformed. What this means is that energy can change from one form to another (e.g., electrical energy passes through a hot plate to produce heat energy) or can be transformed from potential to kinetic energy (e.g., a squirrel eats a nut and then uses this energy to climb a tree), but it can never be lost or created. Thus, the total amount of energy in the universe remains constant.

The **second law of thermodynamics** states that all objects in the universe tend to become more disordered and that the total amount of disorder in the universe is continually increasing. The measure of this degree of disorganization is called **entropy.** Consider this simple illustration: When natural gas burns in a stove, the potential chemical energy stored in the bonds of the gas molecules is converted to light (the blue flame) and heat. Some of the heat energy can be used to boil water on the stove, and some is dissipated into the kitchen, where it is no longer available to do work. This unusable energy represents increased entropy.

Activation Energy

Most chemical reactions require an input of energy to start (e.g., a match is lit, and the heat energy is used to start wood burning in a fireplace). At the chemical level, input energy must break existing chemical bonds before new bonds can form. In thermodynamics, this input energy is called activation energy (figure 31.1).

In a reaction with a net release of energy, the reactant contains more energy than the products. In other words, the amount of this excess energy (called "free energy") released into the environment is greater than the activation energy required to initiate the reaction. These reactions occur spontaneously and are called **exergonic** (L. *ex,* out + Gr. *ergon,* work) (figure 31.2*a*). In contrast, a chemical reaction in which the product contains more energy than the reactants requires a greater input of energy from the environment than is released (figure 31.2*b*). Because these reactions do not occur spontaneously, they are called **endergonic** (Gr. *endon,* within + *ergon,* work).

The amount of reactant substance(s) converted to product substance(s) in a given period of time is the reaction rate. The

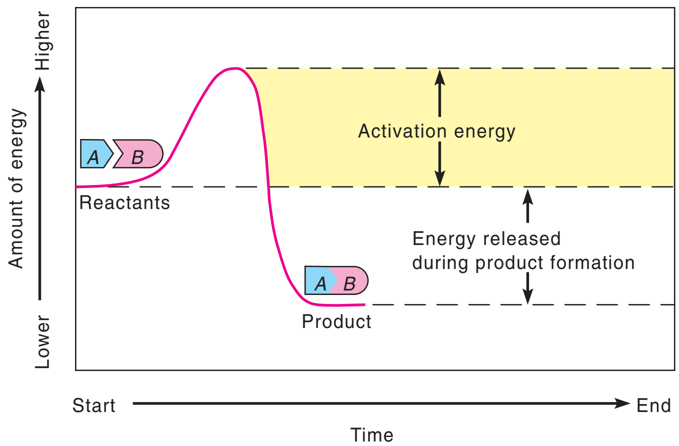


FIGURE 31.1

Energy Diagram. Before a chemical reaction occurs, energy must be supplied to destabilize existing chemical bonds. This energy is called activation energy.

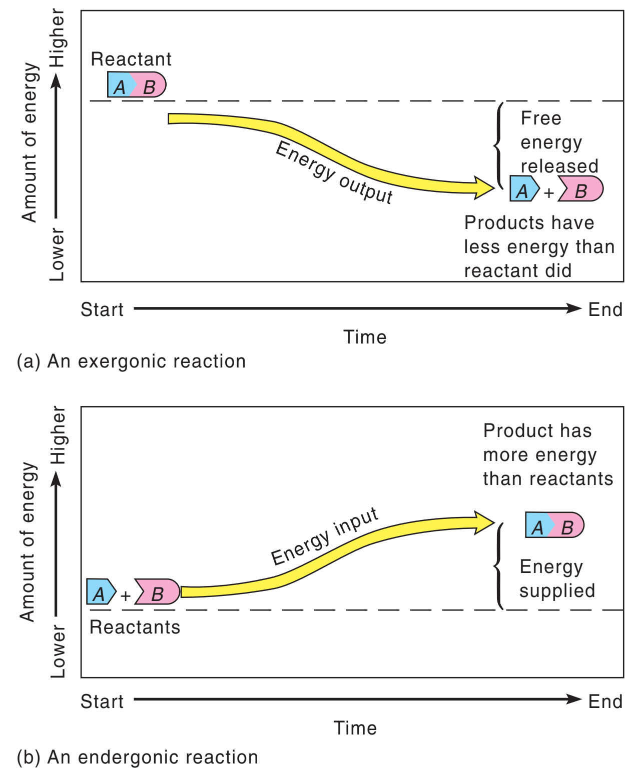


FIGURE 31.2

Exergonic and Endergonic Reactions. *(a)* In an exergonic reaction, the products have less energy than the reactant, and excess energy is released to the environment. *(b)* In an endergonic reaction, the product of the reaction contains more energy than the reactants, so energy input is needed for the reaction to occur.

