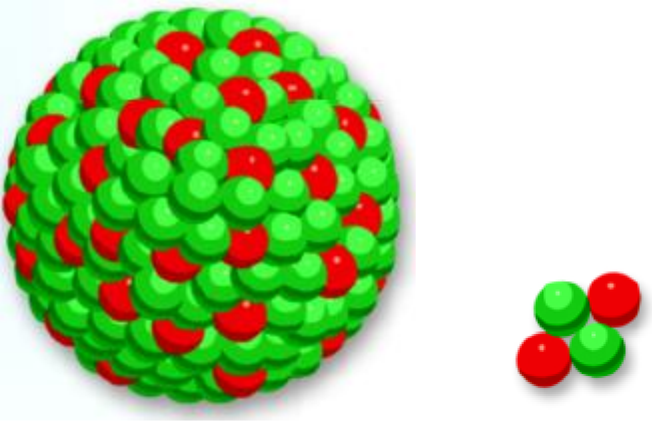
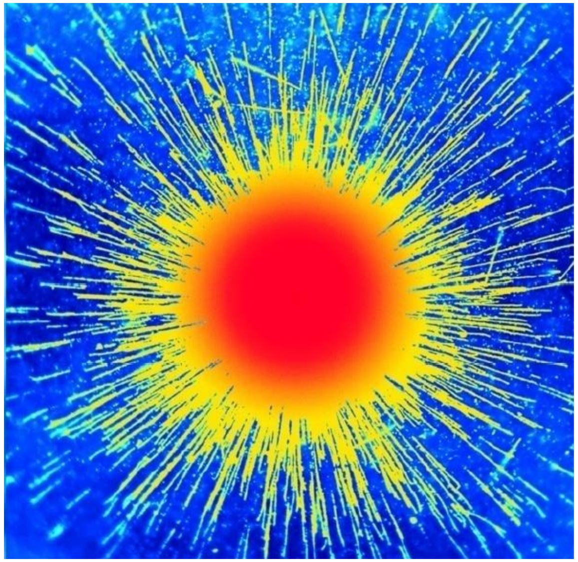


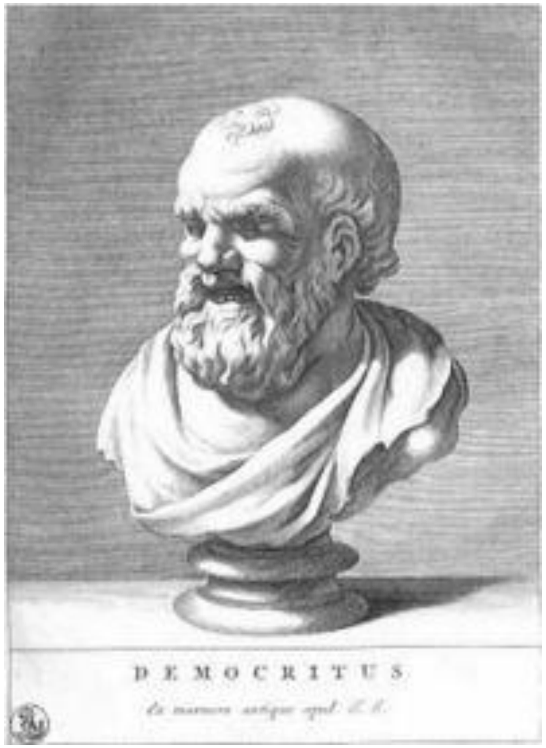
Atoms, Molecules and Ions

Chapter 2



The Atomic Theory

- In the fifth century B.C. the Greek philosopher **Democritus** said matter consists of very small indivisible particles, named **atomos** (meaning uncuttable or indivisible).



The Atomic Theory

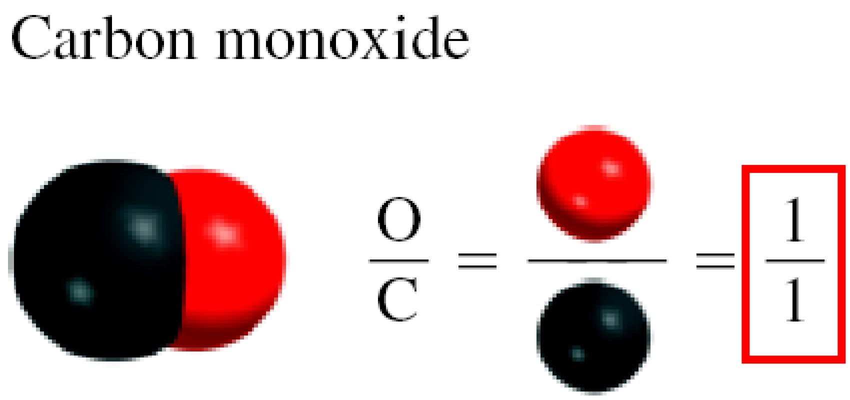
- 1808 - English scientist and school teacher, **John Dalton**, formulated a precise definition of the individual building block of matter that we call **atom**.

Dalton's Atomic Theory (1808)

Marked the beginning of modern era of chemistry, based on ***four hypothesis***:

1. Elements are composed of extremely small particles called ***atoms***.
2. All ***atoms*** of a given element are identical, having the same size, mass and chemical properties. The atoms of one element are different from the atoms of all other elements.
3. ***Compounds*** are composed of atoms of more than one element. In any compound, the ratio of the numbers of atoms of any two of the elements present is either an integer or a simple fraction.
4. A ***chemical reaction*** involves only the separation, combination, or rearrangement of atoms; it does not result in their creation or destruction.

Dalton's Atomic Theory (Hypothesis no. **3**)



Law of Definite Proportions

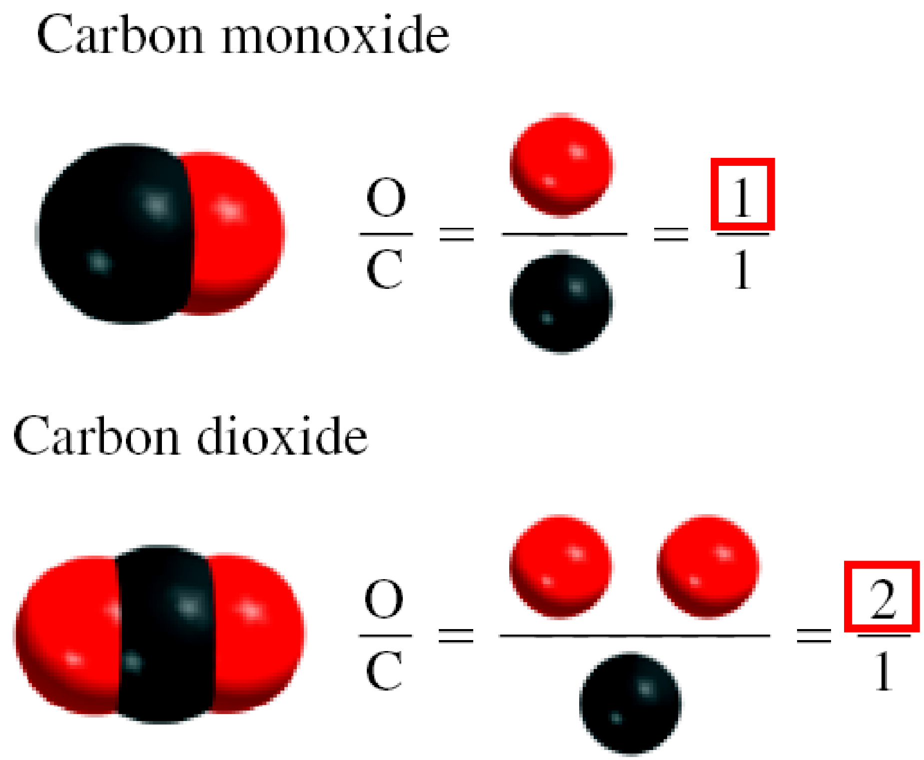
(Joseph Proust 1799)

"different samples of the same compound always contain its constituent elements in the same proportion by mass"

- the ratio of the masses of different elements in a given compound is fixed,
- the ratio of the atoms in the compound is also constant.

Dalton's Atomic Theory (Hypothesis no. **3**)

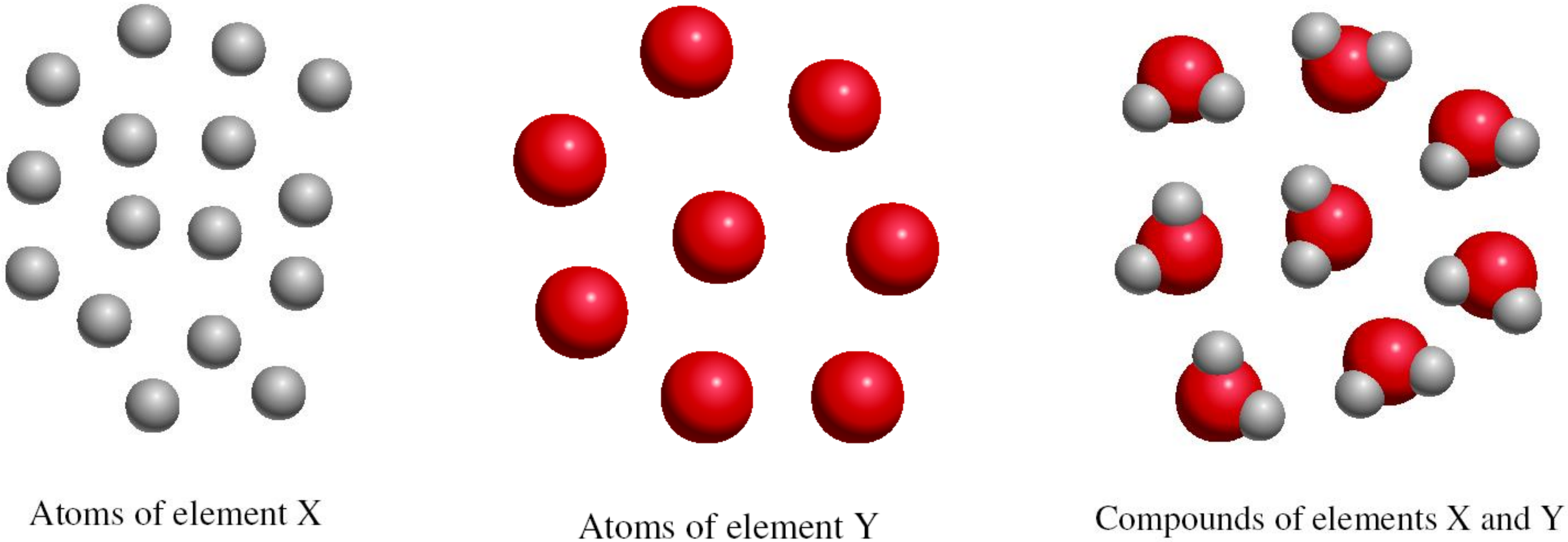
Oxygen in CO & CO_2



Law of Multiple Proportions

"if two elements can combine to form more than one compound, the masses of one element that combine with a fixed mass of the other element are in ratios of small whole number"

