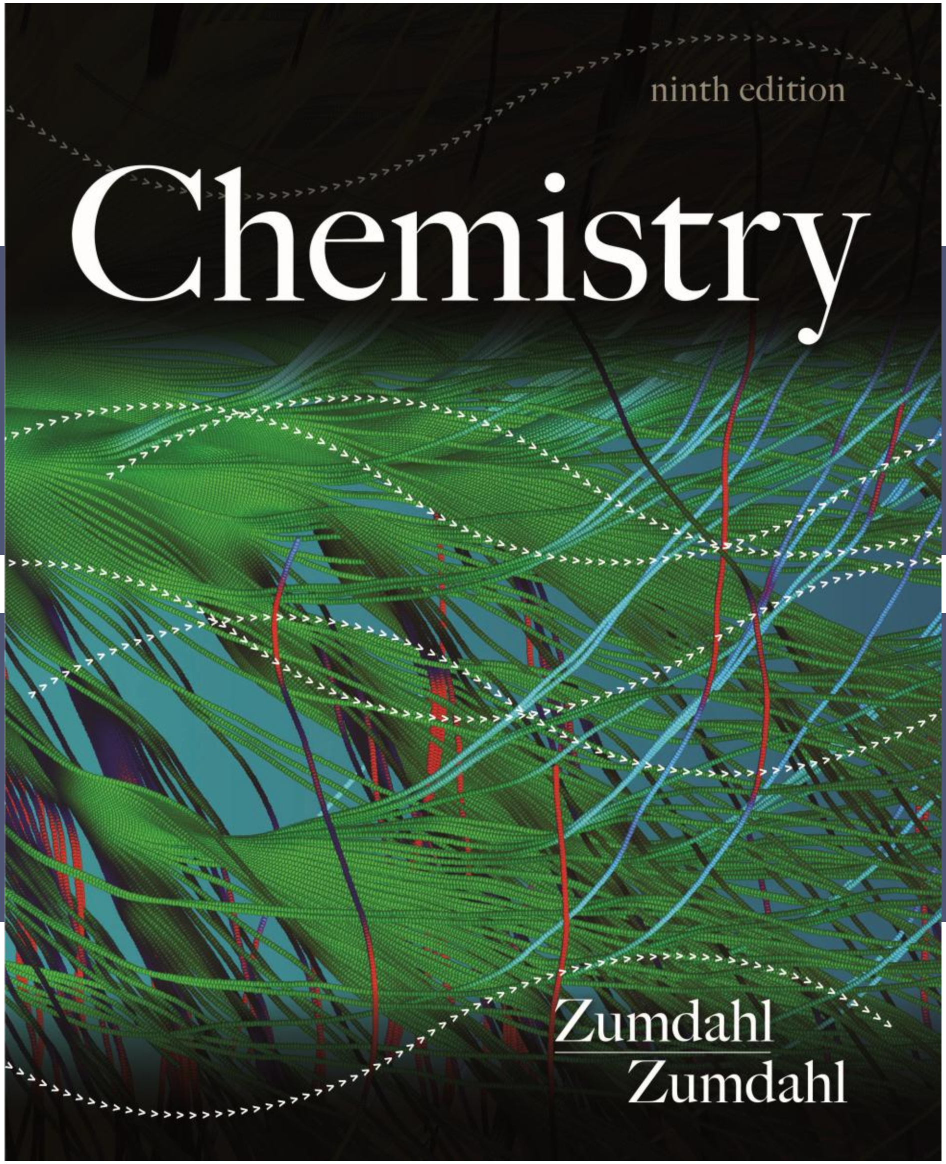


Chapter 2

Atoms, Molecules, and Ions

Chapter 2
Table of Contents

Early History of Chemistry

- Applications of chemistry before 1000 B.C
  - Usage of embalming fluids
  - Production of metals for weapons and ornaments
- The Greeks (400 B.C)
  - Proposed that matter was composed of earth, fire, air, and water
  - Questioned whether matter is infinitely divisible or is composed of small, indivisible particles

Early History of Chemistry - Alchemy

- Alchemists dominated the field of chemistry for 2000 years
  - Helped discover several elements
  - Learned to prepare mineral acids

Modern Chemistry

- Foundation was laid by:
  - Georg Bauer, who developed systematic metallurgy
  - Paracelsus, who discovered the medicinal applications of minerals
- Robert Boyle
  - Performed quantitative experiments to measure the relationship between the pressure and volume of air

Modern Chemistry (Continued 1)

- Developed the first experimental definition of an element
  - A substance is an element unless it can be broken down into two or more simpler substances
- Held on to certain alchemists’ views
  - Metals are not true elements
  - Eventually, a method to change one metal to another will be found

Modern Chemistry (Continued 2)

- 17th and 18th century
  - Rise in interest in the phenomenon of combustion
  - Georg Stahl suggested that a substance called phlogiston flowed out of burning material
    - Substances that burn in a closed container eventually stop burning since the air in the container is saturated with phlogiston

Modern Chemistry (Continued 3)

- Joseph Priestley discovered that oxygen vigorously supported combustion
  - Oxygen was supposed to be low in phlogiston
    - Was originally called dephlogisticated air

Antoine Lavoisier

- Proposed the law of conservation of mass
  - **Law of conservation of mass**: Mass is neither created nor destroyed in a chemical reaction
- Showed that combustion involves oxygen, not phlogiston
- Discovered that life is supported by a process that involves oxygen and is similar to combustion

Joseph Proust

- Proposed the Proust's law or law of definite proportion
  - **Law of definite proportion**: A given compound always contains exactly the same proportion of elements by mass

John Dalton

- Suggested that elements were composed of tiny individual particles
  - A given compound always contains the same combination of these atoms
- Proposed the law of multiple proportions
  - **Law of multiple proportions**: When two elements form a series of compounds:
    - The ratios of the masses of the second element that combine with 1 gram of the first element can always be reduced to small whole numbers

Example 2.1 - Illustrating the Law of Multiple Proportions

- The following data were collected for several compounds of nitrogen and oxygen:

	Mass of Nitrogen That Combines with 1 g of Oxygen
Compound A	1.750 g
Compound B	0.8750 g
Compound C	0.4375 g

  - Show how these data illustrate the law of multiple proportions

Example 2.1 - Solution

- For the law of multiple proportions to hold, the ratios of the masses of nitrogen combining with 1 g of oxygen in each pair of compounds should be small whole numbers
  - Therefore, compute the ratios as follows:

$$\frac{A}{B} = \frac{1.750}{0.8750} = \frac{2}{1}$$

Example 2.1 - Solution (Continued)

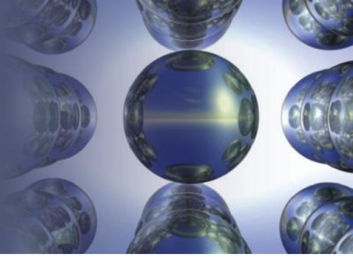
$$\frac{B}{C} = \frac{0.8750}{0.4375} = \frac{2}{1}$$

$$\frac{A}{C} = \frac{1.750}{0.4375} = \frac{4}{1}$$

- These results support the law of multiple proportions

Dalton's Atomic Theory

- Each element is made up of tiny particles called atoms
- Atoms of a given element are identical
  - Atoms of different elements are different in some fundamental way or ways



Dalton's Atomic Theory (Continued)

