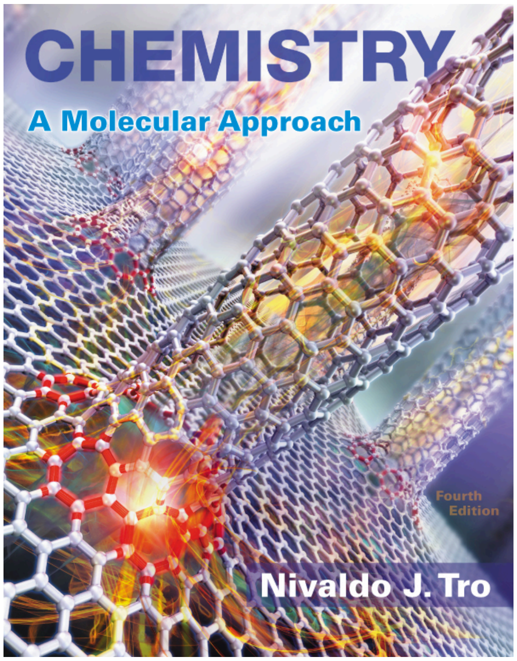


Lecture Presentation

Chapter 4

Chemical Quantities and Aqueous Reactions

Reaction Stoichiometry: How Much Carbon Dioxide?

- The balanced chemical equations for fossil-fuel combustion reactions provide the exact relationships between the amount of fossil fuel burned and the amount of carbon dioxide emitted.

$$2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$$

  – 16 CO_2 molecules are produced for every 2 molecules of octane burned.

Quantities in Chemical Reactions

- The amount of every substance used and made in a chemical reaction is related to the amounts of all the other substances in the reaction.
  - Law of conservation of mass
  - Balancing equations by balancing atoms
- The study of the numerical relationship between chemical quantities in a chemical reaction is called **stoichiometry**.

Reaction Stoichiometry

- **The coefficients in a chemical reaction specify the relative amounts in moles of each of the substances involved in the reaction.**

  $2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$
  - 2 molecules of C_8H_{18} react with 25 molecules of O_2 to form 16 molecules of CO_2 and 18 molecules of H_2O.
  - 2 moles of C_8H_{18} react with 25 moles of O_2 to form 16 moles of CO_2 and 18 moles of H_2O.

2 mol C_8H_{18} : 25 mol O_2 : 16 mol CO_2 : 18 mol H_2O

Making Pizza

- The number of pizzas you can make depends on the amount of the ingredients you use.

1 crust + 5 oz tomato sauce + 2 cups cheese → 1 pizza

This relationship can be expressed mathematically.

1 crust : 5 oz sauce : 2 cups cheese : 1 pizza

- We can compare the amount of pizza that can be made from 10 cups of cheese:

2 cups cheese : 1 pizza, then,

$$10 \text{ cups cheese} \times \frac{1 \text{ pizza}}{2 \text{ cups cheese}} = 5 \text{ pizzas}$$

Making Molecules: Mole-to-Mole Conversions

- We use the ratio from the balanced chemical equation in the same way that we used the ratio from the pizza recipe.

The ratio of the coefficients acts as a conversion factor between the amount in moles of the reactants and products.

$$2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$$

stoichiometric ratio: 2 moles C_8H_{18} : 16 moles CO_2

The ratio acts as a conversion factor between the amount in moles of the reactant, C_8H_{18}, and the amount in moles of the product, CO_2.

Mole-to-Mole Conversions

- Suppose we burn 22.0 moles of C_8H_{18}; how many moles of CO_2 form?

$2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$

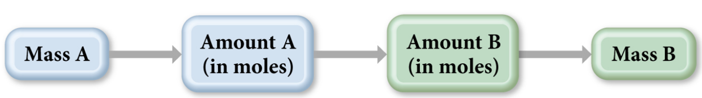
stoichiometric ratio: 2 moles C_8H_{18} : 16 moles CO_2

$$22.0\ \text{mol}\ C_8H_{18} \times \frac{16\ \text{mol}\ CO_2}{2\ \text{mol}\ C_8H_{18}} = 176\ \text{mol}\ CO_2$$

- The combustion of 22.0 moles of C_8H_{18} adds 176 moles of CO_2 to the atmosphere.

Making Molecules: Mass-to-Mass Conversions

- The world burned the equivalent of 3.7×10^{15} g of gasoline (octane) in 2013. We can estimate the mass of CO_2 produced based on the flow chart below.



- We use molar mass as a conversion factor between the mass given and amount in moles.
- We use coefficients as the conversion factor between the reactant, C_8H_{18}, and the amount in moles of the product, CO_2, and then molar mass as the conversion factor to get the mass of CO_2 produced.

Mass-to-Mass Conversions

- If we burn 3.7×10^{15} g C_8H_{18}, how many grams of CO_2 form?

$2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$

molar mass: C_8H_{18} 114.22 g/mol, CO_2 44.01 g/mol
stoichiometric ratio: 2 moles C_8H_{18} : 16 moles CO_2

$$22.0\ \cancel{\text{mol } C_8H_{18}} \times \frac{16\ \text{mol } CO_2}{2\ \cancel{\text{mol } C_8H_{18}}} = 176\ \text{mol } CO_2$$

- The combustion 3.7×10^{15} g C_8H_{18} adds 1.1×10^{16} g CO_2 to the atmosphere.

Limiting Reactant, Theoretical Yield, Percent Yield

- Recall our pizza recipe:

1 crust + 5 oz tomato sauce + 2 cups cheese → 1 pizza

- If we have 4 crusts, 10 cups of cheese, and 15 oz tomato sauce, how many pizzas can we make?

