14.3 Energy and Chemical Reactions

All chemical reactions involve energy. If you have ever sat near a campfire, you have experienced this energy as heat and light. In addition to producing energy, chemical reactions also *use* energy. For example, plants perform photosynthesis, which is a chemical reaction that uses energy from sunlight.

VOCABULARY

exothermic - describes a chemical reaction that releases more energy than it uses.

endothermic - describes a chemical reaction that uses more energy than it releases.

Exothermic and endothermic reactions

Energy is involved in two ways Energy is involved in chemical reactions in two ways: (1) At the start of a chemical reaction, energy is used to break some (or all) bonds between atoms in the reactants so that the atoms are available to form new bonds; and (2) Energy is released when new bonds form as the atoms recombine into the new compounds of the products. We classify chemical reactions based on how the energy used in (1) compares to the energy released in (2).

Exothermic reactions If forming new bonds releases *more* energy than it takes to break the old bonds, the reaction is **exothermic** (Figure 14.16, top). Once started, exothermic reactions tend to keep going because each reaction releases enough energy to start the reaction in neighboring molecules. A good example is the reaction of hydrogen with oxygen. If we include energy, the balanced reaction looks like this:

$$\underset{\text{Oxygen}}{O_2(g)} + \underset{\text{Hydrogen}}{2H_2(g)} \longrightarrow \underset{\text{Water}}{2H_2O(l)} + \text{Energy}$$

Endothermic reactions If forming new bonds in the products releases *less* energy than it took to break the original bonds in the reactants, the reaction is **endothermic** (Figure 14.16, bottom). Endothermic reactions absorb energy. In fact, endothermic reactions need more energy to keep going. An example of an important endothermic reaction is *photosynthesis*. In photosynthesis, plants use energy from sunlight to make glucose and oxygen from carbon dioxide and water. If we include energy, the balance formula looks like this:

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \text{Energy} \longrightarrow \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

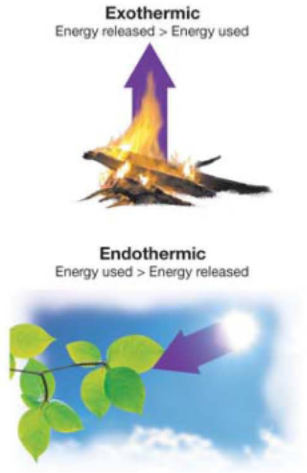
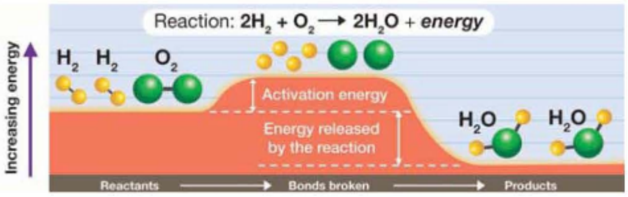


Figure 14.16: *Exothermic and endothermic reactions.*

Activation energy

An interesting question Exothermic reactions occur because the atoms arranged as compounds of the products have lower energy and are more stable than they are when arranged as compounds of the reactants. Chemical reactions—like other systems—move toward more stable circumstances. If this is true, why don't all the elements combine into the molecules that have the lowest possible energy?

Activation energy The answer has to do with **activation energy**, which is the energy needed to begin a reaction and break chemical bonds in the reactants. Without enough activation energy, a reaction will not happen even if it is exothermic. That is why a flammable material such as gasoline does not burn without a spark or flame. The spark supplies the activation energy to start the reaction.



An example of a reaction The diagram above shows how the energy flows in the reaction of hydrogen and oxygen. The activation energy must be supplied to break the molecules of hydrogen and oxygen apart. Energy is then released when the four free hydrogen and two free oxygen atoms combine to form two water molecules. The reaction is exothermic because the energy released by forming water is greater than the activation energy. Once the reaction starts, it supplies its own activation energy and quickly grows (Figure 14.17).

Reactions occur only when conditions are right A reaction begins by itself when thermal energy is greater than the activation energy. However, any reaction that could start by itself probably already has! The compounds and molecules in substances around you need more activation energy to change into anything else. For example, table salt in a dish will remain table salt for a long time unless the conditions change to cause a chemical reaction between the salt and another compound.

VOCABULARY

activation energy - energy needed to break chemical bonds in the reactants to start a reaction.

