The Formation of Ionic Compounds 1.11

At a crime scene, detectives collect many clues and pieces of evidence in order to pinpoint the perpetrator of the crime. Suspects are rarely convicted in a court of law based on only one piece of evidence. It is the supporting evidence that usually leads to a conviction. Similarly, scientists do not usually depend on a single method in order to identify matter. If possible, they collect additional information about a substance's physical and chemical properties.

So far in this unit, you have been introduced to three methods for identifying different types of matter using qualitative analysis:

1. thermal emission spectroscopy (TES), in which substances are identified based on the amount of heat they emit ("Getting Started");
2. light spectroscopy, in which substances are identified by their line spectra, since line spectra are unique to each type of substance (section 1.5);
3. flame tests, in which substances are identified by the colours they emit when placed in a flame (section 1.7).

In this section, you will study a fourth qualitative analysis technique that can be used to identify matter: conductivity.

Conductivity

One physical property that can be used to identify a substance is the ability of the substance to conduct electricity. **Conductivity** is a physical property of metals. Few *compounds* are able to conduct electricity in the solid state at room temperature, however. Many compounds are able to conduct electricity when they are heated to become a liquid or when they are dissolved in water to produce a solution. If the solution is able to conduct electricity when a compound is dissolved in water, the compound is called an **electrolyte**. If the solution does not conduct electricity, the compound is called a **nonelectrolyte** (**Figure 1**). Why are some compounds electrolytes, but not others?

conductivity the ability of a substance to conduct electricity; a physical property of matter

electrolyte a compound that, when dissolved in water, produces a solution that conducts electricity

nonelectrolyte a compound that, when dissolved in water, does not produce a solution that conducts electricity

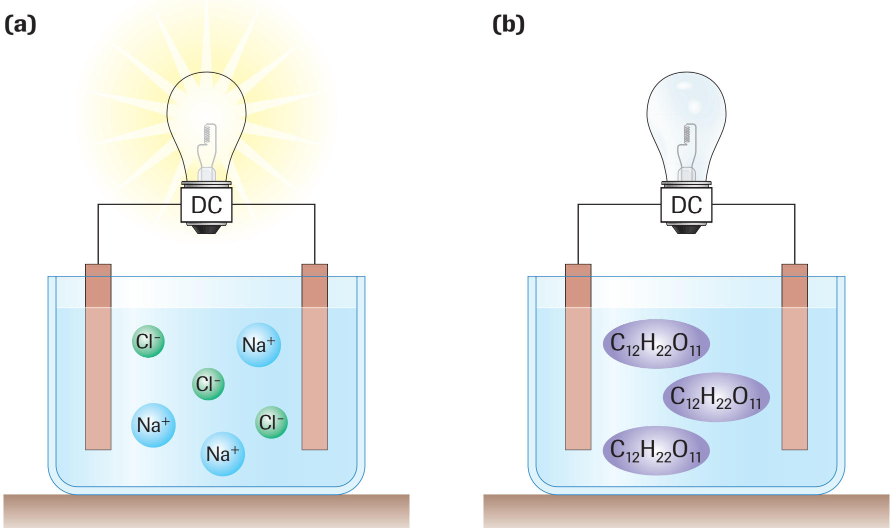

Figure 1
Why do you think the sodium chloride solution can conduct electricity but the sugar solution cannot? To answer this question, look closely at the two diagrams.
(a) Sodium chloride, $NaCl_{(s)}$, is an electrolyte. Scientists know that a sodium chloride solution conducts electricity because the light bulb lights up.
(b) Sugar, $C_{12}H_{22}O_{11(s)}$, is a nonelectrolyte. A sugar solution does not conduct electricity because the bulb remains unlit.

The Formation of Ions

Scientists know that most of the matter on Earth is found as compounds or molecules rather than single atoms. From this evidence, scientists have inferred that most matter is more stable in compound form.

Atoms gain or lose the electrons found in their outermost shells in order to become more stable. Atoms are most stable when their outer shells are full. A full outer shell (except the first shell) contains eight electrons. With the exception of helium, which has two electrons, all noble gases have a full outer shell of eight electrons (**Figure 2**).

