Chapter 4: Solution Stoichiometry – Cont.

Aqueous Solutions

- Molarity (dilution calculations, solution stoichiometry);
- Solubility and Solubility Rules
- Molecular, Ionic and Net Ionic Equations
- Precipitation Reactions
- Acid-Base Reactions

Reading: Sections 4.1 – 4.5, 4.7, 4.8.

Recommended Problems: 27 a&c, 29, 31, 35c, 37a, 45b, 49, 53, 55, 57, 59, 61, 63, 67, 69, 71, 73, 75, 77, 79 and 81.

Aqueous Solutions

- *Recall from Chapter 2*
  Homogeneous mixtures are called **solutions**
- The component of the solution that changes state (e.g. salt in water) is called the **solute**
- The component that keeps its state and does the dissolving is called the **solvent**
  - If both components start in the same state, the *major component* is the solvent
- To describe solutions accurately, we must describe how much of each component is present

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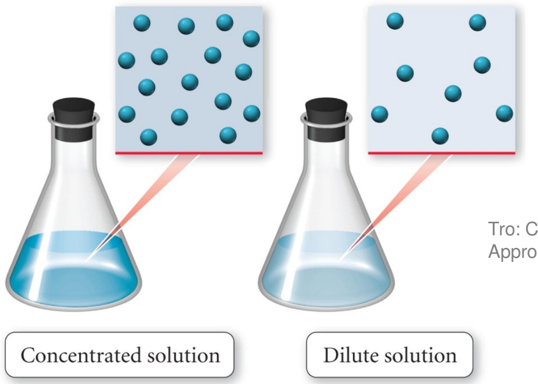
Solution Concentration

- **Dilute solutions** have a small amount of solute compared to solvent
- **Concentrated solutions** have a large amount of solute compared to solvent



Concentrations: Quantitative Descriptions of Solutions

- A more precise method for describing a solution is to quantify the amount of solute in a given amount of solution
- **Concentration** = amount of solute in a given amount of solution
  - occasionally amount of solvent

Solution Concentration: **Molarity**

- Moles of solute in one liter of solution
- Used because it describes how many molecules of solute are in each liter of solution

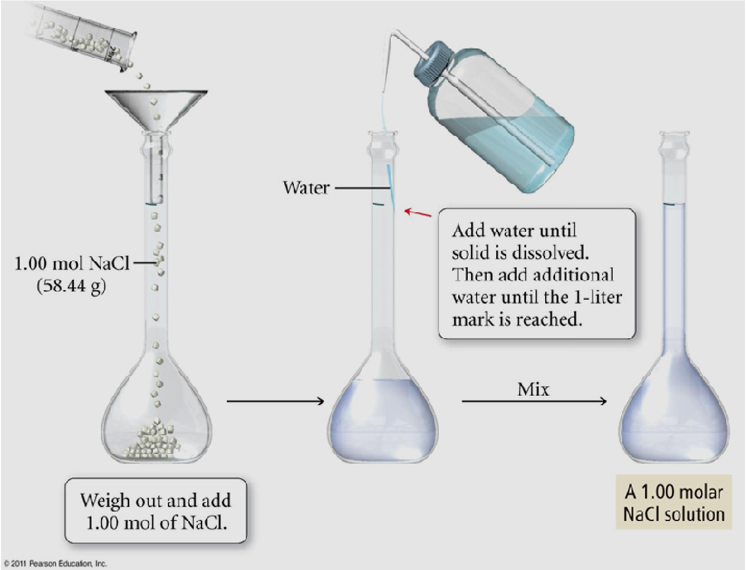
$$\text{Molarity, M} = \frac{\text{amount of solute (in moles)}}{\text{amount of solution (in L)}}$$

or simply

$$\text{M} = \frac{\text{moles of solute}}{\text{L of solution}}$$

Preparing 1 L of a 1.00 M NaCl Solution

Tro: Chemistry: A Molecular Approach, 2/e



Example 4.5: Find the molarity of a solution that has 25.5 g KBr dissolved in 1.75 L of solution

