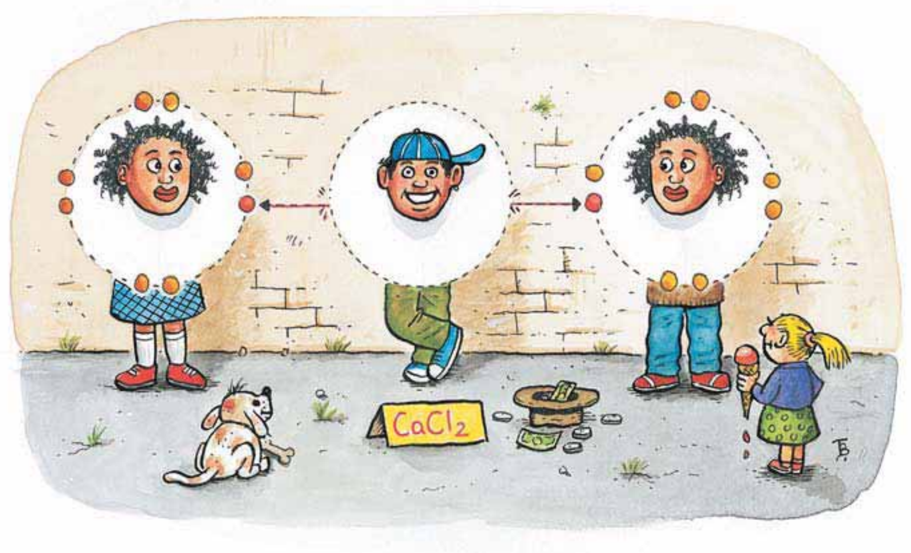
Section 8 The Octet Rule and Bonding

What Do You See?



Learning Outcomes

In this section you will

- **Relate** patterns in ionization energies of elements to patterns in their electron arrangements.
- **Use** your knowledge of electron arrangements and valence electrons to predict formulas for compounds formed by two elements.
- **Contrast** ionic bonding and covalent bonding.
- **Draw** electron-dot diagrams for simple molecules with ionic and covalent bonding.

What Do You Think?

You have learned that the chemical behavior of an atom is determined by the arrangement of the atom's electrons, specifically the valence electrons. The salt that you put on your food is chemically referred to as NaCl—sodium chloride.

- **How might the valence electrons of sodium (Na) and chlorine (Cl) interact to create the bond in NaCl?**

Record your ideas about this question in your *Active Chemistry* log. Be prepared to discuss your responses with your small group and the class.

Investigate

1. In *Section 3* you read that John Dalton assumed that chemical compounds formed from two elements combined in the simplest possible combination. In *Section 6* you began to see that an atom's chemical behavior reflects its excess or deficiency of electrons relative to an atom of the closest noble gas on the periodic table. Use the list of ionization energies in *Section 6* to answer the following questions:

   a) Which atoms have the smallest values for first ionization energies? (Remember, the first ionization energy is the amount of energy required to remove the first electron.)

b) Where are these atoms located on the periodic table?

c) What do you observe about the amount of energy required to remove the second electron from atoms of the elements identified in (a)?

d) Use your understanding of the arrangement of electrons in this group of elements to suggest a reason for the pattern you noted in (c).

e) Which atoms have the smallest values for second ionization energies? Where are these atoms located on the periodic table?

f) Use your understanding of the arrangement of electrons in this group of elements to suggest a reason for the pattern you noted in (e).

2. Once you recognize the role of an atom's electron arrangement—especially the valence electrons—in an atom's chemical activity, you can often predict formulas for compounds formed by two chemical elements. (Recall that valence electrons are the electrons located in the highest energy level, the levels designated by the sublevel having the highest numbers.)

Sodium (Na) has one valence electron in the 3*s* sublevel. By losing that electron, the sodium atom becomes a sodium ion and it has the same stable electron arrangement as neon.

a) What is the stable electron arrangement of neon?

b) What is the stable electron arrangement of sodium after the 3*s* sublevel electron has been removed?

c) What is the electric charge on the resulting Na ion?