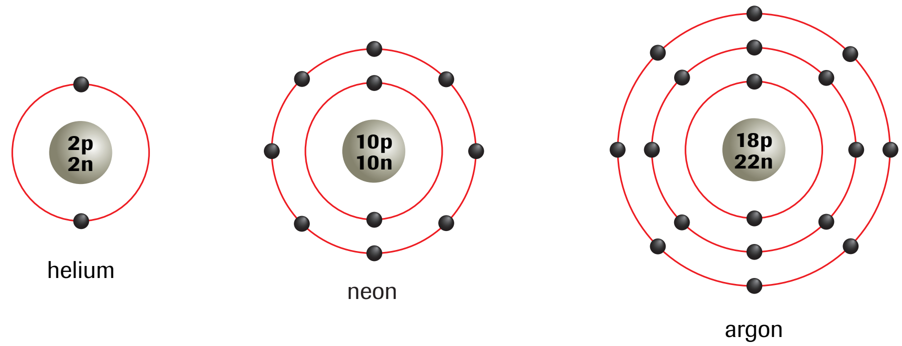

Figure 2
Examine the Bohr–Rutherford diagrams of three of the noble gases. Notice that the outer shells are full and cannot hold any more electrons.

In previous courses, you learned that the noble gases (Group VIII) are the least reactive elements and, therefore, the most stable of all the elements. An atom that loses or gains electrons in order to attain a noble gas configuration is following the **octet rule**.

Atoms that have gained or lost electrons are known as **ions**. If an atom gains electrons, it has more electrons than protons and becomes a negative ion or **anion**. If an atom loses electrons, it has fewer electrons than protons and becomes a positive ion or **cation**.

Whether an atom gains or loses electrons in order to become a cation or anion depends on the number of electrons it possesses in its outer shell. The electrons in an atom's outermost shell are called **valence electrons**. For example, sodium, Na, is a metal in Group I. It has one electron in its third shell. Losing this electron is easier and energetically more favourable than gaining seven electrons in order to fill its outer shell. As a result, sodium loses its valence electron, revealing the underlying second shell, which is full. Since sodium has lost one electron, the number of electrons it has is now one less than the number of protons. Therefore, the sodium ion carries a charge of 1+ (Na^+). The sodium ion is stable because it has the same electron configuration as the noble gas neon, Ne (**Figure 3(a)**).

octet rule Atoms gain or lose electrons in their outermost shells in order to attain a noble gas configuration.

ion an atom (or group of atoms) that has lost or gained one or more electrons

anion an atom that carries an overall negative charge because it has more electrons than protons

cation an atom that carries an overall positive charge because it has fewer electrons than protons

