Keys

Lesson 33 Acids and Bases

Key Words

indicator:	substance used to detect the presence of an acid or a base; acids and bases cause indicators to change color
Arrhenius acid:	substance that produces hydrogen ions when it is in water solution
Arrhenius base:	substance that produces hydroxide ions when it is in water solution
Bronsted-Lowry acid:	a proton donor
Bronsted-Lowry base:	a proton acceptor
hydronium ion:	a hydrated proton or H_3O^+

KEY IDEAS

Observing the properties of acids and bases has led to two main theories. One is the Arrhenius theory, which states that acids produce hydrogen ions and bases produce hydroxide ions. The other is the Bronsted-Lowry theory, which states that acids are proton donors and bases are proton acceptors.

In recent years, acid rain has become a serious environmental problem. Some technicians are working on ways to prevent acid rain from forming. Other workers are trying to cope with the effects of acid rain pollution that have already occurred.

Properties of Acids and Bases. Acids have the following observed properties:

- Acids dissolved in water are electrolytes, which conduct an electric current.
- Acids have a sour taste. Examples are the acids in vinegar and lemon juice.
- Acids react with many metals to produce hydrogen gas.
- Acids change the color of some indicators. An **indicator** (IN-duh-KAYT-uhr) is a substance used to detect the presence of an acid or a base. In the presence of an acid, blue litmus turns red, and red phenolphthalein becomes colorless.
- Acids neutralize bases to produce a salt and water.

Bases have the following observed properties:

- Bases dissolved in water are electrolytes.
- Bases feel slippery.

- Bases change the colors of some indicators. In the presence of a base, red litmus turns blue, and colorless phenolphthalein turns red.
- Bases neutralize acids to produce a salt and water.

✓ **1. What color is litmus in the presence of an acid?** red

✓ **2. What color is phenolphthalein in the presence of a base?** red (pink)

Arrhenius Theory. Arrhenius proposed a theory to explain the behavior of acids and bases. An **Arrhenius acid** (uh-RAY-nee-uhs) is a substance that produces hydrogen ions (H^+) as the only positive ions in water solution. Here is an example:

Equation 1 $\quad HCl \text{ (in } H_2O) \longrightarrow H^+ + Cl^-$

An **Arrhenius base** is a substance that produces hydroxide ions (OH^-) as the only negative ions in water solution. Here is an example:

Equation 2 $\quad NaOH \text{ (in } H_2O) \longrightarrow Na^+ + OH^-$

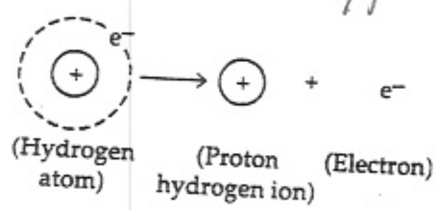
✓ **3. Which symbol represents the hydrogen ion? The hydroxide ion?** H^+ OH^-

Bronsted-Lowry Theory. Bronsted and Lowry proposed another theory to explain acid and base reactions that take place in either a water or a nonwater medium. According to this theory, a **Bronsted-Lowry acid** (BRAHN-stehd LOW-ree) is a proton donor. A **Bronsted-Lowry base** is a proton acceptor.

a c donates H^+

Recall that the hydrogen atom consists of one proton and one electron. As shown in Fig. 33-1, when a hydrogen atom loses an electron, only a proton remains. Thus, a hydrogen ion is a proton.

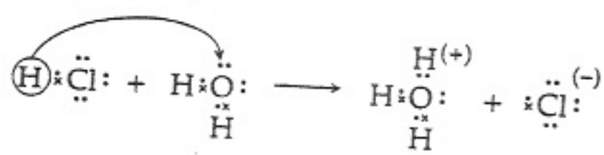
Fig. 33-1



Equation 3 shows HCl reacting with H_2O to produce hydronium ion (H_3O^+).