Given: **Find:**	25.5 g KBr, 1.75 L solution Molarity, M
Conceptual Plan:	$\boxed{\text{g KBr}} \xrightarrow{\frac{1\text{ mol}}{119.00\text{ g}}} \frac{\boxed{\text{mol KBr}}}{\boxed{\text{L sol'n}}} \xrightarrow[M=\frac{\text{mol}}{\text{L}}]{} \boxed{\text{M}}$
Relationships:	1 mol KBr = 119.00 g ← MM_{KBr} M = moles KBr/L solution
Solution:	$25.5\ \cancel{\text{g KBr}} \times \frac{1\text{ mol KBr}}{119.00\ \cancel{\text{g KBr}}} = 0.21\underline{4}29\text{ mol KBr}$ $\text{molarity, M} = \frac{\text{moles KBr}}{\text{L solution}} = \frac{0.21\underline{4}29\text{ mol KBr}}{1.75\text{ L}} = 0.122\text{ M}$

Practice 1: What is the molarity of a solution containing 3.4 g of NH_3 (MM 17.03) in 200.0 mL of solution?

Answer: 0.20 mol NH_3/0.2000 L = 1.0 M NH_3 solution

Practice 2: How many grams of $CaCl_2$ are needed to prepare 250.0 mL of 0.150 M $CaCl_2$ (MM = 110.98)?

Answer: 4.16 g $CaCl_2$

Dilution

- Often, solutions are stored as concentrated **stock solutions**
- To make solutions of lower concentrations from these stock solutions, more solvent is added
- The concentrations and volumes of the stock (M_1, V_1) and dilute solutions (M_2, V_2) are inversely proportional

Dilution equation: $\boxed{M_1 \cdot V_1 = M_2 \cdot V_2}$

Example 4.7: To what volume should you dilute 200 mL of 15.0 M NaOH to make 3.00 M NaOH?

Given: V_1 = 200 mL, M_1 = 15.0 M, M_2 = 3.00 M

Find: **V_2, L**

Conceptual Plan: $V_1, M_1, M_2 \rightarrow V_2$

Useful equation: $M_1V_1 = M_2V_2$ or $\frac{M_1V_1}{M_2} = V_2$

WORK:

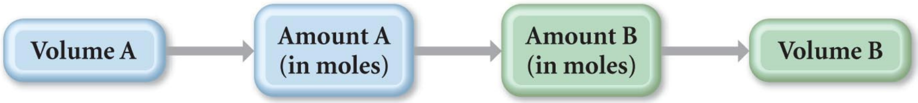
$$V_2 = (15.0\ \cancel{M}) \times \left(\frac{200\ \text{mL}}{3.00\ \cancel{M}}\right) = \boxed{1000\ \text{mL}}$$

Practice: What is the concentration of a solution prepared by diluting 45.0 mL of 8.25 M HNO_3 to 135.0 mL?

Answer: $\frac{M_1 \bullet V_1}{V_2} = M_2 \quad = 2.75\,M$

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



Example 4.8: 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

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

Given:	0.150 M KCl, 0.150 L of 0.175 M $Pb(NO_3)_2$
Find:	Volume in L of KCl
Conceptual Plan:	$\text{L } Pb(NO_3)_2 \xrightarrow{\frac{0.175\ mol}{1\ L\ Pb(NO_3)_2}} \text{mol } Pb(NO_3)_2 \xrightarrow{\frac{2\ mol\ KCl}{1\ mol\ Pb(NO_3)_2}} \text{mol KCl} \xrightarrow{\frac{1\ L\ KCl}{0.150\ mol}} \text{L KCl}$
Relation-ships:	1 L $Pb(NO_3)_2$ = 0.175 mol, 1 L KCl = 0.150 mol, 1 mol $Pb(NO_3)_2$: 2 mol KCl

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Example 4.8 – *Cont.*

Solution:

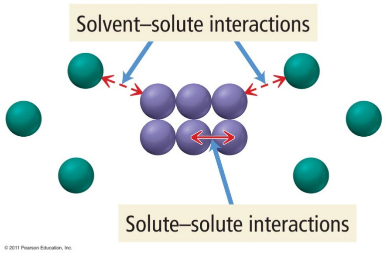
$$0.150\ \cancel{L\ Pb(NO_3)_2} \times \frac{0.175\ \cancel{mol}}{1\ \cancel{L\ Pb(NO_3)_2}} \times \frac{2\ \cancel{mol}\ KCl}{1\ \cancel{mol\ Pb(NO_3)_2}} \times \frac{1\ L\ KCl}{0.150\ \cancel{mol}}$$

$$= 0.350\ L\ KCl$$

Answer: 0.350 L or 350 mL of 0.150 M KCl is needed for the reaction

What Happens When a Solute Dissolves?

- Solute-solute attractive forces exist
- Solvent-solvent attractive forces also exist
- Mix solute with solvent – *What happens?*
- If attractions between solute and solvent are strong enough, the solute will dissolve



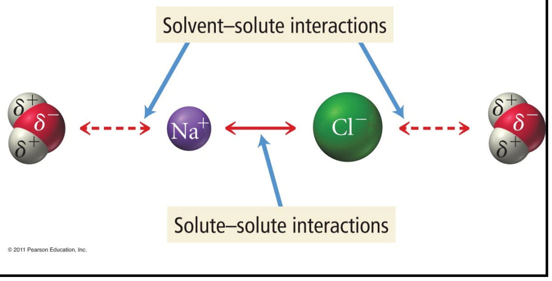
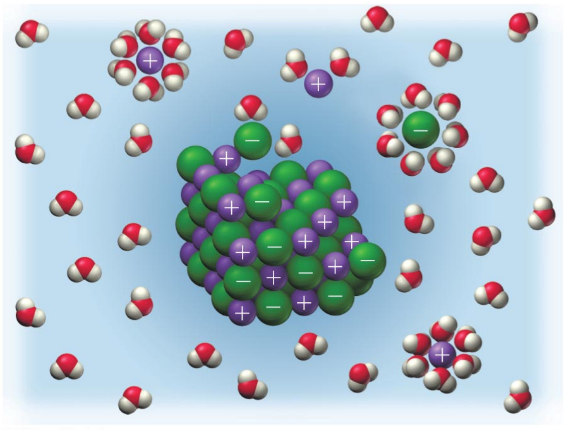


Table Salt Dissolving in Water



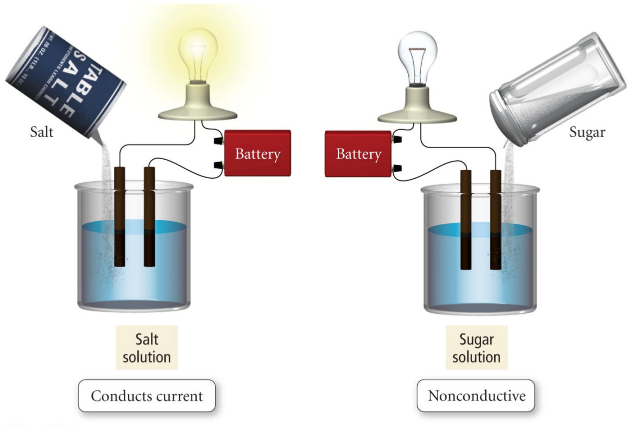
Each ion is attracted to the surrounding water molecules and pulled off and away from the crystal

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

Electrolytes and Nonelectrolytes

- Materials that dissolve in water to form a solution that will conduct electricity are called **electrolytes**
- Materials that dissolve in water to form a solution that will not conduct electricity are called **nonelectrolytes**



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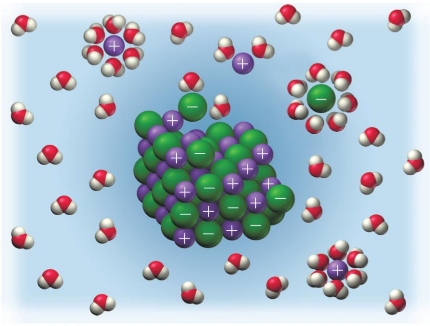
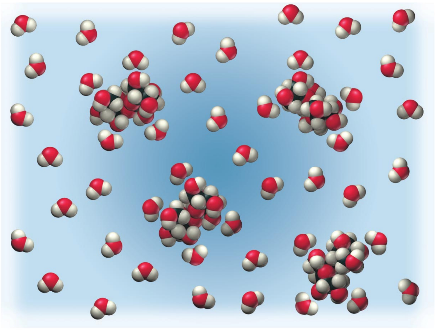
Molecular View of Electrolytes and Nonelectrolytes

