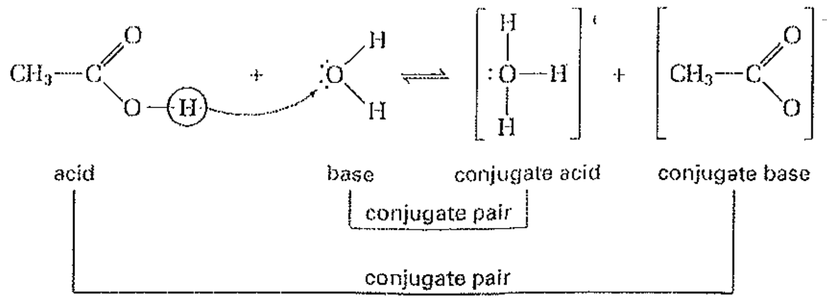


Figure 14.8 Conjugate acid-base pairs in the dissociation of acetic acid in water

Practice Problems

1. When perchloric acid dissolves in water, the following reaction occurs:

$$HClO_{4(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + ClO_4^-{}_{(aq)}$$

Identify the conjugate acid-base pairs.

2. Sodium acetate is a good electrolyte. In water, the acetate ion reacts as follows:

$$CH_3COO^-_{(aq)} + H_2O_{(\ell)} \rightleftharpoons CH_3COOH_{(aq)} + OH^-_{(aq)}$$

Identify the conjugate acid-base pairs.

3. Name and write the formula of the conjugate base of each molecule or ion.

(a) HCl (b) HCO_3^-. (c) H_2SO_4 (d) $N_2H_5^+$

4. Name and write the formula of the conjugate acid of each molecule or ion.

(a) NO_3^- (b) OH^- (c) H_2O (d) HCO_3^-

Acting Like an Acid *or* a Base: Amphoteric Substances

In the Sample Problem on page 556, you saw that H_2O gives up a proton, and thus plays the role of an acid in the dissociation reaction involving ammonia. In Figure 14.7, you saw that H_2O removes a proton, and thus plays the role of a base in the dissociation of acetic acid. Substances that can act as an acid in one reaction and as a base in a different reaction are said to be **amphoteric.**

Amphoteric substances may be molecules, as in the case of water, or anions with an available hydrogen that can dissociate. For example, the hydrogen carbonate ion, HCO_3^-, is amphoteric. When baking soda is mixed with water, HCO_3^- may remove a proton from water, thus acting as a base. Conversely, HCO_3^- may lose a proton to water, thus acting as an acid.

$$HCO_3^-{}_{(aq)} + OH^-_{(aq)} \rightleftharpoons CO_3^{2-}{}_{(aq)} + H_2O_{(\ell)}$$

$$HCO_3^-{}_{(aq)} + H_3O^+_{(aq)} \rightleftharpoons H_2CO_{3(aq)} + H_2O_{(\ell)}$$

In the following Practice Problems, remember that a Brønsted-Lowry acid is a substance that can donate a proton to another substance. A Brønsted-Lowry base is a substance that can accept a proton from an acid. Therefore, look carefully for hydrogen-containing compounds that could provide or accept a proton.

Practice Problems

5. Write equations to show how the hydrogen sulfide ion, HS^-, can be classified as amphoteric. First show the ion acting as an acid. Then show the ion acting as a base.

6. Identify the conjugate acid-base pair in each reaction.

(a) $H_3PO_{4(aq)} + H_2O_{(\ell)} \rightleftharpoons H_2PO_4^-{}_{(aq)} + H_3O^+_{(aq)}$

(b) $O_2^-{}_{(aq)} + H_2O_{(\ell)} \rightleftharpoons 2OH^-_{(aq)}$

7. For each reaction in question 6, identify the amphoteric chemical species, and identify its role as either an acid or a base.

Continued...

