5.2 Compounds and Chemical Bonds

**Example 5.1 - Classification of Matter**

Many of us have a bottle in our medicine cabinet containing a mild disinfectant consisting of hydrogen peroxide and water. The liquid is about 3% hydrogen peroxide, H₂O₂, and about 97% water. Classify each of the following as a pure substance or a mixture. If it is a pure substance, is it an element or a compound?

a. the liquid disinfectant
b. the hydrogen peroxide, H₂O₂, used to make the disinfectant
c. the hydrogen used to make hydrogen peroxide

**Solution**

a. We know that the liquid disinfectant is a **mixture** for two reasons. It is composed of two pure substances (H₂O₂ and H₂O), and it has variable composition.
b. Because hydrogen peroxide can be described with a formula, H₂O₂, it must be a **pure substance**. Because the formula contains symbols for two elements, it represents a **compound**.
c. Hydrogen can be described with a single symbol, H or H₂, so it is a **pure substance** and an **element**.

**Exercise 5.1 - Classification of Matter**

The label on a container of double-acting baking powder tells us that it contains cornstarch, bicarbonate of soda (also called sodium hydrogen carbonate, NaHCO₃), sodium aluminum sulfate, and acid phosphate of calcium (which chemists call calcium dihydrogen phosphate, Ca(H₂PO₄)₂). Classify each of the following as a pure substance or a mixture. If it is a pure substance, is it an element or a compound?

a. calcium
b. calcium dihydrogen phosphate
c. double-acting baking powder

5.2 Compounds and Chemical Bonds

The percentage of H₂O₂ in the mixture of hydrogen peroxide and water that is used as a disinfectant can vary, but the percentage of hydrogen in the compound water is always the same. Why? One of the key reasons that the components of a given compound are always the same, and present in the same proportions, is that the atoms in a compound are joined together by special kinds of attractions called **chemical bonds**. Because of the nature of these attractions, the atoms combine in specific ratios that give compounds their constant composition. This section will introduce you to the different types of chemical bonds and provide you with the skills necessary to predict the types of chemical bonds between atoms of different elements.
Equal and Unequal Sharing of Electrons

Let’s first consider the compound hydrogen chloride, HCl. When HCl is dissolved in water, the resulting mixture is called hydrochloric acid. Not only is this mixture a very common laboratory agent, but it is also used in food processing and to treat the water in swimming pools.

In Section 3.5, we learned about the bond between hydrogen atoms in H₂ molecules. We saw that the two electrons in the H₂ molecule are shared equally between the atoms and can be viewed as an electron-charge cloud surrounding the hydrogen nuclei. This sharing creates a covalent bond that holds the atoms together. There is also a covalent bond between the hydrogen atom and the chlorine atom in each molecule of HCl. It is very similar to the covalent bond in hydrogen molecules, with one important exception.

The difference between the H–Cl bond and the H–H bond is that the hydrogen and chlorine atoms in HCl do not share the electrons in the bond equally. In the hydrogen-chlorine bond, the two electrons are attracted more strongly to the chlorine atom than to the hydrogen atom. The negatively charged electrons in the bond shift toward the chlorine atom, giving it a partial negative charge, δ−, and giving the hydrogen atom a partial positive charge, δ+ (Figure 5.4). The lower case Greek delta, δ, is a symbol that represents partial or fractional.

When the electrons of a covalent bond are shared unequally, the bond is called a polar covalent bond. Due to the unequal sharing of the electrons in the bond, a polar covalent bond has one atom with a partial positive charge, δ+, and one atom with a partial negative charge, δ−.

If the electron-attracting ability of one atom in a bond is much greater than the others, there is a large shift in the electron cloud, and the partial charges are large. If the electron-attracting ability of one atom in a covalent bond is only slightly greater than the others, there is not much of a shift in the electron cloud, and the partial charges are small. When the difference in electron-attracting abilities is negligible (or zero), the atoms in the bond will have no significant partial charges. We call this type of bond a nonpolar covalent bond. The covalent bond between hydrogen atoms in H₂ is an example of a nonpolar covalent bond.
Transfer of Electrons

Sometimes one atom in a bond attracts electrons so much more strongly than the other that one or more electrons are fully transferred from one atom to another. This commonly happens when metallic atoms combine with nonmetallic atoms. A nonmetallic atom usually attracts electrons so much more strongly than a metallic atom that one or more electrons shift from the metallic atom to the nonmetallic atom. For example, when the element sodium combines with the element chlorine to form sodium chloride, NaCl, the chlorine atoms attract electrons so much more strongly than the sodium atoms that one electron is transferred from each sodium atom to a chlorine atom.

When an electron is transferred completely from one uncharged atom to another, the atom that loses the electron is left with one more proton than electron and acquires a +1 charge overall. It therefore becomes a cation. For example, when an uncharged sodium atom with 11 protons and 11 electrons loses an electron, it is left with 11 protons (a charge of +11) and 10 electrons (a charge of −10), yielding an overall +1 charge.

\[
\text{Na} \rightarrow \text{Na}^+ + \text{e}^- \\
11p/11e^- \rightarrow 11p/10e^- \\
+11 + (-10) = 0 \\
+11 + (-10) = +1
\]

In contrast, an uncharged atom that gains an electron will have one more electron than proton, so it forms an anion with a −1 charge. When a chlorine atom gains an electron from a sodium atom, the chlorine atom changes from an uncharged atom with 17 protons and 17 electrons to an anion with 17 protons and 18 electrons and an overall −1 charge.

\[
\text{Cl}^- + \text{e}^- \rightarrow \text{Cl}^- \\
17p/17e^- \rightarrow 17p/18e^- \\
+17 + (-17) = 0 \\
+17 + (-18) = -1
\]

Atoms can transfer one, two, or three electrons. Thus cations can have a +1, +2, or +3 charge, and anions can have a −1, −2, or −3 charge.