Dalton's Atomic Theory (Hypothesis no. **1**, **2**, & **4**)



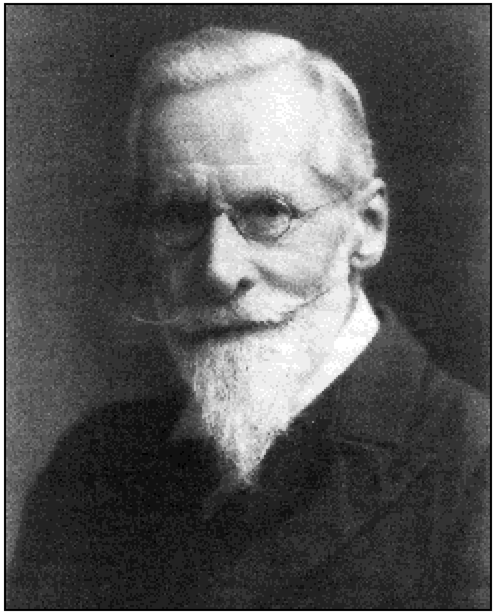
$$16\ X \quad + \quad 8\ Y \longrightarrow 8\ X_2Y$$

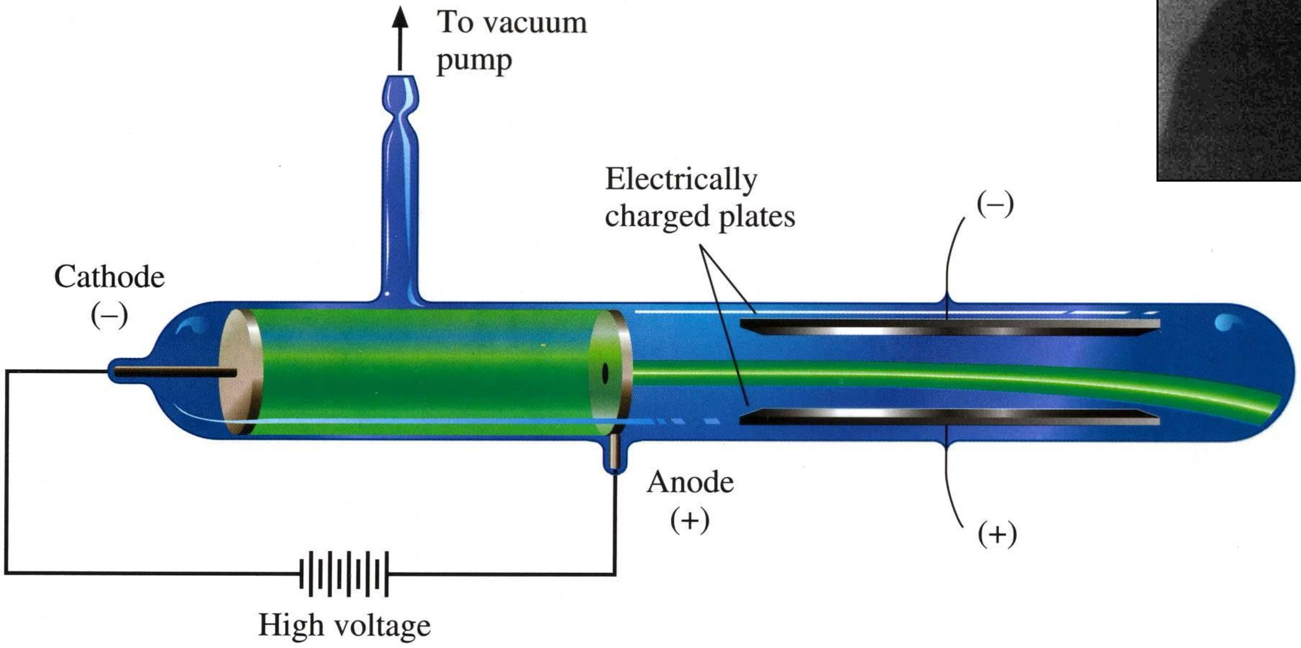
Law of Conservation of Mass

"matter can be neither created nor destroyed"

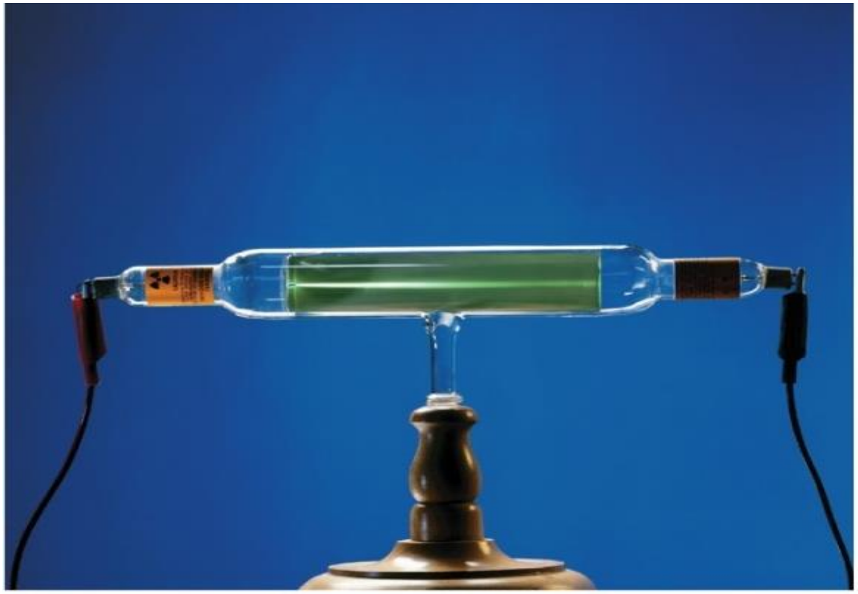
Cathode Ray Tube

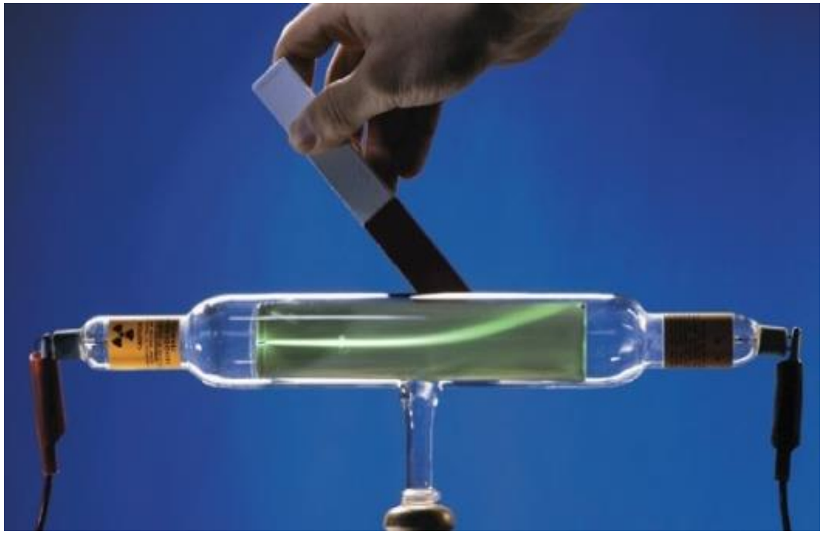
- 1879 - **William Crookes** developed the "**ray tube**" which later allowed us to view electron beams.