14.2 Strong and Weak Acids and Bases

Section Preview/Outcomes

In this section, you will

- **explain,** in terms of the degree to which they dissociate, the difference between strong and weak acids and bases
- **compare,** qualitatively, the relative strengths of acids and bases
- **predict** whether reactants or products are favoured in an acid-base reaction
- **define** Kw, and relate its value to $[H_3O^+]$ and $[OH^-]$
- **define** and **calculate** values associated with pH, pOH, $[H_3O^+]$, and $[OH^-]$
- **communicate** your understanding of the following terms: *strong acid, weak acid, strong base, weak base, ion product constant for water (K_w), pH, pOH*

You have learned that substances such as water and the hydrogen carbonate ion are amphoteric—that is, they can act either as a Brønsted-Lowry acid or a Brønsted-Lowry base in a particular reaction. For example, the hydrogen carbonate ion behaves as an acid in the first of the two chemical equations below, but as a base in the second.

$$HCO_3^-{}_{(aq)} + HPO_4^{2-}{}_{(aq)} \rightleftharpoons CO_3^{2-}{}_{(aq)} + H_2PO_4^-{}_{(aq)}$$

($HCO_3^-{}_{(aq)}$ behaving as an acid)

$$HCO_3^-{}_{(aq)} + HF_{(aq)} \rightleftharpoons H_2CO_{3(aq)} + F^-{}_{(aq)}$$

($HCO_3^-{}_{(aq)}$ behaving as a base)

How could you predict which role the ion plays in each reaction? The answer to this question involves the strength of the ion in relation to the other substances present in each reaction. Keep this idea in mind as you learn about strong and weak acids and bases. You will return to it later in this section.

Strong and Weak Acids

In terms of acid-base reactions, strength refers to the extent to which a substance dissociates in its solvent. An acid that dissociates completely is termed a **strong acid.** As you can see in Figure 14.9, hydrochloric acid is a strong acid. *All* the molecules of hydrochloric acid in an aqueous solution dissociate into H^+ and Cl^- ions. Table 14.4 lists the strong acids. Note that *the concentration of hydronium ions in a dilute solution of a strong acid is equal to the concentration of the acid.* Therefore, a 1.0 mol/L solution of hydrochloric acid contains 1.0 mol/L of hydronium ions and 1.0 mol/L of chloride ions.

Table 14.4
Common Strong Acids

hydrochloric acid, HCl
hydrobromic acid, HBr
hydroiodic acid, HI
nitric acid, HNO_3
sulfuric acid, H_2SO_4
perchloric acid, $HClO_4$

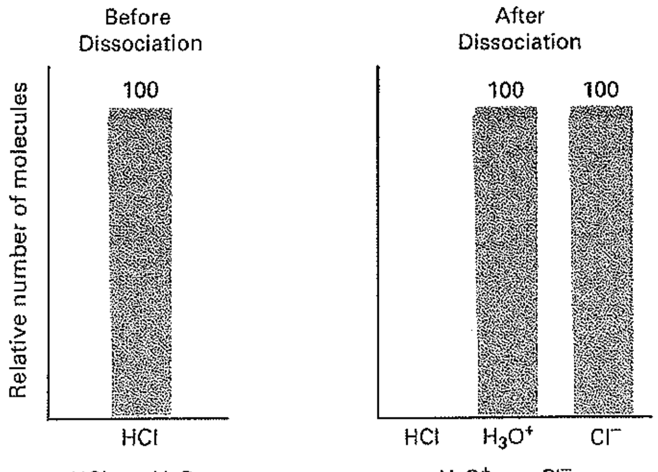


Figure 14.9 When hydrogen chloride molecules enter an aqueous solution, 100% of the hydrogen chloride molecules dissociate. In other words, the percent dissociation of HCl in water is 100%. As a result, the solution contains the same percent of H^+ ions (in the form of H_3O^+) and Cl^- ions: 100%.

