19.1 Acid-Base Theories

Connecting to Your World  
Bracken Cave, near San Antonio, Texas, is home to twenty to forty million bats, which is probably the largest colony of mammals in the world. Visitors to the cave must wear protective goggles and respirators to protect themselves from the dangerous levels of ammonia in the cave. Ammonia is a by-product of the bats’ urine. In this section, you will learn why ammonia is considered a base.

Properties of Acids and Bases

Acids and bases play a central role in much of the chemistry that affects your daily life. Your body needs acids and bases to function properly. Vinegar, carbonated drinks, and foods such as citrus fruits contain acids. The electrolyte in a car battery is an acid. Most manufacturing processes use acids or bases. Bases are present in many commercial products, including antacids and household cleaning agents. Figure 19.1 shows some of the many products that contain acids and bases.

Acids  
Acids have several distinctive properties with which you are probably familiar. Acidic compounds give foods a tart or sour taste. For example, vinegar imparts a tart taste to salad dressing. Vinegar contains ethanoic acid, sometimes called acetic acid. Lemons, which taste sour enough to make your mouth pucker, contain citric acid.

Aqueous solutions of acids are electrolytes. Recall from Chapter 15 that electrolytes conduct electricity. Some acid solutions are strong electrolytes, and others are weak electrolytes. Acids cause certain chemical dyes, called indicators, to change color. Many metals, such as zinc and magnesium, react with aqueous solutions of acids to produce hydrogen gas. Acids react with compounds containing hydroxide ions to form water and a salt. Acids taste sour, will change the color of an indicator, and can be strong or weak electrolytes in aqueous solution.

Guide for Reading

Key Concepts
- What are the properties of acids and bases?
- How did Arrhenius define an acid and a base?
- What distinguishes an acid from a base in the Brønsted-Lowry theory?
- How did Lewis define an acid and a base?

Vocabulary
- monoprotic acids
- diprotic acids
- triprotic acids
- conjugate acid
- conjugate base
- conjugate acid-base pair
- hydronium ion (H₃O⁺)
- amphoteric
- Lewis acid
- Lewis base

Reading Strategy
Building Vocabulary  
As you read the section, write a definition and the formula of an example of each type of substance listed in the key terms list.

Figure 19.1  
Many items contain acids or bases, or produce acids and bases when dissolved in water. Citrus fruit contain citric acid. Tea contains tannic acid. Antacids use bases to neutralize excess stomach acid. The base calcium hydroxide is a component of mortar.

INSTRUCT

Connecting to Your World

Have students study the photograph and read the text that opens the section. Ask, Why do visitors to Bracken Cave in Texas need to wear protective goggles and respirators? (Students will likely suggest that ammonia has a strong, pungent odor and that high levels of ammonia are dangerous.)

Section Resources

Print
- Guided Reading and Study Workbook, Section 19.1
- Core Teaching Resources, Section 19.1
- Transparencies, T213–T214

Technology
- Interactive Textbook with ChemASAP, Animation 25, Problem-Solving 19.1, Assessment 19.1
- Go Online, Section 19.1
Properties of Acids and Bases

Table 19.1

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric acid</td>
<td>HCl</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>HNO₃</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>H₂SO₄</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>H₃PO₄</td>
</tr>
<tr>
<td>Ethanoic acid</td>
<td>CH₃COOH</td>
</tr>
<tr>
<td>Carbonic acid</td>
<td>H₂CO₃</td>
</tr>
</tbody>
</table>

Bases

Bases have properties with which you are less familiar. Bases have a bitter taste, but tasting most bases is hazardous. Soap is a familiar material that has the properties of a base. If you have tasted soap, you know that it has a bitter taste. The slippery feel of soap is another property of bases.

Like acids, aqueous solutions of bases are electrolytes and will cause an indicator to change color. Water and a salt are formed when a base that contains hydroxide ions reacts with an acid. With a few exceptions, none of the foods you eat are bases. Milk of magnesia (a suspension of magnesium hydroxide in water) is a base used to treat the problem of excess stomach acid. Bases taste bitter, feel slippery, will change the color of an acid-base indicator, and can be strong or weak electrolytes in aqueous solution.

Arrhenius Acids and Bases

Although chemists had recognized the properties of acids and bases for many years, they were not able to propose a theory to explain this behavior. Then, in 1887, the Swedish chemist Svante Arrhenius (1859–1927) proposed a revolutionary way of defining and thinking about acids and bases. Arrhenius said that acids are hydrogen-containing compounds that ionize to yield hydrogen ions (H⁺) in aqueous solution. He also said that bases are compounds that ionize to yield hydroxide ions (OH⁻) in aqueous solution.

