Chapter 3 Table of Contents

3.1 Molecules and Chemical Nomenclature ........................................page 2
   Learning Objective, Example 1, Example 2, Example 3, Key Takeaways, Exercises and Answers

3.2 Ions and Ionic Compounds ..............................................................page 11
   Learning Objective, Example 4, Example 5, Key Takeaways, Exercises and Answers

3.3 Acids ................................................................................................page 27
   Learning Objective, Example 6, Key Takeaways, Exercises and Answers

3.4 End-of-Chapter Material .................................................................page 31
Chapter 3

Chemical Compounds

3.1 Molecules and Chemical Nomenclature

LEARNING OBJECTIVES

1. Define molecule.
2. Name simple molecules based on their formulas.
3. Determine a formula of a molecule based on its name.

There are many substances that exist as two or more atoms connected together so strongly that they behave as a single particle. These multiatom combinations are called molecules. A molecule is the smallest part of a substance that has the physical and chemical properties of that substance. In some respects, a molecule is similar to an atom. A molecule, however, is composed of more than one atom.

Some elements exist naturally as molecules. For example, hydrogen and oxygen exist as two-atom molecules. Other elements also exist naturally as diatomic molecules (see Table 3.1 "Elements That Exist as Diatomic Molecules"). As with any molecule, these elements are labeled with a molecular formula, a formal listing of what and how many atoms are in a molecule. (Sometimes only the word formula is used, and its meaning is inferred from the context.) For example, the molecular formula for elemental hydrogen is H₂, with H being the symbol for hydrogen and the subscript 2 implying that there are two atoms of this element in the molecule. Other diatomic elements have similar formulas: O₂, N₂, and so forth. Other elements exist as molecules—for example, sulfur normally exists as an eight-atom molecule, S₈, while phosphorus exists as a four-atom molecule, P₄ (see Figure 3.1 "Molecular Art of S"). Otherwise, we will assume that elements exist as individual atoms, rather than molecules. It is assumed that there is only one atom in a formula if there is no numerical subscript on the right side of an element’s symbol.
Table 3.1 Elements That Exist as Diatomic Molecules

<table>
<thead>
<tr>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>Oxygen</td>
</tr>
<tr>
<td>Nitrogen</td>
</tr>
<tr>
<td>Fluorine</td>
</tr>
<tr>
<td>Chlorine</td>
</tr>
<tr>
<td>Bromine</td>
</tr>
<tr>
<td>Iodine</td>
</tr>
</tbody>
</table>

Figure 3.1 Molecular Art of \(S_8\) and \(P_4\) Molecules

If each green ball represents a sulfur atom, then the diagram on the left represents an \(S_8\) molecule. The molecule on the right shows that one form of elemental phosphorus exists as a four-atom molecule.

Figure 3.1 "Molecular Art of S" shows two examples of how we will be representing molecules in this text. An atom is represented by a small ball or sphere, which generally indicates where the nucleus is in the molecule. A cylindrical line connecting the balls represents the connection between the atoms that make this collection of atoms a molecule. This connection is called a chemical bond. In Chapter 8 "Chemical Bonding", we will explore the origin of chemical bonds. You will see other examples of this “ball and cylinder” representation of molecules throughout this book.

Many compounds exist as molecules. In particular, when nonmetals connect with other nonmetals, the compound typically exists as molecules. (Compounds between a metal and a nonmetal are different and will be considered in Section 3.2 "Ions and Ionic Compounds".) Furthermore, in some cases there are many different kinds of molecules that can be formed between any given elements,
with all the different molecules having different chemical and physical properties. How do we tell them apart?

The answer is a very specific system of naming compounds, called chemical nomenclature. By following the rules of nomenclature, each and every compound has its own unique name, and each name refers to one and only one compound. Here, we will start with relatively simple molecules that have only two elements in them, the so-called binary compounds:

1. Identify the elements in the molecule from its formula. This is why you need to know the names and symbols of the elements back in Table 2.2 "Names and Symbols of Some Common Elements", located in Section 2.1.

2. Begin the name with the element name of the first element. If there is more than one atom of this element in the molecular formula, use a numerical prefix to indicate the number of atoms, as listed in Table 3.3 "Numerical Prefixes Used in Naming Molecular Compounds". Do not use the prefix mono- if there is only one atom of the first element.

### Table 3.3 Numerical Prefixes Used in Naming Molecular Compounds

<table>
<thead>
<tr>
<th>The Number of Atoms of an Element</th>
<th>Prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mono-</td>
</tr>
<tr>
<td>2</td>
<td>di-</td>
</tr>
<tr>
<td>3</td>
<td>tri-</td>
</tr>
<tr>
<td>4</td>
<td>tetra-</td>
</tr>
<tr>
<td>5</td>
<td>penta-</td>
</tr>
<tr>
<td>6</td>
<td>hexa-</td>
</tr>
<tr>
<td>7</td>
<td>hepta-</td>
</tr>
<tr>
<td>8</td>
<td>octa-</td>
</tr>
<tr>
<td>9</td>
<td>nona-</td>
</tr>
<tr>
<td>10</td>
<td>deca-</td>
</tr>
</tbody>
</table>
3. Name the second element by using three pieces:
   a. a numerical prefix indicating the number of atoms of the second element, plus
   b. the stem of the element name (e.g., \textit{ox} for oxygen, \textit{chlor} for chlorine, etc.), plus
   c. the suffix \textit{-ide}.

