# 10.1

# Acid-Base Theories

**Section Preview/ Specific Expectations**

In this section, you will

- **describe** and **compare** the Arrhenius and Brønsted-Lowry theories of acids and bases
- **identify** conjugate acid-base pairs
- **communicate** your understanding of the following terms: *Arrhenius theory of acids and bases, hydronium ion, Brønsted-Lowry theory of acids and bases, conjugate acid-base pair, conjugate base, conjugate acid*

As you can see in Table 10.1, acids and bases are common products in the home. It is easy to identify some products as acids. Often the word "acid" appears in the list of ingredients. Identifying bases is more difficult. Acids and bases have different properties, however, that enable you to distinguish between them.

**Table 10.1** Common Acids and Bases in the Home

| **Acids** | |
|---|---|
| **Product** | **Acid(s) contained in the product** |
| citrus fruits (such as lemons, limes, oranges and tomatoes) | citric acid and ascorbic acid |
| dairy products (such as cheese, milk, and yogurt) | lactic acid |
| vinegar | acetic acid |
| soft drinks | carbonic acid; may also contain phosphoric acid and citric acid |
| underarm odour | 3-methyl-2-hexenoic acid |
| **Bases** | |
| **Product** | **Base contained in the product** |
| oven cleaner | sodium hydroxide |
| baking soda | sodium hydrogen carbonate |
| washing soda | sodium carbonate |
| glass cleaner (some brands) | ammonia |

## Properties of Acids and Bases

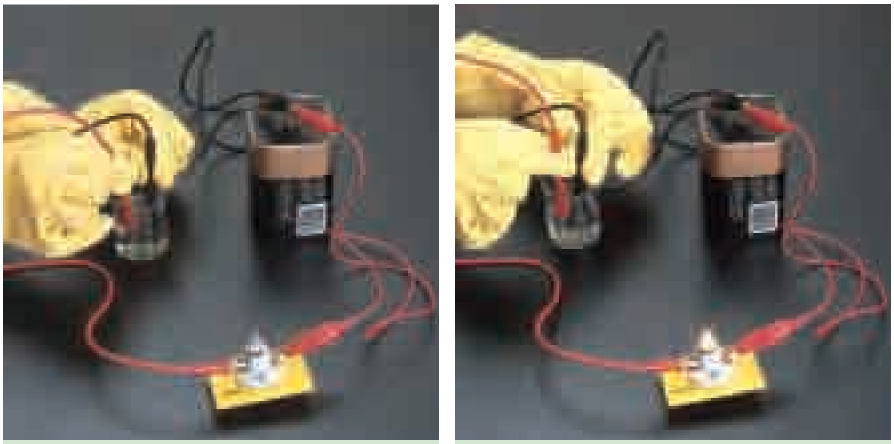
One way to distinguish acids from bases is to describe their observable properties. For example, acids taste sour, and they change colour when mixed with coloured dyes called indicators. Bases taste bitter and feel slippery. They also change colour when mixed with indicators.

**Language LINK**

The word "acid" comes from the Latin *acidus*, meaning "sour tasting." As you will learn in this chapter, bases are the "base" (the foundation) from which many other compounds form. A base that is soluble in water is called an alkali. The word "alkali" comes from an Arabic word meaning "ashes of a plant." In the ancient Middle East, people rinsed plant ashes with hot water to obtain a basic solution. The basic solution was then reacted with animal fats to make soap.

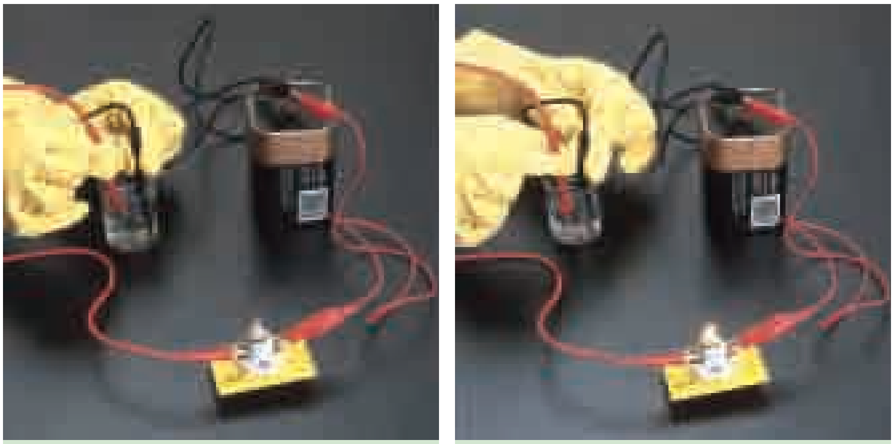
**CAUTION** You should never taste or touch acids, bases, or any other chemicals. Early chemists used their senses of taste and touch to observe the properties of many chemicals. This dangerous practice often led to serious injury, and sometimes death.

