

# 5 The Working Cell

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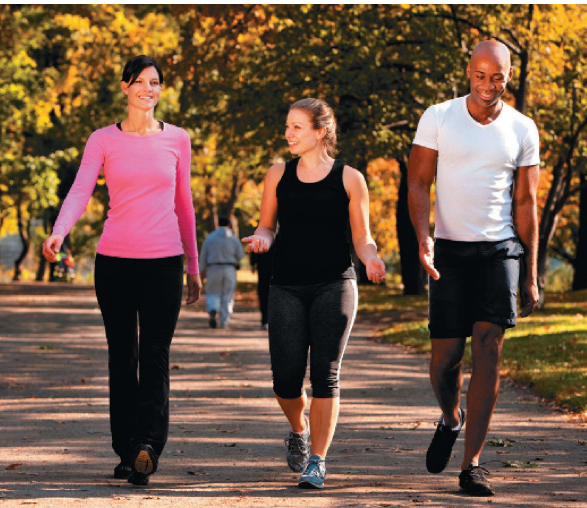
## Why Cellular Functions Matter

Life begins at the level of the cell: Nothing smaller is alive, and a single cell may contain all of the machinery necessary to carry out life's functions. Living cells are dynamic, performing work constantly. It is therefore important for any student of biology to understand how a working cell goes about the business of life.

WHAT DO BEEF JERKY AND RAISINS HAVE IN COMMON? THEY ARE BOTH MADE THROUGH OSMOSIS.



BOTH NERVE GAS AND INSECTICIDES WORK BY CRIPPLING A VITAL ENZYME.



GET MOVING! YOU HAVE TO WALK MORE THAN 2 HOURS TO BURN THE CALORIES IN HALF A PEPPERONI PIZZA.

## CHAPTER THREAD

### Nanotechnology

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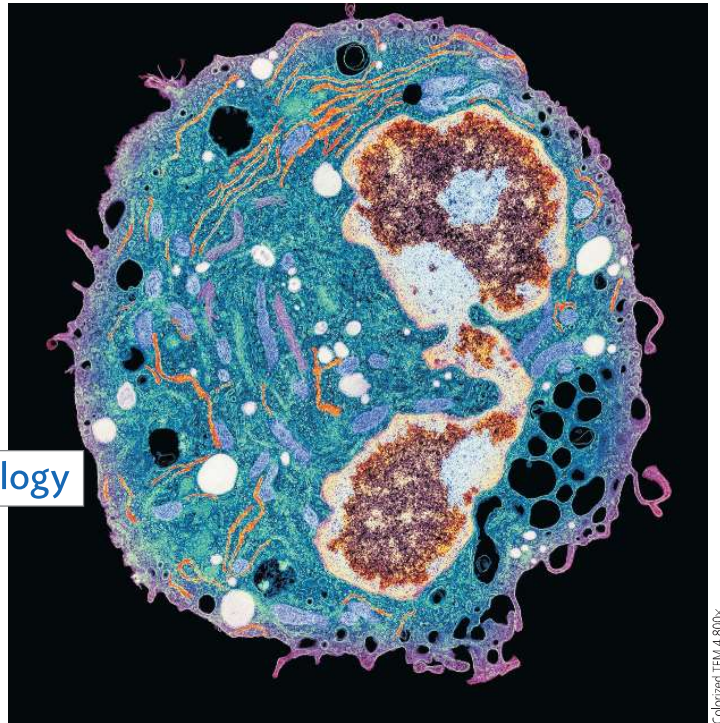
## BIOLOGY AND SOCIETY Nanotechnology

### Harnessing Cellular Structures

Imagine a tiny robot with balls of carbon atoms for wheels, or a microchip carved onto an object 1,000 times smaller than a grain of sand. These are real-world examples of nanotechnology, the manipulation of materials at the molecular scale. When designing devices of such small size, researchers often turn to living cells for inspiration. After all, you can think of a cell as a machine that continuously and efficiently performs a variety of functions, such as movement, energy processing, and manufacturing a wide variety of products. Let's consider one example of cell-based nanotechnology and see how it relates to working cells.

Researchers at Cornell University are attempting to harvest the energy-producing capability of human sperm cells. Like other cells, a sperm cell generates energy by breaking down sugars and other molecules that pass through its plasma membrane. Enzymes within the cell release energy by breaking down glucose. The released energy is used to produce molecules of ATP. Within a living sperm, such ATP provides the energy that propels the cell through the female reproductive tract. In an attempt to harness this energy-producing system, the Cornell researchers attached three enzymes to a computer chip. The enzymes continued to function in this artificial system, producing energy from sugar. The hope is that a larger set of enzymes can eventually be used to power microscopic robots. Such nanorobots could use glucose from the bloodstream to power the delivery of drugs to body tissues, perhaps homing in on cancerous or otherwise abnormal cells. This example is only a glimpse into the incredible potential of new technologies inspired by working cells.

In this chapter, we'll explore three processes common to all living cells: energy metabolism, the use of enzymes to speed chemical reactions, and transport regulation by the plasma membrane. Along the way, we'll further consider nanotechnologies that mimic the natural activities of living cells.



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**Cellular structures.** Even the smallest cell, such as this human white blood cell, is a miniature machine of startling complexity.

# Some Basic Energy Concepts

Energy makes the world go round—both on a planetary scale and on a cellular scale. But what exactly is energy? Our first step in understanding the working cell is to learn a few basic concepts about energy.

## Conservation of Energy

**Energy** is defined as the capacity to cause change. Some forms of energy are used to perform work, such as moving an object against an opposing force—for example, lifting a barbell against the force of gravity. Imagine a diver climbing to the top of a platform and then diving off (**Figure 5.1**). To get to the top of the platform, the diver must perform work to overcome the opposing force of gravity. In this specific case, chemical energy from food is converted to **kinetic energy**, the energy of motion. The kinetic energy takes the form of muscle movement propelling the diver to the top of the platform.

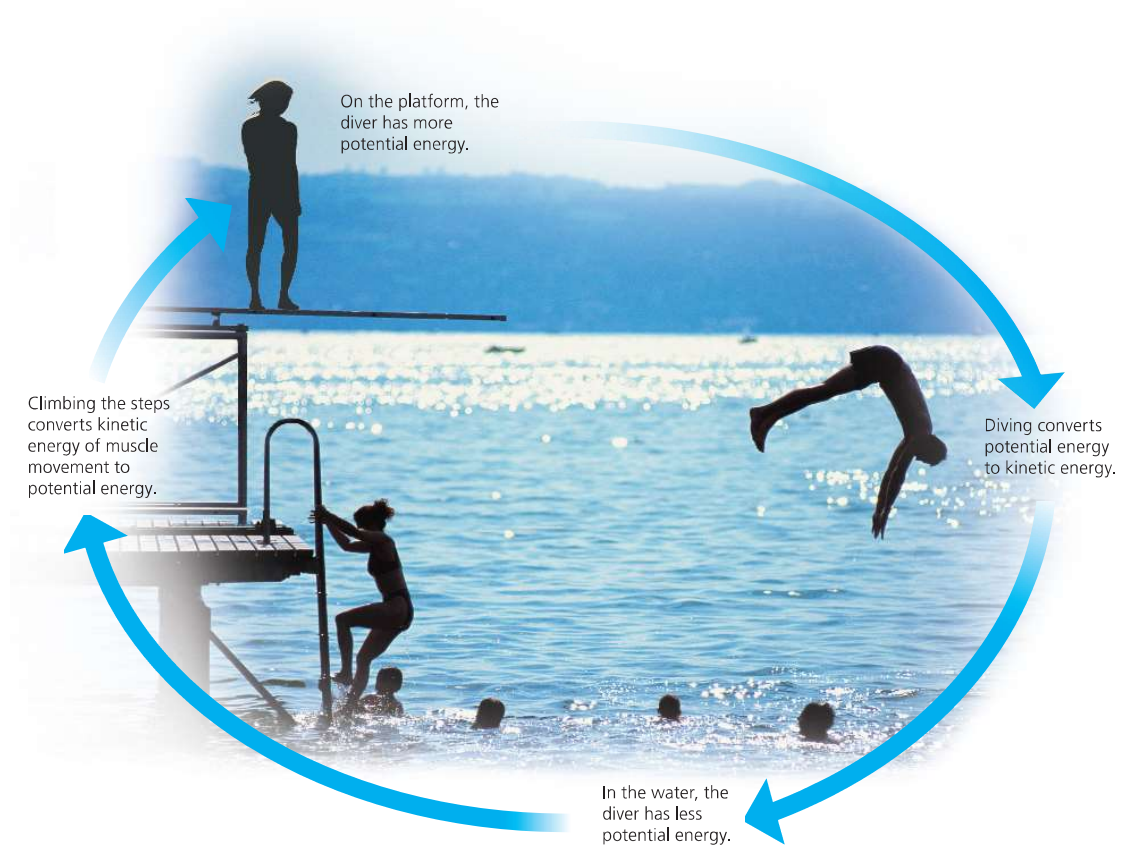
What happens to the kinetic energy when the diver reaches the top of the platform? Does it disappear at that point? In fact, it does not. A physical principle known as **conservation of energy** explains that it is not possible to destroy or create energy. Energy can only be converted from one form to another. A power plant, for example, does not make energy; it merely converts it from one form (such as energy stored in coal) to a more convenient form (such as electricity). That's what happens in the diver's climb up the steps. The kinetic energy of muscle movement is stored as **potential energy**, the energy an object has because of its location or structure. The energy contained by water behind a dam and energy stored by a compressed spring are examples of potential energy. In our example, the diver at the top of the platform has potential energy because of his elevated location. Then the act of diving off the platform into the water converts the potential energy back to kinetic energy. **Life depends on countless similar transformations of energy from one form to another.** ✓

### ✓ CHECKPOINT

Can an object at rest have energy?

