Key Terms
ion
chemical bond
ionic bond
ionic compound

6.1 Ionic Compounds

Each winter, they come out and prowl the icy streets of your community, leaving behind a trail of small, white crystals. Salt trucks, like the one in **Figure 6.1**, spread salt to keep the roads from getting icy. This means, however, that a great deal of road salt is dumped into the environment. Each winter, the Ontario Ministry of Transportation spreads between 500 000 and 600 000 tonnes of salt on the roads. This mass is equivalent to over 300 000 cars!

Why is salt used to reduce ice on roads? How can we avoid or minimize the effects of road salt on the environment? The answers lie in the important properties of road salt—an ionic compound—and the potential alternatives.

Figure 6.1 Road salt is used to keep roads safe for motorists, but it has negative effects on the environment.

Forming Ions

In Chapter 5, you learned that the reactivity of elements is influenced by the arrangement of their valence electrons. Noble gases are the least reactive because their electron arrangements are very stable. This stability is because the outer energy level of electrons is full. Some of the other elements can achieve a full outer energy level, and therefore more stability, by either gaining or losing electrons.

ion a positively or negatively charged atom or molecule

When an atom loses or gains electrons, the balance between positive and negative charges no longer exists and the atom becomes charged. An atom that becomes charged is called an **ion**. As shown in **Figure 6.2**, when an atom loses electrons, it forms an ion that is positively charged because it now has more protons than electrons. Conversely, when an atom gains electrons, it forms an ion that is negatively charged because it now has more electrons than protons.

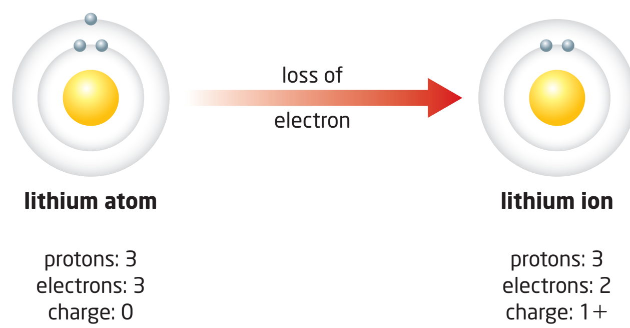


Figure 6.2 When this atom loses an electron, it becomes an ion with more protons than electrons.

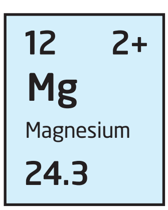


Figure 6.3 An element's square in the periodic table shows what charges an ion of the element might have.

The charge on an ion is equal to the sum of the charges on its protons and electrons. For example, consider a sodium ion that has 11 protons (11+) and 10 electrons (10–). The sum of the charges is +1. The ion is represented as Na^{+}. When ion charges are 1+ or 1–, the number is not included. It is important to remember that an atom cannot lose or gain protons, only electrons.

The periodic table lists the charges that ions of each element can have. For example, as shown in **Figure 6.3**, the only ion charge for magnesium in the periodic table is 2+. This ion is represented as Mg^{2+}.

Ionic Bonds

chemical bond a chemical link between two atoms, which holds the atoms together

ionic bond a chemical bond that forms between oppositely charged ions

ionic compound a compound made of oppositely charged ions

Compounds consist of two or more different elements that are chemically linked together. These chemical links are called **chemical bonds**. One type of chemical bond is the **ionic bond**, which is formed by the attraction between oppositely charged ions. When an **ionic compound** forms, one or more electrons from one atom are transferred to another atom. This electronic rearrangement produces oppositely charged ions that are attracted to each other. An ionic bond forms between the two ions, creating a neutral compound. In the formation of ionic compounds, the loss and gain of valence electrons between the reacting elements allows each ion to have a full outer energy level of electrons.

Recognizing Ionic Compounds

Knowing the types of elements that form ionic compounds and understanding the reasons for this will allow you to identify most ionic compounds. Ionic compounds are usually composed of a metal and one or more non-metals. This is because atoms of metals tend to lose electrons and form positive ions, while atoms of non-metals tend to gain electrons and form negative ions.