4. Combine the two words, leaving a space between them.

Let us see how these steps work for a molecule whose molecular formula is \ce{SO_2}, which has one sulfur atom and two oxygen atoms—this completes step 1. According to step 2, we start with the name of the first element—sulfur. Remember, we don’t use the \textit{mono}-prefix for the first element. Now for step 3, we combine the numerical prefix \textit{di-} (see Table 3.3 "Numerical Prefixes Used in Naming Molecular Compounds") with the stem \textit{ox-} and the suffix \textit{-ide}, to make \textit{dioxide}. Bringing these two words together, we have the unique name for this compound—sulfur dioxide.

Why all this trouble? There is another common compound consisting of sulfur and oxygen whose molecular formula is \ce{SO_3}, so the compounds need to be distinguished. \ce{SO_3} has three oxygen atoms in it, so it is a different compound with different chemical and physical properties. The system of chemical nomenclature is designed to \textit{give this compound its own unique name}. Its name, if you go through all the steps, is sulfur trioxide. Different compounds have different names.

In some cases, when a prefix ends in \textit{a} or \textit{o} and the element name begins with \textit{o} we drop the \textit{a} or \textit{o} on the prefix. So we see \textit{monoxide} or \textit{pentoxide} rather than \textit{monooxide} or \textit{pentaoxide} in molecule names.

One great thing about this system is that it works both ways. From the name of a compound, you should be able to determine its molecular formula. Simply list the element symbols, with a numerical subscript if there is more than one atom of that element, in the order of the name (we do not use a subscript 1 if there is only one atom of the element present; 1 is implied). From the name \textit{nitrogen trichloride}, you should be able to get \ce{NCl_3} as the formula for this molecule. From the name \textit{diphosphorus pentoxide}, you should be able to get the formula \ce{P_2O_5} (note the numerical prefix on the first element, indicating there is more than one atom of phosphorus in the formula).

**EXAMPLE 3**

Name each molecule.

1. \ce{PF_3}
2. \ce{CO}
3. \ce{Se_2Br_2}

\textit{Solution}

1. A molecule with a single phosphorus atom and three fluorine atoms is called phosphorus trifluoride.
2. A compound with one carbon atom and one oxygen atom is properly called carbon monoxide, not carbon monooxide.

3. There are two atoms of each element, selenium and bromine. According to the rules, the proper name here is *diselenium dibromide*.

**Test Yourself**

Name each molecule.

1. SF$_4$
2. P$_2$S$_5$

**Answers**

1. sulfur tetrafluoride
2. diphosphorus pentasulfide

**EXAMPLE 4**

**Give the formula for each molecule.**

1. carbon tetrachloride
2. silicon dioxide
3. trisilicon tetranitride

**Solution**

1. The name *carbon tetrachloride* implies one carbon atom and four chlorine atoms, so the formula is CCl$_4$.

2. The name *silicon dioxide* implies one silicon atom and two oxygen atoms, so the formula is SiO$_2$.

3. We have a name that has numerical prefixes on both elements. *Tri-* means three, and *teta-* means four, so the formula of this compound is Si$_3$N$_4$. 
Test Yourself

Give the formula for each molecule.

1. disulfur difluoride
2. iodine pentabromide

Answers

1. S₂F₂
2. IBr₅

Some simple molecules have common names that we use as part of the formal system of chemical nomenclature. For example, we refer to H₂O as water, not dihydrogen monoxide. NH₃ is called ammonia, while CH₄ is called methane. We will occasionally see other molecules that have common names; we will point them out as they occur.

**KEY TAKEAWAYS**

- Molecules are groups of atoms that behave as a single unit.
- Some elements exist as molecules: hydrogen, oxygen, sulfur, and so forth.
- There are rules that can express a unique name for any given molecule, and a unique formula for any given name.

**EXERCISES**

1. Which of these formulas represent molecules? State how many atoms are in each molecule.
   a. Fe
   b. PCl₃
   c. P₄
   d. Ar
2. Which of these formulas represent molecules? State how many atoms are in each molecule.
   a. I₂
   b. He
   c. H₂O
   d. Al

3. What is the difference between CO and Co?

4. What is the difference between H₂O and H₂O₂ (hydrogen peroxide)?

5. Give the proper formula for each diatomic element.

6. In 1986, when Halley’s comet last passed the earth, astronomers detected the presence of S₂ in their telescopes. Why is sulfur not considered a diatomic element?

7. What is the stem of fluorine used in molecule names? CF₄ is one example.

8. What is the stem of selenium used in molecule names? SiSe₂ is an example.

9. Give the proper name for each molecule.
   a. PF₃
   b. TeCl₂
   c. N₂O₃

10. Give the proper name for each molecule.
    a. NO
    b. CS₂
    c. As₂O₃

11. Give the proper name for each molecule.
    a. XeF₂
    b. O₃F₂
    c. SF₆
12. Give the proper name for each molecule.
   a. $P_4O_{10}$
   b. $B_2O_3$
   c. $P_2S_3$

13. Give the proper name for each molecule.
   a. $N_2O$
   b. $N_2O_4$
   c. $N_2O_5$

14. Give the proper name for each molecule.
   a. $SeO_2$
   b. $Cl_2O$
   c. $XeF_6$

15. Give the proper formula for each name.
   a. dinitrogen pentoxide
   b. tetraboron tricarbide
   c. phosphorus pentachloride

16. Give the proper formula for each name.
   a. nitrogen triiodide
   b. diarsenic trisulfide
   c. iodine trichloride

17. Give the proper formula for each name.
   a. dioxygen dichloride
   b. dinitrogen trisulfide
   c. xenon tetrafluoride
18. Give the proper formula for each name.
   a. chlorine dioxide
   b. selenium dibromide
   c. dinitrogen trioxide

