

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-metal element combinations.	Non-metal and non-metal 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 electrons 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)	Li •	N	[He] 2s ² , p ³ (5 electrons)	• N •
Be	[He] 2s ² (2 electrons)	Be •	O	[He] 2s ² , p ⁴ (6 electrons)	• O •
B	[He] 2s ² , p ¹ (3 electrons)	• B •	F	[He] 2s ² , p ⁵ (7 electrons)	• F •
C	[He] 2s ² , p ² (4 electrons)	• C •	Ne	[He] 2s ² , p ⁶ (8 electrons)	• Ne •

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.

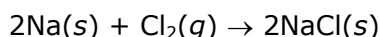
Covalent bonding: Attractions formed when non-metals share electrons to achieve an octet.

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.

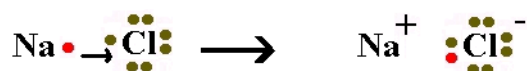
4.4 The Ionic Bond Model

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, **Cl₂(g)** in a violently exothermic reaction where heat is given out to produce **NaCl** ionic solid (composed of Na⁺ and Cl⁻ ions):



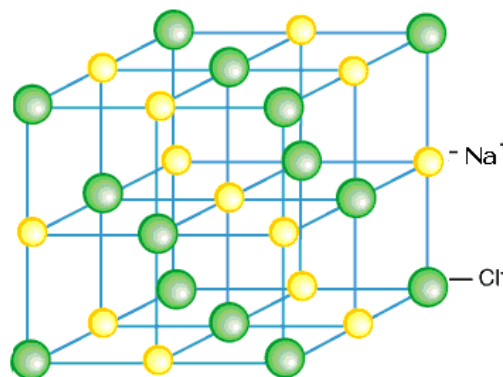
Na(s) lose an electron to chlorine atom and becomes a **Na⁺** (sodium ion) which is isoelectronic to Ne and Cl₂(g) first breaks up to atomic chlorine which then picks the electron lost by the sodium and produce a Cl⁻ (chloride ion) **isoelectronic** to Ar.



Isoelectronic 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^\bullet 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 \ddot{X} becomes \ddot{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 valence electron and become like helium-He forming a **stable cation** - Li^+ .

Non-metals can gain electrons 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.

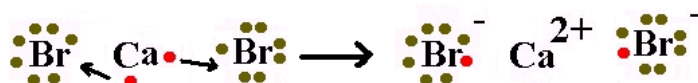
		Predicting charge of Ions of Representative Elements							
Periodic Table Group Number		IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA
Common Lewis symbols		X•	X•	•X•	•X•	•X•	•X•	•X•	•X•
Lewis symbols 2 nd period elements		Li•	Be•	•B•	•C•	•N•	•O•	•F•	•Ne•
Lewis symbols 2 nd period ions		Li ⁺	Be ²⁺	B ⁺³	C ⁻⁴	N ⁻³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

metal
 non-metal

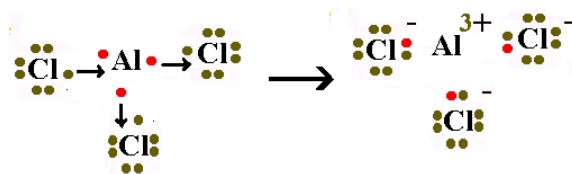
4.6 Lewis Structures for Ionic Compounds

		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, CaBr₂ 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, AlCl₃ Use electron-dot symbols to show the transfer of electrons from aluminum atom to chlorine atoms to form ions Al³⁺ 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 convert 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/ $\text{Ca}^{2+}, \text{O}^{2-}$ / since charge is already balanced formula is **CaO**

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

Getting name from the formula:

Formula	Ions	Name	Formula	Ions	Name
KCl	K^+, Cl^-	potassium chloride	FeCl_3	$\text{Fe}^{+3}, 3\text{Cl}^-$	iron(III) chloride
Mg_3P_2	$3\text{Mg}^{+2}, 2\text{P}^{-3}$	magnesium phosphide	CuCl_2	$\text{Cu}^{+2}, \text{Cl}^-$	copper(II) chloride
$\text{Ca}(\text{NO}_3)_2$	$\text{Ca}^{+2}, 2\text{NO}_3^-$	calcium nitrate	$\text{Na}_2\text{Cr}_2\text{O}_7$	$2\text{Na}^+, \text{Cr}_2\text{O}_7^{-2}$	sodium dichromate
HgCl_2	$\text{Hg}^{+2}, 2\text{Cl}^-$	mercury(II) chloride	K_3PO_4	$3\text{K}^+, \text{PO}_4^{-3}$	potassium phosphate
CaO	$\text{Ca}^{2+}, \text{O}^{2-}$	calcium oxide	CaSO_3	$\text{Ca}^{+2}, \text{SO}_3^{-2}$	calcium sulfite
NH_4NO_3	$\text{NH}_4^+, \text{NO}_3^-$	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. 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 " $\text{Ca}(\text{SO}_4)$ ").

