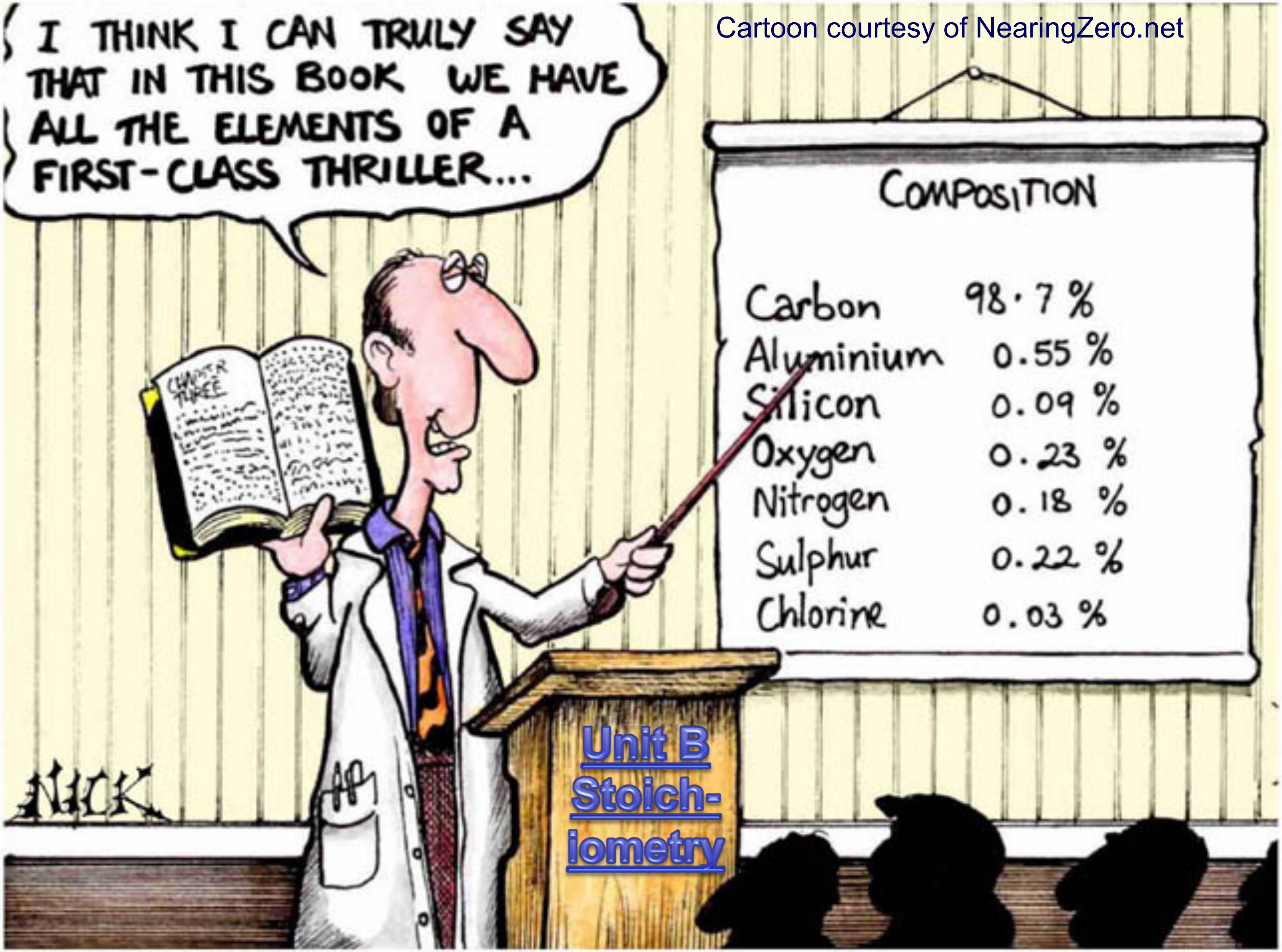
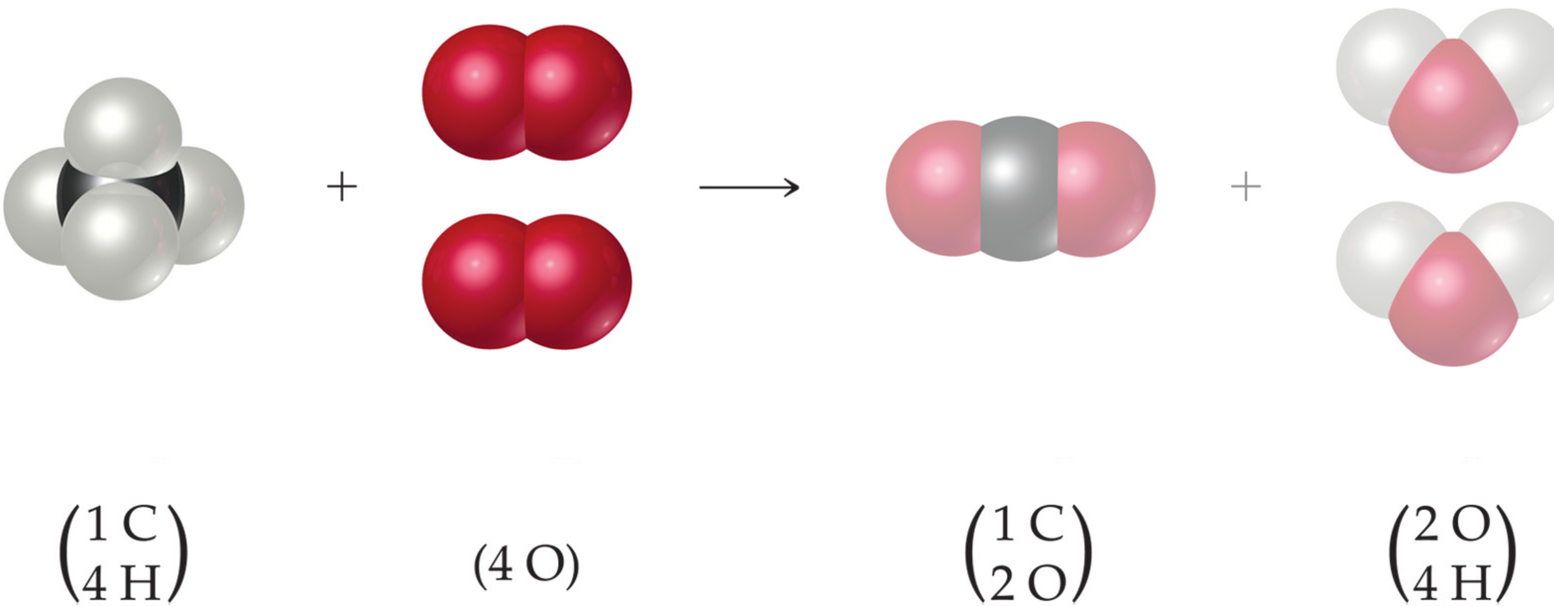


