Metabolism: Energy and Enzymes

Chapter Concepts

A sea otter, surrounded by algae, feeds on a sea urchin. All three are solar powered because the algae uses solar energy to carry on photosynthesis and produce the nutrient molecules that sustain sea urchins, and therefore sea otters also.

In the waters off the coast of California, you will find a lot more algae than sea urchins, and many more sea urchins than sea otters. In the plains of Africa, plentiful grass feeds the gazelles, which are greater in number than the lions that feed on them. Why are photosynthesizers so prevalent and why do prey always outnumber their predators?

Metabolism—all the reactions that occur in a cell—requires energy, and much of what a sea urchin or any animal eats is used to drive the reactions that maintain the organism. Cells use energy-rich nutrients to make ATP (adenosine triphosphate), and ATP fuels the metabolic reactions that produce cell parts and products. When ATP is made and when it is broken down, some energy is lost as heat. In the end only about 10% of the energy in food becomes the organism.

If energy is continually lost as heat, how is it possible to sustain a community of organisms at all? Photosynthesizers capture solar energy and they produce the nutrient molecules that become food for the biosphere. We are just as dependent on photosynthesizers as are sea urchins and sea otters. The sun is the ultimate source of energy for all organisms, whether the organism is an alga, a sea urchin, a sea otter, a gazelle, a lion, or a human.

6.1 Cells and the Flow of Energy

Energy is the ability to do work or bring about a change. Living things are constantly changing—they develop, grow, and reproduce. The need to acquire energy is one of the characteristics of life. Cells use acquired energy to maintain their organization and carry out reactions that allow organisms to develop, grow and reproduce.

Forms of Energy

Energy occurs in two basic forms: kinetic and potential energy. **Kinetic energy** is the energy of motion, as when a ball rolls, the rays of the sun traverse the atmosphere, or a moose lifts its leg (Fig. 6.1). A ball rolling and a muscle contracting are two types of mechanical energy, while the rays of the sun are referred to as solar energy. **Potential energy** is stored energy—its capacity to do work is not being used at the moment. The food we eat has potential energy because it can be converted into various types of kinetic energy. Food is specifically called **chemical energy** because food is composed of organic molecules such as carbohydrates, proteins, and fat. When the moose lifts its leg, it has converted chemical energy into mechanical energy.

