Atoms,
Molecules,
and Ions

Chapter 2

The Early History of Chemistry

- Before 16th Century
  - **Alchemy**: Attempts (scientific or otherwise) to change cheap metals into gold
- 17th Century
  - **Robert Boyle**: First "chemist" to perform quantitative experiments
- 18th Century
  - **George Stahl**: *Phlogiston* flows out of a burning material.
  - **Joseph Priestley**: Discovers oxygen gas, "dephlogisticated air."

Law of Conservation of Mass

- Discovered by Antoine Lavoisier
- Mass is neither created nor destroyed
- Combustion involves oxygen, not phlogiston

Other Fundamental Chemical Laws

Law of Definite Proportion

- A given compound always contains exactly the same proportion of elements by mass.
- Carbon tetrachloride is always 1 atom carbon per 4 atoms chlorine.

$$\frac{35.45 \text{ g Cl} \times 4}{12.01 \text{g C}} = \frac{11.83 \text{ g Cl}}{1.000 \text{ g C}} \qquad CCl_4$$

Other Fundamental Chemical Laws

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.
- The ratio of the masses of oxygen in H_2O and H_2O_2 will be a small whole number ("2").

$$H_2O \quad \frac{8.0 \text{ g O}}{1.0 \text{ g H}}, \quad H_2O_2 \quad \frac{16.0 \text{ g O}}{1.0 \text{ g H}}, \text{ so } \quad \frac{16.0 \text{ g O}}{8.0 \text{ g O}} = 2.0$$

Dalton's Atomic Theory (1808)

- *Each element is made up of tiny particles called atoms.*
- *The atoms of a given element are identical*; the atoms of different elements are different in some fundamental way or ways.

Dalton's Atomic Theory
(continued)

- *Chemical compounds are formed when atoms combine with each other*. A given compound always has the same relative numbers and types of atoms.
- *Chemical reactions involve reorganization of the atoms* - changes in the way they are bound together. The atoms themselves are not changed in a chemical reaction.

Avogadro's Hypothesis (1811)

At the same temperature and pressure, equal volumes of different gases contain the same number of particles.

- 5 liters of oxygen
- 5 liters of nitrogen
- Same number of particles!

Figure 2.4: A representation of some of Gay-Lussac's experimental results on combining gas volumes.

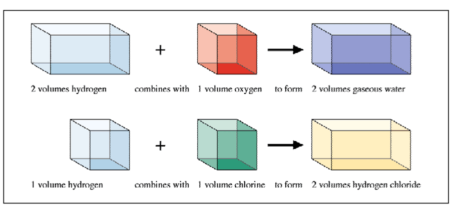
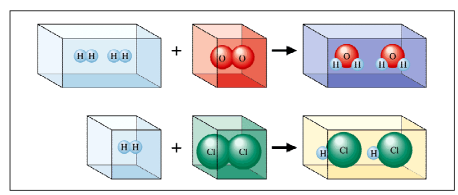


Figure 2.5: A representation of combining gases at the molecular level. The spheres represent atoms in the molecules.



$2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O\ (g)$

$H_2\ (g) + Cl_2\ (g) \rightarrow 2\ HCl\ (g)$

Early Experiments to Characterize the Atom

- J. J. Thomson - postulated the existence of electrons using cathode ray tubes.
- Ernest Rutherford - explained the nuclear atom, containing a dense nucleus with electrons traveling around the nucleus at a large distance.

Figure 2.7: A cathode-ray tube. The fast-moving electrons excite the gas in the tube, causing a glow between the electrodes.

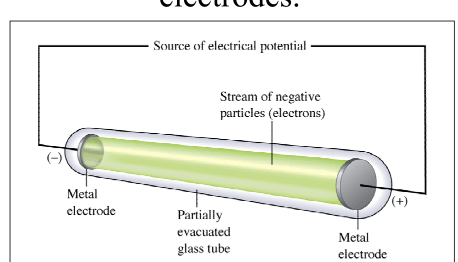


Figure 2.8: Deflection of cathode rays by an applied electric field.