reaction rate of an exergonic reaction does not depend on how much energy the reaction releases, but on the amount of activation energy required for the reaction to begin. The larger the activation energy of a chemical reaction, the more slowly the reaction occurs, because at a given temperature, fewer molecules succeed in overcoming the initial energy hurdle. However, activation energies are not fixed. For example, when certain chemical bonds are stressed, they may break more easily. Affecting a chemical bond in a way that lowers the activation energy of a reaction is **catalysis.** Any substance that performs catalysis is called a catalyst. A **catalyst** (Gr. *kata,* down + *lysis,* a loosening) is a substance that accelerates the rate of a chemical reaction (or allows it to proceed at a lower environmental temperature) by decreasing the activation energy, without itself being used up in the reaction (figure 31.3). In cells, catalysts are almost always protein enzymes.

ENZYMES: BIOLOGICAL CATALYSTS

Most enzymes are proteins; some (**ribozymes**) are nucleic acids (RNA). Enzymes have enormous catalytic power; they greatly enhance the rate at which specific chemical reactions take place. The metabolism of an animal is organized and controlled specifically at the points where catalysis takes place. Therefore, one of the most important foundations in all of biology is that life is a series of chemical processes that enzymes regulate. An **enzyme** (Gr. *enzymos,* leavened) is a biological catalyst that can accelerate a specific chemical reaction by lowering the required activation energy but is unaltered in the process. In other words, the same reaction would have occurred to the same degree in the absence of the catalyst, but it would have progressed at a much slower rate. Because it is unaltered, the enzyme can be used over and over.

An enzyme is extremely selective for the reaction it will catalyze. The reactants of enzymatic reactions are called **substrates.** The precise "fit" between an enzyme and its specific substrate is crucial to cell metabolism. For example, cellular concentrations of many reactants must be kept at low levels to avoid undesirable side reactions. At the same time, concentrations must remain high enough for the required reactions to occur at a rate compatible with life. Metabolism proceeds under these seemingly conflicting conditions because enzymes channel molecules into and through specific chemical pathways. With the exception of the several digestive enzymes that were the first to be discovered (e.g., pepsin and trypsin), all enzyme names end with the suffix ase and are named after their substrate.

ENZYME STRUCTURE

Enzymes are three-dimensional globular protein molecules or nucleic acids with at least one surface region having a crevice or pocket. This crevice occupies only a small portion of the enzyme's surface and is known as the enzyme's active site (figure 31.4). This site is shaped so that a substrate molecule (or several substrate molecules, depending on the reaction) fits into it in a very specific way and is held in place by weak chemical forces, such as hydrogen bonds. Binding of the substrate to the enzyme changes

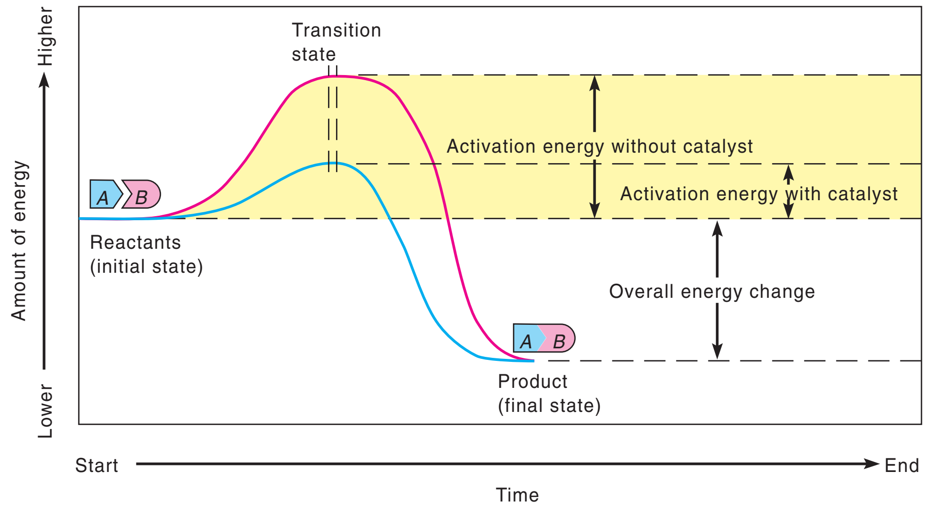


FIGURE 31.3

Function of a Catalyst. Catalysts lower the amount of activation energy required to initiate a chemical reaction. As a result, at the same temperature, the reaction moves to completion much more quickly.

