Chapter 4
Stoichiometry of Chemical Reactions

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Topics to be covered

- Balancing reaction equations
- Stoichiometric calculations
- Limiting reactant, theoretical yield, percent yield
- Precipitation reactions
- Acid-base reactions
- Reduction-oxidation reactions
- Titration

Chemical equations

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

- Reactants on the left side, products on the right side
- An arrow separates the reactant and the product sides of the equation.
- Reaction coefficients represent the relative numbers of reactants and products.
- States of reactants and products should be shown in parentheses. (g): gas,)s): solid, (l): liquid, (aq): aqeuous
- Reaction equation should be balanced. Equal numbers of

  atoms for each element between left and right sides.

Balancing reaction equations

- Zn wire reacts with aqueous HCl solution

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

- Atoms are neither created nor destroyed during chemical reactions
- # of all atoms before and after reaction should be same
- Chemical reaction is wrong (not balanced)
- Why?

Balancing reaction equations

1. List elements found in both reactants and products
2. Count # of reactants and products that contain these elements
3. Element found in fewer reactants and compounds start first
4. Putting numbers (stoichiometry coefficients) in front of reactions and/or products
5. After done, check

$$\_H_2(g) + \_O_2(g) \rightarrow \_H_2O(l)$$

$$\_C_3H_8(g) + \_O_2(g) \rightarrow \_CO_2(g) + \_H_2O(g)$$

$$\_CaCl_2(aq) + \_K_3PO_4(aq) \rightarrow \_Ca_3(PO_4)_2(s) + \_KCl(aq)$$

One more example

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O$$

Reaction coefficients in balanced reaction equation

$$C_6H_{12}O_6(aq) + 6O_2(aq) \rightarrow 6CO_2(aq) + 6H_2O(l)$$

1 mol $C_6H_{12}O_6$ reacts with 6 mol O_2 to produce
6 mol CO_2 and 6 mol H_2O

$$1\text{mol } C_6H_{12}O_6 \Leftrightarrow ?\text{mol } O_2 \Leftrightarrow ?\text{mol } CO_2 \Leftrightarrow ?\text{mol } H_2O$$

Reaction stoichiometry

How many moles of O_2 will be required to burn 0.50 mol of glucose?

Use of mole-to-mole ratio

$$C_6H_{12}O_6(aq) + 6O_2(aq) \rightarrow 6CO_2(aq) + 6H_2O(l)$$

- How many grams of oxygen is required to completely react with 1.00 g of glucose?

- How many grams of CO_2 will be produced in the above reaction?

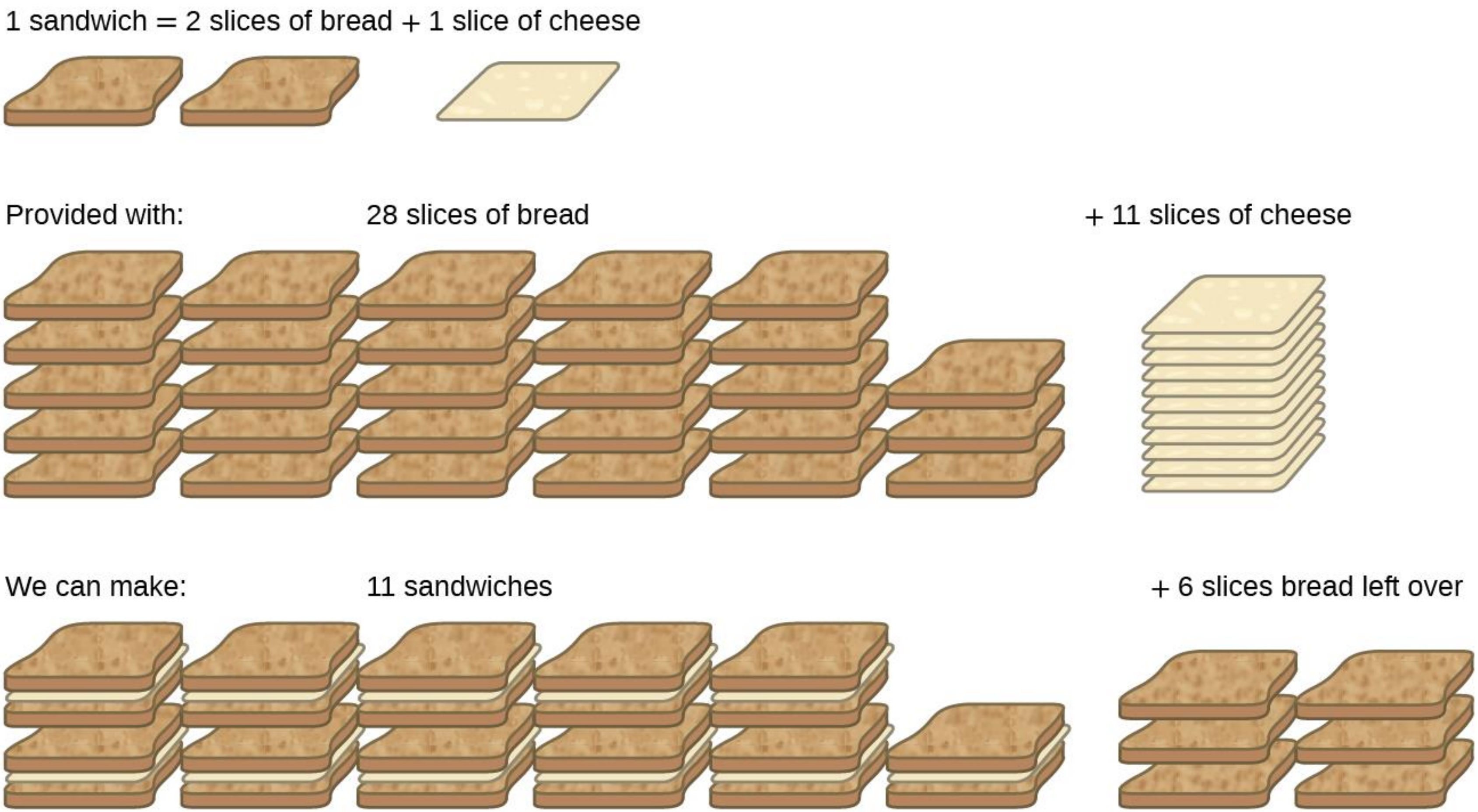
Example: Use of mole-to-mole ratio

$$2Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + 2Fe(l)$$

To produce 86.9 g of iron, how many grams of iron oxide will be required? Assume that we have enough amount of aluminium.

$$86.0 \text{ g Fe} \Leftrightarrow ? \text{ g } Fe_2O_3$$

Limiting and excess reactants



Limiting and excess reactants

- In previous slide, how many sandwich can you make if you are provided with 28 slices of bread and 16 slices of cheese?
- Which ingredient will be left?

