SECTION 1

The Nature of Chemical Reactions

KEY TERMS

reactant
product
chemical energy
exothermic reaction
endothermic reaction

OBJECTIVES

- **Recognize** some signs that a chemical reaction may be taking place.
- **Explain** chemical changes in terms of the structure and motion of atoms and molecules.
- **Describe** the differences between endothermic and exothermic reactions.
- **Identify** situations involving chemical energy.

If someone talks about chemical reactions, you might think about scientists doing experiments in laboratories. But words like *grow, ripen, decay,* and *burn* describe chemical reactions you see every day. Even your own health is due to chemical reactions taking place inside your body. The food you eat reacts with the oxygen you inhale in processes such as respiration and cell growth. The carbon dioxide formed in these reactions is carried to your lungs, and you exhale it into the environment.

Chemical Reactions Change Substances

When sugar, water, and yeast are mixed into flour to make bread dough, a chemical reaction takes place. The yeast acts on the sugar to form new substances, including carbon dioxide and lactic acid. You know that a chemical reaction has happened because lactic acid and carbon dioxide are different from sugar.

Chemical reactions occur when substances undergo chemical changes to form new substances. Often you can tell that a chemical reaction is happening because you will be able to see changes, such as those in **Figure 1**.

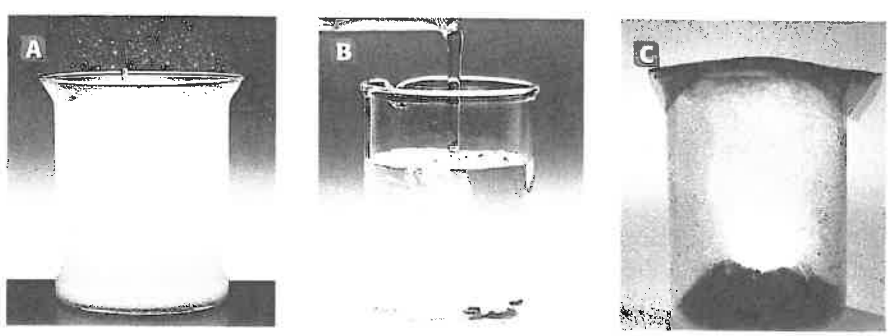


Figure 1

Signs of a Chemical Reaction

A When the calcium carbonate in a piece of chalk reacts with an acid, bubbles of carbon dioxide gas are given off.

B When solutions of sodium sulfide and cadmium nitrate are mixed, a solid—yellow cadmium sulfide—settles out of the solution.

C When ammonium dichromate decomposes, energy is released as light and heat.

Production of gas and change of color are signs of chemical reactions

In bread making, the carbon dioxide gas that is produced expands the dough, causing the bread to rise. This release of gas is a sign that a chemical reaction may be happening.

As the dough bakes, old bonds break and new bonds form. Chemical reactions involving starch and protein make food turn brown when heated. A chemical change happens almost every time there is a change in color.

Chemical reactions rearrange atoms

When gasoline is burned in the engine of a car or boat, a lot of different reactions happen with the compounds that are in the mixture we call gasoline. In a typical reaction, isooctane, C_8H_{18}, and oxygen, O_2, are the **reactants.** They react and form two **products,** carbon dioxide, CO_2, and water, H_2O.

The products and reactants contain the same types of atoms: carbon, hydrogen, and oxygen. New product atoms are not created, and old reactant atoms are not destroyed. Atoms are rearranged as bonds are broken and formed. In all chemical reactions, mass is always conserved.

reactant a substance or molecule that participates in a chemical reaction

product a substance that forms in a chemical reaction

Energy and Reactions

Filling a car's tank with gasoline would be very dangerous if isooctane and oxygen could not be in the same place without reacting. Like most chemical reactions, the isooctane-oxygen reaction needs energy to get started. A small spark provides enough energy to start this reaction. That is why smoking or having any open flame near a gas pump is not allowed.

Energy must be added to break bonds

In each isooctane molecule, like the one shown in ***Figure 2,*** all the bonds to carbon atoms are covalent. In an oxygen molecule, a covalent bond holds the two oxygen atoms together. For the atoms in isooctane and oxygen to react, all of these bonds have to be broken. This takes energy.

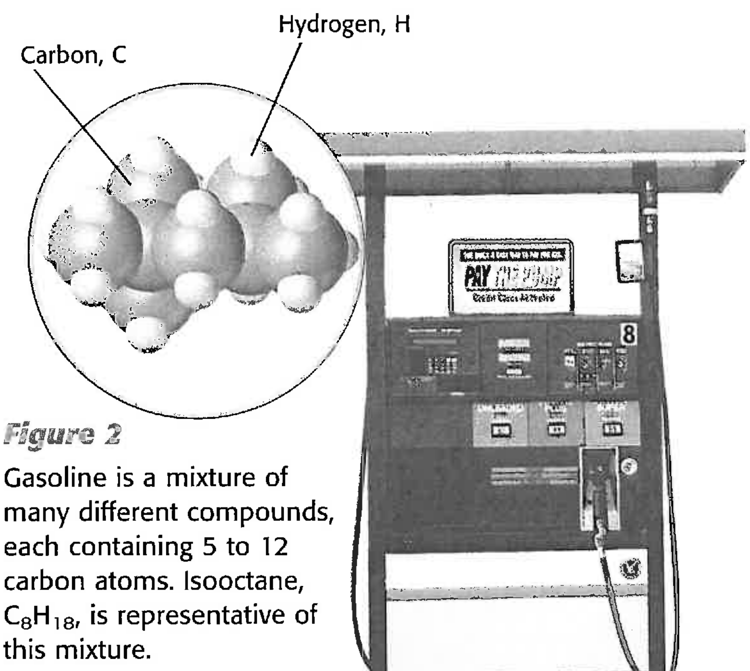
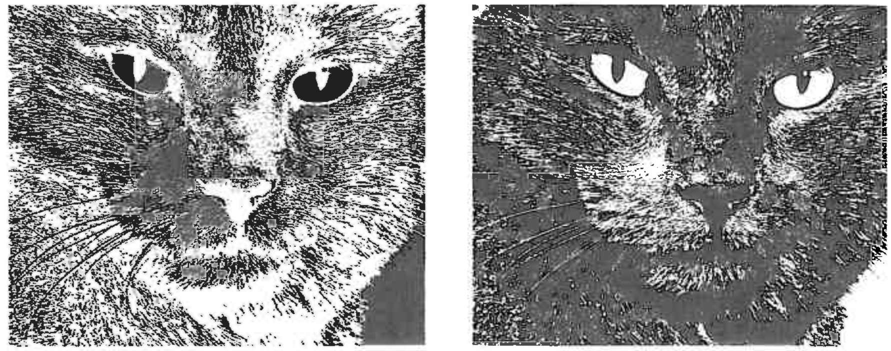


Figure 2
Gasoline is a mixture of many different compounds, each containing 5 to 12 carbon atoms. Isooctane, C_8H_{18}, is representative of this mixture.

Figure 3

A Light passing through a camera lens causes silver bromide crystals on the film to form darker elemental silver on the negative.

B Light passing through the negative onto black and white photographic paper causes another reaction that forms the photograph.



A Negative **B** Photo (positive image)

Many forms of energy can be used to break bonds. Sometimes the energy is transferred as heat, like the spark that starts the isooctane-oxygen reaction. Energy also can be transferred as electricity, sound, or light, as shown in ***Figure 3***. When molecules collide and enough energy is transferred to separate the atoms, bonds can break.

Forming bonds releases energy

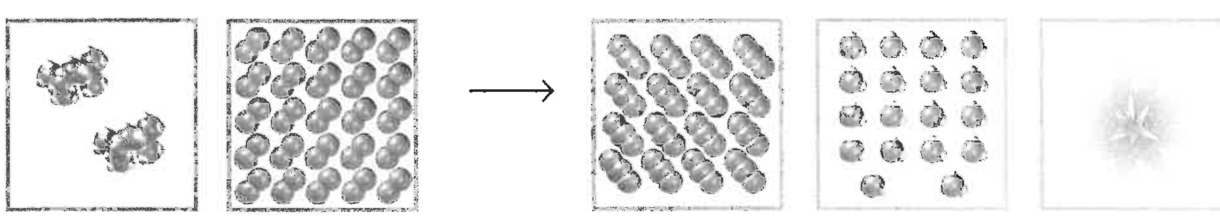
Once enough energy is added to start the isooctane-oxygen reaction, new bonds form to make the products, as shown in ***Figure 4***. Each carbon dioxide molecule has two oxygen atoms connected to the carbon atom with a double bond. A water molecule is made when two hydrogen atoms each form a single bond with the oxygen atom.

When new bonds form, energy is released. When gasoline burns, energy in the form of heat and light is released as the products of the isooctane-oxygen reaction and other gasoline reactions form. Other chemical reactions can produce electrical energy.

Figure 4

The formation of carbon dioxide and water from isooctane and oxygen produces the energy used to power engines.

Reactants				$\longrightarrow$	**Products**				
Isooctane		**Oxygen**		$\longrightarrow$	**Carbon dioxide**		**Water**		**Energy**
C_8H_{18}		O_2		$\longrightarrow$	CO_2		H_2O		energy
$2C_8H_{18}$	+	$25O_2$		$\longrightarrow$	$16CO_2$	+	$18H_2O$	+	energy



Energy is conserved in chemical reactions

Energy may not appear to be conserved in the isooctane reaction. After all, a tiny spark can set off an explosion. The energy for that explosion comes from the bonds between atoms in the reactants. Often this stored energy is called **chemical energy.** The total energy of isooctane, oxygen, and their surroundings includes this chemical energy. The total energy before the reaction is equal to the total energy of the products and their surroundings.

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Reactions that release energy are exothermic

In the isooctane-oxygen reaction, more energy is released as the products form than is absorbed to break the bonds in the reactants. Like all other combustion reactions, this is an **exothermic reaction.** After an exothermic reaction, the temperature of the surroundings rises because energy is released. The released energy comes from the chemical energy of the reactants.

chemical energy the energy released when a chemical compound reacts to produce new compounds

exothermic reaction a chemical reaction in which heat is released to the surroundings

endothermic reaction a chemical reaction that requires heat

Reactions that absorb energy are endothermic

If you put hydrated barium hydroxide and ammonium nitrate together in a flask, the reaction between them takes so much energy from the surroundings that water in the air will condense and then freeze on the surface of the flask. This is an **endothermic reaction** —more energy is needed to break the bonds in the reactants than is given off by forming bonds in the products.

REAL WORLD APPLICATIONS

Self-Heating Meals

Corrosion, the process by which a metal reacts with the oxygen in air or water, is not often desirable. However, corrosion is encouraged in self-heating meals so that the energy from the exothermic reaction can be used. Self-heating meals, as the name implies, have their own heat source.

Each meal contains a package of precooked food, a bag that holds a porous pad containing a magnesium-iron alloy, and some salt water. When the salt water is poured into the bag, the salt water soaks through the holes in the pad of metal alloy and begins to corrode the metals vigorously. Then the sealed food package is placed in the bag. The exothermic reaction raises the temperature of the food by 38°C in 14 minutes.

Applying Information

1. List some people for whom self-heating meals would be useful.
2. What other uses can you think of for this self-heating technology?