- To conduct electricity, a material must have charged particles that are able to flow
- Electrolyte solutions contain ions dissolved in water
  - Ex. Ionic compounds dissolved in water
- Nonelectrolyte solutions contain whole molecules dissolved in the water
  - Generally, molecular compounds do not ionize when they dissolve in water
    - the notable exception being *molecular acids*

Tro: Chemistry: A Molecular Approach, 2/e

Salt vs. Sugar Dissolved in Water





Electrolytes: Compounds that dissociate into ions when they dissolve

Nonelectrolyte: Compounds do not dissociate into ions when they dissolve

Dissociation of Ionic Compounds

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

Dissociation of magnesium chloride:

$$MgCl_2\ (aq) \rightarrow Mg^{+2}\ (aq) + 2\ Cl^-\ (aq)$$

- Polyatomic ions stay together as one ion

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

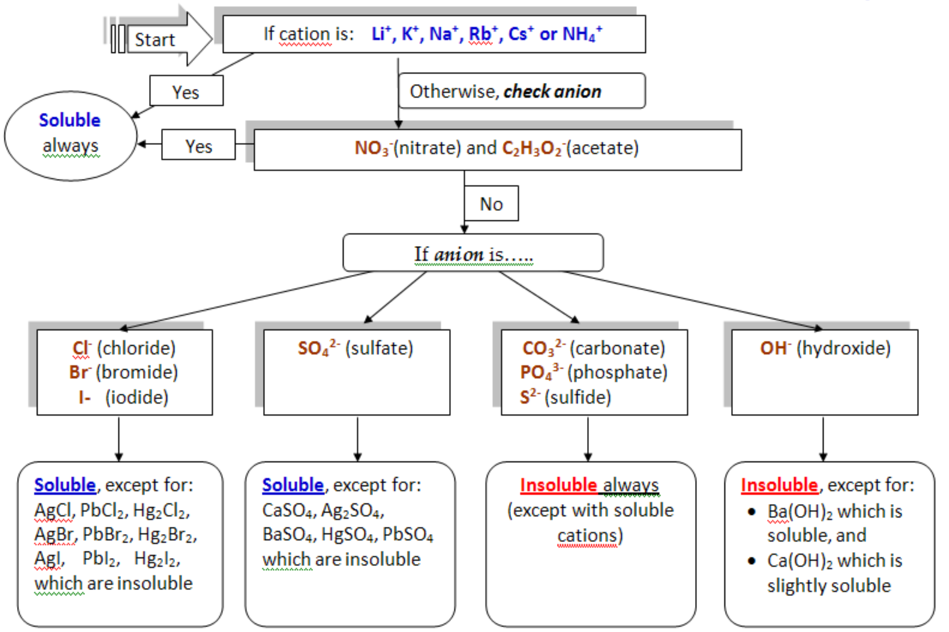
Practice: Write the equation for the process that occurs when the following ionic compounds dissociate in water.

$CaCl_2$	$CaCl_2(aq) \rightarrow Ca^{2+}(aq) + 2\ Cl^{-}(aq)$
$Al(NO_3)_3$	$Al(NO_3)_3\ (aq) \rightarrow Al^{3+}\ (aq) + NO_3^{-}(aq)$
$(NH_4)_2CO_3$	$(NH_4)_2CO_3(aq) \rightarrow 2\ NH_4^{+}(aq) + CO_3^{2-}(aq)$

Solubility of Ionic Compounds

- Some ionic compounds, such as NaCl, dissolve well in water at room temperature
  - Others, such as AgCl, dissolve hardly at all
- 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
- Solubility depends on the temperature

Solubility Chart



Start

If cation is: Li^+, K^+, Na^+, Rb^+, Cs^+ or NH_4^+

Yes

Soluble always

Otherwise, ***check anion***

NO_3^- (nitrate) and $C_2H_3O_2^-$ (acetate)

Yes

No

If *anion* is…..

