Acids, Bases, and Salts

VOCABULARY		
acidity	electrolyte	neutralization
alkalinity	hydrogen ion	pH scale
Arrhenius acid	hydronium ion	salt
Arrhenius base	indicator	titration

Tables K and L in the *Reference Tables for Physical Setting/Chemistry* list a few of the most common acids and bases. But what exactly are acids and bases? Acids and bases are classes of compounds that can be recognized by their easily observed properties. In this chapter you will learn about these properties, the definitions that are used to explain these properties, and the important reactions that occur between acids and bases.

Properties of Acids and Bases

Certain observable properties can be used to identify both acids and bases. Although these properties can indicate whether or not a substance is an acid or a base, they do not explain why acids and bases behave the way they do.

Characterisitic Properties of Acids

- *Dilute solutions of acids have a sour taste.* It would be foolish to taste a substance to see if it is an acid. However, there are acids in many of the foods that we eat. You have probably noticed the sour taste of lemons; the sour taste is due to the presence of citric acid. Vinegar contains acetic acid, and carbonated drinks have carbonic acid as one of the ingredients.
- *Aqueous solutions of acids conduct an electric current.* Substances that conduct an electric current are called **electrolytes**. The ability of a solution to conduct an electric current is dependent on the concentration (number) of ions in solution. That is, the greater the number of ions in solution, the greater the electrical conductivity. If a solution of an acid is a good conductor of electricity, it is called a strong acid. If such a solution is a poor conductor, it is termed a weak acid.
- *Acids react with bases to form water and a salt.* This type of reaction is called a **neutralization** reaction. Neutralization reactions are in fact a type of double replacement reaction. The **salt** that is formed as a product of a neutralization reaction is an ionic substance composed of a positively charged metallic or polyatomic ion and a negative ion other than the hydroxide ion.
- *Acids react with certain metals to produce hydrogen gas.* The metals listed in Table J of the *Reference Tables for Physical Setting/Chemistry* that are above hydrogen (H_2) will react with acids to produce hydrogen gas and a salt. Thus, magnesium will react with hydrochloric acid, whereas copper will not.
- *Acids cause acid-base indicators to change color.* Indicators are substances that have different colors when mixed in acidic and basic solutions. Table M of the *Reference Tables for Physical Setting/Chemistry* lists several common indicators and the color changes that they undergo.

Characterisitic Properties of Bases

- *Bases have a bitter taste.*
- *Bases have a slippery or soapy feeling.*
- *Bases conduct an electric current.* Note that the terminology used to describe the strength of a

base is the same as that used for acids. Thus, a solution of a base with a high concentration of ions that conducts electricity is called a strong base. Weak bases are poor conductors of electricity and are not highly ionized.

- *Bases react with acids to produce water and a salt.*
- *Bases cause acid-base indicators to change color.*

Arrhenius Theory

There have been several attempts to develop explanations for the observable properties of acids and bases. Svante Arrhenius, a Swedish chemist, proposed a commonality of all acids to explain their similar properties. An **Arrhenius acid** is defined as a substance whose water solution contains the hydrogen ion as the only positive ion. For example, hydrochloric acid ionizes in water to form hydrogen and chloride ions.

$$HCl \rightarrow H^+ + Cl^-$$

Not all substances that contain hydrogen are acids. Methane (CH_4) is an organic compound containing hydrogen, yet it is not an acid. The hydrogen atoms in methane are bonded to the carbon by covalent bonds. These hydrogen atoms do not ionize in solution: rather, they remain attached to the molecule. Because the hydrogen atoms do not form ions, methane is neither an electrolyte nor an acid.

The Nature of the Hydrogen Ion

A hydrogen atom consists of a single electron orbiting a nucleus that contains a single proton. As shown in Figure 10-1, when the hydrogen atom becomes a positive ion, the electron is lost, leaving behind the proton. Thus, a positive **hydrogen ion** is a proton.

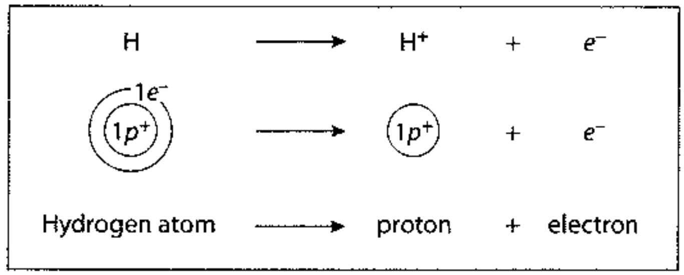


Figure 10-1. An H^+ ion is a proton.

Chemists believe that this proton cannot exist in a water solution as an isolated proton. The positively charged proton is attracted to an unshared pair of electrons in the water molecule. See Figure 10-2. The proton covalently bonds with the water forming H_3O^+, the **hydronium ion.** Acids dissolve in water and react to produce hydronium and negative ions.

$$HCl + H_2O \rightarrow H_3O^+ + Cl^-$$
$$H^+ + H_2O \rightarrow H_3O^+$$

According to the Arrhenius theory, the properties of acids are properties of the hydrogen (hydronium) ion.

As shown in the first equation above, each molecule of hydrochloric acid (HCl) that ionizes in water produces a single hydrogen ion. Hydrochloric acid and other acids that produce a single hydrogen ion are called monoprotic acids. Sulfuric acid (H_2SO_4), however, ionizes in two steps.

$$H_2SO_4 \rightarrow H^+ + HSO_4^-$$
$$HSO_4^- \rightarrow H^+ + SO_4^{2-}$$

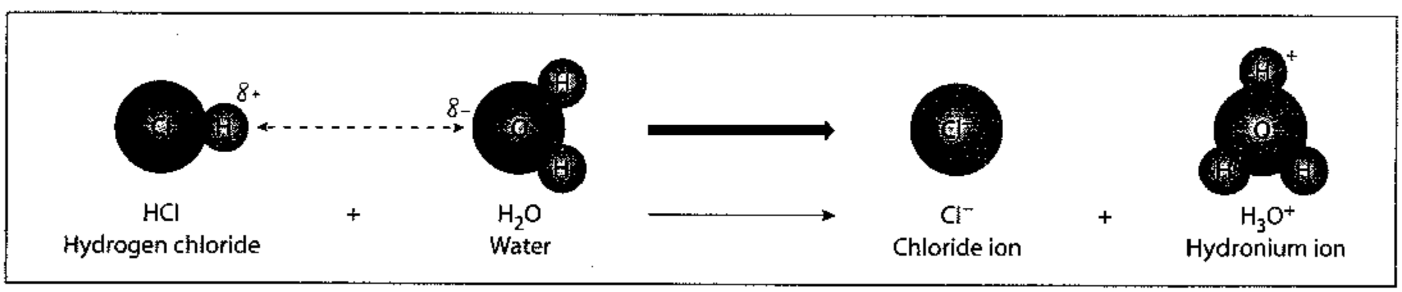


Figure 10-2. Acids react with water to produce the hydronium ion.

