

# CHAPTER 5

## AN INTRODUCTION TO CHEMICAL REACTIONS

**N**ow that you understand the basic structural differences between different kinds of substances, you are ready to begin learning about the chemical changes that take place as one substance is converted into another. Chemical changes are chemists' primary concern. They want to know what, if anything, happens when one substance encounters another. Do the substances change? How and why? Can the conditions be altered to speed the changes up, slow them down, or perhaps reverse them? Once chemists understand the nature of one chemical change, they begin to explore the possibilities that arise from causing other similar changes.

For example, let's pretend that you just bought an old house *as is*, with the water turned off. On moving day, you twist the hot water tap as far as it will go, and all you get is a slow drip, drip, drip. As if the lack of hot water weren't enough to ruin your day, you also have a toothache because of a cavity that you haven't had time to get filled. As a chemist in training, you want to know what chemical changes have caused your troubles. In this chapter, you will read about the chemical change that causes a solid to form in your hot water pipes, eventually blocking the flow of water through them. In Chapter 6, you will find out about a chemical change that will dissolve that solid, and a similar change that dissolves the enamel on your teeth. Chapter 6 will also show you how fluoride in your toothpaste makes a minor chemical change in your mouth that can help fight cavities.

Chemical changes, like the ones mentioned above, are described with chemical equations. This chapter begins with a discussion of how to interpret and write chemical equations.



A chemical reaction causes solids to form in hot water pipes.

- 5.1 Chemical Reactions and Chemical Equations
- 5.2 Solubility of Ionic Compounds and Precipitation Reactions

### Review Skills

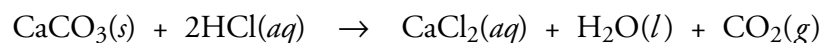
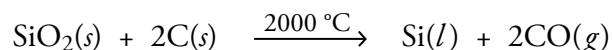
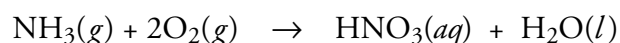
The presentation of information in this chapter assumes that you can already perform the tasks listed below. You can test your readiness to proceed by answering the Review Questions at the end of the chapter. This might also be a good time to read the Chapter Objectives, which precede the Review Questions.

- Write the formulas for the diatomic elements. (Section 3.5)
- Predict whether a bond between two atoms of different elements would be a covalent bond or an ionic bond. (Section 4.2)
- Describe attractions between  $\text{H}_2\text{O}$  molecules. (Section 4.3)
- Describe the structure of liquid water. (Section 4.3)
- Convert between the names and formulas for alcohols, binary covalent compounds, and ionic compounds. (Sections 4.3-4.5)

## 5.1 Chemical Reactions and Chemical Equations



A **chemical change** or **chemical reaction** is a process in which one or more pure substances are converted into one or more different pure substances. Chemical changes lead to the formation of substances that help grow our food, make our lives more productive, cure our heartburn, and much, much more. For example, nitric acid,  $\text{HNO}_3$ , which is used to make fertilizers and explosives, is formed in the chemical reaction of the gases ammonia,  $\text{NH}_3$ , and oxygen,  $\text{O}_2$ . Silicon dioxide,  $\text{SiO}_2$ , reacts with carbon,  $\text{C}$ , at high temperature to yield silicon,  $\text{Si}$ —which can be used to make computers—and carbon monoxide,  $\text{CO}$ . An antacid tablet might contain calcium carbonate,  $\text{CaCO}_3$ , which combines with the hydrochloric acid in your stomach to yield calcium chloride,  $\text{CaCl}_2$ , water, and carbon dioxide. The chemical equations for these three chemical reactions are below.



Once you know how to read these chemical equations, they will tell you many details about the reactions that take place.

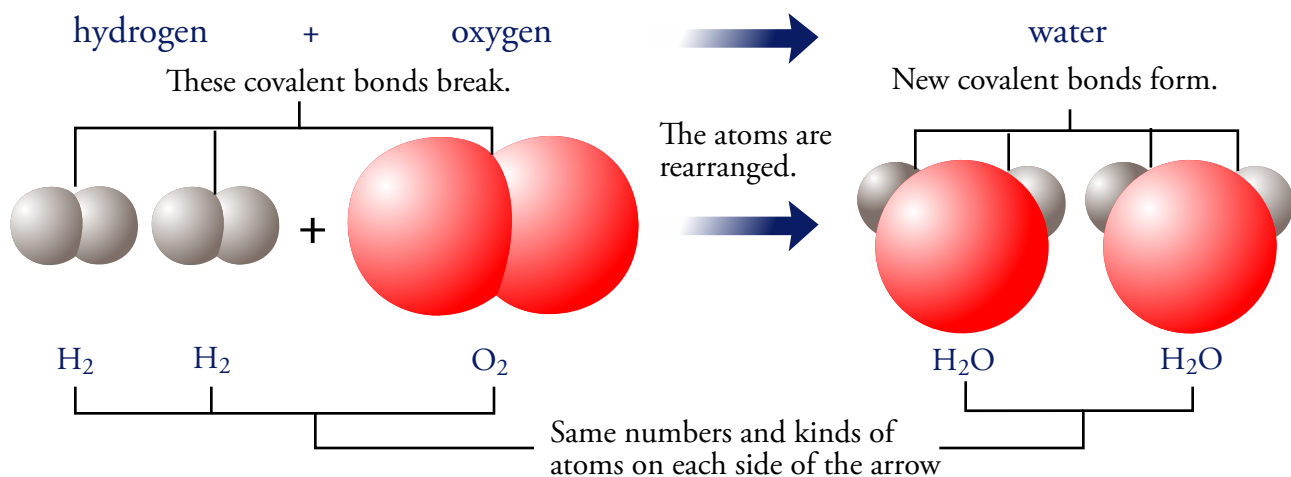
### Interpreting a Chemical Equation

Chemical changes lead to the formation of substances that help grow our food, make our lives more productive, and cure our heartburn.

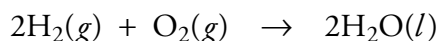
In chemical reactions, atoms are rearranged and regrouped through the breaking and making of chemical bonds. For example, when hydrogen gas,  $\text{H}_2(g)$ , is burned in the presence of gaseous oxygen,  $\text{O}_2(g)$ , a new substance, liquid water,  $\text{H}_2\text{O}(l)$ , forms. The covalent bonds within the  $\text{H}_2$  molecules and  $\text{O}_2$  molecules break, and new covalent bonds form between oxygen atoms and hydrogen atoms (Figure 5.1).

**Figure 5.1**

The Formation of Water from Hydrogen and Oxygen



A chemical equation is a shorthand description of a chemical reaction. The following equation describes the burning of hydrogen gas to form liquid water.

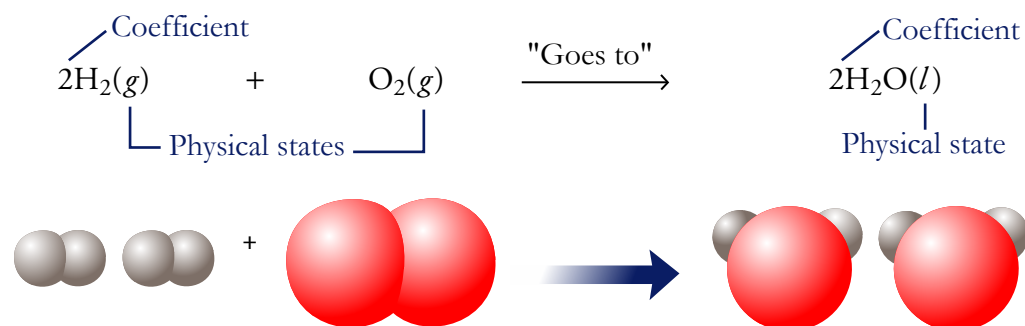


Chemical equations give the following information about chemical reactions.

OBJECTIVE 2

- Chemical equations show the formulas for the substances that take part in the reaction. The formulas on the left side of the arrow represent the **reactants**, the substances that change in the reaction. The formulas on the right side of the arrow represent the **products**, the substances that are formed in the reaction. If there are more than one reactant or more than one product, they are separated by plus signs. The arrow separating the reactants from the products can be read as “goes to” or “yields” or “produces.”
- The physical states of the reactants and products are provided in the equation. A  $(g)$  following a formula tells us the substance is a gas. Solids are described with  $(s)$ . Liquids are described with  $(l)$ . When a substance is dissolved in water, it is described with  $(aq)$  for *aqueous*, which means “mixed with water.”
- The relative numbers of particles of each reactant and product are indicated by numbers placed in front of the formulas. These numbers are called **coefficients**. An equation containing correct coefficients is called a balanced equation. For example, the 2's in front of  $\text{H}_2$  and  $\text{H}_2\text{O}$  in the equation we saw above are coefficients. If a formula in a balanced equation has no stated coefficient, its coefficient is understood to be 1, as is the case for oxygen in the equation above (Figure 5.2).

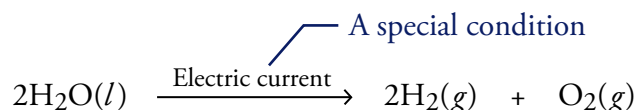
OBJECTIVE 3



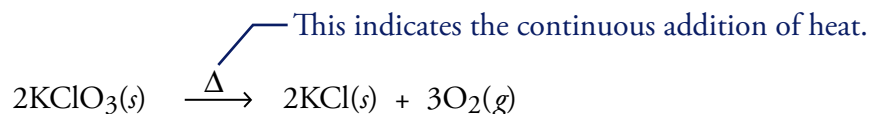
**Figure 5.2**  
The Chemical Equation for  
the Formation of Water from  
Hydrogen and Oxygen

- If special conditions are necessary for a reaction to take place, they are often specified above the arrow. Some examples of special conditions are electric current, high temperature, high pressure, and light.

The burning of hydrogen gas must be started with a small flame or a spark, but that is not considered a special condition. There is no need to indicate it above the arrow in the equation for the creation of water from hydrogen and oxygen. However, the conversion of water back to hydrogen and oxygen does require a special condition—specifically, exposure to an electric current:



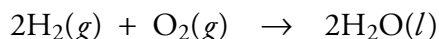
To indicate that a chemical reaction requires the *continuous* addition of heat in order to proceed, we place an upper case Greek delta,  $\Delta$ , above the arrow in the equation. For example, the conversion of potassium chlorate (a fertilizer and food additive) to potassium chloride and oxygen requires the continuous addition of heat:



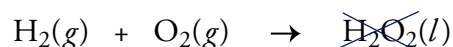
## Balancing Chemical Equations

In chemical reactions, atoms are neither created nor destroyed; they merely change partners. Thus the number of atoms of an element in the reaction's products is equal to the number of atoms of that element in the original reactants. The coefficients we often place in front of one or more of the formulas in a chemical equation reflect this fact. They are used whenever necessary to balance the number of atoms of a particular element on either side of the arrow.

For an example, let's return to the reaction of hydrogen gas and oxygen gas to form liquid water. The equation for the reaction between  $\text{H}_2(g)$  and  $\text{O}_2(g)$  to form  $\text{H}_2\text{O}(l)$  shows there are two atoms of oxygen in the diatomic  $\text{O}_2$  molecule to the left of the arrow, so there should also be two atoms of oxygen in the product to the right of the arrow. Because each water molecule,  $\text{H}_2\text{O}$ , contains only one oxygen atom, two water molecules must form for each oxygen molecule that reacts. The coefficient 2 in front of the  $\text{H}_2\text{O}(l)$  makes this clear. But two water molecules contain four hydrogen atoms, which means that two hydrogen molecules must be present on the reactant side of the equation for the numbers of H atoms to balance (Figure 5.2 on the previous page).



*Note that we do not change the subscripts in the formulas, because that would change the identities of the substances. For example, changing the formula on the right of the arrow in the equation above to  $\text{H}_2\text{O}_2$  would balance the atoms without using coefficients, but the resulting equation would be incorrect.*



Water is  $\text{H}_2\text{O}$ , whereas  $\text{H}_2\text{O}_2$  is hydrogen peroxide, a very different substance from water. (You add water to your hair to clean it; you add hydrogen peroxide to your hair to bleach it.)

The following sample study sheet shows a procedure that you can use to balance chemical equations. It is an approach that chemists often call balancing equations “by inspection.” Examples 5.1 through 5.5, which follow the study sheet, will help to clarify the process.

**TIP-OFF** You are asked to balance a chemical equation.

#### GENERAL STEPS

- Consider the first element listed in the first formula in the equation.  
If this element is mentioned in two or more formulas on the same side of the arrow, skip it until after the other elements are balanced. (*See Example 5.2.*)  
If this element is mentioned in one formula on each side of the arrow, balance it by placing coefficients in front of one or both of these formulas.
- Moving from left to right, repeat the process for each element.
- When you place a number in front of a formula that contains an element you tried to balance previously, recheck that element and put its atoms back in balance. (*See Examples 5.2 and 5.3.*)
- Continue this process until the number of atoms of each element is balanced.

