7.1 Ions

Connecting to Your World Pyrite (FeS_2), a common mineral that emits sparks when struck against steel, is often mistaken for gold—hence its nickname, "fool's gold." Although certainly not worth its weight in gold, pyrite can be used as a source of sulfur in the production of sulfuric acid, a common industrial chemical. Pyrite is an example of a crystalline solid. In crystalline solids, the component particles of the substance are arranged in an orderly, repeating fashion. In this chapter, you will learn about crystalline solids composed of ions that are bonded together. But first you need to understand how ions form from neutral atoms.

Guide for Reading

Key Concepts

- How do you find the number of valence electrons in an atom of a representative element?
- Atoms of which elements tend to gain electrons? Atoms of which elements tend to lose electrons?
- How are cations formed?
- How are anions formed?

Vocabulary

valence electrons
electron dot structures
octet rule
halide ions

Reading Strategy

Summarizing Write a one-paragraph summary of how the octet rule applies to the formation of ions.

Valence Electrons

Mendeleev used similarities in the properties of elements to organize his periodic table. Scientists later learned that all of the elements within each group of the periodic table behave similarly because they have the same number of valence electrons. **Valence electrons** are the electrons in the highest occupied energy level of an element's atoms. The number of valence electrons largely determines the chemical properties of an element.

The number of valence electrons is related to the group numbers in the periodic table. **To find the number of valence electrons in an atom of a representative element, simply look at its group number.** For example, the elements of Group 1A (hydrogen, lithium, sodium, potassium, and so forth) all have one valence electron, corresponding to the 1 in 1A. Carbon and silicon, in Group 4A, have four valence electrons. Nitrogen and phosphorus, in Group 5A, have five valence electrons; and oxygen and sulfur, in Group 6A, have six. The noble gases (Group 8A) are the only exceptions to the group-number rule: Helium has two valence electrons, and all of the other noble gases have eight. Figure 7.1 shows some applications of Group 4A elements.

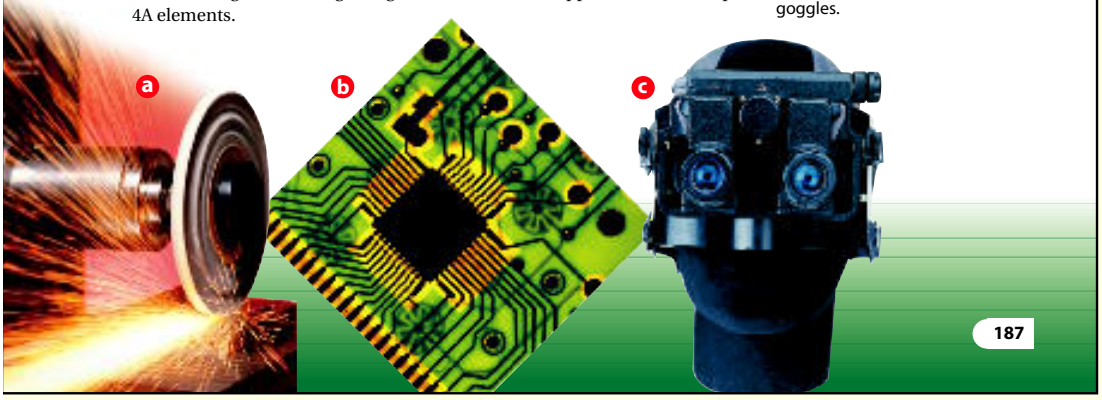

Figure 7.1 Group 4A elements include carbon, silicon, and germanium. (a) This saw blade contains carbon in the form of diamond. (b) Silicon is used in the manufacture of microchips. (c) Germanium is one of the materials used to make thermoscanning goggles.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 7.1
- **Core Teaching Resources,** Section 7.1 Review
- **Transparencies,** T75–T78
- **Small-Scale Chemistry Laboratory Manual,** Lab 10

Technology

- **Interactive Textbook with ChemASAP,** Problem-Solving 7.1, Assessment 7.1
- **Go Online,** Section 7.1

7.1

1 FOCUS

Objectives

7.1.1 **Determine** the number of valence electrons in an atom of a representative element.
7.1.2 **Explain** how the octet rule applies to atoms of metallic and nonmetallic elements.
7.1.3 **Describe** how cations form.
7.1.4 **Explain** how anions form.

