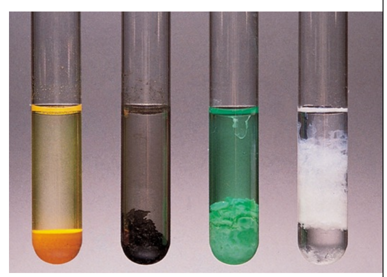
Reactions in Aqueous Solution

Chapter 4



A ***solution*** is a homogenous mixture of 2 or more substances

The ***solute*** is(are) the substance(s) present in the smaller amount(s)

The ***solvent*** is the substance present in the larger amount

Solution	Solvent	Solute
Soft drink(*l*)	H_2O	Sugar, CO_2
Air(*g*)	N_2	O_2, Ar, CH_4
Soft Solder(*s*)	Pb	Sn

aqueous solutions of $KMnO_4$

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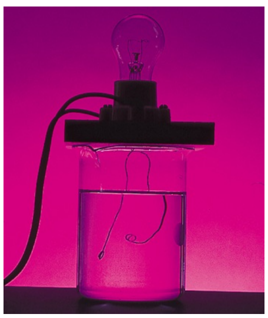
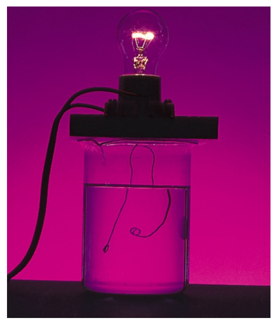
An ***electrolyte*** is a substance that, when dissolved in water, results in a solution that can conduct electricity.

A ***nonelectrolyte*** is a substance that, when dissolved, results in a solution that does not conduct electricity.



nonelectrolyte



weak electrolyte

strong electrolyte

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Conduct electricity in solution?

Cations (+) and Anions (-)

Strong Electrolyte – 100% dissociation

$$NaCl(s) \xrightarrow{H_2O} Na^+(aq) + Cl^-(aq)$$

Weak Electrolyte – not completely dissociated

$$CH_3COOH \rightleftharpoons CH_3COO^-(aq) + H^+(aq)$$

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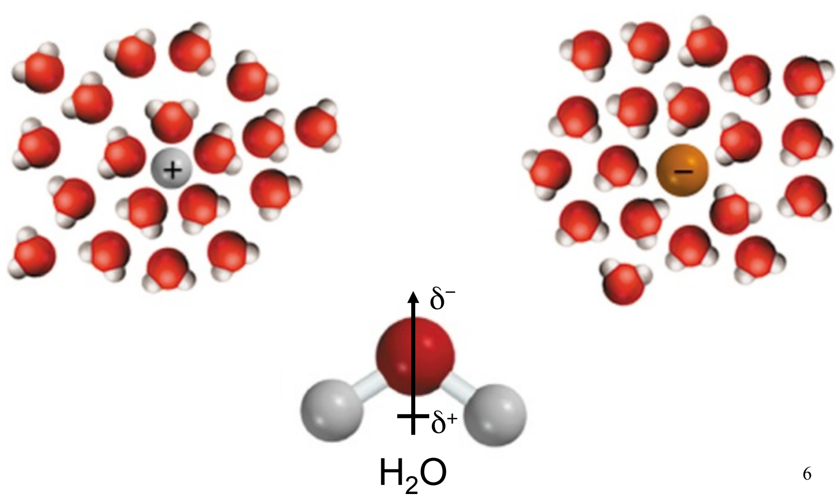
Ionization of acetic acid

$$CH_3COOH \rightleftharpoons CH_3COO^-(aq) + H^+(aq)$$

$\rightleftharpoons$ A ***reversible*** reaction. The reaction can occur in both directions.

Acetic acid is a ***weak electrolyte*** because its ionization in water is incomplete.

Hydration is the process in which an ion is surrounded by water molecules arranged in a specific manner.



Nonelectrolyte does not conduct electricity?

No cations (+) and anions (-) in solution

$$C_6H_{12}O_6(s) \xrightarrow{H_2O} C_6H_{12}O_6(aq)$$

TABLE 4.1 Classification of Solutes in Aqueous Solution

Strong Electrolyte	Weak Electrolyte	Nonelectrolyte
HCl	CH_3COOH	$(NH_2)_2CO$ (urea)
HNO_3	HF	CH_3OH (methanol)
$HClO_4$	HNO_2	C_2H_5OH (ethanol)
H_2SO_4*	NH_3	$C_6H_{12}O_6$ (glucose)
NaOH	H_2O†	$C_{12}H_{22}O_{11}$ (sucrose)
$Ba(OH)_2$		
Ionic compounds		

*H_2SO_4 has two ionizable H^+ ions.
†Pure water is an extremely weak electrolyte.