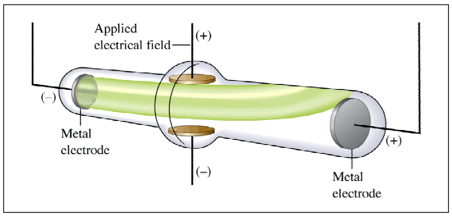


Figure 2.5: The cathode-ray beam travels right to left. Photo courtesy of James

Scherer.

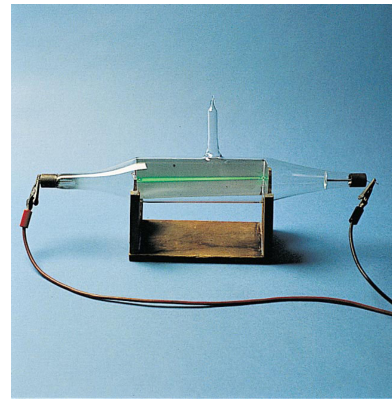


Figure 2.5: The beam of negative particles bends downward. Photo courtesy of James

Scherer.

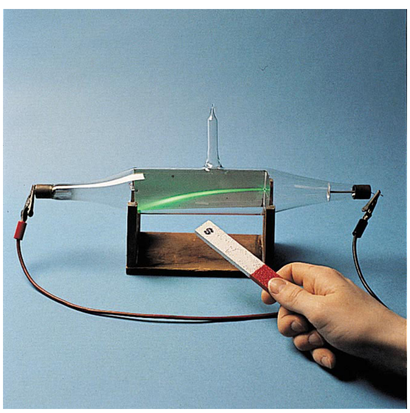
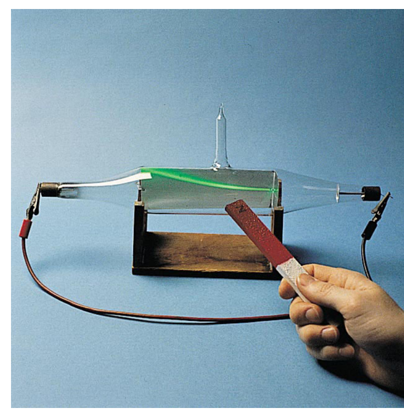


Figure 2.5: The magnet is turned around and the beam bends in opposite direction. Photo courtesy of

James Scherer.



Atomic Theory of Matter

- **The Structure of the Atom**
  - In 1909, U.S. physicist, Robert Millikan had obtained the charge on the electron. (see Figure 2.6)
  - These two discoveries combined provided us with the electron's mass of **9.109×10^{-31} kg**, which is more than 1800 times smaller than the mass of the lightest atom (hydrogen).
  - These experiments showed that the electron was indeed a subatomic particle.

Figure 2.10: A schematic representation of the apparatus Millikan used to determine the charge on the electron.

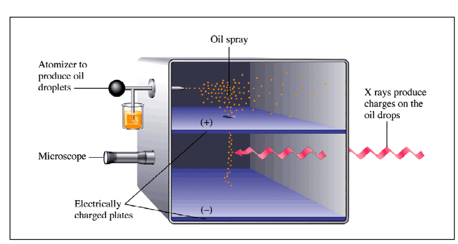


Figure 2.9: The plum pudding model of the atom.

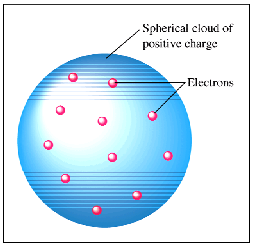


Figure 2.12: Rutherford's experiment on α-particle bombardment of metal foil.

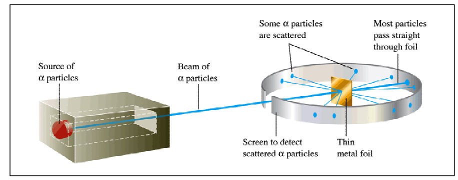
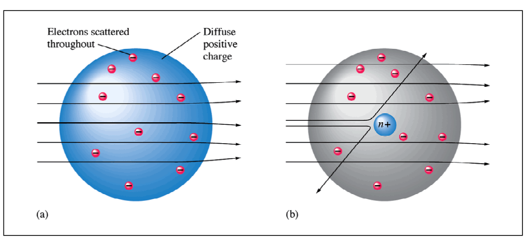


Figure 2.13: (a) The expected results of the metal foil experiment if Thomson's model were correct. (b)Actual results.