Guide for Reading

Build Vocabulary L2

Graphic Organizer Have each student choose a halide ion. Then have students sketch a graphic organizer that shows how a halide ion relates to the other three vocabulary terms.

Reading Strategy L2

Preview Have students skim the headings, look at the visuals, and read the boldfaced text to preview the section.

2 INSTRUCT

Connecting to Your World

Have students study the photograph and read the text that opens the section. Discuss the ways in which iron and sulfur ions can interact to form the regular pyrite crystal structure.

Section 7.1 (continued)

Valence Electrons

Use Visuals L1

Table 7.1 Have students identify the total number of electrons and the number of valence electrons in selected elements from Table 7.1. Reemphasize that the group number equals the number of valence electrons in an atom of a representative element.

TEACHER Demo

Valence Electrons L2

Purpose To model the valence electrons of an atom.

Materials plastic egg, 11 marbles

Procedure Hold up a plastic egg containing 10 marbles. State that the egg represents a sodium atom and that the marbles represent the 10 electrons making up the $n = 1$ and $n = 2$ energy levels. Explain that these electrons cannot be "removed" without "breaking" the egg. Now hold up one additional marble next to the egg. State that this marble represents the eleventh electron, and occupies the $n = 3$ energy level. This is the valence electron. Explain that if this electron is lost, the resulting atom has an overall 1+ charge.

Expected Outcome Students should be able to distinguish valence electrons from nonvalence electrons.

The Octet Rule

Discuss L2

Have students determine the accuracy of this statement: All stable ions of elements result in electronic configurations that are isoelectronic with noble gases. *(Most of the time this statement is true, but there are exceptions. Use Cu(I) as an example. Explain that a noble gas configuration is not generally possible with elements that would have to gain or lose many electrons to become stable.)*

Word *Origins* L2

In music, an octet refers to a group of eight performers, or a composition written for eight musicians. In poetry, an octet refers to a group of eight lines of verse.

Table 7.1

Electron Dot Structures of Some Group A Elements

Period	Group 1A	2A	3A	4A	5A	6A	7A	8A
1	H·							He:
2	Li·	·Be·	·B·	·C·	·N·	·O·	:F·	:Ne:
3	Na·	·Mg·	·Al·	·Si·	·P·	:S·	:Cl·	:Ar:
4	K·	·Ca·	·Ga·	·Ge·	·As·	:Se·	:Br·	:Kr:

Valence electrons are usually the only electrons used in chemical bonds. Therefore, as a general rule, only the valence electrons are shown in electron dot structures. **Electron dot structures** are diagrams that show valence electrons as dots. Table 7.1 shows electron dot structures for atoms of some Group A elements. Notice that all of the elements within a given group (with the exception of helium) have the same number of electron dots in their structures.

Checkpoint ***What is an electron dot structure?***

Word *Origins*

Octet comes from the Greek word *okto*, meaning "eight." There are eight electrons in the highest occupied energy level of the noble gases, except for helium. **How do you think the term *octet* might also be applied to music or poetry?**

The Octet Rule

You learned in Chapter 6 that noble gases, such as neon and argon, are unreactive in chemical reactions. That is, they are stable. In 1916, chemist Gilbert Lewis used this fact to explain why atoms form certain kinds of ions and molecules. He called his explanation the **octet rule:** In forming compounds, atoms tend to achieve the electron configuration of a noble gas. An octet is a set of eight. Recall that each noble gas (except helium) has eight electrons in its highest occupied energy level and a general electron configuration of ns^2np^6. The octet rule takes its name from this fact about noble gases. **Atoms of metals tend to lose their valence electrons, leaving a complete octet in the next-lowest energy level. Atoms of some nonmetals tend to gain electrons or to share electrons with another nonmetal to achieve a complete octet.** Although there are exceptions, the octet rule applies to atoms in most compounds.

Formation of Cations

An atom is electrically neutral because it has equal numbers of protons and electrons; an ion forms when an atom or group of atoms loses or gains electrons. **An atom's loss of valence electrons produces a cation, or a positively charged ion.** Note that for metals, the name of a cation is the same as the name of the element. For example, a sodium atom (Na) forms a sodium cation (Na^+). Likewise, a calcium atom (Ca) forms a calcium cation (Ca^{2+}). Although their names are the same, there are many important chemical differences between metals and their cations. Sodium metal, for example, reacts explosively with water. By contrast, sodium cations are quite unreactive. As you may know, they are a component of table salt, a compound that is very stable in water.