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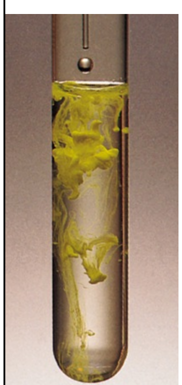
Precipitation Reactions

Precipitate – insoluble solid that separates from solution



PbI$_2$

precipitate ↓

$$Pb(NO_3)_2(aq) + 2NaI(aq) \longrightarrow PbI_2(s) + 2NaNO_3(aq)$$

molecular equation

$$Pb^{2+} + \cancel{2NO_3^-} + \cancel{2Na^+} + 2I^- \longrightarrow PbI_2(s) + \cancel{2Na^+} + \cancel{2NO_3^-}$$

ionic equation

$$Pb^{2+} + 2I^- \longrightarrow PbI_2(s)$$

net ionic equation

Na^+ and NO_3^- are ***spectator*** ions

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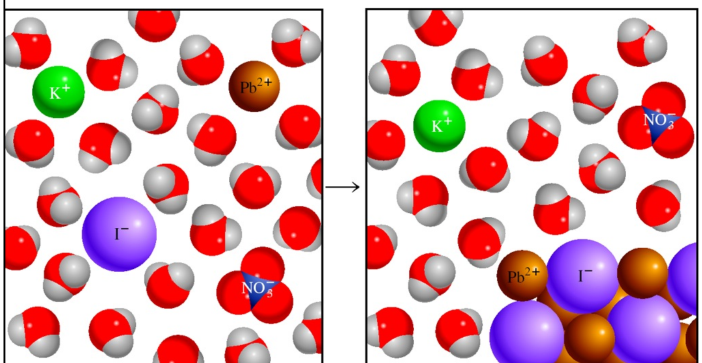
Precipitation of Lead Iodide



$Pb^{2+} + 2I^{-} \longrightarrow PbI_2(s)$

PbI_2

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Solubility is the maximum amount of solute that will dissolve in a given quantity of solvent at a specific temperature.

TABLE 4.2 Solubility Rules for Common Ionic Compounds in Water at 25°C

Soluble Compounds	Insoluble Exceptions
Compounds containing alkali metal ions (Li^+, Na^+, K^+, Rb^+, Cs^+) and the ammonium ion (NH_4^+)	
Nitrates (NO_3^-), bicarbonates (HCO_3^-), and chlorates (ClO_3^-)	
Halides (Cl^-, Br^-, I^-)	Halides of Ag^+, Hg_2^{2+}, and Pb^{2+}
Sulfates (SO_4^{2-})	Sulfates of Ag^+, Ca^{2+}, Sr^{2+}, Ba^{2+}, Hg_2^{2+}, and Pb^{2+}
Insoluble Compounds	**Soluble Exceptions**
Carbonates (CO_3^{2-}), phosphates (PO_4^{3-}), chromates (CrO_4^{2-}), sulfides (S^{2-})	Compounds containing alkali metal ions and the ammonium ion
Hydroxides (OH^-)	Compounds containing alkali metal ions and the Ba^{2+} ion

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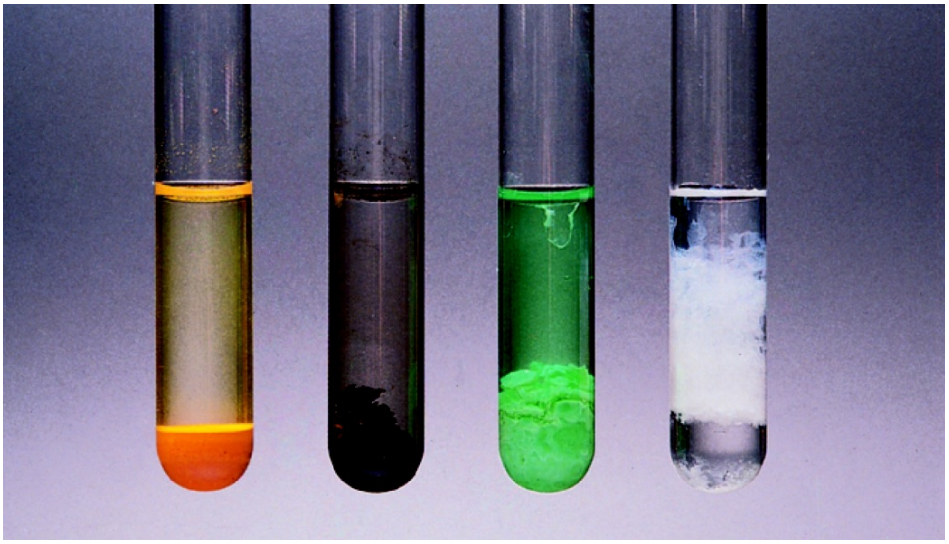
Examples of Insoluble Compounds