Cartoon courtesy of NearingZero.net

Unit B Stoich-iometry

Anatomy of a Chemical Equation

$$CH_{4\,(g)} + 2\;O_{2\,(g)} \longrightarrow CO_{2\,(g)} + 2\;H_2O_{\,(g)}$$

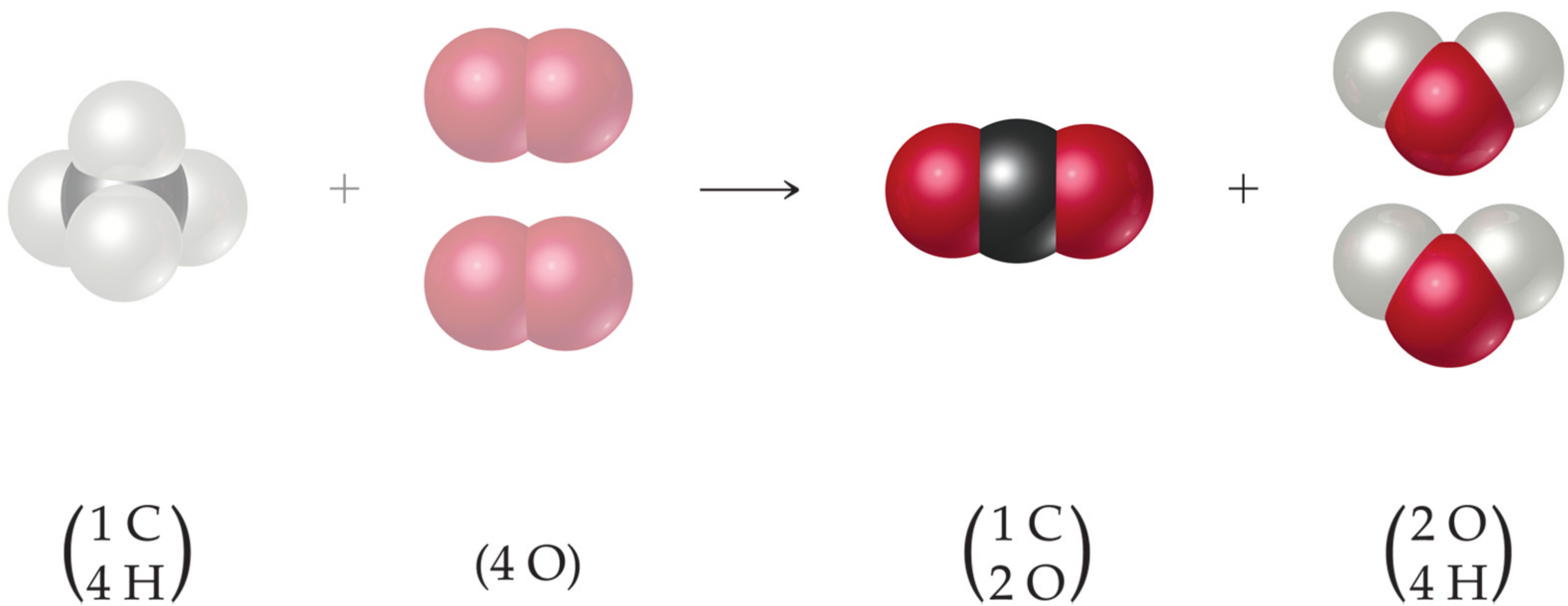


Reactants appear on the left side of the equation.

Stoichiometry

Anatomy of a Chemical Equation

$$CH_{4\,(g)} + 2\,O_{2\,(g)} \longrightarrow CO_{2\,(g)} + 2\,H_2O_{\,(g)}$$

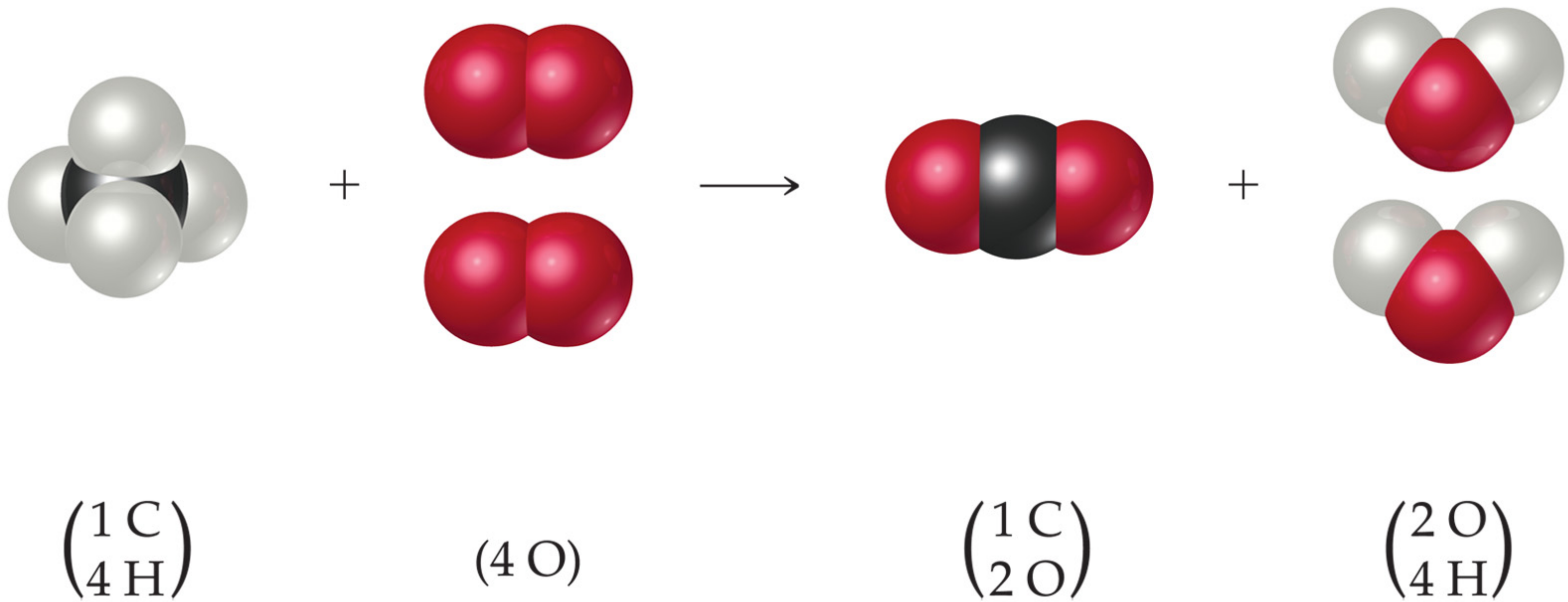


Products appear on the right side of the equation.

