15.1 Water and Its Properties

Connecting to Your World In December of 1968, when the Apollo 8 astronauts first saw their home planet from a distance of thousands of kilometers, they affectionately called it the big blue marble. Water covers about three-quarters of Earth's surface. In addition to making up Earth's oceans, water forms the polar ice caps and cycles through the atmosphere. All life forms that are known to exist are made mostly of water. In this section, you will learn about the properties of water and what makes this unique substance essential to life on Earth.

Guide for Reading

Key Concepts

- How can you account for the high surface tension and low vapor pressure of water?
- How would you describe the structure of ice?

Vocabulary

surface tension

surfactant

Reading Strategy

Monitoring Your Understanding Before you read, list what you already know about water and aqueous systems. After you read, write what you have learned. Is what you already knew correct? If not, how do you need to revise that information?

Water in the Liquid State

When you turn on the faucet, you expect that water will stream out to supply all your needs. You couldn't live without water, nor could all the plants and animals, like those in Figure 15.1 that share space on the "big blue marble." Besides the water visible on Earth's surface, immense reserves of water exist deep underground. Water in the form of ice and snow dominates the polar regions of Earth. Icebergs drift in the oceans, and snow blankets the temperate zones in winter. Water vapor from the evaporation of surface water and from steam spouted from geysers and volcanoes is always present in Earth's atmosphere.

Figure 15.1 Water is vital to life. Animals that live on the grasslands depend on watering holes, such as the one shown here.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 15.1
- **Core Teaching Resources,** Section 15.1 Review
- **Transparencies,** T160–T161

Technology

- **Interactive Textbook with ChemASAP,** Animation 19, 20; Assessment 15.1

15.1

1 FOCUS

Objectives

15.1.1 Explain the high surface tension and low vapor pressure of water in terms of the structure of the water molecule and hydrogen bonding.

15.1.2 Describe the structure of ice.

Guide for Reading

Build Vocabulary L2

Word Parts Tension comes from the Latin *tendere*, which means "to stretch." Thus, surface tension causes the surface of a liquid to appear stretched and taut. Ask students to use the derivation of tension to explain the expression "nervous tension". *(a condition of stress or tautness in an individual brought about by some external cause)*

Reading Strategy L2

Use Prior Knowledge Before students begin to read this chapter, encourage them to review the concepts of polarity and hydrogen bonding in earlier chapters.

2 INSTRUCT

Connecting to Your World

Have students study the photograph and read the text. Ask, **What are the white swirls in the photo?** *(clouds)* **How are the white swirls relevant to the subject matter of this chapter?** *(Clouds are composed of water vapor, water in its gaseous state.)*

Water in the Liquid State

Discuss L2

Tell students that, although three-quarters of Earth's surface is water, only a small fraction of it can be used for drinking. The majority of Earth's surface water is in the oceans and contains too high a concentration of salts for the human body to tolerate.

Use Visuals L1

Figures 15.2, 15.3 Have students study the figures. Ask, **What is meant by the term *polarity*?** *(Polarity refers to the net molecular dipole resulting from electronegativity differences between covalently bonded atoms.)* **What part of the water molecule has a partial negative charge?** *(the oxygen atom)* **What part has a partial positive charge?** *(the hydrogen atoms)* **What kind of substances would you expect to dissolve in water?** *(polar substances, ionic compounds)*

Discuss L2

Write the structural formula of water on the board. Using VSEPR theory, show students how the oxygen's non-bonding electron pairs reduce the bond angle in a water molecule to 105°C. Point out how the net molecular dipole and hydrogen bonding properties of water are due to water's bent shape and the large electronegativity differences between H and O. Note that hydrogen bonding contributes to water's unusually low vapor pressure and high surface tension.