valence electrons electrons that are found in the outermost shell of an atom

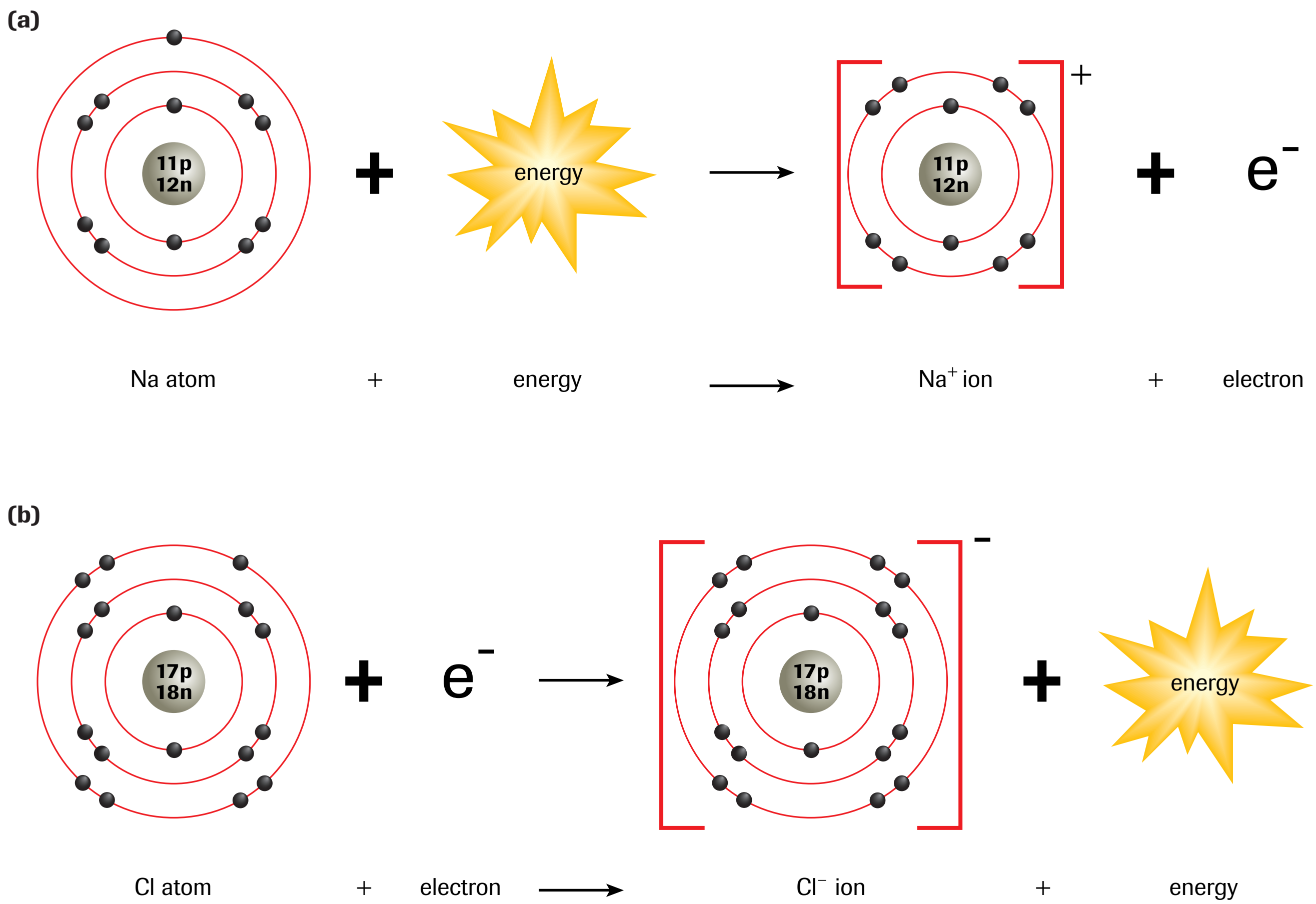

Figure 3
(a) The sodium atom has one lone electron in its third shell. When it loses this electron, it is left with a full second shell. The sodium ion has a net charge of 1+ since it now has 11 protons and 10 electrons. The sodium ion's electron configuration is now identical to neon's electron configuration.
(b) The chlorine atom has 7 electrons in its third shell. When chlorine gains an electron, it attains a net charge of 1– and becomes a chloride ion, with 17 protons and 18 electrons. The chloride ion's electron configuration is identical to argon's electron configuration.

Chlorine is found in Group VII. It has seven valence electrons. Gaining one electron is easier for chlorine than losing seven electrons. Chlorine, therefore, accepts one electron. Since the number of electrons it has is now one more than the number of protons, the chloride ion has a charge of 1− (Cl^-). The chloride ion is stable because it has the same electron configuration as the noble gas argon, Ar (**Figure 3**(**b**)).

In general, in order to become stable, metals lose electrons and become cations while nonmetals gain electrons and become anions. Metals attain the electron configuration of the noble gas that precedes them, while nonmetals attain the electron configuration of the noble gas that follows them.

Lewis Symbols

Lewis symbol a diagram composed of a chemical symbol and dots, depicting the valence electrons of an atom or ion

In previous courses, you learned how to represent atoms using Bohr–Rutherford diagrams. A Bohr–Rutherford diagram depicts the electron structure of the whole atom. Since only the valence electrons take part in chemical reactions, a **Lewis symbol** is used to depict the electrons in an atom's outermost shell. In a Lewis symbol, the valence electrons are represented by dots and are distributed around the element's symbol. Each quadrant surrounding the symbol can hold up to two valence electrons, for a maximum of eight electrons around the symbol. When drawing Lewis symbols, first place electrons, one at a time, at the 12, 3, 6, and 9 o'clock positions, as required. Then, add more electrons by pairing them, one at a time, in the same order as you placed the first four electrons (**Figure 4**).

