Lecture Schedule for 2025 Fall

(2 h) Chapter 3: Chemical Reactions and Reaction Stoichiometry
+ Significant Figures in Chapter 1
+ Nomenclature in Chapter 2

(2 h) Chapter 4: Reactions in Aqueous Solution

(4 h) Chapter 6: Electronic Structure of Atoms

(2 h) Chapter 7: Periodic Properties of the Elements

(4 h) Chapter 8: Basic Concepts of Chemical Bonding

(4 h) Chapter 9: Molecular Geometry and Bonding Theories

(2 h) Chapter 11: Liquids and Intermolecular Forces

Midterm exam (November 9, 14:00-16:00, Sunday)

(4 h) Chapter 13: Properties of Solutions

(4 h) Chapter 14: Chemical Kinetics

(4 h) Chapter 15: Chemical Equilibrium

(4 h) Chapter 16: Acid-Base Equilibria

(2 h) Chapter 17: Additional Aspects of Aqueous Equilibria

(2 h) Chapter 5: Thermochemistry

(4 h) Chapter 19: Chemical Thermodynamics

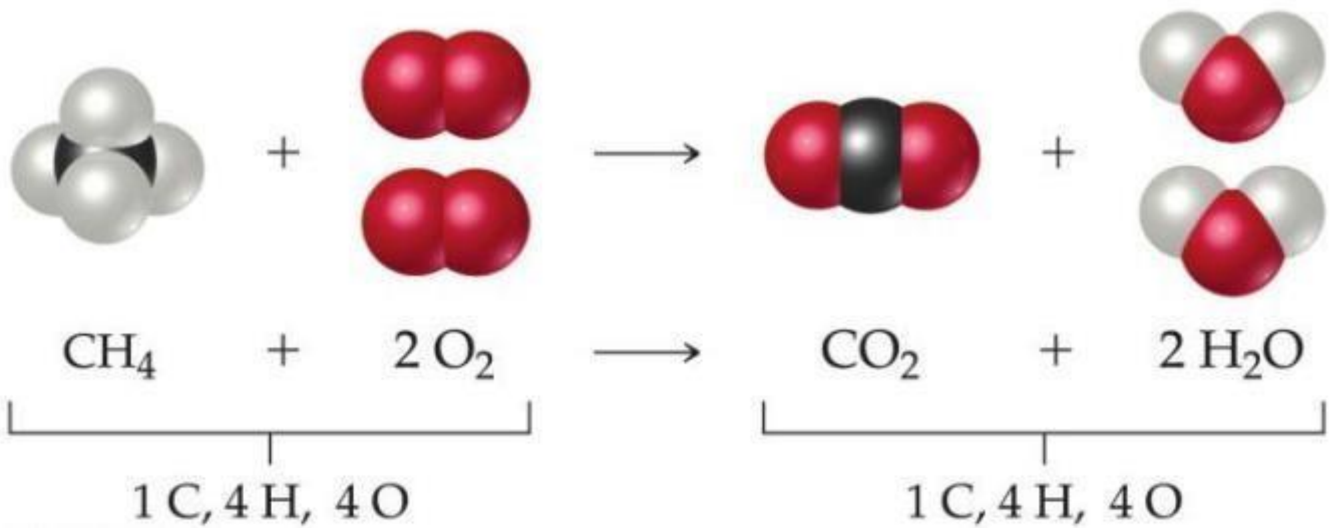
Final exam

Chapter 3

Chemical Reactions and Reaction Stoichiometry

What Is in a <u>Chemical Equation</u>?