A **weak acid** is an acid that dissociates only slightly in a water solution. Thus, only a small percentage of the acid molecules dissociate. Most of the acid molecules remain intact. The majority of acids are weak acids. For example, acetic acid is a weak acid. The percent dissociation of acetic acid molecules is only about 1% in a 0.1 mol/L solution. (The number of acid molecules that dissociate depends on the concentration and temperature of the solution.) Note that the concentration of hydronium ions in a solution of a weak acid is always less than the concentration of the dissolved acid. (See Figure 14.10.)

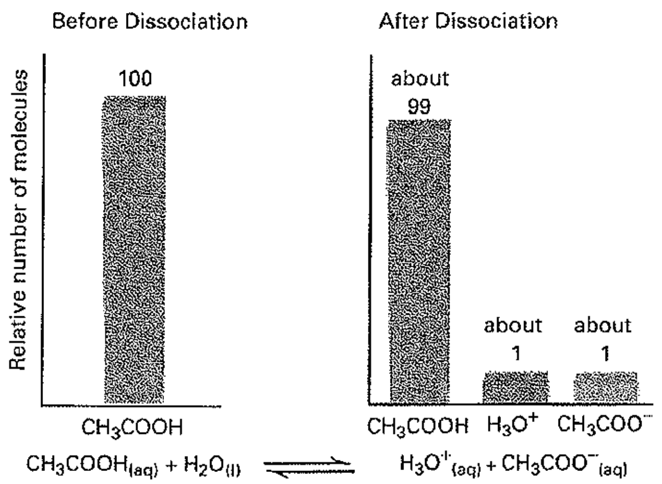


Figure 14.10 When acetic acid molecules enter an aqueous solution, only about 1% of them dissociate. Thus, the number of acetic acid molecules in solution is far greater than the number of hydronium ions and acetate ions.

A few acids contain only a single hydrogen ion that can dissociate. These acids are called *monoprotic acids*. (The prefix mono- means "one." The root -protic refers to "proton.") Hydrochloric acid, hydrobromic acid, and hydroiodic acid are strong monoprotic acids. Hydrofluoric acid, HF, is weak monoprotic acid.

Many acids contain two or more hydrogen ions that can dissociate. For example, sulfuric acid, $H_2SO_{4(aq)}$, has two hydrogen ions that can dissociate. Sulfuric acid is a strong acid, but *only* for its first dissociation.

$$H_2SO_{4(aq)} \rightarrow H^+_{(aq)} + HSO_4{}^-_{(aq)}$$

The resulting aqueous hydrogen sulfate ion, HSO^-_4, is a weak acid. It dissociates to form the sulfate ion in the following equilibrium reaction:

$$HSO_4{}^-_{(aq)} \rightleftharpoons H^+_{(aq)} + SO_4{}^{2-}_{(aq)}$$

Thus, acids that contain two hydrogen ions dissociate to form two anions. These acids are sometimes called *diprotic acids*. (The prefix di-, as you know, means "two.") The acid that is formed by the first dissociation is stronger than the acid that is formed by the second dissociation.

Acids that contain three hydrogen ions are called *triprotic acids*. Phosphoric acid, $H_3PO_{4(aq)}$, is a triprotic acid. It gives rise to three anions, as follows:

$$H_3PO_{4(aq)} + H_2O_{(\ell)} \rightleftharpoons H^+_{(aq)} + H_2PO_4{}^-_{(aq)}$$
$$H_2PO_4{}^-_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H^+_{(aq)} + HPO_4{}^{2-}_{(aq)}$$
$$HPO_4{}^{2-}_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H^+_{(aq)} + PO_4{}^{3-}_{(aq)}$$

CONCEPT CHECK

Notice that the chemical equation for the dissociation of hydrochloric acid—a strong acid—proceeds in a single direction, to the right. The chemical equation for the dissociation of acetic acid—a weak acid—shows an equilibrium reaction. Explain why this makes sense. Look for other instances of single- and double-arrows up to this point in the chapter, and explain what you see.

Here again, the acid that is formed by the first dissociation is stronger than the acid that is formed by the second dissociation. This acid is stronger than the acid that is formed by the third dissociation. Keep in mind, however, that all three of these acids are weak, because only a small proportion of them dissociates.