19. Give the proper formula for each name.
   a. iodine trifluoride
   b. xenon trioxide
   c. disulfur decafluoride

20. Give the proper formula for each name.
   a. germanium dioxide
   b. carbon disulfide
   c. diselenium dibromide

**ANSWERS**

1. a. not a molecule
   b. a molecule; four atoms total
   c. a molecule; four atoms total
   d. not a molecule

3. CO is a compound of carbon and oxygen; Co is the element cobalt.

5. H₂, O₂, N₂, F₂, Cl₂, Br₂, I₂

7. fluor-

9. a. phosphorus trifluoride
   b. tellurium dichloride
   c. dinitrogen trioxide

11. a. xenon difluoride
    b. dioxygen difluoride
    c. sulfur hexafluoride
13. a. dinitrogen monoxide
   b. dinitrogen tetroxide
   c. dinitrogen pentoxide
15. a. N\textsubscript{2}O\textsubscript{5}
   b. B\textsubscript{4}C\textsubscript{3}
   c. PCl\textsubscript{5}
17. a. O\textsubscript{2}Cl\textsubscript{2}
   b. N\textsubscript{2}S\textsubscript{3}
   c. XeF\textsubscript{4}
19. a. IF\textsubscript{3}
   b. XeO\textsubscript{3}
   c. S\textsubscript{2}F\textsubscript{10}

3.2 Ions and Ionic Compounds

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Know how ions form.</td>
</tr>
<tr>
<td>2. Learn the characteristic charges that ions have.</td>
</tr>
<tr>
<td>3. Construct a proper formula for an ionic compound.</td>
</tr>
<tr>
<td>4. Generate a proper name for an ionic compound.</td>
</tr>
</tbody>
</table>

So far, we have discussed elements and compounds that are electrically neutral. They have the same number of electrons as protons, so the negative charges of the electrons is balanced by the positive charges of the protons. However, this is not always the case. Electrons can move from one atom to another; when they do, species with overall electric charges are formed. Such species are called ions. Species with overall positive charges are termed cations, while species with overall negative charges are called anions. Remember that ions are formed only when electrons move from one atom to another; a proton never moves from one atom to another. Compounds formed from positive and negative ions are called ionic compounds.
Individual atoms can gain or lose electrons. When they do, they become *monatomic* ions. When atoms gain or lose electrons, they usually gain or lose a characteristic number of electrons and so take on a characteristic overall charge. Table 3.4 "Monatomic Ions of Various Charges" lists some common ions in terms of how many electrons they lose (making cations) or gain (making anions). There are several things to notice about the ions in Table 3.4 "Monatomic Ions of Various Charges". First, each element that forms cations is a metal, except for one (hydrogen), while each element that forms anions is a nonmetal. This is actually one of the chemical properties of metals and nonmetals: metals tend to form cations, while nonmetals tend to form anions. Second, most main group atoms form ions of a single characteristic charge. The main group elements are those in Groups IA through VIIIA. The other elements are referred to as transition metals (III-B through II-B, or Groups 3 through 12) and the rare earth elements, located as two rows of fourteen elements each, found at the very bottom of most periodic tables. Take sodium, a Group IA element, as an example. When sodium atoms form ions, they always form a 1+ charge, never a 2+ or 3+ or even 1− charge. Thus, if you commit the information in Table 3.4 "Monatomic Ions of Various Charges" to memory, you will always know what charges most atoms form. (In Chapter 8 "Chemical Bonding", we will discuss why atoms form the charges they do.)

Table 3.4 Monatomic Ions of Various Charges

<table>
<thead>
<tr>
<th>Ions formed by losing a single electron</th>
<th>Ions formed by losing two electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>Mg²⁺</td>
</tr>
<tr>
<td>Na⁺</td>
<td>Ca²⁺</td>
</tr>
<tr>
<td>K⁺</td>
<td>Sr²⁺</td>
</tr>
<tr>
<td>Rb⁺</td>
<td>Fe²⁺</td>
</tr>
<tr>
<td>Ag⁺</td>
<td>Co²⁺</td>
</tr>
<tr>
<td>Au⁺</td>
<td>Ni²⁺</td>
</tr>
</tbody>
</table>
| Ions formed by losing three electrons | Cu<sup>2+</sup>  
| Zn<sup>2+</sup>  
| Sn<sup>2+</sup>  
| Hg<sup>2+</sup>  
| Pb<sup>2+</sup>  |
| Ions formed by losing four electrons | Sc<sup>3+</sup>  
| Fe<sup>3+</sup>  
| Co<sup>3+</sup>  
| Ni<sup>3+</sup>  
| Au<sup>3+</sup>  
| Al<sup>3+</sup>  
| Cr<sup>3+</sup>  |
| Ions formed by gaining a single electron | Ti<sup>4+</sup>  
| Sn<sup>4+</sup>  
| Pb<sup>4+</sup>  |
| Ions formed by gaining two electrons | F<sup>-</sup>  
| Cl<sup>-</sup>  
| Br<sup>-</sup>  
| I<sup>-</sup>  
| O<sup>2-</sup>  |
Ions formed by gaining three electrons

| 5^2^- | Se^2- |

Third, the transition metals and rare earth elements are exceptions to the previous point. These metals can form ions with more than one possible charge. For example, iron atoms can form 2+ cations or 3+ cations. Cobalt is another element that can form more than one possible charged ion (2+ and 3+), while lead can form 2+ or 4+ cations. Predicting the charges that these metal ions may have is beyond the scope of this course.