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-}	Na^+	Mg^{2+}	Al^{3+}	Cl^-	O^{2-}	N^{3-}
	K^+	potassium cation					Na^+	sodium cation			
	Ca^{2+}	calcium cation					Mg^{2+}	magnesium cation			
	Zn^{2+}	zinc cation					Al^{3+}	aluminum cation			
	Br^-	bromide anion					Cl^-	chloride anion			
	Li^+	lithium cation					O^{2-}	oxide anion			
	S^{2-}	sulfide anion					N^{3-}	nitride anion			

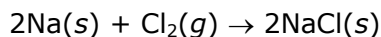
Name the following ions:

- 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):



Na(s) lose an electron and becomes a Na⁺ (sodium ion) which is isoelectronic to Ne and Cl₂(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

An 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 numbers each atom 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
	Ag ⁺	Silver 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 indicate 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	Hg₂²⁺	mercury(I)	mercurous
Cu²⁺	copper(II)	cupric	Hg²⁺	mercury(II)	mercuric
Fe²⁺	iron(II)	ferrous	Pb²⁺	lead(II)	plumbous
Fe³⁺	iron(III)	ferric	Pb⁴⁺	lead(IV)	plumbic
Sn²⁺	tin(II)	stannous	Co²⁺	cobalt(II)	cobaltous
Sn⁴⁺	tin(IV)	stannic	Co³⁺	cobalt(III)	cobaltic
Cr²⁺	chromium(II)	chromous	Ni²⁺	nickel(II)	nickelous
Cr³⁺	chromium(III)	chromic	Ni⁴⁺	nickel(IV)	nickelic
Mn²⁺	manganese(II)	manganous	Au⁺	gold(I)	aurous
Mn³⁺	manganese(III)	manganic	Au³⁺	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**

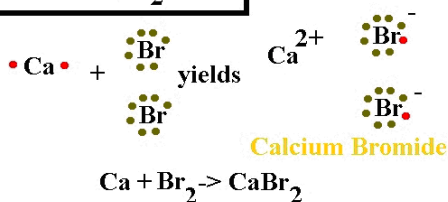
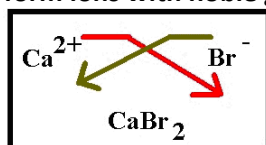
Write ions on a line: **Li⁺¹ S⁻²**

Then remove cation and anion charges and exchange them without charge as subscripts on the metal and nonmetal

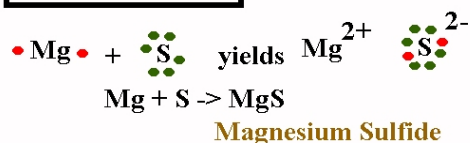
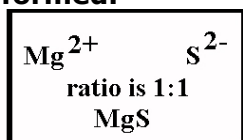
Li⁺¹ S⁻² becomes Li₂S₁

Remember we omit "1" from the subscript **formula becomes Li₂S**

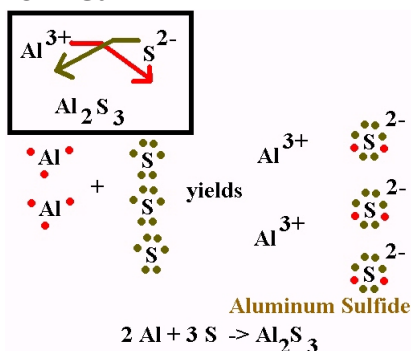
Use electron-dot symbols to show the transfer of electrons from calcium atoms to bromine atoms to form ions with noble gas configurations. Name the compound formed.



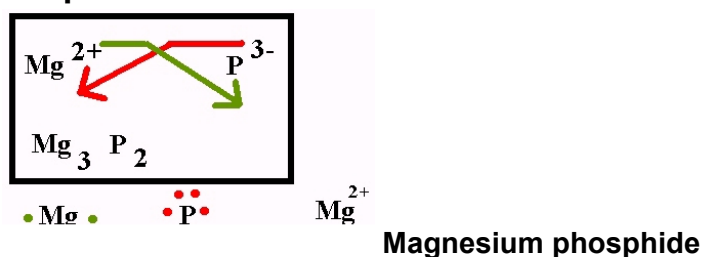
Use electron-dot symbols to show the transfer of electrons from magnesium atoms to sulfur atoms to form ions with noble gas configurations. Name the compound formed.



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.



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

- Potassium chloride
- Magnesium bromide
- Magnesium nitride

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 .

- 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

4.10 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	$\text{Cr}_2\text{O}_7^{2-}$	dichromate
BO_3^{3-}	Borate	AsO_4^{3-}	Arsenate
$\text{C}_2\text{H}_3\text{O}_2^-$	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) $\text{Co}(\text{NO}_3)_3$
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 phosphate
d) sodium sulfite	e) iron (II) nitrate	f) lithium carbonate
g) gold (II) chloride	h) calcium bisulfate	i) potassium bicarbonate

Answers:

a) FeBr₂	b) CuSO₄	c) Na₃PO₄
d) Na₂SO₃	e) Fe(NO₃)₂	f) Li₂CO₃
g) AuCl₂	h) Ca(HSO₄)₂	i) KHCO₃

Name the following ionic compounds:

KNO₂	LiCN	NH₄I	NaNO₃	KMnO₄	CaSO₄
NaHSO₄	Al(OH)₃	Na₂CO₃	KHCO₃	NH₄NO₂	Ca(HSO₄)₂
Na₂HPO₄	(NH₄)₃PO₄	Al(NO₃)₃	NH₄NO₃		
Li₂CO₃	Na₂Cr₂O₇	Ca(C₂H₃O₂)₂	NH₄C₂H₃O₂		

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 Monoatomic and Polyatomic Ions