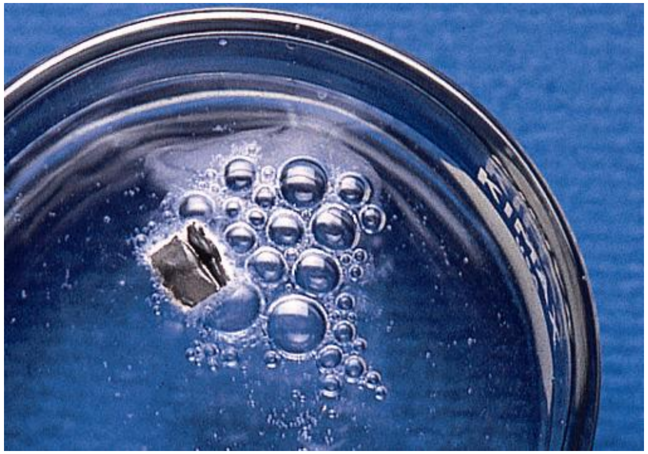
Mass Relationships in Chemical Reactions

Chapter 3



Micro World → Macro World
atoms & molecules → grams

Atomic mass is the mass of an atom in atomic mass units (amu)

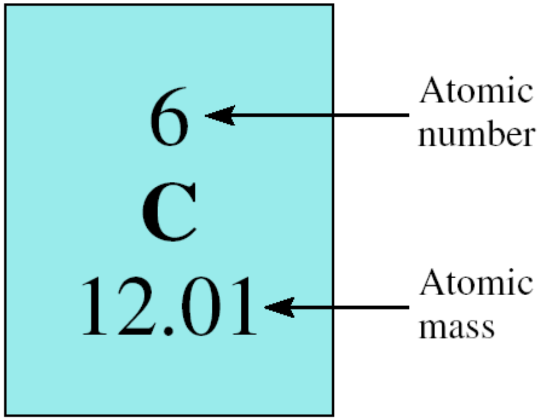
By definition:
1 atom ^{12}C “weighs” 12 amu

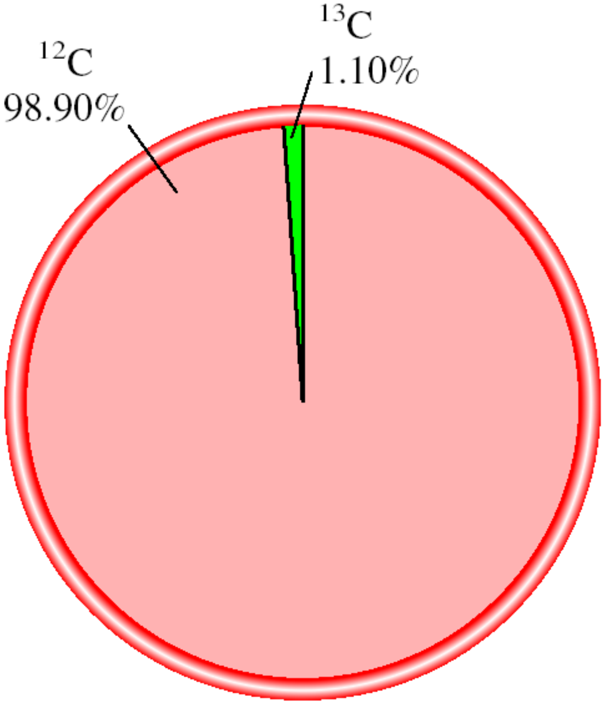
On this scale

^{1}H = 1.008 amu

^{16}O = 16.00 amu

The ***average atomic mass*** is the weighted average of all of the naturally occurring isotopes of the element.





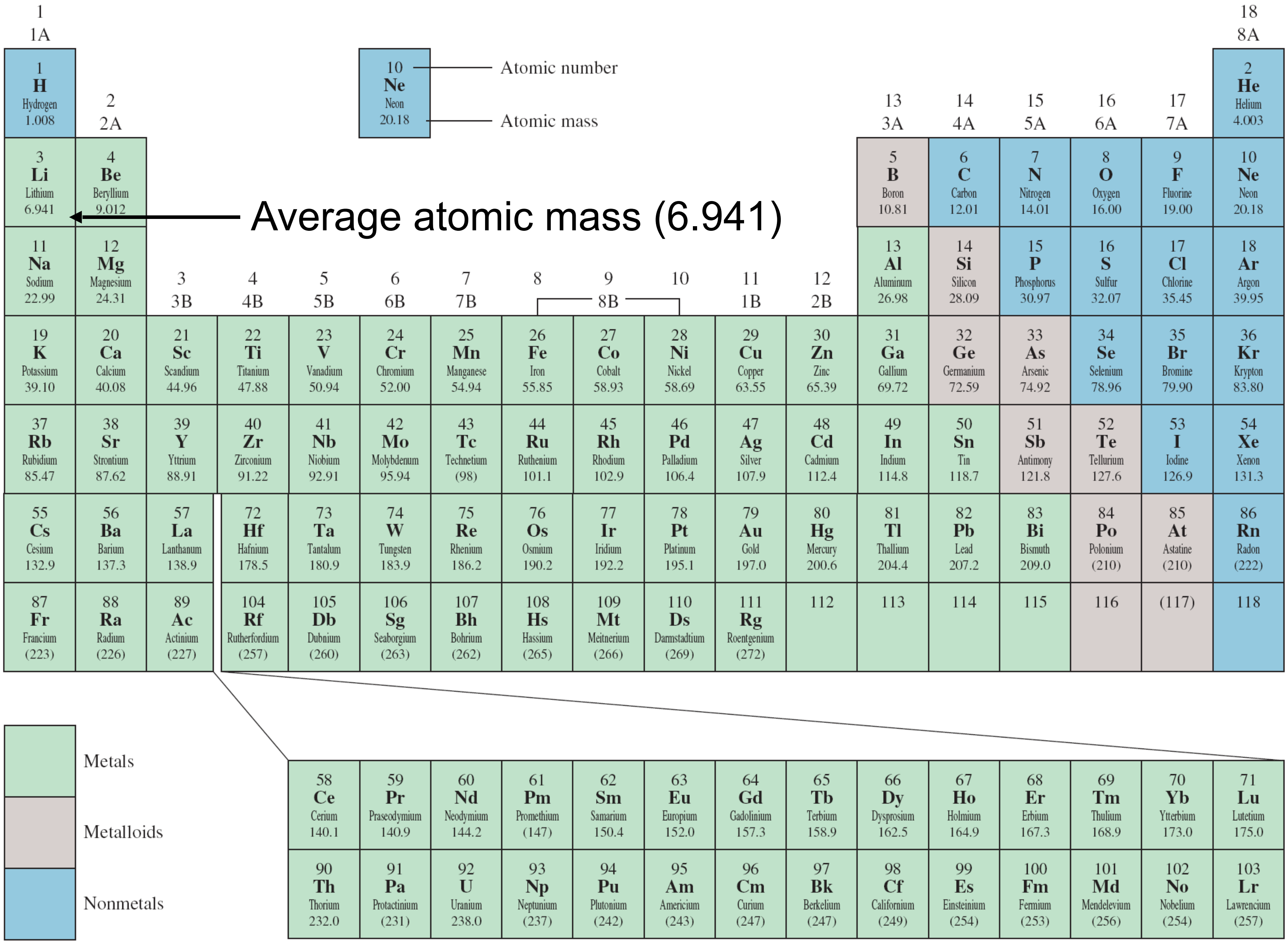
Naturally occurring lithium is:

7.42% ^{6}Li (6.015 amu)

92.58% ^{7}Li (7.016 amu)

Average atomic mass of lithium:

$$\frac{7.42 \text{ x } 6.015 + 92.58 \text{ x } 7.016}{100} = 6.941 \text{ amu}$$



10 **Ne** Neon 20.18

Average atomic mass (6.941)

1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.1	45 **Rh** Rhodium 102.9	46 **Pd** Palladium 106.4	47 **Ag** Silver 107.9	48 **Cd** Cadmium 112.4	49 **In** Indium 114.8	50 **Sn** Tin 118.7	51 **Sb** Antimony 121.8	52 **Te** Tellurium 127.6	53 **I** Iodine 126.9	54 **Xe** Xenon 131.3
55 **Cs** Cesium 132.9	56 **Ba** Barium 137.3	57 **La** Lanthanum 138.9	72 **Hf** Hafnium 178.5	73 **Ta** Tantalum 180.9	74 **W** Tungsten 183.9	75 **Re** Rhenium 186.2	76 **Os** Osmium 190.2	77 **Ir** Iridium 192.2	78 **Pt** Platinum 195.1	79 **Au** Gold 197.0	80 **Hg** Mercury 200.6	81 **Tl** Thallium 204.4	82 **Pb** Lead 207.2	83 **Bi** Bismuth 209.0	84 **Po** Polonium (210)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (257)	105 **Db** Dubnium (260)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 **Ds** Darmstadtium (269)	111 **Rg** Roentgenium (272)	112	113	114	115	116	(117)	118

58 **Ce** Cerium 140.1	59 **Pr** Praseodymium 140.9	60 **Nd** Neodymium 144.2	61 **Pm** Promethium (147)	62 **Sm** Samarium 150.4	63 **Eu** Europium 152.0	64 **Gd** Gadolinium 157.3	65 **Tb** Terbium 158.9	66 **Dy** Dysprosium 162.5	67 **Ho** Holmium 164.9	68 **Er** Erbium 167.3	69 **Tm** Thulium 168.9	70 **Yb** Ytterbium 173.0	71 **Lu** Lutetium 175.0
90 **Th** Thorium 232.0	91 **Pa** Protactinium (231)	92 **U** Uranium 238.0	93 **Np** Neptunium (237)	94 **Pu** Plutonium (242)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (249)	99 **Es** Einsteinium (254)	100 **Fm** Fermium (253)	101 **Md** Mendelevium (256)	102 **No** Nobelium (254)	103 **Lr** Lawrencium (257)

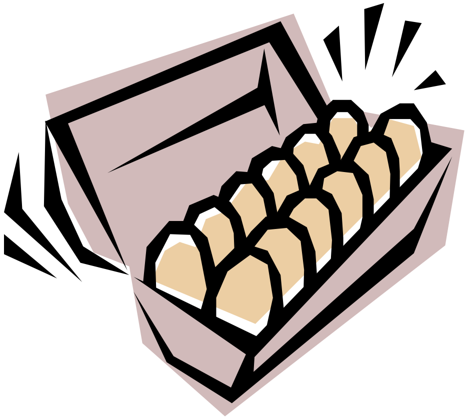
🟩 Metals

▨ Metalloids

🟦 Nonmetals

The Mole (mol): A unit to count numbers of particles

Dozen = 12



Pair = 2

The ***mole (mol)*** is the amount of a substance that contains as many elementary entities as there are atoms in exactly 12.00 grams of ^{12}C

$$1 \text{ mol} = N_A = 6.0221367 \times 10^{23}$$

Avogadro's number (N_A)

