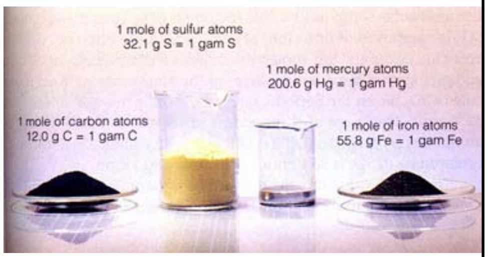
Mass Relationships in Chemical Reactions

Chapter 3

Molar mass and the mole

- one mole is defined as the number of carbon atoms in exactly 12.000000 grams of pure 12C.
- From the sugar example, a mole of $C_{12}H_{22}O_{11}$ would have a mass of 342.299 grams.
- This quantity is known as the **molar mass**, a term that is often used in place of the terms *atomic mass* or *molecular mass.*



Determine the molar mass of NaOH?

NaOH contains one Na atom + one oxygen atom + one hydrogen atom

Molar mass = 1 x mass of Na atom + 1 x mass of O atom + 1 x mass of H atom

The masses of the elements can be obtained from the periodic table.

= 1 x 22.99 + 1 x 16.00 + 1 x 1.008 = 39.99 g

Molar mass of NaOH = 39.99 g

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Calculate the molecular weight of the following:

a) H_2SO_4

MW of H_2SO_4 = 2 x H + 1xS +4xO = 2x1 + 1x32 + 4x16 = 98 g/mole

b) CH_3OH

MW of CH_3OH

= 4x H + 1xC +1xO = 4x1 + 1x12 + 1x16 = 32 g/mole

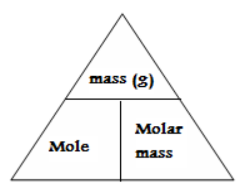
c) Lauric acid $C_3H_{24}O_2$

MW of $C_3H_{24}O_2$ = 24 x H + 3xC +2xO = 24x1 + 3x12 + 2x16 = 92 g/mole

Number of moles

- **To determine the number of moles use the following formula or triangles:**

$$number\ of\ moles = \frac{mass\,(g)}{molar\ mass\,(g\,/\,mole)}$$



How many moles are there in 22.99 g of sodium?

$$\text{number of moles} = \frac{\text{mass (g)}}{\text{molar mass (g / mole)}} = \frac{22.99\,\text{g}}{22.99\,\text{g / mole (from the periodic table)}}$$

number of moles = 1 mole.

How many moles are there in 1 g of chlorine?

$$\text{number of moles} = \frac{\text{mass (g)}}{\text{molar mass (g / mole)}} = \frac{1\,\text{g}}{35.45\,\text{g / mole (from the periodic table)}}$$

number of moles = 0.028 mole.

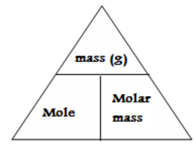
How many grams are there in 0.10 mole of CH_4?

First calculate the molar mass of CH_4

Molar mass of CH_4 = 1 x mass of C atom + 4 x mass of H atoms

= 1 x 12.01 + 4 x 1.008 = 16.02 g / mole

Then use the formula:



mass of CH_4 = number of moles × molar mass of CH_4

= 0.10 mole x16.02 g/ mole = 1.602 g

Which one is the lightest in mass: one mole of hydrogen, one mole of sodium, one mole of iron, one mole of sulfur?

One mole for an element contains the atomic mass of the element.
Atomic mass of H = 1.008 g / mole, Atomic mass of Na = 22.99 g / mole,
Atomic mass of Fe = 55.85 g / mole, Atomic mass of S = 32.07 g / mole.

The lightest one is one mole of hydrogen
The heaviest one mole is the iron.

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• Avogadro's number and the mole

1 mole of anything contains the Avogadro 's Number (N_A) of this thing

Avogadro 's Number (NA) = *6.02214 x 10^{23}*

1 mole of particles= 6.02214 x 1023 particles for any substance

1 mole of shoes= 6.02214 x 1023 shoes

1 mole of cars = 6.02214 x 1023 car

1 mole of carbon atoms= 6.02214 x 1023 carbon atoms

1 mole of water molecules = 6.02214 x 1023 water molecules

Number of particles = number of moles x Avogadro's number

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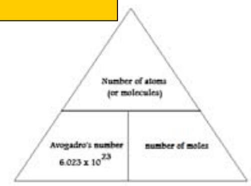
To calculate the number of particles (atoms, molecules, shoes….etc) use the following formula:

Number of particles = number of moles x Avogadro's number



Calculate the number of atoms in 2 mole of hydrogen?