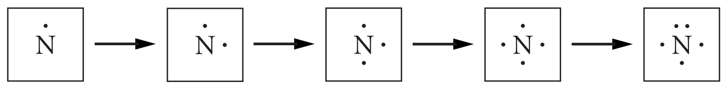

Figure 4
The progressive placement of electrons in a Lewis symbol

The Lewis symbols of elements in the same group of the periodic table have the same number of dots surrounding the symbol (**Figure 5**). For example, the Lewis symbol for magnesium has the same number of dots as the Lewis symbols for calcium and beryllium. Magnesium, calcium, and beryllium, therefore, all have the same number of valence electrons.

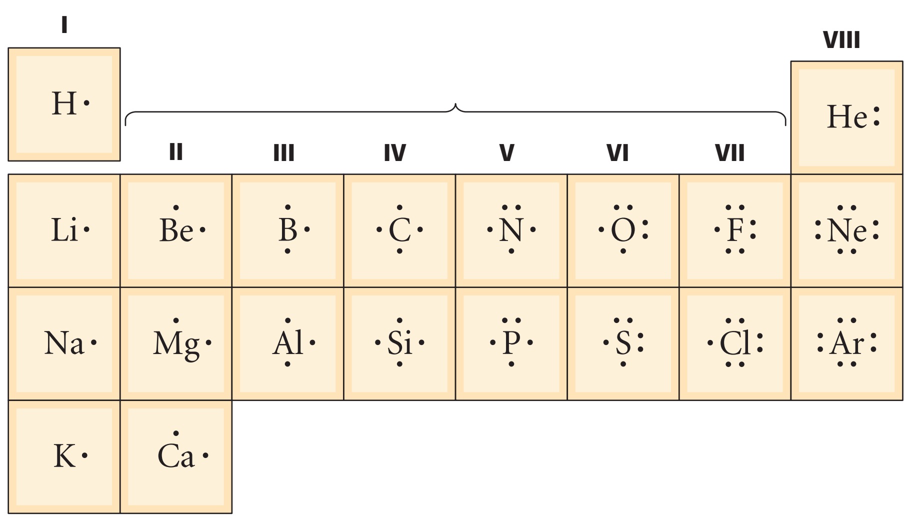

Figure 5
Lewis symbols for the first 20 elements in the periodic table. What do you notice about the Lewis symbols for elements in the same group? What happens to the number of electrons as you go across a period?

Ions can also be represented by Lewis symbols. **Figure 6** shows the Lewis symbol for the chloride ion. The Lewis symbol is enclosed in square brackets. The charge of the ion is placed outside the brackets.

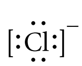

Figure 6
Lewis symbol for Cl^-

Polyatomic Ions

Ions that are composed of one atom are called **monatomic ions**. All the ions that have been mentioned in this section, so far, have been monatomic. When an ion is composed of more than one atom, it is called a **polyatomic ion**. **Table 1** lists some common polyatomic ions and their charges.

monatomic ion an ion that is composed of only one atom

polyatomic ion an ion that is composed of two or more atoms

Ionic Compounds

You have just learned that monatomic ions form in order to become more stable. Now you will learn *how* monatomic ions form. Consider sodium and chlorine. As you know, in order to satisfy the octet rule, chlorine needs to *gain* one electron and sodium needs to *lose* one electron. If a sodium atom and a chlorine atom come in contact under the right chemical conditions, sodium will lose its lone valence electron to chlorine, which has seven valence electrons. The transfer of one electron from sodium to chlorine results in both chlorine and sodium attaining a noble gas configuration. It also results in sodium gaining a positive charge and chlorine gaining a negative charge. Since opposite charges attract, the positive sodium ion is now attracted to the negative chloride ion, and vice versa. The bond that arises from the attraction between the two oppositely charged ions is called an **ionic bond** (**Figure 7**).