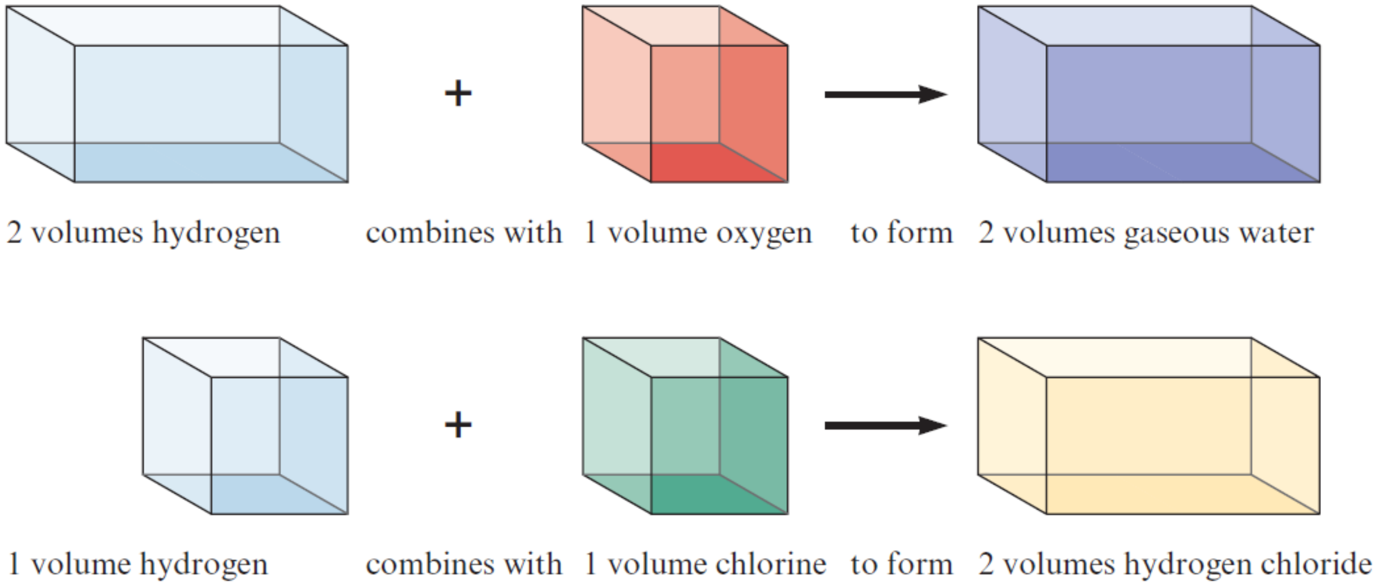
- Chemical compounds are formed when atoms of different elements combine with each other
  - A given compound always has the same relative numbers and types of atoms
- Chemical reactions involve reorganization of the atoms
  - The atoms themselves are not changed in a chemical reaction

Table of Atomic Masses

- Dalton prepared the first table of **atomic masses** (**atomic weights**)
- Assumption - Nature is as simple as possible
  - Many masses were proved to be wrong due to the assumption

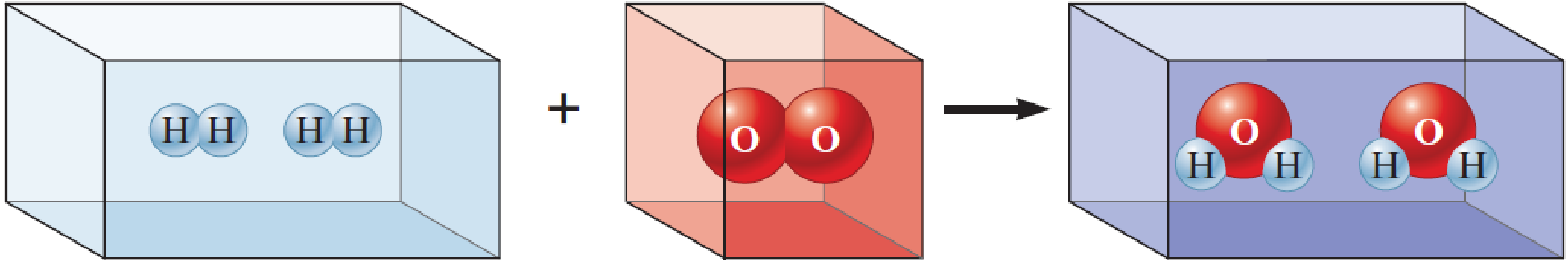
Gay-Lussac

- Measured the volumes of gases that reacted with each other under the same temperature and pressure



Avogadro's Hypothesis

- At the same temperature and pressure, equal volumes of different gases contain the same number of particles
  - Volume of a gas is determined by the number, not the size, of molecules



The spheres represent atoms in the molecules

Combining Gay-Lussac's Result and Avogadro's Hypothesis

- If Avogadro's hypothesis is correct,

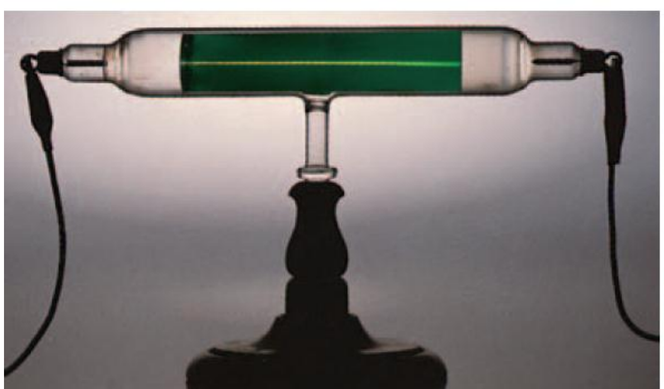
2 volumes of hydrogen react with 1 volume of oxygen
$\rightarrow$ 2 volumes of water vapor

  - Can be expressed as:

2 molecules of hydrogen react with 1 molecule of oxygen
$\rightarrow$ 2 molecules of water

J. J. Thomson

- Studied electric discharge using cathode-ray tubes
  - **Cathode-ray tubes**: Partially evacuated tubes
  - When high voltage was applied to the tube, a cathode ray was produced



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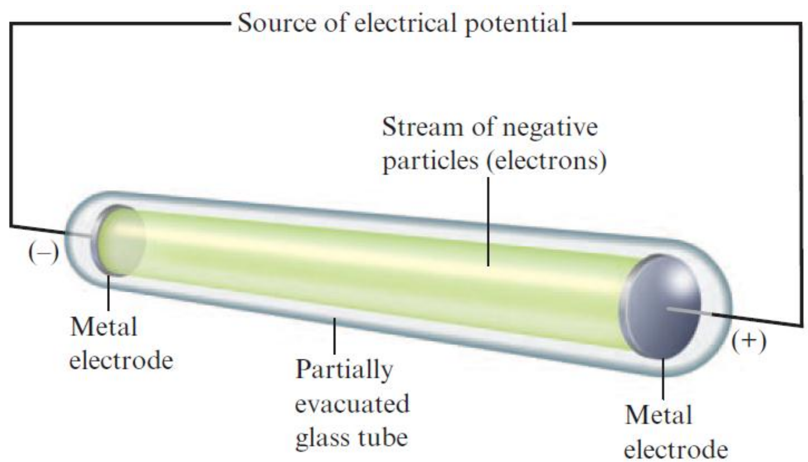
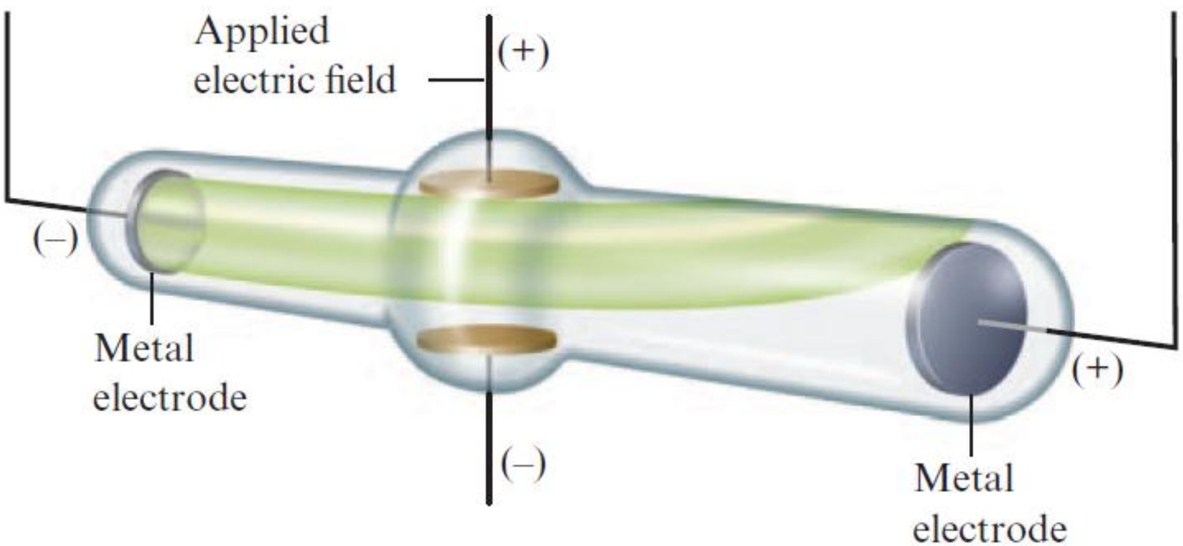