CdS PbS $Ni(OH)_2$ $Al(OH)_3$

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Writing Net Ionic Equations

1. Write the balanced molecular equation.
2. Write the ionic equation showing the strong electrolytes completely dissociated into cations and anions.
3. Cancel the spectator ions on both sides of the ionic equation
4. Check that charges and number of atoms are balanced in the net ionic equation

Write the net ionic equation for the reaction of silver nitrate with sodium chloride.

$$AgNO_3(aq) + NaCl(aq) \longrightarrow AgCl(s) + NaNO_3(aq)$$

$$Ag^+ + \cancel{NO_3^-} + \cancel{Na^+} + Cl^- \longrightarrow AgCl(s) + \cancel{Na^+} + \cancel{NO_3^-}$$

$$Ag^+ + Cl^- \longrightarrow AgCl(s)$$

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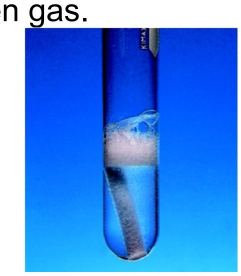
Properties of Acids

Have a sour taste. Vinegar owes its taste to acetic acid. Citrus fruits contain citric acid.

Cause color changes in plant dyes.

React with certain metals to produce hydrogen gas.

$$2HCl(aq) + Mg(s) \longrightarrow MgCl_2(aq) + H_2(g)$$



React with carbonates and bicarbonates to produce carbon dioxide gas

$$2HCl(aq) + CaCO_3(s) \longrightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

Aqueous acid solutions conduct electricity.

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Properties of Bases

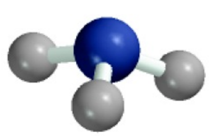
Have a bitter taste.

Feel slippery. Many soaps contain bases.

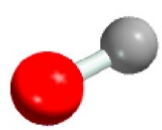
Cause color changes in plant dyes.

Aqueous base solutions conduct electricity.

Examples:



NH_3



OH^-

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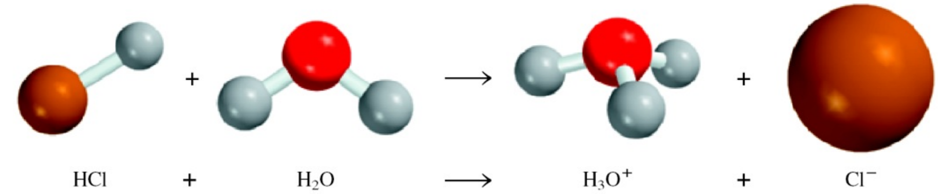
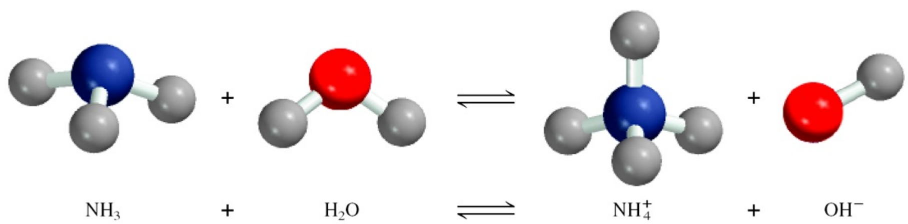
Arrhenius acid is a substance that produces H^+ (H_3O^+) in water



Arrhenius base is a substance that produces OH^- in water



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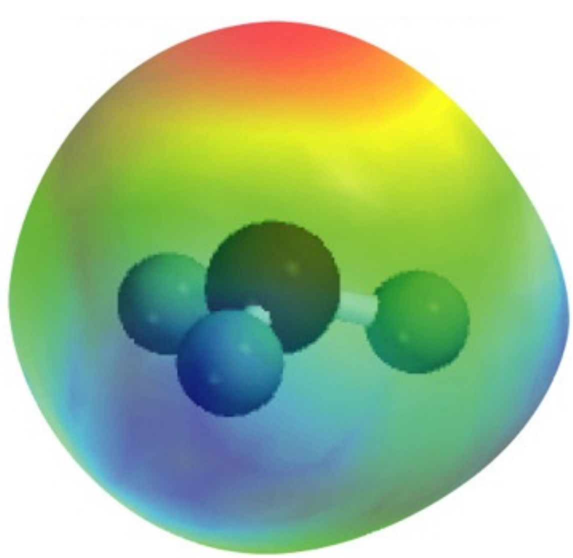
Hydronium ion, hydrated proton, H_3O^+



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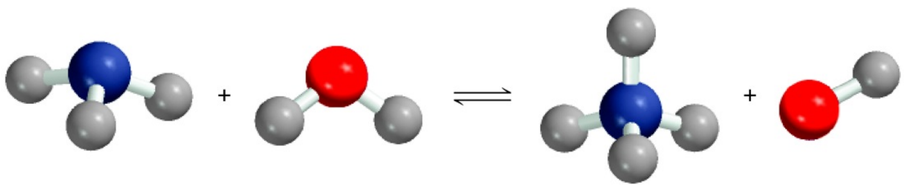
A ***Brønsted acid*** is a proton donor
A ***Brønsted base*** is a proton acceptor



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

base acid acid base

A Brønsted acid must contain at least one ionizable proton!

