Chemistry

Zumdahl, 7th edition

歐亞書局

CH2 Atoms, Molecules, and Ions

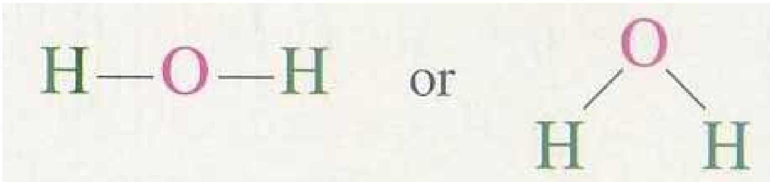
A worker in Thailand piles up salt crystals..

Contents

2.6 Molecules and Ions

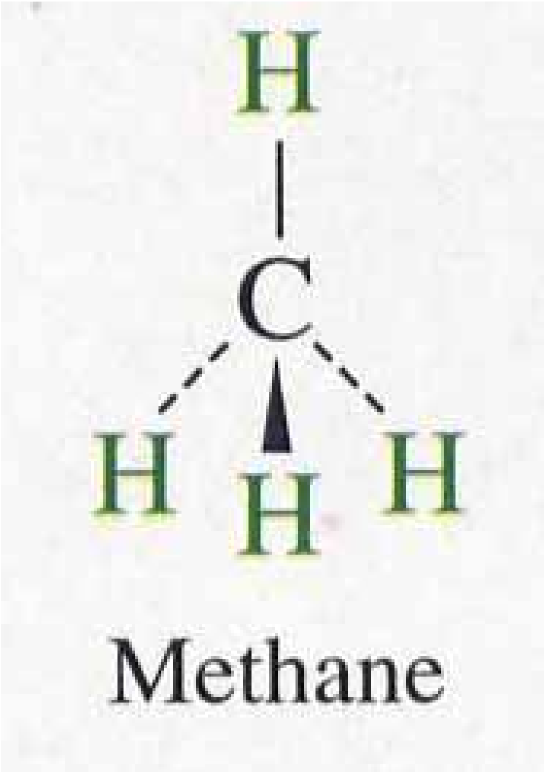
- The forces that hold atoms together in compounds are called **chemical bonds**. One way that atoms can form bonds is by sharing electrons.
- These bonds are called **covalent bonds**, and the resulting collection of atoms is called a **molecule**.
- Molecules can be represented in several different ways. The simplest method is the **chemical formula**, in which the symbols for the elements are used to indicate the types of atoms present and subscripts are used to indicate the relative numbers of atoms.

- More information bout a molecule is given by its **structural formula**, in which the individual bonds are shown (indicated by lines).
- Structural formulas may or may not indicate the actual shape of the molecule.



- Note that atoms connected to the central atom by dashed lines are behind the plane of the paper, and atoms connected to the central atom by wedges are in front of the plane of the paper.
- A molecule of methane gas can be represented in several ways. The structural formula for methane (CH_4) is shown if Fig. 2.16.

Figure 2.16



The structural formula for methane.

- The **space-filling model** of methane, which shows the relative sizes of the atoms as well as their relative orientation in the molecule, is given in Fig. 2.17.
- **Ball-and-stick models** are also used to represent molecules. The ball-and-stick structure of methane is shown in Fig. 2.18.
- A second type of chemical bond results from attractions among ions. An **ion** is an atom or group of atoms that has a net positive or negative charge.

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.

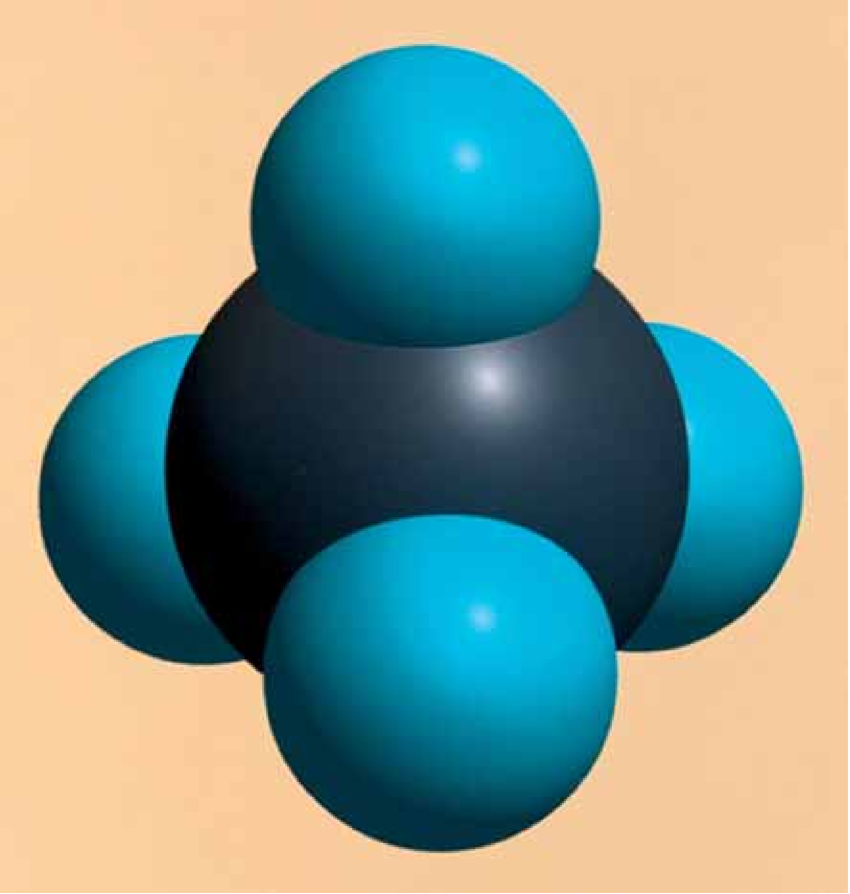


Figure 2.18

Ball-and-stick model of methane.