Consider a chlorine atom.

d) How many valence electrons does a chlorine atom have?

e) How many electrons would a chlorine atom have to lose in order to have a stable electron arrangement like neon?

f) How many electrons does a chlorine atom need to gain to have the same number of electrons as an argon atom?

g) Gaining one electron is much easier than losing seven electrons. When a chlorine atom gains an electron, a chloride ion is formed. The original chlorine atom was electrically neutral. It gained a negative electron to form the ion. What is the electric charge (sign and value) on the resulting ion?

Sodium reacts violently with chlorine gas.

h) Each chlorine atom is capable of accepting one electron to become more stable. Each sodium atom is capable of losing one electron to become more stable. It certainly sounds as if a relationship is in store for the chlorine and sodium atoms.

i) Describe how you think the compound sodium chloride (NaCl) is formed.

j) Look at the *What Do You See?* illustration at the beginning of *Section 7*. Describe what you see in terms of bonding.

3. Consider the reaction between calcium and chlorine. The calcium atom is in Group 2A and has two valence electrons. These electrons are located in the 4*s* sublevel. You can note the two valence electrons in the electron arrangement for calcium shown on the periodic table.

In order to acquire the rather stable electron configuration of argon atoms, the calcium atoms give up their two valence electrons to form calcium ions. Since the original calcium atom was electrically neutral and it lost two negative electrons to form the ion, the resulting ion has a positive charge with a magnitude two times the charge on the electron. It has a plus two charge.

a) Each chlorine atom is capable of accepting one electron. How many chlorine atoms are needed to accept the two electrons that calcium atoms have to give?

b) When writing the formula for a compound, the number of atoms necessary to balance the loss and gain of electrons can be designated through the use of a subscript, such as the 2 in H_2O. There are 2 hydrogen atoms linked to every oxygen atom. How would you write the formula for the *binary compound* calcium chloride?

c) Look at the *What Do You See?* illustration at the beginning of this section. Describe what you see in terms of bonding.

4. Aluminum chloride is another material formed in reactions.

a) Consider an atom of aluminum. How many valence electrons does an aluminum atom have?

b) How many electrons does an aluminum atom need to give up to reach the same chemical stability as a neon atom?

c) What are aluminum atoms called after they give up their valence electrons? What is their electric charge (sign and value)?

d) How many chlorine atoms are needed to accept the electrons given up by an aluminum atom?

e) How would you write the formula for the compound aluminum chloride?

5. Carbon almost always forms *covalent bonds* in which electrons are shared.

a) How many valence electrons does carbon have?

b) How many more electrons does a carbon atom need to achieve the stability of neon?

c) A chlorine atom is capable of sharing one electron. How many chlorine atoms are needed to form a covalent compound with carbon by sharing?

d) Write the chemical formula for this compound.

Chem Talk

FORMING COMPOUNDS

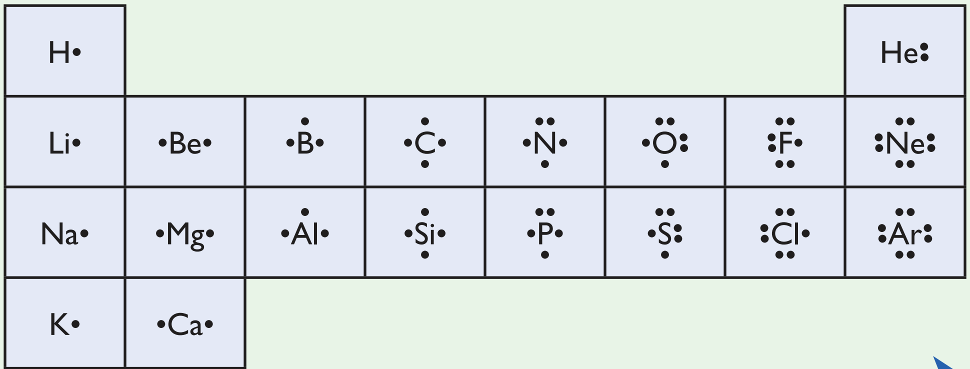
The Octet Rule

In the *Investigate*, you explained the formation of several compounds by determining how many electrons are transferred or shared between atoms. Scientists explain these observations using the **octet rule**. This rule states that atoms or ions tend to be more stable with an outer shell configuration of eight electrons, as is naturally the case with stable noble gases. A filled outer shell of electrons is a driving force for chemical reaction to occur. Therefore, atoms will gain, lose, or share electrons to obtain eight electrons in the outer shell. The octet rule works well with almost all of the elements found in the first three rows of the periodic table. However, there are two exceptions to this rule: The elements in the first row of the periodic table have only two electrons, so only two electrons are needed to fill the 1*s* shell. The other exception is found in the transition metals.