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Monoprotic acids

$HCl \longrightarrow H^+ + Cl^-$	Strong electrolyte, strong acid
$HNO_3 \longrightarrow H^+ + NO_3^-$	Strong electrolyte, strong acid
$CH_3COOH \rightleftharpoons H^+ + CH_3COO^-$	Weak electrolyte, weak acid

Diprotic acids

$H_2SO_4 \longrightarrow H^+ + HSO_4^-$	Strong electrolyte, strong acid
$HSO_4^- \rightleftharpoons H^+ + SO_4^{2-}$	Weak electrolyte, weak acid

Triprotic acids

$H_3PO_4 \rightleftharpoons H^+ + H_2PO_4^-$	Weak electrolyte, weak acid
$H_2PO_4^- \rightleftharpoons H^+ + HPO_4^{2-}$	Weak electrolyte, weak acid
$HPO_4^{2-} \rightleftharpoons H^+ + PO_4^{3-}$	Weak electrolyte, weak acid

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Identify each of the following species as a Brønsted acid, base, or both. (a) HI, (b) CH_3COO^-, (c) $H_2PO_4^-$

$HI\ (aq) \longrightarrow H^+\ (aq) + I^-\ (aq)$ Brønsted acid

$CH_3COO^-\ (aq) + H^+\ (aq) \rightleftharpoons CH_3COOH\ (aq)$ Brønsted base

$H_2PO_4^-\ (aq) \rightleftharpoons H^+\ (aq) + HPO_4^{2-}\ (aq)$ Brønsted acid

$H_2PO_4^-\ (aq) + H^+\ (aq) \rightleftharpoons H_3PO_4\ (aq)$ Brønsted base

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Neutralization Reaction

acid + base $\longrightarrow$ salt + water

$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + H_2O$

$H^+ + \cancel{Cl^-} + \cancel{Na^+} + OH^- \longrightarrow \cancel{Na^+} + \cancel{Cl^-} + H_2O$

$H^+ + OH^- \longrightarrow H_2O$

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Neutralization Reaction Involving a Weak Electrolyte

weak acid + base ⟶ salt + water

$HCN(aq) + NaOH(aq) \longrightarrow NaCN(aq) + H_2O$

$HCN + \cancel{Na^+} + OH^- \longrightarrow \cancel{Na^+} + CN^- + H_2O$

$HCN + OH^- \longrightarrow CN^- + H_2O$

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Neutralization Reaction Producing a Gas

acid + base ⟶ salt + water + CO_2

$2HCl(aq) + Na_2CO_3(aq) \longrightarrow 2NaCl(aq) + H_2O + CO_2$

$2H^+ + \cancel{2Cl^-} + \cancel{2Na^+} + CO_3^{2-} \longrightarrow \cancel{2Na^+} + \cancel{2Cl^-} + H_2O + CO_2$

$2H^+ + CO_3^{2-} \longrightarrow H_2O + CO_2$

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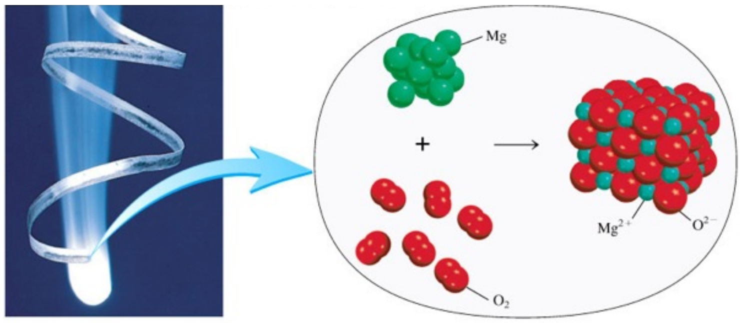
Oxidation-Reduction Reactions

(electron transfer reactions)



$2Mg \longrightarrow 2Mg^{2+} + 4e^-$ ***Oxidation*** half-reaction (lose e^-)

