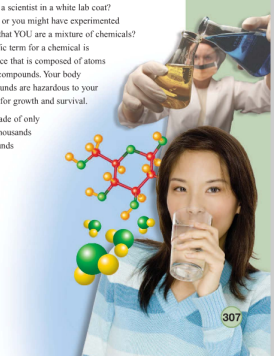
Chapter 13
Compounds

What does the word *chemical* mean to you? Does it make you think of strange, bubbling concoctions in test tubes, mixed by a scientist in a white lab coat? You might have heard or read about a hazardous chemical spill, or you might have experimented with chemicals in a science lab. Would it surprise you to know that YOU are a mixture of chemicals? So are a block of wood and a glass of orange juice. The scientific term for a chemical is *compound*. The word *compound* is used to describe any substance that is composed of atoms bonded together. Water (H_2O) and sodium chloride (NaCl) are compounds. Your body contains thousands of different compounds. While some compounds are hazardous to your health, many such as proteins and carbohydrates, are necessary for growth and survival.

All of the millions upon millions of different compounds are made of only 92 elements combined in different ways. Just as you can spell thousands of words with the same 26 letters, you can make all the compounds from 92 elements.



Key Questions

- ✔ What does the chemical formula H_2O mean?
- ✔ Why do elements tend to combine to form compounds?
- ✔ What compounds is your body made of?

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13.1 Chemical Bonds and Electrons

Most matter exists as compounds, not as pure elements. That's because most pure elements are chemically unstable. They quickly form *chemical bonds* with other elements to make compounds. For example, water (H_2O) is a compound of hydrogen and oxygen. The salt used in food is a compound that contains two elements, sodium and chlorine, that are poisonous by themselves. In this section, you will learn why and how the atoms of elements form compounds.

VOCABULARY

chemical bond - a bond that forms when atoms transfer or share electrons.

covalent bond - a chemical bond formed by atoms that are sharing one or more electrons.

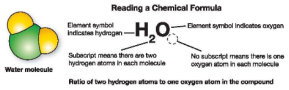
chemical formula - a representation of a compound that includes the symbols and ratios of atoms of each element in the compound.

Covalent bonds

Electrons form chemical bonds A **chemical bond** forms when atoms transfer or share electrons. Almost all elements form chemical bonds easily. This is why most of the matter you experience is in the form of compounds.

Covalent bonds A **covalent bond** forms when atoms share electrons. A group of atoms held together by covalent bonds is called a *molecule*. The bonds between oxygen and hydrogen in a water molecule are covalent bonds (Figure 13.1). There are two covalent bonds in a water molecule, between the oxygen and each of the hydrogen atoms. Each bond represents a shared electron pair.

Chemical formulas A molecule's **chemical formula** tells you the ratio of atoms of each element in the compound. For example, the chemical formula for water is H_2O. The subscript 2 indicates there are two hydrogen atoms in a water molecule. No subscript after the O indicates there is only one oxygen atom for every two hydrogen atoms in the molecule.



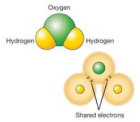


Figure 13.1: *In a covalent bond, electrons are shared between atoms.*

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Ionic bonds

An ion is a charged atom Not all compounds are made of molecules. For example, sodium chloride (NaCl) is a compound of sodium (Na) and chlorine (Cl) in a ratio of one sodium atom per chlorine atom. The difference is that in sodium chloride, the electron is transferred (instead of shared) from the sodium atom to the chlorine atom. When atoms gain or lose an electron, they become **ions**. An ion is a charged atom. By losing an electron, the sodium atom becomes a sodium ion with a charge of +1. By gaining an electron, the chlorine atom becomes a chloride ion with a charge of –1. (Note that when chlorine becomes an ion, the name changes to chl*oride*.)

Ionic bonds Sodium and chlorine form an **ionic bond** because the positive sodium ion is attracted to the negative chloride ion. Ionic bonds are bonds in which one or more electrons are transferred from one atom to another.

Ionic compounds do not form molecules Unlike covalent bonds, ionic bonds are not limited to a single pair of atoms. In sodium chloride, each positive sodium ion is attracted to all of the neighboring chloride ions (Figure 13.2). Likewise, each chloride ion is attracted to all the neighboring sodium ions. Because the bonds are not just between pairs of atoms, ionic compounds do not form molecules. In an ionic compound, each atom bonds with *all* of its neighbors through attraction between positive and negative charges.

The chemical formula for ionic compounds Like covalent compounds, ionic compounds have fixed ratios of elements. For example, there is one sodium ion per chloride ion in sodium chloride (NaCl). This means we can use chemical formulas for ionic compounds just like we do for covalent compounds.

Ions might be multiply charged Sodium chloride involves the transfer of one electron. However, ionic compounds may also be formed by the transfer of two or more electrons. A good example is magnesium chloride ($MgCl_2$). The magnesium atom gives up two electrons to become a magnesium ion with a charge of +2. Each chlorine atom gains one electron to become a chloride ion with a charge of –1. The ion charge is written as a superscript after the element symbol (Mg^{2+}, Cl^-, Fe^{3+}, etc.).