Equation 3 $\quad HCl + H_2O \longrightarrow H_3O^+ + Cl^-$

Fig. 33-2



In the electron-dot diagrams shown in Fig. 33-2, you can see that a proton moves from the HCl to the H_2O. A hydronium ion—H_3O^+—is formed. The **hydronium ion** (hy-DROH-nee-uhm) is also called a hydrated proton because the proton is attached to a water molecule.

base c c e p t s H^+

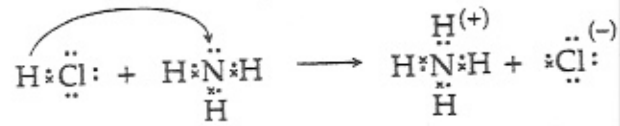
TAKE ANOTHER LOOK

4. **What is the formula for the hydronium ion?** H_3O^+

An acid can give its proton to other substances besides water. In the reaction below, HCl loses its proton to ammonia, NH_3, forming an ammonium ion NH_4^+. This example shows that it is not necessary for the base to contain hydroxide OH^-. See Equation 4 and Fig. 33-3.

Equation 4 $$HCl + NH_3 \longrightarrow NH_4^+ + Cl^-$$

Fig. 33-3



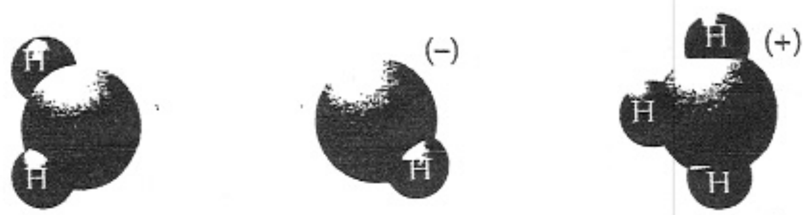
A base, such as NaOH, accepts a proton from an acid, such as HCl.

Equation 5 $$NaOH + HCl \longrightarrow HOH + Na^+ + Cl^-$$

It is not necessary for a base to contain OH^-. For example, in Equation 4 in the reaction between HCl and NH_3, the base is NH_3.

You've seen how electron-dot diagrams represent water molecules, hydroxide ions, and hydronium ions. Fig. 33-4 shows how these particles can be pictured as models made of spheres.

Fig. 33-4



Water molecule H_2O | Hydroxide ion OH^- | Hydronium ion H_3O^+

Indicators appear as different colors in acids and bases. The chart in Fig. 33-5 compares colors of various indicators.

Fig. 33-5

Table of Indicator Colors

Indicator	**Color** Acid	Base
alizarin yellow	yellow	violet
bromthymol blue	yellow	blue
litmus	red	blue
methyl red	red	yellow
phenolphthalein	colorless	red
phenol red	yellow	red

Check Yo Understandi

Fill in the blanks.

5. According to Arrhenius, an acid produces __hydrogen__ ions and a base produces __hydroxide__ ions.
6. The Bronsted-Lowry theory states that an acid is a(n) __proton donor__ and a base is a(n) __proton acceptor__
7. A hydrated proton is called a(n) __hydronium__ ion and has the formula __H_3O^+__.

On the lines under the following equations, write the word *acid* or *base* to identify the substance as either a proton donor or a proton acceptor.

8. $HCl + H_2O \longrightarrow H_3O^+ + Cl^-$

   HCl: __acid__ H_2O: __base__

9. $H_2O + NH_3 \longrightarrow NH_4^+ + OH^-$

   H_2O: __acid__ NH_3: __base__

Wha Do Y Kn w?

Write the correct term in each blank.

10. One property of acids is their __sour__ taste.
11. In an acid solution, the color of litmus is __red__.
12. Compounds that produce hydrogen ions in a water solution are __acids__.
13. In a base solution, the color of phenolphthalein is __red (pink)__.
14. One property of bases is their __slippery__ feel.
15. A(n) __indicator__ is any substance used to detect the presence of an acid or a base.

If the statement is correct, write the word *True*. If the statement is incorrect, write the word *False*.