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



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

(g) = gas; (l) = liquid; (s) = solid;

(aq) = in aqueous solution

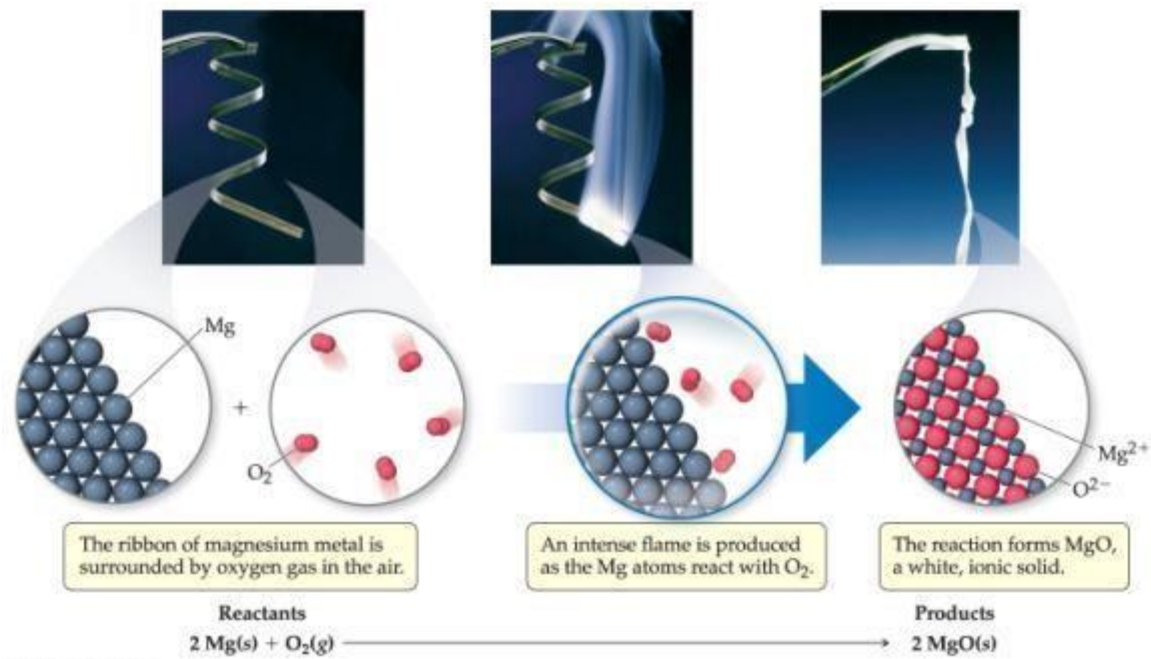
co-efficient

to balance

Three Types of Reactions

- Combination reactions (化合反应)
- Decomposition reactions (分解反应)
- Combustion reactions (燃烧反应)
- Other types of reactions

Combination Reactions



In **combination reactions** two or more substances react to form one product.

- Examples:

$$2\,Mg(s) + O_2(g) \longrightarrow 2\,MgO(s)$$

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

$$C_3H_6(g) + Br_2(l) \longrightarrow C_3H_6Br_2(l)$$

Decomposition Reactions

- In a **decomposition reaction** one substance breaks down into two or more substances.

- Examples:

$$CaCO_3(s) \longrightarrow CaO(s) + CO_2(g)$$

$$2\ KClO_3(s) \longrightarrow 2\ KCl(s) + O_2(g)$$

$$2\ NaN_3(s) \longrightarrow 2\ Na(s) + 3\ N_2(g)$$

100 g **?**

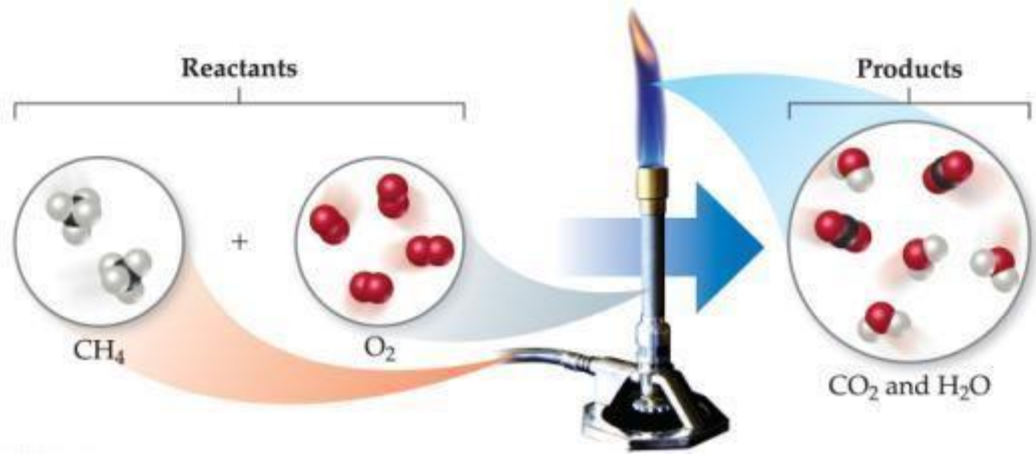
Decomposition Reactions

The decomposition of sodium azide (NaN_3) rapidly releases $N_2(g)$, so this reaction is used to inflate safety air bags in automobiles (◀ **Figure 3.7**):

$$2\,NaN_3(s) \longrightarrow 2\,Na(s) + 3\,N_2(g) \qquad [3.8]$$

The system is designed so that an impact ignites a detonator cap, which in turn causes NaN_3 to decompose explosively. A small quantity of NaN_3 (about 100 g) forms a large quantity of gas (about 50 L).

Combustion (to burn) Reactions



- **Combustion reactions** are generally rapid reactions that produce a flame.
- **Combustion reactions** most often involve oxygen in the air as a reactant.

- Examples:
  - $CH_4(g) + 2\ O_2(g) \longrightarrow CO_2(g) + 2\ H_2O(g)$
  - $C_3H_8(g) + 5\ O_2(g) \longrightarrow 3\ CO_2(g) + 4\ H_2O(g)$

Combustion (to burn) Reactions

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

▲ Figure 3.8 **Propane burning in air.** Liquid propane in the tank, C_3H_8, vaporizes and mixes with air as it escapes through the nozzle. The combustion reaction of C_3H_8 and O_2 produces a blue flame.

Quantities (the amount)

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

reactants consumed

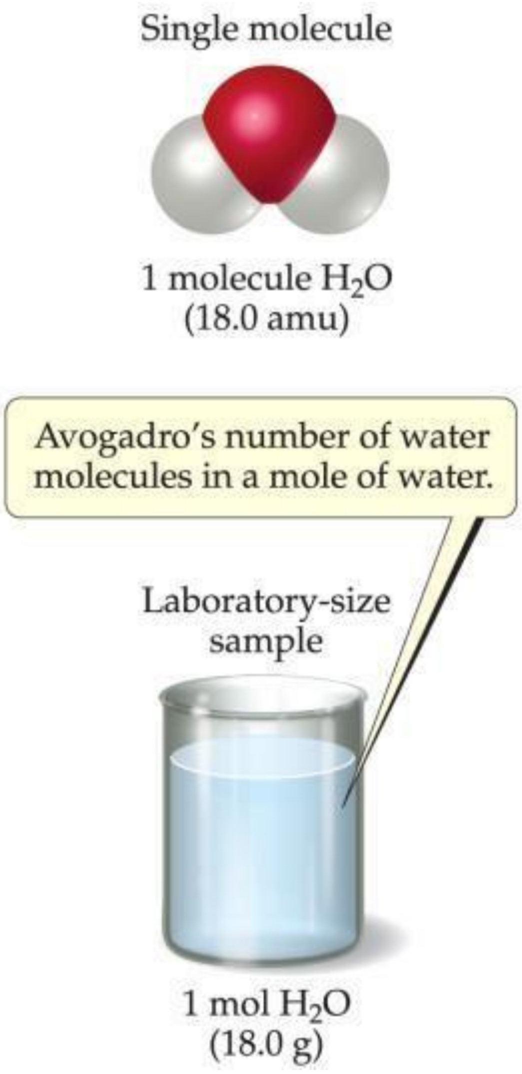
products produced

- **Atoms or molecules are small and light!**
- **Particles (atoms or molecules) ↔ Total mass**
- **Total mass/mass of each particle = <u># of particles</u>**
- **And the # of particles is HUGE!**

Avogadro's Number

One dozen = 12
One mole = 6.02×10^{23}

- In a lab, we cannot work with individual molecules. They are too small.
- 6.02×10^{23} atoms or molecules is an amount that brings us to lab size. It is **ONE MOLE**.
- One mole of ^{12}C has a mass of 12.000 g.