The Modern View of Atomic Structure

The atom contains:

- electrons
- protons: found in the nucleus, they have a positive charge equal in magnitude to the electron's negative charge.
- neutrons: found in the nucleus, virtually same mass as a proton but no charge.

Figure 2.14: A nuclear atom viewed in cross section. Note that this drawing is not to scale.

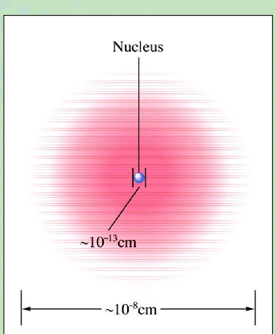


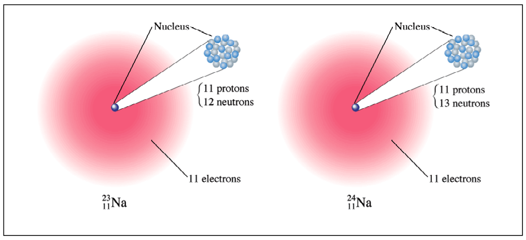
Table 2.2
Properties of the Electron, Proton, and Neutron

Particle	Mass (kg)	Charge (C)	Mass (amu)*	Charge (e)
Electron	9.10939×10^{-31}	-1.60218×10^{-19}	0.00055	−1
Proton	1.67262×10^{-27}	$+1.60218 \times 10^{-19}$	1.00728	+1
Neutron	1.67493×10^{-27}	0	1.00866	0

*The atomic mass unit (amu) equals 1.66054×10^{-27} kg; it is defined in Section 2.4.

1 atomic mass unit (or Dalton) = 1/12 of a ^{12}C atom or 1.66054×10^{-27} kg. You cannot calculate the absolute mass of a ^{12}C nucleus by adding the masses of 6 protons and 6 neutrons - the mass that you calculate will be greater than $(12)(1.66054 \times 10^{-27}$ kg). While mass is conserved in chemical reactions it is not conserved in nuclear reactions and formation of the carbon nucleus from protons & neutrons results in a small mass loss (see Chapter 18, your text.)

Figure 2.15: Two isotopes of sodium. Both have eleven protons and eleven electrons, but they differ in the number of neutrons in their nuclei.



The Chemists' Shorthand: Atomic Symbols

Mass number → 39

Atomic number → 19

K ← Element Symbol

$$^{39}_{19}K$$

For a neutral K atom

Figure 2.14: A modern form of the periodic table.

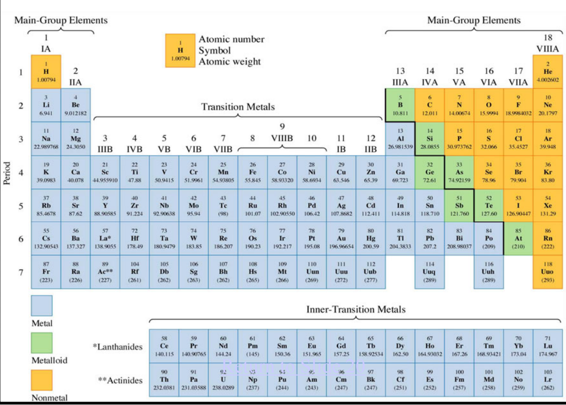


TABLE 2.2 The Symbols for the Elements That Are Based on the Original Names

Current Name	Original Name	Symbol
Antimony	Stibium	Sb
Copper	Cuprum	Cu
Iron	Ferrum	Fe
Lead	Plumbum	Pb
Mercury	Hydrargyrum	Hg
Potassium	Kalium	K
Silver	Argentum	Ag
Sodium	Natrium	Na
Tin	Stannum	Sn
Tungsten	Wolfram	W

Periodic Table

Elements classified by:

- properties
- atomic number

Groups (vertical)

1A = alkali metals

2A = alkaline earth metals

7A = halogens

8A = noble gases

Periods (horizontal)

Ions

Cation: A positive ion

Mg^{2+}, NH_4^+

Anion: A negative ion

Cl^-, SO_4^{2-}

Ionic Bonding: Force of attraction between oppositely charged ions.

