Chapter 2
Atoms, Molecules, and Ions

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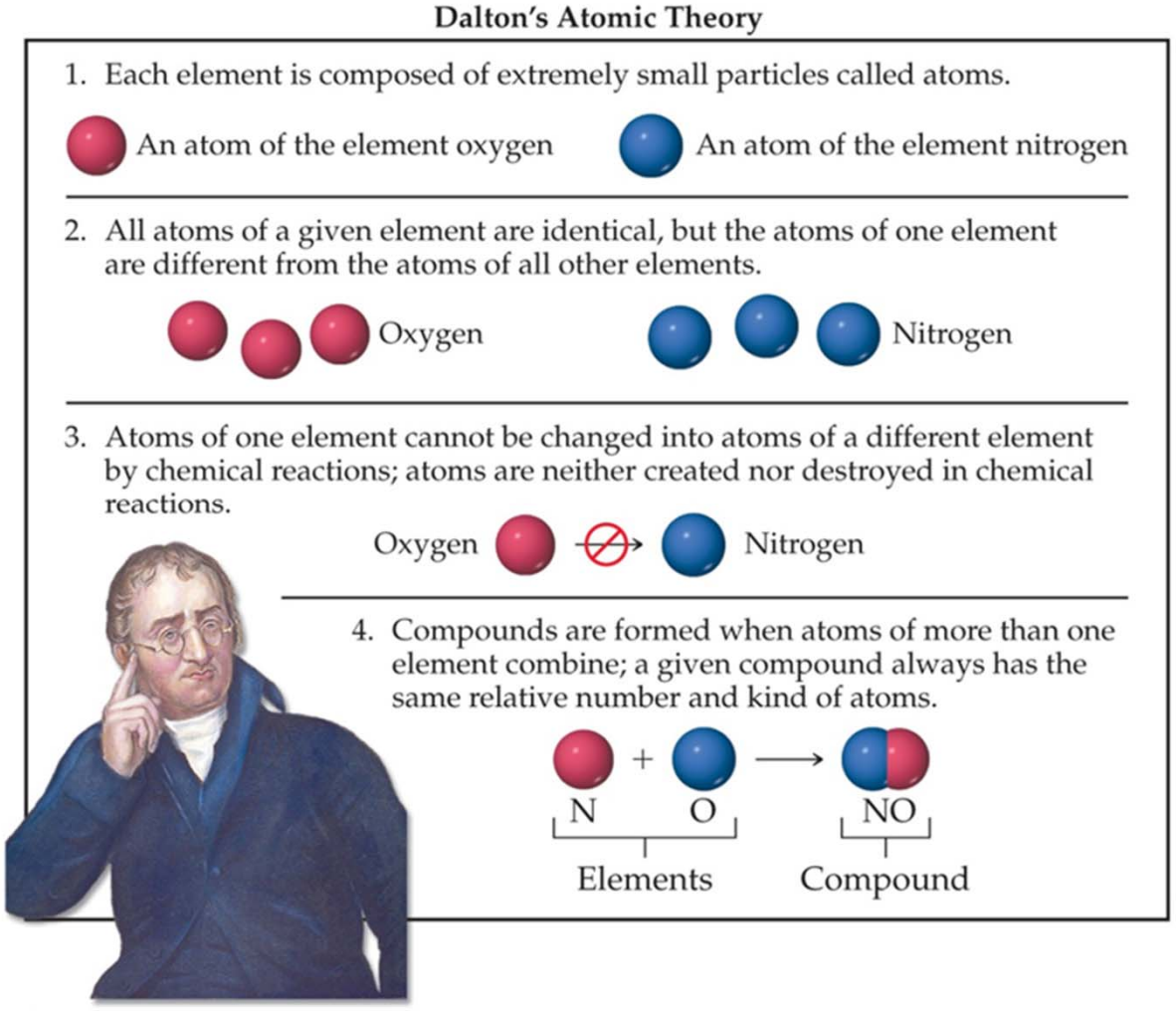
The Atomic Theory of Matter

- Democritus (460–370 bce) and other early Greek philosophers described the material world as made up of tiny, indivisible particles that they called atomos, meaning “indivisible” or “uncuttable.”
- Plato and Aristotle did not embrace the atomic ideas of Leucippus and Democritus.
  - Matter had no smallest parts.
  - Different substances were composed of various proportions of fire, air, earth, and water.
- John Dalton (1766–1844) offered convincing evidence that supported the early atomic ideas of Leucippus and Democritus

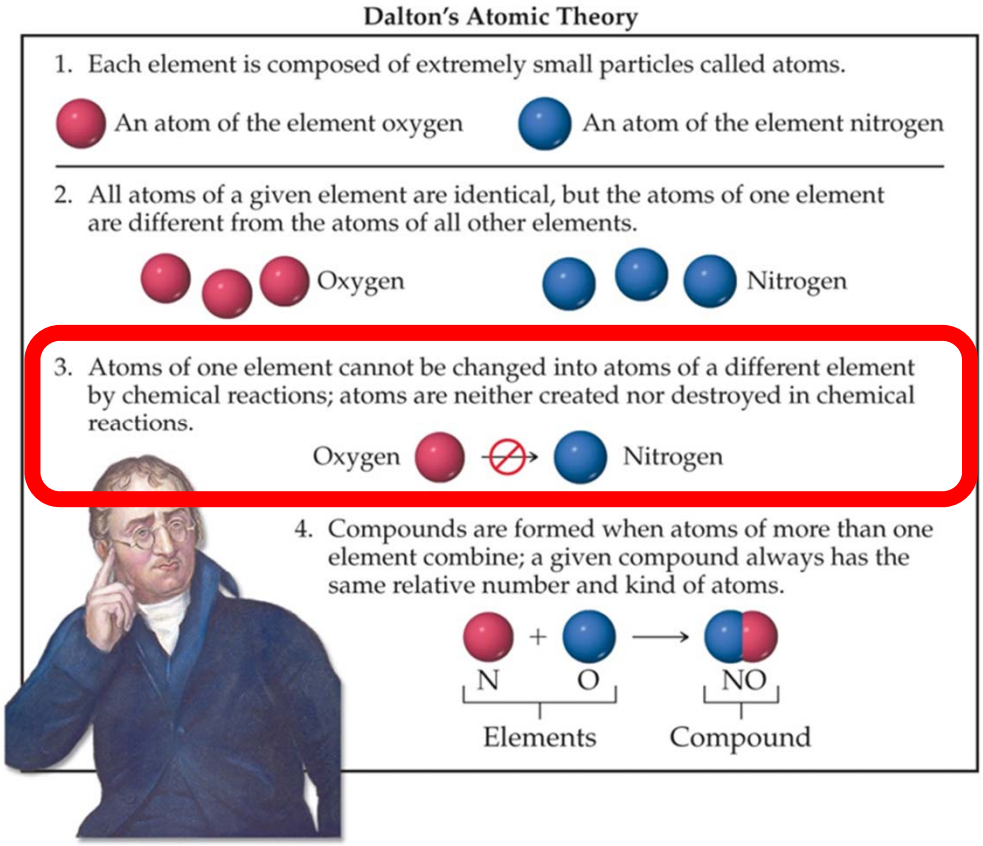
Dalton's theory

- Dalton's Postulates



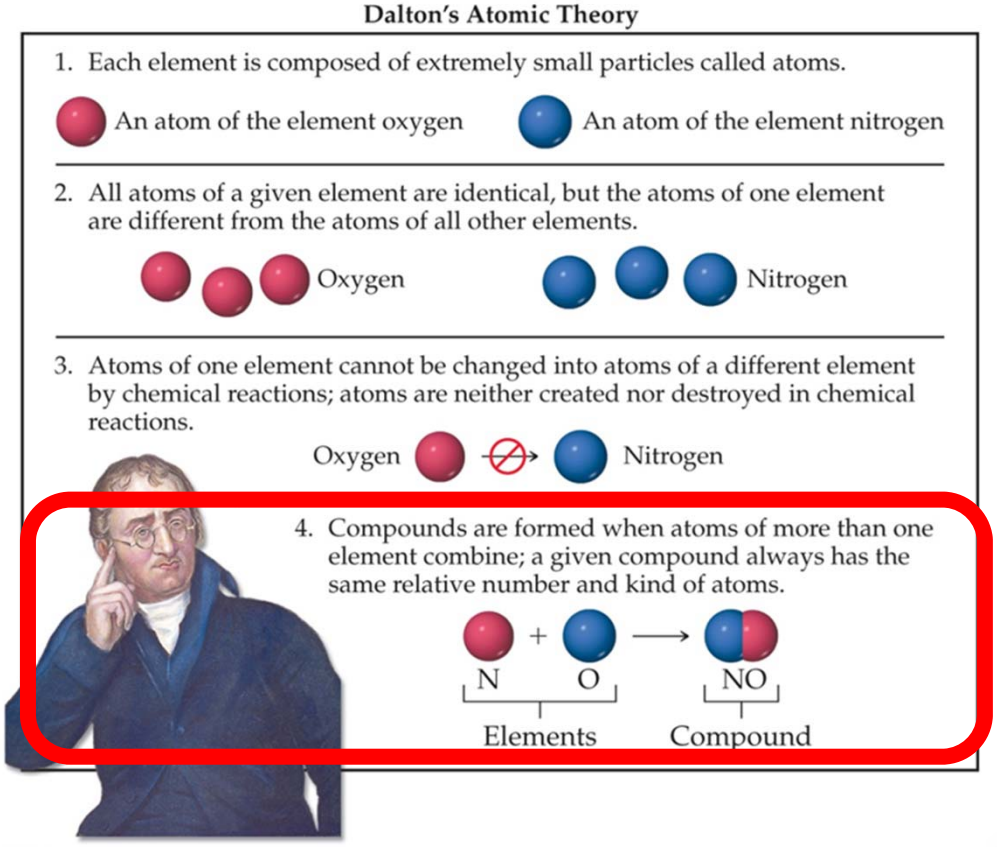
The law of conservation of mass

- The total mass of materials present after a chemical reaction is the same as the total mass present before the reaction



The law of constant composition

- All samples of a given compound, regardless of their source or how they were prepared, have the same proportions of their constituent elements.



Law of Multiple Proportions

- When two elements (call them A and B) form two different compounds, the masses of element B that combine with 1 g of element A can be expressed as a ratio of small whole numbers.
- An atom of A combines with either one, two, three, or more atoms of B (AB_1, AB_2, AB_3, etc.).