- An electron is transferred from a sodium atom to a chlorine atom.
- With one electron stripped off, the sodium, with its 11 protons and only 10 electrons, now has a net 1+ charge—it has become a *positive ion*.
- A positive ion is called a **cation**.
- The sodium ion is written as Na^+, and the process can be represented in shorthand form as

$$Na \longrightarrow Na^+ + e^-$$

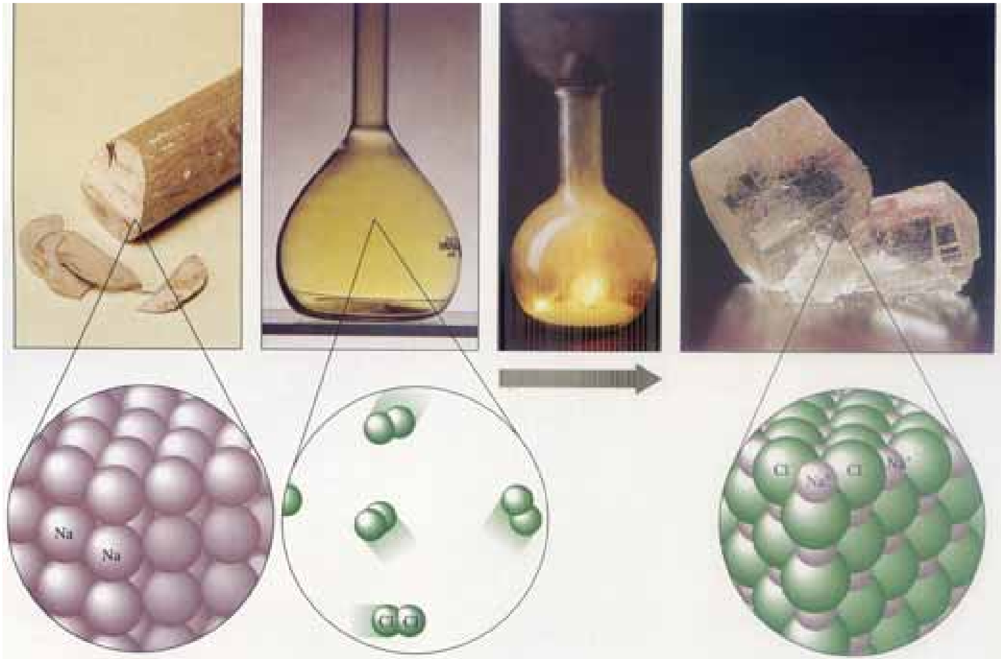
- the 18 electrons produce a net 1− charge; the chlorine has become an ion with a negative charge—an anion. The chloride ion is written as Cl^-, and the process is represented as

$$Cl + e^- \longrightarrow Cl^-$$

- Because anions and cations have opposite charges, they attract each other. This force of attraction between oppositely charged ions is called **ionic bonding**.

- As illustrated in Fig. 2.19, sodium metal and chlorine gas (a green gas composed of Cl_2 molecules) react to form solid sodium chloride, which contains many Na^+ and Cl^- ions packed together and forms the beautiful colorless cubic crystals shown in Fig. 2.19.
- A solid consisting of oppositely charged ions is called an **ionic solid**, or a **salt**.