Answer: Yes, it can have potential energy because of its location or structure. ■

► **Figure 5.1** Energy transformations during a dive.



## Heat

If energy cannot be destroyed, where has the energy gone in our example when the diver hits the water? The energy has been converted to **heat**, a type of kinetic energy contained in the random motion of atoms and molecules. The friction between the body and its surroundings generated heat in the air and then in the water.

All energy transformations generate some heat. Although releasing heat does not destroy energy, it does make it more difficult to harness for useful work. Heat is energy in its most disordered, chaotic form, the energy of aimless molecular movement.

**Entropy** is a measure of the amount of disorder, or randomness, in a system. Consider an analogy from your own room. It's easy to increase the chaos—in fact, it seems to happen spontaneously! But it requires the expenditure of significant energy to restore order once again.

Every time energy is converted from one form to another, entropy increases. The energy transformations during the climb up the ladder and the dive from the platform increased entropy as the diver emitted heat to the surroundings. To climb up the steps again for another dive, the diver must use additional stored food energy. This transformation will also create heat and therefore increase entropy. ✓

## Chemical Energy

How can molecules derived from the food we eat provide energy for our working cells? The molecules of food, gasoline, and other fuels have a form of potential energy called **chemical energy**, which arises from the arrangement of atoms and can be released by a chemical reaction. Carbohydrates, fats, and gasoline have structures that make them especially rich in chemical energy.

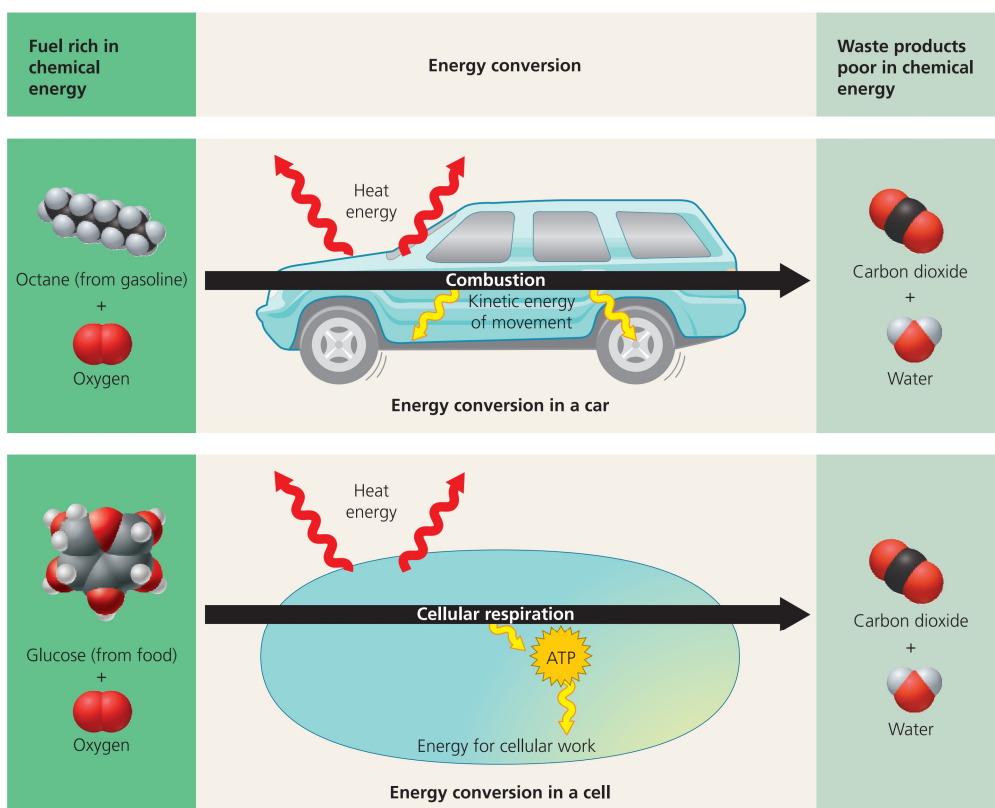
Living cells and automobile engines use the same basic process to make the chemical energy stored in their fuels available for work (**Figure 5.2**). In both cases, this process breaks organic fuel into smaller waste molecules that have much less chemical energy than the fuel molecules did, thereby releasing energy that can be used to perform work.

For example, the engine of an automobile mixes oxygen with gasoline (which is why all cars require an air intake system) in an explosive chemical reaction that breaks down the fuel molecules and pushes the pistons that eventually move the wheels. The waste products emitted from the car's exhaust pipe are mostly carbon dioxide and water. Only about 25% of the energy that an automobile engine extracts from its fuel is converted to the kinetic energy of the car's movement. Most of the rest is converted to heat—so much that the engine would

### ✓ CHECKPOINT

Which form of energy is most randomized and difficult to put to work?

Answer: heat



◀ **Figure 5.2** Energy transformations in a car and a cell. In both a car and a cell, the chemical energy of organic fuel molecules is harvested using oxygen. This chemical breakdown releases energy stored in the fuel molecules and produces carbon dioxide and water. The released energy can be used to perform work.



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melt if the car's radiator did not disperse heat into the atmosphere. That is why high-end performance cars need sophisticated air flow systems to avoid overheating.

Cells also use oxygen in reactions that release energy from fuel molecules. As in a car engine, the “exhaust” from such reactions in cells is mostly carbon dioxide and water. The combustion of fuel in cells is called cellular respiration, which is a more gradual and efficient “burning” of fuel compared with the explosive combustion in an automobile engine. Cellular respiration is the energy-releasing chemical breakdown of fuel molecules and the storage of that energy in a form the cell can use to perform work. (We will discuss the details of cellular respiration in Chapter 6.) You convert about 34% of your food energy to useful work, such as movement of your muscles. The rest of the energy released by the breakdown of fuel molecules generates body heat. Humans and many other animals can use this heat to keep the body at an almost constant temperature (37°C, or 98.6°F, in the case of humans), even when the surrounding air is much colder. You've probably noticed how quickly a crowded room warms up—it's all that released metabolic heat energy! The liberation of heat energy also explains why you feel hot after exercise. Sweating and other cooling mechanisms enable your body to lose the excess heat, much as a car's radiator keeps the engine from overheating.



YOU HAVE TO WALK MORE THAN 2 HOURS TO BURN THE CALORIES IN HALF A PEPPERONI PIZZA.

## Food Calories

Read any packaged food label and you'll find the number of calories in each serving of that food. Calories are units of energy. A **calorie** (cal) is the amount of energy that can raise the temperature of 1 gram (g) of water by 1°C. You could actually measure the caloric content of a peanut by burning it under a container of water to convert all of the stored chemical energy to heat and then measuring the temperature increase of the water.