The Discovery of Atomic Structure

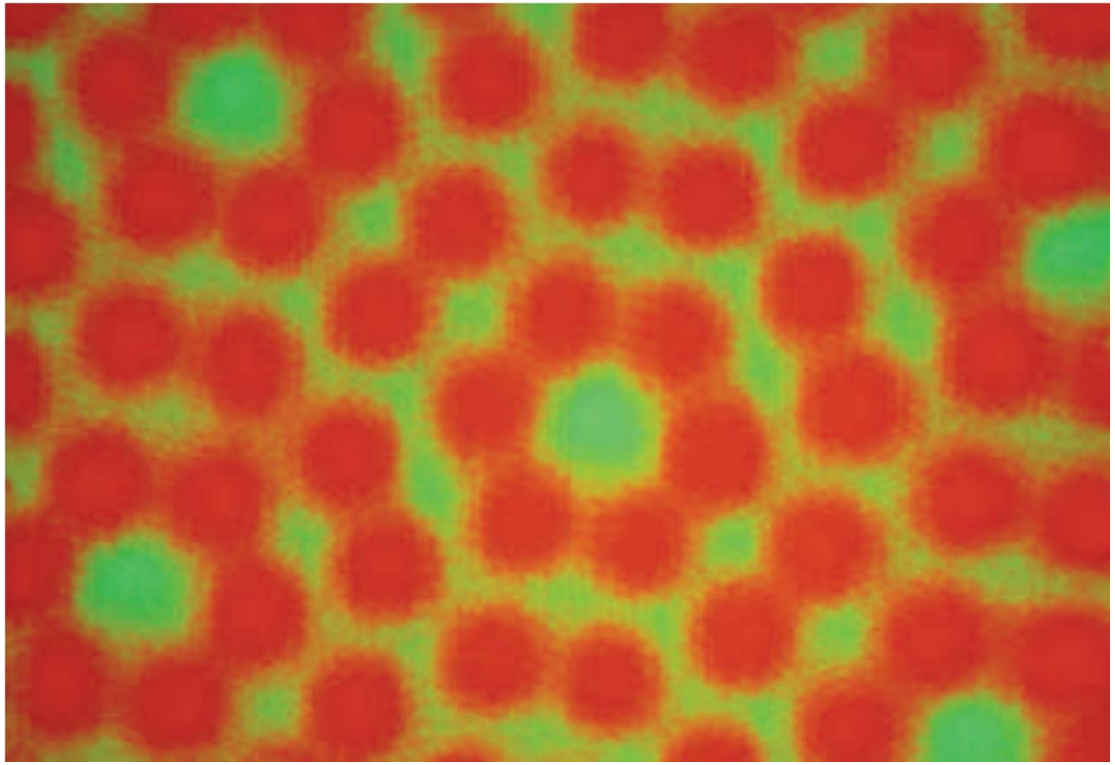


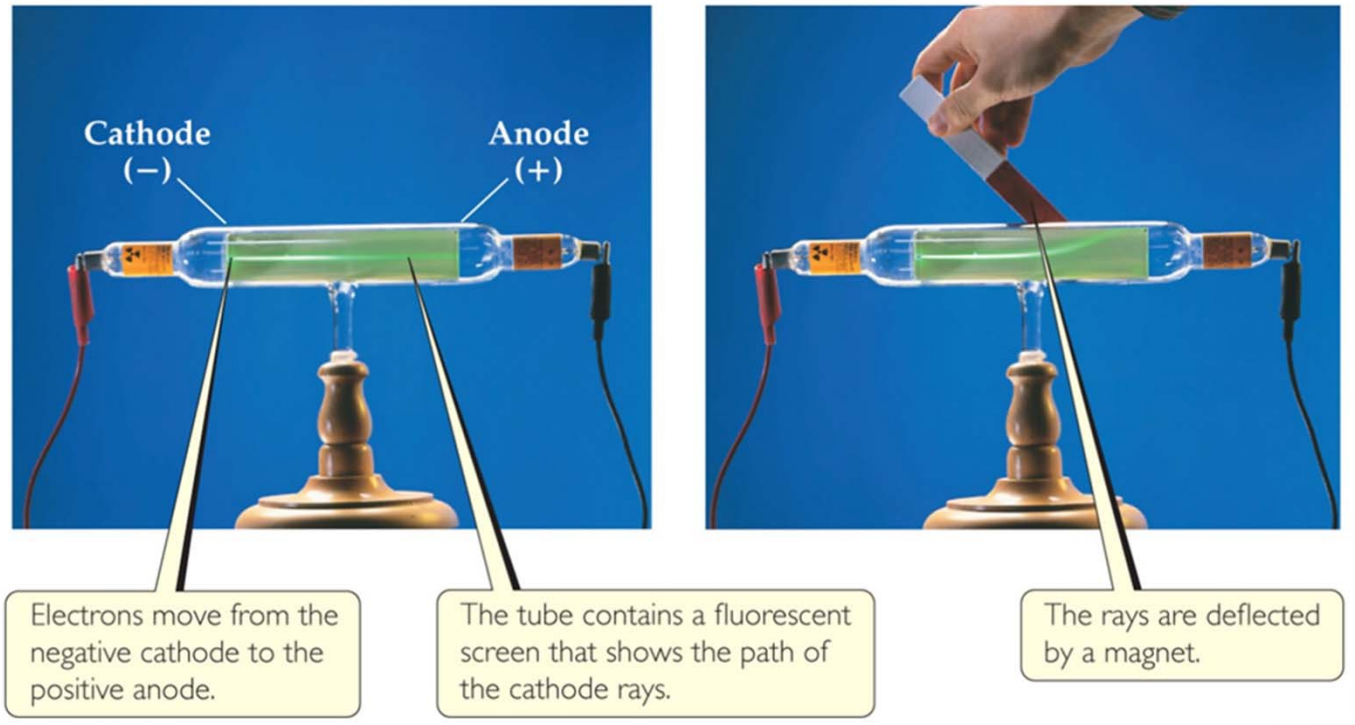
Figure 2.2 An image of the surface of silicon. The image was obtained by a technique called scanning tunneling microscopy. The color was added to the image by computer to help distinguish its features. Each red sphere is a silicon atom.

Discovery of Subatomic Particles

- In Dalton's view, the atom was the smallest particle possible. Many discoveries led to the fact that the atom itself was made up of smaller particles.
- The atom is composed of subatomic particles:
  - Electrons
  - Protons
  - Neutrons

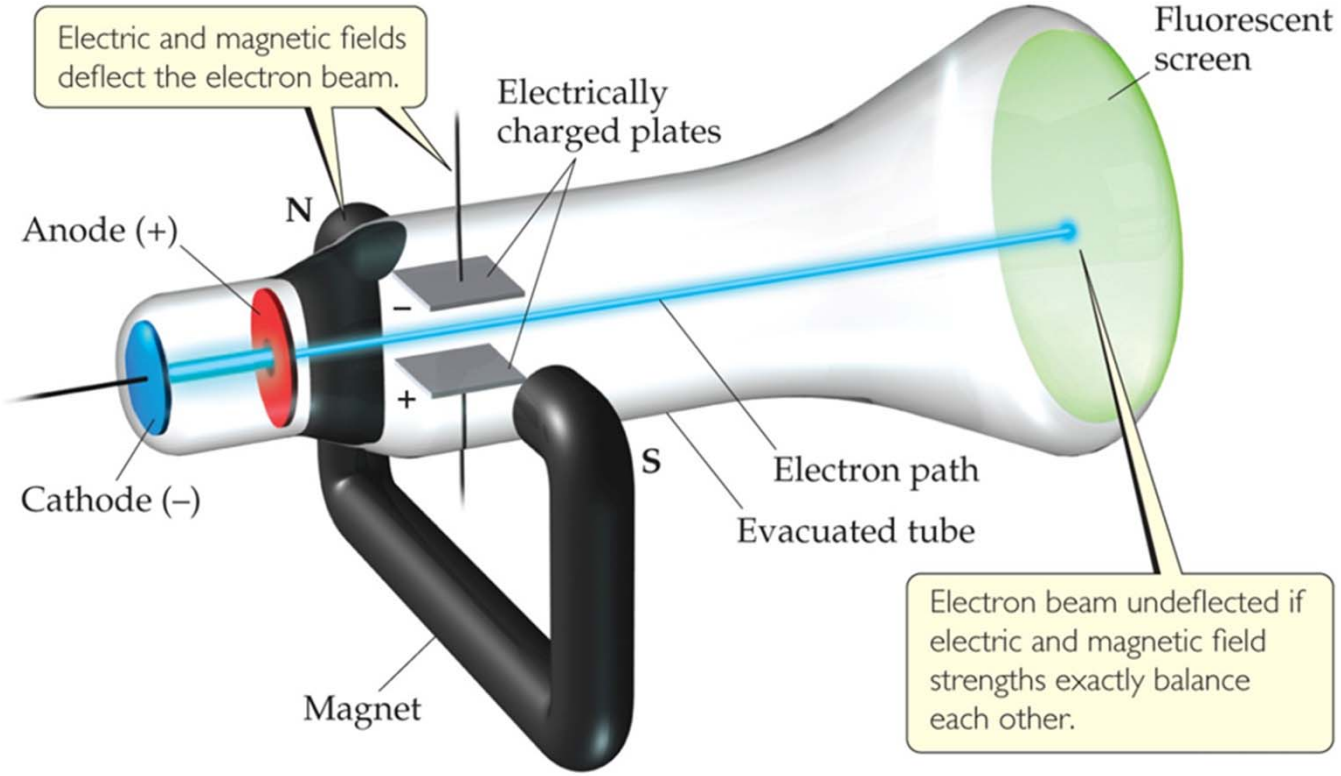
The Electron (Cathode Rays)

- Streams of negatively charged particles were found to emanate from cathode tubes, causing fluorescence.
- J. J. Thomson is credited with their discovery (1897).



