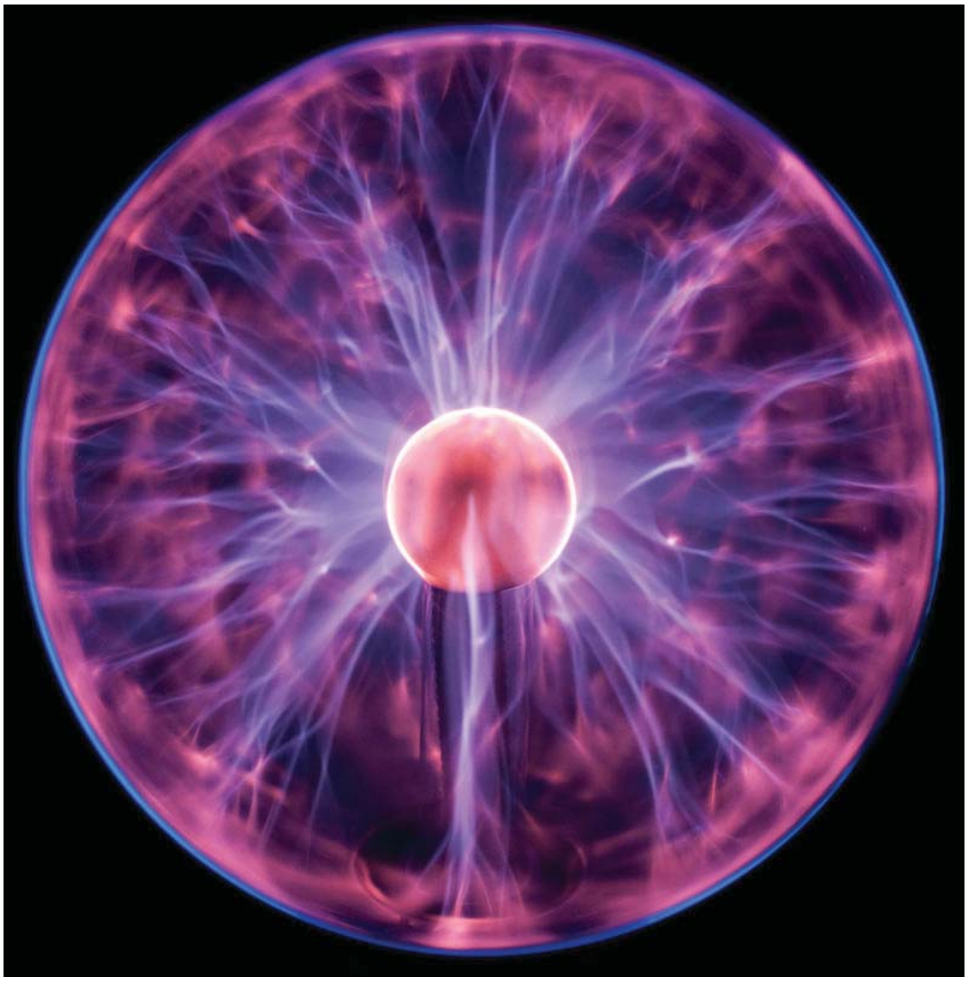
CHAPTER 13 States of Matter

Chapter Outline



Can you guess what this picture shows? The purple and blue "flames" are matter in a particular state. You're probably familiar with the states of matter most common on Earth —solids, liquids, and gases. But these "flames" are a state of matter called plasma. This plasma ball was made by humans. Plasma also occurs in nature. In fact, plasma makes up most of the matter in the universe.

What do you know about plasma? For example, do you know where it is found in nature? In this chapter, you'll find out as you read about plasma and other states of matter.

Tony Hisgett. commons.wikimedia.org/wiki/File:Plasma_ball_%283996244124%29.jpg. CC BY 2.0.

13.1 Solids, Liquids, Gases, and Plasmas

Lesson Objectives

- Describe matter in the solid state.
- State properties of liquid matter
- Identify properties of gases.
- Describe plasma.
- Explain the relationship between energy and states of matter.

Vocabulary

- energy
- gas
- kinetic energy
- kinetic theory of matter
- liquid
- plasma
- solid
- states of matter

Introduction

States of matter are the different forms in which matter can exist. Look at **Figure** 13.1. It represents water in three states: solid (iceberg), liquid (ocean water), and gas (water vapor in the air). In all three states, water is still water. It has the same chemical makeup and the same chemical properties. That's because the state of matter is a physical property.

How do solids, liquids, and gases differ? Their properties are compared in **Figure** 13.2 and described below. You can also watch videos about the three states at these URLs:

http://www.youtube.com/watch?v=s-KvoVzukHo&feature=related (0:52)

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http://www.youtube.com/watch?v=NO9OGeHgtBY&feature=related (1:42)

FIGURE 13.1
This photo represents solid, liquid, and gaseous water. Where is the gaseous water in the picture?

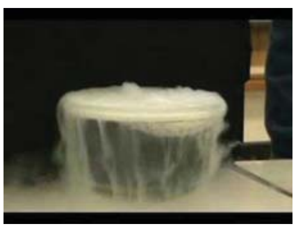

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FIGURE 13.2
These three states of matter are common on Earth. What are some substances that usually exist in each of these states?

Solids

Ice is an example of solid matter. A **solid** is matter that has a fixed volume and a fixed shape. **Figure** 13.3 shows examples of matter that are usually solids under Earth conditions. In the figure, salt and cellulose are examples of crystalline solids. The particles of crystalline solids are arranged in a regular repeating pattern. The steaks and candle wax are examples of amorphous ("shapeless") solids. Their particles have no definite pattern.