$O_2 + 4e^- \longrightarrow 2O^{2-}$ ***Reduction*** half-reaction (gain e^-)

$$2Mg + O_2 + \cancel{4e^-} \longrightarrow 2Mg^{2+} + 2O^{2-} + \cancel{4e^-}$$

$$2Mg + O_2 \longrightarrow 2MgO$$

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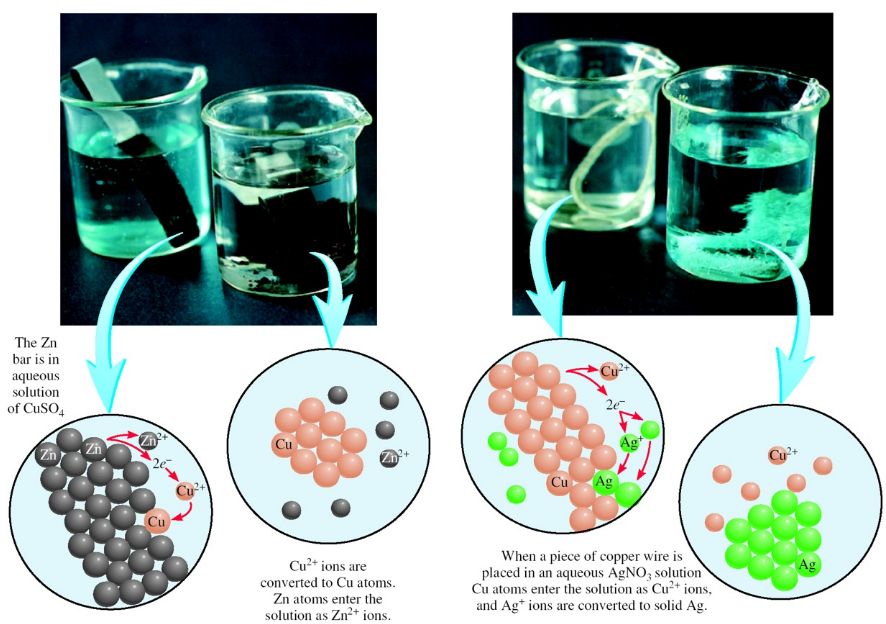

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$$Zn(s) + CuSO_4(aq) \longrightarrow ZnSO_4(aq) + Cu(s)$$

$Zn \longrightarrow Zn^{2+} + 2e^-$ Zn is oxidized Zn is the ***reducing agent***

$Cu^{2+} + 2e^- \longrightarrow Cu$ Cu^{2+} is reduced Cu^{2+} is the ***oxidizing agent***

Copper wire reacts with silver nitrate to form silver metal.
What is the oxidizing agent in the reaction?

$$Cu(s) + 2AgNO_3(aq) \longrightarrow Cu(NO_3)_2(aq) + 2Ag(s)$$

$Cu \longrightarrow Cu^{2+} + 2e^-$

$Ag^+ + 1e^- \longrightarrow Ag$ Ag^+ is reduced Ag^+ is the oxidizing agent

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Oxidation number

The charge the atom would have in a molecule (or an ionic compound) if electrons were completely transferred.

1. Free elements (uncombined state) have an oxidation number of zero.

   $Na, Be, K, Pb, H_2, O_2, P_4 = 0$

2. In monatomic ions, the oxidation number is equal to the charge on the ion.

   $Li^+, Li = +1; Fe^{3+}, Fe = +3; O^{2-}, O = -2$

3. The oxidation number of oxygen is **usually** –2. In H_2O_2 and O_2^{2-} it is –1.

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4.4

4. The oxidation number of hydrogen is +1 *except* when it is bonded to metals in binary compounds. In these cases, its oxidation number is –1.
5. Group IA metals are +1, IIA metals are +2 and fluorine is always –1.
6. The sum of the oxidation numbers of all the atoms in a molecule or ion is equal to the charge on the molecule or ion.
7. Oxidation numbers do not have to be integers. Oxidation number of oxygen in the superoxide ion, O_2^-, is –½.

What are the oxidation numbers of all the elements in HCO_3^- ?

HCO_3^-

O = –2 H = +1

3x(–2) + 1 + ? = –1

C = +4

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The Oxidation Numbers of Elements in their Compounds

1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B
1 H +1 –1									
3 Li +1	4 Be +2								
11 Na +1	12 Mg +2								
19 K +1	20 Ca +2	21 Sc +3	22 Ti +4 +3 +2	23 V +5 +4 +3 +2	24 Cr +6 +5 +4 +3 +2	25 Mn +7 +6 +4 +3 +2	26 Fe +3 +2	27 Co +3 +2	28 Ni +2
37 Rb +1	38 Sr +2	39 Y +3	40 Zr +4	41 Nb +5 +4	42 Mo +6 +4 +3	43 Tc +7 +6 +4	44 Ru +8 +6 +4 +3	45 Rh +4 +3 +2	46 Pd +4 +2
55 Cs +1	56 Ba +2	57 La +3	72 Hf +4	73 Ta +5	74 W +6 +4	75 Re +7 +6 +4	76 Os +8 +4	77 Ir +4 +3	78 Pt +4 +2