The Electron

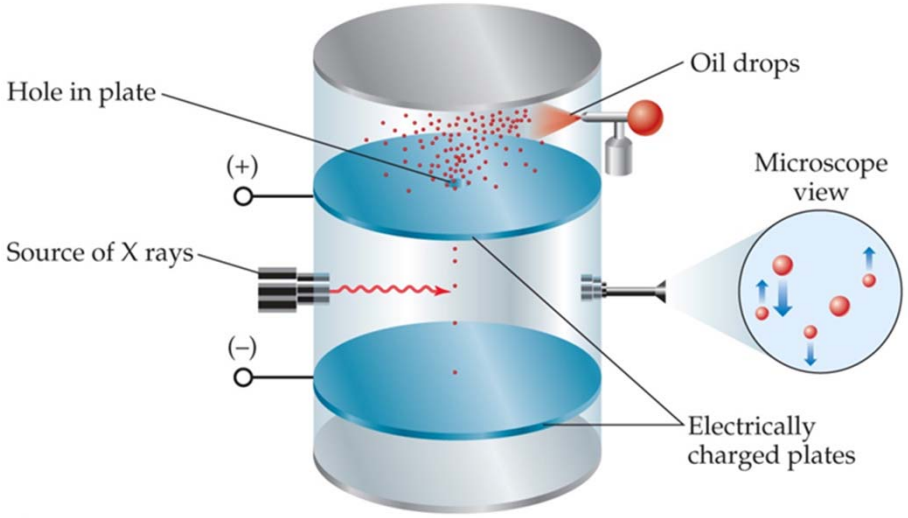
- Thomson measured the charge/mass ratio of the electron to be 1.76X10^{8} coulombs/gram (C/g).



* The coulomb (C) is the SI unit for electrical charge.

Millikan Oil-Drop Experiment (Electrons)

- Robert Millikan determined the charge on the electron in 1909



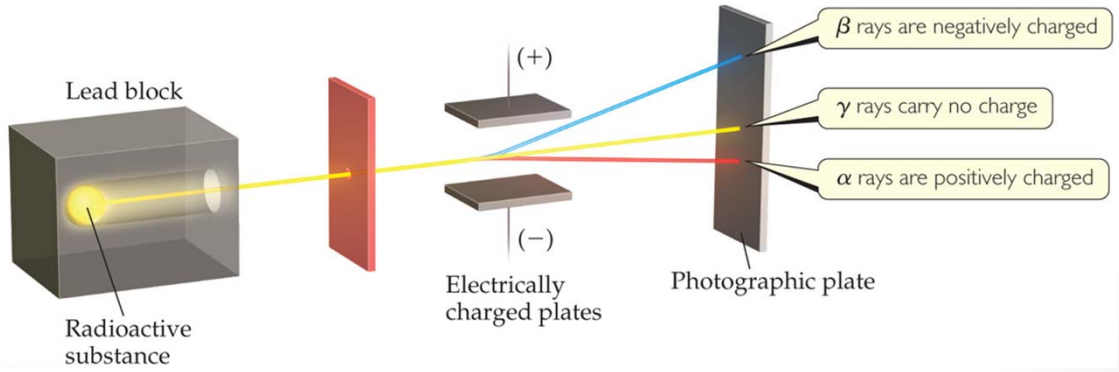
The measured charge on any drop was always a whole-number multiple of -1.60×10^{-19}, the fundamental charge of a single electron.

$$\text{Charge} \times \frac{\text{mass}}{\text{charge}} = \text{mass}$$

Electron mass: $-1.60 \times 10^{-19}\ \cancel{C} \times \dfrac{\text{g}}{-1.76 \times 10^{8}\ \cancel{C}} = 9.10 \times 10^{-28}\ \text{g}$

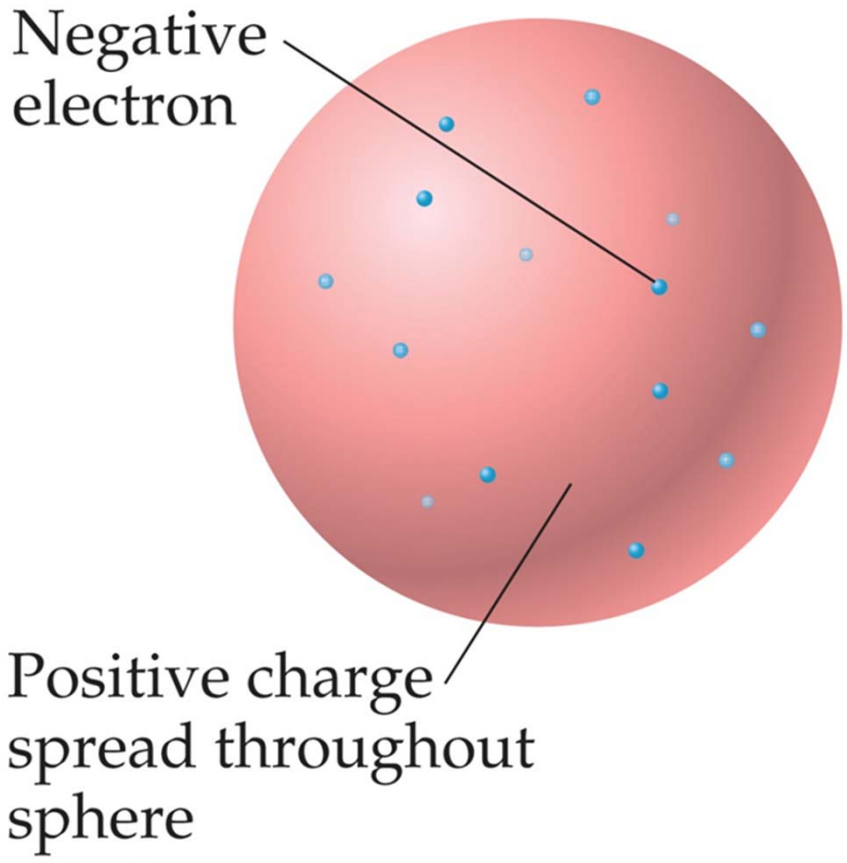
Radioactivity

- In 1896 the French scientist Henri Becquerel (1852–1908) discovered that a compound of uranium spontaneously emits high-energy radiation. This spontaneous emission of radiation is called radioactivity.
- Three types of radiation were discovered by Ernest Rutherford:
  - α particles (positively charged, +2)
  - β particles (negatively charged, -1, like electrons)
  - γ rays (uncharged)



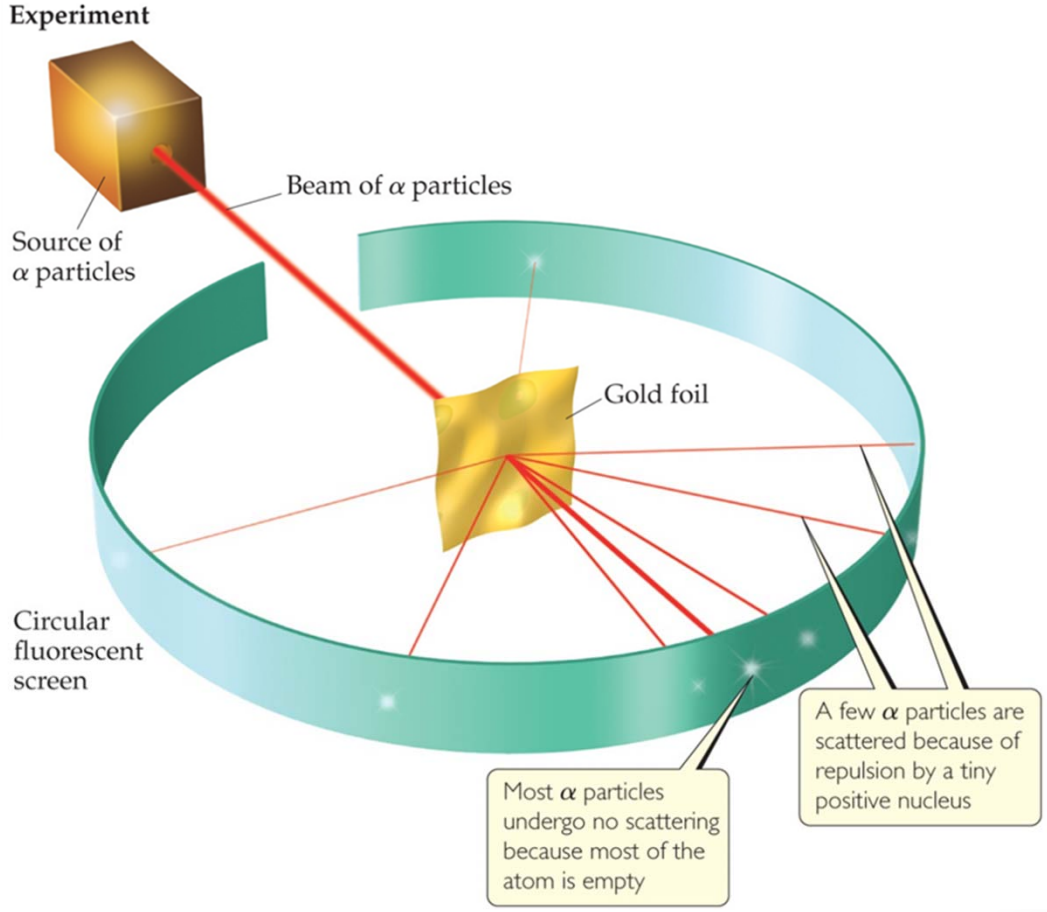
The Nuclear Model of the Atom

- J. J. Thomson's plum-pudding model of the atom.