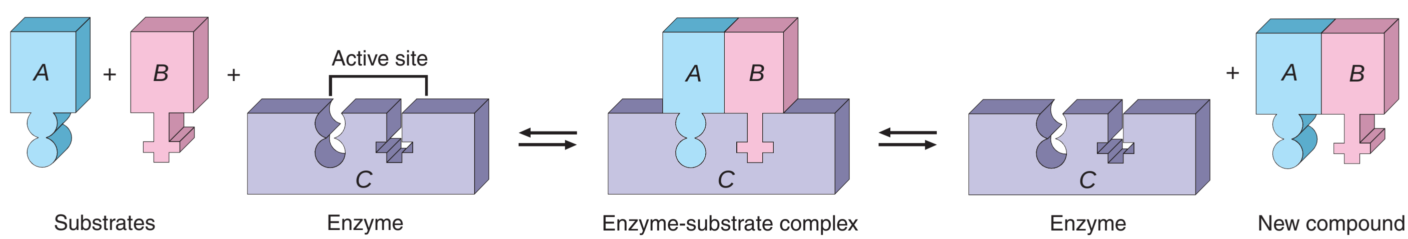


FIGURE 31.4

Enzymes. Enzyme action is like an induced fit. Substrate molecules *A* and *B* fit into the active site of enzyme *C*, forming an enzyme-substrate complex *A* and *B* react to form the new compound *AB*. *AB* is released from the enzyme, and the enzyme recycles. From Ricki Lewis, *Life*, 2d ed. New York, McGraw-Hill. Reprinted by permission of The McGraw-Hill Companies.

the enzyme's shape, a phenomenon called **induced fit.** Induced fit is like a clasping handshake. The active site's embrace of the substrate brings chemical groups of the active site into positions that enhance their ability to work on the substrate and to catalyze the chemical reaction. When the reaction is complete, the product (new compound) of the catalyzed reaction is released, and the enzyme resumes its initial conformation (shape), ready to catalyze another chemical reaction.

Enzyme Function

When a substrate molecule binds to an enzyme's active site, an **enzyme-substrate complex (ES)** forms. This is the essential first step in enzyme catalysis and can be summarized as follows:

$$\text{Enzyme} + \text{substrate} \rightleftharpoons \text{enzyme-substrate complex} \rightleftharpoons \text{products} + \text{enzyme}$$

Once the unstable, high-energy ES forms, amino acid side groups of the enzyme are placed against certain bonds of the substrate. These side groups stress or distort the substrate bonds, lowering the activation energy needed to break the bonds. The bonds break, releasing the substrate, which now reacts to produce the final product and release the enzyme.

Factors Affecting Enzyme Activity

Any condition that alters the three-dimensional shape of an enzyme also affects the enzyme's activity. Two factors that affect enzyme activity are temperature and pH.

As presented in chapter 2, the shape of a protein or nucleic acid is determined largely by its hydrogen bonds (*see figure 2.15*). Temperature changes easily disrupt hydrogen bonds. For example, most higher vertebrates, such as birds and mammals, have enzymes that function best within a relatively narrow temperature