Ionic bonds form between metals and nonmetals. Metals lose their electrons and become positive ions (cations) more easily than other types of elements. Nonmetals easily gain electrons and become negative ions (anions). The combination of cations and anions forms an **ionic compound**. At a temperature of 25°C and a pressure of 101.3 kPa, ionic compounds form solid **ionic crystals** in which large numbers of cations and anions are arranged in a repeating three-dimensional pattern. Ionic crystals are also known as salts or salt crystals (**Figure 8**).

Table 1 Some Common Polyatomic Ions

Ion	Name
NO_3^{-}	nitrate
SO_4^{2-}	sulfate
PO_4^{3-}	phosphate
OH^{-}	hydroxide
CO_3^{2-}	carbonate
BrO_3^{-}	bromate
ClO_3^{-}	chlorate
IO_3^{-}	iodate
$C_2H_3O_2^{-}$	acetate
HCO_3^{-}	hydrogen carbonate

ionic bond the bond that results from the electrostatic force of attraction that holds positive and negative ions together

ionic compound a compound that consists of cations and anions held together by ionic bonds

ionic crystal a solid that consists of large numbers of cations and anions arranged in a repeating three-dimensional pattern

$$Na\cdot + \cdot\ddot{\underset{\cdot\cdot}{Cl}}: \rightarrow [Na]^{+}\,[:\ddot{\underset{\cdot\cdot}{Cl}}:]^{-} + \text{energy}$$

Figure 7
Formation of an ionic bond

(a) (b)

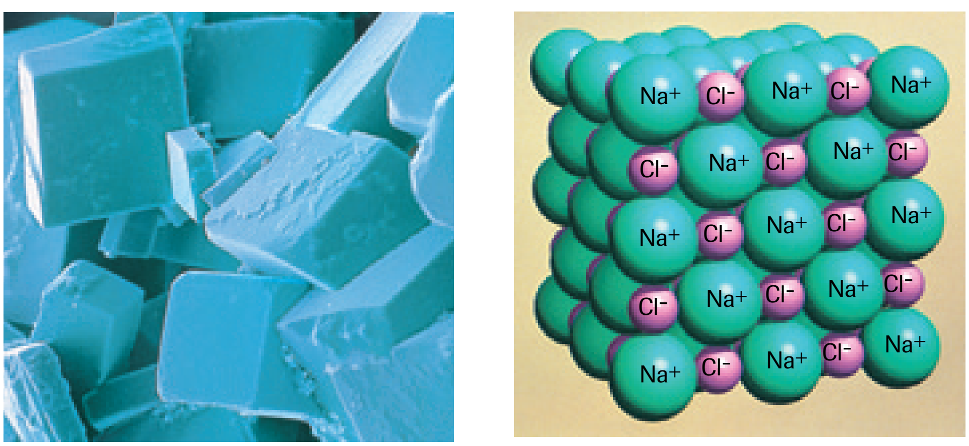

Figure 8
(a) Sodium chloride (table salt) crystals appear as cubes when viewed under a microscope.
(b) A sodium chloride ionic crystal is composed of large numbers of Na^{+} ions and Cl^{-} ions arranged in a repeating three-dimensional pattern. There is one Na^{+} ion for every Cl^{-} ion, thus the ratio of ions is 1:1.

formula unit the smallest amount of a substance having the composition given by its chemical formula

Molecular compounds are made up of individual molecules that contain the types and numbers of atoms given in their molecular formulas. Thus, a single molecule of water, $H_2O_{(l)}$, contains two hydrogen atoms and one oxygen atom. The crystals of ionic compounds, on the other hand, are composed of large numbers of anions and cations. Thus, their chemical formulas do not indicate the types and numbers of ions in the crystal, but rather the types and *ratio* of ions in the crystal. Since a crystal of sodium chloride contains many sodium ions and chloride ions in a 1:1 ratio, the chemical formula for sodium chloride is $NaCl_{(s)}$. The smallest amount of a substance that has the composition given by its chemical formula is called a **formula unit**. Thus, $NaCl_{(s)}$ is the formula unit of sodium chloride because it indicates that sodium chloride contains sodium and chloride ions in a 1:1 ratio (**Figure 9**). Similarly, the formula unit of the ionic compound magnesium bromide is $MgBr_{2(s)}$, indicating that a magnesium bromide crystal contains magnesium ions and bromide ions in a 1:2 ratio.