Note the convention for indicating an ion. The magnitude of the charge is listed as a right superscript next to the symbol of the element. If the charge is a single positive or negative one, the number 1 is not written; if the magnitude of the charge is greater than 1, then the number is usually written before the + or − sign. An element symbol without a charge written next to it is assumed to be the uncharged atom.

Naming an ion is straightforward. For a cation, simply use the name of the element and add the word ion (or if you want to be more specific, add cation) after the element’s name. So Na^+ is the sodium ion; Ca^{2+} is the calcium ion. If the element has more than one possible charge, the value of the charge comes after the element name and before the word ion. Thus, Fe^{2+} is the iron two ion, while Fe^{3+} is the iron three ion. In print, we use roman numerals in parentheses to represent the charge on the ion, so these two iron ions would be represented as the iron(II) cation and the iron(III) cation, respectively.

For a monatomic anion, use the stem of the element name and append the suffix -ide to it, and then add ion. This is similar to how we named molecular compounds. Thus, Cl^− is the chloride ion, and N^{3−} is the nitride ion.

**EXAMPLE 6**

Name each species:

1. O^{2−}
2. Co
3. Co^{2+}

**Solution**

1. This species has a 2− charge on it, so it is an anion. Anions are named using the stem of the element name with the suffix -ide added. This is the oxide anion.
2. Because this species has no charge, it is an atom in its elemental form. This is cobalt.

3. In this case, there is a 2+ charge on the atom, so it is a cation. We note from Table 3.4 "Monatomic Ions of Various Charges" that cobalt cations can have two possible charges, so the name of the ion must specify which charge the ion has. This is the cobalt(II) cation.

### Test Yourself

Name each species.

1. $P^{3-}$
2. $Sr^{2+}$

**Answers**

1. the phosphide anion
2. the strontium cation

Chemical formulas for ionic compounds are called **ionic formulas**. A proper ionic formula has a cation and an anion in it; an ionic compound is never formed between two cations only or two anions only. The key to writing proper ionic formulas is simple: the total positive charge must balance the total negative charge. Because the charges on the ions are characteristic, sometimes we have to have more than one of a cation or an anion to balance the overall positive and negative charges. It is conventional to use the lowest ratio of ions that are needed to balance the charges.

For example, consider the ionic compound between Na$^+$ and Cl$^-$. Each ion has a single charge, one positive and one negative, so we need only one ion of each to balance the overall charge. When writing the ionic formula, we follow two additional conventions: (1) write the formula for the cation first and the formula for the anion next, but (2) do not write the charges on the ions. Thus, for the compound between Na$^+$ and Cl$^-$, we have the ionic formula NaCl (Figure 3.2 "NaCl = Table Salt"). The formula $Na_2Cl_2$ also has balanced charges, but the convention is to use the lowest ratio of ions, which would be one of each. (Remember from our conventions for writing formulas that we don’t write a 1 subscript if there is only one atom of a particular element present.) For the ionic compound between magnesium cations (Mg$^{2+}$) and oxide anions (O$^{2-}$), again we need only one of each ion to balance the charges. By convention, the formula is MgO.

*Figure 3.2 NaCl = Table Salt*

Photo by Dubravko Soric
https://flic.kr/p/6McAtR; CC-BY

The ionic compound NaCl is very common.
For the ionic compound between Mg$^{2+}$ ions and Cl$^{-}$ ions, we now consider the fact that the charges have different magnitudes, 2+ on the magnesium ion and 1− on the chloride ion. To balance the charges with the lowest number of ions possible, we need to have two chloride ions to balance the charge on the one magnesium ion. Rather than write the formula MgClCl, we combine the two chloride ions and write it with a 2 subscript: MgCl$_2$.

What is the formula MgCl$_2$ telling us? There are two chloride ions in the formula. Although chlorine as an element is a diatomic molecule, Cl$_2$, elemental chlorine is not part of this ionic compound. The chlorine is in the form of a negatively charged ion, not the neutral element. The 2 subscript is in the ionic formula because we need two Cl$^{-}$ ions to balance the charge on one Mg$^{2+}$ ion.

**EXAMPLE 7**

Write the proper ionic formula for each of the two given ions.

1. Ca$^{2+}$ and Cl$^{-}$
2. Al$^{3+}$ and F$^{-}$
3. Al$^{3+}$ and O$^{2-}$

**Solution**

1. We need two Cl$^{-}$ ions to balance the charge on one Ca$^{2+}$ ion, so the proper ionic formula is CaCl$_2$.
2. We need three F$^{-}$ ions to balance the charge on the Al$^{3+}$ ion, so the proper ionic formula is AlF$_3$.
3. With Al$^{3+}$ and O$^{2-}$, note that neither charge is a perfect multiple of the other. This means we have to go to a least common multiple, which in this case will be six. To get a total of 6+, we need two Al$^{3+}$ ions; to get 6−, we need three O$^{2-}$ ions. Hence the proper ionic formula is Al$_2$O$_3$.

**Test Yourself**

Write the proper ionic formulas for each of the two given ions.

1. Fe$^{2+}$ and S$^{2-}$
2. Fe$^{3+}$ and S$^{2-}$

**Answers**

1. FeS
2. Fe$_2$S$_3$
Naming ionic compounds is simple: combine the name of the cation and the name of the anion, in both cases omitting the word **ion**. **Do not use numerical prefixes if there is more than one ion necessary to balance the charges.** NaCl is named as sodium chloride, a combination of the name of the cation (sodium) and the anion (chloride), and not as sodium monochloride. MgO is magnesium oxide. MgCl₂ is magnesium chloride—*not* magnesium dichloride. Prefixes are used to indicate the number of atoms for molecular compounds because more than one combination is possible (e.g., carbon monoxide and carbon dioxide.) Prefixes are not needed for ionic compounds because there is only one possible electrically-neutral combination of any two ions.