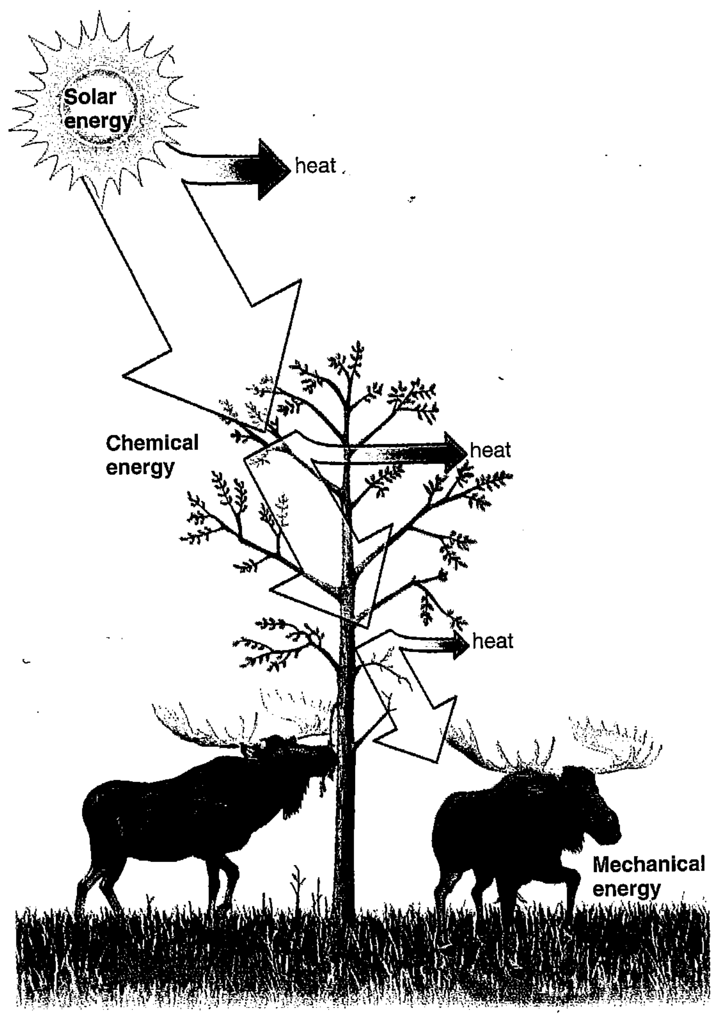


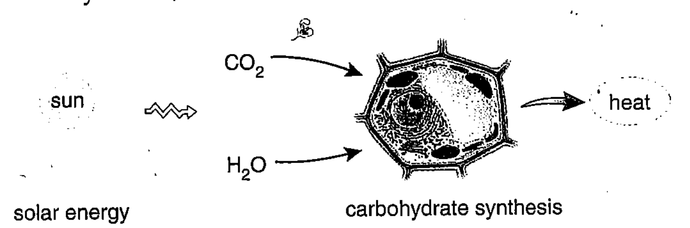
Figure 6.1 Flow of energy.
The plant converts solar energy to the chemical energy of nutrient molecules. The moose converts a portion of this chemical energy to the mechanical energy of motion. Eventually, all solar energy absorbed by the plant dissipates as heat.

Two Laws of Thermodynamics

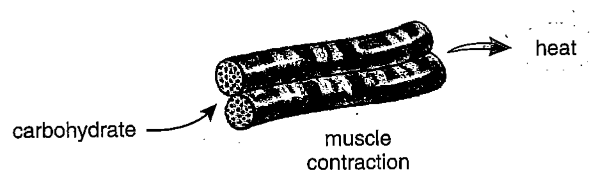
Figure 6.1 also demonstrates the flow of energy in ecosystems. In terrestrial ecosystems, plants capture only a small portion of solar energy and much of it dissipates as heat. When plants photosynthesize and use the food they produce, more heat results. Still, there is enough remaining to sustain moose and other animals in the ecosystem. As animals metabolize nutrient molecules, all the captured solar energy eventually dissipates as heat. Therefore, energy flows and does not cycle. Two laws of thermodynamics explain why energy flows in ecosystems and also in cells. These laws were formulated by early researchers who studied energy relationships and exchanges.

The first law of thermodynamics—the law of conservation of energy—states the following:
Energy cannot be created or destroyed, but it can be changed from one form to another.

One way to demonstrate photosynthesis is to show that leaf cells use solar energy to form carbohydrate molecules from carbon dioxide and water. (Carbohydrates are energy-rich molecules, while carbon dioxide and water are energy-poor molecules.) Not all of the captured solar energy becomes carbohydrates; some becomes heat:



Obviously, the plant did not create the energy it used to produce carbohydrate molecules; that energy came from the sun. Was any energy destroyed? No, because heat is also a form of energy. Similarly, the muscle cells of the moose use the energy derived from carbohydrates to power its muscles. And as muscles convert chemical energy to mechanical energy, heat is given off.



This brings us to the second law of thermodynamics.

The second law of thermodynamics states the following:

Energy cannot be changed from one form to another without a loss of usable energy.

In our example, this law is upheld because some of the solar energy taken in by the plant and some of the chemical energy within the nutrient molecules taken in by a moose becomes heat. When heat dissipates into the environment, it is no longer usable—that is, it is not available to do work. With transformation upon transformation, eventually all usable forms of energy become heat that is lost to the environment. Heat cannot be converted to one of the other forms of energy.

Cells and Entropy

The second law of thermodynamics can be stated another way: Every energy transformation makes the universe less organized and more disordered. The term **entropy** is used to indicate the relative amount of disorganization. Since the processes that occur in cells are energy transformations, the second law means that every process that occurs in cells always does so in a way that increases the total entropy of the universe. Then, too, any one of these processes makes less energy available to do useful work in the future.

Figure 6.2 shows two processes that occur in cells. The second law of thermodynamics tells us that glucose tends to break apart into carbon dioxide and water. Why? Because glucose is more organized, and therefore less stable, than its breakdown products. Also, ions on one side of a membrane tend to move to the other side unless they are prevented from doing so. Why? Because when they are distributed randomly, entropy has increased. As an analogy, you know from experience that a neat room is more organized but less stable than a messy room, which is disorganized but more stable. How do you know a neat room is less stable than a messy room? Consider that a neat room always tends to become more messy.

On the other hand, you know that some cells can make glucose out of carbon dioxide and water and all cells can actively move ions to one side of the membrane. How do they do it? These cellular processes obviously require an input of energy from an outside source. This energy ultimately comes from the sun. Cells, living things, and ecosystems depend on a constant supply of energy from the sun because the ultimate fate of all solar energy in the biosphere is to become randomized in the universe as heat. A living cell is a temporary repository of order purchased at the cost of a constant flow of energy.