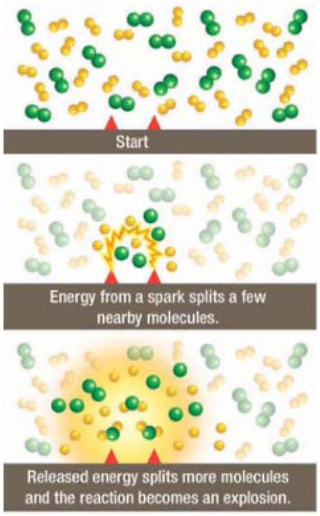


Figure 14.17: *Because energy released by one reaction supplies activation energy for new reactions, exothermic reactions can grow quickly once activation energy has been supplied.*

Examples of endothermic reactions

Endothermic reactions in industry It's certainly useful when chemical reactions *produce* more energy than they use. But how do we benefit from reactions that *use* more energy than they produce? It turns out that most of the reactions used in industry to produce useful materials require more energy than they produce. This is one of the reasons sources of energy are so important to industry. In other words, exothermic reactions are needed to cause endothermic reactions to run. One example of an industry process that frequently uses endothermic reactions is the refining of ores to produce useful metals. Here is a specific example, the refinement of aluminum ore from aluminum oxide.

$$2Al_2O_3\,(s) + \text{Energy} \longrightarrow 4Al\,(s) + 3O_2\,(g)$$

This reaction requires the input of energy because it takes more energy to break the bonds in the aluminum oxide than is released when the products are formed.

Cold packs Have you ever used an instant cold pack as a treatment for a twisted ankle or a bruise? These products, found in your local drugstore, work by using an endothermic chemical reaction. The fact that more energy is used than produced is what makes the cold pack cold. The reaction, shown below, works as follows. The product usually comes in a plastic bag. Inside of the bag is a sealed packet of water surrounded by crystals of ammonium nitrate. To activate the cold pack, you squeeze the plastic bag to break the packet of water. When the water contacts the ammonium nitrate crystals, a reaction occurs and the pack becomes icy cold (Figure 14.18).

$$NH_4NO_3\,(s) + H_2O\,(l) + \text{Energy} \longrightarrow NH_4^+\,(aq) + NO_3^-\,(aq)$$

Dissolution reactions The ice pack gets very cold because it takes energy to dissolve the ionic bonds in the ammonium nitrate. Besides being endothermic, this reaction is also a dissolution reaction. A **dissolution reaction** occurs when an ionic compound, such as ammonium nitrate, dissolves in water to make an ionic solution. In the cold pack reaction, the ions are ammonium (NH_4^+) and nitrate (NO_3^-).

VOCABULARY

dissolution reaction - an endothermic reaction that occurs when an ionic compound dissolves in water to make an ionic solution.

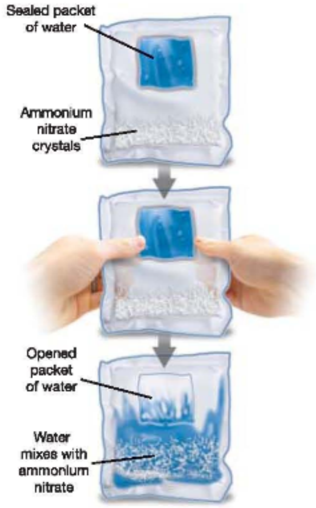


Figure 14.18: *A cold pack works because of an endothermic reaction.*

Reaction rate

Kinetic molecular theory In all phases of matter, atoms and molecules exhibit random motion. This concept is part of the kinetic molecular theory. The speed at which atoms or molecules move depends on the state of matter and the temperature. As you know, gas molecules move faster than molecules in a solid, and warmer substances have greater molecular motion than cold ones.

What is reaction rate? The **reaction rate** for a chemical reaction is the change in concentration of reactants or products over time. For a reaction involving two or more reactants, the reaction only works if the molecules collide. If we want the reaction to go faster, what kinds of things could we do to increase the motion and number of collisions among the reactants?

Increasing collisions For starters, you can add heat to a reaction to increase molecular motion. For example, to dissolve salt faster in water in a dissolution reaction, you increase the temperature of the water. Other ways to increase collisions include stirring the reaction mixture and using powdered reactants. Fine particles in powders have more available surface area for reacting.

Increasing concentration of reactants Another way to increase collisions among atoms or molecules is to increase the concentration of the reactants. When you increase the concentration of a reactant, it is like adding an extra team member to complete a project. If the project involved many calculations, the team could complete them more quickly with six people than with five. As you know, doing calculations by hand takes a while. What if the team had a computer or calculator?

Catalysts and inhibitors A **catalyst** is a molecule that can be added to a reaction to speed it up, but it doesn't get used up. A catalyst is a little like using a computer or a calculator to help you speed up the job of making calculations. Catalysts work by increasing the chances that two molecules will be positioned in the right way for a reaction to occur. Because a catalyst ensures the correct orientation of colliding molecules, less energy is needed in the collision for the reaction to occur. In effect, a catalyst provides a "shortcut" because a lower activation energy is needed for a reaction to proceed (Figure 14.19). Reactions can also be slowed down by molecules called **inhibitors**. Inhibitors bind with reactant molecules and effectively block them from combining to form products.

VOCABULARY

reaction rate - the change in concentration of reactants or products in a chemical reaction over time.

catalyst - a molecule added to a chemical reaction that increases the reaction rate without getting used up in the process.

inhibitor - a molecule that slows down a chemical reaction.

