# AMSAT CHEM IH TOPIC# 10
# STOICHIOMETRY NOTES

## TABLE OF CONTENTS



## MOLAR MASS, % COMPOSITION, EMPIRICAL/MOLECULAR FORMULA SECTION #1

- Intro
  - Composition stoichiometry
    - Mass relationships of elements in compounds
      - Counting atoms
        - The number of atoms in a formula unit/molecule depends on the subscripts and the distributive property
          - $Ca_3(PO_4)_2$ = 3Ca + 2P + (2x4)O = 3Ca + 2P + 8O
          - $CuSO_4 \bullet 5H_2O$ = Cu + S + 4O + 5(2H + O) = Cu + S + 9O +10H
      - Empirical formula
        - Simplest whole number ratio between elements in a compound
        - All ionic compounds (start with a metal or $NH_4^+$) are written in empirical formula (EF).
          - Be careful about the makeup of ions.
          - Ions cannot be reduced from their inherent formula
        - Molecular compounds (compound starts with a nonmetal)
          - Written as molecular formulas (MF)
            - The number of atoms needed to make 1 molecule of the substance
          - May be simplified to an empirical formula but does not reflect the true molecule ($C_6H_6$ – molecular formula; CH – empirical formula)
      - Molar Mass (*MM*)
        - Mass of 1 mole of any substance
          - Use method for counting atoms, but substitute in the atomic mass (in grams) for each element's symbol.
            - Label: g/mol (round to two decimal places (hundredth))
          - $H_2O$ = 2H + O = 2(1.01) + 16 = 18.02 g/mol
          - $CuSO_4 \bullet 5H_2O$= Cu + S + 4O + 10H + 5O
            = 63.55 + 32.07 + 4(16) + 10(1.01) + 5(16) = ______
  - **<u>Sample Problem 9.1</u>** – Molar Mass (*MM*)
    What is the *MM* of barium nitrate, $Ba(NO_3)_2$? Ans: 261.35g/mol

- Practice

  (1) How many moles of atoms of each element are there in one mole of the following compounds? (a) $Al_2S_3$ (b) $NaNO_3$ (c) $Ba(OH)_2$

  (2) Find the MM of each compound. (a) $Al_2S_3$ (b) $NaNO_3$ (c) $Ba(OH)_2$

  Ans: 150.17g/mol, 85.00g/mol, 171.35g/mol

- Molar mass as a conversion factor
  - **<u>Sample Problem 9.2</u>** – *MM* as a Conversion factor

    What is the mass in grams of 2.50 mol of oxygen gas? Ans: 80.0g
  - **<u>Sample Problem 9.3</u>** – *MM* as a Conversion Factor

    Ibuprofen, $C_{13}H_{18}O_2$, is the active ingredient in many nonprescription pain relievers. Its *MM* is 206.29 g/mol.

    (a) If the tablets in the bottle contain a total of 33g of ibuprofen, how many moles of ibuprofen are in the bottle? Ans: 0.16mol

    (b) How many molecules of ibuprofen are in the bottle? Ans: $9.6 \times 10^{22}$ molecules

    (c) What is the total mass in grams of carbon in 33g of ibuprofen? Ans: 25g of C
    - Practice

      (1) How many moles of compound are in the following?

      (a) 6.60g $(NH_4)_2SO_4$ (b) 4.5kg of $Ca(OH)_2$ Ans: a) 0.542mol, (b) 61mol

      (2) What is the mass in grams of 6.25mol of copper (II) nitrate? Ans: 1170g $Cu(NO_3)_2$
- Percentage Composition
  - The mass percentage of each element in a compound

    $$\frac{\text{mass of element in 1 mol of compound}}{\text{molar mass of compound}} \times 100\%$$
    - Known as the percentage composition of the compound
  - **<u>Sample Problem 9.3</u>** – Percent Composition

    Find the percentage composition of copper (I) sulfide, $Cu_2S$. Ans: Cu: 79.9%, S: 20.1%
  - **<u>Sample Problem 9.4</u>** – Percent Composition

