SECTION 2.3

Comparing the Properties of Ionic and Molecular Compounds

Key Terms

melting point
boiling point
dipole
dipole-dipole force
intermolecular forces
electrical conductivity

melting point the temperature at which a compound changes from a solid to a liquid

It is not a coincidence that water melts at 0°C and boils at 100°C. The Celsius temperature scale is based on the melting point and boiling point of water. All compounds have melting points and boiling points, but these temperatures vary widely with the type of substance. What factors determine the melting point and boiling point of a compound? Do the same factors affect the other properties of a compound? This section will answer these and other questions concerning the properties of ionic and molecular compounds.

Melting Points and Boiling Points of Compounds

As you read above, boiling points and melting points are unique to each pure compound. Thus, they can provide important information about the characteristics of the compound. For example, the melting point and boiling point of a compound reveals information about the strength of the attractions that are holding the particles (ions or molecules) of the compound together. Consider what is happening to a compound when it melts or boils.

Melting Point

The **melting point** of a compound is the temperature at which it changes from a solid to a liquid at standard atmospheric pressure (the pressure exerted on the ground by dry air at sea level, or 101.325 kPa). In a solid, the particles—ions or molecules—are so strongly attracted to one another that they cannot pull apart. You can imagine a solid as particles held together by springs, as shown in **Figure 2.24 (A)**.

You might recall from previous science courses that, no matter how low the temperature, all particles have some kinetic energy. So, although the particles in a solid cannot pull away from the surrounding particles, they are always vibrating. You have probably learned that temperature is directly related to the kinetic energy of the particles in a substance. As energy in the form of heat enters a substance, the kinetic energy, and thus the temperature of the substance, increases. When the kinetic energy of the particles is great enough for the particles to pull away from one another, as shown in **Figure 2.24 (B)**, the temperature stops increasing and the compound melts. If the melting point of a compound is very high, you know that a large amount of energy is needed for the particles to pull away from one another. Therefore, the forces holding them together must be very strong. A low melting point tells you that the particles are easily pulled apart, and thus the forces attracting them to one another are relatively weak.

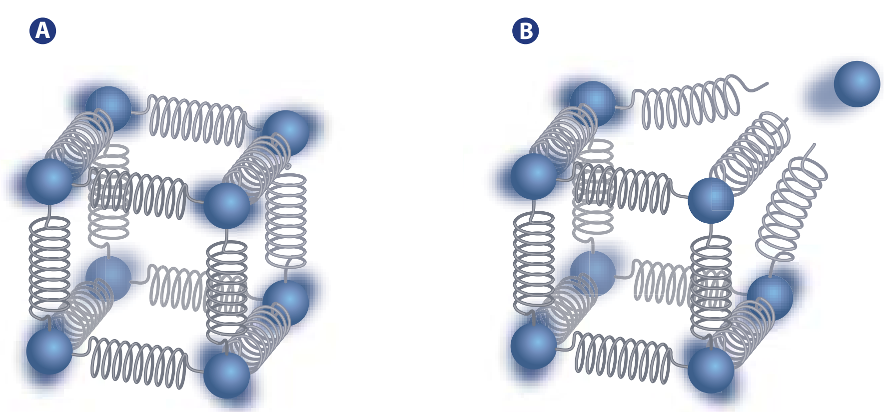


Figure 2.24 **(A)** Even in a solid, all particles are moving. **(B)** As the temperature of a substance increases, more and more particles have enough energy to break away from their nearest neighbour. Note that, in the case of molecular compounds, the spheres represent the entire molecule and the springs represent attractive interactions between individual molecules.

Boiling Point

The **boiling point** of a compound is the temperature at which it changes from a liquid to a gas at standard atmospheric pressure. In a liquid, particles have enough kinetic energy to pull away from one neighbouring particle, only to be attracted to another neighbouring particle. The particles slide past one another. At the boiling point, the particles have enough kinetic energy to completely break away from all the other particles and the compound becomes a gas. Gas particles have enough energy to bounce off one another when they collide rather than sticking together. Thus, the boiling point of a compound, like the melting point, provides information about the strength of the forces between the particles. A high boiling point indicates that the attractive forces between the particles in a liquid are very strong. A low boiling point tells you that these forces are relatively weak.

boiling point the temperature at which a compound changes from a liquid to a gas

Forces between Particles in a Compound

As you read, a comparison of the melting and boiling points of a variety of substances can provide information about the strength of the forces between ions in ionic compounds and between molecules in molecular compounds. Note that when a molecular compound melts or boils, the covalent bonds remain intact.