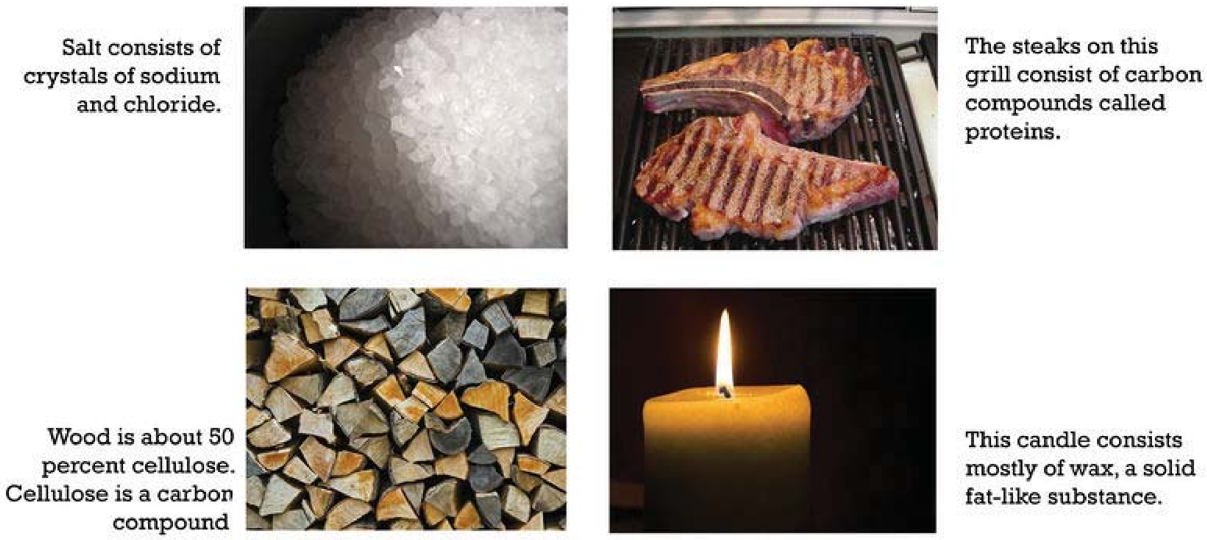

FIGURE 13.3
The volume and shape of a solid can be changed, but only with outside help. How could you change the volume and shape of each of the solids in the figure without changing the solid in any other way?

Liquids

Ocean water is an example of a liquid. A **liquid** is matter that has a fixed volume but not a fixed shape. Instead, a liquid takes the shape of its container. If the volume of a liquid is less than the volume of its container, the top surface will be exposed to the air, like the oil in the bottles in **Figure** 13.4.

Two interesting properties of liquids are surface tension and viscosity.

- Surface tension is a force that pulls particles at the exposed surface of a liquid toward other liquid particles. Surface tension explains why water forms droplets, like those in **Figure** 13.5.
- Viscosity is a liquid's resistance to flowing. Thicker liquids are more viscous than thinner liquids. For example, the honey in **Figure** 13.5 is more viscous than the vinegar.

You can learn more about surface tension and viscosity at these URLs:

- http://io9.com/5668221/an-experiment-with-soap-water-pepper-and-surface-tension

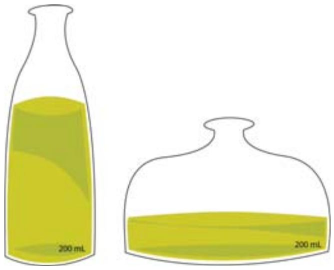

FIGURE 13.4
Each bottle contains the same volume of oil. How would you describe the shape of the oil in each bottle?

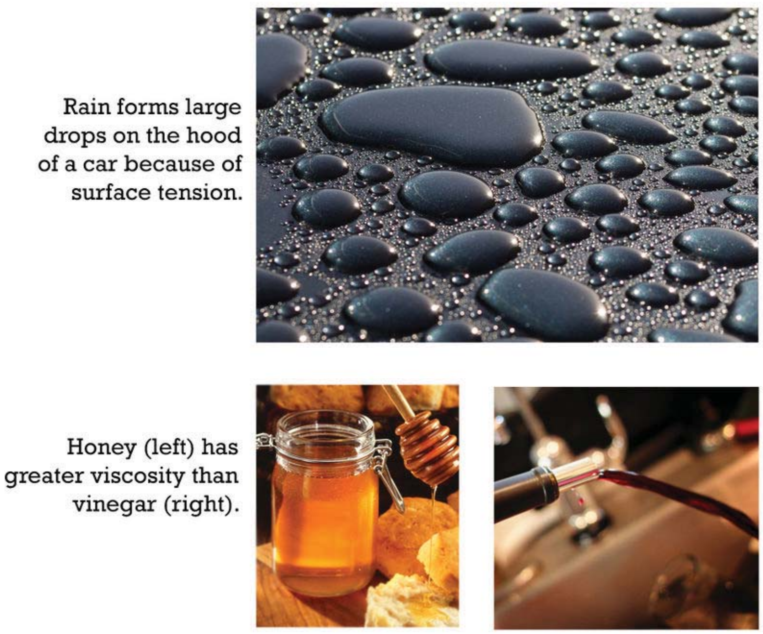

FIGURE 13.5
These images illustrate surface tension and viscosity of liquids.

- http://chemed.chem.wisc.edu/chempaths/GenChem-Textbook/Viscosity-840.html
- http://www.youtube.com/watch?v=u5AxlJSiEEs (1:40)

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Gases

Water vapor is an example of a gas. A **gas** is matter that has neither a fixed volume nor a fixed shape. Instead, a gas takes both the volume and the shape of its container. It spreads out to take up all available space. You can see an example in **Figure** 13.6.

FIGURE 13.6
When you add air to a bicycle tire, you add it only through one tiny opening. But the air immediately spreads out to fill the whole tire.

Plasmas

You're probably less familiar with plasmas than with solids, liquids, and gases. Yet, most of the universe consists of plasma. **Plasma** is a state of matter that resembles a gas but has certain properties that a gas does not have. Like a gas, plasma lacks a fixed volume and shape. Unlike a gas, plasma can conduct electricity and respond to magnetism. That's because plasma contains charged particles called ions. This gives plasma other interesting properties. For example, it glows with light.