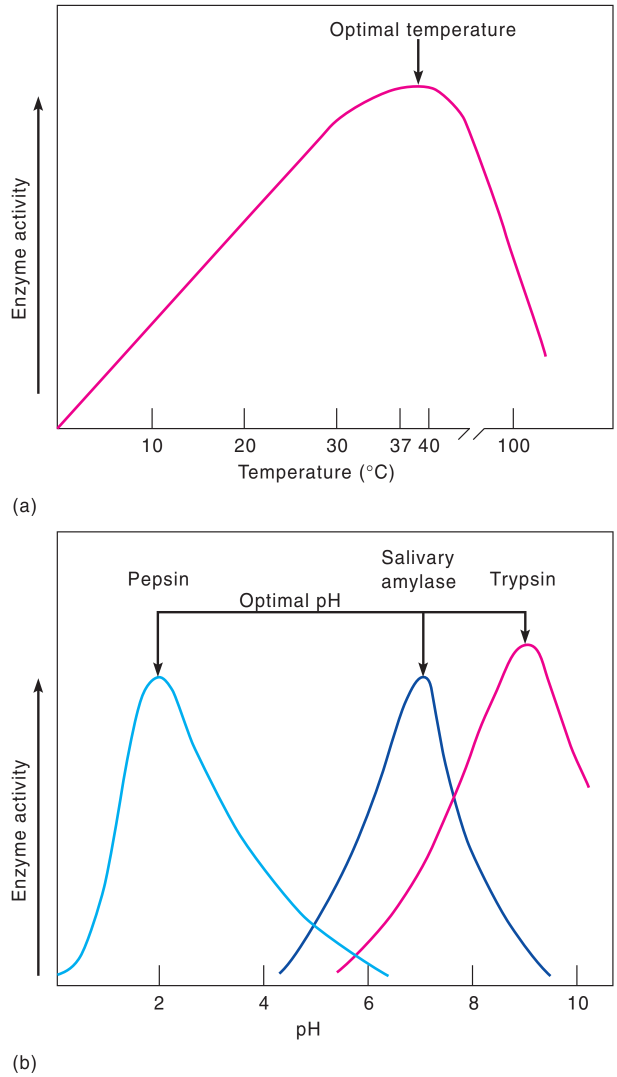


FIGURE 31.5

How the Environment Affects Enzymes. *(a)* Effect of temperature on enzyme activity. *(b)* Effect of pH on three different enzymes. From Stuart Ira Fox, *Human Physiology*, 4th ed. New York, McGraw-Hill. Reprinted by permission of The McGraw-Hill Companies.

range (between 35 and 40° C) (figure 31.5*a*). Below 35° C, the bonds that determine protein shape are not flexible enough to permit the shape change necessary for substrate to fit into a reactive site. Above 40° C, the bonds are too weak to hold the protein in proper position and to maintain its shape. When proper shape is lost, the enzyme is, in essence, destroyed; this loss of shape is called **denaturation.**

Most enzymes also have a pH optimum, usually between 6 and 8 (figure 31.5*b*). For example, when the pH is too low, the H^+ ions combine with the R groups of the enzyme's amino acids, reducing their ability to bind with substrates. Acidic environments can also denature enzymes not adapted to such conditions. Some

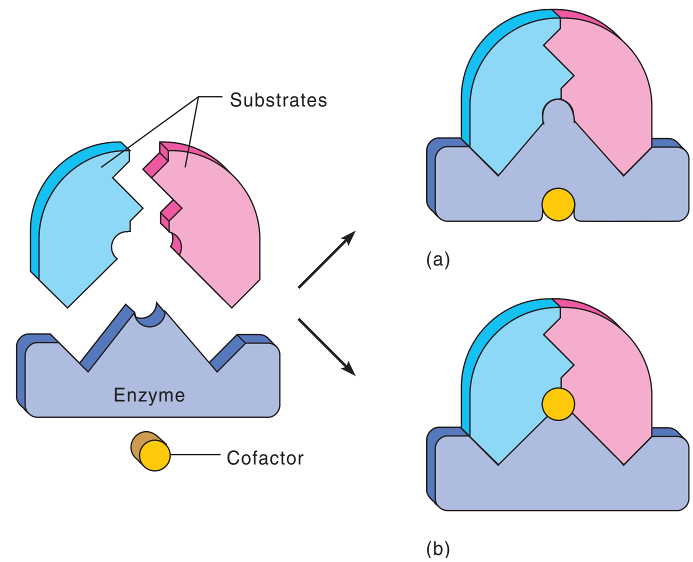


FIGURE 31.6

Cofactors. *(a)* The cofactor changes the conformation of the active site, permitting a better fit between the enzyme and the substrate. *(b)* The cofactor participates in the temporary bonding between the active site of the enzyme and the substrate.

enzymes, however, function at a low pH. For example, pepsin (the enzyme found in the stomach of mammals) has an optimal pH of approximately 2. Pepsin functions at such a low pH because it has an amino acid sequence that maintains its ionic and hydrogen bonds, even in the presence of large numbers of H^+ ions (low pH). Conversely, trypsin is active in the more basic medium (pH 9) found in the small intestine of mammals. Overall, the pH optimum of an enzyme reflects the pH of the body fluid in which the enzyme is found.