Stoichiometry

Anatomy of a Chemical Equation

$$CH_{4\,(g)} + 2\,O_{2\,(g)} \longrightarrow CO_{2\,(g)} + 2\,H_2O_{\,(g)}$$

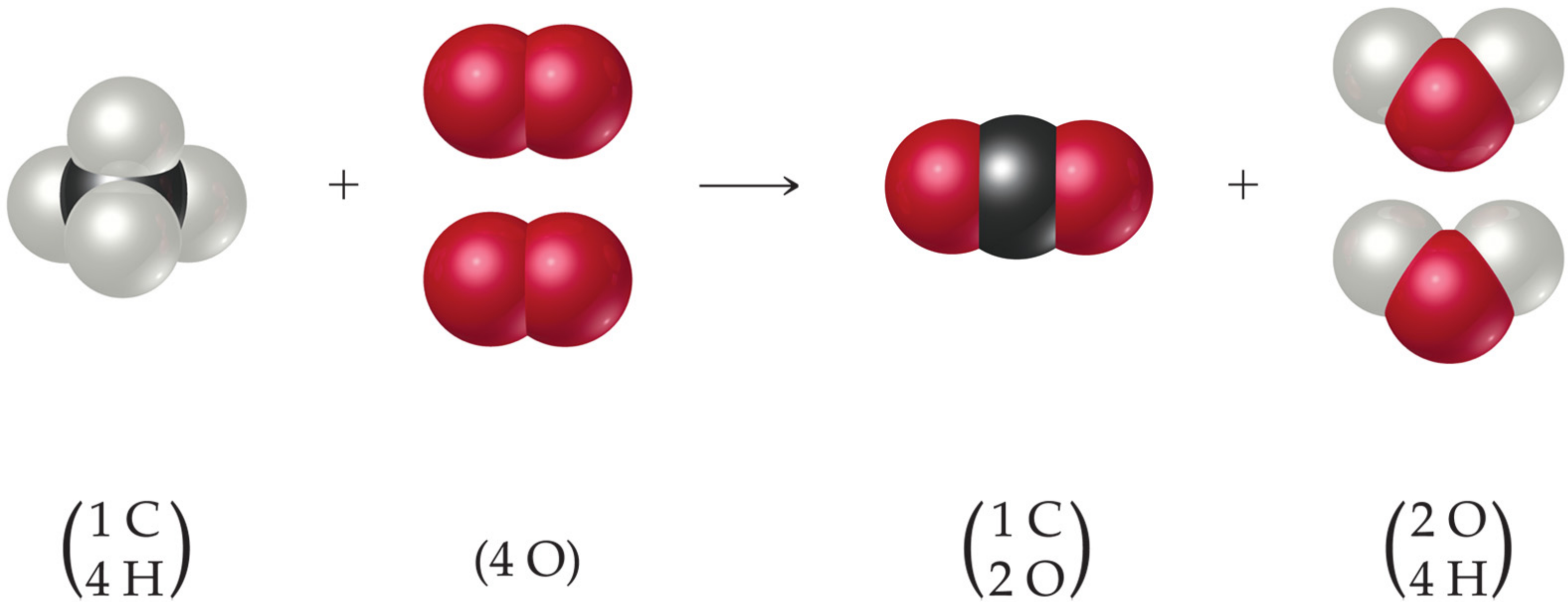


The states of the reactants and products are written in parentheses to the right of each compound.

Stoichiometry

Anatomy of a Chemical Equation

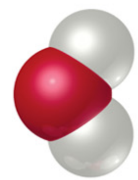
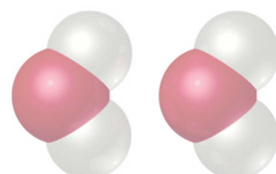
$$CH_{4\,(g)} + 2\ O_{2\,(g)} \longrightarrow CO_{2\,(g)} + 2\ H_2O_{(g)}$$



Coefficients are inserted to balance the equation.

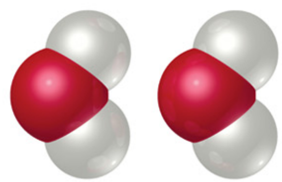
Stoichiometry

Subscripts and Coefficients Give Different Information

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

- Subscripts tell the number of atoms of each element in a molecule

Subscripts and Coefficients Give Different Information

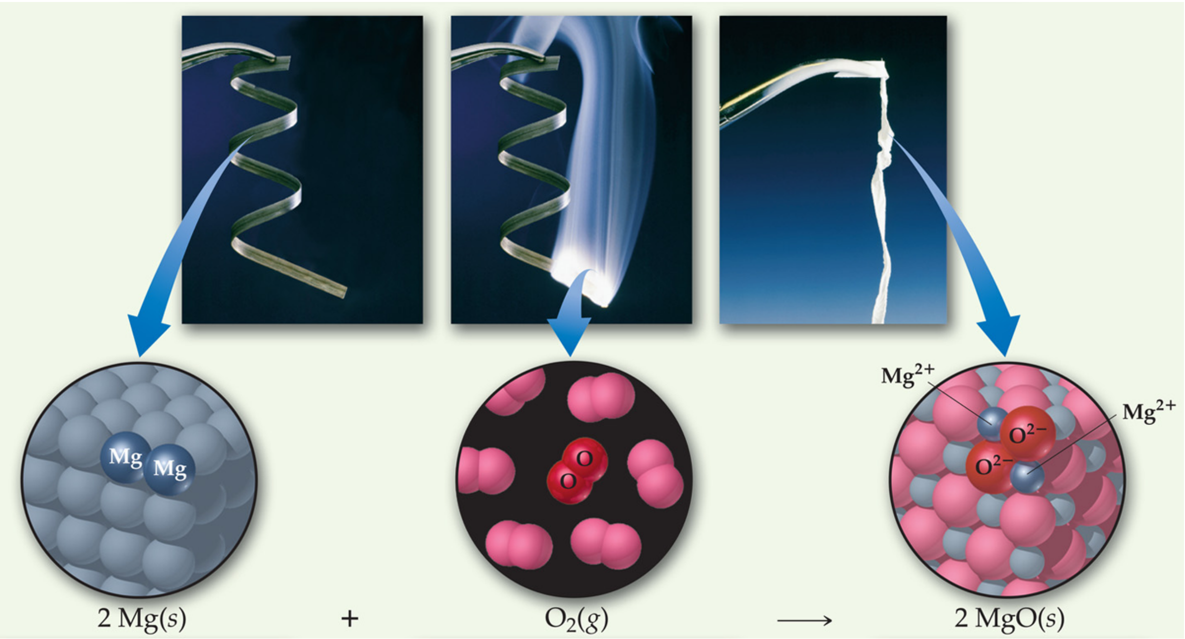
Chemical symbol	Meaning		Composition
H_2O	One molecule of water:		Two H atoms and one O atom
2 H_2O	Two molecules of water:		Four H atoms and two O atoms

- Subscripts tell the number of atoms of each element in a molecule
- Coefficients tell the number of molecules

Reaction Types Review

Stoichiometry

Formation Reactions



- Two or more substances react to form one product

- Examples:

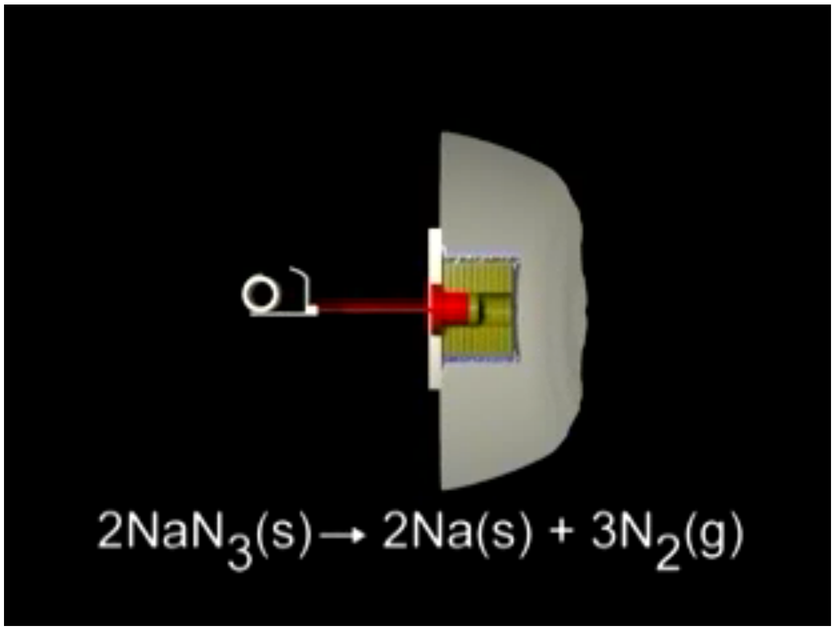
$$N_{2\,(g)} + 3\,H_{2\,(g)} \longrightarrow 2\,NH_{3\,(g)}$$

$$C_3H_{6\,(g)} + Br_{2\,(l)} \longrightarrow C_3H_6Br_{2\,(l)}$$

$$2\,Mg_{\,(s)} + O_{2\,(g)} \longrightarrow 2\,MgO_{\,(s)}$$

Stoichiometry

Decomposition Reactions



- One substance breaks down into two or more substances

- Examples:

$$CaCO_{3\ (s)} \longrightarrow CaO_{\ (s)} + CO_{2\ (g)}$$

$$2\ KClO_{3\ (s)} \longrightarrow 2\ KCl_{\ (s)} + O_{2\ (g)}$$

$$2\ NaN_{3\ (s)} \longrightarrow 2\ Na_{\ (s)} + 3\ N_{2\ (g)}$$

Stoichiometry

Single Replacement Reactions

$$A + BX \rightarrow AX + B$$

$$BX + Y \rightarrow BY + X$$

Examples:

- Metals replaces another metal ion
  - $K(s) + NaCl(aq) \rightarrow Na(s) + KCl(aq)$
- Hydrogen replaces a metal
  - $H_2(g) + 2\,NaCl(aq) \rightarrow Na(s) + 2HCl(aq)$
- Hydrogen in an acid replaced by a metal
  - $Mg(s) + 2HCl(aq) \rightarrow H_2(g) + MgCl_2(aq)$
- Halogens replace halogens
  - $F_2(g) + NaCl(aq) \rightarrow Cl_2(g) + NaF(aq)$

Stoichiometry

Double Replacement Reactions

The ions of two compounds exchange places in an aqueous solution to form two new compounds.

$$AX + BY \rightarrow AY + BX$$

One of the compounds formed is usually a:

- Precipitate

  $Pb(NO_3)_2(aq) + 2NaI(aq) \rightarrow 2NaNO_3(aq) + PbI_2(s)$

- an insoluble gas that bubbles out of solution

- a molecular compound, usually water.

  $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

Stoichiometry

Combustion Reactions

- Rapid reactions that produce a flame
- Most often involve hydrocarbons reacting with oxygen in the air

- Examples:

$$CH_4\,(g) + 2\,O_2\,(g) \longrightarrow CO_2\,(g) + 2\,H_2O\,(g)$$

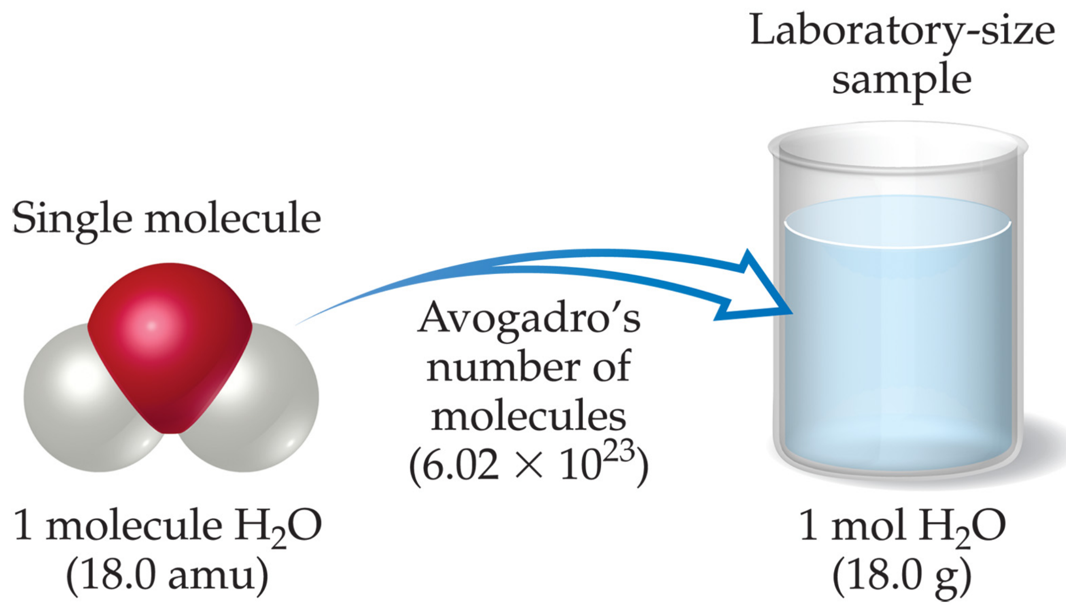
$$C_3H_8\,(g) + 5\,O_2\,(g) \longrightarrow 3\,CO_2\,(g) + 4\,H_2O\,(g)$$

Stoichiometry

Review of Moles

Stoichiometry

Avogadro's Number



- 6.02×10^{23} particles/mol
- (also atoms/mol; molecules/mol; formula units/mol

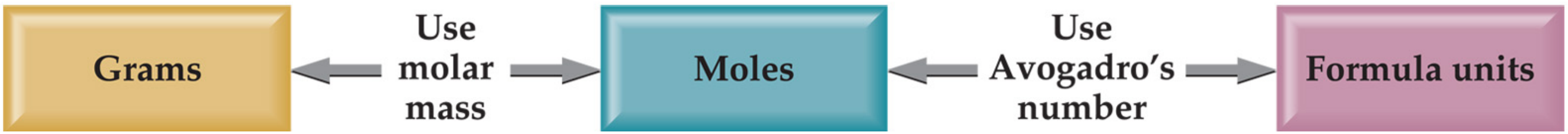
Molar Mass

- By definition, the average mass of 1 mol of a substance (i.e., g/mol)
  - The molar mass of an element is the atomic mass for the element that we find on the periodic table, usually to two decimal places. Ie) Na = 22.99 g/mol
  - The molar mass of a compound is the atomic masses of all the elements added together. Ie) C_2H_6

$$
\begin{array}{lr}
\text{C:} & 2\text{x}12.01 = 24.02 \\
+\ \text{H:} & 6\text{x}1.01 = 6.06 \\
\hline
 & 30.08 \\
 & \text{g/mol}
\end{array}
$$

Stoichiometry

Using Moles



Moles provide a bridge for all conversions

Mole Relationships

Name of substance	Formula	Formula Weight (amu)	Molar Mass (g/mol)	Number and Kind of Particles in One Mole
Atomic nitrogen	N	14.0	14.0	6.022×10^{23} N atoms
Molecular nitrogen	N_2	28.0	28.0	6.022×10^{23} N_2 molecules $2(6.022 \times 10^{23})$ N atoms
Silver	Ag	107.9	107.9	6.022×10^{23} Ag atoms
Silver ions	Ag^+	107.9[a]	107.9	6.022×10^{23} Ag^+ ions
Barium chloride	$BaCl_2$	208.2	208.2	6.022×10^{23} $BaCl_2$ units 6.022×10^{23} Ba^{2+} ions $2(6.022 \times 10^{23})$ Cl^- ions

[a]Recall that the electron has negligible mass; thus, ions and atoms have essentially the same mass.