Where can you find plasmas? Two examples are shown in **Figure** 13.7. The sun and other stars consist of plasma. Plasmas are also found naturally in lightning and the polar auroras (northern and southern lights). Artificial plasmas are found in fluorescent lights, plasma TV screens, and plasma balls like the one that opened this chapter. You can learn more about plasmas at this URL: http://www.youtube.com/watch?v=VkeSI_B5Ljc (2:58).

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Energy and Matter

Why do different states of matter have different properties? It's because of differences in energy at the level of atoms and molecules, the tiny particles that make up matter.

FIGURE 13.7
Both the northern lights (aurora borealis) and a plasma TV contain matter in the plasma state. What other plasmas are shown in the northern lights picture?

Energy

Energy is defined as the ability to cause changes in matter. You can change energy from one form to another when you lift your arm or take a step. In each case, energy is used to move matter —you. The energy of moving matter is called **kinetic energy**.

Kinetic Theory of Matter

The particles that make up matter are also constantly moving. They have kinetic energy. The theory that all matter consists of constantly moving particles is called the **kinetic theory of matter**. You can learn more about it at the URL below.

http://www.youtube.com/watch?v=Agk7_D4-deY (10:55)

Energy and States of Matter

Particles of matter of the same substance, such as the same element, are attracted to one another. The force of attraction tends to pull the particles closer together. The particles need a lot of kinetic energy to overcome the force of attraction and move apart. It's like a tug of war between opposing forces. The kinetic energy of individual particles is on one side, and the force of attraction between different particles is on the other side. The outcome of the "war" depends on the state of matter. This is illustrated in **Figure** 13.8 and in the animation at this URL: http://www.tutorvista.com/content/physics/physics-i/heat/kinetic-molecular-theory.php .

- In solids, particles don't have enough kinetic energy to overcome the force of attraction between them. The particles are packed closely together and cannot move around. All they can do is vibrate. This explains why solids have a fixed volume and shape.
- In liquids, particles have enough kinetic energy to partly overcome the force of attraction between them. They can slide past one another but not pull completely apart. This explains why liquids can change shape but have a fixed volume.
- In gases, particles have a lot of kinetic energy. They can completely overcome the force of attraction between them and move apart. This explains why gases have neither a fixed volume nor a fixed shape.

Lesson Summary

- A solid is matter that has a fixed volume and a fixed shape.
- A liquid is matter that has a fixed volume but not a fixed shape.
- A gas is matter that has neither a fixed volume nor a fixed shape.

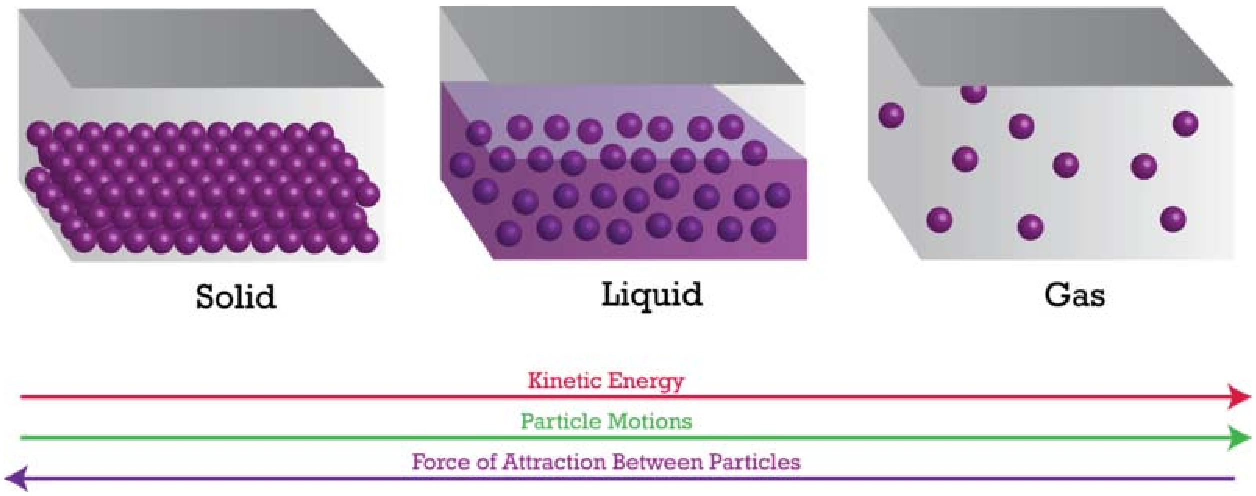

FIGURE 13.8
Kinetic energy is needed to overcome the force of attraction between particles of the same substance.

- Like a gas, plasma lacks a fixed volume and shape. Unlike a gas, it can conduct electricity and respond to magnetism.
- The state of matter depends on the kinetic energy of the particles of matter.

Lesson Review Questions

Recall

1. What are states of matter?
2. What are the properties of solids?
3. State the properties of liquids.
4. Describe properties of gases.
5. How do plasmas compare with gases?

Apply Concepts

6. Apply the concept of surface tension to explain why the surface of water in the glass shown in the **Figure** 13.9 is curved upward. Why doesn't the water overflow the glass?

Think Critically

7. Explain the relationship between energy and states of matter.

FIGURE 13.9
The surface of water in the glass is curved upward. How does surface tension explain this phenomenon?

Points to Consider

You read in this lesson that gases expand to fill their container.

- What if gas were forced into a smaller container? Would it shrink to fit?
- What other properties of the gas might change if its particles were crowded closer together?