Another property that can be used to distinguish acids from bases is their conductivity in solution. As you can see in Figure 10.1, aqueous solutions of acids and bases conduct electricity. This is evidence that ions are present in acidic and basic solutions. Some of these solutions, such as hydrochloric acid and sodium hydroxide (a base), cause the bulb to glow brightly. Most acidic and basic solutions, however, cause the bulb to glow dimly.



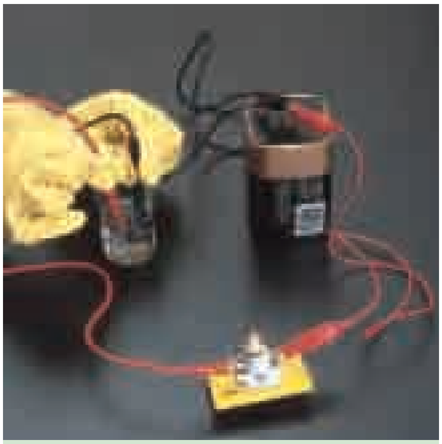
pure water

hydrochloric acid, $HCl_{(aq)}$ (1 mol/L)



acetic acid, $CH_3COOH_{(aq)}$ (1 mol/L)

sodium hydroxide, $NaOH_{(aq)}$ (1 mol/L)



ammonia, $NH_{3(aq)}$ (1 mol/L)

**Figure 10.1** Aqueous solutions of acids and bases can be tested using a conductivity tester. The brightness of the bulb is a clue to the concentration of ions in the solution. Which of these solutions have higher concentrations of ions? Which have lower concentrations?

Table 10.2 on the next page summarizes the observable properties of acids and bases. These observable properties include their physical characteristics and their chemical behaviour. The Express Lab on page xxx provides you with an opportunity to compare some of these properties. What are acids and bases, however? How does chemical composition determine whether a substance is acidic or basic? You will consider one possible answer to this question starting on page 373.

## mind STRETCH

An oxide is a compound of oxygen with a metal or non-metal. Most metal oxides react with water to form basic solutions. For example, calcium oxide is a metal oxide that is important in the construction industry as an ingredient of cement. Calcium oxide reacts with water to form a basic solution of calcium hydroxide.

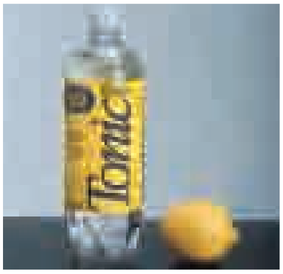
$CaO_{(s)} + H_2O_{(\ell)} \rightarrow Ca(OH)_{2(aq)}$

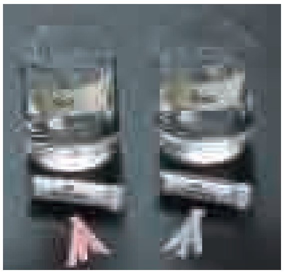
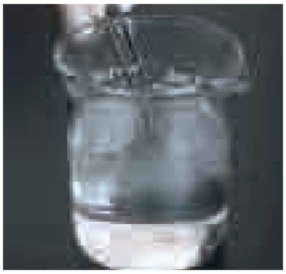
Many municipal water treatment plants use calcium hydroxide to soften very hard water before releasing it for public use. Most non-metal oxides react with water to form acidic solutions. For example, sulfur dioxide gas dissolves in water to form sulfurous acid.

$SO_{2(g)} + H_2O_{(\ell)} \rightarrow H_2SO_{3(aq)}$

The metallic character of the elements in the periodic table, and the acid-base properties of their oxides, show a distinct trend across periods and down groups. Infer what this trend is. In other words, state what you think happens to the acid-base properties of oxides as you go across a period and down a group. Make a quick sketch of the periodic table to illustrate this trend. How would you describe the acid-base properties of the metalloids? (Use your knowledge of the physical properties of the metalloids to help you make your inference.)