Energy exits in several different forms. When energy transformations occur, energy is neither created nor destroyed. However, there is always a loss of usable energy. For this reason, living things are dependent on an outside source of energy that ultimately comes from the sun.

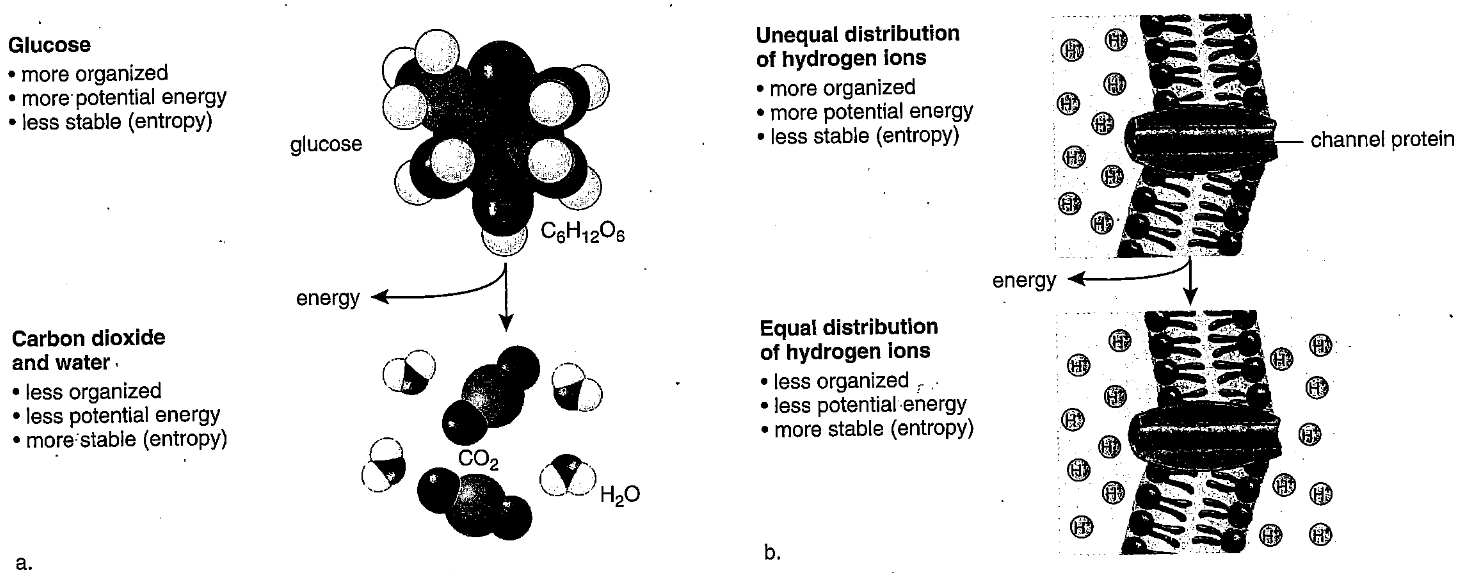


Figure 6.2 Cells and entropy.
The second law of thermodynamics tells us that (a) glucose, which is more organized, tends to break down to carbon dioxide and water, which are less organized. **b.** Similarly, hydrogen ions (H^+) on one side of a membrane tend to move to the other side so that the ions are randomly distributed. Both processes result in a loss of potential energy and an increase in entropy.

6.2 Metabolic Reactions and Energy Transformations

Metabolism is the sum of all the chemical reactions that occur in a cell. **Reactants** are substances that participate in a reaction, while **products** are substances that form as a result of a reaction. In the reaction $A + B \rightarrow C + D$, A and B are the reactants while C and D are the products. How would you know that this reaction will occur spontaneously—that is, without an input of energy? Using the concept of entropy, it is possible to state that a reaction will occur spontaneously if it increases the entropy of the universe. But in cell biology, we don't usually wish to consider the entire universe. We simply want to consider this reaction. In such instances, cell biologists use the concept of free energy instead of entropy. **Free energy** is the amount of energy available—that is, energy that is still "free" to do work after a chemical reaction has occurred. Free energy is denoted by the symbol G after Josiah Gibbs, who first developed the concept. The value of ΔG is calculated by subtracting the free energy content of the reactants from that of the products. A negative ΔG (change in free energy) means that the products have less free energy than the reactants and the reaction will occur spontaneously. In our reaction, if C and D have less free energy than A and B, then the reaction will "go."

