



# CHAPTER 8

## ACIDS, BASES, AND ACID-BASE REACTIONS

It's test day in chemistry class—they've been learning about acids and bases—and Fran unwisely skips breakfast in order to have time for some last-minute studying. As she reads, she chews on a candy bar and sips a cup of coffee. Fran is well aware that the sugary candy sticking to her molars is providing breakfast for the bacteria in her mouth, which in turn produce an acid that will dissolve some of the enamel on her teeth. Feeling a little guilty about all that sugar from the candy, Fran drinks her coffee black, even though she doesn't like the taste. The caffeine in her coffee is a base, and like all bases, it tastes bitter.

Fran's junk-food breakfast and her worrying about the exam combine to give her an annoying case of acid indigestion, which she calms by drinking some baking soda mixed with water. The baking soda contains a base that "neutralizes" some of her excess stomach acid.

After taking the exam, Fran feels happy and confident. All those hours working problems, reviewing the learning objectives, and participating in class really paid off. Now she's ready for some lunch. Before eating, she washes her hands with soap made from the reaction of a strong base and animal fat. One of the reasons the soap is slippery is because all bases feel slippery on the skin. To compensate for her less-than-healthy breakfast, Fran chooses salad with a piece of lean meat on top for lunch. Like all acids, the vinegar in her salad dressing tastes sour. Her stomach produces just enough additional acid to start the digestion of the protein from the meat.

Read on to learn more about the acids and bases that are important in Fran's life and your own: what they are and how they react with each other.



The vinegar in salad dressing tastes sour, as do all acids.

- 8.1 Strong and Weak Acids and Bases
- 8.2 pH and Acidic and Basic Solutions
- 8.3 Arrhenius Acid-Base Reactions
- 8.4 Brønsted-Lowry Acids and Bases

### 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.

- Given a chemical name or formula, decide whether or not it represents an ionic compound. (Section 5.3)
- Describe what occurs when a strong, monoprotic acid, such as HCl, is added to water. (Section 6.3)
- Describe what occurs when a weak, monoprotic acid, such as acetic acid, is added to water. (Section 6.3)
- Describe the structure of liquid water. (Section 7.2)
- Write a description of the changes that take place when an ionic compound is dissolved in water. (Section 7.2)
- Predict ionic solubility. (Section 7.3)
- Predict the products of double-displacement reactions. (Section 7.3)

## 8.1 Strong and Weak Acids and Bases

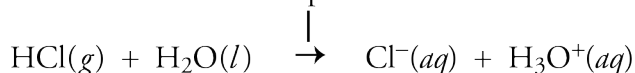
One of the most important goals of this chapter is to broaden your understanding of chemical reactions by describing the chemical changes that take place when an acid is combined with a base. Before we can do that, we need to review some of what we learned about acids in Chapter 6 and learn about the nature of bases. It might be useful for you to reread Section 6.3 before continuing with this section.

### Acid Review

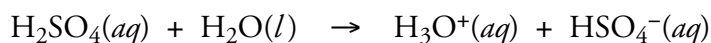
In Chapter 6, we learned that according to the modern form of the Arrhenius theory, an acid is a substance that produces hydronium ions,  $\text{H}_3\text{O}^+$ , when it is added to water, and an acidic solution is a solution with a significant concentration of  $\text{H}_3\text{O}^+$ . Acids can be binary acids—such as  $\text{HF}(aq)$ ,  $\text{HCl}(aq)$ ,  $\text{HBr}(aq)$ , and  $\text{HI}(aq)$ —oxyacids, which have the general formula  $\text{H}_a\text{X}_b\text{O}_c$ , and organic acids, such as acetic acid,  $\text{HC}_2\text{H}_3\text{O}_2$ . An acid, such as hydrofluoric acid,  $\text{HF}(aq)$ , whose molecules can each donate one proton,  $\text{H}^+$ , to a water molecule is called a monoprotic acid. The acids, such as sulfuric acid,  $\text{H}_2\text{SO}_4$ , that can donate two protons are called diprotic, and some acids, such as phosphoric acid,  $\text{H}_3\text{PO}_4$ , are triprotic acids.

A strong acid, such as hydrochloric acid,  $\text{HCl}(aq)$ , is a substance that undergoes a completion reaction with water such that each acid particle reacts to form a hydronium ion,  $\text{H}_3\text{O}^+$ . Thus strong acids form nearly one  $\text{H}_3\text{O}^+$  ion in solution for each acid molecule dissolved in water.

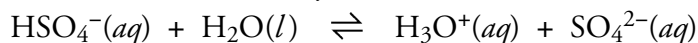
Indicates a completion reaction



Sulfuric acid,  $\text{H}_2\text{SO}_4$ , is a strong diprotic acid. When added to water, each  $\text{H}_2\text{SO}_4$  molecule loses its first hydrogen ion completely.

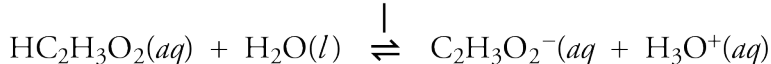


The hydrogen sulfate ion,  $\text{HSO}_4^-$  that forms is a weak acid. It reacts with water in a reversible reaction to form a hydronium ion and a sulfate ion.



A weak acid is a substance that is incompletely ionized in water because of the reversibility of its reaction with water that forms hydronium ion,  $\text{H}_3\text{O}^+$ . Weak acids yield significantly less than one  $\text{H}_3\text{O}^+$  ion in solution for each acid molecule dissolved in water.

Indicates a  
reversible  
reaction



#### OBJECTIVE 5

The strong acids that you will be expected to recognize are hydrochloric acid,  $\text{HCl}(aq)$ , nitric acid,  $\text{HNO}_3$ , and sulfuric acid,  $\text{H}_2\text{SO}_4$ . (There are other strong acids, but they are much less common.) An acid is considered weak if it is not on the list of strong acids.

## Bases

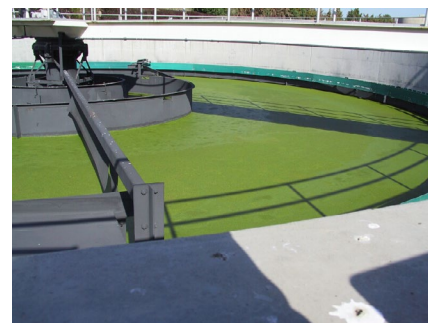
Each year, the US chemical industry produces over 10 billion kilograms of the base sodium hydroxide, NaOH, which is then used for many purposes, including water treatment, vegetable oil refining, the peeling of fruits and vegetables in the food industry, and to make numerous other chemical products, including soaps and detergents. Likewise, over 15 billion kilograms of the base ammonia, NH<sub>3</sub>, is produced each year. Although a water solution of ammonia is a common household cleaner, most of the NH<sub>3</sub> produced in the US is used to make fertilizers and explosives. As you read this section, you will learn about the chemical properties of basic compounds that make them so useful to chemists and others.

According to the modern version of the Arrhenius theory of acids and bases, a **base** is a substance that produces hydroxide ions, OH<sup>-</sup>, when it is added to water. A solution that has a significant concentration of hydroxide ions is called a **basic solution**. Sodium hydroxide, NaOH, is the most common laboratory base. It is designated a **strong base** because for every NaOH unit dissolved, one hydroxide ion is formed in solution.



Compounds that contain hydroxide ions are often called **hydroxides**. All water-soluble hydroxides are strong bases. Examples include lithium hydroxide, LiOH, which is used in storage batteries and as a carbon dioxide absorbent in space vehicles, and potassium hydroxide, KOH, which is used to make some soaps, liquid fertilizers, and paint removers.

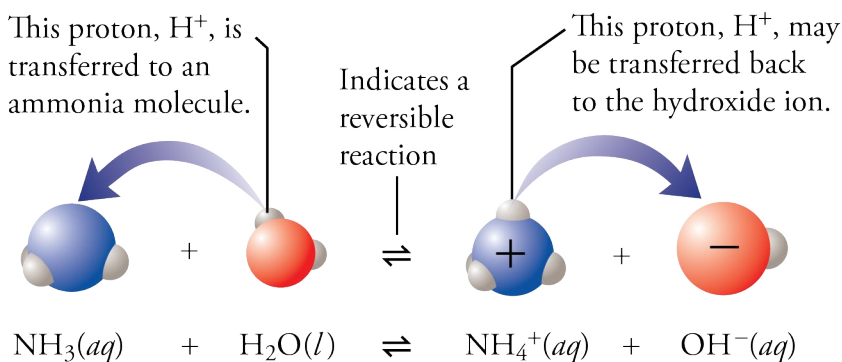
When ammonia, NH<sub>3</sub>, dissolves in water, some hydrogen ions, H<sup>+</sup>, are transferred from water molecules to ammonia molecules, NH<sub>3</sub>, producing ammonium ions, NH<sub>4</sub><sup>+</sup>, and hydroxide ions, OH<sup>-</sup>. The reaction is reversible, so when an ammonium ion and a hydroxide ion meet in solution, the H<sup>+</sup> ion can be passed back to the OH<sup>-</sup> to reform an NH<sub>3</sub> molecule and a water molecule (Figure 8.1).



This water treatment plant uses the base sodium hydroxide, NaOH, to remove impurities from the water.

OBJECTIVE 2

OBJECTIVE 3



**Figure 8.1**  
The Reversible Reaction  
of Ammonia and Water

OBJECTIVE 3

## OBJECTIVE 3

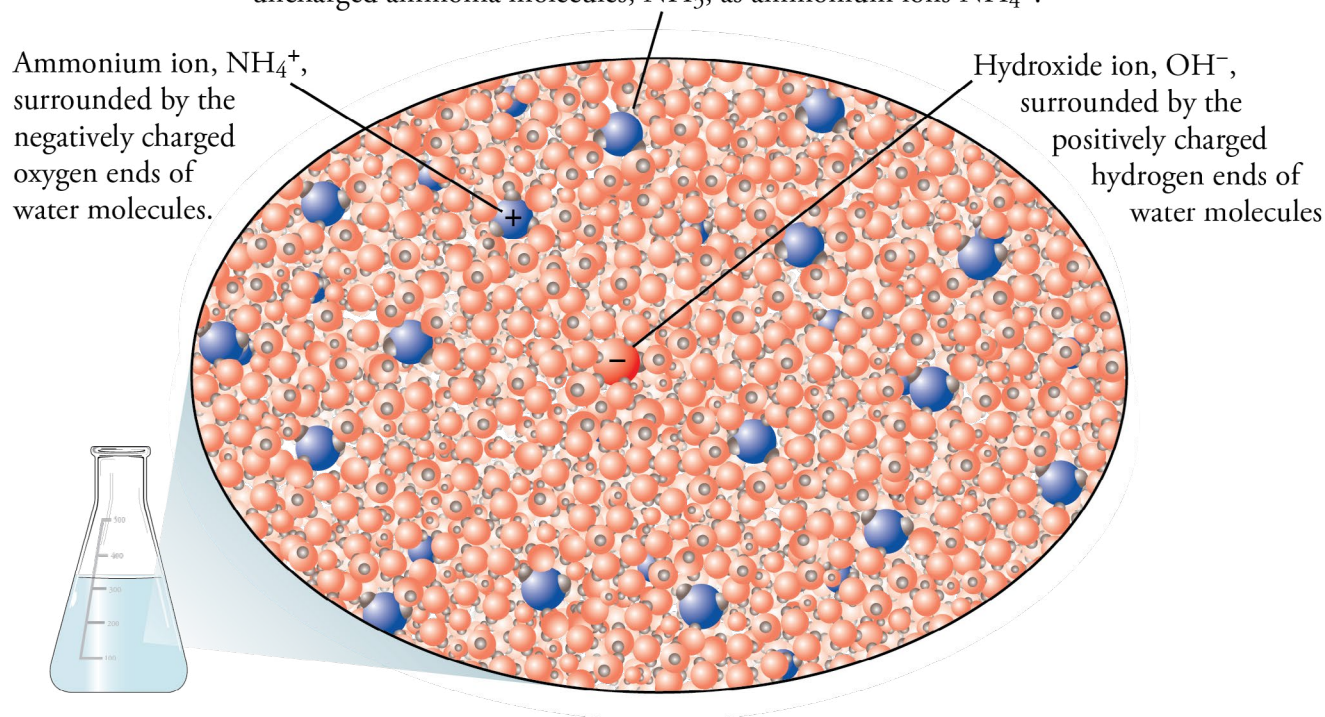
Ammonia is an **Arrhenius base** because it produces  $\text{OH}^-$  ions when added to water. Because the reaction is reversible, however, only some ammonia molecules have acquired protons (creating  $\text{OH}^-$ ) at any given time, so an ammonia solution contains fewer hydroxide ions than would be found in a solution made using an equivalent amount of a strong base. Therefore, we classify ammonia as a **weak base**, which is a base that produces fewer hydroxide ions in water solution than there are particles of base dissolved.

