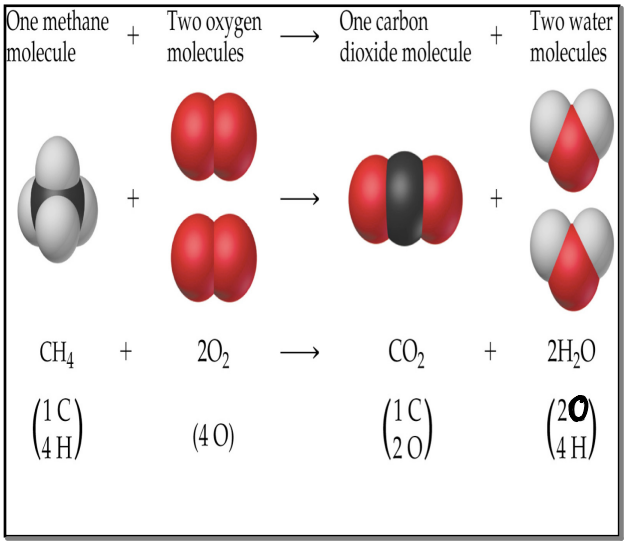
Chapter 3

Stoichiometry

Chemical Stoichiometry

Stoichiometry - The study of quantities of materials consumed and produced in chemical reactions.

A + B → C + D



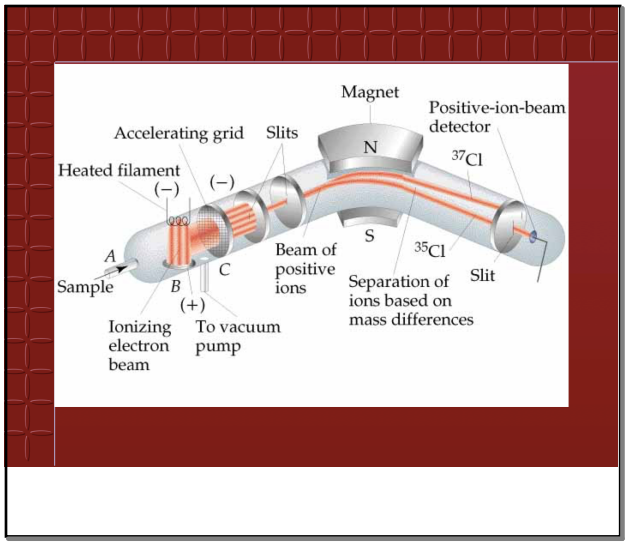
Atomic Masses

Elements occur in nature as mixtures of isotopes

Carbon = 98.89% ^{12}C - 12.000
1.11% ^{13}C
<0.01% ^{14}C

Carbon atomic mass = 12.01 amu

Ave mass = 12 (98.89/100) + 13 (1.11/100) + 14 (0.01/100)



The Mole

The number equal to the number of carbon atoms in exactly 12 grams of pure ^{12}C.

1 mole of anything = 6.022×10^{23} units of that thing

1 doz = 12 anything

Avogadro's number equals 6.022×10^{23} units

Molar Mass

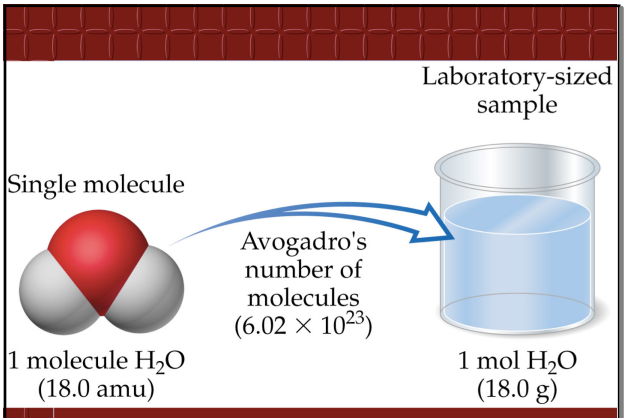
A substance's molar mass (molecular weight) is the mass in grams of one mole of the compound.