The following strategies can be helpful for balancing certain equations.

**STRATEGY 1** Often, an element can be balanced by using the subscript for this element on the left side of the arrow as the coefficient in front of the formula containing this element on the right side of the arrow, and vice versa (using the subscript of this element on the right side of the arrow as the coefficient in front of the formula containing this element on the left side). (*See Example 5.3.*)

**STRATEGY 2** It is sometimes easiest, as a temporary measure, to balance the pure nonmetallic elements ( $\text{H}_2$ ,  $\text{O}_2$ ,  $\text{N}_2$ ,  $\text{F}_2$ ,  $\text{Cl}_2$ ,  $\text{Br}_2$ ,  $\text{I}_2$ ,  $\text{S}_8$ ,  $\text{Se}_8$ , and  $\text{P}_4$ ) with a fractional coefficient ( $\frac{1}{2}$ ,  $\frac{3}{2}$ ,  $\frac{5}{2}$ , etc.). If you do use a fraction during the balancing process, you can eliminate it later by multiplying each coefficient in the equation by the fraction's denominator (which is usually the number 2). (*See Example 5.4.*)

**STRATEGY 3** If polyatomic ions do not change in the reaction, and therefore appear in the same form on both sides of the chemical equation, they can be balanced as though they were single atoms. (*See Example 5.5.*)

**STRATEGY 4** If you find an element difficult to balance, leave it for later.

**EXAMPLE** See Examples 5.1 to 5.5.

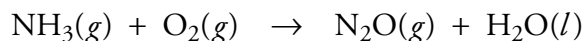
## Sample Study Sheet 5.1 Balancing Chemical Equations

OBJECTIVE 4

## EXAMPLE 5.1 - Balancing Equations

## OBJECTIVE 4

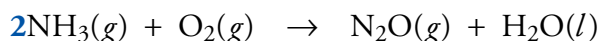
Balance the following equation so that it correctly describes the reaction for the formation of dinitrogen oxide (commonly called nitrous oxide), an anesthetic used in dentistry and surgery.

*Solution*

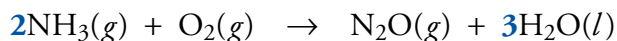
The following table shows that the atoms are not balanced yet.

Element	Left	Right
N	1	2
H	3	2
O	2	2

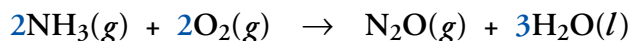
Nitrogen is the first element in the first formula. It is found in one formula on each side of the arrow, so we can try to balance it now. There are two nitrogen atoms on the right side of the equation and only one on the left; we bring them into balance by placing a 2 in front of  $\text{NH}_3$ .



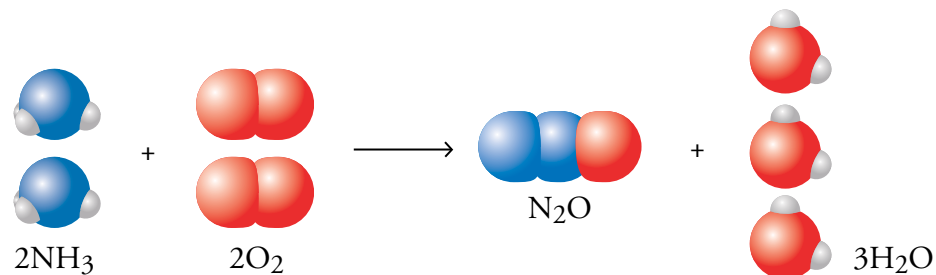
There are now six hydrogen atoms on the left side of the arrow (in the two  $\text{NH}_3$  molecules) and only two H's on the right, so we balance the hydrogen atoms by placing a 3 in front of the  $\text{H}_2\text{O}$ . This gives six atoms of hydrogen on each side.



There are now two oxygen atoms on the left and four on the right (in one  $\text{N}_2\text{O}$  and three  $\text{H}_2\text{O}$ 's), so we balance the oxygen atoms by placing a 2 in front of the  $\text{O}_2$ .



The following space-filling models show how you might visualize the relative number of particles participating in this reaction. You can see that the atoms regroup but are neither created nor destroyed.

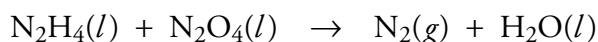


The following table shows that the atoms are now balanced.

Element	Left	Right
N	2	2
H	6	6
O	4	4

### EXAMPLE 5.2 - Balancing Equations

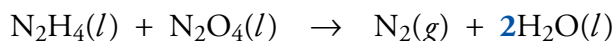
Balance the following equation.



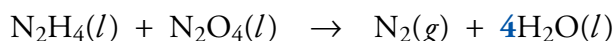
*Solution*

Nitrogen is the first element in the equation; however, because nitrogen is found in two formulas on the left side of the arrow, we will leave the balancing of the nitrogen atoms until later.

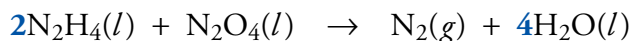
Balance the hydrogen atoms by placing a 2 in front of  $\text{H}_2\text{O}$ .



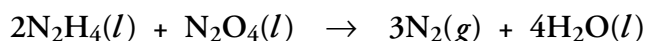
Balance the oxygen atoms by changing the 2 in front of  $\text{H}_2\text{O}$  to a 4.



Because we unbalanced the hydrogen atoms in the process of balancing the oxygen atoms, we need to go back and re-balance the hydrogen atoms by placing a 2 in front of the  $\text{N}_2\text{H}_4$ .



Finally, we balance the nitrogen atoms by placing a 3 in front of  $\text{N}_2$ .



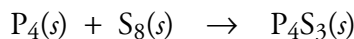
The following table shows that the atoms are now balanced.

Element	Left	Right
N	6	6
H	8	8
O	4	4

OBJECTIVE 4

### EXAMPLE 5.3 - Balancing Equations

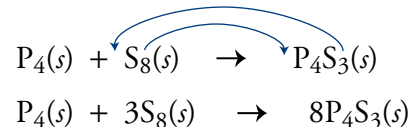
Balance the following equation so that it correctly describes the reaction for the formation of tetraphosphorus trisulfide (used in the manufacture of matches).



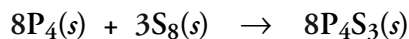
*Solution*

The phosphorus atoms appear to be balanced at this stage.

We can balance the sulfur atoms by using the subscript for the sulfur on the right (3) as the coefficient for  $\text{S}_8$  on the left and using the subscript for the sulfur on the left (8) as the coefficient for the sulfur compound on the right. (Strategy 1)



We restore the balance of the phosphorus atoms by placing an 8 in front of  $\text{P}_4$ .



OBJECTIVE 4

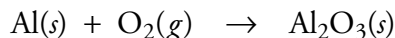


Tetraphosphorus trisulfide is used to make matches.

### EXAMPLE 5.4 - Balancing Equations

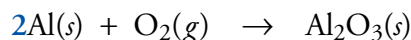
#### OBJECTIVE 4

Balance the following equation so that it correctly describes the reaction for the formation of aluminum oxide (used to manufacture glass).

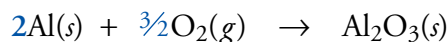


#### Solution

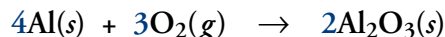
Balance the aluminum atoms by placing a 2 in front of the Al.



There are three oxygen atoms on the right and two on the left. We can bring them into balance by placing  $\frac{3}{2}$  in front of the  $\text{O}_2$ . Alternatively, we could place a 3 in front of the  $\text{O}_2$  and a 2 in front of the  $\text{Al}_2\text{O}_3$ , but that would un-balance the aluminum atoms. By inserting only one coefficient, in front of the  $\text{O}_2$ , to balance the oxygen atoms, the aluminum atoms remain balanced. We arrive at  $\frac{3}{2}$  by asking what number times the subscript 2 of the  $\text{O}_2$  would give us three atoms of oxygen on the left side:  $\frac{3}{2}$  times 2 is 3. (Strategy 2)



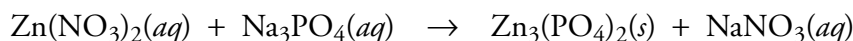
It is a good habit to eliminate the fraction by multiplying all the coefficients by the denominator of the fraction, in this case 2. (Some instructors consider fractional coefficients to be incorrect, so check with your instructor to find out if you will be allowed to leave them in your final answer.)



### EXAMPLE 5.5 - Balancing Equations

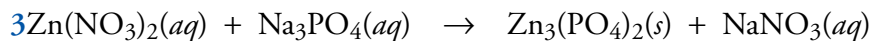
#### OBJECTIVE 4

Balance the following equation for the chemical reaction that forms zinc phosphate (used in dental cements and for making galvanized nails).

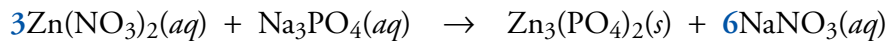


#### Solution

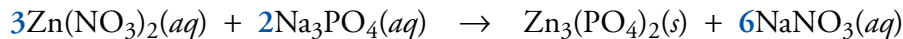
Balance the zinc atoms by placing a 3 in front of  $\text{Zn}(\text{NO}_3)_2$ .



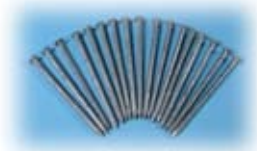
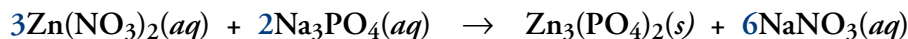
The nitrate ions,  $\text{NO}_3^-$ , emerge unchanged from the reaction, so we can balance them as though they were single atoms. There are six  $\text{NO}_3^-$  ions in three  $\text{Zn}(\text{NO}_3)_2$ . We therefore place a 6 in front of the  $\text{NaNO}_3$  to balance the nitrates. (Strategy 3)



Balance the sodium atoms by placing a 2 in front of the  $\text{Na}_3\text{PO}_4$ .



The phosphate ions,  $\text{PO}_4^{3-}$ , do not change in the reaction, so we can balance them as though they were single atoms. There are two on each side, so the phosphate ions are balanced. (Strategy 3)

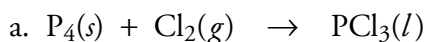


Zinc phosphate is used to galvanize nails.

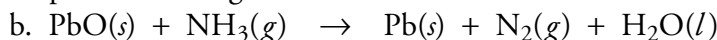


## EXERCISE 5.1 - Balancing Equations

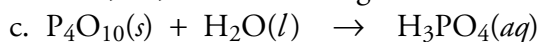
Balance the following chemical equations.



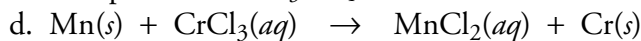
Phosphorus trichloride,  $\text{PCl}_3$ , is an intermediate for the production of pesticides and gasoline additives.



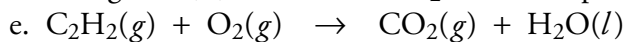
Lead, Pb, is used in storage batteries and as radiation shielding.



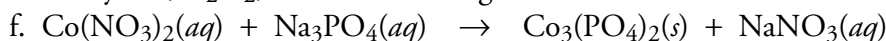
Phosphoric acid,  $\text{H}_3\text{PO}_4$ , is used to make fertilizers and detergents.



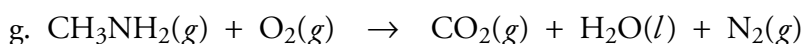
Manganese(II) chloride,  $\text{MnCl}_2$ , is used in pharmaceutical preparations.



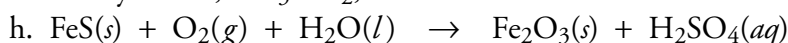
Acetylene,  $\text{C}_2\text{H}_2$ , is used in welding torches.



Cobalt phosphate,  $\text{Co}_3(\text{PO}_4)_2$ , is used to color glass and as an additive to animal feed.



Methylamine,  $\text{CH}_3\text{NH}_2$ , is a fuel additive.



Iron(III) oxide,  $\text{Fe}_2\text{O}_3$ , is a paint pigment.

### OBJECTIVE 4



You can find a computer tutorial that will provide more practice balancing equations at the textbook's Web site.

## 5.2 Solubility of Ionic Compounds and Precipitation Reactions

The reaction that forms the scale in hot water pipes, eventually leading to major plumbing bills, belongs to a category of reactions called precipitation reactions. So does the reaction of calcium and magnesium ions with soap to create a solid scum in your bathtub and washing machine. Cadmium hydroxide, which is used in rechargeable batteries, is made from the precipitation reaction between water solutions of cadmium acetate and sodium hydroxide. To understand the changes that occur in precipitation reactions, to predict when they will take place, and to describe them correctly using chemical equations, we first need a way of visualizing the behavior of ionic compounds in water.

