Chapter 4. Chemical Bonding: The Ionic Bond Model
4.1 Chemical Bonds

Almost all chemical substances are found as aggregates of atoms in the form of molecules and ions produced through the reactions of various atoms of elements except the noble-gas elements which are stable mono-atomic gases.

Chemical bond is a term that describes the attractive force that is holding the atoms of the same or different kind of atoms in forming a molecule or ionic solid that has more stability than the individual atoms. Depending on the kinds of atoms participating in the interaction there seem to be two types of bonding:

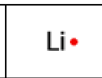
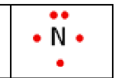
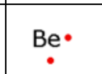
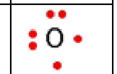
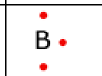
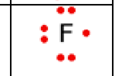
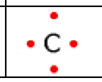
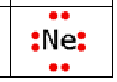
Ionic bonding: Formed between many ions formed by metal and nonmetallic elements.
Covalent bonding: Formed between two atoms of non-metals.

	Ionic Compounds	Covalent Compounds
1.	**Metal** and **non-meal** element combinations.	**Non-metal** and **non-meal** elements combinations.
2.	**High melting brittle** crystalline solids.	**Gases, liquids, or waxy, low melting soft** solids.
3.	Do not conduct as a solid but conducts **electricity** when **molten**.	**Do not** conduct electricity at **any state**.
4.	Dissolved in water produce conducting solutions (**electrolytes**) and few are soluble in non-polar solvents.	Most are soluble in non-polar solvents and few in water. These solutions are non-conducting (**non-electrolytes**).

The differences in these three bonding types are mainly due to the number of valence election of the interacting atoms compared to noble gas elements. Noble gases show no inherent tendency to form any type of bonding apparently due to their closed valence shell electron configurations. Non-metals need only few electrons to achieve a closed shell. We focus mainly on ionic and covalent bonding in this course.

4.2 Valence Electrons and Lewis Symbols

Valence electron configuration of an atom is important in understanding the nature of chemical bonding. Lewis electron-dot symbol is a simple representation of valence electrons around the atomic symbol with dots. E.g. Lewis symbols for the second row of elements in the periodic table are given below:

Li	**[He]** $2s^1$(1 electron)		**N**	**[He]** $2s^2$, p^3 (5 electrons)	
Be	**[He]** $2s^2$(2 electrons)		**O**	**[He]** $2s^2$, p^4 (6 electrons)	
B	**[He]** $2s^2$, p^1 (3 electrons)		**F**	**[He]** $2s^2$, p^5 (7 electrons)	
C	**[He]** $2s^2$, p^2 (4 electrons)		**Ne**	**[He]** $2s^2$, p^6 (8 electrons)	

4.3 The Octet Rule

An atom with eight electrons in the valence shell is a stable atom. All noble gas elements have an octet in their valence shell except the helium atom. When atoms have less than eight electrons, they tend to react and attain an octet of electrons forming more stable compounds.

Covalent bonding: Attractions formed when non-metals share electrons to achieve an octet.

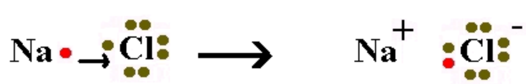
Ionic bonding: Electrical attractions of ions formed by of **metal** and **nonmetal** elements when they lose and gain electrons forming **cations** and **anions** with octets, respectively.

4.4 The Ionic Bond Model

An ionic compound is made up of two or more **ions** (charged particles) which are held together by **electrostatic attraction**. One of the ions has **a positive charge** (called a "**cation**") and the other has a **negative charge** ("**anion**"). **Mono-atomic ions** called cations are usually formed by metal atoms and anions from the non-metals. The **polyatomic ions** which are charged particles with **more than one atom** are formed by various combinations of metal and nonmetal elements. The formations of mono-atomic or polyatomic ions from various **metal** and **nonmetals** are explained by the tendency of single atoms to achieve a **closed shell electron configurations** similar to noble gases.