COFACTORS AND COENZYMES

Cofactors are metal ions, such as Ca^{2+}, Mg^{2+}, Mn^{2+}, Cu^{2+}, and Zn^{2+}. Many enzymes must use these metal ions to change a nonfunctioning active site to a functioning one. In these enzymes, the attachment of a cofactor changes the shape of the protein and allows it to combine with its substrate (figure 31.6*a*). The cofactors of other enzymes participate in the temporary bonds between the enzyme and its substrate when the enzyme-substrate complex forms (figure 31.6*b*).

Coenzymes are nonprotein, organic molecules that participate in enzyme-catalyzed reactions, often by transporting electrons, in the form of hydrogen atoms, from one enzyme to another. Many vitamins (e.g., niacin and riboflavin) function as coenzymes or are used to make coenzymes. Just as a taxi transports people around a city, so coenzymes transport energy, in the form of hydrogen atoms, from one enzyme to another.

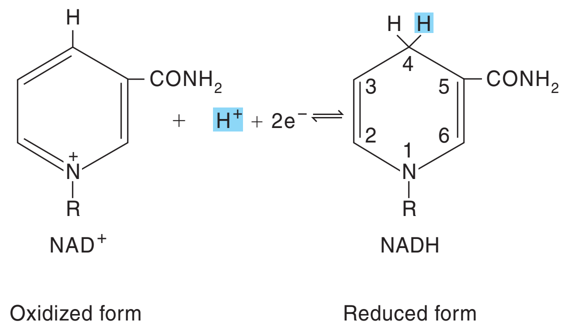


FIGURE 31.7

Nicotinamide Adenine Dinucleotide (NAD): Oxidized (NAD^+) and Reduced (NADH) Forms. When NAD is reduced, one electron attaches to the nitrogen atom at position 1. The second electron attaches to a carbon atom at position 4 and is accompanied by a hydrogen ion.

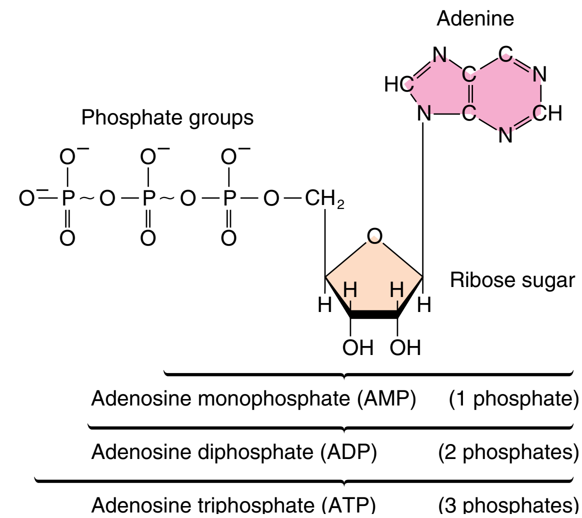


FIGURE 31.8

Structural Formula for Adenosine Triphosphate, or ATP. The ATP molecule is the primary energy currency of the cell. It consists of an adenine portion, the sugar ribose, and three phosphates. The wavy lines (tildes) connecting the last two phosphates represent high-energy chemical bonds that can quickly release energy.

One of the most important coenzymes in the cell is the hydrogen acceptor **nicotinamide adenine dinucleotide (NAD^+)**, which is made from a B vitamin. When NAD^+ acquires a hydrogen atom from an enzyme, it reduces to NADH (figure 31.7). The electron of the hydrogen atom contains energy that the NADH molecule then carries. For example, when various foods are oxidized in the cell, the cell strips electrons from the food molecules and transfers them to NAD^+, which reduces to NADH.

ATP: The Cell's Energy Currency

The major energy currency of all cells is a nucleotide called **adenosine triphosphate (ATP).** Because ATP plays a central role as the energy currency in all organisms, it must have appeared early in the history of life.