We have enough crusts to make $4\ \cancel{\text{crusts}} \times \frac{1\ \text{pizza}}{1\ \cancel{\text{crust}}} = 4\ \text{pizzas}$

We have enough cheese to make $10\ \cancel{\text{cups cheese}} \times \frac{1\ \text{pizza}}{2\ \cancel{\text{cups cheese}}} = 5\ \text{pizzas}$

We have enough tomato sauce to make

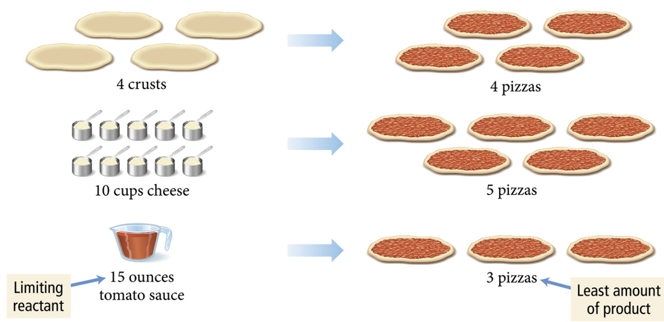
$$15\ \cancel{\text{ounces tomato sauce}} \times \frac{1\ \text{pizza}}{5\ \cancel{\text{ounces tomato sauce}}} = 3\ \text{pizzas}$$

Limiting reactant

Smallest number of pizzas

Limiting Reactant

- We have enough crusts for four pizzas, enough cheese for five pizzas, but enough tomato sauce for only three pizzas.
  - We can make only three pizzas. The tomato sauce *limits* how many pizzas we can make.



Theoretical Yield

- Tomato sauce is the **limiting reactant**, the reactant that makes *the least amount of product.*
  - The limiting reactant is also known as the *limiting reagent.*
- The maximum number of pizzas we can make depends on this ingredient. In chemical reactions, we call this the **theoretical yield**.
  - This is the amount of product that can be made in a chemical reaction based on the amount of limiting reactant.
  - The ingredient that makes the least amount of pizza determines how many pizzas you can make (**theoretical yield**).

Percent Yield

Assume that while making pizzas, we burn a pizza, drop one on the floor, or other uncontrollable events happen so that we make only two pizzas. The actual amount of product made in a chemical reaction is called the **actual yield.**

We can determine the efficiency of making pizzas by calculating the percentage of the maximum number of pizzas we actually make. In chemical reactions, we call this the **percent yield**.

Actual yield

$$\%\text{ yield} = \frac{2\text{ pizzas}}{3\text{ pizzas}} \times 100\% = 67\%$$

Theoretical yield

In a Chemical Reaction

- For reactions with multiple reactants, it is likely that one of the reactants will be completely used before the others.
- When this reactant is used up, the reaction stops and no more product is made.
- The reactant that limits the amount of product is called the **limiting reactant**.
  - It is sometimes called the limiting reagent.
  - The limiting reactant gets completely consumed.
- Reactants not completely consumed are called **excess reactants**.
- The amount of product that can be made from the limiting reactant is called the **theoretical yield**.

Summarizing Limiting Reactant and Yield

- The **limiting reactant** (or **limiting reagent**) is the reactant that is completely consumed in a chemical reaction and limits the amount of product.

- The **reactant in excess** is any reactant that occurs in a quantity greater than is required to completely react with the limiting reactant.

Summarizing Limiting Reactant and Yield

- The **theoretical yield** is the amount of product that can be made in a chemical reaction based on the amount of limiting reactant.
- The **actual yield** is the amount of product actually produced by a chemical reaction.
- The **percent yield** is calculated as follows:

$$\frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

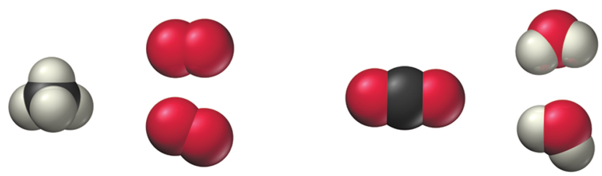
Calculating Limiting Reactant, Theoretical Yield, and Percent Yield

- Recall our balanced equation for the combustion of methane:

$$CH_4(g) + \mathbf{2}\ O_2(g) \rightarrow CO_2(g) + \mathbf{2}\ H_2O(g)$$

  – Our balanced equation for the combustion of methane implies that every one molecule of CH_4 reacts with two molecules of O_2.

$$CH_4(g) + 2\ O_2(g) \longrightarrow CO_2(g) + 2\ H_2O(l)$$



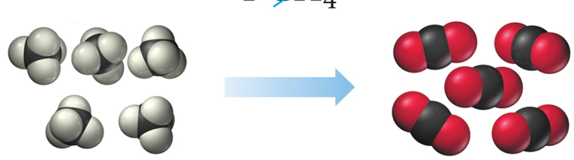
Combustion of Methane

- If we have five molecules of CH_4 and eight molecules of O_2, which is the limiting reactant?

$$CH_4(g) + \mathbf{2}\ O_2(g) \rightarrow CO_2(g) + \mathbf{2}\ H_2O(g)$$

  – First we calculate the number of CO_2 molecules that can be made from five CH_4 molecules.

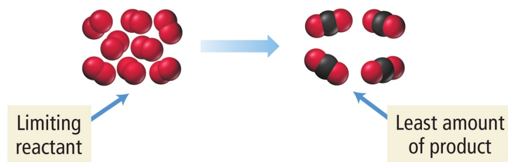
$$5\ \cancel{CH_4} \times \frac{1\ CO_2}{1\ \cancel{CH_4}} = 5\ CO_2$$



Combustion of Methane

- Then we calculate the number of CO_2 molecules that can be made from eight O_2 molecules.

$$8\ \cancel{O_2} \times \frac{1\ CO_2}{2\ \cancel{O_2}} = 4\ CO_2$$



  - We have enough CH_4 to make five CO_2 molecules and four CO_2 molecules.
  - Therefore, O_2 is the limiting reactant, and four CO_2 molecules is the theoretical yield.
  - CH_4 is in excess.

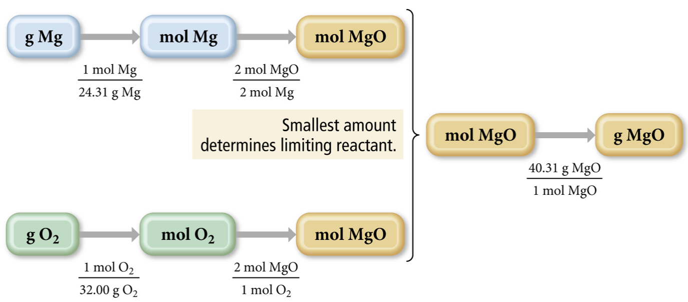
Calculating Limiting Reactant, Theoretical Yield, and Percent Yield from Reactant Masses

- When working in the lab, we normally measure reactant quantities in grams.
- To find the limiting reactant and theoretical yield, we must first convert grams to moles.