16. __True__ Acids and bases are both electrolytes.
17. __True__ A base is a proton acceptor.
18. __False__ The formula for the hydronium ion is OH^-.
19. __False__ A hydrated proton is called a hydroxide.
20. __False__ An acid must always give its proton to water.

Lesson 34 Describing Acid-Base Solutions

Key Words

related acid-base pair: acid and base that differ by one proton

K_a: ionization constant of an acid; it shows the relative strength of acids

pH: scale that shows the concentration of H_3O^+

KEY IDEAS

In acid-base reactions, protons—H^+—move from one substance to another. Not all acids and bases lose or gain protons to the same degree. The extent of proton transfer determines acid or base strength. A pH number describes the concentration of hydrogen ions—H^+—or hydronium ions—H_3O^+.

Human blood is a slightly basic solution with a pH of about 7.4. Changes in the pH of the blood may occur when the body does not function properly. If the pH rises to near 8.0 or drops to below 6.8, the result can be fatal.

Proton Transfer. Recall that an acid is a proton donor. The proton, or H^+, is accepted by a base, which is a proton acceptor. For example, in a reaction between H_2SO_4 and H_2O, a proton moves from the H_2SO_4 to the H_2O, forming H_3O^+ and HSO_4^-.

Equation 1

$$\underset{\text{acid}}{H_2SO_4} + \underset{\text{base}}{H_2O} \longrightarrow \underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{HSO_4^-}$$

The H_2SO_4 is the acid because it donates a proton—H^+. The H_2O is the base because it gains a proton—H^+. As a result of the H_2O gaining a proton, H_3O^+ is formed.

The reverse of this reaction can also occur. In this case, a proton moves from the H_3O^+ to the HSO_4^-, forming H_2O and H_2SO_4.

Equation 2

$$\underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{HSO_4^-} \longrightarrow H_2SO_4 + H_2O$$

The H_3O^+ is an acid because it donates a proton—H^+—to the HSO_4^-. The HSO_4^- is the base because it gains a proton—H^+—from the H_3O^+.

When the products of a chemical reaction react to reform the reactants, the reaction is called a reversible reaction. Equation 3 combines Equation 1 with Equation 2 as one equation, showing a reversible reaction.

Equation 3 $$\underset{\text{acid}}{H_2SO_4} + \underset{\text{base}}{H_2O} \rightleftharpoons \underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{HSO_4^-}$$

Acid-base Pairs. The H_2SO_4 became HSO_4^- when it lost, or donated, a proton. After an acid has donated a proton, the substance remaining is a base. This base forms a related pair with that acid. So H_2SO_4 and HSO_4^- are a **related acid-base pair**. The acid and base in this pair differ by only one proton. (one H^+)

The H_2O became H_3O^+ when it gained, or accepted, a proton. After a base has accepted a proton, the substance remaining is an acid. This acid forms a related pair with that base. So H_3O^+ and H_2O are a related acid-base pair. The acid and base in this pair differ by only one proton. Study Fig. 34-1, which shows acid-base pairs for the reaction in Equation 3.

Fig. 34-1

$$\underset{\text{ACID}}{H_2SO_4} + \underset{\text{BASE}}{H_2O} \rightleftharpoons \underset{\text{ACID}}{H_3O^+} \quad \underset{\text{BASE}}{HSO_4^-}$$

acid/base pairs

acids have one more H^+ than the base in its pair

✓ 1. **On the lines under each substance in the equation, write the word *acid* or *base* to identify the substance.**

HCl + H_2O $\rightleftharpoons$ H_3O^+ + Cl^-

(a) acid (b) base (c) acid (d) base

✓ 2. **The related acid-base pairs in Equation 2 are**
(a) HCl & Cl^- and (b) H_2O & H_3O^+.

Substances That Act As Acids or Bases. Some substances can act as either an acid or a base. When in the presence of an acid, such a substance acts as a base. When in the presence of a strong base, however, the same substance acts as an acid.

Water is an example of such a substance. When water donates a proton to NH_3, which is a strong base, the water is an acid.

