Chapter 6: Energy Flow in the Life of a Cell

OVERVIEW

In this chapter, you will learn about the flow of energy through the universe and particularly through living cells and organisms. You will read about the basic laws of thermodynamics and the basic types of chemical reactions that occur in cells and organisms. The authors also explain how cells use enzymes to control chemical reactions. The runners in the New York Marathon expend lots of energy running the 26-mile course, and more energy traveling between their homes and the race venue. What is energy? Do machines and humans follow the same principle regarding energy? What causes us to heat up when exercising? How do we store energy and use it when we need to? How do our cells "burn" sugar to release its energy?

1) What Is Energy?

Energy is the capacity to do work like making molecules, moving them around, and generating light and heat. **Kinetic energy** is the energy of movement including light, heat, and electricity. **Potential energy** is stored energy, including chemical energy stored in the bonds of molecules. Potential energy can be converted to kinetic energy and vice versa. To understand energy flow, we need to know how much energy is available, and how useful the energy is.

The **laws of thermodynamics** define the basic properties and behavior of energy. The **first law of thermodynamics** (called the law of conservation of energy) is that energy cannot be created or destroyed, although it can be changed from one form to another (chemical energy in gasoline can become the heat and movement of cars, for instance). The **second law of thermodynamics** states that when energy is converted from one form to another, the amount of useful energy decreases, since less useful heat usually is given off. Energy is automatically converted from more useful into less useful forms. Spontaneous energy conversions in nature produce an increase in randomness and disorder, called **entropy**. No process is 100% efficient. Disorder spreads through the universe, and life alone battles against it by using energy from the sun to maintain orderliness within cells.

2) How Does Energy Flow in Chemical Reactions?

A **chemical reaction** converts **reactant** substances into **products**. If the reactant energy is greater than the product energy, the reaction is **exergonic** ("energy out") because energy is released during the chemical reaction. For example, when sugar is heated (**activation energy** is added) with oxygen until it burns, chemical energy within the sugar molecules is then released as heat and light (fire), and the molecules produced (carbon dioxide and water) have less energy. Exergonic reactions release energy.

If the product energy is greater than the reactant energy, the reaction is **endergonic** ("energy in") because energy is added to the reaction as it occurs. For example, green plants use solar energy to make high-energy sugar and oxygen from low-energy water and carbon dioxide. Cells make complex biological molecules like proteins using endergonic reactions.

Coupled reactions link exergonic and endergonic reactions. In a coupled reaction, an exergonic reaction provides the energy for an endergonic reaction. The exergonic reaction of burning gasoline provides the energy for the endergonic reaction of starting a stationary car into motion and keeping it moving, even though much heat energy is lost. In photosynthesis, the exergonic reaction occurs in the sun and the endergonic reaction occurs in the plant. Most of the solar energy is lost as heat, so the second law still applies since useable energy decreases. If the coupled reactions occur in different places within cells, the energy usually is transferred from place to place by energy-carrier molecules like ATP.

3) How Is Cellular Energy Carried Between Coupled Reactions?

The energy from glucose (exergonic reactions) is transferred to reusable **energy-carrier molecules** for transfer to the muscle protein that uses energy to contract (endergonic reactions). Since energy-carrying molecules are somewhat unstable, they are not used for long-term energy storage. They are used only to carry energy from place to place within a cell, not between cells. **Adenosine triphosphate (ATP)** is the most common energy-carrier molecule in cells. Energy from exergonic reactions is used to make ATP from **adenosine diphosphate (ADP)** and phosphate (P). ATP carries the energy to various cellular sites where energy-requiring reactions occur. The ATP then is broken down into ADP and P, releasing energy to drive the endergonic reactions. Heat is released during these energy transfers, resulting in a loss of usable energy (an increase in entropy). Energy may be transported within a cell by other carrier molecules as well as by ATP. Some energy may be captured by electrons, which are carried by molecules called electron carriers to other parts of the cell to be released to drive endergonic reactions. Common electron carriers include nicotinamide adenine dinucleotide (NAD^+) and flavin adenine dinucleotide (FAD).

4) How Do Cells Control Their Metabolic Reactions?

Cell **metabolism** refers to the sum of all chemical reactions within cells; these often occur in sequences called **metabolic pathways**. The biochemistry of cells is controlled in three ways: (1) Cells regulate chemical reactions by using proteins called enzymes, which act as catalysts; (2) Cells couple endergonic and exergonic reactions together; and (3) Cells use energy-carrier molecules to transfer energy from exergonic reactions to endergonic ones

At body temperature, spontaneous reactions proceed too slowly to sustain life. Most reactions can be accelerated by raising the temperature, thus supplying more activation energy, but high temperatures would kill cells. Molecules called **catalysts** reduce activation energy, allowing spontaneous reactions to occur at normal body temperature at rates needed for life. All catalysts speed up spontaneous reactions, but are not permanently changed in the reactions they promote. **Enzymes** are biological catalysts made by living organisms. Enzymes lower the activation energy needed to begin exergonic chemical reactions. Most enzymes are proteins, but some ribosomal RNA molecules also act as biological catalysts. Protein enzymes are quite specific in the type of reactions they catalyze, and their activity is regulated (enhanced or suppressed) by other molecules in cells.