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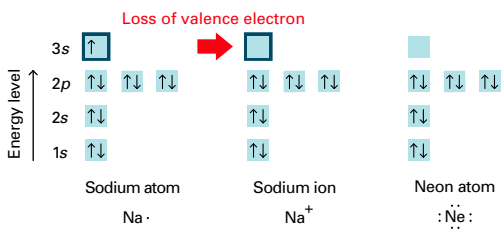
The most common cations are those produced by the loss of valence electrons from metal atoms. Most of these atoms have one to three valence electrons, which are easily removed. Sodium, in Group 1A of the periodic table, is typical. Sodium atoms have a total of eleven electrons, including one valence electron. A sodium atom can lose an electron to become a positively charged sodium ion. The sodium ion has an electron configuration that is identical to the noble gas neon. When forming a compound, a sodium atom loses its one valence electron and is left with an octet (eight electrons) in what is now its highest occupied energy level. Because the number of protons in the sodium nucleus is still eleven, the loss of one unit of negative charge produces a cation with a charge of 1+. You can represent the electron loss, or ionization, of the sodium atom by drawing the complete electron configuration of the atom and of the ion formed.

$$\text{Na}\ \ 1s^2 2s^2 2p^6 3s^1 \xrightarrow{-e^-} \text{Na}^+\ \ 1s^2 \underbrace{2s^2 2p^6}_{\text{octet}}$$

Notice that the electron configuration of the sodium ion ($1s^2 2s^2 2p^6$) is the same as that of a neon atom. The diagrams below help illustrate this point.



Both the sodium ion and the neon atom have eight electrons in their valance shells (highest occupied energy levels). Using electron dot structures, you can show the ionization more simply.

$$\text{Na}\cdot \xrightarrow[\text{ionization}]{\text{loss of valence electron}} \text{Na}^+ + e^-$$

Sodium atom (electrically neutral, charge = 0) → Sodium ion (plus sign indicates one unit of positive charge) + electron (minus sign indicates one unit of negative charge)

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For: Links on Sodium
Visit: www.SciLinks.org
Web Code: cdn-1071

Figure 7.2 The sodium atoms in a sodium-vapor lamp ionize to form sodium cations (Na^+). **Applying Concepts** ***How many electrons are in the highest occupied energy level of Na^+?***

Answers to...
Figure 7.2 8 electrons

Checkpoint A diagram that shows valence electrons as dots.

Section 7.1 (continued)

Discuss L2

One way to determine the number of valence electrons in an atom is to look at the electron configuration of the atom. Explain that any electron in an atom outside the noble-gas core is called a valence electron. Using diagrams such as those on pages 189 and 190, show students several examples of how various atoms of the representative elements form ions and gain a noble-gas electron configuration. Indicate the noble-gas core and valence electrons in your diagrams. Lay pieces of magnesium, zinc, copper, and aluminum on a dry surface in the lab to show that metals do not spontaneously form metal cations.

CLASS Activity

Forming Cations L2

Purpose Students model the formation of cations using equations.

Materials paper, pencil

Procedure Have students write equations similar to that for Mg on student page 190, showing the formation of metal cations from metal atoms. Students should show the electron dot structures for the metal atoms and metal cations that are formed. In addition, you may want students to write out the electron configurations for the metal atoms and cations. Check students' equations to be sure the correct metal ion is formed.

Expected Outcome Students should be able to use electron dot structures to correctly write equations describing the ionization of metal atoms.

Figure 7.3 Walnuts are a good dietary source of magnesium. Magnesium ions (Mg^{2+}) aid in digestive processes.

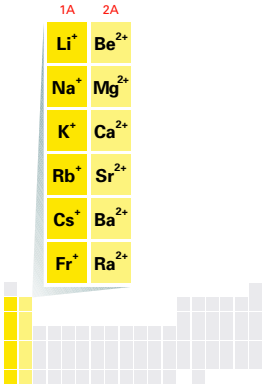


Figure 7.4 Cations of Group 1A elements have a charge of 1+. Cations of Group 2A elements have a charge of 2+.

Magnesium (atomic number 12) belongs to Group 2A of the periodic table, so it has two valence electrons. A magnesium atom attains the electron configuration of neon by losing both valence electrons. The loss of the valence electrons produces a magnesium cation with a charge of 2+.

