

Chemical Reactions

Chapter Preview

- 5.1 The Nature of Chemical Reactions**
Chemical Reactions Change Substances
Energy and Reactions
- 5.2 Reaction Types**
Classifying Reactions
Electrons and Chemical Reactions
- 5.3 Balancing Chemical Equations**
Describing Reactions
Determining Mole Ratios
- 5.4 Rates of Change**
Factors Affecting Reaction Rates
Equilibrium Systems

Before 1900, oil was refined to make kerosene for lights. Gasoline was a useless byproduct of the refining process.

Focus ACTIVITY

Background Early in the morning in May 1961, everything was quiet. Then a blindingly bright light flashed. The ground shook. A deafening roar filled the air. A Redstone rocket propelled a Project Mercury capsule toward the sky, and the first United States astronaut, Alan B. Shepard, soared 186 km above Earth's surface.

The Redstone rocket was powered by the chemical reaction that occurs between kerosene and oxygen. Kerosene has been used as a fuel to provide heat and light since the 1860s. The same chemical reaction that provided light from lighthouses and kerosene lamps in the days of the sailing ships was launching the United States manned space program.

These days, the space shuttle, which has a mass of about 2 000 000 kg at liftoff, uses a different chemical reaction. But the chemical reaction that sends the shuttle orbiting is neither exotic nor difficult to understand. It is the reaction between hydrogen and oxygen that yields water.

Activity 1 Kerosene and gasoline are just two of the fuels generally produced from crude oil. Visit a fuel distributor in your community and find out what kinds of fuels are available and what makes them different.

Activity 2 Research the octane rating system for gasolines. Find out what the different octane ratings are and what they mean.

	
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The Nature of Chemical Reactions

▶ KEY TERMS

reactant
product
chemical energy
exothermic reaction
endothermic reaction

OBJECTIVES

- ▶ Recognize some signs that a chemical reaction is 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.

Figure 5-1
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.

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. For example, sugar tastes sweet and lactic acid tastes sour. Sourdough bread gets its characteristic taste from lactic acid.

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 5-1**.

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, as you learned in Chapter 2.

- ▶ **reactant** a substance that undergoes a chemical change
- ▶ **product** a substance that is the result of a chemical change

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 the 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 5-2**, all the bonds to carbon atoms are covalent. In an oxygen molecule, a double 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.

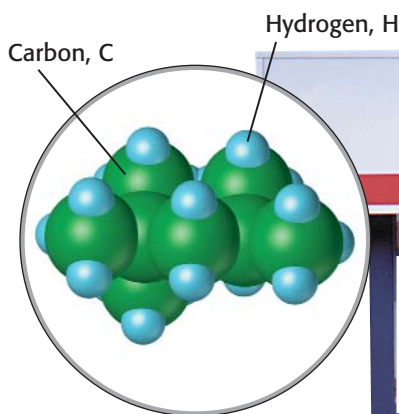


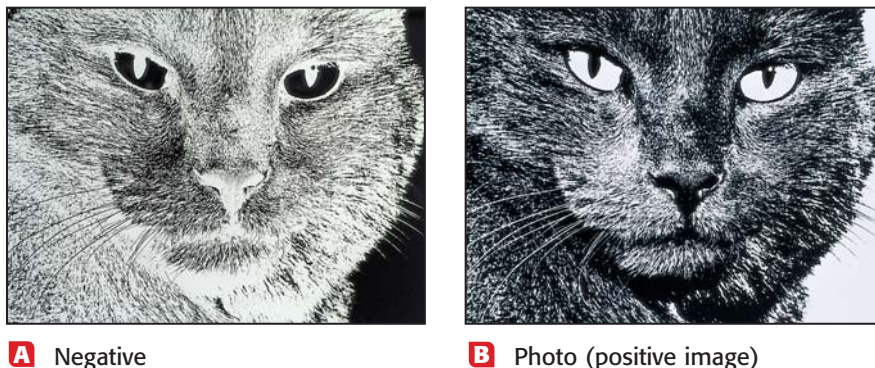
Figure 5-2

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 5-3

In photography, light passing through the camera lens causes a chemical reaction on the film. Silver bromide crystals in the gel on the film react to form darker elemental silver, which becomes the negative (A) that is used to make a black and white photograph (B).



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 5-3**. When molecules collide and enough energy is transferred to separate the atoms, bonds can break.

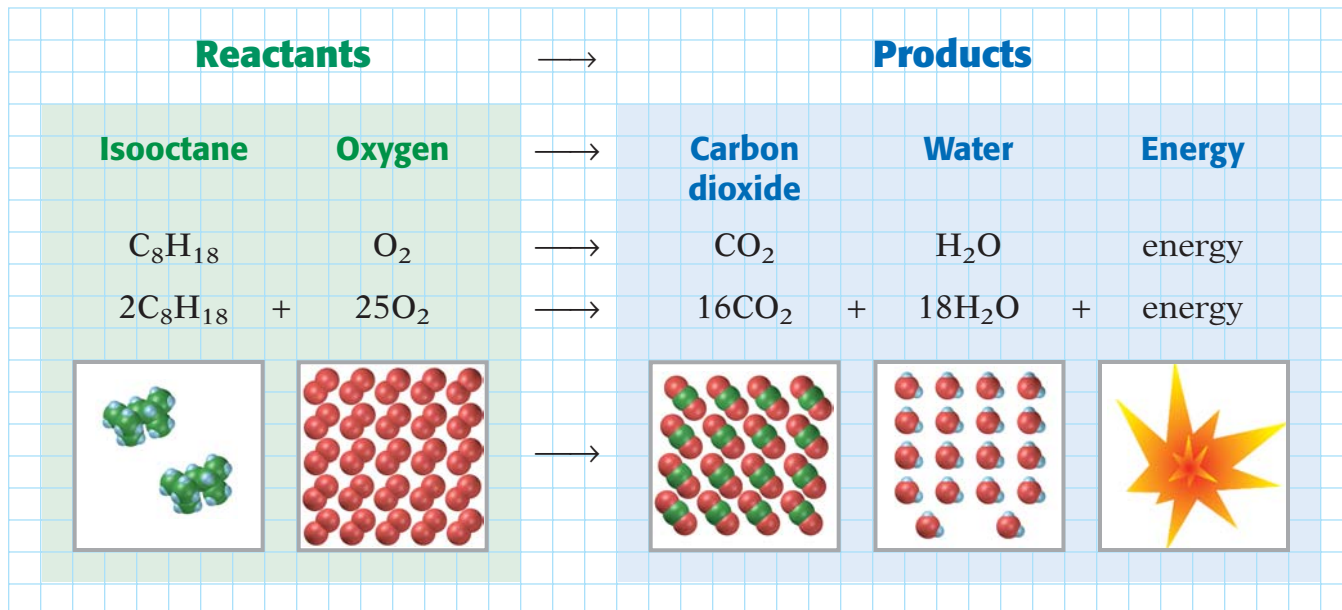
Forming bonds releases energy

Once enough energy is added to start the isooctane-oxygen reaction, new bonds form to make the products, as shown in **Figure 5-4**. 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 5-4

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



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 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.

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.

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.

- ▶ **chemical energy** the energy stored within atoms and molecules that can be released when a substance reacts
- ▶ **exothermic reaction** a reaction that transfers energy from the reactants to the surroundings as heat
- ▶ **endothermic reaction** a reaction in which energy is transferred to the reactants as heat from the surroundings

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REAL WORLD APPLICATIONS

Self-Heating Meals

Corrosion, the process by which a metal reacts with the oxygen in air or water, is not often wanted. 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?