Sodium metal, **Na**(*s*) reacts with chlorine (non-metal) gas, $\mathbf{Cl_2}(g)$ in a violently exothermic reaction where heat is given out to produce **NaCl** ionic solid (composed of Na^+ and Cl^- ions): $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$

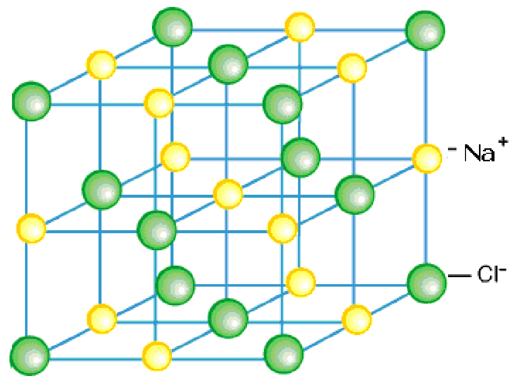
Na(*s*) lose an electron to chorine atom and becomes a $\mathbf{Na^+}$ (sodium ion)which is isolectronic to Ne and $Cl_2(g)$ first breaks up to atomic chlorine which then picks the electron lost by the sodium and produce a Cl^- (chloride ion) **isoelectronic** to Ar.



Isolectronic electron configurations: Electron configurations of an atom or ion with same number and orbital arrangement of electrons. E.g. **He** :$1s^2$ and **Li**$^{+}$:$1s^2$ or **Ne**: $1s^2 2s^2 2p^6$ and **Na**$^{+}$:$1s^2 2s^2 2p^6$

Ionic Solids and Crystal Lattices

Ionic compounds do not usually exist as isolated molecules, such as NaCl, but as a part of a crystal lattice--a three dimensional regular array of cations and anions. Ionic compounds form lattices due to the contributing coulombic attractions of having each cation surrounded by several anions and each anion surrounded by several anions. An example of a ionic crystal lattice giant collection of ions is shown on the side:



4.5 The Sign and Magnitude of Ionic Change

Predicting ionic charge:
Cations:
Remove all electrons form symbol.. Cation charge is equal to electrons removed.

Anions:
Add additional electrons fill valence shell of the symbol.. Anion charge is equal to electrons added.

Lewis dot symbols are useful in showing the ways in which non-noble gas electron configurations could be achieved by losing or gaining electrons.

Using Lewis dot symbols predict the following:
Charge of the cations formed by Group I A: alkali metals (Li, Na, K, Rb, Cs)
Common Lewis symbol of Group I A X• becomes X^{+} (**Ans. +1**)

Charge of the cations formed by Group II A: alkali earth metals (Be, Mg, Ca, Ba) (**Ans. +2**)
Charge of the anions formed by Group VII A: halogens (F, Cl, Br, I)
Common Lewis symbol of Group VII A :X⁚ becomes :X:$^{-}$ (**Ans. -1**)

Metals can **lose** all valence electrons and can achieve closed shell electron configuration of preceding noble gas element. E.g. Lithium-Li could lose its one valance electron and become like helium-He forming a **stable cation** - **Li**$^{+}$.

Non-metals can gain elections and achieve closed shell electron configuration of next noble gas element. E.g. Fluorine-F could can gain an electron and become like neon-Ne forming a

stable anion- **F^-**. Non-metals need a metal to gain electrons and vice versa. In the process ions are formed and they are held together by the attractive forces between cation and ions in the **ionic solid** a collection of ions.

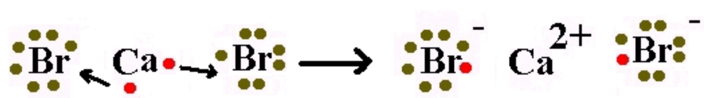
	Predicting charge of Ions of Representative Elements							
Periodic Table Group Number	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA
Common Lewis symbols	X•	•X•	•X• •	•X• ••	•• •X• •	•• :X• •	•• :X• ••	•• :X: ••
Lewis symbols 2^{nd} period elements	Li•	Be• •	• B• •	• •C• •	•• •N• •	•• :O• •	•• :F• ••	•• :Ne: ••
Lewis symbols 2^{nd} period ions	Li^+	Be^{2+}	B^{+3}	C^{-4}	N^{-3}	O^{-2}	F^-	Ne
`Charge on ions of 2^{nd} period elements.	+	2+	+3	-4	-3	-2	-	0

metal (blue) non-metal (yellow)