The ability of ATP to store and release energy stems from the molecule's structure. Each ATP molecule has three subunits: (1) adenine, an organic molecule composed of two carbon-nitrogen rings; (2) ribose, a five-carbon sugar; and (3) three phosphate groups in a linear chain (figure 31.8). The covalent bond connecting these phosphates is indicated by the "tilde" symbol (~) and is a high-energy bond. However, the energy is not localized in the bond itself; it is a property of the entire molecule and is simply released as the phosphate bond breaks. These bonds have a low activation energy and break easily. The breaking of one bond releases about 7.3 kcal (7,300 calories) per mole of ATP as follows:

$$\text{ATP} + H_2O \rightarrow \text{ADP} + P_i + \text{energy (7.3 kcal/mole)}$$

The energy from ATP is sufficient to drive most of the cell's endergonic reactions. In a typical energy reaction, only the outermost of the two high-energy bonds breaks (is hydrolyzed). When this happens, ATP becomes **ADP (adenosine diphosphate).** In some cases, ADP is hydrolyzed to **AMP (adenosine monophosphate)** as follows:

$$\text{ADP} + H_2O \rightarrow \text{AMP} + P_i + \text{energy (7.3 kcal/mole)}$$

Cells contain a reservoir of ADP and phosphate (P_i). As long as a cell is living, ATP is constantly being cleaved into ADP plus phosphate to drive the cell's many energy-requiring processes, enabling the animal to perform biological work (figure 31.9). However, ATP cannot be stored for long. Once formed, ATP lasts only a few seconds before it is used to perform biological work. Thus, cells constantly recycle ADP. With the energy derived from foodstuffs and from stored fats and starches, ADP and phosphate recombine to form ATP, with 7.3 kcal of energy per mole contributed to each newly formed high-energy phosphate bond.

How Cells Convert Energy: An Overview

Within their cells, animals make ATP in two ways: substrate-level phosphorylation and chemiosmosis. As noted earlier, ATP formation from ADP and phosphate requires the input of energy (the same 7.3 kcal released when ATP is hydrolyzed). To get this energy, the reaction is coupled with an exergonic reaction (figure 31.10*a*). An enzyme transfers a phosphate group to ADP from a substrate with a phosphate bond even more easily broken than that of ATP (i.e., the energy from the exergonic reaction is greater