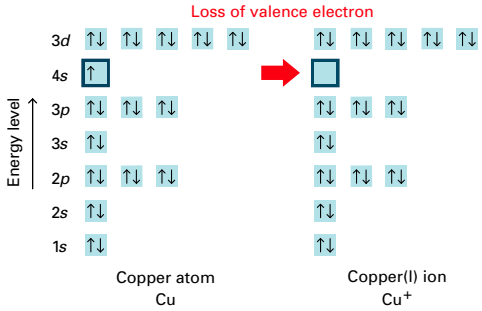
$$\cdot Mg\cdot \longrightarrow Mg^{2+} + 2e^-$$

Magnesium atom (electrically neutral, charge = 0) → Magnesium ion (2+ indicates two units of positive charge) + (2 in front of e^- indicates two units of negative charge)

Figure 7.4 lists the symbols of cations formed by metals in Groups 1A and 2A. Cations of Group 1A elements always have a charge of 1+. Similarly, the cations of Group 2A elements always have a charge of 2+. This consistency can be explained in terms of the loss of valence electrons by metal atoms: The atoms lose enough electrons to attain the electron configuration of a noble gas. For example, all Group 2A elements have two valence electrons. In losing these two electrons, they form 2+ cations.

For transition metals, the charges of cations may vary. An atom of iron, for example, may lose two or three electrons. In the first case, it forms the Fe^{2+} ion. In the second case, it forms the Fe^{3+} ion.

Some ions formed by transition metals do not have noble-gas electron configurations (ns^2np^6) and are therefore exceptions to the octet rule. Silver, with the electron configuration of $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}5s^1$, is an example. To achieve the structure of krypton, which is the preceding noble gas, a silver atom would have to lose eleven electrons. To acquire the electron configuration of xenon, which is the following noble gas, silver would have to gain seven electrons. Ions with charges of three or greater are uncommon, and these possibilities are extremely unlikely. Thus silver does not achieve a noble-gas configuration. But if it loses its $5s^1$ electron, the configuration that results ($4s^24p^64d^{10}$), with 18 electrons in the highest occupied energy level and all of the orbitals filled, is relatively favorable. Such a configuration is known as a pseudo noble-gas electron configuration. Silver forms a positive ion (Ag^+) in this way. Other elements that behave similarly to silver are found at the right of the transition metal block. For example, a copper atom can ionize to form a 1+ cation (Cu^+), as illustrated below.



By losing its lone 4*s* electron, copper attains a pseudo noble-gas electron configuration. Likewise, cations of gold (Au^+), cadmium (Cd^{2+}), and mercury (Hg^{2+}) also have pseudo noble-gas configurations.

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Formation of Anions

An anion is an atom or a group of atoms with a negative charge. **The gain of negatively charged electrons by a neutral atom produces an anion.** Note that the name of an anion of a nonmetallic element is not the same as the element name. The name of the anion typically ends in *-ide*. Thus a chlorine atom (Cl) forms a chloride ion (Cl^-), and an oxygen atom (O) forms an oxide ion (O^{2-}). Figure 7.5 shows the symbols of anions formed by some elements in Groups 5A, 6A, and 7A.

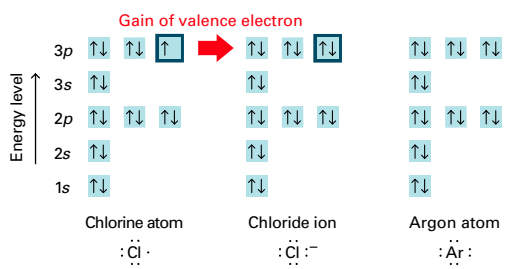
Because they have relatively full valence shells, atoms of nonmetallic elements attain noble-gas electron configurations more easily by gaining electrons than by losing them. For example, chlorine belongs to Group 7A (the halogen family) and has seven valence electrons. A gain of one electron gives chlorine an octet and converts a chlorine atom into a chloride ion.

$$\text{Cl} \quad 1s^2 2s^2 2p^6 3s^2 3p^5 \xrightarrow{+e^-} \text{Cl}^- \quad 1s^2 2s^2 2p^6 \underbrace{3s^2 3p^6}_{\text{octet}}$$

The chloride ion is an anion with a single negative charge. Notice that it has the same electron configuration as the noble gas argon.

$$\text{Ar} \quad 1s^2 2s^2 2p^6 \underbrace{3s^2 3p^6}_{\text{octet}}$$

Chlorine atoms, therefore, need one more valence electron to achieve the electron configuration of the nearest noble gas. The diagrams below illustrate how both the chloride ion and the argon atom have an octet of electrons in their highest occupied energy levels.