Molar mass is the mass of 1 mole of eggs / shoes / marbles / atoms in grams

1 mole ^{12}C atoms = 6.022 x 10^{23} atoms = 12.00 g

1 ^{12}C atom = 12.00 amu

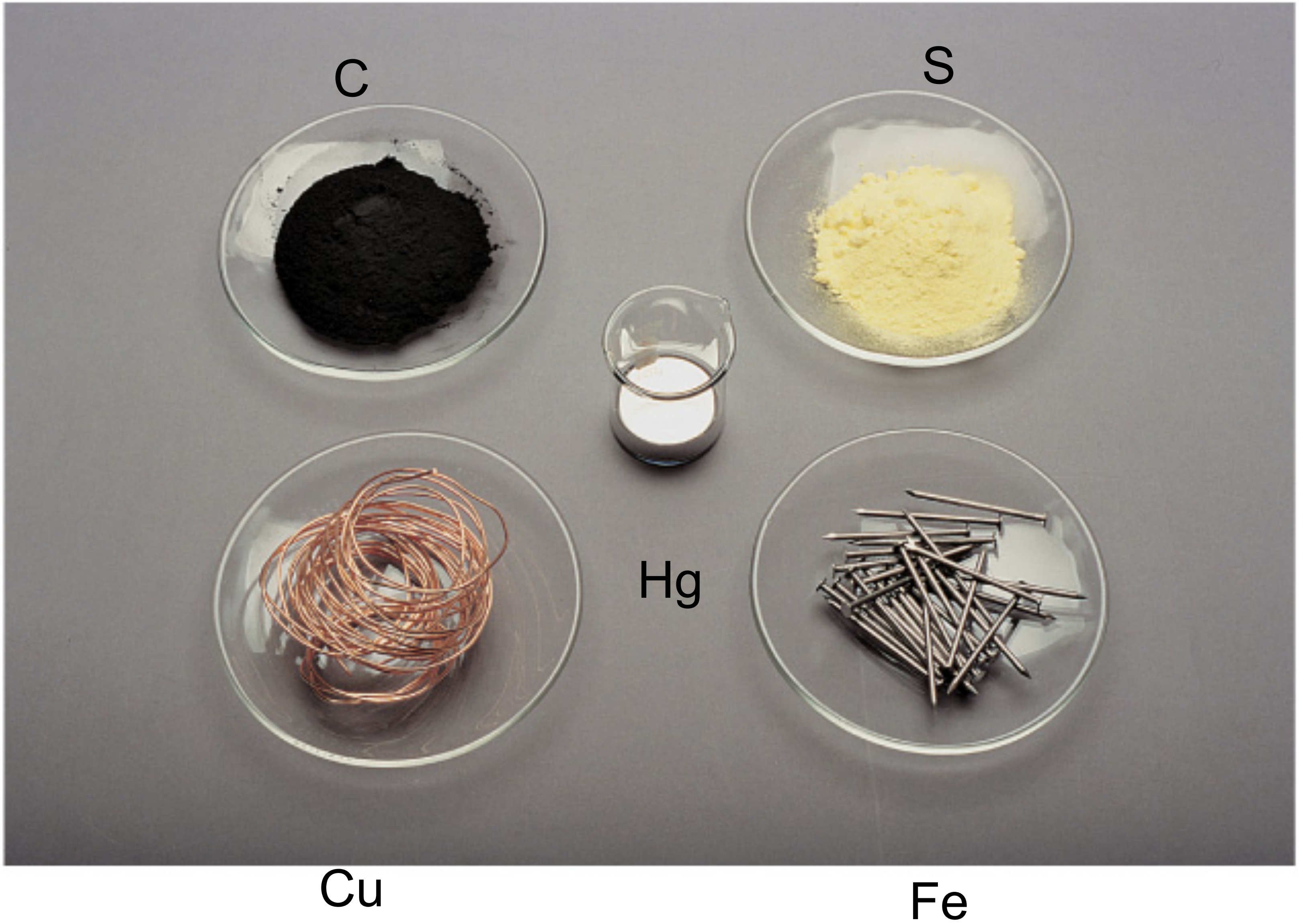
1 mole ^{12}C atoms = 12.00 g ^{12}C

1 mole lithium atoms = 6.941 g of Li

For any element

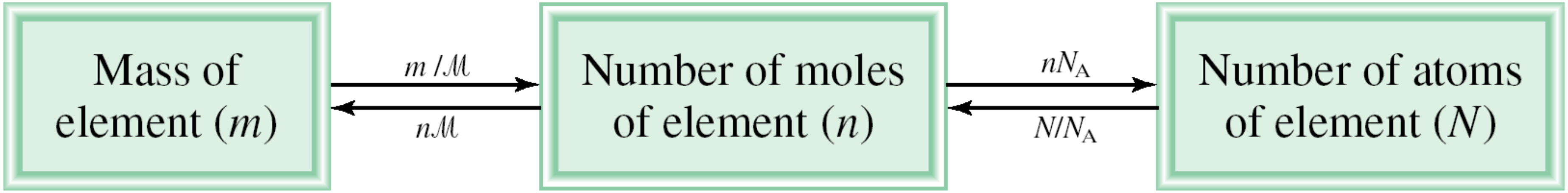
atomic mass (amu) = molar mass (grams)

One Mole of:



$$\frac{1\ {}^{12}\text{C}\ \cancel{\text{atom}}}{12.00\text{ amu}}\ \text{x}\ \frac{12.00\text{ g}}{6.022\text{ x }10^{23}\ {}^{12}\text{C}\ \cancel{\text{atoms}}} = \frac{1.66\text{ x }10^{-24}\text{ g}}{1\text{ amu}}$$

$$1\text{ amu} = 1.66\text{ x }10^{-24}\text{ g} \quad \text{or}\quad 1\text{ g} = 6.022\text{ x }10^{23}\text{ amu}$$



$\mathcal{M}$ = molar mass in g/mol

N_A = Avogadro’s number

How many atoms are in 0.551 g of potassium (K) ?