Calories are tiny units of energy, so using them to describe the fuel content of foods is not practical. Instead, it's conventional to use kilocalories (kcal), units of 1,000 calories. In fact, the Calories (capital C) on a food package are actually kilocalories. For example, one peanut has about 5 Calories. That's a lot of energy, enough to increase the temperature of 1 kg (a little more than a quart) of water by 5°C. And just a handful of peanuts contains enough Calories, if converted

to heat, to boil 1 kg of water. In living organisms, of course, food isn't used to boil water but instead is used to fuel the activities of life. **Figure 5.3** shows the number of Calories in several foods and how many Calories are burned by some typical activities. ✓

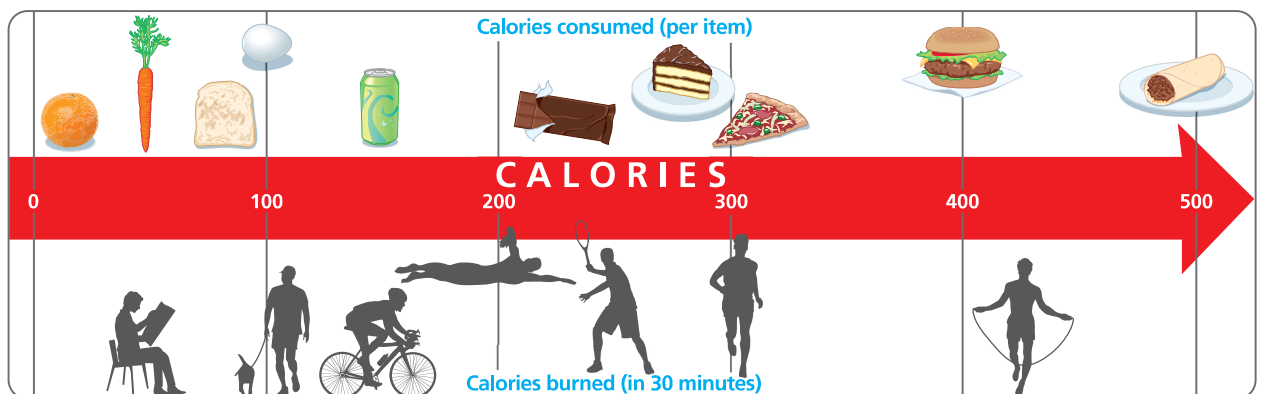
### ✓ CHECKPOINT

According to Figure 5.3, about how long would you have to ride your bicycle to burn off the energy in one slice of pizza?

Answer: about 1 hour (riding a bicycle burns about 150 calories) ■



▼ **Figure 5.3** A comparison of the Calories contained in some common foods and burned by some common activities.



# ATP and Cellular Work

The carbohydrates, fats, and other fuel molecules we obtain from food cannot be used directly as fuel for our cells. Instead, the chemical energy released by the breakdown of organic molecules during cellular respiration is used to generate molecules of ATP. These molecules of ATP then power cellular work. ATP acts like an energy shuttle, storing energy obtained from food and then releasing it as needed at a later time. **Such energy transformations are essential for all life on Earth.**

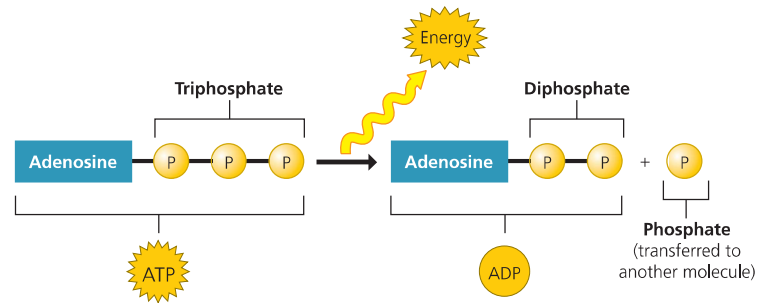
## The Structure of ATP

The abbreviation ATP stands for adenosine triphosphate. **ATP** consists of an organic molecule called adenosine plus a tail of three phosphate groups (**Figure 5.4**). The triphosphate tail is the “business” end of ATP, the part that provides energy for cellular work. Each phosphate group is negatively charged. Negative charges repel each other. The crowding of negative charges in the triphosphate tail contributes to the potential energy of ATP. It’s analogous to storing energy by compressing a spring; if you release the spring, it will relax, and you can use that springiness to do some useful work. For ATP power, it is release of the phosphate at the tip of the triphosphate tail that makes energy available to working cells. What remains is **ADP**, adenosine diphosphate (two phosphate groups instead of three, shown on the right side of **Figure 5.4**).

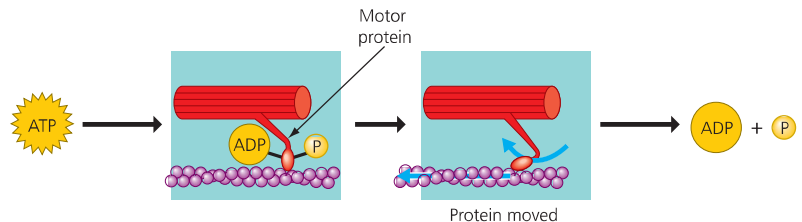
## Phosphate Transfer

When ATP drives work in cells by being converted to ADP, the released phosphate groups don’t just fly off into space. ATP energizes other molecules in cells by transferring phosphate groups to those molecules. When a target molecule accepts the third phosphate group, it becomes energized and can then perform work in the cell. Imagine a bicyclist pedaling up a hill. In the muscle cells of the rider’s legs, ATP transfers phosphate groups to motor proteins. The proteins then change shape, causing the muscle cells to contract (**Figure 5.5a**). This contraction provides the mechanical energy needed to propel the rider. ATP also enables the transport of ions and other dissolved substances across the membranes of the rider’s nerve cells (**Figure 5.5b**), helping them send signals to her legs. And ATP drives the production of a cell’s large molecules from smaller molecular building blocks (**Figure 5.5c**).

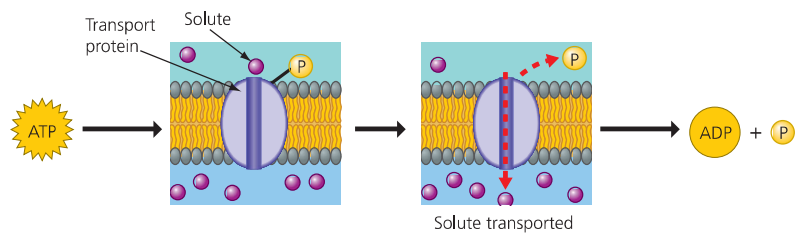
▼ **Figure 5.4 ATP power.** Each **P** in the triphosphate tail of ATP represents a phosphate group, a phosphorus atom bonded to oxygen atoms. The transfer of a phosphate from the triphosphate tail to other molecules provides energy for cellular work.



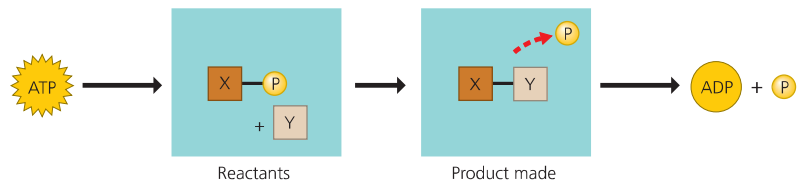
▼ **Figure 5.5 How ATP drives cellular work.** Each type of work shown here is powered when an enzyme transfers phosphate from ATP to a recipient molecule.



(a) **Motor protein performing mechanical work (moving a muscle fiber)**



(b) **Transport protein performing transport work (importing a solute)**



(c) **Chemical reactants performing chemical work (promoting a chemical reaction)**

**✓ CHECKPOINT**

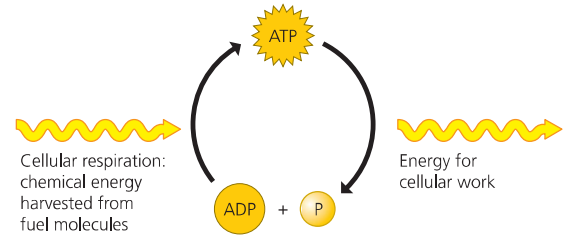
1. Explain how ATP powers cellular work.
2. What is the source of energy for regenerating ATP from ADP?

Answers: 1. ATP transfers a phosphate to another molecule, increasing that molecule's energy. 2. Chemical energy harvested from sugars and other organic fuels via cellular respiration

## The ATP Cycle

Your cells spend ATP continuously. Fortunately, it is a renewable resource. ATP can be restored by adding a phosphate group back to ADP. That takes energy, like recompressing a spring. And that's where food enters the picture. The chemical energy that cellular respiration harvests from sugars and other organic fuels is put to work regenerating a cell's supply of ATP. Cellular work spends ATP, which is recycled when ADP and phosphate are combined using energy released by cellular respiration (Figure 5.6). Thus, energy from processes that yield energy, such as the breakdown of organic fuels, is transferred to processes that consume energy,

▼ **Figure 5.6** The ATP cycle.



such as muscle contraction and other cellular work. The ATP cycle can run at an astonishing pace: Up to 10 million ATPs are consumed and recycled each second in a working muscle cell. ✓