To visualize the reaction between ammonia and water at the molecular level, imagine that you are taking a ride on a nitrogen atom. Your nitrogen would usually be bonded with three hydrogen atoms in an  $\text{NH}_3$  molecule, but occasionally, it would gain an extra  $\text{H}^+$  ion from a water molecule to form  $\text{NH}_4^+$  for a short time. When your  $\text{NH}_4^+$  ion collides with an  $\text{OH}^-$  ion, an  $\text{H}^+$  ion is transferred to the  $\text{OH}^-$  ion to form  $\text{H}_2\text{O}$  and  $\text{NH}_3$ . Ammonia molecules are constantly gaining and losing  $\text{H}^+$  ions, but soon after the initial addition of ammonia to water, both changes proceed at an equal rate. At this point, there will be no more net change in the amounts of ammonia, water, hydroxide, and ammonium ion in the solution. When a typical solution of ammonia stops changing, it is likely to contain about 200  $\text{NH}_3$  molecules for each  $\text{NH}_4^+$  ion. As you study the ammonia solution depicted in Figure 8.2, try to picture about 200 times as many  $\text{NH}_3$  molecules as  $\text{NH}_4^+$  or  $\text{OH}^-$  ions.

**Figure 8.2**  
Ammonia in Water

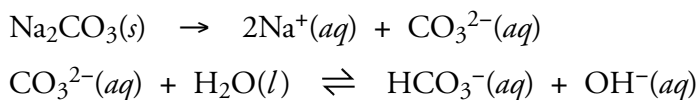
## OBJECTIVE 3

In a typical ammonia solution, there are about 200 times as many uncharged ammonia molecules,  $\text{NH}_3$ , as ammonium ions  $\text{NH}_4^+$ .

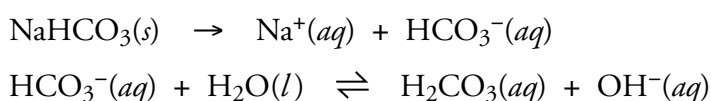




There are many weak Arrhenius bases, but the only ones that you will be expected to recognize are ionic compounds containing carbonate (for example, sodium carbonate,  $\text{Na}_2\text{CO}_3$ ) and hydrogen carbonate (for example, sodium hydrogen carbonate,  $\text{NaHCO}_3$ ). When sodium carbonate, which is used to make glass, soaps, and detergents, dissolves in water, the carbonate ions,  $\text{CO}_3^{2-}$ , react with water in a reversible way to yield hydroxide ions.



In a similar reaction, the hydrogen carbonate ions,  $\text{HCO}_3^-$ , formed when  $\text{NaHCO}_3$  dissolves in water, react to yield hydroxide ions.



Sodium hydrogen carbonate is found in fire extinguishers, baking powders, antacids, and mouthwashes.



These products all contain the weak base sodium hydrogen carbonate.

Table 8.1 summarizes how you can recognize substances as bases and how you can classify them as strong or weak bases. (There are other Arrhenius bases that you may learn about later.)

**Table 8.1**  
Arrhenius Bases

	Strong	Weak
Ionic compounds	Metal hydroxides, such as $\text{NaOH}$	Ionic compounds with $\text{CO}_3^{2-}$ and $\text{HCO}_3^-$ , such as $\text{Na}_2\text{CO}_3$ and $\text{NaHCO}_3$
Certain uncharged molecules	None	$\text{NH}_3$

OBJECTIVE 4

OBJECTIVE 4

OBJECTIVE 5

You can get more information about strong and weak bases on the textbook's Web site.

The following sample study sheet summarizes the ways you can recognize strong and weak acids and bases.

## Sample Study Sheet 8.1

### Identification of Strong and Weak Acids and Bases

#### OBJECTIVE 5

**TIP-OFF** You are asked to identify a substance as either (1) an Arrhenius strong acid, (2) an Arrhenius weak acid, (3) an Arrhenius strong base, or (4) an Arrhenius weak base.

#### GENERAL STEPS

**STEP 1** Identify the substance as an Arrhenius acid or base using the following criteria.

- The names of the acids end in *acid*. Acid formulas have one of these forms:  $HX(aq)$  or  $H_aX_bO_c$ .
- Ionic compounds that contain hydroxide, carbonate, or hydrogen carbonate anions are basic. Ammonia,  $NH_3$ , is also a base.

**STEP 2** If the substance is an acid or base, determine whether it is strong or weak.

- We will consider all acids except  $HCl(aq)$ ,  $HNO_3$ , and  $H_2SO_4$  to be weak.
- We will consider all bases except metal hydroxides to be weak.

**EXAMPLE** See Example 8.1.

### EXAMPLE 8.1 - Identification of Acids and Bases

#### OBJECTIVE 5

Identify (a)  $H_2SO_4$ , (b) oxalic acid, (c)  $NaHCO_3$ , (d) potassium hydroxide, (e)  $HCl(aq)$ , and (f) ammonia as either an Arrhenius strong acid, an Arrhenius weak acid, an Arrhenius strong base, or an Arrhenius weak base.

#### Solution

- The  $H_2SO_4$  is an acid because it has the form of an oxyacid,  $H_aX_bO_c$ . It is on the list of **strong acids**.
- Oxalic acid is not on the list of strong acids— $HCl(aq)$ ,  $HNO_3$ , and  $H_2SO_4$ —so it is a **weak acid**.
- Ionic compounds that contain hydrogen carbonate, such as  $NaHCO_3$ , are **weak bases**.
- Ionic compounds that contain hydroxide, such as potassium hydroxide, are **strong bases**.
- We know that hydrochloric acid,  $HCl(aq)$ , is an acid because its name ends in “acid,” and its formula has the form of a binary acid. It is found on the list of **strong acids**.
- Ammonia,  $NH_3$ , is our one example of an uncharged **weak base**.

There is a tutorial on the textbook's Web site that will provide practice identifying acids and bases.

## EXERCISE 8.1 - Identification of Acids and Bases

Identify each of the following as either an Arrhenius strong acid, an Arrhenius weak acid, an Arrhenius strong base, or an Arrhenius weak base.

- |                      |                            |
|----------------------|----------------------------|
| a. $\text{HNO}_3$    | c. $\text{K}_2\text{CO}_3$ |
| b. lithium hydroxide | d. hydrofluoric acid       |

OBJECTIVE 5

### SPECIAL TOPIC 8.1

## Chemistry and Your Sense of Taste

*“...[T]hat formed of bodies round and smooth are things which touch the senses sweetly, while those which harsh and bitter do appear, are held together bound with particles more hooked, and for this cause are wont to tear their way into our senses, and on entering in to rend the body.”*

Lucretius, a Roman philosopher and poet, about 2000 years ago

Lucretius was mistaken in certain details, but he was correct that the shape of molecules is important in determining whether compounds taste sweet or bitter. Your tongue has about 3000 taste buds, each of which is an onion-shaped collection of 50 to 150 taste cells. Each taste bud is specialized for tasting either sweet, sour, salt, or bitter. It has been suggested that the tongue can also perceive another taste, umami, which is a subtle taste most commonly associated with monosodium glutamate, MSG. At the tips of the bitter and sweet taste cells are receptor molecules shaped to fit parts of certain molecules in our food.

When chocolate, for example, is roasted, caffeine and other compounds are formed that stimulate the bitter taste cells. The molecules of these compounds have a shape that allows them to attach to the taste cell receptors and cause an adjacent nerve cell to fire. This event sends the bitter signal to the brain.

Sugar is added to chocolate to counteract the bitter taste. The arrangement of atoms in sugar molecules allows them to fit into the receptor sites of sweet taste cells. When a sugar molecule such as glucose or sucrose attaches to a receptor of a sweet taste cell, the sweet signal is sent to the brain.

The salt taste is thought to have different mechanisms than the sweet and bitter tastes. It is the presence of sodium ions,  $\text{Na}^+$ , in the sodium chloride,  $\text{NaCl}$ , of table salt that causes the taste. The interior of a salt taste cell is negatively

charged. When such a cell is bathed in saliva that contains dissolved sodium ions, the  $\text{Na}^+$  ions enter the cell and make its interior less negative. This change triggers the release of chemicals called neurotransmitters into the space between the taste cells and nerve cells. The neurotransmitters cause the nerve cells to fire, sending the salt signal to the brain.

Acids cause the sour taste in foods. Vinegar is sour because it contains acetic acid, sour milk contains lactic acid, and lemons contain citric acid. What these acids have in common is that they can lose  $\text{H}^+$  ions in water solutions such as our saliva. Different animal species have different mechanisms for sending the sour signal. In amphibians the  $\text{H}^+$  ions block the normal release of potassium ions from sour taste cells, changing the cells' charge balance and causing them to release neurotransmitters. The neurotransmitters in turn tell the sour nerve cells to fire.

It has been suggested that there are good reasons for the evolution of our sense of taste. The four main tastes either lead us to food we need or warn us away from substances that might be harmful. We need sugar for energy and salt to replace the sodium and potassium ions lost in exercise. On the other hand, spoiled foods produce bitter-tasting substances, and numerous poisons, too, are bitter, while many a bellyache from unripe fruit has been avoided by the warning signal provided by the sour taste.



Bases taste bitter.

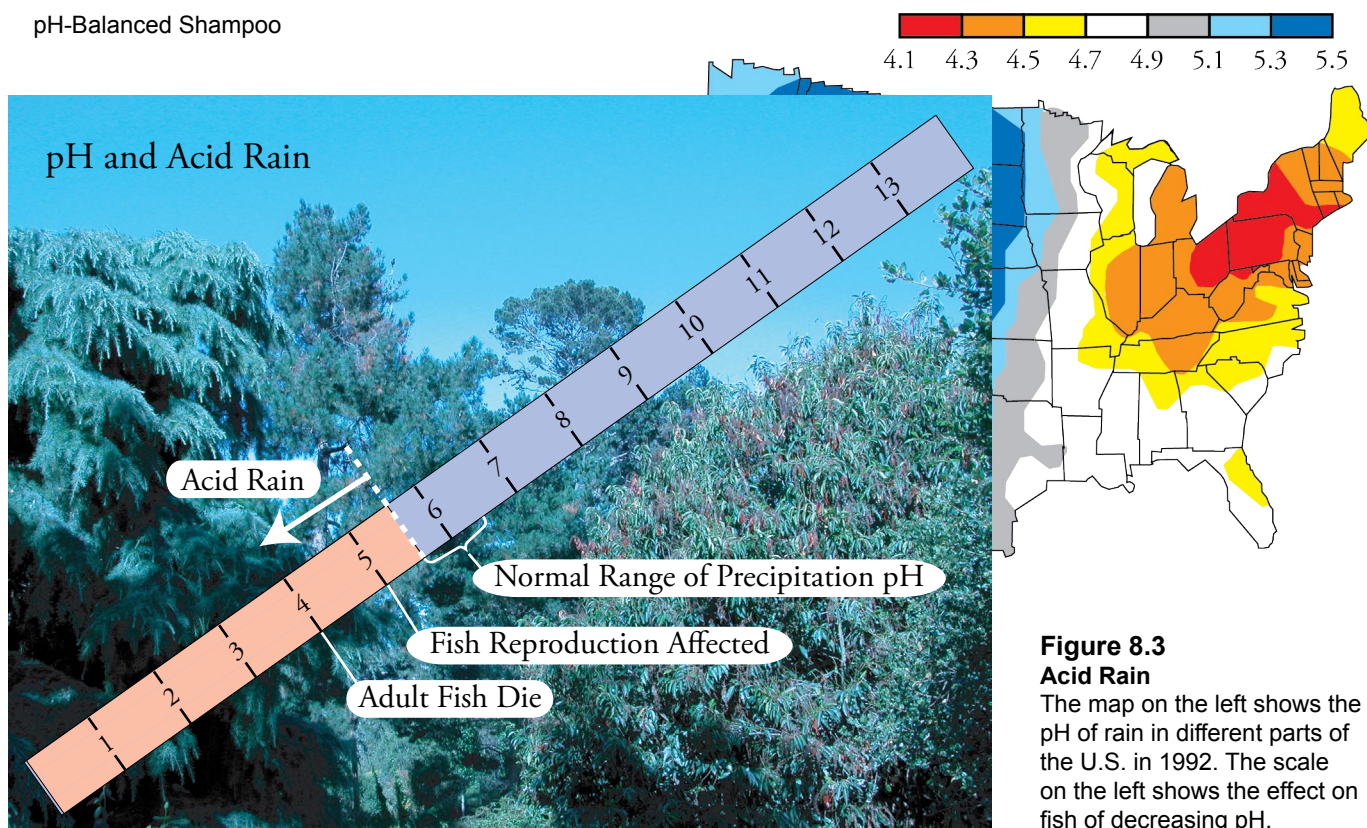


## 8.2 pH and Acidic and Basic Solutions



pH-Balanced Shampoo

The scientific term **pH** has crept into our everyday language. Advertisements encourage us to choose products that are “pH balanced,” while environmentalists point to the lower pH of rain in certain parts of the country as a cause of ecological damage (Figure 8.3). The term was originated by chemists to describe the acidic and basic strengths of solutions.



**Figure 8.3**  
**Acid Rain**

The map on the left shows the pH of rain in different parts of the U.S. in 1992. The scale on the left shows the effect on fish of decreasing pH.

