8.2 Ion Charge and the Formulas of Ionic Compounds

LEARNING TIP
Make connections to your prior knowledge. In mathematics, you learned that a ratio is one thing compared with, or related to, another thing. How does this relate to what you are learning about The Law of Definite Proportions?

An important discovery that led to modern chemistry was the discovery that elements combine with other elements in specific proportions to form compounds that always have the same proportions. The alchemists believed that finding the right mixture would create the substance they desired, but experiments showed that elements could not be combined in just any proportion. For example, when sodium and chlorine react, they never form $NaCl_2$, Na_2Cl, or any combination other than $NaCl$. This was a spectacular discovery. Joseph Proust proposed the **Law of Definite Proportions** in 1799: *A specific compound always contains the same elements in definite proportions.* Early chemists understood how elements combined. They didn't understand, however, why elements combine in specific ways.

Ionic Compounds: Metals Combining with Non-Metals

As you learned in Chapter 7, ions are charged atoms. Ions are formed when an atom gains or loses sufficient electrons to have a full outer shell. When a metal atom collides with a non-metal atom, electrons are transferred to form ions, and the ions are bonded by the electrical force to form compounds. These compounds are called ionic compounds. They are electrically neutral because they have positive and negative charges of equal size. Many common compounds are examples of ionic compounds, such as table salt (sodium chloride), chalk (calcium carbonate), and a decay-preventing ingredient in toothpaste (sodium fluoride).

Formulas for Ionic Compounds with Two Elements Combining

Knowing the ion charge of an element makes it possible to predict how the element will react to form compounds with other elements. Tables 1 and 2 provide ion charges of some metals and non-metals. The common ion charge of elements is also indicated in the Periodic Table at the back of this book.

When ionic compounds form, every electron that is given up by a metal atom must be accepted by a non-metal atom. If the elements have equal but opposite ion charges, then they will combine in the ratio 1:1. For example, if magnesium and oxygen combine, then for every one magnesium atom that gives up two electrons, there will be one oxygen atom that accepts two electrons. If the two elements have unequal and opposite ion charges, then the elements will combine in a ratio so that the total number of electrons transferred equals the total number of electrons accepted. For example, if magnesium and chlorine combine, for every one magnesium atom giving up two electrons, there will be two chlorine atoms accepting one electron each (for a total of two accepted).

To summarize, *the total number of electrons transferred to form a single unit of the compound will be the lowest common multiple (LCM) of the two ion charges.*

Table 1 Ion Charge of Some Metals

Element	Symbol	Ion charge
aluminum	Al	3+
barium	Ba	2+
beryllium	Be	2+
bismuth	Bi	3+
boron	B	3+
calcium	Ca	2+
cesium	Cs	1+
lithium	Li	1+
magnesium	Mg	2+
potassium	K	1+
silver	Ag	1+
sodium	Na	1+
strontium	Sr	2+
zinc	Zn	2+

Table 2 Ion Charge of Some Non-Metals

Element	Symbol	Ion charge
bromine	Br	1−
chlorine	Cl	1−
fluorine	F	1−
iodine	I	1−
oxygen	O	2−
phosphorous	P	3−
sulfur	S	2−

If calcium (2+) combines with phosphorous (3−), the LCM of 2 and 3 is 6. Therefore, 3 calcium atoms ($3 \times 2+$) will be required for every 2 phosphorous atoms ($2 \times 3-$) in order to balance the charges.

Here is a simple procedure for writing the formulas of ionic compounds with two elements.

1. If the ion charges are balanced, the ratio of the ions in the compound is 1:1 (Table 3):

Table 3

Metal	Non-metal	Charge balance	Formula
magnesium Mg^{2+}	sulfur S^{2-}	2+ to 2−	MgS
lithium Li^{+}	bromine Br^{-}	1+ to 1−	$LiBr$

2. If the ion charges are not balanced, use subscripts to create multiples to balance the total charges (number of electrons given/accepted) (Table 4):

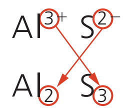
Table 4

Metal	Non-metal	Charge balance	Formula
calcium Ca^{2+}	iodine I^{-}	2+ to 2(1−)	CaI_2
potassium K^{+}	oxygen O^{2-}	2(1+) to 2−	K_2O
aluminum Al^{3+}	sulfur S^{2-}	2(3+) to 3(2−)	Al_2S_3

Al^{3+}	S^{2-}
Al	S

Quick Trick to Balance Charges

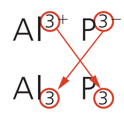
- Write the metal and non-metal elements in their ion form.
- Below them, write the metal and non-metal elements again, without the ion charges (see box to the left).
- Bring the number above the metal element down to be the subscript of the non-metal, and vice versa, as shown below. This is called the crisscross method.