Limiting reagent

- The reactant which determines the amount of product in a chemical reaction <u>occurring in a non-stoichiometric ratio</u> and is completely consumed in the reaction

$$C_2H_4(\mathrm{g}) + H_2O(g) \rightarrow C_2H_5OH(l)$$

Keep in mind that mole # and # of molecules are related.

1 mol	1 mol	stoichiometric ratio
2 mol	2 mol	stoichiometric ratio
3 mol	1 mol	nonstoichiometric ratio
1 mol	3 mol	nonstoichiometric ratio

- Which one is a limiting reagent in third and fourth case?

Limiting reagent

- Now let's consider a chemical reaction in which the stoichiometric ratio between the reactants is NOT one-to-one.

We need to use the "mole ratio" from the reaction equation.

$$C_6H_{12}O_6(aq) + 6O_2(aq) \rightarrow 6CO_2(aq) + 6H_2O(l)$$

Determine which one is the limiting reagent in the following cases.

6 mol $C_6H_{12}O_6$ + 6 mol O_2

6 mol $C_6H_{12}O_6$ + 12 mol O_2

12 mol $C_6H_{12}O_6$ + 6 mol O_2

6 mol $C_6H_{12}O_6$ + 1 mol O_2

Ex. Limiting reagent

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

Which one is the limiting reagent in each case?

2 mol N_2	6 mol H_2
1 mol N_2	4 mol H_2
2 mol N_2	4 mol H_2
1.1 mol N_2	3.5 mol H_2
2.5 mol N_2	0.8 mol H_2

Determination of product amount (nonstoichiometric condition!)

- 1.0 kg of ethylene (C_2H_2) + 0.010 kg of steam (H_2O) in a reaction vessel. How much amount of ethanol will be produced?

$$C_2H_4(\mathrm{g}) + H_2O(g) \rightarrow C_2H_5OH(l)$$

When the masses of reactant are given in the question instead of moles, convert mass to mol first!

Percent yield

$$Percent\ yield = \frac{Actual\ yield}{Theoretical\ yield} \times 100$$

In reality, the amount of product collected less than theoretically calculated.

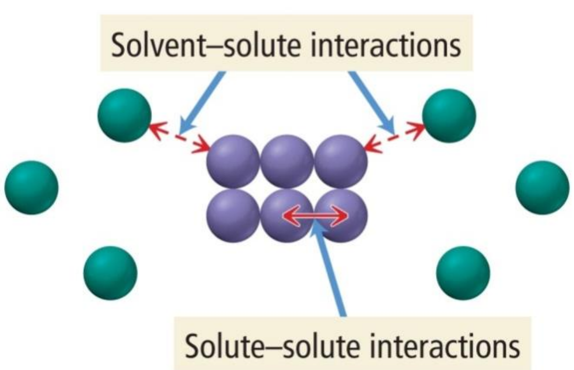
Percent yield calculation

- 12.0 g of P and 35.0 g of $Cl_2(g)$ were mixed and 42.4 g of $PCl_3(l)$ were produced. Calculate the percentage yield of PCl_3.

$$2P(s) + 3Cl_2(g) \rightarrow 2PCl_3(l)$$

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



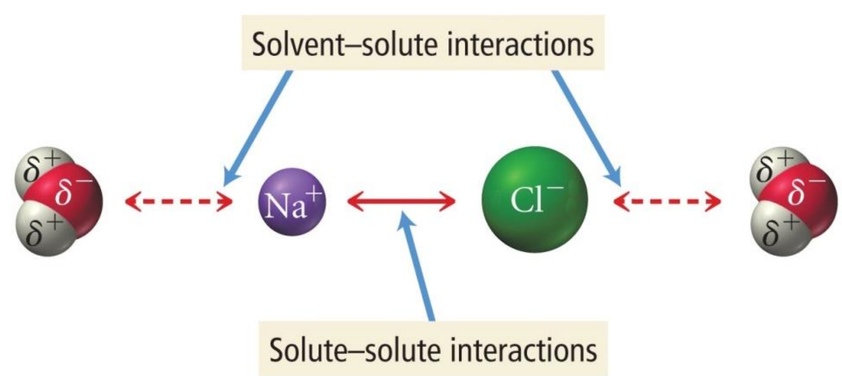
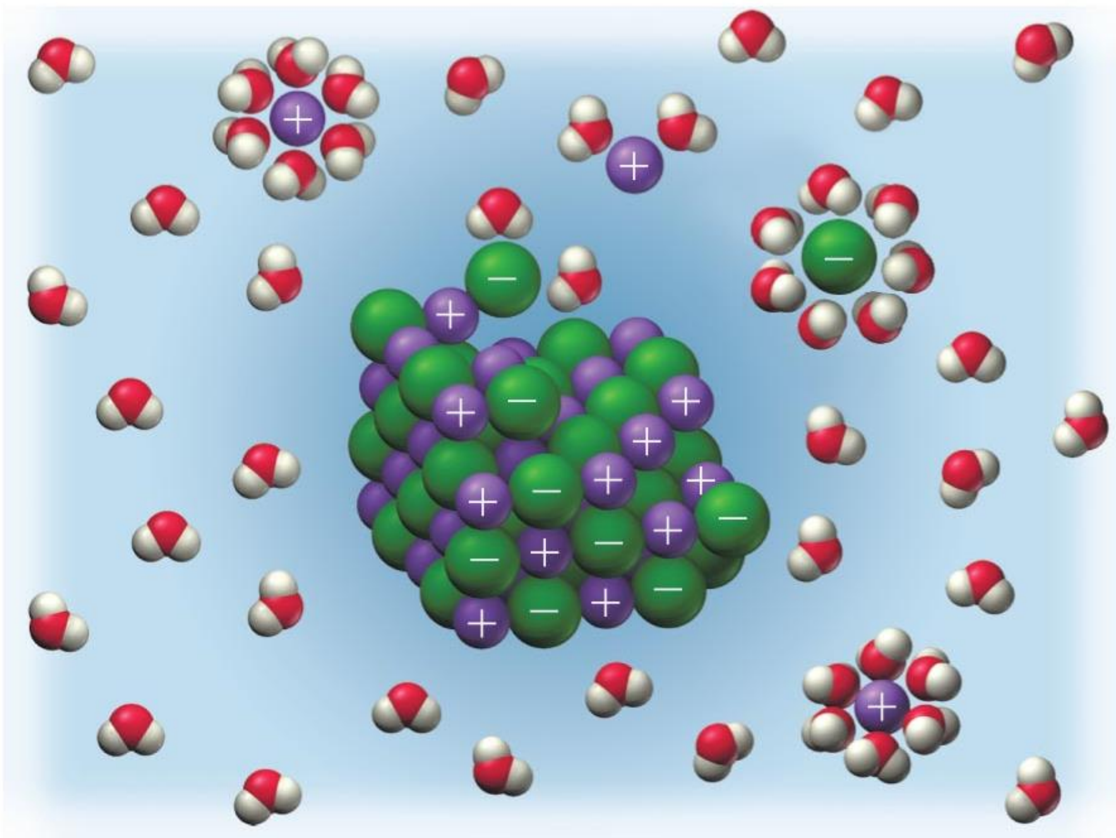


