

Chapter 3: Ions, Ionic Compounds, and Nomenclature.

An **ion** is a small particle having an electrical charge. Ions are either single, charged atoms (**simple ions**), or small charged “molecules” (**polyatomic ions**). Examples of simple ions are Na^+ , Ca^{+2} , Cl^- , and S^{-2} . Examples of polyatomic ions are NH_4^+ , CO_3^{-2} , and OH^- . Positively charged ions are called **cations** (pronounced cat-eye-ons) while negatively charged ions are called **anions** (pronounced an-eye-ons). In many cases, the elements position on the periodic table will help you determine the kind of ion formed (anion or cation) and the size of the ionic charge.

Look at the periodic table (PeriodicTable.pdf or the equivalent). Starting with boron (atomic number 5) and continuing downwards and to the right to astatine (atomic number 85), there is a bold “staircase” shaped red line. Elements to the left of this line are metals, and commonly form cations. Elements to the right of this line are non-metals, and commonly form anions. Some of the elements adjacent to the line are called “metalloids”, but this distinction doesn’t help us, so don’t concern yourself with it.

Starting on the left of the periodic table, we see groups labeled “I A”, “II A”, “III B”, and so on. On some newer versions of the periodic table, the groups are numbered 1 - 18. I will use the older version, and show the new group numbers in parenthesis.

The elements in any particular group tend to form ions with characteristic charges. Please note, some elements are capable of having a range of electrical charges, and therefore form different ions.

Group I A (1) elements form cations with +1 charge.

Group II A (2) elements form cations with +2 charge.

Groups III B through II B (3 – 12) are transition metals. These elements form cations having varying amounts of charge. Charges of +2 or +3 are common, but charges from +1 to +6 can be found. There is no simple way of accurately predicting the charges for these elements.

Group III A (13) metals form cations with +3 charge. Please note that the first element in this group, boron (B) is a non-metal and typically doesn’t form a cation.

Group IV A (14) metals form cations with +4 charge, although tin (Sn) and lead (Pb) can form cations having +2 charge. Generally, metals in this group are treated similarly to the “B” elements. The non-metals carbon (C) and silicon (Si) generally don’t form cations.

Group V A (15) non-metals (nitrogen (N), phosphorous (P)) form anions with a -3 charge. Arsenic (As) anion has -3 charge, but also forms cations with $+3$ or $+5$ charge. Bismuth (Bi) behaves similarly to arsenic.

Group VI (16) non-metals form anions having -2 charge. Polonium (atomic number 84) forms only cations.

Group VII A (17) elements form anions having -1 charge.

Group VIII A (18) elements are normally uncharged.

Figure 3.1 below summarizes the typical charges on anions and cations.

I A		II A		III B to II B					VIII A	
				III A	IV A	V A	VI A	VII A		
Li^+	Be^{+2}					N^{-3}	O^{-2}	F^-		
Na^+	Mg^{+2}			Al^{+3}		P^{-3}	S^{-2}	Cl^-		
K^+	Ca^{+2}			Ga^{+3}		As^{-3}	Se^{-2}	Br^-		
Rb^+	Sr^{+2}			In^{+3}			Te^{-2}	I^-		
Cs^+	Ba^{+2}			Tl^{+3}				At^-		
Fr^+	Ra^{+2}									

Figure 3.1. Pattern of Ionic Charges.

Nomenclature of simple ions

There are only two rules for naming simple ions.

Rule 1: Cations. Naming the element and adding the word “ion” forms the cation name. So, Na^+ is “sodium ion”. Ca^{+2} is “calcium ion”. Al^{+3} is “aluminum ion”. For transition metal cations from groups III B – II B (3 - 12), the cation name is the name of the element, plus the size of the ionic charge. For example, Fe^{+3} is “iron three ion”. Pb^{+2} is “lead two ion”. When writing these names, we commonly use Roman numerals in parenthesis to indicate charge size. “Iron three ion” is written

as Fe(III), while “lead two ion” is written as Pb(II). NOTE: while either Fe^{+3} or Fe(III) can be used to identify the ion, Fe(III)^{+3} is just wrong.