Equation 4 $$\underset{\text{acid}}{H_2O} + \underset{\text{base}}{NH_3} \longrightarrow NH_4^+ + OH^-$$

When water accepts a proton from HCl, which is an acid, the water is a base.

Equation 5 $$\underset{\text{acid}}{HCl} + \underset{\text{base}}{H_2O} \longrightarrow H_3O^+ + Cl^-$$

Water ionizes only slightly. When this happens, one water molecule donates a proton to another water molecule. Water, therefore, acts as both acid and base.

Equation 6 $$\underset{\text{acid}}{H_2O} + \underset{\text{base}}{H_2O} \rightleftharpoons H_3O^+ + OH^-$$

3. What is one substance with which water acts as an acid? What is a substance with which water acts as a base? Sorry!

(a) NH3 **and (b)** HCl

Ionization Constants. An ionization constant, K_a, is used to compare the relative strengths of acids. To compute K_a for an acid, the concentration of the ions is divided by the concentration of the acid. A strong acid yields a large concentration of ions. A weak acid produces few ions in comparison to the number of acid molecules. So the K_a values of strong acids are larger than the K_a values of weak acids.

The chart in Fig. 34-2 lists some acids, the bases with which they form related pairs, and K_a values. The strong acids are at the top of the chart. Compare phosphoric acid—H_3PO_4—with acetic acid CH_3COOH. Phosphoric acid is the stronger acid and is higher on the chart. Also compare the K_a values of the two acids. The K_a of H_3PO_4 is 7.5×10^{-3}. This K_a is larger than the 1.8×10^{-5} value for CH_3COOH. A larger K_a means more ions and a stronger acid.

Fig. 34-2

Strengths of Acids

Related acid-based pairs: ACID				BASE	K_a
HCl	=	H^+	+	Cl^-	large
HNO_3	=	H^+	+	NO_3^-	large
H_2SO_4	=	H^+	+	HSO_4^-	large
HSO_4^-	=	H^+	+	SO_4^{2-}	1.2×10^{-2}
H_3PO_4	=	H^+	+	$H_2PO_4^-$	7.5×10^{-3}
HNO_2	=	H^+	+	NO_2^-	4.6×10^{-4}
HF	=	H^+	+	F^-	3.5×10^{-4}
CH_3COOH	=	H^+	+	CH_3COO^-	1.8×10^{-5}
H_2CO_3	=	H^+	+	HCO_3^-	4.3×10^{-7}
HSO_3^-	=	H^+	+	SO_3^{2-}	1.1×10^{-7}
H_2S	=	H^+	+	HS^-	9.5×10^{-8}
$H_2PO_4^-$	=	H^+	+	HPO_4^{2-}	6.2×10^{-8}
NH_4^+	=	H^+	+	NH_3	5.7×10^{-10}
HCO_3^-	=	H^+	+	CO_3^{2-}	5.6×10^{-11}
HPO_4^{2-}	=	H^+	+	PO_4^{3-}	2.2×10^{-13}
HS^-	=	H^+	+	S^{2-}	1.3×10^{-14}
H_2O	=	H^+	+	OH^-	1.0×10^{-14}

4. **Compare HF with H_2S. Which acid is stronger?** HF.

Acidity as pH. The acidity of solutions can be stated in terms of pH. Neutral solutions have a pH value of 7. Acidic solutions have pH values less than 7. Basic solutions have values greater than 7.

pH < 7 Acidic Solution
pH = 7 Neutral Solution
pH > 7 Basic Solution

Mathematically pH is the negative logarithm, to the base 10, of the concentration of the hydronium ion—H_3O^+. Brackets [ ] around a formula mean concentration in moles/liter.

Equation 7

$$pH = -\log [H_3O^+]$$

When water ionizes, hydronium—H_3O^+—and hydroxide—OH^-—ions are formed. K_w stands for the ionization constant of water. It has a value of 1.0×10^{-14}.