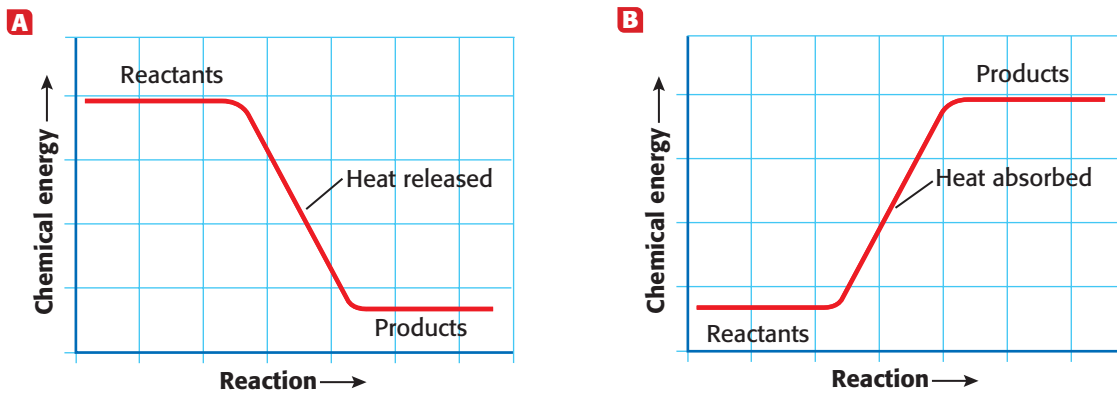


Figure 5-5

The general forms for exothermic reactions (A) and endothermic reactions (B) can be described by energy graphs.

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 5-5**.

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 5-6**.

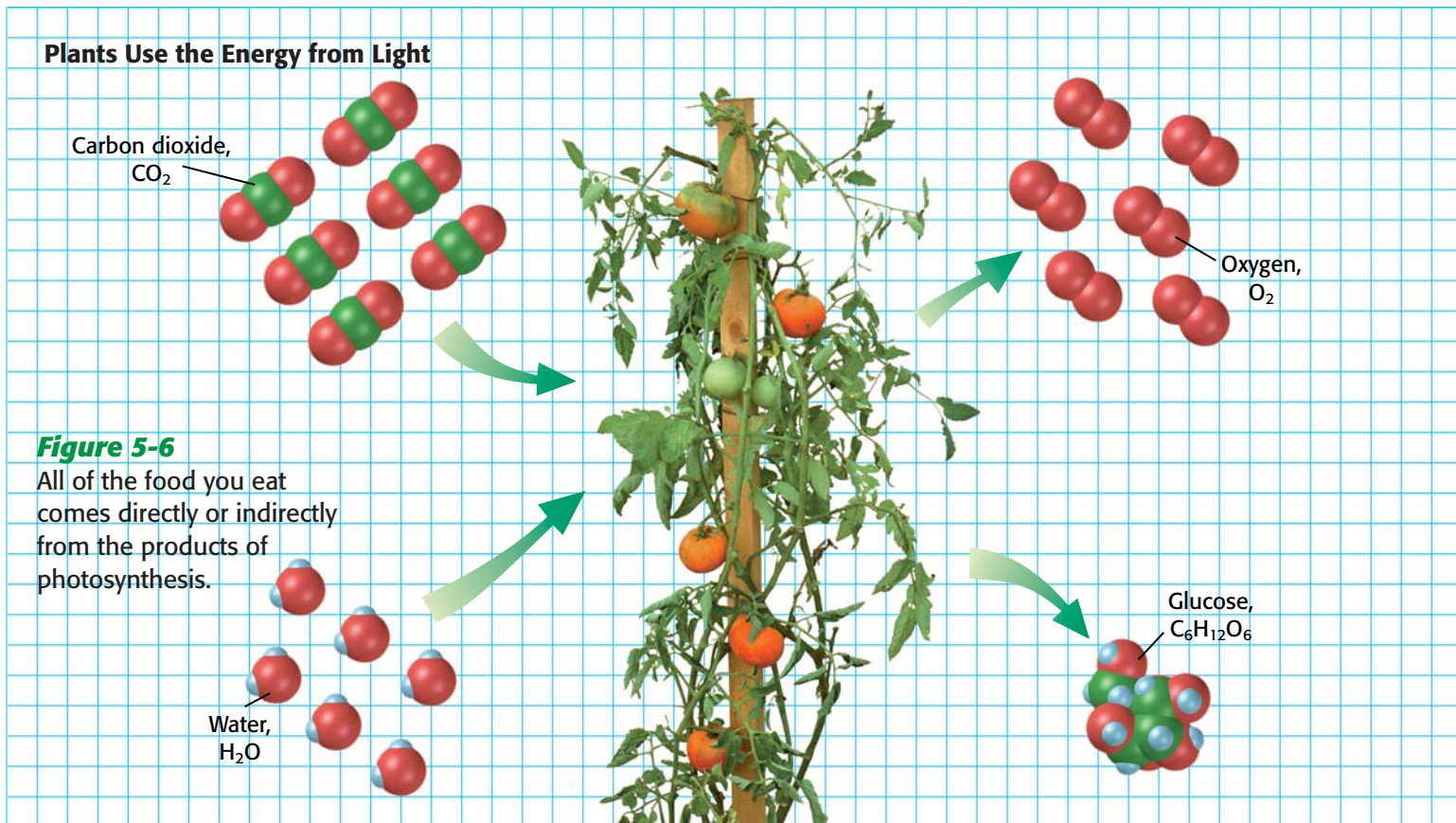


Figure 5-6

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

Figure 5-7

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.

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 5-7**, and respiration are exergonic reactions, and photosynthesis is an endergonic reaction.

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 5.1 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.
- ▶ Chemical energy can be released or absorbed.
- ▶ Energy must be added to the reactants for bonds between atoms to be broken.

CHECK YOUR UNDERSTANDING

- 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, $\text{C}_{12}\text{H}_{22}\text{O}_{11}$, 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.

Reaction Types

KEY TERMS

synthesis reaction
decomposition reaction
electrolysis
combustion reaction
single-displacement reaction
double-displacement reaction
redox reaction
radical

OBJECTIVES

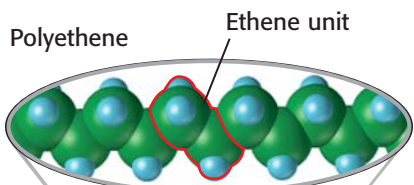
- ▶ Distinguish among five general types of chemical reactions.
- ▶ Predict the products of some reactions based on the reaction type.
- ▶ Describe reactions that transfer or share electrons between molecules, atoms, or ions.

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 of at least two substances that forms a new, more complex compound

Figure 5-8

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



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.

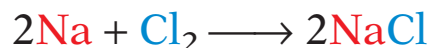
Synthesis reactions combine substances

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 5-8**, 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.



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

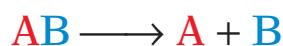


Synthesis reactions always join substances, so the product is a more complex compound than the reactants.

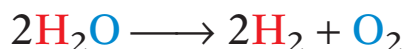
Photosynthesis is another kind of synthesis reaction—the synthesis reaction that goes on in plants. The photosynthesis reaction is shown in **Figure 5-9**.

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.



The following shows the decomposition of water.



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

In Section 5.1 you learned that isooctane forms carbon dioxide and water during combustion. Oxygen is a reactant in every **combustion reaction**, and at least one product of such reactions always contains oxygen.

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 carbon is given off as small particles that make a dark, sooty smoke.