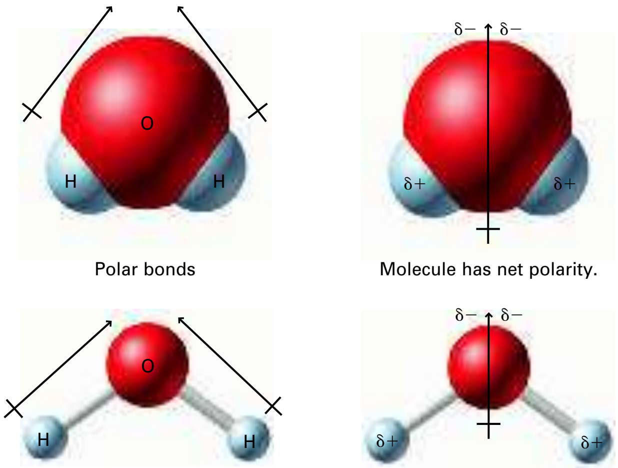

Figure 15.2 In a water molecule, the bond polarities are equal, but the two poles do not cancel each other because a water molecule is bent. The molecule as a whole is polar. **Applying Concepts** ***Which element in water has the higher electronegativity?***

Interactive Textbook

Animation 19 See how hydrogen bonding results in the unique properties of water.

with ChemASAP

Recall that water is a simple triatomic molecule, H_2O. The oxygen atom forms a covalent bond with each of the hydrogen atoms. Because of its greater electronegativity, oxygen attracts the electron pair of the covalent O—H bond to a greater extent than hydrogen. As a result, the oxygen atom acquires a partial negative charge ($\delta-$). The less electronegative hydrogen atoms acquire partial positive charges ($\delta+$). Thus, the O—H bonds are highly polar. How do the polarities of the two O—H bonds affect the polarity of the molecule? The shape of the molecule is the determining factor. The bond angle of the water molecule is approximately 105°, which gives the molecule a bent shape. The two O—H bond polarities do not cancel, so the water molecule as a whole is polar. The net polarity of the water molecule is illustrated in Figure 15.2.

In general, polar molecules are attracted to one another by dipole interactions. The negative end of one molecule attracts the positive end of another molecule. Figure 15.3 shows how this intermolecular attraction among water molecules results in the formation of hydrogen bonds. **Many unique and important properties of water—including its high surface tension and low vapor pressure—result from hydrogen bonding.**

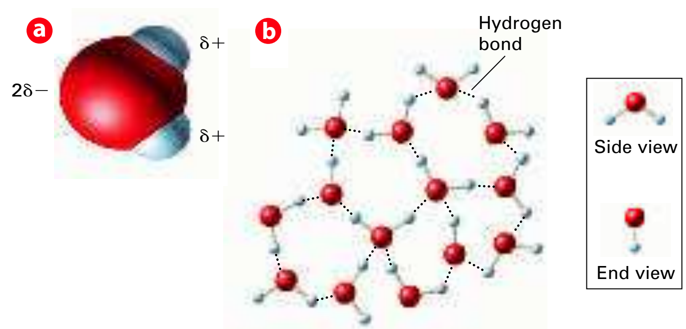

Figure 15.3 The polarity of the water molecule results in hydrogen bonding. **a** Partial negative charges are on each oxygen atom; partial positive charges are on the hydrogen atom. **b** Because of polarity, hydrogen bonds form. **Inferring** ***To form a hydrogen bond, what must be true about the hydrogen and the element to which it is hydrogen bonded?***

Facts and Figures

Availability of Water

Have students compare areas of population density and the distribution of water. Give them two different maps. One map should show the locations of cities and towns. The other should be a regional contour map showing water courses, rivers, lakes, and reservoirs. Ask students why most large cities or even historic sites are located near water sources. What happens when they're not? Have them consider the vast irrigation networks and water channels that crisscross the nation's agricultural areas to bring water to arid regions and to population centers with insufficient fresh water.

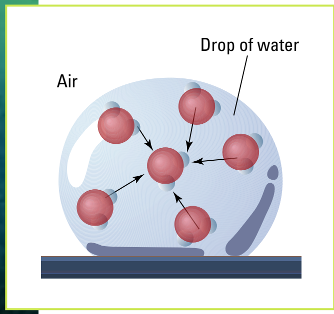

Figure 15.4 Surface tension makes it possible for some insects, such as this water strider, to walk on water. Water molecules at the surface of the water drop above cannot form hydrogen bonds with air molecules, so they are drawn into the body of the liquid, producing surface tension.