11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
							2 He
		5 B +3	6 C +4 +2 –4	7 N +5 +4 +3 +2 +1 –3	8 O +2 –½ –1 –2	9 F –1	10 Ne
		13 Al +3	14 Si +4 –4	15 P +5 +3 –3	16 S +6 +4 +2 –2	17 Cl +7 +6 +5 +4 +3 +1 –1	18 Ar
29 Cu +2 +1	30 Zn +2	31 Ga +3	32 Ge +4 –4	33 As +5 +3 –3	34 Se +6 +4 –2	35 Br +5 +3 +1 –1	36 Kr +4 +2
47 Ag +1	48 Cd +2	49 In +3	50 Sn +4 +2	51 Sb +5 +3 –3	52 Te +6 +4 –2	53 I +7 +5 +1 –1	54 Xe +6 +4 +2
79 Au +3 +1	80 Hg +2 +1	81 Tl +3 +1	82 Pb +4 +2	83 Bi +5 +3	84 Po +2	85 At –1	86 Rn

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What are the oxidation numbers of all the elements in each of these compounds?

$NaIO_3$ IF_7 $K_2Cr_2O_7$

$NaIO_3$

Na = +1 O = -2

3x(-2) + 1 + ? = 0

I = +5

IF_7

F = -1

7x(-1) + ? = 0

I = +7

$K_2Cr_2O_7$

O = -2 K = +1

7x(-2) + 2x(+1) + 2x(?) = 0

Cr = +6

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Types of Oxidation-Reduction Reactions

Combination Reaction

$$A + B \longrightarrow C$$

$$\overset{0}{3Mg} + \overset{0}{N_2} \longrightarrow \overset{+2\ -3}{MgN_2}$$

Decomposition Reaction

$$C \longrightarrow A + B$$

$$\overset{+1\ +5\ -2}{2KClO_3} \longrightarrow \overset{+1\ -1}{2KCl} + \overset{0}{3O_2}$$

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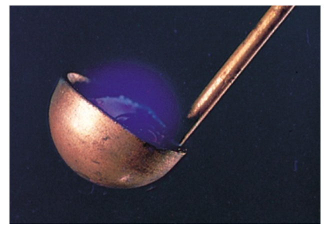
Types of Oxidation-Reduction Reactions

Combustion Reaction

$$A + O_2 \longrightarrow B$$



$$\overset{0}{S} + \overset{0}{O_2} \longrightarrow \overset{+4}{S}\overset{-2}{O_2}$$

$$2\overset{0}{Mg} + \overset{0}{O_2} \longrightarrow 2\overset{+2}{Mg}\overset{-2}{O}$$

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Types of Oxidation-Reduction Reactions

Displacement Reaction

$$A + BC \longrightarrow AC + B$$

$\overset{0}{Sr} + 2\overset{+1}{H_2}O \longrightarrow \overset{+2}{Sr}(OH)_2 + \overset{0}{H_2}$ Hydrogen Displacement

$\overset{+4}{Ti}Cl_4 + 2\overset{0}{Mg} \longrightarrow \overset{0}{Ti} + 2\overset{+2}{Mg}Cl_2$ Metal Displacement

$\overset{0}{Cl_2} + 2K\overset{-1}{Br} \longrightarrow 2K\overset{-1}{Cl} + \overset{0}{Br_2}$ Halogen Displacement

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The Activity Series for Metals

Reducing strength increases ↑

$Li \rightarrow Li^+ + e^-$	React with cold water to produce H_2
$K \rightarrow K^+ + e^-$	
$Ba \rightarrow Ba^{2+} + 2e^-$	
$Ca \rightarrow Ca^{2+} + 2e^-$	
$Na \rightarrow Na^+ + e^-$	
$Mg \rightarrow Mg^{2+} + 2e^-$	React with steam to produce H_2
$Al \rightarrow Al^{3+} + 3e^-$	
$Zn \rightarrow Zn^{2+} + 2e^-$	
$Cr \rightarrow Cr^{3+} + 3e^-$	
$Fe \rightarrow Fe^{2+} + 2e^-$	
$Cd \rightarrow Cd^{2+} + 2e^-$	
$Co \rightarrow Co^{2+} + 2e^-$	React with acids to produce H_2
$Ni \rightarrow Ni^{2+} + 2e^-$	
$Sn \rightarrow Sn^{2+} + 2e^-$	
$Pb \rightarrow Pb^{2+} + 2e^-$	
$H_2 \rightarrow 2H^+ + 2e^-$	
$Cu \rightarrow Cu^{2+} + 2e^-$	Do not react with water or acids to produce H_2
$Ag \rightarrow Ag^+ + e^-$	
$Hg \rightarrow Hg^{2+} + 2e^-$	
$Pt \rightarrow Pt^{2+} + 2e^-$	
$Au \rightarrow Au^{3+} + 3e^-$	