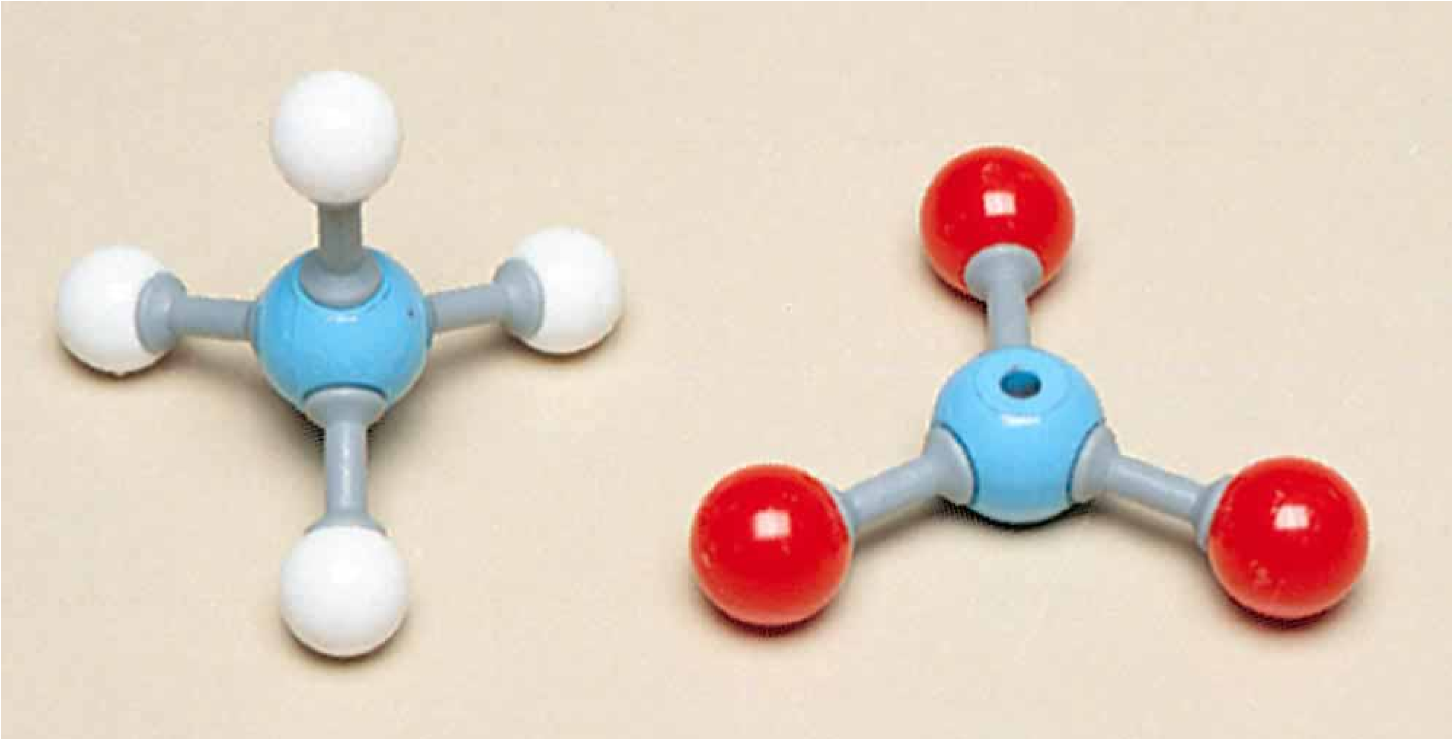
Figure 2.19



Sodium metal (which is so soft it can be cut with a knife and which consists of individual sodium atoms) reacts with chlorine gas (which contains Cl_2 molecules) to form solid sodium chloride (which contains Na^+ and Cl^- ions packed together).

- A solid consisting of oppositely charged ions is called an **ionic solid**, or a **salt**.
- Ionic solids can consist of simple ions, as in sodium chloride, or of polyatomic (many atom) ions, as in ammonium nitrate (NH_4NO_3), which contains ammonium ions (NH_4^+) and nitrate ions (NO_3^-).
- The ball-and-stick models of these ions are shown in Fig 2.20.

Figure 2.20

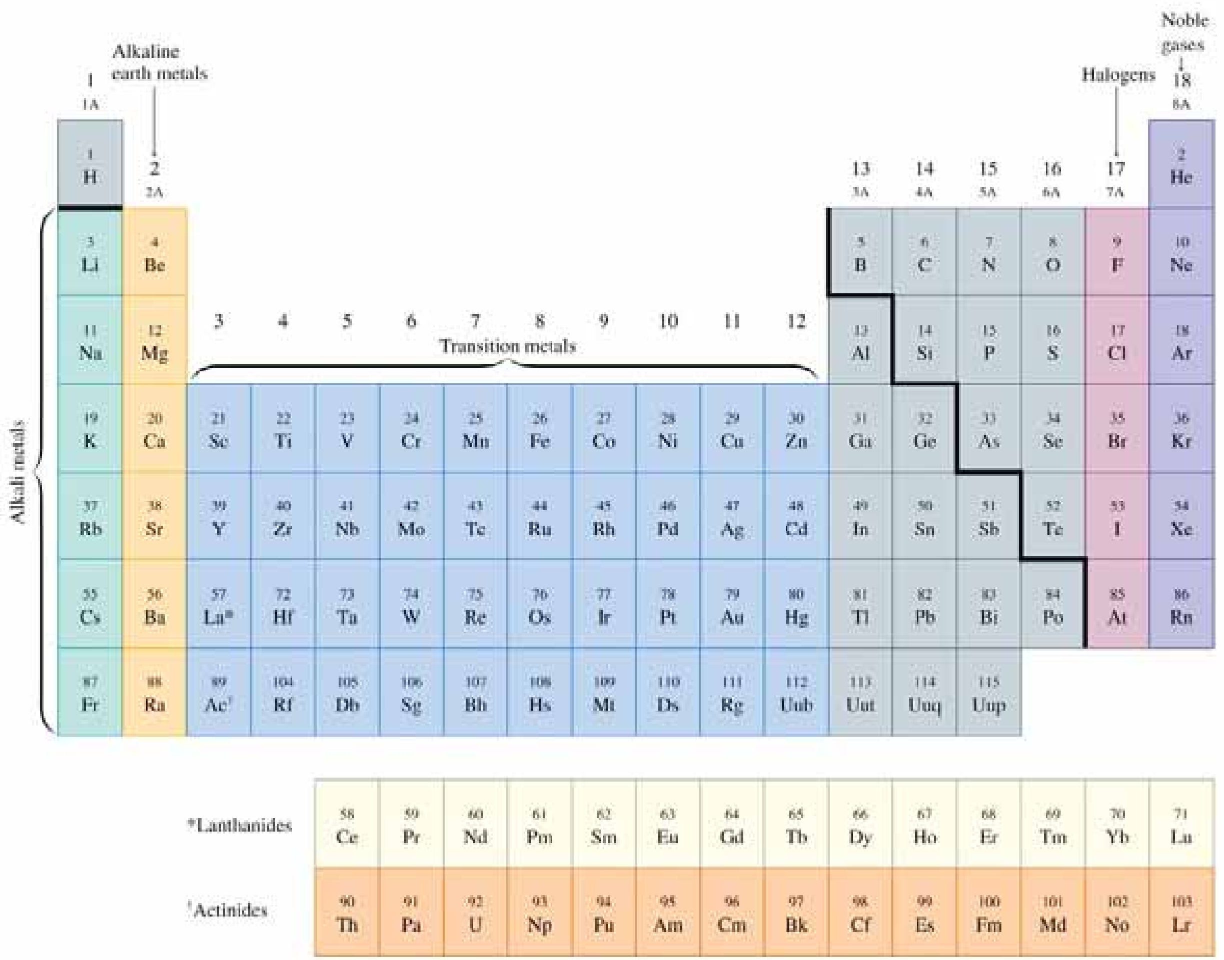


Ball-and-stick models of the ammonium ion (NH_4^+) and the nitrate ion (NO_3^-).

2.7 An Introduction to the Periodic Table

- A simplified version of the periodic table is shown in Fig. 2.21.
- The letters in the boxes are the symbols for the elements; these abbreviations are based on the current element names or the original names (see Table 2.2).
- The number shown above each symbol is the atomic number (number of protons) for that element.
- Most of the elements are **metals**.

Figure 2.21



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

- The relatively few **nonmetals** appear in the upper-right corner of the table (to the right of the heavy line in Fig. 2.21), except hydrogen, a nonmetal that resides in the upper-lift corner.
- The periodic table is arranged so that elements in the same vertical columns (called groups of families) have *similar chemical properties*.
- **Alkali metals**, members of Group 1 A-p-lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr).