Mole Relationships

Table 3.2 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	6.02×10^{23} N atoms
Molecular nitrogen	N_2	28.0	28.0	$\begin{cases} 6.02 \times 10^{23}\ N_2 \text{ molecules} \\ 2(6.02 \times 10^{23})\ N \text{ atoms} \end{cases}$
Silver	Ag	107.9	107.9	6.02×10^{23} Ag atoms
Silver ions	Ag^+	107.9[a]	107.9	6.02×10^{23} Ag^+ ions
Barium chloride	$BaCl_2$	208.2	208.2	$\begin{cases} 6.02 \times 10^{23}\ BaCl_2 \text{ formula units} \\ 6.02 \times 10^{23}\ Ba^{2+} \text{ ions} \\ 2(6.02 \times 10^{23})\ Cl^- \text{ ions} \end{cases}$

[a]Recall that the mass of an electron is more than 1800 times smaller than the masses of the proton and the neutron; thus, ions and atoms have essentially the same mass.

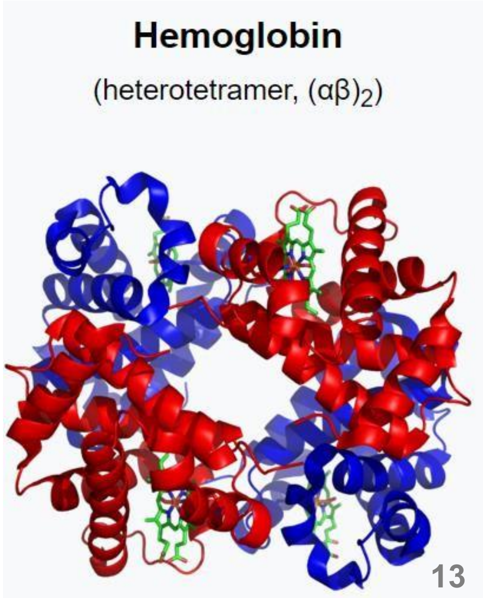
Atomic Mass (原子质量)

- Atoms have extremely small masses.
- The heaviest known atoms have a mass of approximately 4×10^{-22} g.
- A mass scale on the atomic level is used, where an **atomic mass unit (amu)** is the base unit.

➢ 1 amu = 1.66054×10^{-24} g

1 amu = 1 Da

is defined as $\frac{1}{12}$ of the mass of a free carbon-12 atom at rest in its ground state.



64 kDa

The Periodic Table of the Elements

19	← Atomic number
K	← Atomic symbol
39.0983	← Atomic weight

1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012182											5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989770	12 **Mg** Magnesium 24.3050											13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933200	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90545	56 **Ba** Barium 137.327	57 **La** Lanthanum 138.9055	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

1995 IUPAC masses and Approved Names from http://www.chem.qmw.ac.uk/iupac/AtWt/
masses for 107-111 from C&EN, March 13, 1995, p. 35
112 from http://www.gsi.de/z112e.html

Molecular Formulas

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

Percent Composition

One can find the percentage of the mass of a compound that comes from each of the elements in the compound by using this equation:

$$\% \text{ Element} = \frac{(\text{number of atoms})(\text{atomic weight})}{(\text{FW of the compound})} \times 100$$

(FW: formula weight)

Percent Composition

The percentage of carbon in ethane（C_2H_6）is

$$\%C = \frac{(2)(12.011\text{ amu})}{(30.070\text{ amu})}$$

$$= \frac{24.022\text{ amu}}{30.070\text{ amu}} \times 100\%$$

$$= 79.887\%$$

Determining Empirical Formulas

A compound is composed of carbon (61.31%), hydrogen (5.14%), nitrogen (10.21%), and oxygen (23.33%). Find its empirical formula.