13.2 References

1. Etienne Berthier, Université de Toulouse, NASA Goddard Space Flight Center. http://www.flickr.com/photos/gsfc/8741348325/ . CC BY 2.0
2. Christopher Auyeung. . CC BY-NC 3.0
3. Salt: Nate Steiner; Steaks: Jon Sullivan/pdphoto.org; Wood: Horia Varlan; Candle: Jon Sullivan/pdphoto.org;. Salt: http://www.flickr.com/photos/nate/27476159/; Steaks: http://commons.wikimedia.org/wiki/File:Steaks.jpg; Wood: http://www.flickr.com/photos/horiavarlan/4273110809; Candle: http://commons.wikimedia.org/wiki/File:Candle_flame_%281%29.jpg . Salt and Wood: CC BY 2.0; Steaks and Candle: Public Domain
4. Christopher Auyeung. . CC BY-NC 3.0
5. Rain drops: Flickr:Pug50; Honey: Courtesy of Scott Bauer, USDA ARS; Vinegar: Mike McCune (Flickr:mccun934). Rain drops: http://www.flickr.com/photos/pug50/4993906430/; Honey: http://commons.wikimedia.org/wiki/File:Runny_hunny.jpg; Vinegar: http://www.flickr.com/photos/mccun934/4858533603/ . Rain drops: CC BY 2.0; Honey: Public Domain; Vinegar: CC BY 2.0
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8. Christopher Auyeung. . CC BY-NC 3.0
9. Joy Sheng. . CC BY-NC 3.0

CHAPTER 14 Chemistry of Solutions

Chapter Outline

It can be really exciting to explore a big underground cave like the one in this picture. Do you know how caves form? Believe it or not, water is the answer. Water slowly dissolves rocks, especially certain types of rocks such as limestone. How does something as mild and harmless as water cause hard rocks to dissolve? In this chapter, you'll find out.

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14.1 Acids and Bases

Lesson Objectives

- Describe acids and how to detect them.
- Describe bases and how to detect them.
- Explain what determines the strength of acids and bases.
- Outline neutralization reactions and the formation of salts.

Lesson Vocabulary

- acid
- acidity
- base
- neutralization reaction
- pH
- salt

Introduction

No doubt you are familiar with some common acids. Besides orange juice, vinegar and lemon juice are both acids. Look at the boy in **Figure** 14.1. You can tell by the expression on his face that lemon juice tastes sour. In fact, all acids taste sour. They share certain other properties as well. You will learn more about their properties in this lesson. For a musical rendition of lesson content, go to this URL: http://www.youtube.com/watch?v=zTLiJE-j1-I .

FIGURE 14.1
Like other acids, lemon juice tastes sour.

Acids

An **acid** is an ionic compound that produces positive hydrogen ions (H^+) when dissolved in water. An example is hydrogen chloride (HCl). When it dissolves in water, its hydrogen ions and negative chloride ions (Cl^-) separate, forming hydrochloric acid. This can be represented by the equation:

$$HCl \xrightarrow{H_2O} H^+ + Cl^-$$

Properties of Acids

You already know that a sour taste is one property of acids. (**Never** taste an unknown substance to see whether it is an acid!) Acids have certain other properties as well. For example, acids can conduct electricity because they consist of charged particles in solution. Acids also react with metals to produce hydrogen gas. For example, when hydrochloric acid (HCl) reacts with the metal magnesium (Mg), it produces magnesium chloride ($MgCl_2$) and hydrogen (H_2). This is a single replacement reaction, represented by the chemical equation:

$$Mg + 2HCl \rightarrow H_2 + MgCl_2$$

You can see an online demonstration of a similar reaction at this URL: http://www.youtube.com/watch?v=oQz5YEsx7Fo .

Detecting Acids

Certain compounds, called indicators, change color when acids come into contact with them. They can be used to detect acids. An example of an indicator is a compound called litmus. It is placed on small strips of paper that may be red or blue. If you place a few drops of acid on a strip of blue litmus paper, the paper will turn red. You can see this in **Figure** 14.2. Litmus isn't the only indicator for detecting acids. Red cabbage juice also works well, as you can see in this entertaining video: http://www.youtube.com/watch?v=vrOUdoS2BtQ&feature=related .

FIGURE 14.2
Blue litmus paper turns red when placed in an acidic solution.

Uses of Acids

Acids have many important uses, especially in industry. For example, sulfuric acid is used to manufacture a variety of different products, including paper, paint, and detergent. Some other uses of acids are illustrated in **Figure** 14.3.

FIGURE 14.3
Acids are used widely for many purposes.

Bases

A **base** is an ionic compound that produces negative hydroxide ions (OH^-) when dissolved in water. For example, when the compound sodium hydroxide (NaOH) dissolves in water, it produces hydroxide ions and positive sodium ions (Na^+). This can be represented by the equation:

$$NaOH \xrightarrow{H_2O} OH^- + Na^+$$

Properties of Bases

All bases share certain properties, including a bitter taste. (**Never** taste an unknown substance to see whether it is a base!) Did you ever taste unsweetened cocoa powder? It tastes bitter because it is a base. Bases also feel slippery. Think about how slippery soap feels. Soap is also a base. Like acids, bases conduct electricity because they consist of charged particles in solution.

Detecting Bases

Bases change the color of certain compounds, and this property can be used to detect them. A common indicator of bases is red litmus paper. Bases turn red litmus paper blue. You can see an example in **Figure** 14.4. Red cabbage juice can detect bases as well as acids, as you'll see by reviewing this video: http://www.youtube.com/watch?v=vrOUdoS2BtQ&feature=related (3:14).

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FIGURE 14.4
Red litmus paper turns blue when placed in a basic solution.

Uses of Bases

Bases are used for a variety of purposes. For example, soaps contain bases such as potassium hydroxide. Other uses of bases are pictured in **Figure** 14.5.

FIGURE 14.5
Bases are used in many products.

Strength of Acids and Bases

The acid in vinegar is weak enough to safely eat on a salad. The acid in a car battery is strong enough to eat through skin. The base in antacid tablets is weak enough to take for an upset stomach. The base in drain cleaner is strong enough to cause serious burns. What causes these differences in strength of acids and bases?