Table Salt Dissolving in Water

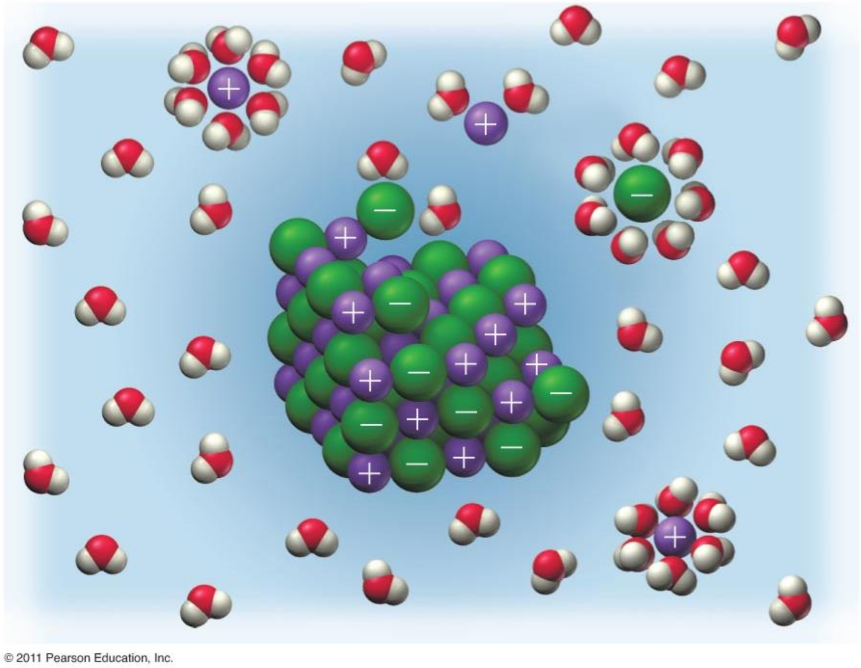


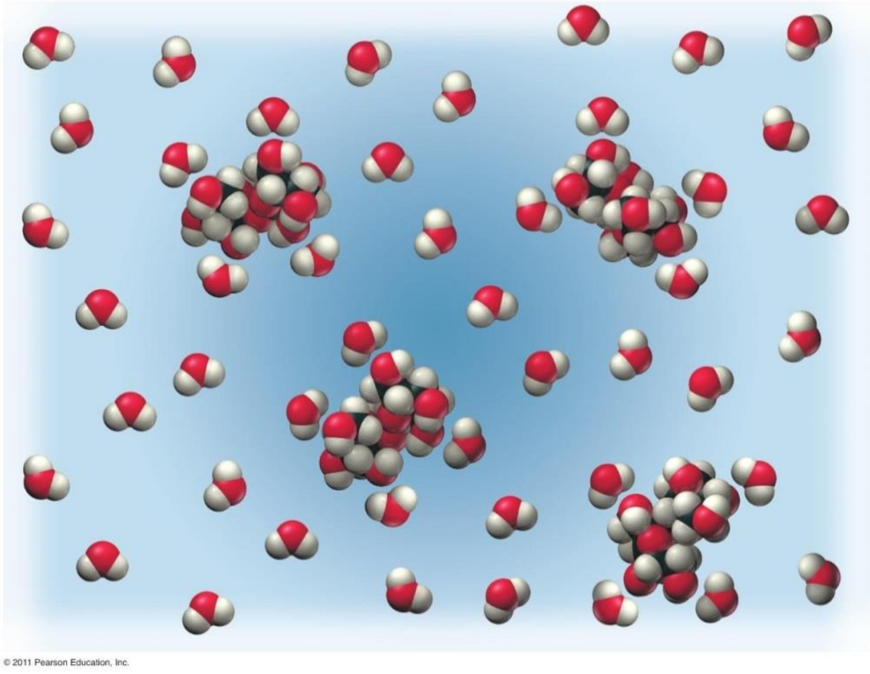
Each ion is attracted to the surrounding water molecules and pulled off and away from the crystal