Figure 2.8 - Deflection of Cathode Rays by an Applied Electrical Field



- The ray was produced at the negative electrode and was repelled by the negative pole of an applied electric field

J. J. Thomson - Contributions

- Postulated the existence of negatively charged particles (**electrons**)
- Determined the charge-to-mass ratio of an electron

$$\frac{e}{m} = -1.76 \times 10^{8}\ \text{C/g}$$

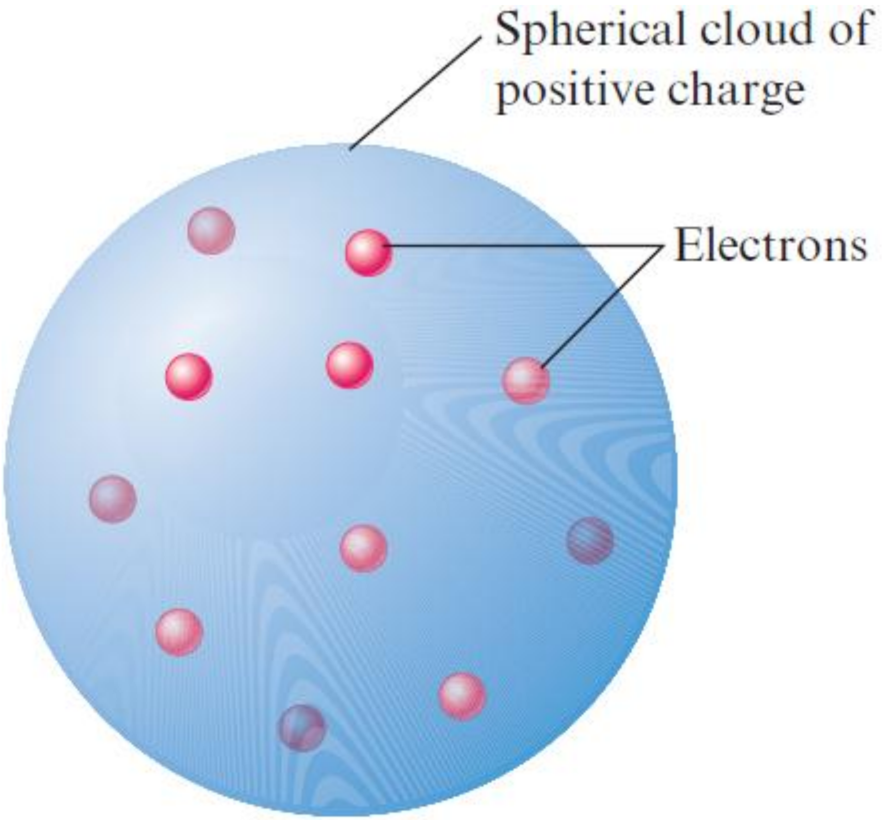
  - *e* - Charge on the electron (in coulombs)
  - *m* - Electron mass (in grams)

J. J. Thomson - The Structure of Atoms

- Thomson attempted to understand the structure of an atom
- Assumptions
  - All atoms contain electrons as electrons can be produced from electrodes made of various metals
  - Atoms must contain some amount of positive charge

J. J. Thomson's Plum Pudding Model

- Atoms consist of a diffuse cloud of positive charge
  - Negative electrons are randomly embedded in it



Robert Millikan

- Performed experiments involving charged oil drops
- Determined the magnitude of the charge on a single electron
- Calculated the mass of an electron
  - 9.11×10^{-31} kg

Radioactivity

- Henri Becquerel
  - Discovered **radioactivity** by observing the spontaneous emission of radiation by uranium
- Types of radioactive emission
  - Gamma rays (γ) - High-energy light
  - Beta particles (β) - High-speed electrons
  - Alpha particles (α) - Particles with a 2+ charge

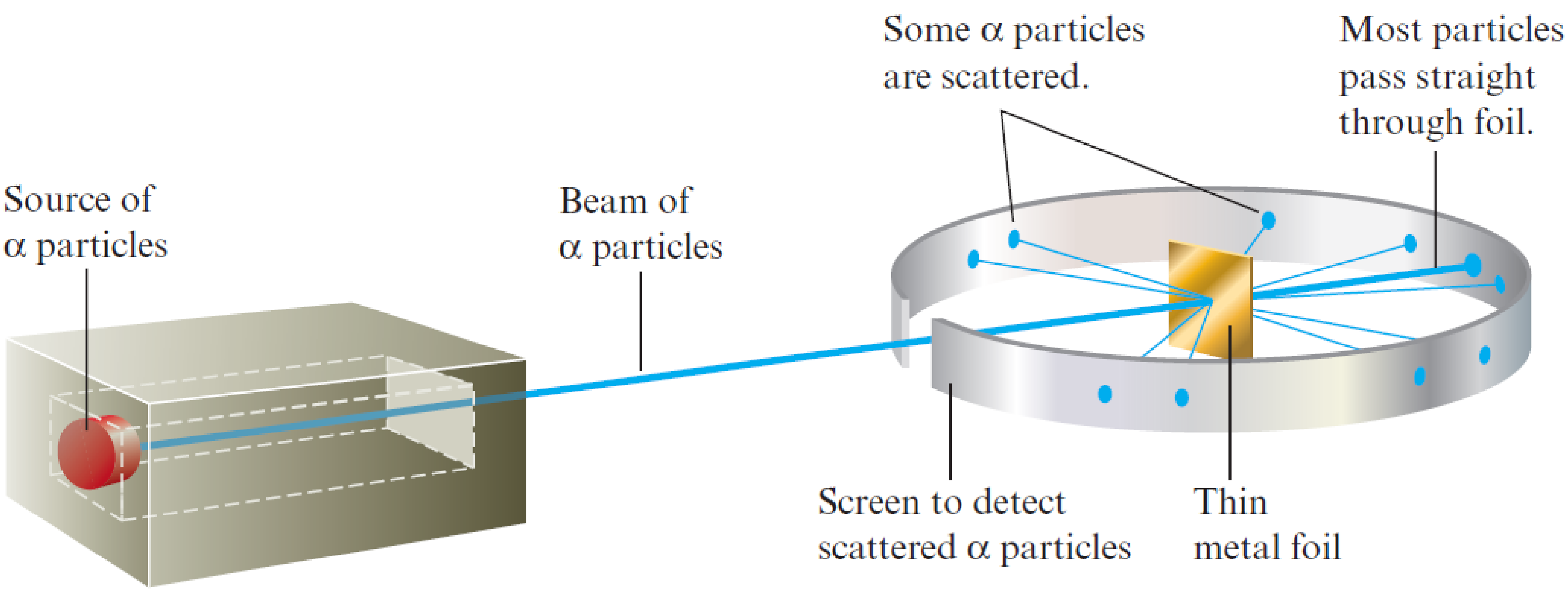
Rutherford's Experiment

- Carried out to test the accuracy of Thomson's plum pudding model
- Involved directing α particles at a thin sheet of metal foil
  - Expectation - α particles will pass through the foil with minor deflections in path