- **alkaline earth metals** : the members of Group 2A—beryllium (Be), magnesium (Mg), calcium (Ca), strontium (Sr), barium (Ba), and radium (Ra).
- Note from Fig. 2.21 that alternate sets of symbols are used to denote the groups.
- The horizontal rows of elements in the periodic table are called **periods**.
- Horizontal row 1 is called the first period (it contains H and He); row 2 is called the *second period* (elements Li through Ne); and so on.

2.8 Naming Simple Compounds

- When chemistry was an infant science, there was no system for naming compounds.
- We will begin with the systems for naming inorganic **binary compounds** — compounds composed of two elements—which we classify into various types for easier recognition.

Binary Ionic Compounds (Type 1)

- **Binary ionic compounds** contain a positive ion (cation) always written first in the formula and a negative ion (anion).

1. The cation is always named first and the anion second.
2. A monatomic (meaning “one-atom”) cation takes its name from the name of the element. For example, Na^+ is called sodium in the names of compounds containing this ion.

3. A monatomic anion is named by taking the root of the element name and adding –*ide*. Thus the Cl^- ion is called chloride. (element name chlorine)

- Some common monatomic cations and anions and their names are given in Table 2.3.

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		

The rules for naming binary ionic compounds are illustrated by the following examples:

Compound	Ions Present	Name
$NaCl$	Na^+, Cl^-	Sodium chloride
KI	K^+, I^-	Potassium iodide
CaS	Ca^{2+}, S^{2-}	Calcium sulfide
Li_3N	Li^+, N^{3-}	Lithium nitride
$CsBr$	Cs^+, Br^-	Cesium bromide
MgO	Mg^{2+}, O^{2-}	Magnesium oxide

Sample Exercise 2.3

Naming Type 1 Binary Compounds

Name each binary compound.

a. CsF **b.** AlCl3 **c.** LiH

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.

See Exercises 2.55

Formulas from Names

- Given the name calcium hydroxide, we can write the formula as $Ca(OH)_2$ because we know hat calcium forms only Ca^{2+} ions and that, since hydroxide is OH^-, two of these anions will be required to give a neutral compound.

Binary Ionic Compounds (Type Ⅱ)

- Another system for naming these ionic compounds that is seen in the older literature was used for metals that form only two ions.
- *The ion with the higher charge has a name ending in-ic, and the one with the lower charge has a name ending in-ous.*
- In this system, Fe^{3+} is called the ferric ion, and Fe^{2+} is called the ferrous ion.

- The names for $FeCl_3$ and $FeCl_2$ are then ferric chloride and ferrous chloride, respectively.
- Table 2.4 lists the systematic names for many common type Ⅱ cations.

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.

Sample Exercise 2.4

Formulas from Names for Type 1 Binary Compounds

Given the following systematic names, write the formula for each compound:

a. potassium iodide

b. calcium oxide

c. gallium bromide

Solution

Name	Formula	Comments
a. potassium iodide	KI	Contains K^+ and I^-.
b. calcium oxide	CaO	Contains Ca^{2+} and O^{2-}.
c. gallium bromide	$GaBr_3$	Contains Ga^{3+} and Br^-. Must have $3Br^-$ to balance charge of Ga^{3+}.

See Exercises 2.55

Sample Exercise 2.5

Naming Type Ⅱ Binary Compounds

1. Give he systematic name for each of the following compounds:

   a. CuCl **b.** HgO **c.** Fe_2O_3

2. Given the following systematic names, write the formula for each compund:

   a. Manganese(Ⅳ) oxide

   b. Lead(Ⅱ)chloride

Sample Exercise 2.5

Solution

1.

Formula	Name	Comments
a. CuCl	Copper(I) chloride	Because the anion is Cl^-, the cation must be Cu^+ (for charge balance), which requires a Roman numeral I.
b. HgO	Mercury(II) oxide	Because the anion is O^{2-}, the cation must be Hg^{2+} [mercury(II)].
c. Fe_2O_3	Iron(III) oxide	The three O^{2-} ions carry a total charge of 6−, so two Fe^{3+} ions [iron(III)] are needed to give a 6+ charge.

2.

Name	Formula	Comments
a. Manganese(IV) oxide	MnO_2	Two O^{2-} ions (total charge 4−) are required by the Mn^{4+} ion [manganese(IV)].
b. Lead(II) chloride	$PbCl_2$	Two Cl^- ions are required by the Pb^{2+} ion [lead(II)] for charge balance.

See Exercises 2.56

- Note that the use of a Roman numeral in a systematic name is required only in cases where more than one ionic compound forms between a given pair of elements.
- This case most commonly occurs for compounds containing transition metals, which often form more than one cation.
- *Elements that form only one cation do not need to be identified by a Roman numeral.*

- Common metals that do not require Roman numerals are the Group 1A elements, which form only 1＋ ions; the Group 2A elements, which form only 2＋ ions: and aluminum, which forms only Al^{3+}.

Sample Exercise 2.6 Naming binary Compounds

1. Give the systematic name for each of the following compounds:

   a. $CoBr_2$ **b.** $CaCl_2$ **c.** Al_2O_3

2. Given the following systematic names, write the formula for each compound:

   a. Chromium(III) chloride

   b. Gallium iodide

Sample Exercise 2.6

Solution

1.