Strong and Weak Bases

Table 14.5
Common Strong Bases

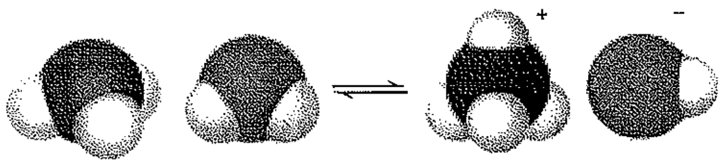
sodium hydroxide, $NaOH$
potassium hydroxide, KOH
calcium hydroxide, $Ca(OH)_2$
strontium hydroxide, $Sr(OH)_2$
barium hydroxide, $Ba(OH)_2$

Like a strong acid, a **strong base** dissociates completely into ions in water. All oxides and hydroxides of the alkali metals—Group 1 (IA)—are strong bases. The oxides and hydroxides of the alkaline earth metals—Group 2 (IIA)—below beryllium are also strong bases.

Recall that the concentration of hydronium ions in a dilute solution of a strong acid is equal to the concentration of the acid. Similarly, the concentration of hydroxide ions in a dilute solution of a strong base is equal to the concentration of the base. For example, a 1.0 mol/L solution of sodium hydroxide (a strong base) contains 1.0 mol/L of hydroxide ions.

Table 14.5 lists some common strong bases. Barium hydroxide, $Ba(OH)_2$, and strontium hydroxide, $Sr(OH)_2$, are strong bases that are soluble in water. Magnesium oxide, MgO, and magnesium hydroxide, $Mg(OH)_2$, are also strong bases, but they are considered to be insoluble. A small amount of these compounds does dissolve in water, however. Virtually all of this small amount dissociates completely.

Most bases are weak. A **weak base** dissociates very slightly in a water solution. The most common weak base is aqueous ammonia. In a 0.1 mol/L solution, only about 1% of the ammonia molecules react with water to form hydroxide ions. This equilibrium is represented in Figure 14.11.



$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

Figure 14.11 Ammonia does not contain hydroxide ions, so it is not an Arrhenius base. As you can see, however, an ammonia molecule can remove a proton from water, leaving a hydroxide ion behind. Thus, ammonia is a Brønsted-Lowry weak base.

Comparing the Relative Strengths of Acids and Bases

Earlier, you saw that the hydrogen carbonate ion may behave as an acid or a base in the following reactions.

$$HCO_3^-{}_{(aq)} + HPO_4^{2-}{}_{(aq)} \rightleftharpoons CO_3^{2-}{}_{(aq)} + H_2PO_4^-{}_{(aq)}$$

($HCO_3^-{}_{(aq)}$ behaving as an acid)

$$HCO_3^-{}_{(aq)} + HF_{(aq)} \rightleftharpoons H_2CO_{3(aq)} + F^-{}_{(aq)}$$

($HCO_3^-{}_{(aq)}$ behaving as a base)

You are now in a position to reconsider the question: How could you predict the role that each ion plays?

Over the centuries, chemists have performed countless experiments involving acids and bases. The data from these experiments have enabled chemists to rank acids and bases according to their strengths in relation to

one another, as shown in Figure 14.12. Using these data, you can easily compare the relative strengths of acids and bases. For example, the chart shows that HCO_3^- is above HPO_4^{2-}. Since the acids are listed in order of increasing strength, you know that HCO_3^- is a stronger acid than HPO_4^{2-}. Therefore, you can (if the remainder of the balanced equation were not given to you) correctly predict the products of the reaction. Why? Because you know that the proton from the acid must go to its conjugate base, $H_2PO_4^{2-}$.