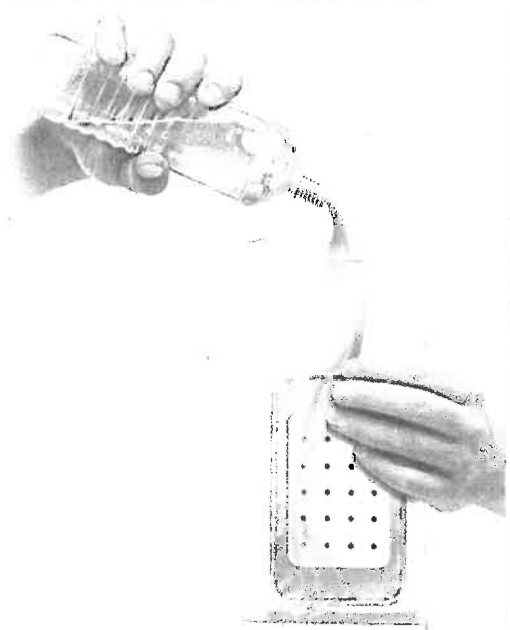
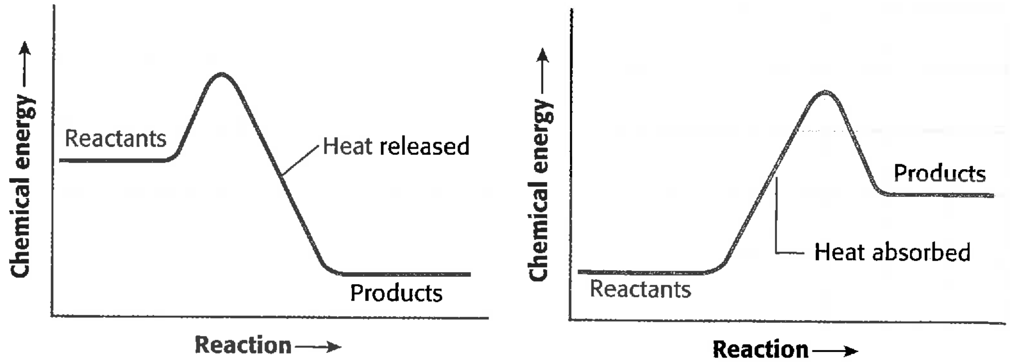


Figure 5

Energy must be added to start both exothermic and endothermic reactions.



A In an exothermic reaction chemical energy is released, often as heat.

B In an endothermic reaction, energy from the surroundings is stored as chemical energy.

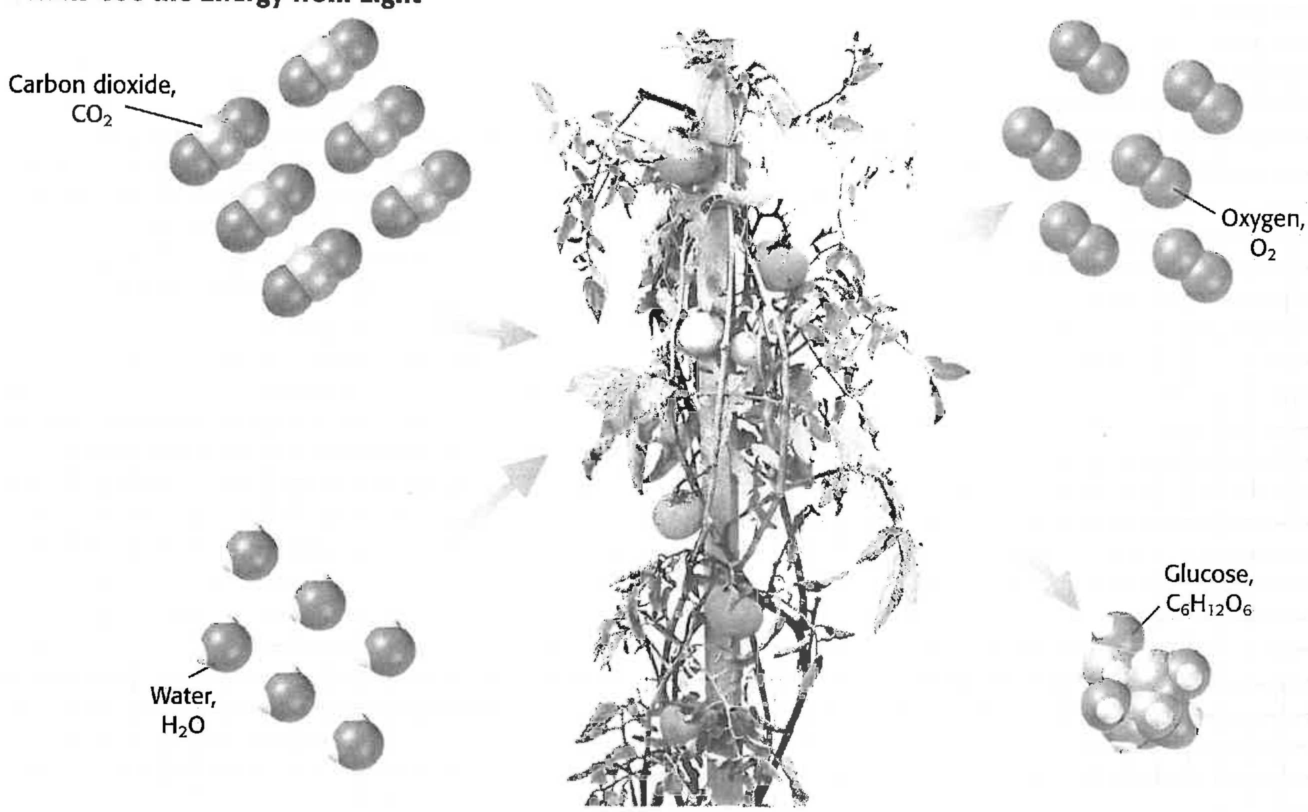
When an endothermic reaction occurs, you may be able to notice a drop in temperature. Some endothermic reactions cannot get enough energy as heat from the surroundings to happen; so energy must be added as heat to cause the reaction to take place. The changes in chemical energy for an exothermic reaction and for an endothermic reaction are shown in Figure 5.

Photosynthesis, like many reactions in living things, is endothermic. In photosynthesis, plants use energy from light to convert carbon dioxide and water to glucose and oxygen, as shown in Figure 6.

Figure 6

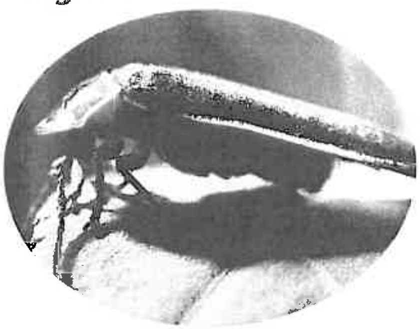
All of the food you eat comes directly or indirectly from the products of photosynthesis.

Plants Use the Energy from Light

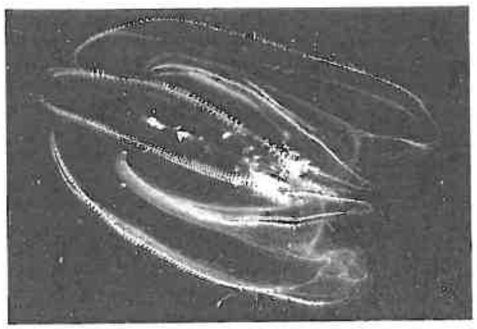


Sometimes, reactions are described as exergonic or endergonic. These terms refer to the ease with which the reactions occur. In most cases in this book, exergonic reactions are exothermic and endergonic reactions are endothermic. Bioluminescence, shown in **Figure 7**, and respiration are exergonic reactions, and photosynthesis is an endergonic reaction.

Figure 7



A Some living things, such as this firefly, produce light through a chemical process called bioluminescence.



B The comb jelly *(Mnemiopsis leidyi)*, shown above, is about 10 cm wide and is native to the Atlantic coast. Comb jellies are not true jellyfish.

INTEGRATING

BIOLOGY

People are charmed by fireflies because these common insects give off light. Scientists have found that fireflies are not alone in this. Some kinds of bacteria, worms, squids, and jellyfish also give off light. This process, called bioluminescence, involves an exothermic reaction made possible by the enzyme luciferase. Scientists can use bacteria that contain luciferase to track the spread of infection in the human body.

SECTION 1 REVIEW

SUMMARY

- During a chemical reaction, atoms are rearranged.
- Signs of a chemical reaction include any of the following: a substance that has different properties than the reactants have; a color change; the formation of a gas or a solid precipitate; or the transfer of energy.
- Mass and energy are conserved in chemical reactions.
- Energy can be released or absorbed in a chemical reaction.
- Energy must be added to the reactants for bonds between atoms to be broken.

1. **Identify** which of the following is a chemical reaction:
   - **a.** melting ice
   - **b.** burning a candle
   - **c.** rubbing a marker on paper
   - **d.** rusting iron
2. **List** three signs that could make you think a chemical reaction might be taking place.
3. **List** four forms of energy that might be absorbed or released during a chemical reaction.
4. **Classify** the following reactions as exothermic or endothermic:
   - **a.** paper burning with a bright flame
   - **b.** plastics becoming brittle after being left in the sun
   - **c.** a firecracker exploding
5. **Predict** which atoms will be found in the products of the following reactions:
   - **a.** mercury(II) oxide, HgO, is heated and decomposes
   - **b.** limestone, $CaCO_3$, reacts with hydrochloric acid, HCl
   - **c.** table sugar, $C_{12}H_{22}O_{11}$, burns in air to form caramel
6. **Critical Thinking** Calcium oxide, CaO, is used in cement mixes. When water is added, heat is released as CaO forms calcium hydroxide, $Ca(OH)_2$. What signs are there that this is a chemical reaction? Which has more chemical energy, the reactants or the products? Explain your answer.

SECTION 2

Reaction Types

KEY TERMS

synthesis reaction
decomposition reaction
electrolysis
combustion reaction
single-displacement reaction
double-displacement reaction
oxidation-reduction reaction
radical

OBJECTIVES

- **Distinguish** among five general types of chemical reactions.
- **Predict** the products of some reactions based on the reaction type.
- **Describe** reactions that transfer or share electrons between molecules, atoms, or ions.

In the last section, you saw how CO_2 is made from sugar by yeast, how isooctane from gasoline burns, and how photosynthesis happens. These are just a few examples of the many millions of possible reactions.

synthesis reaction a reaction in which two or more substances combine to form a new compound

Classifying Reactions

Even though there are millions of unique substances and many millions of possible reactions, there are only a few general types of reactions. Just as you can follow patterns to name compounds, you also can use patterns to identify the general types of chemical reactions and to predict the products of the chemical reactions.

Synthesis reactions combine substances

Polyethene, a plastic often used to make trash bags and soda bottles, is produced by a **synthesis reaction** called polymerization. In polymerization reactions, many small molecules join together in chains to make larger structures called polymers. Polyethene, shown in ***Figure 8,*** is a polymer formed of repeating ethene molecules.

Hydrogen gas reacts with oxygen gas to form water. In a synthesis reaction, at least two reactants join to form a product. Synthesis reactions have the following general form.

$$A + B \longrightarrow AB$$

The following is a synthesis reaction in which the metal sodium reacts with chlorine gas to form sodium chloride, or table salt.

$$2Na + Cl_2 \longrightarrow 2NaCl$$

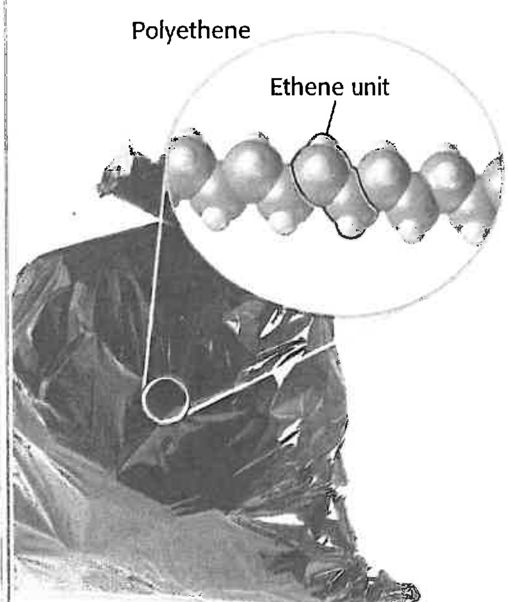


Figure 8
A molecule of polyethene is made up of as many as 3500 units of ethene.