Rutherford's Experiment - Results

- Most α particles passed through the foil
- Many particles were deflected at large angles
- Some particles were reflected
  - Particles did not hit the detector

Figure 2.12 - Rutherford's Experiment on α-Particle Bombardment of a Metal Foil



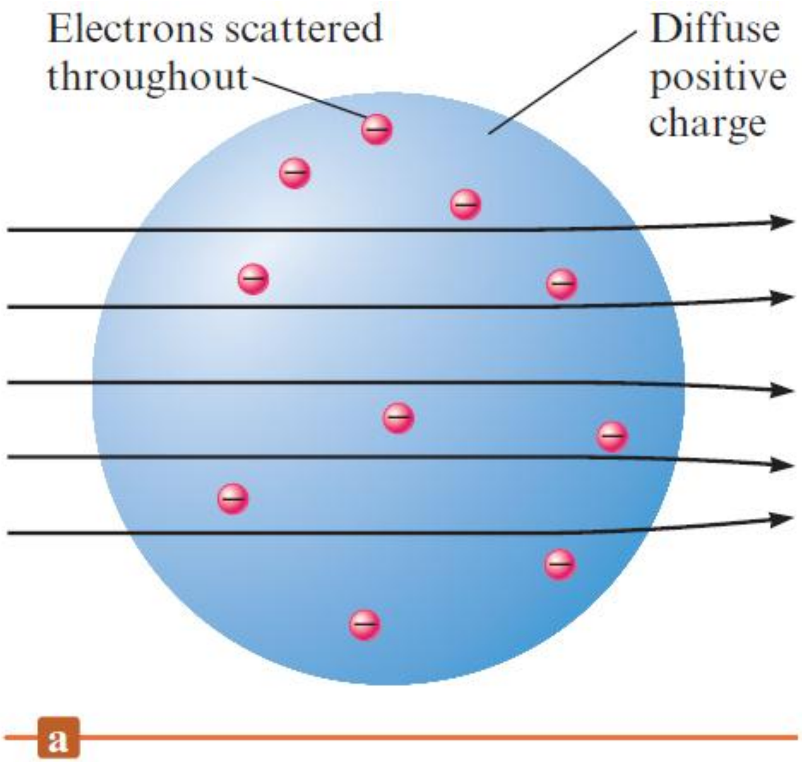
Rutherford's Experiment - Conclusions

- Large deflections of the α particles are caused by a center of concentrated positive charge
  - The center contains most of the atom's mass
  - Deflected α particles had a close encounter with the massive positive center of the atom
    - Reflected α particles made a direct hit on the massive positive center
- Most α particles pass directly through the foil because the atom is mostly open space

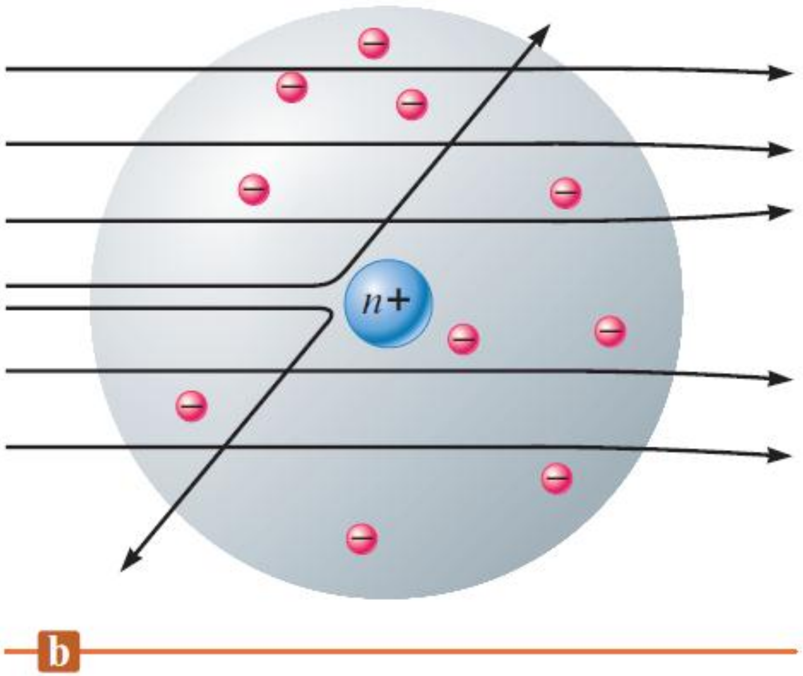
Rutherford's Experiment - Conclusions (Continued)

- **Nuclear atom** has a dense center of positive charge (**nucleus**)
- Electrons travel around the nucleus at a large distance relative to the nucleus

Figure 2.13 - Rutherford's Experiment



The expected results of the metal foil experiment if Thomson's model were correct



Actual results

Critical Thinking

- You have learned about three different models of the atom - Dalton’s model, Thomson’s model, and Rutherford’s model
  - What if Dalton was correct? What would Rutherford have expected from his experiments with gold foil?
  - What if Thomson was correct? What would Rutherford have expected from his experiments with gold foil?

Atomic Structure

- Electrons are negatively charged particles that are found outside the nucleus
- The nucleus contains:
  - **Protons**: Contain positive charge that is equal in magnitude to the electron’s negative charge
  - **Neutrons**: Contain no charge and have virtually the same mass as a proton
- Atoms of different elements show different chemical behavior

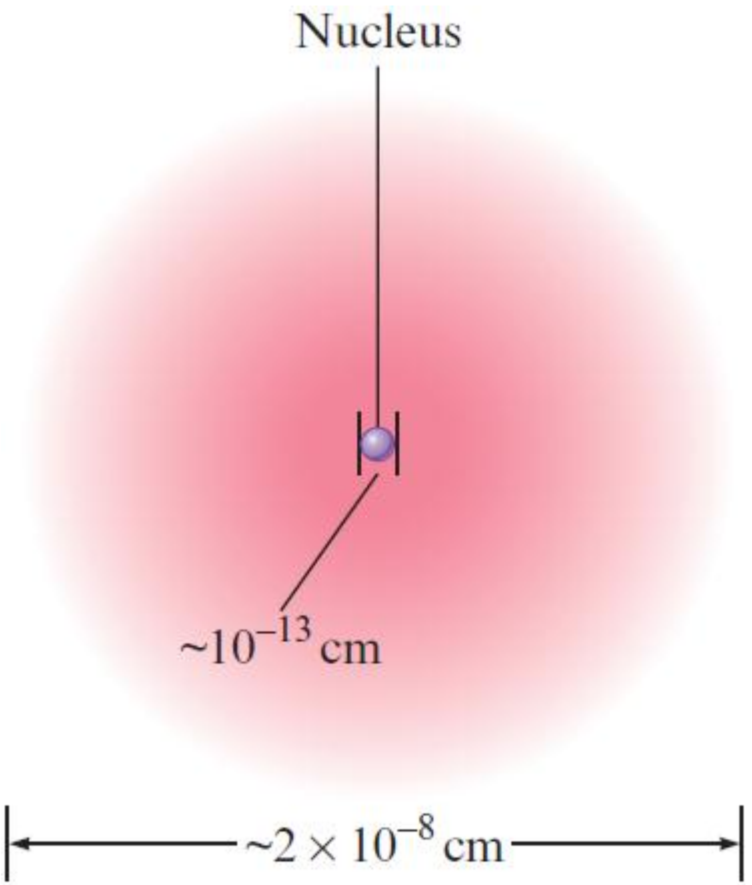
Table 2.1 - The Mass and Charge of the Electron, Proton, and Neutron

Particle	Mass	Charge*
Electron	9.109×10^{-31} kg	1−
Proton	1.673×10^{-27} kg	1+
Neutron	1.675×10^{-27} kg	None

*The magnitude of the charge of the electron and the proton is 1.60×10^{-19} C.