- One mole of atoms, ions, or molecules contains Avogadro's number of those particles
- One mole of molecules or formula units contains Avogadro's number times the number of atoms or ions of each element in the compound

Mole relationships

- Mole to mass relationship

  $n = m/M$ mol = g/(mol/g)

- Mole to particles relationship

  $n = p/P$ mol=parts/(6.02E^{23} part/mol)

- Mole to volume relationship for gases at STP & SATP

  $n = v/V_{STP(22.4L/mol)}$ $n = v/V_{SATP(24.8L/mol)}$

  mol = L/22.4L/mol; mol=L/24.8L/mol

Stoichiometry

Stoichiometry

Stoichiometry Definition

- STOICHIOMETRY: the use of proportions(mole ratio' s) to calculate quantities of substances in balanced chemical equations.
- MOLE RATIO: comparison or division of two coefficients in a balanced chemical equation. (REQUIRED/GIVEN or R/G.)

Stoichiometry

Example of Mole Ratios

- $N_{2(g)}$ + $3H_{2(g)}$ ----> $2NH_{3(g)}$
- The mole ratio between $H_{2(g)}$ & $NH_{3(g)}$ is

$$\frac{3 \text{ mol of } H_2}{2 \text{ mol of } NH_{3(g)}}$$

- The mole ratio between NH_3 & N_2 is

$$\frac{2 \text{ mol of } NH_3}{1 \text{ mol of } N_2}$$

Stoichiometry

Types of Stoichiometry

1. Gravimetric Stoichiometry: dealing with molar mass, mass & mole quantities.

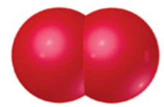
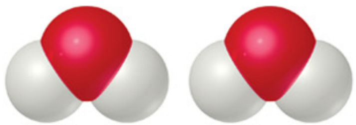
   $n=m/M$; $n=p/P$

2. Solution Stoichiometry: dealing with molar concentration, volume & mole quantities. $n=CV$

3. Gas Stoichiometry: dealing with molar volume, Ideal Gas Law & mole quantities

   $n=v/V$

Stoichiometric Calculations

Equation:	**2 $H_2(g)$**	**+**	**$O_2(g)$**	**⟶**	**2 $H_2O(l)$**
Molecules:	2 molecules H_2	+	1 molecule O_2	⟶	2 molecules H_2O
					
Mass (amu):	4.0 amu H_2	+	32.0 amu O_2	⟶	36.0 amu H_2O
Amount (mol):	2 mol H_2	+	1 mol O_2	⟶	2 mol H_2O
Mass (g):	4.0 g H_2	+	32.0 g O_2	⟶	36.0 g H_2O

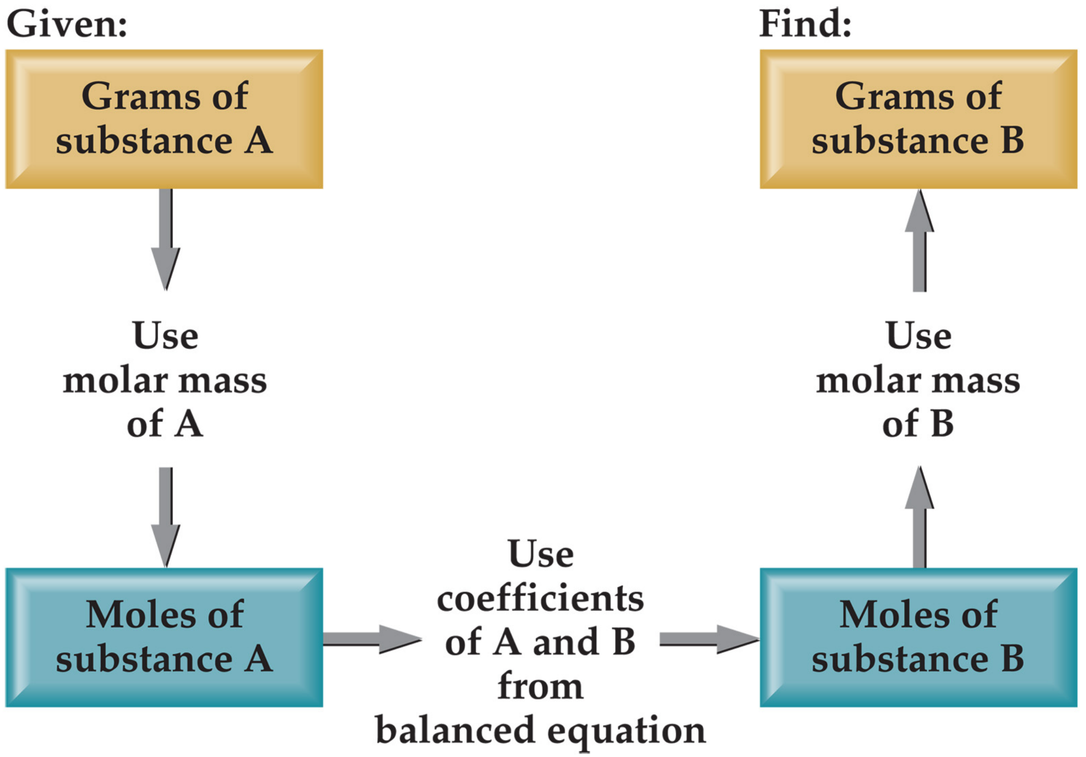
The coefficients in the balanced equation give the ratio of *moles* of reactants and products

Solving a Stoichiometry Problem

1. Balance the reaction. ID the GIVEN (G) & REQUIRED (R) Coefficients in the reaction.
2. Convert GIVEN masses to moles by dividing by the Molar mass. (volumes divide by Molar volumes; particles divide by Avogadro's number)
3. Multiply the moles of GIVEN by the coefficient mole ratios (R/G) to find moles of REQUIRED. (If 2 givens are present you will learn to determine which is limiting)
4. Convert the REQUIRED moles to grams/litres/particles by multiplying by the Molar mass/Molar Volume or Avogadro number).
5. Determine the % error & % yield (will discuss later)

Stoichiometric Calculations

From the mass of Substance A you can use the ratio of the coefficients of A and B to calculate the mass of Substance B formed (if it' s a product) or used (if it' s a reactant)



Mole to Mole Stoichiometry

Ex 1) Nitrogen reacts with hydrogen to form a gas. Find the number of <u>moles</u> of nitrogen required if 6.0 mol of ammonia are formed?