Concentration of Ions

The strength of an acid depends on the concentration of hydrogen ions it produces when dissolved in water. A stronger acid produces a greater concentration of ions than a weaker acid. For example, when hydrogen chloride is added to water, all of it breaks down into H^+ and Cl^- ions. Therefore, it is a strong acid. On the other hand, only about 1 percent of acetic acid breaks down into ions, so it is a weak acid.

The strength of a base depends on the concentration of hydroxide ions it produces when dissolved in water. For example, sodium hydroxide completely breaks down into ions in water, so it is a strong base. However, only a fraction of ammonia breaks down into ions, so it is a weak base.

The pH Scale

The strength of acids and bases is measured on a scale called the pH scale (see **Figure** 14.6). The symbol **pH** represents **acidity**, or the concentration of hydrogen ions (H^+) in a solution. Pure water, which is neutral, has a pH of 7. With a higher concentration of hydrogen ions, a solution is more acidic but has a lower pH. Therefore, acids have a pH less than 7, and the strongest acids have a pH close to zero. Bases have a pH greater than 7, and the strongest bases have a pH close to 14. You can watch a video about the pH scale at this URL: http://www.youtube.com/watch?v=M8tTELZD5Ek (2:23).

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Why pH Matters

Acidity is an important factor for living things. For example, many plants grow best in soil that has a pH between 6 and 7. Fish also need a pH close to 7. Some air pollutants form acids when dissolved in water droplets in the air. This results in acid fog and acid rain, which may have a pH of 4 or even lower (see **Figure** 14.6). **Figure** 14.7 shows the effects of acid fog and acid rain on a forest. Acid rain also lowers the pH of surface waters such as streams and lakes. As a result, the water became too acidic for fish and many other water organisms to survive.

Even normal (not acid) rain is slightly acidic. That's because carbon dioxide in the air dissolves in raindrops, producing a weak acid called carbonic acid. When acidic rainwater soaks into the ground, it can slowly dissolve rocks, particularly those containing calcium carbonate. This is how water forms caves, like the one that opened this chapter.

Reactions of Acids and Bases

As you read above, an acid produces positive hydrogen ions and a base produces negative hydroxide ions. If an acid and base react together, the hydrogen and hydroxide ions combine to form water. This is represented by the equation:

$$H^+ + OH^- \rightarrow H_2O$$

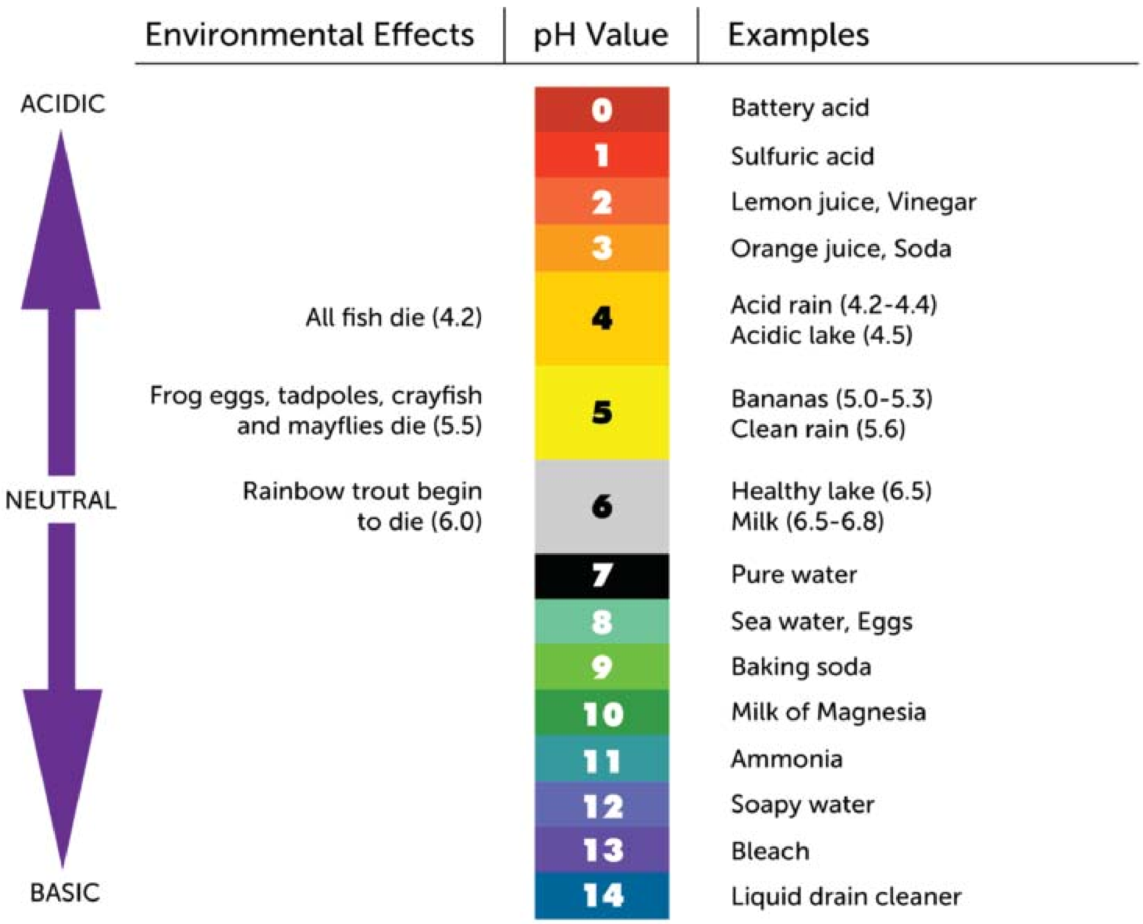


FIGURE 14.6

This pH scale shows the acidity of several common acids and bases. Which substance on this scale is the weakest acid? Which substance is the strongest base?