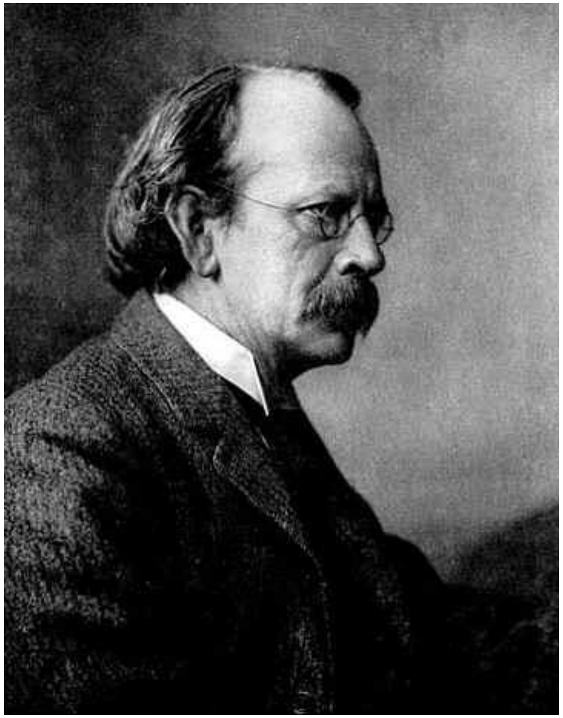
Cathode Ray Tube



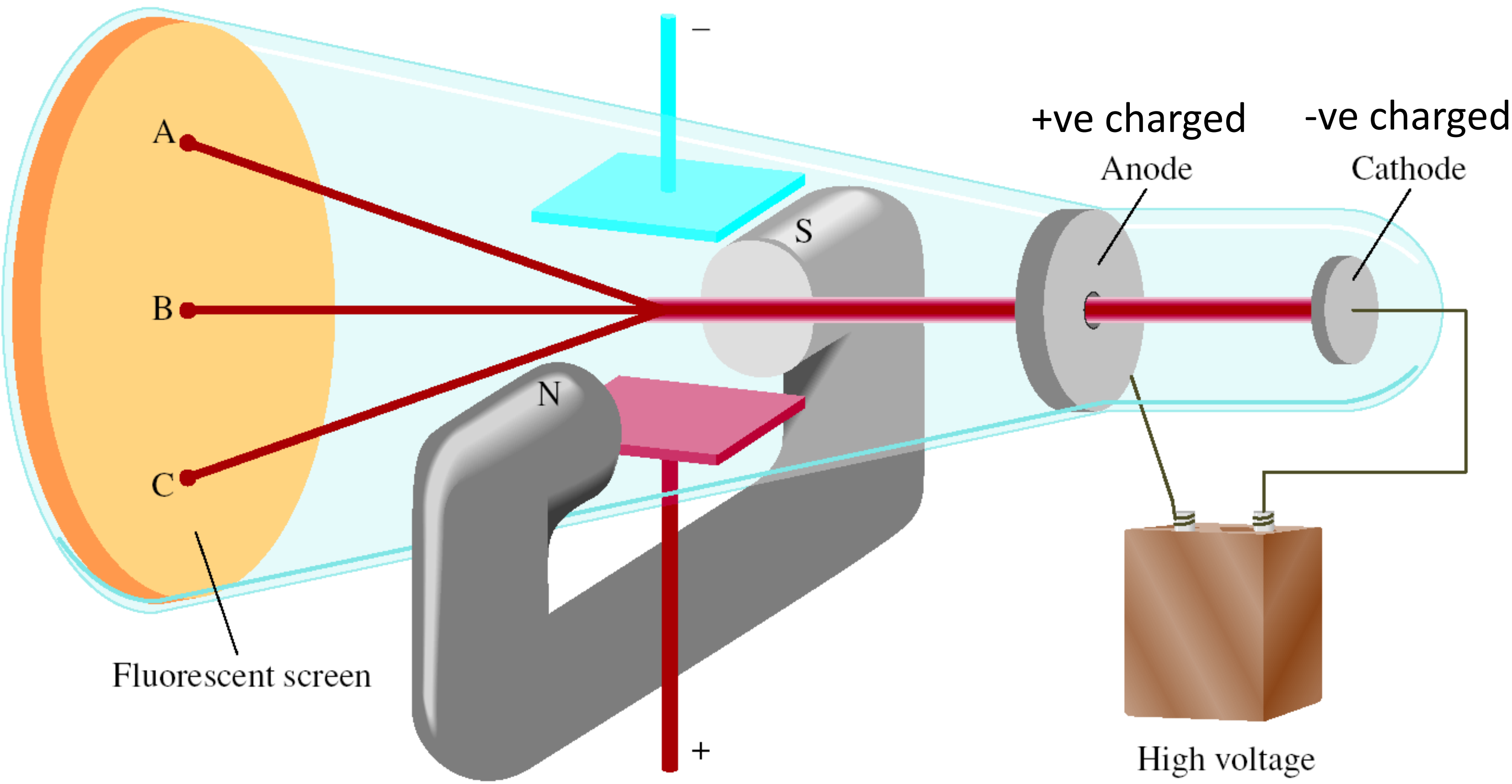


The Electron

- **Joseph John Thomson** (1856 – 1940), British physicist received the Noble Prize in Physics in 1906 for discovering the **electron**.



Cathode Ray Tube



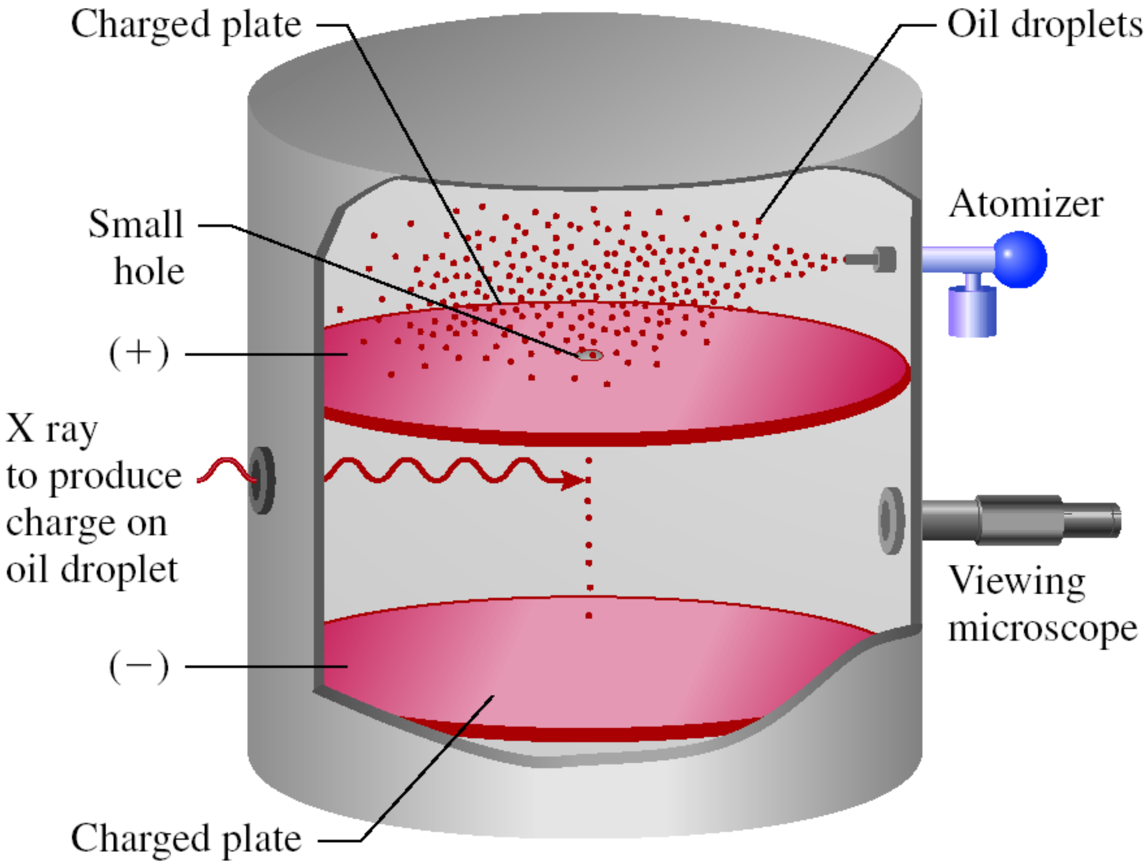
A = mf on
C = ef on
B = both off

J.J. Thomson, measured charge/mass of e^-
(1906 Nobel Prize in Physics)

The Electron

- **Robert Andrew Millikan** (1868 – 1953), American physicist received the Noble Prize in Physics in 1923 for determining the **charge of the electron**.

Millikan's Experiment



Measured charge of e^-

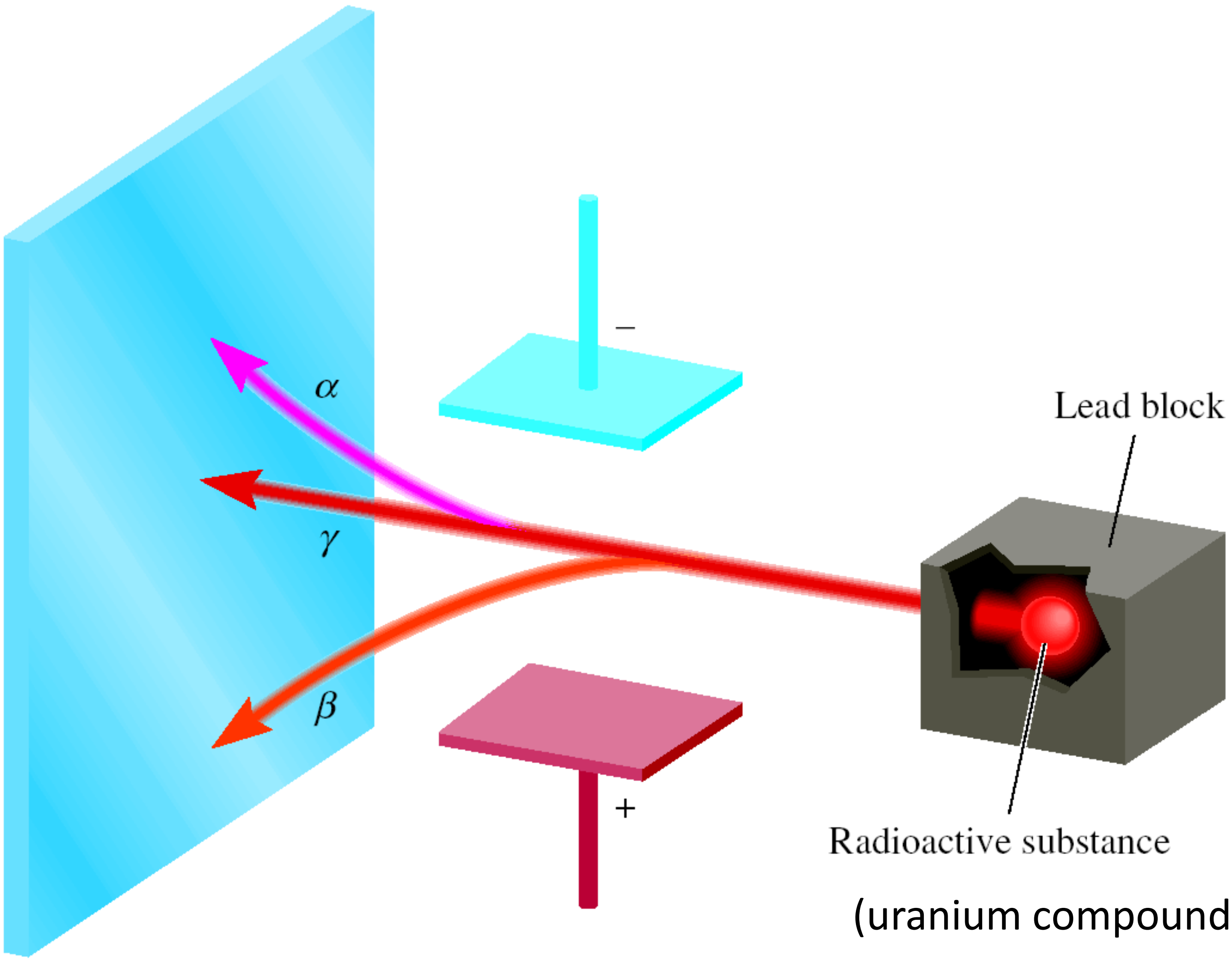
(1923 Nobel Prize in Physics)

