16.3 Colligative Properties of Solutions

Connecting to Your World The wood frog is a remarkable creature because it can survive being frozen. Scientists believe that a substance in the cells of this frog acts as a natural antifreeze, which prevents the cells from freezing. Although fluids surrounding the frog's cells may freeze, the cells themselves do not. In this section, you will discover how a solute can change the freezing point of a solution.

Guide for Reading

Key Concepts

- What are three colligative properties of solutions?
- What factor determines the amount by which a solution's vapor pressure, freezing point, and boiling point differ from those properties of the solvent?

Vocabulary

colligative property

freezing-point depression

boiling-point elevation

Reading Strategy

Relating Text and Visuals

As you read, look carefully at Figure 16.14. In your notebook, explain how this visual explains why equal molar solutions of different substances can have different freezing point depressions and boiling point elevations.

Vapor-Pressure Lowering

You probably won't be surprised to learn that the physical properties of a solution differ from those of the pure solvent used to make the solution. After all, tea is not the same as pure water. But it might surprise you to learn that some of these differences in properties have little to do with the specific identity of the solute. Instead, they depend upon the number of solute particles in the solution. A property that depends only upon the number of solute particles, and not upon their identity is called a **colligative property.** **Three important colligative properties of solutions are vapor-pressure lowering, boiling-point elevation, and freezing-point depression.**

Recall that vapor pressure is the pressure exerted by a vapor that is in dynamic equilibrium with its liquid in a closed system. A solution that contains a solute that is nonvolatile (not easily vaporized) always has a lower vapor pressure than the pure solvent, as shown in Figure 16.13. Glucose, a molecular compound, and sodium chloride, an ionic compound, are examples of nonvolatile solutes. When glucose or sodium chloride is dissolved in a solvent, the vapor pressure of the solution is lower than the vapor pressure of the pure solvent. Why is this true?

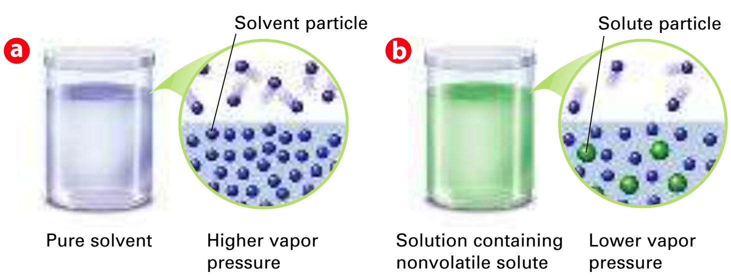

Figure 16.13 The vapor pressure of a solution of a nonvolatile solute is less than the vapor pressure of a pure solvent. **a** In a pure solvent, equilibrium is established between the liquid and the vapor. **b** In a solution, solute particles reduce the number of free solvent particles able to escape the liquid. Equilibrium is established at a lower vapor pressure. **Interpreting Diagrams** ***How is decreased vapor pressure represented in the diagram?***

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 16.3
- **Core Teaching Resources,** Section 16.3 Review
- **Transparencies,** T175–T176

Technology

- **Interactive Textbook with ChemASAP,** Assessment 16.3
- **Go Online,** Section 16.3

16.3

1 FOCUS

Objectives

16.3.1 Identify three colligative properties of solutions.

16.3.2 Explain why the vapor pressure, freezing point, and boiling point of a solution differ from those properties of the pure solvent.

Guide for Reading

Build Vocabulary L2

Word Parts The adjective colligative comes from the Latin *colligare* meaning "to tie." A colligative property is one in which particles are seemingly tied together in their actions and act as a group rather than as individuals.

Reading Strategy L2

Use Prior Knowledge Relate the section to prior knowledge by having students write the chemical equations for the following examples:

- hydrochloric acid in water ($HCl(g) \rightarrow H^+(aq) + Cl^-(aq)$)
- magnesium chloride in water ($MgCl_2(s) \rightarrow Mg^{2+}(aq) + 2Cl^-(aq)$)
- Glucose in water ($C_6H_{12}O_6(s) \rightarrow C_6H_{12}O_6(aq)$)

2 INSTRUCT

Connecting to Your World

Ask, **What is a possible explanation for the wood frog's ability to survive being frozen?** *(The frog's cells contain a natural antifreeze.)* Mention to students that some fish and reindeer also benefit from so-called "natural antifreeze." When water freezes, the water molecules form a crystalline lattice work. **How might a solute change the freezing point of a solid?** *(It might slow down the formation of the crystal lattice.)*

Answers to...