Monatomic Ions

Elements which have an excess or deficit of electrons

Examples: Sodium ion has 11 protons and on 10 electrons. The net charge on the atom is 1+ (obtained by adding the charge of the protons and electrons) We would write the symbol for sodium ion or Na^+

$${}^{23}_{11}Na^+$$

What would be the symbol of an element with atomic number 17 and 18 electrons?

$${}^{35}_{17}Cl^-$$

Chemical Substances; Formulas and Names

- **Rules for predicting charges on monatomic ions**
  - Most of the main group metals form cations with the charge equal to their group number.
  - The charge on a monatomic anion for a nonmetal equals the group number minus 8.
  - Most transition elements form more than one ion, each with a different charge. (see Table 2.5)

Table 2.4
Common Monatomic Ions of the Main-Group Elements*

	IA	IIA	IIIA	IVA	VA	VIA	VIIA
Period 1							H^-
Period 2	Li^+	Be^{2+}	B	C	N^{3-}	O^{2-}	F^-
Period 3	Na^+	Mg^{2+}	Al^{3+}	Si	P	S^{2-}	Cl^-
Period 4	K^+	Ca^{2+}	Ga^{3+}	Ge	As	Se^{2-}	Br^-
Period 5	Rb^+	Sr^{2+}	In^{3+}	Sn^{2+}	Sb	Te^{2-}	I^-
Period 6	Cs^+	Ba^{2+}	Tl^+, Tl^{3+}	Pb^{2+}	Bi^{3+}		

*Elements shown in color do not normally form compounds having monatomic ions.

The Chemists' Shorthand: Formulas

- Chemical Formula:
- Symbols = types of atoms
- Subscripts = relative numbers of each type of atom

CO_2

- Structural Formula:
- Individual bonds are shown by lines.

O=C=O

Chemical Formulas; Molecular and Ionic Substances

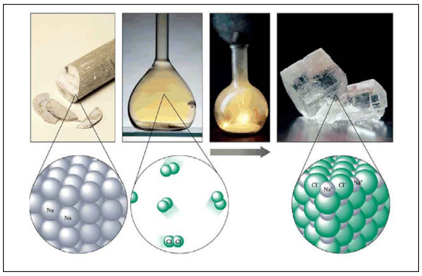
- **Ionic substances**
  - The **formula** of an ionic compound is written by giving the smallest possible whole-number ratio of different ions in the substance.
  - The **formula unit** of the substance is the group of atoms or ions explicitly symbolized by its formula.

$NaCl$ $CaCl_2$

Chemical Formulas; Molecular and Ionic Substances

- **Ionic substances**
  - When an atom picks up extra electrons, it becomes a negatively charged ion, called an **anion**.
  - An atom that loses electrons becomes a positively charged ion, called a **cation**.
  - An **ionic compound** is a compound composed of cations and anions held together by ionic bonds.

Figure 2.19: Sodium metal reacts with chlorine gas to form solid sodium chloride.

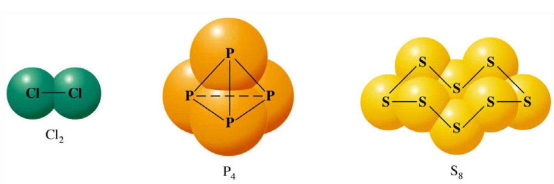


$2Na\ (s) + Cl_2\ (g) \rightarrow 2\ NaCl\ (s)$

Chemical Bonds

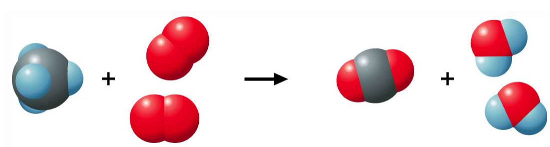
- The forces that hold atoms together in compounds. Covalent bonds result from atoms sharing electrons.
- Molecule: a collection of covalently-bonded atoms.