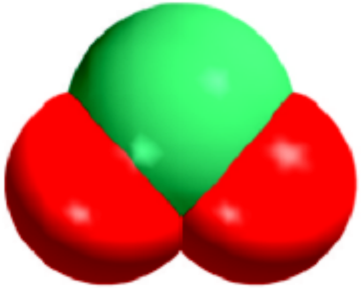
1 mol K = 39.10 g K

1 mol K = 6.022×10^{23} atoms K

$$0.551\ \cancel{\text{g K}} \times \frac{\cancel{\text{1 mol K}}}{39.10\ \cancel{\text{g K}}} \times \frac{6.022 \times 10^{23}\ \text{atoms K}}{\cancel{\text{1 mol K}}} =$$

8.49×10^{21} atoms K

Molecular mass (or molecular weight) is the sum of the atomic masses (in amu) in a molecule.



SO_2

1S	32.07 amu
2O	+ 2 x 16.00 amu
SO_2	64.07 amu

For any molecule

molecular mass (amu) = molar mass (grams)

1 molecule SO_2 = 64.07 amu

1 mole SO_2 = 64.07 g SO_2

How many H atoms are in 72.5 g of C_3H_8O ?

$$1 \text{ mol } C_3H_8O = (3 \times 12) + (8 \times 1) + 16 = 60 \text{ g } C_3H_8O$$

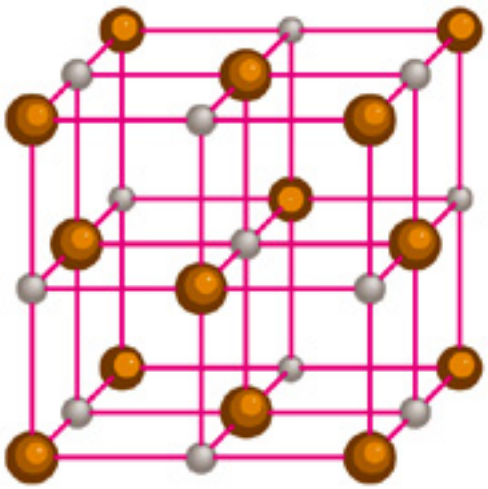
$$1 \text{ mol } C_3H_8O \text{ molecules} = 8 \text{ mol H atoms}$$

$$1 \text{ mol H} = 6.022 \times 10^{23} \text{ atoms H}$$

$$72.5 \cancel{\text{ g } C_3H_8O} \times \frac{1 \cancel{\text{ mol } C_3H_8O}}{60 \cancel{\text{ g } C_3H_8O}} \times \frac{8 \cancel{\text{ mol H}} \text{ atoms}}{1 \cancel{\text{ mol } C_3H_8O}} \times \frac{6.022 \times 10^{23} \text{ H atoms}}{1 \text{ mol} \cancel{\text{ H atoms}}} =$$

$$5.82 \times 10^{24} \text{ atoms H}$$

Formula mass is the sum of the atomic masses (in amu) in a formula unit of an ionic compound.



NaCl

1Na	22.99 amu
1Cl	+ 35.45 amu
NaCl	58.44 amu

For any ionic compound

formula mass (amu) = molar mass (grams)