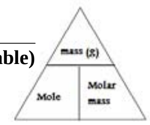
Number of hydrogen atoms =

2 moles of H x 6.02214 x 10^{23} H atom / mole

Number of hydrogen atoms = 1.20 x 10^{24} H atom

Calculate the number of atoms in 6.46 grams of helium (He)?

$$\text{number of moles} = \frac{\text{mass (g)}}{\text{molar mass (g / mole)}} = \frac{6.46\text{ g}}{4.003\text{ g / mole (from the periodic table)}}$$



number of moles = 1.61 mole.

Number of He atoms = number of moles × Avogadro's number

= 1.61 moles of He x 6.02214 x 10^{23} He atom / mole

= 9.66 x 10^{23} He atom

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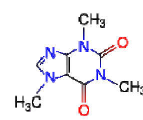
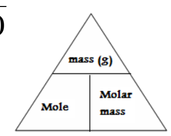
Caffeine is a stimulant drug and it is found in coffee, tea and beans. Its molecular formula is $C_8H_{10}N_4O_2$. Calculate the number of oxygen atoms in 19.40 grams of caffeine.



Molar mass of caffeine = 8 x C + 10 x H + 4 x N + 2 x O

= 8 x 12 + 10 x 1 + 4 x 14 + 2 x 16 = 194 g / mole

$$\text{number of moles} = \frac{\text{mass (g)}}{\text{molar mass (g / mole)}} = \frac{19.40\text{ g}}{194\text{ g / mole (from the periodic table)}}$$



number of moles = 0.10 mole

Total number of $C_8H_{10}N_4O_2$ molecules= number of moles x N_A

= 0.10 moles x 6.022 x 10^{23} molecules / mole

Total number of $C_8H_{10}N_4O_2$ molecules = 6.022 x 10^{22} molecules

$$\text{Number of oxygen atoms} = \frac{\text{number of oxygen atoms}}{\text{molecules}} \text{ x total number of molecules}$$

$$\text{Number of oxygen atoms} = \frac{\text{2 oxygen atoms}}{\text{molecules}} \text{ x } 6.022 \text{ x } 10^{22} \text{ molecules}$$

Number of oxygen atoms = 1.20 x 10^{23} oxygen atoms

Number of carbon atoms = 4.8 x 10^{23} carbon atoms

Number of hydrogen atoms = 6.022 x 10^{23} hydrogen atoms

Number of nitrogen atoms = 2.40 x 10^{23} nitrogen atoms

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Mass Percent

The Mass Percent of an element is defined as:

$$\text{Mass Percent of an element} = \frac{\text{Mass of the element}}{\text{Total molar mass of the sample}} \text{x}100\%$$

What is the mass percent of carbon, hydrogen, and oxygen in pure ethanol C_2H_6O?

-First: calculate the molar mass of C_2H_6O

MW of C_2H_6O = 2 x C + 6 x H + 1 x O

= 2 x 12.01 + 6 x 1.008 + 1 x 16.00

MW C_2H_6O = 46.07 g/mole

-Second: calculate the mass percents

$$\text{Mass \% C} = 100 \text{ x } \left(\frac{\text{mass of C}}{\text{total molar mass}}\right) = 100 \text{ x } \left(\frac{2 \text{ x } 12.01}{46.07}\right) = 52.14\ \%$$

$$\text{Mass \% H} = 100 \text{ x } \left(\frac{\text{mass of H}}{\text{total molar mass}}\right) = 100 \text{ x } \left(\frac{6 \text{ x } 1.008}{46.07}\right) = 13.13\ \%$$

$$\text{Mass \% O} = 100 \text{ x } \left(\frac{\text{mass of O}}{\text{total molar mass}}\right) = 100 \text{ x } \left(\frac{1 \text{ x } 16.00}{46.07}\right) = 34.72\ \%$$

Note that the mass percentages should add up to 100%.

Mass % = Mass % C + Mass % H + Mass % O

= 52.14 % + 13.13 % + 34.72 % = 99.99 %

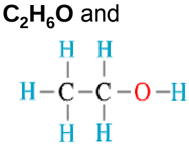
Chemical and structural Formulas

The **chemical formula** tells you how many of each type of atom are in a molecule.

The **structural formula** tells you how many of each type of atoms are in a molecule and also how they are connected.

For example, the chemical formula for ethanol is **C_2H_6O** and

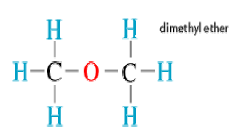
The structural formula of ethanol is



Be carful, the chemical formula could be the same for different molecules, but the structural formula is unique.