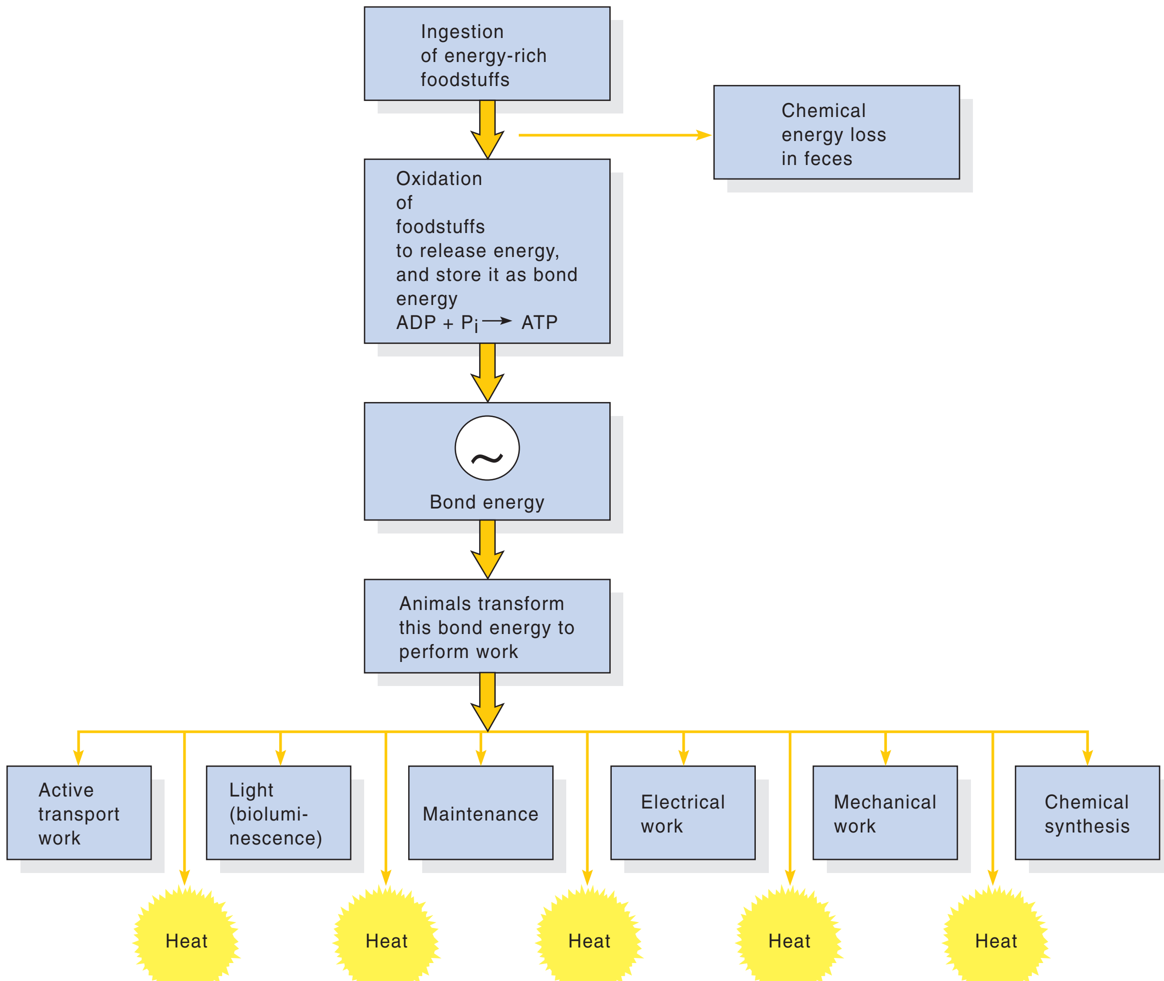


FIGURE 31.9
Some Energy Utilization Pathways in Animals. Notice that heat is lost in every transformation.

than the energy input necessary to drive ATP synthesis). The generation of ATP by coupling strongly exergonic reactions with ATP synthesis from ADP and phosphate is called **substrate-level phosphorylation.** Substrate-level phosphorylation probably appeared very early in the history of organisms because (1) organisms' initial use of carbohydrates as an energy source is accomplished by substrate-level phosphorylation; (2) the mechanism for substrate-level phosphorylation is present in most living animal cells; and (3) substrate-level phosphorylation is one of the most fundamental of all ATP-generating reactions.

Although substrate-level phosphorylation may be the oldest method of generating ATP, far more ATP is generated from another process, called **chemiosmosis** (figure 31.10*b*). Organisms possess transmembrane channels in their mitochondrial membranes that can pump protons. These proton pumps use a flow of electrons to induce a shape change in the protein, which, in turn, causes protons to move out of the inner compartment of a mitochondrion. As the proton (H^+) concentration in the outer compartment of the mitochondrion becomes greater than that of the inside compartment, the outer protons are driven across the membrane by an electrical-chemical proton gradient. As protons move down this gradient between outer and inner mitochondrial compartments, they induce the formation of ATP from ADP, phosphate, and the enzyme ATP synthetase.

The electrons that drive the electron transport system involved in chemiosmosis are obtained from chemical bonds of food molecules in all organisms and from photosynthesis in plants. This electron-stripping process is called **cellular respiration,** or **aerobic respiration** because free oxygen is needed. Basically, aerobic respiration is the oxidation of food molecules to obtain energy.