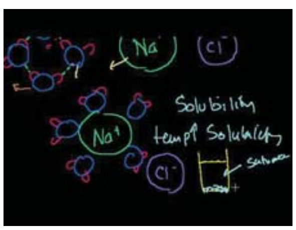
An acid also produces negative ions, and a base also produces positive ions. For example, the acid hydrogen chloride (HCl), when dissolved in water, produces negative chloride ions (Cl^-) as well as hydrogen ions. The base sodium hydroxide (NaOH) produces positive sodium ions (Na^+) in addition to hydroxide ions. These other ions also combine when the acid and base react. They form sodium chloride (NaCl). This is represented by the equation:

$$Na^+ + Cl^- \rightarrow NaCl$$

Sodium chloride is called table salt, but salt is a more general term. A **salt** is any ionic compound that forms when an acid and base react. It consists of a positive ion from the base and a negative ion from the acid. Like pure water, a salt is neutral in pH. That's why reactions of acids and bases are called **neutralization reactions**. Another example of a neutralization reaction is described in **Figure** 14.8. You can learn more about salts and how they form at this

FIGURE 14.7
Acid fog and acid rain killed the trees in this forest.

URL: http://www.youtube.com/watch?v=zjIVJh4JLNo (13:21).



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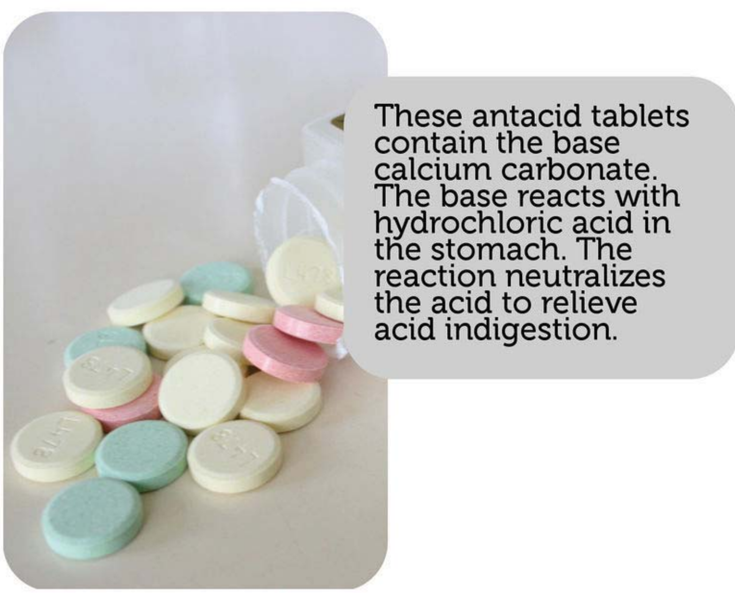

FIGURE 14.8
What neutral products are produced when antacid tablets react with hydrochloric acid in the stomach?

Lesson Summary

- An acid is an ionic compound that produces positive hydrogen ions when dissolved in water. Acids taste sour and turn blue litmus paper red.
- A base is an ionic compound that produces negative hydroxide ions when dissolved in water. Bases taste bitter and turn red litmus paper blue.
- The strength of acids and bases is determined by the concentration of ions they produce when dissolved in water. The concentration of hydrogen ions in a solution is called acidity. It is measured by pH. A neutral substance has a pH of 7. An acid has a pH lower than 7, and a base has a pH greater than 7.
- The reaction of an acid and a base is called a neutralization reaction. It produces a salt and water, both of which are neutral.

Lesson Review Questions

Recall

1. What is an acid? Give one use of acids.
2. What is a base? Name a common product that contains a base.
3. Outline how litmus paper can be used to detect acids and bases.
4. Define acidity. How is it measured?

Apply Concepts

5. An unknown substance has a pH of 7.2. Is it an acid or a base? Explain your answer.
6. If hydrochloric acid (HCl) reacts with the base lithium hydroxide (LiOH), what are the products of the reaction? Write a chemical equation for the reaction.

Think Critically

7. Battery acid is a stronger acid than lemon juice. Explain why.

Points to Consider

Neutralization reactions, like the other chemical reactions you have read about so far, involve electrons. Electrons are outside the nucleus of an atom. Certain other reactions involve the nucleus of an atom instead. These reactions are called nuclear reactions. You will read about them in the next chapter, "Nuclear Chemistry."

- How do you think nuclear reactions might differ from chemical reactions?
- Elements involved in nuclear reactions are radioactive. How do you think radioactive elements differ from other elements?

14.2 Water

Lesson Objectives

- Describe the distribution of Earth's water, and outline the water cycle.
- Identify the chemical structure of water, and explain how it relates to water's unique properties.
- Define solution, and describe water's role as a solvent.
- State how water is used to define acids and bases, and identify the pH ranges of acids and bases.
- Explain why water is essential for life processes.

Introduction

Water, like carbon, has a special role in biology because of its importance to organisms. Water is essential to all known forms of life. Water, H_2O, such a simple molecule, yet it is this simplicity that gives water its unique properties and explains why water is so vital for life.

The Wonder of Water video can be viewed at http://vimeo.com/7508571 .

Water, Water Everywhere

Water is a common chemical substance on Earth. The term water generally refers to its liquid state. Water is a liquid over a wide range of standard temperatures and pressures. However, water can also occur as a solid (ice) or gas (water vapor).

Where Is All the Water?

Of all the water on Earth, about two percent is stored underground in spaces between rocks. A fraction of a percent exists in the air as water vapor, clouds, or precipitation. Another fraction of a percent occurs in the bodies of plants and animals. So where is most of Earth's water? It's on the surface of the planet. In fact, water covers about 70 percent of Earth's surface. Of water on Earth's surface, 97 percent is salt water, mainly in the ocean. Only 3 percent is freshwater. Most of the freshwater is frozen in glaciers and polar ice caps. The remaining freshwater occurs in rivers, lakes, and other freshwater features.