In naming ionic compounds whose cations can have more than one possible charge, we must also include the charge, in parentheses and in roman numerals, as part of the name. Hence FeS is iron(II) sulfide, while Fe₂S₃ is iron(III) sulfide. Again, no numerical prefixes appear in the name. The number of ions in the formula is dictated by the need to balance the positive and negative charges.

### Example 8

**Name each ionic compound:**

1. CaCl₂
2. AlF₃
3. Co₂O₃

**Solution**

1. Using the names of the ions, this ionic compound is named calcium chloride. *It is not calcium(II) chloride* because calcium forms only one cation when it forms an ion, and it has a characteristic charge of 2+.

2. The name of this ionic compound is aluminum fluoride.

3. We know that cobalt can have more than one possible charge; we just need to determine what it is. Oxide always has a 2⁻ charge, so with three oxide ions, we have a total negative charge of 6⁻. This means that the two cobalt ions have to contribute 6+; which for two cobalt ions means that each one is 3+. Therefore, the proper name for this ionic compound is cobalt(III) oxide.

### Test Yourself

Name each ionic compound.

1. Sc₂O₃
2. AgCl
How do you know whether a formula—and by extension, a name—is for a molecular compound or for an ionic compound? Molecular compounds form between nonmetals and nonmetals, while ionic compounds form between metals and nonmetals. The periodic table (Figure 2.2 "A Simple Periodic Table", in chapter 2) can be used to determine which elements are metals and nonmetals.

There also exists a group of ions that contain more than one atom. These are called polyatomic ions. Table 3.5 "Common Polyatomic Ions" lists the formulas, charges, and names of some common polyatomic ions. Only one of them, the ammonium ion, is a cation; the rest are anions. Most of them also contain oxygen atoms, so sometimes they are referred to as oxyanions. Some of them, such as nitrate and nitrite, and sulfate and sulfite, have very similar formulas and names, so care must be taken to get the formulas and names correct. Note that an ion ending in -ite has one less oxygen atom in its formula than the ion with the same charge ending in –ate.

**Table 3.5 Common Polyatomic Ions**

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula and Charge</th>
<th>Name</th>
<th>Formula and Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ammonium</td>
<td>NH₄⁺</td>
<td>hydroxide</td>
<td>OH⁻</td>
</tr>
<tr>
<td>acetate</td>
<td>C₂H₃O₂⁻, or CH₃COO⁻</td>
<td>nitrate</td>
<td>NO₃⁻</td>
</tr>
<tr>
<td>bicarbonate (hydrogen carbonate)</td>
<td>HCO₃⁻</td>
<td>nitrite</td>
<td>NO₂⁻</td>
</tr>
<tr>
<td>bisulfate (hydrogen sulfate)</td>
<td>HSO₄⁻</td>
<td>peroxide</td>
<td>O₂²⁻</td>
</tr>
<tr>
<td>carbonate</td>
<td>CO₃²⁻</td>
<td>perchlorate</td>
<td>ClO₄⁻</td>
</tr>
<tr>
<td>chlorate</td>
<td>ClO₃⁻</td>
<td>phosphate</td>
<td>PO₄³⁻</td>
</tr>
<tr>
<td>chromate</td>
<td>CrO₄²⁻</td>
<td>sulfate</td>
<td>SO₄²⁻</td>
</tr>
<tr>
<td>cyanide</td>
<td>CN⁻</td>
<td>sulfite</td>
<td>SO₃²⁻</td>
</tr>
<tr>
<td>dichromate</td>
<td>Cr₂O₇²⁻</td>
<td>triiodide</td>
<td>I₃⁻</td>
</tr>
</tbody>
</table>

The naming of ionic compounds that contain polyatomic ions follows the same rules as the naming for other ionic compounds: simply combine the name of the cation and the name of the anion. Do |
not use numerical prefixes in the name if there is more than one polyatomic ion; the only exception to this is if the name of the ion itself contains a numerical prefix, such as dichromate or triiodide.

Writing the formulas of ionic compounds has one important difference. If more than one polyatomic ion is needed to balance the overall charge in the formula, enclose the formula of the polyatomic ion in parentheses and write the proper numerical subscript to the right and outside the parentheses. Thus, the formula between calcium ions, Ca\(^{2+}\), and nitrate ions, NO\(_3^−\), is properly written Ca(NO\(_3\))\(_2\), not CaNO\(_3_2\) or CaN\(_2\)O\(_6\). Use parentheses where required. The name of this ionic compound is simply calcium nitrate.

**EXAMPLE 9**

Write the proper formula and give the proper name for each ionic compound formed between the two listed ions.

1. NH\(_4^+\) and S\(^2−\)
2. Al\(^{3+}\) and PO\(_4^{3−}\)
3. Fe\(^{2+}\) and PO\(_4^{3−}\)

**Solution**

1. Because the ammonium ion has a 1+ charge and the sulfide ion has a 2− charge, we need two ammonium ions to balance the charge on a single sulfide ion. Enclosing the formula for the ammonium ion in parentheses, we have (NH\(_4\))\(_2\)S. The compound’s name is ammonium sulfide.

2. Because the ions have the same magnitude of charge, we need only one of each to balance the charges. The formula is AlPO\(_4\), and the name of the compound is aluminum phosphate.

3. Neither charge is an exact multiple of the other, so we have to go to the least common multiple of 6. To get 6+, we need three iron(II) ions, and to get 6−, we need two phosphate ions. The proper formula is Fe\(_3\)(PO\(_4\))\(_2\), and the compound’s name is iron(II) phosphate.

