19.1 Bonding and Molecules

Most of the matter around you and inside of you is in the form of compounds. For example, your body is about 80 percent water. You learned in the last unit that water, H_2O, is made up of hydrogen and oxygen atoms combined in a 2:1 ratio. If a substance is made of a pure element, like an iron nail, chances are (with the exception of the noble gases) it will eventually react with another element or compound to become something else. Why does iron rust? Why is the Statue of Liberty green, even though it is made of copper? The answer is fairly simple: Most atoms are unstable unless they are combined with other atoms. In this section, you will learn how, and *why*, atoms combine with other atoms to form molecules. Molecules are made up of more than one atom. When atoms combine to make molecules, they form chemical bonds.

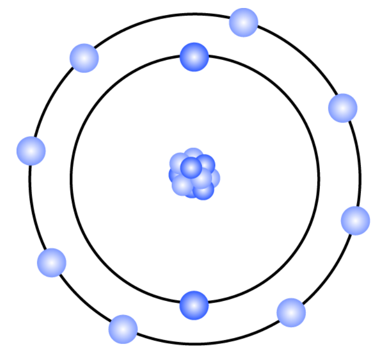


Figure 19.1: *A neon atom is chemically stable because it has a complete octet, or eight valence electrons.*

Why do atoms form chemical bonds?

The outer electrons are involved in bonding

Electrons in atoms are found in energy levels surrounding the nucleus in the form of an electron cloud. The higher the energy level, the more energy is required in order for an electron to occupy that part of the electron cloud. The outermost region of the electron cloud contains the valence electrons and is called the *valence shell*. The maximum number of valence electrons that an atom can have is *eight*. The exception to this rule is the first energy level, which only holds *two* electrons. Valence electrons are the ones involved in forming chemical bonds.

Stable atoms have eight valence electrons

Stable atoms have eight valence electrons. When an atom has eight valence electrons, it is said to have an octet of electrons. Figure 19.1 shows neon with a complete octet. In order to achieve this octet, atoms will lose, gain, or share electrons. An atom with a complete octet is chemically *stable*. An atom with an incomplete octet, like sodium (figure 19.2), is chemically *unstable*. Atoms form bonds with other atoms by either sharing them, or transferring them in order to complete their octet and become stable. This is known as the octet rule.

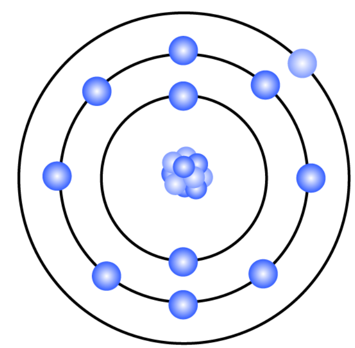


Figure 19.2: *A sodium atom is chemically unstable because it has only one valence electron.*

Exceptions to the octet rule

Look at a periodic table on page 329. Which atoms do you think are an exception to the octet rule? Remember, the first energy level only needs two electrons, not eight. Hydrogen, with only one electron, needs only one more to fill its valence shell. Helium, with two electrons, has a full valence shell (figure 19.3). This means that helium is chemically stable and does not bond with other atoms.

Stable atoms have full valence shells

What about lithium? It has three electrons. This means that its first shell is full but there is one extra electron in the second shell. Would it be easier for lithium (figure 19.4) to gain seven electrons to fill the second shell—or to lose one electron? You probably would guess that it is easier to lose one electron that gain seven. You would be correct in your guess, for lithium loses one electron when it bonds with other atoms. Table 19.1 shows the number of valence electrons and the number needed to complete the octet for the first 18 elements.

Table 19.1: ***Elements, number of valence electrons, and number needed to complete the octet***

element	valence electrons	number needed	element	valence electrons	number needed
H	1	1	Ne	8	0
He	2	0	Na	1	7
Li	1	7	Mg	2	6
Be	2	6	Al	3	5
B	3	5	Si	4	4
C	4	4	P	5	3
N	5	3	S	6	2
O	6	2	Cl	7	1
F	7	1	Ar	8	0

