CHEMICAL COMPOUNDS

Chapter Five

Compounds: A Closer Look

- As we have already seen, compounds are pure substances comprised of two or more elements in an *exact* atom-to-atom ratio
  - Glucose, with molecular formula $C_6H_{12}O_6$, always comes in an exact ratio of 6 C : 12 H : 6 O, down to the atom
  - Brass, which is not a compound but an alloy of copper and zinc, can be made in literally an infinite number of different proportions
  - The atom-to-atom ratio in an alloy is never exact

Compounds: A Closer Look

- The properties of compounds are generally not the same as the properties of the elements of which they are composed
- Consider two examples
  - NaCl
  - NI_3

Constant Composition

- The Law of Constant Composition tells us that, for a given compound, the mass-to-mass ratios of the elements forming the compound must be constant
- Suppose that you have two pure samples of potassium chloride, KCl, with different masses
- The ratio of potassium to chlorine in the compound can be found from the atomic masses:
  1 K : 1 Cl = 39.10 amu : 35.45 amu = 1.103 : 1
- In both samples, we could show that this ratio between the atoms will always occur

Chemical Formulas

- A chemical formula represents the exact atom-to-atom ratio of a compound in a form which is convenient and easy to understand
- In the most simple chemical formulas, the symbol for each element in the compound is listed followed by a whole number if the number in the ratio is greater than one
- Symbols with no number after them are understood to have a value of one in the formula
- Examples:
  N_2O_5 has a ratio of 2 N : 5 O
  CS_2 has a ratio of 1 C : 2 S

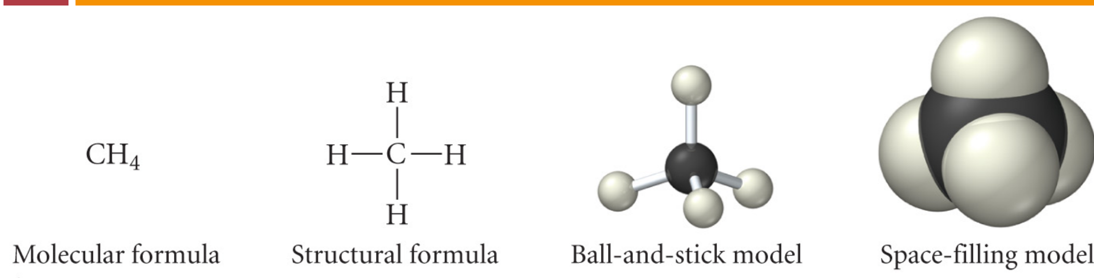
Chemical Formulas

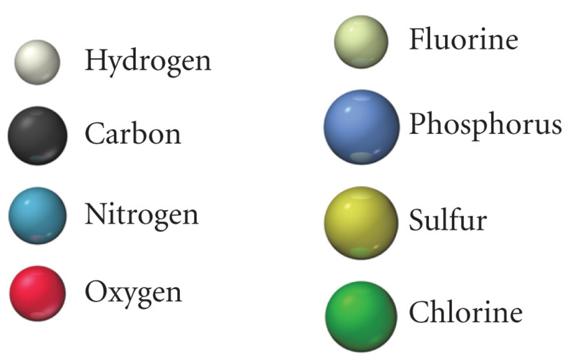
- Many formulas contain polyatomic ions, which are ions containing two or more atoms
  - We will discuss them in depth later
- The compound potassium nitrate has formula KNO_3
- Compare this to the formula for the compound magnesium nitrate, $Mg(NO_3)_2$
- We use parenthesis in a chemical formula to show that a compound contains two or more units of a certain group
- Parenthesis are always followed by a number greater than one in a chemical formula
- Why wouldn't we just write the formula as MgN_2O_6 ?
- What is the exact ratio of elements in aluminum acetate, $Al(C_2H_3O_2)_3$?