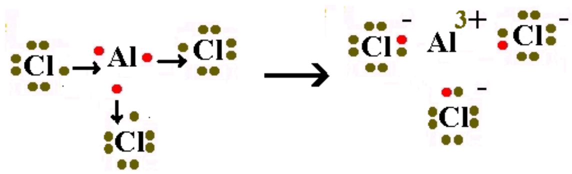
4.6 Lewis Structures for Ionic Compounds

	Lewis Structure of Ions of Representative Elements							
Periodic Table Group Number	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA
Lewis electron-dot symbols 2^{nd} period elements	Li•	Be• •	• B• •	• •C• •	•• •N• •	•• :O• •	•• :F• ••	•• :Ne: ••
Lewis electron-dot symbols of 2^{nd} period ions	Li^+	Be^{2+}	B^{+3}	C^{-4}	N^{-3}	O^{-2}	F^-	Ne
Lewis symbols of 2^{nd} period ions	He:	He:	He:	•• :Ne: ••	•• :Ne: ••	•• :Ne: ••	•• :Ne: ••	•• :Ne: ••

In the formation of calcium bromide, $CaBr_2$ Use electron-dot symbols to show the transfer of electrons from calcium atom to bromine atoms to form ions with noble gas configurations.



In the formation of aluminum chloride, $AlCl_3$ Use electron-dot symbols to show the transfer of electrons from aluminum atom to chlorine atoms to form ions Al^{3+} which is isoelectronic to noble gas Ne and Cl^- ions to Ar.



4.7 Chemical Formulas for Ionic Compounds

Most ionic compounds are made from the combination of metal and nonmetal elements. Ionic compounds also are made up of mono atomic and polyatomic ions and have their own way for naming. It is important to remember the names and charges of ions before you can write the formula or name them. It is important to know how to and covert ionic formula of an ionic compound to a name and vice versa and this will help to apply solve chemical problems involving ionic compounds.

Symbols or Formulas of ions:

Getting name and formulas to ions:

Cations			Anions	
Name	**Formula**		**Name**	**Formula**
Potassium ion	K^+		**Chloride**	Cl^-
Magnesium ion	Mg^{+2}		**Phosphide**	P^{-3}
Calcium ion	Ca^{+2}		**Nitrate**	NO_3^-
Mercury(II) ion	Hg^{+2},		**Oxide**	O^{-2}
Ammonium	NH_4^+		**Dichromate**	$Cr_2O_7^{-2}$
iron(II)	Fe^{+3}		**Phosphate**	PO_4^{-3}
copper(II)	Cu^{+2}		**Sulfite**	SO_3^{-2}

Notice **representative metals** (blue) have fixed charges. Group IA, Group IIA, Group III A etc. except Sn and Pb which shows Pb^{2+}, Pb^{4+}, Sn^{2+}, and Sn^{4+}more than one charge. **Transition elements** have more than one charged ions except Zn, Cd and Ag with fixed charges Zn^{2+}, Cd^{2+}, and Ag^+.

The nomenclature, or naming, of ionic compounds is based on the names of the component ions. The positive ion (cation) is always named first and listed first and then the negative ion (anion) in writing the name/formula for the compound. Mostly a formula or name is given then you need to get either name or formula. **Formula of ionic compound is always empirical** i.e. simple ratio of ions: E.g. CaO is not Ca_2O_2

Binary ionic compounds:

Rule of electrical neutrality: The ionic compounds are always neutral. You can only get the formula of the ionic compound neutral by adjusting the numbers of the positive and negative ions.