Sodium chloride, shown in **Figure 6.4**, is an ionic compound that you consume every day. Sodium, an alkali metal in Group 1, readily loses an electron to form Na^+. It forms an ionic bond with chlorine, a halogen in Group 17 of the periodic table, which readily gains an electron to form Cl^-. The Bohr-Rutherford diagrams in **Figure 6.4** show the electron transfer that occurs in this reaction. Notice how oppositely charged ions form a compound that is neutral. This reaction is an example of how two hazardous substances can be combined to produce an edible product—table salt.

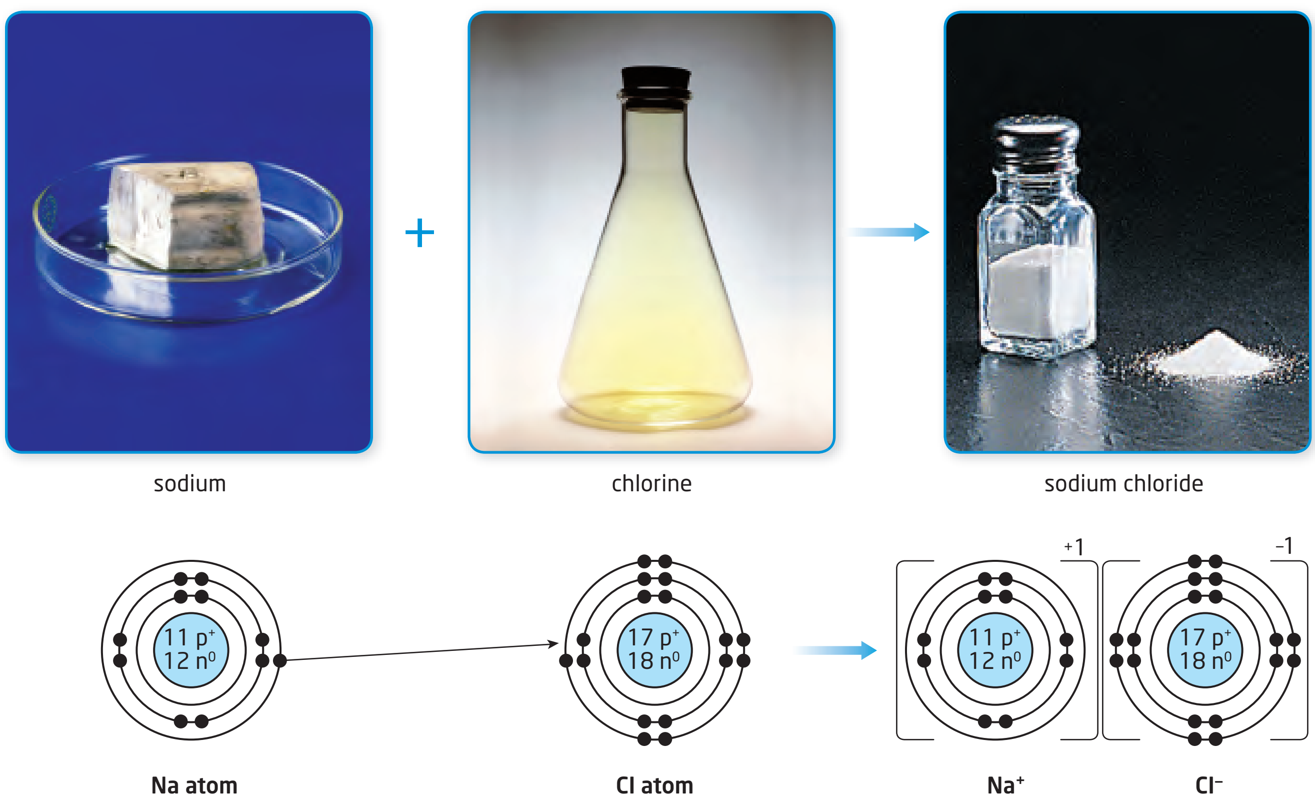


Figure 6.4 When one electron is transferred from sodium to chlorine, both ions end up with a stable electron arrangement. The sodium ion has a charge of 1+ because it has one more proton than the number of electrons. The chloride ion has a charge of 1– because it has one more electron than the number of protons.