Each molecule of H_2SO_4 that ionizes produces two hydrogen ions. Sulfuric acid and other acids that produce two hydrogen ions are called diprotic acids. Similarly, an H_3PO_4 molecule ionizes to yield three hydrogen ions and is called a triprotic acid.

DIGGING DEEPER

Some organic compounds that are acids have chemical formulas that are somewhat misleading. These compounds contain a carboxyl group (–COOH) that gives them the appearance of a base. However, the hydrogen atom in the carboxyl group does ionize in water, thus defining these compounds as acids.

$$CH_3COOH \rightarrow H^+ + CH_3COO^-$$

The Nature of the Hydroxide Ion

In a parallel manner to acids, the properties of bases are explained as properties of the hydroxide ion (OH^-) in solution. Each **Arrhenius base** produces hydroxide ions when dissolved in water. The presence of the hydroxide ion makes the base an electrolyte. It is also the presence of the hydroxide ion that produces the slippery feel and bitter taste common to Arrhenius bases.

Ammonia (NH_3) and organic compounds called amines are bases, though at first glance their chemical formulas do not show the presence of hydroxide ions. However, ammonia reacts with water to form the ammonium and hydroxide ions.

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

Amines are compounds containing carbon and nitrogen that are related to ammonia. Amines also react with water to produce hydroxide ions.

$$CH_3NH_2 + H_2O \rightarrow CH_3NH_3^+ + OH^-$$

There are also other compounds whose formulas do contain an –OH group but which are not bases. The hydroxyl group is composed of an oxygen atom and a hydrogen atom covalently bonded to a carbon chain. This group of organic compounds, called alcohols, are not bases as they do not ionize in water. Thus, they are nonelectrolytes and do not have the characteristics of bases. CH_3OH and CH_3CH_2OH are examples of alcohols, and they do not ionize to produce the hydroxide ion.

MEMORY JOGGER

Electrolytes are substances whose water solutions conduct an electric current. When there are many ions in solution, the substance is termed a strong electrolyte and is a good conductor. Weak electrolytes have relatively few ions in solution and are poor conductors or nonconductors.

Strength of Acids and Bases

Hydrochloric acid is a dangerous acid that can cause severe injury to your skin. Citric acid is present in citrus and other fruits that we commonly eat. Even more surprising, boric acid is used as an eye-washing solution. How can we explain that these substances are all acids, yet have such different effects? The answer involves the strength of each acid.

When one hundred molecules of hydrochloric acid dissolve in water, all one hundred molecules dissociate and form ions. When an acid completely ionizes, it is called a strong acid. Other acids ionize to a much smaller degree. Perhaps only one molecule out of one hundred ionizes. Acids that ionize only slightly are called weak acids.

The degree of ionization is a function of the number of ions that are produced. Highly ionized (strong) acids and bases produce large numbers of ions. These strong acids and bases are strong electrolytes, and hence good conductors of electricity.

Naming Acids and Base

Binary acids are composed of hydrogen and one other element. Hydrogen chloride (HCl) is a molecular gas, but becomes an Arrhenius acid when it reacts with water to produce hydrogen ions. The names of binary acids begin with *hydro-* followed by the name of the other element modified to end with *–ic*. Thus, hydrogen chloride gas becomes hydrochloric acid when dissolved in water. Other binary acids are named in the same fashion.

Ternary acids are also molecular substances that produce hydrogen ions when dissolved in water. They consist of an oxygen-containing polyatomic anion such as nitrate (NO_3^-) or sulfate (SO_4^{2-}). To name a ternary acid, the anion suffixes *–ate* and *–ite* usually are replaced by the suffixes *–ic* and *–ous* respectively. For example,

HNO_3 is nitric acid. Sometimes the names are modified slightly, as in H_2SO_4, sulfuric acid. Table 10-1 lists the names of several common acids.

Table 10-1. Names of Several Acids and Their Ions

Acid Name	Formula of Acid	Anion Name
Hydrochloric	HCl	chloride
Sulfuric	H_2SO_4	sulfate
Sulfurous	H_2SO_3	sulfite
Nitric	HNO_3	nitrate
Nitrous	HNO_2	nitrite

Bases are quite simple to name. The name of the positive ion is not modified, and the name of the base ends with hydroxide. For example, $Ca(OH)_2$ is named calcium hydroxide.

Review Questions

1. According to the Arrhenius theory, when an acidic substance is dissolved in water it will produce a solution containing only one kind of positive ion. To which ion does the theory refer? (1) acetate (2) hydrogen (3) chloride (4) sodium

2. When an Arrhenius base is dissolved in H_2O, the only negative ion present in the solution is (1) OH^- (2) H_3O^- (3) H^- (4) O^{2-}

3. According to the Arrhenius theory of acids, citric acid in oranges and acetic acid in vinegar are classified as acids because their aqueous solutions contain (1) hydrogen ions (2) hydrogen atoms (3) hydroxide ions (4) hydroxide atoms

4. In an aqueous solution, which substance yields hydrogen ions as the only positive ion? (1) C_2H_5OH (2) CH_3COOH (3) KH (4) KOH

5. Which compound is an electrolyte? (1) $C_6H_{12}O_6$ (2) $C_{12}H_{22}O_{11}$ (3) CH_3CH_2OH (4) CH_3COOH

6. If 1 mol of each of the following substances were dissolved in 1 L of water, which solution would contain the highest concentration of OH^- ions? (1) H_2SO_4 (2) NH_4Cl (3) KNO_3 (4) $NaOH$

7. If 1 mol of each of the following substances were dissolved in 1 L of water, which solution would contain the highest concentration of H_3O^+ ions? (1) CH_3COOH (2) $NaCl$ (3) KBr (4) $Ba(OH)_2$

8. When substance X is dissolved in water, the only positive ions in the solution are hydrogen ions. Substance X could be (1) $NaOH$ (2) NaH (3) H_2S (4) NH_3

9. Which species is classified as an Arrhenius base? (1) CH_3OH (2) $LiOH$ (3) PO_4^{3-} (4) CO_3^{2-}

10. As 1 g of sodium hydroxide dissolves in 100 g of water, the conductivity of the water (1) decreases (2) increases (3) remains the same

11. A solution of a base differs from a solution of an acid in that the solution of a base (1) is able to conduct electricity (2) is able to cause an indicator color change (3) has a greater $[H_3O^+]$ (4) has a greater $[OH^-]$

12. A solution of hydrochloric acid is a stronger acid than a solution of acetic acid of the same concentration because (1) it has more hydrogen ions in solution (2) it has more hydroxide ions in solution (3) it has fewer hydrogen ions in solution (4) it has fewer hydroxide ions in solution.