Surface Tension Have you ever seen a glass so filled with water that the water surface is not flat but bulges above the rim? Or have you noticed that water forms nearly spherical droplets at the end of a medicine dropper or when sprayed on a greasy surface? The surface of water acts like a skin, as the water strider shown in Figure 15.4 demonstrates. This skinlike property of water's surface is explained by water's ability to form hydrogen bonds. The molecules within the body of the liquid form hydrogen bonds with other molecules that surround them on all sides. The attractive forces on each of these molecules are balanced. However, water molecules at the surface of the liquid experience an unbalanced attraction. You can see in Figure 15.4 that the water molecules are hydrogen-bonded on only one side of the drop. As a result, water molecules at the surface tend to be drawn inward. The inward force, or pull, that tends to minimize the surface area of a liquid is called **surface tension.**

All liquids have a surface tension, but water's surface tension is higher than most. The surface tension of water tends to hold a drop of liquid in a spherical shape. The drop is not a perfect sphere because the force of gravity tends to pull it down, causing it to flatten. This is why, on some surfaces, water tends to bead up rather than spread out. It is possible to decrease the surface tension of water by adding a surfactant. A **surfactant** is any substance that interferes with the hydrogen bonding between water molecules and thereby reduces surface tension. Soaps and detergents are surfactants. Adding a detergent to beads of water on a greasy surface reduces surface tension, causing the beads of water to collapse and spread out.

Vapor Pressure Hydrogen bonding between water molecules also explains water's unusually low vapor pressure. Remember that the vapor pressure of a liquid is the result of molecules escaping from the surface of the liquid and entering the vapor phase. Because hydrogen bonds hold water molecules to one another, the tendency of these molecules to escape is low and evaporation is slow. Imagine what would happen if it were not. All the lakes and oceans, with their large surface areas, would tend to evaporate!

Checkpoint ***What is surface tension?***

Interactive Textbook
Animation 20
Discover how some insects can walk on water.
with ChemASAP

Discuss L2

To help students understand why liquid water assumes a spherical shape on many surfaces, explain that nature tends to find the path of least resistance. Moving molecules takes work. A spherical shape provides the minimum surface area for a given volume; molecules expend the least energy possible to move into a spherical arrangement while maximizing their interactions with one another in the bulk liquid. This energy efficiency creates the surface tension. In order to adopt any other shape, more work would have to be done. The work "saved" is the surface tension.

Use Visuals L1

Figure 15.4 Point out that the skinlike qualities of water are due to an exceptionally high surface tension that is created by an extensive network of hydrogen bonds. As an analogy, describe the following scene. A crowd of autograph seekers surrounds a celebrity. As each person approaches as closely as possible, an impenetrable circular barrier forms. This barrier will remain intact as long as there is a net attraction toward the circle's center. The process is dynamic. As one person wiggles closer to the celebrity, another is forced to retreat, but the overall shape doesn't change. Similarly, within a drop of water, attractions between individual molecules may shift, but the overall shape remains constant as molecules continue to be drawn toward a central focal point.

Answers to...

Figure 15.2 oxygen

Figure 15.3 The hydrogen atom must be covalently bonded to a very electronegative atom with one or more lone pairs of electrons.

Checkpoint the inward pull that tends to minimize the surface area of a liquid

Section 15.1 (continued)

Quick LAB

Surfactants L2

Objective After completing this activity, students will be able to:

- identify a property of water that results from hydrogen bonding.
- describe the effect of a surfactant on surface tension.

Address Misconceptions

Students may believe that the surface contains a different kind of water molecule than the interior of a volume of water. Remind students that surface tension still exists even after you mix the water sample to redistribute the molecules.

Skills Focus Observing, inferring, drawing conclusions

Prep Time 10 minutes

Advance Prep

- Gather paper clips, rubber bands, detergent, and vegetable oil.

Class Time 20 minutes

Teaching Tips

- Have students dry their hands before touching the paper clips.

Expected Outcome The paper clip floats. The rubber band takes on a circular shape when filled with oil. Detergent destroys the surface tension and causes the rubber band to return to its original, non-circular shape.

Analyze and Conclude

1. The paper clip floated. The surface tension of the water supported the paper clip.
2. No. The surface tension is broken, and the paper clip sinks because it is made of a metal that is more dense than water.
3. The rubber band took a circular shape. The surface tension of the surrounding water pulling the rubber band radially outward is not balanced by the surface tension of the oil.
4. The oil layer was broken, and the rubber band returned to its original shape.

