Chapter 4: Chemical Reactions

Problems: 1-3, 5-6, 11, 18, 20-40, 43b, 44a, 46, 47-56, 59-72, 79-92, 95-98, 101-104

solution: composed of a **solute** dissolved in a **solvent**

solute: component present in smaller amount
solvent: component present in greater amount

aqueous solution: solution where water is the dissolving medium (the *solvent*)

Evidence for Chemical Reactions

1. A gas is produced—indicated by bubbles
2. A precipitate (ppt) is formed when 2 solutions are combined
3. Heat energy change is noted
   – exothermic reaction: releases heat (reaction vessel feels hot)
   – endothermic reaction: absorbs heat (reaction vessel feels cold)

Types of Chemical Reactions

- Precipitation Reactions (also called double-replacement reactions)
- Acid-Base Neutralization Reaction
- Oxidation-Reduction (Redox) Reactions (also called combination, decomposition, and single-replacement reactions)

4.3 PRECIPITATION REACTIONS

soluble = ions stay in solution (no solid/precipitate)
insoluble = solid/precipitate forms

Solubility Rules: Indicate if an ionic compound is soluble/insoluble in water.

Solubility Rules for Ionic Compounds in Water

Soluble if the ionic compound **contains:**

1. Li^+, Na^+, K^+, NH_4^+ (**ALWAYS!**)
2. Nitrate ion (NO_3^-)
3. Acetate ion ($C_2H_3O_2^-$)
4. Halide ions (X^-): chloride (Cl^-), bromide (Br^-), or iodide ion (I^-), ***but*** AgX, PbX_2, and Hg_2X_2 are **insoluble**
5. Sulfate ion (SO_4^{2-}), **but** $CaSO_4$, $BaSO_4$, and $PbSO_4$ are **insoluble**.

Insoluble if the ionic compound **contains:**

6. Carbonate ion (CO_3^{2-}), **but** Li^+, Na^+, K^+, NH_4^+
7. Chromate ion (CrO_4^{2-}), **but** Li^+, Na^+, K^+, NH_4^+
8. Phosphate ion (PO_4^{3-}), **but** Li^+, Na^+, K^+, NH_4^+
9. Sulfide ion (S^{2-}), **but** compounds with Li^+, Na^+, K^+, NH_4^+, and CaS, SrS, and BaS are **soluble**.
10. Hydroxide ion (OH^-), **but** compounds with Li^+, Na^+, K^+, NH_4^+, $Ca(OH)_2$, Sr(OH)2, and $Ba(OH)_2$ are **soluble**.

Ex. 1 Use the Solubility Rules to predict whether the following ionic compounds are soluble or insoluble. Indicate the physical state as (aq) for soluble compounds and (s) for insoluble compounds.

a. NaCl	e. CaS	i. K_2CO_3
b. CuS	f. Li_2CrO_4	j. Ag_3PO_4
c. Na_2SO_4	g. $Mg(OH)_2$	k. Li_2S
d. KOH	h. $BaSO_4$	l. $(NH_4)_2S$

In a precipitation reaction, two solutions react to form a precipitate:

$AX\,(aq) + BZ\,(aq) \rightarrow AZ\,(s) + BX\,(aq)$

To balance and complete the following reactions:

1. Exchange the anions, ***writing the formulas for the products based on the charges of the ions!***
2. Use the Solubility Rules to determine if each product is soluble or insoluble
   – If *one (or more) is/are insoluble*, a precipitate reaction has occurred, so write the formulas for the products, indicating the precipitate as (s), then balance the equation.
   – If *both products are soluble—both (aq)*—then write NR=no reaction.