Ionic and Covalent Bonds

Ionic bonds are formed between two atoms when the valence electrons of one atom are completely transferred to a second atom. Typically, one, two, or three electrons are transferred and two ions are formed—a positive ion and a negative ion. The electrostatic force of attraction between the two charges (ions) is the ionic bond.

Valence electrons and bonding can be illustrated using electron-dot diagrams (sometimes called Lewis structures). In these diagrams, each valence electron is indicated by a dot adjacent to the chemical symbol for the element. The table below shows the electron-dot structures for the first 20 elements.



Chem Words

octet rule: the rule that states that atoms tend to gain or lose electrons during chemical reactions so that the atoms have an outer shell configuration of eight electrons.

ionic bond: the attraction between oppositely charged ions.

Notice that the electrons shown are only the valence electrons, not all the electrons of the element. Also notice that the electron-dot structures are identical for groups of elements in columns. This is why Li, Na, and K have such similar characteristics, as do F and Cl.

Examples of ionic reactions and bonds from your investigation are:

$$Na\bullet + \ddot{\underset{\bullet\bullet}{Cl}}\bullet \rightarrow Na^{+} + :\ddot{\underset{\bullet\bullet}{Cl}}:^{-}$$ or NaCl, sodium chloride

$$Ca: + 2:\ddot{\underset{\bullet\bullet}{Cl}}\bullet \rightarrow Ca^{2+} + 2:\ddot{\underset{\bullet\bullet}{Cl}}:^{-}$$ or $CaCl_2$, calcium chloride

$$\bullet Al: + 3:\ddot{\underset{\bullet\bullet}{Cl}}\bullet \rightarrow Al^{3+} + 3:\ddot{\underset{\bullet\bullet}{Cl}}:^{-}$$ or $AlCl_3$, aluminum chloride

By giving up electrons, the metals Na and Al take on the outer electron shell configuration of the noble gas, neon, which has eight electrons. Calcium metal becomes a calcium ion with the configuration of argon, which also has eight electrons. By taking on an electron, each chlorine atom becomes a chloride ion with the electronic configuration of argon.

You may have noticed that the column headed by carbon in the periodic table has not received a lot of attention so far. In an earlier section, you learned that atoms of carbon contain four valence electrons. To form an ionic compound, carbon would have to lose four electrons and take on a very high charge of +4, or gain four electrons to take on the equally high charge of –4. Either way, carbon would have a very high electrical charge of four. Because such a high charge is unstable, carbon does not typically form ionic compounds.

Instead of giving or taking four electrons, carbon atoms share four electrons to fulfill the octet rule. The result is the formation of **covalent bonds** and molecules. While carbon has the ability to form large, complex molecules by bonding with itself, all elements with four or more valence electrons can form covalent bonds. By sharing electrons, these atoms are associated with eight valence electrons, thereby following the octet rule.

Chem Words

covalent bond: a bond produced by sharing of a pair of electrons between two atoms.

Water is a covalent molecule composed of two hydrogen atoms and one oxygen atom, H_2O. Hydrogen has one valence electron and needs one more to have the electronic structure of helium, a noble gas. Oxygen has six valence electrons and needs two more to have the electronic structure of the nearest noble gas, neon. Using electron-dot diagrams, water can be shown to bond as follows:

2H• + :Ö: → H:Ö:H (with two more dots under the O) or H_2O, water

You can count eight electrons around the oxygen atom in water. You can also see that after the reaction, each hydrogen atom has its required two electrons. Whenever possible, electrons are shown in pairs, and each covalent bond consists of two electrons. The pair of electrons forming the covalent bond between hydrogen and oxygen are called **bonding electrons**. Usually, for ease in writing structures, scientists replace a bonding pair with a single line. The four electrons on the oxygen atom in water that are not used for bonding are called **nonbonding electron pairs** or **lone pairs**. Nonbonding electrons may be shown in an electron-diagram of a molecule. For simplicity, the nonbonding electrons may be omitted, with the understanding that they are part of an octet. An example of each type of diagram for water is shown below.