The formula is Al_2S_3. This can be verified using Bohr diagrams (Figure 1).

LEARNING TIP
Check your understanding. Use Figure 1 to explain to a partner how electrons are given and accepted when an ionic compound is formed.

- If there is a common factor in the subscripts generated, you must reduce the subscripts as a final step.



The formula is not Al_3P_3, but simply AlP.

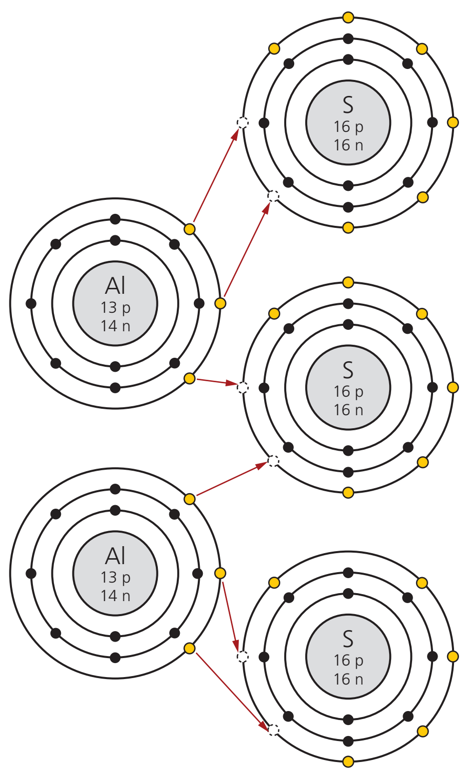


Figure 1 Bohr diagrams for aluminum and sulfur can be used to verify the balance of electrons transferred. The two aluminum atoms give up a total of six electrons, and the three sulfur atoms acquire a total of six electrons.

TRY THIS: *The Compounding Party*

Skills Focus: creating models, communicating

In this activity, you and your classmates will play the roles of metals and non-metals trying to form compounds. The metal atoms must meet non-metal atoms and transfer electrons to become ions. There is a catch, however. Electrons cannot be transferred until an exact match is arranged first.

Materials: approximately 50 pennies, marbles, or other token of exchange; name tags or sticky notes, labelled with an element name and its ion charge (for example, "Hi, my name is Mag Nesium (2+).")

1. Obtain your name tag from your teacher. Metal students will get a number of tokens equal to their ion charge.
2. Metals must give up all their tokens when compounding. Non-metals must accept the number of tokens equal to their ion charge.
3. Circulate around the room and match up with another element to form a compound by transferring tokens. Depending on which element you are, you may need more than two people to form your compound.
4. After the transfer, turn your name tags upside down to indicate that you have formed ions and are no longer available to other atoms. Write down how many people in your compound have the metal name and how many have the non-metal name.

A. What was the formula of your compound?

B. Other compounds were formed in the room? What were their formulas?

C. Was every student in the room able to become part of a compound? Explain why or why not.

Formulas for Ionic Compounds with Polyatomic Ions

Recall that polyatomic ions act as a unit with a shared ion charge (Table 5). To write the formulas for compounds with polyatomic ions, you use the same method you used for two elements combining, but you must keep the atoms of the polyatomic ion together.

Table 5 Ion Charges of Common Polyatomic Ions

Group	Formula	Ion charge
ammonium	NH_4	1+
carbonate	CO_3	2−
hydrogen carbonate	HCO_3	1−
hydroxide	OH	1−
nitrate	NO_3	1−
phosphate	PO_4	3−
sulfate	SO_4	2−

Below is a simple procedure for writing the formulas of ionic compounds with one element and one polyatomic group.

1. If the ion charges are balanced, the ratio of the ions in the compound is 1:1 (Table 6).

Table 6

Metal	Non-metal	Charge balance	Formula
ammonium NH_4^{+}	chlorine Cl^{-}	1+ to 1−	NH_4Cl
barium Ba^{2+}	sulfate SO_4^{2-}	2+ to 2−	$BaSO^4$

2. If the ion charges are not balanced, use subscripts (Table 7). Use brackets to show if more than one polyatomic ion is needed. The number of polyatomic ions goes outside the brackets.

Table 7

Metal	Non-metal	Charge balance	Formula
calcium Ca^{2+}	nitrate NO_3^-	2+ to 2(1−)	$Ca(NO_3)_2$
ammonium NH_4^+	sulfur S^{2-}	2(1+) to 2−	$(NH_4)_2S$
aluminum Al^{3+}	sulfate SO_4^{2-}	2(3+) to 3(2−)	$Al_2(SO_4)_3$

Quick Trick to Balance Charges

Use the same procedure that you used to balance formulas with two elements, but make sure the number of polyatomic ions is outside the brackets.

$$Al^{3+} \quad SO_4^{2-}$$

$$Al_2(SO_4)_3$$

LEARNING TIP

The prefix *mono* indicates one ion charge. The prefix *multi* indicates more than one, or multiple, ion charges.

