FORMULAS AND NOMENCLATURE OF IONIC AND COVALENT COMPOUNDS

Adapted from McMurry/Fay, section 2.10, p. 56-63 and the 1411 Lab Manual, p. 27-31.

TYPES OF COMPOUNDS

Ionic compounds are compounds composed of *ions*, charged particles that form when an atom (or group of atoms) gains or loses electrons. (A *cation* is a positively charged ion; an *anion* is a negatively charged ion.) **Covalent** or **molecular compounds** form when elements share electrons in a covalent bond to form *molecules*. Molecular compounds are electrically neutral.

Metal + Nonmetal ⟶ ionic compound (usually)
Metal + Polyatomic ion ⟶ ionic compound (usually)
Nonmetal + Nonmetal ⟶ covalent compound (usually)
Hydrogen + Nonmetal ⟶ covalent compound (usually)

TYPES OF IONS

Main-Group Metals (Groups IA, IIA, and IIIA)

Group IA, IIA, and IIIA metals tend to form *cations* by losing all of their outermost (valence) electrons. *The charge on the cation is the same as the group number*. The cation is given the same name as the neutral metal atom.

Ions of Some Main-Group Metals (Groups IA – IIIA)

Group	Element	Cation	Ion name	Group	Element	Cation	Ion name
IA	H	H^+	hydrogen ion	IIA	Mg	Mg^{2+}	magnesium ion
	Li	Li^+	lithium ion		Ca	Ca^{2+}	calcium ion
	Na	Na^+	sodium ion		Sr	Sr^{2+}	strontium ion
	K	K^+	potassium ion		Ba	Ba^{2+}	barium ion
	Cs	Cs^+	cesium ion	IIIA	Al	Al^{3+}	aluminum ion

Transition (B-group) and Post-Transition (Group IVA and VA) Metals

These elements usually form ionic compounds; many of them can form more than one cation. (The charges of the transition metals must be memorized; Group IV and V metal cations tend to be either the group number, or the group number minus two.)

Many of these ions have common or trivial names (-*ic* endings go with the higher charge, -*ous* endings go with the lower charge). The systematic names (also known as the *Stock system*) for these ions are derived by naming the metal first, followed in parentheses by the charge written in Roman numerals. For the metals below that typically form only one charge, it is not usually necessary to specify the charge in the compound name.

The mercury I cation is a special case; it consists of two Hg^+ ions joined together, and so is always found as Hg_2^{2+}. (Hence, mercury(I) chloride is Hg_2Cl_2, while mercury (II) chloride is $HgCl_2$.)

Ions of Some Transition Metals and Post-Transition Metals (Groups IVA and VA)

Metal	Ion	Systematic name	Common name
Cadmium	Cd^{2+}	cadmium ion	
Chromium	Cr^{2+}	chromium(II) ion	chromous ion
	Cr^{3+}	chromium(III) ion	chromic ion
Cobalt	Co^{2+}	cobalt(II) ion	cobaltous ion
	Co^{3+}	cobalt(III) ion	cobaltic ion
Copper	Cu^{+}	copper(I) ion	cuprous ion
	Cu^{2+}	copper(II) ion	cupric ion
Gold	Au^{3+}	gold(III) ion	
Iron	Fe^{2+}	iron(II) ion	ferrous ion
	Fe^{3+}	iron(III) ion	ferric ion
Manganese	Mn^{2+}	manganese(II) ion	manganous ion
	Mn^{3+}	manganese(III) ion	manganic ion
Mercury	Hg_2^{2+}	mercury(I) ion	mercurous ion
	Hg^{2+}	mercury(II) ion	mercuric ion
Nickel	Ni^{2+}	nickel(II) ion	
Silver	Ag^{+}	silver ion	
Zinc	Zn^{2+}	zinc ion	
Tin	Sn^{2+}	tin(II) ion	stannous ion
	Sn^{4+}	tin(IV) ion	stannic ion
Lead	Pb^{2+}	lead(II) ion	plumbous ion
	Pb^{4+}	lead(IV) ion	plumbic ion
Bismuth	Bi^{3+}	bismuth(III) ion	
	Bi^{5+}	bismuth(V) ion	

Main-Group Nonmetals (Groups IVA, VA, VIA, and VIIA)

Group IVA, VA, VIA, and VIIA nonmetals tend to form *anions* by gaining enough electrons to fill their valence shell with eight electrons. *The charge on the anion is the group number minus eight*. The anion is named by taking the element stem name and adding the ending *-ide*.