- A low melting point or boiling point means that particles with small amounts of kinetic energy can break away from the adjacent particles. Thus the forces between particles are weak.
- A very high melting point or boiling point means that the particles must have a very large amount of kinetic energy to break away, and thus the forces between particles are strong.

Keeping these relationships in mind, consider the data in **Table 2.12.**

Table 2.12 Melting Points and Boiling Points of Some Common Compounds

Compound	Melting Point (°C)	Boiling Point (°C)
ethanol (grain alcohol), C_2H_5OH	−114	+78.3
ammonia, NH_3	−77.7	−33.3
cesium bromide, CsBr	+636	+1300
hydrogen, H_2	−259	−253
hydrogen chloride, HCl	−114	−85
magnesium oxide, MgO	+2825	+3600
methane (natural gas), CH_4	−182	−161
nitrogen, N_2	−210	−196
sodium chloride, NaCl	+801	+1465
water, H_2O	0	+100

If you analyze the data in **Table 2.12** and classify the compounds into three categories, you will get the results in **Table 2.13**. An analysis of the melting points would give the same categories.

Table 2.13 Categories of Compounds Based on Boiling Point

High Boiling Point	Intermediate Boiling Point	Low Boiling Point
cesium bromide, CsBr	ethanol, C_2H_5OH	hydrogen, H_2
magnesium oxide, MgO	ammonia, NH_3	nitrogen, N_2
sodium chloride, NaCl	hydrogen chloride, HCl	methane, CH_4
	water, H_2O	

Suggested **Investigation**

Inquiry Investigation 2-A, Modelling Ionic Compounds

Compounds with High Melting Points and Boiling Points

Consider the compounds with high boiling points in **Table 2.13**. These compounds are all ionic. Their high boiling points are explained by the fact that the attractive electrostatic forces between oppositely charged particles create very strong bonds. An examination of the structure of ionic compounds will reveal why so much energy is needed to break these bonds. **Figure 2.25** shows the arrangement of sodium and chloride ions in a crystal of sodium chloride. The same structure continues throughout an entire crystal. Notice that each chloride ion is attracted to six adjacent sodium ions, and each sodium ion is attracted to six adjacent chloride ions. Because the attractive forces are all the same, there are no specific pairs of sodium and chloride ions that you could identify as "molecules." Each ion is strongly attracted to all the adjacent ions of the opposite charge. There are continuous chains of ions that are attracted to each other throughout the entire crystal, making the structure very stable. The formula, NaCl, simply means that there is a 1:1 ratio of sodium to chloride ions in the entire crystal. One sodium ion and one chloride ion are referred to as a formula unit of sodium chloride, never as a molecule of sodium chloride.

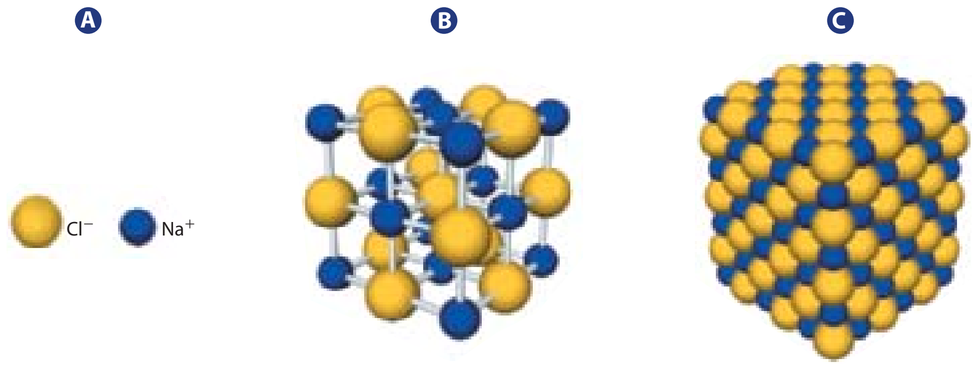


Figure 2.25 **(A)** The yellow spheres represent chloride ions and the blue spheres represent sodium ions. **(B)** This model is called a "ball and stick" model. The balls represent the ions, and the sticks represent the bonds. **(C)** This model is called a "space-filling model." It shows that, in the actual crystal, the ions are packed tightly together.