13. When an Arrhenius acid is dissolved in water, it produces (1) H^+ as the only positive ion in solution (2) NH_3^+ as the only positive ion in solution (3) OH^- as the only negative ion in solution (4) HCO_3^- as the only negative ion in solution

14. What would be the name of ClO_3^- if the name of $HClO_3$ is chloric acid?

15. Name the following acids and bases.

(a) H_2S

(b) HBr

(c) $LiOH$

(d) $Mg(OH)_2$

16. A student tests the conductivity of an unknown substance and determines it to be a good conductor of electricity. Based on this he decides that it is an acid. Criticize the student's conclusion. Is there enough evidence to warrant the conclusion? What additional test or tests could be performed to confirm the conclusion? For each test, indicate the result that would verify the substance to be an acid.

Reactions Involving Acids and Bases

Chemical reactions involving acids and bases are common in industrial and consumer applications, natural processes, and in classroom experiments.

Acids and bases undergo many reactions because they are able to react with each other as well as with other compounds and elements.

Reactions of Acids with Metals

You may recall from Topic 2 that any element in Table J of the *Reference Tables for Physical Setting/Chemistry* will react with the ion of any element below it. Note that hydrogen (H_2) is found near the bottom of the table. Thus, any metal above hydrogen in the table will react with a hydrogen-containing acid to produce H_2 and a salt. The reaction between zinc and hydrochloric acid is an example.

$$Zn(s) + 2HCl(aq) \rightarrow H_2(g) + ZnCl_2(aq)$$

Copper, which is below hydrogen in the table, will not react with a hydrogen-containing acid to produce hydrogen gas.

MEMORY JOGGER

Single-replacement reactions have the general formula:

$$A + BC \rightarrow AC + B$$

Neutralization Reactions

In a neutralization reaction, an Arrhenius acid reacts with an Arrhenius base to produce water and a salt. There are several ways that these reactions can be expressed. For example, consider the neutralization reaction between hydrochloric acid (HCl) and sodium hydroxide (NaOH).

This reaction can be expressed as a word equation:

Hydrochloric acid + Sodium hydroxide → Water + Sodium chloride

Substituting the chemical formulas for words yields the formula equation:

$$HCl(aq) + NaOH(aq) \rightarrow H_2O(\ell) + NaCl(aq)$$

Writing the equation to take the ions in solution into account yields the ionic equation:

$$H^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow H_2O(\ell) + Na^+(aq) + Cl^-(aq)$$

Note that the sodium and chloride ions are present on both sides of the reaction arrow. Because they have not taken part in the reaction, they are called spectator ions and can be omitted.

$$H^+(aq) + \cancel{Cl^-(aq)} + \cancel{Na^+(aq)} + OH^-(aq) \rightarrow H_2O(\ell) + \cancel{Na^+(aq)} + \cancel{Cl^-(aq)}$$

Omitting the spectator ions yields the net ionic equation:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell)$$

Because hydrogen ions exist in solution as hydronium ions (H_3O^+), this equation can also be written as the reaction between hydronium and hydroxide ions.

$$H_3O^+(aq) + OH^-(aq) \rightarrow 2H_2O(\ell)$$

All neutralization reactions have the same net equation. The Arrhenius definition is able to explain the process of neutralization as a reaction between hydrogen (hydronium) ions and hydroxide ions to form water and a salt.

MEMORY JOGGER

When writing equations, first write correct formulas using charges and subscripts. Then balance the equation using coefficients.

WRITING NEUTRALIZATION REACTIONS

Writing neutralization reactions is not a difficult task, as shown in the following Sample Problem.

SAMPLE PROBLEM

Write the equation for the neutralization reaction between dilute nitric acid and potassium hydroxide.

Solution: Identify the known and unknown values.

Known
reactant 1 = nitric acid (HNO_3)
reactant 2 = potassium hydroxide (KOH)

Unknown
neutralization equation = ?

Write a simple word equation for the neutralization reaction.

acid + base → water + salt

Substitute the known compounds into the general word equation.

$$HNO_3 + KOH \rightarrow \text{water} + \text{salt}$$

Picture a box enclosing the hydroxide (OH^-) of the base and the hydrogen (H^+) of the acid. These particles combine to form water (H_2O).

$$HNO_3 + KOH \rightarrow H_2O + \text{salt}$$

The remaining K^+ and NO_3^- ions combine to form the salt KNO_3.

$$HNO_3 + KOH \rightarrow H_2O + KNO_3$$

Now check to see that the equation is balanced. Because the hydroxide and hydrogen ions combine in a 1:1 ratio to form water molecules, they must be present in equal numbers. If needed, the coefficients of the acid and the base are adjusted to balance these ions. In this example, there is one hydroxide ion and one hydrogen ion so the coefficients are both 1. A coefficient of 1 is not written; the above equation is balanced. Note that the spectator ions form the salt.

MEMORY JOGGER

When writing the formula of the salt in a neutralization reaction, check the charge on both ions. If the ionic charges are not equal and opposite, write the charge of one ion as the subscript of the other.

When a diprotic acid reacts with a dihydroxy base, there are two hydrogen ions and two hydroxide ions. These will combine to form two molecules of water. The remaining ions will form the salt.

$$Ca(OH)_2 + H_2SO_4 \rightarrow 2H_2O + CaSO_4$$

Combinations of acids and bases that do not have an equal number of hydroxide and hydrogen ions are also easy to balance. Consider the following unbalanced equation:

$$Mg(OH)_2 + HCl \rightarrow H_2O + MgCl_2$$

Note that there are two hydroxide ions but only one hydrogen ion. Placing a 2 in front of the HCl balances the hydroxide and hydrogen ions that form two molecules of water. The 2 coefficient also supplies the two chloride ions needed to form the salt. The equation is now balanced:

$$Mg(OH)_2 + 2HCl \rightarrow 2H_2O + MgCl_2$$

Salts

As you learned earlier, when a metal reacts with an acid, hydrogen gas and a salt are formed. In a neutralization reaction, an acid and a base react to form water and a salt. The salts in these reactions are ionic substances composed of positively charged metallic or polyatomic ions, and negative ions other than hydroxide ions. Sodium chloride (NaCl) and ammonium phosphate ($(NH_4)_3PO_4$) are examples of salts. Salts are named by using the name of the positive ion of the base, and the negative ion of the acid.