Cations formed from the metallic elements in Groups III A – VII A; gallium (Ga), germanium (Ge), indium (In), tin (Sn), antimony (Sb), thallium (Tl), lead (Pb), and bismuth (Bi), are named like the transition metals. The nonmetals arsenic (As), tellurium (Te) and selenium (Se) are also named like the transition metals, and can form either cations or anions.

Rule 2: anions. The anion name is formed from the name of the element, but “ide” replaces the normal ending in the elements name. So Cl^- is the ion formed from **chlorine** and its name is **chloride ion**. N^{3-} is the ion formed from **nitrogen** and its name is **nitride ion**. S^{2-} is the ion formed from **sulfur** and its name is **sulfide ion**. Sometimes, the names of simple anions are given without “ion”, i.e. chloride, nitride, sulfide. Table 3.1 gives the names of common, simple anions.

Formula	Name	Formula	Name
F^-	fluoride	Cl^-	chloride
Br^-	bromide	I^-	iodide
O^{2-}	oxide	S^{2-}	sulfide
N^{3-}	nitride	P^{3-}	phosphide

Table 3.1. Common, simple anions.

It is critically important that you distinguish between elements and the ions formed from the elements. An element and its ion are related, just as you and your parents are related. However, just as you and your mother are different people, an element and its ion are different chemical species, and they have different physical and chemical properties. Calling *chloride* “chlorine”, or *chlorine* “chloride”, is wrong, confusing, dangerous, and potentially lethal.

Polyatomic ions

While there are many polyatomic ions, there are only a few that are relatively common. You must memorize these polyatomic ions. Make sure you memorize the correct formula, the correct charge, and the name. Flash cards with the formula and charge on one side, and the name on the opposite side, are a good studying tool.

Polyatomic cations:

NH_4^+	ammonium ion (not to be confused with NH_3 , ammonia)
H_3O^+	hydronium ion

Polyatomic anions:

Formula	Name	Formula	Name
OH^-	hydroxide ion	NO_3^-	nitrate ion
		NO_2^-	nitrite ion
CO_3^{2-}	carbonate ion	SO_4^{2-}	sulfate ion
HCO_3^-	hydrogen carbonate (or bicarbonate)	HSO_4^-	hydrogen sulfate ion (bisulfate)
PO_4^{3-}	phosphate ion	SO_3^{2-}	sulfite ion
HPO_4^{2-}	monohydrogen phosphate	HSO_3^-	hydrogen sulfite ion (bisulfite)
H_2PO_4^-	dihydrogen phosphate		
ClO^-	hypochlorite ion	CrO_4^{2-}	chromate ion
ClO_2^-	chlorite ion	$\text{Cr}_2\text{O}_7^{2-}$	dichromate ion
ClO_3^-	chlorate ion		
ClO_4^-	perchlorate ion		
MnO_4^-	permanganate ion	$\text{C}_2\text{H}_3\text{O}_2^-$	acetate ion
CN^-	cyanide ion	$\text{C}_2\text{O}_4^{2-}$	oxalate ion

Hydrogen

Hydrogen is a special case. Hydrogen can form a cation (H^+) or an anion (H^-). Generally, in combination with other non-metals, hydrogen does not form ions. Hydrogen in water (H_2O), ammonia (NH_3), methane (CH_4) and millions of other compounds is neither a cation nor an anion. In a few compounds, called acids,

hydrogen forms hydrogen cations. In even fewer compounds is hydrogen present as the anion.

Ionic Compounds and Their Nomenclature

An ionic compound is a substance composed of oppositely charged ions held together by the attractive forces between opposite charges (Coulomb attractive forces).

There are two general types of ionic compounds. The first type, and the simplest, contains simple cations and anions. If you look at the periodic table, you will notice a stair-step shaped line starting at boron (element 5) and continuing down and right to astatine (element 85). All elements on the left hand side of this line are metals (with the exception of hydrogen), and all elements on the right hand side of this line are nonmetals. We recognize NaCl as an ionic compound since it contains the metal Na and the nonmetal Cl. We know that CO₂ is not an ionic compound, since it is composed only of nonmetallic elements. The substance CoNi is not an ionic compound, since it only contains metals, but Na₂O is an ionic compound, since it contains both a metal and a nonmetal.