Assuming 100.00 g of this compound,

C: $61.31\text{ g} \times \dfrac{1\text{ mol}}{12.01\text{ g}} = 5.105\text{ mol C}$

H: $5.14\text{ g} \times \dfrac{1\text{ mol}}{1.01\text{ g}} = 5.09\text{ mol H}$

N: $10.21\text{ g} \times \dfrac{1\text{ mol}}{14.01\text{ g}} = 0.7288\text{ mol N} \Rightarrow 1\text{ mol}$

O: $23.33\text{ g} \times \dfrac{1\text{ mol}}{16.00\text{ g}} = 1.456\text{ mol O}$

Determining Empirical Formulas

Calculate the mole ratio by dividing by the smallest number of moles:

C: $\dfrac{5.105 \text{ mol}}{0.7288 \text{ mol}} = 7.005 \approx 7$

H: $\dfrac{5.09 \text{ mol}}{0.7288 \text{ mol}} = 6.984 \approx 7$

N: $\dfrac{0.7288 \text{ mol}}{0.7288 \text{ mol}} = 1.000 \rightarrow 1$

O: $\dfrac{1.458 \text{ mol}}{0.7288 \text{ mol}} = 2.001 \approx 2$

E.F. $C_7H_7NO_2$

Determining a Molecular Formula

(empirical formula) x n = molecular formula

empirical formula weight

(real) formula weight or molar mass

- The empirical formula of a compound was found to be CH. (13 g/mol)
- It has a molar mass of 78 g/mol.

What is its molecular formula? (78/13 = 6 =n)
M.F. = 6(EF) = 6(CH) = **C_6H_6**.

Stoichiometric (molar ratio) Calculation

How many grams of water can be produced from 1.00 g of glucose?

$C_6H_{12}O_6(s) + 6\ O_2(g) \rightarrow 6\ CO_2(g) + 6\ H_2O(l)$

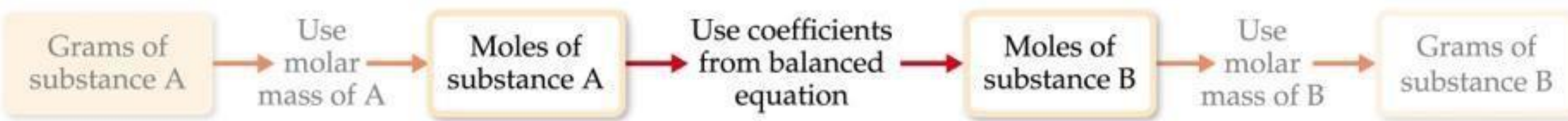
1 mole of glucose will produce 6 moles of water.

- There is 1.00 g of glucose to start.
- The first step is to convert mass (g) it to moles.

Stoichiometric (molar ratio) Calculation

$$C_6H_{12}O_6(s) + 6\ O_2(g) \rightarrow 6\ CO_2(g) + 6\ H_2O(l)$$

$$\frac{\textbf{Glucose}}{\textbf{Water}} = \frac{1}{6} = \frac{\#\textbf{mole of glucose}}{\#\textbf{moles of water}} = \frac{\textbf{1.00 g/180.0 g/mol}}{\textbf{X g/18.0 g/mol}}$$



$$\text{Moles } H_2O = (1.00\ \cancel{g\ C_6H_{12}O_6})\left(\frac{1\ \cancel{mol\ C_6H_{12}O_6}}{180.0\ \cancel{g\ C_6H_{12}O_6}}\right)\left(\frac{6\ mol\ H_2O}{1\ \cancel{mol\ C_6H_{12}O_6}}\right)$$