DIGGING DEEPER

Because salts are produced by neutralization, it would seem logical that a salt would be neutral, that is, neither acidic nor basic. There are, however, acidic, basic, and neutral salts. Salts that were formed from a strong acid and a strong base are neutral salts. If the salt was formed by the reaction of a strong acid and a weak base, it will be acidic. If the opposite is the case, that is, a salt formed from a strong base and a weak acid, the salt will be basic. The acidity or basicity of a salt formed from a weak acid and a weak base must be evaluated on a case-by-case basis.

Review Questions

17. According to the *Reference Tables for Physical Setting/Chemistry*, which metal would react spontaneously with hydrochloric acid? (1) gold (2) silver (3) copper (4) zinc

18. According to the *Reference Tables for Physical Setting/Chemistry*, which of the following metals will react most readily with HCl to release hydrogen gas? (1) aluminum (2) copper (3) silver (4) gold

19. Which metal will release $H_2(g)$ when it reacts with HCl? (1) Au(*s*) (2) Zn(*s*) (3) Hg(ℓ) (4) Ag(*s*)

20. The reaction between one mole of hydrogen ions and one mole of hydroxide ions is called (1) oxidation (2) reduction (3) hydrolysis (4) neutralization

21. Which type of reaction occurs when equal volumes of 0.1 M HCl and 0.1 M NaOH are mixed? (1) neutralization (2) ionization (3) electrolysis (4) hydrolysis

22. Which type of reaction occurs when 50-mL quantities of 1 M $Ba(OH)_2(aq)$ and $H_2SO_4(aq)$ are combined? (1) hydrolysis (2) ionization (3) hydrogenation (4) neutralization

23. Which compound reacts with an acid to produce water and a salt? (1) CH_3Cl (2) CH_3COOH (3) KCl (4) KOH

24. How much water is formed when 1.0 mol of HCl reacts completely with 1.0 mol of NaOH? (1) 1.0 mol (2) 2.0 mol (3) 0.50 mol (4) 0.25 mol

25. A water solution contains 0.50 mol of HCl. How much NaOH should be added to the HCl solution to exactly neutralize it? (1) 1.0 mol (2) 2.0 mol (3) 0.25 mol (4) 0.50 mol

26. Which is the net ionic equation for a neutralization?
(1) $H^+ + H_2O \rightarrow H_3O^+$ (2) $H^+ + NH_3 \rightarrow NH_4^+$
(3) $2H^+ + 2O^{2-} \rightarrow 2OH^-$ (4) $H^+ + OH^- \rightarrow H_2O$

27. Which substance is always produced by a neutralization reaction? (1) water (2) acid (3) ester (4) base

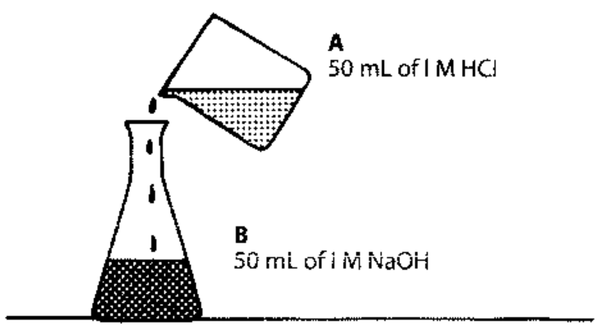
28. Which products are formed when an acid reacts with a base? (1) an alcohol and carbon dioxide (2) an ester and water (3) a soap and glycerin (4) a salt and water

29. Which compound is a salt? (1) Na_3PO_4 (2) H_3PO_4 (3) CH_3COOH (4) $Ca(OH)_2$

30. Which compound is classified as a salt?
(1) CH_3COOH (2) C_2H_5OH (3) NaOH (4) $NaC_2H_3O_2$

31. Which formula represents a salt? (1) KOH (2) KCl (3) CH_3OH (4) CH_3COOH

32. The diagram below shows an acid being added to a base.



As the acid in beaker A is added to the base in flask B, the number of OH^- ions in flask B

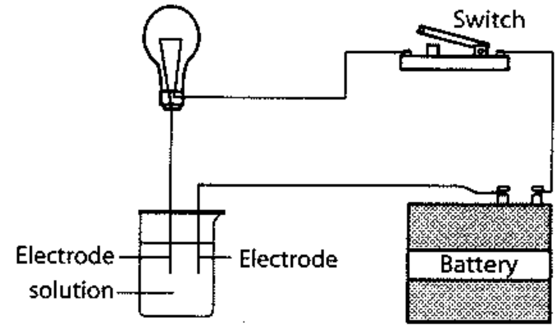
(1) decreases and the number of Na^+ ions decreases

(2) increases and the number of Na^+ ions decreases

(3) decreases and the number of Na^+ ions remains the same

(4) increases and the number of Na^+ ions remains the same

33. The diagram below illustrates an apparatus used to test the conductivity of various solutions.



When the switch is closed, which of the following 1-molar solutions would cause the bulb to glow most brightly?

(1) ammonia (3) carbonic acid
(2) acetic acid (4) sulfuric acid

34. Which salt is formed when hydrochloric acid is neutralized by a potassium hydroxide solution?

(1) potassium chloride (3) potassium chlorite
(2) potassium chlorate (4) potassium perchlorate

35. In the neutralization reaction between hydrochloric acid and sodium hydroxide, the spectator ions are (1) H^+ and OH^- (2) Cl^- and OH^- (3) Na^+ and H^+ (4) Na^+ and Cl^-

36. When NaOH(*aq*) reacts completely with HCl(*aq*) and the resulting solution is evaporated to dryness, the solid remaining is (1) an ester (2) an alcohol (3) a salt (4) a metal

37. Name each of the following.

(a) HF

(b) H_2Se

(c) HI

38. Consult Table J in the *Reference Tables for Physical Setting/Chemistry* to determine if the following reactions actually occur. If a reaction does occur, write the correctly balanced equation. If the reaction does not occur, write "No reaction."

(a) calcium and hydrochloric acid

(b) zinc and dilute nitric acid

(c) lead and carbonic acid

(d) aluminum and acetic acid

(e) copper and phosphoric acid

39. Write the balanced equation for each of the following neutralization reactions, and write the name of the salt formed.