We know that an Arrhenius acid donates  $\text{H}^+$  ions to water to create  $\text{H}_3\text{O}^+$  ions. The resulting solution is called an acidic solution. We also know that when you add a certain amount of a strong acid to one sample of water—say the water’s volume is a liter—and add the same amount of a weak acid to another sample of water whose volume is also a liter, the strong acid generates more  $\text{H}_3\text{O}^+$  ions in solution. Because the concentration of  $\text{H}_3\text{O}^+$  ions in the strong acid solution is higher (there are more  $\text{H}_3\text{O}^+$  ions per liter of solution), we say it is more acidic than the weak acid solution. A solution can also be made more acidic by the addition of more acid (while the amount of water remains the same). The pH scale can be used to describe the relative acidity of solutions.

If you take other chemistry courses, you will probably learn how pH is defined and how the pH values of solutions are determined. For now, all you need to remember is that acidic solutions have pH values less than 7, and that the more acidic a solution is, the lower its pH. A change of one pH unit reflects a ten-fold change in  $\text{H}_3\text{O}^+$  ion concentration. For example, a solution with a pH of 5 has ten times the concentration

OBJECTIVE 6

OBJECTIVE 7



of  $\text{H}_3\text{O}^+$  ions as a solution with a pH of 6. The pH of some common solutions are listed in Figure 8.4. Note that gastric juice in our stomach has a pH of about 1.4, and orange juice has a pH of about 2.8. Thus gastric juice is more than ten times more concentrated in  $\text{H}_3\text{O}^+$  ions than orange juice.

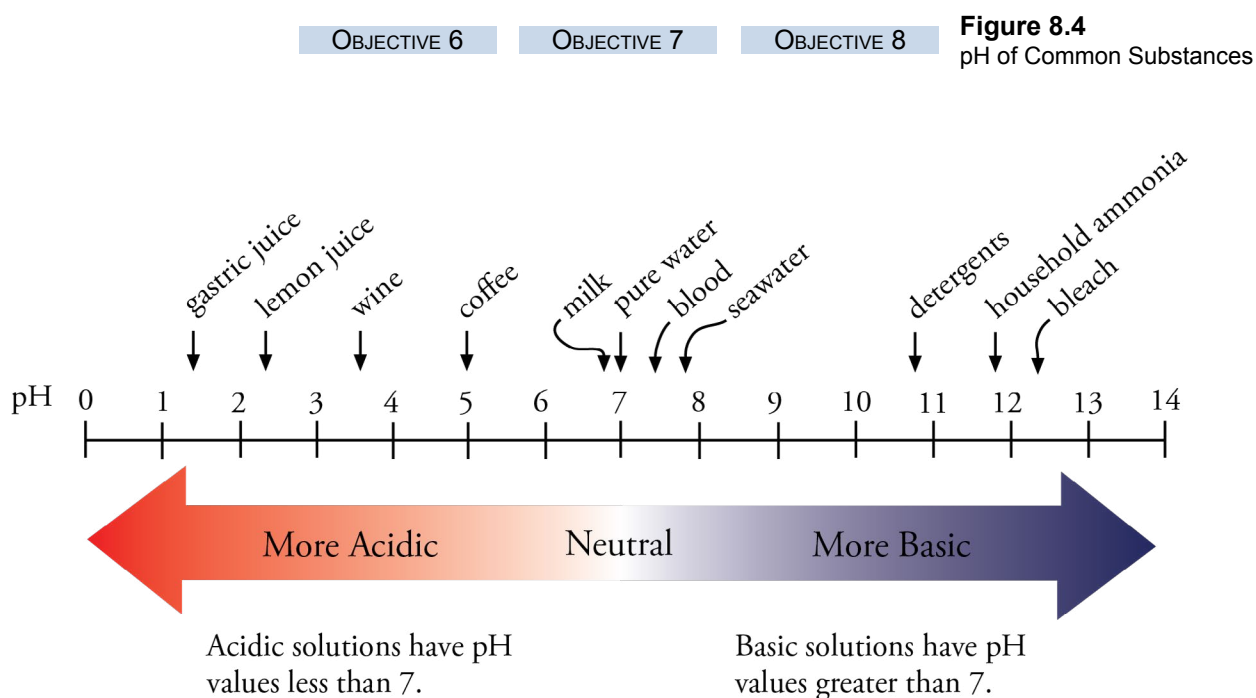
The pH scale is also used to describe basic solutions, which are formed when an Arrhenius base is added to water, generating  $\text{OH}^-$  ions. When you add a certain amount of a strong base to one sample of water—again, let's say a liter—and add the same amount of a weak base to another sample of water whose volume is the same, the strong base generates more  $\text{OH}^-$  ions in solution. Because the concentration of  $\text{OH}^-$  ions in the strong base solution is higher (there are more  $\text{OH}^-$  ions per liter of solution), we say it is more basic than the weak base solution. A solution can also be made more basic by the addition of more base while the amount of water is held constant.

Basic solutions have pH values greater than 7, and the more basic the solution is, the higher its pH. A change of one pH unit reflects a ten-fold change in  $\text{OH}^-$  ion concentration. For example, a solution with a pH of 12 has ten times the concentration of  $\text{OH}^-$  ions as does a solution with a pH of 11. The pH difference of about 4 between household ammonia solutions (pH about 11.9) and seawater (pH about 7.9) shows that household ammonia has about ten thousand ( $10^4$ ) times the hydroxide ion concentration of seawater.

In nature, water contains dissolved substances that make it slightly acidic, but pure water is neutral and has a pH of 7 (Figure 8.4).

OBJECTIVE 6

OBJECTIVE 8



## OBJECTIVE 9

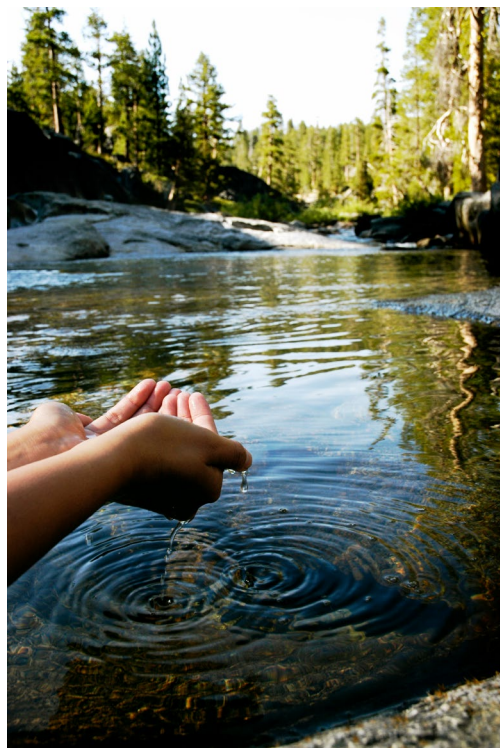
In the laboratory, we can detect acids and bases in solution in several ways. Perhaps the simplest test uses a substance called litmus, a natural dye derived from lichen. It



Litmus, whose natural source is lichen, can be applied to the surface of paper that is then used to identify acidic and basic solutions.

turns red in acidic conditions and blue in basic conditions. Litmus paper is paper that has been coated with litmus. To test if a liquid is acidic, we add a drop of the liquid to blue litmus paper, which is litmus paper that has been made slightly basic and therefore blue. If the paper turns red, the liquid is acidic. To test to see if a liquid is basic, we add a drop of the liquid to red litmus paper, which is litmus paper that has been made slightly acidic and therefore red. If the paper turns blue, the liquid is basic.

### 8.3 Arrhenius Acid-Base Reactions



Neutralization reactions keep our bodies in balance and also maintain the “health” of the world around us.

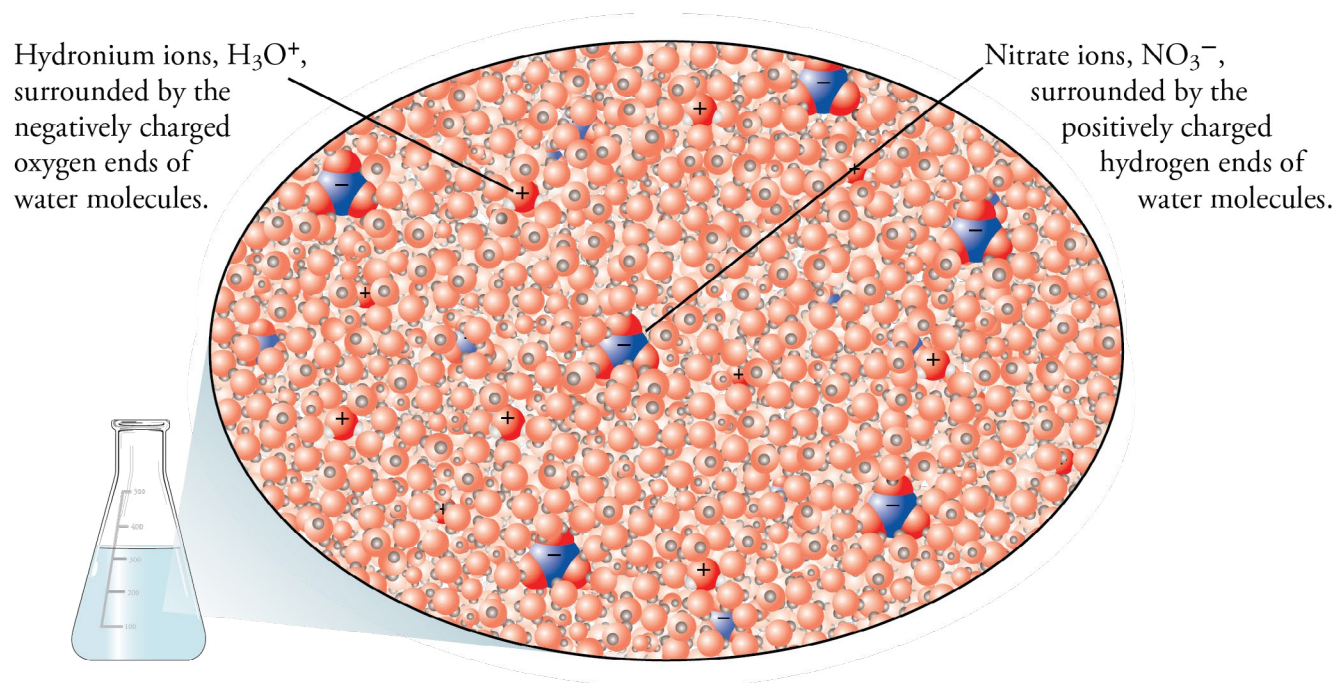
When an Arrhenius acid is combined with an Arrhenius base, we say that they neutralize each other. By this, we mean that the acid counteracts the properties of the base, and the base counteracts the properties of the acid. For example, a strong acid, such as nitric acid, must be handled with extreme caution, because if it gets on your skin, it could cause severe chemical burns. If you accidentally spilled nitric acid on a laboratory bench, however, you could quickly pour a solution of a weak base, such as sodium hydrogen carbonate, on top of the spill to neutralize the acid and make it safer to wipe. In a similar way, a solution of a weak acid, such as acetic acid, can be poured on a strong base spill to neutralize the base before cleanup. Therefore, reactions between Arrhenius acids and bases are often called **neutralization reactions**.

Neutralization reactions are important in maintaining the necessary balance of chemicals in your body, and they help keep a similar balance in our oceans and lakes. Neutralization reactions are used in industry to make a wide range of products, including pharmaceuticals, food additives, and fertilizers. Let's look at some of the different forms of Arrhenius acid-base reactions, how they can be visualized, and how to describe them with chemical equations.

## Reactions of Aqueous Strong Arrhenius Acids and Aqueous Strong Arrhenius Bases

The reaction between the strong acid nitric acid and the strong base sodium hydroxide is our first example. Figure 8.5 shows the behavior of nitric acid in solution. As a strong acid, virtually every  $\text{HNO}_3$  molecule donates an  $\text{H}^+$  ion to water to form a hydronium ion,  $\text{H}_3\text{O}^+$ , and a nitrate ion,  $\text{NO}_3^-$ . Because the reaction goes essentially to completion, you can picture the solution as containing  $\text{H}_2\text{O}$ ,  $\text{NO}_3^-$ , and  $\text{H}_3\text{O}^+$ , with no  $\text{HNO}_3$  remaining. The negatively charged oxygen ends of the water molecules surround the positive hydronium ions, and the positively charged hydrogen ends of water molecules surround the nitrate ions.

OBJECTIVE 10A



**Figure 8.5**  
Aqueous Nitric Acid

Like a water solution of any ionic compound, a solution of sodium hydroxide ( $\text{NaOH}$ ) consists of ions separated and surrounded by water molecules. At the instant that the solution of sodium hydroxide is added to the aqueous nitric acid, there are four different ions in solution surrounded by water molecules:  $\text{H}_3\text{O}^+$ ,  $\text{NO}_3^-$ ,  $\text{Na}^+$ , and  $\text{OH}^-$  (Figure 8.6 on the next page).