Exergonic reactions are ones in which ΔG is negative and energy is released, while **endergonic reactions** are ones in which ΔG is positive and the products have more free energy than the reactants. Endergonic reactions can only occur if there is an input of energy. In the body many reactions such as protein synthesis, nerve conduction, or muscle contraction are endergonic and they occur because the energy released by exergonic reactions is used to drive endergonic reactions. ATP is a carrier of energy between exergonic and endergonic reactions.

ATP: Energy for Cells

ATP (adenosine triphosphate) is the common energy currency of cells; when cells require energy, they "spend" ATP. You may think that this causes our bodies to produce a lot of ATP, and it does. However, the amount on hand at any one moment is minimal because ATP is constantly being generated from **ADP (adenosine diphosphate)** and Ⓟ (Fig. 6.3).

The use of ATP as a carrier of energy has some advantages:

1. It provides a common energy currency that can be used in many different types of reactions.
2. When ATP becomes ADP + Ⓟ, the amount of energy released is sufficient for the biological purpose, and so little energy is wasted.
3. ATP breakdown is coupled to endergonic reactions in such a way that it minimizes energy loss.

Structure of ATP

ATP is a modified nucleotide composed of the nitrogen-containing base adenine and the 5-carbon sugar ribose (together called adenosine) and three phosphate groups. ATP is called a "high-energy" compound because a phosphate group is easily removed. Under cellular conditions, the amount of energy released when ATP is hydrolyzed to ADP + Ⓟ is about 7.3 kcal per mole.[1]

[1] A mole is the number of molecules present in the molecular weight of a substance (in grams).

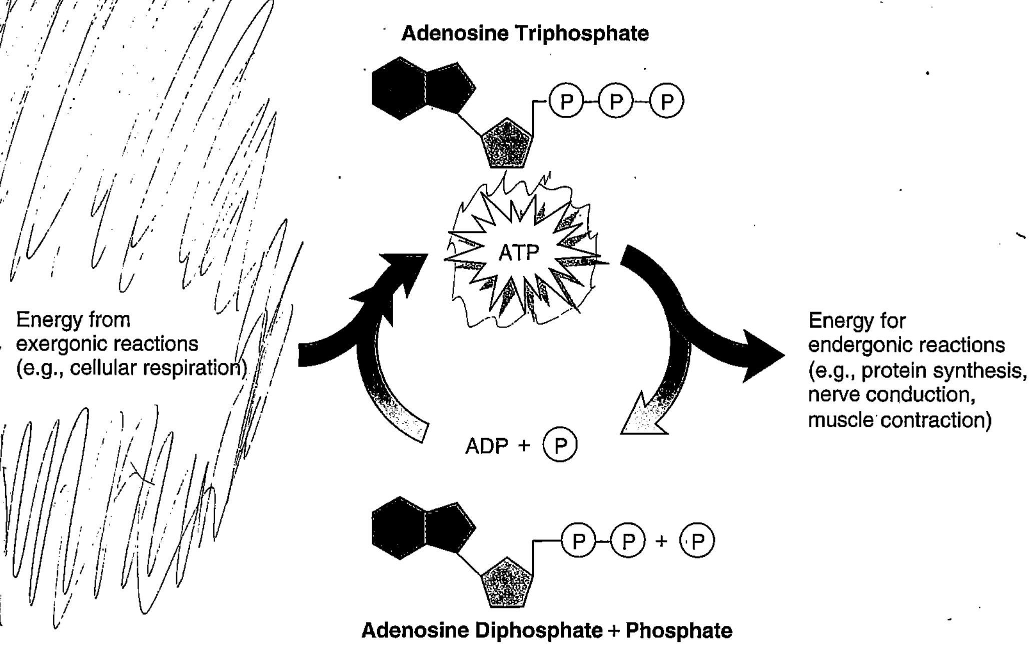
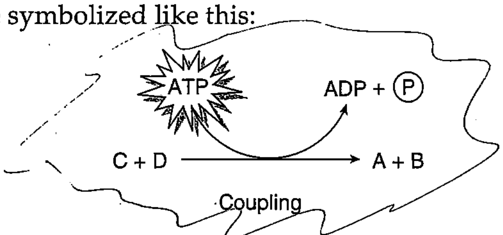


Figure 6.3 **The ATP cycle.**
In cells, ATP carries energy between exergonic reactions and endergonic reactions. When a phosphate group is removed by hydrolysis, ATP releases the appropriate amount of energy for most metabolic reactions.