1. $MgSO_4\,(aq) + NaOH\,(aq) \rightarrow$

2. $CaCl_2\,(aq) + AgNO_3\,(aq) \rightarrow$

3. $KC_2H_3O_2\,(aq) + LiNO_3\,(aq) \rightarrow$

4.4 ACID-BASE (NEUTRALIZATION) REACTIONS:

Arrhenius Definitions:

acid: A substance that releases hydrogen ions (H^+) when dissolved in water
- Some acids are ***monoprotic*** (release only H^+ per molecule)
  - e.g. HCl, HBr, HI, HNO_3, $HClO_4$
- Some acids are ***polyprotic*** (release more than on H^+ per molecule)
  - e.g. H_2SO_4 and H_2CO_3 are both diprotic, H_3PO_4 is triprotic

base: A substance that releases hydroxide ions (OH^-) when dissolved in water

In an acid-base reaction,
- Hydrogen ions (H^+) from acid react with the hydroxide ions (OH^-) from base → water, H_2O
- The cation (M^+) from the base combines with the anion from the acid (X^-) → the **salt**.

A general equation for an acid-base neutralization reaction is shown below:

$$\underset{\text{acid}}{\mathbf{HX\,(aq)}} + \underset{\text{base}}{\mathbf{MOH\,(aq)}} \rightarrow \underset{\text{water}}{\mathbf{H_2O\,(l)}} + \underset{\text{salt}}{\mathbf{MX\,(aq)}}$$

Because water is always produced, an acid always reacts with a base!

Ex. 1 Complete and balance each of the equations below:

a. $HCl\,(aq) + NaOH\,(aq) \rightarrow$

b. $H_2SO_4\,(aq) + KOH\,(aq) \rightarrow$

c. $H_3PO_4\,(aq) + Ca(OH)_2\,(aq) \rightarrow$

Brønsted-Lowry Definitions:

acid: A substance that donates a proton (H^+)

base: A substance that accepts a proton (H^+)
- It need not contain hydroxide ion (OH^-).

According to Brønsted-Lowry, **an acid-base reaction *simply involves a proton transfer***, not necessarily the formation of water and a salt.

Consider the following acid-base reaction:

$$\underset{\text{B-L acid}}{HCl\,(aq)} + \underset{\text{B-L base}}{NH_3\,(aq)} \rightarrow NH_4^+\,(aq) + Cl^-\,(aq)$$

Ex. 1 Indicate the Brønsted-Lowry acid and base in each of the following:

a. $NH_3\,(aq) + H_2O\,(l) \rightleftharpoons NH_4^+\,(aq) + OH^-\,(aq)$

b. $NH_3\,(aq) + HNO_3\,(l) \rightarrow NH_4^+\,(aq) + NO_3^-\,(aq)$

Acid-Base Reactions with Gas Formation
- Some acid-base reactions involve the formation of carbon dioxide gas, CO_2 (g), in addition to water and a salt.
- When the base contain carbonate ion (CO_3^{2-}) or hydrogen carbonate ion (HCO_3^-), then the products of the acid-base reaction are water, carbon dioxide gas, and a salt.

The general equations for the ***unbalanced*** acid-base reactions are below:

$$\underset{\text{acid}}{\mathbf{HX\,(aq)}} + \underset{\text{base}}{\mathbf{MCO_3\,(aq)}} \rightarrow \underset{\text{water}}{\mathbf{H_2O\,(l)}} + \underset{\text{carbon dioxide}}{\mathbf{CO_2\,(g)}} + \underset{\text{salt}}{\mathbf{MX\,(aq)}}$$

$$\underset{\text{acid}}{\mathbf{HX\,(aq)}} + \underset{\text{base}}{\mathbf{MHCO_3\,(aq)}} \rightarrow \underset{\text{water}}{\mathbf{H_2O\,(l)}} + \underset{\text{carbon dioxide}}{\mathbf{CO_2\,(g)}} + \underset{\text{salt}}{\mathbf{MX\,(aq)}}$$

Because water is always produced, an acid always reacts with a base!