Other Ways of Representing Chemical Compounds and Elements

- Chemical formulas are the simplest method for representing chemical compounds
- They tell you which atoms are included and, relatively, how many
- They do not tell you how the atoms are attached, or *bonded*, to each other
- For this, we need more complex methods of representing compounds
- We will cover bonding in detail in Chapter 10. All you need to know now is that bonds hold atoms together to form compounds
  - They also hold some elements together

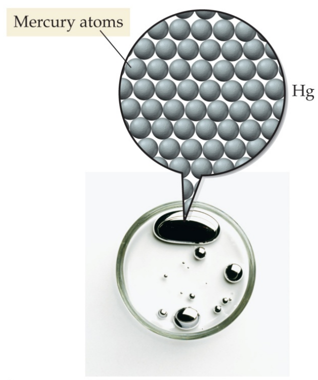
Other Ways of Representing Chemical Compounds and Elements

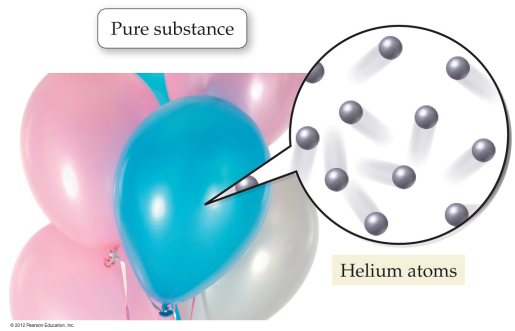




Atomic vs. Molecular Elements

- Most elements are atomic, meaning that they are composed of individual atoms of one type which do not come together in whole-number ratios
- All metals are atomic
- All noble gases are atomic





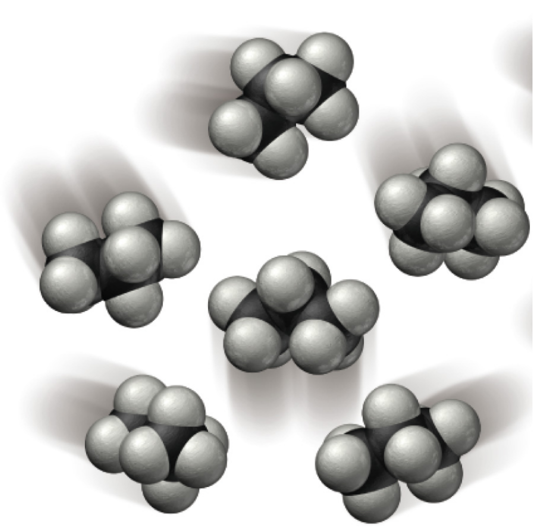
Molecular Elements

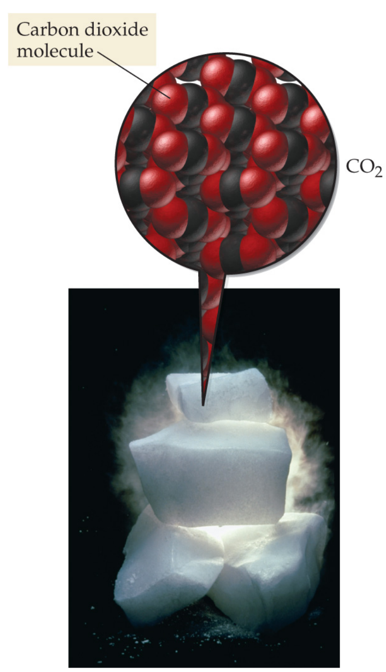
- Many non-metal elements are found in nature as molecules rather than as individual atoms
- Seven common elements are generally found as diatomic molecules, which are molecules containing two atoms
- The formulas of these seven elements are

  H_2, N_2, O_2, F_2, Cl_2, Br_2, and I_2
- Other molecular elements do exist, including P_4 and S_8 but you need not memorize these