Synthesis reactions always join substances, so the product is a more complex compound than the reactants.

Photosynthesis is another kind of synthesis reaction—the synthesis reaction that goes on in plants. The photosynthesis reaction is shown in **Figure 9**.

Decomposition reactions break substances apart

Digestion is a series of reactions that break down complex foods into simple fuels your body can use. Similarly, in what is known as "cracking" crude oil, large molecules made of carbon and hydrogen are broken down to make gasoline and other fuels. Digestion and "cracking" oil are **decomposition reactions,** reactions in which substances are broken apart. The general form for decomposition reactions is as follows.

$$AB \longrightarrow A + B$$

The following shows the decomposition of water.

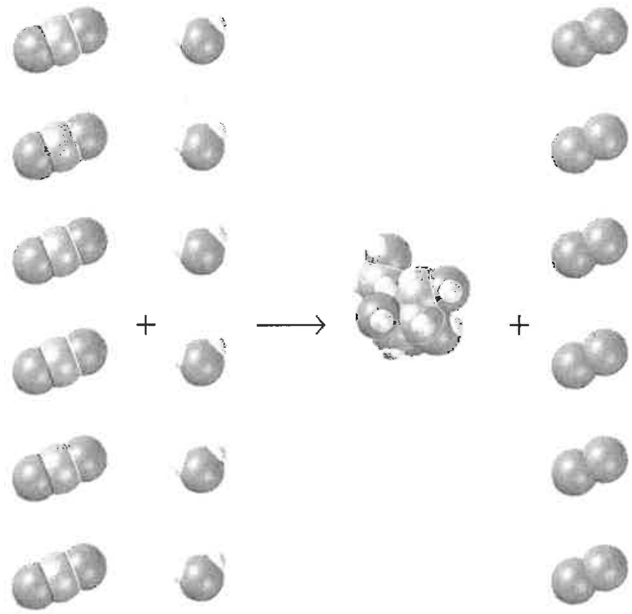
$$2H_2O \longrightarrow 2H_2 + O_2$$

The **electrolysis** of water is a simple decomposition reaction—water breaks down into hydrogen gas and oxygen gas when an electric current flows through the water.

Combustion reactions use oxygen as a reactant

Isooctane forms carbon dioxide and water during combustion. Oxygen is a reactant in every **combustion reaction,** so at least one product of such reactions always contains oxygen. Water is a common product of combustion reactions.

If the air supply is limited when a carbon-containing fuel burns, there may not be enough oxygen gas for all the carbon to form carbon dioxide. In that case, some carbon monoxide may form. Carbon monoxide, CO, is a poisonous gas that lowers the ability of the blood to carry oxygen. Carbon monoxide has no color or odor, so you can't tell when it is present. When there is not a good air supply during a combustion reaction, not all fuels are converted completely to carbon dioxide. In some combustion reactions, you can tell if the air supply is limited because the excess carbon is given off as small particles that make a dark, sooty smoke.



$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

Figure 9

Photosynthesis is the synthesis of glucose and oxygen gas from carbon dioxide and water.

decomposition reaction a reaction in which a single compound breaks down to form two or more simpler substances

electrolysis the process in which an electric current is used to produce a chemical reaction, such as the decomposition of water

combustion reaction the oxidation reaction of an organic compound, in which heat is released

Did You Know?

In the United States, natural gas supplies one-fifth of the energy used. The pipelines that carry this natural gas, if laid end-to-end, would stretch to the moon and back twice.

INTEGRATING

EARTH SCIENCE

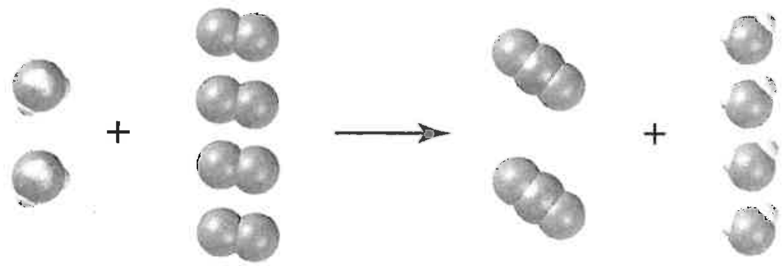
Compounds containing carbon and hydrogen are often called hydrocarbons. Most hydrocarbon fuels are fossil fuels, that is, compounds that were formed millions of years before dinosaurs existed. When prehistoric organisms died, they decomposed, and many were slowly buried under layers of mud, rock, and sand. During the millions of years that passed, the once-living material formed different fuels, such as oil, natural gas, or coal, depending on the kind of material present, the length of time the material was buried, and the conditions of temperature and pressure that existed when the material was decomposing.

In combustion the products depend on the amount of oxygen

To see how important a good air supply is, look at a series of combustion reactions for methane, CH_4. Because methane has only one carbon atom, it is the simplest carbon-containing fuel. Methane is the primary component in natural gas, the fuel often used in stoves, water heaters, and furnaces.

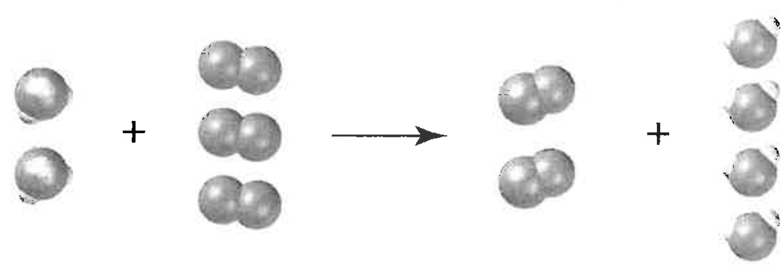
Methane reacts with oxygen gas to make carbon dioxide and water. In the balanced form of the chemical equation, four molecules of oxygen gas are needed for the combustion of two molecules of methane, as shown below.

$$2CH_4 + 4O_2 \longrightarrow 2CO_2 + 4H_2O$$



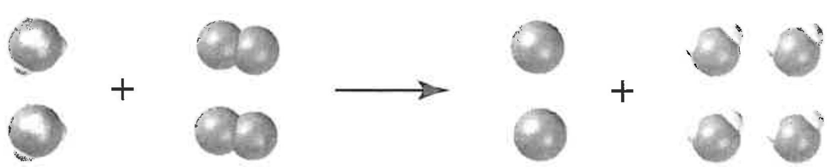
Now look at what happens when less oxygen gas is available. If there are only three molecules of oxygen gas for every two molecules of methane, water and carbon monoxide may form, as shown in the following reaction.

$$2CH_4 + 3O_2 \longrightarrow 2CO + 4H_2O$$



When the air supply is very limited and only two molecules of oxygen gas are available to react with two molecules of methane, water and tiny bits of carbon, or soot, are formed as follows.

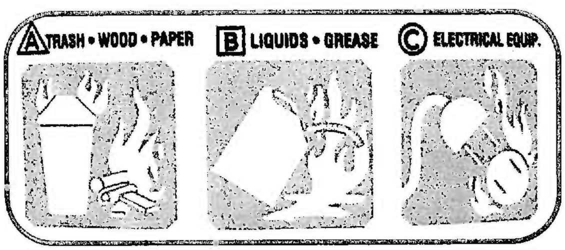
$$2CH_4 + 2O_2 \longrightarrow 2C + 4H_2O$$



Science and the Consumer

Fire Extinguishers: Are They All The Same?

A fire is a combustion reaction in progress that is speeded up by high temperatures. Three things are needed for a combustion reaction to occur: a fuel, some oxygen, and an ignition source. If any of these three is absent, combustion cannot occur. So the goal of firefighting is to remove one or more of these parts. Fire extinguishers are effective in firefighting because they separate the fuel from the oxygen supply, which is most commonly air.



Fire extinguishers display codes indicating which types of fires they can put out.

Classes of Fires

A fire is classified by the type of fuel that combusts to produce it. Class A fires involve solid fuels, such as wood and paper. The fuel in a Class B fire is a flammable liquid, like grease, gasoline, or oil. Class C fires involve "live" electric circuits. And Class D fires are fueled by the combustion of flammable metals.

Types of Fire Extinguishers

Different types of fuels require different firefighting methods. Water extinguishers are used on Class A fires, which involve fuels such as most flammable building materials. The steam that is produced helps to displace the air around the fire, preventing the oxygen supply from reaching the fuel.

A Class B fire, in which the fuel is a liquid, is best put out by cold carbon dioxide gas, CO_2. Because carbon dioxide is more dense than air, it forms a layer underneath the air, cutting off the oxygen supply for the combustion reaction.

Class C fires, which involve a "live" electric circuit, can also be extinguished by CO_2. Liquid water cannot be used, or there will be a danger of electric shock. Some Class C fire extinguishers contain a dry chemical that smothers the fire. The dry chemical smothers the fire by reacting with the intermediates that drive the chain reaction that produces the fire. This stops the chain reaction and extinguishes the fire.

Finally, Class D fires, which involve burning metals, cannot be extinguished with CO_2 or water because these compounds may react with some hot metals. For these fires, nonreactive dry powders are used to cover the metal and keep it separate from oxygen. In many cases, the powders used in Class D extinguishers are specific to the type of metal that is burning.

Most fire extinguishers can be used with more than one type of fire. Check the fire extinguishers in your home and school to find out the kinds of fires they are designed to put out.

Your Choice

1. **Making Decisions** Aside from displacing the air supply, how does water or cold CO_2 gas reduce a fire's severity?
2. **Critical Thinking** How is the chain reaction in a Class C fire interrupted by the contents of a dry chemical extinguisher?

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In single-displacement reactions, elements trade places

Copper(II) chloride dissolves in water to make a bright blue solution. If you add a piece of aluminum foil to the solution, the color fades, and clumps of reddish brown material form. The reddish brown clumps are copper metal. Aluminum replaces copper in the copper(II) chloride, forming aluminum chloride. Aluminum chloride does not make a colored solution, so the blue color fades as the amount of blue copper(II) chloride decreases, as shown in ***Figure 10.***

At first, the copper atoms are in the form of copper(II) ions, as part of copper(II) chloride, and the aluminum atoms are in the form of aluminum metal. After the reaction, the aluminum atoms become ions, and the copper atoms become neutral in the copper metal. Because the atoms of one element appear to move into a compound, and atoms of the other element appear to move out, this is called a **single-displacement reaction.** Single-displacement reactions have the following general form.

single-displacement reaction a reaction in which one element or radical takes the place of another element or radical in a compound

$$AX + B \longrightarrow BX + A$$

The single-displacement reaction between copper(II) chloride and aluminum is shown as follows.

$$3CuCl_2 + 2Al \longrightarrow 2AlCl_3 + 3Cu$$

Generally, in a single-displacement reaction, a more reactive element will take the place of a less reactive one.