    As some salt crystallize from a water solution, they bind water molecules in their crystal structure. Sodium carbonate forms such a *hydrate*, in which 10 water molecules are present for every formula unit of sodium carbonate. Find the mass percentage of water in sodium carbonate decahydrate, $Na_2CO_3 \cdot 10H_2O$, which has a MM of 286.14g/mol. Ans: 63.0% $H_2O$
    - Practice

      (1) Find the percentage composition of the following. (a) $PbCl_2$ (b) $Ba(NO_3)_2$

      (2) Find the mass percentage of water in $ZnSO_4 \cdot 7H_2O$.

      (3) Magnesium hydroxide is 54.87% oxygen by mass. How many grams of oxygen are in 175g of the compound? How many mole of oxygen is this?

      Ans: (1) 74.5% Pb, 25.5%Cl (2) 43.9% $H_2O$ (3) 96.0g O
- Calculating Empirical Formulas
  - Working example 78.1% B and 21.9% H
  - Write elements involved in compound with x, y, z, etc. as subscript variables.
    - $B_xH_y$
  - From percentage composition, assume a 100g sample so percentages become grams
    - 78.1%B and 21.9%H

        - Becomes 78.1g and 21.9g
    - Convert the masses to moles
        - Only moles can be compared to moles, grams of a substance cannot be compared
            - 78.1g/10.81g = 7.22mol B
            - 21.9g/1.01 = 21.7mol H
    - Divide every mole by the smallest moles (solve for subscripts)
        - y = 21.7/7.22 = 3.01
        - x = 7.22/7.22 = 1
            - For every 1 B there are 3 H
    - Substitute for subscripts to determine empirical formula
        - $B_1H_3$
            - Erase any 1's placed as subscripts
                - $BH_3$
        - Empirical mass (EM)
            - Mass of the empirical formula
                - B + 3H = 10.81 + 3(1.01) = 13.84 amu
    - **<u>Sample Problem 9.5</u>** – Empirical Formula

      Quantitative analysis shows that a compound contains 32.38% sodium, 22.65% sulfur, and 44.99% oxygen. Find the empirical formula of this compound.
    - **<u>Sample Problem 9.6</u>** – Empirical Formula

      Analysis of a 10.150g sample of a compound known to contain only phosphorus and oxygen indicates a phosphorus content of 4.433g. What is the empirical formula of this compound?
        - <u>Practice</u>

          (1) A compound is found to contain 63.52% iron and 36.48% sulfur. Find its empirical formula. Ans: FeS

          (2) Find the empirical formula of a compound found to contain 26.56% potassium, 35.41% chromium, and the remainder oxygen. Ans: $K_2Cr_2O_7$

          (3) Analysis of 20.0g of a compound containing only calcium and bromine indicates that 4.00g of calcium are present. What is the empirical formula of the compound formed? Ans: $CaBr_2$

- Calculation of Molecular Formula
    - The ACTUAL formula for the molecular substance.
        - Find EF (empirical formula)
            - $BH_3$
        - Calculate empirical mass.
            - B + 3H = 10.81 + 3(1.01) = 13.84 amu
                - Molecular mass (given) is 27.67 amu
        - Calculate n
            - $n = \frac{\text{molecular mass (or formula mass)}}{\text{empirical mass}} = \frac{27.67}{13.84} = 2$
        - Find molecular formula
            - Multiply the subscripts on the empirical formula by n
                - n(EF)

- $2(BH_3) = B_2H_6$
  - $B_2H_6$ is the molecular formula, the "true formula" for borane
- **<u>Sample Problem 9.7</u>** – Molecular Formula
  In Sample Problem 9.6, the empirical formula of a compound of phosphorus and oxygen was found to be $P_2O_5$. Experimentation shows that the *MM* of this compound is 283.89g/mol. What is the compound's molecular formula? Ans: $P_4O_{10}$
  - <u>Practice</u>
    (1) Determine the molecular formula of the compound with the empirical formula CH and a formula mass of 78.110amu. Ans: $C_6H_6$ (benzene)
    (2) A sample of a compound with a formula mass of 34.00amu is found to consist of 0.44g H and 6.92g O. Find its molecular mass. Ans: $H_2O_2$