What Does Sodium Fluoride Do?

The next time you brush your teeth, look at the list of ingredients on the tube of toothpaste. As shown in **Figure 6.5**, you will probably see an ionic compound named sodium fluoride in the list. This compound is very similar to sodium chloride, the ionic compound just discussed. Sodium fluoride is made of sodium ions (Na^+) and fluoride ions (F^-) and is represented by the formula NaF. The fluoride in sodium fluoride helps to strengthen tooth enamel (the tough outer layer on teeth) and reduce cavities. Because of these benefits, every province in Canada approved adding fluoride to drinking water. Communities that did this experienced a significant decline in the rate of tooth decay.

Go to **scienceontario** to find out more

There is now a controversy, however, associated with adding fluoride to drinking water. The issue revolves around determining the optimum level of exposure to this chemical. Today, people can be exposed to several different sources of fluoride in drinking water, toothpaste, beverages that are made using fluoridated water, and fluoride that is released into the environment from natural and industrial processes. Some scientists suggest that too much fluoride can have negative effects, such as cancer, fragile bones, and improper brain development in children. While many scientists disagree about how harmful fluoride can be, communities are now paying closer attention to the level of fluoride in their water.

Figure 6.5 **A** Sodium fluoride is an ingredient in most toothpastes. It is included to help strengthen teeth and reduce **B** cavities.

Learning Check

1. Which two types of elements usually form ionic compounds?
2. If an atom loses an electron, what kind of particle does it become?
3. Describe the electron arrangement in each atom and compound in **Figure 6.4**.
4. The ions that make up an ionic compound are attracted to each other because they have opposite charges. Describe an everyday situation that involves charged objects sticking together.

Properties of Ionic Compounds

Ionic bonds tend to be very strong, so they require a large amount of energy to break. The strength of these bonds helps to explain many of the properties of ionic compounds.

Physical States

Most ionic compounds exist in a solid arrangement called a *crystal lattice*, shown in **Figure 6.6**. A crystal lattice is a regular repeating pattern of ions. Since each ion in an ionic compound is strongly attracted to the ions around it, almost all ionic compounds are solid at room temperature. Because a large amount of energy is needed to melt most ionic compounds, they tend to have very high melting points. For example, the melting point of sodium chloride is 801°C, and the melting point of sodium fluoride is 993°C.

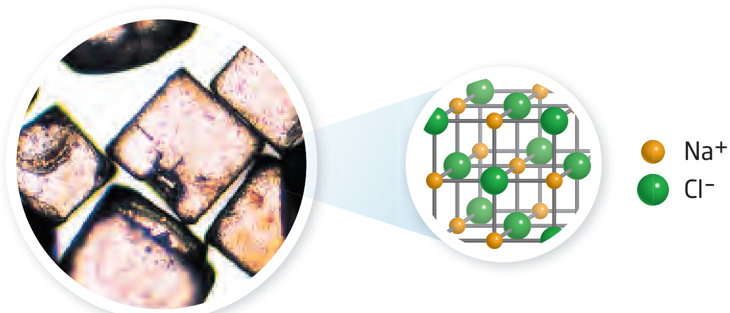


Figure 6.6 The ionic compound sodium chloride exists as a crystal lattice, which consists of a regular repeating pattern of Na^+ and Cl^- ions. Note that this diagram only shows part of the crystal lattice.

The liquid state of most ionic compounds is too hot for us even to observe. The "liquid" version you are most familiar with is actually the aqueous state—ionic solids that have been dissolved in water and exist as solutions. The gaseous state is almost non-existent for most ionic compounds.

Solubility

Many ionic compounds are soluble in water. An ionic compound dissolves because the water separates the positive and negative ions from each other, causing the ionic bonds to break. When the ions are in solution, as shown in **Figure 6.7**, they are able to move about.