Ex. 1 Complete and balance each of the equations below:

a. $HCl(aq) + Na_2CO_3(aq) \rightarrow$

b. $HNO_3(aq) + CaCO_3(aq) \rightarrow$

c. $H_2SO_4(aq) + KHCO_3(aq) \rightarrow$

4.1 Ionic Theory of Solutions and Solubility Rules

Strong Acids	Strong Bases
HCl, HBr , HI, HNO_3, $HClO_4$, H_2SO_4	LiOH, NaOH, KOH, $Ca(OH)_2$, $Sr(OH)_2$, $Ba(OH)_2$

strong electrolytes: substances that are strong/good conductors of electricity
- strong acids, strong bases, all soluble salts
- These substances dissociate to produce many ions in water
  → many ions present to move electrons/conduct electricity
  → strong electrolyte

weak electrolytes: substances that are weak/poor conductors of electricity
- weak acids, weak bases, insoluble salts
- These substances barely dissociate to produce only a few ions in water
  → few ions to move electrons/conduct electricity
  → weak electrolyte

nonelectrolytes: substances that cannot conduct electricity
- sugar (e.g. sucrose), ethanol (C_2H_5OH), and other molecules that are not acids
- These molecules do not break down into ions.
- these compounds remain intact as neutral molecules that have no charge
  → no ions to move electrons/conduct electricity.

4.2 MOLECULAR AND IONIC EQUATIONS

molecular equation: chemical equation showing reactants and products are compounds

total/complete ionic equation:
– shows strong electrolytes as individual ions while all solids, liquids, gases, and weak electrolytes remain intact as compounds

spectator ions: ions that do not form solids, liquids, gases, or weak electrolytes
– appear on both sides of total ionic equation as ions

net ionic equations: shows only solids, liquids, gases, weak electrolytes (weak acids and weak bases), and ions undergoing reaction
– excludes spectator ions

Guidelines for Writing Net Ionic Equations

1. Balance the chemical equation.
2. Convert the molecular equation to total ionic equation
   – Leave solids, liquids, gases, and weak acids and bases as compounds
   – Break down strong acids, strong bases, all aqueous salts—show as (aq)
3. Cancel spectator ions to get net ionic equation
   – If canceling spectator ions eliminates all ions → NO REACTION (NR)
   – If coefficients can be simplified, do so to get the lowest ratio.
4. Make sure total charges (+ve and –ve) are equal on both sides of equation.

Write the net ionic equation for each of the following:

a. $H_2SO_4\,(aq) + NaOH\,(aq) \rightarrow H_2O\,(l) + Na_2SO_4\,(aq)$

b. $H_3PO_4\,(aq) + KOH\,(aq) \rightarrow H_2O\,(l) + K_3PO_4\,(aq)$

c. $Na_2SO_4\,(aq) + Ba(NO_3)_2\,(aq) \rightarrow NaNO_3\,(aq) + BaSO_4\,(s)$

d. $KBr\,(aq) + Cu(C_2H_3O_2)_2\,(aq) \rightarrow CuBr_2\,(aq) + KC_2H_3O_2\,(aq)$

4.10 OXIDATION-REDUCTION (REDOX) REACTIONS

Combination Reactions: A + Z → AZ

– Usually, a metal and a nonmetal react to form a solid ionic compound:

metal + nonmetal $\xrightarrow{\Delta}$ **ionic compound (s)**

where $\xrightarrow{\Delta}$ indicates the reactants are also heated.

Ex. 1 Complete and balance each of the equations below:

a. $Na\,(s) + Cl_2\,(g) \xrightarrow{\Delta}$

b. $Al\,(s) + O_2\,(g) \xrightarrow{\Delta}$

c. $Zn\,(s) + S_8\,(s) \xrightarrow{\Delta}$

Decomposition Reactions: **AZ → A + Z**

Balance the following decomposition reactions:

a. _____ $Ca(HCO_3)_2$ (s) → _____ $CaCO_3$ (s) + _____ H_2O (l) + _____ CO_2 (g)

b. _____ $KClO_3$ (s) $\xrightarrow{\Delta,\ MnO_2}$ _____ KCl (s) + _____ O_2 (g)

ACTIVITY SERIES: Relative order of elements arranged by their

Li > K > Ba > Sr > Ca > Na > Mg > Al > Mn > Zn > Fe > Cd > Co > Ni > Sn > Pb > (H) > Cu > Ag > Au

Note: The Activity Series will be given to you on quizzes and exams.