ACID STRENGTH

Acid	Base
HCl	Cl^-
H_2SO_4	HSO_4^-
HNO_3	NO_3^-
H_3O^+	H_2O
HSO_4^-	SO_4^{2-}
H_2SO_3	HSO_3^-
H_3PO_4	$H_2PO_4^-$
HF	F^-
CH_3COOH	CH_3COO^-
H_2CO_3	HCO_3^-
H_2S	HS^-
HSO_3^-	SO_3^{2-}
$H_2PO_4^-$	HPO_4^{2-}
NH_4^+	NH_3
HCO_3^-	CO_3^{2-}
HPO_4^{2-}	PO_4^{3-}
H_2O	OH^-
HS^-	S^{2-}
OH^-	O^{2-}

BASE STRENGTH

Figure 14.12 **Relative strengths of selected acids and bases. Notice that the strongest acids appear at the top of the list on the left, and the strongest bases appear at the bottom of the list on the right. Notice also that a stronger acid has a weaker conjugate base, and a stronger base has a weaker conjugate acid.**

Figure 14.12 is useful in another way. You can use it to predict the direction in which an acid-base reaction will proceed. Or, to put it another way, you can use the chart to help you determine whether products or reactants are favoured in an acid-base reaction. The direction of an acid-base reaction usually proceeds from a stronger acid and a stronger base to a weaker acid and a weaker base. If the reaction proceeds to the right (that is, if the stronger acid and stronger base are on the left side of the equation), products are favoured. If the reaction goes to the left (if the stronger acid and stronger base are on the right side of the equation), reactants are favoured. Use the next Sample Problem and Practice Problems to help you understand these ideas better.

Sample Problem

Predicting the Direction of an Acid-Base Reaction

Problem

Predict the direction in which the following reaction will proceed. State whether reactants or products are favoured at equilibrium, and briefly defend your reasoning.

$$SO_4{}^{2-}{}_{(aq)} + CH_3COOH_{(aq)} \rightleftharpoons HSO_4{}^{-}{}_{(aq)} + CH_2COO^{-}{}_{(aq)}$$

Solution

Use Figure 14.12 to assess the relative strengths of the acids and bases. You can see that HSO_4^- is above CH_3COOH, so HSO_4^- is a stronger acid than CH_3COOH. Similarly, CH_2COO^- is lower than SO_4^-, so CH_2COO^- is a stronger base. The stronger acid and stronger base form the weaker acid and the weaker base, so the direction proceeds in that direction—that is, to the left.

$$\underset{\text{weaker acid}}{SO_4{}^{2-}{}_{(aq)}} + \underset{\text{weaker base}}{CH_3COOH_{(aq)}} \rightleftharpoons \underset{\text{stronger acid}}{HSO_4{}^{-}{}_{(aq)}} + \underset{\text{stronger base}}{CH_2COO^{-}{}_{(aq)}}$$

the reactants are favoured in this reaction.

Practice Problems

10. Predict the direction for the following equations. State whether reactants or products are favoured, and give reasons to support your decision.

(a) $NH_4{}^{+}{}_{(aq)} + H_2PO_4{}^{-}{}_{(aq)} \rightleftharpoons NH_{3(aq)} + H_3PO_{4(aq)}$

(b) $H_2O_{(\ell)} + HS^{-}{}_{(aq)} \rightleftharpoons OH^{-}{}_{(aq)} + H_2S_{(aq)}$

(c) $HF_{(aq)} + SO_4{}^{2-}{}_{(aq)} \rightleftharpoons F^{-}{}_{(aq)} + HSO_4{}^{-}{}_{(aq)}$

11. In which direction will the following reactions proceed? Explain why in each case.

(a) $HPO_4{}^{2-}{}_{(aq)} + NH_4{}^{+}{}_{(aq)} \rightleftharpoons H_2PO_4{}^{-} + NH_{3(aq)}$

(b) $H_2SO_{4(aq)} + H_2O_{(\ell)} \rightleftharpoons HSO_4{}^{-}{}_{(aq)} + OH^{-}{}_{(aq)}$

(c) $H_2S + NH_{3(aq)} \rightleftharpoons HS^{-}{}_{(aq)} + NH_4{}^{+}{}_{(aq)}$