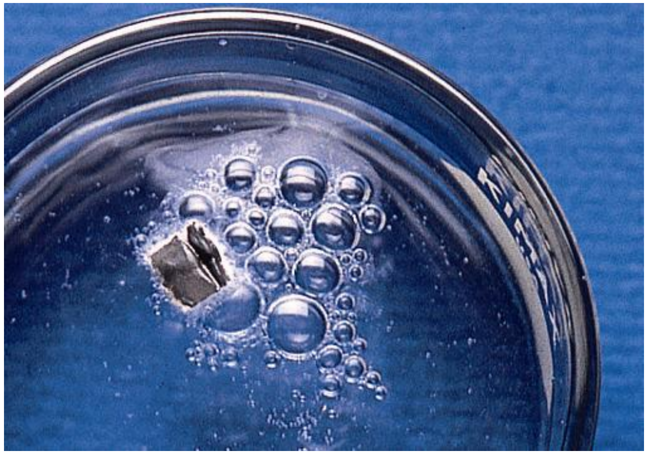
Mass Relationships in Chemical Reactions

Chapter 3



Atomic Mass & Atomic Mass Unit (amu)

Micro World atoms & molecules	$\longrightarrow$	Macro World grams

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

One ***atomic mass unit***: a mass exactly equal to one-twelfth the mass of one carbon-12 atom.

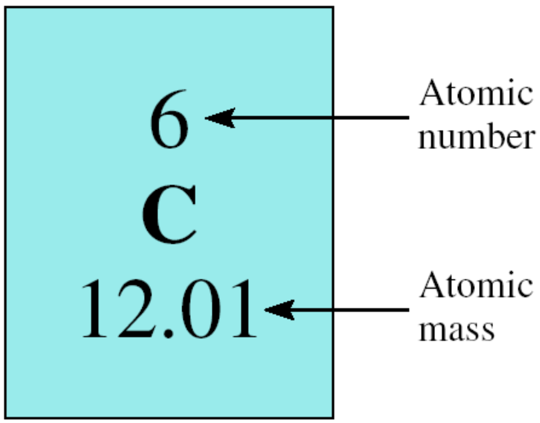
By definition:
1 atom ^{12}C "weighs" 12 amu

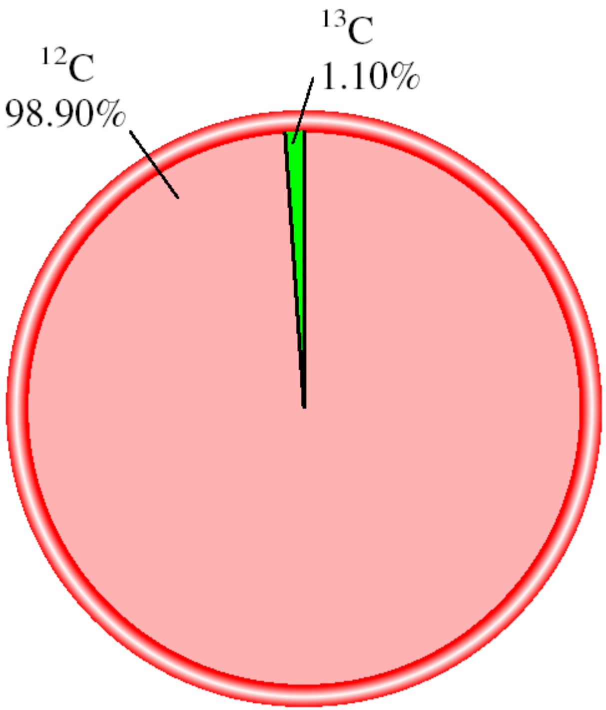
On this scale:
^{1}H = 1.008 amu; ^{16}O = 16.00 amu

a H atom is 8.400% as massive as ^{12}C atom;
atomic mass of H is 0.084 x 12 amu = 1.008 amu

Average Atomic Mass

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





Average Atomic Mass

Naturally occurring lithium is:

7.42% ^{6}Li (6.015 amu)

92.58% ^{7}Li (7.016 amu)

Average atomic mass of lithium:

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

10 **Ne** Neon 20.18 — 10: Atomic number; 20.18: Atomic mass

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)