(a) nitric acid and sodium hydroxide

(b) nitric acid and magnesium hydroxide

(c) sulfuric acid and magnesium hydroxide

(d) sulfuric acid and potassium hydroxide

(e) phosphoric acid and lithium hydroxide

(f) phosphoric acid and calcium hydroxide

Acid–Base Titration

Titration is the process of adding measured volumes of an acid or a base of known concentration to an acid or a base of unknown concentration until neutralization occurs. The solution of known concentration is called the standard solution. Knowing the volumes of acid and base used in the titration, together with the known concentration of the standard solution, it is possible to calculate the concentration of the unknown solution.

In all neutralization reactions there must be a 1:1 ratio between the moles of hydrogen ions (H^+) and the moles of hydroxide ions (OH^-). The equation for concentration shows the relationship among number of moles, volume in liters, and molarity.

$$\text{molarity} = \frac{\text{moles}}{\text{volume}}$$

or

$$\text{moles} = \text{molarity} \times \text{volume}$$

In a neutralization reaction, the number of moles of H^+ ions must equal the number of moles of OH^- ions. Thus, equating mol H^+ and mol OH^- yields the following equation.

$$\text{molarity } H^+ \times \text{volume}_{\text{acid}} = \text{molarity } OH^- \times \text{volume}_{\text{base}}$$

or

$$M_A \times V_A = M_B \times V_B$$

In the above equation, M_A = molarity of H^+, V_A = volume of acid in milliliters, M_B = molarity of OH^-, and V_B = volume of base in milliliters.

To solve any titration problem, the molarity of the acid and base must be expressed as the molarity of the hydrogen ion (H^+) and the molarity of the hydroxide ion (OH^-), respectively. In the case of monoprotic acids such as HCl, the molarity of the H^+ is the same as the molarity of the acid. Thus, a 2.0 M HCl solution has a 2.0 M H^+ concentration. The same applies to monohydroxy bases. That is, a 2.5 M NaOH solution has a 2.5 M OH^- concentration.

The case is different for diprotic and triprotic acids. Consider the complete ionization of a 1.0 M solution of sulfuric acid (H_2SO_4).

$$H_2SO_4(aq) \rightarrow 2H^+(aq) + SO_4^{2-}(aq)$$

One liter of 1.0 M solution of H_2SO_4 yields 2 mol of H^+ ions. The molarity of the H^+ ions will be twice the molarity of the acid solution. Similarly, a triprotic acid produces an H^+ ion molarity three times that of the molarity of the acid solution.

The following examples summarize the relationships between the concentration of an acid or base and the resulting concentration of hydrogen ions (H^+) or hydroxide ions (OH^-) in solution for mono-, di-, and triprotic acids and mono- and dihydroxy bases.

MONOPROTIC ACIDS The H^+ molarity equals the molarity of the acid solution. Hydrochloric acid is an example.

$$2.5 \text{ M HCl} = 2.5 \text{ M } H^+$$

DIPROTIC ACIDS The H^+ molarity is twice the molarity of the acid solution. Sulfuric acid is an example.

$$2.5 \text{ M } H_2SO_4 = 5.0 \text{ M } H^+$$

TRIPROTIC ACIDS The H^+ molarity is three times the molarity of the acid solution. Phosphoric acid is an example.

$$2.0 \text{ M } H_3PO_4 = 6.0 \text{ M } H^+$$

MONOHYDROXY BASES The OH^- molarity equals the molarity of the base solution. Sodium hydroxide is an example.

$$3.0 \text{ M NaOH} = 3.0 \text{ M } OH^-$$

DIHYDROXY BASES The OH^- molarity is twice the molarity of the base solution. Barium hydroxide is an example.

$$0.5 \text{ M Ba(OH)}_2 = 1.0 \text{ M } OH^-$$

MEMORY JOGGER

Square brackets [ ] are used to indicate concentration of a particle in units of moles per liter, molarity (M). For example, $[OH^-]$ stands for the concentration of OH^- ions in units of moles of OH^- per liter of solution.

SAMPLE PROBLEM

What is the concentration of a hydrochloric acid solution if 50.0 mL of a 0.250 M KOH are needed to neutralize 20.0 mL of the HCl solution of unknown concentration?

Solution: Identify the known and unknown values.

Known	*Unknown*
molarity of KOH = 0.250 M	M_A = molarity of HCl = ? M
V_B = volume of KOH = 50.0 mL	
V_A = volume of HCl = 20.0 mL	

Write the balanced equation for the neutralization reaction.

$$KOH + HCl \rightarrow H_2O + KCl$$

Determine the molarity of the hydroxide ion. Because KOH is a monohydroxy base, the molarity of the hydroxide ion is the same as the molarity of the base solution.

$$M_B = \text{molarity KOH} = 0.250\ M$$

Solve the neutralization reaction equation for M_A, substitute the known values, and solve.

$$M_A \times V_A = M_B \times V_B$$
$$M_A = (M_B \times V_B)/V_A$$
$$M_A = \frac{(0.250\ M)(50.0\ mL)}{20.0\ mL}$$
$$M_A = 0.625\ M$$

The molarity of the hydrogen ion is 0.625 M. Because HCl is a monprotic acid, the molarity of the acid is also 0.625 M.

SAMPLE PROBLEM

What is the concentration of a sulfuric acid solution if 50. mL of a 0.25 M KOH are needed to neutralize 20. mL of the H_2SO_4 solution of unknown concentration?

Solution: Identify the known and unknown values.

Known	*Unknown*
molarity of KOH = 0.25 M	M_A = molarity of H_2SO_4 = ? M
V_B = volume of KOH = 50. mL	
V_A = volume of H_2SO_4 = 20. mL	

Write the balanced equation for the neutralization reaction.

$$2KOH + H_2SO_4 \rightarrow 2H_2O + K_2SO_4$$

Determine the molarity of the hydroxide ion. Because KOH is a monohydroxy base, the molarity of the hydroxide ion is the same as the molarity of base solution.

$$M_B = \text{molarity KOH} = 0.25\ M$$

Solve the neutralization reaction equation for M_A, substitute the known values and solve.

$$M_A \times V_A = M_B \times V_B$$
$$M_A = (M_B \times V_B)/V_A$$
$$M_A = \frac{(0.250\ M)(50.0\ mL)}{20.0\ mL}$$
$$M_A = 0.625\ M$$

To determine the molarity of the H_2SO_4, adjust for the fact that the acid is diprotic. That is, the molarity of the acid is only half that of the hydrogen ion.