**Test Yourself**

Write the proper formula and give the proper name for each ionic compound formed between the two listed ions.

1. NH\(_4^+\) and PO\(_4^{3−}\)
2. Co\(^{3+}\) and NO\(_2^−\)
Food and Drink App: Sodium in Your Food

The element sodium, at least in its ionic form as Na\(^+\), is a necessary nutrient for humans to live. In fact, the human body is approximately 0.15% sodium, with the average person having one-twentieth to one-tenth of a kilogram in their body at any given time, mostly in fluids outside cells and in other bodily fluids.

Sodium is also present in our diet. The common table salt we use on our foods is an ionic sodium compound. Many processed foods also contain significant amounts of sodium added to them as a variety of ionic compounds. Why are sodium compounds used so much? Usually sodium compounds are inexpensive, but, more importantly, most ionic sodium compounds dissolve easily. This allows processed food manufacturers to add sodium-containing substances to food mixtures and know that the compound will dissolve and distribute evenly throughout the food. Simple ionic compounds such as sodium nitrite (NaNO\(_2\)) are added to cured meats, such as bacon and deli-style meats, while a compound called sodium benzoate is added to many packaged foods as a preservative. Table 3.6 "Some Sodium Compounds Added to Food" is a partial list of some sodium additives used in food. Some of them you may recognize after reading this chapter. Others you may not recognize, but they are all ionic sodium compounds with some negatively charged ions also present.

Table 3.6 Some Sodium Compounds Added to Food

<table>
<thead>
<tr>
<th>Sodium Compound</th>
<th>Use in Food</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium acetate</td>
<td>preservative, acidity regulator</td>
</tr>
<tr>
<td>Sodium adipate</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium alginate</td>
<td>thickener, vegetable gum, stabilizer, gelling agent, emulsifier</td>
</tr>
<tr>
<td>Sodium aluminum phosphate</td>
<td>acidity regulator, emulsifier</td>
</tr>
<tr>
<td>Sodium aluminosilicate</td>
<td>anticaking agent</td>
</tr>
<tr>
<td>Sodium ascorbate</td>
<td>Antioxidant</td>
</tr>
<tr>
<td>Sodium benzoate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium Compound</td>
<td>Use in Food</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td>mineral salt</td>
</tr>
<tr>
<td>Sodium bisulfite</td>
<td>preservative, antioxidant</td>
</tr>
<tr>
<td>Sodium carbonate</td>
<td>mineral salt</td>
</tr>
<tr>
<td>Sodium carboxymethylcellulose</td>
<td>Emulsifier</td>
</tr>
<tr>
<td>Sodium citrates</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium dehydroacetate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium erythorbate</td>
<td>Antioxidant</td>
</tr>
<tr>
<td>Sodium erythorbin</td>
<td>Antioxidant</td>
</tr>
<tr>
<td>Sodium ethyl para-hydroxybenzoate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium ferrocyanide</td>
<td>anticaking agent</td>
</tr>
<tr>
<td>Sodium formate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium fumarate</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium gluconate</td>
<td>Stabilizer</td>
</tr>
<tr>
<td>Sodium hydrogen acetate</td>
<td>preservative, acidity regulator</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>mineral salt</td>
</tr>
<tr>
<td>Sodium lactate</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium malate</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium metabisulfite</td>
<td>preservative, antioxidant, bleaching agent</td>
</tr>
<tr>
<td>Sodium methyl para-hydroxybenzoate</td>
<td>Preservative</td>
</tr>
</tbody>
</table>
# Sodium Compound Use in Food

<table>
<thead>
<tr>
<th>Sodium Compound</th>
<th>Use in Food</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium nitrate</td>
<td>preservative, color fixative</td>
</tr>
<tr>
<td>Sodium nitrite</td>
<td>preservative, color fixative</td>
</tr>
<tr>
<td>Sodium orthophenyl phenol</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium propionate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium propyl para-hydroxybenzoate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium sorbate</td>
<td>Preservative</td>
</tr>
<tr>
<td>Sodium stearoyl lactylate</td>
<td>Emulsifier</td>
</tr>
<tr>
<td>Sodium succinates</td>
<td>acidity regulator, flavor enhancer</td>
</tr>
<tr>
<td>Sodium salts of fatty acids</td>
<td>emulsifier, stabilizer, anticaking agent</td>
</tr>
<tr>
<td>Sodium sulfite</td>
<td>mineral salt, preservative, antioxidant</td>
</tr>
<tr>
<td>Sodium sulfite</td>
<td>preservative, antioxidant</td>
</tr>
<tr>
<td>Sodium tartrate</td>
<td>food acid</td>
</tr>
<tr>
<td>Sodium tetraborate</td>
<td>Preservative</td>
</tr>
</tbody>
</table>

The use of so many sodium compounds in prepared and processed foods has alarmed some physicians and nutritionists. They argue that the average person consumes too much sodium from his or her diet. The average person needs only about 500 mg of sodium every day; most people consume more than this—up to 10 times as much. Some studies have implicated increased sodium intake with high blood pressure; newer studies suggest that the link is questionable. However, there has been a push to reduce the amount of sodium most people ingest every day: avoid processed and manufactured foods, read labels on packaged foods (which include an indication of the sodium content), don’t oversalt foods, and use other herbs and spices besides salt in cooking.
Food labels include the amount of sodium per serving. This particular label shows that there are 75 mg of sodium in one serving of this particular food item.