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

NaCl vs. Sugar Dissolved in Water



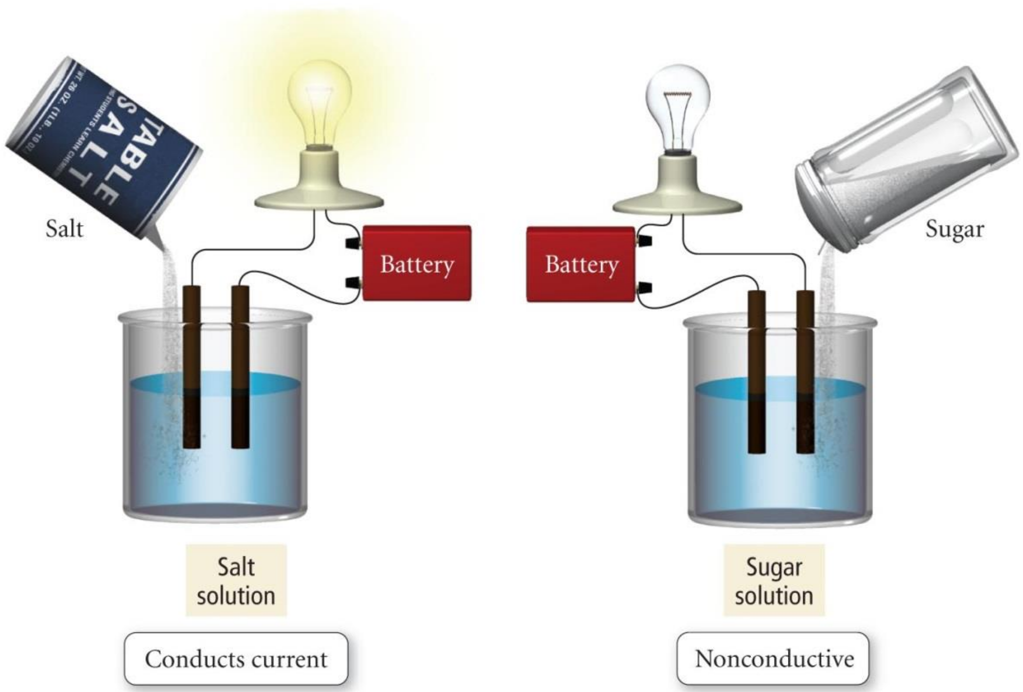


ionic compounds dissociate into ions when they dissolve

molecular compounds do not dissociate when they dissolve

Electrolytes and Nonelectrolytes

- Materials that dissolve in water to form a solution that will conduct electricity are called **electrolytes (produce ions, ionic compounds, NaCl, KCl, etc)**



- Materials that dissolve in water to form a solution that will not conduct electricity are called **nonelectrolytes (do not produce ions, molecular compounds, sugar, ethanol, etc)**

Exceptions: 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

- 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**

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

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 **molecular compounds** (e.g. strong acids) dissolve in water, the molecule **ionizes** into H^+ and anions

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

Write the equation for the process that occurs when the following strong electrolytes dissolve in water

$CaCl_2$

HNO_3

$(NH_4)_2CO_3$

Concentration of ions from strong electrolytes

- 0.10 M KCl

- 0.10 M $CaCl_2$

- 0.10 M Na_3PO_4

Solubility of Ionic Compounds

- Some ionic compounds, such as NaCl, dissolve very well in water at room temperature
- Other ionic compounds, such as AgCl, dissolve hardly at all in water at room temperature
- Compounds that dissolve in a solvent are said to be **soluble**, where as those that do not are said to be **insoluble**
  - NaCl is soluble in water, AgCl is insoluble in water
  - the degree of solubility depends on the temperature
  - even insoluble compounds dissolve, just not enough to be meaningful

Solubility Rules
Compounds that are Generally Soluble in Water

Compounds Containing the Following Ions are Generally Soluble	**Exceptions** **(when combined with ions on the left, the compound is insoluble)**
Li^+, Na^+, K^+, NH_4^+	none
NO_3^-, $C_2H_3O_2^-$	none
Cl^-, Br^-, I^-	Ag^+, Hg_2^{2+}, Pb^{2+}
SO_4^{2-}	Ag^+, Ca^{2+}, Sr^{2+}, Ba^{2+}, Pb^{2+}

Solubility Rules
Compounds that are Generally Insoluble in Water

Compounds Containing the Following Ions are Generally Insoluble	Exceptions (when combined with ions on the left the compound is soluble or slightly soluble)
OH^-	Li^+, Na^+, K^+, NH_4^+, Ca^{2+}, Sr^{2+}, Ba^{2+}
S^{2-}	Li^+, Na^+, K^+, NH_4^+
CO_3^{2-}, PO_4^{3-}	Li^+, Na^+, K^+, NH_4^+