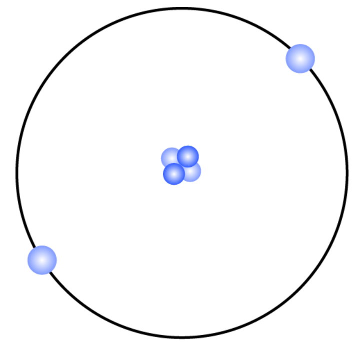


Figure 19.3: *Helium atoms have only two electrons, both of which are in the outermost level. Helium is an exception to the octet rule.*

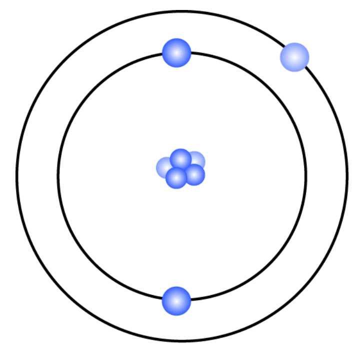


Figure 19.4: *Lithium atoms have three electrons. Since the first energy level only holds two electrons, lithium has one valence electron. If lithium loses that electron, it will have a full valence shell with two electrons.*

Using the periodic table to determine valence electrons

Do you remember how the periodic table is organized? With the exception of the transition metals, the *column* of the table tells you how many valence electrons each element has. For example, the atoms of the elements in column 1 have only *one* valence electron. Elements in column 2 have *two* valence electrons. Next, we skip to column 13 headed by boron. Atoms in this column have three valence electrons. Columns 14 through 18 have *four*, *five*, *six*, *seven*, and *eight* valence electrons, respectively.

Partial Periodic Table

Number of valence electrons in parentheses

Transition metals - groups 3 - 12
(Variable number of valence electrons)

(1) 1	(2) 2	3	4	5	6	7	8	9	10	11	12	(3) 13	(4) 14	(5) 15	(6) 16	(7) 17	(8) 18
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54

How do you show valence electrons in a diagram?

Valence electrons are often represented using *dot diagrams*. This system was developed in 1916 by G.N. Lewis, an American chemist. The symbol of the element in the diagram represents the nucleus of an atom and all of its electrons except for the valence electrons. The number of dots placed around the symbol of the element is equal to the number of valence electrons. The arrangement of the dots has no special significance and does not show the actual location of the electrons around the nucleus of the atom. Dots are shown in pairs around the four sides of the symbol as a reminder that electrons occur in pairs in the valence shell. Electrons begin to pair up only when no more single spaces are left. This is why the first four electrons are shown as single dots around the symbol, as in the diagram for carbon in figure 19.5.

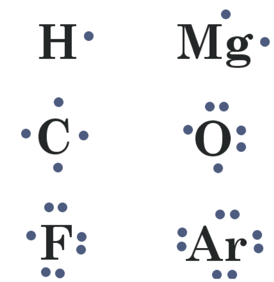
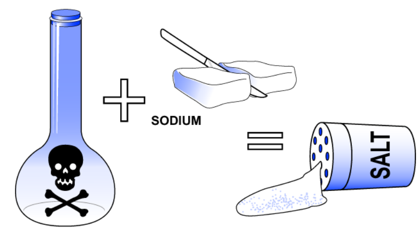


Figure 19.5: *Dot diagrams show the numbers of valence electrons.*

Types of chemical bonds

Chemical bonds result in molecules with different properties

Sodium is a soft, silvery metal so reactive that it must be stored so it does not come into contact with the air. Chlorine exists as a yellow-green gas that is very poisonous. When atoms of these two elements chemically bond, they become the white crystals that you use to make your food taste better: sodium chloride, also known as table salt. When chemical bonds form between atoms, the molecules formed are very different from the original elements they are made out of. What is the "glue" that helps hold atoms together to form so many different compounds? To answer this question, we must study the *types* of chemical bonds.



Ionic bonds

Recall that atoms will gain, lose, or share electrons in order to gain eight valence electrons in their outermost shell, that being the most stable configuration. **Ionic bonds** are formed when atoms gain or lose electrons. Sodium has one valence electron in its third energy level. If sodium loses that electron, its second energy level becomes full and stable with eight electrons. Chlorine has seven valence electrons. If chlorine gains only one electron, its valence shell will be full and stable. Do you think these two atoms are likely to bond?