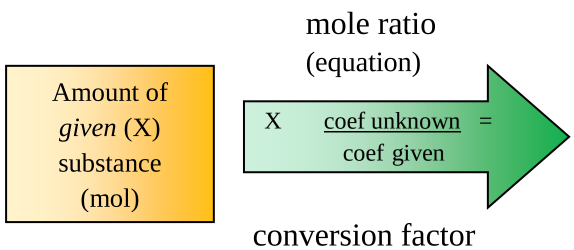
## INTRODUCTION TO STOICHIOMETRY SECTION #2

- Reaction stoichiometry
  - Mass relationships between reactants and products
  - Problem Type 1
    - Given (X) and unknown (Y) are amounts in moles
      - Plan
        - X mol → Y mol
  - Problem Type 2
    - Given (X) in moles and unknown in grams
      - Plan
        - X mol → Y mol → Y grams
  - Problem Type 3
    - Given (x) in grams and unknown in moles
      - Plan
        - X grams → X mol → Y mol
  - Problem Type 4
    - Given (X) in grams and unknown in grams
      - Plan
        - X grams → X mol → Y mol → Y grams
  - Mole Rations
    - Used to convert moles of X into moles of Y
      - The coefficients of a balanced equation
      - A conversion factor relating the amounts in moles of any two substances involved in a reaction

        a A b B c C
        - $2Al_2O_3(l) \rightarrow 4Al(s) + 3O_2(g)$
          - Mole ratio
            - 2:4:3 → x:y:z or a:b:c

# IDEAL STOICHIOMETRIC CALCULATIONS SECTION #3

- Intro
  - Assume reactions occur in ideal conditions
    - All reactants are converted to products
      - Ideal conditions very rarely occur in a laboratory
    - These reactions are considered theoretical due to the assumption of ideal conditions
      - Thus calculations involving these reactions yield theoretical answers
        - Used math to compute, then the amount is theoretical
    - Real world (experimental) work yields actual amounts
      - So, we have theoretical and actual results
        - One is done mathematically and the other experimentally
- Conversions of Moles X to Moles Y




Plan:

amount of *given* (mol) → amount of *unknown* (mol)

- **Sample Problem 9.8** – Mole to Mole Conversions

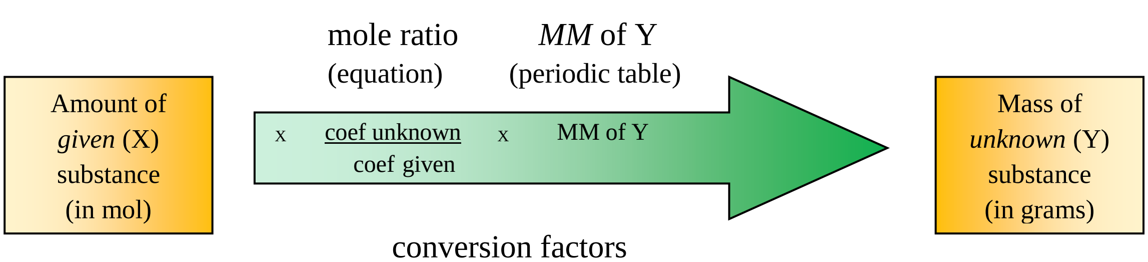
  In a spacecraft, the carbon dioxide exhaled by astronauts can be removed by its reaction with lithium hydroxide, LiOH, according to the following chemical equation. $CO_2(g) + 2LiOH(s) \rightarrow Li_2CO_3(s) + H_2O(l)$. How many moles of lithium hydroxide are required to react with 20mol of $CO_2$, the average amount exhaled by a person each day? Ans: 40 mol LiOH