Figure 16.13 by fewer solvent particles in the space above the liquid

Vapor-Pressure Lowering

Discuss L2

Remind students that ionic compounds and certain molecular compounds, such as HCl, produce two or more particles when they dissolve in water. Most molecular compounds, such as glucose, do not dissociate when they dissolve in water. For each formula unit of $MgCl_2$ that dissolves, three particles are formed in solution. Ask, **How many particles are formed when $FeCl_3$ dissolves in water?** *(4)*

Freezing-Point Depression

Use Visuals L2

Figure 16.14 Emphasize that colligative properties do not depend on the kind of particles, but on their concentration. For colligative properties, a mole of one kind of particle has the same effect as a mole of any other kind of particle. Ask, **Which produces a greater change in colligative properties—an ionic solid or a molecular solid?** *(An ionic solid produces a greater change because it will produce two or more moles of ions for every mole of solid that dissolves.)*

Go Online NSTA SCILINKS

Download a worksheeet on **Solutions** for students to complete, and find additional teacher support from NSTA SciLinks.

Figure 16.14 Particle concentrations differ for dissolved covalent and ionic compounds in water. **a** Three moles of glucose dissolved in water produce 3 mol of particles because glucose does not dissociate. **b** Three moles of sodium chloride dissolved in water produce 6 mol of particles because each formula unit of NaCl dissociates into two ions. **c** Three moles of calcium chloride dissolved in water produce 9 mol of particles because each formula unit of $CaCl_2$ dissociates into three ions.

In an aqueous solution of sodium chloride, sodium ions and chloride ions are dispersed throughout the liquid water. Both within the liquid and at the surface, the ions are surrounded by layers of associated water molecules, or shells of water of solvation. The formation of these shells of water of solvation reduces the number of solvent molecules that have enough kinetic energy to escape as vapor. Thus, the solution has a lower vapor pressure than the pure solvent (water) would have at the same temperature.

Ionic solutes that dissociate, such as sodium chloride and calcium chloride, have greater effects on the vapor pressure than does a nondissociating solute such as glucose. Recall that each formula unit of the ionic compound sodium chloride (NaCl) produces two particles in solution, a sodium ion and a chloride ion. Each formula unit of calcium chloride ($CaCl_2$) produces three particles, a calcium ion and two chloride ions. When glucose dissolves, the molecules do not dissociate. Figure 16.14 compares the number of particles in three solutions of the same concentration. The vapor-pressure lowering caused by 0.1 mol of sodium chloride in 1000 g of water is twice that caused by 0.1 mol of glucose in the same quantity of water. In the same way, 0.1 mol $CaCl_2$ in 1000 g of water produces three times the vapor-pressure lowering as 0.1 mol of glucose in the same quantity of water. **The decrease in a solution's vapor pressure is proportional to the number of particles the solute makes in solution.**

Checkpoint ***Which compound affects the vapor pressure of a solution the least: glucose, sodium chloride, or calcium chloride?***

Freezing-Point Depression

When a substance freezes, the particles of the solid take on an orderly pattern. The presence of a solute in water disrupts the formation of this pattern because of the shells of water of solvation. As a result, more kinetic energy must be withdrawn from a solution than from the pure solvent to cause the solution to solidify. The freezing point of a solution is lower than the freezing point of the pure solvent. The difference in temperature between the freezing point of a solution and the freezing point of the pure solvent is the **freezing-point depression.**

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Facts and Figures

Osmotic Pressure

Another colligative property, which is important in many biological processes, is osmotic pressure: the tendency for solvent to flow through a semipermeable membrane from a region of low solute concentration to a region of higher solute concentration. Osmotic pressure helps regulate the movement of fluids across cell membranes. Cells remain healthy as long as they are continually bathed in an isotonic medium, which maintains the correct osmotic balance between the inside and outside of the cell membrane. Physicians make use of the osmotic effect to treat patients with kidney failure. Afflicted individuals undergo dialysis, a process in which the blood is circulated through a machine equipped with a semipermeable membrane. In the machine, osmotic pressure is used to separate waste materials from the blood.