Molecular Compounds

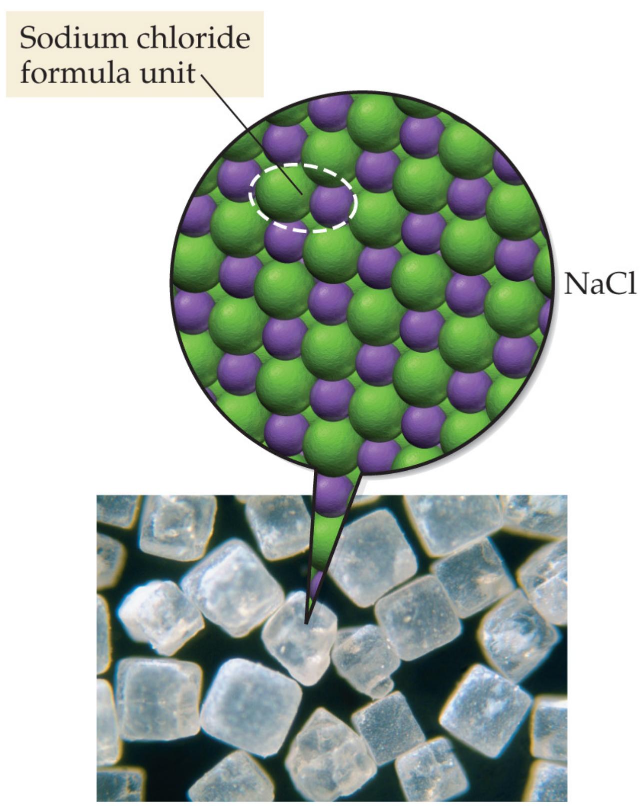
- We commonly encounter compounds in two different forms: molecular compounds and ionic compounds
- Molecular compounds consist of individual molecules which contain exactly the number of each element in the formula
  - You can generally identify molecular compounds from their formula because they contain only non-metals in their formula
    - This is not *always* true, but is in almost every case we will see in this class



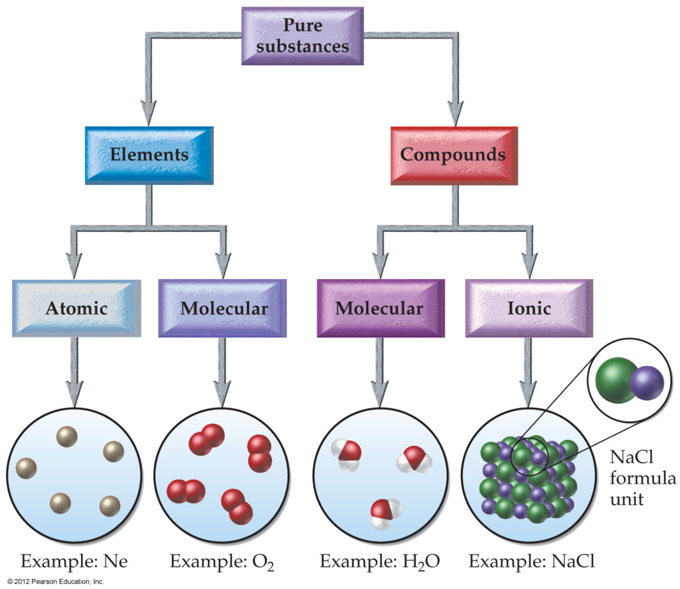


Ionic Compounds

- Ionic compounds are composed of ions of opposite charge
- The formulas of such compounds typically contain metal cations with non-metal anions ($NaCl$, CaF_2, etc.)
- Other ionic compounds may contain polyatomic ions, such as nitrate (NO_3^-) or sulfate (SO_4^{2-})
- Unlike molecular compounds, ionic compounds do not come in individual units
- Instead, the numbers in the chemical formulas only tell you the atom-to-atom ratio in the compound
- A formula unit is a group of ions within an ionic compound which contains exactly the number of ions in the chemical formula