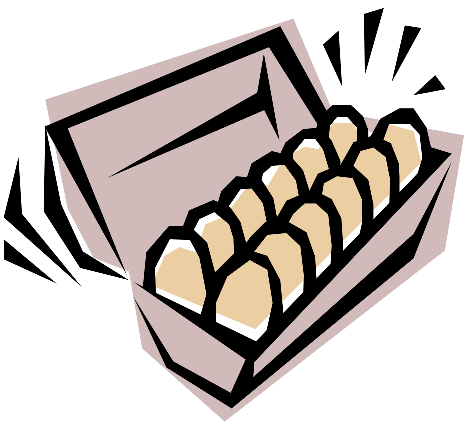
Metals

Metalloids

Nonmetals

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

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

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

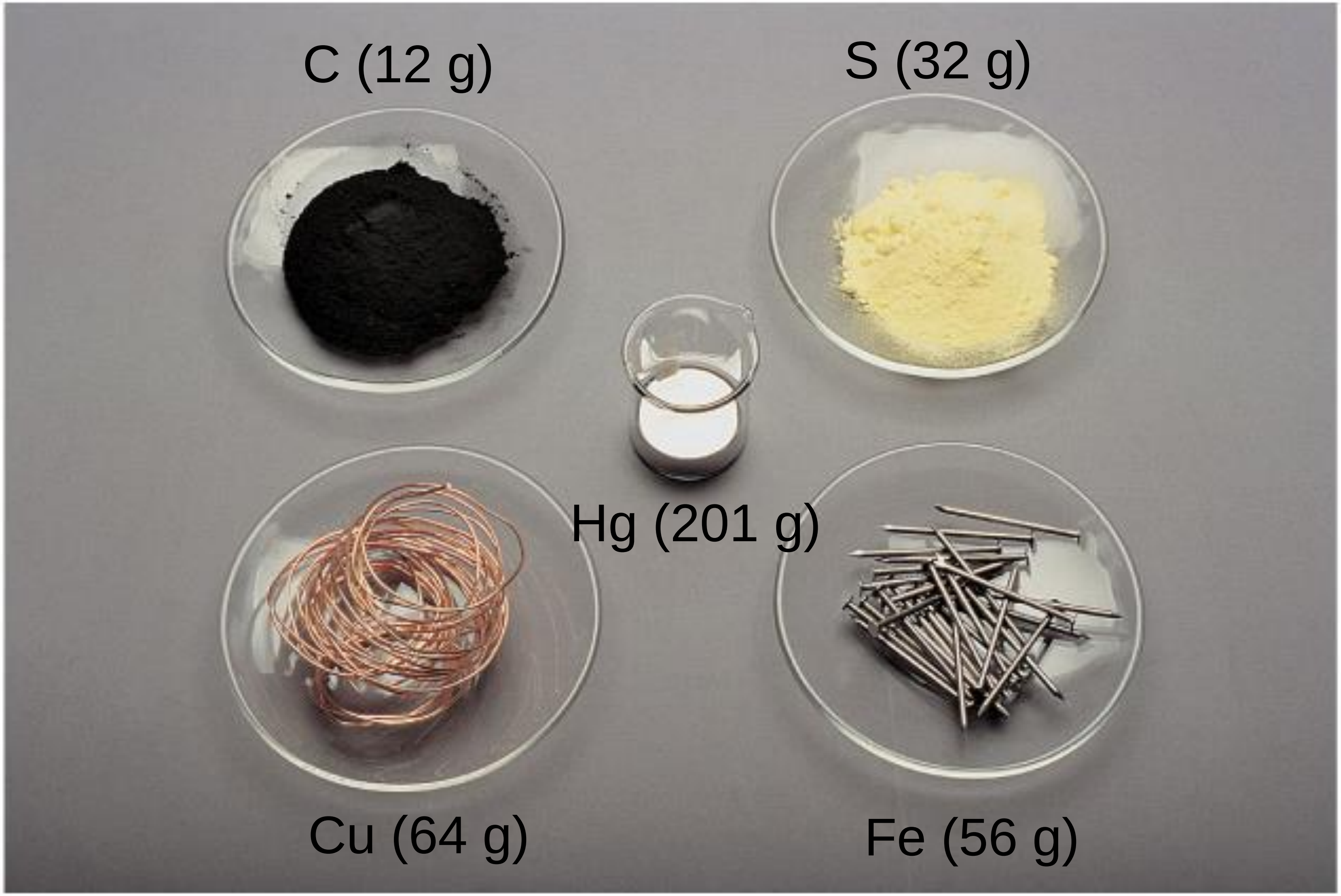
1 ^{12}C atom = 12.00 amu

For any element
atomic mass (amu) = molar mass (grams)