1 formula unit NaCl = 58.44 amu

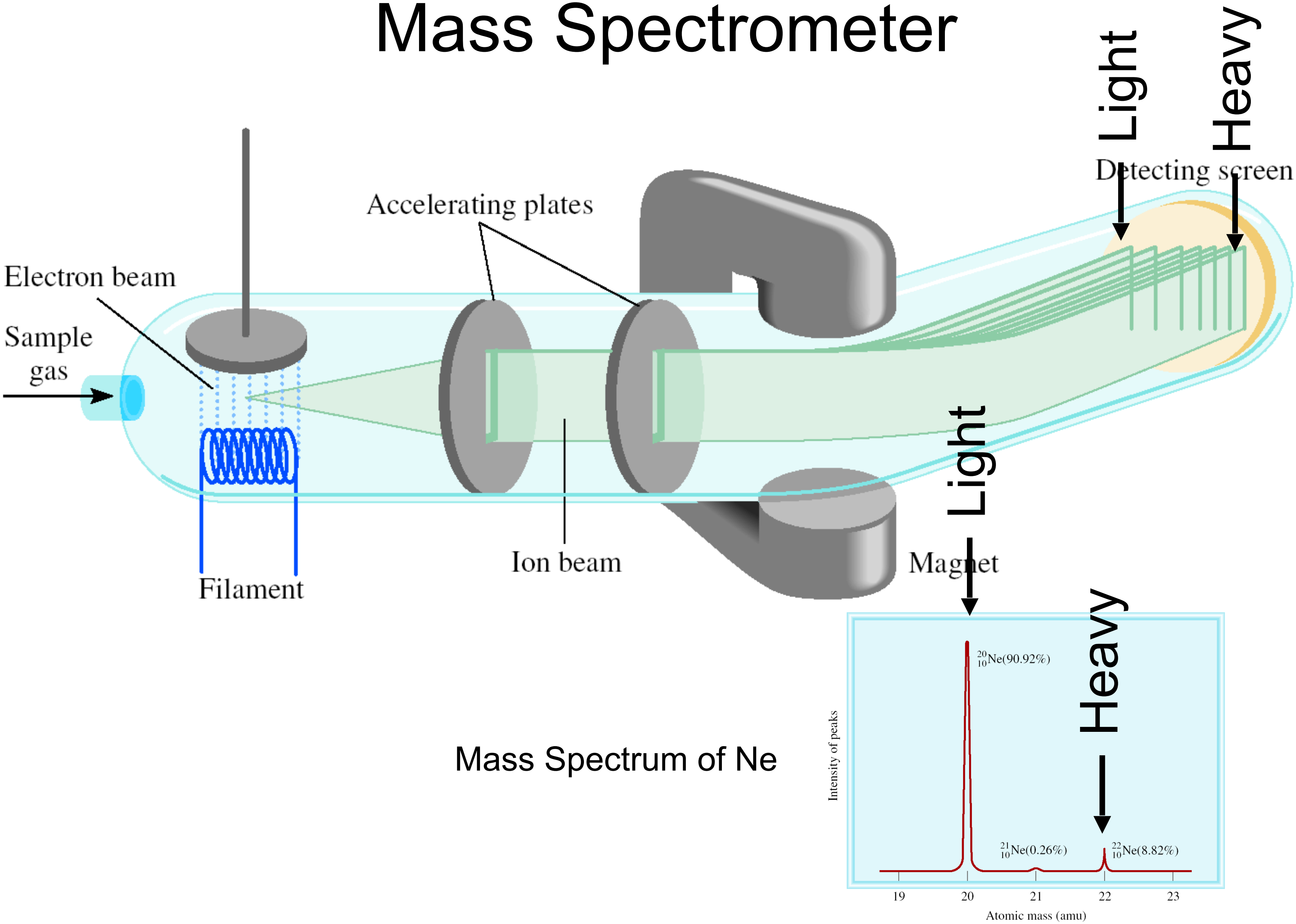
1 mole NaCl = 58.44 g NaCl

What is the formula mass of $Ca_3(PO_4)_2$?

1 formula unit of $Ca_3(PO_4)_2$

3 Ca		3 x 40.08
2 P		2 x 30.97
8 O	+	8 x 16.00
		310.18 amu

Mass Spectrometer

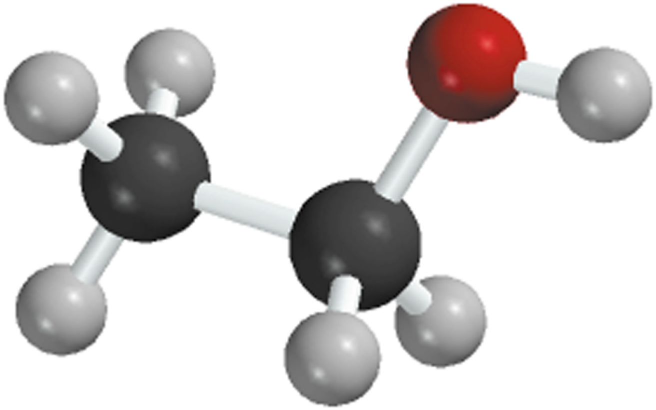


Mass Spectrum of Ne

Percent composition of an element in a compound =

$$\frac{n \text{ x molar mass of element}}{\text{molar mass of compound}} \text{ x } 100\%$$

n is the number of moles of the element in 1 mole of the compound



C_2H_6O

$$\%C = \frac{2 \text{ x } (12.01 \text{ g})}{46.07 \text{ g}} \text{ x } 100\% = 52.14\%$$

$$\%H = \frac{6 \text{ x } (1.008 \text{ g})}{46.07 \text{ g}} \text{ x } 100\% = 13.13\%$$

$$\%O = \frac{1 \text{ x } (16.00 \text{ g})}{46.07 \text{ g}} \text{ x } 100\% = 34.73\%$$

$$52.14\% + 13.13\% + 34.73\% = 100.0\%$$

Percent Composition and Empirical Formulas

Mass percent

↓ Convert to grams and divide by molar mass

Moles of each element

↓ Divide by the smallest number of moles

Mole ratios of elements

↓ Change to integer subscripts

Empirical formula

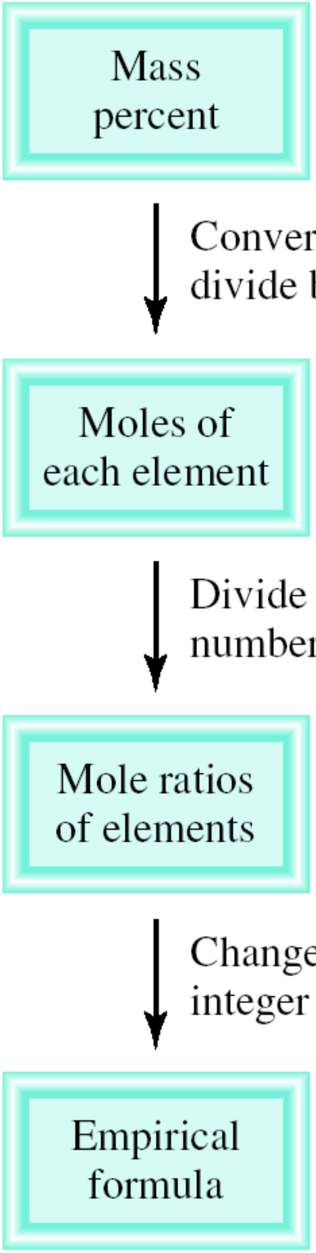
Determine the empirical formula of a compound that has the following percent composition by mass:
K 24.75, Mn 34.77, O 40.51 percent.

$$n_K = 24.75\ \cancel{\text{g K}} \times \frac{1\ \text{mol K}}{39.10\ \cancel{\text{g K}}} = 0.6330\ \text{mol K}$$

$$= 34.77\ \cancel{\text{g Mn}} \times \frac{1\ \text{mol Mn}}{54.94\ \cancel{\text{g Mn}}} = 0.6329\ \text{mol Mn}$$

$$n_O = 40.51\ \cancel{\text{g O}} \times \frac{1\ \text{mol O}}{16.00\ \cancel{\text{g O}}} = 2.532\ \text{mol O}$$