R G

Step 1) $1\ N_{2(g)} + 3\ H_{2(g)} \rightarrow 2\ NH_{3(g)}$

Step 2) NO CONVERSION → 6.0 mol

Step 3) $6.0 \text{ mol of } NH_3 \times \dfrac{1 \text{ mol of } N_2}{2 \text{ mol of } NH_3} = 3.0 \text{ mol of } N_2$

Step 4) NO CONVERSION; 3.0 mol of N_2 is the final answer (2 significant digits)

Stoichiometry

Mole to Mole Stoichiometry

Ex 2) Find the moles of hydrogen if 0.600 mol of ammonia are produced?

R G

Step 1) $1\ N_{2(g)} + 3\ H_{2(g)} \rightarrow 2NH_{3(g)}$

Step 2) NO CONVERSION; 0.600 mol of NH_3

Step 3) 0.600 mol of NH_3 x $\frac{3 \text{ mol of } H_2}{2 \text{ mol of } NH_3}$ = 0.900 mol of H_2

Step 4) NO CONVERSION; 0.900 mol of H_2 is the final answer (3 significant digits)

Stoichiometry

Mole to Mole Stoichiometry

Ex 3) Find the moles of water produced if 6.32 mol of hydrogen are used?

G R

Step 1) $2\ H_{2(g)} + 1\ O_{2(g)} \rightarrow 2\ H_2O_{(g)}$

Step 2) NO CONVERSION → 6.32 mol

Step 3) 6.32 mol of H_2 x $\frac{2 \text{ mol of } H_2O}{2 \text{ mol of } H_2}$ = 6.32 mol of H_2O

Step 4) NO CONVERSION: 6.32 mol of H_2O is the final answer

Stoichiometry

B) Mole to Quantity Stoichiometry

Ex 1) 5.00 mol of nitrogen reacts with excess hydrogen. How many litres of ammonia are produced at SATP?

G R

Step 1) $1\ N_{2(g)} + 3\ H_{2(g)} \rightarrow 2\ NH_{3(g)}$

Step 2) NO CONVERSION → 5.00 mol

Step 3) $5.00 \text{ mol of } N_2 \times \frac{2 \text{ mol of } NH_3}{1 \text{ mol of } N_2} = 10.0 \text{ mol of } NH_3$

Step 4) v=nV = 10.0 mol x 24.8L/mol

= 248 L of HN_3 (3 significant digits)

B) Mole to Quantity Stoichiometry

Ex 2) Aluminum reacts with calcium nitrate. If 0.900 mol of calcium forms, find the mass of aluminum required?

R G

1) $2Al_{(s)} + 3Ca(NO_3)_{2(aq)} \rightarrow 3Ca_{(s)} + 2Al(NO_3)_{3(aq)}$
2) No Conversion
3) $0.900 \text{ mol of Ca} \times \dfrac{2 \text{mol of Al}}{3 \text{ mol of Ca}} = 0.600 \text{ mol of Al}$
4) $m = nM = 0.600\text{mol} \times 26.98\text{g/mol} = 16.188 \text{ g}$

$m = 16.2$ g of Al (3 significant digits)

Stoichiometry

Mole to Quantity Stoichiometry

Ex 3) 1.20 mol of Cu react with silver nitrate. How many particles of precipitate are produced?

G R

1) $1Cu_{(s)} + 2AgNO_{3(aq)} \rightarrow 2Ag_{(s)} + Cu(NO_3)_{2(aq)}$

2) No conversion; 1.20 mol

3) $1.20 \text{ mol of Cu} \times \frac{2 \text{ mol of Ag}}{1 \text{ mol of Cu}} = 2.40 \text{ mol of Ag}$

4) p=nP = 2.40 mol of Ag x 6.02E23 =1.448.. E 24

1.45×10^{24} particles of Ag

C) Quantity to Mole Stoichiometry

Ex 1) 4.00 L of nitrogen reacts with excess hydrogen to form ammonia. How many moles of ammonia are produced at STP?

G R

1) $1\ N_{2(g)} + 3\ H_{2(g)} \rightarrow 2\ NH_{3(g)}$

2) $n = v/V = 4.00L/22.4L/mol$ of N_2 = 0.17857… mol of N_2

3) 0.17857…mol of N_2 x 2 mol of NH_3/1mol of N_2 =0.35714…mol of $NH_{3(g)}$

4) No Conversion; 0.357 mol of $NH_{3(g)}$ (3 sig digs)

Stoichiometry

Quantity to Mole Stoichiometry

Ex 2) Iron reacts with oxygen. Find the number of moles of oxygen if 4.0×10^{23} formula units (ionic compound) are produced at SATP.

R G

1) $4\ Fe_{(s)} + 3\ O_{2(g)} \rightarrow 2\ Fe_2O_{3(s)}$

2) n=p/P=4.0E23formunits/6.02E23 formunits/mol

n= 0.6644···mol of $Fe_2O_{3(s)}$

3) $0.6644\cdots \text{mol } Fe_2O_{3(s)} \times \frac{3\text{mol } O_2}{2 \text{ mol } Fe_2O_{3(s)}} = 0.9966\text{mol } O_2$

4) No Conversion; 1.0 mol of O_2

Quantity to Mole Stoichiometry

Ex 3) 27 g of Sucrose burns. Find the number of moles of water that is produced.

G R

1) $1\ C_{12}H_{22}O_{11} + 12\ O_{2(g)} \rightarrow 12\ CO_{2(g)} + 11\ H_2O_{(g)}$
2) $n = m/M = 27g/342.30g/mol = 0.07887..mol$
3) $0.07887..mol\ sucrose \times \frac{11 mol\ H_2O}{1\ mol\ sucrose} = 0.8676..mol H_2O$
4) No conversion; 0.87mol of $H_2O_{(g)}$ (2 sig digs)

Stoichiometry

D) Quantity to Quantity Stoichiometry

Ex 1) Calculate the volume of NH_3 produced at STP when 5.40g of hydrogen reacts with nitrogen.

G R

1) $1\ N_{2(g)} + 3\ H_{2(g)} \rightarrow 2\ NH_{3(g)}$

2) $n = m/M = 5.40g/2.02g/mol$ of H_2 = 2.67326… mol of H_2

3) $2.67326\ldots \text{mol of } H_2 \times \dfrac{2 \text{ mol of } NH_3}{3 \text{mol of } H_2} = 1.7821\ldots \text{mol} NH_3$

4) $v = nV = 1.7821 \text{ mol} \times 22.4 L/mol = 39.92\ldots\ L$

39.9 L of $NH_{3(g)}$

Stoichiometry

D) Quantity to Quantity Stoichiometry

Ex 2) Find the molecules of hydrogen produced if 24.0 L of water decomposes at SATP conditions. G R

1) $2\ H_2O_{(l)} \rightarrow 2\ H_{2(g)} + 1\ O_{2(g)}$

2) n=v/V=24.0L / 24.8L/mol = 0.9677..mol H2O

3) $0.9677..\text{mol } H_2O \times \dfrac{2 \text{ mol } H_2}{2 \text{ mol } H_2O} = 0.9677..\text{mol } H_2$

4) $p = nP = 0.9677..\text{mol } H_2 \times 6.02E23 \text{molecules/mol}$

$= 5.825..E23$ molecules of H_2

$= 5.83\ E23$ molecules of H_2

Stoichiometry

Limiting Reactants

Stoichiometry

How Many Cookies Can I Make?