1 atom O = 16.00 amu

1 mole O = 16.00 g O

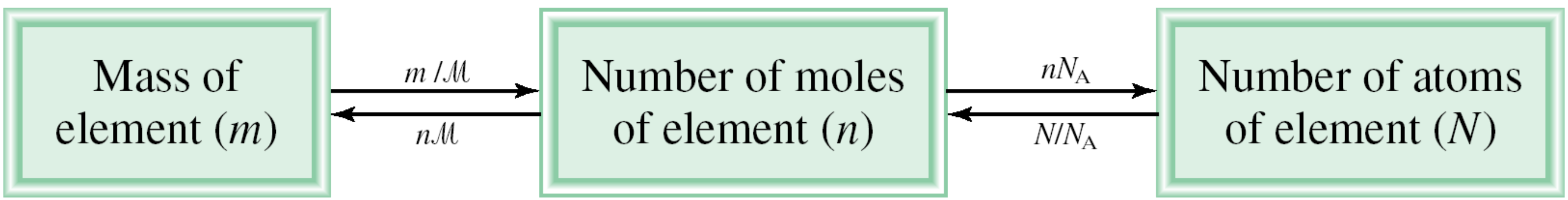
One Mole of:



Relationship between amu & gram

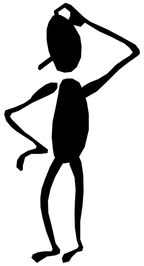
$$\frac{1\ {}^{12}\text{C}\ \cancel{\text{atom}}}{12.00\ \text{amu}} \times \frac{12.00\ \text{g}}{6.022 \times 10^{23}\ {}^{12}\text{C}\ \cancel{\text{atoms}}} = \frac{1.66 \times 10^{-24}\ \text{g}}{1\ \text{amu}}$$

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



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

N_A = Avogadro's number



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

$$1 \text{ mol K} = 39.10 \text{ g K}$$

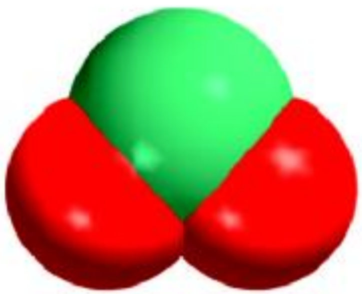
$$1 \text{ mol K} = 6.022 \times 10^{23} \text{ atoms K}$$

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

$$8.49 \times 10^{21} \text{ atoms K}$$

Molecular Mass

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



SO_2

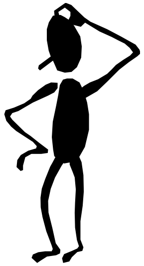
1S	32.07 amu
2O	+ 2 x 16.00 amu
SO_2	64.07 amu

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?

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

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

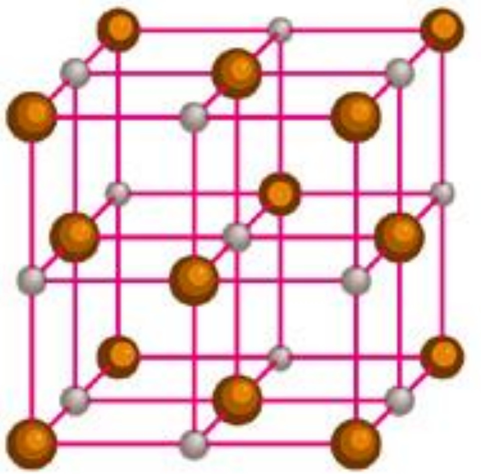
$$1 \text{ mol H} = 6.022 \times 10^{23} \text{ atoms H}$$