Displacement Reactions: A + BZ → AZ + B

metal A + aqueous soln B → aqueous soln A + metal B

To balance and complete the following rxns:

– Check the Activity Series to see which metal is more active.
  → The *more active* metal will prefer to be *in solution (aq).*

1. Mg (s) + $CdSO_4$ (aq) →

2. Cd (s) + $CuSO_4$ (aq) →

3. Cu (s) + $ZnSO_4$ (aq) →

To balance and complete the following rxns:

– Check the Activity Series to see which metal is more active, the metal or H.
→ The *more active* metal will prefer to be *in solution (aq).*

metal A + aqueous acid solution → aqueous solution A + $H_{2\,(g)}$

1. $Zn\,(s) + HCl\,(aq) \rightarrow$

2. $Cu\,(s) + HCl\,(aq) \rightarrow$

ACTIVE METALS: Li > K > Ba > Sr > Ca > Na
— React directly with water

active metal + H_2O (l) → metal hydroxide + H_2 (g)

1. $Na + H_2O\,(l) \rightarrow$

2. $Fe + H_2O\,(l) \rightarrow$

COMBUSTION RXNS: $\mathbf{C_xH_y + O_2\,(g) \xrightarrow{\Delta} H_2O\,(g) + CO_2\,(g)}$
$\mathbf{C_xH_yO_z + O_2\,(g) \xrightarrow{\Delta} H_2O\,(g) + CO_2\,(g)}$

1. $C_3H_8\,(g) + O_2\,(g) \xrightarrow{\Delta}$

2. $C_6H_6O\,(l) + O_2\,(g) \xrightarrow{\Delta}$

3. $C_2H_2\,(g) + O_2\,(g) \rightarrow$

OXIDATION NUMBERS: actual or hypothetical charge of an atom in a compound if it existed as a monatomic ion

Guidelines for Assigning Oxidation Numbers

1. The oxidation number of an element in its natural form is 0.
   – e.g. the oxidation number is **zero** for each element in H_2, O_2, Cl_2, P_4, Na, etc.
2. The oxidation number of a monatomic ion is the charge on the ion.
   – e.g. the oxidation number of Na in Na^+ is +1; the oxidation number of N in N^{3-} is -3; the oxidation numbers for Al_2O_3 are +3 for Al and –2 in O.
3. In a compound or polyatomic ion,
   – Group I elements are always +1.
   – Group II elements are always +2.
   – Fluorine is always –1.
   – Oxygen is usually –2 (except in the peroxide ion, O_2^{2-}, when O is –1)
   – Hydrogen is usually +1
   (except when it is with a metal, like NaH or CaH_2, then it is –1)
4. In a compound, the sum of all oxidation numbers must equal 0.
   In a polyatomic ion, the sum of all oxidation numbers must equal charge.

Example: Determine the oxidation number for each element in the following:

a. H_2SO_4: H: _____, S: _____, O: _____

b. $KClO_3$: K: _____, Cl: _____, O: _____

c. $CaCr_2O_7$: Ca: _____, Cr: _____, O: _____

d. $C_2O_4^{2-}$: C: _____, O: _____

e. $Ni(OH)_2$: Ni: _____, O: _____, H: _____

Oxidation: lose electrons (oxidation number goes up)
Reduction: gain electrons (oxidation number goes down)

In a redox reaction
– One reactant **Loses Electrons/is Oxidized (LEO)**
– Another reactant **Gains Electrons/is Reduced (GER)**

An easy way to remember is **"LEO the lion goes GER!"**

– The element or reactant that **is oxidized** is the **reducing agent**.
– The element or reactant that **is reduced** is the **oxidizing agent**.