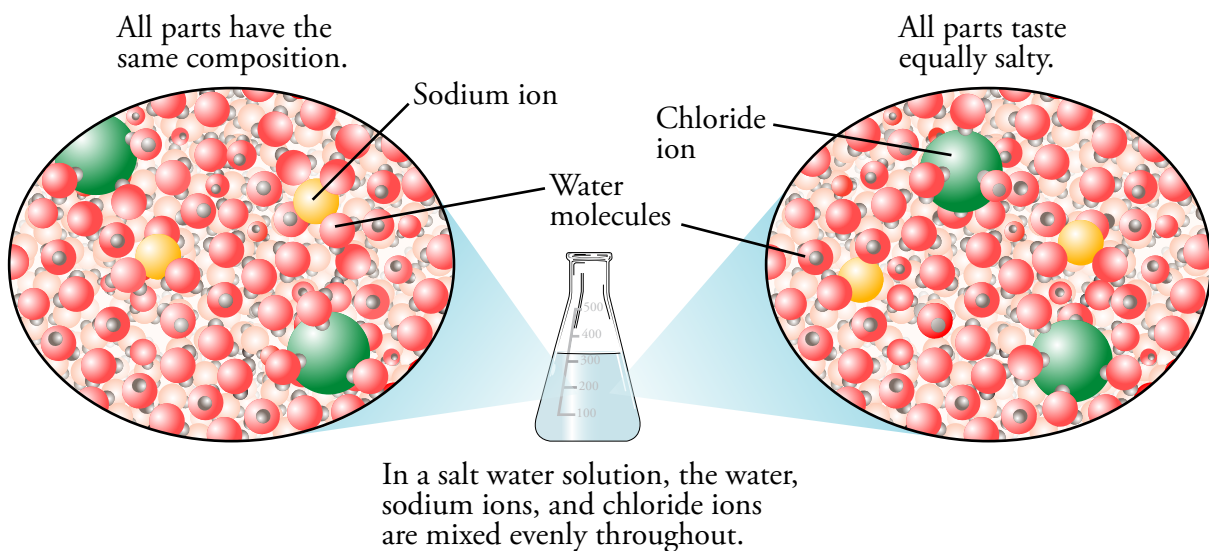
### Water Solutions of Ionic Compounds

A **solution**, also called a homogeneous mixture, is a mixture whose particles are so evenly distributed that the relative concentrations of the components are the same throughout. When salt dissolves in water, for example, the sodium and chloride ions from the salt spread out evenly throughout the water. Eventually, every part of the solution has the same proportions of water molecules and ions as every other part (Figure 5.3). Ionic compounds are often able to mix with water in this way, in which



An aqueous solution forms when dye is added to water (left). Soon the mixture will be homogeneous (right).

case we say they are “soluble in water.” Many of the chemical reactions we will study take place in water solutions—that is, solutions in which the substances are dissolved in water. Chemists refer to these as **aqueous solutions**.



**Figure 5.3**  
Solution (Homogeneous Mixture)

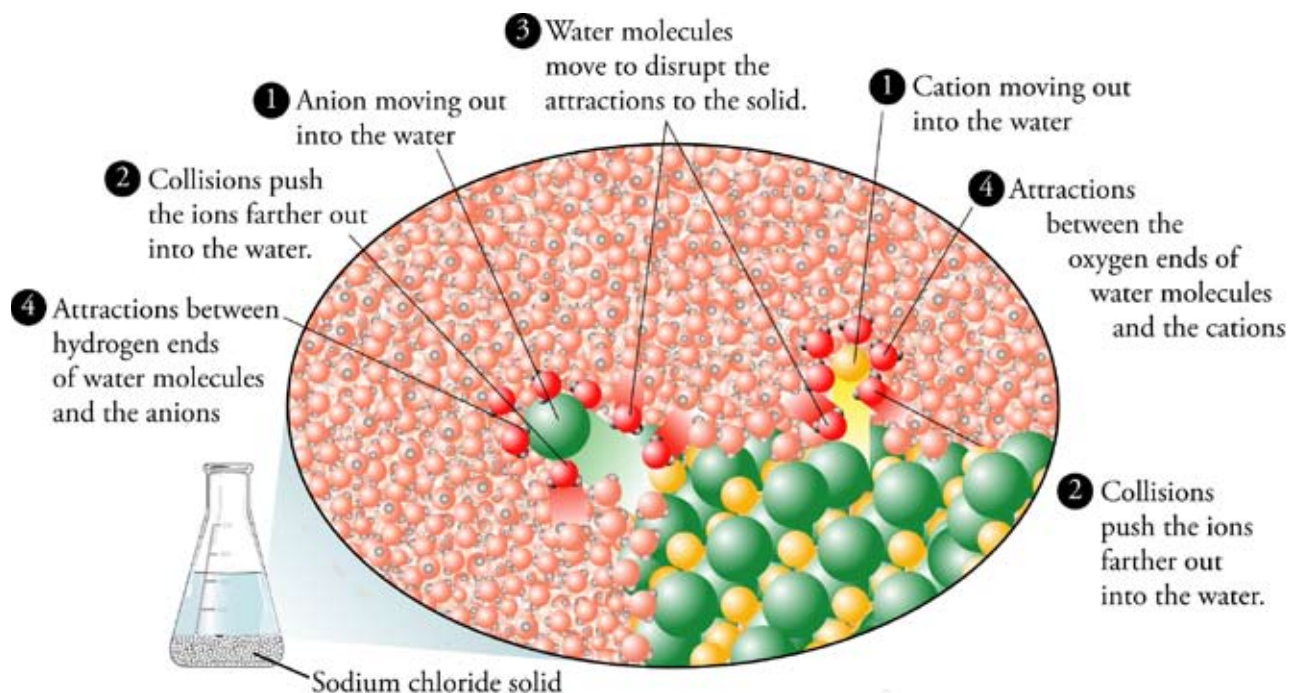
Remember how a model made it easier for us to picture the structures of solids, liquids, and gases in Chapter 3? In order to develop a mental image of the changes that take place on the microscopic level as an ionic compound dissolves in water, chemists have found it helpful to extend that model. We will use table salt or sodium chloride,  $\text{NaCl}$ , as an example in our description of the process through which an ionic compound dissolves in water. Before you read about this process, you might want to return to the end of Section 4.3 and review the description of the structure of liquid water.

**OBJECTIVE 5**

When solid  $\text{NaCl}$  is first added to water, it settles to the bottom of the container. Like the particles of any solid, the sodium and chloride ions at the solid's surface are constantly moving, although their mutual attractions are holding them more or less in place. For example, if you were riding on a sodium ion at the surface of the solid, you might move out and away from the surface and into the water at one instant, and back toward the surface at the next (pulled by the attractions between your sodium ion and the chloride ions near it). When you move back toward the surface, collisions there might push you away from the surface once again. In this way, all of the ions at the solid's surface, both sodium ions and chloride ions, can be viewed as repeatedly moving out into the water and returning to the solid's surface (Figure 5.4).

**OBJECTIVE 5**

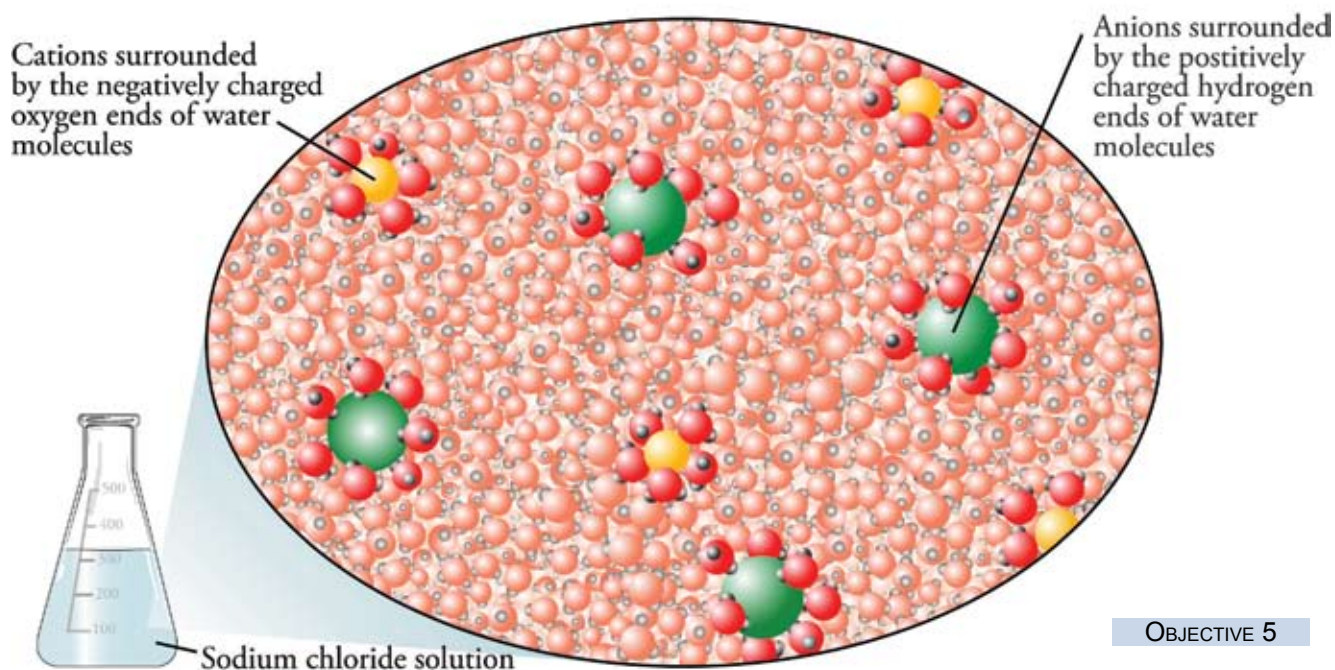
Sometimes when an ion moves out into the water, a water molecule collides with it, pushing the ion out farther into the liquid and helping to break the ionic bond. Other water molecules move into the space between the ion and the solid and shield the ion from the attractions exerted by the ions at the solid's surface (Figure 5.4). The ions that escape the solid are then held in solution by attractions between their own charge and the partial charges of the polar water molecules. The negative oxygen ends of the water molecules surround the cations, and the positive hydrogen ends surround the anions (Figure 5.5).



OBJECTIVE 5

**Figure 5.4**

**Sodium Chloride Dissolving in Water** This shows the mixture immediately after sodium chloride has been added to water. Certain water molecules are highlighted to draw attention to their role in the process.



OBJECTIVE 5

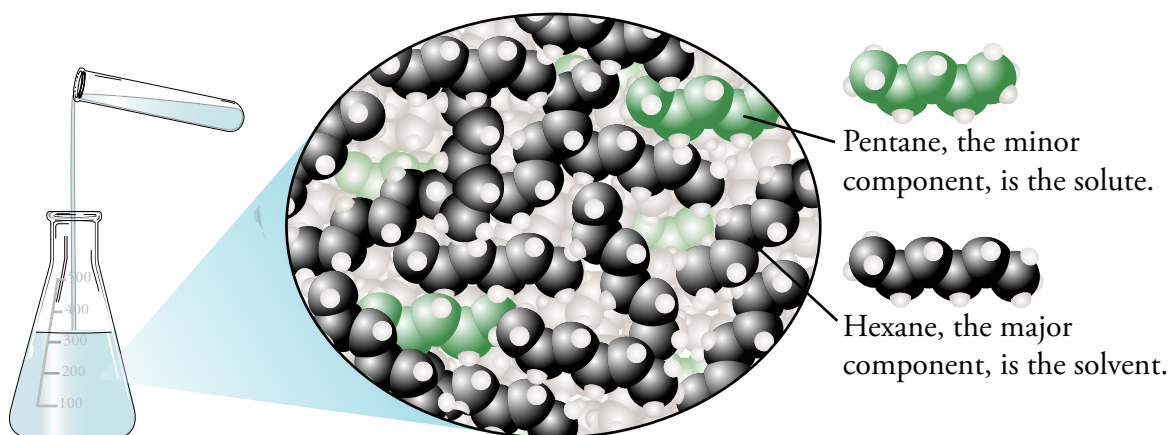
**Figure 5.5**

**Aqueous Sodium Chloride** This image shows a portion of the solution that forms when sodium chloride dissolves in water. Certain water molecules are highlighted to draw attention to their role in the process.

You can find an animation that illustrates the process by which sodium chloride dissolves at the textbook's Web site.