Equation 8

$$K_w = [H_3O^+][OH^-] = 1.0 \times 10^{-14}$$

In pure water, $[H_3O^+] = [OH^-] = 1.0 \times 10^{-14}$. Therefore, the $[H_3O^+]$ and the $[OH^-]$ must both be 1×10^{-7} because $(1 \times 10^{-7})(1 \times 10^{-7}) = (1 \times 10^{-14})$.

Substituting the concentration of 1×10^{-7} into Equation 7, you can calculate the pH of water as 7.00.

The pH of a solution can be easily found with a calculator. Use your calculator and the following procedure shown in Fig. 34-3.

Fig. 34-3

1. Enter 1.0 Exp -7 2. Then push (1/x) 3. Then push (Log)

Repeat the procedure to find the pH of a 0.1 M HCl solution. See Fig 34-4.

Fig. 34-4

1. Enter 0.1 2. Then push (1/x) 3. Then push (Log) Answer is pH = 1.00

You can estimate pH using the system shown in Fig 34-5.

Fig. 34-5

1.0×10^{-3}

If this number is exactly 1, then this number is the pH

5. (a) What is the pH of a solution with $[H_3O^+] = 1.0 \times 10^{-12}$? 12

(b) Is this solution an acid or a base? Base

TAKE ANOTHER LOOK

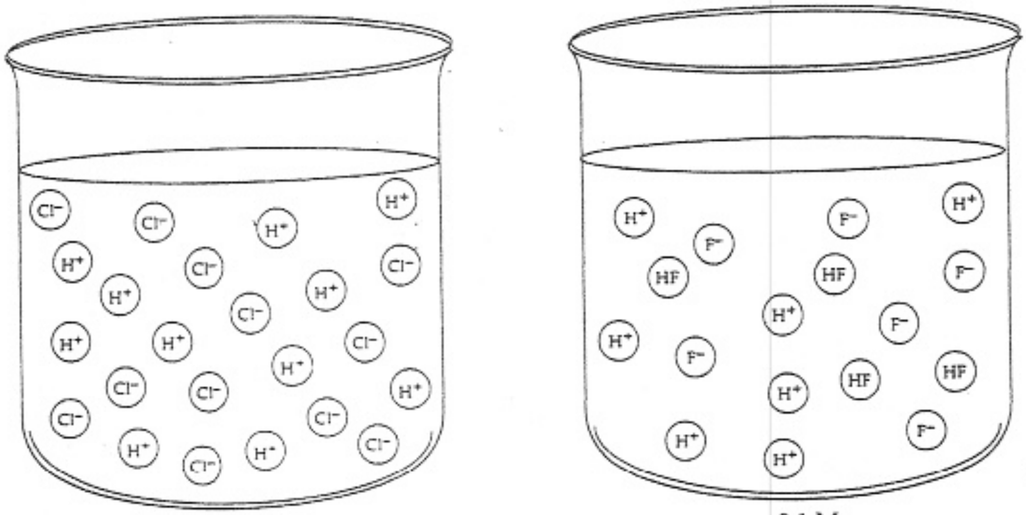
The scale in Fig. 34-6 shows $[H_3O^+]$ and pH. On this scale, you can see that a solution with $[H_3O^+] = 1 \times 10^{-7}$ has a pH of 7 and is neutral. Acidic solutions have a pH less than 7. Basic solutions have a pH greater than 7.

Fig. 34-6

$[H_3O^+]$	1×10^{0}	1×10^{-1}	1×10^{-2}	1×10^{-3}	1×10^{-4}	1×10^{-5}	1×10^{-6}	1×10^{-7}	1×10^{-8}	1×10^{-9}	1×10^{-10}	1×10^{-11}	1×10^{-12}	1×10^{-13}	1×10^{-14}
pH	0	1	2	3	4	5	6	7 Neutral	8	9	10	11	12	13	14

Fig. 34-7 compares a strong acid and a weaker acid. The strong acid—HCl—produces many ions in solution. The weaker acid—HF—produces fewer ions.

Fig. 34-7



0.1 M HCl

0.1 M HF

Remember that pH is based upon the concentration of the hydronium (or hydrogen) ion. Low pH numbers mean a high hydronium (or hydrogen) ion concentration and a solution that is acidic. High pH numbers mean that many hydroxide ions are present and the solution is basic.