Compounds with Intermediate Melting Points and Boiling Points

Now consider the compounds with intermediate boiling points in the second column of **Table 2.13**. If you look for a similarity among these compounds, you will find that they are all molecular compounds. As well, they all have one or more polar bonds. Depending on the overall structure of a molecule that has polar bonds, the entire molecule can be polar. **Figure 2.26** shows models of water and ammonia to illustrate why they are polar. One end of each molecule is slightly negative, while the other end is slightly positive.

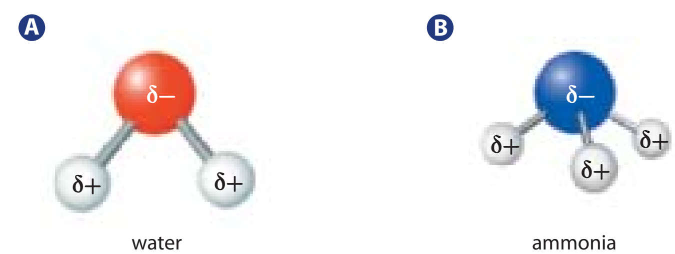


Figure 2.26 The white spheres represent hydrogen atoms, the red sphere represents an oxygen atom, and the blue sphere represents a nitrogen atom. You can think of the polarity as being caused by the electrons spending more time around the oxygen atom in water **(A)** and the nitrogen atom in ammonia **(B)** and less time around the hydrogen atoms.

Representing Polar Molecules

A polar molecule is often represented as an oval shape with a slightly positively charged end (positive pole) and a slightly negatively charged end (negative pole). Because a polar molecule has one slightly positive end and one slightly negative end, it is often called a **dipole**. **Figure 2.27** shows how the positive ends of polar molecules attract the negative ends of other polar molecules. This attractive force, called a **dipole-dipole force**, is much smaller than the forces between ions. The dipole-dipole force is the main attractive force that acts between polar molecules. The intermediate strength of this force results in the intermediate boiling points of compounds that are composed of polar molecules.

dipole a molecule with a slightly positively charged end (positive pole) and a slightly negatively charged end (negative pole)

dipole-dipole force the attractive force between the positive end of one molecule and the negative end of another molecule

intermolecular forces attractive forces that act between molecules

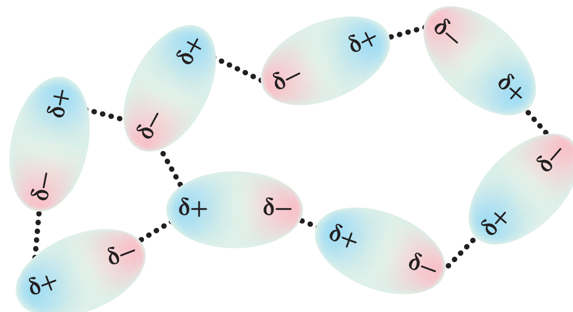
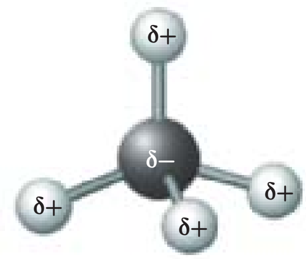


Figure 2.27 Each oval represents a polar molecule. As the positively charged end of one molecule is attracted to the negatively charged end of another, the molecules form a continuous network.

Compounds with Low Melting Points and Boiling Points

Finally, consider the compounds in **Table 2.13** that have low boiling points. Notice that their molecules are all non-polar. The bonds between the carbon and hydrogen atoms in methane are slightly polar, but the molecule, as shown in **Figure 2.28**, is symmetrical. Therefore, the polarities of the bonds cancel one another in the whole molecule. Nevertheless, some attractive forces exist between the molecules. Although non-polar molecules have no distinct separation of charge, it is still possible for the positive nuclei of atoms in one molecule to attract the electrons in a neighbouring molecule. These attractions are very weak. As a consequence of these weak forces, compounds that are composed of non-polar molecules have much lower boiling points than compounds that are composed of polar molecules of a similar size.