The second type of ionic compound is composed either partly or entirely of polyatomic ions such as ammonium (NH₄⁺), sulfate (SO₄⁻²), carbonate (CO₃⁻²), etc. In order to recognize these types of ionic compounds, you must be able to recognize the polyatomic ions when you see them in chemical formulas. **NOTE:** in chemical formulas, the ion charges are **NOT** shown – you need to know the charge each polyatomic ion has in its ionic form. For example, when ammonium ions combine with chloride ions, the formula for the compound is NH₄Cl, and **NOT** NH₄⁺Cl⁻. Showing the charges of ions when they are combined into compounds is **WRONG!**

In writing the chemical formulas of ionic compounds, it is customary to indicate the cation(s) first, and then the anion(s). If sodium ions combine with carbonate ions we represent this compound as Na₂CO₃. If ammonium ions combine with sulfate ions, we represent this compound as (NH₄)₂SO₄.

The formula for our first compound clearly indicates two sodium ions (Na⁺) combined with a single carbonate ion (CO₃⁻²). The two +1 charges provided by the sodium ions exactly cancel the single -2 charge from the carbonate ion, and the resulting compound has a net charge of zero (it is electrically neutral).

The formula for our second compound is slightly more complicated, but is not particularly difficult. The formula shows the ammonium ion, NH₄⁺, enclosed within a set of parenthesis. These parenthesis are used whenever needed to prevent writing two or more subscripts consecutively. Using the representation (NH₄⁺)₂ allows us to see that there are two separate ammonium ions present in this

compound. Without the parenthesis, $\text{NH}_4^+ 2$ would be confusing. In this compound, the two +1 charges from the ammonium ions exactly cancel the single -2 charge from the sulfate ion.

For an electrically neutral ionic compound, the sum of the positive charges must exactly equal the sum of the negative charges. We use this rule to guide us in writing the formulas of ionic compounds. Consider the examples in Table 3.3 below.

Ions	Cl^-	CO_3^{-2}	OH^-	SO_4^{-2}
Na^+	NaCl	Na_2CO_3	NaOH	Na_2SO_4
NH_4^+	NH_4Cl	$(\text{NH}_4)_2\text{CO}_3$	NH_4OH	$(\text{NH}_4)_2\text{SO}_4$
Mg^{+2}	MgCl_2	MgCO_3	$\text{Mg}(\text{OH})_2$	MgSO_4
Fe^{+3}	FeCl_3	$\text{Fe}_2(\text{CO}_3)_3$	$\text{Fe}(\text{OH})_3$	$\text{Fe}_2(\text{SO}_4)_3$

Table 3.3. Examples of formulas of ionic compounds.

Naming these compounds is relatively simple. First name the cation, then the anion. The compound's name is the name of the cation followed by the name of the anion, omitting in both cases the additional term "ion". So, for our compound composed of sodium ions and carbonate ions, the name of this material is "sodium carbonate". Similarly, the name of our compound made of ammonium ion and sulfate ion is "ammonium sulfate".

NOTE: in naming ionic compounds, if all of the cations are identical and all of the anions are identical, then we NEVER use any kind of numerical prefix to indicate the number of ions of a given type present in the compound. We never call sodium carbonate "disodium carbonate" and it is wrong to call ammonium sulfate "diammonium sulfate". The reason is clear: carbonate has a -2 charge, and sodium has a +1 charge. The only way for the compound to be electrically neutral is to have 2 sodium ions and 1 carbonate. Similarly, ammonium has a +1 charge and sulfate has a -2 charge. The only way for this compound to be electrically neutral is to have 2 ammonium ions and 1 sulfate.

What if we had 1 sodium ion combined with 1 carbonate? Well, the material would be represented as NaCO_3^- , because only 1 of the 2 negative charges on carbonate would be neutralized by the single positive charge provided by a single sodium ion. The species produced would not be a neutral compound: since it still possesses an electrical charge, it would be an ion!!

What if we have two or more cations (or anions) in a compound? The same rules for writing the formula and naming the compound would apply. A compound made of potassium ion (K^+), lithium ion (Li^+) and sulfate anion would be

represented as KLiSO_4 and would be named potassium lithium sulfate. These types of compounds are relatively rare, and not particularly helpful in learning the rules of nomenclature.