Check Your Understanding

Use the key terms from the beginning of this lesson to fill in the blanks.

6. An acid and a base that differ by only one proton are called pairs.

7. Relative strengths of acids are compared using ionization constants

8. The concentration of H_3O^+ in solution is expressed in terms of pH.

Circle the correct term.

9. The ionization constant, K_a, for acetic acid—CH_3COOH—is
   a. 1.2×10^{-2}. b. 3.5×10^{-4}. c. 1.8×10^{-5}. d. 5.6×10^{-11}.

10. A sample of water contains
    a. equal concentrations of H_3O^+ and OH^-.
    b. greater concentrations of H_3O^+ than OH^-.
    c. lower concentrations of H_3O^+ than OH^-.
    d. no H_3O+ or OH^-.

11. In the reaction $H_2O + H_2O \rightarrow H_3O^+ + OH^-$, the water is acting as
    a. both an electron receiver and an electron donor.
    b. neither an electron receiver nor an electron donor.
    c. neither a proton donor nor a proton accepter.
    d. both a proton donor and a proton acceptor.

12. In the reaction $H_2S + H_2O \rightarrow H_3O^+ + HS^-$, a related acid base pair is
    a. H_2S and H_2O.
    b. H_2O and H_3O^+.
    c. H_3O^+ and HS^-.
    d. H_2O and HS^-.

13. What is the pH of a solution if the $[H_3O^+]$ is 1×10^{-8}?
    a. 1 b. 6 c. 8 d. 14

14. Pure water has a pH of
    a. 1×10^{-7}. b. 7. c. 1. d. 1×10^{-14}.

Lesson 35 Acid-Base Reactions

Key Words

neutralization: reaction between an acid and a base to make a salt and water

salt: compound of a positive ion other than H^+ and a negative ion other than OH^-

titration: process of finding the concentration of an unknown solution by reacting it with a standard solution

standard solution: solution of known concentration

end point: point in titration at which chemically equivalent amounts of acid and base are present

phenolphthalein: indicator that is colorless in the presence of an acid and red in the presence of a base

KEY IDEAS

Acids and bases neutralize each other. If the strength of one of two solutions that neutralize each other is known, titration can be used to find the strength of the second solution.

Technicians in medical and in environmental laboratories use titration to analyze solutions. These workers need to be skilled in titration techniques and must be able to interpret the results.

Neutralization. The reaction that takes place when an acid and a base react to form a salt and water is **neutralization** (noo-truhl-ih-ZAY-shun). Look at these reactions:

Equation 1	HCl hydrochloric acid	+	$NaOH$ sodium hydroxide	—>	$NaCl$ sodium chloride	+	H_2O water
Equation 2	HNO_3 nitric acid	+	KOH potassium hydroxide	—>	KNO_3 potassium nitrate	+	H_2O water

In each reaction, an acid and a base neutralize each other. In each reaction, water and a **salt** are formed. A salt is a compound with a positive ion other than the hydrogen ion—H^+—and a negative ion other than the hydroxide ion—OH^-.

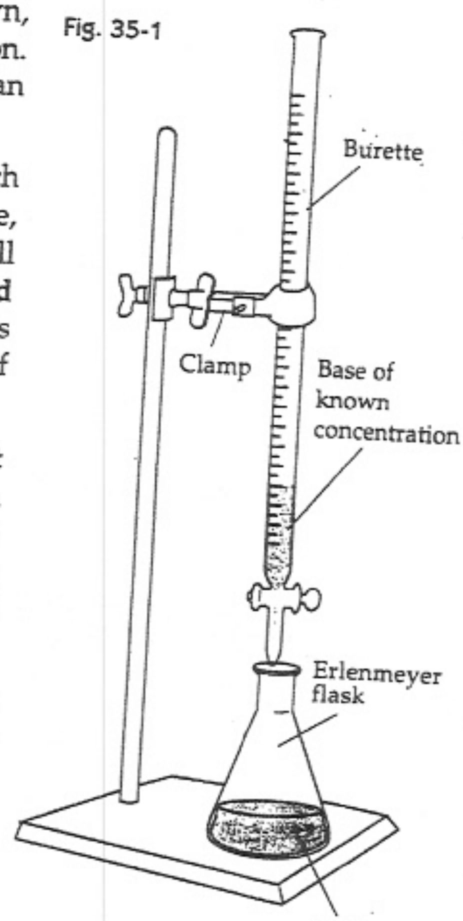
The salt NaCl was formed in the first reaction. The salt KNO_3 was formed in the second reaction. In each case, the salt is the result of the combination of the positive ion from the base with the negative ion of the acid.