Quantitative Information from Balanced Equations

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

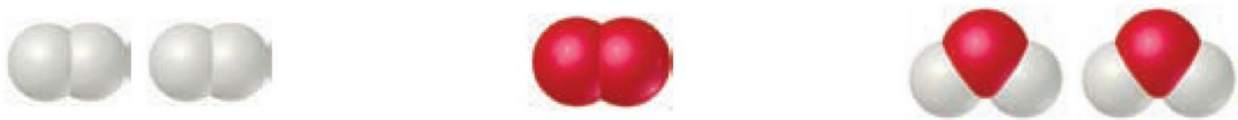
2 molecules	1 molecule	2 molecules
$2(6.02 \times 10^{23}$ molecules)	$1(6.02 \times 10^{23}$ molecules)	$2(6.02 \times 10^{23}$ molecules)
2 mol	1 mol	2 mol

$$2 \text{ mol } H_2 \;\hat{=}\; 1 \text{ mol } O_2 \;\hat{=}\; 2 \text{ mol } H_2O$$

where the $\hat{=}$ symbol means "is stoichiometrically equivalent to."

Quantitative Information from Balanced Equations

Chemical equation:	$2\ H_2(g)$ +	$O_2(g)$ $\longrightarrow$	$2\ H_2O(l)$
Molecular interpretation:	2 molecules H_2	1 molecule O_2	2 molecules H_2O
Mole-level interpretation:	2 mol H_2	1 mol O_2	2 mol H_2O
	Convert to grams (using molar masses)		
	4.0 g H_2	32.0 g O_2	36.0 g H_2O



Notice the conservation of mass
(4.0 g + 32.0 g = 36.0 g)

Limiting Reactants (Reagents)

$\underline{C_6H_{12}O_6(s)}$	+	$\underline{6\ O_2(g)}$	$\rightarrow$	$6\ CO_2(g) + 6\ H_2O(l)$

1 mole — 6 moles (molar ratio)

2 moles — 12 moles (perfect!)

2 moles (deficient/limiting) — 15 moles (12 + 3 moles of O_2 in excess)

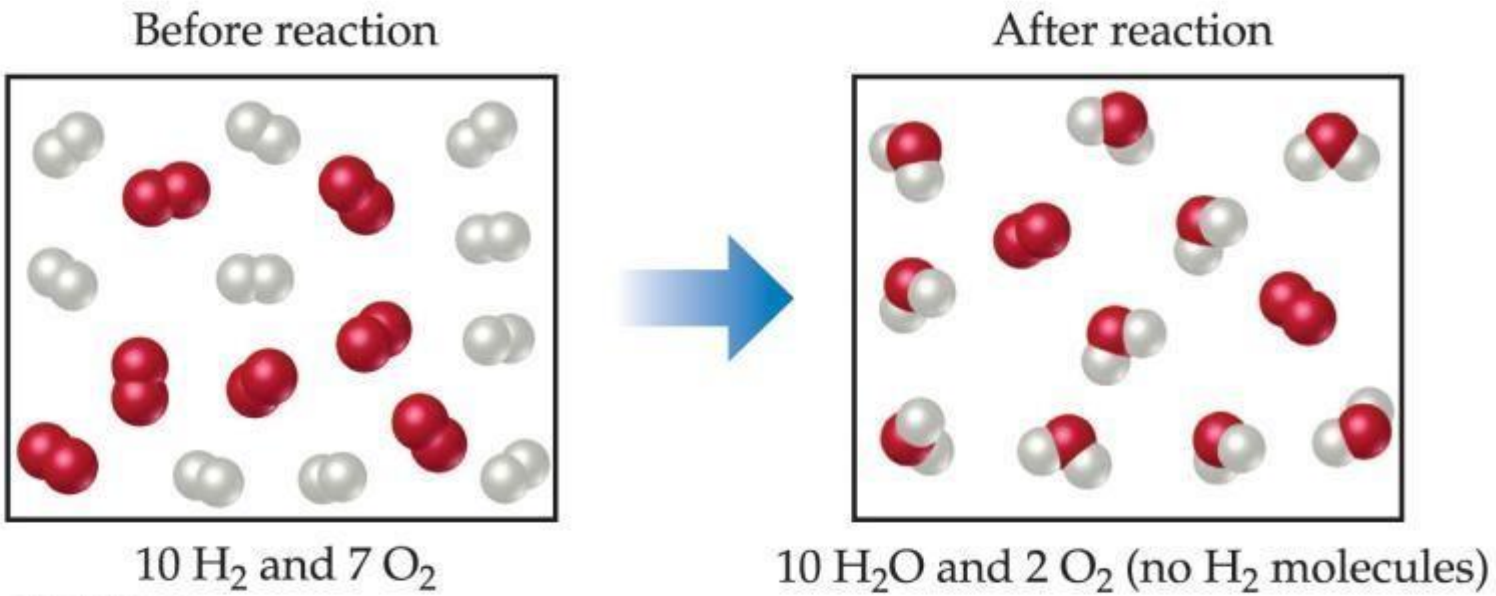
2 moles (excess) — 11 moles (12 - 1) --- O_2 (deficient/limiting)