Due to its three-dimensional shape, a particular protein enzyme is very specific, catalyzing at most only a few types of reactions. The **active site** region of an enzyme has a distinctive shape and distribution of electrical charges that is complementary to those of its reactants (called **substrates**). Several steps occur when an enzyme catalyzes a reaction. In step 1, substrates enter active sites in specific orientations. In step 2, both substrate and active site change shape, promoting the specific chemical reaction catalyzed by the particular enzyme. In step 3, after the final reaction between the substrates is finished, the product(s) no longer fit properly into the active site and are expelled. The enzyme resumes its original configuration and, thus, is not permanently changed by the reaction it catalyzes.

Cells regulate the amount and the activity of their enzymes in several ways. Cells regulate the synthesis of enzymes to meet their changing needs. Cells make some enzymes in inactive form and activate them only when needed (some digestive enzymes are active only in the acidic environment of the stomach). Cells inhibit enzymes when adequate amounts of the enzyme's product are available (in **feedback inhibition**, an enzyme's activity is inhibited by its own product or by a subsequent product of the metabolic pathway). Certain enzymes are subject to **allosteric regulation**, when the enzyme's action is enhanced or inhibited by small organic molecules (not substrates or products) that act as regulators, binding to special allosteric regulatory sites and causing a change in the structure of the active site and the enzyme becomes either more or less able to bind its substrate. Finally, **competitive inhibition** may occur when two or more molecules somewhat similar in structure compete for the active site of an enzyme. Some poisons are competitive inhibitors that keep an enzyme from breaking down its normal substrate.

The activity of enzymes is influenced by their environment, such as pH, temperature, salt concentration, or the availability of **coenzyme** molecules (often derived from water-soluble vitamins) necessary to aid enzymes in interacting with substrates.

KEY TERMS AND CONCEPTS

Fill-In: From the following list of terms, fill in the blanks below.

active site	entropy	metabolic pathway
adenosine triphosphate (ATP)	enzyme	metabolism
catalyst	exergonic	potential energy
coenzyme	feedback inhibition	product
coupled reaction	1st law of thermodynamics	reactant
endergonic	kinetic energy	2nd law of thermodynamics
energy		

1. A substance that speeds up a chemical reaction without itself being permanently changed in the process is a __________________. Specifically, a protein that speeds up the rate of a particular biological reaction is an ______________________. The region of this protein that binds to substrates is called the __________________.

2. The __________________ states that within any isolated system, energy can be neither created nor destroyed, however, energy can be converted from one form to another. The __________________ states that any change in an isolated system causes the amount of useful energy to decrease, and the amount of randomness and disorder to increase. The measure of the amount of randomness and disorder in a system is __________________.

3. ______________________ is the capacity to do work. When it involves movement, it is called __________________ such as light, heat, and mechanical movement. When it is stored energy, such as in the bonds of molecules, it is called __________________.

4. A molecule composed of ribose sugar, adenine, and three phosphate groups is an __________________ molecule. It is the major energy carrier in cells.

5. A molecule bound to an enzyme that is required for its proper functioning is called a ______________. These molecules are made from water-soluble vitamins.

6. A __________________ is a molecule used up in a chemical reaction to form the __________________, the molecule that results from a chemical reaction.

7. A ______________________ is a sequence of chemical reactions within a cell. However, __________________ refers to the total of all chemical reactions occurring within a cell or organism.

8. When the product of a reaction inhibits an enzyme involved in making the product, _______________ is occurring.

9. When a pair of reactions, one exergonic and one endergonic, are linked together so that the energy produced by one provides the energy needed for the other, this pair is called a _________________.

10. An _________________ reaction is a chemical reaction requiring an input of energy to proceed. An _________________ reaction is a chemical reaction that liberates energy and increases entropy.