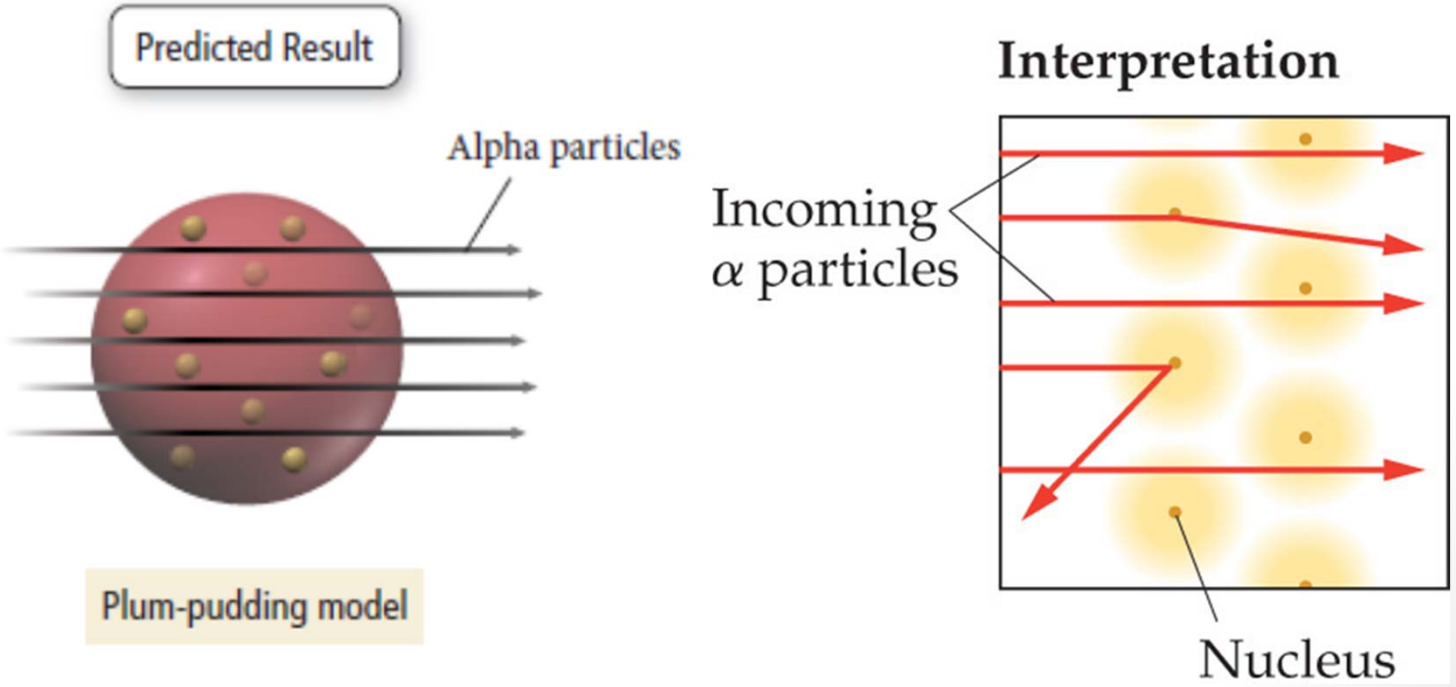
Rutherford's Gold Foil Experiment

- Ernest Rutherford shot α particles at a thin sheet of gold foil and observed the pattern of scatter of the particles.



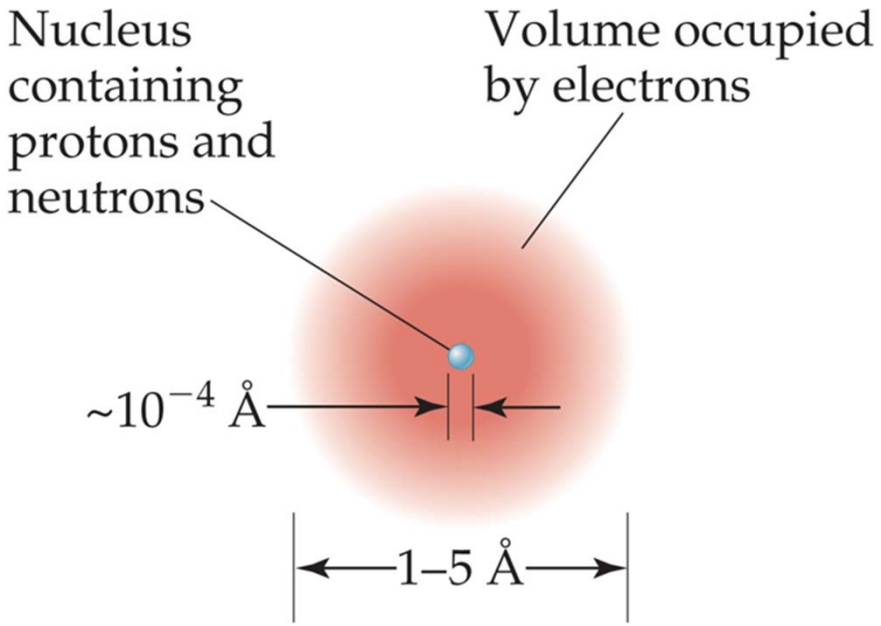
Rutherford's Gold Foil Experiment

- The Rutherford experiment gave an unexpected result. A majority of the particles did pass directly through the foil, but some particles were deflected, and some (approximately 1 in 20,000) even bounced back.



The Nuclear Atom

- Rutherford postulated a very small, dense nucleus with the electrons around the outside of the atom.
- Most of the volume is empty space.
- Atoms are very small; 1 – 5 Å or 100 – 500 pm.



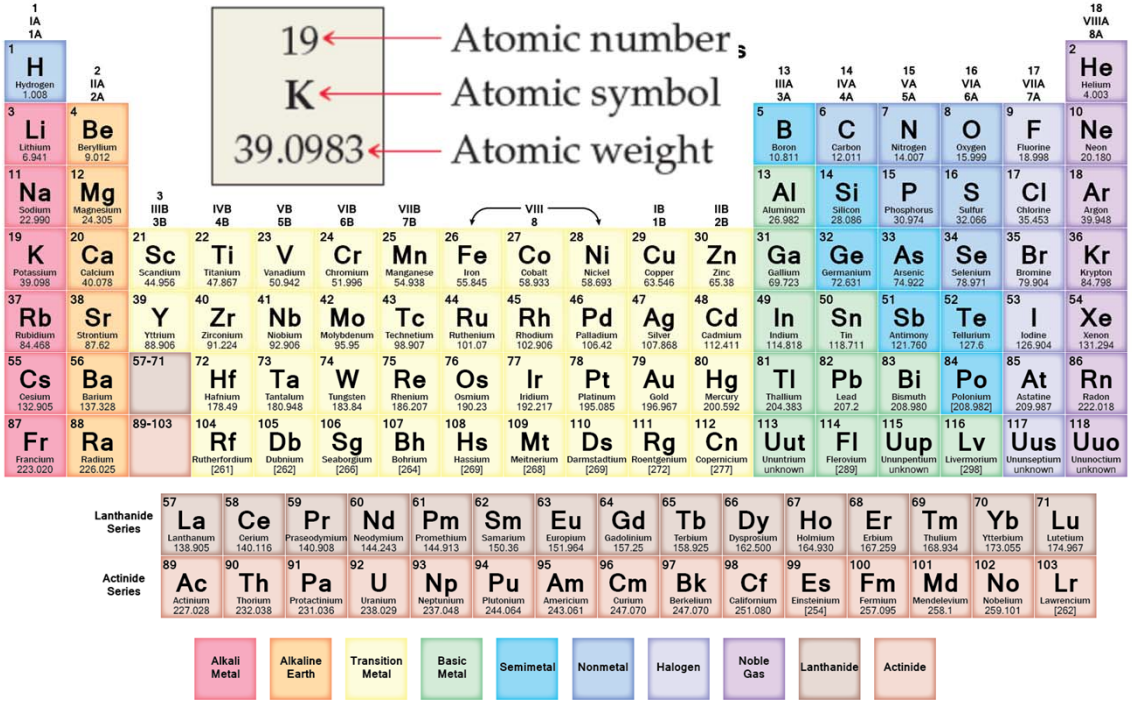
angstrom (A°), where 1 A° = 1 * 10^{-10} m

Subatomic Particles

- Protons (+1) and electrons (–1) have a charge; neutrons are neutral.
- Protons and neutrons have essentially the same mass (relative mass 1). The mass of an electron is so small we ignore it (relative mass 0).
- Protons and neutrons are found in the nucleus; electrons travel around the nucleus

Periodic Table

- Each element is identified by a unique atomic number and with a unique chemical symbol.
- The chemical symbol is either a one- or two-letter abbreviation listed directly below its atomic number on the periodic table.



Atomic Mass

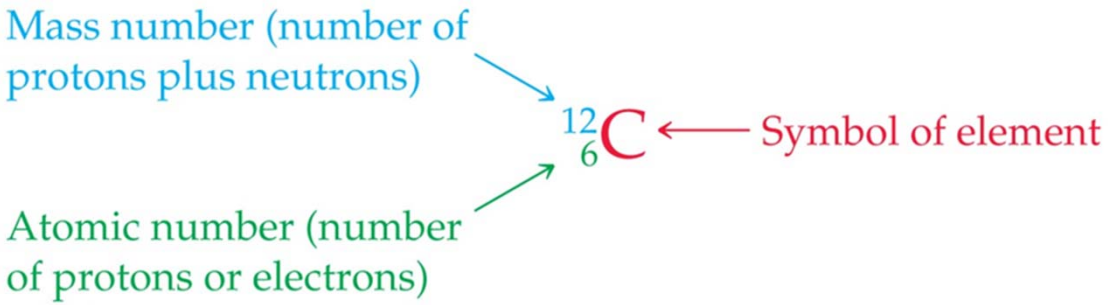
- Atoms have extremely small masses.
- The heaviest known atoms have a mass of approximately 4×10^{-22} g.
- A mass scale on the atomic level is used, where an atomic mass unit (amu) is the base unit.
  - 1 amu = 1.66054×10^{-24} g

Table 2.1 Comparison of the Proton, Neutron, and Electron

Particle	Charge	Mass (amu)
Proton	Positive (1+)	1.0073
Neutron	None (neutral)	1.0087
Electron	Negative (1−)	5.486×10^{-4}

Atomic Numbers, Mass Numbers,

- The atoms of each element have a characteristic number of protons. The number of protons in an atom of any particular element is called that element's **atomic number**.
- The mass number, is the number of protons plus neutrons in the atom



Quiz:

- What does "X" represent in the following symbol? $^{80}_{35}X$
- Determine the number of protons, neutrons and electrons in the following $^{40}_{18}X$

Isotopes

- Isotopes are atoms of the same element with different masses.
- Isotopes have different numbers of neutrons, but the same number of protons

Table 2.2 Some Isotopes of Carbon[a]

Symbol	Number of Protons	Number of Electrons	Number of Neutrons
^{11}C	6	6	5
^{12}C	6	6	6
^{13}C	6	6	7
^{14}C	6	6	8

[a]Almost 99% of the carbon found in nature is ^{12}C.