Millikan's e^- charge = -1.60×10^{-19} C

Thomson's charge/mass of e^- = -1.76×10^{8} C/g

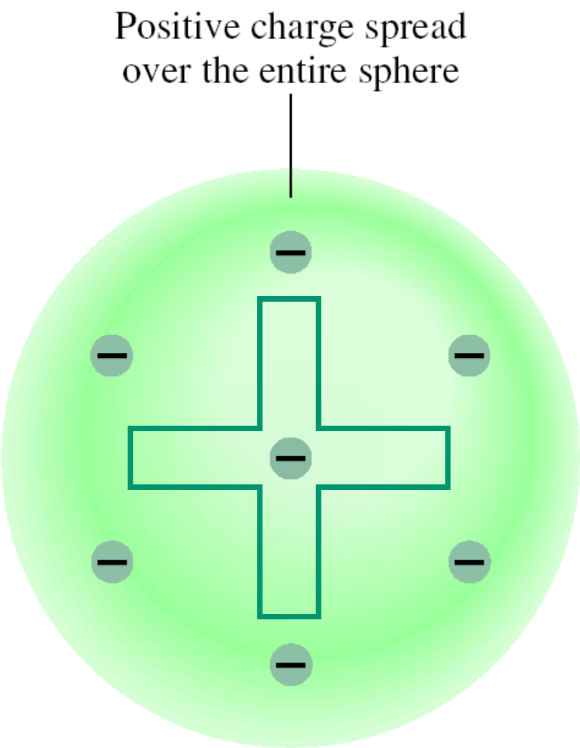
e^- mass = 9.10×10^{-28} g

Types of Radioactivity



(uranium compound)

Thomson's Model



J. J. Thomson

pulm-pudding model

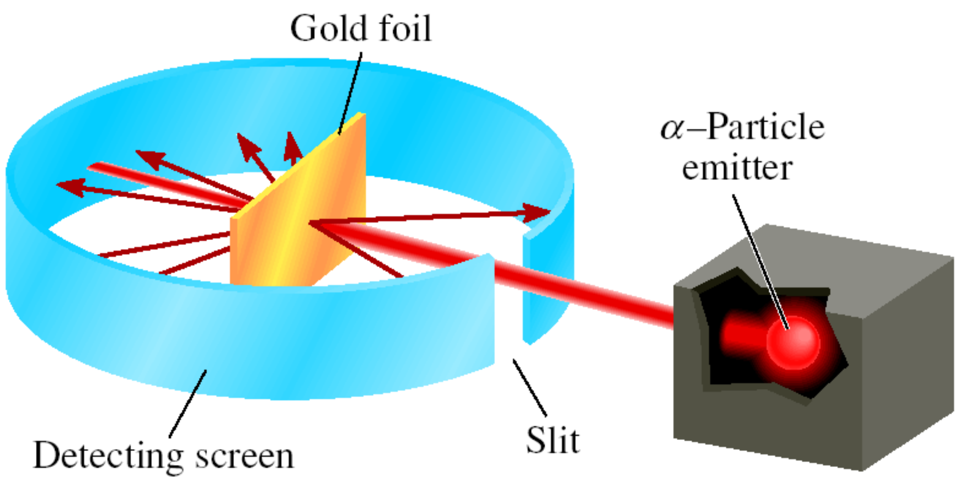
Thomson believed that the electrons were like plums embedded in a positively charged "**pudding**," thus it was called the "**plum pudding**" model.

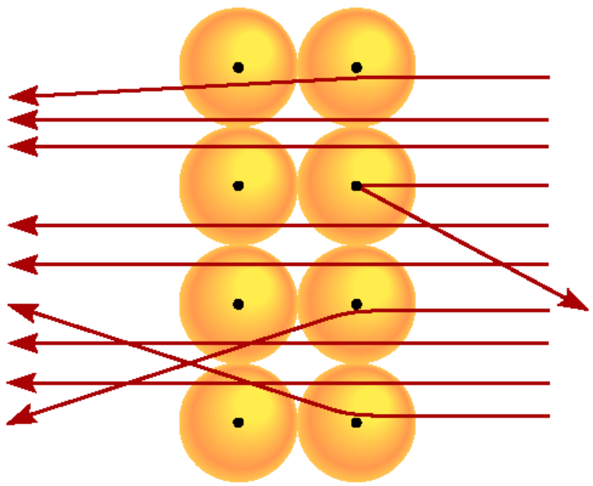
The Proton and the Nucleus

- **Ernest Rutherford** (1871 – 1937), New Zealand Physicist worked in England received the Noble Prize in Chemistry in 1908 for discovering the **structure of atomic nucleus**.

Rutherford's Experiment

(1908 Nobel Prize in Chemistry)





α particle velocity ~ 1.4×10^7 m/s
(~5% speed of light)

1. atoms positive charge is concentrated in the nucleus
2. proton (p) has opposite (+) charge of electron (-)
3. mass of p is 1840 x mass of e^- (1.67×10^{-24} g)

The Neutron

- **James Chadwick** (1891 – 1972), British physicist received the Noble Prize in Physics in 1935 for discovering the **neutrons**.

Chadwick's Experiment (1932)

(1935 Noble Prize in Physics)

H atoms - 1 p; He atoms - 2 p

mass He/mass H should = 2

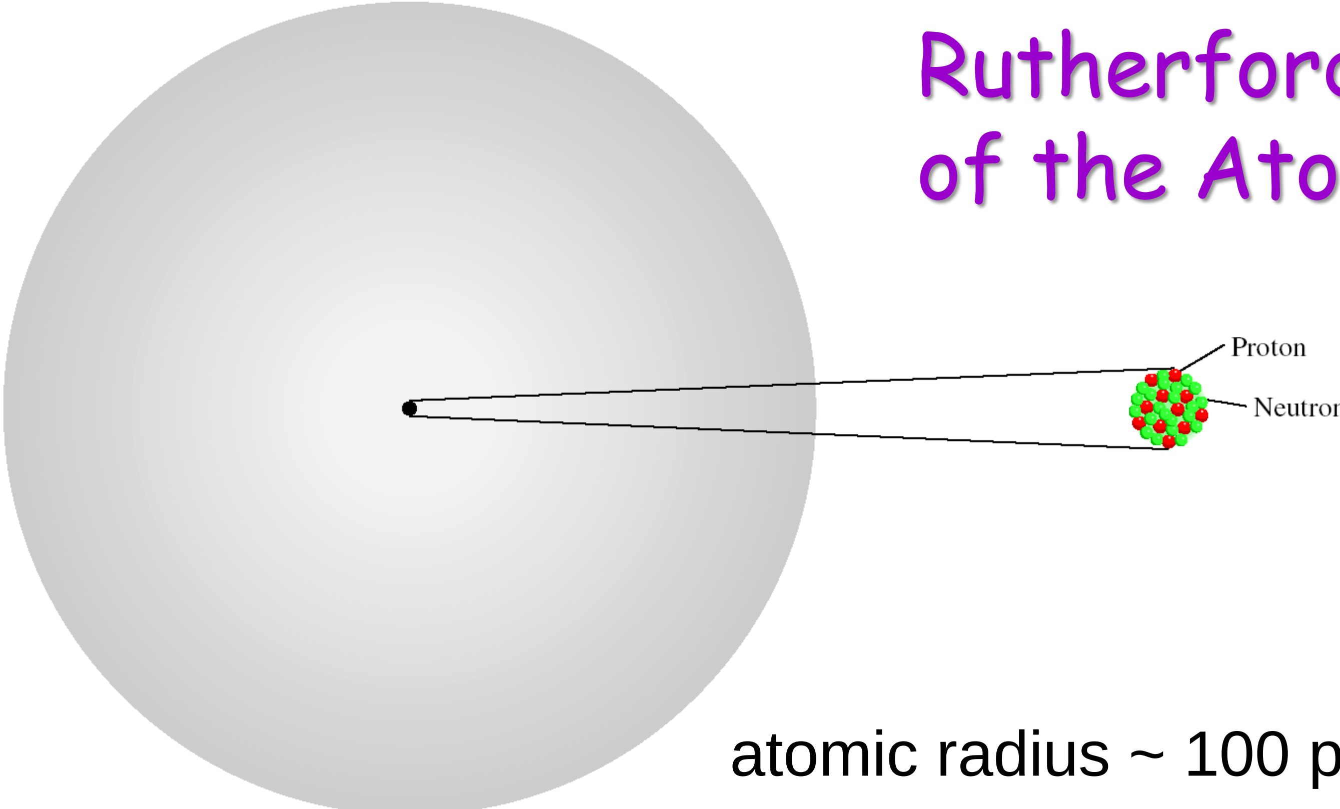
measured mass He/mass H = 4

$$\alpha + {}^{9}\text{Be} \longrightarrow {}^{1}\text{n} + {}^{12}\text{C} + \text{energy}$$

neutron (n) is neutral (charge = 0)

n mass ~ p mass = 1.67×10^{-24} g

Rutherford's Model of the Atom



atomic radius ~ 100 pm = 1 x 10^{-10} m

nuclear radius ~ 5 x 10^{-3} pm = 5 x 10^{-15} m

"If the atom is the Dhaka Stadium, then the nucleus is a marble on the goal line."

Subatomic Particles

TABLE 2.1 Mass and Charge of Subatomic Particles

Particle	Mass (g)	Charge	
		Coulomb	Charge Unit
Electron*	9.10938×10^{-28}	-1.6022×10^{-19}	-1
Proton	1.67262×10^{-24}	$+1.6022 \times 10^{-19}$	$+1$
Neutron	1.67493×10^{-24}	0	0

*More refined measurements have given us a more accurate value of an electron's mass than Millikan's.

mass p ≈ mass n ≈ 1840 x mass e^-

Atomic number and Mass number

Atomic number (Z) = number of protons in nucleus

Mass number (A) = number of protons + number of neutrons

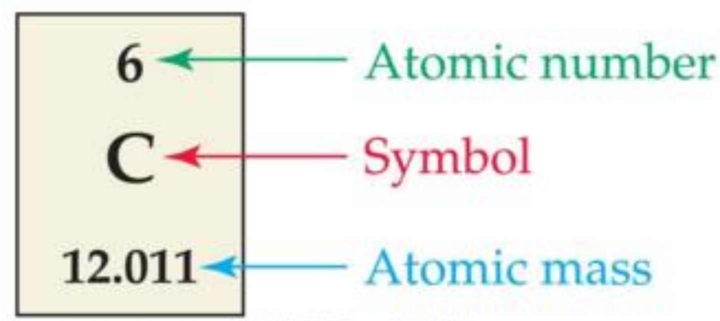
= atomic number (Z) + number of neutrons

Mass Number → A

Atomic Number → Z

$${}^{A}_{Z}X$$

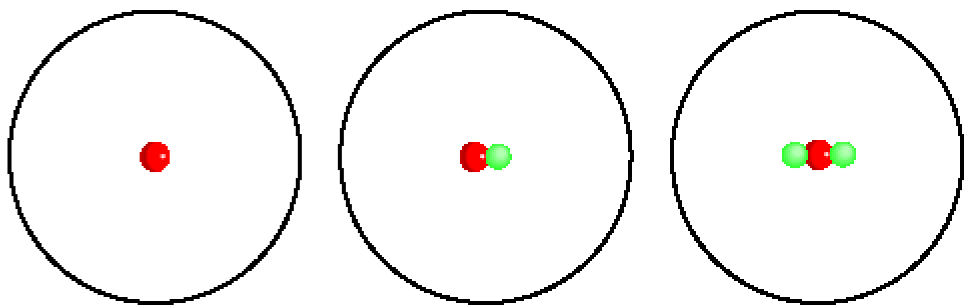
← Element Symbol



Isotopes

Atoms of a given element **do not** all have the same mass.