Quick LAB

Surfactants

Purpose
To observe an unusual surface property of water that results from hydrogen bonding.

Materials
- shallow dish or Petri dish
- water
- paper clip
- rubber band, approximately 5 cm in diameter
- micropipets or droppers (2)
- vegetable oil
- liquid dish detergent

Procedure
1. Thoroughly clean and dry the dish.
2. Fill the dish almost full with water. Dry your hands.
3. Being careful not to break the surface, gently place the paper clip on the water. Observe what happens.
4. Repeat Steps 1 and 2.
5. Gently place the open rubber band on the water.
6. Slowly add oil drop by drop onto the water encircled by the rubber band until that water is covered with a layer of oil. Observe for 15 seconds.
7. Allow one drop of dish detergent to fall onto the center of the oil layer. Observe the system for 15 seconds.

Analyze and Conclude
1. What happened to the paper clip in Step 3? Why?
2. If a paper clip becomes wet, does it float? Explain your answer.
3. What shape did the rubber band take when the water inside it was covered with oil? Why did it take the observed shape?
4. Describe what happened when dish detergent was dropped onto the layer of oil.

Water in the Solid State

You have seen that water in the liquid state exhibits some unique properties. The same is true for water in the solid state. For example, ice cubes float in your glass of iced tea because solid water has a lower density than liquid water. This is not usual for liquids. As a typical liquid cools, it begins to contract and its density increases gradually. Increasing density means that the molecules of the liquid move closer together so that a given volume of the liquid contains more molecules and thus more mass. If the cooling continues, the liquid eventually solidifies with a density greater than the density of the liquid. Because the density of a typical solid is greater than that of the corresponding liquid, the solid sinks in its own liquid.

As water begins to cool, it behaves initially like a typical liquid. It contracts slightly and its density gradually increases, as shown in Table 15.1. Notice that at 4°C, the density of water is at its maximum of 1.000 g/cm^3. When the temperature of the water falls below 4°C, the density of water actually starts to decrease. Below 4°C, water no longer behaves like a typical liquid. Ice, which forms at 0°C, has about a 10 percent lower density than water at 0°C. You may have noticed that ice begins to form at the surface of a pond when the temperature reaches 0°C, but the ice does not sink. It floats at the surface, making ice skating and ice fishing possible. Ice is one of only a few solids that float in their own liquid.

Table 15.1
Density of Liquid Water and Ice

Temperature (°C)	Density (g/cm^3)
100 (liquid water)	0.9584
50	0.9881
25	0.9971
10	0.9997
4	1.000*
0 (liquid water)	0.9998
0 (ice)	0.9168

*Most dense

Checkpoint *At what temperature does water have its maximum density?*

For Enrichment L3

Water striders depend on the surface tension of water for moving around and capturing food. Tell students that detergents are increasingly found as pollutants in bodies of water in nature. Have students design an experiment to determine the concentration of detergent at which water can no longer support the weight of a water strider.

Differentiated Instruction

Gifted and Talented L3

The structure of ice was determined using X-ray diffraction, a method that was also used by Rosalind Franklin in her work with DNA. This work contributed to the discovery of the helical structure of DNA by James Watson and Francis Crick. Have students research how X-ray diffraction is used to determine the structure of a substance.