1. **What salt would form if HCl neutralized KOH?** KCl

Titration. If the strength of only the acid or the base is known, the strength of the other solution can be measured by titration. **Titration** (ty-TRAY-shuhn) measures the concentration of an unknown solution by reacting it with a standard solution.

To find the concentration of an acid, such as HCl, a burette such as the one in Fig. 35-1 is filled with a standard solution of a base, such as NaOH. The NaOH solution is titrated, or added in small amounts, into the HCl until the end point is reached. A **standard solution** is a solution of known concentration. The **end point** is that point in titration at which chemically equivalent amounts of acid and base are present.

Fig. 35-1



The burette is a tool that can be used to measure the exact amount of a base of known concentration that will react with an acid of unknown strength. If phenolphthalein is present in the acid, a red color will appear at the end point. **Phenolphthalein** (fee-nohl-THAYL-een) is an indicator that is colorless in the presence of an acid and red in the presence of a base.

Sample Problem: Suppose 10 m*l* of a solution of HCl is titrated to the end point with 25.0 m*l* of 1.00 *M* NaOH. What is the molarity of the HCl solution?

molarity = moles/liters
1.00 *M* = moles of NaOH/0.0250 liters of NaOH
moles of NaOH = 0.0250

The equation for the neutralization in this problem is

$$HCl + NaOH \longrightarrow NaCl + H_2O$$

In this equation, the moles of acid, HCl, neutralized is also 0.0250.

molarity = moles/liters
molarity = 0.0250 moles of HCl/0.0100 liters of HCl
molarity = 2.50 *M*

2. **What is the molarity of 25.0 m*l* of HCl solution if it is neutralized by 30.0 mL of 5.00 *M* NaOH?**

M_A = molarity of acid
V_A = volume of acid
M_B = molarity of base
V_B = volume of base

$M_A V_A = M_B V_B$

$M_A \times 25.0 = 5.00 \times 30.0$

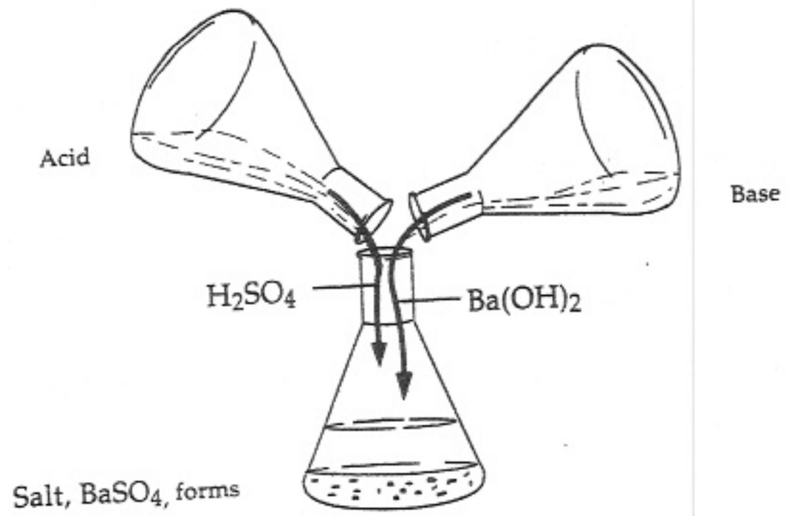
$\frac{M_A \times 25.0}{25.0} = \frac{150}{25.0}$

$M_A = 6.0 M$

TAKE ANOTHER LOOK

An acid and a base neutralize each other to make a salt and water. An example is the reaction of sulfuric acid—H_2SO_4—and barium hydroxide $Ba(OH)_2$. Fig. 35-2 shows $Ba(OH)_2$ neutralizing H_2SO_4. The salt barium sulfate—$BaSO_4$—is forming as a solid at the bottom of the flask.

