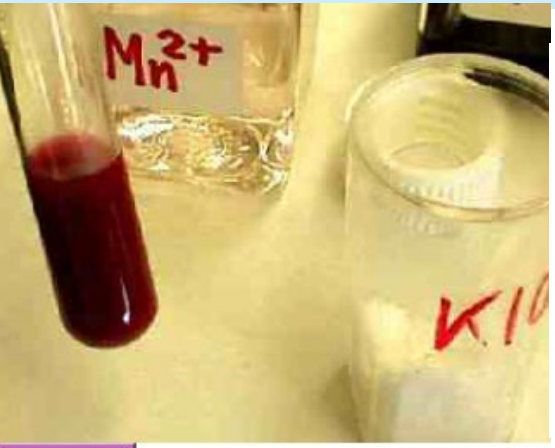
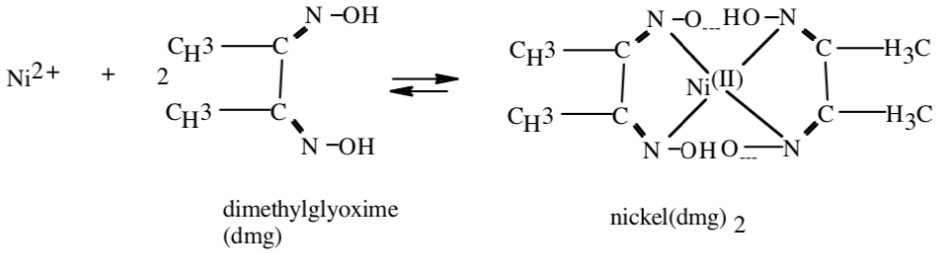
CHAPTER 3
CHEMICAL REACTIONS



$$Fe^{3+} + SCN^{-} \rightleftharpoons Fe(SCN)^{2+} \quad \text{(deep red)}$$



MnO_4^-

COOKING

$Fe_3[Fe(CN)_6]_2$

FIREWORKS

TYPES OF COMBUSTION REACTIONS

A reaction which generally involves the presence of oxygen and releases energy (exothermic).

- **Hydrocarbons and other organic compounds combine with excess oxygen to form carbon dioxide and water.**

Propanol ($CH_3CH_2CH_2OH$) is burned completely in air.

$$CH_3CH_2CH_2OH(l) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$$

- **Metals combine with oxygen to form metallic oxides.**

Calcium metal is heated strongly in the presence of oxygen.

$$Ca(s) + 2O_2(g) \rightarrow CaO(g)$$

- **Nonmetallic hydrides combine with oxygen to form water and nonmetal oxides.**

Gaseous diborane, B_2H_6, is burned in excess oxygen.

$$B_2H_6(g) + 3O_2(g) \rightarrow B_2O_3(s) + 3H_2O(g)$$

TYPES OF COMBUSTION Rx

LECTURE QUIZ

Q1: If nonmetallic sulfides combine with oxygen to form sulfur dioxide and nonmetal oxides, give the formula for the nonmetal oxide produced when Carbon disulfide vapor is burned in excess oxygen.

Write the balanced chemical equation.

Q2: In general, if sulfur is present then SO_2 is formed and if nitrogen is present, NO_2 is formed. Write a balanced chemical equation for the reaction of oxygen with ammonia(NH_3) in the presence of a catalyst, platinum.

$$NH_3(g) + O_2(g) \rightarrow NO_2(g) + H_2O(g)$$

SYNTHESIS or COMBINATION REACTIONS

- **A metal combines with a nonmetal to form a binary salt.**

Sodium metal is dropped into a container of chlorine gas.

$$2Na_{(s)} + Cl_{2(g)} \rightarrow 2NaCl_{(s)}$$

Lithium metal is dropped into a container of nitrogen gas.

$$6Li(s) + N_2(g) \rightarrow 2Li_3N(s)$$ **lithium azide**

- **Nonmetallic oxides and water form acids. (The nonmetal retains its oxidation number).**

Dinitrogen pentoxide is bubbled into water.

$$N_2O_5(g) + H_2O(l) \rightarrow 2\ HNO_3(aq)$$

CHAT QUESTION:

What gas must be bubbled into water to make nitrous acid?

$$HNO_2(aq) \text{ nitrous acid with } N^{+3} = N_2O_3(g)$$

SYNTHESIS or COMBINATION REACTIONS

- **Metallic oxides and nonmetallic oxides form salts.**

Solid calcium oxide is added to sulfur trioxide.

$$CaO(s) + SO_3(aq) \rightarrow CaSO_4(s)$$

LECTURE QUIZ

Propose an equation for the reaction between solid iron(II) oxide and carbon dioxide.