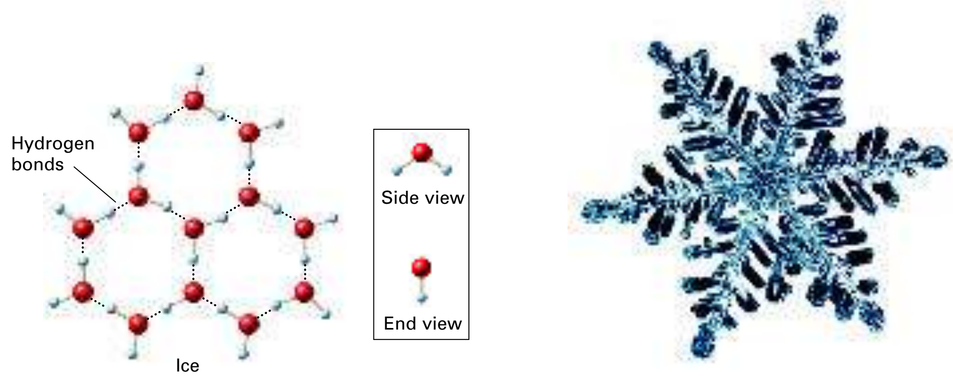

Figure 15.5 Extensive hydrogen bonding in ice holds the water molecules farther apart in a more ordered arrangement than in liquid water. The hexagonal symmetry of a snowflake reflects the structure of the ice crystal.

Why is ice less dense than liquid water? As you can see in Figure 15.5, hydrogen bonds hold the water molecules in place in the solid phase. **The structure of ice is a regular open framework of water molecules arranged like a honeycomb.** When ice melts, the framework collapses and the water molecules pack closer together, making liquid water more dense than ice.

The fact that ice floats has important consequences for organisms. A layer of ice on the top of a pond acts as an insulator for the water beneath, preventing it from freezing solid except under extreme conditions. Because the liquid water at the bottom of an otherwise frozen pond is warmer than 0°C, fish and other aquatic life are better able to survive. If ice were denser than liquid water, bodies of water would tend to freeze solid during the winter months, destroying many types of organisms.

Ice melts at 0°C. This is a high melting temperature for a molecule with such a low molar mass. A considerable amount of energy is required to return water molecules in the solid state to the liquid state. The heat absorbed when 1 g of water changes from a solid to a liquid is 334 J. This same amount of energy is needed to raise the temperature of 1 g of liquid water from 0°C to 80°C.

15.1 Section Assessment

1. **Key Concept** What causes the high surface tension and low vapor pressure of water?
2. **Key Concept** How would you describe the structure of ice?
3. What effect does a surfactant have on the surface tension of water?
4. What are two factors that determine how spherical a drop of a liquid will be?
5. The molecules water (H_2O) and methane (CH_4) have similar masses, but methane changes from a gas to a liquid at -161°C. Water becomes a gas at 100°C. What could account for the difference?

Writing Activity

Short Story Use your imagination to write a short children's story about a water strider whose "magic" ability to walk on water saved him from a predator bird. For your young readers, be sure to include an explanation of the life-saving magic.

Interactive Textbook

Assessment 15.1 Test yourself on the concepts in Section 15.1.

with ChemASAP

Section 15.1 Assessment

1. Water molecules are hydrogen-bonded to each other, but not to air molecules. Net attraction is inward, minimizing the water surface area. Hydrogen bonding makes it more difficult for water molecules to escape from the liquid phase to the vapor phase.
2. Ice has a honeycomb-like structure of hydrogen-bonded water molecules.
3. Surfactants lower the surface tension of water by interfering with hydrogen bonding.
4. The surface tension of a liquid tends to hold a drop of liquid in a spherical shape; gravity tends to flatten the drop.
5. Water has intermolecular hydrogen bonding between its molecules; methane does not.

Water in the Solid State

Use Visuals L2

Table 15.1 Have students note that the density of liquid water increases with decreasing temperature. Ask, **Why doesn't this trend continue below 4°C?** *(Below 4°C, the kinetic energy of the molecules is insufficient to overcome hydrogen bonding, which holds the water molecules in fixed positions.)*

3 ASSESS

Evaluate Understanding L2

Ask, **Why is the surface tension of water so high compared to that of other liquids?** *(Water molecules form a large number of hydrogen bonds, in addition to dipole-dipole forces between molecules.)* **Why does water form a meniscus in a narrow tube?** *(Water molecules have a greater attraction to the molecules on the surface of the glass than they do to each other.)*

Reteach L1

Have students explain what property of water allows ice to float in its liquid phase. *(Ice has a lower density than liquid water. Because there is more space between water molecules in the solid state than in the liquid state, there are fewer molecules in any given volume. Less mass per volume results in a lower relative density of ice as compared to water.)*

Writing Activity

Stories will vary in imaginative scope, but should include a simplified explanation of surface tension.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 15.1.

with ChemASAP

Answers to...

Checkpoint 4°C