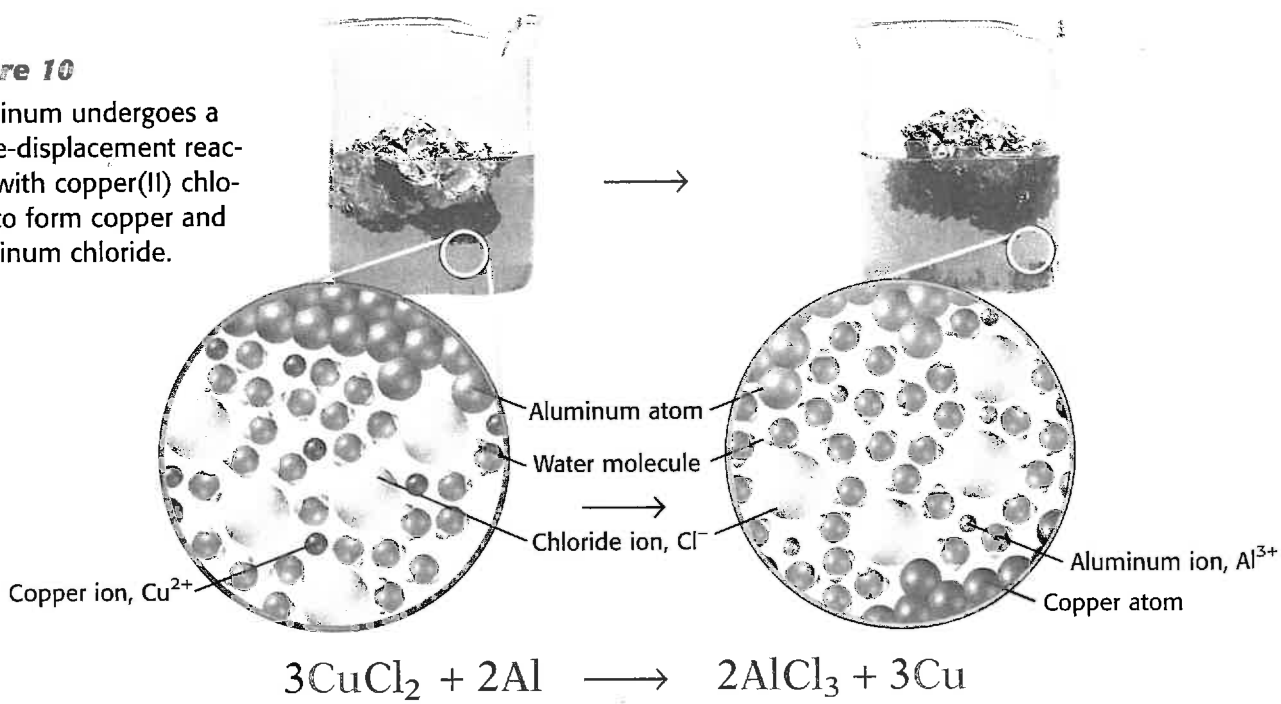
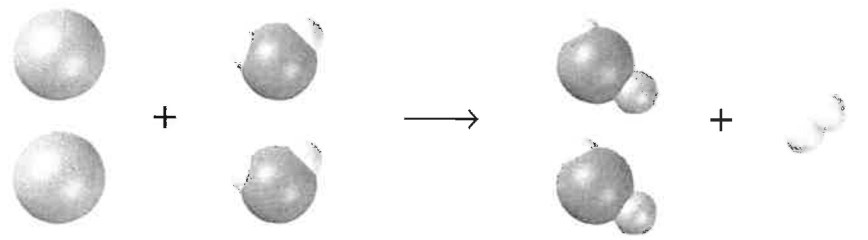


Figure 10
Aluminum undergoes a single-displacement reaction with copper(II) chloride to form copper and aluminum chloride.



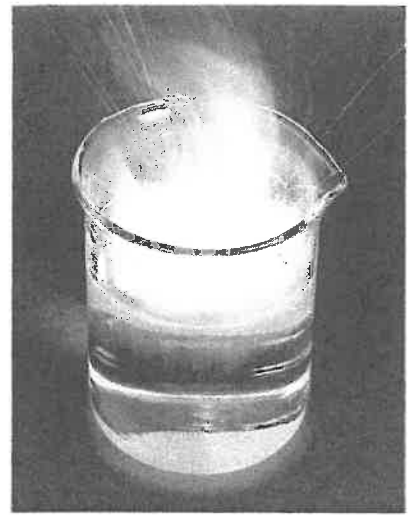


Figure 11
Potassium reacts with water in a single-displacement reaction.

Alkali metals react with water to form ions

Potassium metal is so reactive that it undergoes a single-displacement reaction with water. A potassium ion appears to take the place of one of the hydrogen atoms in the water molecule. Potassium ions, K^+, and hydroxide ions, OH^-, are formed. The hydrogen atoms displaced from the water join to form hydrogen gas, H_2.

The potassium and water reaction, shown in ***Figure 11***, is so exothermic that the H_2 may explode and burn instantly. All alkali metals and some other metals undergo single-displacement reactions with water to form hydrogen gas, metal ions, and hydroxide ions.

All of these reactions happen rapidly and give off heat but some alkali metals are more reactive than others. Lithium reacts steadily with water to form lithium ions, hydroxide ions, and hydrogen gas. Sodium and water react vigorously to make sodium ions, hydroxide ions, and hydrogen gas. Rubidium and cesium are so reactive that the hydrogen gas will explode as soon as they are put into water.

In double-displacement reactions, ions appear to be exchanged between compounds

The yellow lines painted on roads are colored with lead chromate, $PbCrO_4$. This compound can be formed by mixing solutions of lead nitrate, $Pb(NO_3)_2$, and potassium chromate, K_2CrO_4. In solution, these compounds form the ions Pb^{2+}, NO_3^-, K^+, and CrO_4^{2-}. When the solutions are mixed, the yellow lead chromate compound that forms doesn't dissolve in water, so it settles to the bottom. A **double-displacement reaction,** such as this one, occurs when two compounds appear to exchange ions. The general form of a double-displacement reaction is as follows.

double-displacement reaction a reaction in which a gas, a solid precipitate, or a molecular compound forms from the apparent exchange of atoms or ions between two compounds

$$AX + BY \longrightarrow AY + BX$$

The double-displacement reaction that forms lead chromate is as follows.

$$Pb(NO_3)_2 + K_2CrO_4 \longrightarrow PbCrO_4 + 2KNO_3$$

Electrons and Chemical Reactions

The general classes of reactions described earlier in this section were used by early chemists, who knew nothing about the parts of the atom. With the discovery of the electron and its role in chemical bonding, another way to classify reactions was developed. We can understand many reactions as transfers of electrons.

oxidation-reduction reaction any chemical change in which one species is oxidized (loses electrons) and another species is reduced (gains electrons); also called *redox reaction*

radical an organic group that has one or more electrons available for bonding

Electrons are transferred in redox reactions

The following **oxidation-reduction reaction** is an example of electron transfer. When the metal iron reacts with oxygen to form rust, Fe_2O_3, each iron atom loses three electrons to form Fe^{3+} ions, and each oxygen atom gains two electrons to form the O^{2-} ions.

Substances that accept electrons are said to be *reduced;* substances that give up electrons are said to be *oxidized.* One way to remember this is that the gain of electrons will reduce the positive charge on an ion or will make an uncharged atom a negative ion. Reduction and oxidation are linked. In all redox reactions, one or more reactants is reduced and one or more is oxidized.

Some redox reactions do not involve ions. In these reactions, oxidation is a gain of oxygen or a loss of hydrogen, and reduction is the loss of oxygen or the gain of hydrogen. Respiration and combustion are redox reactions because oxygen gas reacts with carbon compounds to form carbon dioxide. Carbon atoms in CO_2 are oxidized, and oxygen atoms in O_2 are reduced.

Radicals have electrons available for bonding

Many synthetic fibers, as well as plastic bags and wraps, are made by polymerization reactions, as you have already learned. Polymerization reactions can occur when **radicals** are formed.

When a covalent bond is broken such that at least one unpaired electron is left on each fragment of the molecule, these fragments are called radicals. Because an uncharged hydrogen atom has one electron available for bonding, it is a radical. Radicals react quickly to form covalent bonds with other substances, making new compounds. Often, when you see chemical radicals mentioned in the newspaper or hear about them on the radio or television, they are called free radicals.

Connection to FINE ARTS

Metal sculptures often corrode because of redox reactions. The Statue of Liberty, which is covered with 200 000 pounds of copper, was as bright as a new penny when it was erected. However, after more than 100 years, the statue had turned green. The copper reacted with the damp air of New York harbor. More importantly, oxidation reactions between the damp, salty air and the internal iron supports made the structure dangerously weak. The statue was closed for several years in the 1980s while the supports were cleaned and repaired.

Making the Connection

1. Metal artwork in fountains often rusts very quickly. Suggest a reason for this.
2. Why do you think the most detailed parts of a sculpture are the first to appear worn away?

Radicals are part of many everyday reactions besides the making of polymers, such as those shown in ***Figure 12.*** Radicals can also be formed when coal and oil are processed or burned. The explosive combustion of rocket fuel is another reaction involving the formation of radicals.

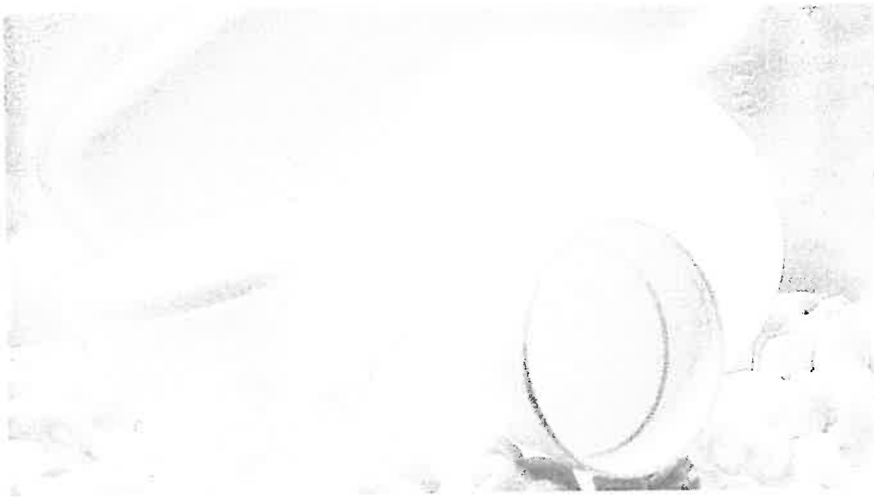


Figure 12
Radical reactions are used to make polystyrene. Polystyrene foam is often used to insulate or to protect things that can break.

SECTION 2 REVIEW

SUMMARY

- Synthesis reactions make larger molecules.
- Decomposition breaks compounds apart.
- In combustion, substances react with oxygen.
- Elements appear to trade places in single-displacement reactions.
- In double-displacement reactions, ions appear to move between compounds, resulting in a solid that settles out of solution, a gas that bubbles out of solution, and/or a molecular substance.
- In redox reactions, electrons transfer from one substance to another.

1. **Classify** each of the following reactions by type:
   a. $S_8 + 8O_2 \longrightarrow 8SO_2 + \text{heat}$
   b. $6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$
   c. $2NaHCO_3 \longrightarrow Na_2CO_3 + H_2O + CO_2$
   d. $Zn + 2HCl \longrightarrow ZnCl_2 + H_2$
2. **Identify** which element is oxidized and which element is reduced in the following reaction.
   $$Zn + CuSO_4 \longrightarrow ZnSO_4 + Cu$$
3. **Define** *radical.*
4. **Compare and Contrast** single-displacement and double-displacement reactions based on the number of reactants. Use the terms *compound, atom* or *element,* and *ion.*
5. **Explain** why charcoal grills or charcoal fires should never be used for heating inside a house. (**Hint:** Doors and windows are closed when it is cold, so there is little fresh air.)
6. **Contrast** synthesis and decomposition reactions.
7. **List** three possible results of a double-displacement reaction.
8. **Creative Thinking** Would you expect larger or smaller molecules to be components of a more viscous liquid? Which is likely to be more viscous, crude oil or oil after cracking?