H—Ö—H (with two more dots under the O) or H—O—H

Naming Compounds

You may have noted that the names of the ionic compounds you have studied have all started with the name of the metal. This is followed by the nonmetal part. All of these compounds are **binary compounds**—that is, made of two elements. The names of binary compounds always end with the suffix "ide." There are exceptions, such as compounds with common names like water (H_2O) and ammonia (NH_3).

The International Union of Pure and Applied Chemists (IUPAC) is the world authority on naming chemicals, and it has detailed rules for naming every chemical ever discovered or made. However, only a few basic rules are needed here.

1. For binary compounds, the element with the most metallic character is placed first and the name usually ends in "ium."
2. The nonmetal part of the binary compound is placed last and the name usually ends in "ide."

Ionic names for nonmetal families are as follows:

The nitrogen family: nitride, phosphide, arsenide

The oxygen family: oxide, sulfide, selenide

The halogen family: fluoride, chloride, bromide, iodide

Chem Words

bonding electrons: the two electrons that are shared between two atoms.

nonbonding electron pair (or lone pair): a pair of electrons that are not used in forming a bond, but are located as a pair on the atom.

binary compound: a compound formed from the combining of two different elements.

Checking Up

1. When naming a binary compound, which element is named first, the metal or the nonmetal? Give an example to explain your answer.
2. Explain the difference between an ionic and a covalent bond.
3. Draw electron-dot diagrams showing covalent bonding in the following compounds:

a) water (two atoms of hydrogen, one atom of oxygen). Note: Since the noble gas nearest hydrogen is helium, with only two valence electrons, hydrogen atoms need be associated with only two valence electrons.

b) methane (four atoms of hydrogen, one atom of carbon)

c) ammonia (three atoms of hydrogen, one atom of nitrogen)

d) carbon tetrachloride (four atoms of chlorine, one atom of carbon)

What Do You Think Now?

At the beginning of the section you were asked the following:

- **How might the valence electrons of sodium (Na) and chlorine (Cl) interact to create the bond in NaCl?**

In the *Investigate* you described how sodium chloride (NaCl) forms. Describe how calcium bromide ($CaBr_2$) forms. That is, for this binary compound, show which element will lose electron(s) and which one will gain electron(s).

Chem

Essential Questions

What does it mean?

Chemistry explains a *macroscopic* phenomenon (what you observe) with a description of what happens at the *nanoscopic* level (atoms and molecules) using *symbolic* structures as a way to communicate. Complete the chart below in your *Active Chemistry* log.

MACRO	NANO	SYMBOLIC
Sodium and chlorine can combine to make salt. Hydrogen and oxygen can combine to make water. From the Investigate *section in this chapter, list one chemical reaction that you have observed.*	*The sharing of electrons between two atoms is a covalent bond. When the electron(s) of one element is transferred to another atom it is called an ionic bond. Describe what happens to the electrons when sodium and chlorine combine to create NaCl.*	*In order to help you keep track of the electrons during bond formation you can use symbolic structures called Lewis diagrams. Show the creation of NaCl using Lewis diagrams.*

How do you know?

Sodium chloride is written as NaCl and is composed of one sodium ion and one chloride ion. Calcium chloride is written as $CaCl_2$ and is composed of one calcium ion and two chloride ions. How would you know that two chloride ions are required to create calcium chloride?

Why do you believe?

The recipe to make brownies requires one cup of sugar, 8 oz of chocolate and one oven. If you wanted to double the recipe, how much sugar, chocolate and oven(s) are required?

Why should you care?

Knowing the number of valence electrons for the elements will make it easy to write correct formulas for compounds. How will your game include fun and creative ways for naming compounds as they form?

Reflecting on the Section and the Challenge

In this section, you learned that atoms of two chemical elements will interact with each other in order to achieve a stable electron arrangement like that of nearby noble gases. The way in which atoms interact is based on their excess or deficiency of electrons relative to atoms of the closest noble gas on the periodic table. An atom's excess or deficiency of electrons relative to the closest noble gas is readily indicated by the position of an element on the periodic table. In this way, the periodic table can be used to predict the chemical formulas when two elements interact to form a compound. This information can be deduced from the periodic table. Perhaps you can invent a way to make this more explicit as you create your periodic table game. How might you incorporate this information into your game to meet the *Chapter Challenge*?