In summary, these three interactions (strong attractive forces between ions, weaker dipole-dipole attractive forces between polar molecules, and very weak attractive forces between non-polar molecules), determine the boiling points and melting points of pure substances. Because the dipole-dipole forces and the weak attractive forces act between molecules, they are called **intermolecular forces**. This distinguishes them from the covalent bonds that act within molecules. The intermolecular forces determine the melting points and boiling points of molecular compounds.



methane

Figure 2.28 The black sphere represents a carbon atom and the white spheres represent hydrogen atoms in this methane molecule. Each bond is slightly polar, but the symmetry of the molecule makes it non-polar.

Learning Check

13. Explain what is happening, on the level of ions and molecules, when a substance is melting.

14. One compound has a melting point of 714°C. Another compound, which is similar in size and appearance, has a melting point of 146°C. How would you classify these compounds based on their melting points?

15. Why is it incorrect to refer to a "molecule" of a compound such as potassium iodide?

16. What is a dipole-dipole force?

17. Why do non-polar molecules have very low melting and boiling points?

18. What forces are included within the category of intermolecular forces?

Other Properties of Ionic and Molecular Compounds

The strength and the type of bonds and intermolecular forces that exist among ions and molecules affect several properties, in addition to melting points and boiling points. Among these properties are solubility in water and electrical conductivity.

Solubility in Water

Whether or not a substance dissolves in water is an important property. For example, many vitamins and nutrients in food (**Figure 2.29**) move through your bloodstream from your digestive system to all of the tissues in your body because they are soluble in water. Similarly, waste materials that are water soluble are carried to your kidneys where they are eliminated from your body. Many chemical processes can take place only when the compounds are dissolved in water. It is not always possible to predict whether a compound will dissolve in water. However, differing trends in solubility can be clearly seen when considering the polarities of substances.

Figure 2.29 All of the nutrients in these foods are critical to good health. The nutrients that are soluble in water reach your bloodstream and are carried to your tissues quickly.

For a substance to dissolve in water, the water molecules must be more strongly attracted to particles of that substance than to other water molecules. As you know, water molecules are polar, having a slightly positive end and a slightly negative end. The positive end will attract a negative ion or the negatively charged end of another polar molecule. Likewise, the negative end of a water molecule will attract a positive ion or the positively charged end of another polar molecule. Consequently, water is likely to dissolve ionic compounds and polar compounds. For example, table sugar (sucrose) is a polar molecular compound, and table salt (sodium chloride) is an ionic compound. Both are soluble in water.

Water molecules are much more strongly attracted to each other than to non-polar molecules. Therefore, most non-polar compounds do not dissolve in water. For example, fats and oils are non-polar compounds and they do not dissolve in water.

Note that not all ionic compounds and polar molecular compounds are soluble in water. In Unit 4, you will read more about solubility and learn how to determine whether a particular compound is soluble in water.

Electrical Conductivity

Electrical conductivity is the ability of a substance to allow an electric current to exist within it. A substance can conduct an electric current only if charges (electrons or ions) can move independently of one another. In a pure metal, electrons can move somewhat freely because they are not tightly bound to the metal atoms. When a pure metal is conducting an electric current, electrons are moving with ease from one metal atom to the next.

electrical conductivity the ability of a substance or an object to allow an electric current to exist within it

In any type of compound, electrons are held tightly by the atoms. In an ionic compound, electrons have moved from a metal atom to a non-metal atom. Once they are bound to the non-metal atom, however, they are held tightly. A pure ionic compound can only conduct an electric current under conditions in which entire ions can move independently of one another.

As you know, ionic compounds are solid at room temperature. In a solid, the oppositely charged ions are held rigidly together. Therefore, in their solid form, ionic compounds cannot conduct an electric current. When an ionic compound is in the liquid state, however, the ions are free to move independently of one another. This occurs only at very high temperatures, but, at these temperatures, ionic compounds can conduct an electric current.

Ionic compounds can also conduct an electric current when in an aqueous state, as shown in **Figure 2.30**. When an ionic compound is dissolved in water, the ions are free of other ions because they are surrounded by water molecules. Thus, ionic solutions can also conduct an electric current.