Balancing Chemical Equations

KEY TERMS
chemical equation
mole ratio

OBJECTIVES

- **Demonstrate** how to balance chemical equations.
- **Interpret** chemical equations to determine the relative number of moles of reactants needed and moles of products formed.
- **Explain** how the law of definite proportions allows for predictions about reaction amounts.
- **Identify** mole ratios in a balanced chemical equation.
- **Calculate** the relative masses of reactants and products from a chemical equation.

You may have seen a combustion reaction in the lab or at home if you have a gas stove. When natural gas burns, methane, the main component, reacts with oxygen gas to form carbon dioxide and water. Energy is also released as heat and light, as shown in ***Figure 13A***.

chemical equation a representation of a chemical reaction that uses symbols to show the relationship between the reactants and the products

Describing Reactions

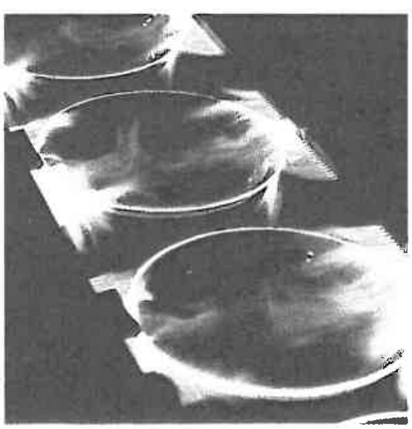
You can describe this reaction in many ways. You could take a photograph or make a videotape. One way to record the products and reactants of this reaction is to write a word equation.

methane + oxygen ⟶ carbon dioxide + water

Chemical equations summarize reactions

In Section 1, you learned that all chemical reactions are rearrangements of atoms. This is shown clearly in ***Figure 13B***. A better way to write the methane combustion reaction is as a **chemical equation**, using the formulas for each substance.

Figure 13



A A methane flame is used to polish the edges of these glass plates.

B Methane burns with oxygen gas to make carbon dioxide and water.

Unbalanced Chemical Equation

$CH_4 + O_2$	$\longrightarrow$	$CO_2 + H_2O$
reactants	"give" or "yield"	products

In a chemical equation, such as the one above, the reactants, which are on the left-hand side of the arrow, form the products, which are on the right-hand side. When chemical equations are written, $\longrightarrow$ means "gives" or "yields." People all over the world write chemical equations the same way, as shown in ***Figure 14.***

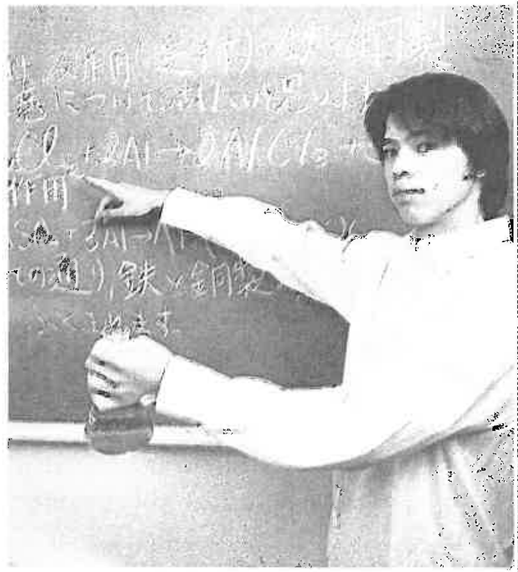


Figure 14
This student is giving a talk on reactions that use copper. You can read the chemical equations even if you can't read Japanese.

Balanced chemical equations account for the conservation of mass

The chemical equation shown above can be made more useful. As written, it does not tell you anything about the amount of the products that will be formed from burning a given amount of methane. When the number of atoms of each element on the right-hand side of the equation matches the number of atoms of each element on the left, then the chemical equation is said to be *balanced.* A balanced chemical equation is the standard way of writing equations for chemical reactions because it follows the law of conservation of mass.

How to balance chemical equations

In the previous equation, the number of atoms on each side of the arrow did not match for all of the elements in the equation. Carbon is balanced because one carbon atom is on each side of the equation. However, four hydrogen atoms are on the left, and only two are on the right. Also, two oxygen atoms are on the left, and three are on the right. This can't be correct because atoms can't be created or destroyed in a chemical reaction.

Remember that you cannot balance an equation by changing the chemical formulas. You have to leave the subscripts in the formulas alone. Changing the formulas would mean that different substances were in the reaction. An equation can be balanced only by putting numbers, called coefficients, in front of the chemical formulas.

Because there is a total of four hydrogen atoms in the reactants, a total of four hydrogen atoms must be in the products. Instead of a single water molecule, this reaction makes two water molecules to account for all four hydrogen atoms. To show that two water molecules are formed, a coefficient of 2 is placed in front of the formula for water.

$$CH_4 + O_2 \longrightarrow CO_2 + 2H_2O$$

Connection to SOCIAL STUDIES

No one can be sure when fireworks were first used. When the Mongols attacked China in 1232, the defenders used "arrows of flying fire," which some historians think were rockets fired by gunpowder. The Arabs probably used rockets when they invaded the Spanish peninsula in 1249. For hundreds of years, the main use of rockets was to add terror and confusion to battles. In the late 1700s, rockets were used with some success against the British in India. Because of this, Sir William Congreve began to design rockets for England. Congreve's rockets were designed to explode in the air or be fired along the ground.

Making the Connection

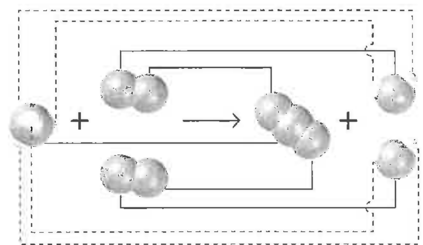
British forces used Congreve's rockets during the War of 1812. Research the battle of Fort McHenry. Find out what happened, who won the battle, and what lyrics the rockets inspired.

Next look at the oxygen. There is a total of four oxygen atoms in the products. Two are in the CO_2, and each water molecule contains one oxygen atom. To get four oxygen atoms on the left side of the equation, two oxygen molecules must react. That would account for all four oxygen atoms.

Balanced Chemical Equation

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Now the numbers of atoms for each element are the same on each side, and the equation is balanced, as shown below.



Information from a balanced equation

You can learn a lot from a balanced equation. In our example, you can tell that each molecule of methane requires two oxygen molecules to react. Each methane molecule that burns forms one molecule of carbon dioxide and two molecules of water. Balanced chemical equations are the standard way chemists write about reactions to describe both the substances in the reaction and the amounts involved.

If you know the formulas of the reactants and products in a reaction, like the one shown in **Figure 15**, you can always write a balanced equation, as shown on the following pages.

PHYSICAL SCIENCE INTERACTIVE TUTOR

Disc One, Module 5:
Chemical Equations
Use the Interactive Tutor to learn more about this topic.

Figure 15
Magnesium in these fireworks gives off energy as heat and light when it burns to form magnesium oxide.

Math Skills

Balancing Chemical Equations Write the equation that describes the burning of magnesium in air to form magnesium oxide.

1 Identify the reactants and products.

Magnesium and oxygen gas are the reactants that form the product, magnesium oxide.

2 Write a word equation for the reaction.

magnesium + oxygen ⟶ magnesium oxide

3 Write the equation using formulas for the elements and compounds in the word equation.

Remember that some gaseous elements, like oxygen, are molecules, not atoms. Oxygen in air is O_2, not O.

$$Mg + O_2 \longrightarrow MgO$$

4 Balance the equation one element at a time.

The same number of each kind of atom must appear on both sides. So far, there is one atom of magnesium on each side of the equation.

Atom	Reactants	Products	Balanced?
Mg	1	1	✓
O	2	1	✗

But there are two oxygen atoms on the left and only one on the right. To balance the number of oxygen atoms, you need to double the amount of magnesium oxide:

$$Mg + O_2 \longrightarrow 2MgO$$

Atom	Reactants	Products	Balanced?
Mg	1	2	✗
O	2	2	✓

This equation gives you two magnesium atoms on the right and only one on the left. So you need to double the amount of magnesium on the left, as follows.

$$2Mg + O_2 \longrightarrow 2MgO$$

Atom	Reactants	Products	Balanced?
Mg	2	2	✓
O	2	2	✓

Now the equation is balanced. It has an equal number of each type of atom on both sides.

Practice HINT

- Sometimes changing the coefficients to balance one element may cause another element in the equation to become unbalanced. So always check your work.

Practice

Balancing Chemical Equations

1. Copper(II) sulfate, $CuSO_4$, and aluminum react to form aluminum sulfate, $Al_2(SO_4)_3$, and copper. Write the balanced equation for this single-displacement reaction.
2. In a double-displacement reaction, sodium sulfide, Na_2S, reacts with silver nitrate, $AgNO_3$, to form sodium nitrate, $NaNO_3$, and silver sulfide, Ag_2S. Balance this equation.
3. Hydrogen peroxide, H_2O_2, is sometimes used as a bleach or as a disinfectant. Hydrogen peroxide decomposes to give water and molecular oxygen. Write a balanced equation for the decomposition reaction.

Determining Mole Ratios

Look at the reaction of magnesium with oxygen to form magnesium oxide.

$$\text{magnesium} + \text{oxygen} \longrightarrow \text{magnesium oxide}$$

$$2Mg + O_2 \longrightarrow 2MgO$$

The single molecule of oxygen in the equation might be shown as $1O_2$. However, a coefficient of 1 is never written.

Balanced equations show the conservation of mass

Other ways of looking at the amounts in the reaction are shown in ***Figure 16.*** Notice that there are equal numbers of magnesium and oxygen atoms in the product and in the reactants. The total mass of the reactants is always the same as the total mass of the products.

Figure 16 **Information from the Balanced Equation: $2Mg + O_2 \longrightarrow 2MgO$**

Equation:	**2Mg**	**+**	**O_2**	$\longrightarrow$	**2MgO**
Amount (mol)	2		1	$\longrightarrow$	2
Molecules	$(6.022 \times 10^{23}) \times 2$		$(6.022 \times 10^{23}) \times 1$	$\longrightarrow$	$(6.022 \times 10^{23}) \times 2$
Mass (g)	24.3 g/mol × 2 mol		32.0 g/mol × 1 mol	$\longrightarrow$	40.3 g/mol × 2 mol
Total mass (g)	48.6		32.0	$\longrightarrow$	80.6
Model				$\longrightarrow$	

The law of definite proportions

What if you want 4 mol of magnesium to react completely? If you have twice as much magnesium as the balanced equation calls for, you will need twice as much oxygen. Twice as much magnesium oxide will be formed. No matter what amounts of magnesium and oxygen are combined or how the magnesium oxide is made, the balanced equation does not change. This follows the law of definite proportions, which states:

A compound always contains the same elements in the same proportions, regardless of how the compound is made or how much of the compound is formed.

Mole ratios can be derived from balanced equations

Whether the magnesium-oxygen reaction starts with 2 mol or 4 mol of magnesium, the proportions remain the same. One way to understand this is to look at the **mole ratios** from the balanced equation. For 2 mol of magnesium and 1 mol of oxygen, the ratio is 2:1. If 4 mol of magnesium is present, 2 mol of oxygen is needed to react. The ratio is 4:2, which reduces to 2:1.

mole ratio the relative number of moles of the substances required to produce a given amount of product in a chemical reaction

The mole ratio for any reaction comes from the balanced chemical equation. For example, in the following equation for the electrolysis of water, the mole ratio for H_2O:H_2:O_2, using the coefficients, is 2:2:1.

$$2H_2O \longrightarrow 2H_2 + O_2$$

As you can see in ***Figure 17,*** the hydrogen gas produced occupies twice the volume of the oxygen gas. That is because there are twice as many molecules of hydrogen gas produced in electrolysis as there are molecules of oxygen gas.