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

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

Formula Mass

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



NaCl

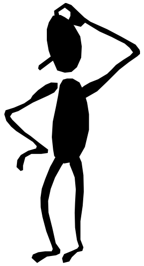
1Na	22.99 amu
1Cl	+ 35.45 amu
NaCl	58.44 amu

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 $Ca_3(PO_4)_2$

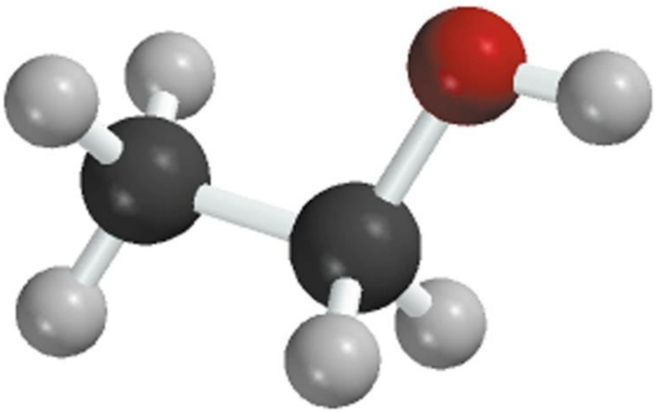
3 Ca		3 x 40.08
2 P		2 x 30.97
8 O	+	8 x 16.00
		310.18 amu

Percent Composition of Compounds

Percent composition of an element in a compound =

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

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



C_2H_6O

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

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

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

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

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.

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

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

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

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

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

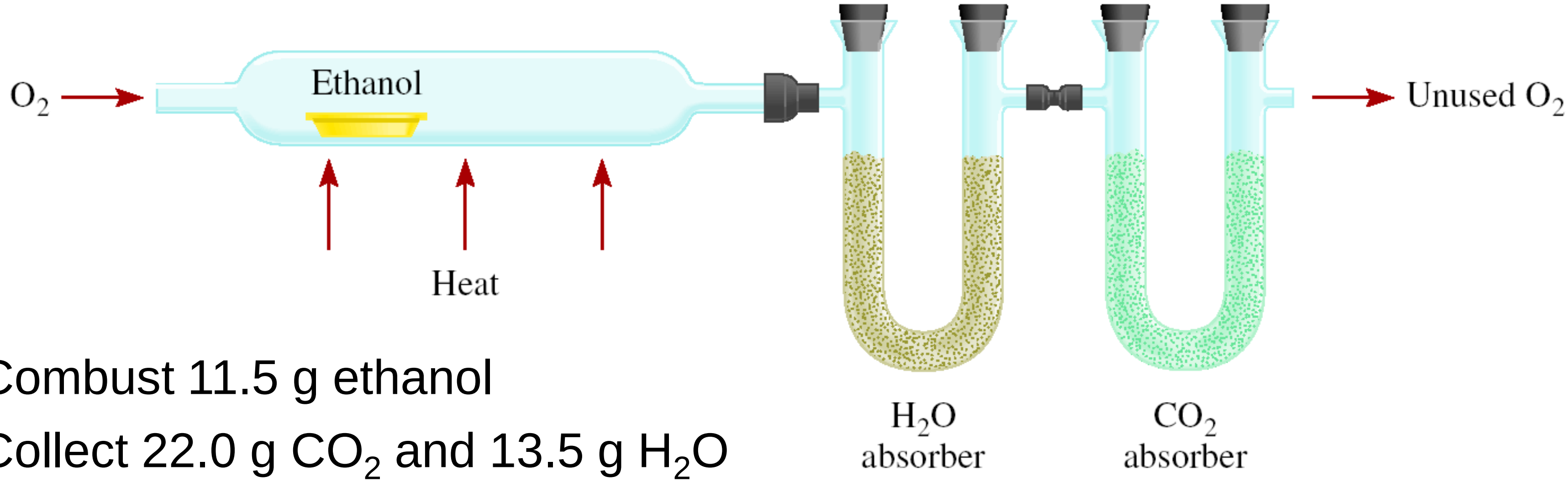
$$\text{K}: \frac{0.6330}{0.6329} \approx 1.0$$

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

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

$KMnO_4$

Experimental Determination of Empirical Formulas



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

Determination of Molecular Formulas

To calculate molecular formula we must know the *approximate* molar mass of the compound in addition to its empirical formula.