Calculating Limiting Reactant, Theoretical Yield, and Percent Yield from Reactant Masses

- A reactant mixture contains 42.5 g Mg and 33.8 g O_2. What is the limiting reactant and theoretical yield?

$$2\ Mg(s) + O_2(g) \rightarrow \mathbf{2}\ MgO(s)$$



Calculating Limiting Reactant, Theoretical Yield, and Percent Yield from Reactant Masses

$$42.5\ \text{g Mg} \times \frac{1\ \text{mol Mg}}{24.31\ \text{g Mg}} \times \frac{2\ \text{mol MgO}}{2\ \text{mol Mg}} = \mathbf{1.7483\ mol\ MgO}$$

Limiting reactant (42.5 g Mg)

Least amount of product (1.7483 mol MgO)

$$33.8\ \text{g}\ O_2 \times \frac{1\ \text{mol}\ O_2}{32.00\ \text{g}\ O_2} \times \frac{2\ \text{mol MgO}}{1\ \text{mol}\ O_2} = \mathbf{2.1125\ mol\ MgO}$$

$$\mathbf{1.7483\ mol\ MgO} \times \frac{40.31\ \text{g MgO}}{1\ \text{mol MgO}} = \mathbf{70.5\ g\ MgO}$$

Solution Concentration and Solution Stoichiometry

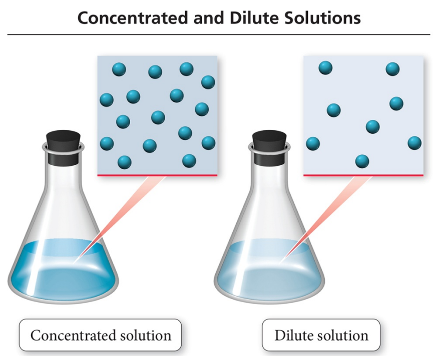
- When table salt is mixed with water, it seems to disappear or become a liquid; the mixture is homogeneous.
  - The salt is still there, as you can tell from the taste or simply boiling away the water.
- Homogeneous mixtures are called **solutions**.
- The majority component is the **solvent**.
- The minority component is the **solute**.
- A solution in which water is the solvent is an **aqueous solution**.

Solution Concentration

- Because solutions are mixtures, the composition can vary from one sample to another.
  - Pure substances have constant composition.
  - Saltwater samples from different seas or lakes have different amounts of salt.
- So, to describe solutions accurately, we quantify the amount of solute relative to solvent, or **concentration of solution**.

Solution Concentration

- Solutions are often described quantitatively, as dilute or concentrated.
- **Dilute solutions** have a small amount of solute compared to solvents.
- **Concentrated solutions** have a large amount of solute compared to solvents.

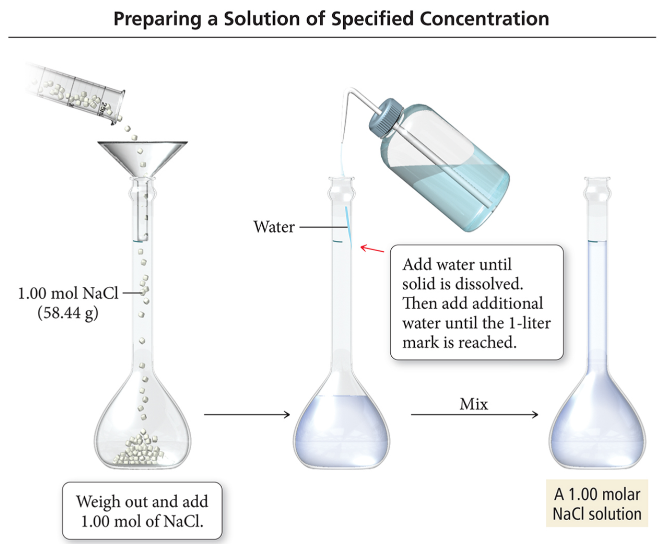


Solution Concentration: Molarity

- A common way to express solution concentration is **molarity (*M*)**.
  - Molarity is the amount of solute (in moles) divided by the volume of solution (in liters).

$$\text{Molarity (M)} = \frac{\text{amount of solute (in mol)}}{\text{volume of solution (in L)}}$$

Preparing 1 L of a 1.00 M NaCl Solution



Using Molarity in Calculations

- We can use the molarity of a solution as a conversion factor between moles of the solute and liters of the solution.
  - For example, a 0.500 M NaCl solution contains 0.500 mol NaCl for every liter of solution.

$\frac{0.500 \text{ mol NaCl}}{\text{L solution}}$ *converts* **L solution** → **mol NaCl**

$\frac{\text{L solution}}{0.500 \text{ mol NaCl}}$ *converts* **mol NaCl** → **L solution**

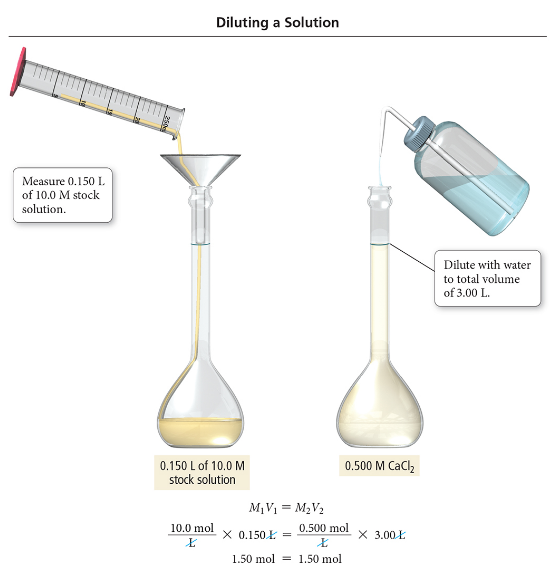
Solution Dilution

- Often, solutions are stored as concentrated **stock solutions**.
- To make solutions of lower concentrations from these stock solutions, more solvent is added.
  - **The amount of solute doesn't change, just the volume of solution:**

  moles solute in solution 1 = moles solute in solution 2
- The concentrations and volumes of the stock and new solutions are inversely proportional:

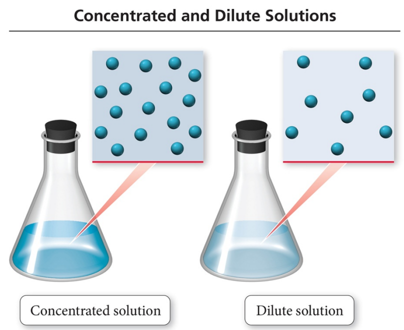
$$\mathbf{M_1 \cdot V_1 = M_2 \cdot V_2}$$

Preparing 3.00 L of 0.500 M $CaCl_2$ from a 10.0 M Stock Solution



Solution Stoichiometry

- Because molarity relates the moles of solute to the liters of solution, it can be used to convert between amount of reactants and/or products in a chemical reaction.
  - The general conceptual plan for these kinds of calculations begins with the volume of a reactant or product.