Summary of Element and Compound Types

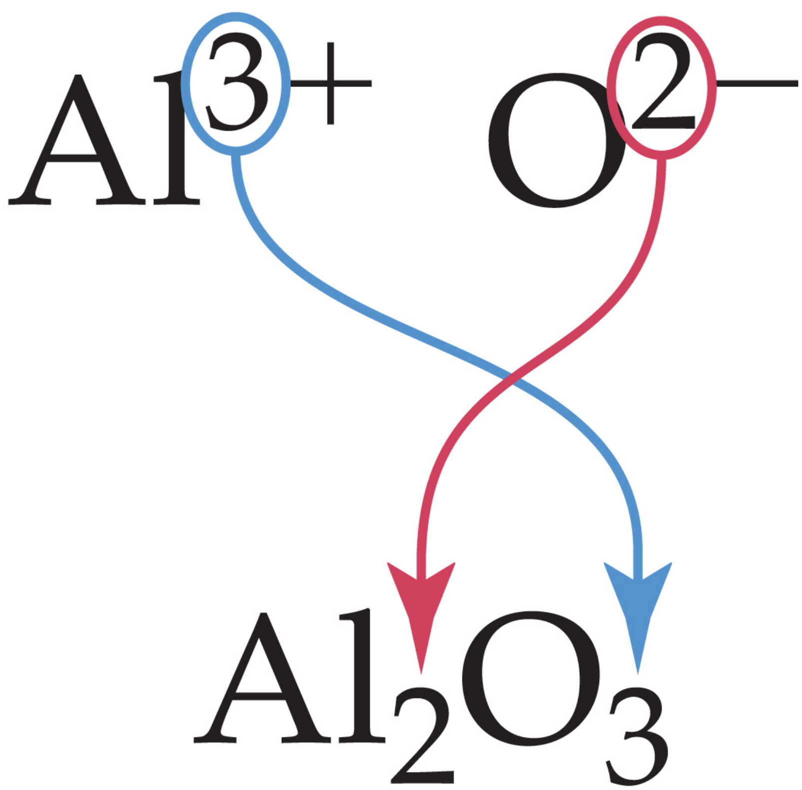


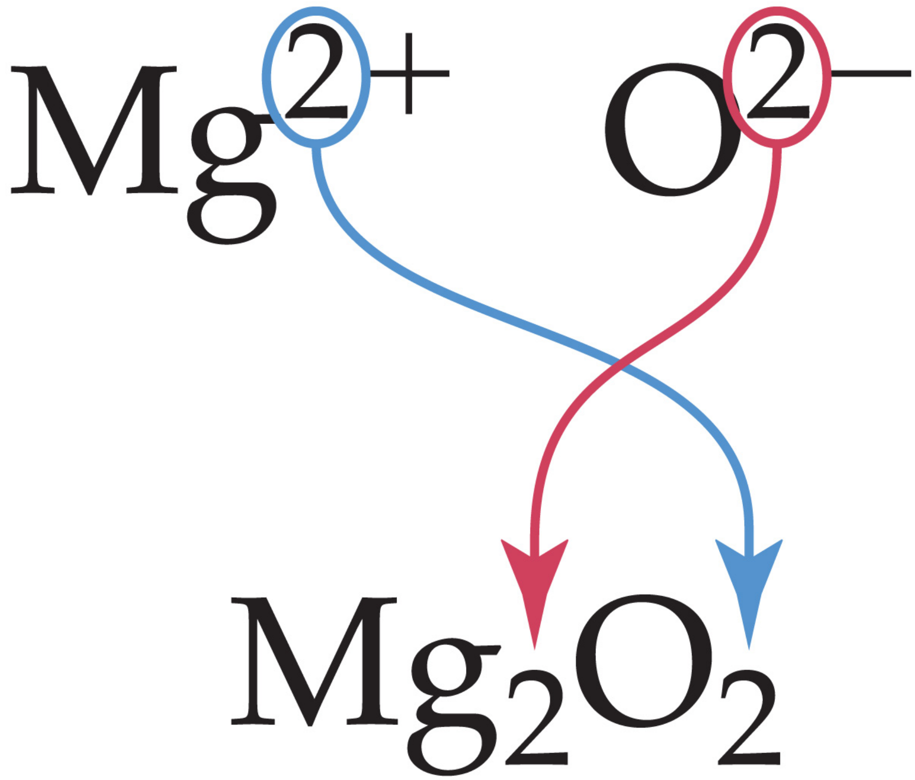
Formulas of Ionic Compounds

- An ionic compound should have no total charge in its formula.
- Ions of opposite charge are paired in such a way as to cancel out charges. Recall:
  - Positively charged ions are called <u>cations.</u>
  - Negatively charged ions are called <u>anions.</u>
- Example:
  One Na^+ combines with one Cl^- to give the neutral ionic compound NaCl.
  Two Na^+ combine with one O^{2-} to give the neutral ionic compound Na_2O.
- Notice that the cation is <u>always</u> listed first in the formula.