## Enzymes

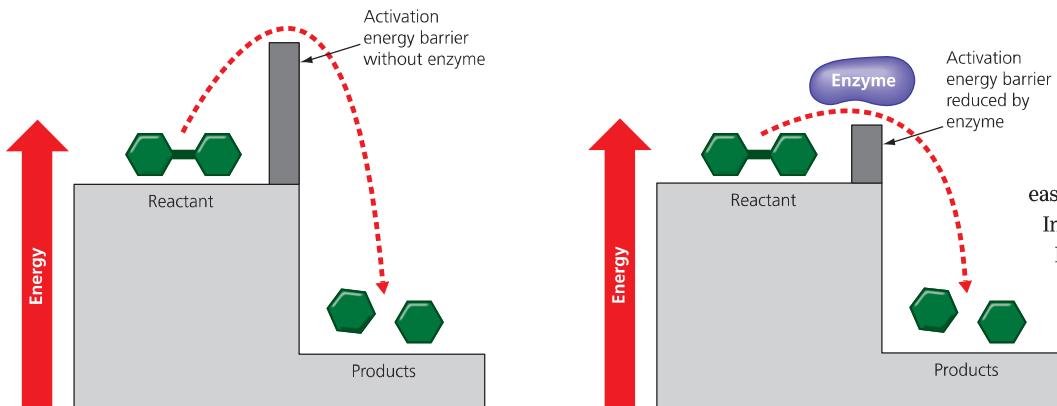
A living organism contains a vast collection of chemicals, and countless chemical reactions constantly change the organism's molecular makeup. In a sense, a living organism is a complex “chemical square dance,” with the molecular “dancers” continually changing partners through chemical reactions. The total of all the chemical reactions in an organism is called **metabolism**. **Illustrating the theme of system interactions, a cell's metabolism depends on the coordination of many molecular players.** In fact, almost no metabolic reactions occur without help. Most require the assistance of **enzymes**, molecules that speed up chemical reactions without being consumed by those reactions. All living cells contain thousands of different enzymes, each promoting a different chemical reaction. Almost all enzymes are proteins, but some RNA molecules also function as enzymes.

**✓ CHECKPOINT**

How does an enzyme affect the activation energy of a chemical reaction?

Answer: An enzyme lowers the activation energy.

▼ **Figure 5.7** Enzymes and activation energy.



(a) **Without enzyme.** A reactant molecule must overcome the activation energy barrier before a chemical reaction can break the molecule into products.

(b) **With enzyme.** An enzyme speeds the chemical reaction by lowering the activation energy barrier.

## Activation Energy

For a chemical reaction to begin, chemical bonds in the reactant molecules must be broken. (The first step in swapping partners during a square dance is to let go of your current partner's hand.) This process requires that the molecules absorb energy from their surroundings. In other words, for most chemical reactions, a cell has to spend a little energy first. You can easily relate this concept to your own life: It takes effort to clean your room, but this will save you more energy in the long run because you won't have to hunt for your belongings. The energy that must be invested to start a reaction is called **activation energy** because it activates the reactants and triggers the chemical reaction.

Enzymes enable metabolism to occur by reducing the amount of activation energy required to break the bonds of reactant molecules. Without an enzyme, the activation energy barrier might never be breached. For example, lactose (milk sugar) can sit for years without breaking down into its components. But if you add a small amount of the enzyme lactase, all the lactose will be broken down in seconds. If you think of the activation energy as a barrier to a chemical reaction, an enzyme's function is to lower that barrier (Figure 5.7). It does so by binding to reactant molecules and putting them under physical or chemical stress, making it easier to break their bonds and start a reaction. In our analogy of cleaning your room, this is like a friend offering to help you. You start and end in the same place whether solo or assisted, but your friend's help lowers your activation energy, making it more likely that you'll proceed. Next, we'll return to our theme of nanotechnology to see how enzymes can be engineered to be even more efficient. ✓

## Can Enzymes Be Engineered?

### BACKGROUND

Like all other proteins, enzymes are encoded by genes. Observations of genetic sequences suggest that many of our genes were formed through a type of molecular evolution: One ancestral gene duplicated, and the two copies diverged over time through random genetic changes, eventually becoming distinct genes.

### METHOD

Scientists often use the natural world as inspiration for new experiments. For example, in 2015, a group of researchers from the University of British Columbia used a technique called directed evolution to produce a better version of a particular enzyme. This enzyme cuts the molecular tags that appear on the outside of red blood cells; these tags are responsible for the different blood types (A, B, AB, and O). If a patient receives a transfusion of blood that contains tags that are incompatible with the patient's blood, a potentially deadly rejection could result. The researchers hoped to alleviate such problems by producing an enzyme

that efficiently removes the problematic tags from donated blood, thereby making all blood donations safe.

In their attempt to mimic the natural process of evolution, the researchers randomly mutated many copies of the gene that codes for the enzyme (**Figure 5.8**). Each mutated gene was screened for its ability to code for an enzyme that removes the molecular tags from red blood cells. Any genes that were not efficient were removed from the experimental pool. The genes for the enzymes that were most effective were kept, then subjected to several more rounds of duplication, mutation, and screening.

### RESULTS

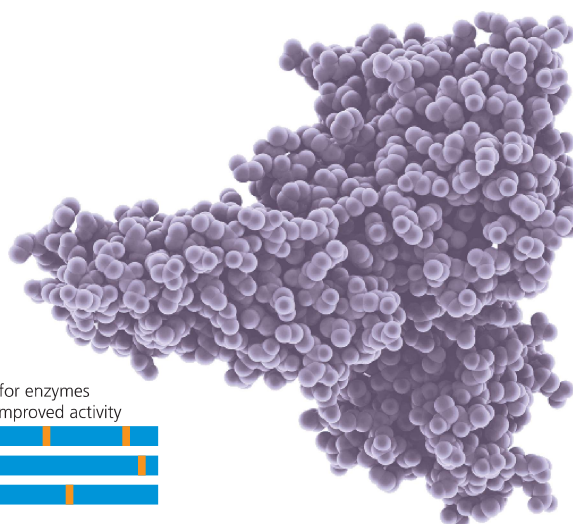
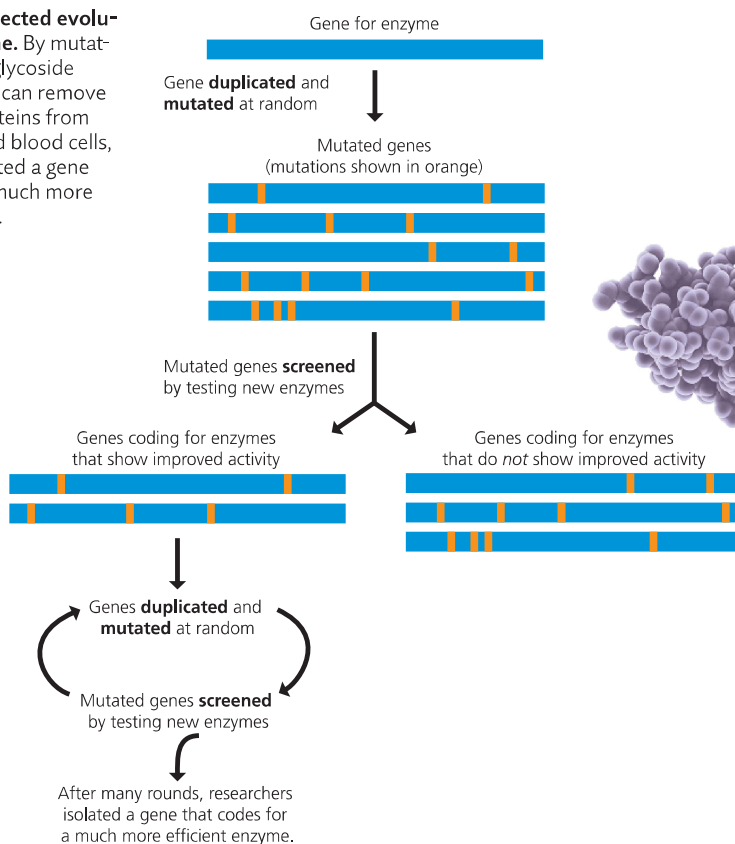
After many rounds of directed evolution, the researchers isolated a gene that codes for an enzyme that is 170 times more efficient at promoting the reaction than the original enzyme. Testing of this new enzyme is now underway. These results are another example of how scientists can mimic natural processes to modify cellular components into useful medical tools.

### Thinking Like a Scientist

In what ways does directed evolution mimic natural selection? In what ways does it differ?

For the answer, see Appendix D.

► **Figure 5.8** Directed evolution of an enzyme. By mutating the gene for glycoside hydrolase, which can remove compatibility proteins from the outside of red blood cells, researchers isolated a gene that codes for a much more effective enzyme.



Computer-generated model of the enzyme glycoside hydrolase

## Enzyme Activity

An enzyme is very selective in the reaction it catalyzes. The specific molecule that an enzyme acts on is called the enzyme's **substrate**. **Enzymes illustrate the close relationship between structure and function.** Each kind of enzyme has a unique three-dimensional shape that determines what specific chemical reaction the enzyme promotes. A region of the enzyme called the **active site** has a shape and chemistry that fit the substrate molecule. The active site is typically a pocket or groove on the surface of the enzyme. When a substrate slips into this docking station, the active site changes shape slightly to embrace the substrate and catalyze the reaction. This interaction is called **induced fit** because the entry of the substrate induces the enzyme to change shape slightly, making the fit between substrate and active site snuggier. Think of a handshake: As your hand makes contact with another hand, it changes shape slightly to make a better fit.