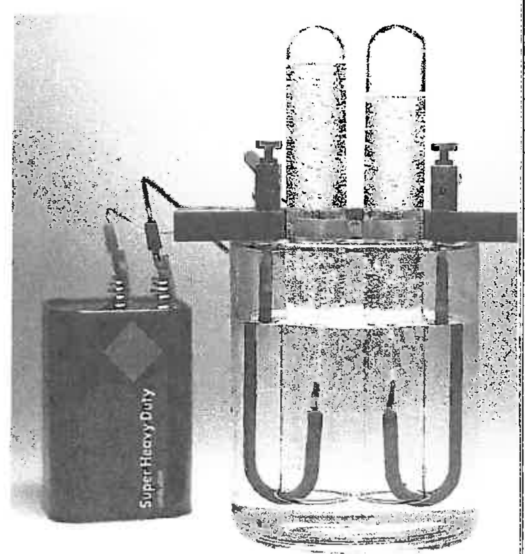


Figure 17
Electrical energy causes the decomposition of water into oxygen (in the test tube on the left) and hydrogen (on the right).

Mole ratios allow you to calculate the mass of the reactants

If you know the mole ratios of the substances involved in a reaction, you can determine the relative masses of the substances required to react completely.

The most convenient way to determine the relative masses is by multiplying the molecular mass of each substance by the mole ratio from the balanced equation. For example, for the reaction shown in ***Figure 16,*** the atomic mass of magnesium, 24.3 g/mol, is multiplied by 2 to get a total mass of 48.6 g. The mass of molecular oxygen, 32.0 g/mol, is multiplied by 1. This means that in order for magnesium to react completely with oxygen, there must be 32 g of oxygen available for every 48.6 g of magnesium.

Quick Lab

Can you determine the products of a reaction?

Materials *7 test tubes; test-tube rack; labels or wax pencil; 10 mL graduated cylinder; bottles of the following solutions: sodium chloride, NaCl; potassium bromide, KBr; potassium iodide, KI; and silver nitrate, $AgNO_3$*

SAFETY CAUTION Wear safety goggles and an apron. Silver nitrate will stain your skin and clothes.

1. Label three test tubes, one each for NaCl, KBr, and KI.
2. Using the graduated cylinder, measure 5 mL of each solution into the properly labeled test tube. Rinse the graduated cylinder between each use.
3. Add 1 mL of $AgNO_3$ solution to each of the test tubes. Record your observations.

Analysis

1. What did you observe as a sign that a double-displacement reaction was occurring?
2. Identify the reactants and products for each reaction.
3. Write the balanced equation for each reaction.
4. Which ion(s) produced a solid with silver nitrate?
5. Does this test let you identify all the ions? Why or why not?

SECTION 3 REVIEW

SUMMARY

- A chemical equation shows the reactants that combine and the products that result from the reaction.
- Balanced chemical equations show the proportions of reactants and products needed for the mass to be conserved.
- A compound always contains the same elements in the same proportions, regardless of how the compound is made or how much of the compound is formed.
- A mole ratio relates the amounts of any two or more substances involved in a chemical reaction.

1. **Identify** which of the following is a complete and balanced chemical equation:
   a. $H_2O \longrightarrow H_2 + O_2$ **c.** $Fe + S \longrightarrow FeS$
   b. $NaCl + H_2O$ **d.** $CaCO_3$
2. **Balance** the following equations:
   a. $KOH + HCl \longrightarrow KCl + H_2O$
   b. $Pb(NO_3)_2 + KI \longrightarrow KNO_3 + PbI_2$
   c. $NaHCO_3 \longrightarrow H_2O + CO_2 + Na_2CO_3$
   d. $NaCl + H_2SO_4 \longrightarrow Na_2SO_4 + HCl$
3. **Explain** why the numbers in front of chemical formulas, not the subscripts, must be changed to balance an equation.
4. **Describe** the information needed to calculate the mass of a reactant or product for the following balanced equation:
   $$FeS + 2HCl \longrightarrow H_2S + FeCl_2$$
5. **Critical Thinking** Ammonia is manufactured by the Haber process in the reaction shown below:
   $$N_2 + 3H_2 \rightleftharpoons 2NH_3 + \text{heat}$$
   This involves the reaction of nitrogen with hydrogen. What mass of nitrogen is needed to make 34 g of ammonia?

SECTION 4

Rates of Change

OBJECTIVES

- **Describe** the factors affecting reaction rates.
- **Explain** the effect a catalyst has on a chemical reaction.
- **Explain** chemical equilibrium in terms of equal forward and reverse reaction rates.
- **Apply** Le Châtelier's principle to predict the effect of changes in concentration, temperature, and pressure in an equilibrium process.

KEY TERMS

catalyst
enzyme
substrate
chemical equilibrium

Chemical reactions can occur at different speeds or rates. Some reactions, such as the explosion of nitroglycerin, shown in ***Figure 18,*** are very fast. Other reactions, such as the burning of carbon in charcoal, are much slower. But what if you wanted to slow down the nitroglycerin reaction to make it safer? What if you wanted to speed up the reaction by which yeast make carbon dioxide, so bread would rise in less time? If you think carefully, you may already know some things about how to change reaction rates.

internet connect
www.scilinks.org
Topic: Factors Affecting Reaction Rate
SciLinks code: HK4051
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Factors Affecting Reaction Rates

Think about the following observations:

- A potato slice takes 5 minutes to fry in oil at 200°C but takes 10 minutes to cook in boiling water at 100°C. Therefore, potatoes cook faster at higher temperatures.
- Potato slices take 10 minutes to cook in boiling water, but whole potatoes take about 30 minutes to cook. Therefore, potatoes cook faster if you cut them up into smaller pieces.

These observations relate to the speed of chemical reactions. For any reaction to occur, the particles of the reactants must collide with one another. In each situation where the potatoes cooked faster, the contact between particles was greater, so the cooking reaction went faster.

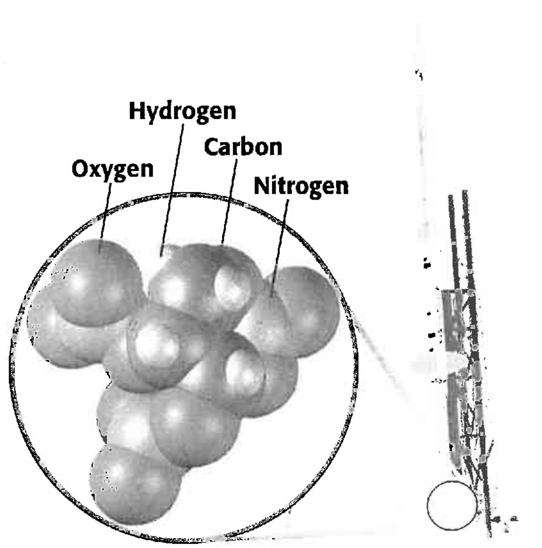
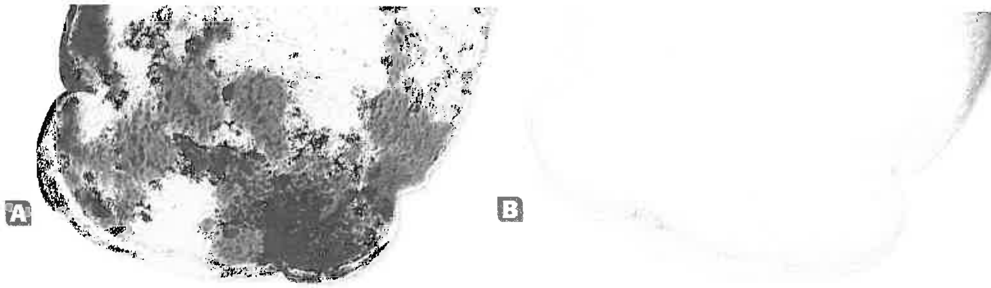


Figure 18
Nitroglycerin can be used as a rocket fuel as well as a medicine for people with heart ailments.

Figure 19

A Mold will grow on bread stored at room temperature. **B** Bread stored in the freezer for the same length of time will be free of mold when you take it out.



Most reactions go faster at higher temperatures

Heating food speeds up the chemical reactions that happen in cooking. Cooling food slows down the chemical reactions that result in spoiling, as shown in ***Figure 19.***

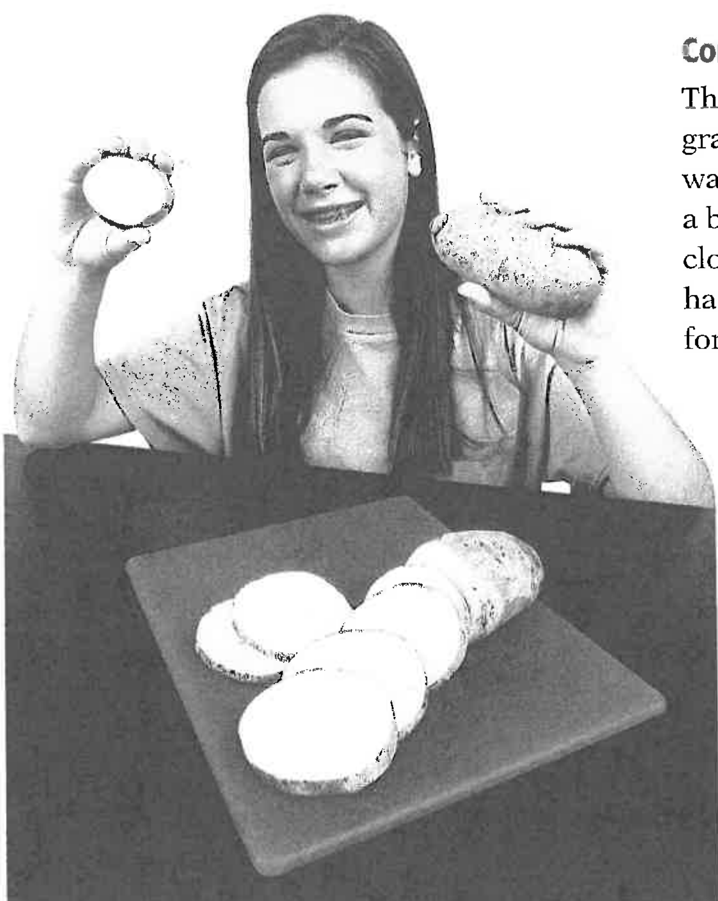
The kinetic theory states that particles move faster at higher temperatures. The faster moving particles collide more often, and there are more chances for the particles to react. Therefore, the reaction will be faster.

A large surface area speeds up reactions

When a whole potato is placed in boiling water, only the outside is in direct contact with the boiling water. The energy transferred from the water takes longer to reach the center of the potato than it would if the potato were sliced. As ***Figure 20*** shows, cutting potatoes into pieces allows parts that were inside the potato to be exposed. In other words, the *surface area* of the potato is increased. The surface area of a solid is the amount of the surface that is exposed. Generally solids that have a large surface area react more rapidly because more particles can come in contact with the other reactants.

Figure 20

When a solid is divided into pieces, the total surface area becomes larger.



Concentrated solutions react faster

Think about a washing machine full of clothes with grass stains on them. If you put a drop of bleach in the water, little will happen to the dirty clothes. If you pour a bottle of bleach into the washing machine, the stained clothes will be clean. The more concentrated solution has more bleach particles. This means a higher chance for particle collisions with the stains.

Reactions are faster at higher pressure

The concentration of a gas can be thought of as the number of particles in a given volume. A gas at high pressure is more concentrated than the same amount of a gas at a low pressure because the gas at high pressure has been squeezed into a smaller volume. Gases react faster at higher pressures; the particles have less space, so they have more collisions.