**KEY TAKEAWAYS**

- Ions form when atoms lose or gain electrons.
- Ionic compounds have positive ions and negative ions.
- Ionic formulas balance the total positive and negative charges.
- Ionic compounds have a simple system of naming.
- Groups of atoms can have an overall charge and make ionic compounds.

**EXERCISES**

1. Explain how cations form.
2. Explain how anions form.
3. Give the charge each atom takes when it forms an ion. If more than one charge is possible, list both.
   a. K
   b. O
   c. Co

4. Give the charge each atom takes when it forms an ion. If more than one charge is possible, list both.
   a. Ca
   b. I
   c. Fe

5. Give the charge each atom takes when it forms an ion. If more than one charge is possible, list both.
   a. Ag
   b. Au
   c. Br

6. Give the charge each atom takes when it forms an ion. If more than one charge is possible, list both.
   a. S
   b. Na
   c. H

7. Name the ions from Exercise 3.

8. Name the ions from Exercise 4.

9. Name the ions from Exercise 5.

10. Name the ions from Exercise 6.

11. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Mg$^{2+}$ and Cl$^-$
   b. Fe$^{2+}$ and O$^{2-}$
   c. Fe$^{3+}$ and O$^{2-}$
12. Give the formula and name for each ionic compound formed between the two listed ions.
   a. K\(^+\) and S\(^2^-\)
   b. Ag\(^+\) and Br\(^-\)
   c. Sr\(^{2+}\) and N\(^3^-\)

13. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Cu\(^{2+}\) and F\(^-\)
   b. Ca\(^{2+}\) and O\(^2^-\)
   c. K\(^+\) and P\(^3^-\)

14. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Na\(^+\) and N\(^3^-\)
   b. Co\(^{2+}\) and I\(^-\)
   c. Au\(^{3+}\) and S\(^2^-\)

15. Give the formula and name for each ionic compound formed between the two listed ions.
   a. K\(^+\) and SO\(_4^{2-}\)
   b. NH\(_4^+\) and S\(^2^-\)
   c. NH\(_4^+\) and PO\(_4^{3-}\)

16. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Ca\(^{2+}\) and NO\(_3^-\)
   b. Ca\(^{2+}\) and NO\(_2^-\)
   c. Sc\(^{3+}\) and C\(_2\)H\(_3\)O\(_2^-\)

17. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Pb\(^{4+}\) and SO\(_4^{2-}\)
   b. Na\(^+\) and I\(_3^-\)
   c. Li\(^+\) and Cr\(_2\)O\(_7^{2-}\)
18. Give the formula and name for each ionic compound formed between the two listed ions.
   a. NH₄⁺ and N³⁻
   b. Mg²⁺ and CO₃²⁻
   c. Al³⁺ and OH⁻

19. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Ag⁺ and SO₃²⁻
   b. Na⁺ and HCO₃⁻
   c. Fe³⁺ and ClO₃⁻

20. Give the formula and name for each ionic compound formed between the two listed ions.
   a. Rb⁺ and O₂²⁻
   b. Au³⁺ and HSO₄⁻
   c. Sr²⁺ and NO₂⁻

21. What is the difference between SO₃ and SO₃²⁻?
22. What is the difference between NO₂ and NO₂⁻?

**ANSWERS**

1. Cations form by losing electrons.
3. a. 1+
   b. 2−
   c. 2+, 3+
5. a. 1+
   b. 1+, 3+
   c. 1−
7. a. the potassium ion
   b. the oxide ion
   c. the cobalt(II) and cobalt(III) ions, respectively
9. a. the silver ion  
   b. the gold(I) and gold(III) ions, respectively  
   c. the bromide ion  
11. a. magnesium chloride, MgCl₂  
   b. iron(II) oxide, FeO  
   c. iron(III) oxide, Fe₂O₃  
13. a. copper(II) fluoride, CuF₂  
   b. calcium oxide, CaO  
   c. potassium phosphide, K₃P  
15. a. potassium sulfate, K₂SO₄  
   b. ammonium sulfide, (NH₄)₂S  
   c. ammonium phosphate, (NH₄)₃PO₄  
17. a. lead(IV) sulfate, Pb(SO₄)₂  
   b. sodium triiodide, NaI₃  
   c. lithium dichromate, Li₂Cr₂O₇  
19. a. silver sulfite, Ag₂SO₃  
   b. sodium hydrogen carbonate, NaHCO₃  
   c. iron(III) chlorate, Fe(ClO₃)₃  
21. SO₃ is sulfur trioxide, while SO₃²⁻ is the sulfite ion.

3.3 Acids

**LEARNING OBJECTIVES**

1. Define *acid*.
2. Name a simple acid.
There is one other group of compounds that is important to us—acids—and these compounds have interesting chemical properties. Initially, we will define an **acid** as a compound that increases the concentration of $H^+$ cation when dissolved in water. To indicate that something is dissolved in water, we will use the phase label (aq) next to a chemical formula (where aq stands for “aqueous,” a word that describes something dissolved in water). If the formula does not have this label, then the compound might be viewed as a molecular compound rather than an acid. For example, HCl(aq) specifically denotes hydrochloric acid, that is, HCl dissolved in water, whereas the formula HCl might denote HCl(g), which is hydrogen chloride gas, a molecular compound, or HCl(aq), which is hydrochloric acid, a mixture of HCl and water.

Acids have their own nomenclature system. If an acid is composed of only hydrogen and one other element, the name is **hydro**- + the stem of the other element + **-ic acid**. For example, the compound HCl(aq) is hydrochloric acid, while H$_2$S(aq) is hydrosulfuric acid. (If these acids were not dissolved in water, the compounds would be called hydrogen chloride and hydrogen sulfide, respectively. Both of these substances are well known as molecular compounds; when dissolved in water, however, they are treated as acids, because they increase the number of hydrogen ions in solution.)