Percent Composition and Empirical Formulas



Mass percent

Convert to grams and divide by molar mass

Moles of each element

Divide by the smallest number of moles

Mole ratios of elements

Change to integer subscripts

Empirical formula

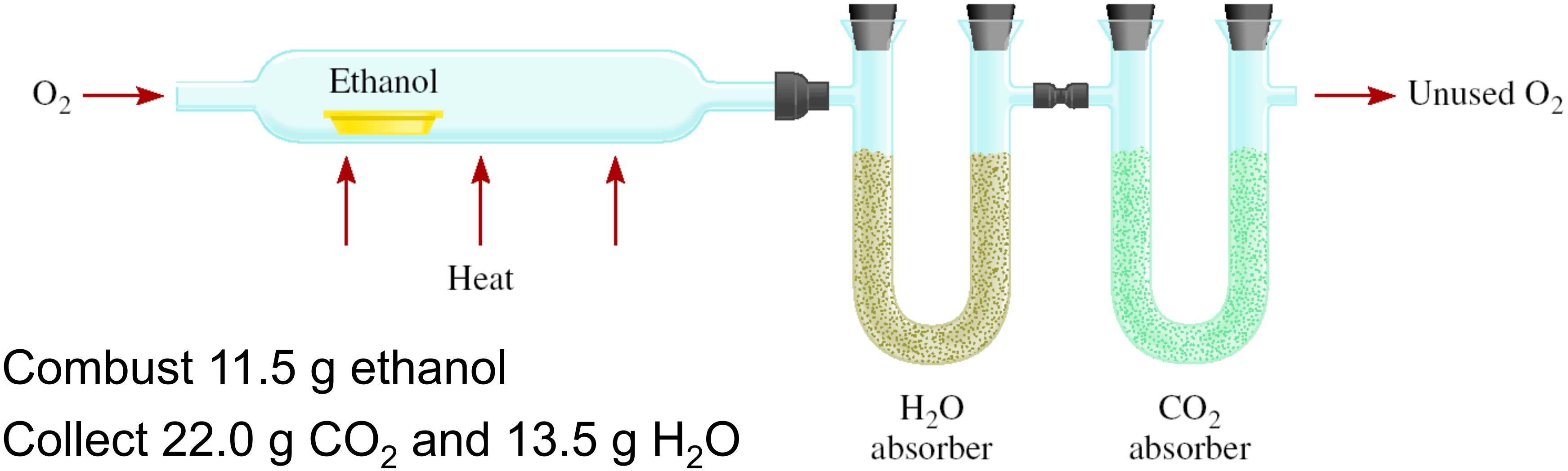
$$n_K = 0.6330, \; n_{Mn} = 0.6329, \; n_O = 2.532$$

$$K: \frac{0.6330}{0.6329} \approx 1.0$$

$$Mn: \frac{0.6329}{0.6329} = 1.0$$

$$O: \frac{2.532}{0.6329} \approx 4.0$$

$$KMnO_4$$



Combust 11.5 g ethanol

Collect 22.0 g CO_2 and 13.5 g H_2O

g CO_2 $\longrightarrow$ mol CO_2 $\longrightarrow$ mol C $\longrightarrow$ g C   6.0 g C = 0.5 mol C

g H_2O $\longrightarrow$ mol H_2O $\longrightarrow$ mol H $\longrightarrow$ g H   1.5 g H = 1.5 mol H

g of O = g of sample – (g of C + g of H)   4.0 g O = 0.25 mol O

Empirical formula $C_{0.5}H_{1.5}O_{0.25}$

Divide by smallest subscript (0.25)

Empirical formula C_2H_6O

A process in which one or more substances is changed into one or more new substances is a ***chemical reaction***

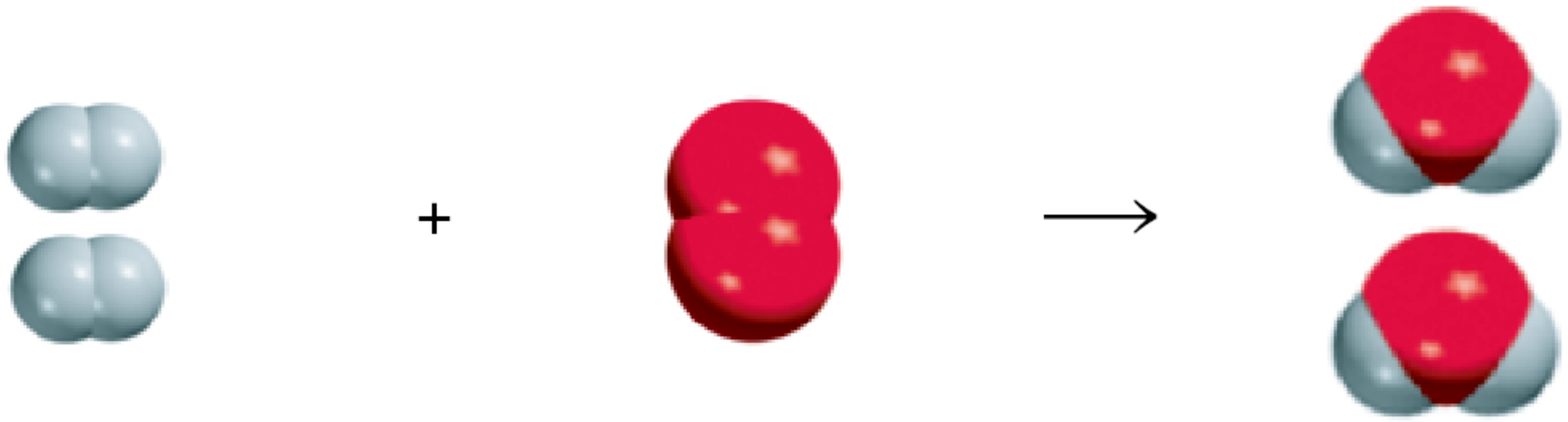
A ***chemical equation*** uses chemical symbols to show what happens during a chemical reaction