A sample of a compound contains 1.52 g of nitrogen and 3.47 g of oxygen. The molar mass of this compound is between 90 g and 95 g. Determine the molecular formula and the accurate molar mass of the compound.

$$n_N = 1.52 \cancel{\text{ g}} \text{ N} \times \frac{1 \text{ mol N}}{14.01 \cancel{\text{ g}} \text{ N}} = 0.108 \text{ mol N}$$

$$n_O = 3.47 \cancel{\text{ g}} \text{ O} \times \frac{1 \text{ mol O}}{16.00 \cancel{\text{ g}} \text{ O}} = 0.217 \text{ mol O}$$

$N_{0.108}O_{0.217}$; smallest subscript 0.108

Empirical formula NO_2

Determination of Molecular Formulas (contd.)

Empirical molar mass = 14.01 g + 2(16.00 g) = 46.01 g

Ratio between molar mass and empirical molar mass,

$$\frac{\text{Molar mass}}{\text{Empirical molar mass}} = \frac{90\text{ g}}{46.01\text{ g}} \approx 2$$

Molar mass is *twice* the empirical molar mass.

There are two NO_2 units in each molecule of the compound.

Molecular formula is $(NO_2)_2$ or N_2O_4.

Chemical Reactions & Chemical Equations

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

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

Writing Chemical Equations

When H_2 gas burns in air (which contains O_2) to form H_2O,

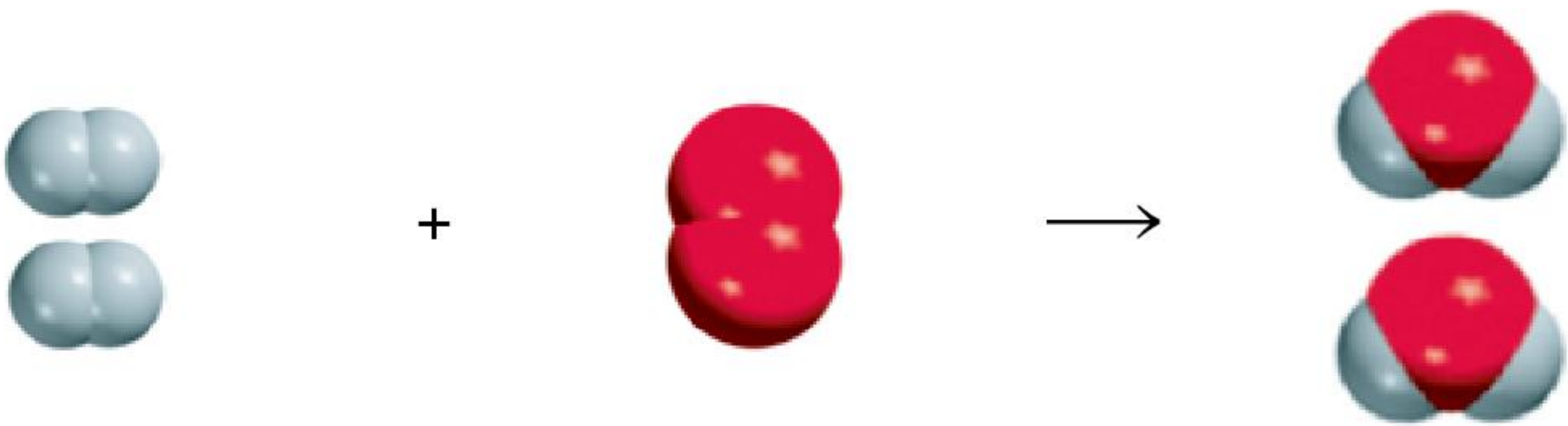
$$2H_2 + O_2 \longrightarrow 2H_2O$$

"plus" means "reacts with" & arrow means "to yield"

3 ways of representing the above reaction (for mass balance x 2):

Two hydrogen molecules + One oxygen molecule $\longrightarrow$ Two water molecules

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



Writing Chemical Equations

Chemical equation is the chemist's shorthand description of a reaction.