  - Practice

    (1) Ammonia, $NH_3$, is widely used as a fertilizer and in many household cleaners. How many moles of ammonia are produced when 6mol of hydrogen gas react with an excess of nitrogen gas? Ans: 4mol $NH_3$

    (2) The decomposition of potassium chlorate, $KClO_3$, is used as a source of oxygen in the laboratory. How many moles of potassium chlorate are needed to produce 15 mol of oxygen? Ans: 10. mol $KClO_3$

- Conversion of Moles X to Mass Y

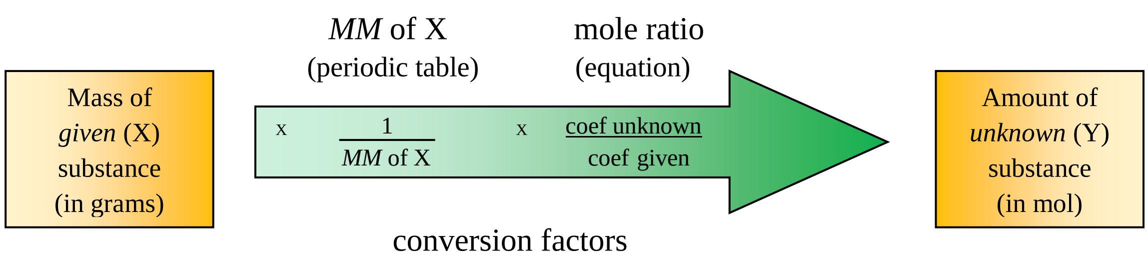



Plan: *MM* of unknown (Y)

amount of *given* (mol) → amount *unknown* (mol) → mass of *unknown* (grams)

- **Sample Problem 9.9** – Mole to Mass
  In photosynthesis, plants use energy from the sun to produce glucose, $C_6H_{12}O_6$, and oxygen from the reaction of carbon dioxide and water. What mass of glucose is produced when 3.00mol of water react with carbon dioxide? Ans: 90.1g $C_6H_{12}O_6$
- **Sample Problem 9.10** – Mole to Mass
  What mass of carbon dioxide is needed to react with 3.00mol of $H_2O$ in the photosynthesis reaction described above? Ans: 132g $CO_2$
  - Practice
    (1) When magnesium burns in air, it combines with oxygen to form magnesium oxide according to the following equation. $2Mg + O_2 \rightarrow 2MgO$
    What mass of magnesium oxide is produced from 2.00mol of magnesium?
    Ans: 80.6g MgO
    (2) What mass of oxygen combines with 2.00mol of magnesium in this same reaction?
    Ans: 32.0g $O_2$
    (3) What mass of glucose can be produced from a photosynthesis reaction that occurs using 10mol $CO_2$? $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ Ans: 300g $C_6H_{12}O_6$

- Conversion of Mass X to Moles Y

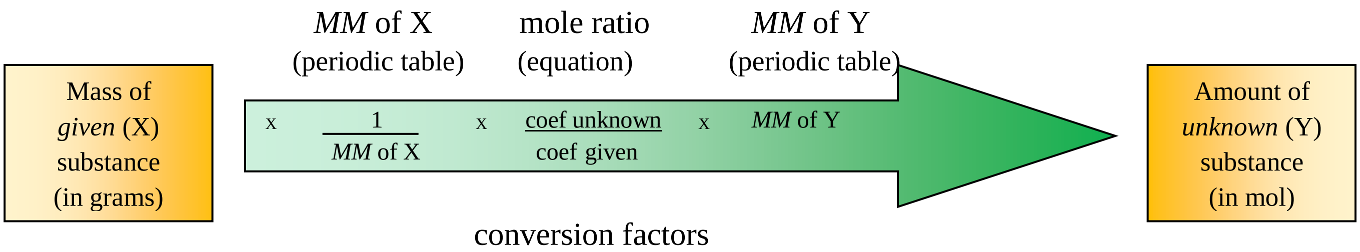



Plan:

mass of *given* (grams) → amount *given* (mol) → moles of *unknown* (mol)
*MM* of X (given)