If a compound is composed of hydrogen ions and a polyatomic anion, then the name of the acid is derived from the stem of the polyatomic ion’s name. Typically, if the anion name ends in -ate, the name of the acid is the stem of the anion name plus **-ic acid**; if the related anion’s name ends in -ite, the name of the corresponding acid is the stem of the anion name plus **-ous acid**. **Table 3.7 "Names and Formulas of Acids"** lists the formulas and names of a variety of acids that you should be familiar with. You should recognize most of the anions in the formulas of the acids.

**Table 3.7 Names and Formulas of Acids**

<table>
<thead>
<tr>
<th>Formula</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC$_2$H$_3$O$_2$</td>
<td>acetic acid</td>
</tr>
<tr>
<td>HClO$_3$</td>
<td>chloric acid</td>
</tr>
<tr>
<td>HCl</td>
<td>hydrochloric acid</td>
</tr>
<tr>
<td>HBr</td>
<td>hydrobromic acid</td>
</tr>
<tr>
<td>HI</td>
<td>hydriodic acid</td>
</tr>
<tr>
<td>HF</td>
<td>hydrofluoric acid</td>
</tr>
<tr>
<td>HNO$_3$</td>
<td>nitric acid</td>
</tr>
<tr>
<td>H$_2$C$_2$O$_4$</td>
<td>oxalic acid</td>
</tr>
<tr>
<td>Formula</td>
<td>Name</td>
</tr>
<tr>
<td>---------</td>
<td>--------------</td>
</tr>
<tr>
<td>HClO₄</td>
<td>perchloric acid</td>
</tr>
<tr>
<td>H₃PO₄</td>
<td>phosphoric acid</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>sulfuric acid</td>
</tr>
<tr>
<td>H₂SO₃</td>
<td>sulfurous acid</td>
</tr>
</tbody>
</table>

Note: The “aq” label is omitted for clarity.

**EXAMPLE 10**

Name each acid without consulting Table 3.7 "Names and Formulas of Acids".

1. HBr
2. H₂SO₄

**Solution**

1. As a binary acid, the acid’s name is hydro- + stem name + -ic acid. Because this acid contains a bromine atom, the name is hydrobromic acid.

2. Because this acid is derived from the sulfate ion, the name of the acid is the stem of the anion name + -ic acid. The name of this acid is sulfuric acid.

---

**Test Yourself**

Name each acid.

1. HF
2. HNO₂

**Answers**

1. hydrofluoric acid
2. nitrous acid

All acids have some similar properties. For example, acids have a sour taste; in fact, the sour taste of some of our foods, such as citrus fruits and vinegar, is caused by the presence of acids in food. Many acids react with some metallic elements to form metal ions and elemental hydrogen. Acids
make certain plant pigments change colors; indeed, the ripening of some fruits and vegetables is
cause by the formation or destruction of excess acid in the plant.

Acids are very prevalent in the world around us. We have already mentioned that citrus fruits
contain acid; among other compounds, they contain citric acid, \( \text{H}_3\text{C}_6\text{H}_5\text{O}_7(\text{aq}) \). Oxalic acid,
\( \text{H}_2\text{C}_2\text{O}_4(\text{aq}) \), is found in spinach and other green leafy vegetables. Hydrochloric acid not only is found
in the stomach (stomach acid) but also can be bought in hardware stores as a cleaner for concrete
and masonry. Phosphoric acid is an ingredient in some soft drinks.

**KEY TAKEAWAYS**

- An acid is a compound of the H\(^+\) ion dissolved in water.
- Acids have their own naming system.
- Acids have certain chemical properties that distinguish them from other compounds.

**EXERCISES**

1. Give the formula for each acid.
   a. perchloric acid
   b. hydriodic acid
2. Give the formula for each acid.
   a. hydrosulfuric acid
   b. phosphorous acid
3. Name each acid.
   a. HF(aq)
   b. HNO\(_3\)(aq)
   c. H\(_2\)C\(_2\)O\(_4\)(aq)
4. Name each acid.
   a. H\(_2\)SO\(_4\)(aq)
   b. H\(_3\)PO\(_4\)(aq)
   c. HCl(aq)
5. Name an acid found in food.
6. Name some properties that acids have in common.

ANSWERS

1. a. HClO₄(aq)
   b. HI(aq)
3. a. hydrofluoric acid
   b. nitric acid
   c. oxalic acid
5. oxalic acid (answers will vary)

3.4 End-of-Chapter Material

ADDITIONAL EXERCISES

1. What is the name corresponding to the formula N₂O₅?
2. What is the name corresponding to the formula SCl₆?
3. What is the name corresponding to the formula KF?
4. What is the name corresponding to the formula LiBr?
5. What is the charge on the common ion of magnesium?
6. What is the charge on the common ion of sulfur?
7. What is the name of the acid with the formula HBr?
8. What is the name of the acid with the formula HF?
9. What is the formula of the acid with the name sulfuric acid?
10. What is the formula of the acid with the name phosphoric acid?
<table>
<thead>
<tr>
<th>ANSWERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. dinitrogen pentoxide (dinitrogen pentaoxide is OK, too)</td>
</tr>
<tr>
<td>3. potassium fluoride</td>
</tr>
<tr>
<td>5. +2</td>
</tr>
<tr>
<td>7. hydrobromic acid</td>
</tr>
<tr>
<td>9. $\text{H}_2\text{SO}_4$</td>
</tr>
</tbody>
</table>