The solubility of ionic compounds in water is essential for most living things on Earth. The human body is an aqueous environment. Your body relies on dissolved ions for many vital processes. For example, sodium ions (Na^+) and potassium ions (K^+) are important for the transmission of nerve impulses and the control of muscular contractions. Carbonate ions (CO_3^{2-}) are essential in blood. Severe dehydration can be caused by extreme exercising, working outside in the sunlight on very hot days, or vomiting and diarrhea. When dehydration occurs, not only water but also essential ions, called electrolytes, are lost. In such cases, it is important to replenish the electrolytes as well as the water. For example, fluid supplements that are recommended for people who become dehydrated due to illness contain potassium ions and sodium ions.

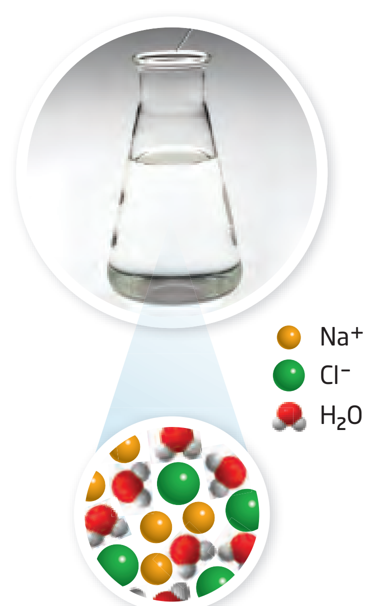


Figure 6.7 When an ionic compound dissolves, the ions exist as separate particles.

Solubility and Plant Fertilizers

Ionic compounds also play a vital role in the health of plants and crops. Many crops are treated with fertilizers that provide nitrogen, phosphorus, and potassium in the form of ionic compounds, such as ammonium nitrate (NH_4NO_3), ammonium phosphate ($(NH_4)_3PO_4$), and potassium chloride (KCl). All three nutrients, which are water soluble, are taken in through the roots of the plants and are necessary for plant growth.

Fertilizers provide many benefits, which include faster plant growth and the ability to grow more plants in less space. As a result, farms can produce more crops with less spoilage and lower labour costs. This helps to reduce the cost of the food that is produced from the crops, making the food more affordable for consumers.

Although fertilizers provide benefits in food production, overusing them can create problems. If plants do not take up all the dissolved fertilizers, the ionic compounds in the fertilizers can be carried by water into nearby streams and lakes, shown in **Figure 6.8**. As discussed in Chapter 1, the overuse of fertilizers can introduce excess nutrients and affect ecosystems by disrupting such things as the nitrogen and phosphorus cycles. For example, additional nutrients can increase the growth of algae. After the algae die, microscopic organisms use the oxygen dissolved in the water to decompose their remains. As a result, little or no oxygen is left in the water, and fish and other living organisms may die from lack of oxygen.

Study Toolkit

Making Inferences Read the paragraphs on this page. Draw a table like the one shown on page 220 to make an inference about fertilizers and the environment. This will help you gain a better understanding of fertilizer use and its impact on society.

Figure 6.8 Fertilizers can improve plant growth, increase crop yields, and restore nutrients to the soil. Excessive run-off, however, can have harmful effects on ecosystems.

Conductivity

A substance can conduct an electric current if charged particles, such as electrons or ions, are free to move around. Metals are good electrical conductors because they have electrons that are free to move throughout them. In Chapter 10, the principles of conductivity and uses for conducting materials are discussed in more detail.

Ionic compounds are also good electrical conductors—under the right conditions. In the solid state, an ionic compound is a poor conductor because the ions are locked into position in their crystal structure. In the liquid state, however, the ions of an ionic compound are free to move around. So, an ionic compound is a good conductor when it is melted. Similarly, when an ionic compound has been dissolved in water, the ions are free to move around and will conduct electricity. For example, pure water is a poor conductor. In comparison, tap water tends to have quite a few naturally occurring ionic compounds dissolved in it and, therefore, is a better conductor than pure water. Salt water is a very good conductor, as seen in **Figure 6.9**.