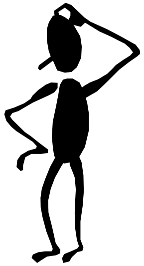
Isotopes are atoms of the same element (X) with different numbers of neutrons in their nuclei



$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$

Hydrogen Deuterium Tritium

$^{235}_{92}U$ $^{238}_{92}U$



Counting Protons, Neutrons & Electrons

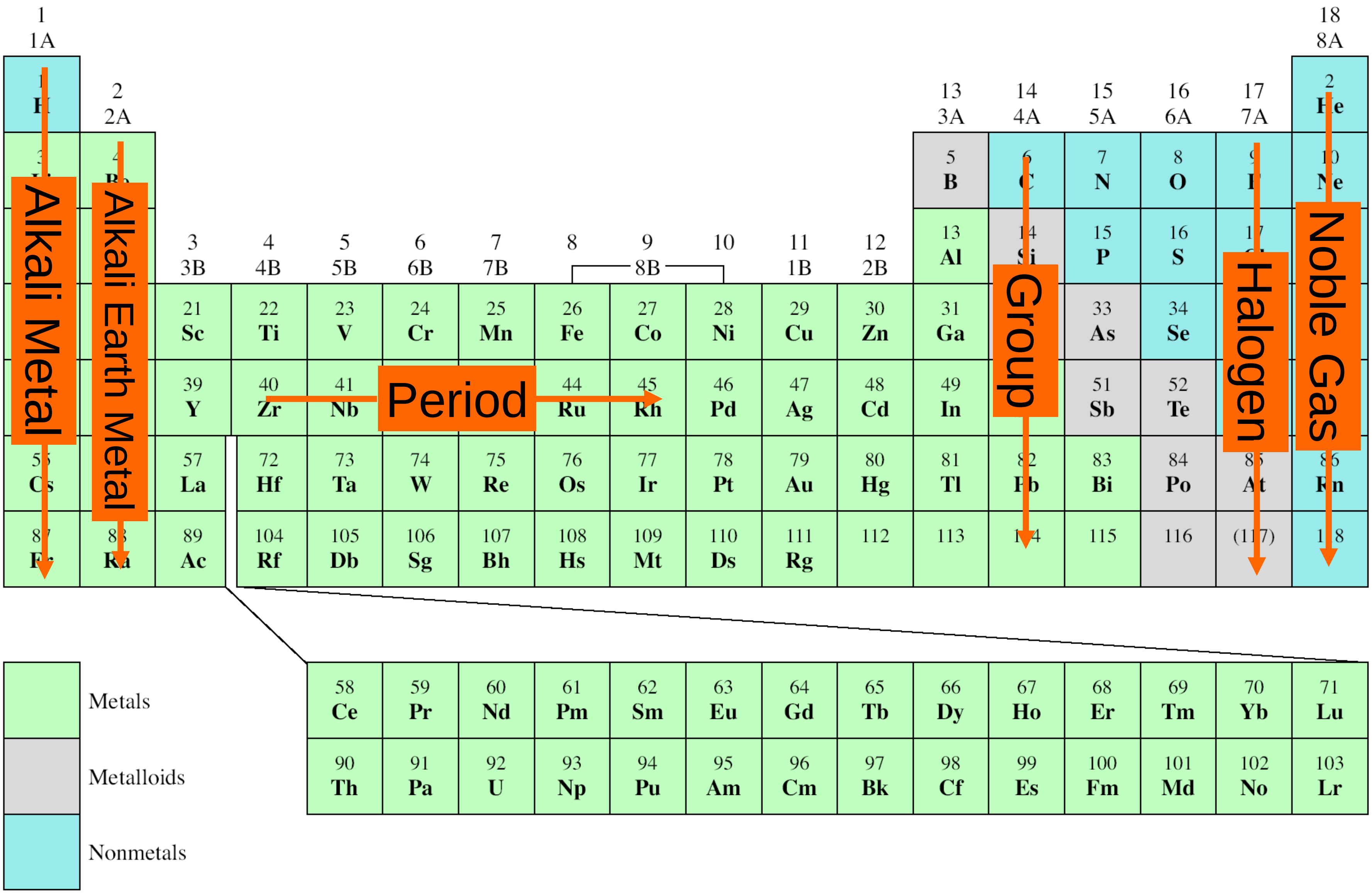
How many protons, neutrons, and electrons are in ${}^{14}_{6}C$?

6 protons, 8 (14 - 6) neutrons, 6 electrons

How many protons, neutrons, and electrons are in ${}^{11}_{6}C$?

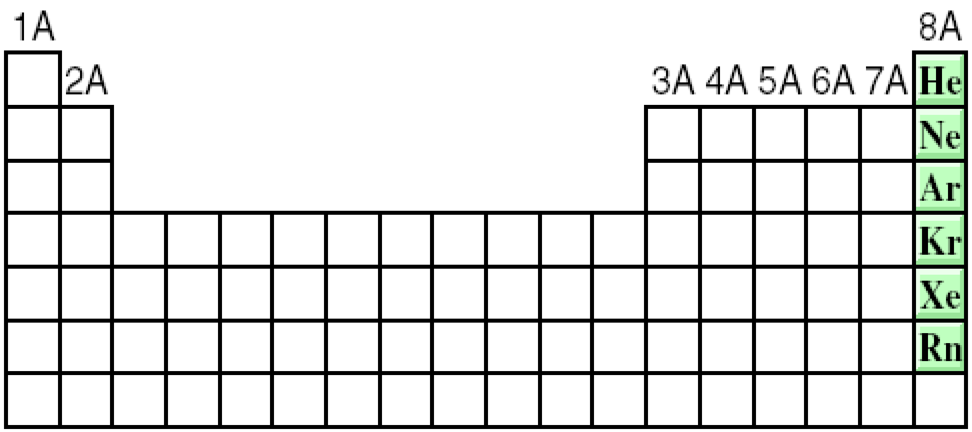
6 protons, 5 (11 - 6) neutrons, 6 electrons

The Modern Periodic Table



Molecules and Ions

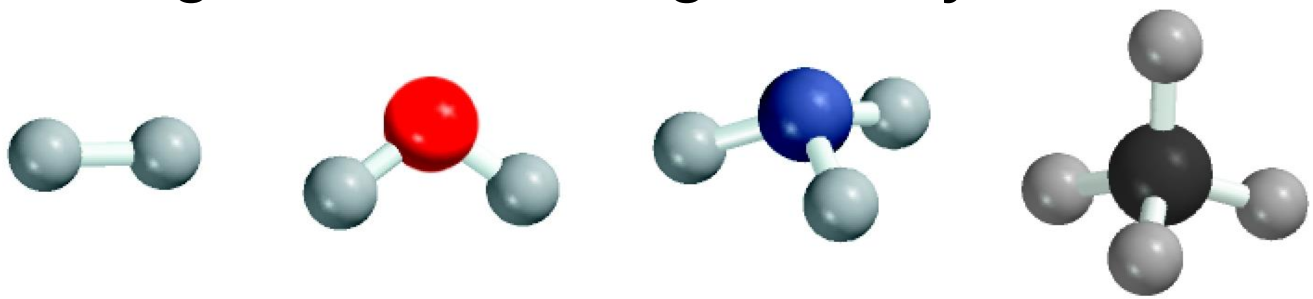
Of all the elements, only the six noble gases in Group 8A exist in nature as single atoms, called ***monatomic*** gases.



Most matter is composed of molecules or ions formed by atoms.

Molecules: diatomic & polyatomic

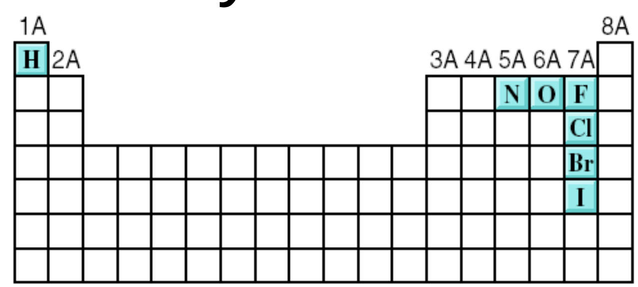
A ***molecule*** is an aggregate of two or more atoms in a definite arrangement held together by chemical forces.



H_2 H_2O NH_3 CH_4

A ***diatomic molecule*** contains only two atoms.

H_2, N_2, O_2, Br_2, HCl, CO



diatomic elements

A ***polyatomic molecule*** contains more than two atoms.

O_3, H_2O, NH_3, CH_4

Ions: cation & anion

An ***ion*** is an atom, or group of atoms, that has a net positive or negative charge.

cation – ion with a positive charge: If a neutral atom **loses** one or more electrons it becomes a cation.

Na

11 protons
11 electrons

Na^+

11 protons
10 electrons

anion – ion with a negative charge: If a neutral atom **gains** one or more electrons it becomes an anion.