reactants → products

3 ways of representing the reaction of H_2 with O_2 to form H_2O

Two hydrogen molecules + One oxygen molecule → Two water molecules

$$2H_2 + O_2 \longrightarrow 2H_2O$$



How to “Read” Chemical Equations

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

2 atoms Mg + 1 molecule O_2 makes 2 formula units MgO

2 moles Mg + 1 mole O_2 makes 2 moles MgO

48.6 grams Mg + 32.0 grams O_2 makes 80.6 g MgO

NOT

2 grams Mg + 1 gram O_2 makes 2 g MgO

Balancing Chemical Equations

1. Write the **correct** formula(s) for the reactants on the left side and the **correct** formula(s) for the product(s) on the right side of the equation.

Ethane reacts with oxygen to form carbon dioxide and water

$$C_2H_6 + O_2 \longrightarrow CO_2 + H_2O$$

2. Change the numbers in front of the formulas (***coefficients***) to make the number of atoms of each element the same on both sides of the equation. Do not change the subscripts.

$2C_2H_6$ **NOT** C_4H_{12}

Balancing Chemical Equations

3. Start by balancing those elements that appear in only one reactant and one product.

$$C_2H_6 + O_2 \longrightarrow CO_2 + H_2O$$

start with C or H but not O

2 carbon on left

1 carbon on right

multiply CO_2 by 2

$$C_2H_6 + O_2 \longrightarrow 2CO_2 + H_2O$$

6 hydrogen on left

2 hydrogen on right

multiply H_2O by 3

$$C_2H_6 + O_2 \longrightarrow 2CO_2 + 3H_2O$$

Balancing Chemical Equations

4. Balance those elements that appear in two or more reactants or products.

$C_2H_6 + O_2 \longrightarrow 2CO_2 + 3H_2O$ multiply O_2 by $\frac{7}{2}$

2 oxygen on left

4 oxygen (2x2) + 3 oxygen (3x1) = 7 oxygen on right

$C_2H_6 + \frac{7}{2}O_2 \longrightarrow 2CO_2 + 3H_2O$ remove fraction multiply both sides by 2

$2C_2H_6 + 7O_2 \longrightarrow 4CO_2 + 6H_2O$

Balancing Chemical Equations

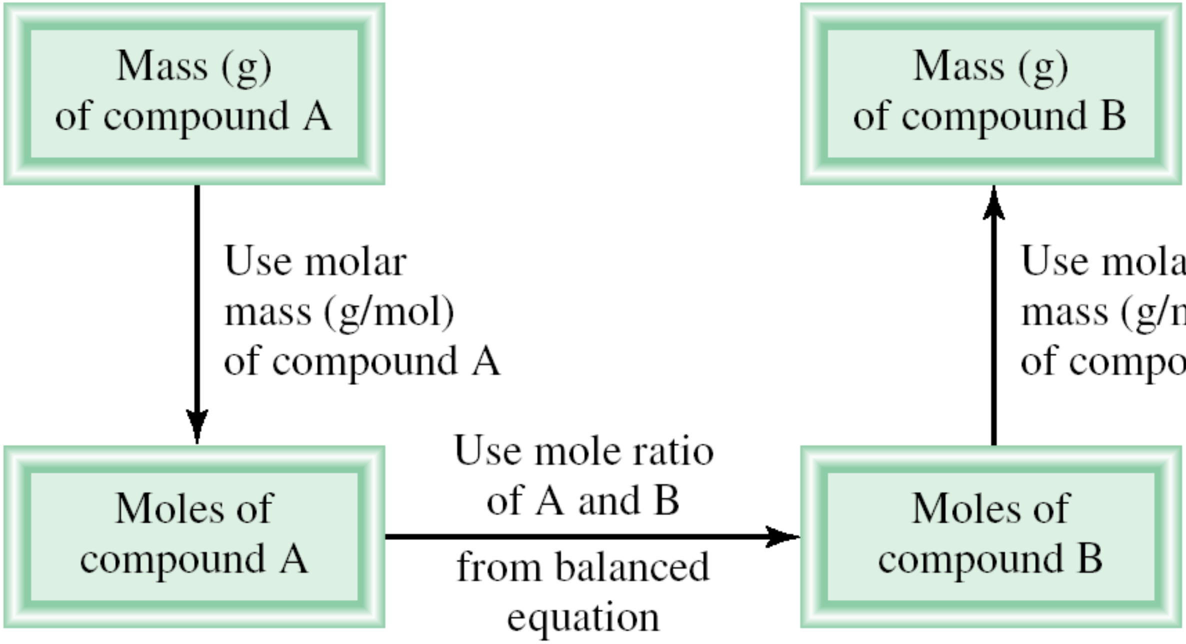
5. Check to make sure that you have the same number of each type of atom on both sides of the equation.

$$2C_2H_6 + 7O_2 \longrightarrow 4CO_2 + 6H_2O$$

4 C (2 x 2)	4 C
12 H (2 x 6)	12 H (6 x 2)
14 O (7 x 2)	14 O (4 x 2 + 6)

Reactants	Products
4 C	4 C
12 H	12 H
14 O	14 O

Amounts of Reactants and Products



1. Write balanced chemical equation
2. Convert quantities of known substances into moles
3. Use coefficients in balanced equation to calculate the number of moles of the sought quantity
4. Convert moles of sought quantity into desired units

Methanol burns in air according to the equation

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

If 209 g of methanol are used up in the combustion, what mass of water is produced?