Quiz

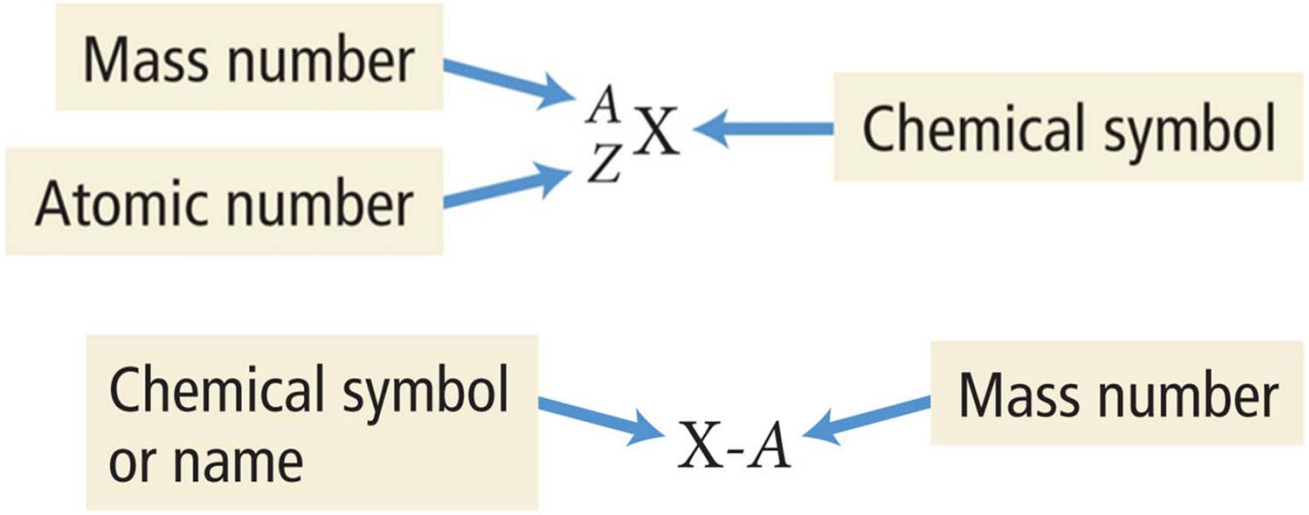
- How many protons, neutrons and electrons does sulfur-31 and sulfur-32 have?

Determining the Number of Subatomic Particles in Atoms

- How many protons, neutrons, and electrons are in an atom of

  (a) ^{197}Au, (b) strontium-90?

Note: Gold has atomic number 79.
The atomic number of strontium is 38.



Atomic Weights

- Most elements occur in nature as mixtures of isotopes. We can determine the average atomic mass of an element, usually called the element's atomic weight

Atomic Weight = Σ [(isotope mass) × (fractional natural abundance)].

EX: carbon is composed of 98.93% ^{12}C and 1.07% ^{13}C. The masses of these isotopes are 12 amu (exactly) and 13.00335 amu

The atomic weight of carbon:

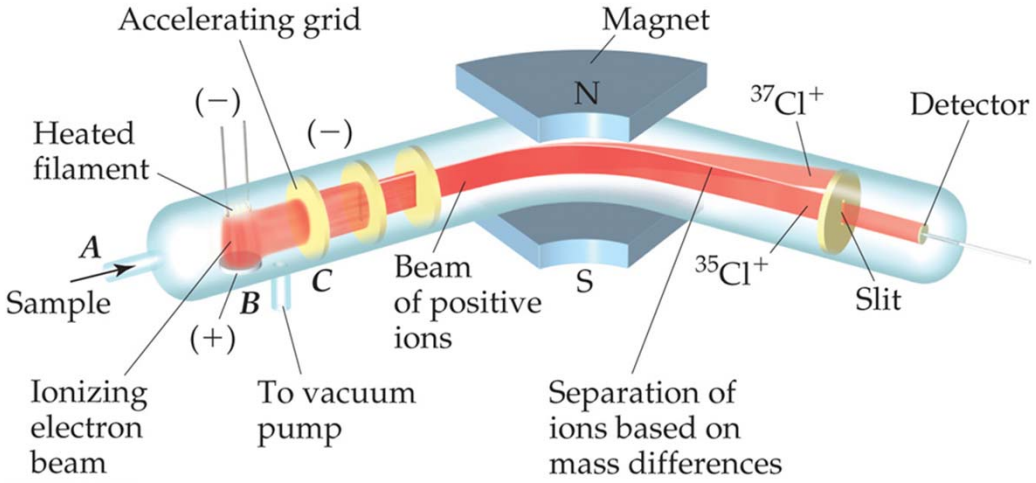
(0.9893)(12 amu) + (0.0107)(13.00335 amu) = 12.01 amu

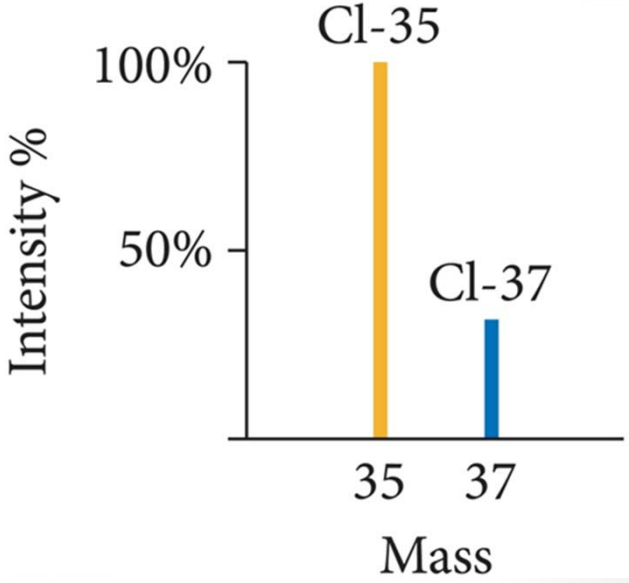
Quiz

- Calculate the atomic mass of element "X", if it has 2 naturally occurring isotopes with the following masses and natural abundances:
  - X-45: 44.8776 amu 32.88%
  - X-47: 46.9443 amu 67.12%

The Mass Spectrometer

- The most accurate means for determining atomic weights is provided by the mass spectrometer





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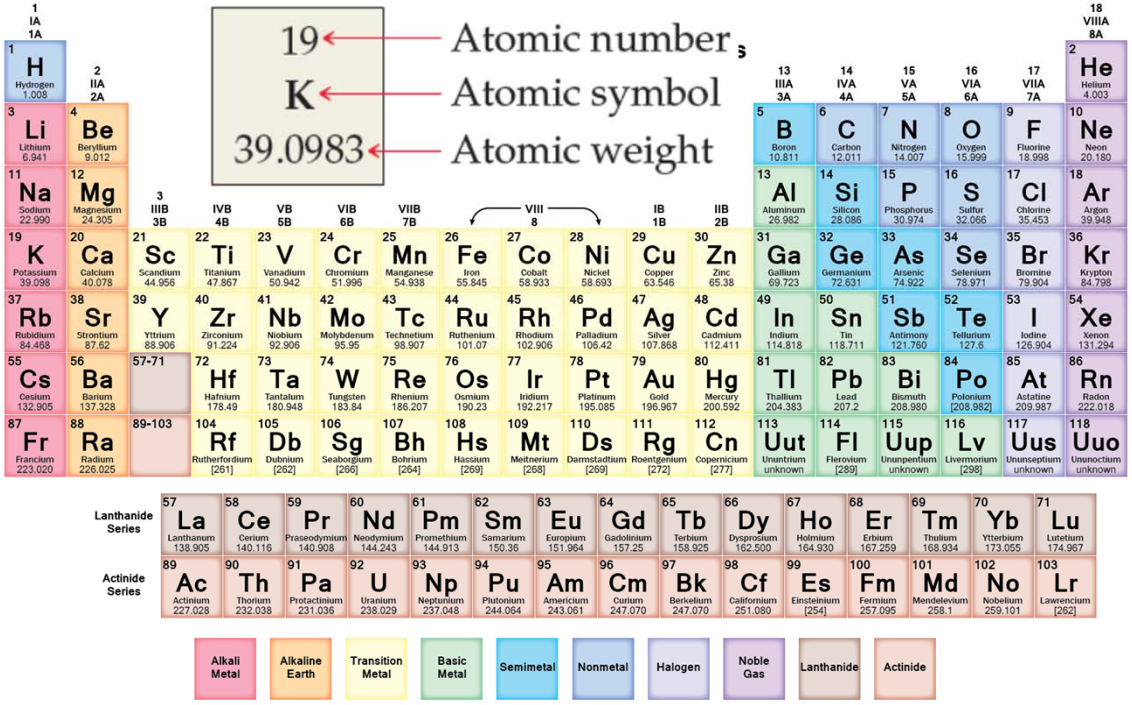
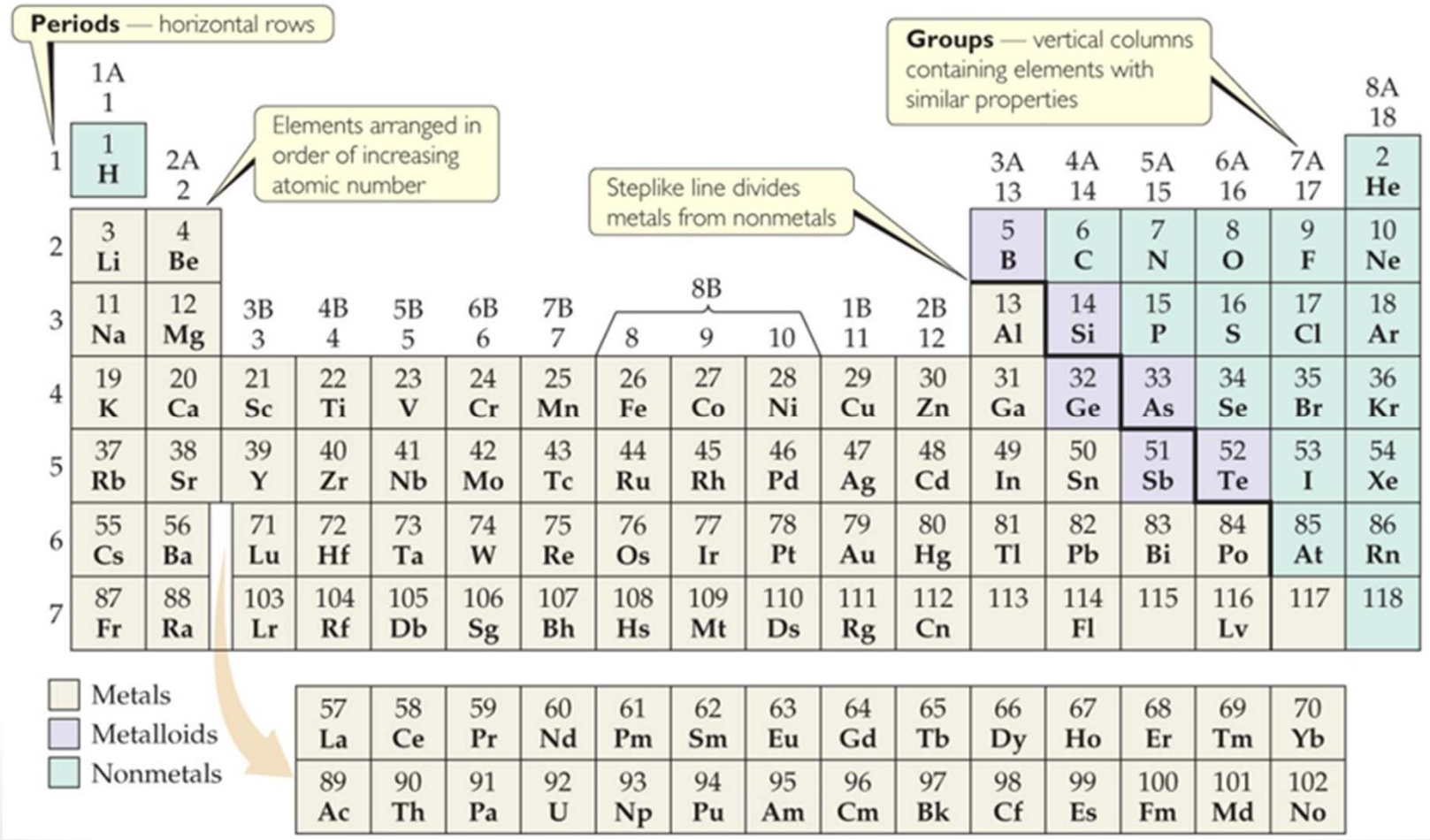