Although clean freshwater is essential to human life, in many parts of the world it is in short supply. The amount of freshwater is not the issue. There is plenty of freshwater to go around, because water constantly recycles on Earth. However, freshwater is not necessarily located where it is needed, and clean freshwater is not always available.

How Water Recycles

Like other matter on Earth, water is continuously recycled. Individual water molecules are always going through the water cycle (see the *Principles of Ecology* chapter). In fact, water molecules on Earth have been moving through the water cycle for billions of years. In this cycle, water evaporates from Earth's surface (or escapes from the surface in other ways), forms clouds, and falls back to the surface as precipitation. This cycle keeps repeating. Several processes change water from one state to another during the water cycle. They include:

- **Evaporation**—Liquid water on Earth's surface changes into water vapor in the atmosphere.

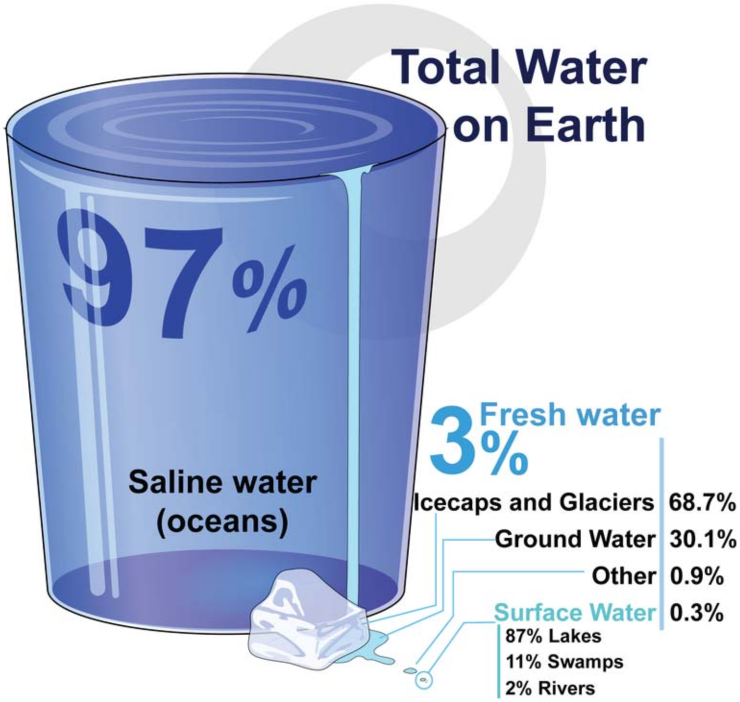

FIGURE 14.9
Most of the water on Earth consists of saltwater in the oceans. What percent of Earth's water is fresh water? Where is most of the fresh water found?

- **Sublimation**—Snow or ice on Earth's surface changes directly into water vapor in the atmosphere.
- **Transpiration**—Plants give off liquid water, most of which evaporates into the atmosphere.
- **Condensation**—Water vapor in the atmosphere changes to liquid water droplets, forming clouds or fog.
- **Precipitation**—Water droplets in clouds are pulled to Earth's surface by gravity, forming rain, snow, or other type of falling moisture.

Chemical Structure and Properties of Water

You are probably already familiar with many of water's properties. For example, you no doubt know that water is tasteless, odorless, and transparent. In small quantities, it is also colorless. However, when a large amount of water is observed, as in a lake or the ocean, it is actually light blue in color. These and other properties of water depend on its chemical structure.

The transparency of water is important for organisms that live in water. Because water is transparent, sunlight can pass through it. Sunlight is needed by water plants and other water organisms for photosynthesis (see *Biomes, Ecosystems, and Communities* chapter).

Chemical Structure of Water

Each molecule of water consists of one atom of oxygen and two atoms of hydrogen, so it has the chemical formula H_2O. The arrangement of atoms in a water molecule, shown in **Figure** 14.10, explains many of water's chemical properties. In each water molecule, the nucleus of the oxygen atom (with 8 positively charged protons) attracts electrons much more strongly than do the hydrogen nuclei (with only one positively charged proton). This results in a negative electrical charge near the oxygen atom (due to the "pull" of the negatively charged electrons toward the oxygen nucleus) and a positive electrical charge near the hydrogen atoms. A difference in electrical charge between different parts of a molecule is called **polarity**. A polar molecule is a molecule in which part of the molecule is positively charged and part of the molecule is negatively charged.

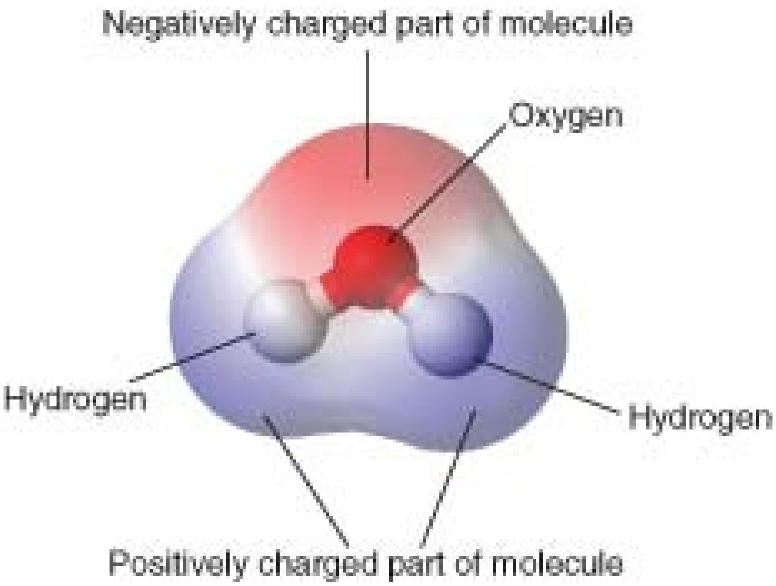

FIGURE 14.10

This model shows the arrangement of oxygen and hydrogen atoms in a water molecule. The nucleus of the oxygen atom attracts electrons more strongly than do the hydrogen nuclei. As a result, the middle part of the molecule near oxygen has a negative charge, and the other parts of the molecule have a positive charge. In essence, the electrons are "pulled" toward the nucleus of the oxygen atom and away from the hydrogen atom nuclei. Water is a polar molecule, with an unequal distribution of charge throughout the molecule.