The Nucleus

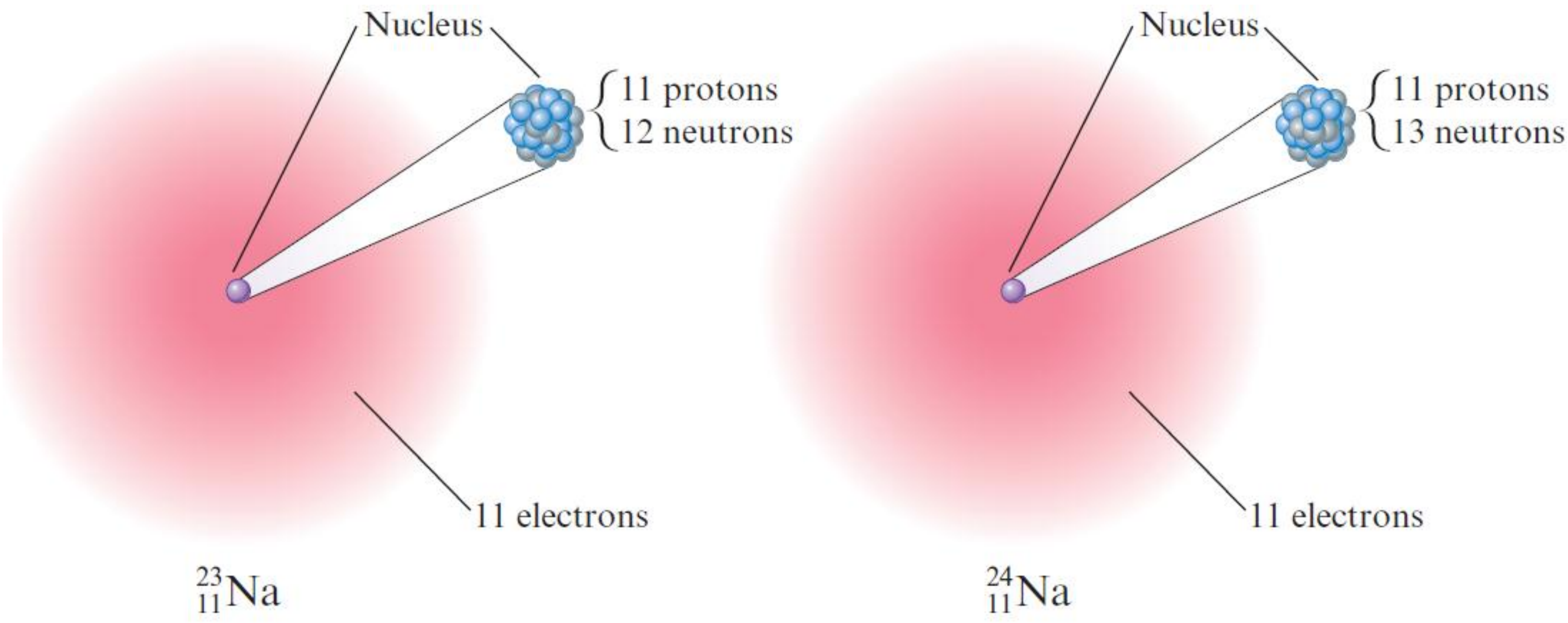
- Small compared to the overall size of the atom
- High in density
  - Accounts for almost all of the atom’s mass



Isotopes

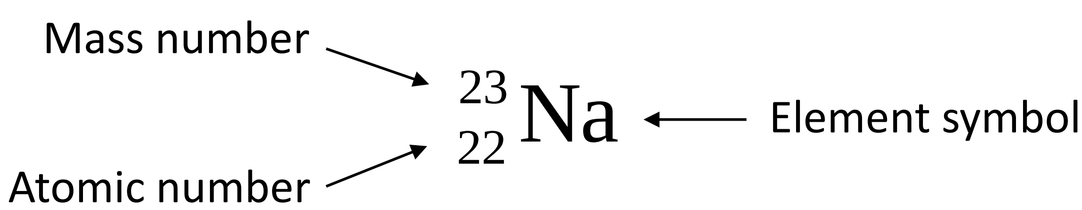
- Atoms with the same number of protons but different numbers of neutrons
- Depict almost identical chemical properties
- In nature, most elements contain mixtures of isotopes

Figure 2.15 - Two Isotopes of Sodium



Identifying Isotopes

- **Atomic number** (Z): Number of protons
  - Written as a subscript
- **Mass number** (A): Total number of protons and neutrons
  - Written as a superscript



Critical Thinking

- The average diameter of an atom is 2×10^{-10} m
  - What if the average diameter of an atom were 1 cm?
  - How tall would you be?

Interactive Example 2.2 - Writing the Symbols for Atoms

- Write the symbol for the atom that has an atomic number of 9 and a mass number of 19
  - How many electrons and how many neutrons does this atom have?

Interactive Example 2.2 - Solution

- The atomic number 9 means the atom has 9 protons
  - This element is called fluorine, symbolized by F
  - The atom is represented as follows:

$$^{19}_{9}\mathrm{F}$$

    - The atom is called fluorine nineteen

Interactive Example 2.2 - Solution (Continued)

- Since the atom has 9 protons, it also must have 9 electrons to achieve electrical neutrality
- The mass number gives the total number of protons and neutrons, which means that this atom has 10 neutrons

Exercise

- How many protons and neutrons are in the nucleus of each of the following atoms?
  - In a neutral atom of each element, how many electrons are present?

1. ^{79}Br **35 p, 44 n, 35 e**
2. ^{81}Br **35 p, 46 n, 35 e**
3. ^{239}Pu **94 p, 145 n, 94 e**
4. ^{133}Cs **55 p, 78 n, 55 e**

Chemical Bonds

- Forces that hold atoms together in a compound
- Can be formed by sharing of electrons
  - Leads to the formation of a **covalent bond**
  - **Molecule**: Collection of atoms

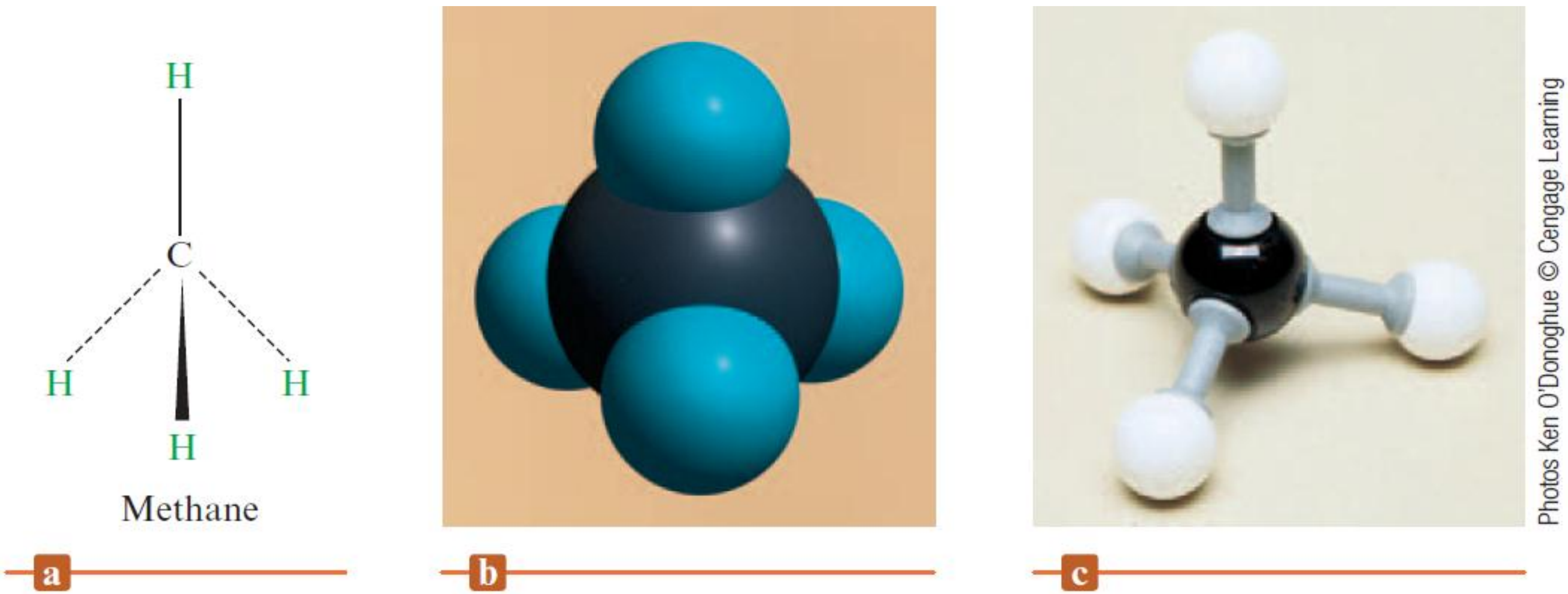
Chemical Formula

- Symbols of elements used to indicate types of atoms present in the molecule
  - Subscript indicates the relative number of atoms
  - Example - Formula for carbon dioxide is CO_2
    - Implies that each molecules of CO_2 contains one atom of carbon and two atoms of oxygen