Practice – Determine if each of the following is soluble in water

KOH

AgBr

$CaCl_2$

$Pb(NO_3)_2$

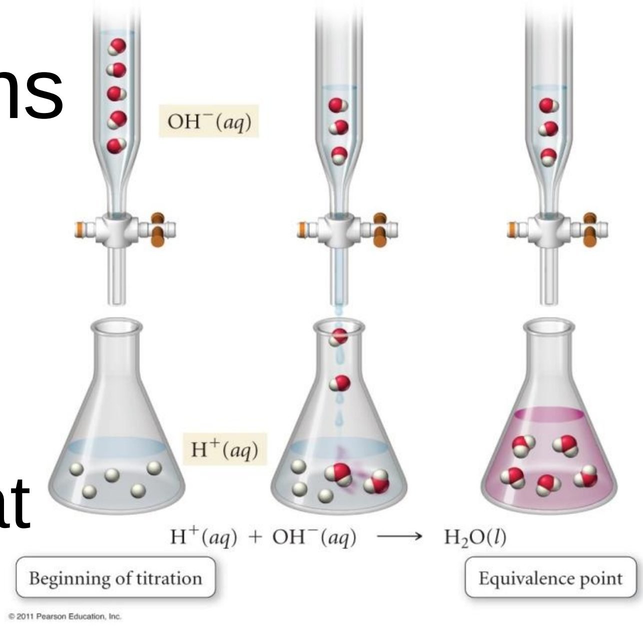
$PbSO_4$

Types of Reactions

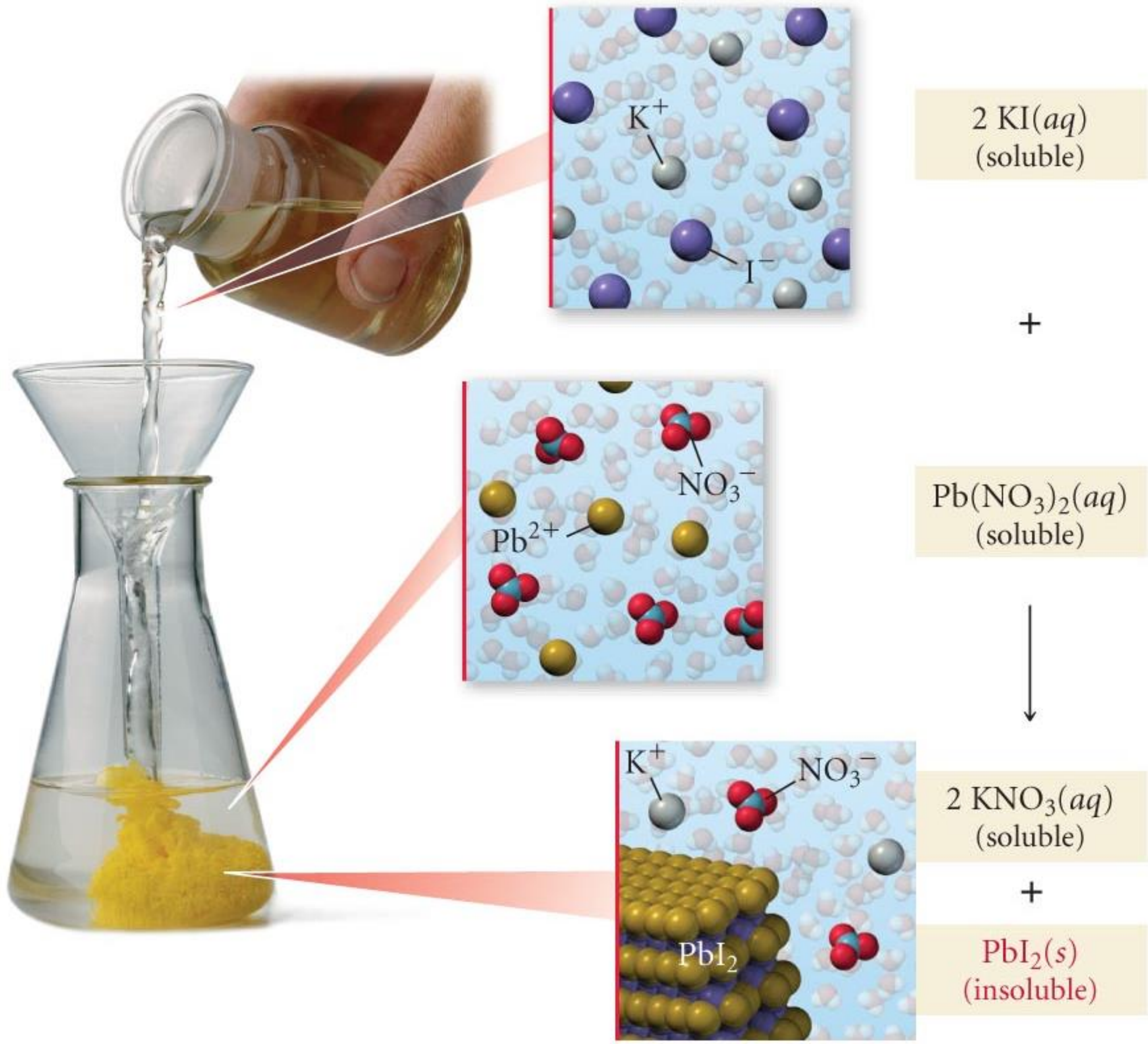
- **Precipitation reactions**
- **Acid-base reaction**
- **Oxidation-reduction reaction**

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**



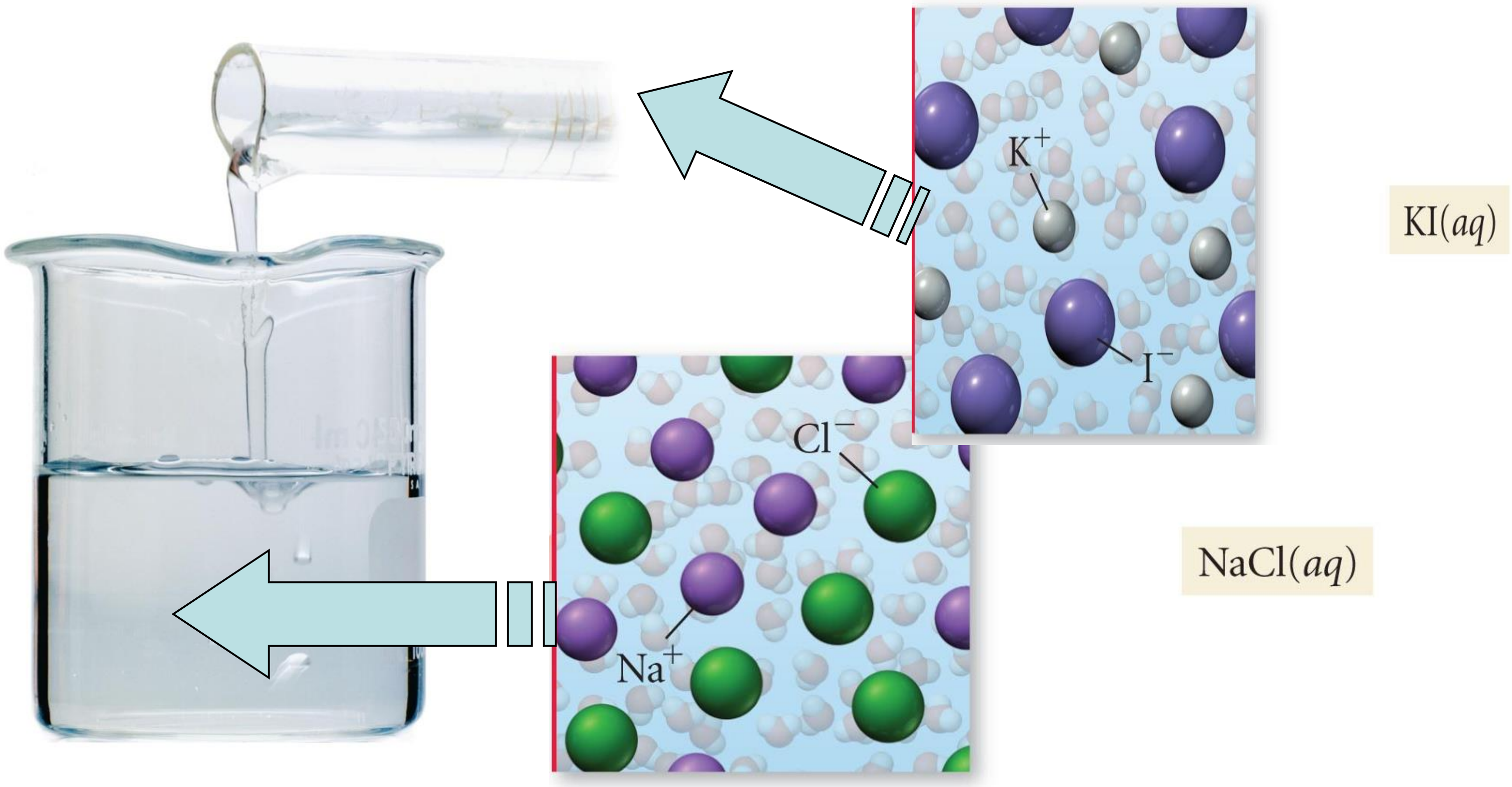
$$2\,KI(aq) + Pb(NO_3)_2(aq) \rightarrow PbI_2(s) + 2\,KNO_3(aq)$$



No Precipitate Formation = No Reaction

KI(*aq*) + NaCl(*aq*) $\rightarrow$ no reaction

all ions still present



Predict the products and balance the equation

$KCl(aq) + AgNO_3(aq) \rightarrow$

$Na_2S(aq) + CaCl_2(aq) \rightarrow$

Molecular vs. Ionic Equations

- Equations that describe the chemicals put into the water and the product molecules are called **molecular equations**