The chemical formula for dimethyl ether is **C_2H_6O** and

The structural formula of dimethyl ether is:



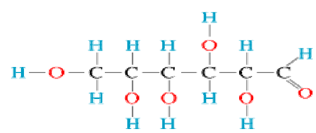
Empirical Formulas (simplest formula)

- It shows the simplest whole number ratio of atoms in a molecule.
- For example, hydrogen peroxide's **chemical formula** is H_2O_2, but its **empirical formula** is HO

$$\text{Molecular Formula} = \left(\frac{\text{Molecular weight of unknown (g/mole)}}{\text{mass of Emperical formula}}\right) \text{x} \text{Emperical formula}$$

Write the different formulas for the glucose molecule

The chemical formula for glucose is $C_6H_{12}O_6$, but its empirical formula is CH_2O, and its structural formula is



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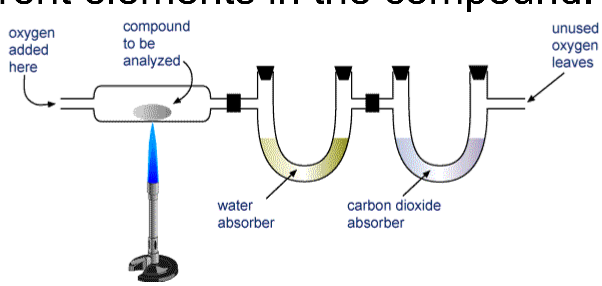
Combustion Analysis

- It is used to determine the mass % for different elements in the compound.



The sample is burned in the presence of excess oxygen which converts all the carbon to carbon dioxide and all the hydrogen to water.

The CO_2 and H_2O produced are absorbed in two different stages and their masses determined by measuring the increase in weight of the absorbers.

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- **Ascorbic acid (vitamin C) contains only C, H, and O. Combustion of 1.000 g of Ascorbic acid produced 40.9% C and 4.5% H. What is the empirical formula for Ascorbic Acid?**

First: calculate the mass percent of Oxygen.

Since the sample contains C, H, and O, then the remaining

100% - 40.9% - 4.5% = 54.6% is Oxygen

Second: Suppose 100 g of this substance

Steps		C	H	O
1	Mass /g	40.9	4.5	54.6
2	No. of moles = $\frac{\text{mass}}{\text{molar mass}}$	$\frac{40.9}{12}$ =3.4	$\frac{4.5}{1}$ =4.5	$\frac{54.6}{16}$ =3.4
3	÷ smallest number (3.4)	1	1.3	1
4	x by a number to make step 3 integer numbers (x 3)	1 x 3 = 3	1.3 x 3 = 4	1 x 3 = 3
5	Empirical formula $C_3H_4O_3$	3 C	4 H	3 O

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What is the molecular formula if the molecular mass of Ascorbic Acid was founded to be 176 g/mole?

$$\text{Molecular Formula} = \left(\frac{\text{Molecular weight of unknown (g/mole)}}{\text{mass of emperical formula}}\right) \text{x empirical Formula}$$

$$\text{Molecular Formula} = \left(\frac{176\ \text{(g/mole)}}{3\text{x}12 + 4\text{x}1 + 3\text{x}16}\right) \text{x } C_3H_4O_3 =$$

$$= 2 \text{ x } C_3H_4O_3 = C_6H_8O_6$$

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Chemical Reactions

It is process in which one or more pure substances are converted into one or more different pure substance.

All chemical reactions involve a change in substances and a change in energy.

Neither matter nor energy is created or destroyed in a chemical reaction, only changed.

Chemical equation

- When a chemical reaction occurs, it can be described by an equation.
- This shows the chemicals that react (***reactants***) on the left-hand side, and the chemicals that they produce (***products***) on the right-hand side.

Reactants $\xrightarrow{\text{Reaction conditions}}$ **Products**

Reaction between hydrogen gas and oxygen gas to produce liquid water

hydrogen gas + oxygen gas $\longrightarrow$ liquid water

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

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Balancing chemical equations

- first write the correct formula for both reactants and products and then **balance** all of the atoms on the left side of the reaction with the atoms on the right side.

Write the chemical equation which represents the burning of glucose in presence of oxygen gas which produces carbon dioxide and water.