E.g. calcium oxide/ Ca^{2+},O^{-2}/ since charge is already balanced formula is **CaO**

E.g. aluminum chloride/ Al^{3+},Cl^{-}/ Al^{3+},3Cl^{-}/formula is $AlCl_3$

Getting name from the formula:

Formula	Ions	Name	Formula	Ions	Name
KCl	**K^{+},Cl^{-}**	**potassium chloride**	**$FeCl_3$**	**Fe^{+3},3Cl^{-}**	**iron(II) chloride**
Mg_3P_2	**3Mg^{+2},2P^{-3}**	**magnesium phosphide**	**$CuCl_2$**	**Cu^{+2},Cl^{-}**	**copper(II) chloride**
$Ca(NO_3)_2$	**Ca^{+2},2NO_3^{-}**	**calcium nitrate**	**$Na_2Cr_2O_7$**	**2Na^{+},$Cr_2O_7^{-2}$**	**sodium dichromate**
$HgCl_2$	**Hg^{+2},2Cl^{-}**	**mercury(II) chloride**	**K_3PO_4**	**3K^{+},PO_4^{-3}**	**potassium phosphate**
CaO	**Ca^{2+},O^{-2}**	**calcium oxide**	**$CaSO_3$**	**Ca^{+2},SO_3^{-2}**	**calcium sulfite**
NH_4NO_3	**NH_4^{+},NO_3^{-}**	**ammonium nitrate**			

Type I mono atomic cations with **fixed charge are in blue; Type II** mono atomic cations with **more than one charges are** – red
Monoatomic anions- **green**; polyatomic anions- **black; Polyatomic cation-?**

Summary for getting name from formula

- The cation is always named first. Cations can be metals or polyatomic ions.
- For metal ions that have fixed charge the name of the metal is used. Examples are Group I metals, Group II metals, aluminum, zinc, silver
- For metal ions that can have more than one charge the name of the metal is succeeded by the charge in capital Roman numerals in brackets E.g. E.g. Iron(II)-**Fe^{+2}** and Iron(III)-**Fe^{+3}** **OR** by using the suffix -ous for the lowest charge and -ic for the highest charge and sometimes with the Latinised name for the metal. E.g. Ferrous-**Fe^{+2}** and Ferric-**Fe^{+3}**
- Anions can be a negatively charged element or a polyatomic ion. Negatively charged elements have the suffix -ide
  E.g. Examples are oxide (O^{2-}), sulfide (S^{2-}), fluoride (F^{-}), chloride (Cl^{-}), bromide (Br^{-}), iodide (I^{-}), nitride (N^{3-}), hydride (H^{-}).
- Polyatomic ions which include oxygen in the anion have the suffixes -ate or -ite. "ate" means there is more oxygen in the anion than one ending in "ite"
  Examples: sulfate (SO_4^{2-}) has more oxygen than sulfite (SO_3^{2-}), nitrate (NO_3^{-}) has more oxygen in the anion than nitrite (NO_2^{-}). Other examples are carbonate (CO_3^{2-}), phosphate (PO_4^{3-}) and permanganate (MnO_4^{-}). Exception: OH^{-} is named hydroxide .
- Note: parentheses and a subscript are not used unless more than one of a polyatomic ion is present in the formula unit (e.g., the formula unit for calcium sulfate is "$CaSO_4$" not "$Ca(SO_4)$").

E.g. Name the following ions:

a) K^+ Ca^{2+} Zn^{2+} Br^- Li^+ S^{2-}
b) Na^+ Mg^{2+} Al^{3+} Cl^- O^{2-} N^{3-}

K^+ Ca^{2+} Zn^{2+} Br^- Li^+ S^{2-}

K^+	potassium cation
Ca^{2+}	calcium cation
Zn^{2+}	zinc cation
Br^-	bromide anion
Li^+	lithium cation
S^{2-}	sulfide anion

Na^+ Mg^{2+} Al^{3+} Cl^- O^{2-} N^{3-}

Na^+	sodium cation
Mg^{2+}	magnesium cation
Al^{3+}	aluminum cation
Cl^-	chloride anion
O^{2-}	oxide anion
N^{3-}	nitride anion