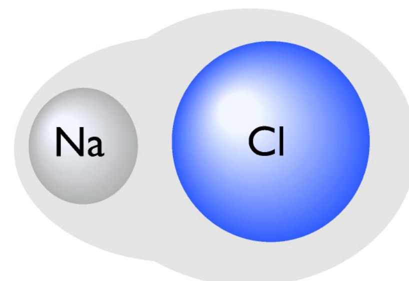


Figure 19.6: *Sodium and chlorine form an ionic bond to make sodium chloride (table salt).*

Ionization

In the last unit, you learned that all atoms are electrically neutral because they have the same number of protons and electrons. When atoms gain or lose electrons, they become **ions**, or atoms that have an electrical charge.

A neutral sodium atom has 11 positively charged protons and 11 negatively charged electrons. When sodium loses one electron to become more stable, it has 11 protons (+) and 10 electrons (-) and becomes an ion with a charge of +1. This is because it now has one more positive charge than negative charges (figure 19.7).

A neutral chlorine atom has 17 protons and 17 neutrons. When chlorine gains one electron to complete its stable octet, 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 (figure 19.8).

Opposites attract

Because the sodium ion has a positive charge and the chlorine ion has a negative charge, the two atoms become attracted to each other and form an ionic bond. Recall that opposite charges attract. When sodium, with its +1 charge, comes into contact with chlorine, with its -1 charge, they become electrically neutral as long as they are together. This is because +1 and -1 cancel each other out. This also explains why sodium and chlorine combine in a 1:1 ratio to make sodium chloride (figure 19.9).

Covalent bonds

Most atoms *share* electrons to in order to gain a stable octet. When electrons are shared between two atoms, a **covalent bond** is formed. Covalent bonds can form between two different types of atoms, or between two or more atoms of the same type. For example, chlorine, with seven valence electrons, sometimes shares an electron with another chlorine atom (figure 19.10). With this configuration, both atoms can share an electron through a covalent bond to become more stable. Many elemental gases in our atmosphere exist in pairs of covalently bonded atoms. The gases nitrogen (N_2), oxygen (O_2) and hydrogen (H_2) are a few examples. We call these covalently bonded atoms of the same type **diatomic molecules** (see Table 20.1, "Elements that exist as diatomic molecules," on page 358).

Figure 19.7: *When sodium loses an electron, it becomes an ion with a +1 charge.*

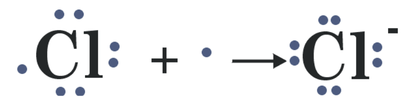


Figure 19.8: *When chlorine gains an electron, it becomes an ion with a -1 charge.*

Figure 19.9: *Sodium and chlorine form an ionic bond. The compound sodium chloride is electrically neutral as long as the two ions stay together.*

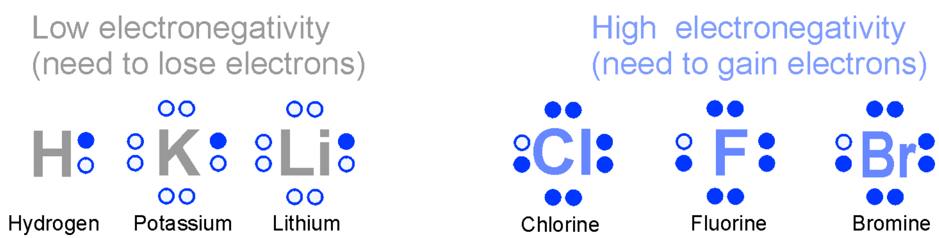
Figure 19.10: *Two chlorine atoms share the pair of electrons between them to form a covalent bond.*

How can you tell whether a bond is ionic or covalent?

Ionic bonds are formed by the attraction of two oppositely charged particles, while covalent bonds are formed when atoms share electrons. Which pairs of atoms are more likely to form ionic bonds? Which are more likely to form covalent bonds? Elements can be classified as *metals, metalloids,* and *nonmetals*. The periodic table inside the cover of this book shows these classifications. Generally, bonds between a metal and a nonmetal tend to be ionic in character while bonds between two nonmetals can be classified as covalent. However, electron pairs are sometimes shared *unequally* in covalent bonds. The attraction an atom has for the shared pair of electrons in a covalent bond is called an atom's **electronegativity**.