VOCABULARY

ion - an atom (or group of atoms) that has an electric charge other than zero, created when an atom (or group of atoms) gains or loses electrons.

ionic bond - a bond that transfers one or more electrons from one atom to another, resulting in attraction between oppositely charged ions.

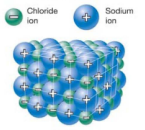

Figure 13.2: *Sodium chloride is an ionic compound in which each positive sodium ion is attracted to all of its negative chloride ion neighbors and vice versa.*

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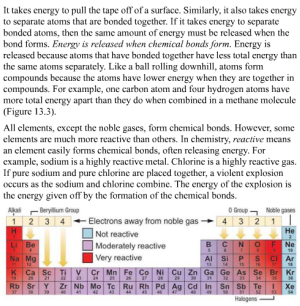
Why chemical bonds form

Atoms form bonds to reach a lower energy state It takes energy to pull the tape off of a surface. Similarly, it also takes energy to separate atoms that are bonded together. If it takes energy to separate bonded atoms, then the same amount of energy must be released when the bond forms. *Energy is released when chemical bonds form.* Energy is released because atoms that have bonded together have less total energy than the same atoms separately. Like a ball rolling downhill, atoms form compounds because the atoms have lower energy when they are together in compounds. For example, one carbon atom and four hydrogen atoms have more total energy apart than they do when combined in a methane molecule (Figure 13.3).

Chemical reactivity All elements, except the noble gases, form chemical bonds. However, some elements are much more reactive than others. In chemistry, *reactive* means an element easily forms chemical bonds, often releasing energy. For example, sodium is a highly reactive metal. Chlorine is a highly reactive gas. If pure sodium and pure chlorine are placed together, a violent explosion occurs as the sodium and chlorine combine. The energy of the explosion is the energy given off by the formation of the chemical bonds.



Some elements are more reactive than others The closer an element is to having the same number of electrons as a noble gas, the more reactive the element is. The alkali metals are very reactive because they are just one electron away from the noble gases. The halogens are also very reactive because they are also one electron away from the noble gases. The beryllium group and the oxygen group are less reactive because each element in these groups is two electrons away from a noble gas.

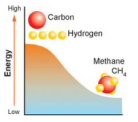


Figure 13.3: *The methane (CH_4) molecule has lower total energy than four separate hydrogen atoms and one separate carbon atom.*

CHALLENGE

The noble gases (He, Ne, Ar, etc.) are called *inert* because they do not ordinarily react with anything. You can put sodium in an atmosphere of pure helium and nothing will happen. However, scientists have found that a few noble gases *do* form compounds in very special circumstances. Research this topic and see if you can find a compound involving a noble gas.

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Valence electrons

Compounds contain particular ratios of elements The discovery of energy levels in the atom solved a 2,000-year-old mystery. Why do elements combine with other elements only in particular ratios (or not at all)? For example, why do two hydrogen atoms bond with one oxygen atom to make water? Why isn't there a molecule with three (H_3O) or even four (H_4O) hydrogen atoms? Why does sodium chloride have a precise ratio of one sodium ion to one chloride ion? Why don't helium, neon, and argon form compounds with any other elements? The answers have to do with the electrons in the outermost energy levels.

What are valence electrons? Chemical bonds are formed only between the electrons in the highest unfilled energy level. These electrons are called **valence electrons.** You can think of valence electrons as the outer "skin" of an atom. Electrons in the inner (filled) energy levels do not interact with other atoms because they are shielded by the valence electrons. For example, chlorine has seven valence electrons. The first 10 of chlorine's 17 electrons are in the inner (filled) energy levels (Figure 13.4).

Most elements bond to reach eight valence electrons It turns out that eight is the stable number for chemical bonding. All the elements heavier than boron form chemical bonds to acquire a configuration with eight valence electrons. For example, sodium and chlorine form an ionic bond so each can have a configuration of eight valence electrons (Figure 13.5). Eight is a stable number because eight electrons completely fill a part of the outermost energy level. The noble gases already have a stable number of eight valence electrons. They don't form chemical bonds because they don't need to react to achieve this stable number.

Light elements bond to reach two valence electrons For elements with an atomic number of five (boron) or less, the stable number is two instead of eight. For these light elements, two valence electrons completely fill the *first* energy level. The elements H, He, Li, Be, and B form bonds to reach the stable number of two valence electrons.

Hydrogen is special Because of its single electron, hydrogen can also have zero valence electrons. Zero is a stable number for hydrogen, as well as two. This flexibility makes hydrogen a very "friendly" element; hydrogen can bond with almost any other element.

VOCABULARY

valence electrons - the electrons in the highest unfilled energy level of an atom.