- You can make cookies until you run out of one of the ingredients
- Once this family runs out of sugar, they will stop making cookies (at least any cookies you would want to eat)

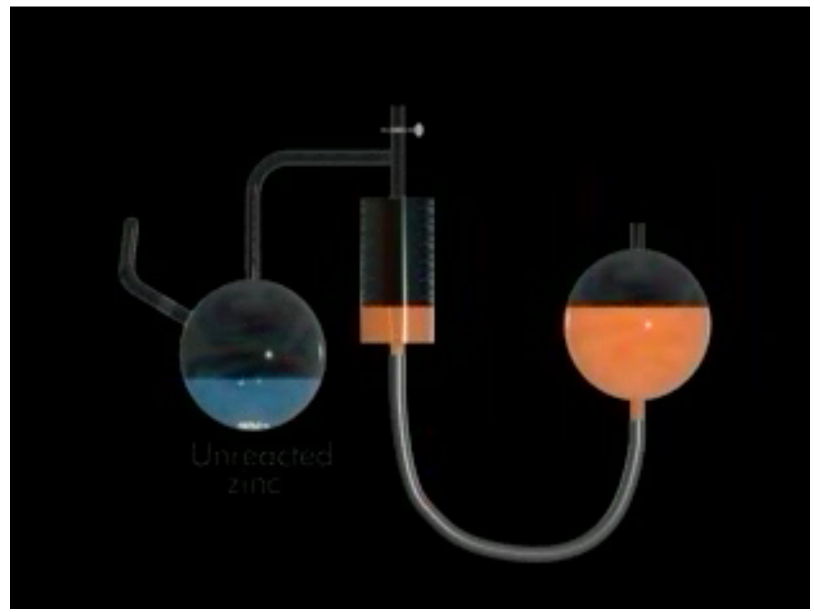
Stoichiometry

How Many Cookies Can I Make?

- In this example the sugar would be the limiting reactant, because it will limit the amount of cookies you can make

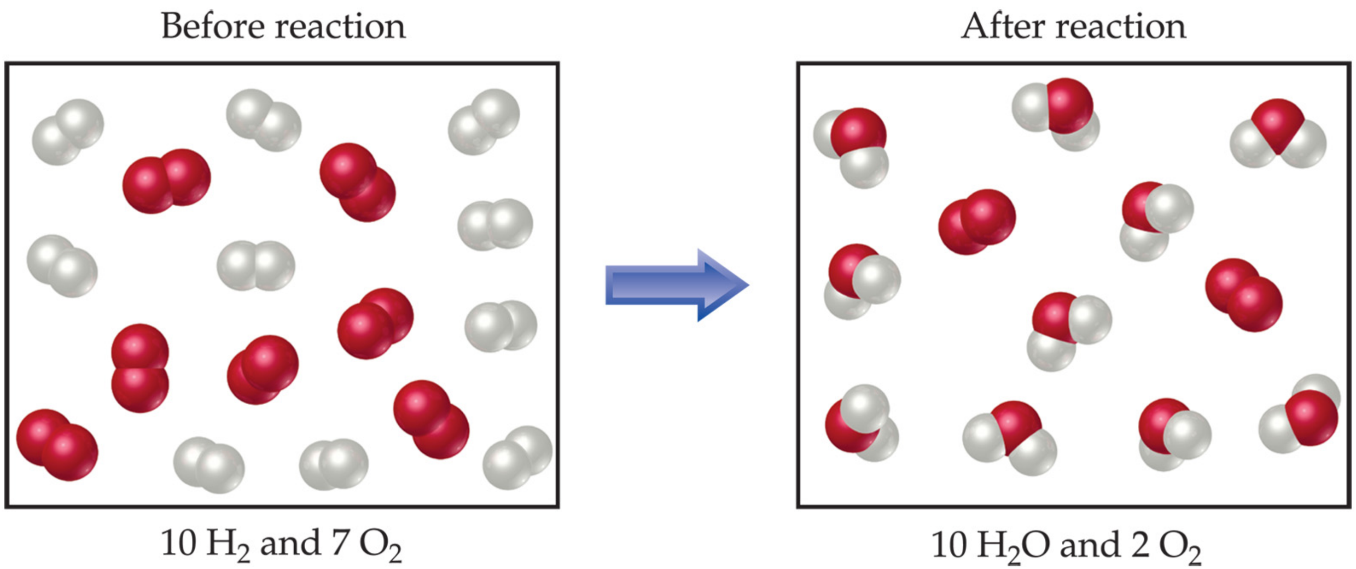
Limiting Reactants

The limiting reactant is the reactant present in the smallest stoichiometric amount



Limiting Reactants

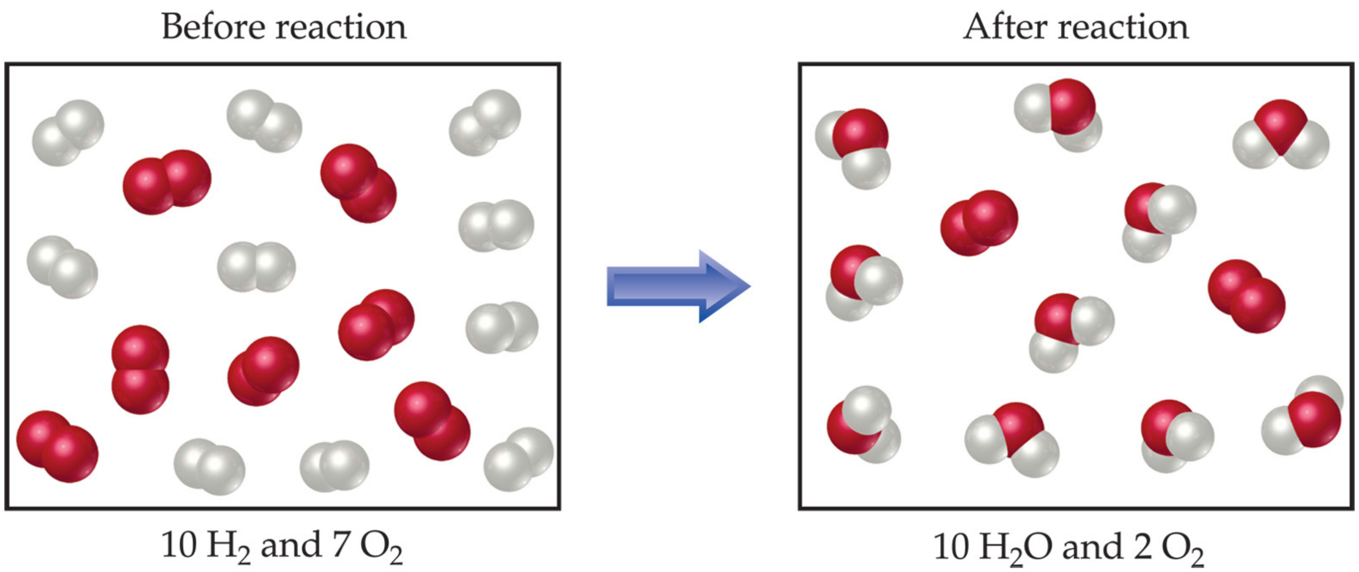
- The limiting reactant is the reactant present in the smallest stoichiometric amount
  - In other words, it’s the reactant you’ll run out of first (in this case, the H_2)



Stoichiometry

Limiting Reactants

In the example below, the O_2 would be the excess reagent



Limiting Reagents

- Definition: and reactant that is all used up and determines the amount of product in a chemical reaction.
- Excess reagent: the reactant that is not all used up.
- Why worry about limiting reagents?
  - Because they determine the amount of product that is formed in the reaction.