Formulas of Ionic Compounds

- Further examples
  - Note that the formula of an ionic compound shows the *smallest whole number ratio* between the ions.
  - So, when Ca^{2+} and O^{2-} combine, the formula of the product is CaO, <u>not</u> Ca_2O_2.
  - Sometimes, the ratio between ions is more complex, like with Al^{3+} and O^{2-}.





Example

- What is the formula of the ionic compound which contains ions of each of the two elements below?
  - sodium and sulfur
  - barium and nitrogen
  - selenium and calcium

Types of Ions

- Ions are classified according to how many atoms they contain
  - If an ion is derived from a single atom, it is called a *monatomic ion.*
    - Examples include Na^+, O^{2-}, and Pb^{4+}.
  - Ions which are derived from two or more atoms are called *polyatomic ions.*

Polyatomic Ions

- Polyatomic ions can be described as molecules which have collectively gained or lost electrons to become an ion.
- Being molecules, the ions themselves are held together by covalent bonds.
- From this, you would expect the atoms in a polyatomic ion to all be nonmetals.
  - Examples: NO_3^-, ClO_4^-, NH_4^+
- However, some polyatomic ions contain metals which are able to covalently bond.
  - Examples: $Cr_2O_7^{2-}$, MnO_4^-

Polyatomic Ions

- All but one of the more common polyatomic ions are anions.
- The *ammonium ion*, NH_4^+, is the only common polyatomic cation.
- The common polyatomic ions must be memorized, and you must learn to recognize them in a formula on sight.

Polyatomic Ions

Ions to be memorized:

1- anions			
OH^-	hydroxide	NO_3^-	nitrate
CN^-	cyanide	ClO_3^-	chlorate
OCN^-	cyanate	BrO_3^-	bromate
SCN^-	thiocyanate	IO_3^-	iodate
MnO_4^-	permanganate	$C_2H_3O_2^-$	acetate

Polyatomic Ions

2- anions			
CO_3^{2-}	carbonate	SO_4^{2-}	sulfate
CrO_4^{2-}	chromate	$Cr_2O_7^{2-}$	dichromate
$C_2O_4^{2-}$	oxalate	SiO_3^{2-}	silicate
$S_2O_3^{2-}$	thiosulfate	O_2^{2-}	peroxide
3- anions			
PO_4^{3-}	phosphate	BO_3^{3-}	borate

Classifications of Compounds

- When naming inorganic compounds, two different naming systems are used, depending on the type of compound you are considering.
- *Binary nonmetals* (sometimes called *molecular compounds*) contain atoms from exactly two different nonmetals.
  - Examples: NO, CO_2, CO, SO_2, H_2S.
- *Ionic compounds* are composed of a cation and an anion.
  - For the purposes of this course, if a compound is not a binary nonmetal, it is an ionic compound.
  - The ions may be monatomic and/or polyatomic.
  - Examples: NaCl, $CaCl_2$, NH_4Cl, $CaCO_3$, Na_3PO_4.

Examples

- Classify each of these compounds as binary nonmetals or as ionic compounds.
  - KBr
  - Na_2CO_3
  - NaCN
  - N_2O_4
  - NaH_2PO_4
  - P_2O_5
  - NH_4NO_3

Naming Binary Nonmetals

- Nonmetals can bond with one another in many possible combinations.
  - For example, nitrogen and oxygen make compounds such as NO, NO_2, and N_2O.
- Although these compounds contain the same elements (and may even contain them in the same ratio), these chemicals have considerably different chemical and physical properties.
- Therefore, each must be given its own distinct name to distinguish it.

Naming Binary Nonmetals

- The compound is named by putting prefixes before the name of the element to indicate how many atoms of each type are in the molecule.
- The ending of the name of the second element is changed to "-ide".

Naming Binary Nonmetals

The first ten prefixes must be memorized:

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

Naming Binary Nonmetals

- For example, a compound with formula S_2O_3 would be named disulfur trioxide.
- Exceptions:
  - Do not use the prefix "mono-" with the first element in the formula; just stating the name of the element implies that there is only one of it in the formula.
    - For example, CO_2 is carbon dioxide, not monocarbon dioxide.
    - What is the name of SO_3?