Coupled Reactions

In **coupled reactions,** the energy released by an exergonic reaction is used to drive an endergonic reaction. ATP breakdown is often coupled to cellular reactions that require an input of energy. Coupling, which requires that the exergonic reaction and the endergonic reaction be closely tied, can be symbolized like this:



Notice that the word energy does not appear following ATP breakdown. Why not? Because this energy was used to drive forward the coupled reaction. Figure 6.4 tells us that ATP breakdown provides the energy necessary for muscular contraction to occur. The energy released when ATP becomes ADP + Ⓟ is used to drive muscle contraction. How is a cell assured of a supply of ATP? Recall that glucose breakdown during cellular respiration provides the energy for the buildup of ATP in mitochondria. Only 39% of the free energy of glucose is transformed to ATP; the rest is lost as heat. When ATP breaks down to drive the reactions mentioned, some energy is lost as heat, and the overall reaction becomes exergonic.

Function of ATP

Recall that at various times we have mentioned at least three uses for ATP.

Chemical work. ATP supplies the energy needed to synthesize macromolecules that make up the cell, and therefore the organism.

Transport work. ATP supplies the energy needed to pump substances across the plasma membrane.

Mechanical work. ATP supplies the energy needed to permit muscles to contract, cilia and flagella to beat, chromosomes to move, and so forth.

In most cases, ATP is the immediate source of energy for these processes.

ATP is a carrier of energy in cells. It is the common energy currency because it supplies energy for many different types of reactions.

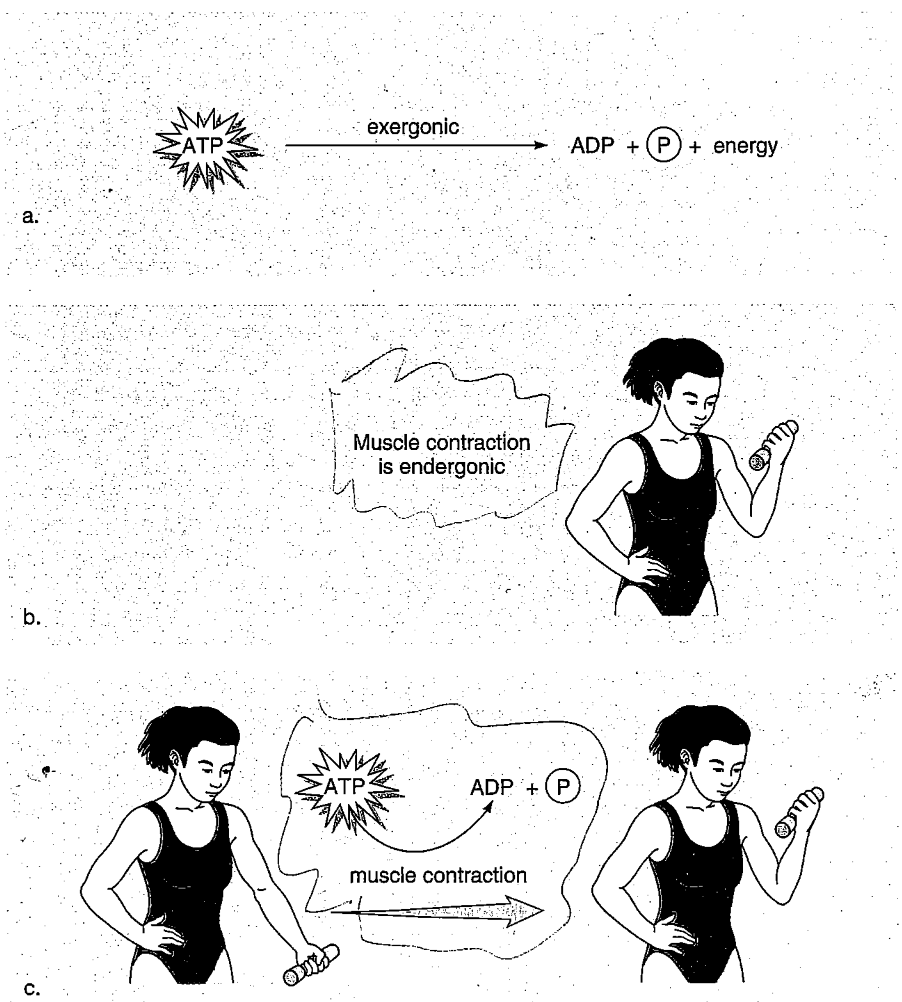


Figure 6.4 Coupled reactions.
a. The breakdown of ATP is exergonic. **b.** Muscle contraction is endergonic and therefore cannot occur without an input of energy. **c.** When muscle contraction is coupled to ATP breakdown, the overall process becomes exergonic. Now muscle contraction can occur.