After the products are released from the active site, the enzyme can accept another molecule of substrate. In fact, the ability to function repeatedly is a key characteristic of enzymes. **Figure 5.9** follows the action of the enzyme lactase, which breaks down the disaccharide lactose (the substrate). This enzyme is underproduced or defective in lactose-intolerant people. Like lactase, many enzymes are named for their substrates, with an *-ase* ending. ✓

### ✓ CHECKPOINT

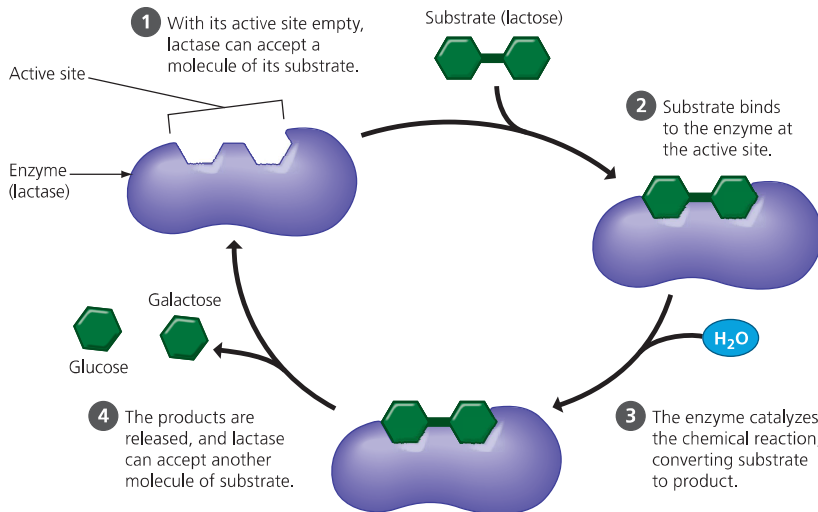
How does an enzyme recognize its substrate?

*Answer: The substrate and the enzyme's active site are complementary in shape and chemistry.*

## Enzyme Inhibitors

Certain molecules called **enzyme inhibitors** can inhibit a metabolic reaction by binding to an enzyme and disrupting its function (**Figure 5.10**). Some of these inhibitors are substrate imposters that plug up the active site. (You can't shake a person's hand if someone else puts a banana in it first!) Other inhibitors bind to the enzyme at a site remote

▼ **Figure 5.9** How an enzyme works. Our example is the enzyme lactase, named for its substrate, lactose.



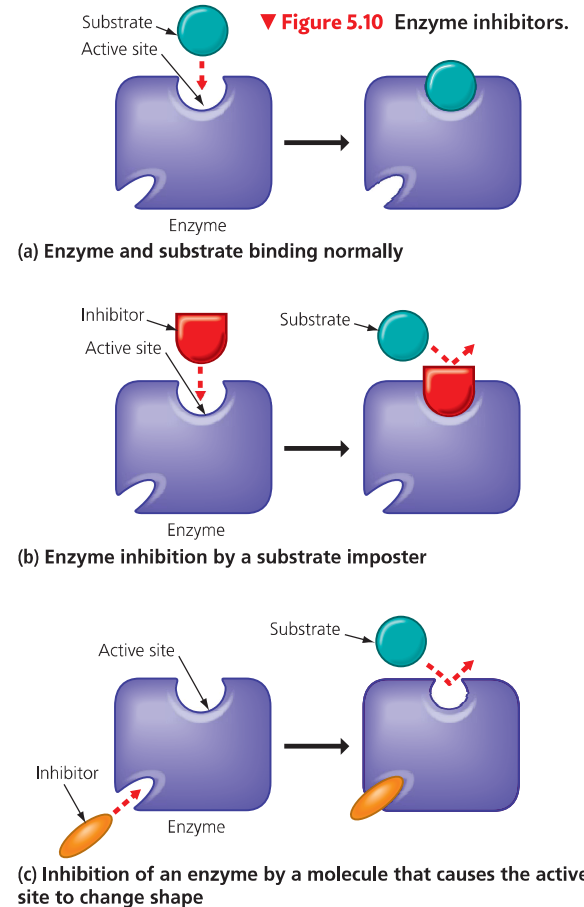
from the active site, but the binding changes the enzyme's shape. (Imagine trying to shake hands when someone is tickling your ribs, causing you to clench your hand.) In each case, an inhibitor disrupts the enzyme by altering its shape.

In some cases, the binding of an inhibitor is reversible. For example, if a cell is producing more of a certain product than it needs, that product may reversibly inhibit an enzyme required for its production. This feedback regulation keeps the cell from wasting resources by building an unneeded product.

Many beneficial drugs work by inhibiting enzymes. Penicillin blocks the active site of an enzyme that bacteria use in making cell walls. Ibuprofen inhibits an enzyme involved in sending pain signals. Many cancer drugs inhibit enzymes that promote cell division. Many toxins and poisons also work as inhibitors. Nerve gases (a form of chemical warfare) irreversibly bind to the active site of an enzyme vital to transmitting nerve impulses, leading to rapid paralysis and death. Many pesticides are toxic to insects because they inhibit this same enzyme.



**BOTH NERVE GAS AND INSECTICIDES WORK BY CRIPPLING A VITAL ENZYME.**



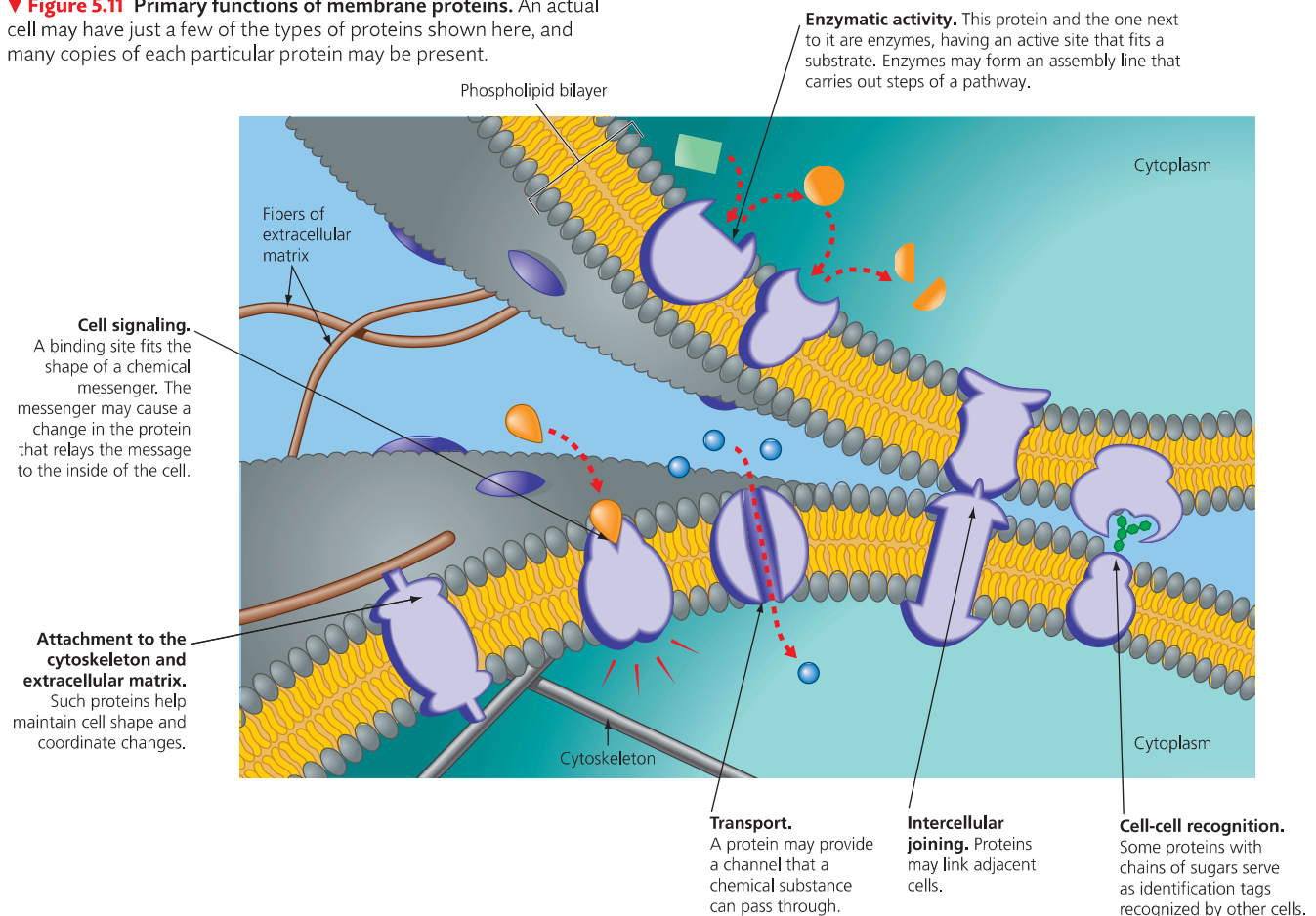
# Membrane Function

So far, we have discussed how cells control the flow of energy and how enzymes affect the pace of chemical reactions. In addition to these vital processes, cells must also regulate the flow of materials to and from the environment. The plasma membrane consists of a double layer of fat with embedded proteins—a phospholipid bilayer (see Figure 4.5). **Figure 5.11** describes the major functions of these membrane proteins. Of all the functions shown in the figure, one of the most important is the regulation of transport in and out of the cell. A steady traffic of small molecules moves across a cell's plasma membrane in both directions. But this traffic flow is never willy-nilly. Instead, all biological membranes are selectively permeable—that is, they only allow certain molecules to pass. Let's explore this in more detail.