**Table 10.2** Some Observable Properties of Acids and Bases

| | Property | | |
|---|---|---|---|
| | **Taste** | **Electrical conductivity in solution** | **Feel of solution** |
| **ACIDS** | taste sour | conduct electricity | have no characteristic feel |
| **BASES** | taste bitter | conduct electricity | feel slippery |
| |  |  |  |

| | Property | | |
|---|---|---|---|
| | **Reaction with litmus paper** | **Reaction with active metals** | **Reaction with carbonate compounds** |
| **ACIDS** | Acids turns blue litmus red | produce hydrogen gas | produce carbon dioxide gas |
| **BASES** | Bases turn red litmus blue | do not react | do not react |
| |  |  |  |

## ExpressLab Clean a Penny

Many cleaning products contain an acid or a base. For example, some window cleaners contain vinegar (acetic acid). Other window cleaners contain ammonia (a base). Oven cleaners, however, contain only bases. This activity will help you infer why.

### Safety Precautions

### Materials

water
vinegar
100 mL graduated cylinder
spoon or scoopula
baking soda
3 small beakers (about 200 mL)
3 tarnished pennies

### Procedure

1. Predict which solution(s) will clean the penny best. Give reasons for your prediction.
2. In one beaker, mix 50 mL of vinegar with about 150 mL of water. In a second beaker, mix about 20 mL to 30 mL spoonfuls of baking soda with 150 mL of water. In the third beaker, put only 150 mL of water.
3. Place a tarnished penny in each beaker. Observe what happens for about 15 min.

### Analysis

1. Which solution was the best cleaner? How did your observations compare with your prediction?
2. What results would you expect if you tried cleaning a penny in a solution of lemon juice? What if you used a dilute solution of ammonia? **Note:** If you want to test your predictions, ask your teacher for the concentrations of the solutions you should use.
3. The base that is often used in oven cleaners is sodium hydroxide. This base is very corrosive, and it can burn skin easily. A corrosive acid, such as hydrochloric acid, could also remove baked-on grease and grime from ovens. Why are bases a better choice for oven cleaners?

## The Arrhenius Theory of Acids and Bases

In Figure 10.1, you saw evidence that ions are present in solutions of acids and bases. When hydrogen chloride dissolves in water, for example, it dissociates (breaks apart) into hydrogen ions and chloride ions.

$$HCl_{(aq)} \rightarrow H^{+}_{(aq)} + Cl^{-}_{(aq)}$$

When sodium hydroxide dissolves in water, it dissociates to form sodium ions and hydroxide ions.

$$NaOH_{(aq)} \rightarrow Na^{+}_{(aq)} + OH^{-}_{(aq)}$$

The dissociations of other acids and bases in water reveal a pattern. This pattern was first noticed in the late nineteenth century by a Swedish chemist named Svanté Arrhenius. (See Figure 10.2.)

$$HBr_{(aq)} \rightarrow \mathbf{H^{+}}_{(aq)} + Br^{-}_{(aq)}$$

$$H_2SO_{4(aq)} \rightarrow \mathbf{H^{+}}_{(aq)} + HSO^{-}_{4(aq)}$$

$$HClO_{4(aq)} \rightarrow \mathbf{H^{+}}_{(aq)} + ClO^{-}_{4(aq)}$$

acids dissociating in water, and their resulting ions

$$LiOH_{(aq)} \rightarrow Li^{+}_{(aq)} + \mathbf{OH^{-}}_{(aq)}$$

$$KOH_{(aq)} \rightarrow K^{+}_{(aq)} + \mathbf{OH^{-}}_{(aq)}$$

$$Ba(OH)_{2(aq)} \rightarrow Ba^{+}_{(aq)} + 2\mathbf{OH^{-}}_{(aq)}$$

bases dissociating in water, and their resulting ions

**Figure 10.2** **Svanté Arrhenius (1859–1927).**

**Web LINK**

**www.school.mcgrawhill.ca/resources/**

Scientists did not embrace the Arrhenius theory when they first heard about it during the 1880s. Why were they unimpressed with this theory? What was necessary to convince them? Arrhenius is featured on several web sites on the Internet. To link with these web sites, go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next.

In 1887, Arrhenius published a theory to explain the nature of acids and bases. It is called the **Arrhenius theory of acids and bases**.

**The Arrhenius Theory of Acids and Bases**

- An acid is a substance that dissociates in water to produce one or more hydrogen ions, $H^+$.
- A base is a substance that dissociates in water to form one or more hydroxide ions, $OH^-$.