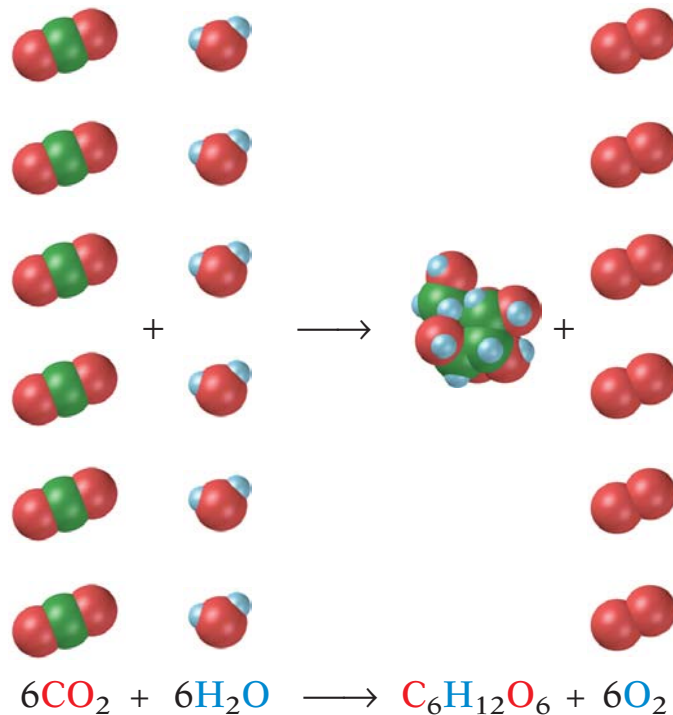


Figure 5-9

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

- ▶ **decomposition reaction** a reaction in which one compound breaks into at least two products
- ▶ **electrolysis** the decomposition of a compound by an electric current
- ▶ **combustion reaction** a reaction in which a compound and oxygen burn

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TOPIC: Types of reactions
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INTEGRATING

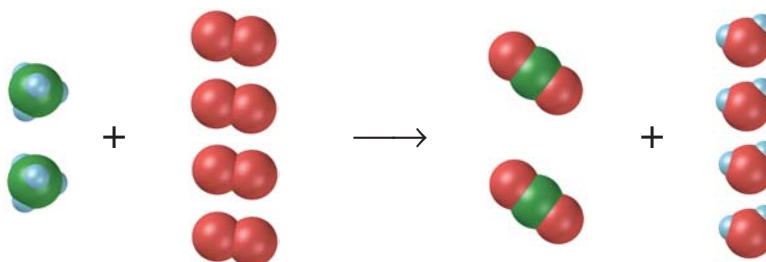
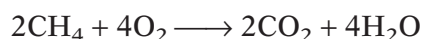


EARTH SCIENCE

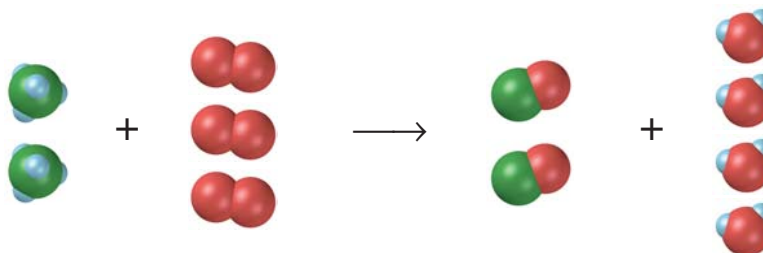
Compounds containing carbon and hydrogen are often called hydrocarbons. Most hydrocarbon fuels are fossil fuels, that is, compounds that were formed millions of years before dinosaurs existed. When prehistoric organisms died, they decomposed, and many were slowly buried under layers of mud, rock, and 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.

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. Two molecules of oxygen gas are needed for the combustion of each molecule of methane. Therefore, four molecules of oxygen gas are needed for the combustion of two molecules of methane, as shown below.



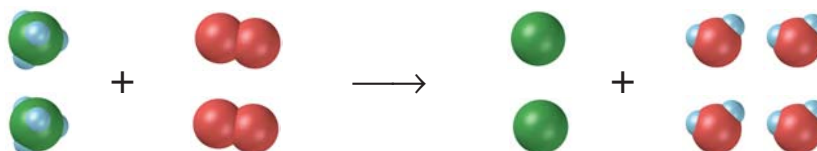
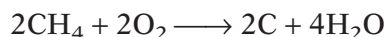
Now look at what happens when less oxygen gas is available. If there are only three molecules of oxygen gas for every two molecules of methane, water and carbon monoxide may form, as shown in the following reaction.



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.

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.



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 5-10**.

The copper atoms are in the form of copper(II) ions, as part of copper(II) chloride, and the aluminum atoms are in the 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.



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



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

▶ single-displacement reaction a reaction in which atoms of one element take the place of atoms of another element in a compound

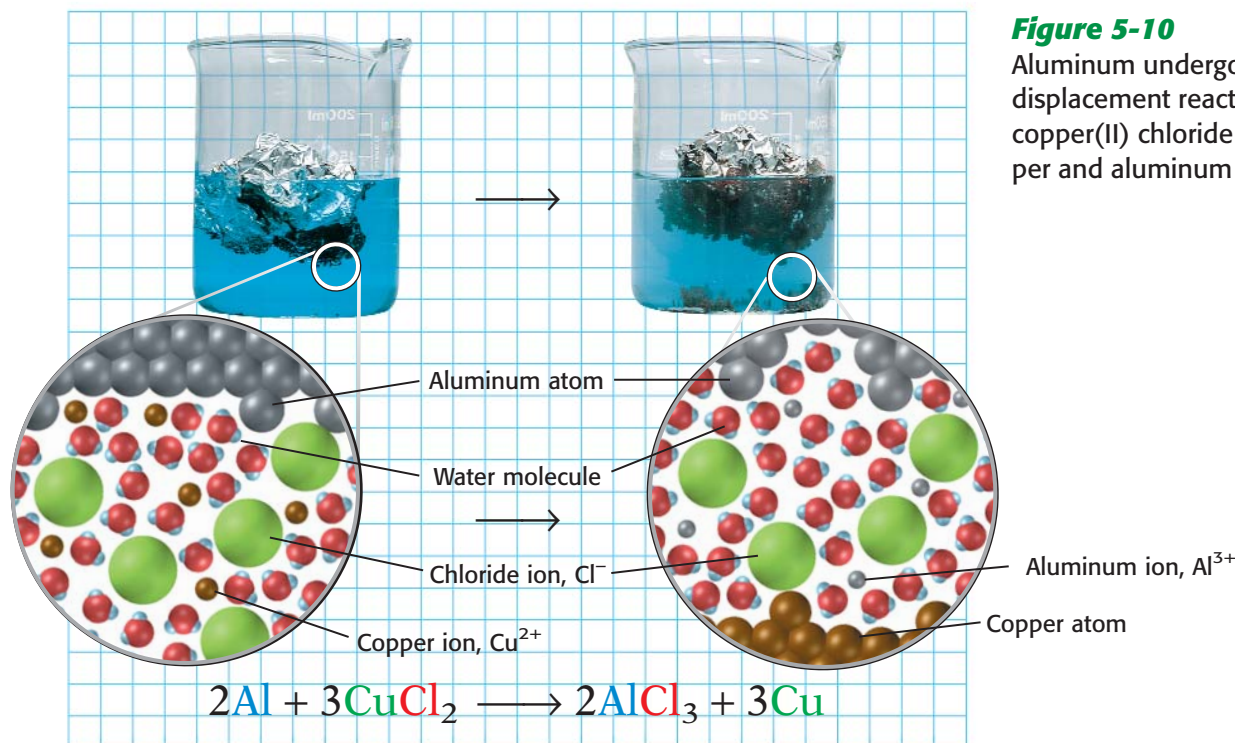
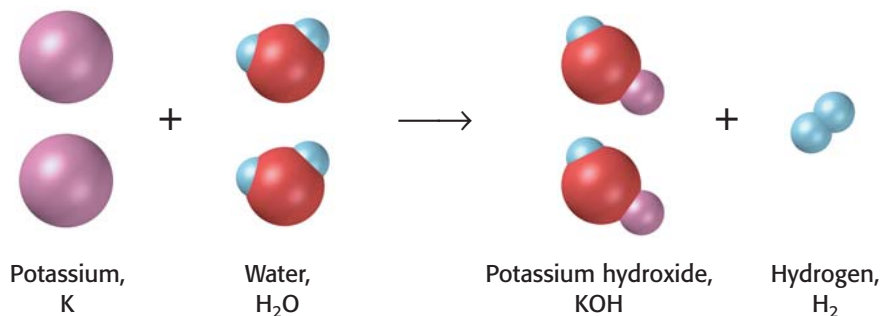




Figure 5-11

Potassium reacts with water in a single-displacement reaction.



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 5-11**, 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.