CO_2 = 44.01 grams per mole

$12.01115 + 2(15.999) = 44.01$

$1\ mol\ CO_2 = 44.01\ g\ CO_2$

$1\ mol\ CO_2 = 6.022 \times 10^{23}\ molec.\ CO_2$



Determine the formula weights of each of the following compounds: (a) N_2O_5, (b) $CuSO_4$, (c) $(NH_4)_3PO_4$, (d) $Ca(HCO_3)_2$, (e) aluminum sulfide, (f) iron(III) sulfate, (g) disilicon hexabromide.

g. How many bromine atoms in 5.0 g

Formula Si_2Br_6

molar mass = 535.596 g/mol

$5.0\ g\ Si_2Br_6 \times \frac{1\ mol\ Si_2Br_6}{535.596\ g\ Si_2Br_6} \times \frac{6\ mol\ Br}{1\ mol\ Si_2Br_6} \times \frac{6.022 \times 10^{23}\ atoms\ Br}{1\ mol\ Br} = 6.75 \times 10^{21}\ atoms\ Br$

$= 3.4 \times 10^{22}$

Calculate the following quantities:

(a) mass, in grams, of 1.906×10^{-2} mol BaI_2

$1\ mol\ BaI_2 = 391.13\ g\ BaI_2$

$1.906 \times 10^{-2}\ mol\ BaI_2 \times \frac{391.13\ g\ BaI_2}{1\ mol\ BaI_2}$

$= 7.455\ g\ BaI_2$

(b) number of moles of NH_4Cl in 48.3 g of this substance

$48.3\ g\ NH_4Cl \times \frac{1\ mol\ NH_4Cl}{53.492\ g\ NH_4Cl}$

$= 0.903\ mol\ NH_4Cl$

c) number of molecules in 0.05752 mol $HCHO_2$

$1\ mol\ HCHO_2 = 6.022 \times 10^{23}\ molec.\ HCHO_2$

$0.05752\ mol\ HCHO_2 \times \frac{6.022 \times 10^{23}\ molec}{1\ mol\ HCHO_2}$

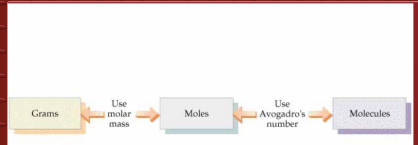
$= 3.464 \times 10^{22}\ molec.\ HCHO_2$

(d) number of O atoms in 4.88×10^{-3} mol $Al(NO_3)_3$

$1\ molec.\ Al(NO_3)_3 =$ 9 molec. O

$4.88 \times 10^{-3}\ mol\ Al(NO_3)_3 \times \frac{9\ mol\ O\ atoms}{1\ mol\ Al(NO_3)_3} \times \frac{6.022 \times 10^{23}\ O\ atoms}{1\ mol\ O\ atoms} = 2.645 \times 10^{22}\ O\ atoms$

$1\ mol\ Al(NO_3)_3 = 9\ mol\ O\ atoms$



Have 5.0 g CH_3Br

1. # mol = 5.27×10^{-2} mol CH_3Br
2. # molec = 3.17×10^{22} molec
3. mass of one molec.

1. $5.0\ g\ CH_3Br \times \frac{1\ mol\ CH_3Br}{94.94\ g\ CH_3Br} \times \frac{6.022 \times 10^{23}\ molec}{1\ mol\ CH_3Br}$

3. $\frac{5.0\ g}{3.17 \times 10^{22}\ molec} = 1.58 \times 10^{-22}\ \frac{g}{molec}$

The molecular formula of allicin, the compound responsible for the characteristic smell of garlic, is $C_6H_{10}OS_2$. (a) What is the molar mass of allicin? (b) How many moles of allicin are present in 5.00 mg of this substance? (c) How many molecules of allicin are in 5.00 mg of this substance? (d) How many S atoms are present in 5.00 mg of allicin?

Percent Composition

Mass percent of an element:

$$\text{mass \%} = \frac{\text{mass of element in compound}}{\text{mass of compound}} \times 100\%$$

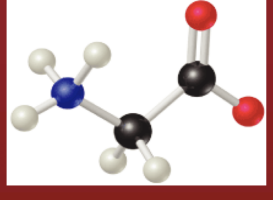
For iron in iron (III) oxide, (Fe_2O_3)

$$\text{mass \% Fe} = \frac{111.69}{159.69} \times 100\% = 69.94\%$$

$$\text{mass \% O} = \frac{47.9982}{159.69} \times 100 = \frac{30.057\%}{100}$$

$3(15.9994) = 47.9982\ g/mol$

Glycine, an amino acid used by organisms to make proteins, is represented by the molecular model below. (a) Write its molecular formula. (b) Determine its molecular mass. (c) Calculate the percent nitrogen by mass in glycine.]



a.) $C_2H_5O_2N$

b.) 75.07 amu

c.) mass % N: $\frac{14.00}{75.07} \times 100 = 18.6\%\ N$

Formulas

molecular formula = (empirical formula)$_n$
[n = integer]

molecular formula = C_6H_6 = $(CH)_6$ — molar mass 78.06 amu

empirical formula = CH — 12.00 + 1.008 = 13.01

% comp. — 13.01 × 6 = 78.06

3.40 What is the molecular formula of each compound?

(a) Empirical formula CH_2 ($\mathcal{M}$ = 42.08 g/mol)