Arrhenius Acids

Table 19.1 lists some common acids. Acids that contain one ionizable hydrogen, such as nitric acid (HNO₃), are called monoprotic acids. Acids that contain two ionizable hydrogens, such as sulfuric acid (H₂SO₄), are called diprotic acids. Acids that contain three ionizable hydrogens, such as phosphoric acid (H₃PO₄), are called triprotic acids. Not all compounds that contain hydrogen are acids, however. Also, not all the hydrogens in an acid may be released as hydrogen ions. Only the hydrogens in very polar bonds are ionizable. In such bonds, hydrogen is joined to a very electronegative element. When a compound that contains such bonds dissolves in water, it releases hydrogen ions because the hydrogen ions are stabilized by solvation. An example is the hydrogen chloride molecule, shown in Figure 19.2. Hydrogen chloride is a polar covalent molecule. It ionizes to form an aqueous solution of hydrochloric ions and chloride ions.

Figure 19.2

Hydrochloric acid is actually an aqueous solution of hydrogen chloride. The hydrogen ion forms hydronium ions, making this compound an acid.

Facts and Figures

Acid Names and Uses

Acids can often be purchased at hardware and home supply stores, but they are often labeled with “old names.” For example, muriatic acid, a term no longer used in chemistry, is hydrochloric acid. Among other uses, this acid is purchased to clean lime deposits from tile and porcelain and to clean mortar stains from brick and tile.
In contrast, the four hydrogens in methane (CH₄) are attached by weakly polar C—H bonds. Methane has no ionizable hydrogens and is not an acid. Ethanoic (acetic) acid (CH₃COOH), used in the manufacture of plastics, pharmaceuticals, and photographic chemicals, is different. Although this molecule contains four hydrogens, ethanoic acid is a monoprotic acid. The structural formula shows why.

```
  H—C—C—O—H
/       \
H
```
Ethanoic acid (CH₃COOH)

The three hydrogens attached to the carbon are in weakly polar bonds. They do not ionize. Only the hydrogen bonded to the highly electronegative oxygen can be ionized. As you gain more experience looking at written formulas for acids, you will be able to recognize which hydrogen atoms can be ionized.

**Arrhenius Bases** Table 19.2 lists some common bases. The base with which you are perhaps most familiar is sodium hydroxide (NaOH). Sodium hydroxide is commonly known as lye. Sodium hydroxide is an ionic solid. It dissociates into sodium ions and hydroxide ions in aqueous solution.

\[
\text{NaOH}(s) \rightarrow \text{Na}^+ (aq) + \text{OH}^- (aq)
\]

Because of its extremely caustic nature, sodium hydroxide is a major component of consumer products used to clean clogged drains.

Potassium hydroxide (KOH) is another ionic solid that dissociates to form potassium ions and hydroxide ions in aqueous solution.

\[
\text{KOH}(s) \rightarrow \text{K}^+ (aq) + \text{OH}^- (aq)
\]

Sodium and potassium are Group 1A elements. The elements in Group 1A, the alkali metals, react with water to produce solutions that are basic. Sodium metal reacts violently with water to form sodium hydroxide and hydrogen gas. The following equation illustrates the reaction of sodium metal with water.

\[
2\text{Na}(s) + 2\text{H}_2\text{O}(l) \rightarrow 2\text{NaOH}(aq) + \text{H}_2(g)
\]

Table 19.2

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Solubility in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium hydroxide</td>
<td>KOH</td>
<td>High</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>NaOH</td>
<td>High</td>
</tr>
<tr>
<td>Calcium hydroxide</td>
<td>Ca(OH)₂</td>
<td>Very low</td>
</tr>
<tr>
<td>Magnesium hydroxide</td>
<td>Mg(OH)₂</td>
<td>Very low</td>
</tr>
</tbody>
</table>
Section 19.1 (continued)

**Brønsted-Lowry Acids and Bases**

**Discuss**

Brønsted arrived at his theory of acids and bases through his work in kinetics and thermodynamics. Brønsted noticed that a great many compounds that would not be classified as acids and bases by the Arrhenius definition behaved like acids and bases in his experiments. He found that these compounds were capable of hydrogen-ion transfer reactions. This led him to define acids as hydrogen-ion donors and bases as hydrogen-ion acceptors in chemical reactions. Some students may think the conjugate base of an acid in a given reaction appears on the same side of the equation as the acid. Explain that an acid does not react with its conjugate base but instead produces it or is produced by it in a reaction.