Hydrogen Displacement Reaction

$$M + BC \longrightarrow MC + B$$

M is metal

BC is acid or H_2O

B is H_2

$$Ca + 2H_2O \longrightarrow Ca(OH)_2 + H_2$$

~~$Pb + 2H_2O \longrightarrow Pb(OH)_2 + H_2$~~

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The Activity Series for Halogens

$$F_2 > Cl_2 > Br_2 > I_2$$

Halogen Displacement Reaction

$$\overset{0}{Cl_2} + 2K\overset{-1}{Br} \longrightarrow 2K\overset{-1}{Cl} + \overset{0}{Br_2}$$

~~$I_2 + 2KBr \longrightarrow 2KI + Br_2$~~

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Classify each of the following reactions.

$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3$ Precipitation

$NH_3 + H^+ \longrightarrow NH_4^+$ Acid-Base

$Zn + 2HCl \longrightarrow ZnCl_2 + H_2$ Redox (H_2 Displacement)

$Ca + F_2 \longrightarrow CaF_2$ Redox (Combination)

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Solution Stoichiometry

The ***concentration*** of a solution is the amount of solute present in a given quantity of solvent or solution.

$$M = \textbf{\textit{molarity}} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

What mass of KI is required to make 500. mL of a 2.80 *M* KI solution?

$$\text{volume of KI solution} \xrightarrow{M\ \text{KI}} \text{moles KI} \xrightarrow{\mathcal{M}\ \text{KI}} \text{grams KI}$$

$$500.\ \text{mL} \times \frac{1\ \text{L}}{1000\ \text{mL}} \times \frac{2.80\ \text{mol KI}}{1\ \text{L soln}} \times \frac{166\ \text{g KI}}{1\ \text{mol KI}} = 232\ \text{g KI}$$

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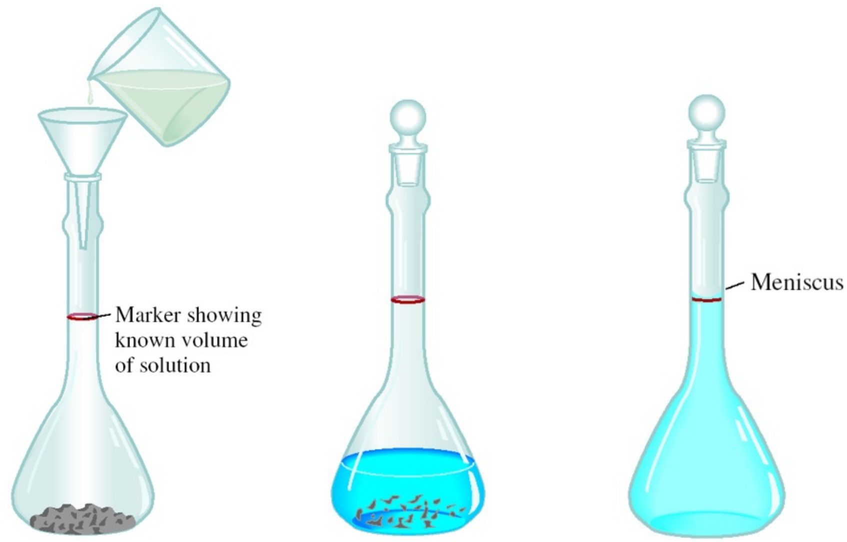
Preparing a Solution of Known Concentration



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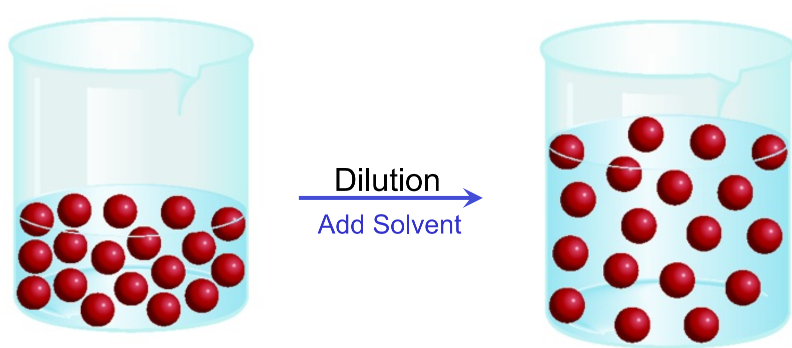
Dilution is the procedure for preparing a less concentrated solution from a more concentrated solution.