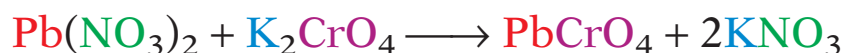
All of these reactions happen rapidly and give off heat but some alkali metals are more reactive than others. Lithium reacts steadily with water to form lithium ions, hydroxide ions, and hydrogen gas. Sodium and water react vigorously to make sodium ions, hydroxide ions, and hydrogen gas. For potassium, the reaction with water is more violent. 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.



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



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

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.

Electrons are transferred in redox reactions

The following **reduction/oxidation 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?

▶ **reduction/oxidation (redox) reaction** a reaction that occurs when electrons are transferred from one reactant to another

▶ **radicals** the fragments of molecules that have at least one electron available for bonding

Figure 5-12

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



Radicals are part of many everyday reactions besides the making of polymers, such as those shown in **Figure 5-12**. 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.

SECTION 5.2 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.

CHECK YOUR UNDERSTANDING

- 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

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.

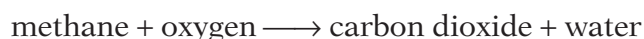
KEY TERMS

chemical equation
mole ratio

Figure 5-13 shows a combustion reaction you learned about in Section 5.2. You may have seen this 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.

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.



▶ **chemical equation** an equation that uses chemical formulas and symbols to show the reactants and products in a chemical reaction

Chemical equations summarize reactions

In Section 5.1, you learned that all chemical reactions are rearrangements of atoms. This is shown clearly in **Figure 5-13**. A better way to write the methane combustion reaction is as a **chemical equation**, using the formulas for each substance.

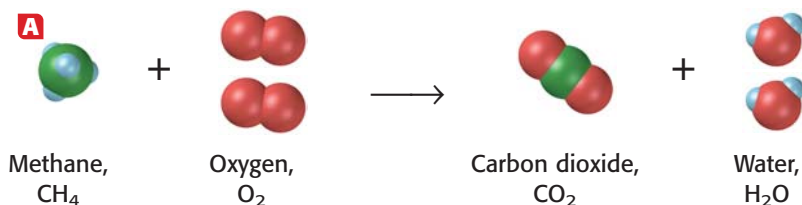
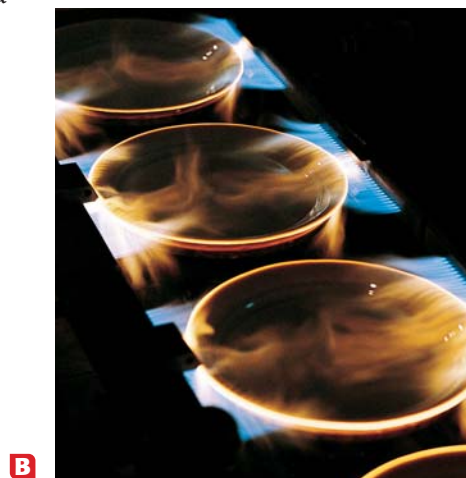
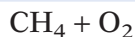


Figure 5-13

(A) Methane burns with oxygen gas to make carbon dioxide and water.
(B) A methane flame is used to polish the edges of these glass plates.



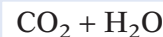
Unbalanced Chemical Equation



reactants



"give" or "yield"



products



Figure 5-14

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

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 5-14**.

Balanced chemical equations account for the conservation of mass

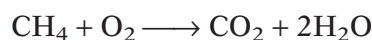
The chemical equation shown above can be made more useful. As written, it does not tell you anything about the amount of the products that will be formed from burning a given amount of methane. When the number of atoms of each element on the right-hand side of the equation matches the number of atoms of each element on the left, then the chemical equation is said to be *balanced*. A balanced chemical equation 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, as you learned in Chapter 2.

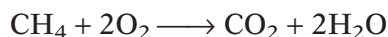
Remember that you cannot balance an equation by changing the chemical formulas. You have to leave the subscripts in the formulas alone. Changing the formulas would mean that different substances were in the reaction. An equation can be balanced only by putting numbers, called coefficients, in front of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

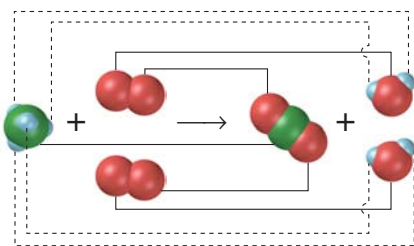


Next look at the oxygen. There is a total of four oxygen atoms in the products. Two are in the CO_2 , and each water molecule contains one oxygen atom. To get four oxygen atoms on the left side of the equation, two oxygen molecules must react. That would account for all four oxygen atoms.

Balanced Chemical Equation



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 5-15**, you can always write a balanced equation, as shown on the following pages.



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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.



Disc One, Module 5:

Chemical Equations

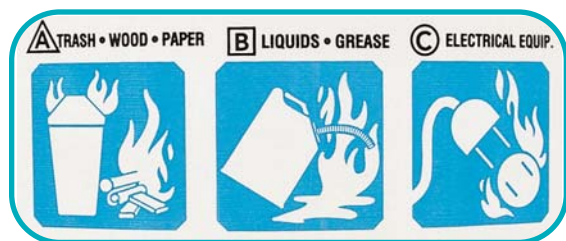
Use the Interactive Tutor to learn more about this topic.

Figure 5-15

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

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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TOPIC: Fire extinguishers
GO TO: www.scilinks.org
KEYWORD: HK1057

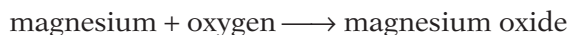
Math Skills

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

1 Identify the reactants and products.

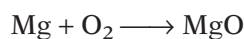
Magnesium and oxygen gas are the reactants that form the product, magnesium oxide.

2 Write a word equation for the reaction.



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 .

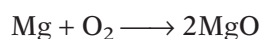


4 Balance the equation one element at a time.

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.

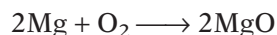
Atom	Reactants	Products	Balanced?
Mg	1	1	✓
O	2	1	✗

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:



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.



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

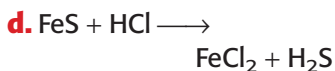
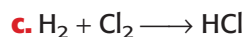
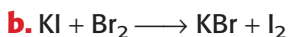
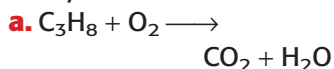
Balancing Chemical Equations

1. Copper(II) sulfate, CuSO_4 , and aluminum react to form aluminum sulfate, $\text{Al}_2(\text{SO}_4)_3$, 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.
4. Hydrogen sulfide, H_2S , is a gas that smells like rotten eggs. Write and balance an equation for the oxidation by molecular oxygen of hydrogen sulfide to make sulfuric acid, H_2SO_4 .
5. Propane gas, C_3H_8 , is commonly used as a fuel for camping stoves and gas barbecue grills. Write and balance the equation for the synthesis of propane from methane in which molecular hydrogen, H_2 , is also a product.

Quick ACTIVITY

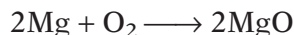
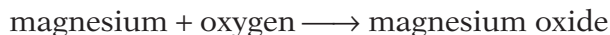
Candy Chemistry

Look at the partial equations below. Using different-colored gumdrops to show atoms of different elements, make models of the reactions by connecting the "atoms" with toothpicks. Use your models to help you balance the following equations. Classify each reaction.



Determining Mole Ratios

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



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

Balanced equations indicate particles and moles

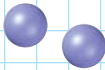

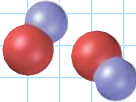
One way to read the equation is to say that two atoms of magnesium can react with one molecule of oxygen to give two units of magnesium oxide. This is a good way to understand the reaction. But reactions almost always involve more than one or two atoms.

The equation can also be read as describing mole quantities—2 mol of magnesium can react with 1 mol of oxygen to produce 2 mol of magnesium oxide.

Balanced equations show the conservation of mass

Other ways of looking at the amounts in the reaction are shown in **Figure 5-16**. 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 5-16 Information from the Balanced Equation: $2\text{Mg} + \text{O}_2 \longrightarrow 2\text{MgO}$

Equation:	2Mg	+	O_2	\longrightarrow	2MgO
Amount (mol)	2		1	\longrightarrow	2
Molecules	$(6.02 \times 10^{23}) \times 2$		$(6.02 \times 10^{23}) \times 1$	\longrightarrow	$(6.02 \times 10^{23}) \times 2$
Mass (g)	$24.3 \text{ g/mol} \times 2 \text{ mol}$		$32.0 \text{ g/mol} \times 1 \text{ mol}$	\longrightarrow	$40.3 \text{ g/mol} \times 2 \text{ mol}$
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.