## OBJECTIVE 6

The substances that mix to make a solution, such as our solution of sodium chloride and water, are called the **solute** and the **solvent**. In solutions of solids dissolved in liquids, we call the solid the **solute** and the liquid the **solvent**. Therefore, the NaCl in an aqueous sodium chloride solution is the solute, and the water is the solvent. In solutions of gases in liquids, we call the gas the **solute** and the liquid the **solvent**. Therefore, when gaseous hydrogen chloride,  $\text{HCl}(g)$ , is dissolved in liquid water to form a mixture known as hydrochloric acid,  $\text{HCl}(aq)$ , the hydrogen chloride is the solute, and water is the solvent. In other solutions, we call the minor component the **solute** and the major component the **solvent**. For example, in a mixture that is 5% liquid pentane,  $\text{C}_5\text{H}_{12}$ , and 95% liquid hexane,  $\text{C}_6\text{H}_{14}$ , the pentane is the solute, and the hexane is the solvent (Figure 5.6).



**Figure 5.6**

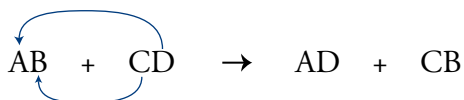
**Liquid-Liquid Solution** The carbon atoms in the pentane molecules are shown in green to distinguish them from the hexane molecule.

## OBJECTIVE 6

## Precipitation Reactions

Precipitation reactions, such as the ones we will see in this section, belong to a general class of reactions called **double-displacement reactions**. (Double displacement reactions are also called **double-replacement**, **double-exchange**, or **metathesis reactions**.) Double displacement reactions have the following form, signifying that the elements in two reacting compounds change partners.

## OBJECTIVE 7



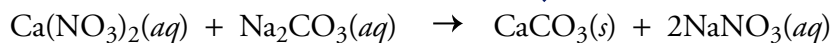
Precipitation reactions take place between ionic compounds in solution. For example, in the precipitation reactions that we will see, A and C represent the cationic

(or positively charged) portions of the reactants and products, and B and D represent the anionic (or negatively charged) portions of the reactants and products. The cation of the first reactant (A) combines with the anion of the second reactant (D) to form the product AD, and the cation of the second reactant (C) combines with the anion of the first reactant to form the product CB.

Sometimes a double-displacement reaction has one product that is insoluble in water. As that product forms, it emerges, or precipitates, from the solution as a solid. This process is called **precipitation**, such a reaction is called a **precipitation reaction**, and the solid is called the **precipitate**. For example, when water solutions of calcium nitrate and sodium carbonate are mixed, calcium carbonate precipitates from the solution while the other product, sodium nitrate, remains dissolved.

## OBJECTIVE 8

This solid precipitates from the solution. It is a precipitate.



One of the goals of this section is to help you to visualize the process described by this equation. Figures 5.7, 5.8, and 5.9 will help you do this.

First, let us imagine the particles making up the  $\text{Ca}(\text{NO}_3)_2$  solution. Remember that when ionic compounds dissolve, the ions separate and become surrounded by water molecules. When  $\text{Ca}(\text{NO}_3)_2$  dissolves in water (Figure 5.7), the  $\text{Ca}^{2+}$  ions separate from the  $\text{NO}_3^-$  ions, with the oxygen ends of water molecules surrounding the calcium ions, and the hydrogen ends of water molecules surrounding the nitrate ions.

## OBJECTIVE 8

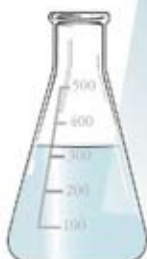
**Figure 5.7**  
**Aqueous Calcium Nitrate**

There are twice as many -1 nitrate ions as +2 calcium ions.

When calcium nitrate,  $\text{Ca}(\text{NO}_3)_2$ , dissolves in water, the calcium ions,  $\text{Ca}^{2+}$ , become separated from the nitrate ions,  $\text{NO}_3^-$ .

Calcium cations,  $\text{Ca}^{2+}$ , surrounded by the oxygen ends of water molecules

Nitrate anions,  $\text{NO}_3^-$ , surrounded by the hydrogen ends of water molecules



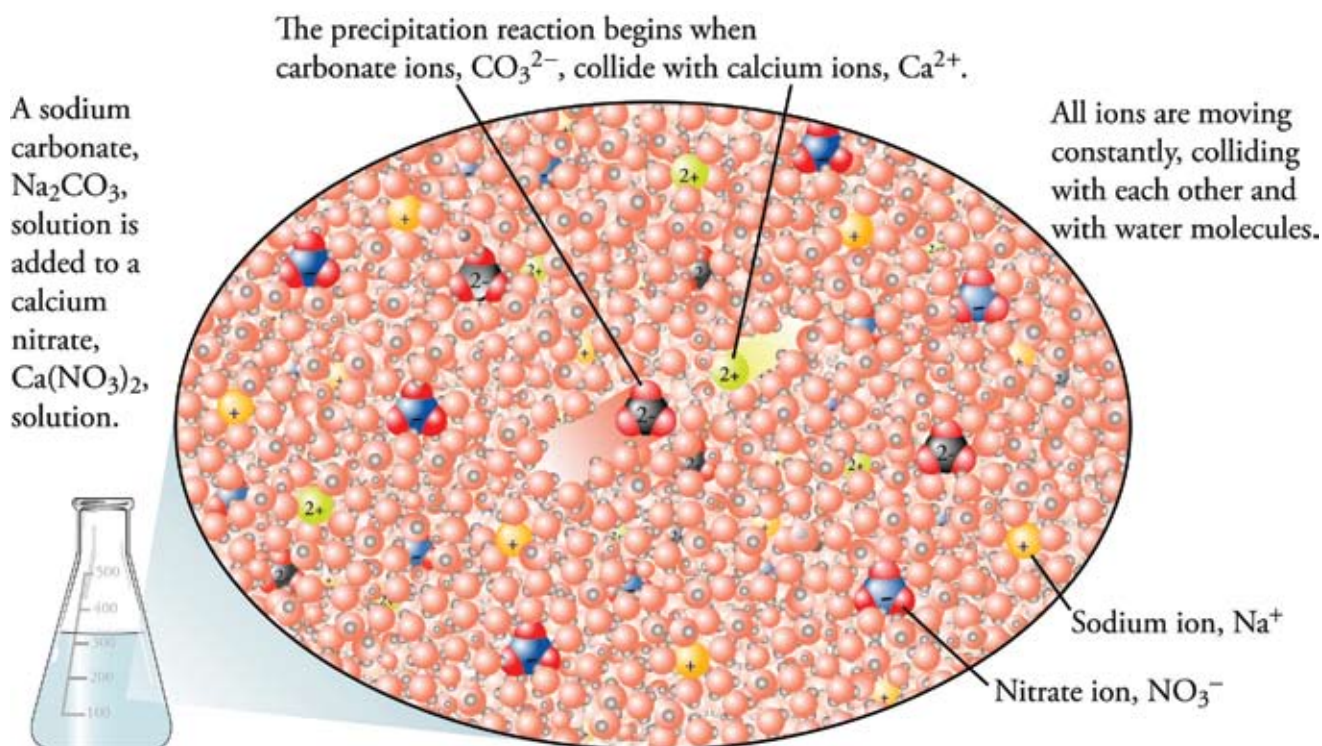
## OBJECTIVE 8

An aqueous solution of sodium carbonate also consists of ions separated and surrounded by water molecules, much like the solution of calcium nitrate. If time were to stop at the instant that the solution of sodium carbonate was added to aqueous calcium nitrate, there would be four different ions in solution surrounded by water molecules:  $\text{Ca}^{2+}$ ,  $\text{NO}_3^-$ ,  $\text{Na}^+$ , and  $\text{CO}_3^{2-}$ . The oxygen ends of the water molecules surround the calcium and sodium ions, and the hydrogen ends of water molecules surround the nitrate and carbonate ions. Figure 5.8 shows the system at the instant just after solutions of calcium nitrate and sodium carbonate are combined and just before the precipitation reaction takes place. Because a chemical reaction takes place as soon as the  $\text{Ca}(\text{NO}_3)_2$  and  $\text{Na}_2\text{CO}_3$  solutions are combined, the four-ion system shown in this figure lasts for a very short time.

Figure 5.8

Mixture of  $\text{Ca}(\text{NO}_3)_2(\text{aq})$  and  $\text{Na}_2\text{CO}_3(\text{aq})$  at the Instant They Are Combined

## OBJECTIVE 8

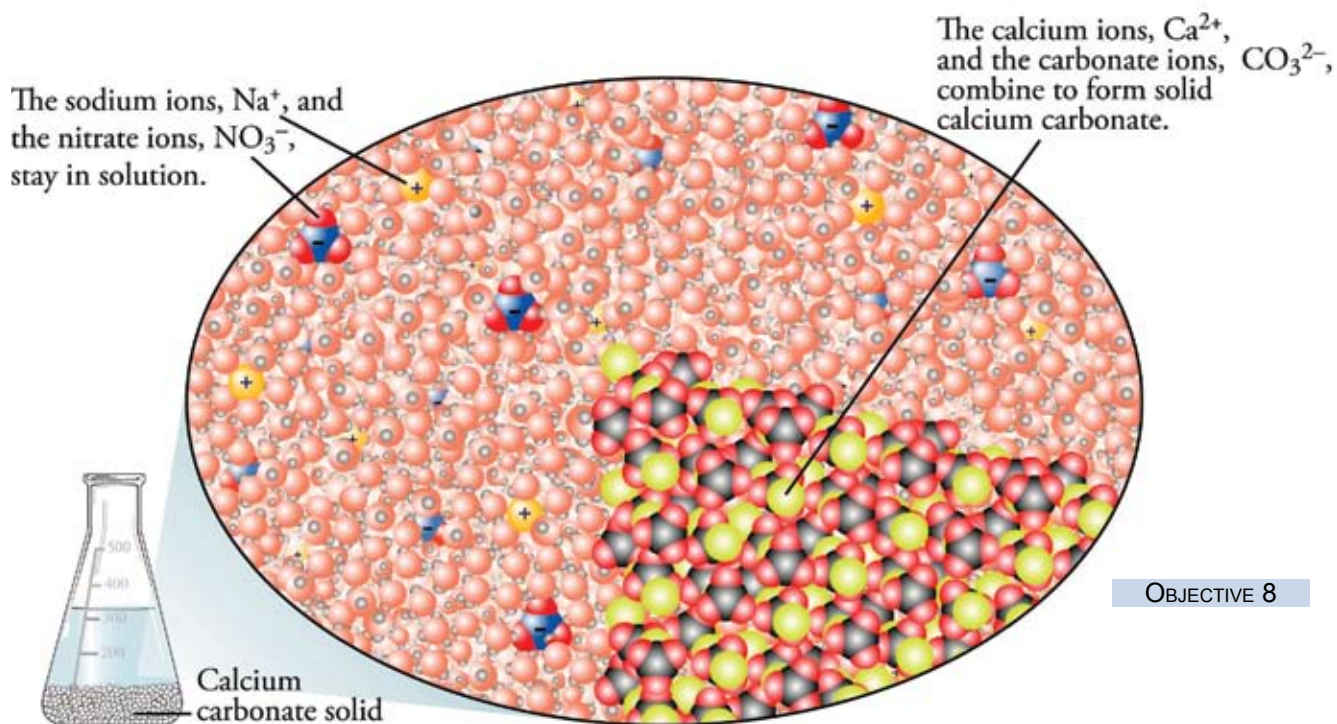


## OBJECTIVE 8

The ions in solution move in a random way, like any particle in a liquid, so they will constantly collide with other ions. When two cations or two anions collide, they repel each other and move apart. When a calcium ion and a nitrate ion collide, they may stay together for a short time, but the attraction between them is too weak to keep them together when water molecules collide with them and push them apart. The same is true for the collision between sodium ions and carbonate ions. After colliding, they stay together for only an instant before water molecules break them apart again.

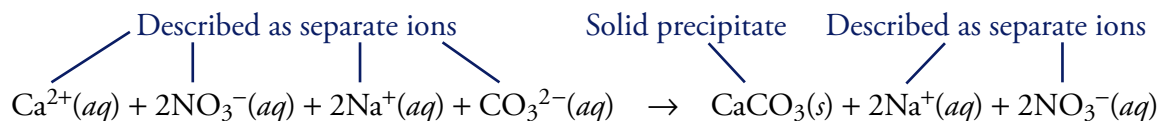
When calcium ions and carbonate ions collide, however, they stay together longer because the attraction between them is stronger than the attractions between the other pairs of ions. They might eventually be knocked apart, but while they are together,

other calcium ions and carbonate ions can collide with them. When another  $\text{Ca}^{2+}$  or  $\text{CO}_3^{2-}$  ion collides with a  $\text{CaCO}_3$  pair, a trio forms. Other ions collide with the trio to form clusters of ions that then grow to become small **crystals**—solid particles whose component atoms, ions, or molecules are arranged in an organized, repeating pattern. Many crystals form throughout the system, so the solid  $\text{CaCO}_3$  at first appears as a cloudiness in the mixture. The crystals eventually settle to the bottom of the container (Figures 5.8 and 5.9).