- **Sample Problem 9.11** – Mass to Mole
  The first step in the industrial manufacture of nitric acid is the catalytic oxidation of ammonia. $NH_3 + O_2 \rightarrow NO + H_2O$. The reaction is run using 824g of $NH_3$ and excess oxygen.
  (a) How many moles of NO are formed? Ans: 48.4mol NO
  (b) How many moles of $H_2O$ are formed? Ans: 72.5mol $H_2O$
  - Practice
    Oxygen was discovered by Joseph Priestly in 1774 when he heated mercury (II) oxide and it decomposed into its constituent elements.
    (1) How many moles of mercury (II) oxide, HgO, are needed to produce 125g of oxygen, $O_2$? Ans: 7.81 moles HgO
    (2) How many moles of mercury are produced? Ans: 7.81 moles Hg

- Mass to Mass Calculations




Plan:

MM of unknown (Y)

mass *given* (grams) → mole *given* (mol) → mol *unknown* (mol) → mass *unknown* (grams)

*MM* of given (X)

- **<u>Sample Problem 9.12</u>** – Mass to Mass
  Tin (II) fluoride, $SnF_2$, is used in some toothpaste. It is made by the reaction of tin with hydrogen fluoride according to the following equation. $Sn + 2HF \rightarrow SnF_2 + H_2$ How many grams of $SnF_2$ are produced from the reaction of 30.00g of HF with Sn? Ans: 117.5g $SnF_2$
  - <u>Practice</u>
    (1) Laughing gas (nitrous oxide, $N_2O$) is sometimes used as an anesthetic in dentistry. It is produced when ammonium nitrate is decomposed according to the following reaction. $NH_4NO_3 \rightarrow N_2O + H_2O$
    (a) How many grams of $NH_4NO_3$ are required to produce 33.0g of $N_2O$?Ans: 60.0g $NH_4NO_3$
    (b) How many grams of water are produced in this reaction? Ans: 27.0g $H_2O$
    (2) When copper metal is added to silver nitrate in solution, silver metal and copper (II) nitrate are produced. What mass of silver is produced from 100.g of Cu? Ans: 339g
    (3) What mass of aluminum is produced by the decomposition of 5.0kg of $Al_2O_3$? Ans: 2.6kg

## LIMITING REACTANT AND PERCENT YIELD SECTION #4

- Limiting reactant/Excess reactant
  - Limiting and excess reactant go hand in hand
    - If a reactant is not the limiting reactant then it is the excess reactant
  - Limiting reactant (limiting reagent) (LR)
    - Limits the amt of products that can be produced.
    - 100% of the limiting reactant will be used during the reaction
  - Excess reactant (ER)
    - Is not used up in the reaction
      - Always be a certain amt left over after reaction has gone to completion
    - Take the reaction between carbon and oxygen
      $C(s) + O_2(g) \rightarrow CO_2\ (g)$
      - 1 mole of C reacts with 1 mole of $O_2$ to produce 1 mole of $CO_2$
        - When we have equal amounts of the two reactants
      - What is the LR when we have 5 mol of C and 10 mole of $O_2$?

1mol C + 1mol $O_2$ = 1mol $CO_2$ (using mole ratios from equation)
5mol C + 10mol $O_2$ = 5mol $CO_2$ + 5mol $O_2$(not used)
-or-
5 **C** atoms + 10 $O_2$ molecules → 5 $CO_2$ molecules + 5 $O_2$ molecules
(LR) (ER) (unused ER)