Inquiry

Lab

Can you write balanced chemical equations?

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, AgNO₃

Procedure

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 AgNO₃ solution to each of the test tubes. Record your observations.

Analysis

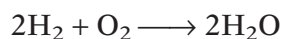
1. What did you observe as a sign that a double-displacement reaction was occurring?
2. Identify the reactants and products for each reaction.
3. Write the balanced equation for each reaction.
4. Which ion(s) produced a solid with silver nitrate?
5. Does this test let you identify all the ions? Why or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

▶ **mole ratio** the smallest relative number of moles of the substances involved in a reaction

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.

The mole ratio for any reaction comes from the balanced chemical equation. For example, in the following equation for the synthesis of water, the mole ratio for $\text{H}_2:\text{O}_2:\text{H}_2\text{O}$, using the coefficients, is 2:1:2.



SECTION 5.3 REVIEW

SUMMARY

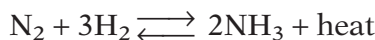
- ▶ A chemical equation shows the reactants that combine and the products that result from the reaction.
- ▶ Balanced chemical equations show the proportions of reactants and products needed for the mass to be conserved.
- ▶ A compound always contains the same elements in the same proportions, regardless 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.

CHECK YOUR UNDERSTANDING

- 1. Identify** which of the following is a complete and balanced chemical equation:
 - a. $\text{H}_2\text{O} \longrightarrow \text{H}_2 + \text{O}_2$
 - b. $\text{NaCl} + \text{H}_2\text{O}$
 - c. $\text{Fe} + \text{S} \longrightarrow \text{FeS}$
 - d. CaCO_3
- 2. Balance** the following equations:
 - a. $\text{KOH} + \text{HCl} \longrightarrow \text{KCl} + \text{H}_2\text{O}$
 - b. $\text{Pb}(\text{NO}_3)_2 + \text{KI} \longrightarrow \text{KNO}_3 + \text{PbI}_2$
 - c. $\text{NaHCO}_3 \longrightarrow \text{H}_2\text{O} + \text{CO}_2 + \text{Na}_2\text{CO}_3$
 - d. $\text{NaCl} + \text{H}_2\text{SO}_4 \longrightarrow \text{Na}_2\text{SO}_4 + \text{HCl}$
- 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:



- 5. Critical Thinking** Ammonia is manufactured by the Haber process.



This involves the reaction of nitrogen with hydrogen to form ammonia. What mass of nitrogen is needed to make 34 g of ammonia?

WRITING SKILL

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
equilibrium
Le Châtelier's principle

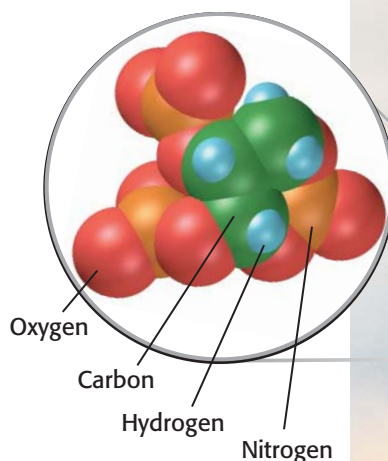
Chemical reactions can occur at different speeds or rates. Some reactions, such as the explosion of nitroglycerin, shown in **Figure 5-17**, are very fast. Other reactions, such as the burning of carbon in charcoal, are much slower. But what if you wanted to slow down the nitroglycerin reaction to make 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.

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 boil. 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.



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Figure 5-17

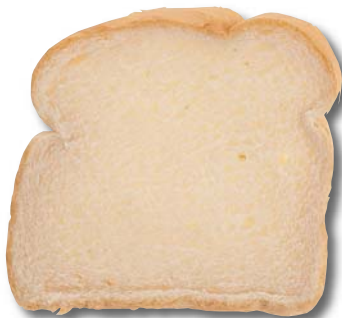
Nitroglycerin can be used as a rocket fuel as well as a medicine for people with heart ailments.



Figure 5-18



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.



Figure 5-19

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

Most reactions go faster at higher temperatures

A potato slice cooks faster in hot oil than in boiling water. 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 5-18**.

In Chapter 2, you learned that one of the assumptions of the kinetic theory is that particles move faster at higher temperatures. This faster motion increases the energy of the particles and increases the chances that the particles will collide. This means that there are more chances for the particles to react. Because the particles have more chances to react, the reaction will be faster.

A large surface area speeds up reactions

You can save time making mashed potatoes by cutting the potatoes into small pieces before boiling them, because sliced potatoes cook more quickly than whole potatoes. When a whole potato is placed in boiling water, only the outside is in direct contact with the boiling water. As **Figure 5-19** 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.

The same holds true for most chemical reactants. If you crush a solid into a powder or dissolve it in a solution, more of the solid surface is exposed. Generally solids that have a large surface area react more rapidly because more particles can come in contact with the other reactants.

Concentrated solutions react faster

Think about a washing machine full of clothes with grass stains on them. If you put a few drops of bleach in the washing machine full of 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. In fact, they may not have any color left. The more concentrated solution has more bleach particles. This means a higher chance for particle collisions with the stains.

Reactions are quicker at higher pressure

Like the concentration of a liquid, 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 a gas at 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, which you studied in Chapter 2, 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.

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.

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 5-1**. Most enzymes are fragile. If they are kept too cold or too warm, they tend to decompose. Most enzymes stop working above 45°C.

Did You Know?

In our atmosphere at room temperature, a molecule of oxygen, O₂, will have about four billion (4×10^9) collisions in 1 s. In interstellar space due to the differences in both temperature and pressure, hydrogen will have a collision about once every 8 days.

- ▶ **catalyst** a substance that changes the rate of chemical reactions without being consumed
- ▶ **enzyme** a protein that speeds up a specific biochemical reaction

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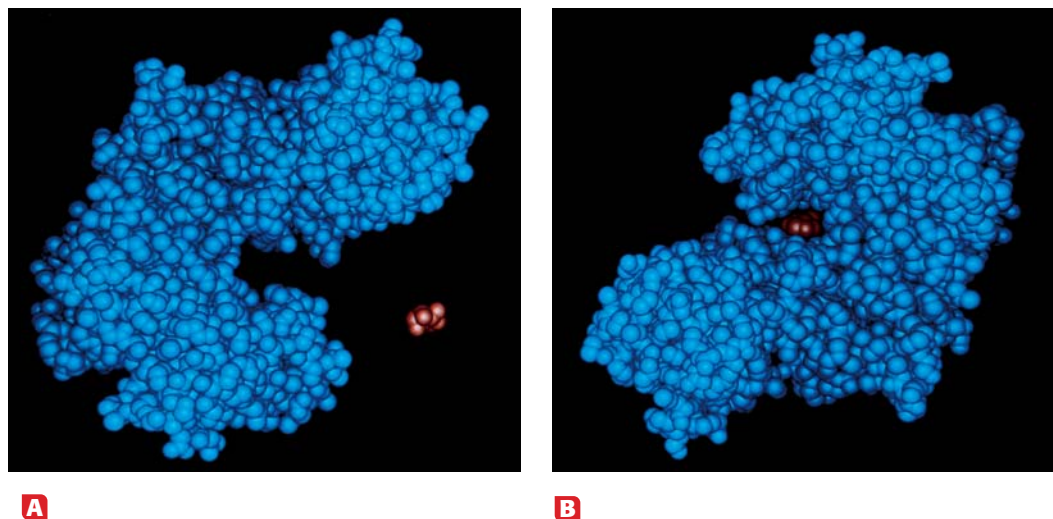
TOPIC: Catalysts
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Table 5-1 Common Enzymes and Their Uses

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.