Naming Binary Nonmetals

- Exceptions:
  - If the last letter of the prefix is an "a" or an "o", and the first letter of the element after the prefix is an "o", drop the last letter of the prefix; it looks and sounds awkward.
    - Example: CO is carbon monoxide, not carbon monooxide.
    - P_2O_5 should be named diphosphorus pentoxide, which is preferable to diphosphorus pentaoxide (which is *technically* acceptable).

Naming Binary Nonmetals: Common Names

- In three cases, the naming rules are totally ignored, and the common name is used.
- These three are
  - H_2O, which is always called water.
  - NH_3, which is always called ammonia.
  - PH_3, commonly known as phosphine.
- Other common names do exist, but are omitted here (they are *less* common).

Naming Binary Nonmetals: Hydrogen-Containing Formulas

- When hydrogen appears first in the formula of a binary nonmetal, do not use prefixes at all. Simply name the compound without them.
  - There will be as many hydrogens bonded to the other nonmetal as are necessary to give it a complete octet.
  - So, $H_2S_{(g)}$ is named hydrogen sulfide, and $HCl_{(g)}$ is named hydrogen chloride.
  - Note that the (g) means "gas", an important fact which must be specified in the formula for these types of compounds.

Naming Binary Nonmetals: Hydrogen-Containing Formulas

- If the hydrogen-containing binary nonmetal is dissolved in water, a different name is used.
- In the formula, the notation (aq) is used, meaning *aqueous*, to indicate that it is dissolved in water.
- These compounds are named as *acids*.
  - These are not to be confused with *oxyacids*, which will have a different naming system.

Naming Acids of Binary Nonmetals

- The prefix "hydro-" is put before the name of the element.
- The ending of the name of the element is changed to "-ic", followed by the word "acid".
  - Examples:

    $HCl_{(aq)}$ is hydrochloric acid
    $HBr_{(aq)}$ is hydrobromic acid
    $HI_{(aq)}$ is hydroiodic acid
    $H_2S_{(aq)}$ is hydrosulfuric acid

CAUTION: Do not confuse this with sulfuric acid, which is H_2SO_4!

Examples

Name each of the following:

N_2O_5

SO_2

$HF_{(aq)}$

$HF_{(g)}$

$H_2Se_{(aq)}$

NH_3

XeF_4

$H_2S_{(aq)}$

Naming Ionic Compounds

- The naming system for ionic compounds is different than that for binary nonmetals.
- Most importantly: The prefixes used for binary nonmetals (mono, di, tri, etc.) are never used to name ionic compounds.
  - This is, by far, the most common mistake made by students in naming compounds.

Naming Individual Ions: Cations

- Some cations always have the same charge in virtually all compounds.
- These include
  - Group I cations, which only form 1+ ions
    - Ex.: Li^+, Na^+, K^+, Rb^+, Cs^+
  - Group II cations, which only form 2+ ions
    - Ex.: Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}
  - Group III cations, which only form 3+ ions
    - Al^{3+}, (Ga^{3+} if it is forming an ionic compound)
    - Note that this is not true for elements below Ga

Naming Individual Ions: Cations

- Three additional common metals also only form one ion.
- These must be memorized. They are
  - Zinc: Zn^{2+}
  - Cadmium: Cd^{2+}
  - Silver: Ag^+
- For all other metals, the charge must be specified in naming the cation.

Naming Individual Ions: Cations

- The name of the individual cation is stated by simply stating the name of the metal, followed by the word "ion".
- Examples:
  - Na^{+} is the sodium ion.
  - Ba^{2+} is the barium ion.
  - Zn^{2+} is the zinc ion.

Naming Individual Ions: Cations

- The new method for naming all other cations places the charge of ion in Roman numerals in parenthesis after the name of the metal.
  - Cu^{2+} is the copper (II) ion.
  - Cu^{+} is the copper (I) ion.
  - Pb^{4+} is the lead (IV) ion.
  - Pb^{2+} is the lead (II) ion.
- Remember, you only use Roman numerals for those ions that form multiple charges.