OBJECTIVE 10A

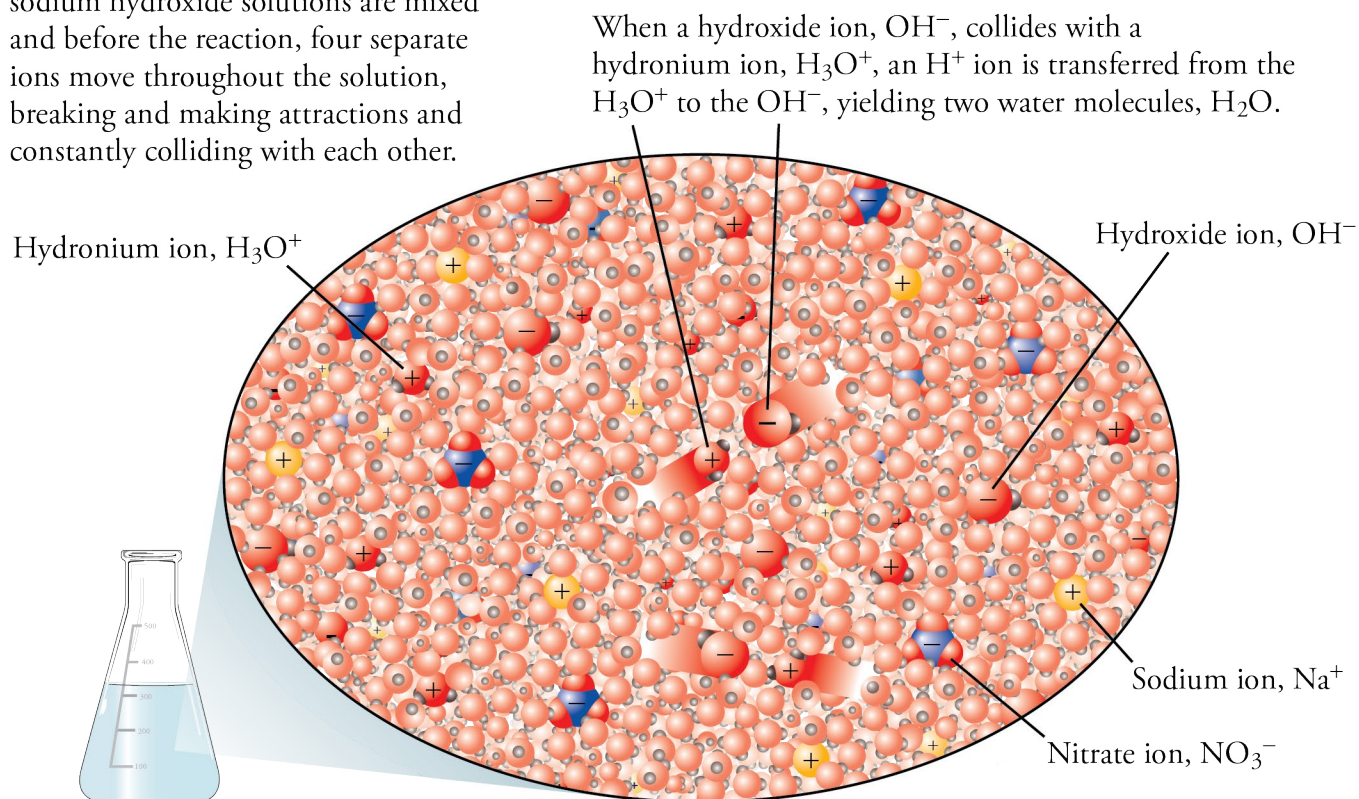


**Figure 8.6**

Water Solution of Nitric Acid and Sodium Hydroxide before Reaction

OBJECTIVE 10A

At the instant after nitric acid and sodium hydroxide solutions are mixed and before the reaction, four separate ions move throughout the solution, breaking and making attractions and constantly colliding with each other.

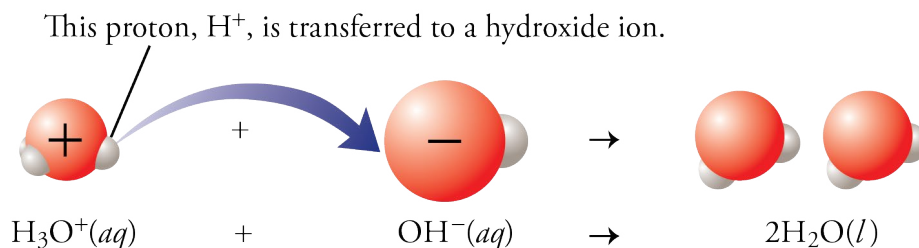


OBJECTIVE 10A

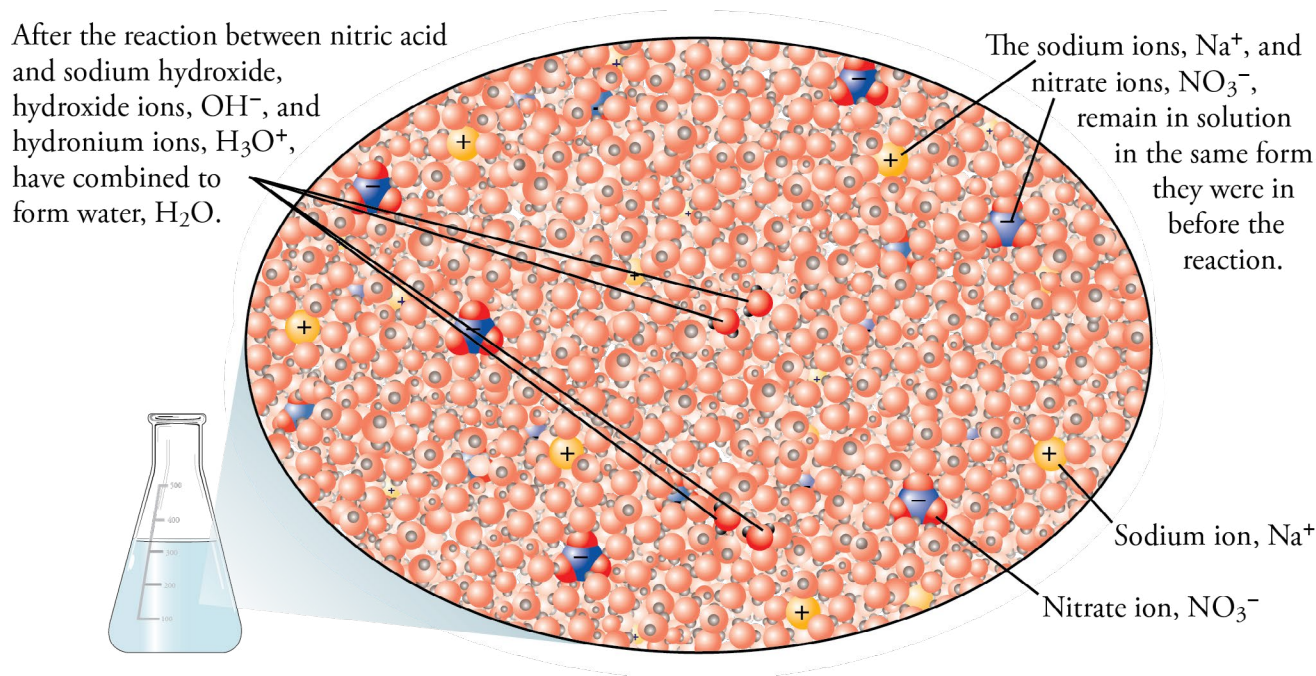
The ions in solution move in a random way, like any particles in a liquid, so they will constantly collide with other ions. When two cations or two anions collide, they repel each other and move apart. When a hydronium ion and a nitrate ion collide, it is possible that the  $\text{H}_3\text{O}^+$  ion will return an  $\text{H}^+$  ion to the  $\text{NO}_3^-$  ion, but nitrate ions are stable enough in water to make this unlikely. When a sodium ion collides with a hydroxide ion, they may stay together for a short time, but their attraction is too weak and water molecules collide with them and push them apart. When hydronium ions and hydroxide ions collide, however, they react to form water (Figure 8.7), so more water molecules are shown in Figure 8.8 than in Figure 8.6.

**Figure 8.7**

Reaction Between Hydronium Ion and Hydroxide Ion





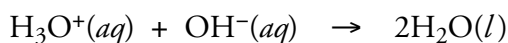


OBJECTIVE 10A

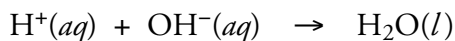
**Figure 8.8**

After Reaction of Nitric Acid and Sodium Hydroxide

The sodium and nitrate ions are unchanged in the reaction. They were separate and surrounded by water molecules at the beginning of the reaction, and they are still separate and surrounded by water molecules after the reaction. They were important in delivering the hydroxide and hydronium ions to solution, but they did not actively participate in the reaction. In other words, they are spectator ions, so they are left out of the net ionic chemical equation. The net ionic equation for the reaction is therefore



Most chemists are in the habit of describing reactions such as this one in terms of  $\text{H}^+$  rather than  $\text{H}_3\text{O}^+$ , even though hydrogen ions do not exist in a water solution in the same sense that sodium ions do. When an acid loses a hydrogen atom as  $\text{H}^+$ , the proton immediately forms a covalent bond to some other atom. In water, it forms a covalent bond to a water molecule to produce the hydronium ion. Although  $\text{H}_3\text{O}^+$  is a better description of what is found in acid solutions, it is still convenient and conventional to write  $\text{H}^+$  in equations instead. You can think of  $\text{H}^+$  as a shorthand notation for  $\text{H}_3\text{O}^+$ . Therefore, the following net ionic equation is a common way to describe the net ionic equation above.



## Writing Equations for Reactions Between Acids and Bases

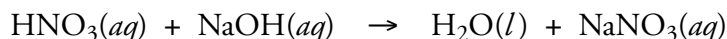
The procedure for writing equations for acid-base reactions is very similar to that used to write equations for precipitation reactions in Section 7.3.

The first step in writing an equation for the reaction between nitric acid,  $\text{HNO}_3$ , and the base sodium hydroxide,  $\text{NaOH}$ , is to predict the formulas for the products by recognizing that most Arrhenius neutralization reactions, like the reaction between

OBJECTIVE 10A

OBJECTIVE 11

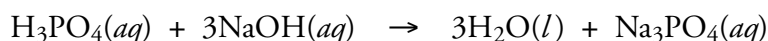
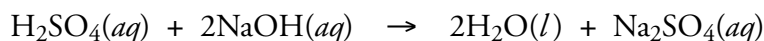
nitric acid and sodium hydroxide, are double-displacement reactions.



## OBJECTIVE 11

We consider the positive portion of the acid to be  $\text{H}^+$ , so for the reaction above, A is  $\text{H}^+$ , B is  $\text{NO}_3^-$ , C is  $\text{Na}^+$ , and D is  $\text{OH}^-$ . When  $\text{H}^+$  ions combine with  $\text{OH}^-$  ions, they form HOH (that is, water,  $\text{H}_2\text{O}$ ). The ion formulas  $\text{Na}^+$  and  $\text{NO}_3^-$  are combined in the complete equation as the CB formula,  $\text{NaNO}_3$ .

In picturing reactions of a polyprotic acid with a strong base, we shall assume that enough base is added to react with all of the acidic hydrogen atoms. The following complete equations describe the reactions of the diprotic acid sulfuric acid and the triprotic acid phosphoric acid with sodium hydroxide. Each equation represents the sum of a series of reactions in which the acidic hydrogen atoms are removed one at a time.

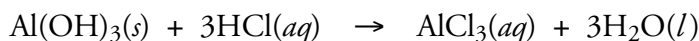


## OBJECTIVE 11

The problems at the end of the chapter ask you to write complete equations for reactions like these. Note that these too are double-displacement reactions. In each of these examples, A is  $\text{H}^+$ , C is  $\text{Na}^+$ , and D is  $\text{OH}^-$ . In the first reaction, B is  $\text{SO}_4^{2-}$ , and in the second reaction, B is  $\text{PO}_4^{3-}$ .

## OBJECTIVE 10B

One of the useful properties of acids is that they will react with insoluble ionic compounds that contain basic anions. Because the products of such reactions are soluble, acids can be used to dissolve normally insoluble ionic compounds (See Special Topic 8.2: *Precipitation, Acid-Base Reactions, and Tooth Decay*). For example, water-insoluble aluminum hydroxide dissolves in a hydrochloric acid solution.



## EXAMPLE 8.2 - Neutralization Reactions

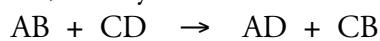
## OBJECTIVE 11

Write the complete equations for the neutralization reactions that take place when the following water solutions are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic hydroxide ions.)