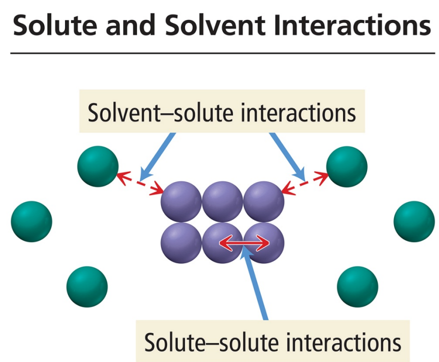


Types of Aqueous Solutions and Solubility

- Consider two familiar aqueous solutions: saltwater and sugar water.
  - Saltwater is a homogeneous mixture of NaCl and H_2O.
  - Sugar water is a homogeneous mixture of $C_{12}H_{22}O_{11}$ and H_2O.
- As you stir either of these two substances into the water, it seems to disappear.
  - How do solids such as salt and sugar dissolve in water?

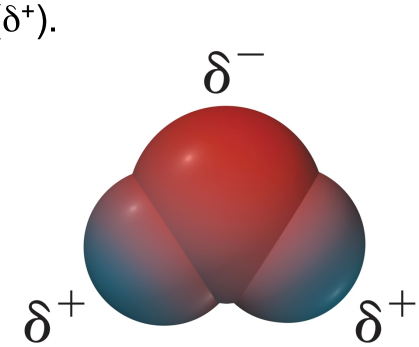
What Happens When a Solute Dissolves?

- There are attractive forces between the solute particles holding them together.
- There are also attractive forces between the solvent molecules.
- When we mix the solute with the solvent, there are attractive forces between the solute particles and the solvent molecules.
- If the attractions between solute and solvent are strong enough, the solute will dissolve.



Charge Distribution in a Water Molecule

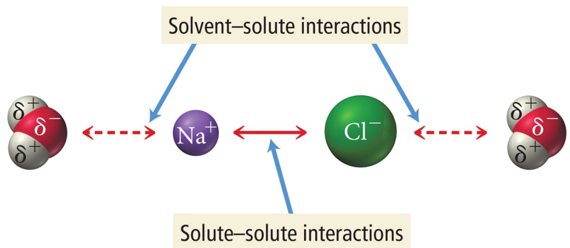
- There is an uneven distribution of electrons within the water molecule.
  - This causes the oxygen side of the molecule to have a partial negative charge (δ^-) and the hydrogen side to have a partial positive charge (δ^+).



Solute and Solvent Interactions in a Sodium Chloride Solution

- When sodium chloride is put into water, the attraction of Na^+ and Cl^- ions to water molecules competes with the attraction among the oppositely charged ions themselves.

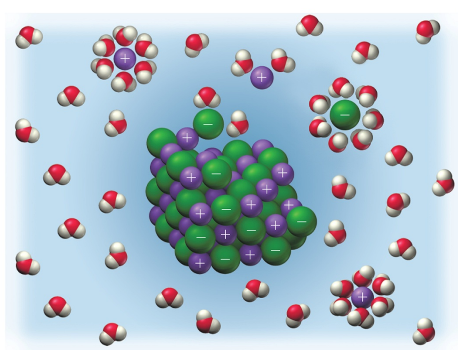
Interactions in a Sodium Chloride Solution



Dissolution of Ionic Compounds

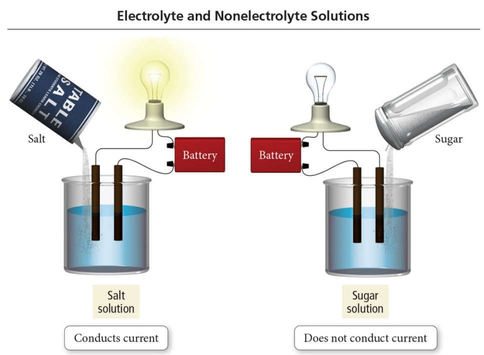
- Each ion is attracted to the surrounding water molecules and pulled off and away from the crystal.
- When it enters the solution, the ion is surrounded by water molecules, insulating it from other ions.
- The result is a solution with free-moving, charged particles able to conduct electricity.

Dissolution of an Ionic Compound



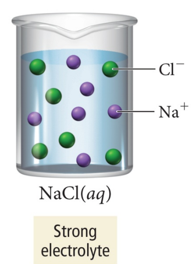
Electrolyte and Nonelectrolyte Solutions

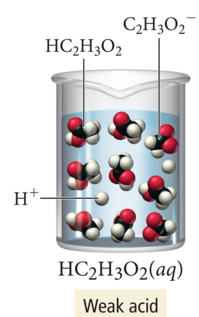
- Materials that dissolve in water to form a solution containing ions will conduct electricity. These are called **electrolytes**.
- Materials that dissolve in water to form a solution with no ions will not conduct electricity. These are called **nonelectrolytes**.
- A solution of salt (an electrolyte) conducts electrical current. A solution of sugar (a nonelectrolyte) does not.