Study Toolkit

Monitoring Comprehension
Read the two paragraphs on this page. Use the Monitoring Comprehension strategy on page 220 to check whether you understand what you have just read.

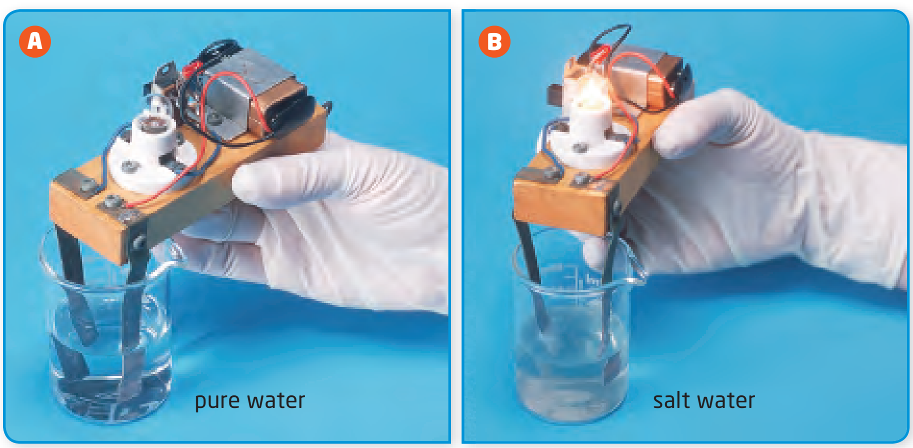


Figure 6.9 **A** Pure water is a poor conductor, so the bulb does not light. The sodium and chloride ions that are present in **B** salt water can conduct an electric current, so the bulb lights up.

Learning Check

5. Sketch the ionic compound sodium fluoride as it exists in the solid state.
6. What solvent do most ionic compounds dissolve in? Draw a sketch that represents the ions when an ionic compound is dissolved in this solvent.
7. Explain why the human body can conduct electricity.
8. Give two examples of ionic compounds that you use every day.

Road Salt

When road salt, shown in **Figure 6.10**, is used in the winter, it dissolves into any water on the road. Normally, water becomes ice at a temperature of 0°C, which is called the freezing point of water. When salt is added to the water, however, it interacts with the water and makes ice formation more difficult. A lower temperature is needed for ice to form. Therefore, road salt lowers the freezing point of water on the road and prevents the formation of ice. In addition, the saltwater mixture forms a layer between the road and the snow and ice. As vehicles drive on the road, their tires break up the snow and ice, which can then be more easily plowed from the road. Ultimately, using road salt makes the road safer for vehicles. It reduces injuries and deaths due to poor road conditions and also reduces the medical and insurance costs associated with accidents.

Activity 6-2 is another example of how we can use the ability of salt to lower the freezing point of water, but in an enjoyable way.

Sense of place

Sifto Canada's salt mine in Goderich, Ontario, reaches a depth of 533 m, is about 2.4 km wide, and extends 3.2 km into Lake Huron. The chambers from which the salt is removed have ceilings that are nearly 14 m high.

Figure 6.10 Cities and towns in Ontario use stockpiles of road salt to reduce the build-up of ice on roads.

Activity 6-2

Making Ice Cream

In this activity, you will take advantage of the ability of salt to lower the freezing point of water as you convert a mixture into ice cream.

Safety Precautions

- Wear safety goggles.
- Do not eat the ice cream, unless instructed by your teacher.

Materials

- measuring cups and spoons
- plastic spoons
- 5 mL of sugar
- 60 mL of milk
- 2 drops of vanilla extract
- 250 mL resealable plastic bag
- 500 mL of ice
- 150 mL of rock salt (sodium chloride)
- 1 L resealable plastic bag
- thermometer
- sheet of newspaper

Procedure

1. Read over the procedure. Then make a table to record your observations. Give your table a title.
2. Put the sugar, milk, and vanilla extract into the 250 mL plastic bag, and seal the bag.
3. Place the ice and salt in a 1 L plastic bag. Measure the temperature of the ice. Place the smaller bag with the ingredients inside the larger bag. Top up the larger bag with ice, and then seal it closed. Wrap the bag in the newspaper.
4. Rock the large bag covered in newspaper back and forth.
5. Every 5 min, unwrap the bag and measure the temperature of the ice and saltwater mixture. Record the temperature and your observation of what the ice cream ingredients look like. The ice cream should form in about 15 to 20 min.