- $\text{HCl}(aq) + \text{KOH}(aq)$
- $\text{H}_2\text{SO}_4(aq) + \text{KOH}(aq)$
- $\text{HNO}_3(aq) + \text{Mn}(\text{OH})_2(s)$

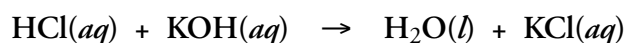
### Solution

- Neutralization reactions between strong monoprotic acids, such as  $\text{HCl}(aq)$ , and ionic compounds, such as  $\text{KOH}$ , are double-displacement reactions, so they have the form

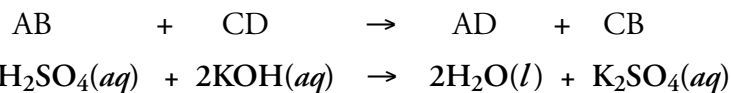


For  $\text{HCl}$ , A is  $\text{H}^+$ , and B is  $\text{Cl}^-$ . For  $\text{KOH}$ , C is  $\text{K}^+$ , and D is  $\text{OH}^-$ .

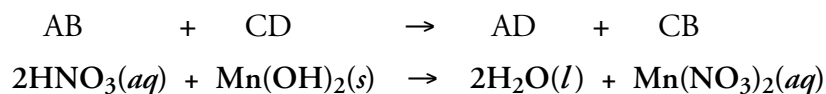
Therefore, AD is HOH or  $\text{H}_2\text{O}$ , which we know is a liquid, and CB is  $\text{KCl}$ , which is a water-soluble ionic compound and thus aqueous.



- b. For  $\text{H}_2\text{SO}_4$  in a double-displacement reaction, A is  $\text{H}^+$ , and B is  $\text{SO}_4^{2-}$ . (In neutralization reactions, you can assume that all of the acidic hydrogen atoms are lost to the base. Monoprotic acids lose one  $\text{H}^+$  ion, diprotic acids such as  $\text{H}_2\text{SO}_4$  lose two  $\text{H}^+$  ions, and triprotic acids such as  $\text{H}_3\text{PO}_4$  lose three  $\text{H}^+$  ions.) For  $\text{KOH}$ , C is  $\text{K}^+$ , and D is  $\text{OH}^-$ . Thus AD is  $\text{H}_2\text{O}$ , and CB is  $\text{K}_2\text{SO}_4$ , a water-soluble ionic compound. The two  $\text{H}^+$  ions from the diprotic acid  $\text{H}_2\text{SO}_4$  react with the two  $\text{OH}^-$  ions from two units of  $\text{KOH}$  to form two  $\text{H}_2\text{O}$  molecules.



- c. For  $\text{HNO}_3$  in a double-displacement reaction, A is  $\text{H}^+$ , and B is  $\text{NO}_3^-$ . For  $\text{Mn}(\text{OH})_2$ , C is  $\text{Mn}^{2+}$ , and D is  $\text{OH}^-$ . Thus AD is  $\text{H}_2\text{O}$ , and CB is  $\text{Mn}(\text{NO}_3)_2$ , a water-soluble ionic compound. Two  $\text{H}^+$  ions from two nitric acid molecules react with the two  $\text{OH}^-$  ions from the  $\text{Mn}(\text{OH})_2$  to form two  $\text{H}_2\text{O}$  molecules.



## EXERCISE 8.2 - Neutralization Reactions

Write the complete equation for the neutralization reactions that take place when the following water solutions are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic hydroxide ions.)

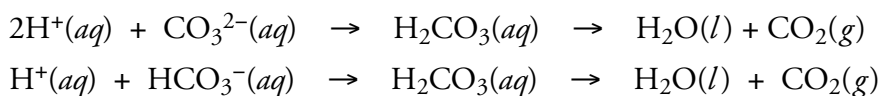
- $\text{HCl}(\text{aq}) + \text{NaOH}(\text{aq})$
- $\text{HF}(\text{aq}) + \text{LiOH}(\text{aq})$
- $\text{H}_3\text{PO}_4(\text{aq}) + \text{LiOH}(\text{aq})$
- $\text{Fe}(\text{OH})_3(\text{s}) + \text{HNO}_3(\text{aq})$

There is an animation that will help you visualize reactions between acids and bases at the textbook's Web site.

OBJECTIVE 11

## Reactions of Arrhenius Acids and Ionic Compounds Containing Carbonate or Hydrogen Carbonate

The reaction between an acid and an ionic compound containing either carbonate or hydrogen carbonate leads to carbon dioxide and water as products. The addition of  $\text{H}^+$  ions to  $\text{CO}_3^{2-}$  or  $\text{HCO}_3^-$  forms carbonic acid,  $\text{H}_2\text{CO}_3$ . Carbonic acid, however, is unstable in water, so when it forms, it decomposes into carbon dioxide,  $\text{CO}_2(\text{g})$ , and water,  $\text{H}_2\text{O}(\text{l})$ .

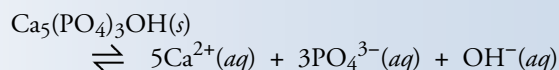


OBJECTIVE 10C

OBJECTIVE 12

## SPECIAL TOPIC 8.2 Precipitation, Acid-Base Reactions, and Tooth Decay

Teeth have a protective coating of hard enamel that is about 2 mm thick and consists of about 98% hydroxyapatite,  $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ . Like any ionic solid surrounded by a water solution, the hydroxyapatite is constantly dissolving and reprecipitating.

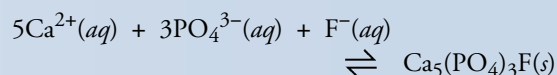


Your saliva provides the calcium ions and the phosphate ions for this process, and as long as your saliva does not get too acidic, it will contain enough hydroxide to keep the rate of solution and the rate of precipitation about equal. Thus there is no net change in the amount of enamel on your teeth.

Unfortunately, certain foods can upset this balance. The bacteria in your mouth break down your food, especially food high in sugar, to form acids such as acetic acid and lactic acid. These acids neutralize the hydroxide in your saliva, slowing the precipitation of enamel. The  $\text{Ca}_5(\text{PO}_4)_3\text{OH}$  continues to go into solution, so there is a net loss of the protective coating on the teeth.

Fluoride in our drinking water and our toothpaste can help minimize the damage described above. The fluoride ion takes the place of the hydroxide ion to precipitate fluorapatite,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , a compound very similar to the

original enamel.



Fluorapatite is 100 times less soluble than hydroxyapatite, so it is less likely to be affected by the acid formed by the bacteria.



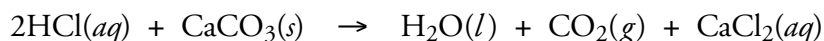
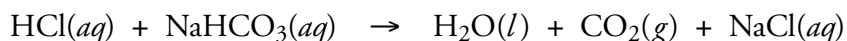
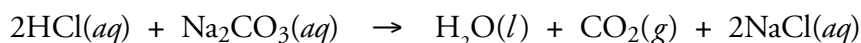
The natural enamel that coats teeth is mostly  $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ . Fluoride in our water or toothpaste leads to the less soluble  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  replacing  $\text{Ca}_5(\text{PO}_4)_3\text{OH}$  in tooth enamel, helping to protect our teeth from tooth decay.

### OBJECTIVE 11



Acids can be used to make limestone more permeable to oil by converting solid calcium carbonate into water-soluble calcium chloride.

Thus, when  $\text{H}_2\text{CO}_3$  would be predicted as a product for a double-displacement reaction, write " $\text{H}_2\text{O}(l) + \text{CO}_2(g)$ " instead. Three examples are below.



The third equation above describes a reaction that helps the oil industry extract more oil from a well. For oil to be pumped from deep in the earth to the surface, it must first seep through underground rock formations to the base of the oil well's pipes. Limestone, which is composed of  $\text{CaCO}_3$ , can be made more permeable to oil by pumping hydrochloric acid down into the limestone formations, converting the insoluble calcium carbonate to soluble calcium chloride.

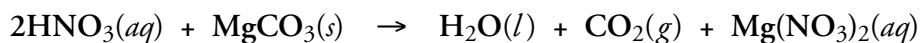


### EXAMPLE 8.3 - Neutralization Reactions with Compounds Containing Carbonate

Write the complete equation for the reaction between  $\text{HNO}_3(aq)$  and water-insoluble solid  $\text{MgCO}_3$ .

*Solution*

Translated into the general format of double-displacement reactions, A is  $\text{H}^+$ , B is  $\text{NO}_3^-$ , C is  $\text{Mg}^{2+}$ , and D is  $\text{CO}_3^{2-}$ . Compound AD would therefore be  $\text{H}_2\text{CO}_3$ , but this decomposes to form  $\text{H}_2\text{O}(l)$  and  $\text{CO}_2(g)$ . Compound CB is  $\text{Mg}(\text{NO}_3)_2$ , which is a water-soluble ionic compound and thus aqueous.



OBJECTIVE 11

### EXERCISE 8.3 - Neutralization Reactions with Carbonate Containing Compounds

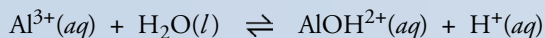
Write the complete equation for the neutralization reaction that takes place when water solutions of sodium carbonate,  $\text{Na}_2\text{CO}_3$ , and hydrobromic acid,  $\text{HBr}$ , are mixed.

OBJECTIVE 11

## SPECIAL TOPIC 8.3 Saving Valuable Books

Before the 19th century, paper in Europe was made from linen or old rags. Supplies of these materials dwindled as the demand for paper soared, and new manufacturing methods and raw materials were sought. Paper began to be made from wood pulp, but the first such products contained microscopic holes that caused the ink to bleed and blur. To fill these holes, the paper was saturated with “alum,” which is aluminum sulfate,  $\text{Al}_2(\text{SO}_4)_3$ . The new process seemed to make a suitable paper, but as time passed, serious problems emerged.

The aluminum ions in alum, like many metal ions, are acidic in the Arrhenius sense, reacting with moisture from the air to release  $\text{H}^+$  ions.

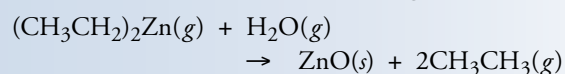
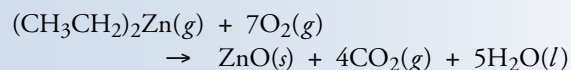


The  $\text{H}^+$  ions react in turn with the paper and weaken it. Many valued books are so brittle that they cannot be handled without their pages crumbling.

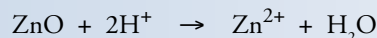
Several techniques are now being developed to neutralize the acid in the paper. As we have seen, most acid-base reactions take place in water, and there are obvious problems with dunking a book in an aqueous solution of base. The challenge, then, has been to develop a technique in which a gas is used to neutralize acid in the paper without causing further damage.

One such technique is called the DEZ treatment. DEZ, or diethyl zinc,  $(\text{CH}_3\text{CH}_2)_2\text{Zn}$ , can be made gaseous near room temperature. It reacts with either oxygen or water

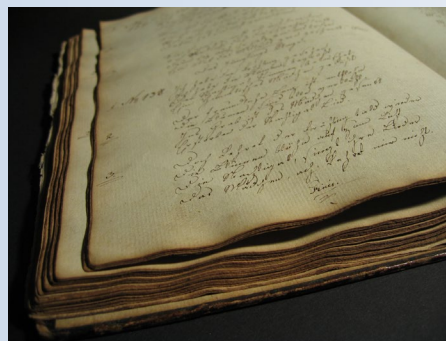
vapor to form zinc oxide,  $\text{ZnO}(s)$ , which is deposited evenly on the paper.



The zinc oxide contains the basic anion oxide,  $\text{O}^{2-}$ , which reacts with  $\text{H}^+$  ions to neutralize the acid in the paper.



Damage that has already been done cannot be reversed, so the goal is to save as many books as possible before they deteriorate so much that they cannot be handled.

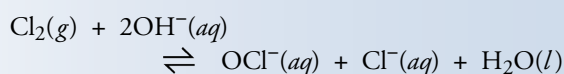


The acid in the paper used to make some books damages the paper and leaves it brittle. The paper in the book above was made with a process that left the paper acidic.

Do you want to know why bleach bottles have a warning label that tells you not to mix the bleach with acidic cleaning agents, such as toilet bowl cleaners? The explanation is in Special Topic 8.4 below.

## SPECIAL TOPIC 8.4 Be Careful with Bleach

Common bleach, used for household cleaning and laundering, is a water solution of sodium hypochlorite,  $\text{NaClO}(aq)$ . The hypochlorite ion is made by reacting chlorine gas with a basic solution.



This reaction is reversible, so the chlorine atoms are constantly switching back and forth from  $\text{Cl}_2$  to  $\text{OCl}^-$ . In a basic solution, the forward reaction is fast enough to ensure that most of the chlorine in the bottle of bleach is in the  $\text{OCl}^-$  form.

If the bleach is added to an acidic solution, the hydroxide ions in the basic solution of bleach react with the acidic  $\text{H}^+$  ions to form water. With fewer hydroxide ions available, the reaction between the  $\text{OH}^-$  and the  $\text{Cl}_2$  slows down, but the reverse reaction continues at the same pace. This creates

potentially dangerous levels of chlorine gas and is the reason that the labels on bleach bottles warn against mixing bleach with other cleaning agents such as toilet bowl cleaners. Toilet bowl cleaners are usually acidic, containing acids such as phosphoric acid,  $\text{H}_3\text{PO}_4$ , or hydrogen sulfate,  $\text{HSO}_4^-$ .