Ions of Some Nonmetals (Groups IVA - VIIA)

Group	Element	Anion	Ion name	Group	Element	Anion	Ion name
IVA	C	C^{4-}	carbide ion	VIA	Se	Se^{2-}	selenide ion
	Si	Si^{4-}	silicide ion		Te	Te^{2-}	telluride ion
VA	N	N^{3-}	nitride ion	VIIA	F	F^{-}	fluoride ion
	P	P^{3-}	phosphide ion		Cl	Cl^{-}	chloride ion
	As	As^{3-}	arsenide ion		Br	Br^{-}	bromide ion
VIA	O	O^{2-}	oxide ion		I	I^{-}	iodide ion
	S	S^{2-}	sulfide ion	IA	H	H^{-}	hydride ion

Polyatomic Ions

Polyatomic ions are ions that are composed of two or more atoms that are linked by covalent bonds, but that still have a net deficiency or surplus of electrons, resulting in an overall charge on the group. A metal plus a polyatomic ion yields an ionic compound.

Formulas and Names of Some Polyatomic Ions

NH_4^+	ammonium	CO_3^{2-}	carbonate
H_3O^+	hydronium	HCO_3^-	hydrogen carbonate (bicarbonate)
OH^-	hydroxide	OCN^-	cyanate
CN^-	cyanide	SCN^-	thiocyanate
O_2^{2-}	peroxide	$S_2O_3^{2-}$	thiosulfate
N_3^-	azide	CrO_4^{2-}	chromate
NO_2^-	nitrite	$Cr_2O_7^{2-}$	dichromate
NO_3^-	nitrate	SO_4^{2-}	sulfate
ClO^-	hypochlorite	SO_3^{2-}	sulfite
ClO_2^-	chlorite	HSO_4^-	hydrogen sulfate (bisulfate)
ClO_3^-	chlorate	PO_4^{3-}	phosphate
ClO_4^-	perchlorate	HPO_4^{2-}	monohydrogen phosphate
MnO_4^-	permanganate	$H_2PO_4^-$	dihydrogen phosphate
$C_2H_3O_2^-$	acetate (OAc^-)	HSO_3^-	hydrogen sulfite (bisulfite)
$C_2O_4^{2-}$	oxalate		

There are some regularities in the names of these polyatomic ions.

a. *Thio*- implies replacing an oxygen with a sulfur:

SO_4^{2-} = sulfate $S_2O_3^{2-}$ = thiosulfate
OCN^- = cyanate SCN^- = thiocyanate

b. Replacing the first element with another element from the same group gives a polyatomic ion with the same charge, and a similar name:

Group VIIA		Group VIA		Group VA		Group IVA	
ClO_3^-	chlorate	SO_4^{2-}	sulfate	PO_4^{3-}	phosphate	CO_3^{2-}	carbonate
BrO_3^-	bromate	SeO_4^{2-}	selenate	AsO_4^{3-}	arsenate	SiO_3^{2-}	silicate
IO_3^-	iodate	TeO_4^{2-}	tellurate				

c. Some nonmetals form a series of polyatomic ions with oxygen (all having the same charge): ClO^-, hypochlorite; ClO_2^-, chlorite; ClO_3^-, chlorate; ClO_4^-, perchlorate. The general rule for such series is:

XO_n^{y-}	*stem* + *-ate*	SO_4^{2-}	sulfate
XO_{n-1}^{y-}	*stem* + *-ite*	SO_3^{2-}	sulfite
XO_{n-2}^{y-}	*hypo-* + *stem* + *-ite*	SO_2^{2-}	hyposulfite
XO_{n+1}^{y-}	*per-* + *stem* + *-ate*	SO_5^{2-}	persulfate
X^{y-}	*stem* + *-ide* (the monatomic ion)	S^{2-}	sulfide

Note that in some cases, the *-ate* form has three oxygens, and in some cases four oxygens. (These forms must be memorized.)