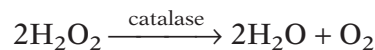
Figure 5-20

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.



▶ **substrate** the specific substance affected by an enzyme

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



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 5-20**. Enzymes are very efficient. In 1 minute, one molecule of catalase can catalyze the decomposition of 6 million molecules of hydrogen peroxide.

Inquiry

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

Procedure

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.

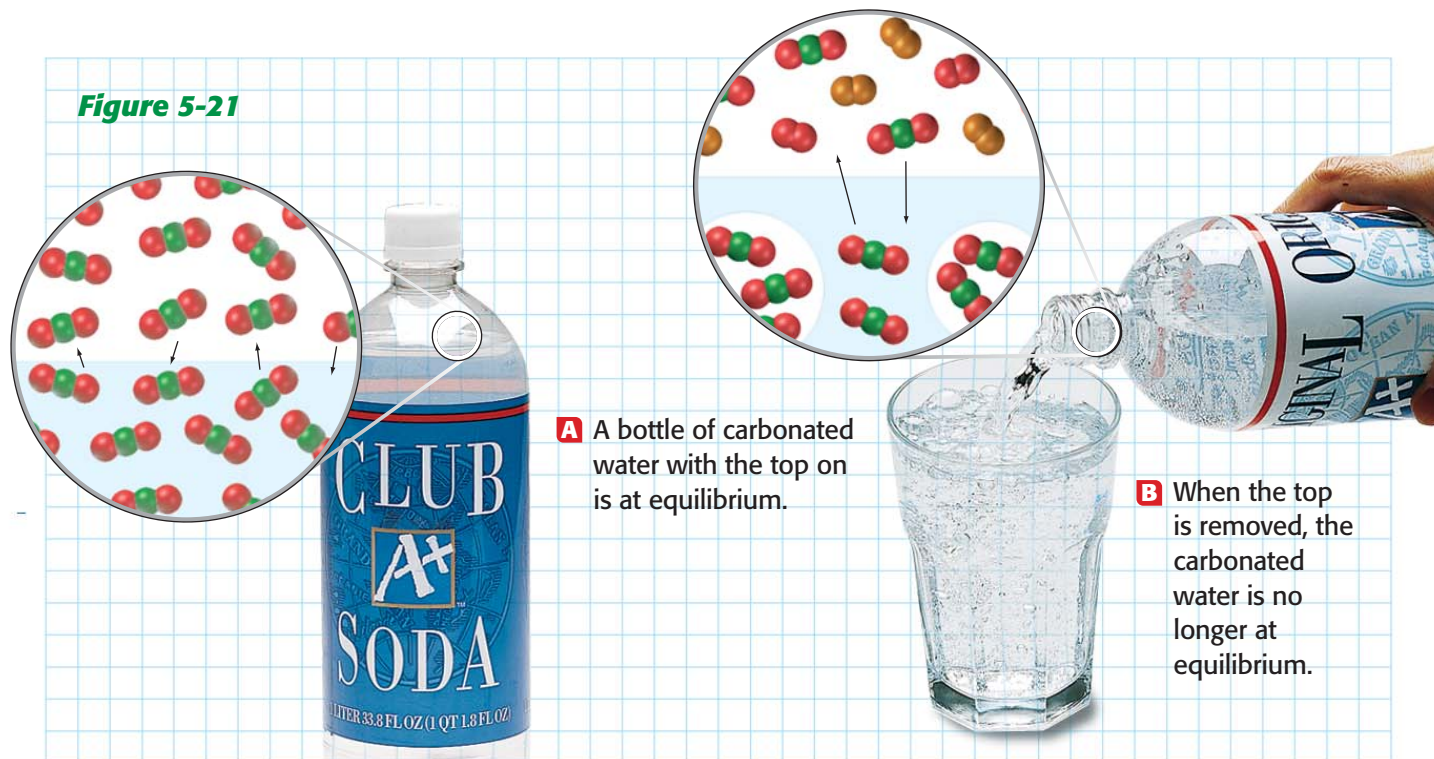
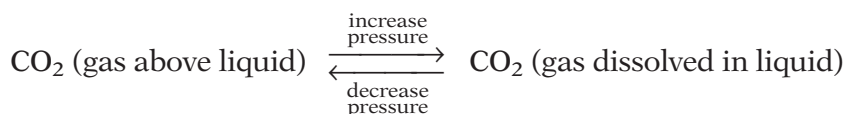
Equilibrium Systems

When nitroglycerin explodes, nothing much 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 reactions are reversible.

For example, carbonated drinks, such as the soda shown in **Figure 5-21**, 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.



Quick ACTIVITY

Catalysts in Action

1. Pour 2 percent 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?

▶ **equilibrium** the state in which a chemical reaction and its reverse occur at the same time and at the same rate

VOCABULARY Skills Tip

*Equilibrium comes from the Latin *aequilibrium* 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.*



Figure 5-22

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

The reaction 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.

Equilibrium results when rates balance

When a carbonated drink is in a closed bottle, you can't see any changes. The system is in **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.

Systems in equilibrium respond to minimize change

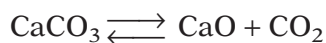
When the top is removed from a carbonated drink, the drink is no longer at equilibrium, and CO_2 leaves as bubbles. For equilibrium to be reached, none of the reactants or products can escape.

An example of an equilibrium system is the conversion of limestone, CaCO_3 , to lime, CaO . 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 5-22**, were probably built with cement made by this reaction.



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.



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 remain the same.

Table 5-2 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 less gas.
Concentration	Increasing the concentration of one substance favors the reaction that produces less of that substance.

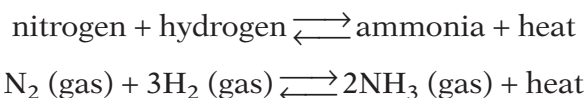
Le Châtelier's principle predicts changes in equilibrium

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 5-2**.

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 5-23**. The Haber process, which is used to make ammonia industrially, is exothermic; it releases energy.



At an ammonia-manufacturing plant, such as the one shown in **Figure 5-24**, 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 .



Figure 5-24 Ammonia, which is manufactured in plants such as this, is used to make ammonium perchlorate—one of the space shuttle's fuels.



Figure 5-23 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.

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.

If you raise the temperature, Le Châtelier's principle indicates that the equilibrium will shift to the left, the direction that absorbs energy and makes less ammonia. If you raise the pressure, the equilibrium will move to reduce the pressure according to Le Châtelier's principle. One way to reduce the pressure is to have fewer gas molecules. This means the equilibrium moves to the right—more ammonia—because there are fewer gas molecules on the right side. So to get the most ammonia from this reaction, you need to use a high pressure and a low temperature. The Haber process is a good example of balancing equilibrium conditions to make the most product.

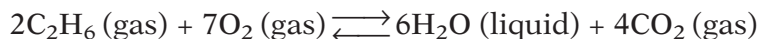
SECTION 5.4 REVIEW

SUMMARY

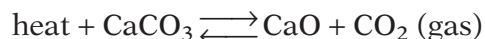
- ▶ Increasing the temperature, surface area, concentration, or pressure of reactants may speed up chemical reactions.
- ▶ Catalysts alter the rate of chemical reactions. Most catalysts speed up chemical reactions. Others, called inhibitors, slow reactions down.
- ▶ In a chemical reaction, chemical equilibrium is achieved when reactants change to products and products change to reactants at the same time and the same rate.
- ▶ At chemical equilibrium, no changes are apparent even though individual particles are reacting.
- ▶ Le Châtelier's principle states that for any change made to a system in equilibrium, the equilibrium will shift to minimize the effects of the change.