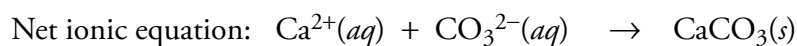
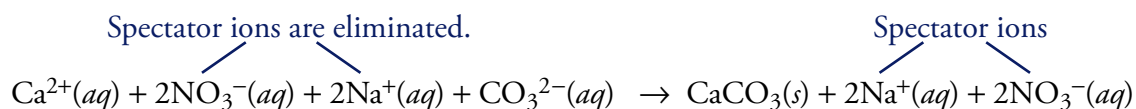
**Figure 5.9**  
Product Mixture for the  
Reaction of  $\text{Ca}(\text{NO}_3)_2(aq)$   
and  $\text{Na}_2\text{CO}_3(aq)$

The equation that follows, which is often called a **complete ionic equation**, describes the forms taken by the various substances in solution. The ionic compounds dissolved in the water are described as separate ions, and the insoluble ionic compound is described with a complete formula.

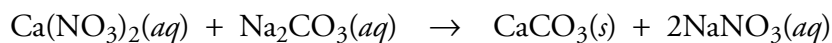


The sodium and nitrate ions remain unchanged in this reaction. They were separate and surrounded by water molecules at the beginning, and they are still separate and surrounded by water molecules at the end. They were important in delivering the calcium and carbonate ions to solution (the solutions were created by dissolving solid calcium nitrate and solid sodium carbonate in water), but they did not actively participate in the reaction. When ions play this role in a reaction, we call them **spectator ions**.

Because spectator ions are not involved in the reaction, they are often left out of the chemical equation. The equation written without the spectator ions is called a **net ionic equation**.



We call the equation that shows the complete formulas for all of the reactants and products the **complete equation**, or, sometimes, the **molecular equation**.



You can find an animation that shows this precipitation reaction at the textbook's Web site.

## Predicting Water Solubility

In order to predict whether a precipitation reaction will take place when two aqueous ionic compounds are mixed, you need to be able to predict whether the possible products of the double-displacement reaction are soluble or insoluble in water.

When we say that one substance is soluble in another, we mean that they can be mixed to a significant degree. More specifically, chemists describe the **solubility** of a substance as the maximum amount of it that can be dissolved in a given amount of solvent at a particular temperature. This property is often described in terms of the maximum number of grams of solute that will dissolve in 100 milliliters (or 100 grams) of solvent. For example, the water solubility of calcium nitrate is 121.2 g  $\text{Ca}(\text{NO}_3)_2$  per 100 mL water at 25 °C. This means that when calcium nitrate is added steadily to 100 mL of water at 25 °C, it will dissolve until 121.2 g  $\text{Ca}(\text{NO}_3)_2$  have been added. If more  $\text{Ca}(\text{NO}_3)_2$  is added to the solution, it will remain in the solid form.

When we say an ionic solid is insoluble in water, we do not mean that none of the solid dissolves. There are always some ions that can escape from the surface of an ionic solid in water and go into solution. Thus, when we say that calcium carbonate is insoluble in water, what we really mean is that the solubility is very low (0.0014 g  $\text{CaCO}_3$  per 100 mL  $\text{H}_2\text{O}$  at 25 °C).



Solubility is difficult to predict with confidence. The most reliable way to obtain a substance's solubility is to look it up on a table of physical properties in a reference book. When that is not possible, you can use the following guidelines for predicting whether some substances are soluble or insoluble in water. They are summarized in Table 5.1.

## OBJECTIVE 9

- Ionic compounds with group 1 (or 1A) metallic cations or ammonium cations,  $\text{NH}_4^+$ , form soluble compounds no matter what the anion is.
- Ionic compounds with acetate,  $\text{C}_2\text{H}_3\text{O}_2^-$ , or nitrate,  $\text{NO}_3^-$ , ions form soluble compounds no matter what the cation is.
- Compounds containing chloride,  $\text{Cl}^-$ , bromide,  $\text{Br}^-$ , or iodide,  $\text{I}^-$ , ions are water-soluble except with silver ions,  $\text{Ag}^+$  and lead(II) ions,  $\text{Pb}^{2+}$ .
- Compounds containing the sulfate ion,  $\text{SO}_4^{2-}$ , are water-soluble except with barium ions,  $\text{Ba}^{2+}$ , and lead(II) ions,  $\text{Pb}^{2+}$ .
- Compounds containing carbonate,  $\text{CO}_3^{2-}$ , phosphate,  $\text{PO}_4^{3-}$ , or hydroxide,  $\text{OH}^-$ , ions are insoluble in water except with group 1 metallic ions and ammonium ions.

**Table 5.1** Water Solubility of Ionic Compounds

## OBJECTIVE 9

Category	Ions	Except with these ions	Examples
Soluble cations	Group 1 metallic ions and ammonium, $\text{NH}_4^+$	No exceptions	$\text{Na}_2\text{CO}_3$ , $\text{LiOH}$ , and $(\text{NH}_4)_2\text{S}$ are soluble.
Soluble anions	$\text{NO}_3^-$ and $\text{C}_2\text{H}_3\text{O}_2^-$	No exceptions	$\text{Bi}(\text{NO}_3)_3$ , and $\text{Co}(\text{C}_2\text{H}_3\text{O}_2)_2$ are soluble.
Usually soluble anions	$\text{Cl}^-$ , $\text{Br}^-$ , and $\text{I}^-$	Soluble with some exceptions, including with $\text{Ag}^+$ and $\text{Pb}^{2+}$	$\text{CuCl}_2$ is water soluble, but $\text{AgCl}$ is insoluble.
	$\text{SO}_4^{2-}$	Soluble with some exceptions, including with $\text{Ba}^{2+}$ and $\text{Pb}^{2+}$	$\text{FeSO}_4$ is water soluble, but $\text{BaSO}_4$ is insoluble.
Usually insoluble	$\text{CO}_3^{2-}$ , $\text{PO}_4^{3-}$ , and $\text{OH}^-$	Insoluble with some exceptions, including with group 1 elements and $\text{NH}_4^+$	$\text{CaCO}_3$ , $\text{Ca}_3(\text{PO}_4)_2$ , and $\text{Mn}(\text{OH})_2$ are insoluble in water, but $(\text{NH}_4)_2\text{CO}_3$ , $\text{Li}_3\text{PO}_4$ , and $\text{CsOH}$ are soluble.

### EXERCISE 5.2 - Predicting Water Solubility

## OBJECTIVE 9

Predict whether each of the following is soluble or insoluble in water.

- a.  $\text{Hg}(\text{NO}_3)_2$  (used to manufacture felt)
- b.  $\text{BaCO}_3$  (used to make radiation resistant glass for color TV tubes)
- c.  $\text{K}_3\text{PO}_4$  (used to make liquid soaps)
- d.  $\text{PbCl}_2$  (used to make other lead salts)
- e.  $\text{Cd}(\text{OH})_2$  (in storage batteries)



Sodium phosphate (or trisodium phosphate),  $\text{Na}_3\text{PO}_4$ , is an all-purpose cleaner.

You can find a computer tutorial that will provide more practice predicting water solubility at the textbook's Web site.

## Sample Study Sheet 5.2

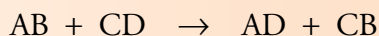
### Predicting Precipitation Reactions and Writing Precipitation Equations

#### OBJECTIVE 10

**TIP-OFF** You are asked to predict whether a precipitation reaction will take place between two aqueous solutions of ionic compounds, and if the answer is yes, to write the complete equation for the reaction.

#### GENERAL STEPS

**Step 1** Determine the formulas for the possible products using the general double-displacement equation. (Remember to consider ion charges when writing your formulas.)



**Step 2** Predict whether either of the possible products is water-insoluble. If either possible product is insoluble, a precipitation reaction takes place, and you may continue with step 3. If neither is insoluble, write “No reaction.”

**Step 3** Follow these steps to write the complete equation.

- Write the formulas for the reactants separated by a + sign.
- Separate the formulas for the reactants and products with an arrow.
- Write the formulas for the products separated by a + sign.
- Write the physical state for each formula.
  - The insoluble product will be followed by (s).
  - Water-soluble ionic compounds will be followed by (aq).
- Balance the equation.

**EXAMPLES** See Examples 5.6-5.8.

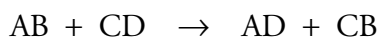
### EXAMPLE 5.6 - Predicting Precipitation Reactions

#### OBJECTIVE 10

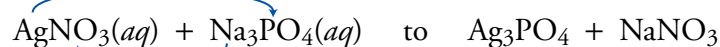
Predict whether a precipitate will form when water solutions of silver nitrate,  $\text{AgNO}_3(aq)$ , and sodium phosphate,  $\text{Na}_3\text{PO}_4(aq)$ , are mixed. If there is a precipitation reaction, write the complete equation that describes the reaction.

*Solution*

**Step 1** Determine the possible products using the general double-displacement equation.



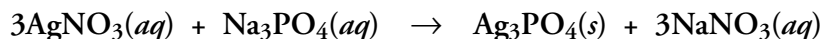
In  $\text{AgNO}_3$ ,  $\text{Ag}^+$  is A, and  $\text{NO}_3^-$  is B. In  $\text{Na}_3\text{PO}_4$ ,  $\text{Na}^+$  is C, and  $\text{PO}_4^{3-}$  is D. The possible products from the mixture of  $\text{AgNO}_3(aq)$  and  $\text{Na}_3\text{PO}_4(aq)$  are  $\text{Ag}_3\text{PO}_4$  and  $\text{NaNO}_3$ . (Remember to consider charge when you determine the formulas for the possible products.)



**Step 2** Predict whether either of the possible products is water-insoluble.

According to our solubility guidelines, most phosphates are insoluble, and compounds with  $\text{Ag}^+$  are not listed as an exception. Therefore, silver phosphate,  $\text{Ag}_3\text{PO}_4$ , which is used in photographic emulsions, would be insoluble. Because compounds containing  $\text{Na}^+$  and  $\text{NO}_3^-$  are soluble,  $\text{NaNO}_3$  is soluble.

**Step 3** Write the complete equation. (Don't forget to balance it.)



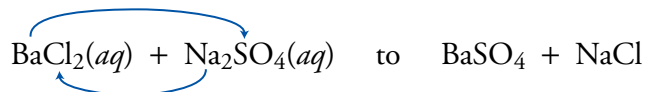
**EXAMPLE 5.7 - Predicting Precipitation Reactions**

OBJECTIVE 10

Predict whether a precipitate will form when water solutions of barium chloride,  $\text{BaCl}_2(aq)$ , and sodium sulfate,  $\text{Na}_2\text{SO}_4(aq)$ , are mixed. If there is a precipitation reaction, write the complete equation that describes the reaction.

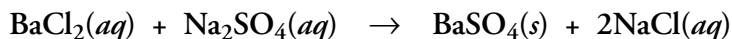
*Solution*

**Step 1** In  $\text{BaCl}_2$ , A is  $\text{Ba}^{2+}$ , and B is  $\text{Cl}^-$ . In  $\text{Na}_2\text{SO}_4$ , C is  $\text{Na}^+$ , and D is  $\text{SO}_4^{2-}$ . The possible products from the reaction of  $\text{BaCl}_2(aq)$  and  $\text{Na}_2\text{SO}_4(aq)$  are  $\text{BaSO}_4$  and  $\text{NaCl}$ .



**Step 2** According to our solubility guidelines, most sulfates are soluble, but  $\text{BaSO}_4$  is an exception. It is insoluble and would precipitate from the mixture. Because compounds containing  $\text{Na}^+$  (and most containing  $\text{Cl}^-$ ) are soluble,  $\text{NaCl}$  is soluble.

**Step 3**



This is the reaction used in industry to form barium sulfate, which is used in paint preparations and in x-ray photography.

You can find a description of the procedure for writing complete ionic equations and net ionic equations for Examples 5.6 and 5.7 at the textbook's Web site.

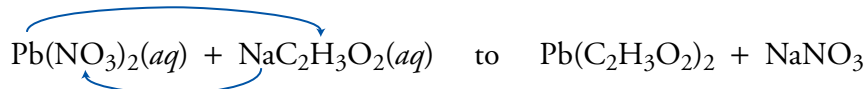
**EXAMPLE 5.8 - Predicting Precipitation Reactions**

OBJECTIVE 10

Predict whether a precipitate will form when lead(II) nitrate,  $\text{Pb}(\text{NO}_3)_2(aq)$ , and sodium acetate,  $\text{NaC}_2\text{H}_3\text{O}_2(aq)$ , are mixed. If there is a precipitation reaction, write the complete equation that describes the reaction.