Periodic Table



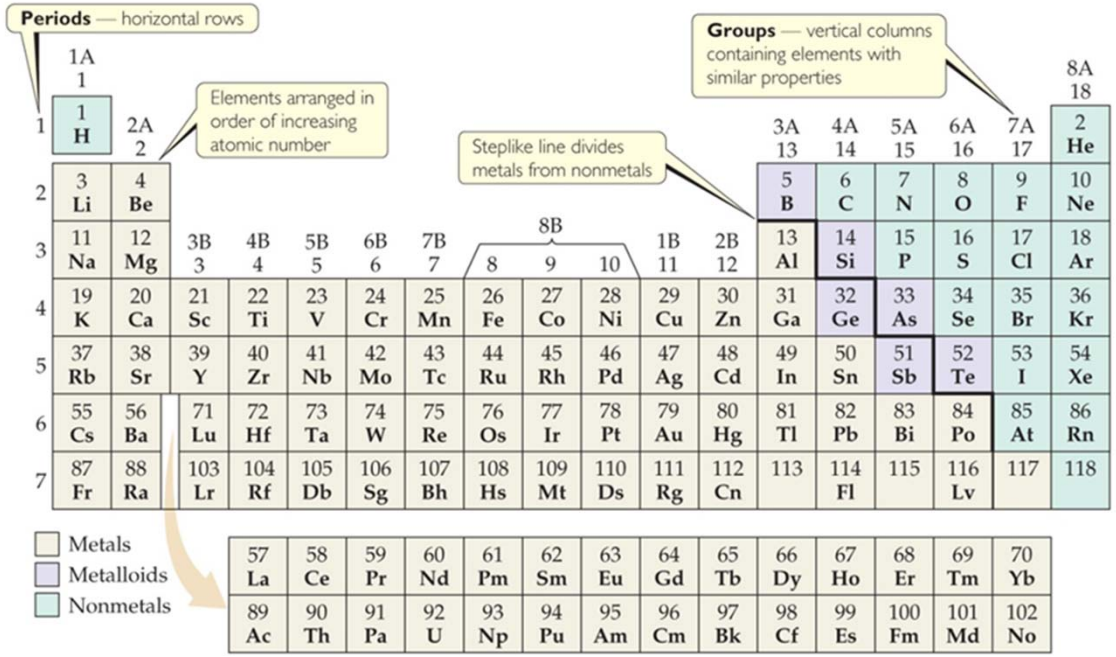
Groups

Table 2.3 Names of Some Groups in the Periodic Table

Group	Name	Elements
1A	Alkali metals	Li, Na, K, Rb, Cs, Fr
2A	Alkaline earth metals	Be, Mg, Ca, Sr, Ba, Ra
6A	Chalcogens	O, S, Se, Te, Po
7A	Halogens	F, Cl, Br, I, At
8A	Noble gases (or rare gases)	He, Ne, Ar, Kr, Xe, Rn

Classification of Elements

- Elements in the periodic table are classified as the following:
  - Metals
  - Nonmetals
  - Metalloids (類金屬)



Metals

- Metals lie on the lower left side and middle of the periodic table and share some common properties:
  - They are good conductors of heat and electricity.
  - They can be pounded into flat sheets (malleability).
  - They can be drawn into wires (ductility).
  - They are often shiny.
  - They tend to lose electrons when they undergo chemical changes.

Nonmetals

- Nonmetals lie on the upper right side of the periodic table.
- Nonmetals as a whole tend to
  - be poor conductors of heat and electricity.
  - be not ductile and not malleable.
  - gain electrons when they undergo chemical changes
- There are a total of 17 nonmetals:
  - Five are solids at room temperature (C, P, S, Se, and I)
  - One is a liquid at room temperature (Br)
  - Eleven are gases at room temperature (H, He, N, O, F, Ne, Cl, Ar, Kr, Xe, and Rn)

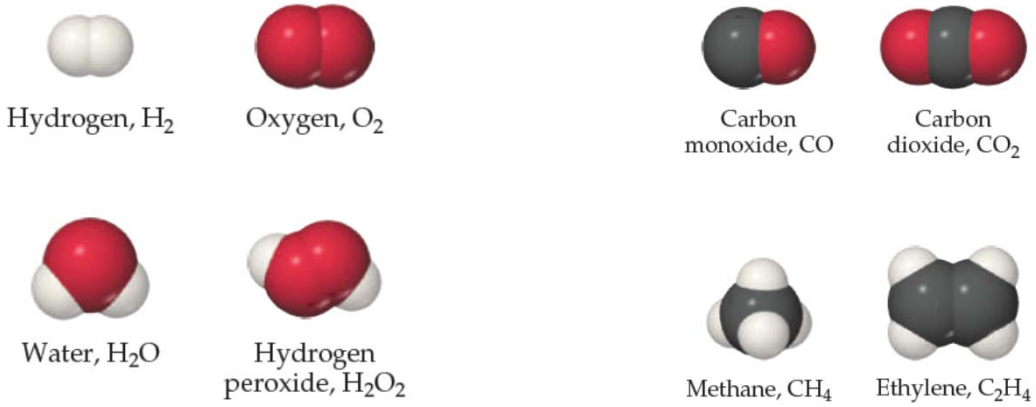
Metalloids (類金屬)

- Metalloids are sometimes called semimetals.
- They are elements that lie along the zigzag diagonal line that divides metals and nonmetals.
- They exhibit mixed properties.
- Several metalloids are also classified as semiconductors because of their intermediate (and highly temperature-dependent) electrical conductivity.

13	14	15	16	17
5 B	6 C	7 N	8 O	9 F
13 Al	14 Si	15 P	16 S	17 Cl
31 Ga	32 Ge	33 As	34 Se	35 Br
49 In	50 Sn	51 Sb	52 Te	53 I

Molecules and Molecular Compounds

- Most of the oxygen in air consists of molecules that contain two oxygen atoms. (chemical formula O_2)
- The subscript tells us that two oxygen atoms are present in each molecule. A molecule made up of two atoms is called a diatomic molecule.
- Compounds composed of molecules contain more than one type of atom and are called molecular compounds.
- Most molecular substances we will encounter contain only nonmetals.



Types of Formulas

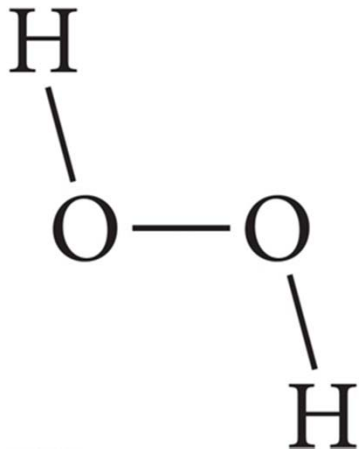
- Empirical formulas give the lowest whole-number ratio of atoms of each element in a compound.
- Molecular formulas give the exact number of atoms of each element in a compound.
- If we know the molecular formula of a compound, we can determine its empirical formula. The converse is not true!

EX:

- For C_4H_8, the greatest common factor is 4. The empirical formula is therefore CH_2.
- For C_3H_6, the greatest common factor is 3. The empirical formula is therefore CH_2.
- For CCl_4, the only common factor is 1, so the empirical formula and the molecular formula are identical.

Structural formula

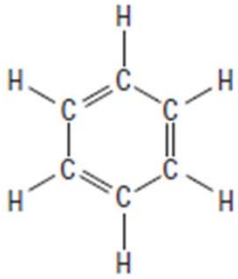
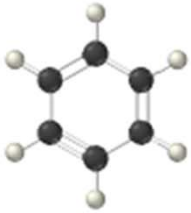
- A structural formula shows which atoms are attached to which, as in the following example



- The atoms are represented by their chemical symbols, and lines are used to represent the bonds that hold the atoms together

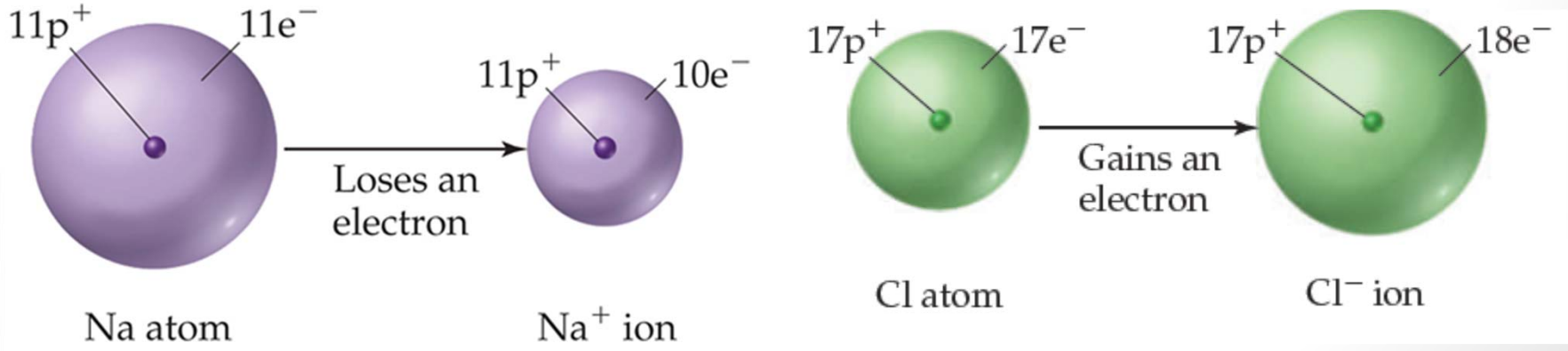
Molecular Models

- A ball-and-stick molecular model represents atoms as balls and chemical bonds as sticks; how the two connect reflects a molecule's shape.
- In a space-filling molecular model, atoms fill the space between each other to more closely represent our best estimates for how a molecule might appear if scaled to visible size.