Chem to Go

1. Find the following pairs of elements in the periodic table on the back inside cover. Identify the excess or deficiency of electrons in each atom relative to an atom of the closest noble gas. Then predict the formula of the compound formed when these elements interact:
   a) sodium and chlorine (to form sodium chloride)
   b) calcium and oxygen (to form calcium oxide)
   c) magnesium and chlorine (to form magnesium chloride)
   d) aluminum and oxygen (to form aluminum oxide)
2. a) In your *Active Chemistry* log, draw a simplified periodic table that contains only the first three rows of the periodic table. Your table should have three rows and eight columns. It should contain the elements with atomic numbers 1 through 18.
   b) In the box for each element, write the symbol for the element.
   c) In the columns headed by lithium, beryllium, and boron, indicate the charge (sign and value) of the ion formed when atoms of these elements give up electrons to get a more stable electron arrangement.
   d) In the columns headed by nitrogen, oxygen, and fluorine, indicate how many electrons atoms of those elements gain to get a more stable electron arrangement.
3. You know the formula for sodium chloride (NaCl). From this knowledge you can also write the formula for potassium chloride, cesium bromide, lithium iodide, and sodium fluoride.
   a) What tool makes it possible for you to do this, even though you may have never investigated these compounds?
   b) Using the periodic table, explain what information you used to help explain how you arrived at the formulas.
4. The formula for calcium chloride is $CaCl_2$. From this knowledge you should be able to write the formulas of the alkaline earth metals (Group 2) and halogens combining.
   a) Write the formula for magnesium bromide, strontium iodide, beryllium fluoride, barium chloride, and calcium iodide.
   b) What information from the periodic table did you use to write the formulas of these compounds?
5. A compound that was used previously is aluminum chloride ($AlCl_3$). Use your understanding of why elements are grouped together and are called a family to write the formula for each of the following compounds:
   a) boron fluoride
   b) aluminum bromide
   c) gallium iodide
   d) indium (III) chloride
   e) thallium (III) bromide

6. You have explored how the alkali, alkaline earth metals, and 3A group (boron, aluminum, gallium, indium, and thallium) combine with the halogens. How do these metals combine with the Group 6A elements (oxygen, sulfur, selenium, tellurium, and polonium)? Look at a few compounds, such as sodium oxide, which has a formula of Na_2O. Alkali metals like sodium have low ionization energy values. When they react to form an ionic compound, an electron is lost and they become the positive ion (cation) of the new compound. A nonmetal like oxygen has a high ionization energy value. In reacting to form an ionic compound it gains electrons, becoming the negative ion (anion) of the compound. Therefore, when the alkali metals combine with oxygen or other elements of Group 6A, they should have a similar formula.

   a) Write the formula and electron-dot structure for each of the following compounds:

      i) potassium sulfide ii) rubidium selenide iii) lithium telluride

      iv) sodium sulfide v) cesium oxide

   You can do the same thing with the alkaline earth metals combining with the Group 6A elements. Calcium oxide has the formula CaO. The alkaline earth metals have low ionization energies and react to form the positive ion with a +2 charge. Again, the nonmetal oxygen will form an anion with a charge of −2. Thus, the alkaline earth metals and the Group 6 elements will combine in a 1:1 ratio.

   b) Write the formula and electron-dot structure for each of the following compounds:

      i) magnesium sulfide ii) strontium selenide iii) barium oxide

      iv) beryllium telluride v) calcium sulfide

   Finally, look closely at the carbon atom. It is unique in its ability to form millions of covalent compounds by bonding with itself. It also forms smaller molecules by bonding with hydrogen, Group 6A and Group 7A atoms. These compounds share electrons and do not have full electronic charges as ions do. Carbon compounds are a class of compounds called organic compounds. They often have their own unique names.

   c) Write the formula and electron-dot structure for each of the following compounds:

      i) carbon dioxide ii) carbon tetrachloride iii) carbon disulfide

      iv) carbon tetrafluoride v) methane (1 carbon with hydrogens)

Inquiring Further

Creating compounds with "inert" gases

For a long period of time the noble gases were called the inert elements because it was assumed that they were nonreactive and did not gain or lose electrons. Research to find out if compounds can be formed with the noble gases. Record your finding in your *Active Chemistry* log. If time permits, share your findings with the class.