Methods of Representing Molecules

- **Structural formula**: Depicts individual bonds in a molecule
  - May or may not indicate the actual shape of the molecule
- **Space-filling model**: Illustrates the relative sizes of atoms and their relative orientations in a molecule
- **Ball-and-stick model**

Figure 2.16 - Structure of Methane



Structural formula

Space-filling model

Ball-and-stick model

Ion

- Atom or group of atoms with a net positive or negative charge
  - Chemical bonds can be a result of ionic attraction
  - **Cation**: Positive ion formed by losing electrons
  - **Anion**: Negative ion formed by gaining electrons
- **Ionic bonding**: Force of attraction between oppositely charged ions

Ionic Solids

- Solids containing oppositely charged ions
- Can consist of:
  - Simple ions
    - Example - Sodium chloride (common salt)
  - **Polyatomic ions**: Composed of many atoms
    - Example - Ammonium nitrate (NH_4NO_3)

Exercise

- Would you expect each of the following atoms to gain or lose electrons when forming ions?
  - What ion is the most likely in each case?

a. Ra — **Loses 2 e^- to form Ra^{2+}**

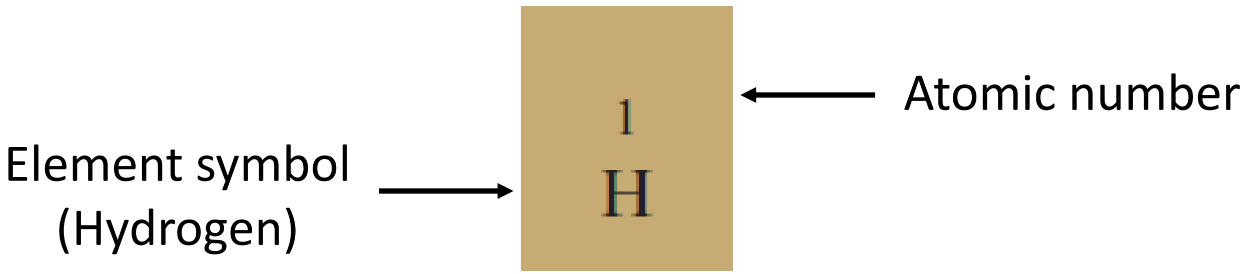
b. In — **Loses 3 e^- to form In^{3+}**

c. P — **Gains 3 e^- to form P^{3-}**

d. Te — **Gains 2 e^- to form Te^{2-}**

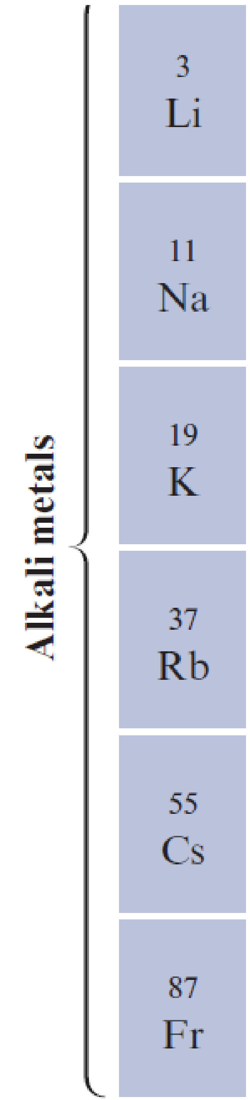
The Periodic Table

- A chart that provides information about elements
  - Letters in boxes are symbols of elements
  - Number above every symbol is the element’s atomic number



Structure of the Periodic Table

- **Groups** or **families**: Elements in the vertical columns with similar chemical properties



Structure of the Periodic Table (Continued)

- **Periods**: Horizontal rows of elements

87 Fr	88 Ra	89 Ac†	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Table of Common Charges

Group or family	Charge
Alkali metals (1A)	1+
Alkaline earth metals (2A)	2+
Halogens (7A)	1–
Noble gases (8A)	0

Metals and Nonmetals

- **Metals**
  - Lose electrons to form positive ions
  - Efficient conductors of heat and electricity
  - Malleable, ductile, and have lustrous appearance
- **Nonmetals**
  - Gain electrons to form negative ions
  - Appear in the upper-right corner of the periodic table
  - Form covalent bonds

Binary Compounds

- Composed of two elements
- Include covalent and ionic compounds
    - **Binary ionic compounds**: Contain a cation, which is written first in the formula, and an anion

Naming Binary Ionic Compounds (Type I)

- The cation is always named first and the anion second
- A monatomic cation takes its name from the name of the parent element
- A monatomic anion is named by taking the root of the element name and adding –ide

Table 2.3 - Common Monatomic Cations and Anions

Cation	Name	Anion	Name
H^+	Hydrogen	H^-	Hydride
Li^+	Lithium	F^-	Fluoride
Na^+	Sodium	Cl^-	Chloride
K^+	Potassium	Br^-	Bromide
Cs^+	Cesium	I^-	Iodide
Be^{2+}	Beryllium	O^{2-}	Oxide
Mg^{2+}	Magnesium	S^{2-}	Sulfide
Ca^{2+}	Calcium	N^{3-}	Nitride
Ba^{2+}	Barium	P^{3-}	Phosphide
Al^{3+}	Aluminum		

Interactive Example 2.3 - Naming Type I Binary Compounds

- Name each binary compound
  a. CsF
  b. $AlCl_3$
  c. LiH

Interactive Example 2.3 - Solution

a. CsF is cesium fluoride
b. $AlCl_3$ is aluminum chloride
c. LiH is lithium hydride

- Notice that, in each case, the cation is named first and then the anion is named

Binary Ionic Compounds (Type II)

- Metals in such compounds form more than one type of positive ion
- Naming
  - Charge on the metal ion must be specified
    - Roman numeral indicates the charge of the metal cation
      - Compounds containing transition metals usually require a Roman numeral
      - Elements that form only one cation do not need to be identified by a Roman numeral