DECOMPOSITION REACTIONS

- **Metallic carbonates decompose into metallic oxides and carbon dioxide.**

A sample of magnesium carbonate is heated.

$$MgCO_3(s) \rightarrow MgO(s) + CO_2(g)$$

- **Metallic chlorates decompose into metallic chlorides and oxygen.**

A sample of magnesium chlorate is heated.

$$Mg(ClO_3)_2(s) \rightarrow MgCl_2(s) + O_2(g)$$

Ammonium carbonate decomposes into ammonia, water, and carbon dioxide.

$$(NH_4)_2CO_{3(s)} \rightarrow CO_2(g) + H_2O(g) + 2NH_3(g)$$

DECOMPOSITION

Some common reactions should be **memorized.**

- **Sulfurous acid (H_2SO_3) decomposes into sulfur dioxide and water.**

$$H_2SO_3\ (aq) \rightarrow SO_2\ (g) + H_2O(l)$$

- **Carbonic acid (H_2CO_3) decomposes into carbon dioxide and water.**

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

- **Hydrogen peroxide decomposes into water and oxygen.**

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

- **Ammonium hydroxide decomposes into ammonia and water.**

$$NH_4OH\ (aq) \rightarrow NH_3\ (g) + H_2O(l)$$

SINGLE REPLACEMENT/DISPLACEMENT

Use a standard reduction potential table or the Activity Series

For metal displacements, the metal with the more POSITIVE reduction potential (i.e. *less* active) will be replaced; for halogens, the displacement order follows the periodic table, fluorine being the *most* reactive. Consider the following example:

Magnesium metal is added to an aqueous solution of nickel sulfate.

$$Mg(s) + NiSO_4\,(aq) \rightarrow Ni(s) + MgSO_4\,(aq)$$

Aluminum turnings are added to a solution of iron(III) chloride.

$$Al(s) + FeCl_3\,(aq) \rightarrow Fe(s) + AlCl_3\,(aq)$$

- **Active nonmetals replace less active nonmetals from their compounds in aqueous solution.**

Chlorine gas is bubbled into a solution of potassium iodide.

$$KI(aq) + Cl_2\,(g) \rightarrow KCl(aq) + I_2\,(g)$$

In the previous single replacement reaction examples, the reaction was written as molecular equations. Although this equation shows the reactants and products of the reaction, it does not give a very clear picture of what truly occurs in solution. In fact, such an aqueous solution actually contains individual IONS, not molecules, in solution. Ions such as these that do NOT participate directly in the reaction are called spectator ions. *Net Ionic equations* include only those solution components directly involved in the reaction. Chemists usually write the net ionic equation for a reaction in solution because it gives the actual forms of the reactants and products and only includes the species that undergo a change. Write the following single displacement reactions as net ionic equations.

- **Active metals replace hydrogen in acids.**

Lithium is added to hydrochloric acid (HCl).

$$Li(s) + 2HCl(aq) \rightarrow LiCl(aq) + H_2(g)$$

- **Active metals replace hydrogen in water.**

Sodium is added to water.

$$Na(s) + H_2O(l) \rightarrow NaOH(aq) + H_2(g)$$

ACTIVITY SERIES OF SOME SELECTED METALS

A brief activity series of selected metals, hydrogen and halogens are shown below. The series are listed in descending order of chemical reactivity, with the most active metals and halogens at the top (the elements most likely to undergo oxidation). Any metal on the list will replace the ions of those metals (to undergo reduction) that appear anywhere underneath it on the list.

More reactive

METALS	HALOGENS
K (most oxidized	F_2
Ca	Cl_2
Na	Br_2
Mg	I_2
Al	
Zn	
Fe	
Ni	
Sn	
Pb	
H	
Cu	
Ag	
Hg	
Au(least oxidized)	

Least reactive

Oxidation refers to the loss of electrons and reduction refers to the gain of electrons

DOUBLE REPLACEMENT (or metathesis)

All double replacement reactions must have a driving force to allow for it to go to completion. This driving force is the removal of at least one pair of ions from solution, which can occur in one of two ways:

1. **formation of a precipitate***
2. **formation of a gas**

*** formation of a precipitate – apply the solubility rules**

Solubility Rules: ***Please note that "soluble" refers to the ability to dissolve in a solvent, while "insoluble" refers to a solid or precipitate. The Solubility Rules are summarized on the next slide.***

NEGATIVE ION	POSITIVE ION	SOLUBILITY
Chloride (Cl^-), Bromide (Br^-), Iodide (I^-)	Ag^+, Pb^{2+}, Hg_2^{2+}, Cu^+	Insoluble
Phosphate (PO_4^{3-}) Carbonate (CO_3^{2-}), Sulfite (SO_3^{2-}), Hydroxide (OH^-),	All positive ions EXCEPT alkali ions and NH_4^+	Insoluble
Sulfate (SO_4^{2-})	Ca^{2+}, Sr^{2+}, Ba^{2+}, Ra^{2+}, Ag^+, Pb^{2+}	Insoluble
Sulfide (S^{2-})	All positive ions EXCEPT alkali ions, alkaline earth ions, NH_4^+	Insoluble

*** All nitrates, perchlorates, and most acetates are soluble.***

Example: A solution of potassium chloride is mixed with a solution of silver nitrate.

$K^+(aq) + Cl^-(aq) + Ag^+(aq) + NO_3^-(aq) \rightarrow AgCl(s) + K^+(aq) + NO_3^-(aq)$

Formation of a Gas

Common gases formed in metathesis reaction are listed below:

H_2S Any sulfide (salt of S^{2-}) plus any acid form $H_2S(g)$ and a salt.

Solid iron(II) sulfide is mixed with hydrochloric acid.

$$FeS(s) + 2HCl(aq) \rightarrow FeCl_2(aq) + H_2S(g)$$

$$FeS(s) + 2H^+(aq) \rightarrow Fe^{2+}(aq) + H_2S(g) \quad \textit{net ionic}$$

CO_2 Any carbonate (salt of CO_3^{2-}) plus any acid form $CO_2(g)$, H_2O, and a salt.

Potassium carbonate is reacted with nitric acid.

$$K_2CO_3(aq) + 2HNO_3(aq) \rightarrow H_2CO_3(aq) + 2KNO_3(aq)$$

$$K_2CO_3(aq) + 2HNO_3(aq) \rightarrow H_2O(l) + CO_2(g) + 2KNO_3(aq)$$

$$K^+CO_3^{2-}(aq) + 2H^+NO_3^-(aq) \rightarrow H_2O(l) + CO_2(g) + 2K^+NO_3^-(aq)$$

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

Formation of a Gas

Common gases formed in metathesis reaction are listed below:

SO_2 Any sulfite (salt of SO_3^{2-}) plus any acid form $SO_2(g)$, H_2O, and a salt.

Sodium sulfite is combined with hydrochloric acid.

$$Na_2SO_3(s) + 2HCl(aq) \rightarrow 2NaCl(aq) + SO_2(g) + H_2O(l)$$

$$Na_2SO_3(s) + 2H^+(aq) \rightarrow Na^+(aq) + SO_2(g) + H_2O(l) \quad \textit{net ionic}$$

SO_2 Any sulfite (salt of SO_3^{2-}) plus any acid form $SO_2(g)$, H_2O, and a salt.

LECTURE QUIZ

Potassium sulfite is combined with nitric acid.

ACID/BASE REACTIONS:

Acid + Base → Salt + Water

One mole of hydrogen ions will react with one mole of hydroxide ions to produce one mole of water. Diprotic (acids with two ionizable hydrogens) and triprotic (acids with three ionizable hydrogens) acids will also be encountered.

A. Arrhenius Acid – a compound that releases H^+ (proton)/ H_3O^+ (hydronium ion) in water.

An aqueous nitric acid solution: $HNO_{3(aq)} \xrightarrow{H_2O(l)} H_3O^+_{(aq)} + NO_3^-{}_{(aq)}$

B. Arrhenius Base – a compound that produces OH^- in water.

Potassium hydroxide pellets are dissolved in water:

$$KOH_{(s)} \xrightarrow{H_2O(l)} K^+ + OH^-$$

C. Brønsted-Lowry Acid – proton donor.

Nitric acid reacts with potassium hydroxide.

$$HNO_{3(aq)} + KOH(s) \rightarrow H_2O(l) + KNO_{3(aq)}$$

$$H^+NO_3^-{}_{(aq)} + KOH(s) \rightarrow H_2O(l) + K^+_{(aq)} + NO_3^-{}_{(aq)}$$

net ionic

ACID/BASE REACTIONS:

Acid + Base → Salt + Water

D. Brønsted-Lowry Base – proton acceptor

Sulfuric acid reacts with barium hydroxide.

$$H_2SO_{4(aq)} + Ba(OH)_{2(aq)} \rightarrow H_2O_{(l)} + BaSO_{4(s)}$$

E. Strong Acid – fully dissociates in solution, releasing H^+ ion(s)

Hydrobromic acid reacts with calcium hydroxide.

$$HBr_{(aq)} + Ca(OH)_{2(aq)} \rightarrow H_2O_{(l)} + CaBr_{2(aq)}$$

F. Weak Acid – does NOT fully dissociate in solution

Acetic acid reacts with potassium hydroxide.

$$HC_2H_3O_{2(aq)} + KOH_{(aq)} \leftrightarrow KC_2H_3O_{2(aq)} + H_2O_{(l)}$$

LECTURE QUIZ

G. Strong Base – completely protonated in solution

Hydrochloric acid reacts with sodium hydroxide.

H. Weak Base – NOT completely protonated in solution

Nitric acid reacts with ammonium hydroxide.

ACID/BASE REACTIONS:

STRONG	vs	WEAK
_ completely ionized		_ partially ionized
_ strong electrolyte		_ weak electrolyte
_ ionic/very polar bonds		_ some covalent bonds

Strong Acids:

$HClO_4$

H_2SO_4

HI

HBr

HCl

HNO_3

Strong Bases:

LiOH

NaOH

KOH

$Ca(OH)_2$

$Sr(OH)_2$

$Ba(OH)_2$

OXIDATION/REDUCTION

(commonly abbreviated REDOX)

The last set of reactions that we will cover involve the transfer of electrons between reactants. Such reactions are called oxidation-reduction reactions, or REDOX.

Leo Ger

When an atom, ion, or molecule has become more positively charged, we say that is has been oxidized. Loss of electrons by a substance is called oxidation. For example, when solid calcium loses two electrons, it is oxidized to Ca^{+2} in solution. This can be represented by the following half-reaction:

$$Ca \rightarrow Ca^{+2} + 2e^-$$

Oxidation = loss of e-

In contrast, when an atom, ion, or molecule has become more negatively charged, we say that it is reduced. Gain of electrons by a substance is called reduction. For example, when fluorine gains electrons, it is converted to the fluoride ion as shown in the following half-reaction:

Reducton = gain of e-

$$F_2 + 2e^- \rightarrow 2F^-$$

Overall, when one reactant loses electrons, another reactant must gain them. As such, the oxidation of one substance is ALWAYS accompanied by the reduction of another as electrons are transferred between them.

ELECTRON TRANSFER

Reduction-Oxidation Rx (REDOX)

A reaction in which electrons are transferred from one species to another.

- **oxidation means the loss of electrons**
- **reduction means the gain of electrons**

- **electrolyte is a substance dissolved in water which produces an electrically conducting solution**
- **nonelectrolyte is a substance dissolved in water which does not conduct electricity.**

Combustion reactions are redox reactions

$$CH_4(g) + \text{element} \rightarrow 2H_2O(g) + CO_2(g)$$

Rusting is a redox reaction:

$$\text{element} + \text{element} \rightarrow 2Fe_2O_3(s)$$

Electrochemistry involves redox reactions:

$$\text{element} + 2AgNO_3(aq) \rightarrow \text{element} + Cu(NO_3)_2(aq)$$

CHEMICAL EQUILIBRIA

$$H_2CO_3 \Leftrightarrow CO_2 + H_2O$$

$$CaCO_3 \Leftrightarrow CaO + CO_2$$

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

$$NH_3 + H_2O \Leftrightarrow NH_4OH$$

SELF-STUDY QUIZ FOR CHEMICAL REACTIONS

Predict and balance the following reactions, making sure to include the phases of all reactants and products where possible. Write NR if No Reaction occurs.

1. A piece of sodium is added to a container of iodine vapor.

2. An aluminum strip is immersed in a solution of silver nitrate.

3. Cobalt(II) chloride is combined with silver nitrate.

4. Potassium sulfide is reacted with nitric acid.

5. Iodine crystals are added to a solution of sodium chloride.

6. Zinc acetate and cesium hydroxide are mixed.

7. Butanol (C_4H_9OH) is burned completely in air.

8. A solution of iron(III) chloride is poured over a piece of platinum wire.