Formulas for Ionic Compounds with More Than One Ion Charge

Many elements are **monovalent**—they have only one ion charge. Through experiments, however, chemists found that some elements have multiple ion charges. These elements are called **multivalent** and only occur after atomic number 20. Their electron shells are more complicated than those of the first 20 elements in the Periodic Table. Some common examples are shown in Table 8. Note that Roman numerals are used in the name to indicate the different ion charges of the same elements.

Table 8 Common Multivalent Metals and Their Ion Charges

Element	Symbol	Ion charge
chromium(II)	Cr	2+
chromium(III)	Cr	3+
copper(I)	Cu	1+
copper(II)	Cu	2+
iron(II)	Fe	2+
iron(III)	Fe	3+
lead(II)	Pb	2+
lead(IV)	Pb	4+
nickel(II)	Ni	2+
nickel(III)	Ni	3+

A difference in the ion charge makes copper(I) and copper(II) very different ions. The compounds they form have different properties. For example, copper(II) ions form compounds that tend to be blue or blue-green in colour. Copper(I) ions form compounds that tend to be white. Copper metal left unprotected outdoors acquires a patina on the surface (Figure 2). Which ion of copper is in a patina? Another example is iron(II) and iron(III): iron(III) oxide (rust) is dark red and often used in pigments, while iron(II) oxide is jet-black.

Figure 2 The Legislative Building in Victoria, B.C. The blue-green colour of the copper roof is due to copper(II) ions that form as the copper metal reacts with the atmosphere.

Some examples of compounds made from multivalent elements are given in Table 9.

Table 9 Formulas for Some Compounds with Multivalent Elements

Name	Formula
iron(III) chloride	$FeCl_3$
iron(II) chloride	$FeCl_2$
copper(I) hydroxide	$CuOH$
copper(II) hydroxide	$Cu(OH)_2$

The name of the multivalent ion indicates the ion charge (Table 10). The rules for writing formulas with multivalent ions are the same as the rules you previously learned in this section.

Table 10

Metal	Non-metal	Charge balance	Formula
chromium(II)	chlorine	2+ to 2(1−)	$CrCl_2$
iron(III)	sulfate	2(3+) to 3(2−)	$Fe_2(SO_4)_3$
lead(IV)	oxygen	4+ to 2(2+)	PbO_2

8.2

CHECK YOUR Understanding

1. Define the Law of Definite Proportions in your own words.
2. How do you recognize the difference between the ion charge of a metal and the ion charge of a non-metal?
3. What happens to the charge on individual ions when they form compounds?
4. Define "polyatomic ion". Give three examples of polyatomic ions.
5. What is the ion charge of each of the following individual or polyatomic ions?
   (a) calcium
   (b) aluminum
   (c) copper(II)
   (d) ammonium
   (e) iron(II)
   (f) sulfur
   (g) oxygen
   (h) fluorine
   (i) nitrate
   (j) carbonate
6. What is the basic rule for predicting how the ions of a metal and a non-metal will react to form a compound? Give an example.
7. Define monovalent and give an illustrative example.
8. Explain why the names of some metal ions such as iron(III) have a Roman numeral after them.
9. Write the symbol for each of the following ions
   (a) sodium
   (b) chloride
   (c) sulfate
   (d) ammonium
   (e) chromium(II)
   (f) chromium(III)
10. Write the formulas for the compounds formed in each of the following:
   (a) magnesium and chlorine
   (b) silver and sulfur
   (c) cobalt(III) and oxygen
   (d) zinc and bromine
   (e) calcium and nitrogen
   (f) copper(I) and nitrate
11. Write the names of the two ions in each of the following compounds.
   (a) $Al_2(SO_4)_3$
   (b) $CaCl_2$
   (c) Na_2O
   (d) $AgCl$
   (e) Na_3PO_4
   (f) CaF_2
   (g) NH_4OH
   (h) $Ca(NO_3)_2$
12. Identify which of the following compound formulas are *incorrect*. Provide the correct formula for those that are incorrect.
   (a) calcium and oxygen, CaO_2
   (b) sodium and oxygen, NaO_2
   (c) barium and chlorine, $BaCl_3$
   (d) strontium and oxygen, SrO_2
   (e) sulfur and sodium, SNa_2
   (f) ammonium and nitrate, NH_4NO_3
   (g) sodium and calcium, NaCl
13. You are given a sample of copper compounded with chlorine. The sample is in the form of a blue-green powder. What is the name and the formula of the compound? Recall that copper ions are either copper(I) or copper(II).