Fig. 35-2



$$H_2SO_4 + Ba(OH)_2 \longrightarrow BaSO_4 + 2H_2O$$

Fig. 35-3

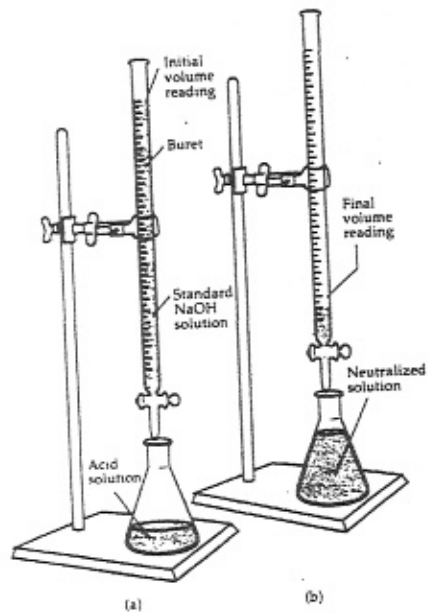


Fig. 35-3 shows the procedure for titrating HCl with a standard NaOH solution. A known volume of HCl and phenolphthalein is placed in the flask. A standard NaOH solution is poured into the burette. The volumes of the NaOH solution at the beginning and at the end of the titration are recorded. The volume of NaOH used is found by subtraction.

Check Your Understanding

Use the Key Words from the beginning of this lesson to fill in the blanks.

3. An acid and a base react to form a salt and water in a reaction called neutralization.

4. A compound made of a positive ion other than H^+ and a negative ion other than OH^- is a(n) salt.

5. The process used to measure the concentration of an unknown solution by reacting it with a standard solution is titration.

6. A solution of known concentration is a(n) Standard solution.

7. The point of titration when chemically equivalent amounts of acid and base are present is the end point.

What Do You Know?

Fill in the blanks with the correct word or answer to the problem.

8. When hydrobromic acid—HBr—neutralizes NaOH, the formula of the salt is $Na^{1+}Br^{1-} = NaBr$.

9. If the salt formed during neutralization is calcium sulfate—$CaSO_4$, the formula of the acid used is H_2SO_4. The formula of the base used is $Ca(OH)_2$.

10. What is the molarity of 40 m*l* of NaOH if it is completely neutralized by 10 m*l* of 6.0 *M* HCl? 1.5M

    $M_AV_A = M_BV_B$ $\quad 6.0 \times 10 = M_B \cdot 40$ $\quad \frac{60}{40} = \frac{M_B \cdot 40}{40}$ $\quad M_B = 1.5$

Use $M_AV_A = M_BV_B$

11. How many m*l* of 2.0 *M* KOH will be needed to neutralize 30 m*l* of 0.50 *M* HNO_3? 7.5mL

    $30 \times 0.50 = 2.0 \times V_B$
    $15 = 2.0 \cdot V_B$

12. How many liters of 2.5 *M* H_2SO_4 are needed to neutralize 2.5 liters of 5.0 *M* $Ca(OH)_2$? 5.0L

13. A 30-m*l* sample of HCl is neutralized by 10 m*l* of 1.5 *M* KOH. What is the molarity of the HCl? 0.5 M

14. If 30 m*l* of water is added to the HCl in question 13, how much more KOH will be needed for complete neutralization? 13.3 mL

    $0.5 \times 40 = 1.5 \cdot V_B$
    $\frac{20}{1.5} = \frac{1.5 \cdot V_B}{1.5}$
    $V_B =$