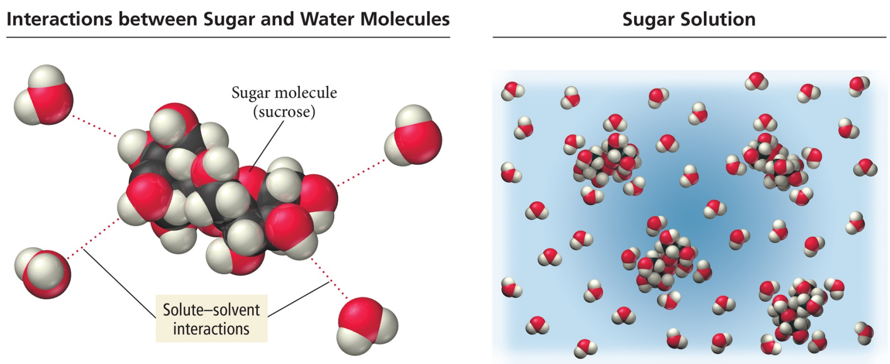
Electrolyte and Nonelectrolyte Solutions

- Ionic substances, such as sodium chloride, that completely dissociate into ions when they dissolve in water, are **strong electrolytes**.
- Except for acids, most molecular compounds, for example sugar, dissolve in water as intact molecules, or **nonelectrolytes**.
- Acids ionize to varying degrees in water. Those that completely ionize are **strong acids**. Those that don't are **weak acids**.





Sugar Dissolution in Water



Acids

- Acids are molecular compounds that **ionize** when they dissolve in water.
  - The molecules are pulled apart by their attraction for the water.
  - When acids ionize, they form H^+ cations and also anions.
- The percentage of molecules that ionize varies from one acid to another.
- Acids that ionize virtually 100% are called **strong acids**.

$$HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$$

- Acids that only ionize a small percentage are called **weak acids**.

$$HF(aq) \rightleftharpoons H^+(aq) + F^-(aq)$$

Strong and Weak Electrolytes

- **Strong electrolytes** are materials that dissolve completely as ions.
  - Ionic compounds and strong acids.
  - Solutions are good conductors of electricity.
- **Weak electrolytes** are materials that dissolve mostly as molecules but partially as ions.
  - Weak acids.
  - Solutions conduct electricity, but not well.

Dissociation and Ionization

- When ionic compounds dissolve in water, the anions and cations are separated from each other. This is called **dissociation**.

$$Na_2S(aq) \rightarrow 2\ Na^+(aq) + S^{2-}(aq)$$

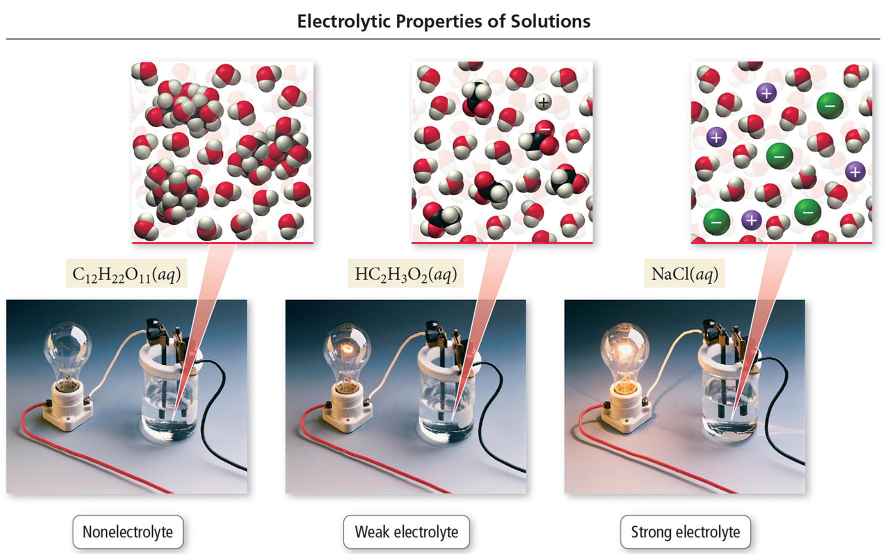
- When compounds containing polyatomic ions dissociate, the polyatomic group stays together as one ion.

$$Na_2SO_4(aq) \rightarrow 2\ Na^+(aq) + SO_4^{2-}(aq)$$

- When strong acids dissolve in water, the molecule **ionizes** into H^+ and anions.

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

Classes of Dissolved Materials

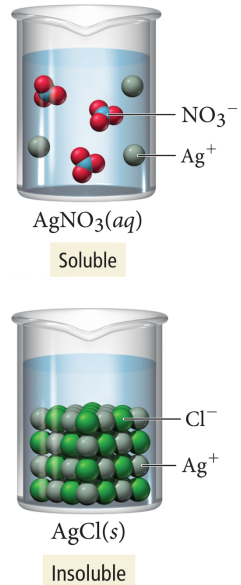


The Solubility of Ionic Compounds

- When an ionic compound dissolves in water, the resulting solution contains not the intact ionic compound itself but its component ions dissolved in water.
- However, not all ionic compounds dissolve in water. For example, AgCl remains solid and appears as a white powder at the bottom of the water.
- In general, a compound is termed **soluble** if it dissolves in water and **insoluble** if it does not.

Solubility of Salts

- If we mix solid $AgNO_3$ with water, it dissolves and forms a strong electrolyte solution.
- Silver chloride, on the other hand, is almost completely insoluble.
  - If we mix solid AgCl with water, virtually all of it remains as a solid within the liquid water.



When Will a Salt Dissolve?

- Whether a particular compound is soluble or insoluble depends on several factors.
- Predicting whether a compound will dissolve in water is not easy.
- The best way to do it is to conduct experiments to test whether a compound will dissolve in water, and then develop some rules based on those experimental results.
  - We call this method the **empirical method**.

Solubility Rules

TABLE 4.1 Solubility Rules for Ionic Compounds in Water

Compounds Containing the Following Ions Are Generally Soluble	Exceptions
Li^+, Na^+, K^+, and NH_4^+	None
NO_3^- and $C_2H_3O_2^-$	None
Cl^-, Br^-, and I^-	When these ions pair with Ag^+, Hg_2^{2+}, or Pb^{2+}, the resulting compounds are insoluble.
SO_4^{2-}	When SO_4^{2-} pairs with Sr^{2+}, Ba^{2+}, Pb^{2+}, Ag^+, or Ca^{2+}, the resulting compound is insoluble.
Compounds Containing the Following Ions Are Generally Insoluble	**Exceptions**
OH^- and S^{2-}	When these ions pair with Li^+, Na^+, K^+, or NH_4^+, the resulting compounds are soluble.
	When S^{2-} pairs with Ca^{2+}, Sr^{2+}, or Ba^{2+}, the resulting compound is soluble.
	When OH^- pairs with Ca^{2+}, Sr^{2+}, or Ba^{2+}, the resulting compound is slightly soluble.
CO_3^{2-} and PO_4^{3-}	When these ions pair with Li^+, Na^+, K^+, or NH_4^+, the resulting compounds are soluble.