Mixing bleach and toilet bowl cleaners can be dangerous.

## 8.4 Brønsted-Lowry Acids and Bases

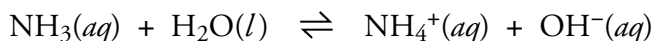
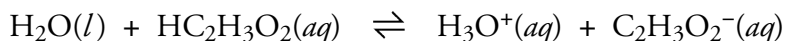
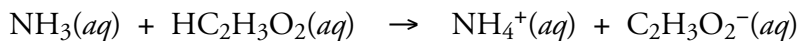
Although the Arrhenius definitions of acid, base, and acid-base reaction are very useful, an alternate set of definitions is also commonly employed. In this system, a **Brønsted-Lowry acid** is a proton ( $\text{H}^+$ ) donor, a **Brønsted-Lowry base** is a proton acceptor, and a **Brønsted-Lowry acid-base reaction** is a proton transfer. Table 8.2 summarizes the definitions of acid and base in the Arrhenius and Brønsted-Lowry systems.

**Table 8.2**  
Definitions of Acid and Base

System	Acid Definition	Base Definition
Arrhenius	Generates $\text{H}_3\text{O}^+$ when added to water	Generates $\text{OH}^-$ when added to water
Brønsted-Lowry	Proton ( $\text{H}^+$ ) Donor in Reaction	Proton ( $\text{H}^+$ ) Acceptor in Reaction

To better understand the differences and to understand why new definitions were suggested, consider the following reactions.

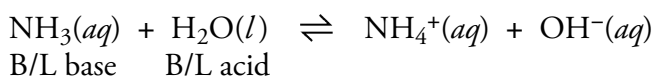
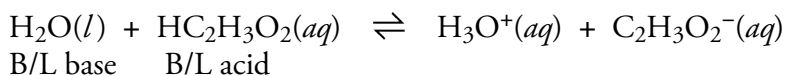
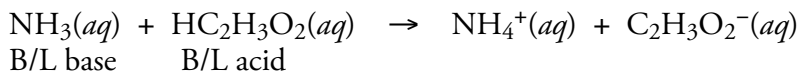
## OBJECTIVE 13



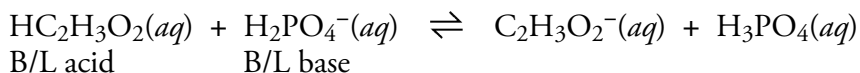
These reactions are very similar, but only the first reaction would be considered an acid-base reaction in the Arrhenius system. In each of the reactions, an  $\text{H}^+$  is transferred from one reactant to another, but only the first is a reaction between an Arrhenius acid and an Arrhenius base. In the first reaction, an  $\text{H}^+$  is transferred from the Arrhenius weak acid acetic acid,  $\text{HC}_2\text{H}_3\text{O}_2(aq)$ , to the Arrhenius weak base ammonia,  $\text{NH}_3(aq)$ . In the second reaction, an  $\text{H}^+$  is transferred from the Arrhenius weak acid acetic acid,  $\text{HC}_2\text{H}_3\text{O}_2(aq)$ , to water, which is not considered an acid or a base in the Arrhenius sense. In the third reaction, an  $\text{H}^+$  is transferred from water, which is not considered an acid or base in the Arrhenius sense, to the Arrhenius weak base ammonia,  $\text{NH}_3(aq)$ .

The Brønsted-Lowry system allows us to describe all of these reactions as acid-base reactions. They are repeated below, with the Brønsted-Lowry acids and bases labeled. Note that in each case, the acid loses an  $\text{H}^+$  ion as it reacts, and the base gains an  $\text{H}^+$  ion.

## OBJECTIVE 13



Acetic acid reacts with the dihydrogen phosphate polyatomic ion,  $\text{H}_2\text{PO}_4^-$ , in a reversible reaction. In the forward reaction, acetic acid acts as the Brønsted-Lowry acid and dihydrogen phosphate acts as the Brønsted-Lowry base



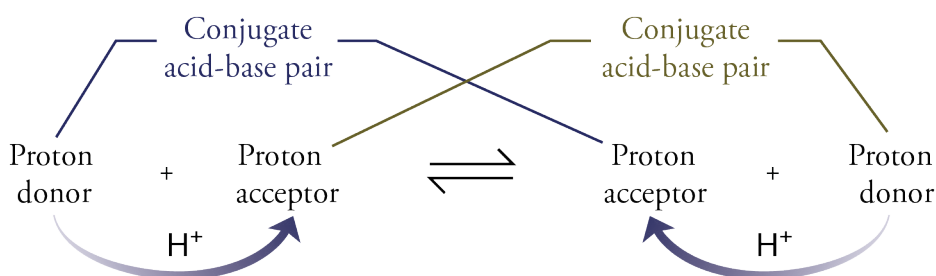
The reverse reaction, too, is a Brønsted-Lowry acid-base reaction. An  $\text{H}^+$  ion is transferred from  $\text{H}_3\text{PO}_4$  (the acid) to a  $\text{C}_2\text{H}_3\text{O}_2^-$  ion (the base). The Brønsted-Lowry base for the forward reaction ( $\text{H}_2\text{PO}_4^-$ ) gains an  $\text{H}^+$  ion to form  $\text{H}_3\text{PO}_4$ , which then acts as a Brønsted-Lowry acid in the reverse reaction and returns the  $\text{H}^+$  ion to  $\text{C}_2\text{H}_3\text{O}_2^-$ . Chemists say that  $\text{H}_3\text{PO}_4$  is the conjugate acid of  $\text{H}_2\text{PO}_4^-$ . The **conjugate acid** of a molecule or ion is the molecule or ion that forms when one  $\text{H}^+$  ion is added. The formulas  $\text{H}_3\text{PO}_4$  and  $\text{H}_2\text{PO}_4^-$  represent a **conjugate acid-base pair**, molecules or ions that differ by one  $\text{H}^+$  ion.

## OBJECTIVE 14

## OBJECTIVE 15

Likewise, the Brønsted-Lowry acid for the forward reaction ( $\text{HC}_2\text{H}_3\text{O}_2$ ) loses an  $\text{H}^+$  ion to form  $\text{C}_2\text{H}_3\text{O}_2^-$ , which acts as a Brønsted-Lowry base in the reverse reaction and regains the  $\text{H}^+$  ion. Chemists say that  $\text{C}_2\text{H}_3\text{O}_2^-$  is the conjugate base of  $\text{HC}_2\text{H}_3\text{O}_2$ . The **conjugate base** of a molecule or ion is the molecule or ion that forms when one  $\text{H}^+$  ion is removed. The formulas  $\text{HC}_2\text{H}_3\text{O}_2$  and  $\text{C}_2\text{H}_3\text{O}_2^-$  represent a conjugate acid-base pair (Figure 8.9).

**Figure 8.9**  
Conjugate Acid-Base Pairs



## EXAMPLE 8.4 - Conjugate Acids

## OBJECTIVE 14

Write the formula for the conjugate acid of (a)  $\text{F}^-$ , (b)  $\text{NH}_3$ , (c)  $\text{HSO}_4^-$ , and (d)  $\text{CrO}_4^{2-}$ .

*Solution*

In each case, the formula for the conjugate acid is derived by adding one  $\text{H}^+$  ion to the formulas above.

- a.  $\text{HF}$    b.  $\text{NH}_4^+$    c.  $\text{H}_2\text{SO}_4$    d.  $\text{HCrO}_4^-$

## EXERCISE 8.4 - Conjugate Acids

## OBJECTIVE 14

Write the formula for the conjugate acid of (a)  $\text{NO}_2^-$ , (b)  $\text{HCO}_3^-$ , (c)  $\text{H}_2\text{O}$ , and (d)  $\text{PO}_4^{3-}$ .

## EXAMPLE 8.5 - Conjugate Bases

## OBJECTIVE 15

Write the formula for the conjugate base of (a)  $\text{HClO}_3$ , (b)  $\text{H}_2\text{SO}_3$ , (c)  $\text{H}_2\text{O}$ , and (d)  $\text{HCO}_3^-$ .

*Solution*

In each case, the formula for the conjugate base is derived by removing one  $\text{H}^+$  ion from the formulas above.

- a.  $\text{ClO}_3^-$    b.  $\text{HSO}_3^-$    c.  $\text{OH}^-$    d.  $\text{CO}_3^{2-}$

## EXERCISE 8.5 - Conjugate Bases

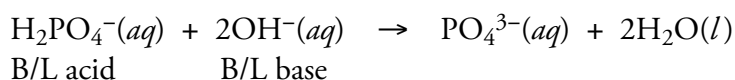
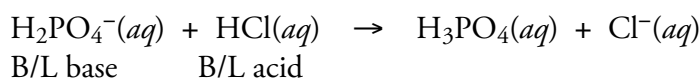
## OBJECTIVE 15

Write the formula for the conjugate base of (a)  $\text{H}_2\text{C}_2\text{O}_4$ , (b)  $\text{HBrO}_4$ , (c)  $\text{NH}_3$ , and (d)  $\text{H}_2\text{PO}_4^-$ .



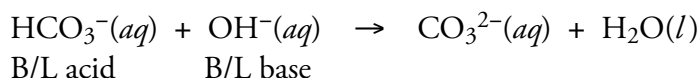
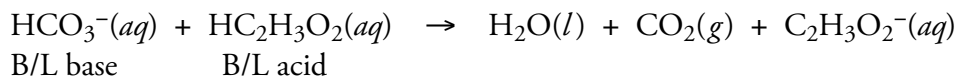
## OBJECTIVE 16

Some substances can act as a Brønsted-Lowry acid in one reaction and a Brønsted-Lowry base in another. Consider the following net ionic equations for the reaction of dihydrogen phosphate ion with either the acid hydrochloric acid or the strong base hydroxide.



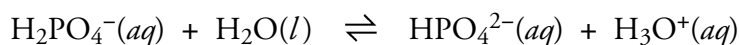
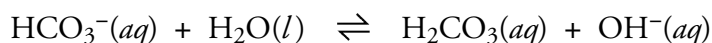
In the first reaction, the dihydrogen phosphate acts as a Brønsted-Lowry base, and in the second reaction, it acts as a Brønsted-Lowry acid. A substance that can act as either a Brønsted-Lowry acid or a Brønsted-Lowry base, depending on the circumstances, is called an **amphoteric** substance.

The hydrogen carbonate ion is another example of an amphoteric substance. In the first reaction below, it acts as a Brønsted-Lowry base, and in the second reaction, it acts as a Brønsted-Lowry acid.



Because both dihydrogen phosphate and hydrogen carbonate (and other substances like them) can be either Brønsted-Lowry acids or bases, they cannot be described as a Brønsted-Lowry acid or base except with reference to a specific acid-base reaction. For this reason, the Arrhenius definitions of acids and bases are the ones used to categorize isolated substances on the stockroom shelf. A substance generates either hydronium ions, hydroxide ions, or neither when added to water, so it is always either an acid, a base, or neutral in the Arrhenius sense. Hydrogen carbonate is an Arrhenius base because it yields hydroxide ions when added to water. Dihydrogen phosphate is an Arrhenius acid because it generates hydronium ions when added to water.

## OBJECTIVE 17

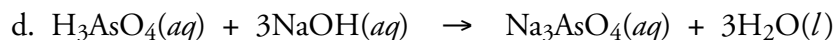
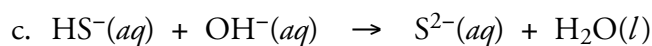
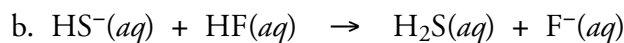
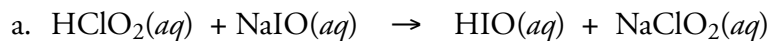


Thus we have two systems for describing acids, bases, and acid-base reactions. The Brønsted-Lowry system is often used to describe specific acid-base reactions, but the Arrhenius system is used to describe whether isolated substances are acids, bases, or neither.

### EXAMPLE 8.6 - Brønsted-Lowry Acids and Bases

#### OBJECTIVE 18

Identify the Brønsted-Lowry acid and base for the forward reaction in each of the following equations..



#### Solution

a. The  $\text{HClO}_2$  loses an  $\text{H}^+$  ion, so it is the **Brønsted-Lowry acid**. The  $\text{IO}^-$  in the  $\text{NaIO}$  gains the  $\text{H}^+$  ion, so the  $\text{NaIO}$  is the **Brønsted-Lowry base**.

b. The  $\text{HF}$  loses an  $\text{H}^+$  ion, so it is the **Brønsted-Lowry acid**. The  $\text{HS}^-$  gains the  $\text{H}^+$  ion, so it is the **Brønsted-Lowry base**.