Figure 2.17: Molecular models of some elementary substances.



An *elemental substance* is composed of molecules containing atoms from only one element.

Figure 2.25: Representation of the reaction of methane with oxygen.

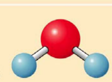
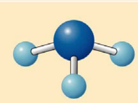
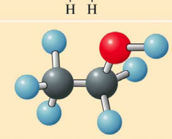
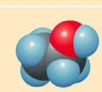


$$CH_4\ (g) + 2\ O_2\ (g) \rightarrow CO_2\ (g) + 2\ H_2O\ (g)$$

Chemical Formulas; Molecular and Ionic Substances

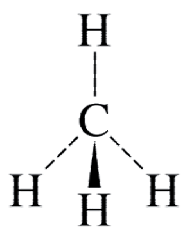
- **Molecular substances** (see Figure 2.16)
  - A **molecule** is a definite group of atoms that are chemically bonded together – that is, tightly connected by attractive forces.
  - A **molecular substance** is a substance that is composed of molecules, all of which are alike.
  - A **molecular formula** gives the exact number of atoms of elements in a molecule.
  - **Structural formulas** show how the atoms are bonded to one another in a molecule.

Figure 2.16: Molecular and structural formulas and molecular models.

	Water	Ammonia	Ethanol
Molecular formula	H_2O	NH_3	C_2H_6O
Structural formula	H–O–H	H–N(–H)–H	CH_3–CH_2–O–H (H–C(H)(H)–C(H)(H)–O–H)
Molecular model (ball-and-stick type)			
Molecular model (space-filling type)			

Return to Slide 26

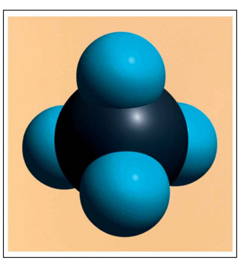
Figure 2.16: The structural formula for methane.



Methane

Figure 2.18: Ball-and-stick model of methane.

Figure 2.17: Space-filling model of methane. This type of model shows both the relative sizes of the atoms in the molecule and their spatial relationships.



Chemical Formulas; Molecular and Ionic Substances

- The **chemical formula** of a substance is a notation using atomic symbols with subscripts to convey the relative proportions of atoms of the different elements in a substance.
  - Consider the formula of aluminum oxide, Al_2O_3. This formula implies that the compound is composed of aluminum atoms and oxygen atoms in the ratio 2:3.

Chemical Substances; Formulas and Names

- **Ionic compounds (Type I binary compounds**
  - Most ionic compounds ***contain metal and nonmetal atoms***; for example, NaCl.
  - You **name an ionic compound** by giving the name of the cation followed by the name of the anion.
  - A **monatomic ion** is an ion formed from a single atom.

Naming Compounds

Binary Ionic Compounds:

1. Cation first, then anion
2. Monatomic cation = name of the element

   Ca^{2+} = calcium ion
3. Monatomic anion = root + -ide

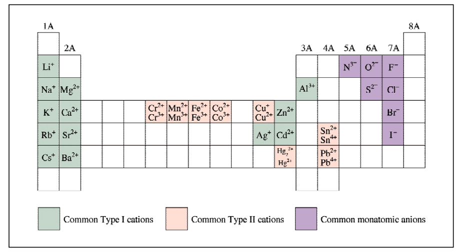
   Cl^- = chloride

   $CaCl_2$ = calcium chloride

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		
Ag^+	Silver		

Figure 2.22: The common cations and anions



Naming Compounds
(continued)

Binary Ionic Compounds (Type II):

- metal forms more than one cation (transition metals)
- use Roman numeral in name