*Solution*

**Step 1** The possible products from the mixture of  $\text{Pb}(\text{NO}_3)_2(aq)$  and  $\text{NaC}_2\text{H}_3\text{O}_2(aq)$  are  $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2$  and  $\text{NaNO}_3$ .

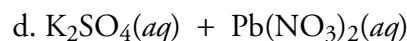
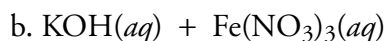
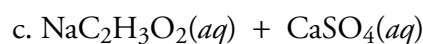
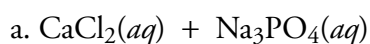


**Step 2** According to our solubility guidelines, compounds with nitrates and acetates are soluble, so both  $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2$  and  $\text{NaNO}_3$  are soluble. **There is no precipitation reaction.**

**EXERCISE 5.3 - Precipitation Reactions**

OBJECTIVE 10

Predict whether a precipitate will form when each of the following pairs of water solutions is mixed. If there is a precipitation reaction, write the complete equation that describes the reaction.



## Having Trouble?

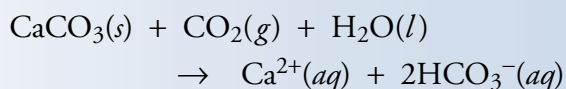
Are you having trouble with the topics in this chapter? People often do. To complete each of the lessons in it successfully, you need to have mastered the skills taught in previous sections. Here is a list of the things you need to know how to do to solve the problems at the end of this chapter. Work through these items in the order presented, and be sure you have mastered each before going on to the next.

- Convert between names and symbols for the common elements. See Table 3.1.
- Identify whether an element is a metal or a nonmetal. See Section 3.3.
- Determine the charges on many of the monatomic ions. See Figure 4.17.
- Convert between the names and formulas for polyatomic ions. See Table 4.6.
- Convert between the names and formulas for ionic compounds. See Section 4.5.
- Balance chemical equations. See Section 5.1.
- Predict the products of double-displacement reactions. See Section 5.2.
- Predict whether ionic compounds are soluble or insoluble in water. See Section 5.2.

## SPECIAL TOPIC 4.1 Hard Water and Your Hot Water Pipes

A precipitation reaction that is a slight variation on the one depicted in Figures 4.8 and 4.9 helps explain why a solid scale forms more rapidly in your hot water pipes than in your cold water pipes.

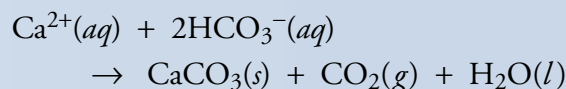
We say water is hard if it contains calcium ions, magnesium ions, and in many cases, iron ions. These ions come from rocks in the ground and dissolve into the water that passes through them. For example, limestone rock is calcium carbonate,  $\text{CaCO}_3(s)$ , and dolomite rock is a combination of calcium carbonate and magnesium carbonate, written as  $\text{CaCO}_3 \cdot \text{MgCO}_3(s)$ . Water alone will dissolve very small amounts of these minerals, but carbon dioxide dissolved in water speeds the process.



If the water were removed from the product mixture, calcium hydrogen carbonate,

$\text{Ca}(\text{HCO}_3)_2$ , would form, but this compound is much more soluble than calcium carbonate and does not precipitate from our tap water.

When hard water is heated, the reverse of this reaction occurs, and the calcium and hydrogen carbonate ions react to reform solid calcium carbonate.



Thus, in your hot water pipes, solid calcium carbonate precipitates from solution and collects as scale on the inside of the pipes. After we have discussed acid-base reactions in Chapter 5, it will be possible to explain how the plumber can remove this obstruction.



**Chemical reaction or chemical change** The conversion of one or more pure substances into one or more different pure substances.

**Reactants** The substances that change in a chemical reaction. Their formulas are on the left side of the arrow in a chemical equation.

**Products** The substances that form in a chemical reaction. Their formulas are on the right side of the arrow in a chemical equation.

**Coefficients** The numbers in front of chemical formulas in a balanced chemical equation.

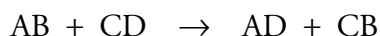
**Solution** A mixture whose particles are so evenly distributed that the relative concentrations of the components are the same throughout. Solutions can also be called homogeneous mixtures.

**Aqueous solution** A solution in which water is the solvent.

**Solute** The gas in a solution of a gas in a liquid. The solid in a solution of a solid in a liquid. The minor component in other solutions.

**Solvent** The liquid in a solution of a gas in a liquid. The liquid in a solution of a solid in a liquid. The major component in other solutions.

**Double-displacement reaction** A chemical reaction that has the following form:



**Precipitation reaction** A reaction in which one of the products is insoluble in water and comes out of solution as a solid.

**Precipitate** A solid that comes out of solution.

**Precipitation** The process of forming a solid in a solution.

**Crystals** Solid particles whose component atoms, ions, or molecules are arranged in an organized, repeating pattern.

**Complete ionic equation** A chemical equation that describes the actual form for each substance in solution. For example, ionic compounds that are dissolved in water are described as separate ions.

**Spectator ions** Ions that play a role in delivering other ions into solution to react but that do not actively participate in the reaction themselves.

**Complete equation or molecular equation** A chemical equation that includes uncharged formulas for all of the reactants and products. The formulas include the spectator ions, if any.

**Net ionic equation** A chemical equation for which the spectator ions have been eliminated, leaving only the substances actively involved in the reaction.

**Solubility** The maximum amount of solute that can be dissolved in a given amount of solvent.

## Chapter Objectives

**The goal of this chapter is to teach you to do the following.**

1. Define all of the terms in the Chapter Glossary.

### Section 5.1 Chemical Reactions and Chemical Equations

2. Describe the information given by a chemical equation.
3. Write the symbols used in chemical equations to describe solid, liquid, gas, and aqueous.
4. Balance chemical equations.

### Section 5.2 Ionic Solubility and Precipitation Reactions

5. Describe the process for dissolving an ionic compound in water. Your description should include mention of the nature of the particles in solution and the attractions between the particles in the solution.
6. Given a description of a solution, identify the solute and the solvent.
7. Describe double-displacement reactions.
8. Describe precipitation reactions. Your descriptions should include mention of the nature of the particles in the system before and after the reaction, a description of the cause of the reaction, and a description of the attractions between the particles before and after the reaction.
9. Given the formula for an ionic compound, predict whether it is soluble in water or not.
10. Given formulas for two ionic compounds;
  - a. Predict whether a precipitate will form when the water solutions of the two are mixed,
  - b. If there is a reaction, predict the products of the reaction and write their formulas,
  - c. If there is a reaction, write the complete equation that describes the reaction.

## Review Questions

1. Write the formulas for all of the diatomic elements.
2. Predict whether atoms of each of the following pairs of elements would be expected to form ionic or covalent bonds.
  - a. Mg and F
  - b. O and H
  - c. Fe and O
  - d. N and Cl
3. Describe the structure of liquid water, including a description of water molecules and the attractions between them.
4. Write formulas that correspond to the following names.
  - a. ammonia
  - b. methane
  - c. propane
  - d. water

5. Write formulas that correspond to the following names.
- |                        |                       |
|------------------------|-----------------------|
| a. nitrogen dioxide    | c. dibromine monoxide |
| b. carbon tetrabromide | d. nitrogen monoxide  |
6. Write formulas that correspond to the following names.
- |                       |                              |
|-----------------------|------------------------------|
| a. lithium fluoride   | d. sodium carbonate          |
| b. lead(II) hydroxide | e. chromium(III) chloride    |
| c. potassium oxide    | f. sodium hydrogen phosphate |

Complete the following statements by writing one of these words or phrases in each blank.

Key Ideas

above	minor
charge	negative
chemical bonds	none
coefficients	organized, repeating
complete formula	partial charges
continuous	positive
converted into	precipitate
created	precipitates
delta, $\Delta$	precipitation
destroyed	same proportions
equal to	separate ions
gas	shorthand description
homogeneous mixture	solute
left out	solvent
liquid	subscripts
major	very low

7. A chemical change or chemical reaction is a process in which one or more pure substances are \_\_\_\_\_ one or more different pure substances.
8. In chemical reactions, atoms are rearranged and regrouped through the breaking and making of \_\_\_\_\_.
9. A chemical equation is a(n) \_\_\_\_\_ of a chemical reaction.
10. If special conditions are necessary for a reaction to take place, they are often specified \_\_\_\_\_ the arrow in the reaction's chemical equation.
11. To indicate that a chemical reaction requires the \_\_\_\_\_ addition of heat in order to proceed, we place an upper-case Greek \_\_\_\_\_ above the arrow in the reaction's chemical equation.
12. In chemical reactions, atoms are neither \_\_\_\_\_ nor \_\_\_\_\_; they merely change partners. Thus the number of atoms of an element in the reaction's products is \_\_\_\_\_ the number of atoms of that element in the original reactants. The \_\_\_\_\_ we often place in front of one or more of the formulas in a chemical equation reflect this fact.
13. When balancing chemical equations, we do not change the \_\_\_\_\_ in the formulas.

14. A solution, also called a(n) \_\_\_\_\_, is a mixture whose particles are so evenly distributed that the relative concentrations of the components are the same throughout.
15. Every part of a water solution of an ionic compound has the \_\_\_\_\_ of water molecules and ions as every other part.
16. When an ionic compound dissolves in water, the ions that escape the solid are held in solution by attractions between their own \_\_\_\_\_ and the \_\_\_\_\_ of the polar water molecules. The \_\_\_\_\_ oxygen ends of the water molecules surround the cations, and the \_\_\_\_\_ hydrogen ends surround the anions.
17. In solutions of solids dissolved in liquids, we call the solid the \_\_\_\_\_ and the liquid the \_\_\_\_\_.
18. In solutions of gases in liquids, we call the \_\_\_\_\_ the solute and the \_\_\_\_\_ the solvent.
19. In solutions of two liquids, we call the \_\_\_\_\_ component the solute and the \_\_\_\_\_ component the solvent.
20. Sometimes a double-displacement reaction has one product that is insoluble in water. As that product forms, it emerges, or \_\_\_\_\_, from the solution as a solid. This process is called \_\_\_\_\_, and the solid is called a(n) \_\_\_\_\_.
21. Crystals are solid particles whose component atoms, ions, or molecules are arranged in a(n) \_\_\_\_\_ pattern.
22. In a complete ionic equation, which describes the forms taken by the various substances in solution, the ionic compounds dissolved in the water are described as \_\_\_\_\_, and the insoluble ionic compound is described with a(n) \_\_\_\_\_.
23. Because spectator ions are not involved in the reaction, they are often \_\_\_\_\_ of the chemical equation.
24. When we say an ionic solid is insoluble in water, we do not mean that \_\_\_\_\_ of the solid dissolves. Thus, when we say that calcium carbonate is insoluble in water, what we really mean is that the solubility is \_\_\_\_\_.

## Chapter Problems

OBJECTIVE 2

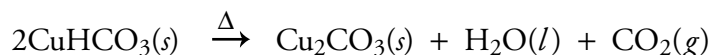
OBJECTIVE 3

OBJECTIVE 2

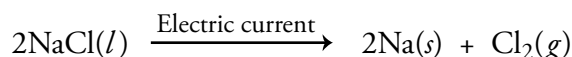
OBJECTIVE 3

### Section 5.1 Chemical Reactions and Chemical Equations

25. Describe the information given in the following chemical equation.



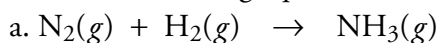
26. Describe the information given in the following chemical equation.



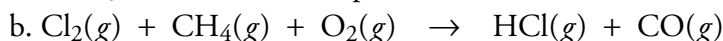


## OBJECTIVE 4

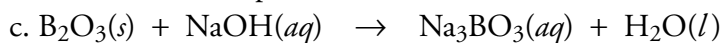
27. Balance the following equations.



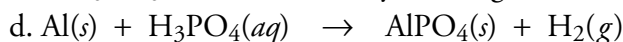
$\text{NH}_3$  is used to make explosives and rocket fuel.



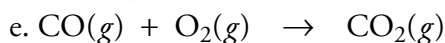
$\text{HCl}$  is used to make vinyl chloride, which is then used to make polyvinyl chloride (PVC) plastic.



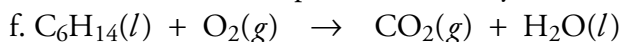
$\text{Na}_3\text{BO}_3$  is used as an analytical reagent.