## Passive Transport: Diffusion across Membranes

Molecules are restless. They constantly vibrate and wander randomly. One result of this motion is **diffusion**, the movement of molecules spreading out evenly into the available space. Each molecule moves randomly, but the overall diffusion of a population of molecules is usually directional, from a region where the molecules are more concentrated to a region where they are less concentrated. For example, imagine many molecules of perfume inside a bottle. If you remove the bottle top, every molecule of perfume will move randomly about, but the overall movement will be out of the bottle, and the whole room will eventually smell of the perfume. You could, with great effort, return the perfume molecules to its bottle, but the molecules would never all return spontaneously.

▼ **Figure 5.11** Primary functions of membrane proteins. An actual cell may have just a few of the types of proteins shown here, and many copies of each particular protein may be present.



For an example closer to a living cell, imagine a membrane separating pure water from a mixture of dye dissolved in water (Figure 5.12). Assume that this membrane has tiny holes that allow dye molecules to pass. Although each dye molecule moves randomly, there will be a net migration across the membrane to the side that began as pure water. Movement of the dye will continue until both solutions have equal concentrations. After that, there will be a dynamic equilibrium: Molecules will still be moving, but at that point as many dye molecules move in one direction as in the other, so the concentration of dye molecules in water remains steady.

**✓ CHECKPOINT**

1. What does it mean to say that molecules move “down the concentration gradient”?
2. Why is facilitated diffusion a form of passive transport?

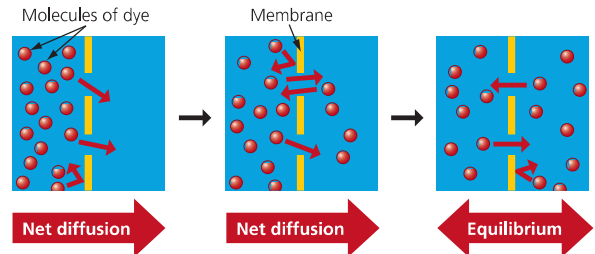
Answers: 1. The molecule moves from where it is more concentrated to where it is less concentrated. 2. It uses proteins to transport materials down a concentration gradient without expending energy.

Diffusion of dye across a membrane is an example of **passive transport**—*passive* because no energy is needed for the diffusion to happen. In passive transport, a substance diffuses down its **concentration gradient**, from where the substance is more concentrated to where it is less concentrated. In our lungs, for example, there is more oxygen gas (O<sub>2</sub>) in the air than in the blood. Therefore, oxygen moves by passive transport from the air into the bloodstream. But remember that the cell membrane is selectively permeable. For example, small molecules such as oxygen (O<sub>2</sub>) generally pass through more readily than larger molecules such as amino acids. But the membrane

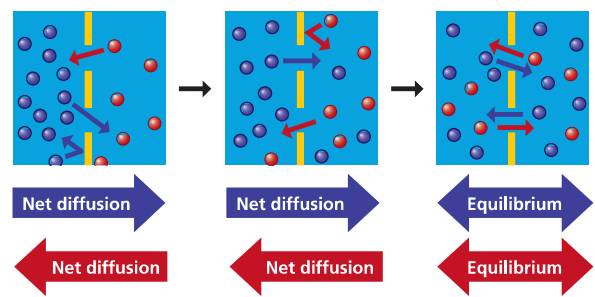
is relatively impermeable to even some very small substances, such as most ions, which are too hydrophilic to pass through the fatty phospholipid bilayer.

Substances that do not cross membranes spontaneously—or otherwise cross very slowly—can be transported by proteins that act as corridors for specific molecules (see Figure 5.11). This assisted transport is called **facilitated diffusion**. For example, water molecules can move through the plasma membrane of some cells by way of transport proteins—each of which can help 3 billion water molecules per second pass through! People with a rare mutation in the gene that encodes these water-transport proteins have defective kidneys that cannot reabsorb water; such people must drink 20 liters of water every day to prevent dehydration. On the flip side, a common complication of pregnancy is fluid retention, the culprit responsible for swollen ankles and feet, often caused by increased synthesis of water channel proteins. Other specific transport proteins move glucose across cell membranes 50,000 times faster than diffusion. Even at this rate, facilitated diffusion is a type of passive transport because it does not require the cell to expend energy. As in all passive transport, the driving force is the concentration gradient. ✓

▼ **Figure 5.12** **Passive transport: diffusion across a membrane.** A substance will diffuse from where it is more concentrated to where it is less concentrated. Put another way, a substance tends to diffuse down its concentration gradient.



(a) **Passive transport of one type of molecule.** The membrane is permeable to these dye molecules, which diffuse down the concentration gradient. At equilibrium, the molecules are still restless, but the rate of transport is equal in both directions.

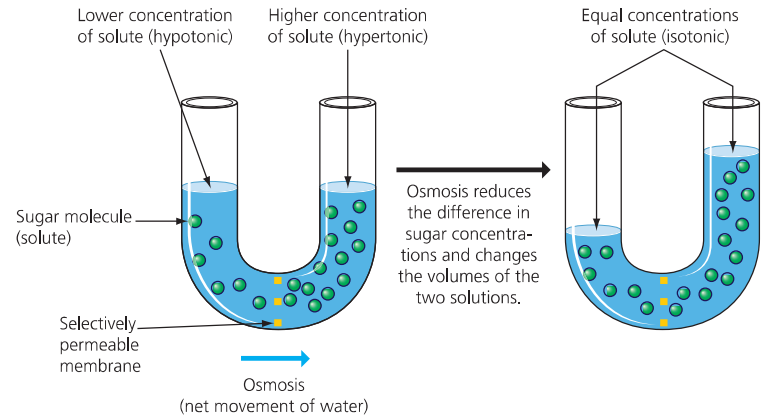


(b) **Passive transport of two types of molecules.** If solutions have two or more solutes, each will diffuse down its own concentration gradient.

## Osmosis and Water Balance

The diffusion of water across a selectively permeable membrane is called **osmosis** (Figure 5.13). A **solute** is a substance that is dissolved in a liquid solvent, and the resulting mixture is called a solution. For example, a solution of salt water contains salt (the solute) dissolved in water (the solvent). Imagine a membrane separating two solutions with different concentrations of a solute. The solution with a higher concentration of solute is

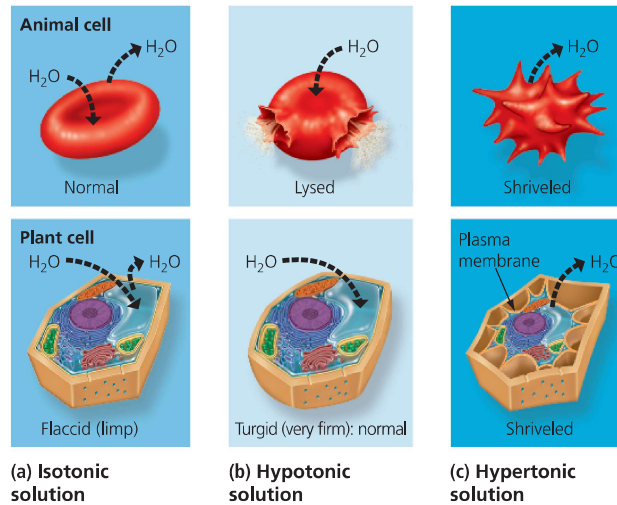
▼ **Figure 5.13** **Osmosis.** A membrane separates two solutions with different sugar concentrations. Water molecules can pass through the membrane, but the sugar molecules cannot.



said to be **hypertonic** to the other solution. The solution with the lower solute concentration is said to be **hypotonic** to the other. Note that the hypotonic solution, by having the lower solute concentration, has the higher water concentration (less solute = more water). Therefore, water will diffuse across the membrane along its concentration gradient from an area of higher water concentration (hypotonic solution) to one of lower water concentration (hypertonic solution). This reduces the difference in solute concentrations and changes the volumes of the two solutions.