Naming Individual Ions: Cations

- The old names for many ions are still in use and must be learned.
- The names of the ions must be memorized, noting the following:
  - The ion possessing the higher charge ends in "-ic"
  - That possessing the lower charge ends in "-ous"
  - Ex.: Fe^{3+} is the ferric ion, Fe^{2+} is the ferrous ion.

Naming Individual Ions: Cations

Ion	Common Name	Ion	Common Name
Cu^{2+}	cupric ion	Cu^{+}	cuprous ion
Fe^{3+}	ferric ion	Fe^{2+}	ferrous ion
Pb^{4+}	plumbic ion	Pb^{2+}	plumbous ion
Sn^{4+}	stannic ion	Sn^{2+}	stannous ion
Hg^{2+}	mercuric ion	Hg_2^{2+}	mercurous ion
Cr^{3+}	chromic ion	Cr^{2+}	chromous ion
Co^{3+}	cobaltic ion	Co^{2+}	cobaltous ion
Mn^{3+}	manganic ion	Mn^{2+}	manganous ion

Examples

Name the following cations:

Rb^{+}

Fe^{3+}

Hg^{2+}

Hg_2^{2+}

Cd^{2+}

Ca^{2+}

Naming Individual Ions: Anions

- The charge on a monatomic anion is simply 8 minus the group number of the element.
  - For example, nitrogen is in group 5, so it will only make a N^{3-} ion. (8-5=3)
- Monatomic anions are named by simply changing the ending of the element's name to "ide".
- Examples:
  - S^{2-} is the sulfide ion
  - O^{2-} is oxide ion
  - P^{3-} is the phosphide ion
- CAUTION: Do <u>not</u> confuse these monatomic ions (nitride, sulfide, phosphide, etc.) with the similar-sounding oxyanions (nitrate, sulfate, phosphate, etc.)

Naming Ionic Compounds

- To name the ionic compound, simply state the cation, followed by the anion. Do not use the word "ion" in the name of a neutral compound.
- Examples:
  - NaCl is sodium chloride
  - $CaBr_2$ is calcium bromide
  - CuO is copper (II) oxide, or cupric oxide
  - Cu_2O is copper (I) oxide, or cuprous oxide

Naming Ionic Compounds

- Again, notice that we <u>never</u> use the prefixes used for binary nonmetals (mono-, di-, tri-, etc.) when naming ionic compounds!
- This is because ionic compounds always form predictable ratios, as we have already seen.
  - Na^+ and Cl^- can only come together as NaCl.
  - Cu^{2+} and O^{2-} come together as CuO.
  - Cu^+ and O^{2-} come together as Cu_2O.
- Recall that the total charges of the cations and anions must neutralize.

Examples

Name each of the following ionic compounds:

$AgCl$

KNO_3

$PbCl_2$

$ZnBr_2$

NH_4NO_3

$Hg(ClO_3)_2$

$CdSO_4$

$SnCl_4$

Oxyanions

- The oxyanions include many polyatomic anions which contain oxygen.
  - OH^- and O_2^{2-} are not considered oxyanions.
- So far, we have only encountered those oxyanions whose names end in "-ate."
- Related oxyanions have different numbers of oxygen atoms but the same charge.
- Examples:
  - SO_4^{2-} is the sulfate anion, SO_3^{2-} is the sulfite anion.
  - ClO_3^- is the chlorate anion, ClO_4^- is the perchlorate anion.

Naming Oxyanions

- Let us consider the chlorate ion, which we know has formula ClO_3^-.
- It is very important that we know how many oxygen atoms are in the "-ate" ion.
- If the ion has one more oxygen in its formula than that of the "-ate" ion, add the prefix "per-" to its name.
- So ClO_4^- is perchlorate, SO_5^{2-} would be persulfate, etc.

Naming Oxyanions

- Again, consider the chlorate ion, ClO_3^-.
- Taking away one oxygen from the "-ate" anion changes its ending from "-ate" to "-ite."
  - Therefore, ClO_2^- is the chlorite ion, and SO_3^{2-} is the sulfite ion.
- Taking away two oxygens from the "-ate" anion changes its ending from "-ate" to "-ite," <u>and</u> you must add the prefix "hypo-"
  - So, ClO^- is the hypochlorite ion, and SO_2^{2-} is the hyposulfite ion.