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

$$\text{reactants} \longrightarrow \text{products}$$

Reactants are the starting materials in a chemical reaction, *e.g.*, H_2 & O_2; written on the left of the arrow.

Products are the substances formed as a result of a chemical reaction, *e.g.*, H_2O; written on the right of the arrow.

$$\text{reactants} \rightleftharpoons \text{products}$$

Writing Chemical Equations

Physical states *are represented by* ***g(gas)****,* ***l(liquid)*** *&* ***s(solid)****:*

$$2CO(g) + O_2(g) \longrightarrow 2CO_2(g)$$

$$2HgO(s) \longrightarrow 2Hg(l) + O_2(g)$$

$$NaCl(s) \xrightarrow{H_2O} NaCl(aq)$$

$$KBr(aq) + AgNO_3(aq) \longrightarrow KNO_3(aq) + AgBr(s)$$

[No reaction in solid phase]

How to "Read" Chemical Equations

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

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: Mole method

How much reactant? or How much product?

Stoichiometry: *the quantitative study of reactants and products in a chemical reaction.*

We use **moles** to calculate the amount of products formed.

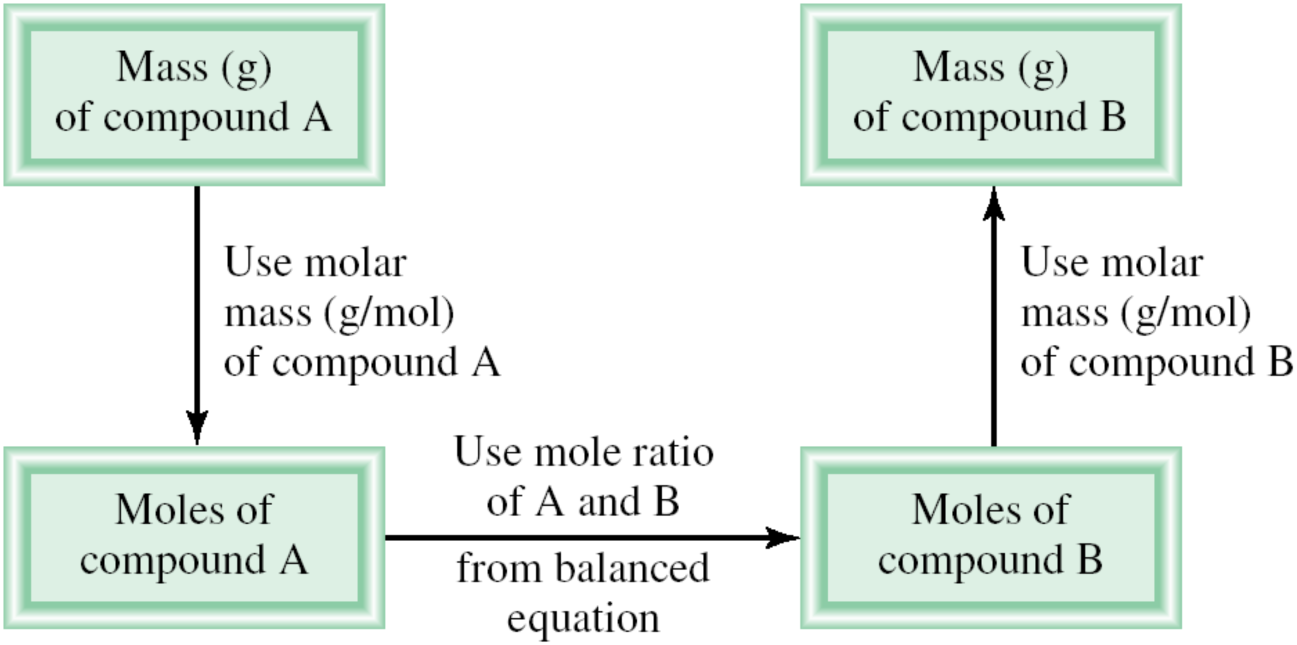
Mole method: *the stoichiometric coefficients in a chemical equation can be interpreted as the number of moles of each substance.*