Atoms in column 17 have high electronegativity

For example, in a bond between hydrogen and chlorine, that electron pair is pulled toward the chlorine nucleus. This is because chlorine has very high electronegativity. Atoms in column 17 of the periodic table tend to have very high electronegativity. *Based on what you have learned about valence electrons and stability of atoms, why do you think this is true?* If you suppose that it is because these atoms only need one more electron to complete their octet, you are correct! Atoms with high electronegativity tend to want to *gain* electrons to complete their octet.



Atoms in columns 1 and 2 have low electronegativity

Conversely, atoms in the first two columns of the periodic table tend to have the lowest electronegativity. This is because they want to *get rid* of the electrons in their highest level so that their next level has a full octet. Bonds between atoms with opposite electronegativities tend to be *ionic*.

Linus Pauling

Linus Pauling developed a system for assigning electronegativity values for each element. This is just one of his many accomplishments. He is the only person to have won two unshared Nobel prizes, for chemistry in 1954, and for peace in 1962. His passion was to warn the public about the dangers of nuclear weapons, but he was equally dedicated to chemistry as it helps humanity.

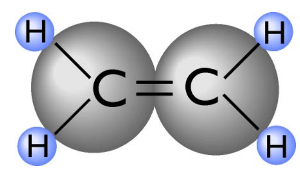


Figure 19.11: *The ethylene molecule is the building block, or subunit, of synthetic plastics. That is why plastics are often referred to as "polyethylenes."*

Environmental Issue: Paper or Plastic?

What is plastic?

Plastics are polymers. You may already know that the prefix *poly-* means "many" and the suffix *-mer* means "unit." A polymer is a large molecule that is composed of repeating smaller molecules. The building block or subunit of synthetic plastics is a molecule called ethylene (figure 19.11). Paper is made out of a natural polymer called cellulose. Cellulose, the most abundant polymer on Earth, is made out of many subunits of glucose molecules. The difference between a natural polymer like cellulose, and the man-made polymer that is used to make a bag or a soda bottle is that cellulose is easily digested by microorganisms. In contrast, synthetic plastics are not easily broken down. For this reason, when you throw a plastic cup away, there isn't much chance it will decompose quickly or at all.

Why can't microorganisms digest plastic?

In order for microorganisms to be able to break down a plastic molecule, they must have access to an exposed end or side branch of the molecule. Because synthetic plastics are such long chains of carbon surrounded by hydrogens, there are no places for microorganisms to begin "biting" on the molecule. Since most plastics we use are man-made, microorganisms are not able to consume them.

Biodegradable plastics

One way to approach the plastics problem is to make them *biodegradable*. This means that microbes such as bacteria and fungi can "eat" the plastic. Making biodegradable plastics involves creating exposed ends on the molecules so microbes can get a start. This is done by inserting a food item that microbes readily eat into into a plastic. For instance, starch can be inserted in the polyethylene molecule. Once microbes have eaten the starch, two ends of polyethylene are exposed. Many plastic grocery bags contain starch.

Recycling plastics

You may be familiar with the recycling symbols on the bottoms of plastic bottles. Those symbols allow you to sort the different plastics that make up each kind of plastic. Choosing the kind of plastic that is used for a certain product is a careful decision. Think about the wide variety of plastic containers (and don't forget their lids) that are used for certain products. In order to recycle plastic, you need to melt it so that it can be remolded into new containers or extruded into a kind of fabric that is used for sweatshirts.

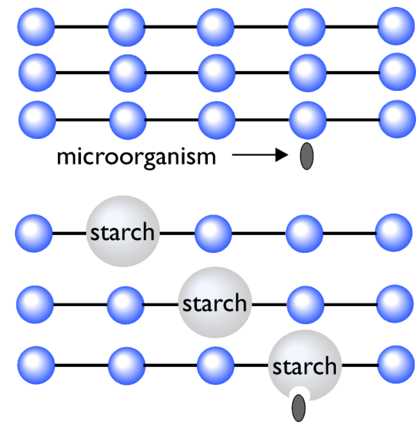


Figure 19.12: *Inserting starch molecules into the polyethylene chain provides a place for microorganisms to begin breaking it down.*

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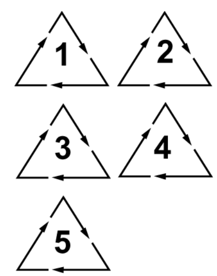

Figure 19.13: *Recycling symbols found on plastic products tell you the type of plastic and are used in sorting the plastics for recycling. Can you find these symbols on products you use every day?*