Because particles with opposite charges attract each other, there is an attraction between cations and anions. This attraction is called an ionic bond. For example, when an electron is transferred from a sodium atom to a chlorine atom, the attraction between the +1 sodium cation and the −1 chlorine anion is an ionic bond (Figure 5.5 on the next page).

You will see as you read more of this book that substances that have ionic bonds are very different from those that have all covalent bonds. For example, compounds that have ionic bonds, such as the sodium chloride in table salt, are solids at room temperature and pressure, but compounds with all covalent bonds, such as hydrogen chloride and water, can be gases and liquids as well as solids.
Chapter 5  Chemical Compounds

Summary of Covalent and Ionic Bond Formation

- When atoms of different elements form chemical bonds, the electrons in the bonds can shift from one bonding atom to another.
- The atom that attracts electrons more strongly will acquire a negative charge, and the other atom will acquire a positive charge.
- The more the atoms differ in their electron-attracting ability, the more the electron cloud shifts from one atom toward another.
- If there is a large enough difference in electron-attracting ability, one, two, or three electrons can be viewed as shifting completely from one atom to another. The atoms become positive and negative ions, and the attraction between them is called an ionic bond.
- If the electron transfer is significant but not enough to form ions, the atoms acquire partial positive and partial negative charges. The bond in this situation is called a polar covalent bond.
- If there is no shift of electrons or if the shift is negligible, no significant charges will form, and the bond will be a nonpolar covalent bond.

It might help, when thinking about these different kinds of bonds, to compare them to a game of tug-of-war between two people. The people are like the atoms with a chemical bond between them, and the rope is like the electrons in the bond. If the two people tugging have the same (or about the same) strength, the rope will not move (or not move much). This leads to a situation that is like the nonpolar covalent bond. If one person is stronger than the other person, the rope will shift toward that person, the way the electrons in a polar covalent bond shift toward the atom that attracts them more. If one person can pull a lot harder than the other person can, the stronger person pulls the rope right out of the hands of the weaker one. This is similar to the formation of ions and ionic bonds, when a nonmetallic atom pulls one or more electrons away from a metallic atom.
Figure 5.6 summarizes the general differences between nonpolar covalent bonds, polar covalent bonds, and ionic bonds.

**Nonpolar Covalent Bond**
Equal sharing of electrons
Both atoms attract electrons equally (or nearly so).
No significant charges form.

**Polar Covalent Bond**
Unequal sharing of electrons
Partial positive charge
This atom attracts electrons more strongly.
Partial negative charge.

**Ionic Bond**
Strong attraction between positive and negative charges.
This atom loses one or more electrons and gains a positive charge.
This atom attracts electrons so much more strongly than the other atom that it gains one or more electrons and gains a negative charge.

**Predicting Bond Type**
The simplest way to predict whether a bond will be ionic or covalent is to apply the following rules.

- When a nonmetallic atom bonds to another nonmetallic atom, the bond is covalent.
- When a metallic atom bonds to a nonmetallic atom, the bond is usually ionic.

Some bonds between a metallic atom and a nonmetallic atom are better described as ionic. For now, however, we will keep our guidelines simple. All nonmetal-nonmetal combinations lead to covalent bonds, and except when you are told otherwise, you can assume that all bonds between metallic atoms and nonmetallic atoms are ionic bonds.
Classifying Compounds

Compounds can be classified as molecular or ionic. **Molecular compounds** are composed of molecules, which are uncharged collections of atoms held together by all covalent bonds. **Ionic compounds** contain cations and anions held together by ionic bonds (Figure 5.7). You will see some exceptions later in this text, but for now, if a formula for a compound indicates that all the elements in it are nonmetals, you can assume that all of the bonds are covalent bonds, which form molecules, and that the compound is a molecular compound. We will assume that metal-nonmetal combinations lead to ionic bonds and ionic compounds.

**Figure 5.7**
Classifying Compounds

**Example 5.2 - Classifying Compounds**

Classify each of the following as either a molecular compound or an ionic compound.

a. calcium chloride, CaCl₂ (used for de-icing roads)

b. ethanethiol, C₂H₅SH (a foul-smelling substance used to odorize natural gas)

**Solution**

a. Calcium, Ca, is a metal, and chlorine, Cl, is a nonmetal. We expect the bonds between them to be ionic, so calcium chloride is an **ionic compound**.

b. Carbon, hydrogen, and sulfur are all nonmetallic elements, so we expect the bonds between them to be covalent bonds. The formula, C₂H₅SH, tells us that ethanethiol is composed of molecules that each contain two carbon atoms, six hydrogen atoms, and one sulfur atom. Ethanethiol is a **molecular compound**.

**Exercise 5.2 - Classifying Compounds**

Classify each of the following substances as either a molecular compound or an ionic compound.

a. formaldehyde, CH₂O (used in embalming fluids)

b. magnesium chloride, MgCl₂ (used in fireproofing wood and in paper manufacturing)