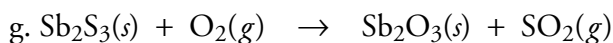
$\text{AlPO}_4$  is used in dental cements.



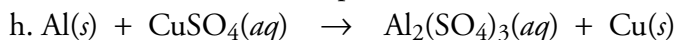
This reaction takes place in the catalytic converter of your car.



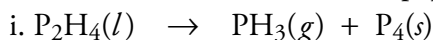
This is one of the chemical reactions that take place when gasoline is burned.



$\text{Sb}_2\text{O}_3$  is used to flameproof cloth.



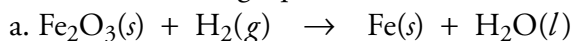
$\text{Al}_2(\text{SO}_4)_3$  has been used in paper production.



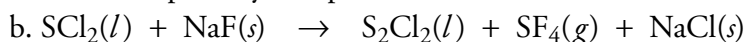
$\text{PH}_3$  is used to make semiconductors, and  $\text{P}_4$  is used to manufacture phosphoric acid.

28. Balance the following equations.

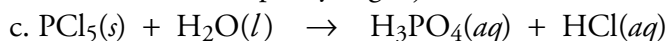
## OBJECTIVE 4



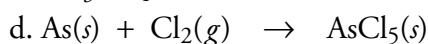
$\text{Fe}$  is the primary component in steel.



$\text{S}_2\text{Cl}_2$  is used to purify sugar juices.



$\text{H}_3\text{PO}_4$  is used to make fertilizers, soaps, and detergents.



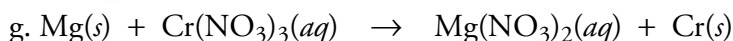
$\text{AsCl}_5$  is an intermediate in the production of arsenic compounds.



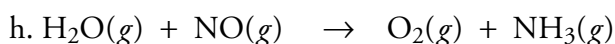
$\text{C}_2\text{H}_5\text{SH}$  is added to natural gas to give it an odor. Without it or something like it, you would not know when you have a gas leak.



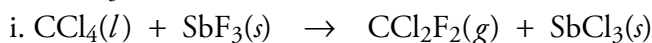
$\text{NO}_2$  is used in rocket fuels.



$\text{Cr}$  is used to make stainless steel.



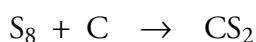
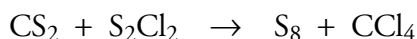
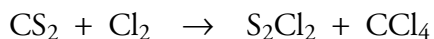
$\text{NH}_3$  is used to make fertilizers.



$\text{CCl}_2\text{F}_2$  is a chlorofluorocarbon called CFC-12. Although it has had many uses in the past, its use has diminished greatly due to the damage it can do to our protective ozone layer.

## OBJECTIVE 4

29. Because of its toxicity, carbon tetrachloride is prohibited in products intended for home use, but it is used industrially for a variety of purposes, including the production of chlorofluorocarbons (CFCs). It is made in a three-step process. Balance their equations:



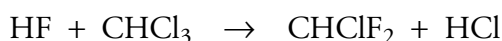
## OBJECTIVE 4

30. Chlorofluorocarbons (CFCs) are compounds that contain carbon, fluorine, and chlorine. Because they destroy ozone that forms a protective shield high in earth's atmosphere, their use is being phased out, but at one time they were widely employed as aerosol propellants and as refrigerants. Balance the following equation that shows how the CFCs dichlorodifluoromethane,  $\text{CCl}_2\text{F}_2$ , and trichlorofluoromethane,  $\text{CCl}_3\text{F}$ , are produced.



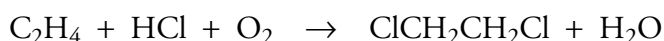
## OBJECTIVE 4

31. Hydrochlorofluorocarbons (HCFCs), which contain hydrogen as well as carbon, fluorine, and chlorine, are less damaging to the ozone layer than the chlorofluorocarbons (CFCs) described in problem 30. HCFCs are therefore used instead of CFCs for many purposes. Balance the following equation that shows how the HCFC chlorodifluoromethane,  $\text{CHClF}_2$ , is made.



## OBJECTIVE 4

32. The primary use of 1,2-dichloroethane,  $\text{ClCH}_2\text{CH}_2\text{Cl}$ , is to make vinyl chloride, which is then converted into polyvinyl chloride (PVC) for many purposes, including plastic pipes. Balance the following equation, which describes the industrial reaction for producing 1,2-dichloroethane.



### Section 5.2 Ionic Solubility and Precipitation Reactions

## OBJECTIVE 5

33. Describe the process for dissolving the ionic compound lithium iodide,  $\text{LiI}$ , in water, including the nature of the particles in solution and the attractions between the particles in the solution.

## OBJECTIVE 5

34. Describe the process for dissolving the ionic compound potassium nitrate,  $\text{KNO}_3$ , in water, including the nature of the particles in solution and the attractions between the particles in the solution.

## OBJECTIVE 5

35. Describe the process for dissolving the ionic compound sodium sulfate,  $\text{Na}_2\text{SO}_4$ , in water. Include mention of the nature of the particles in solution and the attractions between the particles in the solution.

## OBJECTIVE 5

36. Describe the process for dissolving the ionic compound calcium chloride,  $\text{CaCl}_2$ , in water. Include mention of the nature of the particles in solution and the attractions between the particles in the solution.

37. Solid camphor and liquid ethanol mix to form a solution. Which of these substances is the solute and which is the solvent?
38. Gaseous propane and liquid diethyl ether mix to form a solution. Which of these substances is the solute and which is the solvent?
39. Consider a solution of 10% liquid acetone and 90% liquid chloroform. Which of these substances is the solute and which is the solvent?
40. Black and white photographic film has a thin layer of silver bromide deposited on it. Wherever light strikes the film, silver ions are converted to uncharged silver atoms, creating a dark image on the film. Describe the precipitation reaction that takes place between water solutions of silver nitrate,  $\text{AgNO}_3(aq)$ , and sodium bromide,  $\text{NaBr}(aq)$ , to form solid silver bromide,  $\text{AgBr}(s)$ , and aqueous sodium nitrate,  $\text{NaNO}_3(aq)$ . Include mention of the nature of the particles in the system before and after the reaction, a description of the cause of the reaction, and a description of the attractions between the particles before and after the reaction.
41. Magnesium carbonate is used as an anti-caking agent in powders and as an antacid. Describe the precipitation reaction that takes place between water solutions of magnesium nitrate,  $\text{Mg}(\text{NO}_3)_2(aq)$ , and sodium carbonate,  $\text{Na}_2\text{CO}_3(aq)$ , to form solid magnesium carbonate,  $\text{MgCO}_3(s)$ , and aqueous sodium nitrate,  $\text{NaNO}_3(aq)$ . Include mention of the nature of the particles in the system before and after the reaction, a description of the cause of the reaction, and a description of the attractions between the particles before and after the reaction.
42. Predict whether each of the following substances is soluble or insoluble in water.
- $\text{Na}_2\text{SO}_3$  (used in water treatment)
  - iron(III) acetate (a wood preservative)
  - $\text{CoCO}_3$  (a red pigment)
  - lead(II) chloride (used in the preparation of lead salts)
43. Predict whether each of the following substances is soluble or insoluble in water.
- $\text{MgSO}_4$  (fireproofing)
  - barium sulfate (used in paints)
  - $\text{Bi}(\text{OH})_3$  (used in plutonium separation)
  - ammonium sulfite (used in medicine and photography)
44. Predict whether each of the following substances is soluble or insoluble in water.
- zinc phosphate (used in dental cements)
  - $\text{Mn}(\text{C}_2\text{H}_3\text{O}_2)_2$  (used in cloth dyeing)
  - nickel(II) sulfate (used in nickel plating)
  - $\text{AgCl}$  (used in silver plating)
45. Predict whether each of the following substances is soluble or insoluble in water.
- copper(II) chloride (used in fireworks and as a fungicide)
  - $\text{PbSO}_4$  (a paint pigment)
  - potassium hydroxide (used in soap manufacture)
  - $\text{NH}_4\text{F}$  (used as an antiseptic in brewing)

OBJECTIVE 6

OBJECTIVE 6

OBJECTIVE 6

OBJECTIVE 8



OBJECTIVE 8

OBJECTIVE 9

OBJECTIVE 9

OBJECTIVE 9



OBJECTIVE 9

## OBJECTIVE 10

46. For each of the following pairs of formulas, predict whether the substances they represent would react in a precipitation reaction. The products formed in the reactions that take place are used in ceramics, cloud seeding, photography, electroplating, and paper coatings. If there is no reaction, write, “No Reaction.” If there is a reaction, write the complete equation for the reaction.
- $\text{Co}(\text{NO}_3)_2(aq) + \text{Na}_2\text{CO}_3(aq)$
  - $\text{KI}(aq) + \text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2(aq)$
  - $\text{CuSO}_4(aq) + \text{LiNO}_3(aq)$
  - $\text{Ni}(\text{NO}_3)_2(aq) + \text{Na}_3\text{PO}_4(aq)$
  - $\text{K}_2\text{SO}_4(aq) + \text{Ba}(\text{NO}_3)_2(aq)$

## OBJECTIVE 10

47. For each of the following pairs of formulas, predict whether the substances they represent would react in a precipitation reaction. If there is no reaction, write, “No Reaction.” If there is a reaction, write the complete equation for the reaction.
- $\text{NaCl}(aq) + \text{Pb}(\text{NO}_3)_2(aq)$
  - $\text{NH}_4\text{Cl}(aq) + \text{CaSO}_3(aq)$
  - $\text{NaOH}(aq) + \text{Zn}(\text{NO}_3)_2(aq)$
  - $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2(aq) + \text{Na}_2\text{SO}_4(aq)$

48. Phosphate ions find their way into our water system from the fertilizers dissolved in the runoff from agricultural fields and from detergents that we send down our drains. Some of these phosphate ions can be removed by adding aluminum sulfate to the water and precipitating the phosphate ions as aluminum phosphate. Write the net ionic equation for the reaction that forms the aluminum phosphate.

## OBJECTIVE 10

## OBJECTIVE 10

49. The taste of drinking water can be improved by removing impurities from our municipal water by adding substances to the water that precipitate a solid (called a flocculent) that drags down impurities as it settles. One way this is done is to dissolve aluminum sulfate and sodium hydroxide in the water to precipitate aluminum hydroxide. Write the complete equation for this reaction.

## OBJECTIVE 10

50. Cadmium hydroxide is used in storage batteries. It is made from the precipitation reaction of cadmium acetate and sodium hydroxide. Write the complete equation for this reaction.

## OBJECTIVE 10

51. Chromium(III) phosphate is a paint pigment that is made in a precipitation reaction between water solutions of chromium(III) chloride and sodium phosphate. Write the complete equation for this reaction.

**Additional Problems**

## OBJECTIVE 4

52. Balance the following chemical equations.
- $\text{SiCl}_4 + \text{H}_2\text{O} \rightarrow \text{SiO}_2 + \text{HCl}$
  - $\text{H}_3\text{BO}_3 \rightarrow \text{B}_2\text{O}_3 + \text{H}_2\text{O}$
  - $\text{I}_2 + \text{Cl}_2 \rightarrow \text{ICl}_3$
  - $\text{Al}_2\text{O}_3 + \text{C} \rightarrow \text{Al} + \text{CO}_2$

## OBJECTIVE 4

53. Balance the following chemical equations.
- $\text{HClO}_4 + \text{Fe}(\text{OH})_2 \rightarrow \text{Fe}(\text{ClO}_4)_2 + \text{H}_2\text{O}$
  - $\text{NaClO}_3 \rightarrow \text{NaCl} + \text{O}_2$
  - $\text{Sb} + \text{Cl}_2 \rightarrow \text{SbCl}_3$
  - $\text{CaCN}_2 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + \text{NH}_3$

54. Balance the following chemical equations.

OBJECTIVE 4

- $\text{NH}_3 + \text{Cl}_2 \rightarrow \text{N}_2\text{H}_4 + \text{NH}_4\text{Cl}$
- $\text{Cu} + \text{AgNO}_3 \rightarrow \text{Cu}(\text{NO}_3)_2 + \text{Ag}$
- $\text{Sb}_2\text{S}_3 + \text{HNO}_3 \rightarrow \text{Sb}(\text{NO}_3)_3 + \text{H}_2\text{S}$
- $\text{Al}_2\text{O}_3 + \text{Cl}_2 + \text{C} \rightarrow \text{AlCl}_3 + \text{CO}$

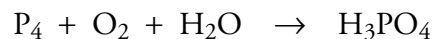
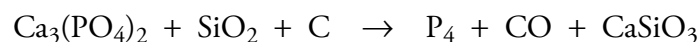
55. Balance the following chemical equations.