(b) Empirical formula NH_2 ($\mathcal{M}$ = 32.05 g/mol)

(c) Empirical formula NO_2 ($\mathcal{M}$ = 92.02 g/mol)

(d) Empirical formula CHN ($\mathcal{M}$ = 135.14 g/mol)

b. for NH_2 ≈ 16 amu × 2 = 32 amu

$(NH_2)_2 \rightarrow N_2H_4$

d. $C_5H_5N_5$

CHN molar mass (27 amu)5 = 135

Chemical symbol	Meaning	Composition
H_2O	One molecule of water:	Two H atoms and one O atom
$2H_2O$	Two molecules of water:	Four H atoms and two O atoms
H_2O_2	One molecule of hydrogen peroxide:	Two H atoms and two O atoms

Empirical Formula Determination

1. Base calculation on 100 grams of compound.
2. Determine moles of each element in 100 grams of compound.
3. Divide each value of moles by the smallest of the values.
4. Multiply each number by an integer to obtain all whole numbers.

Find molar ratios

3.45 Find the empirical formula of each of the following compounds: (a) 0.063 mol of chlorine atoms combined with 0.22 mol of oxygen atoms; (b) 2.45 g of silicon combined with 12.4 g of chlorine; (c) 27.3 mass % carbon and 72.7 mass % oxygen.

a.) $\frac{0.063 \text{ mol Cl}}{0.063} = 1 \text{ mol Cl} \times 2 = 2\text{Cl}$

$\frac{0.22 \text{ mol O}}{0.063} = 3.5 \text{ mol O} \times 2 = 7\text{O}$

C_2O_7

b. $2.45\text{ g Si} \times \frac{1 \text{ mol Si}}{28.086\text{ g}} = \frac{0.087 \text{ mol Si}}{0.087} = 1$

$12.4\text{ g Cl} \times \frac{1 \text{ mol Cl}}{35.45\text{ g}} = \frac{0.350 \text{ mol Cl}}{0.087} = 4$

$SiCl_4$

c.) 27.3 % C

72.7 % O

$27.3\text{ g C} \times \frac{1 \text{ mol C}}{12.01\text{ g}} =$ mol C

$72.7\text{ g O} \times \frac{1 \text{ mol O}}{16.00\text{ g}} =$ mol O

CO_2

3.46 A sample of 0.600 mol of a metal M reacts completely with excess fluorine to form 46.8 g of MF_2.

(a) How many moles of F are in the sample of MF_2 that forms?

(b) How many grams of M are in this sample of MF_2?

(c) What element is represented by the symbol M?

a.) MF_2

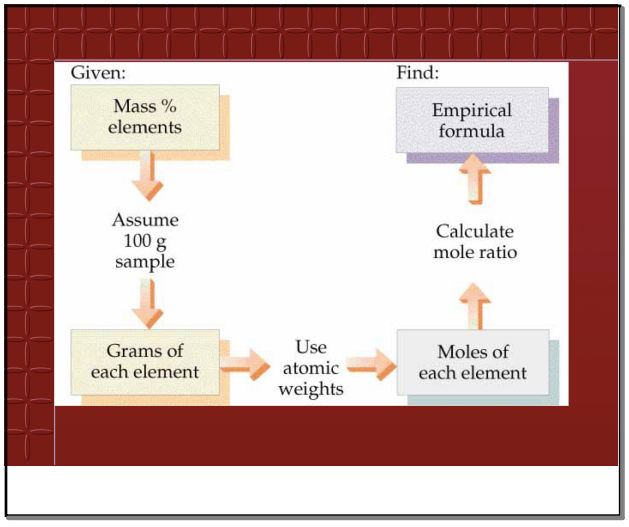
$0.600 \text{ mol M} \times \frac{2 \text{ mol F}}{1 \text{ mol M}} = 1.200 \text{ mol F}$