According to the Arrhenius theory, acids increase the concentration of $H^+$ in aqueous solutions. Thus, an Arrhenius acid must contain hydrogen as the source of $H^+$. You can see this in the dissociation reactions for acids on the previous page.

Bases, on the other hand, increase the concentration of $OH^-$ in aqueous solutions. An Arrhenius base must contain the hydroxyl group, —OH, as the source of $OH^-$. You can see this in the dissociation reactions for bases on the previous page.

## Limitations of the Arrhenius Theory

The Arrhenius theory is useful if you are interested in the ions that result when an acid or a base dissociates in water. It also helps explain what happens when an acid and a base undergo a neutralization reaction. In such a reaction, an acid combines with a base to form an ionic compound and water. Examine the following reactions:

$$HCl_{(aq)} + NaOH_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(\ell)}$$

The net ionic equation for this reaction shows the principal ions in the Arrhenius theory.

$$H^+_{(aq)} + OH^-_{(aq)} \rightarrow H_2O_{(\ell)}$$

Since acids and bases produce hydrogen ions and hydroxide ions, water is an inevitable result of acid-base reactions.

Problems arise with the Arrhenius theory, however. One problem involves the ion that is responsible for acidity: $H^+$. Look again at the equation for the dissociation of hydrochloric acid.

$$HCl_{(aq)} \rightarrow H^+_{(aq)} + Cl^-_{(aq)}$$

This dissociation occurs in aqueous solution, but chemists often leave out $H_2O$ as a component of the reaction. They simply assume that it is there. What happens if you put $H_2O$ into the equation?

$$HCl_{(aq)} + H_2O_{(\ell)} \rightarrow H^+_{(aq)} + Cl^-_{(aq)} + H_2O_{(\ell)}$$

Notice that the water is unchanged when the reaction is represented this way. However, you learned earlier that water is a polar molecule. The O atom has a partial negative charge, and the H atoms have partial positive charges. Thus, $H_2O$ must interact in some way with the ions $H^+$ and $Cl^-$. In fact, chemists made a discovery in the early twentieth century. They realized that protons do not exist in isolation in aqueous solution. (The hydrogen ion is simply a proton. It is a positively charged nuclear particle.) Instead, protons are always *hydrated*: they are attached to water molecules. A hydrated proton is called a **hydronium ion,** $H_3O^+_{(aq)}$. (See Figure 10.3.)

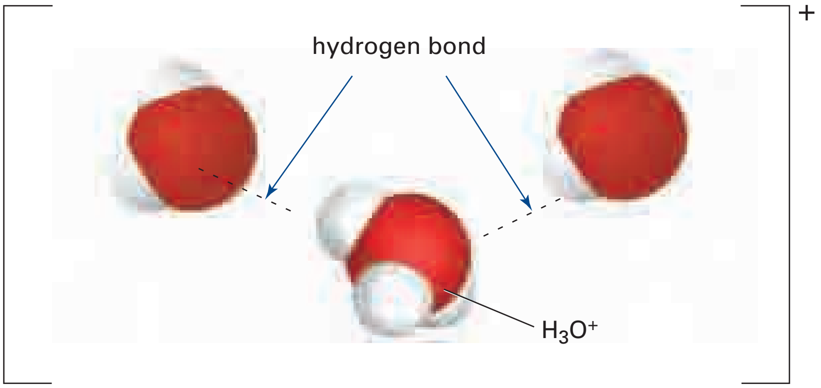


**Figure 10.3** **For convenience, chemists often use $H^+_{(aq)}$ as a shorthand notation for the hydronium ion, $H_3O^+_{(aq)}$. Hydronium ions do not exist independently. Instead, they form hydrogen bonds with other water molecules. Thus, a more correct formula is $H^+(H_2O)_n$, where *n* is usually 4 or 5.**

There is another problem with the Arrhenius theory. Consider the reaction of ammonia, $NH_3$, with water.

$$NH_{3(g)} + H_2O_{(\ell)} \rightarrow NH^+_{4(aq)} + OH^-_{(aq)}$$

Ammonia is one of several substances that produce basic solutions in water. As you can see, ammonia does not contain hydroxide ions. However, it does produce these ions when it reacts with water. Ammonia also undergoes a neutralization reaction with acids. The Arrhenius theory cannot explain the basic properties of ammonia. Nor can it explain the fact that certain other substances, such as salts that contain carbonate ions, also have basic properties.