People can take advantage of osmosis to preserve foods. Salt is often applied to meats—like beef and fish—to cure them into jerky; the salt causes water to move out of food-spoiling bacteria and fungi. Food can also be preserved in honey because a high sugar concentration draws water out of food.

When the solute concentrations are the same on both sides of a membrane, water molecules will move at the same rate in both directions, so there will be no net change in solute concentration. Solutions of equal solute concentration are said to be **isotonic**. For example, many marine animals, such as sea stars and crabs, are isotonic to seawater, so that overall they neither gain nor lose water from the environment. In your body, red blood cells are isotonic to the bloodstream in which they flow.



◀ **Figure 5.14** Osmotic environments. Animal cells (such as a red blood cell) and plant cells behave differently in different osmotic environments.

### Water Balance in Plant Cells

Problems of water balance are somewhat different for cells that have rigid cell walls, such as those from plants, fungi, many prokaryotes, and some protists. A plant cell immersed

in an isotonic solution is flaccid (floppy), and the plant wilts (Figure 5.14a, bottom). In contrast, a plant cell is turgid (very firm) and healthiest in a hypotonic environment, with a net inflow of water (Figure 5.14b, bottom). Although the elastic cell wall expands a bit, the back pressure it exerts prevents the cell from taking in too much water and bursting. Turgor is necessary for plants to retain their upright posture and the extended state of their leaves (Figure 5.15). However, in a hypertonic environment, a plant cell is no better off than an animal cell. As a plant cell loses water, it shrivels, and its plasma membrane pulls away from the cell wall (Figure 5.14c, bottom). This usually kills the cell. Thus, plant cells thrive in a hypotonic environment, whereas animal cells thrive in an isotonic one. ✓

▼ **Figure 5.15** Plant turgor. Watering a wilted plant will make it regain its turgor.



### ✓ CHECKPOINT

1. An animal cell shrivels when it is \_\_\_\_\_ compared with its environment.
2. What would happen if you placed one of your cells in pure water?

Answers: 1. hypotonic 2. Water would rush in (because it is more concentrated outside the cell and would burst the cell).

### Water Balance in Animal Cells

The survival of a cell depends on its ability to balance water uptake and loss. When an animal cell is immersed in an isotonic solution, the cell's volume remains constant because the cell gains water at the same rate that it loses water (Figure 5.14a, top). But what happens if an animal cell is in contact with a hypotonic solution, which has a lower solute concentration than the cell? Due to osmosis, the cell would gain water, swell, and possibly burst (lyse) like an overfilled water balloon (Figure 5.14b, top). A hypertonic environment is also harsh on an animal cell; the cell shrivels from water loss (Figure 5.14c, top).

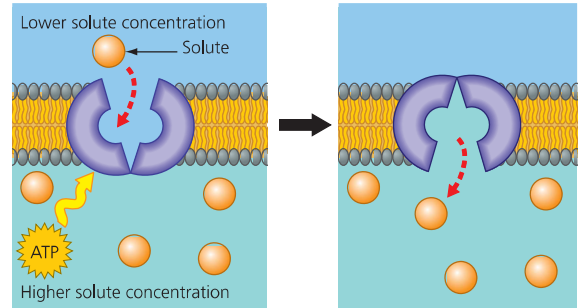
For an animal to survive a hypotonic or hypertonic environment, the animal must have a way to balance the uptake and loss of water. The control of water balance is called **osmoregulation**. For example, a freshwater fish has kidneys and gills that work constantly to prevent an excessive buildup of water in the body. Humans can suffer consequences of osmoregulation failure. Dehydration (consumption of too little water) can cause fatigue and even death. Drinking too much water—called hyponatremia, or “water intoxication”—can also cause death by overdiluting necessary ions.

## Active Transport: The Pumping of Molecules across Membranes

In contrast to passive transport, **active transport** requires that a cell expend energy to move molecules across a membrane. Cellular energy (usually provided by ATP) is used to drive a transport protein that pumps a solute *against* the concentration gradient—that is, in the direction that is opposite the way it would naturally flow (Figure 5.16). Movement against a force, like rolling a boulder uphill against gravity, requires a considerable expenditure of energy. Consider this analogy: During a storm, water spontaneously flows downhill into a basement (passive transport) but requires a powered sump pump to move it back uphill (active transport).

Active transport allows cells to maintain internal concentrations of small solutes that differ from environmental concentrations. For example, compared with its surroundings, an animal nerve cell has a much higher concentration of potassium ions and a much lower concentration of sodium ions. The plasma membrane helps maintain these differences by pumping sodium out of the

▼ **Figure 5.16 Active transport.** Transport proteins are specific in their recognition of atoms or molecules. This transport protein (purple) has a binding site that accepts only a certain solute. Using energy from ATP, the protein pumps the solute against its concentration gradient.



cell and potassium into the cell. This particular case of active transport (called the sodium-potassium pump) is vital to the nervous system of most animals. ✓

### ✓ CHECKPOINT

1. In what sense is active transport “active”?
2. What molecule is the usual energy source for active transport?

Answer: 1. Energy must be expended for the reaction to proceed. 2. ATP

## Exocytosis and Endocytosis: Traffic of Large Molecules

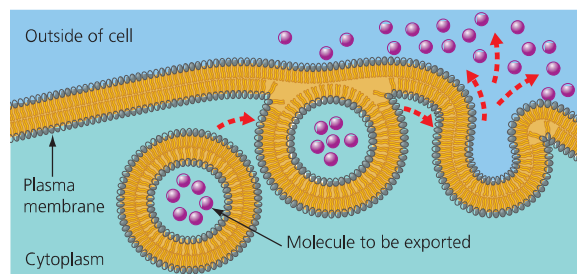
So far, we’ve focused on how water and small solutes enter and leave cells by moving through the plasma membrane. The story is different for large molecules such as proteins, which are much too big to fit through the membrane. Their traffic into and out of the cell depends on the ability of the cell to package large molecules inside sacs called vesicles. You have already seen an example of this: During protein production by the cell, secretory proteins exit the cell from transport vesicles that fuse with the plasma membrane, spilling the contents outside the cell (see Figures 4.13 and 4.17). That process is called **exocytosis** (Figure 5.17). When you cry, for example, cells in your tear glands use exocytosis to export the salty tears. In your brain, the exocytosis of neurotransmitter chemicals such as dopamine helps neurons communicate.

In **endocytosis**, a cell takes in material by vesicles that bud inward (Figure 5.18). For example, in a process called

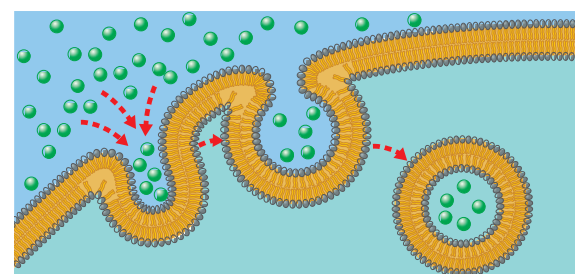
**phagocytosis** (“cellular eating”), a cell engulfs a particle and packages it within a food vacuole. Other times, a cell “gulps” droplets of fluid into vesicles. Endocytosis can also be triggered by the binding of certain external molecules to specific receptor proteins built into the plasma membrane. This binding causes the local region of the membrane to form a vesicle that transports the specific substance into the cell. In human liver cells, this process is used to take up cholesterol from the blood. An inherited defect in the receptors on liver cells can lead to an inability to process cholesterol, which can lead to heart attacks at ages as young as 5. Cells of your immune system use endocytosis to engulf and destroy invading bacteria and viruses.

Because all cells have a plasma membrane, it is logical to infer that membranes first formed early in the evolution of life on Earth. In the final section of this chapter, we’ll consider the evolution of membranes.