Cl^- (chloride)
Br^- (bromide)
I- (iodide)

Soluble, except for:
AgCl, $PbCl_2$, Hg_2Cl_2,
AgBr, $PbBr_2$, Hg_2Br_2,
AgI, PbI_2, Hg_2I_2,
which are insoluble

SO_4^{2-} (sulfate)

Soluble, except for:
$CaSO_4$, Ag_2SO_4,
$BaSO_4$, $HgSO_4$, $PbSO_4$
which are insoluble

CO_3^{2-} (carbonate)
PO_4^{3-} (phosphate)
S^{2-} (sulfide)

Insoluble always
(except with soluble cations)

OH^- (hydroxide)

Insoluble, except for:
- $Ba(OH)_2$ which is soluble, and
- $Ca(OH)_2$ which is slightly soluble

Practice: Determine if each of the following is soluble in water.

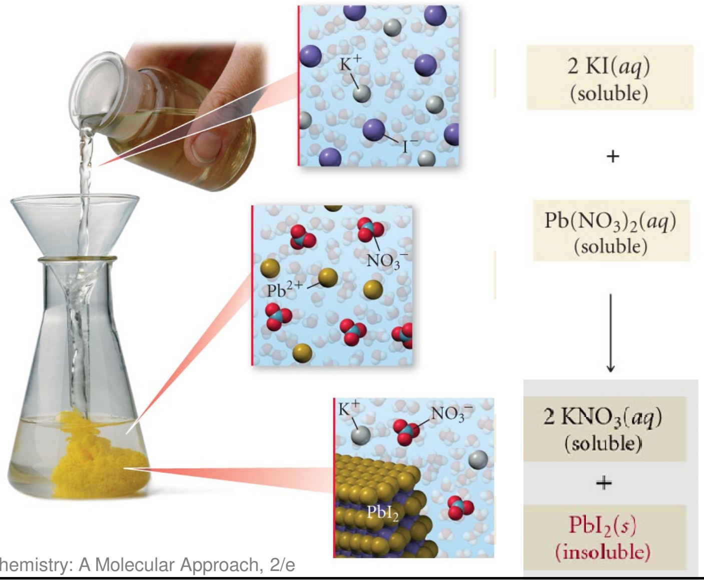
KOH	KOH is soluble because it contains K^+
AgBr	AgBr is insoluble; most bromides are soluble, but AgBr is an exception
$CaCl_2$	$CaCl_2$ is soluble; most chlorides are soluble, and $CaCl_2$ is not an exception
$Pb(NO_3)_2$	$Pb(NO_3)_2$ is soluble because it contains NO_3^-
$PbSO_4$	$PbSO_4$ is insoluble; most sulfates are soluble, but $PbSO_4$ is an exception

Precipitation Reactions

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

$$2\ KI(aq) + Pb(NO_3)_2(aq) \rightarrow \mathbf{PbI_2\ (s)} + 2\ KNO_3(aq)$$

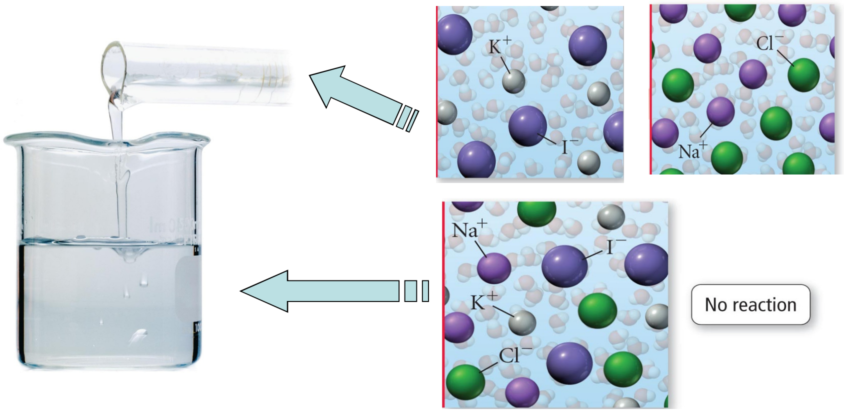
insoluble



No Precipitate Formation = No Reaction

$$\text{KI}\ (aq) + \text{NaCl}\ (aq) \rightarrow \text{KCl}\ (aq) + \text{NaI}\ (aq)$$