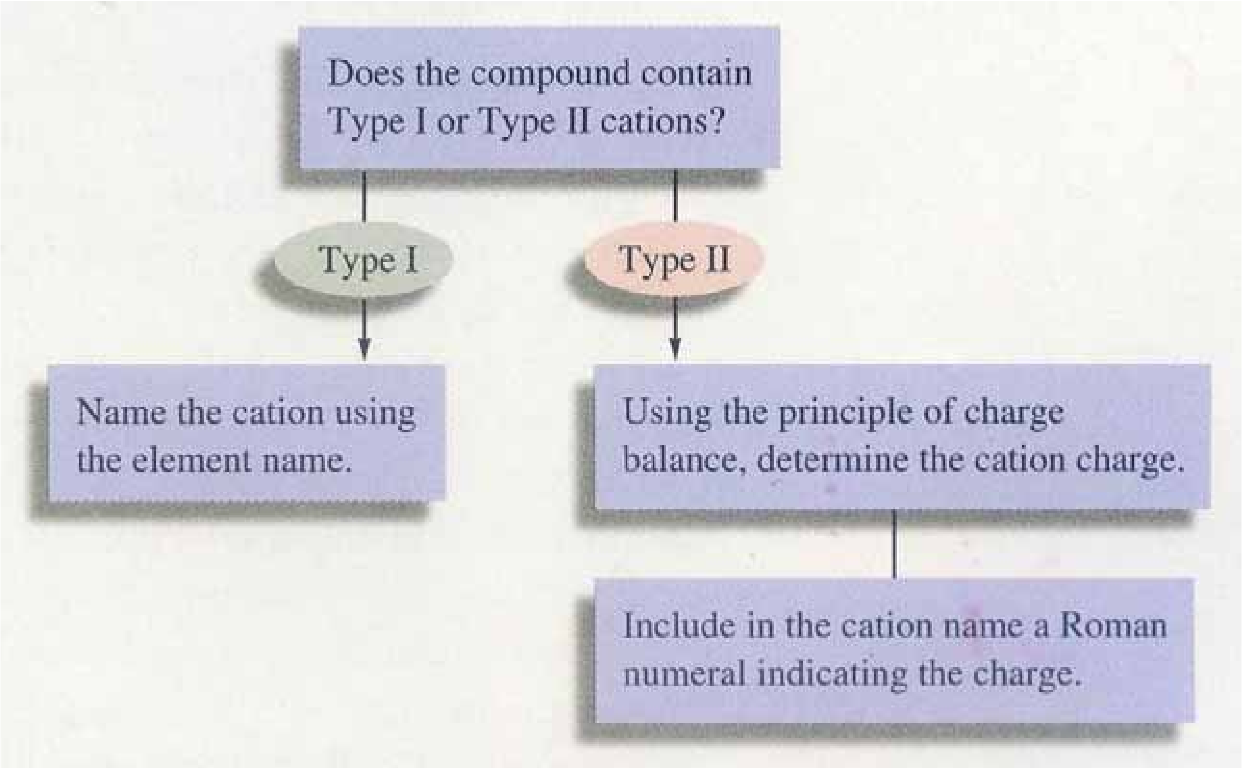
Formula	Name	Comments
a. $CoBr_2$	Cobalt(II) bromide	Cobalt is a transition metal; the compound name must have a Roman numeral. The two Br^- ions must be balanced by a Co^{2+} ion.
b. $CaCl_2$	Calcium chloride	Calcium, an alkaline earth metal, forms only the Ca^{2+} ion. A Roman numeral is not necessary.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

2.

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

See Exercises 2.57 and 2.58

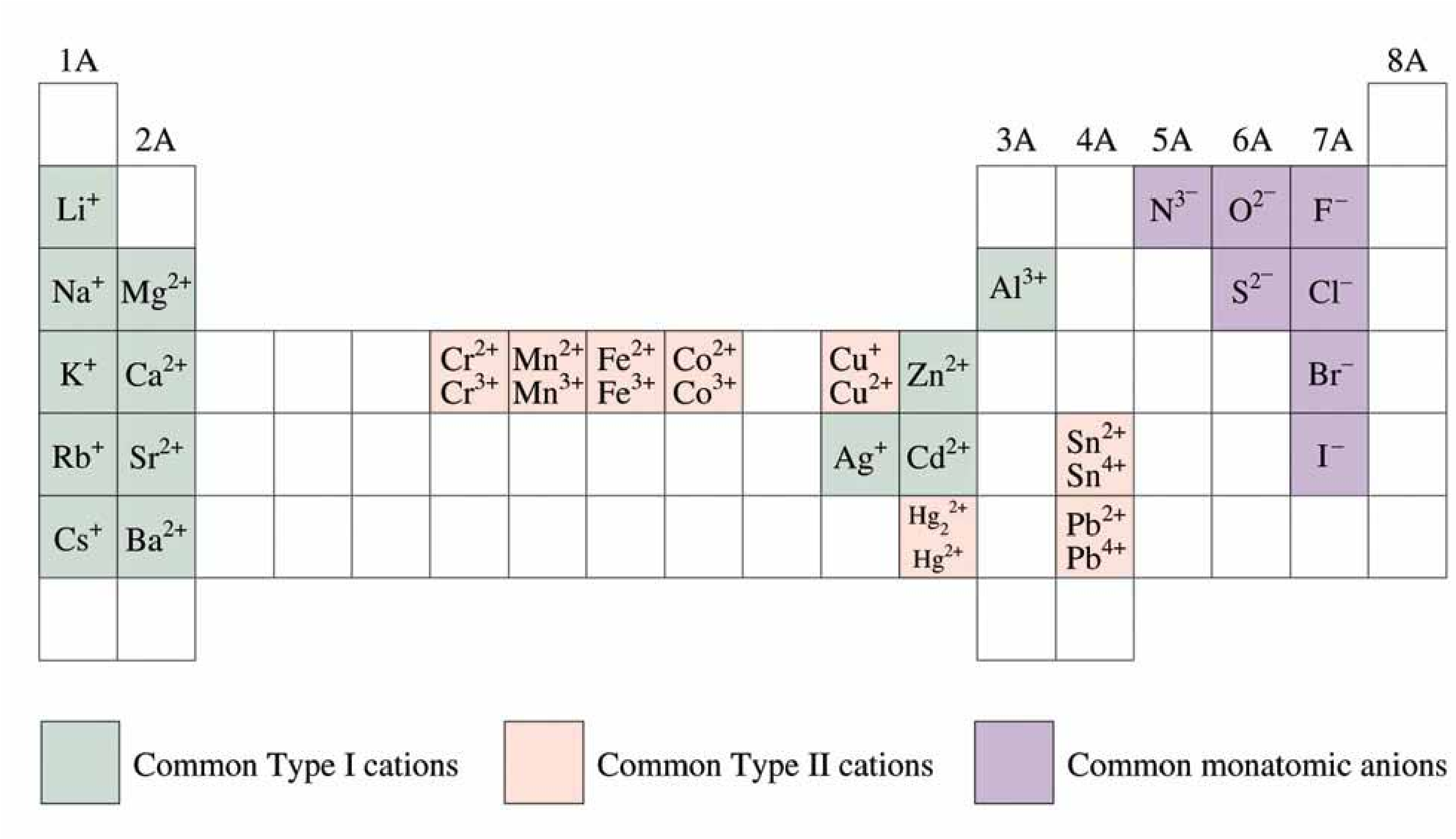
The following flowchart is useful when you are naming binary ionic compounds:



- The common Type I and Type II ions are summarized in Fig. 2.22.
- Also shown in Fig. 2.22 are the common monatomic ions.

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.

Figure 2.22



The common cations and anions.

Ionic Compounds with Polyatomic Ions

- The most important polyatomic ions and their names are listed in Table 2.5.
- Note in Table 2.5 that several series of anions contain an atom of a given element and different numbers of oxygen atoms.
- These anions are called **oxyanions**.

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 (bicarbonate is a widely used common name)
NO_3^-	Nitrate		
SO_3^{2-}	Sulfite		
SO_4^{2-}	Sulfate	ClO^-	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

Sample Exercise 2.7 Naming Compounds containing Polyatomic Ions

1. Give the systematic name for each of the following compounds:

   a. Na_2SO_4 **b.** KH_2PO_4 **c.** $Fe(NO_3)_3$

   d. $Mn(OH)_2$ **e.** Na_2SO_3 **f.** Na_2CO_3

2. Given the following systematic names, write the formula for each compound:

   a. Sodium hydrogen carbonate **b.** Cesium perchlorate

   c. Sodium hypochlorite **d.** Sodium selenate

   e. Potassium bromate

Sample Exercise 2.7

Solution

1.

Formula	Name	Comments
a. Na_2SO_4	Sodium sulfate	
b. KH_2PO_4	Potassium dihydrogen phosphate	
c. $Fe(NO_3)_3$	Iron(III) nitrate	Transition metal—name must contain a Roman numeral. The Fe^{3+} ion balances three NO_3^- ions.
d. $Mn(OH)_2$	Manganese(II) hydroxide	Transition metal—name must contain a Roman numeral. The Mn^{2+} ion balances three OH^- ions.
e. Na_2SO_3	Sodium sulfite	
f. Na_2CO_3	Sodium carbonate	

Sample Exercise 2.7

2.

Name	Formula	Comments
a. Sodium hydrogen carbonate	$NaHCO_3$	Often called sodium bicarbonate.
b. Cesium perchlorate	$CsClO_4$	
c. Sodium hypochlorite	$NaOCl$	
d. 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).
e. Potassium bromate	$KBrO_3$	As above, BrO_3^- is bromate, like ClO_3^- (chlorate).

See Exercises 2.59 and 2.60

Binary Covalent Compounds (Type III)

- **Binary covalent compounds** are formed between two nonmetals.
- In the naming of binary covalent compounds, the following rules apply:

1. The first element in the formula is named first, using the full element name.
2. The second element is named as if it were an anion.
3. Prefixes are used to denote the numbers of atoms present. These prefixes are given in Table 2.6.

4. The prefix mono- is never used for naming the first element. For example, CO is called carbon monoxide, not monocarbon monoxide.

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

To see how these rules apply, we will now consider the names of the several covalent compounds formed by nitrogen and oxygen:

Compound	Systematic Name	Common Name
N_2O	Dinitrogen monoxide	Nitrous oxide
NO	Nitrogen monoxide	Nitric oxide
NO_2	Nitrogen dioxide	
N_2O_3	Dinitrogen trioxide	
N_2O_4	Dinitrogen tetroxide	
N_2O_5	Dinitrogen pentoxide	

- Notice from the preceding examples that to avoid awkward pronunciations, we often drop the final *o* or *a* of the prefix when the element begins with a vowel.

tetr~~a~~oxide → tetroxide

pent~~a~~oxide → pentoxide

Sample Exercise 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
   c. Carbon dioxide

Sample Exercise 2.8

Solution

1.

Formula	**Name**
a. PCl_5	Phosphorus pentachloride
b. PCl_3	Phosphorus trichloride
c. SO_2	Sulfur dioxide