Questions

1. What was the temperature of the ice and saltwater mixture at the point when the ice cream had formed?
2. Why was sodium chloride added to the ice?

For ice cream to form, the temperature must be below 0°C.

The Harmful Effects of Road Salt

Although road salt is very effective for reducing ice on roads, there are negative effects associated with its use. For example, the presence of salt on a road attracts animals, such as the moose in **Figure 6.11**. This causes hazardous conditions for both drivers and animals.

Conductivity and Rusting

The increased conductivity of water when it contains dissolved salt leads to increased corrosion, or rusting, of iron. Bridges must be regularly painted to keep rust from forming. Cars and trucks must also be protected because steel is an alloy of iron. This is why, in areas such as Ontario, anti-corrosion products are very popular. They are applied as protective coatings to help "rustproof" vehicles.

Suggested Investigation

Inquiry Investigation 6-A, What Causes Rusting of Iron Nails?, on page 249

Figure 6.11 Although salt improves driving conditions, it attracts animals to roads.

Effects of Road Salt on Ecosystems

When salt is used on roads, it can be quite harmful to local ecosystems. When the ice and snow melt, the road salt enters the environment through the soil, ground water, and surface water. The chart in **Figure 6.12** shows the numerous pathways that road salt can take into our environment. High levels of salt in the soil can inhibit or slow plant growth, which can eventually affect the animals that rely on the plants for food. Once in the waterways, high salt concentrations can affect aquatic plant and animal species. Even high levels of salt in drinking water can lead to increased salt consumption by people, which can negatively affect health.

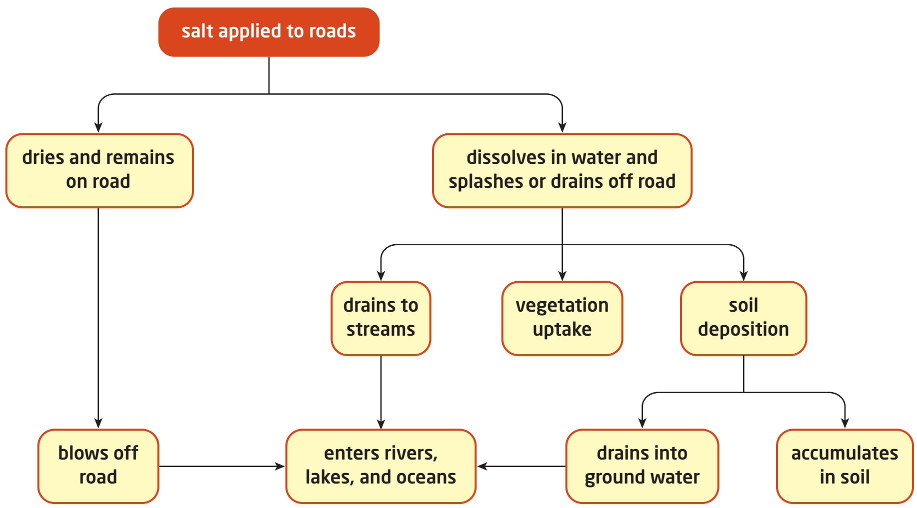


Figure 6.12 Salt that is used on roads may eventually find its way into the environment, along different pathways.

Although the most extensively used road salt is sodium chloride, calcium chloride and magnesium chloride are also used. All three of these compounds can leave high concentrations of chloride ion residue, which is particularly damaging. Although de-icing alternatives that have a lower impact on the environment have been studied, salts such as sodium chloride remain the most popular. Therefore, as shown in **Figure 6.13**, deciding how to use road salt most effectively is important for many towns and cities in Canada.