For some compounds containing polyatomic anions, several different names can be assigned to the same material. Some of these names are customary or trivial names, while some are based upon more formalized rules of nomenclature. For example, the compound with the formula NaH_2PO_4 has at least six different names still currently used: sodium phosphate monobasic, monosodium orthophosphate, monosodium phosphate, sodium acid phosphate, sodium biphosphate, and sodium dihydrogen phosphate. Perhaps someday common sense will break out and everyone will name this substance sodium dihydrogen phosphate, but I won't hold my breath.

As a practical matter, compounds containing one divalent or higher cation and several monovalent anions, such as AlClBrI , are so rarely encountered that the student need not worry about them. More commonly encountered are substances such as NaKO , or BaKN . Rules for naming these materials are the same as for their polyatomic anion analogs. These compounds are sodium potassium oxide and barium potassium nitride respectively.

The last class of ionic compounds is those containing transition metal cations. Since these cations have a range of positive charges, we write the cation name with the charge indicated by Roman numerals in parenthesis. The formula for a compound containing Fe^{+3} and Cl^- ions is FeCl_3 , and its name is "iron (III) chloride". This allows us to distinguish between this compound and a related material composed of Fe^{+2} ions and Cl^- ions. The formula for this compound is FeCl_2 , and the name is "iron (II) chloride". Simply calling either of these substances "iron chloride" is not useful, because this name doesn't distinguish between the two varieties of iron cations. Once again, a numerical prefix such as di, tri, tetra, and so on, is neither required nor correct when the compound is composed of one type of cation and anion. Naming iron (III) chloride "iron trichloride" is just wrong.

Vocabulary. The following terms are defined and explained in the text. Make sure that you are familiar with the meanings of the terms as used in chemistry. Understand that you may have been given incomplete or mistaken meanings for these terms in earlier courses. The meanings given in the text are correct and proper.

Ion	Simple ion	Polyatomic ion
Cation	Anion	

Homework:

1. For the following elements, write the formula including charge of the simple ion that is commonly formed, and the name of the ion formed.

Ca	Br	Na
S	I	O
K	N	Al
Mg	Ba	Sr
Li	Cl	F

2. From the following names of ions, write the chemical formula of the ion and the correct electrical charge. Be sure to include the proper sign (+ or -).

Iron(III)	Sulfide	Manganese(VII)
Acetate	Hg(II)	Chromium(III)
Ammonium	Tin(IV)	Phosphate
Vanadium(II)	Hypochlorite	Hydrogen carbonate
Hydronium	Nitrite	Chloride

3. In the blank spaces, write the correct formula for the ionic compound made from the indicated cations and anions. Follow the pattern shown in Table 3.3.

	Br^-	$\text{C}_2\text{O}_4^{2-}$	OH^-	SO_4^{2-}	PO_4^{3-}	NO_3^-
Li^+						
NH_4^+						
K^+						
Sr^{+2}						
Cu^{+2}						
Pb^{+2}						
Fe^{+3}						
Al^{+3}						
Nb^{+3}						
Fe^{+2}						
H^+						

4. For the following compounds, write all ions needed to form the compound (including the charge). Write the name of the compound.

CaSO_4	NaOH	AlBr_3
SrS	LiI	Na_2O
KClO	Na_3N	Al_2S_3
$\text{Mg}(\text{OH})_2$	BaCO_3	$\text{Sr}(\text{NO}_3)_2$
LiF	SnCl_4	FeF_3

5. For the following compounds, write the correct formula.

Iron (III) nitrate	Barium sulfide	Manganese (IV) chloride
Copper (II) acetate	Mercury (II) bromide	Chromium (III) oxide
Ammonium carbonate	Tin (IV) sulfate	Strontium hydrogen phosphate
Calcium chloride.	Magnesium perchlorate	Zinc (II) nitrite

Answers:

1.

Ca⁺² Calcium ion	Br⁻ Bromide	Na⁺ Sodium ion
S⁻² Sulfide	I⁻ Iodide	O⁻² Oxide
K⁺ Potassium ion	N⁻³ Nitride	Al⁺³ Aluminum ion
Mg⁺² Magnesium ion	Ba⁺² Barium ion	Sr⁺² Strontium ion
Li⁺ Lithium ion	Cl⁻ Chloride	F⁻ Fluoride

2.