Stoichiometry

Solving Limiting Reagent Stoich Problems

1. Balance the reaction. ID the GIVENs (G) & REQUIRED (R) Coefficients in the reaction.
2. Convert GIVEN masses to moles by multiplying by the Molar mass.
3. Multiply the moles of GIVENs by the coefficient mole ratios (r/g) to find moles of REQUIRED. (Do it 2x) Determine which GIVEN is the LIMITING reagent by seeing which GIVEN in step 3 produces the smallest required product. Use this required product in step 4
4. Convert from the REQUIRED moles to grams by multiplying by the Molar mass.
5. %yield & % error

Stoichiometry

Limiting Reagents

Ex 1) If **2.0 mol of nitrogen** was reacted with 5.0 mol of hydrogen, what would the excess and limiting reagents be?

G1 **G2** R

1) $3\ H_{2(g)} + \mathbf{1}\ N_{2(g)} \rightarrow 2\ NH_{3(g)}$

2) No Conversion

3) G1: $5.0 \text{ mol } H_2 \times \dfrac{2 \text{ mol } NH_3}{3 \text{ mol of } H_2} = 3.3 \text{ mol } NH_3$ (limiting)

G2: $\mathbf{2.0 \text{ mol } N_2} \times \dfrac{2 \text{ mol } NH_3}{\mathbf{1 \text{ mol } N_2}} = 4.0 \text{ mol } NH_3$ **(excess)**

Stoichiometry

Limiting Reagents

Ex 2) There is 6.70 mol of Na & 3.20 mol of Cl_2.What are the limiting and the excess reagents?

G1 **G2** **R**

1) $2\ Na + 1\ Cl_{2(g)} \rightarrow 2\ NaCl_{(s)}$

2) No Conversion

1) G1: $6.70 \text{ mol Na} \times \dfrac{2 \text{ mol NaCl}}{2 \text{ mol of Na}} = 6.70 \text{ mol NaCl}$ (excess)

G2: $3.20 \text{ mol } Cl_2 \times \dfrac{2 \text{ mol NaCl}}{1 \text{ mol } Cl_2} = 6.20 \text{ mol } NH_3$ **(limiting)**

Stoichiometry

Limiting Reagents

Ex 3) How many moles of carbon dioxide are produced when 2.70 mol of ethane reacts with 6.30 mol of oxygen?

G1 G2 R

1) $1\ C_2H_{6(g)} + 3.5\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 3\ H_2O_{(g)}$

2) No Conversion

3) G1: $2.70 \text{ mol } C_2H_6 \times \frac{2 \text{ mol } CO_2}{1 \text{ mol of } H_2} = 5.40 \text{ mol } CO_2$ (excess)

G2: $6.30 \text{ mol } O_2 \times \frac{2 \text{ mol } CO_2}{3.5 \text{ mol } O_2} = 3.60 \text{ mol } CO_2$ **(limiting)**

4) No Conversion; the limiting is used → 3.60 mol

Limiting Reagents

Ex 4) Iron (III) oxide reacts with carbon monoxide to produce iron and carbon dioxide.

a)If 84.80 g of iron (III) oxide reacted with 31.5 L of carbon monoxide at STP, how many litres of carbon dioxide would be produced?

R

1) $Fe_2O_{3(s)}$ + $3CO_{(g)}$ → $Fe_{(s)}$ + $3CO_{2(g)}$

2) 84.80/159.69 **31.5L/22.4L/mol**

n= 0.531..mol **n=1.406..mol**

3) X 3mol/1mol x 3mol/**3mol**

= 1.593..mol **1.406..mol of CO2**

Excess **Limiting**

4) **v=nV = 1.406..mol x 22.4L/mol = 31.5 L of CO2**

Limiting Reagents

Ex 4) CHALLENGE: How many moles of excess reagent would remain? How many grams?

R G

$Fe_2O_{3(s)}$ + $3CO_{(g)}$ → $Fe_{(s)}$ + $3CO_{2(g)}$

31.5L/22.4L/mol

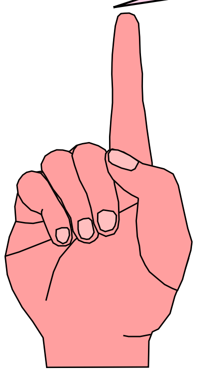
Stoichiometry

Percent Yield

- Definition: The ratio of the actual yield to the theoretical yield for a chemical reaction expressed as a percentage.
- Theoretical Yield (ideal): The maximum amount of product that could be formed from a given amount of reactant. This is solved using stoichiometry (required value).
- Actual Yield (experimental): The amount of product that forms when a reaction is carried out in a laboratory.

Theoretical yield vs. Actual yield

Suppose the theoretical yield for an experiment was calculated to be 19.5 grams, and the experiment was performed, but only 12.3 grams of product were recovered. Determine the % yield.



Theoretical yield = 19.5 g based on limiting reactant

Actual yield = 12.3 g experimentally recovered

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

$$\% \text{ yield} = \frac{12.3}{19.5} \times 100 = 63.1\% \text{ yield}$$

Percent Yield

What is the % yield if **24.8 g of $CaCO_3$** is heated to **produce 13.1 g (TY) of CaO**?

$CaCO_3 \rightarrow CaO_{(s)} + CO_{2(g)}$

Stoichiometry

Percent Error

- Definition: A calculation that indicated the amount of error made in the laboratory
- Why is it not 0%?
  - Instrumental errors
    - Precision of instruments
  - Experimental errors
    - Conditions of room, contaminates in air
    - Reaction doesn't go to completion
    - Excess reagent becomes part of the product
  - Human errors
    - These should and can be avoided
      - Precipitate going through filter paper
      - "I didn't measure the right mass"

Percent Error

- Formula: $\frac{|\text{actual-theoretical}|}{\text{theoretical}} \times 100$

The lines represent absolute value – answer is always positive. NOTE: Please do the subtraction first; then divide by theoretical.

Percent Error

Iron (II) oxide reacts with carbon monoxide to form iron and carbon dioxide. There is 49.3 g of iron produced when 84.8 g of iron oxide reacts with 12.0 g of carbon monoxide. What is the % yield & % error?