Cl

17 protons
17 electrons

Cl^-

17 protons
18 electrons

Monatomic Ions & Polyatomic Ions

A ***monatomic ion*** contains only one atom

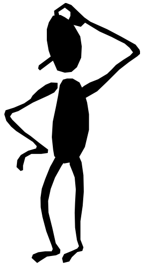
Na^{+}, Cl^{-}, Ca^{2+}, O^{2-}, Al^{3+}, N^{3-}

A ***polyatomic ion*** contains more than one atom

OH^{-}, CN^{-}, NH_4^{+}, NO_3^{-}

Common Ions Shown on the Periodic Table

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
Li^{+}													C^{4-}	N^{3-}	O^{2-}	F^{-}	
Na^{+}	Mg^{2+}											Al^{3+}		P^{3-}	S^{2-}	Cl^{-}	
K^{+}	Ca^{2+}				Cr^{2+} Cr^{3+}	Mn^{2+} Mn^{3+}	Fe^{2+} Fe^{3+}	Co^{2+} Co^{3+}	Ni^{2+} Ni^{3+}	Cu^{+} Cu^{2+}	Zn^{2+}				Se^{2-}	Br^{-}	
Rb^{+}	Sr^{2+}									Ag^{+}	Cd^{2+}		Sn^{2+} Sn^{4+}		Te^{2-}	I^{-}	
Cs^{+}	Ba^{2+}									Au^{+} Au^{3+}	Hg_2^{2+} Hg^{2+}		Pb^{2+} Pb^{4+}				



Counting Protons, Neutrons & Electrons

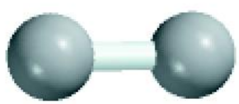
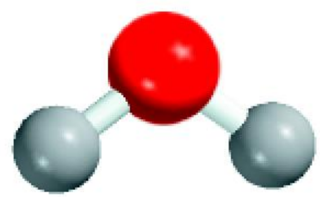
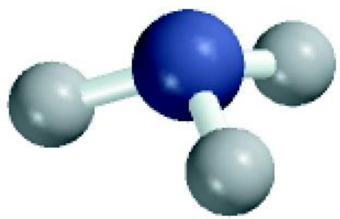
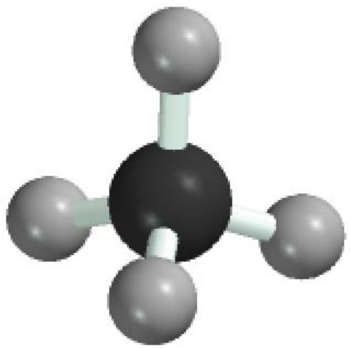
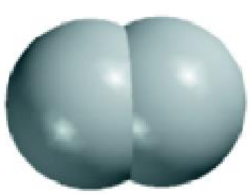
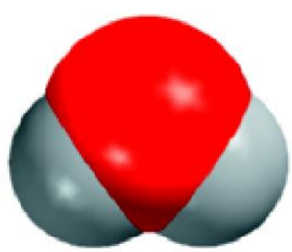
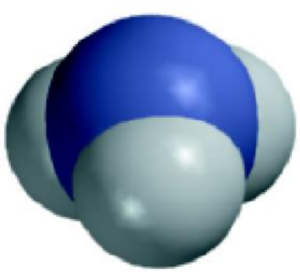
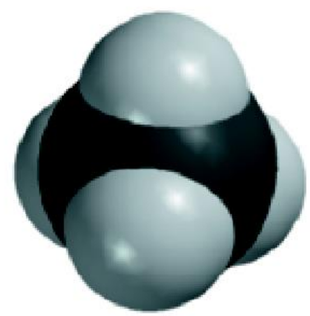
How many protons, neutrons and electrons are in ${}^{27}_{13}Al^{3+}$?

13 protons, 14 neutrons, 10 (13 – 3) electrons

How many protons, neutrons and electrons are in ${}^{78}_{34}Se^{2-}$?

34 protons, 44 neutrons, 36 (34 + 2) electrons

Formulas and Models

	Hydrogen	Water	Ammonia	Methane
Molecular formula	H_2	H_2O	NH_3	CH_4
Structural formula	H—H	H—O—H	$\begin{array}{c} H-N-H \\ \vert \\ H \end{array}$	$\begin{array}{c} H \\ \vert \\ H-C-H \\ \vert \\ H \end{array}$
Ball-and-stick model				
Space-filling model				

Molecular & Empirical Formulas

A ***molecular formula*** shows the exact number of atoms of each element in the smallest unit of a substance.

An ***empirical formula*** shows the simplest whole-number ratio of the atoms in a substance.

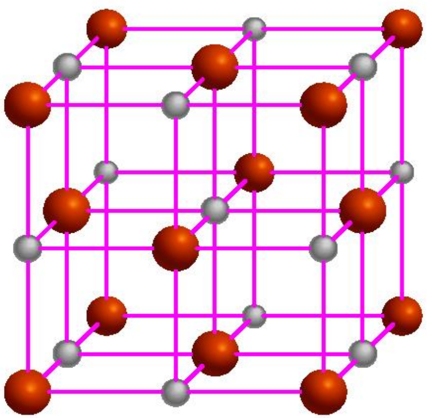
molecular	**empirical**
H_2O	H_2O
$C_6H_{12}O_6$	CH_2O
O_3	O
O_2	O
N_2H_4	NH_2

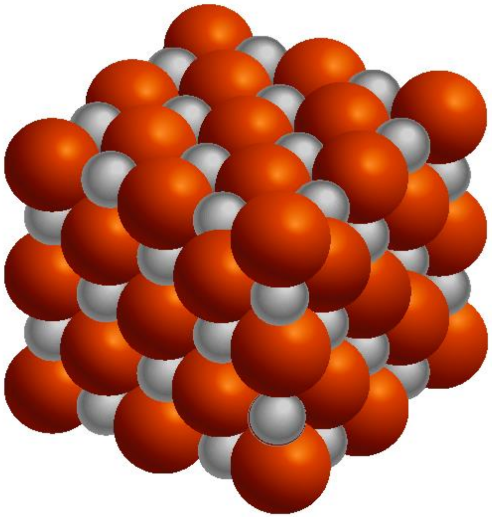
Ionic Compounds

Ionic compounds consist of a combination of cations and an anions.

- The formula is usually the same as the empirical formula.
- The sum of the charges on the cation(s) and anion(s) in each formula unit must equal zero.

The ionic compound NaCl





Formula of Ionic Compounds

$2 \times +3 = +6$ $3 \times -2 = -6$

Al_2O_3

Al^{3+} O^{2-}

$1 \times +2 = +2$ $2 \times -1 = -2$

$CaBr_2$

Ca^{2+} Br^{-}

$2 \times +1 = +2$ $1 \times -2 = -2$

Na_2CO_3

Na^{+} CO_3^{2-}

Naming Compounds

- **Organic compounds**
  - Contain carbon, usually in combination with elements such as H, O, N, and S
- **Inorganic compounds**
  - All other compounds are classified as inorganic compounds, including, CO, CO_2, CS_2, and compounds containing CN^-, CO_3^{2-}, and HCO_3^- groups

Naming Compounds

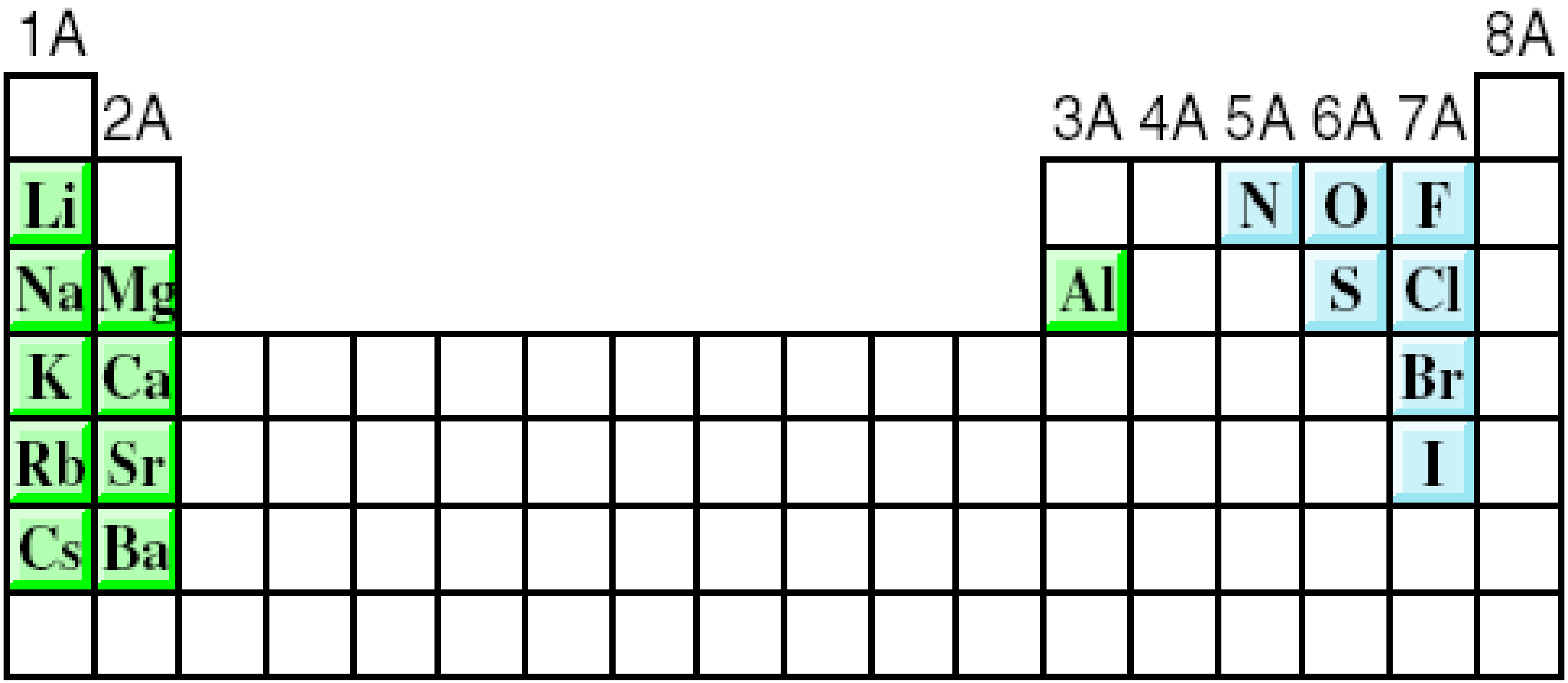
- **Inorganic compounds** are divided into four categories:
  - **Ionic compounds**
  - **Molecular compounds**
  - **Acids and bases**
  - **Hydrates**

Chemical Nomenclature

- **Ionic Compounds**
  - Often a metal + nonmetal
  - Anion (nonmetal), add “ide” to element name

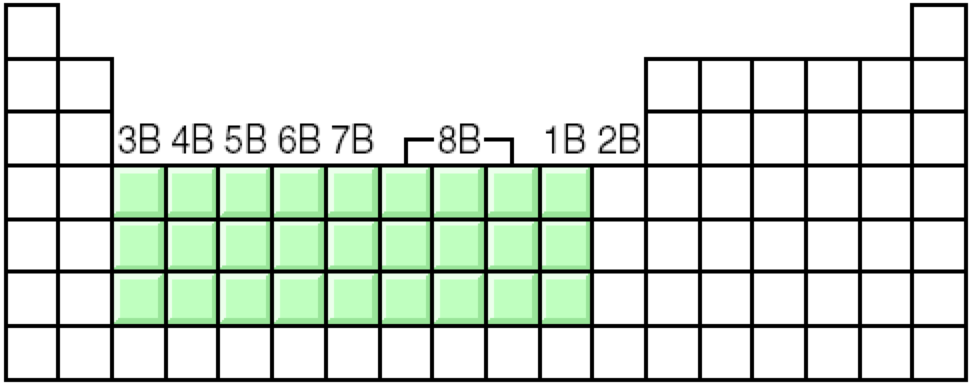
$BaCl_2$	barium chloride
K_2O	potassium oxide
$Mg(OH)_2$	magnesium hydroxide
KNO_3	potassium nitrate

Ionic Compounds



The most reactive **metals** (green) and the most reactive **nonmetals** (blue) combine to form ionic compounds.