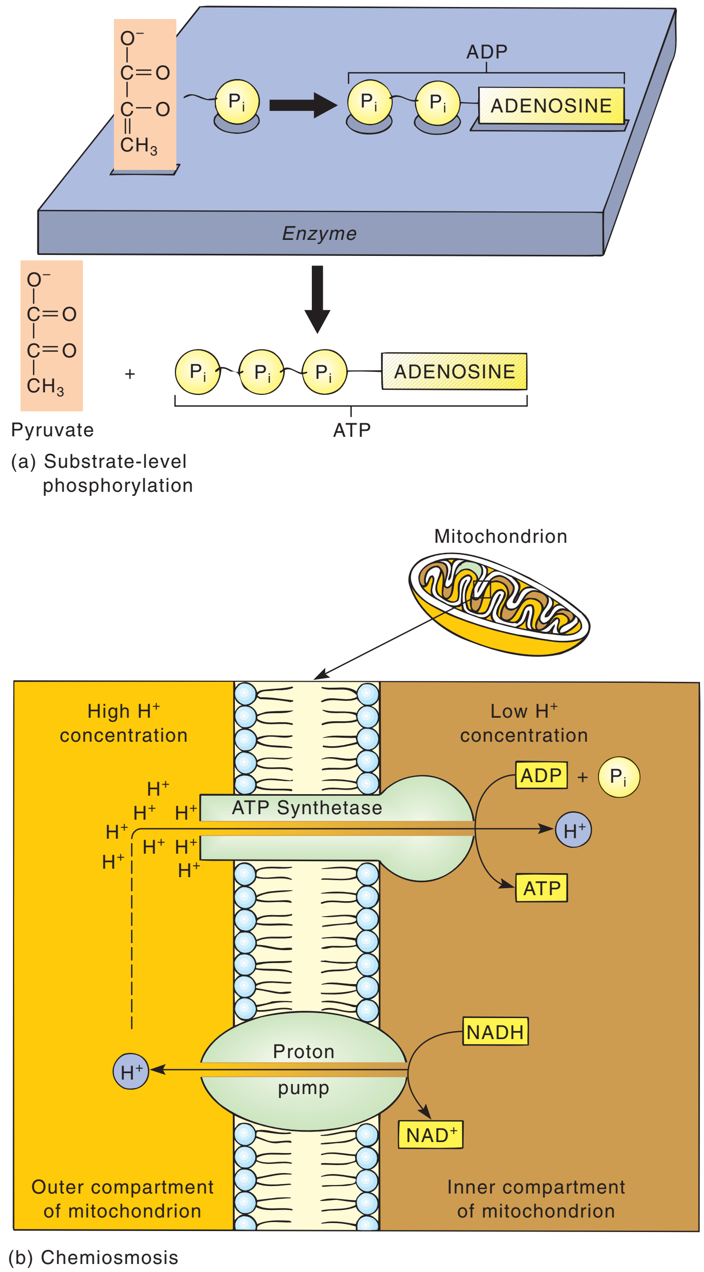


FIGURE 31.10

ATP Generation. *(a)* Substrate-level phosphorylation. In this example, a phosphate group is transferred from an enzyme-substrate complex to ADP to form ATP. This reaction takes place because the high-energy bond of the substrate has higher energy than the phosphate bonds of ADP. *(b)* Chemiosmosis occurs as hydrogen ions cross from one side of a membrane to the other, generating a proton gradient across the membrane. When protons move back across the membrane through special channels, their passage generates ATP from ADP and P_i.

Summary

1. Energy is the capacity to do work. Kinetic energy is the energy that is actively engaged in doing work, whereas potential energy is stored energy. Animals convert potential energy into kinetic energy to perform biological work, which is the transfer of energy.
2. The first law of thermodynamics states that the amount of energy in the universe is fixed and that energy cannot be created or destroyed. However, energy can be converted from one form to another.
3. The second law of thermodynamics states that the randomness or disorder in the universe is increasing. This process is called entropy.
4. The speed of a chemical reaction depends on the amount of activation energy required to break existing bonds. Catalysis is the chemical process of increasing the reaction rate by lowering the amount of activation energy required to initiate the reaction. Enzymes are the biological catalysts of cells.
5. Enzymes have a specific three-dimensional shape, with one or more reactive sites that bind substrates. Cells contain many different enzymes, each of which catalyzes a different chemical reaction.
6. Factors such as temperature, pH, substrate concentration, cofactors, and coenzymes can affect the reaction rate of an enzyme.
7. Cells focus their energy resources on the manufacture of ATP from ADP and phosphate, a process that require cells to supply 7.3 kcal/mole of energy, which it obtains from electrons stripped from foodstuffs. Mitochondrial membranes are the main site of ATP production. Cells use ATP to drive endergonic reactions and accomplish biological work.
8. Chemical energy is harvested via either substrate-level phosphorylation or chemiosmosis. In substrate-level phosphorylation, a phosphate group is transferred from an enzyme-substrate complex to ADP by coupling an endergonic reaction to a highly exergonic one. In chemiosmosis, electrons are transported to an electron transport system in the mitochondrial membrane. In the process, a gradient of H^+ ions (protons) is established that powers ATP synthesis.

Selected Key Terms

anabolism
catabolism
catalysis
catalyst
ecosystem
endergonic
energy
entropy
enzyme
enzyme-substrate complex (ES)
exergonic

Critical Thinking Questions

1. Does the living state of an animal violate the second law of thermodynamics? In other words, how does an animal maintain a high degree of organization, even though the universal trend is toward disorganization?
2. Why are the two laws of thermodynamics called laws, whereas the central organizing concept of biology—evolution—is called a theory?
3. Living organisms are constantly transforming energy via many different mechanisms. Give several examples in animals where one form of energy is transformed into another form.
4. As you read this statement, you are losing energy. At the risk of losing even more, describe what this means with respect to entropy.
5. Why is ATP the major energy-carrying molecule in all organisms?