The limiting reactant runs out (is consumed) first.

!!! The amount of a product produced is dependent on the limiting reactant.

Limiting Reactants

$2\ H_2 + O_2 \rightarrow 2\ H_2O$



- ? H_2 molecules are needed for 7 O_2 molecules.
- 14 H_2 molecules are needed for 7 O_2 molecules.
- H_2 is thus limiting and runs out first.
- O_2 is in excess with a certain amount unreacted.

Percent Yield

One finds the **percent yield** by dividing the amount actually obtained (actual or real yield) to the amount it was possible to make (theoretical or perfect yield):

(from experiment)

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

(from calculation – a prefect reaction)

$$\underline{C_6H_{12}O_6(s) + 6\ O_2(g) \rightarrow 6\ CO_2(g) + 6\ H_2O(l)}$$

1.00 g of glucose reacts with an excess amount of O_2 afforded 0.42 g water.

$$\frac{\textbf{Glucose}}{\textbf{Water}} = \frac{1}{6} = \frac{\#\textbf{mole of glucose}}{\#\textbf{moles of water}} = \frac{1.00/180.0}{x/18.0}$$

- Theoretical yield?
- Actual yield?
- Percentage yield?
- The exact amount of O_2 to react with 1.00 g of glucose?
- How many grams of CO_2 may be perfectly produced by reacting <u>1.00 g</u> of glucose with <u>0.27 g</u> of O_2?
- How many grams of glucose are left unreacted?

SAMPLE EXERCISE 3.4 Writing Balanced Equations for Combustion Reactions

Write the balanced equation for the reaction that occurs when methanol, $CH_3OH(l)$, is burned in air.

SAMPLE EXERCISE 3.7 Estimating Numbers of Atoms

Without using a calculator, arrange these samples in order of increasing numbers of carbon atoms: 12 g ^{12}C, 1 mol C_2H_2, 9×10^{23} molecules of CO_2.

SAMPLE EXERCISE 3.19 Calculating the Amount of Product Formed from a Limiting Reactant

The reaction

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

is used to produce electricity in a hydrogen fuel cell. Suppose a fuel cell contains 150 g of $H_2(g)$ and 1500 g of $O_2(g)$ (each measured to two significant figures). How many grams of water can form?

SAMPLE EXERCISE 3.20 Calculating Theoretical Yield and Percent Yield

Adipic acid, $H_2C_6H_8O_4$, used to produce nylon, is made commercially by a reaction between cyclohexane (C_6H_{12}) and O_2:

$$2\,C_6H_{12}(l) + 5\,O_2(g) \longrightarrow 2\,H_2C_6H_8O_4(l) + 2\,H_2O(g)$$

(**a**) Assume that you carry out this reaction with 25.0 g of cyclohexane and that cyclohexane is the limiting reactant. What is the theoretical yield of adipic acid? (**b**) If you obtain 33.5 g of adipic acid, what is the percent yield for the reaction?