- Transition metal ionic compounds
  - indicate charge on metal with Roman numerals



$FeCl_2$	2 Cl^- -2 so Fe is +2	iron(II) chloride
$FeCl_3$	3 Cl^- -3 so Fe is +3	iron(III) chloride
Cr_2S_3	3 S^{-2} -6 so Cr is +3 (6/2)	chromium(III) sulfide

TABLE 2.2 The "-ide" Nomenclature of Some Common Monatomic Anions According to Their Positions in the Periodic Table

Group 4A	Group 5A	Group 6A	Group 7A
C carbide (C^{4-})*	N nitride (N^{3-})	O oxide (O^{2-})	F fluoride (F^-)
Si silicide (Si^{4-})	P phosphide (P^{3-})	S sulfide (S^{2-})	Cl chloride (Cl^-)
		Se selenide (Se^{2-})	Br bromide (Br^-)
		Te telluride (Te^{2-})	I iodide (I^-)

*The word "carbide" is also used for the anion C_2^{2-}.

TABLE 2.3 Names and Formulas of Some Common Inorganic Cations and Anions

Cation	Anion
aluminum (Al^{3+})	bromide (Br^-)
ammonium (NH_4^+)	carbonate (CO_3^{2-})
barium (Ba^{2+})	chlorate (ClO_3^-)
cadmium (Cd^{2+})	chloride (Cl^-)
calcium (Ca^{2+})	chromate (CrO_4^{2-})
cesium (Cs^+)	cyanide (CN^-)
chromium(III) or chromic (Cr^{3+})	dichromate ($Cr_2O_7^{2-}$)
cobalt(II) or cobaltous (Co^{2+})	dihydrogen phosphate ($H_2PO_4^-$)
copper(I) or cuprous (Cu^+)	fluoride (F^-)
copper(II) or cupric (Cu^{2+})	hydride (H^-)
hydrogen (H^+)	hydrogen carbonate or bicarbonate (HCO_3^-)
iron(II) or ferrous (Fe^{2+})	hydrogen phosphate (HPO_4^{2-})
iron(III) or ferric (Fe^{3+})	hydrogen sulfate or bisulfate (HSO_4^-)
lead(II) or plumbous (Pb^{2+})	hydroxide (OH^-)
lithium (Li^+)	iodide (I^-)
magnesium (Mg^{2+})	nitrate (NO_3^-)
manganese(II) or manganous (Mn^{2+})	nitride (N^{3-})
mercury(I) or mercurous (Hg_2^{2+})*	nitrite (NO_2^-)
mercury(II) or mercuric (Hg^{2+})	oxide (O^{2-})
potassium (K^+)	permanganate (MnO_4^-)
rubidium (Rb^+)	peroxide (O_2^{2-})
silver (Ag^+)	phosphate (PO_4^{3-})
sodium (Na^+)	sulfate (SO_4^{2-})
strontium (Sr^{2+})	sulfide (S^{2-})
tin(II) or stannous (Sn^{2+})	sulfite (SO_3^{2-})
zinc (Zn^{2+})	thiocyanate (SCN^-)

*Mercury(I) exists as a pair as shown.

- **Molecular compounds**
  - Nonmetals or nonmetals + metalloids
  - Common names
    - H_2O, NH_3, CH_4,
  - Element furthest to the left in a period and closest to the bottom of a group on periodic table is placed first in formula
  - If more than one compound can be formed from the same elements, use prefixes to indicate number of each kind of atom
  - Last element name ends in *ide*

TABLE 2.4

Greek Prefixes Used in Naming Molecular Compounds

Prefix	Meaning
mono-	1
di-	2
tri-	3
tetra-	4
penta-	5
hexa-	6
hepta-	7
octa-	8
nona-	9
deca-	10

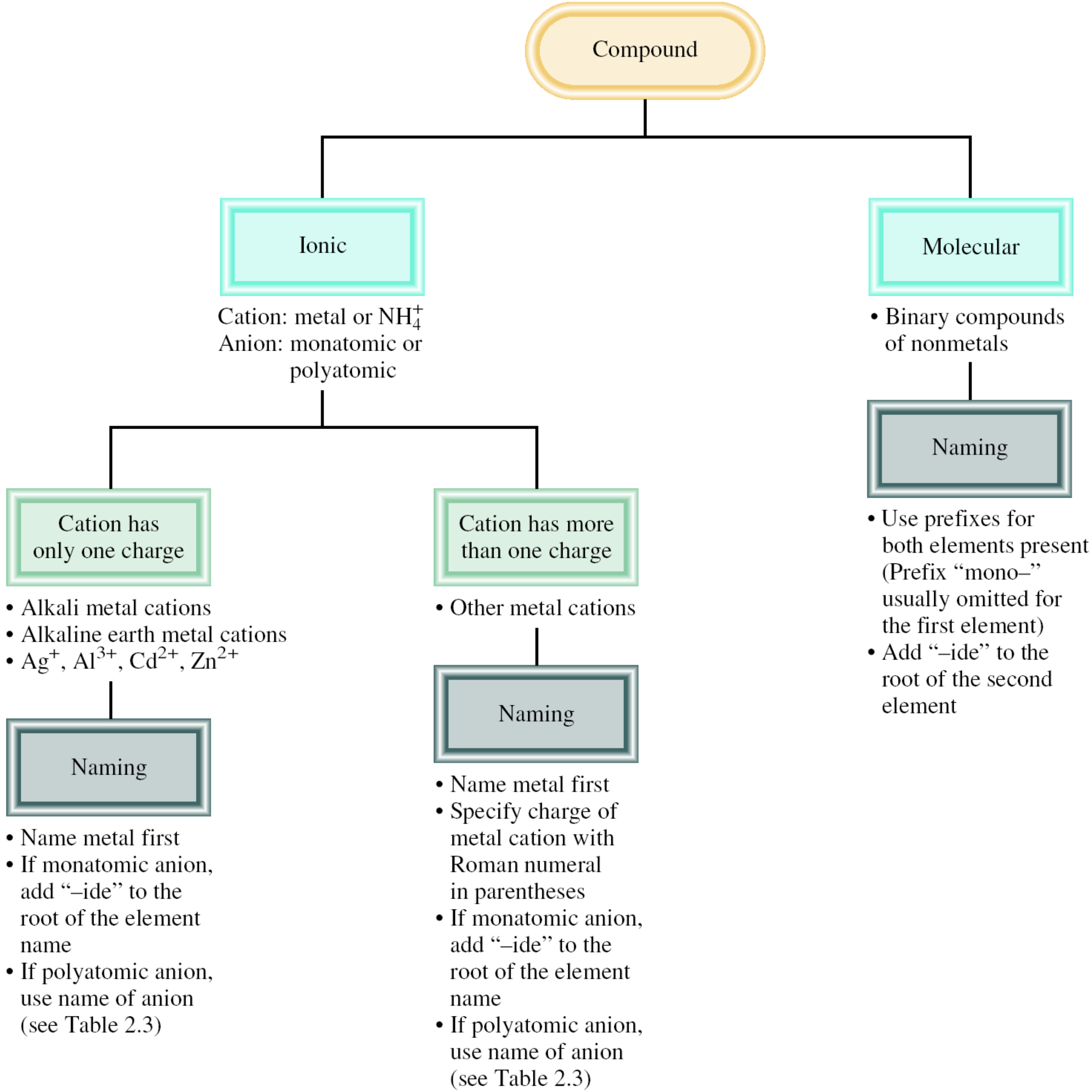
Molecular Compounds

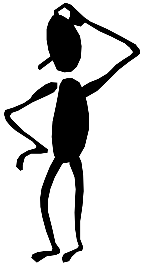
HI	hydrogen iodide
NF_3	nitrogen trifluoride
SO_2	sulfur dioxide
N_2Cl_4	dinitrogen tetrachloride
NO_2	nitrogen dioxide
N_2O	dinitrogen monoxide

Molecular Compounds

- Exceptions
  - exceptions to the use of Greek preixes are molecular compounds containing hydrogen
  - called by their common name
  - do not indicate the number of hydrogen atom present
  - order of writing elements in the formulas is irregular

B_2H_6	diborane
CH_4	methane
SiH_4	silane
NH_3	ammonia
PH_3	phosphine
H_2O	water
H_2S	hydrogen sulfide


Compound
Ionic
Cation: metal or NH_4^+
Anion: monatomic or polyatomic
Molecular
• Binary compounds of nonmetals
Naming
• Use prefixes for both elements present (Prefix "mono–" usually omitted for the first element)
• Add "–ide" to the root of the second element
Cation has only one charge
• Alkali metal cations
• Alkaline earth metal cations
• Ag^+, Al^{3+}, Cd^{2+}, Zn^{2+}
Naming
• Name metal first
• If monatomic anion, add "–ide" to the root of the element name
• If polyatomic anion, use name of anion (see Table 2.3)
Cation has more than one charge
• Other metal cations
Naming
• Name metal first
• Specify charge of metal cation with Roman numeral in parentheses
• If monatomic anion, add "–ide" to the root of the element name
• If polyatomic anion, use name of anion (see Table 2.3)



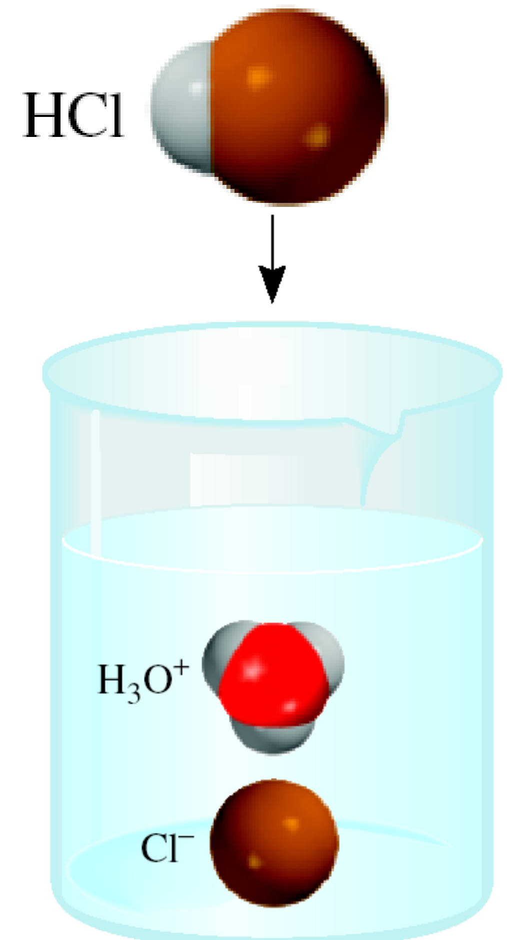
Name the following compounds and which are likely to be ionic or molecular?