$$\text{molarity } H_2SO_4 = \frac{[H^+]}{2} = \frac{0.625\ M}{2} = 0.31\ M$$

Review Questions

40. Which compound reacts with an acid to form a salt and water? (1) CH_3F (2) C_2H_5COOH (3) LiCl (4) LiOH

41. To neutralize 1 mol of sulfuric acid, 2 mol of sodium hydroxide are required. How many liters of 1 M NaOH are needed to exactly neutralize 1 L of 1 M H_2SO_4? (1) 1 (2) 2 (3) 0.5 (4) 4

42. How many moles of sodium hydroxide (NaOH) are required to completely neutralize 2 mol of nitric acid (HNO_3)? (1) 1 (2) 2 (3) 40 (4) 63

43. During an acid-base neutralization, how many moles of hydroxide ions will react with one mole of hydrogen ions? (1) 1.0 mol (2) 0.5 mol (3) 17.0 mol (4) 22.4 mol

44. How many moles of KOH are needed to exactly neutralize 500. mL of 1.0 M HCl? (1) 1.0 mol (2) 2.0 mol (3) 0.25 mol (4) 0.50 mol

45. One liter of 1 M NaOH will completely neutralize one liter of (1) 1 M H_2SO_4 (2) 0.5 M H_2SO_4 (3) 2 M H_2SO_4 (4) 1.5 M H_2SO_4

For questions 46–54, show all of your work.

46. Consider the following reaction.

$$KOH + HCl \rightarrow H_2O + HOH$$

How many milliliters of 2.0 M KOH are necessary to neutralize 50. mL of 1.0 M HCl?

47. How many milliliters of 0.20 M H_2SO_4 are required to completely neutralize 40. mL of 0.10 M $Ca(OH)_2$?

48. How many milliliters of 2.5 M HCl are required to exactly neutralize 1.5 L of 5.0 M NaOH?

49. How many milliliters of 0.200 M NaOH are needed to neutralize 100. mL of 0.100 M HCl?

50. A 2.0-mL sample of NaOH solution is exactly neutralized by 4.0 mL of 3.0 M HCl solution. What is the concentration of the NaOH solution?

51. A 10.-mL sample of hydrochloric acid neutralizes 15 mL of a 0.40 M solution of NaOH. What is the molarity of the hydrochloric acid?

52. How many mL of 0.20 M hydrochloric acid is required to neutralize 100. mL of 0.80 M potassium hydroxide?

53. A 3.0-mL sample of HNO_3 solution is exactly neutralized by 6.0 mL of 0.50 M KOH. What is the molarity of the HNO_3 solution?

54. What is the molarity of hydrogen ions in a 2.7 M solution of the strong acid HCl?

55. Write the electron dot diagram of a hydrogen chloride molecule.

56. Write the electron dot diagram for the hydronium ion (H_3O^+).

57. Write the electron dot diagram for the hydroxide ion (OH^-).

58. Write the word equation form of the net ionic equation for all neutralization equations.

59. Write the electron dot diagram for the net ionic equation for a neutralization reaction. Be sure to include the charge on any ionic substance.

60. Phosphoric acid is neutralized by a solution of sodium hydroxide. What is the name of the salt formed from the neutralization?

Acidity and Alkalinity of Solutions

Although water is a covalently bonded substance, it does ionize to a very small extent as shown by the equation below.

$$HOH \leftrightarrow H^+ + OH^-$$

It can be seen that in pure water $[H^+] = [OH^-]$. Le Châtelier's principle tells us that if one of these factors increases, the other decreases. When HCl is added to pure water, the concentration of the hydrogen ion increases, and the concentration of the hydroxide ion decreases. When $[H^+] > [OH^-]$, the solution is acidic. If the reverse is true, and the concentration of OH^- is greater than the concentration of the H^+, the solution is alkaline, or basic. The terms **acidity** and **alkalinity** (or basicity) refer to the relative strength of the acid or base in terms of their H^+ and OH^- concentrations.

pH Scale

A scale, called the **pH scale,** has been developed to express $[H^+]$ as a number from 0 to 14. A pH of 0 is strongly acidic, a pH of 7 is neutral, and a pH of 14 is strongly basic. The pH scale is logarithmic. Each change of a single pH unit signifies a tenfold change in the concentration of the hydrogen ion. Thus the $[H^+]$ is ten times greater in a solution with a pH of 5 as in a solution with a pH of 6.

Because $[H^+]$ and $[OH^-]$ are directly related, a pH change of one unit represents a tenfold increase or decrease of both the hydrogen ion and hydroxide ion concentration. As the concentration of the hydrogen ion increases, the concentration of the hydroxide ion decreases.

Acid-Base Indicators

An **indicator** is a substance that changes its color when it gains or loses a proton. Phenolphthalein is a common indicator that is colorless when it is protonated, that is, when it contains a hydrogen atom. When a base is gradually added to an acid containing phenolphthalein, the solution is initially colorless. Once the acid has been neutralized by the addition of the base, the base then reacts with the hydrogen atom of the indicator. As the phenolphthalein loses its hydrogen (proton), it turns pink. This color change is why phenolphthalein is an indicator; the color change in the phenolphthalein shows (indicates) when a titration has reached an end point.

Other indicators react in a similar way to phenolphthalein, but each has a unique color change that occurs over a specific pH range. Table M of the *Reference Tables for Physical Setting/Chemistry* lists several common indicators, the color changes they undergo, and the pH range over which the color change occurs.

HIn	→	$H^+ + In^-$
(colorless)		(pink)

Figure 10-3. Color change in phenolphthalein: Indicators are weak acids that have different colors depending on the presence or absence of hydrogen. In the diagram above, HIn represents the indicator phenolphthalein.

Another example of an indicator is methyl orange. An acid solution with a pH of 2.0 containing methyl orange is red in color. As a base is added to the acid solution, the pH slowly increases. Between pH 3.2 and 4.4, the solution contains both the red and the yellow forms of the indicator, resulting in an orange color. When a pH of 4.4 is achieved, there is no longer an appreciable number of red molecules present, and the solution appears yellow. This same process occurs in other indicators as well. That is, indicators tend to have a distinct color at each end of their useful pH range and pass through an intermediate color region that is a mixture of these two colors.