Sodium hydroxide and potassium hydroxide are very soluble in water. Concentrated solutions of these compounds can be readily prepared. Such solutions, like other basic solutions, would have a bitter taste and slippery feel. However, they are extremely caustic to the skin and can cause deep, painful, slow-healing wounds if not immediately washed off.

Calcium hydroxide (\(\text{Ca(OH)}_2\)) and magnesium hydroxide (\(\text{Mg(OH)}_2\)) are compounds of Group 2A metals. These compounds are not very soluble in water. Their solutions are always very dilute, even when saturated. The concentration of hydroxide ions in such solutions is correspondingly low. A saturated solution of calcium hydroxide contains only 0.165 g \(\text{Ca(OH)}_2\) per 100 g of water. Magnesium hydroxide is much less soluble than calcium hydroxide. A saturated solution contains only 0.0009 g \(\text{Mg(OH)}_2\) per 100 g of water. Suspensions of magnesium hydroxide in water contain low concentrations of hydroxide ion. People take these suspensions internally as milk of magnesia, shown in Figure 19.3, which is an antacid and a mild laxative.

**Brønsted-Lowry Acids and Bases**

The Arrhenius definition of acids and bases is not a very comprehensive one. It defines acids and bases rather narrowly and does not include certain substances that have acidic or basic properties. For example, aqueous solutions of sodium carbonate (\(\text{Na}_2\text{CO}_3(\text{aq})\)) and ammonia (\(\text{NH}_3(\text{aq})\)) are basic. Neither of these compounds is a hydroxide, however, and neither would be classified as a base under the Arrhenius definition. In 1923, the Danish chemist Johannes Brønsted (1879–1947) and the English chemist Thomas Lowry (1874–1936) independently proposed a new definition. The Brønsted-Lowry theory defines an acid as a hydrogen-ion donor, and a base as a hydrogen-ion acceptor. All the acids and bases included in the Arrhenius theory are also acids and bases according to the Brønsted-Lowry theory. Some compounds not included in the Arrhenius theory are classified as bases in the Brønsted-Lowry theory.

**Why Ammonia is a Base**

The behavior of ammonia as a base can be understood by using the Brønsted-Lowry theory. Ammonia gas is very soluble in water. When ammonia dissolves in water, it acts as a base because it accepts a hydrogen ion from water.

\[
\text{NH}_3(\text{aq}) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NH}_4^+(\text{aq}) + \text{OH}^-(\text{aq})
\]

In this reaction, ammonia is the hydrogen-ion acceptor and therefore is a Brønsted-Lowry base. Water, the hydrogen-ion donor, is a Brønsted-Lowry acid. Hydrogen ions are transferred from water to ammonia, as is shown in Figure 19.5. This causes the hydroxide-ion concentration to be greater than it is in pure water. As a result, solutions of ammonia are basic.

**Checkpoint** Why is ammonia considered to be a Brønsted-Lowry base?
Conjugate Acids and Bases Because all gases become less soluble in water as temperature increases, increasing the temperature of an aqueous solution of ammonia releases ammonia gas. As ammonia gas leaves the solution, the equilibrium in the equation shifts to the left. The ammonium ion (NH₄⁺) reacts with OH⁻ to form NH₃ and H₂O. When the reaction goes from right to left, NH₄⁺ gives up a hydrogen ion; it acts as a Brønsted-Lowry acid. The hydroxide ion accepts an H⁺; it acts as a Brønsted-Lowry base. Overall, then, this equilibrium has two acids and two bases.

\[
\text{NH}_3(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NH}_4^+(aq) + \text{OH}^-(aq) \\
\text{Base} \quad \text{Acid} \quad \text{Conjugate} \quad \text{Conjugate} \\
\]

When ammonia dissolves and then reacts with water, NH₄⁺ is the conjugate acid of the base NH₃. A conjugate acid is the particle formed when a base gains a hydrogen ion. Similarly, OH⁻ is the conjugate base of the acid water. A conjugate base is the particle that remains when an acid has donated a hydrogen ion. Conjugate acids and bases are always paired with a base or an acid, respectively. A conjugate acid-base pair consists of two substances related by the loss or gain of a single hydrogen ion. The ammonia molecule and ammonium ion are a conjugate acid-base pair. The water molecule and hydroxide ion are also a conjugate acid-base pair.

\[
\text{NH}_3(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NH}_4^+(aq) + \text{OH}^-(aq) \\
\text{Base} \quad \text{Acid} \quad \text{Conjugate} \quad \text{Conjugate} \\
\]

The Brønsted-Lowry theory also applies to acids. Consider the dissociation of hydrogen chloride in water.