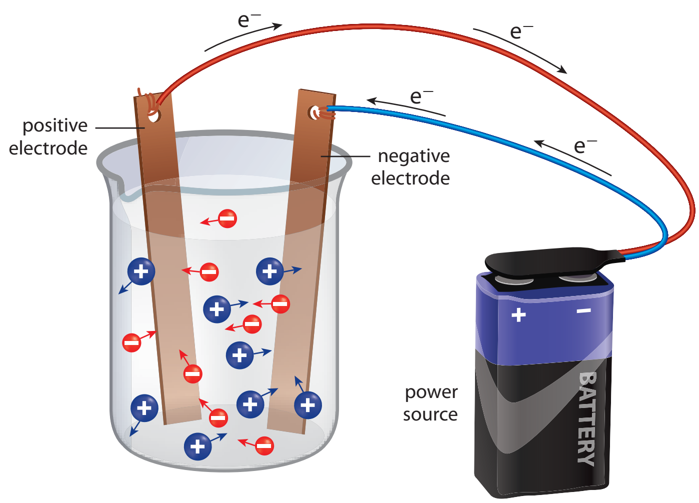


Figure 2.30 Positive ions are attracted to a negative electrode, and negative ions are attracted to a positive electrode. The ions create an electric current as they move around each other in opposite directions.

When atoms are bound together in a molecular compound, they are sharing electrons. The electrons never leave one atom completely. Therefore, there are no positive and negative charges that are independent of one another. This means that molecular compounds cannot conduct an electric current regardless of whether they are non-polar or polar. If a polar compound is dissolved in water and electrodes are placed in the water, the molecules will orient themselves so that their positively charged end is directed toward the negative electrode and their negatively charged end is directed toward the positive electrode. However, the charges never leave the molecules. Thus, even in a water solution, molecular compounds cannot conduct an electric current. You might recall that acids are molecular compounds when in a pure form but come apart and become ionic when dissolved in water. Therefore, aqueous solutions of acids do conduct an electric current.

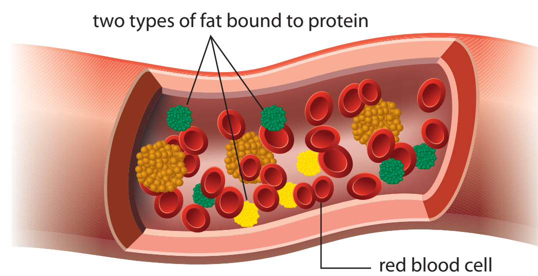
Section 2.3 REVIEW

Section Summary

- The strength of the attractive forces acting between ions or molecules determines the melting point and boiling point of a compound.
- Ionic compounds usually have the highest melting points and boiling points. Polar molecules have intermediate melting points and boiling points, and non-polar molecules have the lowest melting points and boiling points for molecules of similar sizes.
- Ionic and polar compounds are likely to be soluble in water. Non-polar compounds are insoluble in water.
- For a substance to conduct an electric current, oppositely charged particles must be free to move independently of one another.

Review Questions

1. K/U Explain the basis of the Celsius temperature scale.
2. K/U Describe, on the level of individual particles, what happens to a substance when it is heated.
3. K/U What property of particles determines whether they will pull away from adjacent particles?
4. K/U How would you classify a compound that has a boiling point of −182°C? Explain your answer.
5. K/U Explain why compounds consisting of polar molecules are likely to have a higher melting point than compounds consisting of non-polar molecules.
6. T/I What would you predict about the melting point of a compound that will not dissolve in water? Explain your thinking.
7. K/U Explain how an attractive force can exist between non-polar molecules.
8. T/I If a compound has very high melting and boiling points, is the compound likely to be soluble in water? Explain the relationship between these two properties of a compound.
9. C Use sketches to show how a non-polar molecule can have polar bonds.
10. K/U Describe what must happen, on a particle level, for a substance to dissolve in water.
11. K/U Glycerol is a compound that dissolves readily in water. The water solution of glycerol, however, will not conduct an electric current. What would you predict about the properties of glycerol?
12. K/U Under what two conditions can an ionic compound conduct an electric current?
13. K/U Can polar molecular compounds conduct electric current under either of the conditions that you described in question 12? Explain why or why not.
14. A To be transported throughout the body in the bloodstream, fat molecules must be bound to protein molecules, as shown in the following figure. Explain why you think this is necessary.



15. A You might have heard the saying, "Like dissolves like." From what you have learned about solubility, comment on the validity of this statement.
16. T/I Two molecular compounds, X and Y, have similar masses. Compound X is solid at room temperature, has a melting point of 146°C, and is soluble in water. Compound Y is liquid at room temperature, has a melting point of −10°C, and is not soluble in water.
    - **a.** What would you predict about the polarities of compound X and compound Y?
    - **b** Based on your predictions, explain the differences in their melting points and solubilities.