CHECK YOUR UNDERSTANDING

- 1. Identify** which of the following are examples of chemical equilibrium:
 - a. $2\text{NO}_2 \rightleftharpoons \text{N}_2\text{O}_4$
 - b. $2\text{H}_2\text{O} \longrightarrow 2\text{H}_2 + \text{O}_2$
 - c. $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3 + \text{heat}$
 - d. $\text{H}_2 + \text{I}_2 \rightleftharpoons 2\text{HI}$
- 2. List** five factors that may affect the rate of a chemical reaction.
- 3. Identify and Explain** an example of Le Châtelier's principle.
- 4. Compare and Contrast** a catalyst and an inhibitor.
- 5. Analyze** the error in reasoning in the following situation: A person claims that because the overall amounts of reactants and products don't change, a reaction must have stopped.
- 6. Describe** what can happen to the reaction rate of a system that is heated and then cooled.
- 7. Decide** which way an increase in pressure will shift the following equilibrium system involving ethane, C_2H_6 , oxygen, O_2 , water, H_2O , and carbon dioxide, CO_2 .



- 8. Decision Making** Consider the decomposition of solid calcium carbonate to solid calcium oxide and carbon dioxide gas.



What conditions of temperature and pressure would you choose to get the most decomposition of CaCO_3 ? Explain your reasoning.

Chapter Highlights

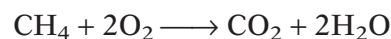
Before you begin, review the summaries of the key ideas of each section, found on pages 153, 160, 168, and 176. The key vocabulary terms are listed on pages 148, 154, 161, and 169.

UNDERSTANDING CONCEPTS

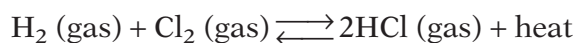
- When a chemical reaction occurs, atoms are never _____.
 - ionized
 - rearranged
 - destroyed
 - vaporized
- In an exothermic reaction, _____.
 - energy is conserved
 - the formation of bonds in the product releases more energy than is required to break the bonds in the reactants
 - energy is released as bonds form
 - All of the above
- $A + B \longrightarrow AB$ is an example of a _____.
 - synthesis reaction
 - decomposition reaction
 - single-displacement reaction
 - double-displacement reaction
 - redox reaction
- Which of the following reactions is not an example of a redox reaction?
 - combustion
 - rusting
 - dissolving in salt water
 - respiration
- Radicals _____.
 - form ionic bonds with other ions
 - result from broken covalent bonds
 - usually break apart to form smaller components
 - bind molecules together
- In any chemical equation, the arrow means _____.
 - “equals”
 - “is greater than”
 - “yields”
- Hydrogen peroxide, H_2O_2 , decomposes to produce water and oxygen gas. The balanced equation for this reaction is _____.
 - $H_2O_2 \longrightarrow H_2O + O_2$
 - $2H_2O_2 \longrightarrow 2H_2O + O_2$
 - $2H_2O_2 \longrightarrow H_2O + 2O_2$
 - $2H_2O_2 \longrightarrow 2H_2O + 2O_2$
- Most reactions speed up when _____.
 - the temperature is lowered
 - equilibrium is achieved
 - the concentration of the products is increased
 - the reactants are in small pieces
- Enzymes _____.
 - can be used to speed up almost any chemical reaction
 - rely on increased surface area to catalyze reactions
 - catalyze specific biological reactions
 - always work faster at higher temperatures
- A system in chemical equilibrium _____.
 - has particles that don't move
 - responds to minimize change
 - is undergoing visible change
 - is stable only when all of the reactants have been used

Using Vocabulary

- Explain what it means when a system in equilibrium shifts to favor the products.
- 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*.
- Translate the following chemical equation into a sentence.

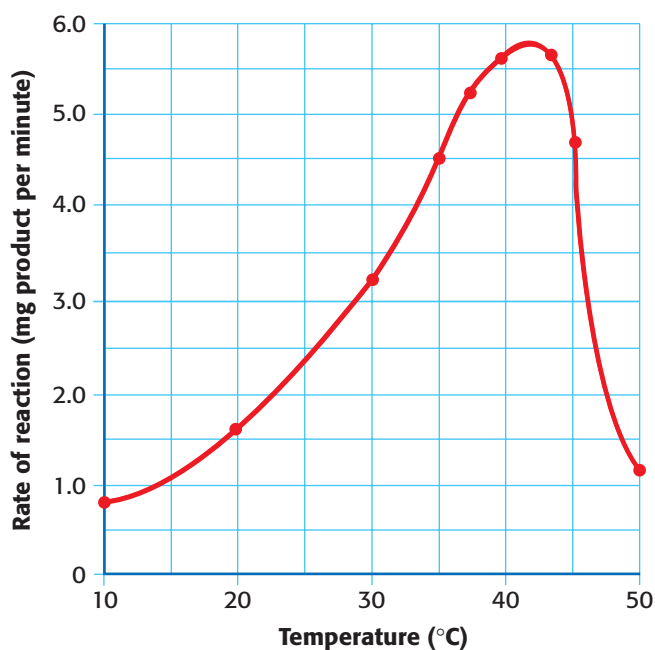


- 14.** For each of the following changes to the equilibrium system below, predict which reaction will be favored—forward (to the right), reverse (to the left), or neither.



- addition of Cl_2
- removal of HCl
- increased pressure
- decreased temperature
- removal of H_2

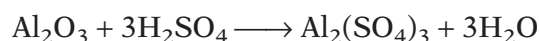
BUILDING MATH SKILLS



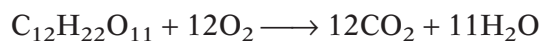
- 15. Graphing** A technician carried out an experiment to study the effect of increasing temperature on a certain reaction. Her results are shown in the graph above.
- Between which temperatures does the rate of the reaction rise?
 - Between which temperatures does the rate of the reaction slow down?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

- 16. 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.

- 17. Chemical Equations** Aluminum sulfate, $\text{Al}_2(\text{SO}_4)_3$, is used to fireproof fabrics and to make antiperspirants. It can be formed from a reaction between aluminum oxide, Al_2O_3 , and H_2SO_4 .

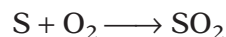


- How many moles of $\text{Al}_2(\text{SO}_4)_3$ would be produced if 6 mol of H_2SO_4 reacted with an unlimited amount of Al_2O_3 ?
 - How many moles of Al_2O_3 are required to make 9 mol of H_2O ?
 - If 588 mol of Al_2O_3 reacts with unlimited H_2SO_4 , how many moles of each of the products will be produced?
- 18. Chemical Equations** Sucrose, $\text{C}_{12}\text{H}_{22}\text{O}_{11}$, is a sugar used to sweeten many foods. Inside the body, it is broken down to produce H_2O and CO_2 .



List all of the mole ratios that can be determined from this equation.

- 19. Chemical Equations** Sulfur burns in air to form sulfur dioxide.

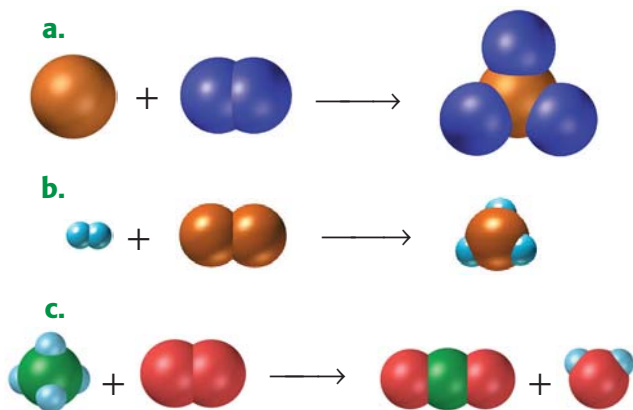


- What mass of SO_2 is formed from 64 g of sulfur?
 - What mass of sulfur is necessary to form 256 g of SO_2 ?
- 20. Chemical Equations** Zinc metal will react with hydrochloric acid, HCl , to produce hydrogen gas and zinc chloride, ZnCl_2 . Write and balance the chemical equation for this reaction.

THINKING CRITICALLY

- 21. Designing Systems** Paper consists mainly of cellulose, a complex compound made up of simple sugars. Suggest a method for turning old newspapers into sugars using an enzyme. What problems would there be? What precautions would need to be taken?
- 22. Applying Knowledge** Molecular models of some chemical reactions are pictured below. Correct the drawings by adding coefficients or drawing molecules with a computer drawing program to reflect balanced equations.

COMPUTER SKILL



- 23. Understanding Systems** Why is it dangerous to leave a car engine running when the car is in a closed garage?