Moles of solute before dilution (i) = Moles of solute after dilution (f)

$$M_iV_i = M_fV_f$$

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How would you prepare 60.0 mL of 0.200 *M* HNO_3 from a stock solution of 4.00 *M* HNO_3?

$$M_iV_i = M_fV_f$$

M_i = 4.00 *M* M_f = 0.200 *M* V_f = 0.0600 L V_i = ? L

$$V_i = \frac{M_fV_f}{M_i} = \frac{0.200\ M \times 0.0600\ \text{L}}{4.00\ M} = 0.00300\ \text{L} = 3.00\ \text{mL}$$

Dilute 3.00 mL of acid with water to a total volume of 60.0 mL.

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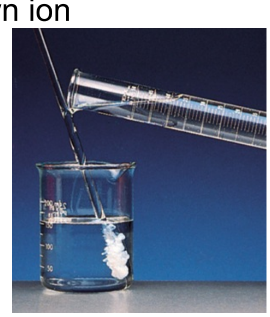
Gravimetric Analysis

1. Dissolve unknown substance in water
2. React unknown with known substance to form a precipitate
3. Filter and dry precipitate
4. Weigh precipitate
5. Use chemical formula and mass of precipitate to determine amount of unknown ion



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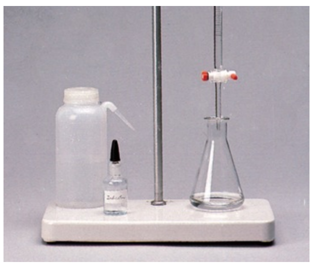
Titrations

In a ***titration*** a solution of accurately known concentration is added gradually added to another solution of unknown concentration until the chemical reaction between the two solutions is complete.

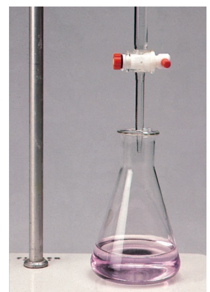
Equivalence point – the point at which the reaction is complete

Indicator – substance that changes color at (or near) the equivalence point



Slowly add base to unknown acid UNTIL

the indicator changes color



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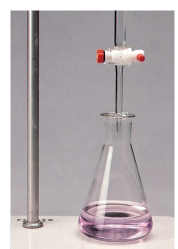
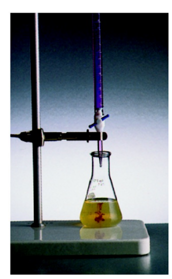
Titrations can be used in the analysis of

Acid-base reactions

$H_2SO_4 + 2NaOH \longrightarrow 2H_2O + Na_2SO_4$



Redox reactions



$5Fe^{2+} + MnO_4^- + 8H^+ \longrightarrow Mn^{2+} + 5Fe^{3+} + 4H_2O$

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What volume of a 1.420 *M* NaOH solution is required to titrate 25.00 mL of a 4.50 *M* H_2SO_4 solution?

WRITE THE CHEMICAL EQUATION!

$$H_2SO_4 + 2NaOH \longrightarrow 2H_2O + Na_2SO_4$$

$$\text{volume acid} \xrightarrow[\text{acid}]{M} \text{moles red} \xrightarrow[\text{coef.}]{\text{rxn}} \text{moles base} \xrightarrow[\text{base}]{M} \text{volume base}$$

$$25.00\ \text{mL} \times \frac{4.50\ \text{mol}\ H_2SO_4}{1000\ \text{mL soln}} \times \frac{2\ \text{mol NaOH}}{1\ \text{mol}\ H_2SO_4} \times \frac{1000\ \text{ml soln}}{1.420\ \text{mol NaOH}} = 158\ \text{mL}$$

16.42 mL of 0.1327 *M* $KMnO_4$ solution is needed to oxidize 25.00 mL of an acidic $FeSO_4$ solution. What is the molarity of the iron solution?

WRITE THE CHEMICAL EQUATION!

$$5Fe^{2+} + MnO_4^{-} + 8H^{+} \longrightarrow Mn^{2+} + 5Fe^{3+} + 4H_2O$$

$$\text{volume red} \xrightarrow[\text{red}]{M} \text{moles red} \xrightarrow[\text{coef.}]{\text{rxn}} \text{moles oxid} \xrightarrow[\text{oxid}]{V} M\ \text{oxid}$$

16.42 mL = 0.01642 L

25.00 mL = 0.02500 L

$$0.01642\ \text{L} \times \frac{0.1327\ \text{mol}\ KMnO_4}{1\ \text{L}} \times \frac{5\ \text{mol}\ Fe^{2+}}{1\ \text{mol}\ KMnO_4} \times \frac{1}{0.02500\ \text{L}\ Fe^{2+}} = 0.4358\ M$$