- **<u>Sample Problem 9.13</u>** – Limiting/Excess Reactant
  Silicon dioxide (quartz) is usually quite unreactive but reacts readily with hydrogen fluoride according to the following equation. $SiO_2(s) + 4HF(g) \rightarrow SiF_4(g) + 2H_2O(l)$If 2.0mol of HF are exposed to 4.5 mol of $SiO_2$, which is the limiting reactant? Ans: HF
  - <u>Practice</u>
    (1) Some rocket engines use a mixture of hydrazine, $N_2H_4$, and hydrogen peroxide, $H_2O_2$, as the propellant. The reaction is given by the following equation.
    $$N_2H_4 + H_2O_2 \rightarrow N_2 + 4H_2O$$
    (a) Which is the LR in this reaction when 0.750mol of $N_2H_4$ is mixed with 0.500mol of $H_2O_2$? Ans: $H_2O_2$
    (b) How much of the ER, in moles, remains unchanged? Ans: 0.500mol $N_2H_4$
    (c) How much of each product, in moles, is formed? Ans: 0.250mol $N_2$, 1.00mol $H_2O$
    (2) If 20.5g of chlorine is reacted with 20.5g of sodium, which reactant is in excess? How do you know? Ans: sodium is in excess because only 0.578mol Na is needed.
- **<u>Sample Problem 9.14</u>** – Limiting Reactant (LR)
  The black oxide of iron, $Fe_3O_4$, occurs in nature as the mineral magnetite. This substance can also be made in the laboratory by the reaction between red-hot iron and steam according to the following equation. $3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$
  (a) When 36.0g of $H_2O$ is mixed with 167g of Fe, which is the LR? Ans: $H_2O$
  (b) What mass of black iron oxide is produced? Ans: 116g $Fe_3O_4$
  (c) What mass of ER remains when the reaction is completed? Ans: 83.2g Fe remaining
  - <u>Practice</u>
    (1) Zinc and sulfur react to form zinc sulfide according to the following reaction.
    $$8Zn(s) + S_8(s) \rightarrow 8ZnS(s).$$
    (a) If 2.00mol of Zn are heated with 1.00mol of $S_8$, identify the limiting reactant. Ans: Zn
    (b) How many moles of excess reactant remain? Ans: 0.75mo $S_8$ remains
    (c) How many moles of the product are formed? Ans: 2.00mol ZnS
    (2) Carbon reacts with steam, $H_2O(g)$, at high temperatures to produce hydrogen and carbon monoxide.
    (a) If 2.40 mol of carbon are exposed to 3.10mol of steam, identify the limiting reactant. Ans: carbon
    (b) How many moles of product are formed? Ans: 2.40mol $H_2$ and 2.40 mol CO
    (c) What mass of each product is formed? Ans: 4.85g $H_2$ and 67.2gCO

- Percent Yield
  - Theoretical yield
    - Calculated using the masses given within the problem

- Assume 100% conversion of one of the reactants into product
    - In an Ideal world
  - Life is messy and reactions do not have 100% conversion
- Actual yield
  - The actual conversion measured form an actual experiment not one done on Ideal world (see above under theoretical).
- $\%\text{yield} = \frac{\text{actual mass}}{\text{theoretical mass}} \times 100\%$
- **<u>Problem 9.15</u>** – Percent Yield
  - Chlorobenzene, $C_6H_5Cl$, is used in the production of many important chemicals, such as aspirin, dyes, and disinfectants. One industrial method of preparing chlorobenzene is to react benzene, $C_6H_6$, with chlorine, as represented by the following equation.

    $$C_6H_6(l) + Cl_2(g) \rightarrow C_6H_5Cl(s) + HCl(g)$$

    When 36.8g of $C_6H_6$ react with an excess $Cl_2$, the actual yield of $C_6H_5Cl$ is 38.8g. What is the percent yield of $C_6H_5Cl$? Ans: 73.2%
  - <u>Practice</u>

    (1) Methanol can be produced through the reaction of CO with $H_2$ in the presence of a catalyst. $CO(g) + 2H_2(g) \rightarrow CH_3OH(l)$. If 75.0g of CO reacts to produce 68.4g $CH_3OH$, what is the percent yield of $CH_3OH$? Ans: 79.8%

    (2) Aluminum reacts with excess copper (II) sulfate according to the reaction given below. If 1.85g of Al reacts and the percent yield of Cu if 56.6%, what mass of Cu is produced? $Al(s) + CuSO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + Cu(s)$ (unbalanced)

    Ans: 3.70g

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