Writing Formulas of Ionic Compounds

1. The positive ion is given first, followed by the monatomic or polyatomic anion.
2. The subscripts in the formula must produce an electrically neutral formula unit. (That is, the total positive charge must equal the total negative charge.)
3. The subscripts should be the smallest set of whole numbers possible.
4. If there is only one of a polyatomic ion in the formula, do not place parentheses around it; e.g., $NaNO_3$, not $Na(NO_3)$. If there is more than one of a polyatomic ion in the formula, put the ion in parentheses, and place the subscript after the parentheses; e.g., $Ca(OH)_2$, $Ba_3(PO_4)_2$, etc. [Remember the Prime Directive in writing formulas: $Ca(OH)_2 \neq CaOH_2$!]

Na^+	Cl^-	$NaCl$
Ca^{2+}	Br^-	$CaBr_2$
Na^+	S^{2-}	Na_2S
Mg^{2+}	O^{2-}	MgO
Fe^{3+}	O^{2-}	Fe_2O_3
Na^+	SO_4^{2-}	Na_2SO_4
Mg	NO_3^-	$Mg(NO_3)_2$
NH_4^+	SO_4^{2-}	$(NH_4)_2SO_4$

Nomenclature of Ionic and Covalent Compounds

1. **Binary Ionic Compounds Containing a Metal and a Nonmetal.** A *binary compound* is a compound formed from *two different elements.* There may or may not be more than one of each element. A *diatomic compound* (or diatomic molecule) contains two atoms, which may or may not be the same.

Cl_2	Not binary (only one type of atom), but diatomic (two atoms).
BrCl	Binary and diatomic. (Two atoms, and they're different elements.)
H_2O	Binary, since there are only two types of atoms.
CH_4	Binary, since there are only two types of atoms.
$CHCl_3$	Not binary or diatomic.

Metals combine with nonmetals to give ionic compounds. When naming binary ionic compounds, name the cation first (specifying the charge, if necessary), then the nonmetal anion (element stem + *-ide*). Do NOT use prefixes to indicate how many of each element is present; this information is implied in the name of the compound.

NaCl	Sodium chloride
$AlBr_3$	Aluminum bromide
Ca_3P_2	Calcium phosphide
SrI_2	Strontium iodide
$FeCl_2$	Iron(II) chloride or ferrous chloride

2. **Ionic Compounds Containing a Metal and a Polyatomic Ion.** Metals combine with polyatomic ions to give ionic compounds. Name the cation first (specifying the charge, if necessary), then the polyatomic ion as listed in the table above. Do NOT use prefixes to

indicate how many of each element is present; this information is implied in the name of the compound.

$NaOH$	Sodium hydroxide
$Ca(NO_3)_2$	Calcium nitrate
K_3PO_4	Potassium phosphate
$(NH_4)_2SO_4$	Ammonium sulfate
NH_4F	Ammonium fluoride
$CaCO_3$	Calcium carbonate
$Mg(C_2H_3O_2)$	Magnesium acetate
$Fe(OH)_3$	Iron(III) hydroxide
$Cr_3(PO_4)_2$	Chromium(II) phosphate
$CrPO_4$	Chromium(III) phosphate
$NaHCO_3$	Sodium hydrogen carbonate *or* sodium bicarbonate

3. **Acids and Acid Salts.** Acids are compounds in which the "cation" is H^+. (These are not really ionic compounds, but we'll get into that later.) These can be named as compounds as in the previous cases, e.g., HCl is "hydrogen chloride", but are more frequently given special "acid names" (especially when dissolved in water, which is most frequently the case.) The word "hydrogen" is omitted, and the word "acid" is used at the end; the suffix is determined from the name of the anion portion:

Compound name	Acid name	Example	Compound Name	Acid name
-ate	*-ic* + acid	$HClO_3$	hydrogen chlorate	chloric acid
		H_2SO_4	hydrogen sulfate	sulfuric acid
-ite	*-ous* + acid	$HClO_2$	hydrogen chlorite	chlorous acid
-ide	*hydro- -ic* + acid	HCl	hydrogen chloride	hydrochloric acid

Acid salts are ionic compounds that still contain an acidic hydrogen, such as $NaHSO_4$. In naming these salts, specify the number of acidic hydrogens still in the salt. For instance:

$NaHSO_4$	sodium hydrogen sulfate
NaH_2PO_4	sodium dihydrogen phosphate
Na_2HPO_4	sodium hydrogen phosphate
$NaHCO_3$	sodium hydrogen carbonate *or* sodium bicarbonate

The prefix *bi-* implies an acidic hydrogen: $NaHCO_3$, sodium bicarbonate (or sodium hydrogen carbonate); $NaHSO_3$, sodium bisulfite (or sodium hydrogen sulfite), etc.

4. **Binary Compounds Between Two Nonmetals.** Two nonmetals combine to form a *covalent* or *molecular compound* (i.e., one that is held together by covalent bonds, not ionic bonds). In many cases, two elements can combine in several different ways to make completely different compounds. (This cannot happen with ionic compounds.) For instance, carbon can share electrons with one oxygen, to make CO (carbon monoxide), or with two oxygens to make CO_2 (carbon dioxide). For this reason, it is necessary to specify how many of each element is present within the compound.

The more electropositive element (the one further to the left on the periodic table) is placed first, then the more electronegative element (the one further to the right on the periodic table). [*Important exception:* when the compound contains oxygen and a halogen, the halogen is placed first. If both elements are in the same group, the one with the higher period number is named first.] The first element in the formula is given the neutral element name, and the second one is named by replacing the ending of the neutral element name with *-ide*. A prefix is used in front of each element name to indicate how many of that element is present:

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

If there is only one of the first element in the formula, the *mono-* prefix is dropped.

SO_2	sulfur dioxide	NO_2	nitrogen dioxide
SO_3	sulfur trioxide	N_2O_4	dinitrogen tetroxide
N_2O	dinitrogen monoxide	N_2O_5	dinitrogen pentoxide
NO	nitrogen monoxide		

5. Hydrocarbons. *Hydrocarbons* contain only carbon and hydrogen, and are the simplest type of organic compound. *Alkanes* contain only carbon-carbon single bonds, and are the simplest of the hydrocarbons. The simplest of the alkanes are the straight-chain alkanes, in which all of the carbon atoms are linked together in a line, with no branches. (They don't get simpler than that!) Alkanes have the general formula C_nH_{2n+2}, and are the constituents of several important fuels, such as natural gas and gasoline.

Organic chemistry has a completely different set of rules for nomenclature; straight-chain alkanes are named using a prefix plus the suffix *–ane*. (Notice that after C_4, the prefixes are the same as those listed above for binary covalent compounds.)

CH_4	methane	C_6H_{14}	hexane
C_2H_6	ethane	C_7H_{16}	heptane
C_3H_8	propane	C_8H_{18}	octane
C_4H_{10}	butane	C_9H_{20}	nonane
C_5H_{12}	pentane	$C_{10}H_{22}$	decane

Molecular Masses from Chemical Formulas

The **molecular mass** (or **molecular weight**) of a compound is obtained by adding up the atomic masses of all of the atoms present within a unit of the substance. For ionic compounds, the term *formula mass* or *formula weight* is used instead, since there aren't really any molecules present.

For example, the molecular weight of water would be obtained by the following process:

$$\begin{aligned}\text{Molecular mass of } H_2O &= (2 \times \text{atomic mass of H}) + (1 \times \text{atomic mass of O}) \\ &= (2 \times 1.008) + (1 \times 16.00)\text{ amu} \\ &= 18.02\text{ amu}\end{aligned}$$