Based on the diagrams above, you use electron dot structures to write an equation showing the formation of a chloride ion from a chlorine atom.

$$:\ddot{\underset{..}{\text{Cl}}}\cdot + e^- \xrightarrow[\text{valence electron}]{\text{gain of one}} :\ddot{\underset{..}{\text{Cl}}}:^-$$

Chlorine atom → Chloride ion (Cl^-)

In this equation, each dot in the electron dot structure represents an electron in the valence shell in the electron configuration diagram.

Checkpoint ***Which noble gas has the same electron configuration as a chloride ion?***

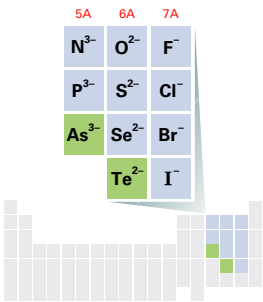


Figure 7.5 Atoms of nonmetals and metalloids form anions by gaining enough valence electrons to attain the electron configuration of the nearest noble gas.
Interpreting Diagrams ***In which group of the periodic table do the elements bromine and iodine belong?***

Formation of Anions

Use Visuals L1

Figure 7.5 Explain that the elements arsenic (As) and tellurium (Te) are metalloids, not nonmetals. However, they form anions that are named according to the same convention as nonmetal anions are named (arsenide, telluride).

Discuss L2

Explain to students that when one atom forms an ion, that ion is called a monatomic ion. Explain that the prefix *mon-* or *mono-* means "one." Ask students to predict what ions might be called if they contained more than one atom. Tell students that they will study such ions in Chapter 8.

Facts and Figures

Water Purification

Chlorine gas is often used to purify drinking water; it kills a variety of microorganisms, including those that carry diseases. But chlorine also reacts with organic substances in the water to produce chlorinated compounds such as chloroacetonitrile. Chloroacetonitrile has been shown to cause inflammation of the digestive tract in laboratory animals. As an alternative to chlorine, some countries have begun purifying water with ozone. Ozone kills microorganisms even more effectively than chlorine. About one percent of the water supply in the United States is now purified with ozone. It is estimated that it would cost $6 billion to switch completely to ozone for treating all the drinking water supplies.

Answers to...

Figure 7.5 Group 7A

Checkpoint argon

Section 7.1 (continued)

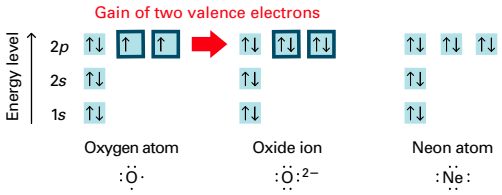
Discuss L2

Discuss with students how certain elements can form either anions or cations. Have students write the electron configuration of nitrogen ($1s^2 2s^2 2p^3$). Ask, **How can a nitrogen atom form a cation that has the electron configuration of a noble gas?** *(It can lose five electrons.)* **How can a nitrogen atom form an anion that has the electron configuration of a noble gas?** *(It can gain three electrons.)* Have them repeat this process for carbon. Explain that atoms that have few electrons to gain or lose to achieve an octet are more likely to form ions. Other atoms are not likely to form ions, and the process they undergo will be studied in Chapter 8.

Figure 7.6 The six most abundant ions in seawater are chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+).

The ions that are produced when atoms of chlorine and other halogens gain electrons are called **halide ions.** All halogen atoms have seven valence electrons and need to gain only one electron to achieve the electron configuration of a noble gas. Thus all halide ions (F^-, Cl^-, Br^-, and I^-) have a charge of 1−. The seawater in Figure 7.6 contains many different ions, but the negatively charged ions—the anions—are mostly chloride ions.

Look at another example. Oxygen is in Group 6A, and oxygen atoms each have six valence electrons. Oxygen atoms attain the electron configuration of neon by gaining two electrons, as shown in the diagrams below.



The resulting oxide ions have charges of 2− and are written as O^{2-}. Using electron dot structures, you can write the equation for the formation of oxide ions as follows.

$$:\ddot{\underset{\cdot\cdot}{O}}\cdot + 2e^- \longrightarrow :\ddot{\underset{\cdot\cdot}{O}}:^{2-}$$

Table 7.2 lists some common anions that you will be learning about in this book. Note that not all of the anions listed end with the suffix *-ide*.