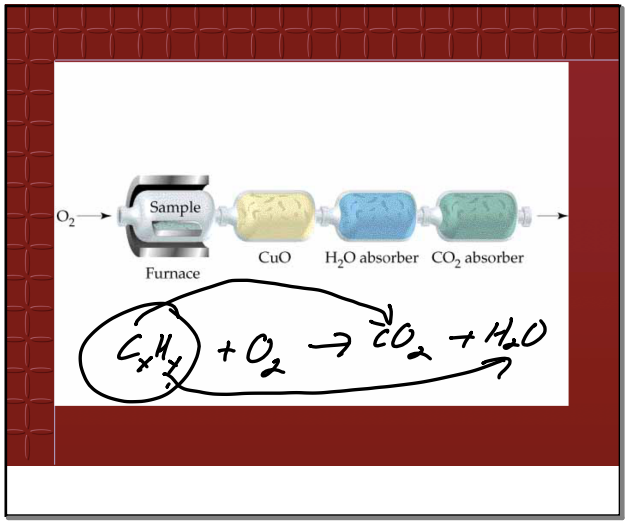
b) $1.200 \text{ mol F} \times \frac{19\text{ g F}}{1 \text{ mol}} = 22.8\text{ g F}$

46.8 − 28.80 = 24.0 g M

c. $\frac{24.0\text{ g M}}{0.600 \text{ mol}} = 400 \text{ g/mol}$ Ca

CaF_2





3.48 Menthol ($\mathcal{M}$ = 156.3 g/mol), the strong-smelling substance in many cough drops, is a compound of carbon, hydrogen, and oxygen. When 0.1595 g of menthol was burned in a combustion apparatus, 0.449 g of CO_2 and 0.184 g of H_2O formed. What is menthol's molecular formula?

$C_{10}H_{20}O$

$0.449\,g\ CO_2 \times \frac{1\ mol\ CO_2}{44\,g\ CO_2} \times \frac{1\ mol\ C}{1\ mol\ CO_2} = \frac{0.010\ mol\ C}{0.0012}$

$0.184\,g\ H_2O \times \frac{1\ mol\ H_2O}{18\,g\ H_2O} \times \frac{2\ mol\ H}{1\ mol\ H_2O} = \frac{0.020\ mol\ H}{0.0012}$

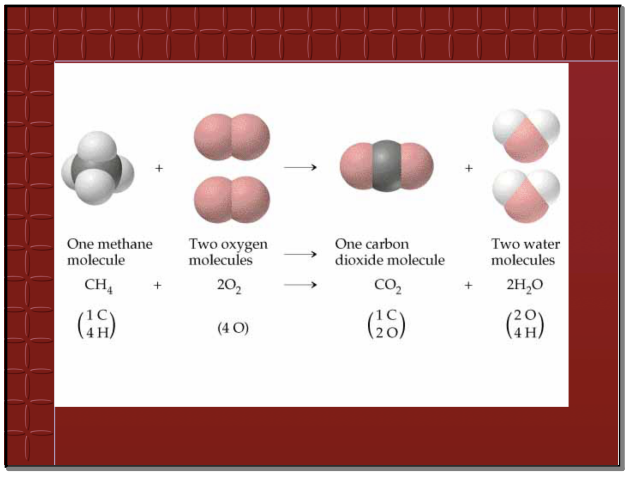
$0.1595\,g - 0.12\,g\ C - 0.020\,g\ H = 0.0195\,g\ O$

$0.0195\,g\ O \times \frac{1\ mol\ O}{16\,g\ O} = \frac{0.0012\ mol\ O}{0.0012}$

C : 8 = 10 H : 16 = 20 O : 1 $C_{10}H_{20}O$

Chemical Equations

Chemical change involves a reorganization of the atoms in one or more substances.



Chemical Equation

A representation of a chemical reaction:

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$

reactants products

Chemical Equation

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$

The equation is balanced.

1 mole of ethanol reacts with 3 moles of oxygen

to produce

2 moles of carbon dioxide and 3 moles of water

$2\,CH_3CH + 3O_2 \rightarrow 4H_2O + 2CO_2$

Calculating Masses of Reactants and Products

1. Balance the equation.
2. Convert mass to moles.
3. Set up mole ratios.
4. Use mole ratios to calculate moles of desired substituent.
5. Convert moles to grams, if necessary.

Consider the Combustion of Propane (C_3H_8)

If 5.0 g of propane is burned in excess oxygen:

1. What mass of CO_2 is produced?

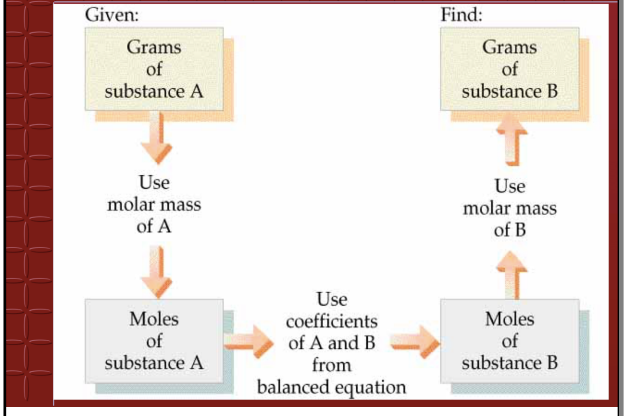
2. How many grams of O_2 are needed for complete combustion of the propane?