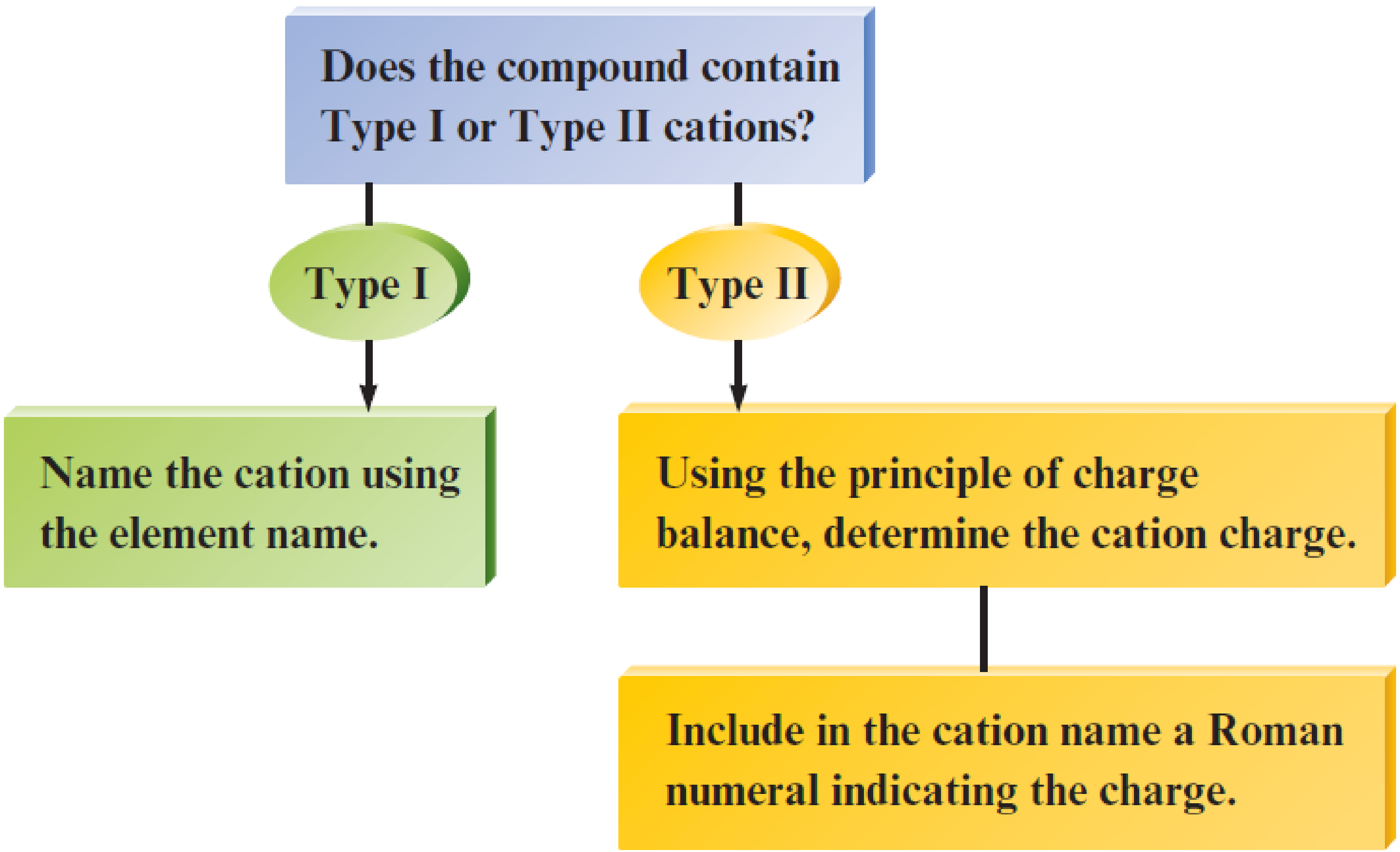
Common Metals That Do Not Require a Roman Numeral

- Group 1A elements
- Group 2A elements
- Aluminum
- Silver
- Zinc

Critical Thinking

- We can use the periodic table to tell us something about the stable ions formed by many atoms
  - For example, the atoms in column 1 always form 1+ ions
  - The transition metals, however, can form more than one type of stable ion
  - What if each transition metal ion had only one possible charge?
  - How would the naming of compounds be different?

Figure 2.20 - Flowchart for Naming Binary Ionic Compounds



Interactive Example 2.6 - Naming Binary Compounds

1. Give the systematic name for each of the following compounds:
   a. $CoBr_2$
   b. $CaCl_2$
2. Given the following systematic names, write the formula for each compound:
   a. Chromium(III) chloride
   b. Gallium iodide

Interactive Example 2.6 - Solution (1)

Formula	Name	Comments
$CoBr_2$	Cobalt(II) bromide	Cobalt is a transition metal; the compound name must have a Roman numeral The two Br^- ions must be balanced by a Co^{2+} ion
$CaCl_2$	Calcium chloride	Calcium, an alkaline earth metal, forms only the Ca^{2+} ion A Roman numeral is not necessary
Al_2O_3	Aluminium oxide	Aluminum forms only the Al^{3+} ion A Roman numeral is not necessary

Interactive Example 2.6 - Solution (2)

Name	Formula	Comments
Chromium(III) chloride	$CrCl_3$	Chromium(III) indicates that Cr^{3+} is present, so 3 Cl^- ions are needed for charge balance
Gallium iodide	GaI_3	Gallium always forms 3+ ions, so 3 I^- ions are required for charge balance

Polyatomic Ions

- Assigned special names that must be memorized for naming compounds
- **Oxyanions**: Anions that contain an atom of a given element and different numbers of O_2 atoms
  - When there are two elements in the series:
    - Name of the element with the smaller number of O_2 atoms ends with -ite
    - Name of the element with the larger number of O_2 atoms ends with -ate

Polyatomic Ions (Continued)

- When more than two oxyanions make up a series:
  - Use the prefix hypo- (less than) to name members of the series with the fewest O_2 atoms
  - Use the prefix per- (more than) to name members of the series with the most O_2 atoms

Table 2.5 - Common Polyatomic Ions

Ion	Name	Ion	Name
Hg_2^{2+}	Mercury(I)	NCS^- or SCN^-	Thiocyanate
NH_4^+	Ammonium	CO_3^{2-}	Carbonate
NO_2^-	Nitrite	HCO_3^-	Hydrogen carbonate (bicarbonate is a widely used common name)
NO_3^-	Nitrate		
SO_3^{2-}	Sulfite		
SO_4^{2-}	Sulfate	ClO^- or OCl^-	Hypochlorite
HSO_4^-	Hydrogen sulfate (bisulfate is a widely used common name)	ClO_2^-	Chlorite
		ClO_3^-	Chlorate
		ClO_4^-	Perchlorate
OH^-	Hydroxide	$C_2H_3O_2^-$	Acetate
CN^-	Cyanide	MnO_4^-	Permanganate
PO_4^{3-}	Phosphate	$Cr_2O_7^{2-}$	Dichromate
HPO_4^{2-}	Hydrogen phosphate	CrO_4^{2-}	Chromate
$H_2PO_4^-$	Dihydrogen phosphate	O_2^{2-}	Peroxide
		$C_2O_4^{2-}$	Oxalate
		$S_2O_3^{2-}$	Thiosulfate

Interactive Example 2.7 - Naming Compounds Containing Polyatomic Ions

1. Give the systematic name for each of the following compounds:
   a. Na_2SO_4
   b. $Mn(OH)_2$
2. Given the following systematic names, write the formula for each compound:
   a. Sodium hydrogen carbonate
   b. Sodium selenate

Interactive Example 2.7 - Solution (1)

Formula	Name	Comments
Na_2SO_4	Sodium sulfate	
$Mn(OH)_2$	Manganese(II) hydroxide	Transition metal—name must contain a Roman numeral The Mn^{2+} ion balances three OH^- ions

Interactive Example 2.7 - Solution (2)

Name	Formula	Comments
Sodium hydrogen carbonate	$NaHCO_3$	Often called sodium bicarbonate
Sodium selenate	Na_2SeO_4	Atoms in the same group, like sulfur and selenium, often form similar ions that are named similarly Thus SeO_4^{2-} is selenate, like SO_4^{2-} (sulfate)

Binary Covalent Compounds (Type III)

- Formed between two nonmetals
- Naming binary covalent compounds
  - The first element in the formula is named first, using the full element name
  - The second element is named as if it were an anion
  - Prefixes are used to denote the numbers of atoms present
  - The prefix mono- is never used for naming the first element

Table 2.6 - Prefixes Used to Indicate Number in Chemical Names

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

Interactive Example 2.8 - Naming Type III Binary Compounds

1. Name each of the following compounds:
   a. PCl_5
   b. PCl_3
   c. SO_2
2. From the following systematic names, write the formula for each compound:
   a. Sulfur hexafluoride
   b. Sulfur trioxide