Checkpoint ***How many electrons do halogen atoms need to gain in order to achieve the electron configuration of a noble gas?***

Table 7.2

Some Common Anions

1−		2−		3−	
F^-	fluoride	O^{2-}	oxide	N^{3-}	nitride
Cl^-	chloride	S^{2-}	sulfide	P^{3-}	phosphide
Br^-	bromide	SO_4^{2-}	sulfate	PO_4^{3-}	phosphate
I^-	iodide	CO_3^{2-}	carbonate		
OH^-	hydroxide				
ClO^-	hypochlorite				
NO_3^-	nitrate				
$C_2H_3O_2^-$	acetate				
HCO_3^-	hydrogen carbonate				

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CONCEPTUAL PROBLEM 7.1

Writing the Symbols and Names of Ions

The beaker shown on the right contains iodine vapor. Write the symbol and name of the ion formed when

a. an iodine atom gains one electron.
b. a strontium atom loses two electrons.

1 Analyze ***Identify the relevant concepts.***

a. An atom that gains electrons forms a negatively charged ion (anion). The name of an anion of a nonmetallic element ends in *-ide*.
b. An atom that loses electrons forms a positively charged ion (cation). The name of a cation of a metallic element is the same as the name of the element.

2 Solve ***Apply concepts to this situation.***

a. I^-, iodide ion (an anion)
b. Sr^{2+}, strontium ion (a cation)

Practice Problems

1. Write the name and symbol of the ion formed when
   a. a sulfur atom gains two electrons.
   b. an aluminum atom loses three electrons.
2. How many electrons are lost or gained in forming each ion?
   a. Ba^{2+} **b.** As^{3-} **c.** Cu^{2+}

Interactive Textbook
Problem-Solving 7.1 Solve Problem 1 with the help of an interactive guided tutorial.
with ChemASAP

7.1 Section Assessment

3. **Key Concept** How can you determine the number of valence electrons in an atom of a representative element?
4. **Key Concept** Atoms of which elements tend to gain electrons? Atoms of which elements tend to lose electrons?
5. **Key Concept** How do cations form?
6. **Key Concept** How do anions form?
7. How many valence electrons are in each atom?
   a. potassium **b.** carbon
   c. magnesium **d.** oxygen
8. Draw the electron dot structure for each element in Question 7.
9. How many electrons will each element gain or lose in forming an ion?
   a. calcium (Ca) **b.** fluorine (F)
   c. aluminum (Al) **d.** oxygen (O)
10. Write the name and symbol of the ion formed when
    a. a potassium atom loses one electron.
    b. a zinc atom loses two electrons.
    c. a fluorine atom gains one electron.
11. Write the electron configuration of Cd^{2+}.

Connecting Concepts

Ionization Energy Reread page 173 in Section 6.3. How does the octet rule explain the large increase in energy between the first and second ionization energies of Group 1A metals?

Interactive Textbook
Assessment 7.1 Test yourself on the concepts in Section 7.1.
with ChemASAP

3 ASSESS

Evaluate Understanding L2

Have students refer to the periodic table on page162. To determine the students' knowledge about the formation of elemental anions and cations, ask the students to determine whether the following ions are likely to exist and why: H^- *(yes, isoelectronic with He);* H^+ *(yes, but without electrons, there is no comparable noble-gas configuration);* Sr^{2+} *(yes, isoelectronic with Kr);* Al^{3+} *(yes, isoelectronic with Ne);* Xe^- *(no, cannot form ions easily due to stable electron configuration);* Zn^{6-} *(no, isoelectronic with Kr but formation would require a gain of too many electrons);* Zn^{2+} *(yes, not isoelectronic with a noble gas but has pseudo-noble-gas electron configuration with eighteen electrons filling up the outer energy level:* $3s^2 3p^6 3d^{10}$*)*

Reteach L1

Select groups from the periodic table in random order and ask students to predict the common ions that could be formed from elements of each group. Note that predicting is fairly easy for groups at the far left or far right of the table, but more difficult for groups in the center of the table, which have partially filled d and f orbitals.

Connecting Concepts

The amount of energy needed to remove the one valence electron of a Group 1A metal atom (first ionization energy) is low. After this electron is lost, the outer energy level contains an octet and is stable. If it loses another electron, it will be less stable, so the second ionization energy is high.

Interactive Textbook
If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 7.1.
with ChemASAP

Answers to...

Checkpoint 1 electron