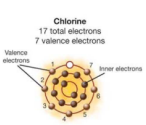

Figure 13.4: *Chlorine has 7 valence electrons. The other 10 electrons are in filled (inner) energy levels.*

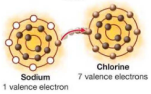

Figure 13.5: *Chlorine and sodium bond so each can reach a configuration with eight valence electrons.*

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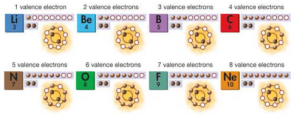
Valence electrons and the periodic table

Period 2 elements The illustration below shows how the electrons in the elements in the second period (lithium to neon) fill the energy levels. Two of lithium's three electrons go in the first energy level. Lithium has one valence electron because its third electron is the only one in the second energy level.

Each successive element has one more valence electron Going from left to right across a period, each successive element has one more valence electron. Beryllium has two valence electrons, boron has three, and carbon has four. Each element in the second period adds one more electron until all eight spots in the second energy level are full at atomic number 10, which is neon, a noble gas. Neon has eight valence electrons.



Bonding Oxygen has six valence electrons. To get to the magic number of eight, oxygen needs to add two electrons. Oxygen forms chemical bonds that provide these two extra electrons. For example, a single oxygen atom combines with two hydrogen atoms because each hydrogen can supply only one electron (Figure 13.6).

Double bonds share two electrons Carbon has four valence electrons. That means two oxygen atoms can bond with a single carbon atom, with each oxygen sharing two of carbon's four valence electrons. The bonds in carbon dioxide (CO_2) are *double bonds* because each bond involves four electrons (Figure 13.7), two from carbon and two from oxygen. Each oxygen has two lone pairs of electrons (see the in-text diagram on the next page).

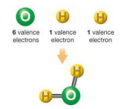


Figure 13.6: *Oxygen has 6 valence electrons and hydrogen has 2. In a water molecule, each hydrogen supplies one electron to make a total of 8 valence electrons.*

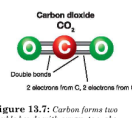


Figure 13.7: *Carbon forms two double bonds with oxygen to make carbon dioxide.*

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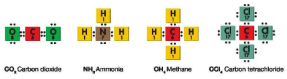
Lewis dot diagrams

Dot diagrams of the elements A **Lewis dot diagram** is a way to represent an atom's valence electrons. A dot diagram shows the element symbol surrounded by one to eight dots representing its valence electrons. Each dot represents one electron. Lithium has one dot, beryllium has two, boron has three, etc. Figure 13.8 shows dot diagrams for some of the elements.

Dot diagrams of molecules Each element forms bonds to reach one of the stable numbers of valence electrons: two or eight. In dot diagrams of a complete molecule, each element symbol has either two or eight dots around it. Both configurations correspond to completely filled (or empty) energy levels.



Example dot diagrams Carbon has four dots and hydrogen has one. One carbon atom bonds with four hydrogen atoms because this allows the carbon atom to have eight valence electrons (eight dots)—four of its own and four shared with four hydrogen atoms. The picture above shows dot diagrams for carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4), and carbon tetrachloride (CCl_4).

The formation of an ionic bond A sodium atom is neutral with 11 positively charged protons and 11 negatively charged electrons. When sodium loses one electron, it has 11 protons (+) and 10 electrons (–) and becomes an ion with a net charge of +1. This is because it now has one more positive charge than its negative charges. A chlorine atom is neutral with 17 protons and 17 electrons. When chlorine gains one electron to have a stable eight electrons, it has 17 protons (+) and 18 electrons (–) and becomes an ion with a charge of –1. This is because it has gained one negative charge. When sodium and chlorine form an ionic bond, the resulting compound is neutral (+1) + (–1) = 0.

VOCABULARY

Lewis dot diagram - a method for representing an atom's valence electrons using dots around the element symbol.

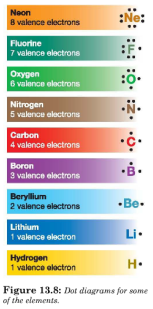


Figure 13.8: *Dot diagrams for some of the elements.*

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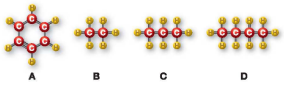
Section 13.1 Review

1. Molecules are held together by:
   a. ionic bonds
   b. covalent bonds
   c. both a and b
2. How many atoms of chlorine (Cl) are in the carbon tetrachloride molecule (CCl_4)?
3. Which of the compounds below has a chemical formula of C_3H_8?



4. True or False: Ionic compounds do not form molecules.
5. Atoms form chemical bonds using:
   a. electrons in the innermost energy level.
   b. electrons in the outermost energy level.
   c. protons and electrons.
6. Which of the diagrams in Figure 13.9 shows an element with three valence electrons? What is the name of this element?
7. Name two elements that have the Lewis dot diagram shown in Figure 13.10.
8. Draw dot diagrams for the following.
   a. silicon
   b. xenon
   c. calcium
   d. H_2O

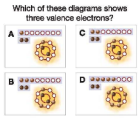


Figure 13.9: *Question 6.*

Figure 13.10: *Question 7.*

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