For each of the following reactions,
1. Balance the equation.
2. Identify the reactant that is oxidized and the reactant that is reduced.
3. Identify the oxidizing agent and the reducing agent.

a. $Zn\ (s) + AgNO_3\ (aq) \rightarrow Zn(NO_3)_2\ (aq) + Ag\ (s)$

b. $Mn\ (s) + O_2\ (g) \rightarrow MnO_2\ (s)$

c. $Ca\ (s) + H_2O\ (l) \rightarrow Ca(OH)_2\ (aq) + H_2\ (g)$

d. $C_2H_2\ (g) + O_2\ (g) \rightarrow CO_2\ (g) + H_2O\ (g)$

e. $KClO_3\ (s) \rightarrow KCl\ (s) + O_2\ (g)$

f. $H_2O_2\ (aq) \rightarrow H_2O\ (l) + O_2\ (g)$

Example f is a **disproportionation reaction,** where an element in one oxidation state is simultaneously oxidized and reduced.

WORKING WITH SOLUTIONS

4.7 Molar Concentration = Molarity

$$\textbf{Molarity} = \frac{\textbf{moles of solute}}{\textbf{liters (L) of solution}}$$ (reported in units of **M=molar**)

Ex. 1 Find the molarity of a solution prepared by dissolving 0.100 mol of NaCl in 250.0 mL of solution:

Ex. 2 Find the molarity of a solution prepared by dissolving 1.25 g of KOH in 250.0 mL of solution:

Ex. 3 Indicate the molarity of each ion in the solutions indicated below:

a. $[Cl^-]$ = _____ in 0.500 M $CaCl_2$ (aq)

b. $[Na^+]$ = _____ in 0.125 M Na_3PO_4 (aq)

c. $[NO_3^-]$ = _____ in 1.500 M $Mg(NO_3)_2$ (aq)

d. $[SO_4^{2-}]$ = _____ in 1.250 M $Al_2(SO_4)_3$ (aq)

Ex. 4 Circle the solution in each set with the highest $[H^+]$:

a. 0.100 M HF (aq) 0.100 M HCl (aq) 0.100 M HNO_2

b. 0.100 M H_2CO_3 (aq) 0.100 M H_2SO_3 (aq) 0.100 M H_2SO_4(aq)

Ex. 5 Explain why the hydroxide ion concentration, $[OH^-]$, in a 1.00 M NH_4OH solution is not 1.00 M.

4.8 Diluting Solutions

Dilution Equation: $M_1 V_1 = M_2 V_2$

where M_1=initial molarity, V_1=initial volume, M_2=final molarity, V_2=final volume

Ex. 1: What is the molarity of a HCl solution prepared by diluting 15.0 mL of 6.00 M HCl to give a total volume of 100.0 mL?

Ex. 2: What is the molarity of a NaOH solution prepared by diluting 12.5 mL of 0.500 M NaOH to give a total volume of 50.0 mL?

Writing Molar Concentration Unit Factors and Molarity Calculations:

Ex. 1 Write 2 unit factors for each of the following:

a. 6.00 M HCl solution

b. 0.125 M NaCl solution

Ex. 2 Calculate the number of moles of HCl present in 50.0 mL of 6.00 M HCl.

Ex. 3 Calculate the mass of NaOH in 25.0 mL of a 0.500 M NaOH solution.

Ex. 4 What volume (in L) of a 0.250 M NaCl solution contains 5.00 g of NaCl?

Solution Stoichiometry

Ex1. One important property of oxalic acid ($H_2C_2O_4$) is its ability to remove rust (Fe_2O_3), as shown in the following equation:

$$Fe_2O_3(s) + 6\ H_2C_2O_4(aq) \rightarrow 2\ Fe(C_2O_4)_3^{-3}(aq) + 3\ H_2O(l) + 6\ H^+(aq)$$

Calculate the mass of rust in grams that can be removed with 175 mL of a 0.250 M oxalic acid solution.

Ex2. Barium hydroxide and sodium sulfate react to form barium sulfate precipitate.

$$2\ AgNO_3(aq) + CaCl_2(aq) \rightarrow 2\ AgCl(s) + Ca(NO_3)_2(aq)$$

Calculate the amount of precipitate formed when 22.75 mL of 0.820 M silver nitrate reacts with excess calcium chloride.