Fe⁺³	S⁻²	Mn⁺⁷
C₂H₃O₂⁻	Hg⁺²	Cr⁺³
NH₄⁺	Sn⁺⁴	PO₄⁻³
V⁺²	ClO⁻	HCO₃⁻
H₃O⁺	NO₂⁻	Cl⁻

3.

	Br ⁻	C ₂ O ₄ ⁻²	OH ⁻	SO ₄ ⁻²	PO ₄ ⁻³	NO ₃ ⁻
Li ⁺	LiBr	Li₂C₂O₄	LiOH	Li₂SO₄	Li₃PO₄	LiNO₃
NH ₄ ⁺	NH₄Br	(NH₄)₂C₂O₄	NH₄OH	(NH₄)₂SO₄	(NH₄)₃PO₄	NH₄NO₃
K ⁺	KBr	K₂C₂O₄	KOH	K₂SO₄	K₃PO₄	KNO₃
Sr ⁺²	SrBr₂	SrC₂O₄	Sr(OH)₂	SrSO₄	Sr₃(PO₄)₂	Sr(NO₃)₂
Cu ⁺²	CuBr₂	CuC₂O₄	Cu(OH)₂	CuSO₄	Cu₃(PO₄)₂	Cu(NO₃)₂
Pb ⁺²	PbBr₂	PbC₂O₄	Pb(OH)₂	PbSO₄	Pb₃(PO₄)₂	Pb(NO₃)₂
Fe ⁺³	FeBr₃	Fe₂(C₂O₄)₃	Fe(OH)₃	Fe₂(SO₄)₃	FePO₄	Fe(NO₃)₃
Al ⁺³	AlBr₃	Al₂(C₂O₄)₃	Al(OH)₃	Al₂(SO₄)₃	AlPO₄	Al(NO₃)₃
Nb ⁺³	NbBr₃	Nb₂(C₂O₄)₃	Nb(OH)₃	Nb₂(SO₄)₃	NbPO₄	Nb(NO₃)₃
Fe ⁺²	FeBr₂	FeC₂O₄	Fe(OH)₂	FeSO₄	Fe₃(PO₄)₂	Fe(NO₃)₂
H ⁺	HBr	H₂C₂O₄	HOH	H₂SO₄	H₃PO₄	HNO₃

4.

CaSO ₄ Ca⁺², SO₄⁻ Calcium sulfate	NaOH Na⁺, OH⁻ Sodium hydroxide	AlBr ₃ Al⁺³, Br⁻ Aluminum bromide
SrS Sr⁺², S⁻² Strontium sulfide	LiI Li⁺, I⁻ Lithium iodide	Na ₂ O Na⁺, O⁻² Sodium oxide
KClO K⁺, ClO⁻ Potassium hypochlorite	Na ₃ N Na⁺, N⁻³ Sodium nitride	Al ₂ S ₃ Al⁺³, S⁻² Aluminum sulfide
Mg(OH) ₂ Mg⁺², OH⁻ Magnesium hydroxide	BaCO ₃ Ba⁺², CO₃⁻ Barium carbonate	Sr(NO ₃) ₂ Sr⁺², NO₃⁻ Strontium nitrate
LiF Li⁺, F⁻ Lithium fluoride	SnCl ₄ Sn⁺⁴, Cl⁻ Tin (IV) chloride	FeF ₃ Fe⁺³, F⁻ Iron (III) fluoride

5.

Iron (III) nitrate $\text{Fe}(\text{NO}_3)_3$	Barium sulfide BaS	Manganese (IV) chloride MnCl_4
Copper (II) acetate $\text{Cu}(\text{C}_2\text{H}_3\text{O}_2)_2$	Mercury (II) bromide HgBr_2	Chromium (III) oxide Cr_2O_3
Ammonium carbonate $(\text{NH}_4)_2\text{CO}_3$	Tin (IV) sulfate $\text{Sn}(\text{SO}_4)_2$	Strontium hydrogen phosphate SrHPO_4
Calcium chloride CaCl_2	Magnesium chlorate $\text{Mg}(\text{ClO}_3)_2$	Zinc (II) nitrite $\text{Zn}(\text{NO}_2)_2$