$$\text{grams } CH_3OH \longrightarrow \text{moles } CH_3OH \longrightarrow \text{moles } H_2O \longrightarrow \text{grams } H_2O$$

molar mass
CH_3OH

coefficients
chemical equation

molar mass
H_2O

$$209 \text{ g } \cancel{CH_3OH} \times \frac{1 \text{ mol } \cancel{CH_3OH}}{32.0 \text{ g } \cancel{CH_3OH}} \times \frac{4 \text{ mol } \cancel{H_2O}}{2 \text{ mol } \cancel{CH_3OH}} \times \frac{18.0 \text{ g } H_2O}{1 \text{ mol } \cancel{H_2O}} =$$

235 g H_2O

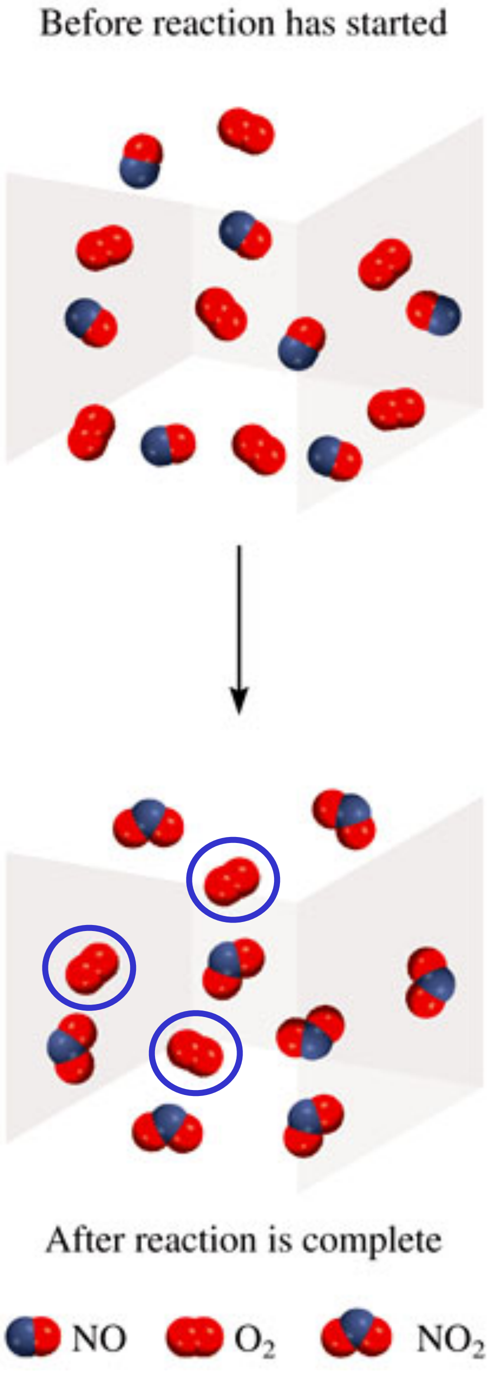
Limiting Reagent:

Reactant used up first in the reaction.

$$2NO + O_2 \longrightarrow 2NO_2$$

NO is the limiting reagent

O_2 is the excess reagent



In one process, 124 g of Al are reacted with 601 g of Fe_2O_3

$$2Al + Fe_2O_3 \longrightarrow Al_2O_3 + 2Fe$$

Calculate the mass of Al_2O_3 formed.

g Al ⟶ mol Al ⟶ mol Fe_2O_3 needed ⟶ g Fe_2O_3 needed

OR

g Fe_2O_3 ⟶ mol Fe_2O_3 ⟶ mol Al needed ⟶ g Al needed

$$124\ \cancel{\text{g Al}} \times \frac{1\ \cancel{\text{mol Al}}}{27.0\ \cancel{\text{g Al}}} \times \frac{1\ \cancel{\text{mol Fe}_2\text{O}_3}}{2\ \cancel{\text{mol Al}}} \times \frac{160.\ \text{g Fe}_2\text{O}_3}{1\ \cancel{\text{mol Fe}_2\text{O}_3}} = 367\ \text{g Fe}_2\text{O}_3$$

Start with 124 g Al ⟶ need 367 g Fe_2O_3

Have more Fe_2O_3 (601 g) so Al is limiting reagent

Use limiting reagent (Al) to calculate amount of product that can be formed.

$$\text{g Al} \longrightarrow \text{mol Al} \longrightarrow \text{mol } Al_2O_3 \longrightarrow \text{g } Al_2O_3$$

$$2Al + Fe_2O_3 \longrightarrow Al_2O_3 + 2Fe$$

$$124\ \cancel{\text{g Al}} \times \frac{1\ \cancel{\text{mol Al}}}{27.0\ \cancel{\text{g Al}}} \times \frac{1\ \cancel{\text{mol } Al_2O_3}}{2\ \cancel{\text{mol Al}}} \times \frac{102.\ \text{g } Al_2O_3}{1\ \cancel{\text{mol } Al_2O_3}} = 234\ \text{g } Al_2O_3$$

At this point, all the Al is consumed and Fe_2O_3 remains in excess.

Reaction Yield

Theoretical Yield is the amount of product that would result if all the limiting reagent reacted.

Actual Yield is the amount of product actually obtained from a reaction.

$$\textbf{\% Yield} = \frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\%$$

Chemistry In Action: Chemical Fertilizers

Plants need: N, P, K, Ca, S, & Mg

$$3H_2\ (g) + N_2\ (g) \longrightarrow 2NH_3\ (g)$$

$$NH_3\ (aq) + HNO_3\ (aq) \longrightarrow NH_4NO_3\ (aq)$$

fluorapatite

$$2Ca_5(PO_4)_3F\ (s) + 7H_2SO_4\ (aq) \longrightarrow$$

$$3Ca(H_2PO_4)_2\ (aq) + 7CaSO_4\ (aq) + 2HF\ (g)$$