Massive, bulky molecules react slower

The size and shape of the reactant molecules affect the rate of reaction. You know from the kinetic theory of matter that massive molecules move more slowly than less massive molecules at the same temperature. This means that for equal numbers of massive and "light" molecules of about the same size, the molecules with more mass collide less often with other molecules.

Some molecules, such as large biological compounds, must fit together in a particular way to react. They can collide with other reactants many times, but if the collision occurs on the wrong end of the molecule, they will not react. Generally these compounds react very slowly because many unsuccessful collisions may occur before a successful collision begins the reaction.

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Topic: Catalysts
SciLinks code: HK4018

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Catalysts change the rates of chemical reactions

Why add a substance to a reaction if the substance may not react? This is done all the time in industry when **catalysts** are added to make reactions go faster. Catalysts are not reactants or products. They speed up or slow reactions. Catalysts that slow reactions are called *inhibitors*. Catalysts are used to help make ammonia, to process crude oil, and to accelerate making plastics. Catalysts can be expensive and still be profitable because they can be cleaned or renewed and reused. Sometimes the name of the catalyst is written over the reaction arrow of a chemical equation when a catalyst is present.

catalyst a substance that changes the rate of a chemical reaction without being consumed or changed significantly

enzyme a type of protein that speeds up metabolic reactions in plants and animals without being permanently changed or destroyed

Catalysts work in different ways. Most solid catalysts, such as those in car exhaust systems, speed up reactions by providing a surface where the reactants can collect and react. Then the reactants can form new bonds to make the products. Most solid catalysts are more effective if they have a large surface area.

Enzymes are biological catalysts

Enzymes are proteins that are catalysts for chemical reactions in living things. Enzymes are very specific. Each enzyme controls one reaction or set of similar reactions. Some common enzymes and the reactions they control are listed in ***Table 1***. Most enzymes are fragile. If they are kept too cold or too warm, they tend to decompose. Most enzymes stop working above 45°C.

Table 1 **Common Enzymes and Their Uses**

Enzyme	Substrate	What the enzyme does
Amylase	starch	breaks down long starch molecules into sugars
Cellulase	cellulose	breaks down long cellulose molecules into sugars
DNA polymerase	nucleic acid	builds up DNA chains in cell nuclei
Lipase	fat	breaks down fat into smaller molecules
Protease	protein	breaks down proteins into amino acids

Catalase, an enzyme produced by humans and most other living organisms, breaks down hydrogen peroxide. Hydrogen peroxide is the **substrate** for catalase.

substrate a part, substance, or element that lies beneath and supports another part, substance, or element; the reactant in reactions catalyzed by enzymes

$$2H_2O_2 \xrightarrow{\text{catalase}} 2H_2O + O_2$$

For an enzyme to catalyze a reaction, the substrate and the enzyme must fit exactly—like a key in a lock. This fit is shown in ***Figure 21***. Enzymes are very efficient. In 1 minute, one molecule of catalase can catalyze the decomposition of 6 million molecules of hydrogen peroxide.

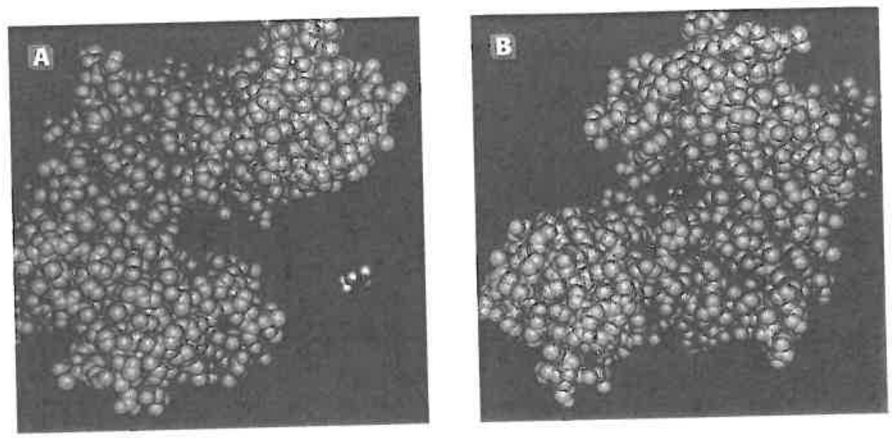


Figure 21
The enzyme hexokinase catalyzes the addition of phosphate to glucose. This model shows the enzyme, in blue, before **A** and after **B** it fits with a glucose molecule, shown in red.

Quick Lab

What affects the rates of chemical reactions?

Materials *Bunsen burner, paper clip, 6 test tubes, paper ash, sandpaper, tongs, matches, 2 sugar cubes, steel wool ball, 2 cm diameter, graduated cylinder, vinegar, magnesium ribbon, copper foil strip, zinc strip; each 3 cm long, uniform width*

SAFETY CAUTION Wear safety goggles and an apron.

1. Label three test tubes 1, 2, and 3. Place 10 mL of vinegar in each test tube. Sandpaper the metals until they are shiny. Then add the magnesium to test tube 1, the zinc to test tube 2, and the copper to test tube 3. Record your observations.
2. Using tongs, hold a paper clip in the hottest part of the burner flame for 30 s. Repeat with a ball of steel wool. Record your observations.
3. Label three more test tubes A, B, and C. To test tube A, add 10 mL of vinegar; to test tube B, add 5 mL of vinegar and 5 mL of water; and to test tube C, add 2.5 mL of vinegar and 7.5 mL of water. Add a piece of magnesium ribbon to each test tube. Record your observations.
4. Using tongs, hold a sugar cube and try to ignite it with a match. Rub paper ash on another cube and try again. Record your observations.

Analysis

1. Describe and interpret your results.
2. For each step, list the factor(s) that influenced the rate of reaction.

Equilibrium Systems

When nitroglycerin explodes, not much nitroglycerin is left. When an iron nail rusts, given enough time, all the iron is converted to iron(III) oxide and only the rust remains. Even though an explosion occurs rapidly and rusting occurs slowly, both reactions go to completion. Most of the reactants are converted to products, and the amount that is not converted is not noticeable and usually is not important.

Some changes are reversible

You may get the idea that all chemical reactions go to completion if you watch a piece of wood burn or see an explosion. However, reactions don't always go to completion; some are reversible.

For example, carbonated drinks, such as the soda shown in **Figure 22,** contain carbon dioxide. These drinks are manufactured by dissolving carbon dioxide in water under pressure. To keep the carbon dioxide dissolved, you need to maintain the pressure by keeping the top on the bottle. Opening the soda allows the pressure to decrease. When this happens, some of the carbon dioxide comes out of solution, and you see a stream of carbon dioxide bubbles. This carbon dioxide change is reversible.

$$CO_2\text{ (gas above liquid)} \underset{\text{decrease pressure}}{\overset{\text{increase pressure}}{\rightleftharpoons}} CO_2\text{ (gas dissolved in liquid)}$$

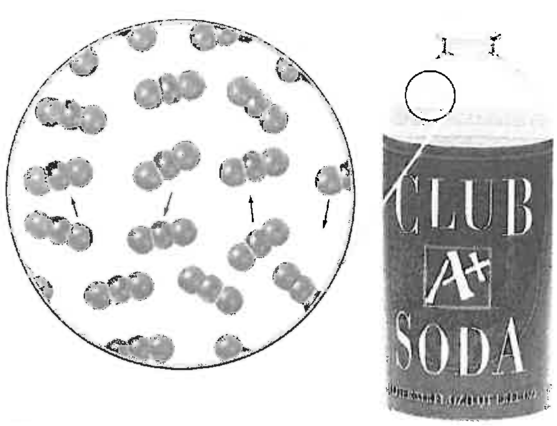
The physical change can go in either direction. The $\rightleftharpoons$ sign indicates a reversible change. Compare it with the arrow you normally see in chemical reactions, $\longrightarrow$, which indicates a change that goes in one direction—toward completion.

Quick ACTIVITY

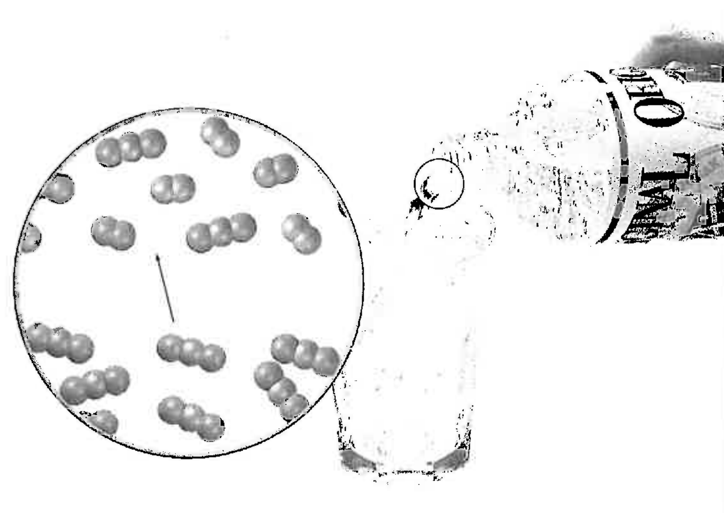
Catalysts in Action

1. Pour 2% hydrogen peroxide into a test tube to a depth of 2 cm.
2. Pour 2 cm of water into another test tube.
3. Drop a small piece of raw liver into each test tube.
4. Liver contains the enzyme catalase. Watch carefully, and describe what happens. Explain your observations.
5. Repeat steps 1–4 using a piece of liver that has been boiled for 3 minutes. Explain your result.
6. Repeat steps 1–4 again using iron filings instead of liver. What happens?

Figure 22



A A bottle of carbonated water with the top on is at equilibrium.



B When the top is removed, the carbonated water is no longer at equilibriu

Equilibrium results when rates balance

When a carbonated drink is in a closed bottle, you can't see any changes. The system is in **chemical equilibrium** —a balanced state. This balanced state is dynamic. No changes are apparent, but changes are occurring. If you could see individual molecules in the bottle, you would see continual change. Molecules of CO_2 are coming out of solution constantly. However, CO_2 molecules from the air above the liquid are dissolving at the same time and the same rate.

The result is that the amount of dissolved and undissolved CO_2 doesn't change, even though individual CO_2 molecules are moving in and out of the solution. This is similar to the number of players on the field for a football team. Although different players can be on the field at any time, eleven players are always on the field for each team.

chemical equilibrium
a state of balance in which the rate of a forward reaction equals the rate of the reverse reaction and the concentrations of products and reactants remain unchanged

VOCABULARY Skills Tip

Equilibrium comes from the Latin aequilibris *meaning equally balanced. In Latin,* aequil *means equal, and* libra *means a balance scale. You may have seen the constellation called Libra. The stars in the constellation roughly represent a balance.*

Systems in equilibrium respond to minimize change

When the top is removed from a carbonated drink, the drink is no longer at equilibrium, and CO_2 leaves as bubbles. For equilibrium to be reached, none of the reactants or products can escape.

The conversion of limestone, $CaCO_3$, to lime, CaO, is a chemical reaction that can lead to equilibrium. Limestone and seashells, which are also made of $CaCO_3$, were used to make lime more than 2000 years ago. By heating limestone in an open pot, lime was produced to make cement. The ancient buildings in Greece and Rome, such as the one shown in **Figure 23**, were probably built with cement made by this reaction.

$$CaCO_3 + \text{heat} \longrightarrow CaO + CO_2$$

Because the CO_2 gas can escape from an open pot, the reaction proceeds until all of the limestone is converted to lime.