Name the following ions:
Fe^{2+} Cu^+ I^- Fe^{3+} Cu^{2+} Sn^{2+} Sn^{4+} Ag^+

Fe^{2+} Cu^+ I^- Fe^{3+} Cu^{2+} Sn^{2+} Sn^{4+} Ag^+

Fe^{2+}	iron (II) ion or ferrous ion
Cu^+	copper (I) ion or cuprous ion
I^-	iodide ion
Fe^{3+}	iron (III) or ferric ion
Cu^{2+}	copper (II) ion or cupric ion
Sn^{2+}	tin (II) ion or stannous ion
Sn^{4+}	tin (IV) ion or stannic ion
Ag^+	silver ion

4.8 The Structure of Ionic Compounds

Sodium metal, Na(*s*) reacts with chlorine (non-metal) gas, $Cl_2(g)$ in a violently exothermic reaction where heat is given out to produce NaCl (composed of Na^+ and Cl^- ions):

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

Na(*s*) lose an electron and becomes a Na^+ (sodium ion)which is isoelectronic to Ne and Cl_2(*g*) first breaks up to atomic chlorine which then picks the electron lost by the sodium and produce a Cl^- (chloride ion) isoelectronic to Ar.

4.9 Recognizing and Naming Binary Ionic Compounds

A ionic compound is given systematic name of substance according to certain rules. Before the rules are made common names was given without following systematic rules: E.g. Rock salt for sodium chloride. The "shorthand" symbol for a compound is its formula. Formula gives types atoms and number each one in the Chemical compound.

A **binary ionic compound** (a salt) is consisting of only **monatomic ions** of two elements in which one of is a cation formed by a metal and other an anion formed by a non-metal. When naming these compounds, its composition must be considered. **Type 1** binary ionic compounds are those in which the cation has only one form, or **fixed charge**. **Type 2** binary ionic compounds are those in which the cation can have **more than one charge**. Ionic compound containing polyatomic ions will follow similar but distinct set of naming rules.

Naming Compounds and Writing Formulas of Compounds

Names of ionic compounds are based on names of the ions making them. Ions are classified as monatomic or polyatomic.

In naming ionic compounds containing **Type 1 ions** in which the cation has a **fixed charge,** the current system or **Stock system** assumes the cation charge bases on the group in which metal is found. E.g. Group IA, +1 charge and Group IIA has +2 charges.

Charges on monatomic ions of metals and nonmetals. Symbols and Names of monoatomic ions:

"Representative = Fixed Charge " ions:

Type 1 Cations			Common Monatomic Anions		
Group	**Symbol**	**Name**	**Group**	**Symbol**	**Name**
IA	H^+	Hydrogen ion	IA	H^-	Hydride ion
IA	Li^+	Lithium ion	VIIA	F^-	Fluoride ion
IA	Na^+	Sodium ion	VIIA	Cl^-	Chloride ion
IA	K^+	Potassium ion	VIIA	Br^-	Bromide ion
IIA	Be^{2+}	Beryllium ion	VIIA	I^-	Iodide ion
IIA	Mg^{2+}	Magnesium ion	VIIA	O^{2-}	Oxide ion
IIA	Ca^{2+}	calcium ion	VIA	S^{2-}	Sulfide ion
IIA	Ba^{2+}	barium ion	VA	N^{3-}	Nitride ion
	Zn^{2+}	zinc ion	VA	P^{3-}	Phosphide ion

*Cation charge is equal to group number for metals and anion charge is equal to 8- group number

In naming ionic compounds containing **Type 2 ions** in which there are cations with **more than one charge,** the current system or **Stock system** uses a Roman numeral after the element name to indicates the charge of the cation. This system is preferred over the older "common nomenclature" system.

"Type 2: Variable Charge" Cations

Ion Symbol	(Stock-system)	Common-system)	Ion Symbol	(Stock system)	Common-system
Cu^{+}	copper(I)	cuprous	Hg_2^{2+}	mercury(I)	mercurous
Cu^{2+}	copper(II)	cupric	Hg^{2+}	mercury(II)	mercuric
Fe^{2+}	iron(II)	ferrous	**Pb^{2+}**	**lead(II)**	**plumbous**
Fe^{3+}	iron(III)	ferric	**Pb^{4+}**	**lead(IV)**	**plumbic**
Sn^{2+}	tin(II)	stannous	Co^{2+}	cobalt(II)	cobaltous
Sn^{4+}	**tin(IV)**	**stannic**	Co^{3+}	cobalt(III)	cobaltic
Cr^{2+}	chromium(II)	chromous	Ni^{2+}	nickel(II)	nickelous
Cr^{3+}	chromium(III)	chromic	Ni^{4+}	nickel(IV)	nickelic
Mn^{2+}	manganese(II)	manganous	Au^{+}	gold(I)	aurous
Mn^{3+}	manganese(III)	manganic	Au^{3+}	gold(III)	auric