all ions still present, ∴ no reaction



Predicting the Products of a Precipitation Reaction

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

Predicting the Products of a Precipitation Reaction

5. If any of the possible products are insoluble, write ***(s)*** after the formula to indicate **solid**. Write any soluble products with ***(aq)*** after the formula to indicate soluble compounds
6. Balance the equation
   – remember to only change coefficients, not subscripts

Example 4.10: Write the equation for the precipitation reaction between an aqueous solution of *potassium carbonate* and an aqueous solution of *nickel(II) chloride*

1. Write the formulas of the reactants

$K_2CO_3 \ + \ NiCl_2 \ \rightarrow$

2. Determine the possible products

   a) Determine the ions present

   $(K^+ + CO_3^{2-}) \ + \ (Ni^{2+} + Cl^-) \rightarrow$

   b) Exchange the ions

   $(K^+ + CO_3^{2-}) + (Ni^{2+} + Cl^-) \rightarrow (K^+ + Cl^-) + (Ni^{2+} + CO_3^{2-})$

   c) Write the formulas of the products - balance charges

   $K_2CO_3(aq) + NiCl_2(aq) \rightarrow KCl \ + NiCO_3$

3. Determine the solubility of each product
    - KCl is soluble
    - $NiCO_3$ is *insoluble*
4. If <u>both</u> products are <u>soluble</u>, write **N.R.** (no reaction)
    - Does not apply because $NiCO_3$ is insoluble
5. Write (*aq*) next to soluble compounds and (*s*) next to insoluble compounds

$$K_2CO_3\,(aq) + NiCl_2\,(aq) \rightarrow KCl\,(aq) + NiCO_3\,(s)$$

6. Balance the equation

$$K_2CO_3\,(aq) + NiCl_2\,(aq) \rightarrow 2\,KCl\,(aq) + NiCO_3\,(s)$$

Practice: Predict the products and balance the equation

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

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

$$KCl\,(aq) + AgNO_3\,(aq) \rightarrow KNO_3 + \boxed{AgCl}\ \textbf{insoluble}$$

$$KCl\,(aq) + AgNO_3\,(aq) \rightarrow KNO_3\,(aq) + AgCl\,(s)$$

Practice: Write an equation for the reaction that takes place when an aqueous solution of ammonium sulfate is mixed with an aqueous solution of lead (II) acetate.

$(NH_4)_2SO_4\,(aq) + Pb(C_2H_3O_2)_2\,(aq) \rightarrow$

$(NH_4^+ + SO_4^{2-}) + (Pb^{2+} + C_2H_3O_2^-) \rightarrow (NH_4^+ + C_2H_3O_2^-) + (Pb^{2+} + SO_4^{2-})$

$(NH_4)_2SO_4\,(aq) + Pb(C_2H_3O_2)_2\,(aq) \rightarrow NH_4C_2H_3O_2 + PbSO_4$

Insoluble

$(NH_4)_2SO_4\,(aq) + Pb(C_2H_3O_2)_2\,(aq) \rightarrow NH_4C_2H_3O_2\,(aq) + PbSO_4\,(s)$

Finally, balance the equation:

$(NH_4)_2SO_4\,(aq) + Pb(C_2H_3O_2)_2\,(aq) \rightarrow 2\,NH_4C_2H_3O_2\,(aq) + PbSO_4\,(s)$

Equations written to represent **precipitation reactions** can be written in one of three ways:

- Molecular Equations
  - All reactants and products are written as if they are molecules
- Ionic Equations
  - All soluble reactants and products are written as ions
  - Only the precipitate is written as if it were a molecule
- Net Ionic Equations
  - Only the reactants and product taking part in the reaction are written in the equation --- reactants as ions; product as molecule.
  - *Spectator ions* are not included in the equation

Reference: http://www.ausetute.com.au/ppteeqtn.html

Molecular Equations

- In **molecular equations**, all reactants and products are written as if they are *molecules*
  - Species in solution must include the soluble compounds (aq) and the precipitate (s)

Example:

$$\mathbf{NaCl}_{(aq)} + \mathbf{AgNO_3}_{(aq)} \text{ -----> } \mathbf{NaNO_3}_{(aq)} + \mathbf{AgCl}_{(s)}$$

http://www.ausetute.com.au/ppteeqtn.html

Ionic Equations

- In **ionic equations**, all species in solution are written as *ions*; the precipitate is written as if it were a molecule.

Example:

$$\mathbf{Na^+}_{(aq)} + \mathbf{Cl^-}_{(aq)} + \mathbf{Ag^+}_{(aq)} + \mathbf{NO_3^-}_{(aq)} \text{ ----> } \mathbf{Na^+}_{(aq)} + \mathbf{NO_3^-}_{(aq)} + \mathbf{AgCl}_{(s)}$$

http://www.ausetute.com.au/ppteeqtn.html

Net Ionic Equations

- **Net ionic equations** are written like ionic equations except that *spectator ions* are not included in the equation:

Example:

Ionic: $Na^+(aq) + Cl^-(aq) + Ag^+(aq) + NO_3^-(aq) \text{ ----> }$
$Na^+(aq) + NO_3^-(aq) + AgCl(s)$

Insoluble chloride

Net ionic: $Ag^+(aq) + Cl^-(aq) \text{ ------> } AgCl(s)$

http://www.ausetute.com.au/ppteeqtn.html

Ionic Equations – *Cont.*

- Ions that are both reactants and products are called **spectator ions** (Ex. Na^+ and NO_3^- ions below)

$$\boxed{Na^+_{(aq)}} + Cl^-_{(aq)} + Ag^+_{(aq)} + \boxed{NO_3^-}_{(aq)} \rightarrow \boxed{Na^+_{(aq)}} + \boxed{NO_3^-}_{(aq)} + AgCl_{(s)}$$

insoluble

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

Example: $Cl^-_{(aq)} + Ag^+_{(aq)} \rightarrow AgCl_{(s)}$

  - ➢ Remember to name and write the metal cation first in an ionic compound

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Practice: Write the ionic and net ionic equation for each of the reactions below.

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

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

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

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

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

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

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 % of molecules that ionize varies from one acid to another
- Acids that ionize virtually 100% are called **strong acids** *Example:* Hydrochloric acid, HCl

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

Hydrochloric acid	**Hydrogen ion**	**Chloride anion**

- Acids that only ionize a small percentage are called **weak acids**. *Example:* Hydrofluoric acid, HF

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

Hydrofluoric acid	**Hydrogen ion**	**Fluoride anion**

Strong and Weak Electrolytes

- **Strong electrolytes** are materials that dissolve completely as ions
  - ionic compounds and strong acids
  - their solutions conduct electricity well
- **Weak electrolytes** are materials that dissolve mostly as molecules, but partially as ions
  - weak acids
  - their solutions conduct electricity, but not well
- When compounds containing a polyatomic ion dissolve, the polyatomic ion stays together

$$HC_2H_3O_2\ (aq) \Leftrightarrow H^+\ (aq) + C_2H_3O_2^-\ (aq)$$

Acetic acid **acetate ion**

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Ionization – *Cont.*

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

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

Sulfuric acid **Hydrogen ion** **Sulfate (anion)**

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Bases

Recall: Acids ionize in water to form **H^+** ions

- H from the acid 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

Examples of base dissociation

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

A base with OH-

$$NH_3\ (g) + H_2O\ (l) \rightarrow NH_4^+\ (aq) + OH^-\ (aq)$$

A base without OH-