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

- Equations that describe the material's structure when dissolved are called **complete ionic equations**
  - aqueous strong electrolytes are written as ions
    - soluble salts, strong acids, strong bases
  - insoluble substances, weak electrolytes, and nonelectrolytes are written in molecule form
    - solids, liquids, and gases are not dissolved, therefore molecule form

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

Ionic Equations

- Ions that are both reactants and products are called **spectator ions (not involved in chemical reactions)**

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

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

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

Write the ionic and net ionic equation for each

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

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

Acids and Bases in Solution

- Acids ionize in water to form H^+ ions (proton)
  - 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 (hydroxide)
  - 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

acid + base $\rightarrow$ salt + water

Acid-Base Reactions

- 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

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

Common Acids

Chemical Name	Formula	Uses	Strength
Perchloric Acid	$HClO_4$	explosives, catalyst	Strong
Nitric Acid	HNO_3	explosives, fertilizer, dye,	Strong
Sulfuric Acid	H_2SO_4	explosives, fertilizer, dye, glue, batteries	Strong
Hydrochloric Acid	HCl	metal cleaning, food prep, ore refining, stomach acid	Strong
Phosphoric Acid	H_3PO_4	fertilizer, plastics & rubber, food preservation	Moderate
Chloric Acid	$HClO_3$	explosives	Moderate
Acetic Acid	$HC_2H_3O_2$	plastics & rubber, food preservation, vinegar	Weak
Hydrofluoric Acid	HF	metal cleaning, glass	Weak
Carbonic Acid	H_2CO_3	soda water	Weak
Hypochlorous	$HClO$	sanitizer	Weak
Boric Acid	H_3BO_3	eye wash	Weak

Common Bases

Chemical Name	Formula	Common Name	Uses	Strength
sodium hydroxide	$NaOH$	lye, caustic soda	soap, plastic, petrol refining	Strong
potassium hydroxide	KOH	caustic potash	soap, cotton, electroplating	Strong
calcium hydroxide	$Ca(OH)_2$	slaked lime	cement	Strong
sodium bicarbonate	$NaHCO_3$	baking soda	cooking, antacid	Weak
magnesium hydroxide	$Mg(OH)_2$	milk of magnesia	antacid	Weak
ammonium hydroxide	NH_4OH, $\{NH_3(aq)\}$	ammonia water	detergent, fertilizer, explosives, fibers	Weak

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

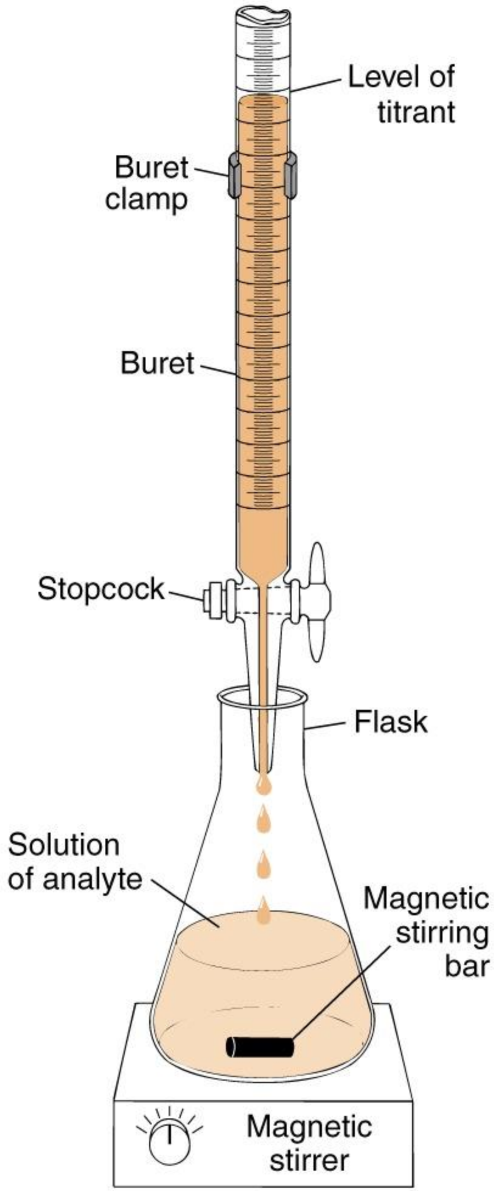
Write the molecular, ionic, and net-ionic equation for the reaction of aqueous nitric acid (HNO_3) with aqueous calcium hydroxide ($Ca(OH)_2$)

Predict the products and balance the equation

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

$H_2SO_4(aq) + Sr(OH)_2(aq) \rightarrow$

Titration



- a solution's unknown concentration can be determined by reacting it with another solution with known concentration and using stoichiometry – this process is called **titration**
- In the titration, the unknown solution is added to a known amount of another reactant until the reaction is just completed (endpoint) At this point, called the **endpoint**.
- the unknown solution is added slowly from an instrument called a **burette**
  - a long glass tube with precise volume markings that allows small additions of solution

Acid-Base Titrations

- In acid-base titrations, because both the reactant and product solutions are usually colorless, a chemical is added that changes color when the solution undergoes large changes in acidity/alkalinity
  - the chemical is called an **indicator**

- From the stoichiometry, we can decide the concentration of unknown solution

Indicator: Color Change in Titration

The titration of 10.00 mL of HCl solution of unknown concentration requires 20 mL of 0.100 M NaOH solution to reach the end point. What is the concentration of the unknown HCl solution?