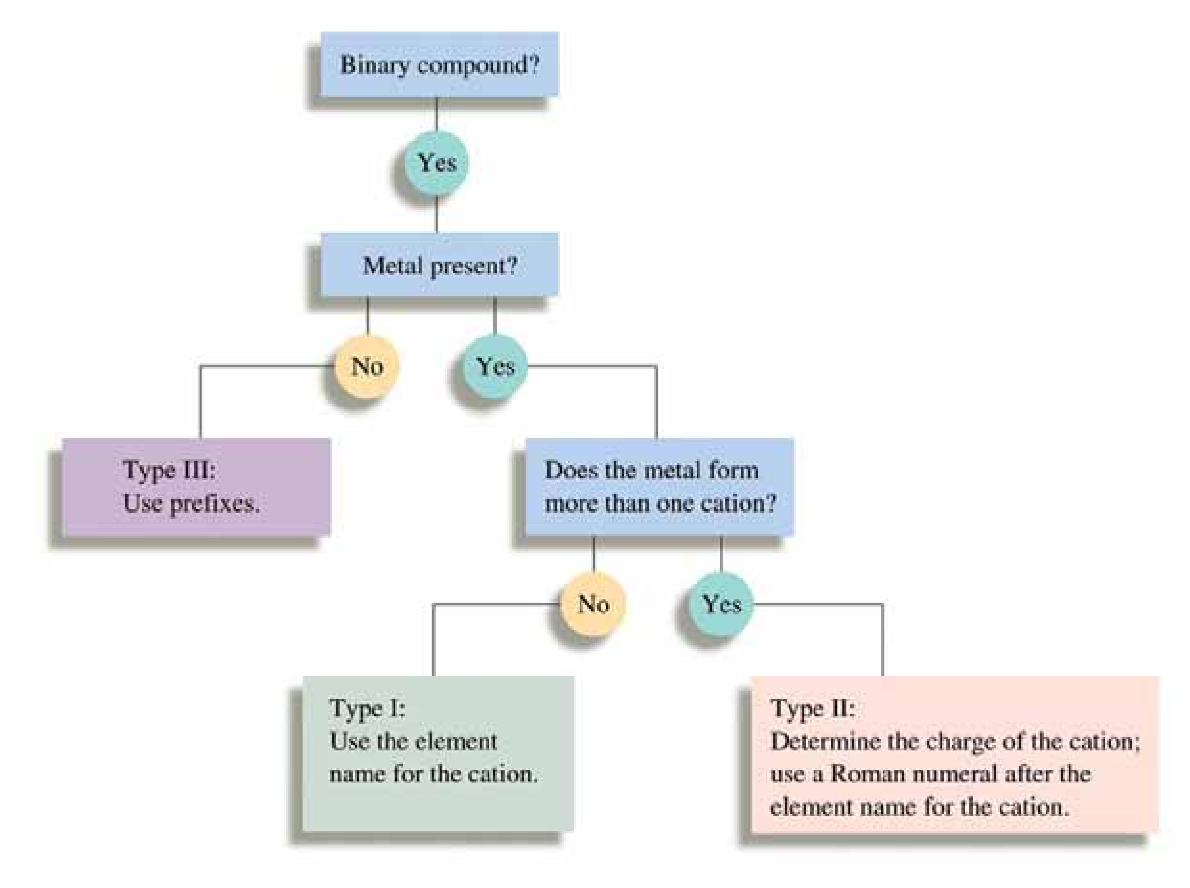
2.

Name	**Formula**
a. Sulfur hexafluoride	SF_6
b. Sulfur trioxide	SO_3
c. Carbon dioxide	CO_2

See Exercises 2.61 and 2.62

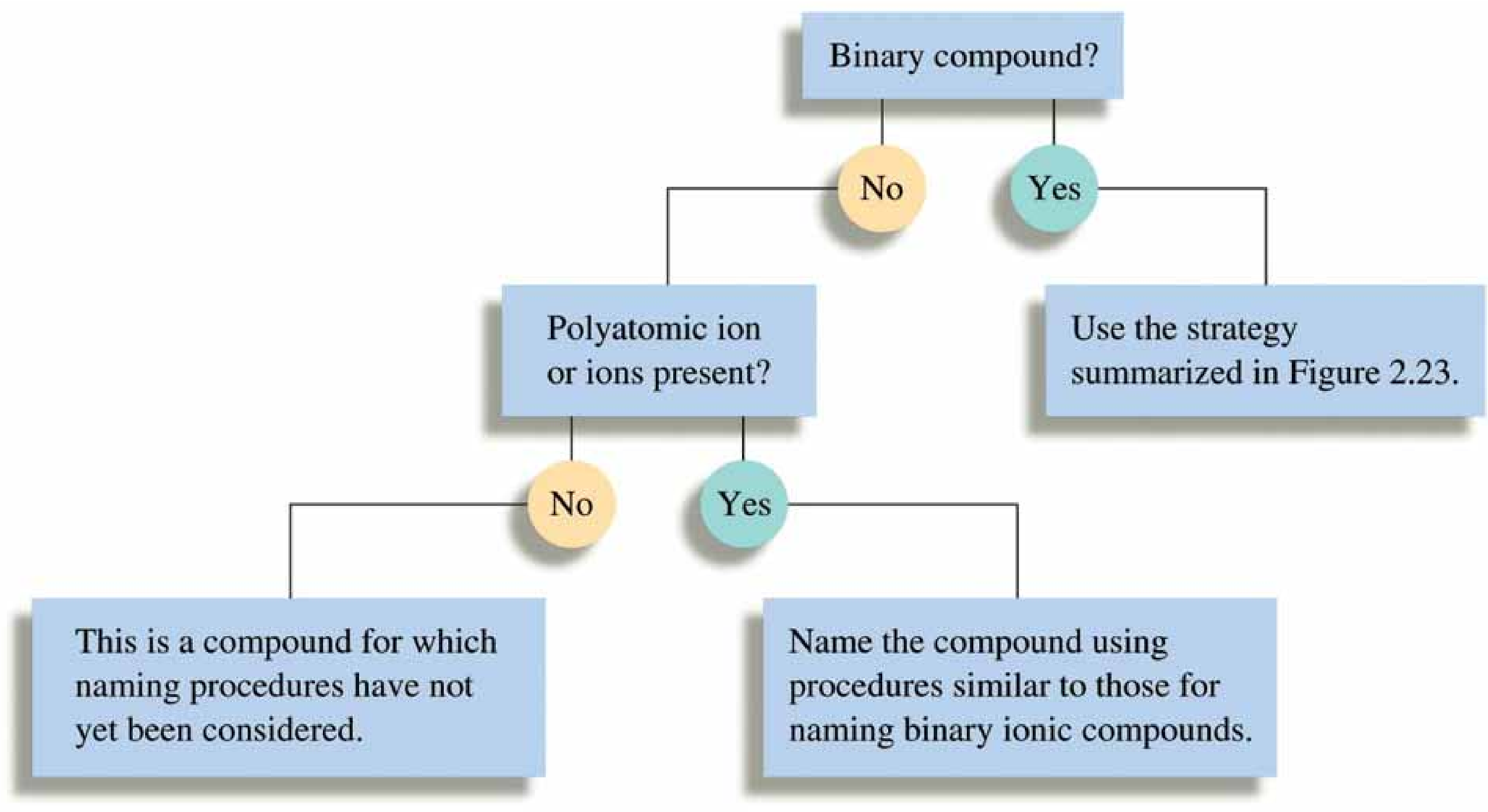
- The rules for naming binary compounds are summarized in Fig. 2.23.
- Prefixes to indicate the number of atoms are used only in Type III binary compounds (those containing two nonmetals).
- An overall strategy for naming compounds is given in Fig. 2.24.