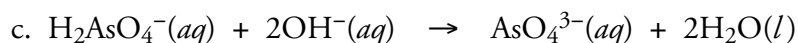
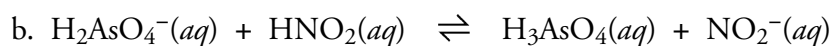
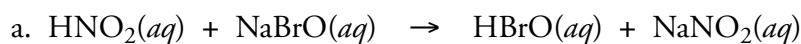
c. The  $\text{HS}^-$  loses an  $\text{H}^+$  ion, so it is the **Brønsted-Lowry acid**. The  $\text{OH}^-$  gains the  $\text{H}^+$  ion, so it is the **Brønsted-Lowry base**.

d. The  $\text{H}_3\text{AsO}_4$  loses three  $\text{H}^+$  ions, so it is the **Brønsted-Lowry acid**. Each  $\text{OH}^-$  in  $\text{NaOH}$  gains an  $\text{H}^+$  ion, so the  $\text{NaOH}$  is the **Brønsted-Lowry base**.

### EXERCISE 8.6 - Brønsted-Lowry Acids and Bases

#### OBJECTIVE 18

Identify the Brønsted-Lowry acid and base in each of the following equations..



## Chapter Glossary

**Arrhenius base** A substance that produces hydroxide ions,  $\text{OH}^-$ , when added to water.

**Basic solution** A solution with a significant concentration of hydroxide ions,  $\text{OH}^-$ .

**Strong base** A substance that generates at least one hydroxide ion in solution for every unit of substance added to water.

**Weak base** A substance that produces fewer hydroxide ions in water solution than particles of the substance added.

**Neutralization reaction** A chemical reaction between an acid and a base.

**Brønsted-Lowry acid-base reaction** A chemical reaction in which a proton,  $\text{H}^+$ , is transferred.

**Brønsted-Lowry Acid** A substance that donates protons,  $\text{H}^+$ , in a Brønsted-Lowry acid-base reaction.

**Brønsted-Lowry Base** A substance that accepts protons,  $\text{H}^+$ , in a Brønsted-Lowry acid-base reaction.

**Conjugate acid** The molecule or ion that forms when one  $\text{H}^+$  ion is added to a molecule or ion.

**Conjugate base** The molecule or ion that forms when one  $\text{H}^+$  ion is removed from a molecule or ion.

**Conjugate acid-base pair** Two molecules or ions that differ by one  $\text{H}^+$  ion.

**Amphoteric substance** A substance that can act as either a Brønsted-Lowry acid or a Brønsted-Lowry base, depending on the circumstances.

You can test yourself on the glossary terms at the textbook's Web site.

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

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

Chapter  
Objectives

### Section 8.1 Strong and Weak Acids and Bases

2. Identify ionic compounds containing hydroxide ions as strong bases.
3. Describe the changes that take place when ammonia,  $\text{NH}_3$ , is dissolved in water, and use this description to explain why ammonia is a weak Arrhenius base.
4. Describe the changes that take place when an ionic compound containing carbonate or hydrogen carbonate ions is dissolved in water, and use this description to explain why these anions are weak Arrhenius bases.
5. Given a name or formula for a substance, identify it as either (1) an Arrhenius strong acid, (2) an Arrhenius weak acid, (3) an Arrhenius strong base, or (4) an Arrhenius weak base.

### Section 8.2 pH and Acidic and Basic Solutions

6. Given the pH of a solution, identify the solution as acidic, basic, or neutral.
7. Given the pH of two acidic solutions, identify which solution is more acidic.
8. Given the pH of two basic solutions, identify which solution is more basic.
9. Describe how litmus paper can be used in the laboratory to identify whether a solution is acidic or basic.

### Section 8.3 Arrhenius Acid-Base Reactions

10. Describe the process that takes place at the molecular level for (a) a strong, monoprotic acid, such as  $\text{HNO}_3$ , and an aqueous strong base, such as  $\text{NaOH}$ , (b) a strong monoprotic acid, such as  $\text{HCl}(aq)$ , and an insoluble ionic compound, such as  $\text{Al}(\text{OH})_3$ , and (c) any monoprotic acid and a solution containing carbonate ions or hydrogen carbonate ions. Your description should include mention of the particles in solution before and after the reaction. It should also include a description of the process that leads to the reaction.
11. Given the names or formulas for a monoprotic or polyprotic acid and an ionic compound containing hydroxide, carbonate, or hydrogen carbonate ions, write the complete balanced equation that describes the neutralization reaction that takes place between them.
12. Identify  $\text{H}_2\text{O}(l)$  and  $\text{CO}_2(g)$  as the products of the reaction of an acid with carbonate,  $\text{CO}_3^{2-}$ , or hydrogen carbonate,  $\text{HCO}_3^-$ .

**Section 8.4 Brønsted-Lowry Acids and Bases**

13. Explain why the Brønsted-Lowry definitions for *acid* and *base* are often used, instead of the Arrhenius definitions, to describe acid-base reactions.
14. Given a formula for a molecule or ion, write the formula for its conjugate acid.
15. Given a formula for a molecule or ion, write the formula for its conjugate base.
16. Explain why a substance can be a Brønsted-Lowry acid in one reaction and a Brønsted-Lowry base in a different reaction. Give an example to illustrate your explanation.
17. Explain why the Arrhenius definitions for *acid* and *base*, and not the Brønsted-Lowry definitions, are used to describe whether an isolated substance is an acid or base.
18. Given a Brønsted-Lowry acid-base equation, identify the Brønsted-Lowry acid and Brønsted-Lowry base.

**Review Questions**

1. Define the following terms.
  - a. aqueous
  - b. spectator ion
  - c. double-displacement reaction
  - d. net ionic equation
2. Write the name of the polyatomic ions represented by the formulas  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$ .
3. Write the formulas for the polyatomic ions dihydrogen phosphate ion and acetate ion.
4. Which of the following formulas represents an ionic compound?
  - a.  $\text{MgCl}_2$
  - b.  $\text{PCl}_3$
  - c.  $\text{KHSO}_4$
  - d.  $\text{Na}_2\text{SO}_4$
  - e.  $\text{H}_2\text{SO}_3$
5. Write the names that correspond to the formulas  $\text{KBr}$ ,  $\text{Cu}(\text{NO}_3)_2$ , and  $(\text{NH}_4)_2\text{HPO}_4$ .
6. Write the formulas that correspond to the names nickel(II) hydroxide, ammonium chloride, and calcium hydrogen carbonate.
7. Predict whether each of the following is soluble or insoluble in water.
  - a. iron(III) hydroxide
  - b. barium sulfate
  - c. aluminum nitrate
  - d. copper(II) chloride
8. Describe how the strong monoprotic acid hydrochloric acid,  $\text{HCl}$  acts when it is added to water, including a description of the nature of the particles in solution before and after the reaction with water. If there is a reversible reaction with water, describe the forward and the reverse reactions.
9. Describe how the weak monoprotic acid acetic acid,  $\text{HC}_2\text{H}_3\text{O}_2$ , acts when it is added to water, including a description of the nature of the particles in solution before and after the reaction with water. If there is a reversible reaction with water, describe the forward and the reverse reactions.
10. Describe the process by which the ionic compound sodium hydroxide dissolves in water.
11. Write the complete equation for the precipitation reaction that takes place when water solutions of zinc chloride and sodium phosphate are mixed.



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

10-fold	greater than 7
acceptor	higher
added	hydroxide ions, OH <sup>-</sup> ,
amphoteric	hydroxides
Arrhenius	less than 7
basic	lower
blue	neutralize
Brønsted-Lowry	red
carbon dioxide, CO <sub>2</sub> ,	removed
donor	strong bases
double-displacement	transfer
fewer	water

12. According to the modern version of the Arrhenius theory of acids and bases, a base is a substance that produces \_\_\_\_\_ when it is added to water.
13. A solution that has a significant concentration of hydroxide ions is called a(n) \_\_\_\_\_ solution.
14. Compounds that contain hydroxide ions are often called \_\_\_\_\_.
15. All water-soluble hydroxides are \_\_\_\_\_.
16. A weak base is a base that produces \_\_\_\_\_ hydroxide ions in water solution than there are particles of base dissolved.
17. Acidic solutions have pH values \_\_\_\_\_, and the more acidic a solution is, the \_\_\_\_\_ its pH. A change of 1 pH unit reflects a(n) \_\_\_\_\_ change in H<sub>3</sub>O<sup>+</sup> ion concentration.
18. Basic solutions have pH values \_\_\_\_\_, and the more basic the solution is, the \_\_\_\_\_ its pH.
19. Litmus, a natural dye, is derived from lichen. It turns \_\_\_\_\_ in acidic conditions and \_\_\_\_\_ in basic conditions.
20. When an Arrhenius acid is combined with an Arrhenius base, we say that they \_\_\_\_\_ each other.
21. When hydronium ions and hydroxide ions collide in solution they react to form \_\_\_\_\_.
22. Most Arrhenius neutralization reactions, such as the reaction between nitric acid and sodium hydroxide, are \_\_\_\_\_ reactions.
23. Carbonic acid is unstable in water, so when it forms in aqueous solutions, it decomposes into \_\_\_\_\_ and water, H<sub>2</sub>O(*l*).
24. A Brønsted-Lowry acid is a proton (H<sup>+</sup>) \_\_\_\_\_, a Brønsted-Lowry base is a proton \_\_\_\_\_, and a Brønsted-Lowry acid-base reaction is a proton \_\_\_\_\_.
25. The conjugate acid of a molecule or ion is the molecule or ion that forms when one H<sup>+</sup> ion is \_\_\_\_\_.
26. The conjugate base of a molecule or ion is the molecule or ion that forms when one H<sup>+</sup> ion is \_\_\_\_\_.
27. A substance that can act as either a Brønsted-Lowry acid or a Brønsted-Lowry base, depending on the circumstances, is called a(n) \_\_\_\_\_ substance.
28. The \_\_\_\_\_ system is often used to describe specific acid-base reactions, but the \_\_\_\_\_ system is used to describe whether isolated substances are acids, bases, or neither.

Chapter  
Problems

OBJECTIVE 3

OBJECTIVE 5

OBJECTIVE 5

OBJECTIVE 6

OBJECTIVE 6

OBJECTIVE 7

OBJECTIVE 8

OBJECTIVE 10A

**Section 8.1 Strong and Weak Acids and Bases**

29. Describe the changes that take place when ammonia,  $\text{NH}_3$ , is dissolved in water, and use this description to explain why ammonia is a weak Arrhenius base.

30. Classify each of these substances as a weak acid, strong acid, weak base, or strong base in the Arrhenius acid-base sense.

- |                            |                     |
|----------------------------|---------------------|
| a. $\text{H}_2\text{CO}_3$ | e. $\text{NH}_3$    |
| b. cesium hydroxide        | f. chlorous acid    |
| c. $\text{HF}(aq)$         | g. $\text{HCl}(aq)$ |
| d. sodium carbonate        | h. benzoic acid     |

31. Classify each of the substances as a weak acid, strong acid, weak base, or strong base in the Arrhenius acid-base sense.

- |                     |                            |
|---------------------|----------------------------|
| a. $\text{HNO}_3$   | e. $\text{H}_2\text{SO}_4$ |
| b. ammonia          | f. nitrous acid            |
| c. $\text{LiOH}$    | g. $\text{NaHCO}_3$        |
| d. phosphorous acid |                            |

**Section 8.2 pH and Acidic and Basic Solutions**

32. Classify each of the following solutions as acidic, basic, or neutral.

- Tomato juice with a pH of 4.53
- Milk of magnesia with a pH of 10.4
- Urine with a pH of 6.8

33. Classify each of the following solutions as acidic, basic, or neutral.

- Saliva with a pH of 7.0
- Beer with a pH of 4.712
- A solution of a drain cleaner with a pH of 14.0

34. Which is more acidic, carbonated water with a pH of 3.95 or milk with a pH of 6.3?

35. Which is more basic, a soap solution with a pH of 10.0 or human tears with a pH of 7.4?

36. Identify each of the following characteristics as associated with acids or bases.

- tastes sour
- turns litmus red
- reacts with  $\text{HNO}_3$

37. Identify each of the following properties as characteristic of acids or of bases.

- turns litmus blue
- reacts with carbonate to form  $\text{CO}_2(g)$

**Section 8.3 Arrhenius Acid-Base Reactions**

38. Describe the process that takes place between the participants in the neutralization reaction between the strong acid hydrochloric acid,  $\text{HCl}(aq)$ , and the strong base sodium hydroxide,  $\text{NaOH}(aq)$ , forming water and sodium chloride,  $\text{NaCl}(aq)$ . Mention the nature of the particles in the solution before and after the reaction.