Review Questions

61. Which pH value indicates the most basic solution? (1) 7 (2) 8 (3) 3 (4) 11

62. Which pH value represents a solution with the lowest OH^- ion concentration? (1) 1 (2) 7 (3) 10 (4) 14

63. When tested, a solution turns red litmus to blue. This indicates that the solution contains more (1) H^+ ions than OH^- ions (2) H_3O^+ ions than OH^- ions (3) OH^- ions than H_3O^+ ions (4) H^+ and OH^- ions than H_2O molecules

64. Pure water at 25°C has a pH of (1) 1 (2) 5 (3) 7 (4) 14

65. If an aqueous solution turns blue litmus red, which relationship exists between the hydronium ion and hydroxide ion?
(1) $[H_3O^+] < [OH^-]$ (3) $[H_3O^+] > [OH^-]$
(2) $[H_3O^+] = [OH^-]$ (4) neither ion is present

66. The pH of a 0.1 M CH_3COOH solution is (1) less than 1 (2) greater than 1, but less than 7 (3) equal to 7 (4) greater than 7 but less than 14

67. As 0.1 M HCl is added to 0.1 M KOH, the pH of the basic solution (1) decreases and the basicity decreases (2) decreases and the acidity decreases (3) increases and the basicity decreases (4) increases and the acidity decreases

68. As an acidic solution is added to a basic solution, the pH of the basic solution (1) decreases (2) increases (3) remains the same

69. As the H_3O^+ ion concentration of a solution increases, the pH of the solution (1) decreases (2) increases (3) remains the same

70. As a strong acid is added to a beaker containing NaOH, the number of OH^- ions in the beaker (1) decreases and the number of Na^+ ions decreases (2) decreases and the number of Na^+ ions remains the same (3) increases and the number of Na^+ ions decreases (4) increases and the number of Na^+ ions remains the same

71. An indicator was used to test a water solution with a pH of 12. Which indicator color would be observed? (1) colorless phenolphthalein (2) red litmus (3) colorless litmus (4) pink phenolphthalein

Answer questions 72–75 using complete sentences.

72. A blue solution containing an acid-base indicator was tested with a pH meter and found to have a pH of 5.5. Which of the indicators on Table M of the *Reference Tables for Physical Setting/Chemistry* could be this indicator?

73. A solution was yellow in bromthymol blue and blue in bromcresol green. According to Table M of the *Reference Tables for Physical Setting/Chemistry*, what could be the pH of the solution?

74. A solution was tested with a pH meter and found to have a pH of 7.8. What color would the solution have if the following indicators were added?

(a) bromthymol blue

(b) thymol blue

75. Acid was added to a solution containing an indicator until the solution turned from blue to yellow. Which of the following would be most acidic?

(a) a yellow solution containing bromthymol blue

(b) a yellow solution containing bromcresol green

(c) a yellow solution containing thymol blue

ADDITIONAL MATERIAL

The coverage of Brønsted-Lowry theory and conjugate acid-base pairs on page 150 is not required by the Regents core curriculum in chemistry. You will not be tested on these topics in the Regents Examination for the Physical Setting/Chemistry.

Brønsted-Lowry Acids and Bases

There are other acid-base definitions that expand upon the Arrhenius definition of acids and bases. One of these, the Brønsted-Lowry theory, defines an acid as any substance that donates a hydrogen ion (H^+). As you know, a hydrogen ion is a hydrogen atom without an electron, that is, it is simply a proton. Thus, a Brønsted-Lowry acid is defined as a proton donor. All Arrhenius acids are also Brønsted-Lowry acids. Brønsted-Lowry theory expands upon the Arrhenius concept by including proton donors that are not in aqueous solution.

The Brønsted-Lowry theory defines a base as any substance that accepts a proton (H^+). Like the Arrhenius definition, the Brønsted-Lowry definition treats the hydroxide ion (OH^-) as a base. Compared with the Arrhenius definition, however, the Brønsted-Lowry definition greatly expands the number of substances that are considered bases.

CONJUGATE ACID-BASE PAIRS When an acid loses a proton, the remaining portion of the acid has an unshared pair of electrons that can act as a base. Consider the following reaction.

$$HCl \rightarrow H^+ + Cl^-$$

HCl is an acid because it donates a proton. The chloride ion is a base because it is capable of accepting a proton to form HCl. Note that HCl and Cl^- differ only by a hydrogen ion (H^+). A pair of chemical formulas that differ only by the presence of a hydrogen ion are known as a conjugate acid-base pair. HCl cannot donate a proton unless there is a proton acceptor (base) available to accept the proton.

The reaction between HNO_3 and water illustrates the reaction between a Brønsted acid and a Brønsted base.

|—— Conjugate pair ——|

|– Conjugate pair –|

$$\underset{\text{acid}}{HNO_3} + \underset{\text{base}}{H_2O} \rightarrow \underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{NO_3^-}$$

The HNO_3 acts as an acid, donating its proton to the water (which acts as a base) producing the hydronium and nitrate ions. If the reaction is reversed, the hydronium ion acts as an acid, donating its proton to the nitrate ion (which acts as a base) to produce nitric acid and water. Note that HNO_3 and NO_3^- are a conjugate acid-base pair because they differ by a hydrogen ion. Likewise, H_2O and H_3O^+ are also a conjugate acid-base pair.

LEWIS ACIDS AND BASES In still a further expansion of the definition of acids and bases, the great American chemist Gilbert Lewis defined acids as electron acceptors and bases as electron donors. Each of the acid-base definitions has advantages for certain situations. In terms of the concepts needed to answer acid-base questions on the Regents Examination in Chemistry, understanding the Arrhenius acid-base definitions are adequate.

Questions for Regents Practice

Part A

1. According to the Arrhenius theory, the only negative ions in an aqueous solution of a base are
   (1) OH^- ions
   (2) HS^- ions
   (3) H^- ions
   (4) HCO_3^- ions

2. Which statement best describes the solution produced when an Arrhenius acid is dissolved in water?
   (1) The only negative ion in solution is OH^-.
   (2) The only negative ion in solution is HCO_3^-.
   (3) The only positive ion in solution is H^+.
   (4) The only positive ion in solution is NH_4^+.