However, if some dry limestone is sealed in a closed container and heated, the result is different. As soon as some CO_2 builds up in the container, the reverse reaction starts. Once the concentrations of the $CaCO_3$, CaO, and CO_2 stabilize, equilibrium is established.

$$CaCO_3 \rightleftharpoons CaO + CO_2$$

If there aren't any changes in the pressure or the temperature, the forward and reverse reactions continue to take place at the same rate. The concentration of CO_2 and the amounts of $CaCO_3$ and CaO in the container do not change.

Figure 23
Cement for ancient buildings, like this one in Limeni, Greece, probably contained lime made from seashells.

Table 2 The Effects of Change on Equilibrium

Condition	Effect
Temperature	Increasing temperature favors the reaction that absorbs energy.
Pressure	Increasing pressure favors the reaction that produces fewer molecules of gas.
Concentration	Increasing the concentration of one substance favors the reaction that produces less of that substance.

Le Châtelier's principle predicts changes in equilibrium

Le Châtelier's principle is a general rule that describes the behavior of equilibrium systems.

If a change is made to a system in chemical equilibrium, the equilibrium shifts to oppose the change until a new equilibrium is reached.

The effects of different changes on an equilibrium system are shown in **Table 2**.

Ammonia is a chemical building block used to make fertilizers, dyes, plastics, cosmetics, cleaning products, and fire retardants, such as those you see being applied in ***Figure 24***. The Haber process, which is used to make ammonia industrially, is exothermic; it releases energy.

$$\text{nitrogen} + \text{hydrogen} \rightleftharpoons \text{ammonia} + \text{heat}$$

$$N_2\ (\text{gas}) + 3H_2\ (\text{gas}) \rightleftharpoons 2NH_3\ (\text{gas}) + \text{heat}$$

At an ammonia-manufacturing plant production chemists must choose the conditions that favor the highest yield of NH_3. In other words, the equilibrium should favor the production of NH_3.

INTEGRATING

ENVIRONMENTAL SCIENCE

All living things need nitrogen, which cycles through the environment. Nitrogen gas, N_2, is changed to ammonia by bacteria in soils. Different bacteria in the soil change the ammonia to nitrites and nitrates. Nitrogen in the form of nitrates is needed by plants to grow. Animals eat the plants and deposit nitrogen compounds back in the soil. When plants or animals die, nitrogen compounds are also returned to the soil. Additional bacteria change the nitrogen compounds back to nitrogen gas, and the cycle can start again.

Figure 24

Ammonium sulfate and ammonium phosphate are being dropped from the airplane as fire retardants. The red dye used for identification fades away after a few days.

CHAPTER 6 REVIEW

Chapter Highlights

Before you begin, review the summaries of the key ideas of each section, found at the end of each section. The key vocabulary terms are listed on the first page of each section.

UNDERSTANDING CONCEPTS

1. When a chemical reaction occurs, atoms are never
   a. ionized.
   b. rearranged.
   c. destroyed.
   d. vaporized.

2. In an exothermic reaction,
   a. energy is conserved.
   b. the formation of bonds in the product releases more energy than is required to break the bonds in the reactants.
   c. energy is released as bonds form.
   d. All of the above

3. Which of the following is an endothermic reaction?
   a. fireworks exploding in the sky
   b. water boiling
   c. photosynthesis
   d. respiration

4. $A + B \longrightarrow AB$ is an example of a
   a. synthesis reaction.
   b. decomposition reaction.
   c. single-displacement reaction.
   d. double-displacement reaction.
   e. redox reaction.

5. Which of the following reactions is not an example of a redox reaction?
   a. combustion
   b. rusting
   c. dissolving in salt water
   d. cellular respiration

6. Radicals
   a. form ionic bonds with other ions.
   b. result from broken covalent bonds.
   c. usually break apart to form smaller components.
   d. bind molecules together.

7. In any chemical equation, the arrow means
   a. "equals."
   b. "is greater than."
   c. "yields."

8. Hydrogen peroxide, H_2O_2, decomposes to produce water and oxygen gas. The balanced equation for this reaction is
   a. $H_2O_2 \longrightarrow H_2O + O_2$.
   b. $2H_2O_2 \longrightarrow 2H_2O + O_2$.
   c. $2H_2O_2 \longrightarrow H_2O + 2O_2$.
   d. $2H_2O_2 \longrightarrow 2H_2O + 2O_2$.

9. Which of the following chemical equations is balanced?
   a. $Fe + O_2 \longrightarrow Fe_2O_3$
   b. $Ca + SbCl_3 \longrightarrow Si + Sb + 3CaCl_2$
   c. $3CuCl_2 + 2Al \longrightarrow 2AlCl_3 + 3Cu$
   d. $CS_2 + 2O_2 \longrightarrow CO_2 + SO_2$

10. Most reactions speed up when
    a. the temperature is lowered.
    b. equilibrium is achieved.
    c. the concentration of the products is increased.
    d. the reactants are in small pieces.

11. Enzymes
    a. can be used to speed up almost any chemical reaction.
    b. rely on increased surface area to catalyze reactions.
    c. catalyze specific biological reactions.
    d. always work faster at higher temperatures.

12. A system in chemical equilibrium
    a. has particles that don't move.
    b. responds to minimize change.
    c. is undergoing visible change.
    d. is stable only when all of the reactants have been used.

USING VOCABULARY

13. Explain what it means when a system in equilibrium shifts to favor the products.

14. When wood is burned, energy is released in the forms of heat and light. Describe the reaction, and explain why this change does not violate the law of conservation of energy. Use the terms *combustion, exothermic,* and *chemical energy.* **WRITING SKILL**

15. Translate the following chemical equation into a sentence.

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

16. Explain the difference between an *exothermic reaction* and an *endothermic reaction,* and give an example of each.

17. How is a *synthesis reaction* different from a *decomposition reaction*?

18. How does a *combustion* reaction differ from other chemical reactions?

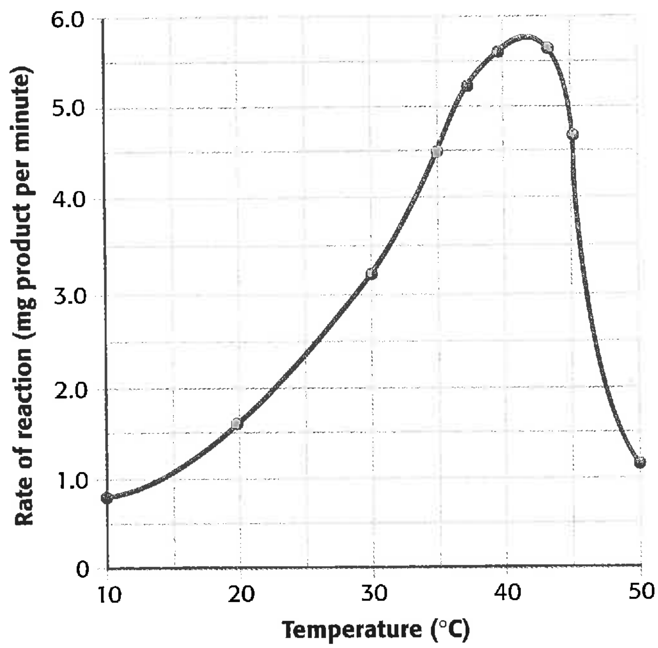
19. Use the *kinetic theory* to explain how an increase in the surface area of a reactant and higher temperatures can increase the rate of a chemical reaction.

20. For each of the following changes to the equilibrium system below, predict which reaction will be favored—forward (to the right), reverse (to the left), or neither.

$$H_2 \text{ (gas)} + Cl_2 \text{ (gas)} \rightleftharpoons 2HCl \text{ (gas)} + \text{heat}$$

a. addition of Cl_2
b. removal of HCl
c. increased pressure
d. decreased temperature
e. removal of H_2

BUILDING GRAPHING SKILLS



21. **Graphing** A technician carried out an experiment to study the effect of increasing temperature on a certain reaction. Her results are shown in the graph above.
    a. Between which temperatures does the rate of the reaction rise?
    b. Between which temperatures does the rate of the reaction slow down?
    c. At what temperature is the rate of the reaction fastest?

BUILDING MATH SKILLS

22. **Chemical Equations** In 1774, Joseph Priestly discovered oxygen when he heated solid mercury(II) oxide, HgO, and produced the element mercury and oxygen gas. Write and balance this equation.

23. **Chemical Equations** Write the balanced chemical equation for methane, CH_4, reacting with oxygen gas to produce water and carbon dioxide.

Skills Practice Lab

Introduction

How can you show that the rate of a chemical reaction depends on the temperature of the reactants?

Objectives

- ***Measure*** the volume of gas evolved to determine the average rate of the reaction between zinc and hydrochloric acid.
- USING SCIENTIFIC METHODS ***Determine*** how the rate of this reaction depends on the temperature of the reactants.

Materials

- beaker to hold a 10 mL graduated cylinder
- graduated cylinder, 10 mL
- graduated cylinder, 25 mL
- heavy scissors
- hydrochloric acid, 1.0 M
- ice
- metric ruler
- rubber tubing
- sidearm flasks with rubber stoppers (2)
- stopwatch
- strips of thick zinc foil, 10 mm wide
- thermometer
- water bath to hold a sidearm flask

Measuring the Rate of a Chemical Reaction

Procedure

Observing the Reaction Between Zinc and Hydrochloric Acid

1. On a blank sheet of paper, prepare a table like the one shown at right.
   SAFETY CAUTION Hydrochloric acid can cause severe burns. Wear a lab apron, gloves, and safety goggles. If you get acid on your skin or clothing, wash it off at the sink while calling to your teacher. If you get acid in your eyes, immediately flush it out at the eyewash station while calling to your teacher. Continue rinsing for at least 15 minutes or until help arrives.
2. Fill a 10 mL graduated cylinder with water. Turn the cylinder upside down in a beaker of water, taking care to keep the cylinder full. Place one end of the rubber tubing under the spout of the graduated cylinder. Attach the other end of the tubing to the arm of the flask. Place the flask in a water bath at room temperature. Record the initial gas volume of the cylinder and the temperature of the water bath in your data table.
3. Cut a piece of zinc about 50–75 mm long. Measure the length, and record this in your data table. Place the zinc in the sidearm flask.
4. Measure 25 mL of hydrochloric acid in a graduated cylinder.
5. Carefully pour the acid from the graduated cylinder into the flask. Start the stopwatch as you begin to pour. Stopper the flask as soon as the acid is transferred.
6. Record any signs of a chemical reaction you observe.
7. After 15 minutes, determine the amount of gas given off by the reaction. Record the volume of gas in your data table.

	Length of zinc strip (mm)	Initial gas volume (mL)	Final gas volume (mL)	Temperature (°C)	Reaction time (s)
Reaction 1					
Reaction 2					

Designing Your Experiment

8. With your lab partners decide how you will answer the question posed at the beginning of the lab. By completing steps 1–7, you have half the data you need to answer the question. How can you collect the rest of the data?
9. In your lab report, list each step you will perform in your experiment. Because temperature is the variable you want to test, the other variables in your experiment should be the same as they were in steps 1–7.
10. Before you carry out your experiment, your teacher must approve your plan.

Performing Your Experiment

11. After your teacher approves your plan, carry out your experiment. Record your results in your data table.
12. How do the two reactions differ?

Analysis

1. Express the rate of each reaction as mL of gas evolved in 1 minute.
2. Which reaction was more rapid?
3. Divide the faster rate by the slower rate, and express the reaction rates as a ratio.
4. According to your results, how does decreasing the temperature affect the rate of a chemical reaction?

Conclusions

5. How could you test the effect of temperature on this reaction without using an ice bath?
6. How can you express the rate of each of the two reactions you conducted as a function of the surface area of the zinc?
7. How would you design an experiment to test the effect of surface area on this reaction?