Oxyanions Containing Hydrogen

- Some common polyatomic anions have an H^+ "within" their formula.
  - In these ions, the H is always listed first, and the normal charge of the ion is changed by +1.
  - The name of the ion is changed by adding one of the following:
    - The prefix "bi-", or
    - The word "hydrogen" before the name of the anion (sometimes you might see "monohydrogen" instead.)
  - For example, HCO_3^- is commonly called the "bicarbonate ion" or the "hydrogen carbonate ion."
  - What would HSO_3^- be called?

Oxyanions Containing Hydrogen

- Occasionally you may also see two hydrogen atoms added to the ion. This is rare, except in the case of phosphate.
- This would increase the charge of the original anion by +2.
- The word "dihydrogen" is added to the name of the anion.
- So $H_2PO_4^-$ is the "dihydrogen phosphate" ion.
- KH_2PO_4 is called "potassium dihydrogen phosphate."
- NOTE: In all these examples, H^+ is not the cation; we should consider it an "attachment" of the anion for naming purposes.

Examples

Name each of the following compounds:

KIO_4

$NaHCO_3$

$Al_2(SO_3)_3$

$CuHPO_3$

LiH_2PO_4

$NaClO$

$Co(NO_2)_3$

Oxyacids

- Oxyacids are compounds which contain exactly as many H^+ ions as are necessary to cancel out the negative charge of an oxyanion.
  - For example, SO_4^{2-} would need two H^+ ions to balance out the 2- charge of sulfate; the oxyacid has the formula H_2SO_4.
  - Note that the H^+ ions are
    - the <u>only</u> cations in the formula, and
    - always listed first in the formula.

Naming Oxyacids

- The naming rules for oxyacids are similar to those for oxyanions.
  - The name of the oxyacid depends on how many oxygen atoms are in the corresponding oxyanion.
- For those oxyanions which end in "-ate", change the ending to "-ic acid."
  - So, CO_3^{2-} is the carbonate ion
  - H_2CO_3 is carbonic acid
  - HNO_3 is named ____________________
  - Slightly "weird" cases: H_2SO_4 is sulfuric acid, and H_3PO_4 is phosphoric acid.

Naming Oxyacids

- An oxyanion that begins with "per-" follows the same rules.
- Simply change the ending to "-ic acid."
  - $HClO_4$ is called perchloric acid.
  - HIO_4 is called periodic acid.
- Any oxyanion that ends in "-ite" has its ending changed to "-ous acid"
  - H_2SO_3 is called sulfurous acid.
  - $HClO_2$ is called chlorous acid.

Naming Oxyacids

- The acids of oxyanions which begin with “hypo-” likewise have their ending changed to “-ous acid”.
  - HBrO would be called hypobromous acid.
  - HNO would be called hyponitrous acid.

Examples

Name the following oxyacids:

H_3PO_4

HNO_3

HNO_2

HIO_2

H_2CO_3

HIO

The Cyanide Ion

- One last random bit of information…
- The cyanide ion (CN^-) often behaves like a halogen, so naming rules for it are similar to those of F^-, Cl^-, etc.
- $HCN_{(g)}$ is called "hydrogen cyanide."
- $HCN_{(aq)}$ is called hydrocyanic acid.

Hydrates

- A hydrate is an ionic compound which has "trapped" a fixed number of water molecules within its structure
- For example, the following compound is called copper (II) sulfate pentahydrate:

$$CuSO_4 \cdot 5\ H_2O$$

  - The formula tells us that there are five water molecules in the structure for every unit of copper (II) sulfate
- The naming of other hydrates is similar:
  - State the name of the salt
  - End with a prefix indicating how many water molecules are present, followed by the word "hydrate"

Hydrates

Name each of the following hydrates:

$BaCl_2 \cdot 2\ H_2O$

$MgSO_4 \cdot 7\ H_2O$

Final Examples

Name each of the following compounds.

BrO_4
$Cu(ClO_4)_2$
H_2SO_3
$HF_{(aq)}$
$LiHCO_3$
NH_3
N_2O
F_2
HIO_3