Quick LAB

Solutions and Colloids

Purpose
To classify mixtures as solutions or colloids using the Tyndall effect.

Materials
- sodium hydrogen carbonate
- cornstarch
- stirring rod
- distilled water (or tap water)
- flashlight
- masking tape
- 3 jars with parallel sides
- teaspoon
- cup

Procedure
1. In a cup, make a paste by mixing $\frac{1}{2}$ teaspoon cornstarch with 4 teaspoons water.
2. Fill one jar with water. Add one half teaspoon sodium hydrogen carbonate to a second jar and fill with water. Stir to mix. Add the cornstarch paste to the third jar and fill with water. Stir to mix.
3. Turn out the lights in the room. Shine the beam of light from the flashlight at each of the jars and record your observations.

Analyze and Conclude
1. In which of the jars was it possible to see the path of the beam of light?
2. What made the light beam visible?
3. If a system that made the light beam visible were filtered, would the light beam be visible in the filtrate? Explain.
4. Predict what you would observe if you were to replace the sodium hydrogen carbonate with sucrose (cane sugar) or sodium chloride (table salt).
5. Predict what you would observe if you were to replace the cornstarch with flour or diluted milk.
6. Explain how you could use this method to distinguish a colloid from a suspension.

Freezing-point depression is another colligative property. **The magnitude of the freezing-point depression is proportional to the number of solute particles dissolved in the solvent and does not depend upon their identity.** The addition of 1 mol of solute particles to 1000 g of water lowers the freezing point by 1.86°C. For example, if you add 1 mol (180 g) of glucose to 1000 g of water, the solution freezes at –1.86°C. However, if you add 1 mol (58.5 g) of sodium chloride to 1000 g of water, the solution freezes at –3.72°C, double the change for glucose. This is because 1 mol NaCl produces 2 mol of particles, and thus doubles the freezing-point depression. The freezing-point depression of aqueous solutions makes walks and driveways safer when people, like the man in Figure 16.15, sprinkle salt on icy surfaces to make the ice melt. The melted ice forms a solution with a lower freezing point than that of pure water. Similarly, ethylene glycol ($C_2H_6O_2$, antifreeze) is added to the water in automobile cooling systems to depress the freezing point of the water below 0°C. Automobiles can thus withstand subfreezing temperatures without freezing up.

Figure 16.15 Surfaces can be free of ice even at temperatures below freezing if salt is applied. **Inferring** ***Why would calcium chloride ($CaCl_2$) be a better salt for this purpose than sodium chloride (NaCl)?***

Quick LAB

Solutions and Colloids L2

Objective After completing this activity, students will be able to
- Classify mixtures as solutions or colloids using the Tyndall effect.

Skills Focus observing, inferring, predicting

Prep Time 30 minutes
Class Time 20 minutes

Expected Outcome The beam of light is visible in the cornstarch/water mixture but not in water or sodium hydrogen carbonate solution.

Analyze and Conclude
1. undissolved cornstarch
2. Cornstarch particles reflect light.
3. yes for a colloid; no for a suspension
4. Because two solutions form, the beam of light would not be visible.
5. Because flour and milk do not dissolve, the beam of light will be visible.
6. Cannot; both reflect light.

For Enrichment L3
Have students test and classify various household mixtures using the Tyndall effect.

CLASS Activity

Freezing Point Depression L1
Purpose To observe the freezing point depression of ice by the addition of rock salt (NaCl) to a slurry of ice-water

Materials thermometer, foam cup, rock salt, water, and ice.

Procedure Have students make an ice-water slurry in their cups. Ask them to measure the initial temperature of the ice-water slurry and the lowest temperature reached after the addition of the rock salt. Explain that the observed difference in temperature is the freezing point depression for this solution of NaCl in water.

Answers to...

Figure 16.15 $CaCl_2$ produces three ions in solution; NaCl produces two.