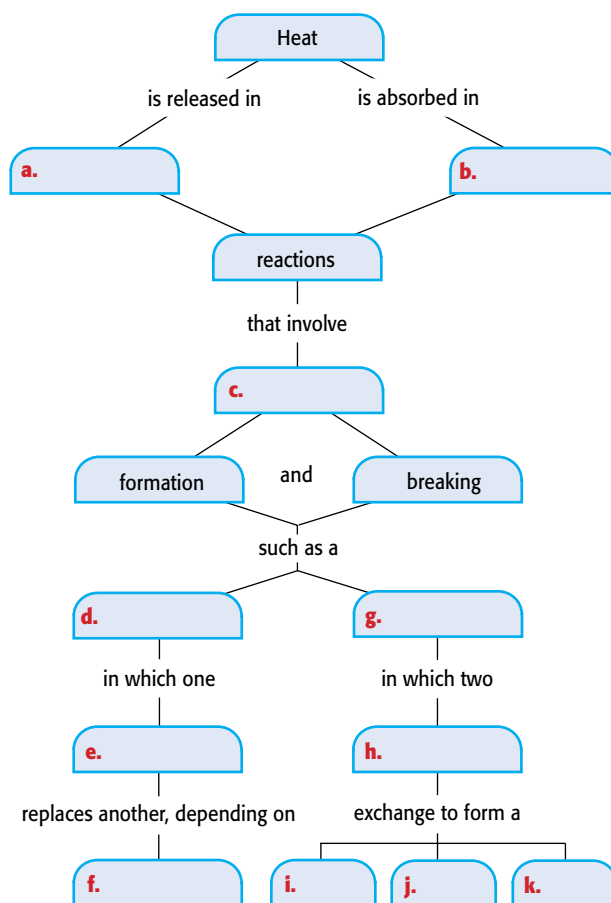
DEVELOPING LIFE/WORK SKILLS

- 24. Making Decisions** Cigarette smoke contains carbon monoxide. Why do you think carbon monoxide is in the smoke? Why is smoking bad for your health?
- 25. Interpreting and Communicating** Choose several items labeled “biodegradable,” and research the decomposition reactions involved. Write balanced chemical equations for the decomposition reactions. Be sure to note any conditions that must occur for the

substance to biodegrade. Present your information to the class to inform the students about what products are best for the environment.

INTEGRATING CONCEPTS

- 26. Concept Mapping** Copy the unfinished concept map given below onto a sheet of paper. Complete the map by writing the correct word or phrase in the lettered box.



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SCILINKS
NSTA

TOPIC: Biodegradable
GO TO: www.scilinks.org
KEYWORD: HK1056

Design Your Own 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 rate of the reaction between zinc and hydrochloric acid.
- ▶ **Determine** how the rate of this reaction depends on the temperature of the reactants.

Materials

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

Safety Needs



lab apron
safety goggles
polyethylene gloves

Measuring the Rate of a Chemical Reaction

▶ 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?

► Analyzing Your Results

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?

► Defending Your 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?

How Should Life-Saving Inventions Be Introduced?

Researchers are developing better fire-proof materials to use inside passenger airplanes. But the new materials are much more expensive than the ones currently used.

Should the Federal Aviation Administration (FAA) require that the new materials be used on all new and old planes, or should it be up to the plane manufacturers and airlines to decide whether to use the new materials?

A similar debate occurs whenever life-saving inventions are introduced, from automobile airbags to better child-safety seats. If the inventions should be used, who should bear the cost? Should it be the federal government, an insurance company, a manufacturer, or the customers?

If the device shouldn't be required at all times, how do you decide when it should be used? When are the risks so small that it doesn't make sense to spend money on another safety device?

What do you think?

> FROM: Stacey F., Rochester, MN.

It should be up to the plane manufacturers because not all companies would be able to afford the cost. The FAA should look into the budgets of all plane companies and companies that can afford it should be required to use the new material.

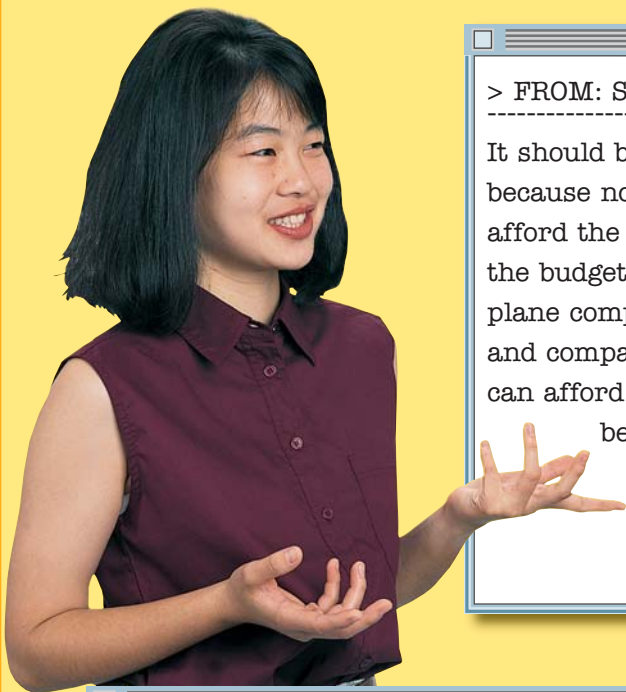
> FROM: Emily B., Coral Springs, FL

I think it should be up to the plane manufacturers and airlines. The new materials shouldn't be required on planes that are already built or on planes that are being built, because of expenses. However, it would be to an airline's advantage to have the best safety material possible for their customers' sake.

> FROM: Virginia M., Houston, TX

The airlines are responsible for the lives of their passengers, so they should decide. But the FAA should pass a law stating that if the airlines refuse new safety measures, the airlines will accept total responsibility for any accidents that occur.

Leave the Decisions to the Companies Involved



> FROM: April R., Coral Springs, FL

If it can save just one life, it's worth spending money and time on. Eventually the technology will be required on all planes anyway. If an airline chose not to use these materials and there were an accident, there would be liability cases because lives might have been saved. Most people will have no problem spending more for a plane ticket if their safety is ensured.

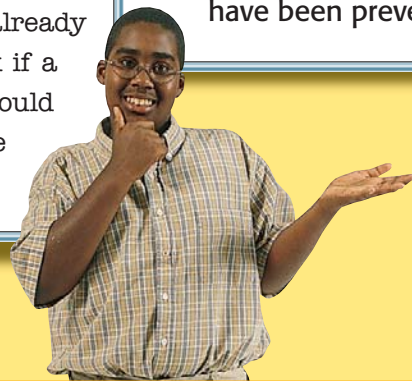
Require Safety Immediately

> FROM: Carlene de C., Chicago, IL

The FAA should require that all planes—those currently in use and those being built—have fireproof materials. Otherwise, passengers could sue the airline company if they were hurt in a fire and it could have been prevented.

> FROM: Shannon B., Bowling Green, KY

They should put the new fireproof materials on all planes, even the ones that have already been built. The public's health is at risk if a plane malfunctions, and the airlines should want to keep everybody safe. Otherwise they will lose customers.



Your Turn

- 1. Critiquing Viewpoints** Select one of the statements on this page that you *agree* with. Identify and explain at least one weak point in the statement. What would you say to respond to someone who brought up this weak point as a reason you were wrong?
- 2. Critiquing Viewpoints** Select one of the statements on this page that you *disagree* with. Identify and explain at least one strong point in the statement. What would you say to respond to someone who brought up this point as a reason they were right?
- 3. Evaluating Science** Identify and describe another example in which research into new materials or technologies resulted in a life-saving invention. Evaluate the impact this research had on society.
- 4. Life/Work Skills** Imagine that you are preparing to testify in a congressional hearing about this matter. Choose the four most important points you'd make, and draft a statement that explains all of them persuasively.

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TOPIC: Lifesaving technology
GO TO: go.hrw.com
KEYWORD: HK1Lifesavers

What do you think should be done? Why? Share your views on this issue and learn about other viewpoints at the HRW Web site.