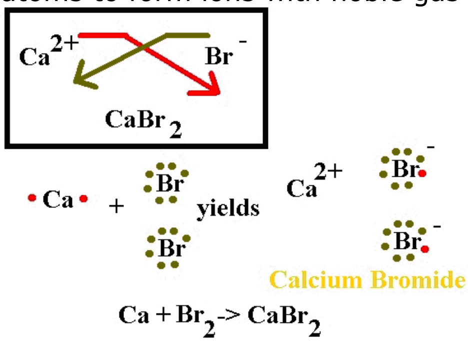
Writing Formulas of Ionic Compounds

For ionic compounds, the name of the positive ion (cation) is given first, followed by the name of the negative ion (anion). There for conversion of name to formula is easy if you know the metal and nonmetal ion symbols and charges. Use the periodic table to decide the charge on both the cation and anion (or the tables) and determine the formula of the compound(s) formed in each case. For transition metals the common ionic charges are given in after the metal name in parenthesis.

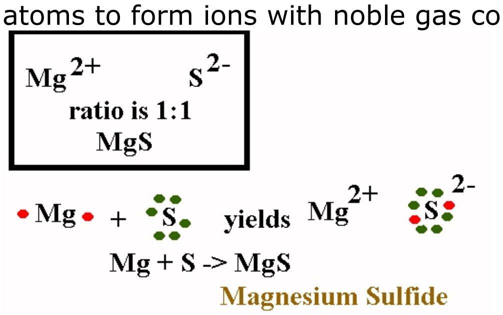
Writing basic ionic compound formulas.

Examples: lithium sulfide; lithium $=Li^{+1}$; sulfide $=S^{-2}$
Write ions on a line: Li^{+1} S^{-2}
Then remove cation and anion charges and exchange them without charge as subscripts on the metal and nonmetal
Li^{+1} S^{-2} becomes Li_2S_1
Remember we omit "1" from the subscript **formula becomes Li_2S**

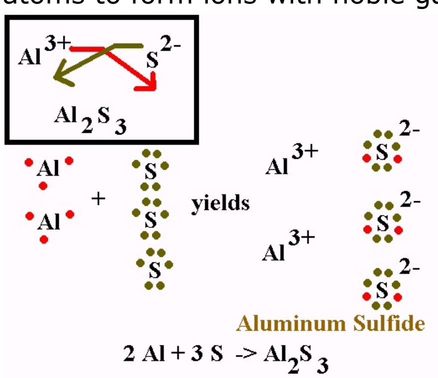
Use electron-dot symbols to show the transfer of electrons from calcium atoms to bromine atoms to form ions with noble gas configurations. Name the compound formed.



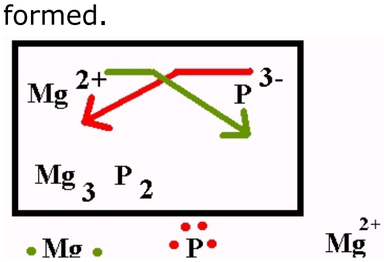
Use electron-dot symbols to show the transfer of electrons from magnesium atoms to sulfur atoms to form ions with noble gas configurations. Name the compound formed.



Use electron-dot symbols to show the transfer of electrons from aluminum atoms to sulfur atoms to form ions with noble gas configurations. Name the compound formed.



Use electron-dot symbols to show the transfer of electrons from magnesium atoms to phosphorous atoms to form ions with noble gas configurations. Name the compound formed.