▼ **Figure 5.17 Exocytosis.**



▼ **Figure 5.18 Endocytosis.**



## The Origin of Membranes

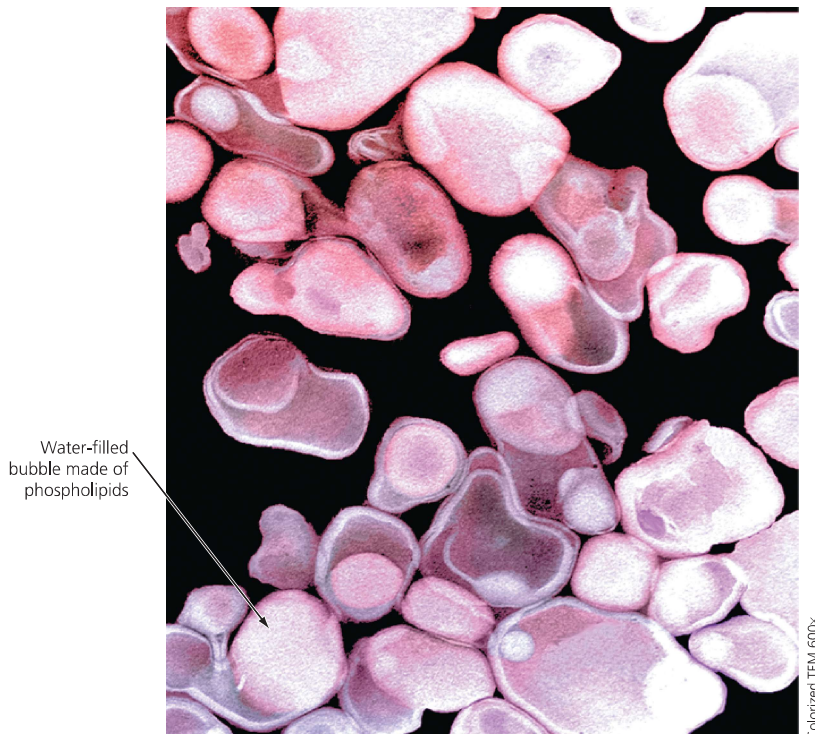
By simulating conditions found on the early Earth, scientists have been able to demonstrate that many of the molecules important to life can form spontaneously. (See Figure 15.3 and the accompanying text for a description of one such experiment.) Such results suggest that phospholipids, the key ingredients in all membranes, were probably among the first organic compounds that formed from chemical reactions on the early Earth. Once formed, they could self-assemble into simple membranes. When a mixture of phospholipids and water is shaken, for example, the phospholipids organize into bilayers, forming water-filled bubbles of membrane (Figure 5.19). This assembly requires neither genes nor other information beyond the properties of the phospholipids themselves.

The tendency of lipids in water to spontaneously form membranes has led biomedical engineers to produce liposomes (a type of artificial vesicle) that can encase specific chemicals. In the future, these engineered liposomes may be used to deliver nutrients or medications to specific sites within the body. In fact, over a dozen drugs have been approved for delivery by liposomes, including ones that target fungal infections, influenza, and hepatitis. Thus, membranes—like the other cellular components discussed in the Biology and Society and the Process of Science sections—have inspired novel nanotechnologies.

The formation of membrane-enclosed collections of molecules would have been a critical step in the evolution of the first cells. A membrane can enclose a solution that is different in composition from its surroundings. A plasma membrane that allows cells to regulate their chemical exchanges with the

environment is a basic requirement for life. Indeed, all cells are enclosed by a plasma membrane that is similar in structure and function—illustrating the evolutionary unity of life.

▼ **Figure 5.19** The spontaneous formation of membranes: a key step in the origin of life.



## Chapter Review

### SUMMARY OF KEY CONCEPTS

#### Some Basic Energy Concepts

##### Conservation of Energy

Machines and organisms can transform kinetic energy (energy of motion) to potential energy (stored energy) and vice versa. In all such energy transformations, total energy is conserved. Energy cannot be created or destroyed.

##### Heat

Every energy transformation releases some randomized energy in the form of heat. Entropy is a measure of disorder, or randomness.

##### Chemical Energy

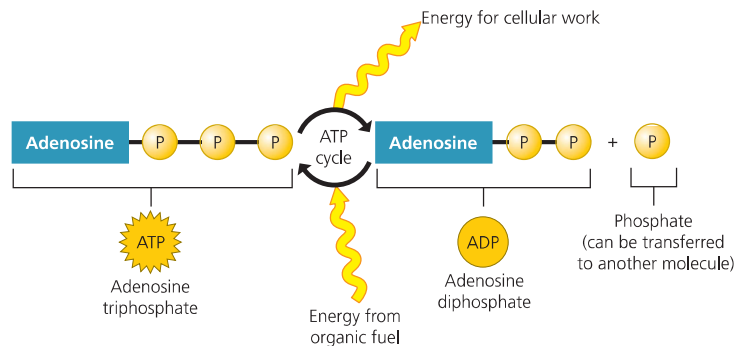
Molecules store varying amounts of potential energy in the arrangement of their atoms. Organic compounds are relatively rich in such chemical energy. The combustion of gasoline within a car's engine and the breakdown of glucose by cellular respiration within living cells are both examples of how the chemical energy stored in molecules can be converted to useful work.

##### Food Calories

Food Calories, actually kilocalories, are units used to measure the amount of energy in our foods and the amount of energy we expend in various activities.

## ATP and Cellular Work

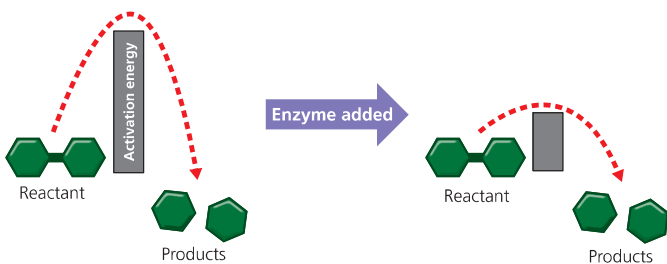
Your cells recycle ATP: As ATP is broken down to ADP to drive cellular work, new molecules of ATP are built from ADP using energy obtained from food.



## Enzymes

### Activation Energy

Enzymes are biological catalysts that speed up metabolic reactions by lowering the activation energy required to break the bonds of reactant molecules.



### Enzyme Activity

The entry of a substrate into the active site of an enzyme causes the enzyme to change shape slightly, allowing for a better fit and thereby promoting the interaction of enzyme with substrate.

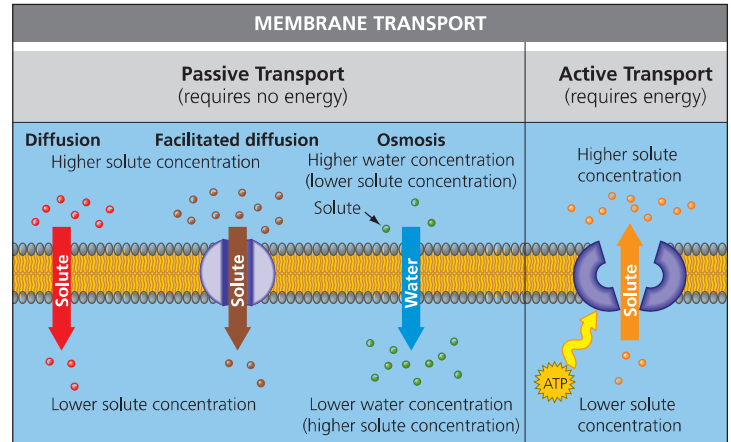
### Enzyme Inhibitors

Enzyme inhibitors are molecules that can disrupt metabolic reactions by binding to enzymes, either at the active site or elsewhere.

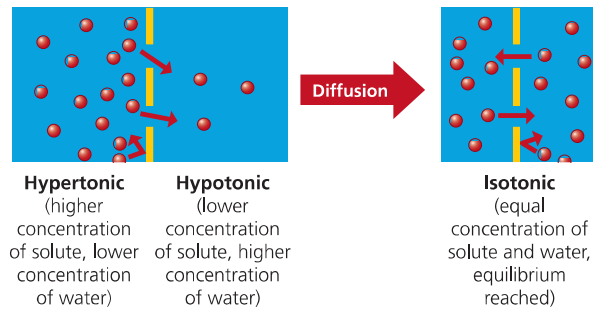
## Membrane Function

Proteins embedded in the plasma membrane perform a wide variety of functions, including regulating transport, anchoring to other cells or substances, promoting enzymatic reactions, and recognizing other cells.

## Passive Transport, Osmosis, and Active Transport

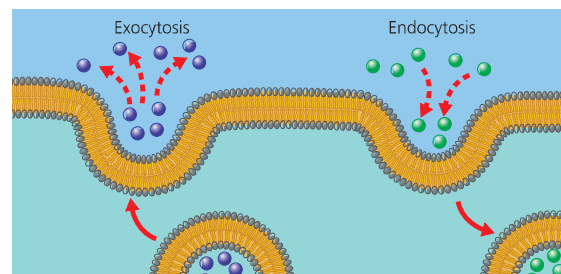


Most animal cells require an isotonic environment, with equal concentrations of water within and outside the cell. Plant cells need a hypotonic environment, which causes water to flow inward, keeping walled cells turgid.



## Exocytosis and Endocytosis: Traffic of Large Molecules

Exocytosis is the secretion of large molecules within vesicles. Endocytosis is the import of large substances by vesicles into the cell.



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