Movie

$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

$5.0\,g\,C_3H_8 \times \frac{1\,mol\,C_3H_8}{44.09\,g\,C_3H_8} \times \frac{3\,mol\,CO_2}{1\,mol\,C_3H_8} \times \frac{44.01\,g\,CO_2}{1\,mol\,CO_2} = 15.5\,g\,CO_2$

$5.0\,g\,C_3H_8 \times \frac{1\,mol\,C_3H_8}{44.09\,g\,C_3H_8} \times \frac{5\,mol\,O_2}{1\,mol\,C_3H_8} \times \frac{32.00\,g\,O_2}{1\,mol\,O_2} = 18.1\,g\,O_2$



3.70 Bismuth oxide reacts with carbon to form bismuth metal:

$$Bi_2O_3(s) + 3C(s) \longrightarrow 2Bi(s) + 3CO(g)$$

When 0.607 mol of Bi_2O_3 reacts with excess carbon, how many (a) moles of Bi and (b) grams of CO form?

a.) $0.607\,mol\,Bi_2O_3 \times \frac{2\,mol\,Bi}{1\,mol\,Bi_2O_3} = 1.214\,mol\,Bi$

b.) $0.607\,mol\,Bi_2O_3 \times \frac{3\,mol\,CO}{1\,mol\,Bi_2O_3} \times \frac{28.0\,g\,CO}{1\,mol\,CO}$

$= 51.006\,g\,CO$

51.0

Calcium hydride reacts with water to produce calcium hydroxide and hydrogen gas.

A. Write a balanced chemical equation for the reaction.

B. How many grams of calcium hydride are needed to produce 5.0 g of hydrogen gas.

$CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2$

$5.0\,g\,H_2$

$5.0\,g\,H_2 \times \frac{1\,mol\,H_2}{2.0\,g\,H_2} \times \frac{1\,mol\,CaH_2}{2\,mol\,H_2} \times \frac{42.09\,g\,CaH_2}{1\,mol\,CaH_2}$

$= 52.2\,g\,CaH_2$

3.72 Chromium(III) oxide reacts with hydrogen sulfide (H_2S) gas to form chromium(III) sulfide and water:

$$Cr_2O_3(s) + 3H_2S(g) \longrightarrow Cr_2S_3(s) + 3H_2O(l)$$

To produce 421 g of Cr_2S_3, how many (a) moles of Cr_2O_3 and (b) grams of Cr_2O_3 are required?

Limiting Reactant

The limiting reactant is the reactant that is consumed first, limiting the amounts of products formed.

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Solving a Stoichiometry Problem

1. Balance the equation.
2. Convert masses to moles.
3. Determine which reactant is limiting.
4. Use moles of limiting reactant and mole ratios to find moles of desired product.
5. Convert from moles to grams.

3.82 In the following reaction, 2.35 mol of NH_3 reacts with 2.75 mol of O_2; how many moles of water form?

$$4NH_3(g) + 5O_2(g) \longrightarrow 4NO(g) + 6H_2O(l)$$

excess

$$2.35\ mol\ NH_3 \times \frac{6\ mol\ H_2O}{4\ mol\ NH_3} = 3.525\ mol\ H_2O$$

$$2.75\ mol\ O_2 \times \frac{6\ mol\ H_2O}{5\ mol\ O_2} = 3.30\ mol\ H_2O$$

limiting reactant

Find excess NH_3

$$2.75\ mol\ O_2 \times \frac{4\ mol\ NH_3}{5\ mol\ O_2} = 2.20\ mol\ NH_3$$

$$2.35 - 2.20 = 0.15\ mol\ NH_3$$

$$2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$$

Given 1.0 g of CH_3OH and 1.0 g of O_2, how much CO_2 will be produced in this combustion reaction?

limiting

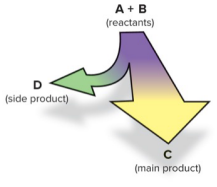
$0.92\ g\ CO_2$

For Friday

How much CH_3OH is left in grams

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 \qquad (3.8)$$

By definition, the actual yield is less than the theoretical yield, so the percent yield is *always* less than 100%.



3.95 When 20.5 g of methane and 45.0 g of chlorine gas undergo a reaction that has a 75.0% yield, what mass (g) of chloromethane (CH_3Cl) forms? Hydrogen chloride also forms.

END