Key Terms and Definitions

activation energy: in a chemical reaction, the energy needed to force the electron shells of reactants together, prior to the formation of products.

active site: the region of an enzyme molecule that binds substrates and performs the catalytic function of the enzyme.

adenosine diphosphate (a-den´-ō-sēn dī-fos´-fāt; ADP): a molecule composed of the sugar ribose, the base adenine, and two phosphate groups; a component of ATP.

adenosine triphosphate (a-den´-ō-sēn trī-fos´-fāt; ATP): a molecule composed of the sugar ribose, the base adenine, and three phosphate groups; the major energy carrier in cells. The last two phosphate groups are attached by "high-energy" bonds.

allosteric regulation: the process by which enzyme action is enhanced or inhibited by small organic molecules that act as regulators by binding to the enzyme and altering its active site.

catalyst (kat´-uh-list): a substance that speeds up a chemical reaction without itself being permanently changed in the process; lowers the activation energy of a reaction.

chemical reaction: the process that forms and breaks chemical bonds that hold atoms together.

coenzyme: an organic molecule that is bound to certain enzymes and is required for the enzymes' proper functioning; typically, a nucleotide bound to a water-soluble vitamin.

competitive inhibition: the process by which two or more molecules that are somewhat similar in structure compete for the active site of an enzyme.

coupled reaction: a pair of reactions, one exergonic and one endergonic, that are linked together such that the energy produced by the exergonic reaction provides the energy needed to drive the endergonic reaction.

electron carrier: a molecule that can reversibly gain or lose electrons. Electron carriers generally accept high-energy electrons produced during an exergonic reaction and donate the electrons to acceptor molecules that use the energy to drive endergonic reactions.

endergonic (en-der-gon´-ik): pertaining to a chemical reaction that requires an input of energy to proceed; an "uphill" reaction.

energy: the capacity to do work.

energy-carrier molecule: a molecule that stores energy in "high-energy" chemical bonds and releases the energy to drive coupled endothermic reactions. In cells, ATP is the most common energy-carrier molecule.

entropy (en´-trō-pē): a measure of the amount of randomness and disorder in a system.

enzyme (en´zīm): a protein catalyst that speeds up the rate of specific biological reactions.

exergonic (ex-er-gon´-ik): pertaining to a chemical reaction that liberates energy (either as heat or in the form of increased entropy); a "downhill" reaction.

feedback inhibition: in enzyme-mediated chemical reactions, the condition in which the product of a reaction inhibits one or more of the enzymes involved in synthesizing the product.

first law of thermodynamics: the principle of physics that states that within any isolated system, energy can be neither created nor destroyed but can be converted from one form to another.

kinetic energy: the energy of movement; includes light, heat, mechanical movement, and electricity.

laws of thermodynamics: the physical laws that define the basic properties and behavior of energy.

metabolic pathway: a sequence of chemical reactions within a cell, in which the products of one reaction are the reactants for the next reaction.

metabolism: the sum of all chemical reactions that occur within a single cell or within all the cells of a multicellular organism.

potential energy: "stored" energy, normally chemical energy or energy of position within a gravitational field.

product: an atom or molecule that is formed from reactants in a chemical reaction.

reactant: an atom or molecule that is used up in a chemical reaction to form a product.

second law of thermodynamics: the principle of physics that states that any change in an isolated system causes the quantity of concentrated, useful energy to decrease and the amount of randomness and disorder (entropy) to increase.

substrate: the atoms or molecules that are the reactants for an enzyme-catalyzed chemical reaction.

THINKING THROUGH THE CONCEPTS

True or False: Determine if the statement given is true or false. If it is false, change the underlined word(s) so that the statement reads true.

11. _____ Within a closed system, the amount of energy is variable over time.
12. _____ A fire creates energy.
13. _____ The second law of thermodynamics is concerned with entropy.
14. _____ Photosynthesis and similar reactions decrease entropy.
15. _____ Eventually, all molecules in the universe will become randomly dispersed.
16. _____ Reactions that release energy are endergonic.
17. _____ Enzymes increase the activation energy needed for chemical reactions to occur.
18. _____ ATP contains a six-carbon sugar.
19. _____ Conversion of ATP to ADP releases energy.
20. _____ In coupled reactions, the "downhill" reaction liberates less energy than the "uphill" reaction.

Matching: Chemical reactions.

21. _____ Once started, these will continue by themselves.
22. _____ These need "activation energy" to get started.
23. _____ Reactants have more energy than products.
24. _____ Photosynthesis is classified as this.
25. _____ Products have more energy than reactants.
26. _____ Energy is released from the reaction.
27. _____ This usually involves energy-carrier molecules.
28. _____ Burning wood in a fireplace is classified as this.

Choices:

a. exergonic reactions
b. endergonic reactions
c. both of these
d. coupled reactions

Identify: Determine whether the following statements refer to **catalysts** in general, specifically to **enzymes**, or to **both**.

29. _______________ Are protein molecules.
30. _______________ Can speed up chemical reactions.
31. _______________ Are not changed in the reactions they affect.
32. _______________ Generally, these are very specific as to the reaction they affect.
33. _______________ Cannot cause energetically unfavorable reactions to occur.
34. _______________ Their activity can be regulated.
35. _______________ Does not have to be a protein molecule.