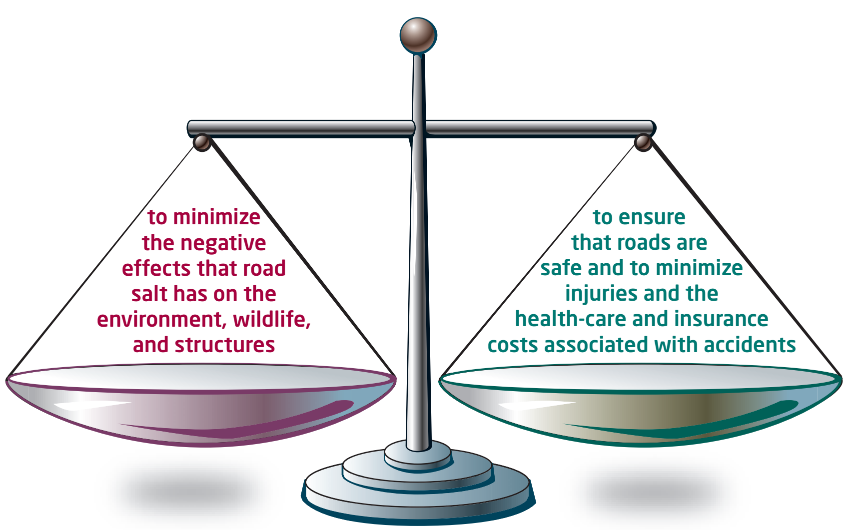


Figure 6.13 Deciding how to manage road-salt application involves carefully balancing two major factors.

Section 6.1 Review

Section Summary

- The formation of ions involves the loss or gain of electrons. The ion(s) formed by an atom will depend on its atomic structure and the number of valence electrons.
- Ionic compounds form when there is a transfer of electrons between atoms. An ionic bond is the attraction that holds positive ions and negative ions together.
- Most ionic compounds are composed of a metal and a non-metal. Ionic compounds have high melting points and tend to be soluble in water. Ionic compounds are good electrical conductors when melted or when dissolved in water.
- Road salt is used in the winter to reduce icy driving conditions. Nevertheless, because of its harmful effects on the environment, the frequency and amount of road salt used should be carefully considered.

Review Questions

K/U **1.** How can a negative ion form from an atom?

K/U **2.** Identify each of the following compounds as ionic or not ionic.
a. KCl **b.** CO_2 **c.** CF_4 **d.** NaI

T/I **3.** Is an ionic compound likely to form between fluorine and chlorine? Explain your reasoning.

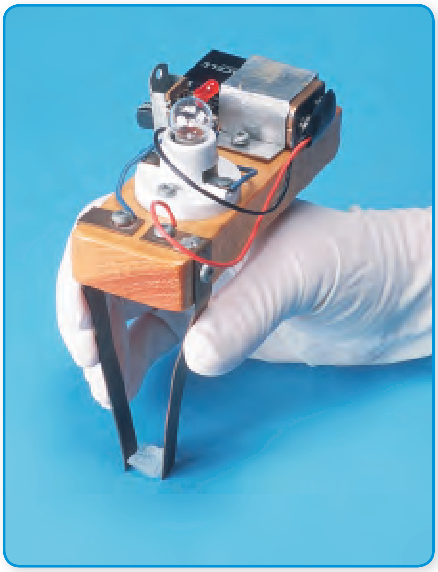
C **4.** Write an explanation for a classmate about why ionic compounds tend to have high melting points.

K/U **5.** In what form are the nutrients in fertilizers? What are important nutrients that fertilizers provide?

T/I **6.** Ionic compounds tend to be good conductors of electric current, but the light on the conductivity tester in the photograph on the right is not glowing. Why does the ionic compound shown not conduct electric current? What could you do to make the light glow?

K/U **7.** According to **Figure 6.12**, what are two ways that road salt can enter rivers and lakes?

A **8.** Which area do you think has more problems with rust: a town along the Atlantic Ocean or a town in a remote area of the Northwest Territories? Explain.



The light is not glowing because this substance does not conduct electricity.