**CHECKPOINT**

Use the idea of the hydronium ion to complete the following equation:

$$HCl_{(aq)} + H_2O_{(\ell)} \rightarrow$$

There is yet another problem with the Arrhenius theory. It is limited to acid-base reactions in a single solvent, water. Many acid-base reactions take place in other solvents, however.

## The Brønsted-Lowry Theory of Acids and Bases

In 1923, two chemists working independently of each other, proposed a new theory of acids and bases. (See Figure 10.4.) Johannes Brønsted in Copenhagen, Denmark, and Thomas Lowry in London, England, proposed what is called the **Brønsted-Lowry theory of acids and bases.** This theory overcame the problems related to the Arrhenius theory.

### The Brønsted-Lowry Theory of Acids and Bases

- An acid is a substance from which a proton ($H^+$ ion) can be removed.
- A base is a substance that can remove a proton ($H^+$ ion) from an acid.

**Figure 10.4** **Johannes Brønsted (1879–1947), left, and Thomas Lowry (1874–1936), right. Brønsted published many more articles about ions in solution than Lowry did. Thus, some chemistry resources refer to the "Brønsted theory of acids and bases."**

**CHEM FACT**

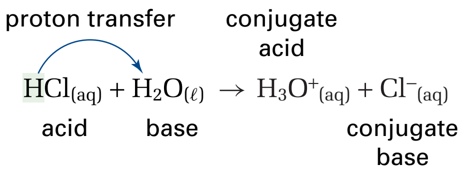
In many chemistry references, Brønsted-Lowry acids are called "proton donors." Brønsted-Lowry bases are called "proton acceptors." Although these terms are common, they create a false impression about the energy that is involved in acid-base reactions. Breaking bonds always requires energy. For example, removing a proton from a hydrochloric acid molecule requires $1.4 \times 10^3$ kJ/mol. This is far more energy than the word "donor" implies.

Like an Arrhenius acid, a Brønsted-Lowry acid must contain H in its formula. This means that all Arrhenius acids are also Brønsted-Lowry acids. However, any negative ion (not just $OH^-$) can be a Brønsted-Lowry base. In addition, water is not the only solvent that can be used.

According to the Brønsted-Lowry theory, there is only one requirement for an acid-base reaction. One substance must provide a proton, and another substance must receive the same proton. In other words, *an acid-base reaction involves the transfer of a proton.*

The idea of proton transfer has major implications for understanding the nature of acids and bases. According to the Brønsted-Lowry theory, any substance can behave as an acid, but only if another substance behaves as a base at the same time. Similarly, any substance can behave as a base, but only if another substance behaves as an acid at the same time.

For example, consider the reaction between hydrochloric acid and water shown in Figure 10.5. In this reaction, hydrochloric acid is an acid because it provides a proton ($H^+$) to the water. The water molecule receives the proton. Therefore, according to the Brønsted-Lowry theory, water is a base in this reaction. When the water receives the proton, it becomes a hydronium ion ($H_3O^+$). Notice the hydronium ion on the right side of the equation.



$$\underset{\text{acid}}{HCl_{(aq)}} + \underset{\text{base}}{H_2O_{(\ell)}} \rightarrow \overset{\text{conjugate acid}}{H_3O^+_{(aq)}} + \underset{\text{conjugate base}}{Cl^-_{(aq)}}$$

**Figure 10.5** **The reaction between hydrochloric acid and water, according to the Brønsted-Lowry theory**

Two molecules or ions that are related by the transfer of a proton are called a **conjugate acid-base pair.** (Conjugate means "linked together.") The **conjugate base** of an acid is the particle that remains when a proton is removed from the acid. The **conjugate acid** of a base is the particle that results when the base receives the proton from the acid. In the reaction between hydrochloric acid and water, the hydronium ion is the conjugate acid of the base, water. The chloride ion is the conjugate base of the acid, hydrochloric acid.

According to the Brønsted-Lowry theory, every acid has a conjugate base, and every base has a conjugate acid. The conjugate base and conjugate acid of an acid-base pair are linked by the transfer of a proton. The conjugate base of the acid-base pair has one less hydrogen than the acid. It also has one more negative charge than the acid. The conjugate acid of the acid-base pair has one more hydrogen than the base. It also has one less negative charge than the base.

These ideas about acid-base reactions and conjugate acid-base pairs will become clearer as you study the following Sample Problems and Practice Problems.