Magnesium phosphide

Problem: What is the formula of the following compounds given their names?

a. Potassium chloride
b. Magnesium bromide
c. Magnesium nitirde

Answer: First get the formula of ions in the compound. Potassium consists of cation K^+ and chloride Cl^-. Look in the table to get charges on the ions and one need to balance the opposite charges. If charges are equal already formula has 1:1 anions and cation like in K^+ and Cl^-, therefore formula become KCl. If charges are different like in Mg^{2+} and N^{3-} to get the formula usually cross multiply with charges to obtain 3 Mg^{2+} and 2 N^{3-}) and drop the charges and write formula Mg_3N_2.

a. Potassium chloride (one K^+ and one Cl^-) KCl
b. Magnesium bromide (one Mg^{2+} and two Br^-) $MgBr_2$
c. Magnesium nitride (three Mg^{2+} and two N^{3-}) Mg_3N_2

a. Polyatomic Ions

Symbols and Charges for Polyatomic Anions

Ion Formula	Polyatomic Ion Name	Ion Formula	Polyatomic Ion Name
NO_3^-	nitrate	CO_3^{2-}	carbonate
NO_2^-	nitrite	SO_4^{2-}	sulfate
CN^-	cyanide	SO_3^{2-}	sulfite
MnO_4^-	permanganate	PO_4^{3-}	phosphate
OH^-	hydroxide	PO_3^{3-}	phosphite
O_2^{2-}	peroxide	ClO_4^-	perchlorate
HCO_3^-	hydrogen carbonate(bicarbonate)	CN-	cyanide
HSO_4^-	hydrogen sulfate (bisulfate)	ClO_3^-	chlorate
HSO_3^-	hydrogen sulfite (bisulfite)	ClO_2^-	chlorite
HPO_4^{2-}	hydrogen phosphate	ClO^-	hypochlorite
$H_2PO_4^-$	dihydrogen phosphate	CrO_4^{2-}	chromate
SiO_3^{-2}	Silicate	$Cr_2O_7^{2-}$	dichromate
BO_3^{-3}	Borate	AsO_4^{-3}	Arsenate
$C_2H_3O_2$	Acetate $^-$	AsO_4^{-3}	Arsenate
		AsO_3^{-3}	Arsenite

4.11 Chemical Formulas and Names for Ionic Compounds Containing Polyatomic Ions

Problem: Give formula of following ionic compounds

a) aluminum phosphate	b) calcium sulfate	c) cobalt(III) nitrate
d) potassium nitrate	e) potassium permanganate	f) potassium chromate
g) Sodium cyanide	h)	i)

Answers:

a) $AlPO_4$	b) $CaSO_4$	c) $Co(NO_3)_3$
d) KNO_3	e) $KmnO_4$	f) K_2CrO_4
g) NaCN	h)	i)

Problem: Give names of following ionic compounds

a) iron(II) bromide	b) copper(II) sulfate	c) Sodium phospate
d) Sodium sulfite	e) Iron (II) nitrate	f) lithium carbonate
g) Gold (II) chloride	h) calcium bisulfate	i) potassium bicarbonate

Answers:

a) $FeBr_2$	b) $CuSO_4$	c) Na_3PO_4
d) Na_2SO_3	e) $Fe(NO_3)_2$	f) Li_2CO_3
g) $AuCl_2$	h) $Ca(HSO_4)_2$	i) $KHCO_3$

Name the following ionic compounds:

KNO_2	LiCN	NH_4I	$NaNO_3$	$KMnO_4$	$CaSO_4$
$NaHSO_4$	$Al(OH)_3$	Na_2CO_3	$KHCO_3$	NH_4NO_2	$Ca(HSO_4)_2$
Na_2HPO_4	$(NH_4)_3PO_4$	$Al(NO_3)_3$	NH_4NO_3		
Li_2CO_3	$Na_2Cr_2O_7$	$Ca(C_2H_3O_2)_2$	$NH_4C_2H_3O_2$		

Chemistry at a Glance: Nomenclature of Ionic Compounds
Chemical Connections: Fresh Water, Seawater, Hard Water, and Soft Water: A Matter of Ions; Tooth Enamel: A Combination of Monoatomoc and Polyatomic Ions