$2CO(g)$	+	$O_2(g)$	$\rightarrow$	$2CO_2(g)$
2 molecule		1 molecule		2 molecule
2(6.022×10^{23} molecules)		6.022×10^{23} molecules		2(6.022×10^{23} molecules)
2 mol		1 mol		2 mol

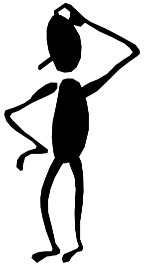
Grams of CO $\rightarrow$ moles of CO $\rightarrow$

moles of CO_2 $\rightarrow$ grams of CO_2

Amounts of Reactants and Products: Mole method



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

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

$$235 \text{ g } H_2O$$

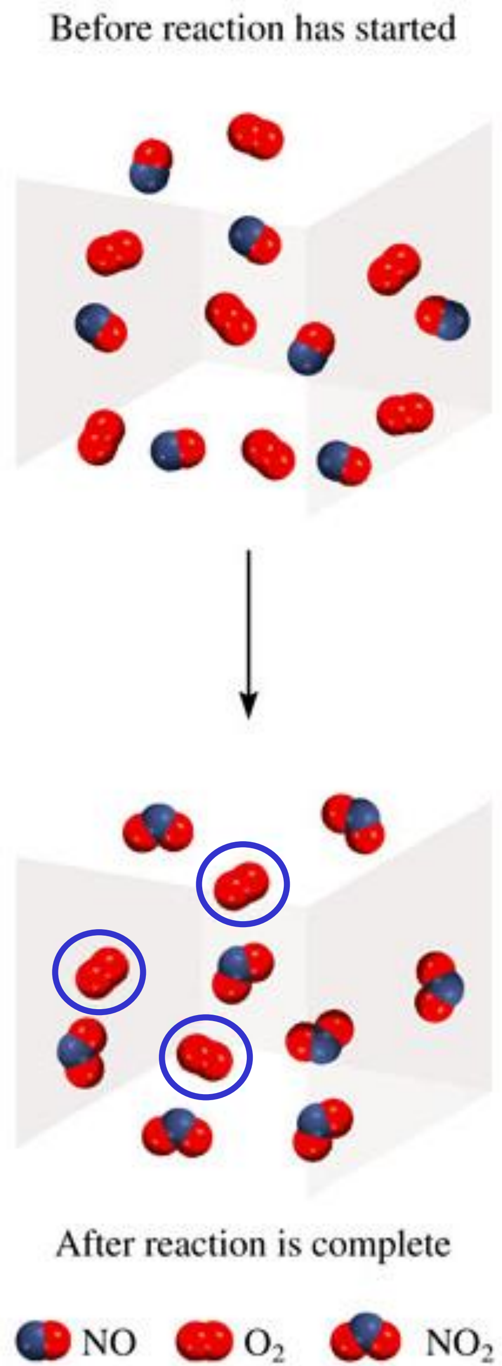
Limiting Reagent

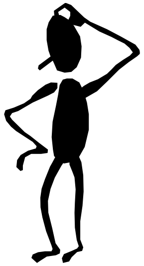
Reactant used up first in the reaction.

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

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:

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

Calculate the mass of Al_2O_3 formed.

g Al $\longrightarrow$ mol Al $\longrightarrow$ mol Fe_2O_3 needed $\longrightarrow$ g Fe_2O_3 needed

OR

g Fe_2O_3 $\longrightarrow$ mol Fe_2O_3 $\longrightarrow$ mol Al needed $\longrightarrow$ g Al needed

$$\cancel{124\ \text{g Al}} \times \frac{1\ \cancel{\text{mol Al}}}{\cancel{27.0\ \text{g Al}}} \times \frac{1\ \cancel{\text{mol } Fe_2O_3}}{2\ \cancel{\text{mol Al}}} \times \frac{160.\ \text{g } Fe_2O_3}{1\ \cancel{\text{mol } Fe_2O_3}} = 367\ \text{g } Fe_2O_3$$

Start with 124 g Al $\longrightarrow$ 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.

g Al $\longrightarrow$ mol Al $\longrightarrow$ mol Al_2O_3 $\longrightarrow$ g Al_2O_3

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

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

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