Titration

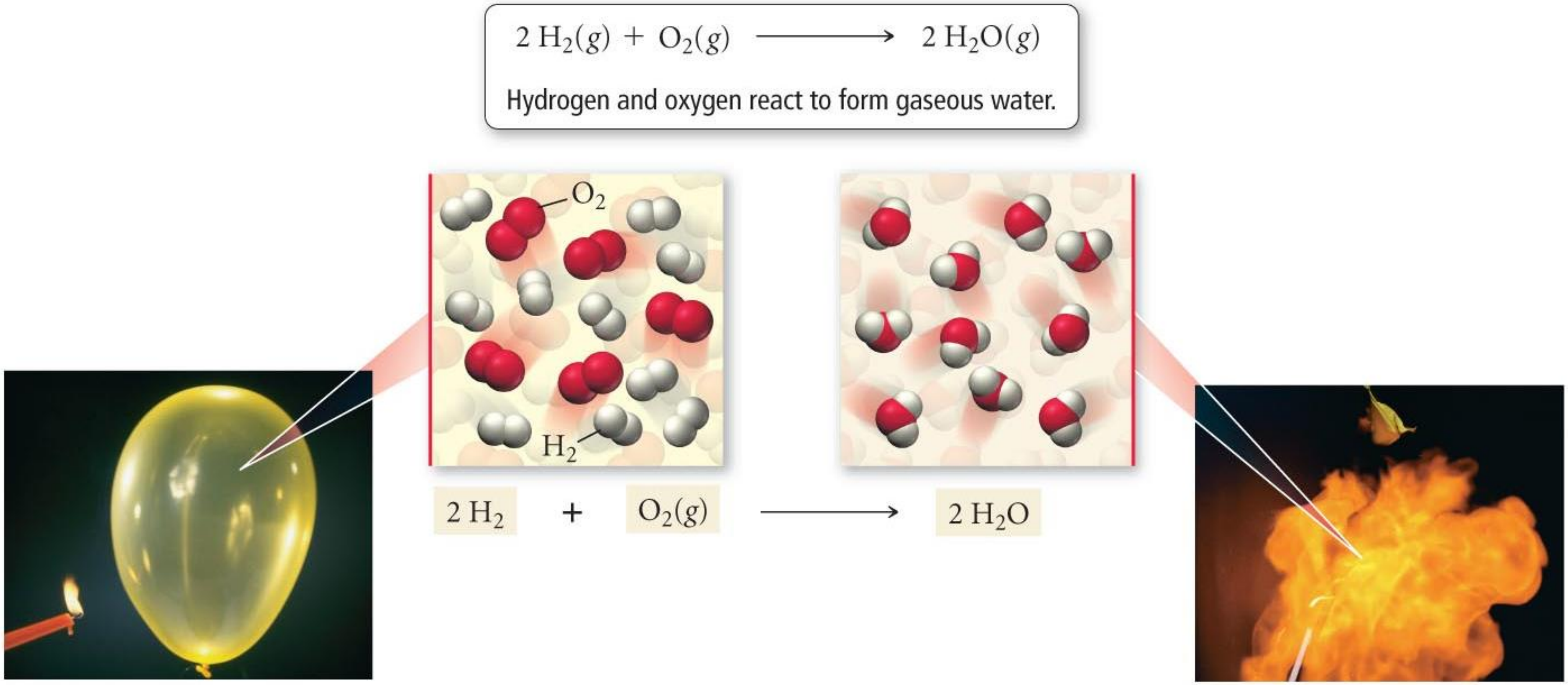
- 28.40mL of 0.150 M NaOH wad added to titrate 25.00 mL of HCH_3COO solution. What is the concentration (M) of CH_3COOH?

Oxidation-Reduction Reactions

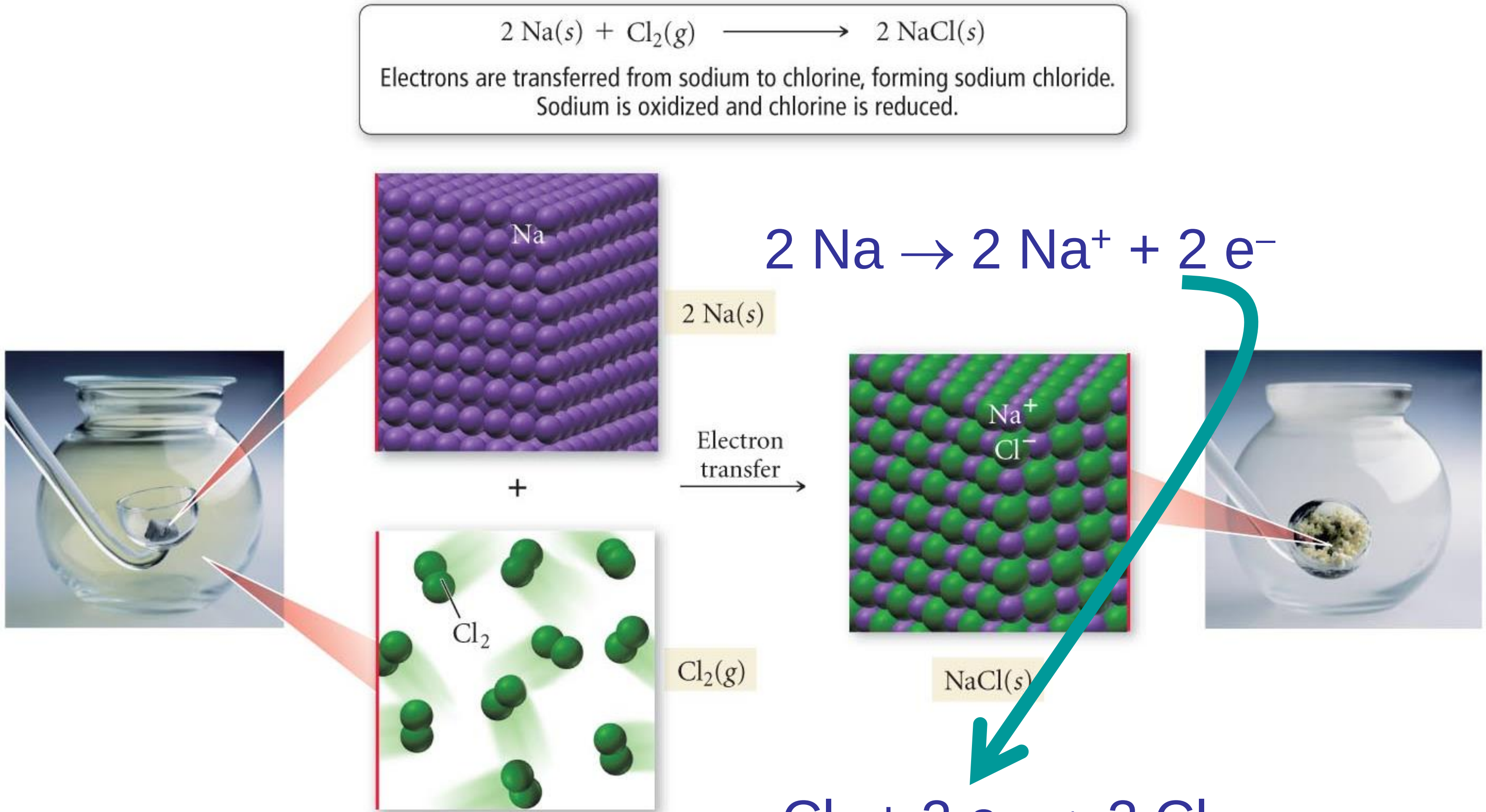
- involve transferring electrons from one atom to another
- also known as redox reactions
  - many involve the reaction of a substance with $O_2(g)$

$$4\ Fe(s) + 3\ O_2(g) \rightarrow 2\ Fe_2O_3(s)$$

Combustion as Redox
$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$



Redox without Combustion
$2\,Na(s) + Cl_2(g) \rightarrow 2\,NaCl(s)$



$2\,Na \rightarrow 2\,Na^+ + 2\,e^-$

$Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$

Oxidation and Reduction

- Reactions where electrons are transferred from one atom to another are redox reactions
- Atoms that lose electrons are being oxidized, atoms that gain electrons are being reduced