Precipitation Reactions

- **Precipitation reactions** are reactions in which a solid forms when we mix two solutions.
  - Reactions between aqueous solutions of ionic compounds produce an ionic compound that is insoluble in water.
  - The insoluble product is called a **precipitate**.

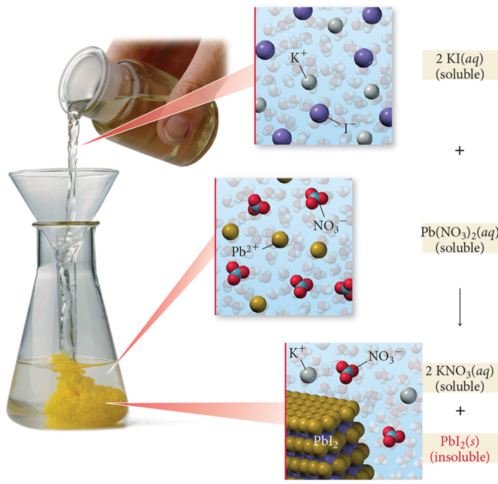
Precipitation of Lead(II) Iodide

Precipitation Reaction

$$2\ KI(aq) + Pb(NO_3)_2(aq) \longrightarrow PbI_2(s) + 2\ KNO_3(aq)$$

(soluble) (soluble) (insoluble) (soluble)

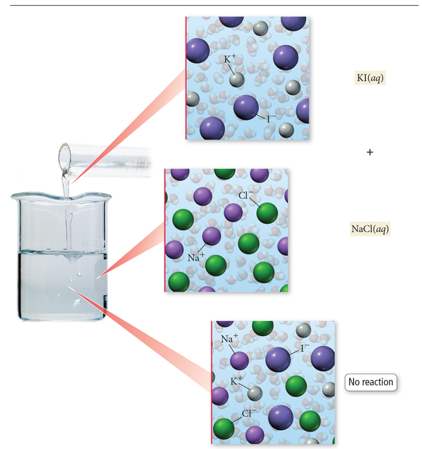
When a potassium iodide solution is mixed with a lead(II) nitrate solution, a yellow lead(II) iodide precipitate forms.



No Precipitation Means No Reaction

- Precipitation reactions do not always occur when two aqueous solutions are mixed.
  - Nothing happens when combining solutions of KI and NaCl.

No Reaction



$KI(aq) + NaCl(aq) \rightarrow$ No Reaction

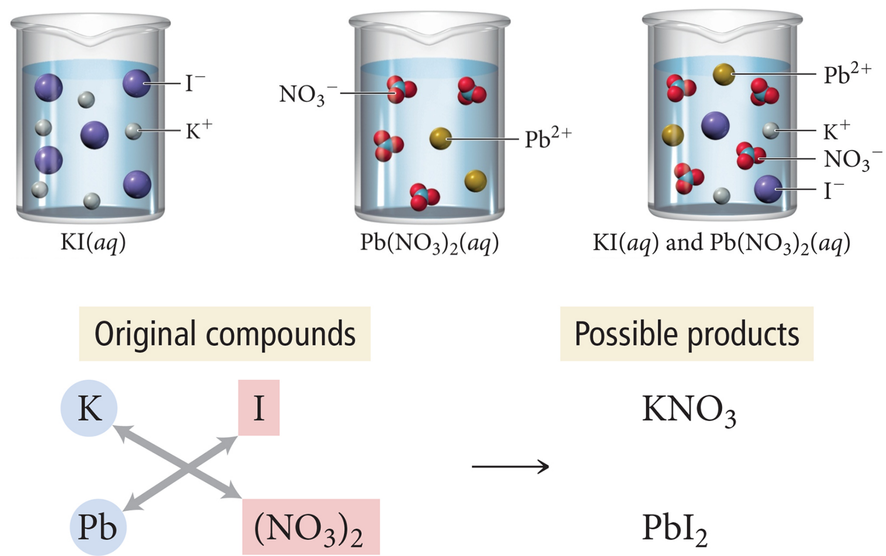
Predicting Precipitation Reactions

1. Determine what ions each aqueous reactant has.
2. Determine formulas of possible products.
   - Exchange ions.
     - (+) ion from one reactant with (–) ion from other
   - Balance charges of combined ions to get the formula of each product.
3. Determine solubility of each product in water.
   - Use the solubility rules.
   - If the product is insoluble or slightly soluble, it will precipitate.
4. If neither product will precipitate, write **no reaction** after the arrow.

Predicting Precipitation Reactions

5. If any of the possible products are insoluble, write their formulas as the products of the reaction using **(*s*)** after the formula to indicate **solid**. Write any soluble products with **(*aq*)** after the formula to indicate ***aqueous***.
6. Balance the equation.
   - Remember to change only coefficients, not subscripts.

Predicting Precipitation Reactions



Representing Aqueous Reactions

- An equation showing the complete neutral formulas for each compound in the aqueous reaction as if they existed as molecules is called a **molecular equation**.

  $2\ KOH(aq) + Mg(NO_3)_2(aq) \rightarrow 2\ KNO_3(aq) + Mg(OH)_2(s)$

- In actual solutions of soluble ionic compounds, dissolved substances are present as ions. Equations that describe the nature of the dissolved species in solution are called **complete ionic equations**.