CH_4	Methane, molelular
NaBr	Sodium bromide, ionic
BaF_2	Barium fluoride, ionic
CCl_4	Carbon tetrachloride, molecular
ICl	Iodine (I) chloride, molecular
CsCl	Cesium chloride, ionic
NF_3	Nitrogen trifluoride, molecular

- **Acid and Bases**

An ***acid*** can be defined as a substance that yields hydrogen ions (H^+) when dissolved in water.

For example: HCl gas and HCl in water



- Pure substance, hydrogen chloride

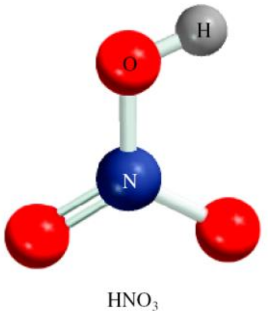
- Dissolved in water (H_3O^+ and Cl^-), hydrochloric acid

TABLE 2.5 Some Simple Acids

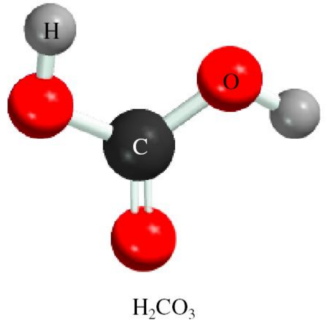
Anion	Corresponding Acid
F^- (fluoride)	HF (hydrofluoric acid)
Cl^- (chloride)	HCl (hydrochloric acid)
Br^- (bromide)	HBr (hydrobromic acid)
I^- (iodide)	HI (hydroiodic acid)
CN^- (cyanide)	HCN (hydrocyanic acid)
S^{2-} (sulfide)	H_2S (hydrosulfuric acid)

An ***oxoacid*** is an acid that contains hydrogen, oxygen, and another element.

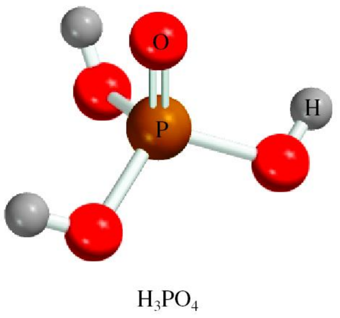
HNO_3 nitric acid



H_2CO_3 carbonic acid



H_3PO_4 phosphoric acid



A ***base*** can be defined as a substance that yields hydroxide ions (OH^-) when dissolved in water.

$NaOH$	sodium hydroxide
KOH	potassium hydroxide
$Ba(OH)_2$	barium hydroxide
NH_4OH	ammonium hydroxide (NH_3 dissolved in water)

- **Hydrates**

Compounds that have a specific number of water molecules attached to them.

$BaCl_2 \cdot 2H_2O$	barium chloride dihydrate
$LiCl \cdot H_2O$	lithium chloride monohydrate
$MgSO_4 \cdot 7H_2O$	magnesium sulfate heptahydrate
$Sr(NO_3)_2 \cdot 4H_2O$	strontium nitrate tetrahydrate

$CuSO_4 \cdot 5H_2O$ →

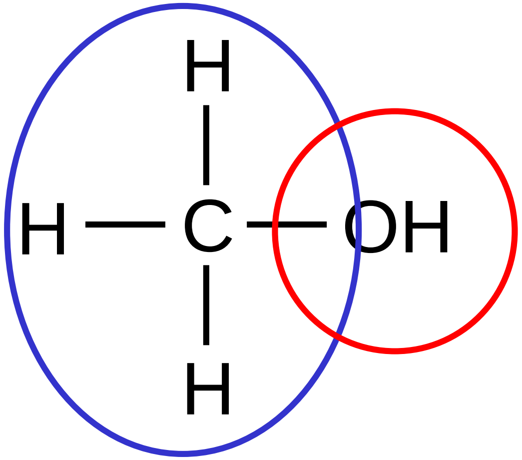
← $CuSO_4$

TABLE 2.7 Common and Systematic Names of Some Compounds

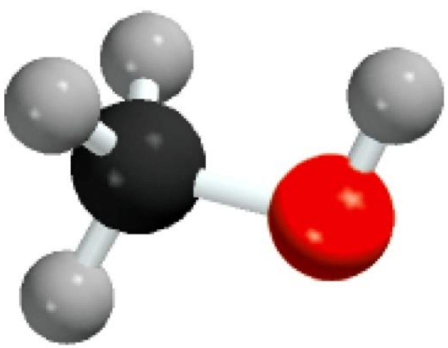
Formula	Common Name	Systematic Name
H_2O	Water	Dihydrogen monoxide
NH_3	Ammonia	Trihydrogen nitride
CO_2	Dry ice	Solid carbon dioxide
$NaCl$	Table salt	Sodium chloride
N_2O	Laughing gas	Dinitrogen monoxide
$CaCO_3$	Marble, chalk, limestone	Calcium carbonate
CaO	Quicklime	Calcium oxide
$Ca(OH)_2$	Slaked lime	Calcium hydroxide
$NaHCO_3$	Baking soda	Sodium hydrogen carbonate
$Na_2CO_3 \cdot 10H_2O$	Washing soda	Sodium carbonate decahydrate
$MgSO_4 \cdot 7H_2O$	Epsom salt	Magnesium sulfate heptahydrate
$Mg(OH)_2$	Milk of magnesia	Magnesium hydroxide
$CaSO_4 \cdot 2H_2O$	Gypsum	Calcium sulfate dihydrate

Organic chemistry is the branch of chemistry that deals with carbon compounds.

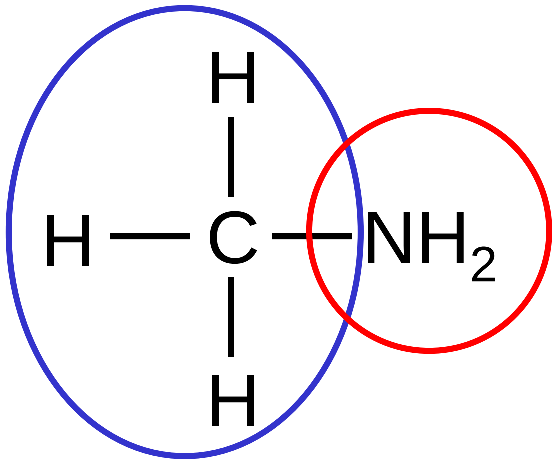
Functional Groups



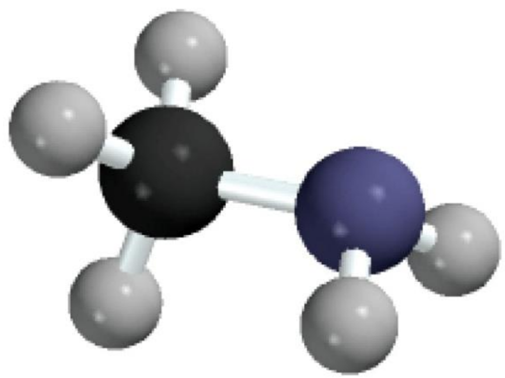
methanol



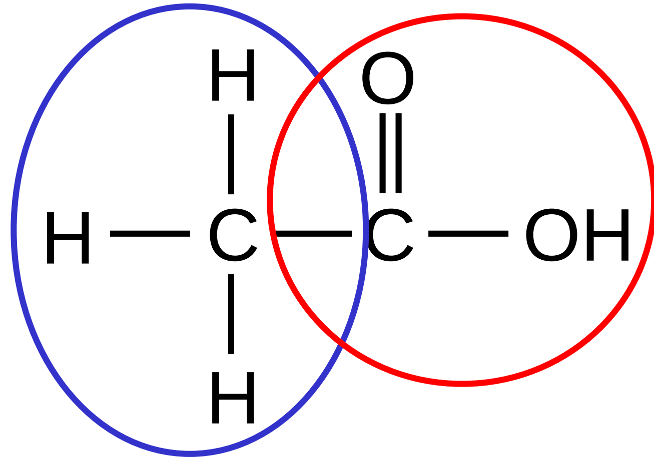
CH_3OH



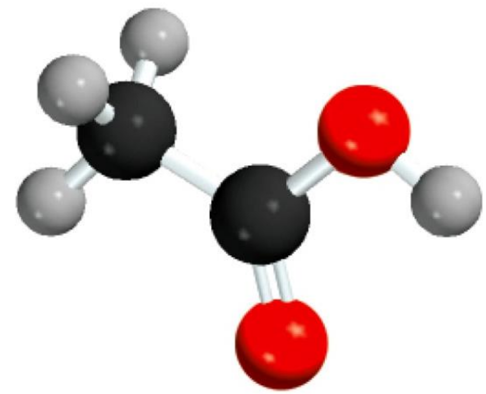
methylamine



CH_3NH_2

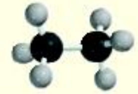
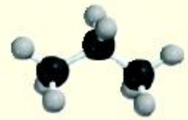
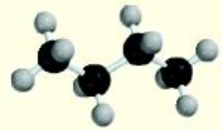
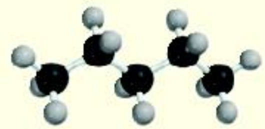
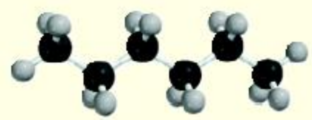
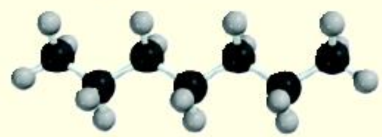
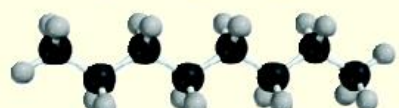


acetic acid



CH_3COOH

TABLE 2.8 The First Ten Straight-Chain Alkanes

Name	Formula	Molecular Model
Methane	CH_4	
Ethane	C_2H_6	
Propane	C_3H_8	
Butane	C_4H_{10}	
Pentane	C_5H_{12}	
Hexane	C_6H_{14}	
Heptane	C_7H_{16}	
Octane	C_8H_{18}	
Nonane	C_9H_{20}	
Decane	$C_{10}H_{22}$