Figure 2.23



A flowchart for naming binary compounds.

Figure 2.24



Overall strategy for naming chemical compounds.

Acids

- When dissolved in water, certain molecules produce a solution containing free H^+ ions (protons).
- Theses substances, **acids**, will be discussed in detail in Chapters 4. 14. and 15. Here we will simple present the rules for naming acids.
- When the *anion contains oxygen*, the acidic name is formed from the root name of the anion with a suffix of –ic or –ous, depending on the name of the anion.

1. If the anion name ends in –ate, the suffix –ic is added to the root name. For example, H_2SO_4 contains the sulfate anion (SO_4^{2-}) and is called sulfuric acid: H_3PO_4 contains the phosphate anion (PO_4^{3-}) and is called phosphoric acid: and $HC_2H_3O_2$ contains the acetate ion ($C_2H_3O_2^{-}$) and is called acetic acid.

2. If the anion has an –ite ending, the –ite is replaced by –ous. For example, H_2SO_3, which contains sulfite (SO_3^{2-}), is named sulfurous acid: and HNO_2, which contains nitrite (NO_2^{-}), is named nitrous acid.

- The application of these rules can be seen in the names of the acids of the oxyanions of chlorine:

Acid	Anion	Name
$HClO_4$	Perchlor*ate*	Perchlor*ic* acid
$HClO_3$	Chlor*ate*	Chlor*ic* acid
$HClO_2$	Chlor*ite*	Chlor*ous* acid
$HClO$	Hypochlor*ite*	Hypochlor*ous* acid

- The names of the most important acids are given in Tables 2.7 and 2.8. An overall strategy for naming acids is shown in Fig. 2.25.

TABLE 2.7 Names of Acids That Do Not Contain Oxygen

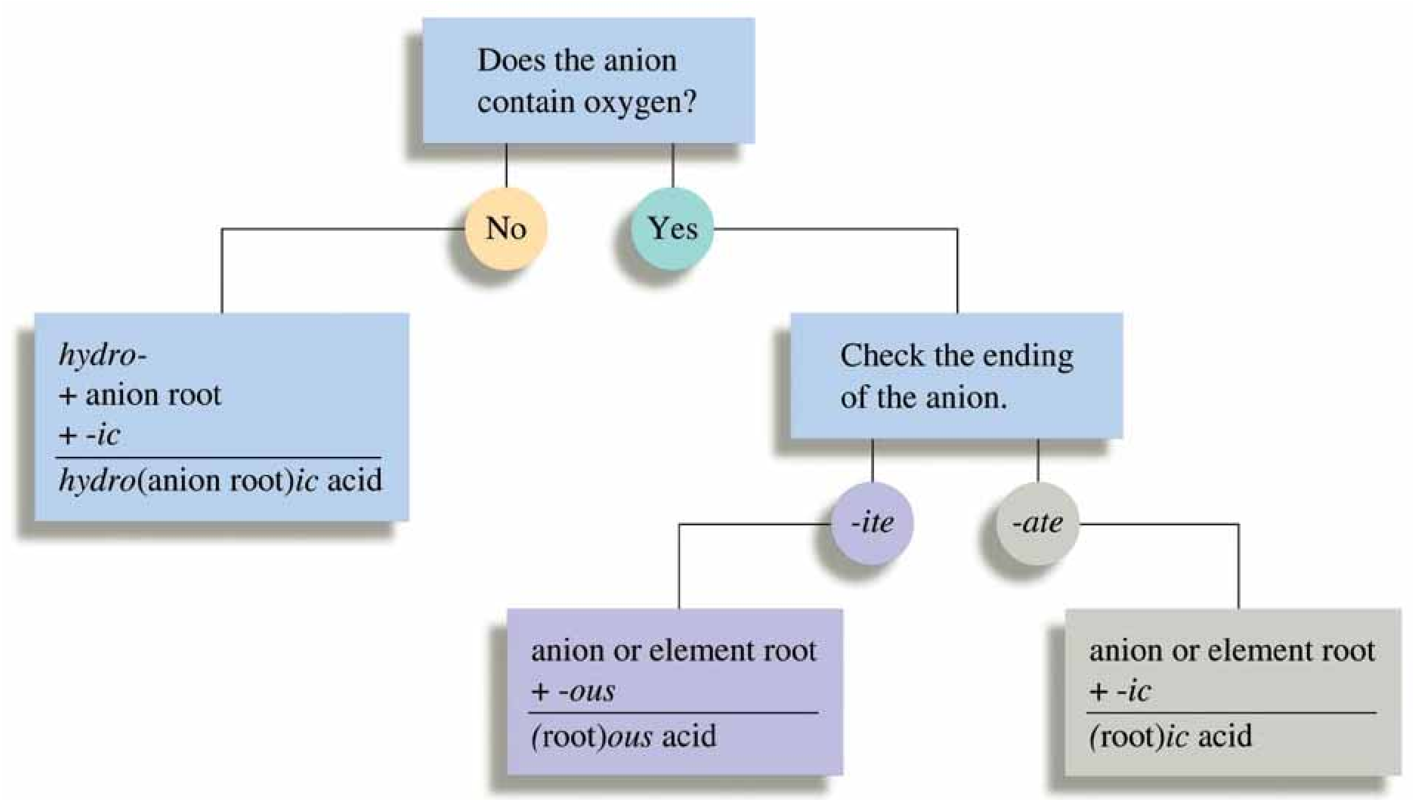
Acid	Name
HF	Hydrofluoric acid
HCl	Hydrochloric acid
HBr	Hydrobromic acid
HI	Hydroiodic acid
HCN	Hydrocyanic acid
H_2S	Hydrosulfuric acid

*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.