Interactive Example 2.8 - Solution

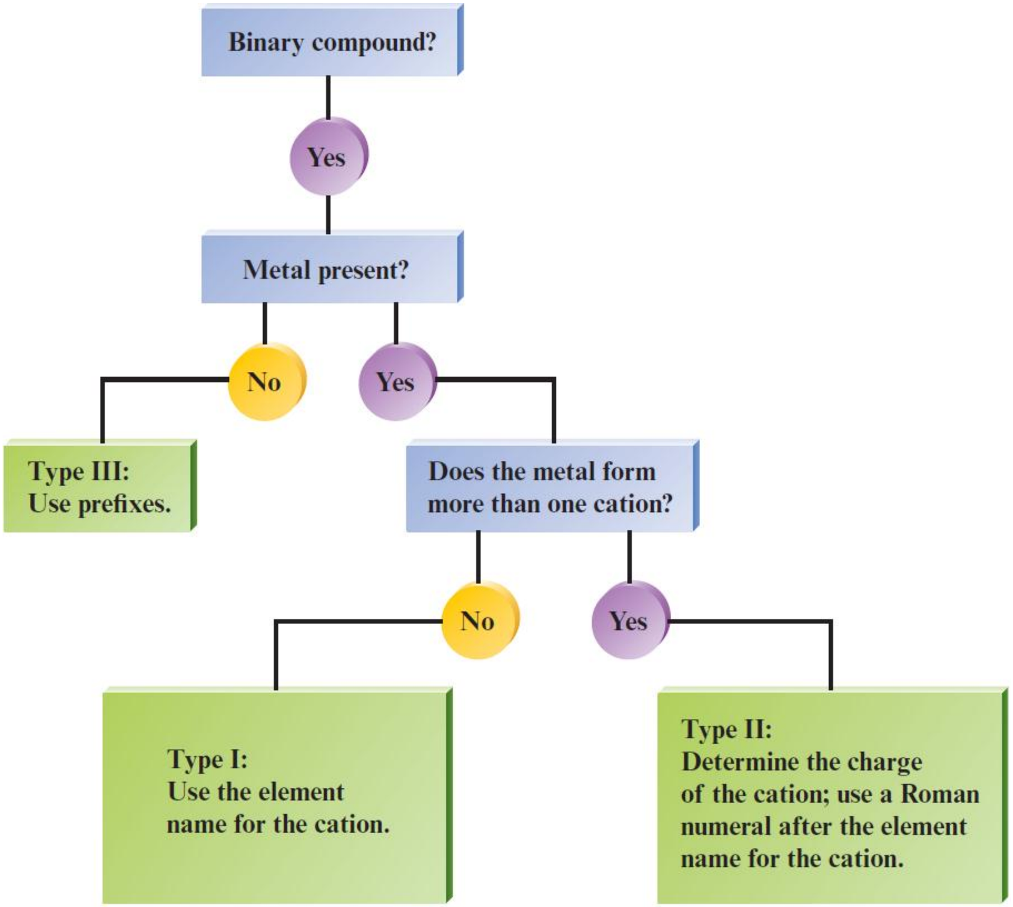
1.

Formula	Name
PCl_5	Phosphorus pentachloride
PCl_3	Phosphorus trichloride
SO_2	Sulfur dioxide

2.

Name	Formula
Sulfur hexafluoride	SF_6
Sulfur trioxide	SO_3

Figure 2.22 - A Flowchart for Naming Binary Compounds



Acids

- Molecules in which one or more H^+ ions are attached to an anion
- Naming acids
  - The acid is named with the prefix hydro- and the suffix -ic if the anion ends in -ide

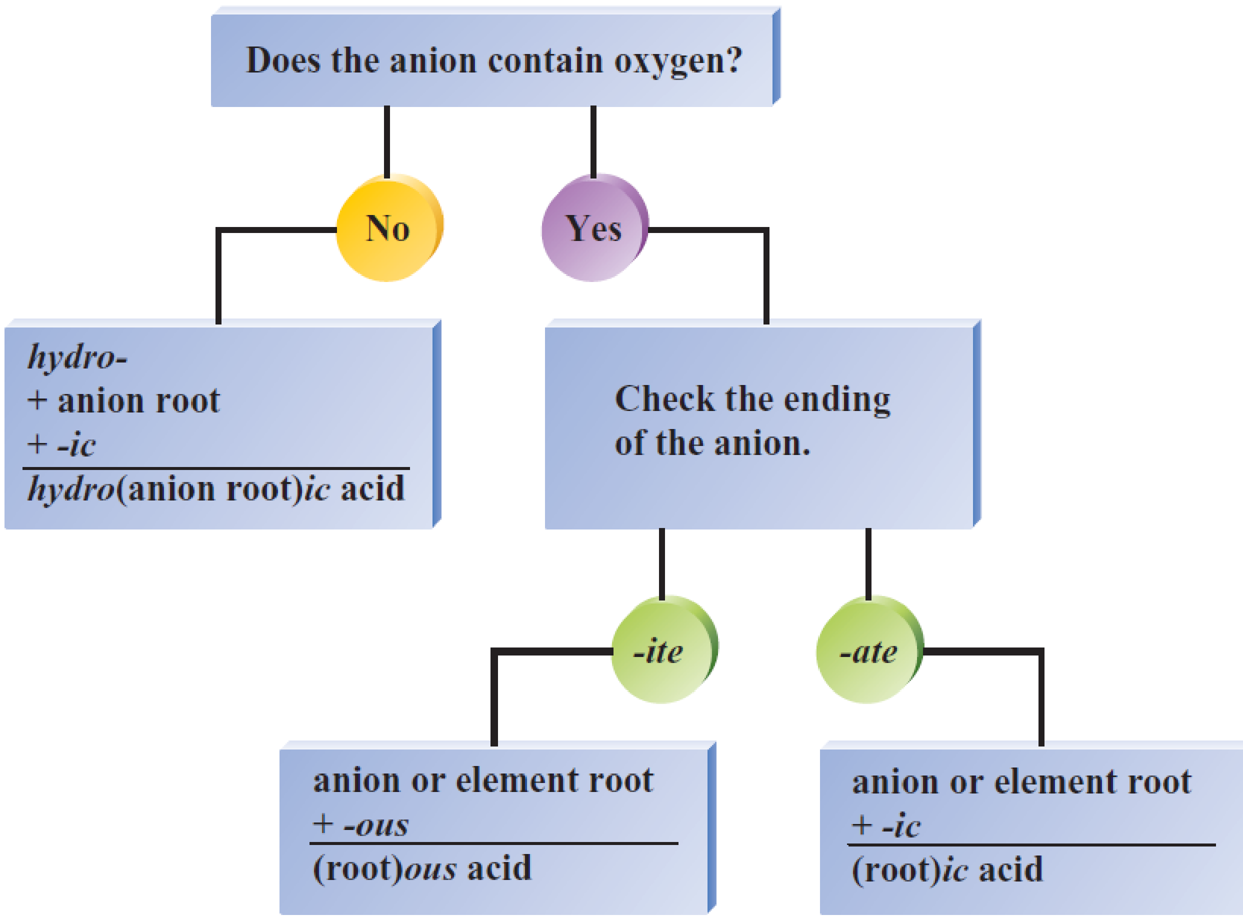
Acids (Continued)

- If the anion contains oxygen:
  - The suffix -ic is added to the root name if the anion name ends in -ate
  - The suffix -ous is added to the root name if the anion name ends in -ite

Critical Thinking

- In this chapter, you have learned a systematic way to name chemical compounds
  - What if all compounds had only common names?
  - What problems would this cause?

Figure 2.24 - Flowchart for Naming Acids



Exercise

- Name each of the following compounds:

a. CuI — **Copper(I) iodide**

b. S_4N_4 — **Tetrasulfur tetranitride**

c. $NaHCO_3$ — **Sodium hydrogen carbonate or sodium bicarbonate**

d. $BaCrO_4$ — **Barium chromate**