Multiple Choice: Pick the most correct choice for each question.

36. In exergonic chemical reactions
    a. reactants have more energy than products
    b. reactants have less energy than products
    c. reactants and products have equal amounts of energy
    d. energy is stored in the reactions
    e. enzymes are not necessary

37. Which of the following statements about catalysts is false?
    a. Biological catalysts usually are enzymes.
    b. Catalysts increase energy of activation requirements.
    c. Catalysts often increase the rate of reaction.
    d. Catalysts are not permanently altered during the reaction.
    e. Enzymes affect the amount of activation energy required in reactions.

38. Cells regulate enzyme activity in all the following ways except
    a. the amount of enzyme manufactured may be regulated
    b. enzymes may be synthesized in an inactive form
    c. feedback inhibition may occur
    d. energy carrier molecules may be used to regulate enzyme activity

39. The second law of thermodynamics states that
    a. light can be converted into heat
    b. within an isolated system, the total amount of energy remains constant
    c. energy always flows from an area of higher concentration to an area of lower concentration
    d. useful energy increases within an isolated system
    e. useful energy decreases within an isolated system

40. When a muscle cell requires energy for contraction, what happens to ATP?
    a. ATP makes more ATP.
    b. ATP enters a metabolic pathway.
    c. ATP is broken down.
    d. ATP is phosphorylated.
    e. ATP is synthesized.

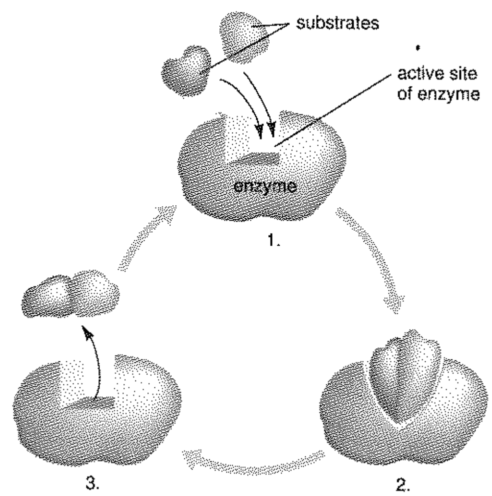
41. Which is the most common short-term energy-storage molecule?
    a. glycogen
    b. fat
    c. sucrose
    d. adenosine triphosphate

42. The statement that "energy is neither created nor destroyed" is part of
    a. entropy
    b. first law of thermodynamics
    c. second law of thermodynamics
    d. allosteric inhibition

43. What causes us to heat up and sweat when exercising?
    a. The clothes we wear make us feel hot.
    b. The room heats up and makes us feel hot.
    c. As we break down sugar, half the energy released is heat.
    d. The people exercising near us give off heat and make us feel hot.
    e. The sugar we break down turns to warm water that is given off as sweat.

44. Do the same laws of thermodynamics hold true for humans and for machines?
    a. Both laws do.
    b. The first law does, but the second law does not.
    c. The first law does not, but the second law does.
    d. Neither law does.
    e. Humans can circumvent the physical laws of nature.

Refer to the figure below to answer the following questions.



45. Which of the following statements are true?
    a. Substrates enter an enzyme's active site in a random orientation.
    b. While in the active site, substrates change their shape.
    c. The active site changes its shape once the substrates are present.
    d. Products fit the active site just as well as substrates do.
    e. Enzymes are permanently changed during chemical reactions.

46. If the figure depicts an endergonic reaction, which of the following statements are true?
    a. The substrates have more energy than the products.
    b. The products have more energy than the substrates.
    c. ATP could be produced from energy released by this reaction
    d. ATP could be used up to provide energy for this reaction
    e. The enzyme will be destroyed by the reaction.

APPLYING THE CONCEPTS

These practice questions are intended to sharpen your ability to apply critical thinking and analysis to biological concepts covered in this chapter.

47. When paper burns, it gives off both heat and light. Thus, the reaction is exergonic. Why, then, doesn't the paper this book contains spontaneously burst into flames? If you touched the book with a burning match, you could set it on fire. What role does the energy supplied by the match play in this process?

____

48. When a person drinks methanol (wood alcohol), it is broken down into formaldehyde, which causes blindness. To prevent the blindness, doctors will administer ethanol (grain alcohol) to the patient. How does this treatment prevent blindness?

49. Why is using a concentrated salt solution, such as pickling in a vinegar-salt solution, effective in preventing bacterial spoilage of foods?

50. Marathon runners often will take a cup of water and pour it over their heads during the race to "cool off" as they continue to run. Why are they "heating up" during the race, and why does the water soaking help?

51. Because of the phenomenon associated with the second law of thermodynamics, most automobiles need radiators and engine fans. Explain.

52. Why would you quickly die if not for the action of enzymes in your cells?