Name of Compound	Empirical Formula	Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
Benzene	CH	C_6H_6			
Acetylene	CH	C_2H_2	H—C≡C—H		

Ions and Ionic Compounds

- The nucleus of an atom is unchanged by chemical processes, but some atoms can readily gain or lose electrons. If electrons are removed from or added to an atom, a charged particle called an ion is formed. An ion with a positive charge is a cation; a negatively charged ion is an anion.



Exercise

- Give the chemical symbol, including superscript indicating mass number, for (a) the ion with 22 protons, 26 neutrons, and 19 electrons.

Sol:

The number of protons is the atomic number of the element. A periodic table or list of elements tells us that the element with atomic number 22 is titanium (Ti). The mass number (protons plus neutrons) of this isotope of titanium is $22 + 26 = 48$. Because the ion has three more protons than electrons, it has a net charge of 3+ and is designated $^{48}Ti^{3+}$.

Quiz

Which species has 54 electrons?

A) $^{132}_{54}Xe^{+}$

B) $^{128}_{52}Te^{2-}$

C) $^{118}_{50}Sn^{2+}$

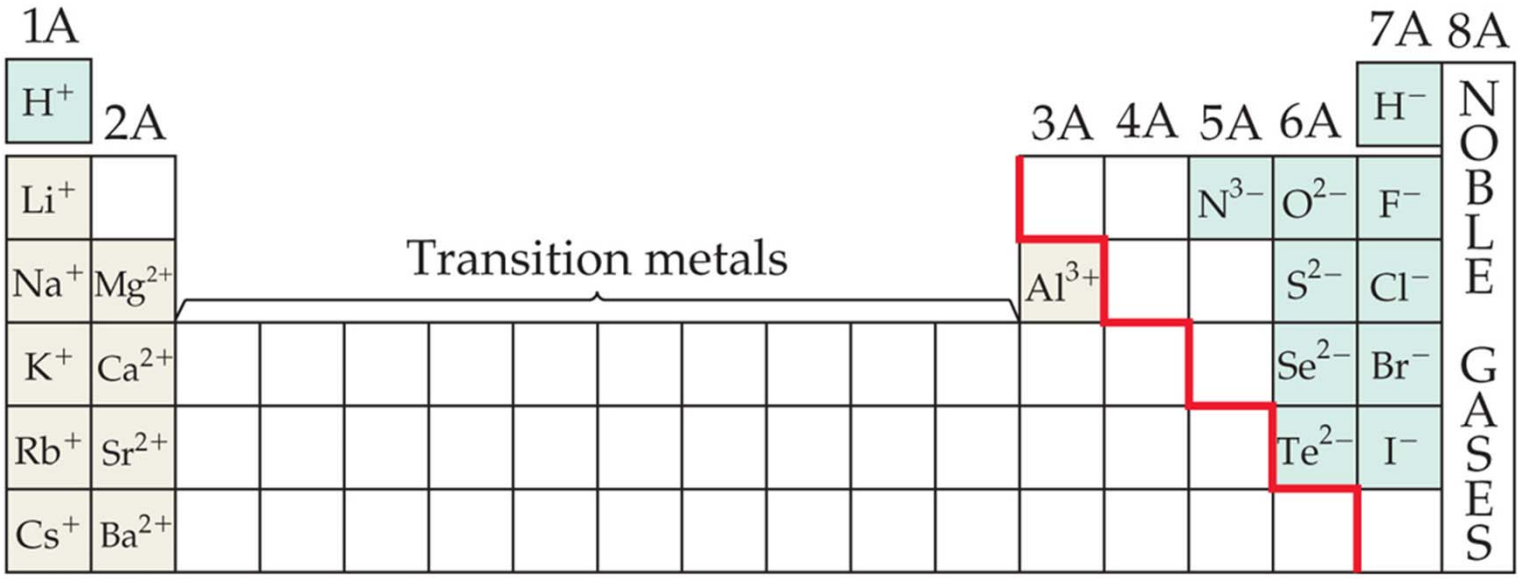
D) $^{112}_{48}Cd$

E) $^{132}_{54}Xe^{2+}$

Polyatomic Ion

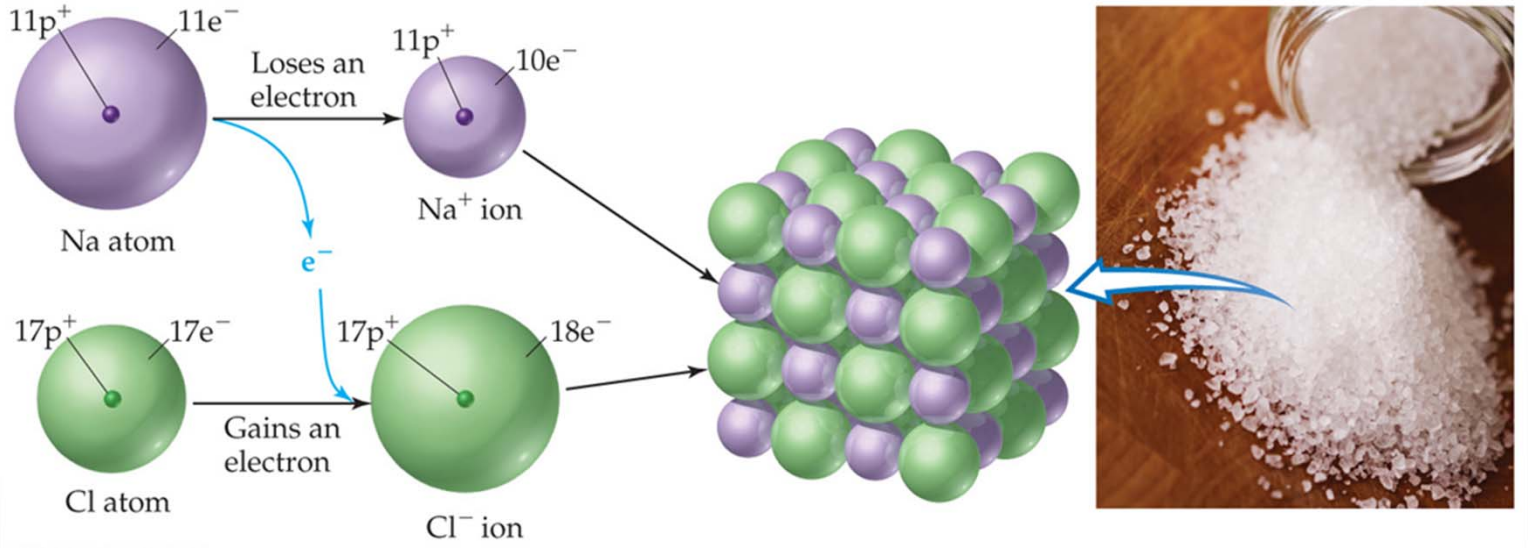
- Many common ionic compounds contain ions that are themselves composed of a group of covalently bonded atoms with an overall charge. This group of charged species is called polyatomic ions.
  - NH_4^+ (ammonium ion)
  - SO_4^{2-} (sulfate ion),

Predicting Ionic Charge



Ionic Compounds

- Ionic compounds are generally formed between metals and nonmetals. (Ex: NaCl)
- Electrons are transferred from the metal to the nonmetal. The oppositely charged ions attract each other. Only empirical formulas are written.



Identifying Ionic and Molecular Compounds

- Which of these compounds would you expect to be ionic: N_2O, Na_2O, $CaCl_2$, SF_4?

SOLUTION

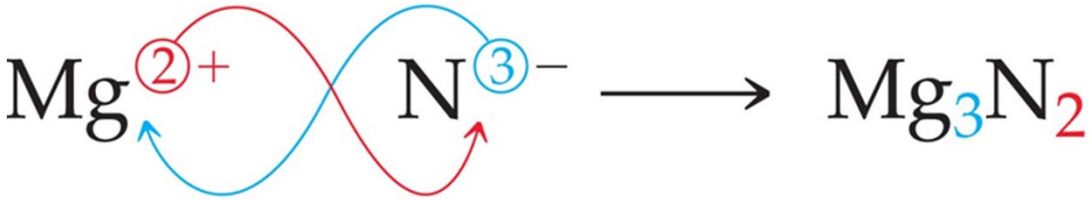
We predict that Na_2O and $CaCl_2$ are ionic compounds because they are composed of a metal combined with a nonmetal. We predict (correctly) that N_2O and SF_4 are molecular compounds because they are composed entirely of nonmetals.

Quiz

- The formula for a salt is XBr. The X-ion in this salt has 46 electrons. The metal X is _____

Writing Formulas

- Because compounds are electrically neutral, one can determine the formula of a compound this way:
  - The charge on the cation becomes the subscript on the anion.
  - The charge on the anion becomes the subscript on the cation.
  - If these subscripts are not in the lowest whole-number ratio, divide them by the greatest common factor.



Names and Formulas of Ionic Compounds

- Ionic compounds are usually composed of metals and nonmetals. (EX: $MgSO_4$)
- Ionic compounds can be categorized into two types, depending on the metal in the compound.
  - The first type contains a metal whose charge is invariant from

Na^+	sodium ion	Zn^{2+}	zinc ion	Al^{3+}	aluminum ion

  - The second type of ionic compound contains a metal with a charge that can differ in different compounds

Fe^{2+}	iron(II) ion	Cu^+	copper(I) ion
Fe^{3+}	iron(III) ion	Cu^{2+}	copper(II) ion

Fe^{2+}	ferrous ion	Cu^+	cuprous ion
Fe^{3+}	ferric ion	Cu^{2+}	cupric ion

Names and Formulas of Ionic Compounds

- Cations formed from nonmetal atoms have names that end in -ium:

NH_4^+	ammonium ion	H_3O^+	hydronium ion

Anions

- The names of monatomic anions are formed by replacing the ending of the name of the element with -ide:

Fluorine	F^-	fluor	Fluoride
Chlorine	Cl^-	chlor	Chloride
Bromine	Br^-	brom	Bromide
Iodine	I^-	iod	Iodide

Oxygen	O^{2-}	ox	Oxide
Sulfur	S^{2-}	sulf	Sulfide
Nitrogen	N^{3-}	nitr	Nitride
Phosphorus	P^{3-}	phosph	Phosphide

Names and Formulas of Ionic Compounds

Anions

- Polyatomic anions containing oxygen have names ending in either -ate or –ite and are called oxyanions.
  - the one with more oxygen atoms has the ending –ate
  - the one with fewer has the ending -ite.