To answer this question, follow the following steps:

1. *Identify the reactants and the products and put an arrow in between.*

glucose + oxygen gas $\longrightarrow$ carbon dioxide + water

2. Try to figure out the correct formula for the reactants and products,

Glucose is $C_6H_{12}O_6$, oxygen gas is O_2, carbon dioxide is CO_2, and water is H_2O.

$$C_6H_{12}O_6 + O_2 \longrightarrow CO_2 + H_2O$$

3.Count the number of each atom at both sides of the equation:

$$C_6H_{12}O_6 + O_2 \longrightarrow CO_2 + H_2O$$

(6 C + 12 H + 6 O) + (2 O) $\longrightarrow$ (1C + 2 O) + (2H + 1 O)

Total: (6 C + 12 H + 8 O) $\longrightarrow$ (1C + 2H + 3 O)

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Balance C first, then H, and finally O:

At the left side there are 6 C atoms and at the right side there are 1 C atom, so multiply CO_2 by 6 (x 6)

$$C_6H_{12}O_6 + O_2 \longrightarrow \mathbf{6}\ CO_2 + H_2O$$

At the left side there are 12 H atoms and at the right side there are 2 H atom, so multiply H_2O by 6 (x 6)

$$C_6H_{12}O_6 + O_2 \longrightarrow \mathbf{6}\ CO_2 + \mathbf{6}H_2O$$

At the left side there are 8 O atoms and at the right side there are 18 O atom, so multiply O_2 by 6 (x 6)

$$C_6H_{12}O_6 + \mathbf{6}O_2 \longrightarrow \mathbf{6}\ CO_2 + \mathbf{6}H_2O$$

Recount all atoms again,

$$C_6H_{12}O_6 + \mathbf{6}O_2 \longrightarrow \mathbf{6}\ CO_2 + \mathbf{6}H_2O$$

(6 C + 12 H + 6 O) + (12 O)	(6C + 12 O) + (12H + 6 O)
Total: (6 C + 12 H + 18 O)	(6 C + 12 H + 18 O)

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Amount of reactants and products problems

$$aA \longrightarrow bB$$

In this type of problems, you are given the mass (#moles) of the reactant and you calculate the mass (#moles) of the product.

You can use the following formula to calculate the #moles of B:

$$\text{number of moles of (B)} = \text{number of moles of (A)} \times \left(\frac{b}{a}\right)$$

You can use the following formula to calculate the mass of B:

$$\text{mass of (B)} = \left(\frac{\text{mass of (A)}}{\text{Molar mass of (A)}}\right) \times \left(\frac{b}{a}\right) \times \text{Molar mass of (B)}$$

How many grams of water are produced when 7.00 grams of oxygen react with an excess of hydrogen according to the reaction shown below?

$2H_2(g) + O_2(g) \text{ ----> } 2H_2O(g)$

✓The "excess" reactant has nothing to do with the problem.

✓Identify which is the "given" and which is the unknown.

$2H_2(g) + O_2(g) \text{ ----> } 2H_2O(g)$

7 g ?

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- Use the formula:

$$\text{mass of }(H_2O) = \left(\frac{\text{mass of } O_2}{\text{Molar mass of } O_2}\right) x \left(\frac{2(H_2O)}{1(O_2)}\right) x \text{ Molar mass of }(H_2O)$$

$$\text{mass of }(H_2O) = \left(\frac{7.0\,g}{32\,g/mole}\right) x \left(\frac{2(H_2O)}{1(O_2)}\right) x\,18\,g/mole$$

Mass of H_2O = 7.89 g

Calculate the number of moles of CO_2 resulted from the reaction of 3.5 moles of C_2H_6 with excess oxygen according to the equation

$$2\,C_2H_6 + 7\,O_2 \rightarrow 4\,CO_2 + 6\,H_2O$$

•Use the formula:

$$\text{number of moles of }(CO_2) = \text{number of moles of }(C_2H_6) x \left(\frac{4(C_2H_6)}{2(CO_2)}\right)$$

$$\text{number of moles of }(CO_2) = 3.5\text{ moles of }(C_2H_6) x \left(\frac{4(C_2H_6)}{2(CO_2)}\right)$$

Number of moles of CO_2 = 7.0 moles

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Calculate the mass of chlorine that reacts with 4.770 g of hydrogen to form hydrogen chloride according the following equation:

$$H_2 + Cl_2 \rightarrow 2\,HCl$$

•Use the formula:

$$\text{mass of }(Cl_2) = \left(\frac{\text{mass of } H_2}{\text{Molar mass of } H_2}\right) x \left(\frac{1(H_2)}{1(Cl_2)}\right) x \text{ Molar mass of }(Cl_2)$$

$$\text{mass of }(Cl_2) = \left(\frac{4.770\text{g of } H_2}{2.0\text{g/mole}}\right) x \left(\frac{1(H_2)}{1(Cl_2)}\right) x\,71.0\text{g/mole}$$

Mass of Cl_2 = 169.3 g

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Limiting Reagents

$$aA + bB \longrightarrow dD$$

When two substances A and B are present in random quantities and react with each other to produce D, the <u>first consumed</u> one is *the limiting reagent* and the <u>second one</u> is remained in *excess*.