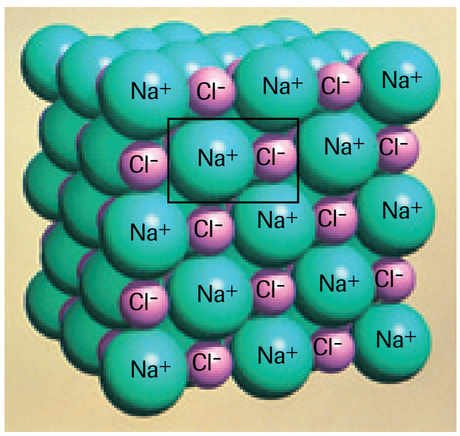

Figure 9
Although a sodium chloride crystal contains large numbers of sodium ions and chloride ions, sodium chloride contains sodium and chloride ions in a 1:1 ratio. Thus, the chemical formula for sodium chloride is $NaCl_{(s)}$.

dissociate separate into positive and negative ions

When soluble ionic compounds are placed in aqueous solution, they conduct electricity: that is, they are electrolytes, as discussed at the beginning of this section. A sodium chloride solution (**Figure 1(a)**) conducts electricity. When placed in water, the positive sodium ions separate from the negative chloride ions. In other words, the sodium chloride compound **dissociates** into its respective ions. To test a solution for its ability to conduct electricity, electrodes, which are attached to the positive and negative terminals of a battery, are placed in the solution. The electrode that is positively charged by the battery attracts the negatively charged ions. The electrode that is negatively charged by the battery attracts the positively charged ions. The movement of ions causes current to flow through the solution. (You will learn more about electrochemistry in Unit 5.)

As mentioned earlier, sugar molecules (**Figure 1(b)**) are not ionic and do not dissociate when they dissolve in water. Instead, the sugar molecules remain neutral, whole molecules in aqueous solution. Since an aqueous solution of sugar molecules does not conduct electric current, sugar is a nonelectrolyte.

Chemical Nomenclature: Naming Elements and Compounds

In the early days of chemistry, when few compounds were known, chemists used common names—such as sugar of lead, quicklime, and milk of magnesia—to identify compounds. To date, nearly five million different compounds have been invented or discovered. Assigning each compound a unique common name, and then keeping track of them all, is almost impossible. The solution is to develop a system for naming compounds in which the name reveals something about the composition of the compound. An international organization of scientists, called the International Union of Pure and Applied Chemistry, or **IUPAC**, develops and sets international rules for chemical names and symbols. See Appendix C6 to review IUPAC rules for naming inorganic compounds. You will learn IUPAC rules for naming organic compounds in Unit 3.

IUPAC International Union of Pure and Applied Chemistry, the organization that establishes the conventions used by chemists

Section 1.11 *Questions*

Understanding Concepts

1. Distinguish between an electrolyte and a nonelectrolyte.
2. Explain why some atoms have a tendency to form ions. Which combinations of atoms tend to form ions? Why?
3. Which types of elements form ionic bonds? How?
4. Draw a Lewis symbol for each of the following atoms:
   (a) potassium
   (b) cesium
   (c) iodine
   (d) silicon
   (e) antimony
   (f) krypton
   (g) barium
5. Predict the charge on the most stable ion that is formed by each of the following elements. Write the ion's symbol, including its charge.
   (a) hydrogen
   (b) potassium
   (c) fluorine
   (d) magnesium
   (e) sulfur
6. Draw Lewis symbols for the element ions in question 5. What similarity do you notice? State the rule that is being followed.
7. Using Lewis symbols and the octet rule, illustrate how each of the following pairs of atoms bond:
   (a) potassium and chlorine
   (b) magnesium and sulfur

Applying Inquiry Skills

8. (a) Design an experiment to investigate the conductivity of an ionic solid. With your teacher's approval, perform your experiment.
   (b) Research the conductivity of molten (liquid) ionic compounds.

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   (c) Use your findings to write a report about the conductivity of ionic compounds in the different states: solid, liquid, and aqueous.
   (d) State a hypothesis for the properties you observe.