$2\ Na(s) + Cl_2(g) \rightarrow 2\ Na^+Cl^-(s)$

$Na \rightarrow Na^+ + 1\ e^-$ oxidation

$Cl_2 + 2\ e^- \rightarrow 2\ Cl^-$ reduction

- **oxidation state** can be used to determine the electron flow in the reaction
  - even though they look like them, **oxidation states are not ion charges**

Rules for Assigning Oxidation States

- Rules are in order of priority

1. free elements have an oxidation state = 0
   - Na = 0 and Cl_2 = 0 in 2 Na(*s*) + Cl_2(*g*)
2. monatomic ions have an oxidation state equal to their charge
   - Na = +1 and Cl = −1 in NaCl
3. (a) the sum of the oxidation states of all the atoms in a compound is 0
   - Na = +1 and Cl = −1 in NaCl, (+1) + (−1) = 0

Rules for Assigning Oxidation States

3. (b) the sum of the oxidation states of all the atoms in a polyatomic ion equals the charge on the ion
   - N = +5 and O = −2 in NO_3^-, (+5) + 3(−2) = −1
4. (a) Group I metals have an oxidation state of +1 in all their compounds
   - Na = +1 in NaCl
4. (b) Group II metals have an oxidation state of +2 in all their compounds
   - Mg = +2 in $MgCl_2$

Rules for Assigning Oxidation States

5. in their compounds, nonmetals have oxidation states according to the table below
   - nonmetals higher on the table take priority

Nonmetal	Oxidation State	Example
F	−1	CF_4
H	+1	CH_4
O	−2	CO_2
Group 7A	−1	CCl_4
Group 6A	−2	CS_2
Group 5A	−3	NH_3

Assign an oxidation state to each element in the following

- Br_2
- K^+
- LiF
- CO_2
- SO_4^{2-}
- Na_2O_2

Oxidation and Reduction
Another Definition

- Oxidation occurs when an atom's oxidation state increases during a reaction
- Reduction occurs when an atom's oxidation state decreases during a reaction

$$\underset{-4\ +1}{CH_4} + 2\ \underset{0}{O_2} \rightarrow \underset{+4\ -2}{CO_2} + 2\ \underset{+1\ -2}{H_2O}$$

oxidation

reduction

Oxidation–Reduction

- The reactant that reduces an element in another reactant is called the **reducing agent**
  - the reducing agent contains the element that is oxidized
- The reactant that oxidizes an element in another reactant is called the **oxidizing agent**
  - the oxidizing agent contains the element that is reduced

$$2\ Na(s) + Cl_2(g) \rightarrow 2\ Na^+Cl^-(s)$$

Na is oxidized, Cl is reduced

Na is the reducing agent, Cl_2 is the oxidizing agent

$$Sn^{4+} + Ca \rightarrow Sn^{2+} + Ca^{2+}$$

$$F_2 + S \rightarrow SF_4$$

Oxidation Number

- Ag
- Br_2
- K^+
- NO
- NO_2
- NO_3^-
- FeO_3
- $KMnO_4$

$$Fe + MnO_4^- + 4\,H^+ \rightarrow Fe^{3+} + MnO_2 + 2\,H_2O$$

Balancing Oxidation-Reduction Reactions

- *Law of conservation of mass*: the amount of each element present at the beginning of the reaction must be present at the end.
- *Conservation of charge*: electrons are not lost in a chemical reaction.
- The half-reactions for

$$Sn^{2+}(aq) + 2Fe^{3+}(aq) \rightarrow Sn^{4+}(aq) + 2Fe^{2+}(aq)$$

are

Oxidation: $Sn^{2+}(aq) \rightarrow Sn^{4+}(aq) + 2e^{-}$

Reduction: $2Fe^{3+}(aq) + 2e^{-} \rightarrow 2Fe^{2+}(aq)$

Exercise: Balance Half Reactions

a. $Sn^{2+}(aq) \rightarrow Sn^{4+}(aq)$

b. $TiO_2(s) \rightarrow Ti^{2+}(aq)$ (acidic condition)

c. $ClO_3^-(aq) \rightarrow Cl^-(aq)$ (acidic condition)

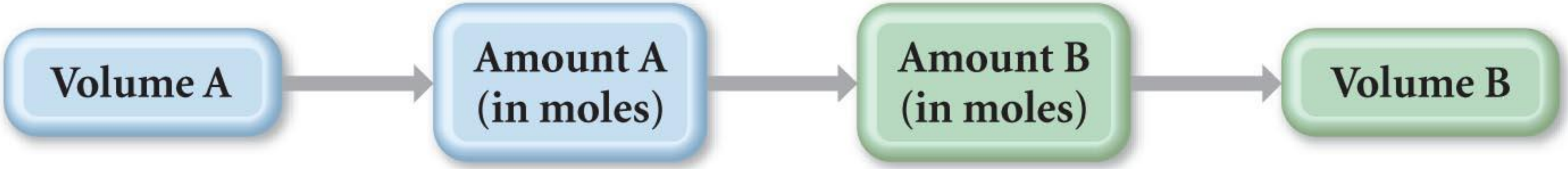
Sample Exercise (Acidic Condition)

a. $Cr_2O_7^{2-}(aq) + Cl^-(aq) \rightarrow Cr^{3+}(aq) + Cl_2(g)$

b. $Cu(s) + NO_3^-(aq) \rightarrow Cu^{2+}(aq) + NO_2(g)$

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



What volume of 0.150 M KCl is required to completely react with 0.150 L of 0.175 M $Pb(NO_3)_2$ in the reaction

$$2\ KCl(aq) + Pb(NO_3)_2(aq) \rightarrow PbCl_2(s) + 2\ KNO_3(aq)?$$

- 43.8 mL of 0.107 M HCl is needed to neutralize 37.6 mL of $Ba(OH)_2$ solution. What is the molarity of the base?

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

Homework

TBA