39. Describe the process that takes place between the participants in the neutralization reaction between the strong acid nitric acid,  $\text{HNO}_3(aq)$ , and the strong base potassium hydroxide,  $\text{KOH}(aq)$ , forming water and potassium nitrate,  $\text{KNO}_3(aq)$ . Mention the nature of the particles in the solution before and after the reaction. **OBJECTIVE 10A**
40. Describe the process that takes place between the participants in the neutralization reaction between the strong acid nitric acid,  $\text{HNO}_3(aq)$ , and water insoluble nickel(II) hydroxide,  $\text{Ni}(\text{OH})_2(s)$ , forming nickel(II) nitrate,  $\text{Ni}(\text{NO}_3)_2(aq)$ , and water. Mention the nature of the particles in the solution before and after the reaction. **OBJECTIVE 10B**
41. Describe the process that takes place between the participants in the neutralization reaction between the strong acid hydrochloric acid,  $\text{HCl}(aq)$ , and water insoluble chromium(III) hydroxide,  $\text{Cr}(\text{OH})_3(s)$ , forming chromium(III) chloride,  $\text{CrCl}_3(aq)$ , and water. Mention the nature of the particles in the solution before and after the reaction. **OBJECTIVE 10B**
42. Describe the process that takes place between the participants in the neutralization reaction between the strong acid hydrochloric acid,  $\text{HCl}(aq)$ , and the weak base potassium carbonate,  $\text{K}_2\text{CO}_3(aq)$ , forming water, carbon dioxide,  $\text{CO}_2(g)$ , and potassium chloride,  $\text{KCl}(aq)$ . Mention the nature of the particles in the solution before and after the reaction. **OBJECTIVE 10C**
43. Describe the process that takes place between the participants in the neutralization reaction between the strong acid nitric acid,  $\text{HNO}_3(aq)$ , and the weak base lithium hydrogen carbonate,  $\text{LiHCO}_3(aq)$ , forming water, carbon dioxide,  $\text{CO}_2(g)$ , and lithium nitrate,  $\text{LiNO}_3(aq)$ . Mention the nature of the particles in the solution before and after the reaction. **OBJECTIVE 10C**
44. Write the complete equation for the neutralization reactions that take place when the following water solutions are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic hydroxide ions.) **OBJECTIVE 11**
- $\text{HCl}(aq) + \text{LiOH}(aq)$
  - $\text{H}_2\text{SO}_4(aq) + \text{NaOH}(aq)$
  - $\text{KOH}(aq) + \text{HF}(aq)$
  - $\text{Cd}(\text{OH})_2(s) + \text{HCl}(aq)$
45. Write the complete equation for the neutralization reactions that take place when the following water solutions are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic hydroxide ions.) **OBJECTIVE 11**
- $\text{LiOH}(aq) + \text{HNO}_2(aq)$
  - $\text{Co}(\text{OH})_2(s) + \text{HNO}_3(aq)$
  - $\text{H}_3\text{PO}_4(aq) + \text{KOH}(aq)$
46. Write the complete equation for the reaction between  $\text{HI}(aq)$  and water-insoluble solid  $\text{CaCO}_3$ . **OBJECTIVE 11**  
**OBJECTIVE 12**
47. Write the complete equation for the reaction between  $\text{HCl}(aq)$  and water-insoluble solid  $\text{Al}_2(\text{CO}_3)_3$ . **OBJECTIVE 11**  
**OBJECTIVE 12**

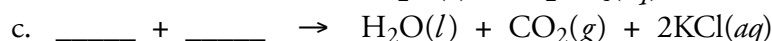
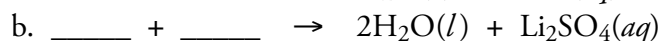
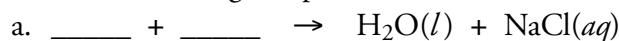
## OBJECTIVE 11

48. Iron(III) sulfate is made in industry by the neutralization reaction between solid iron(III) hydroxide and aqueous sulfuric acid. The iron(III) sulfate is then added with sodium hydroxide to municipal water in water treatment plants. These compounds react to form a precipitate that settles to the bottom of the holding tank, taking impurities with it. Write the complete equations for both the neutralization reaction that forms iron(III) sulfate and the precipitation reaction between water solutions of iron(III) sulfate and sodium hydroxide.

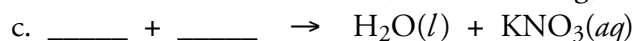
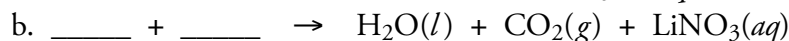
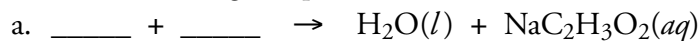
## OBJECTIVE 11

49. Industrial chemists make hydrofluoric acid (which is used in aluminum and uranium processing, to etch glass, and to make CFCs) from the reactions of aqueous calcium fluoride and aqueous sulfuric acid. Write the complete equation for this reaction.

50. Complete the following equations by writing the formulas for the acid and base that could form the given products.



51. Complete the following equations by writing the formulas for the acid and base that could form the given products.



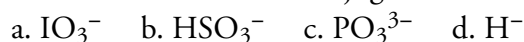
## Section 8.4 Brønsted-Lowry Acids and Bases

## OBJECTIVE 13

52. Explain why the Brønsted-Lowry definitions for acid and base are often used instead of the Arrhenius definitions to describe acid-base reactions.

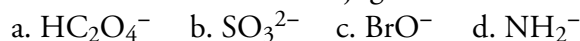
## OBJECTIVE 14

53. Write the formula for the conjugate acid of each of the following.



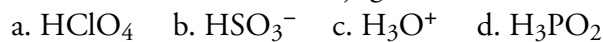
## OBJECTIVE 14

54. Write the formula for the conjugate acid of each of the following.



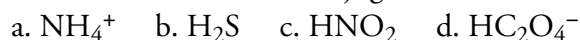
## OBJECTIVE 15

55. Write the formula for the conjugate base of each of the following.



## OBJECTIVE 15

56. Write the formula for the conjugate base of each of the following.



## OBJECTIVE 16

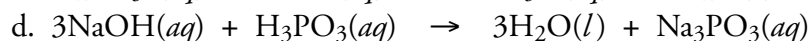
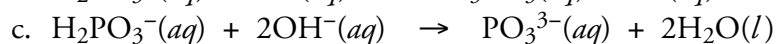
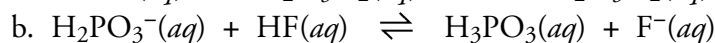
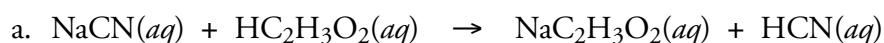
57. Explain why a substance can be a Brønsted-Lowry acid in one reaction and a Brønsted-Lowry base in a different reaction. Give an example to illustrate your explanation.

## OBJECTIVE 17

58. Explain why the Arrhenius definitions for acid and base and not the Brønsted-Lowry definitions are used to describe whether an isolated substance is an acid or base.

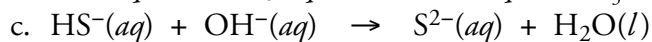
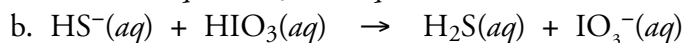
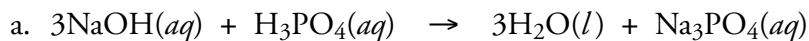
## OBJECTIVE 18

59. For each of the following equations, identify the Brønsted-Lowry acid and base for the forward reaction.





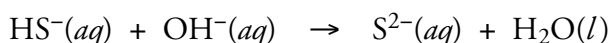
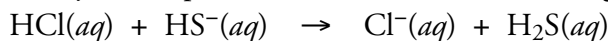
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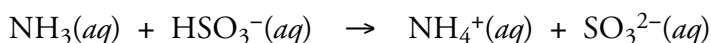
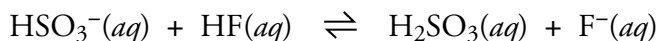
61. Butanoic acid,  $\text{CH}_3\text{CH}_2\text{CH}_2\text{CO}_2\text{H}$ , is a monoprotic weak acid that is responsible for the smell of rancid butter. Write the formula for the conjugate base of this acid. Write the equation for the reaction between this acid and water, and indicate the Brønsted-Lowry acid and base for the forward reaction. (The acidic hydrogen atom is on the right side of the formula.)

62. One of the substances that give wet goats and dirty gym socks their characteristic odors is hexanoic acid,  $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CO}_2\text{H}$ , which is a monoprotic weak acid. Write the formula for the conjugate base of this acid. Write the equation for the reaction between this acid and water, and indicate the Brønsted-Lowry acid and base for the forward reaction. (The acidic hydrogen atom is on the right side of the formula.)

63. Identify the amphoteric substance in the following equations.

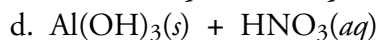
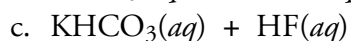
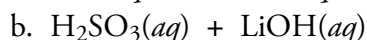
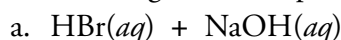


64. Identify the amphoteric substance in the following equations.

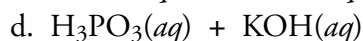
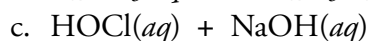
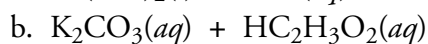
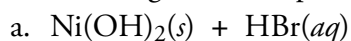


### Additional Problems

65. For each of the following pairs of compounds, write the complete equation for the neutralization reaction that takes place when the substances are mixed. (You can assume that there is enough base to remove all of the acidic hydrogen atoms, that there is enough acid to neutralize all of the basic hydroxide ions, and that each reaction goes to completion.)



66. For each of the following pairs of compounds, write the complete equation for the neutralization reaction that takes place when the substances are mixed. (You can assume that there is enough base to remove all of the acidic hydrogen atoms, that there is enough acid to neutralize all of the basic hydroxide ions, and that each reaction goes to completion.)



OBJECTIVE 18

OBJECTIVE 11

OBJECTIVE 12

OBJECTIVE 11

OBJECTIVE 12

## OBJECTIVE 6

67. Classify each of the following substances as acidic, basic, or neutral.

- An apple with a pH of 2.9
- Milk of Magnesia with a pH of 10.4
- Fresh egg white with a pH of 7.6

## OBJECTIVE 6

68. Classify each of the following substances as acidic, basic, or neutral.

- A liquid detergent with a pH of 10.1
- Maple syrup with a pH of 7.0
- Wine with a pH of 3.2

## OBJECTIVE 6

69. The pH of processed cheese is kept at about 5.7 to prevent it from spoiling. Is this acidic, basic, or neutral?

## OBJECTIVE 6

70. Is it possible for a weak acid solution to have a lower pH than a strong acid solution? If so, how?

71. The walls of limestone caverns are composed of solid calcium carbonate. The ground water that makes its way down from the surface into these caverns is often acidic. The calcium carbonate and the  $\text{H}^+$  ions from the acidic water react to dissolve the limestone. If this happens to the ceiling of the cavern, the ceiling can collapse, leading to what is called a sinkhole. Write the net ionic equation for the reaction between the solid calcium carbonate and the aqueous  $\text{H}^+$  ions.

72. Magnesium sulfate, a substance used for fireproofing and paper sizing, is made in industry from the reaction of aqueous sulfuric acid and solid magnesium hydroxide. Write the complete equation for this reaction.

73. Manganese(II) phosphate is used to coat steel, aluminum, and other metals to prevent corrosion. It is produced in the reaction between solid manganese(II) hydroxide and aqueous phosphoric acid. Write the complete equation for this reaction.

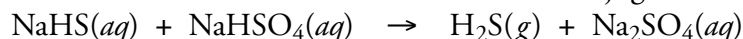
74. The smell of Swiss cheese is, in part, due to the monoprotic weak acid propanoic acid,  $\text{CH}_3\text{CH}_2\text{CO}_2\text{H}$ . Write the equation for the complete reaction between this acid and sodium hydroxide. (The acidic hydrogen atom is on the right.)

75. Lactic acid,  $\text{CH}_3\text{CH}(\text{OH})\text{CO}_2\text{H}$ , is used in cosmetic lotions, some of which claim to remove wrinkles. The lactic acid is thought to speed the removal of dead skin cells. Write the equation for the complete reaction between this acid and potassium hydroxide. (The acidic hydrogen atom is on the right.)

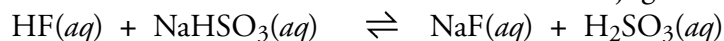
76. Malic acid,  $\text{HO}_2\text{CCH}_2\text{CH}(\text{OH})\text{CO}_2\text{H}$ , is a diprotic weak acid found in apples and watermelon. Write the equation for the complete reaction between this acid and sodium hydroxide. (The acidic hydrogen atoms are on each end of the formula.)

77. One of the substances used to make nylon is hexanedioic acid,  $\text{HO}_2\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CO}_2\text{H}$ . This diprotic weak acid is also called adipic acid. Write the equation for the complete reaction between this acid and sodium hydroxide. (The acidic hydrogen atoms are on each end of the formula.)

78. For the following equation, identify the Brønsted-Lowry acid and base for the forward reaction, and write the formulas for the conjugate acid-base pairs.



79. For the following equation, identify the Brønsted-Lowry acid and base for the forward reaction, and write the formulas for the conjugate acid-base pairs.



**Discussion Problems**

80. Assume you are given a water solution and told that it contains either hydrochloric acid or sodium chloride. Describe how you could determine which of these is present.
81. Assume that you are given a water solution that contains either sodium hydroxide or sodium chloride. Describe how you could determine which is in solution.
82. Assume that you are given a water solution that contains either sodium carbonate or sodium hydroxide. Describe how you could determine which is in solution.