$PbCl_2$

Pb^{2+} is the cation

$PbCl_2$ = lead (II) chloride

TABLE 2.4 Common Type II Cations

Ion	Systematic Name
Fe^{3+}	Iron(III)
Fe^{2+}	Iron(II)
Cu^{2+}	Copper(II)
Cu^+	Copper(I)
Co^{3+}	Cobalt(III)
Co^{2+}	Cobalt(II)
Sn^{4+}	Tin(IV)
Sn^{2+}	Tin(II)
Pb^{4+}	Lead(IV)
Pb^{2+}	Lead(II)
Hg^{2+}	Mercury(II)
Hg_2^{2+}*	Mercury(I)
Ag^+	Silver†
Zn^{2+}	Zinc†
Cd^{2+}	Cadmium†

*Note that mercury(I) ions always occur bound together to form Hg_2^{2+} ions.
†Although these are transition metals, they form only one type of ion, and a Roman numeral is not used.

Crystals of copper(II) sulfate.

Various chromium compounds dissolved in water. From left to right; $CrCl_2$, $K_2Cr_2O_7$, $Cr(NO_3)_3$, $CrCl_3$, K_2CrO_4.

Chemical Substances; Formulas and Names

- **Polyatomic ions**
  - A **polyatomic ion** is an ion consisting of two or more atoms chemically bonded together and carrying a net electric charge.
  - Table 2.6 lists some common polyatomic ions. Here a few examples.

NO_3^- nitrate SO_4^{2-} sulfate

NO_2^- nitrite SO_3^{2-} sulfite

Figure 2.20: Ball-and-stick models of the ammonium ion and the nitrate ion.

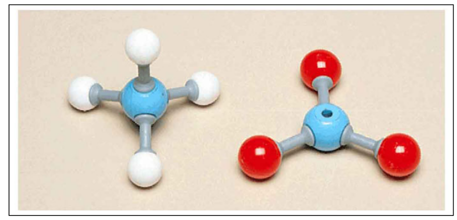


TABLE 2.5 Common Polyatomic Ions

Ion	Name	Ion	Name
Hg_2^{2+}	Mercury(I)	NCS^-	Thiocyanate
NH_4^+	Ammonium	CO_3^{2-}	Carbonate
NO_2^-	Nitrite	HCO_3^-	Hydrogen carbonate
NO_3^-	Nitrate		(bicarbonate is a widely
SO_3^{2-}	Sulfite		used common name)
SO_4^{2-}	Sulfate	ClO^-	Hypochlorite
HSO_4^-	Hydrogen sulfate	ClO_2^-	Chlorite
	(bisulfate is a widely	ClO_3^-	Chlorate
	used common name)	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

Polyatomic Ions You Should Know

- NH_4^+ - Ammonium
- OH^- - Hydroxide
- CN^- - Cyanide
- SO_4^{2-} - Sulfate
- HSO_4^- - bisulfate
- ClO_4^- - Perchlorate
- NO_3^- - Nitrate
- NO_2^- - Nitrite
- O_2^{2-} - Peroxide
- PO_4^{3-} - Phosphate
- HPO_4^{2-} - monohydro-gen phosphate
- $H_2PO_4^-$ - dihydrogen phosphate
- CO_3^{2-} - Carbonate
- HCO_3^- - Bicarbonate

More Practice

- Na_2SO_4 Sodium Sulfate — Na_2SO_3 Sodium Sulfite
- AgCN Silver Cyanide — $Cd(OH)_2$ Cadmium Hydroxide
- $Ca(OCl)_2$ Calcium Hypochlorite — $KClO_4$ Potassium Perchlorate

Naming Compounds
(continued)

Binary molecular compounds (Type III):

- Compounds between two nonmetals
- First element in the formula is named first.
- Second element is named as if it were an anion.
- Use prefixes
- Never use mono- for the first element in formula

P_2O_5 = diphosphorus pentoxide

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

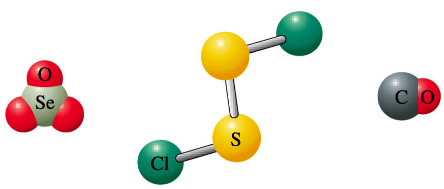
For binary molecular compounds, use the following to determine the order of the nonmetal or metalloid elements in the formula:

Element: B Si,C Sb,As,P,N H Te,Se,S I,Br,Cl O F
Group IIIA IVA VA VIA VIIA

H-P-H is written PH_3
H

Practice

2.79 Write the systematic name for each of the following compounds represented by a molecular model.



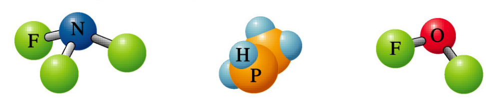
(a) Selenium trioxide, SeO_3

(b) disulfur dichloride S_2Cl_2

(c) carbon monoxide CO

Practice

2.80 Write the systematic name for each of the following molecules represented by a molecular model.



(a) Nitrogen trifluoride NF_3

(b) diphosphorous tetrahydride P_2H_4

(c) oxygen difluoride OF_2

Figure 2.23: A flowchart for naming binary compounds.

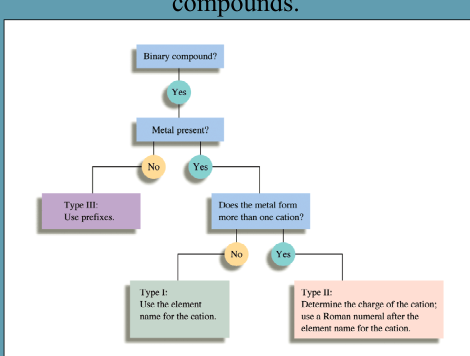
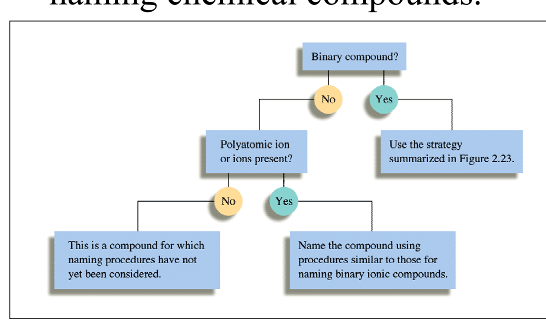


Figure 2.24: Overall strategy for naming chemical compounds.



Chemical Substances; Formulas and Names

- **Acids**
  - **Acids** are traditionally defined as compounds with a potential H^+ as the cation.
  - **Binary acids** consist of a hydrogen ion and any single anion. For example, HCl is hydrochloric acid.
  - An **oxoacid** is an acid containing hydrogen, oxygen, and another element. An example is HNO_3, nitric acid. (see Figure 2.23)

TABLE 2.7 Names of Acids* That Do Not Contain Oxygen

Acid	Name
HF	Hydrofluoric acid
HCl	Hydrochloric acid
HBr	Hydrobromic acid
HI	Hydroiodic acid
HCN	Hydrocyanic acid
H_2S	Hydrosulfuric acid

*Note that these acids are aqueous solutions containing these substances.

TABLE 2.8 Names of Some Oxygen-Containing Acids

Acid	Name
HNO_3	Nitric acid
HNO_2	Nitrous acid
H_2SO_4	Sulfuric acid
H_2SO_3	Sulfurous acid
H_3PO_4	Phosphoric acid
$HC_2H_3O_2$	Acetic acid

Figure 2.25: A flowchart for naming acids. An acid is best considered as one or more H+ ions attached to an anion.

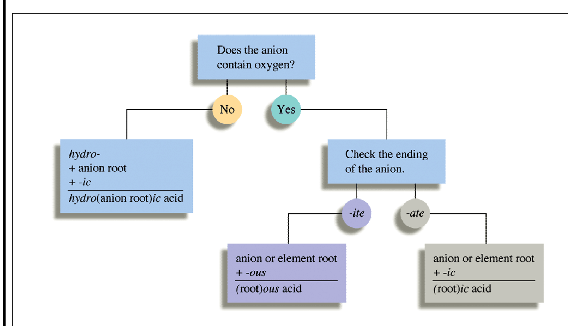


Figure 2.23: Molecular model of nitric acid.

HNO_3