The amount of product should be calculated from the amount of the limiting reactant

To determine the limiting reagent from given moles of substance, do the followings:

1- Calculate the ratio for each reagent, by dividing the given moles of a reagent to its factor in the chemical equation.

2- Compare the ratios for the reagents and the limiting reagent is ***the smallest one***.

If 5 moles of NO were mixed with 5 moles of O_2 to react as: $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$

Determine the limiting reagent.

The ratio of $NO = \frac{5\,mol\,(given)}{2\,mol\,(factor)} = 2.5$

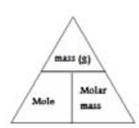
The ratio of $O_2 = \frac{5\,mol}{1\,mol} = 5$

The limiting reactant is NO because it is the smallest

If 400g Fe were mixed with 300g O_2 to react as:

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s)$$

Determine the limiting reagent.



Step 1: Change the mass in grams into moles for the given substances

$400g\,Fe \times \frac{1\,mol\,Fe}{55.8\,g/mole\,Fe} = 7.17\,mol\,Fe$ $\quad 300g\,O_2 \times \frac{1\,mole\,O_2}{32\,g/mole\,O_2} = 9.38\,mol\,O_2$

Step2: Calculate the ratio and compare

$Fe = \frac{7.17\,mol}{4\,mol} = 1.793$ $\quad O_2 = \frac{9.38\,mol}{3\,mol} = 3.127$ **Fe is the limiting reactant**

Chemical Reaction Yield

- For any chemical reaction there are theoretical and actual (practical) yield.
- *Theoretical yield (T.Y.)* is the amount of product that would result if all the limiting reactant reacted.
- *Actual yield (A.Y.)* is the amount of product actually obtained from a reaction.
- Due to many factors can affected on the reaction, A.Y. is always less than T.Y.
- *Percent yield* is the efficient for a given reaction:

$$\%\ \text{yield} = \frac{\text{A.Y.}}{\text{T.Y.}} \times 100$$

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Many tons of urea ($CO(NH_2)_2$) are produced every year in fertilizer industries. When 119 g ammonia react with 80 g CO2 as the equation: $2NH_3(g) + CO_2(g) \rightarrow CO(NH_2)_2(s) + H_2O$

and produce 100 g urea, calculate % yield?

- Step 1: Determine the limiting reagent

- Change the mass in grams into moles for the given substances

$$119\text{g}\ NH_3 \times \frac{1\ \text{mole}\ NH_3}{17\ \text{g}\ NH_3} = 7\ \text{mol}\ NH_3 \qquad 80\text{g}\ CO_2 \times \frac{1\ \text{mole}\ CO_2}{44\ \text{g}\ CO_2} = 1.82\ \text{mol}\ CO_2$$

- Calculate the ratio and compare

$$NH_3 = \frac{7\ \text{mol}}{2\ \text{mol}} = 3.5 \qquad CO_2 = \frac{1.82\ \text{mol}}{1\ \text{mol}} = 1.82$$

CO_2 is the limiting reagent

Now, ignore NH_3 and compare between CO_2 and $CO(NH_2)_2$ only.

- Step 2: Calculate the Theoretical Yield [#moles of $CO(NH_2)_2$]

$$\text{number of moles of (B)} = \text{number of moles of (A)} \text{x} \left(\frac{b}{a}\right)$$

$$\#\text{moles}\ CO(NH_2)_2 = \#\text{moles of}\ CO_2 \text{x} \left(\frac{1}{1}\right) = 1.82\text{moles}\ CO_2 \text{x1}$$

Number of moles of $CO(NH_2)_2$ = 1.82 moles

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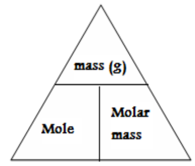
Step 3: Calculate the Theoretical Yield [mass of $CO(NH_2)_2$] produces:

The T.Y. $= 1.82\,\text{mole urea} \times \dfrac{60\,\text{g urea}}{1\,\text{mole urea}} = 109\,\text{g urea}$



Step 4: Calculate the %Yield of $CO(NH_2)_2$:

$$\%\ \text{yield} = \frac{\text{A.Y.}}{\text{T.Y.}} \times 100$$

$$\%\ \text{yield} = \frac{100}{109} \times 100 = 91.7\,\%$$