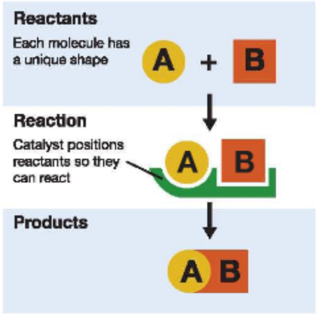


Figure 14.19: *By bringing together reactants, a catalyst lowers the activation energy needed.*

Chemical equilibrium

The direction of a chemical reaction Up until now, we have thought about chemical reactions as going in only one direction. Reactants react to make products. This has been shown in chemical equations with a right-pointing arrow that points toward the products of the reaction. Therefore, chemical reactions are commonly described as proceeding to the right. In some cases, once a reaction goes to the right, the reaction reverses and goes to the left. The products become reactants and the reactants become products (Figure 14.20).

Chemical equilibrium Eventually, a reaction might reach **chemical equilibrium**, the state in which the rate of the forward reaction equals the rate of the reverse reaction. When we talk about chemical equilibrium, we acknowledge that the reaction can go left and right simultaneously. Chemical equilibrium is represented by arrows going both ways, or a double-headed arrow (Figure 14.20).

Characteristics of chemical equilibrium Because chemical reactions are often open systems, the reactants and products can easily react with other compounds. If this happens, the products cannot revert back to reactants because they are unavailable. A gas that is a product, for example, easily leaves the reaction system. Therefore, for chemical equilibrium to be established, the chemical reaction has to occur in a closed system. When a chemical reaction occurs in a closed system at a constant temperature, the forward and reverse reactions occur at the same rate, and the amounts of reactants and products are constant.

An advanced topic: Le Chatelier's principle Let's say you have a chemical reaction at chemical equilibrium in a closed container in your laboratory. You leave the system alone but someone turns up the heat by accident and the room you are in gets hotter and hotter. What happens to the chemical reaction in the container? A change in temperature is considered to be a stress on the system. In response to this stress, the system reacts until chemical equilibrium is reestablished. This phenomenon is called *Le Chatelier's principle*. This principle states that a chemical reaction at chemical equilibrium reacts to any stress on the system until equilibrium is re-established. A stress could include increasing the concentration of a reactant or product, or changing the temperature or pressure conditions of the reaction.

VOCABULARY

chemical equilibrium - the state in a chemical reaction at which the rate of the forward reaction equals the rate of the reverse reaction.

A reaction going to the right

Reactants ⟶ Products

A + B ⟶ AB

A reaction going to the left

Products ⟵ Reactants

A + B ⟵ AB

Chemical equilibrium

Products ⟷ Reactants

A + B ⟷ AB

Figure 14.20: *The direction of a reaction is indicated with an arrow. When a reaction is in chemical equilibrium, a double-headed arrow is used.*

Section 14.3 Review

1. List the two ways that energy is involved in chemical reactions.
2. Identify the following statements as describing either an exothermic or an endothermic reaction.
   a. More energy is released than is used by the reaction.
   b. The chemical reaction involved in burning wood
   c. Less energy is released than is used by the reaction.
3. Why is a spark of energy required to begin the chemical reaction of burning a fossil fuel? What is another name for this spark of energy?
4. The reaction below is an exothermic reaction.
   $K_2O\ (s) + CO_2\ (g) \rightarrow K_2CO_3\ (s)$
   a. Rewrite this reaction and add "+ energy" in the correct location.
   b. Describe how the energy level of the reactants compares to the energy level of the products.
5. The reaction below is an endothermic reaction.
   $2HgO\ (s) \rightarrow 2Hg\ (l) + O_2\ (g)$
   a. Rewrite this reaction and add "+ energy" in the correct location.
   b. Describe how the energy level of the reactants compares to the energy level of the products.

Table 14.2: A Review of the Factors Affecting Reaction Rate

Action	Do collisions increase?	Does the energy of the collisions increase?
Stirring	Yes	No
Increasing temperature	Yes	Yes
Increasing surface area	Yes	No
Increasing concentration	Yes	No
Adding a catalyst	Improves the effectiveness of collisions so less energy is needed for a reaction	
Adding an inhibitor	Prevents or diminishes the effectiveness of collisions so more energy is needed for a reaction	

SCIENCE FACT

Many reactions in the human body require enzymes, a kind of catalyst, to get reactions going. Not surprisingly, the temperature of the human body, 37°C or 98°F, is ideal for enzymes to work well.

Getting a mild fever indicates that you might be sick. However, you are dangerously ill if you have a high fever for too long. Based on the information above, what might be a consequence of having a high fever in terms of how your body works?

CHALLENGE

Table 14.2 organizes information related to the factors affecting reaction rate.

(1) List the two most effective factors in increasing reaction rate. Explain your choices.

(2) What is the most effective way to slow down a reaction rate? Explain your choice.

(3) Would stirring affect a chemical reaction that has chemical equilibrium? Explain your answer.