Checkpoint glucose

Boiling-Point Elevation

3 ASSESS

Evaluate Understanding L2

Have students explain how the addition of solute particles to a solvent causes the vapor pressure and freezing point of the solution to decrease relative to the pure solvent and the boiling point to increase.

Reteach L1

Remind students that colligative properties are those physical properties of solutions that depend only on the number of particles of solute in solution and not on the chemical composition of the particles. The magnitudes of the observed physical changes are proportional to the quantity of solute particles in solution.

Connecting Concepts

Volatile solutes quickly evaporate at higher temperatures and so would not be present to cause the elevation of the solvent's boiling point.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 16.3

with ChemASAP

Figure 16.16 Cooling the boiling mixture, when the temperature on the candy thermometer reaches a certain value, gives you solid fudge.

Boiling-Point Elevation

The boiling point of a substance is the temperature at which the vapor pressure of the liquid phase equals atmospheric pressure. As you just learned, adding a nonvolatile solute to a liquid solvent decreases the vapor pressure of the solvent. Because of the decrease in vapor pressure, additional kinetic energy must be added to raise the vapor pressure of the liquid phase of the solution to atmospheric pressure and initiate boiling. Thus the boiling point of a solution is higher than the boiling point of the pure solvent. The difference in temperature between the boiling point of a solution and the boiling point of the pure solvent is the **boiling-point elevation.** The same antifreeze, added to automobile engines to prevent freeze-ups in winter, protects the engine from boiling over in summer.

Remember that boiling-point elevation is a colligative property; it depends on the concentration of particles, not on their identity. Thus you can think about boiling-point elevation in terms of particles. It takes additional kinetic energy for the solvent particles to overcome the attractive forces that keep them in the liquid. Thus the presence of a solute elevates the boiling point of the solvent. **The magnitude of the boiling-point elevation is proportional to the number of solute particles dissolved in the solvent.** The boiling point of water increases by 0.512°C for every mole of particles that the solute forms when dissolved in 1000 g of water.

Apparent applications of boiling point elevation are sometimes erroneous or misleading. For example, to make fudge, a lot of sugar and some flavorings are mixed with water and the solution is boiled, as shown in Figure 16.16. As the water slowly boils away, the concentration of sugar in the solution increases. This may appear to be a case of boiling point elevation caused by an increased concentration of the solute, sugar. The real reason for the boiling point elevation is that the sugar decomposes into different substances as it is heated and this new mixture has a higher boiling point. The composition of the mixture will, when it is cooled, give you a delicious tasting treat.

16.3 Section Assessment

24. **Key Concept** What are three colligative properties of solutions?

25. **Key Concept** What factor determines how much the vapor pressure, freezing point, and boiling point of a solution differ from those properties of the pure solvent?

26. Would a dilute or a concentrated sodium fluoride solution have a higher boiling point? Explain.

27. An equal number of moles of KI and MgI_2 are dissolved in equal volumes of water. Which solution has the higher

a. boiling point?
b. vapor pressure?
c. freezing point?

28. Explain why the vapor pressure, boiling point, and freezing point of an aqueous solution of a nonvolatile solute are not the same as those of the pure solvent.

Connecting Concepts

Vapor Pressure Review what you learned in Section 13.2 about the relationship between the vapor pressure of liquids and their boiling points. Explain why only nonvolatile solutes cause the elevation of the solvent's boiling point.

Interactive Textbook

Assessment 16.3 Test yourself on the concepts in Section 16.3.

with ChemASAP

Section 16.3 Assessment

24. vapor-pressure lowering, boiling-point elevation, and freezing-point depression

25. the number of solute particles dissolved in the solvent

26. concentrated sodium fluoride, because the magnitude of the boiling-point elevation is proportional to the number of solute particles dissolved in the solvent

27. **a.** MgI_2 solution **b.** KI solution **c.** KI solution

28. Formation of solvation shells around solute particles reduces the number of water molecules with sufficient kinetic energy to escape the solution. Therefore, the vapor pressure is lower relative to pure solvent. More energy must be supplied to reach the boiling point; therefore the boiling point is elevated relative to pure solvent. Solvation shells interfere with the formation of hydrogen-bonded ice structure. This results in depression of the freezing point relative to the pure solvent.