Rules for Writing a Complete Ionic Equation

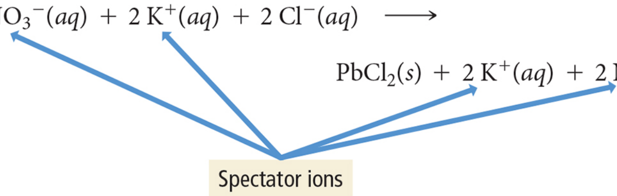
- Aqueous strong electrolytes (soluble salts, strong acids, strong bases) are written as ions.
- Insoluble substances, weak electrolytes, and nonelectrolytes are written in molecule form.
  - Solids, liquids, and gases are not dissolved, hence molecule form

$$2\ K^+_{(aq)} + 2\ OH^-_{(aq)} + Mg^{2+}_{(aq)} + 2\ NO_3^-{}_{(aq)} \rightarrow$$
$$2\ K^+_{(aq)} + 2\ NO_3^-{}_{(aq)} + Mg(OH)_{2(s)}$$

Ionic Equation

- Notice that in the complete ionic equation, some of the ions in solution appear unchanged on both sides of the equation.
- These ions are called **spectator ions** because they do not participate in the reaction (soluble salts, strong acids, and strong bases).

$$Pb^{2+}(aq) + 2\ NO_3^-(aq) + 2\ K^+(aq) + 2\ Cl^-(aq) \longrightarrow$$
$$PbCl_2(s) + 2\ K^+(aq) + 2\ NO_3^-(aq)$$



Net Ionic Equation

- An ionic equation in which the spectator ions are removed is called a **net ionic equation**.

$$2\,K^+_{(aq)} + 2\,OH^-_{(aq)} + Mg^{2+}_{(aq)} + 2\,NO_3{}^-_{(aq)} \rightarrow 2\,K^+_{(aq)} + 2\,NO_3{}^-_{(aq)} + Mg(OH)_{2(s)}$$

- The net ionic equation is

$$2\,OH^-_{(aq)} + Mg^{2+}_{(aq)} \rightarrow Mg(OH)_{2(s)}$$

Examples

- Write the ionic and net ionic equation for each of the following:

1. $K_2SO_4(aq) + 2\,AgNO_3(aq) \rightarrow 2\,KNO_3(aq) + Ag_2SO_4(s)$

   $2\,K^+(aq) + SO_4{}^{2-}(aq) + 2\,Ag^+(aq) + 2\,NO_3{}^-(aq) \rightarrow$
   $2\,K^+(aq) + 2\,NO_3{}^-(aq) + Ag_2SO_4(s)$

   $2\,Ag^+(aq) + SO_4{}^{2-}(aq) \rightarrow Ag_2SO_4(s)$

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

   $2\,Na^+(aq) + CO_3{}^{2-}(aq) + 2\,H^+(aq) + 2\,Cl^-(aq) \rightarrow$
   $2\,Na^+(aq) + 2\,Cl^-(aq) + CO_2(g) + H_2O(l)$

   $CO_3{}^{2-}(aq) + 2\,H^+(aq) \rightarrow CO_2(g) + H_2O(l)$

Acid–Base and Gas-Evolution Reactions

- Two other important classes of reactions that occur in aqueous solution are
  1. acid–base reactions and
  2. gas-evolution reactions.
- Acid–base reaction:
  – An **acid–base reaction** is also called a **neutralization reaction**.
  – An acid reacts with a base, and the two neutralize each other, producing water (or in some cases a weak electrolyte).

Acid–Base and Gas-Evolution Reactions

- In a **gas-evolution reaction**, a gas is produced, resulting in bubbling.
- In both acid–base and gas-evolution reactions, as in precipitation reactions, the reactions occur when the anion from one reactant combines with the cation of the other.
- Many gas-evolution reactions are also acid–base reactions.

Acid–Base Reactions

Arrhenius Definitions:

- Acid: Substance that produces H^+ in aqueous solution. $HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$
- In solution, H^+ bonds with water to produce the **hydronium ion**, H_3O+.
- **Polyprotic acids** contain more than one ionizable proton and release them sequentially.
- The first ionizable proton is strong while subsequent ionizable protons are weak.
- Base: Substance that produces OH^- ions in aqueous solution.

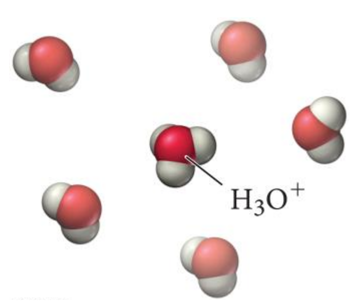
  $NaOH(aq) \rightarrow Na^+(aq) + OH^-(aq)$

Acid–Base Reactions

- These reactions are called **neutralization reactions** because the acid and base neutralize each other's properties.

  $2\ HNO_3(aq) + Ca(OH)_2(aq) \rightarrow Ca(NO_3)_2(aq) + 2\ H_2O(l)$
- The net ionic equation for an acid–base reaction is

  $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$
  - As long as the salt that forms is soluble in water.



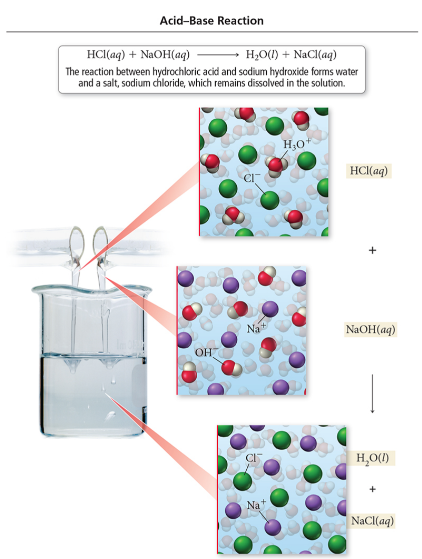
Acids and Bases in Solution

- Acids ionize in water to form H^+ ions.
  - More precisely, the H^+ from the acid molecule is donated to a water molecule to form **hydronium ion, H_3O^+**.
    - Most chemists use H^+ and H_3O^+ interchangeably.
- Bases dissociate in water to form OH^- ions.
  - Bases, such as NH_3, that do not contain OH^- ions, produce OH^- by pulling H^+ off water molecules.
- In the reaction of an acid with a base, the H^+ from the acid combines with the OH^- from the base to make water.
- The cation from the base combines with the anion from the acid to make the salt.

$$\underset{\text{Acid}}{HCl(aq)} + \underset{\text{Base}}{NaOH(aq)} \longrightarrow \underset{\text{Water}}{H_2O(l)} + \underset{\text{Salt}}{NaCl(aq)}$$

Acid–Base Reaction

- $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$



Some Common Acids and Bases

TABLE 4.2 Some Common Acids and Bases

Name of Acid	Formula	Name of Base	Formula
Hydrochloric acid	HCl	Sodium hydroxide	$NaOH$
Hydrobromic acid	HBr	Lithium hydroxide	$LiOH$
Hydroiodic acid	HI	Potassium hydroxide	KOH
Nitric acid	HNO_3	Calcium hydroxide	$Ca(OH)_2$
Sulfuric acid	H_2SO_4	Barium hydroxide	$Ba(OH)_2$
Perchloric acid	$HClO_4$	Ammonia*	NH_3 (weak base)
Formic acid	$HCHO_2$ (weak acid)		
Acetic acid	$HC_2H_3O_2$ (weak acid)		
Hydrofluoric acid	HF (weak acid)		

*Ammonia does not contain OH^-, but it produces OH^- in a reaction with water that occurs only to a small extent: $NH_3(aq) + H_2O(l) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$.