3. Which substance can act as an Arrhenius acid in aqueous solution?
   (1) NaI
   (2) HI
   (3) LiH
   (4) NH_3

4. Unlike an acid, an aqueous solution of a base
   (1) causes some indicators to change color
   (2) conducts electricity
   (3) contains more H^+ than OH^-
   (4) contains more OH^- than H^+

5. According to the Arrhenius theory, when a base is dissolved in water it will produce a solution containing only one kind of negative ion. To which ion does the theory refer?
   (1) hydride
   (2) hydroxide
   (3) hydrogen
   (4) hydronium

6. Acidic solutions are those that contain an excess of
   (1) H_2 molecules
   (2) H_2O molecules
   (3) H^+ ions
   (4) OH^- ions

7. What are the relative ion concentrations in an acid solution?
   (1) more H^+ ions than OH^- ions
   (2) fewer H^+ ions than OH^- ions
   (3) an equal number of H^+ ions and OH^- ions
   (4) H^+ ions, but no OH^- ions

8. What color is phenolphthalein in a basic solution?
   (1) blue (3) yellow
   (2) pink (4) colorless

9. Which substance is always produced by a neutralization reaction?
   (1) water (3) ester
   (2) acid (4) base

10. The reaction between one mole of hydrogen ions and one mole of hydroxide ions is called
    (1) oxidation
    (2) reduction
    (3) hydrolysis
    (4) neutralization

11. Pure water has a pH of
    (1) 1 (3) 10
    (2) 7 (4) 4

Part B

12. Which substance is classified as a salt?
    (1) $Ca(OH)_2$
    (2) C_2H_4OH
    (3) CCl_4
    (4) $CaCl_2$

13. Consider this neutralization reaction.

$$H_2SO_4 + 2KOH \rightarrow K_2SO_4 + 2HOH$$

    Which compound is a salt?
    (1) KOH
    (2) H_2SO_4
    (3) K_2SO_4
    (4) HOH

14. An aqueous solution turns litmus red. The pH of the solution could be
(1) 14
(2) 11
(3) 8
(4) 4

15. If equal volumes of 0.1 M NaOH and 0.1 M HCl are mixed, the resulting solution will contain a salt and
(1) HCl
(2) NaOH
(3) H_2O
(4) NaCl

16. If equal volumes of 0.1 M NaOH and 0.1 M H_2SO_4 are mixed, the resulting solution will contain water,
(1) H_2SO_4 and Na_2SO_4
(2) H_2SO_4 and NaOH
(3) NaOH and Na_2SO_4
(4) and Na_2SO_4

17. A sample of a solution with a pH of 10 is tested separately with phenolphthalein and litmus. The colors of the indicators are as follows:
(1) litmus is blue; phenolphthalein is pink
(2) litmus is red; phenolphthalein is pink
(3) litmus is blue; phenolphthalein is colorless
(4) litmus is red; phenolphthalein is colorless

18. A student observes that an unknown solution conducts electricity and turns blue litmus red. The student should be able to conclude that the unknown solution is most likely
(1) an acid
(2) a base
(3) an ester
(4) an alcohol

19. An aqueous solution of an ionic compound turns red litmus blue, conducts electricity, and reacts with an acid to form a salt and water. This compound could be
(1) HCl
(2) NaI
(3) KNO_3
(4) LiOH

20. What will be the concentration of 150. mL of a 2.4 M NaOH solution if it is diluted to form 200. mL of solution? (1) 1.6 M (2) 1.8 M (3) 2.0 M (4) 3.2 M

21. Both HNO_3 and CH_3COOH can be classified as
(1) Arrhenius acids that turn blue litmus red
(2) Arrhenius bases that turn blue litmus red
(3) Arrhenius acids that turn red litmus blue
(4) Arrhenius bases that turn red litmus blue

22. A substance is added to a water solution containing phenolphthalein, causing the solution to turn pink. Which substance would produce this result?
(1) $HC_2H_3O_2$
(2) H_2CO_3
(3) KOH
(4) CH_3OH

23. A student accidentally spills an unknown chemical on her hand. She quickly washes it off, and notices that her skin feels slippery. She has a electrical conductivity tester at her lab station and tests the conductivity of the solution. It is a good conductor of electricity. She then places a strip of litmus paper in a sample of the liquid and it turns blue. She can conclude that the liquid is
(1) a strong base
(2) a weak base
(3) a strong acid
(4) a weak acid

24. What ions are present in a 1.0 M solution of HCl?

25. What is the molarity of the hydrogen (hydronium) ion in a 2.0 M solution of sulfuric acid, assuming 100% ionization?

26. What are the formulas of the two products formed when nitric acid dissolves in water?

27. What is the name of the acid formed when hydrogen sulfide is dissolved in water?

28. Write the balanced equation for the reaction of aluminum metal with hydrochloric acid.

29. Write the balanced equation for the reaction of sulfuric acid with lithium hydroxide.

30. What is known about the pH of a solution if an aqueous solution of the substance is pink after phenolphthalein is added?

31. What is the name of the salt formed when phosphoric acid is neutralized with potassium hydroxide?

32. Describe the differences in composition of a basic (alkaline) solution and an acidic solution.

33. A solution with a pH of 10 is to be titrated to achieve a pH of 7. Which indicator is the best choice for this titration? How would you know when a pH of 7 is reached?

Part C

34. A certain solution makes methyl orange turn yellow and bromthymol blue turn yellow. What are the upper and lower pH limits of the solution? [1]

35. Alizarin yellow is an indicator that changes from yellow to red as the pH changes from 10.0 to 12.0. Explain why alizarin yellow is not a suitable indicator to use during the neutralization titration of hydrochloric acid and potassium hydroxide. Select a more suitable indicator from Table M of the *Reference Tables for Physical Setting/Chemistry* and explain why your selection would be better. [2]

36. Write the balanced equation for the reaction of hydrogen ions and water. Draw the Lewis dot diagram of the product. [2]

37. How many moles of hydroxide ion are there in 500 mL of 2.0M NaOH solution? [2]

38. A student dilutes 49.0 g H_2SO_4 with water to make a total of 1000 mL of solution.

(a) What is the molarity of the solution? [1]

(b) Assuming complete ionization, what is the concentration of hydrogen ions? [1]

(c) How many milliliters of 2.0M NaOH are be needed to completely neutralize 1000 mL of the solution? [1]

39. Dilute solutions of acetic acid and ammonia are both poor conductors of electricity. When the two undergo a neutralization reaction, the resulting solution is a good conductor. Use your knowledge of chemistry to explain why this is so. [2]

40. Liquid HCl is a nonconductor, but aqueous HCl is a good conductor. Use your knowledge of chemistry to explain why this is so. [2]

41. A student obtained the following data from a titration lab.

Standard solution: 2.50M HCl
Unknown solution: NaOH of unknown concentration

Four titrations were performed. In each case 20.0 mL of acid were used. The results of each trial are shown below. For each trial, the volume of NaOH used is given, along with the student's comments.

Trial	NaOH Added	Comments
1	26.4 mL	phenolphthalein turned a dark pink
2	22.0 mL	phenolphthalein turned a light pink
3	21.8 mL	phenolphthalein turned a light pink
4	22.0 mL	phenolphthalein turned a light pink

The student discarded the results from Trial 1 and calculated the average molarity of the sodium hydroxide.

(a) Give a reason why the student was justified in not using the results from Trial 1. [1]

(b) Calculate the average molarity of the sodium hydroxide. Exclude the data from Trial 1. [3]