4.6 Volumetric Analysis

standard solution: an acid or base solution where the concentration is known, generally to 3 sig figs

— used to analyze properties of substances, such as neutralizing power of commercial antacids, tartness of wine, etc.

acid-base indicators:

– Solutions that are pH sensitive & change color
– Generally have their color change occurring for pH≈7 since reactions monitored are neutralization reactions, which are complete at pH=7

titration: The gradual addition of standard solution to another solution of unknown concentration until the reaction between the two is complete, as signaled by an indicator changing color

endpoint: When one reactant has completely reacted with the other reactant, as evidenced by an indicator changing color

Ex1. Find the molarity of a HCl solution if 25.50 mL of HCl is required to neutralize 0.375 g of Na_2CO_3 as shown in the following equation:

$$2\ HCl\,(aq) + Na_2CO_3\,(aq) \rightarrow 2\ NaCl\,(aq) + H_2O\,(l) + CO_2\,(l)$$

Ex2. Find the molarity of a NaOH solution if 42.15 mL of NaOH is required to neutralize 0.424 g of oxalic acid, $H_2C_2O_4$, as shown in the following balanced equation:

$$2\ NaOH\,(aq) + H_2C_2O_4\,(aq) \rightarrow Na_2C_2O_4\,(aq) + 2\ H_2O\,(l)$$

Ex 3. A 10.0 mL sample of vinegar (or acetic acid, $HC_2H_3O_2$) requires 37.55 mL of a 0.255 M NaOH solution for complete neutralization. Calculate the molarity of the acetic acid solution if the balanced equation for the reaction is:

$$HC_2H_3O_2\,(aq) + NaOH\,(aq) \rightarrow H_2O\,(l) + NaC_2H_3O_2\,(aq)$$

Ex 4. A 10.0 mL sample of battery acid (H_2SO_4) is titrated with 0.275 M NaOH. If the acid concentration is 0.555 M, what volume of NaOH is required for the titration?

$$H_2SO_4\,(aq) + 2\ NaOH\,(aq) \rightarrow 2\ H_2O\,(l) + Na_2SO_4\,(aq)$$

Ex 5. Citric acid (abbreviated H_3Cit) is a triprotic acid—ie. it has three H+ ions that can react to produce water. If 36.10 mL of 0.223 M NaOH is used to neutralize a 0.515 g sample of citric acid, what is the molar mass of the acid?

$$H_3Cit\,(aq) + 3\ NaOH\,(aq) \rightarrow Na_3Cit\,(aq) + 3\ H_2O\,(l)$$

solution: composed of a **solute** dissolved in a **solvent**

solute: component present in smaller amount
solvent: component present in greater amount

MASS PERCENT CONCENTRATION (M/M%)

$$\textbf{M/M\%} = \frac{\textbf{mass of solute}}{\textbf{mass of solution}} \times 100\% = \frac{\textbf{mass of solute}}{\textbf{mass of solute + mass of solvent}} \times 100\%$$

Ex1. What is the mass percent concentration of a solution made by dissolving 25.0 g of HCl in 65.0 g of water? (What is the solute, and what is the solvent?)

Ex2. A person accused of a DUI violation submitted a 5.00 g sample of blood for alcohol content analysis. The analysis determined the presence of 4.59 mg of alcohol in the blood. If a person with a blood alcohol content (mass percent of alcohol in the blood) of 0.08% is considered legally impaired, was this person driving while impaired—i.e., was the blood alcohol content greater than or equal to 0.08%?

Ex3. Intravenous injections of glucose are sometimes administered to patients with low blood sugar. If a normal glucose solution is 5.00%, what is the mass of solution that contains 12.7 g of glucose?

Ex4. Intravenous saline injections are sometimes administered to restore electrolyte balance in trauma patients. What is the mass of water required to dissolve 2.00 g of NaCl for a 0.90% saline solution?