\[
\text{HCl}(g) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{Cl}^-(aq) \\
\text{Acid} \quad \text{Base} \quad \text{Conjugate} \quad \text{Conjugate} \\
\]

In this reaction, hydrogen chloride is the hydrogen-ion donor. Thus it is a Brønsted-Lowry acid. Water is the hydrogen-ion acceptor and therefore water is a Bronsted-Lowry base. A water molecule that gains a hydrogen ion becomes a positively charged hydronium ion \(\text{H}_3\text{O}^+\). The chloride ion is the conjugate base of the acid HCl. The hydronium ion is the conjugate acid of the base water.
An amphibious airplane is designed to take off from and land on either land or water. The prefix, *amph-* is also used in *amphibian* which is an animal that has aquatic larvae, with gills that grow into air-breathing adults with lungs.

**Word Origins**

Amphoteric comes from the Greek word *amphoteros*, meaning “partly one and partly the other.” An amphoteric substance can act as both an acid and a base. What makes an amphibious airplane different from other airplanes?

**Lewis Acids and Bases**

Discuss

Point out that Lewis was the first scientist to discuss the significance of electron pairs in bonding (Lewis electron-dot diagrams). His theory of acids and bases was an extension of his concept of electron pairs. A Lewis acid accepts a pair of electrons to form a covalent bond and a Lewis base donates a pair of electrons to form a covalent bond.

A third theory of acids and bases was proposed by Gilbert Lewis (1875–1946). Lewis proposed that an acid accepts a pair of electrons during a reaction, while a base donates a pair of electrons. This concept is more general than either the Arrhenius theory or the Brønsted-Lowry theory. A Lewis acid is a substance that can accept a pair of electrons to form a covalent bond. A Lewis base is a substance that can donate a pair of electrons to form a covalent bond.

A hydrogen ion (Brønsted-Lowry acid) can accept a pair of electrons in forming a bond. A hydrogen ion, therefore, is also a Lewis acid. A Brønsted-Lowry base, or a substance that accepts a hydrogen ion, must have a pair of electrons available and, therefore, is also a Lewis base. Consider the reaction of \( \text{H}^+ / \text{H}_3\text{O}^+ \) and \( \text{OH}^- / \text{H}_2\text{O} \).

In this reaction, a hydroxide ion is a Lewis base. It is also a Brønsted-Lowry base. The hydrogen ion is both a Lewis acid and a Brønsted-Lowry acid. The Lewis definition also includes some compounds not classified as Brønsted-Lowry acids or bases.

Ammonia dissolved in water is another example of a Lewis acid and Lewis base. In this reaction, the hydrogen ion from the dissociation of water is an electron-pair acceptor and is a Lewis acid. Ammonia is an electron-pair donor and is a Lewis base.

**Table 19.4**

<table>
<thead>
<tr>
<th>Acid-Base Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Arrhenius</td>
</tr>
<tr>
<td>Brønsted-Lowry</td>
</tr>
<tr>
<td>Lewis</td>
</tr>
</tbody>
</table>
1. Identify the Lewis acid and Lewis base in each reaction.
   a. \( \text{H}^+ + \text{O} \rightarrow \text{H}_2\text{O}^+ \)
   b. \( \text{AlCl}_3 + \text{Cl}^- \rightarrow \text{AlCl}_4^- \)

2. Would you predict \( \text{PCl}_3 \) to be a Lewis acid or a Lewis base in typical reactions? Explain your prediction.

3. **Key Concept** What are the properties of acids and bases?
4. **Key Concept** How did Arrhenius define an acid and a base?
5. **Key Concept** How are acids and bases defined by the Brønsted-Lowry theory?
6. **Key Concept** What is the Lewis theory of acids and bases?
7. a. What is a conjugate acid-base pair?
   b. Write equations for the ionization of \( \text{HNO}_3 \) in water and the reaction of \( \text{CO}_2 \) with water. For each equation, identify the hydrogen-ion donor and hydrogen-ion acceptor. Then label the conjugate acid-base pairs in each equation.

8. Identify the following acids as monoprotic, diprotic, or triprotic. Explain your reasoning.
   a. \( \text{H}_2\text{CO}_3 \)
   b. \( \text{H}_3\text{PO}_4 \)
   c. \( \text{HCl} \)
   d. \( \text{H}_2\text{SO}_4 \)

Write a Report Household drain cleaners contain pellets of sodium hydroxide (NaOH) and small metal particles. Use the library or Internet to find out how drain cleaners work. Include the identity of the metal particles in your written report.