Predict the Product of the Reactions

1. $HCl(aq) + Ba(OH)_2(aq) \rightarrow$

$$(H^+ + Cl^-) + (Ba^{2+} + OH^-) \rightarrow (H^+ + OH^-) + (Ba^{2+} + Cl^-)$$

$$HCl(aq) + Ba(OH)_2(aq) \rightarrow H_2O(l) + BaCl_2$$

$$2\ HCl(aq) + Ba(OH)_2(aq) \rightarrow 2\ H_2O(l) + BaCl_2(aq)$$

2. $H_2SO_4(aq) + LiOH(aq) \rightarrow$

$$(H^+ + SO_4^{2-}) + (Li^+ + OH^-) \rightarrow (H^+ + OH^-) + (Li^+ + SO_4^{2-})$$

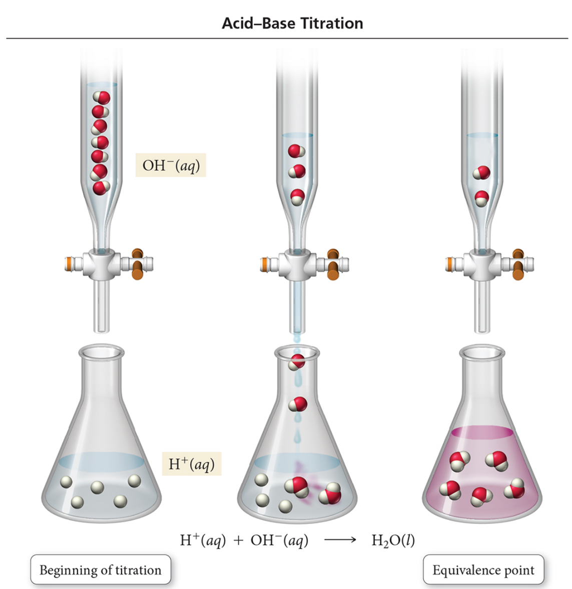
$$H_2SO_4(aq) + LiOH(aq) \rightarrow H_2O(l) + Li_2SO_4$$

$$H_2SO_4(aq) + 2\ LiOH(aq) \rightarrow 2\ H_2O(l) + Li_2SO_4(aq)$$

Acid–Base Titrations

- A **titration** is a laboratory procedure where a substance in a solution of known concentration (**titration**) is reacted with another substance in a solution of unknown concentration (**analyte**).
- The **equivalence point** is the point in the titration when the H^+ and OH^- from reactants are in their stoichiometric ratio and are completely reacted.
- An **indicator** is a dye whose color depends on the acidity or basicity of solution.

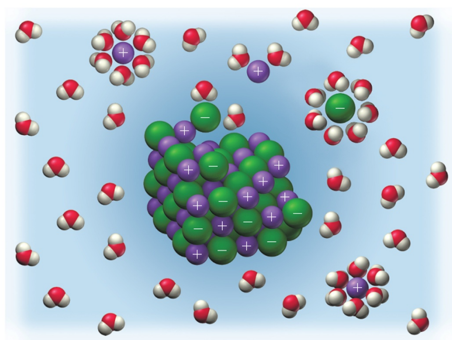
Acid–Base Titration



Titration

In this titration, NaOH is added to a dilute HCl solution. When the NaOH and HCl reach stoichiometric proportions (the equivalence point), the phenolphthalein indicator changes color to pink.

Dissolution of an Ionic Compound



Gas-Evolving Reactions

- Some reactions form a gas directly from the ion exchange.

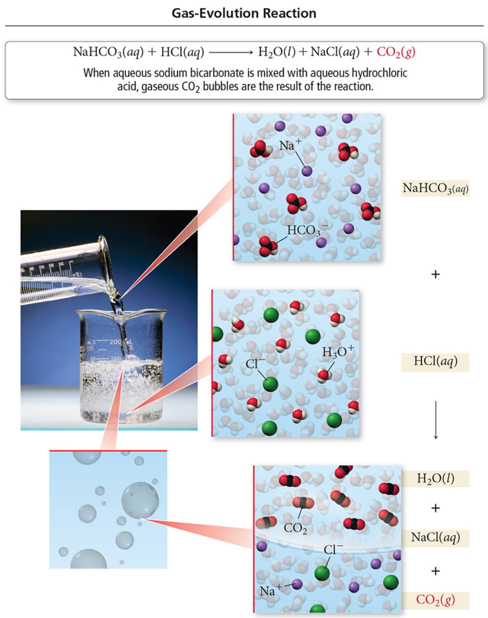
$$K_2S(aq) + H_2SO_4(aq) \rightarrow K_2SO_4(aq) + H_2S(g)$$

- Other reactions form a gas by the subsequent decomposition of one of the ion exchange products into a gas and water.

$$NaHCO_3(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2CO_3(aq)$$

$$H_2CO_3(aq) \rightarrow H_2O(l) + CO_2(g)$$

Gas-Evolution Reaction



Types of Compounds That Undergo Gas-Evolution Reactions

TABLE 4.3 Types of Compounds That Undergo Gas-Evolution Reactions

Reactant Type	Intermediate Product	Gas Evolved	Example
Sulfides	None	H_2S	$2\ HCl(aq) + K_2S(aq) \longrightarrow H_2S(g) + 2\ KCl(aq)$
Carbonates and bicarbonates	H_2CO_3	CO_2	$2\ HCl(aq) + K_2CO_3(aq) \longrightarrow H_2O(l) + CO_2(g) + 2\ KCl(aq)$
Sulfites and bisulfites	H_2SO_3	SO_2	$2\ HCl(aq) + K_2SO_3(aq) \longrightarrow H_2O(l) + SO_2(g) + 2\ KCl(aq)$
Ammonium	NH_4OH	NH_3	$NH_4Cl(aq) + KOH(aq) \longrightarrow H_2O(l) + NH_3(g) + KCl(aq)$