OBJECTIVE 4

- $\text{AsH}_3 \rightarrow \text{As} + \text{H}_2$
- $\text{H}_2\text{S} + \text{Cl}_2 \rightarrow \text{S}_8 + \text{HCl}$
- $\text{Co} + \text{O}_2 \rightarrow \text{Co}_2\text{O}_3$
- $\text{Na}_2\text{CO}_3 + \text{C} \rightarrow \text{Na} + \text{CO}$

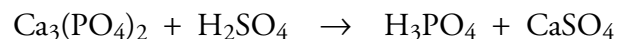
56. Phosphoric acid,  $\text{H}_3\text{PO}_4$ , is an important chemical used to make fertilizers, detergents, pharmaceuticals, and many other substances. High purity phosphoric acid is made in a two-step process called the furnace process. Balance its two equations:

OBJECTIVE 4



57. For most applications, phosphoric acid is produced by the “wet process” (whose results are less pure than those of the furnace process described in problem 56). Balance the following equation that describes the reaction for this process.

OBJECTIVE 4



58. Predict whether each of the following substances is soluble or insoluble in water.

OBJECTIVE 9

- manganese(II) chloride (used as a dietary supplement)
- $\text{CdSO}_4$  (used in pigments)
- copper(II) carbonate (used in fireworks)
- $\text{Co}(\text{OH})_3$  (used as a catalyst)

59. Predict whether each of the following substances is soluble or insoluble in water.

OBJECTIVE 9

- copper(II) hydroxide (used as a pigment)
- $\text{BaBr}_2$  (used to make photographic compounds)
- silver carbonate (used as a laboratory reagent)
- $\text{Pb}_3(\text{PO}_4)_2$  (used as a stabilizing agent in plastics)

60. For each of the following pairs of formulas, predict whether the substances they represent would react to yield a precipitate. (The products formed in the reactions that take place are used to coat steel, as a fire-proofing filler for plastics, in cosmetics, and as a topical antiseptic.) If there is no reaction, write, “No Reaction”. If there is a reaction, write the complete equation for the reaction.

OBJECTIVE 10

- $\text{NaCl}(aq) + \text{Al}(\text{NO}_3)_3(aq)$
- $\text{Ni}(\text{NO}_3)_2(aq) + \text{NaOH}(aq)$
- $\text{MnCl}_2(aq) + \text{Na}_3\text{PO}_4(aq)$
- $\text{Zn}(\text{C}_2\text{H}_3\text{O}_2)_2(aq) + \text{Na}_2\text{CO}_3(aq)$

## OBJECTIVE 10

61. For each of the following pairs of formulas, predict whether the substances they represent would react to yield a precipitate. (The products formed in the reactions that take place are used as a catalyst, as a tanning agent, as a pigment, in fertilizers, as a food additive, and on photographic film.) If there is no reaction, write, "No Reaction". If there is a reaction, write the complete equation for the reaction.
- $\text{KOH}(aq) + \text{Cr}(\text{NO}_3)_3(aq)$
  - $\text{Fe}(\text{NO}_3)_3(aq) + \text{K}_3\text{PO}_4(aq)$
  - $\text{NaBr}(aq) + \text{AgNO}_3(aq)$
  - $\text{Mg}(\text{C}_2\text{H}_3\text{O}_2)_2(aq) + \text{NaCl}(aq)$

*Before working Chapter Problems 62 through 78, you might want to review the procedures for writing chemical formulas that are described in Chapter 4. Remember that some elements are described with formulas containing subscripts (as in  $\text{O}_2$ ).*

## OBJECTIVE 4

62. Hydrochloric acid is used in the cleaning of metals (called pickling). Hydrogen chloride, used to make hydrochloric acid, is made industrially by combining hydrogen and chlorine. Write a balanced equation, without including states, for this reaction.

## OBJECTIVE 4

63. Potassium hydroxide has many uses, including the manufacture of soap. It is made by running an electric current through a water solution of potassium chloride. Both potassium chloride and water are reactants, and the products are potassium hydroxide, hydrogen, and chlorine. Write a balanced equation, without including states, for this reaction.

## OBJECTIVE 4

64. Aluminum sulfate, commonly called alum, is used to coat paper made from wood pulp. (It fills in tiny holes in the paper and thus keeps the ink from running.) Alum is made in the reaction of aluminum oxide with sulfuric acid,  $\text{H}_2\text{SO}_4$ , which produces aluminum sulfate and water. Write a balanced equation, without including states, for this reaction.

## OBJECTIVE 4

65. Under the right conditions, methanol reacts with oxygen to yield formaldehyde,  $\text{CH}_2\text{O}$ , and water. Most of the formaldehyde made in this way is used in the production of other substances, including some important plastics. Formaldehyde, itself now a suspected carcinogen, was once used in insulation foams and in plywood adhesives. Write a balanced equation, without including states, for the reaction that produces formaldehyde from methanol.

## OBJECTIVE 4

66. Hydrogen fluoride is used to make chlorofluorocarbons (CFCs) and in uranium processing. Calcium fluoride reacts with sulfuric acid,  $\text{H}_2\text{SO}_4$ , to form hydrogen fluoride and calcium sulfate. Write a balanced equation, without including states, for this reaction.

## OBJECTIVE 4

67. Sodium sulfate, which is used to make detergents and glass, is one product of the reaction of sodium chloride, sulfur dioxide, water, and oxygen. The other product is hydrogen chloride. Write a balanced equation, without including states, for this reaction.

## OBJECTIVE 4

68. Sodium hydroxide, which is often called caustic soda, is used to make paper, soaps, and detergents. For many years, it was made from the reaction of sodium carbonate with calcium hydroxide (also called slaked lime). The products are sodium hydroxide and calcium carbonate. Write a balanced equation, without including states, for this reaction.

69. In the modern process for making sodium hydroxide, an electric current is run through a sodium chloride solution, forming hydrogen and chlorine along with the sodium hydroxide. Both sodium chloride and water are reactants. Write a balanced equation, without including states, for this reaction. OBJECTIVE 4
70. For over a century, sodium carbonate (often called soda ash) was made industrially by the Solvay process. This process was designed by Ernest Solvay in 1864 and was used in the United States until extensive natural sources of sodium carbonate were found in the 1970s and 1980s. Write a balanced equation, without including states, for each step in the process: OBJECTIVE 4
- Calcium carbonate (from limestone) is heated and decomposes into calcium oxide and carbon dioxide.
  - Calcium oxide reacts with water to form calcium hydroxide.
  - Ammonia reacts with water to form ammonium hydroxide.
  - Ammonium hydroxide reacts with carbon dioxide to form ammonium hydrogen carbonate.
  - Ammonium hydrogen carbonate reacts with sodium chloride to form sodium hydrogen carbonate and ammonium chloride.
  - Sodium hydrogen carbonate is heated and decomposes into sodium carbonate, carbon dioxide, and water.
  - Ammonium chloride reacts with calcium hydroxide to form ammonia, calcium chloride, and water.
71. All of the equations for the Solvay process described in problem 70 can be summarized by a single equation, called a net equation, that describes the overall change for the process. This equation shows calcium carbonate reacting with sodium chloride to form sodium carbonate and calcium chloride. Write a balanced equation, without including states, for this net reaction. OBJECTIVE 4
72. Nitric acid,  $\text{HNO}_3$ , which is used to make fertilizers and explosives, is made industrially in the three steps described below. Write a balanced equation, without including states, for each of these steps.
- Ammonia reacts with oxygen to form nitrogen monoxide and water.
  - Nitrogen monoxide reacts with oxygen to form nitrogen dioxide.
  - Nitrogen dioxide reacts with water to form nitric acid and nitrogen monoxide.
73. All of the equations for the production of nitric acid described in problem 72 can be summarized in a single equation, called a net equation, that describes the overall change for the complete process. This equation shows ammonia combining with oxygen to yield nitric acid and water. Write a balanced equation, without including states, for this net reaction. OBJECTIVE 4
74. Ammonium sulfate, an important component in fertilizers, is made from the reaction of ammonia and sulfuric acid,  $\text{H}_2\text{SO}_4$ . Write a balanced equation, without including states, for the reaction that summarizes this transformation. OBJECTIVE 4
75. Hydrogen gas has many practical uses, including the conversion of vegetable oils into margarine. One way the gas is produced by the chemical industry is by reacting propane gas with gaseous water to form carbon dioxide gas and hydrogen gas. Write a balanced equation for this reaction, showing the states of reactants and products. OBJECTIVE 4

## OBJECTIVE 4

76. Sodium tripolyphosphate,  $\text{Na}_5\text{P}_3\text{O}_{10}$ , is called a “builder” when added to detergents. It helps to create the conditions in laundry water necessary for the detergents to work most efficiently. When phosphoric acid,  $\text{H}_3\text{PO}_4$ , is combined with sodium carbonate, three reactions take place in the mixture that lead to the production of sodium tripolyphosphate. Write a balanced equation, without including states, for each of the reactions:
- Phosphoric acid reacts with sodium carbonate to form sodium dihydrogen phosphate, water, and carbon dioxide.
  - Phosphoric acid also reacts with sodium carbonate to form sodium hydrogen phosphate, water, and carbon dioxide.
  - Sodium dihydrogen phosphate combines with sodium hydrogen phosphate to yield sodium tripolyphosphate and water.

## OBJECTIVE 4

77. Pig iron is iron with about 4.3% carbon in it. The carbon lowers the metal’s melting point and makes it easier to shape. To produce pig iron, iron(III) oxide is combined with carbon and oxygen at high temperature. Three changes then take place to form molten iron with carbon dispersed in it. Write a balanced equation, without including states, for each of these changes:
- Carbon combines with oxygen to form carbon monoxide.
  - Iron(III) oxide combines with the carbon monoxide to form iron and carbon dioxide.
  - Carbon monoxide changes into carbon (in the molten iron) and carbon dioxide.

## OBJECTIVE 4

78. The United States chemical industry makes more sulfuric acid than any other chemical. One process uses hydrogen sulfide from “sour” natural gas wells or petroleum refineries as a raw material. Write a balanced equation, without including states, for each of the steps leading from hydrogen sulfide to sulfuric acid:
- Hydrogen sulfide (which could be called dihydrogen monosulfide) combines with oxygen to form sulfur dioxide and water.
  - The sulfur dioxide reacts with more hydrogen sulfide to form sulfur and water. (Sulfur is described as both S and  $\text{S}_8$  in chemical equations. Use S in this equation).
  - After impurities are removed, the sulfur is reacted with oxygen to form sulfur dioxide.
  - Sulfur dioxide reacts with oxygen to yield sulfur trioxide.
  - Sulfur trioxide and water combine to make sulfuric acid,  $\text{H}_2\text{SO}_4$ .
79. Assume you are given a water solution that contains either sodium ions or aluminum ions. Describe how you could determine which of these is in solution.
80. Assume that you are given a water solution that contains either nitrate ions or phosphate ions. Describe how you could determine which of these is in solution.

## OBJECTIVE 10

81. Write a complete, balanced chemical equation for the reaction between water solutions of iron(III) chloride and silver nitrate.

## OBJECTIVE 10

82. Write a complete, balanced chemical equation for the reaction between water solutions of sodium phosphate and copper(II) chloride.

## OBJECTIVE 4

83. When the solid amino acid methionine,  $\text{C}_5\text{H}_{11}\text{NSO}_2$ , reacts with oxygen gas, the products are carbon dioxide gas, liquid water, sulfur dioxide gas, and nitrogen gas. Write a complete, balanced equation for this reaction.



84. When the explosive liquid nitroglycerin,  $C_3H_5N_3O_9$ , decomposes, it forms carbon dioxide gas, nitrogen gas, water vapor, and oxygen gas. Write a complete, balanced equation for this reaction.

### Discussion Problem

85. The solubility of calcium carbonate is 0.0014 g of  $CaCO_3$  per 100 mL of water at 25 °C, and the solubility of sodium nitrate is 92.1 grams of  $NaNO_3$  per 100 mL of water at 25 °C. We say that calcium carbonate is insoluble in water, and sodium nitrate,  $NaNO_3$ , is soluble.
- In Section 5.6, the following statement was made: *“When we say an ionic solid is insoluble in water, we do not mean that none of the solid dissolves. There are always some ions that can escape from the surface of an ionic solid in water and go into solution.”* Discuss the process by which calcium and carbonate ions can escape from the surface of calcium carbonate solid in water and go into solution. You might want to draw a picture to illustrate this process.
  - If the calcium and carbonate ions are constantly going into solution, why doesn't the calcium carbonate solid all dissolve?
  - Why do you think sodium nitrate,  $NaNO_3$ , dissolves to a much greater degree than calcium carbonate?
  - Why is there a limit to the solubility of even the “soluble” sodium nitrate?