For example,

- NO_3^- is ***nitrate***
- NO_2^- is ***nitrite***

SO_4^{2-} is ***sulfate***
SO_3^{2-} is ***sulfite***

Oxyanions

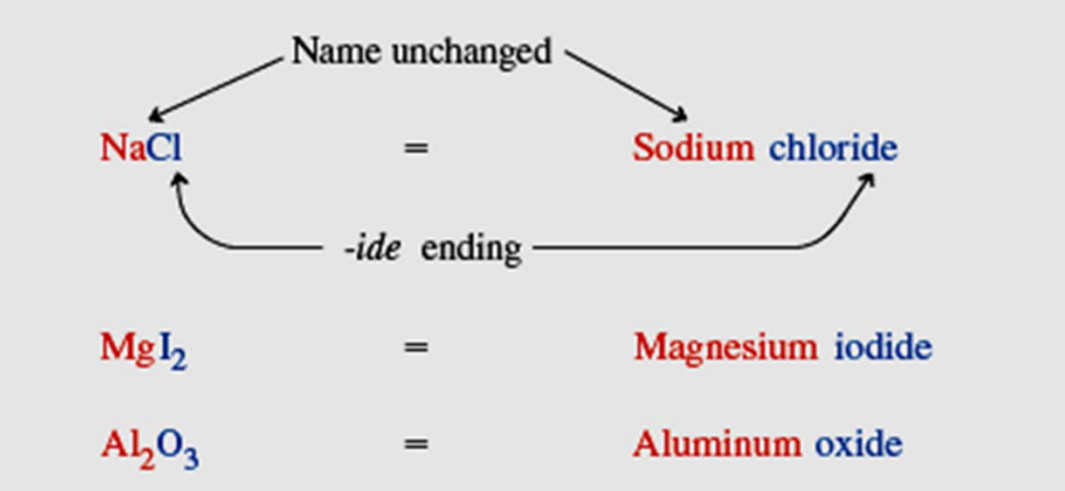
- If there are more than two ions in the series then the prefixes hypo-, meaning less than, and per-, meaning more than, are used.

ClO^-	***hypo*chlor*ite***	BrO^-	***hypo*brom*ite***
ClO_2^-	chlor***ite***	BrO_2^-	brom***ite***
ClO_3^-	chlor***ate***	BrO_3^-	brom***ate***
ClO_4^-	***per*chlor*ate***	BrO_4^-	***per*brom*ate***

- Anions derived by adding H^+ to an oxyanion are named by adding as a prefix the word hydrogen or dihydrogen

CO_3^{2-}	carbonate ion	PO_4^{3-}	phosphate ion
HCO_3^-	hydrogen carbonate ion	$H_2PO_4^-$	dihydrogen phosphate ion

Naming Ionic Compounds



$CaCl_2$	calcium chloride
$Al(NO_3)_3$	aluminum nitrate
$Cu(ClO_4)_2$	copper(II) perchlorate (or cupric perchlorate)

Names and Formulas of Acids

- Binary acids have H^+ cation and nonmetal anion.
  - Write a hydro- prefix.
  - Follow with the nonmetal name.
  - Change ending on nonmetal name to –ic.
  - Write the word acid at the end of the name

EX: HCl hydrochloric acid

- Oxyacids have H^+ cation and polyatomic anion contain oxygen.
  - If polyatomic ion name ends in –ate, then change ending to –ic suffix.
  - If polyatomic ion name ends in –ite, then change ending to –ous suffix.
  - Write word acid at the end of all names

EX: ClO_4^- perchlorate ClO^- hypochlorite

$HClO_4$ perchloric acid HClO hypochlorous acid

Nomenclature of Binary Molecular Compounds

Table 2.3 Numeric Prefixes in Names of Binary Molecular Compounds

Number of Atoms	Prefix	Examples[a]
1	mono	NO nitrogen monoxide
2	di	NO_2 nitrogen dioxide
3	tri	N_2O_3 dinitrogen trioxide
4	tetra	N_2O_4 dinitrogen tetroxide
5	penta	N_2O_5 dinitrogen pentoxide
6	hexa	SF_6 sulfur hexafluoride
7	hepta	IF_7 iodine heptafluoride
8	octa	P_4O_8 tetraphosphorus octoxide
9	nona	P_4S_9 tetraphosphorus nonasulfide
10	deca	As_4O_{10} tetraarsenic decoxide

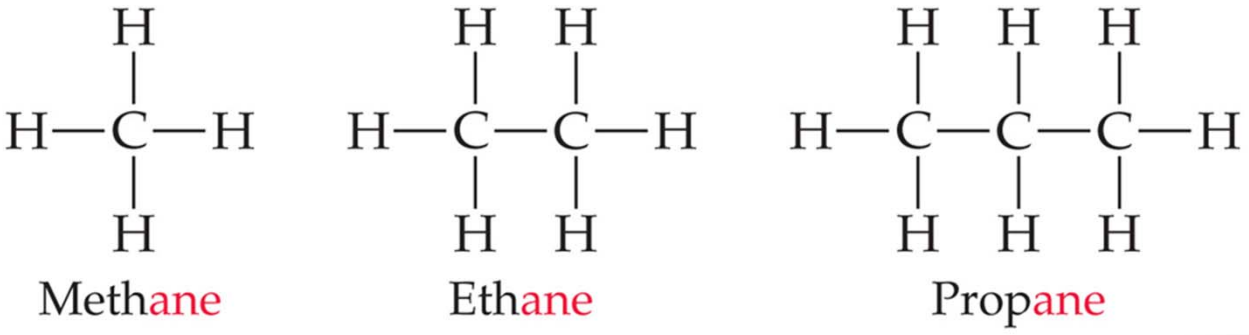
[a] When the prefix ends in "a" or "o" and the element name begins with "a" or "o," the final vowel of the prefix is usually dropped for ease of pronunciation. For example, nitrogen *mon*oxide and not nitrogen *mono*oxide, and

Nomenclature of Binary Molecular Compounds

- The ending on the second element is changed to -ide.
  - CO_2: carbon dioxide
  - CCl_4: carbon tetrachloride
- If the prefix ends with a or o and the name of the element begins with a vowel, the two successive vowels are often elided into one.
  - N_2O_5: dinitrogen pentoxide

Nomenclature of Organic Compounds

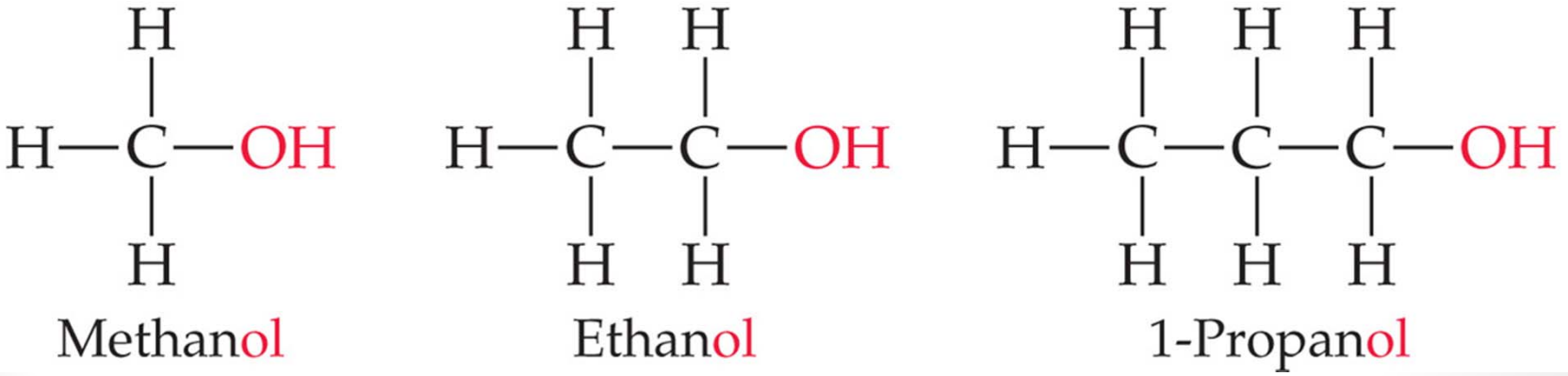
- Organic chemistry is the study of carbon.
- Organic chemistry has its own system of nomenclature.
- The simplest hydrocarbons (compounds containing only carbon and hydrogen) are alkanes.
- The first part of the names just listed correspond to the number of carbons (meth- = 1, eth- = 2, prop- = 3, etc.)



Nomenclature of Organic Compounds

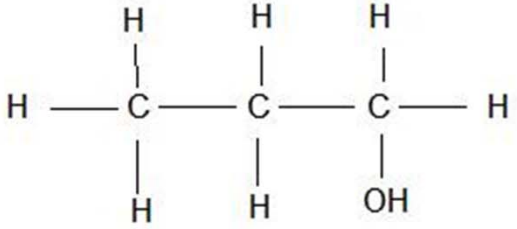
- When a hydrogen in an alkane is replaced with something else (a functional group, like -OH in the compounds above), the name is derived from the name of the alkane.
- The ending denotes the type of compound.

EX: An alcohol ends in -ol.

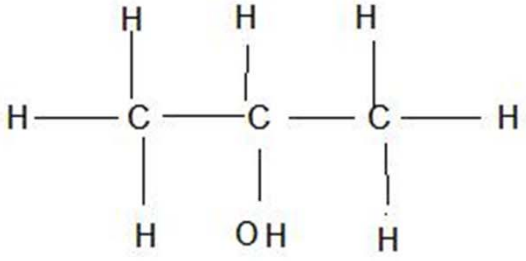


Isomer

- Compounds with the same molecular formula but different arrangements of atoms are called isomers.
- EX: 1-propanol and 2-propanol are structural isomers



1-propanol



2- propanol

Question

- An ion has 8 protons, 9 neutrons, and 10 electrons. The symbol for the ion is _____

- How many protons (p) and neutrons (n) are in an atom of $^{90}_{38}Sr$?

- Gallium has an atomic mass of 69.723 amu. The Ga-69 (68.926 amu) is 60.11%. What is the amu of the other isotope?