Opposite electrical charges attract one another other. Therefore, the positive part of one water molecule is attracted to the negative parts of other water molecules. Because of this attraction, bonds form between hydrogen and oxygen atoms of adjacent water molecules, as demonstrated in **Figure** 14.11. This type of bond always involves a hydrogen atom, so it is called a **hydrogen bond**. Hydrogen bonds are bonds between molecules, and they are not as strong as bonds within molecules. Nonetheless, they help hold water molecules together.

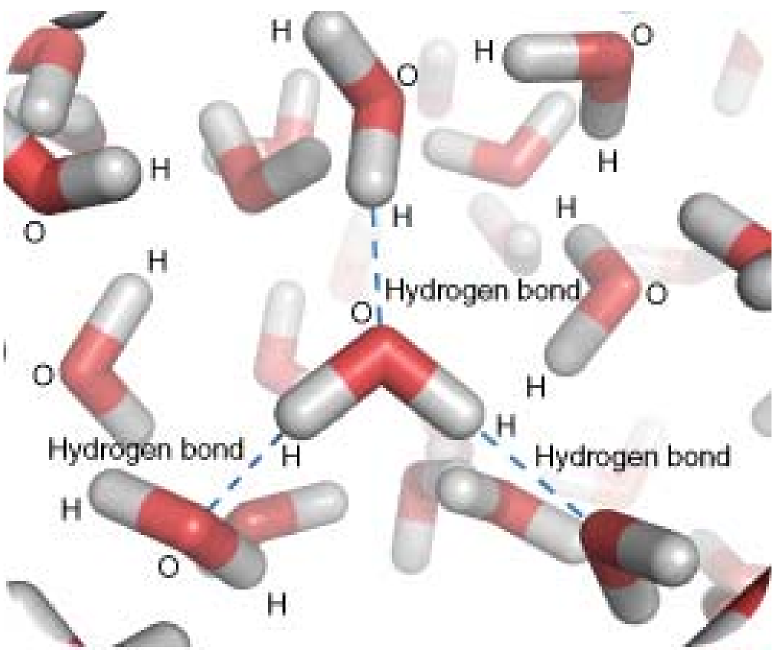

FIGURE 14.11

Hydrogen bonds form between positively and negatively charged parts of water molecules. The bonds hold the water molecules together.

Hydrogen bonds can also form within a single large organic molecule (see the *Organic Compounds* lesson). For example, hydrogen bonds that form between different parts of a protein molecule bend the molecule into a distinctive shape, which is important for the protein's functions. Hydrogen bonds also hold together the two nucleotide chains of a DNA molecule.

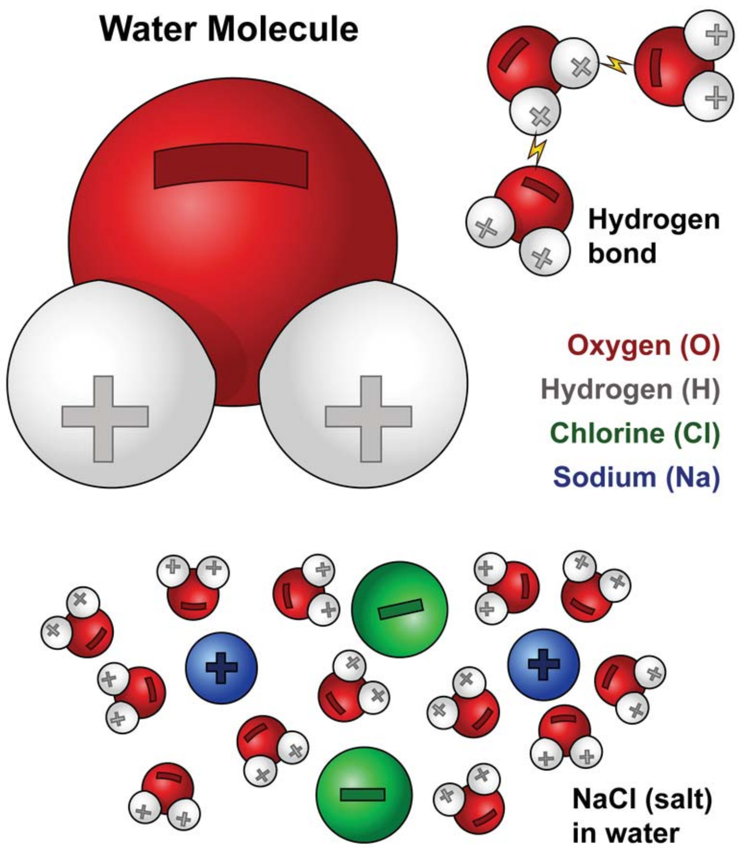

FIGURE 14.12
Water Molecule. This diagram shows the positive and negative parts of a water molecule. It also depicts how a charge, such as on an ion (Na or Cl, for example) can interact with a water molecule.

Sticky, Wet Water

Water has some unusual properties due to its hydrogen bonds. One property is the tendency for water molecules to stick together. For example, if you drop a tiny amount of water onto a very smooth surface, the water molecules will stick together and form a droplet, rather than spread out over the surface. The same thing happens when water slowly drips from a leaky faucet. The water doesn't fall from the faucet as individual water molecules but as droplets of water. The tendency of water to stick together in droplets is also illustrated by the dew drops in **Figure** 14.13.

Hydrogen bonds also explain why water's boiling point (100° C) is higher than the boiling points of similar substances without hydrogen bonds. Because of water's relatively high boiling point, most water exists in a liquid state on Earth. Liquid water is needed by all living organisms. Therefore, the availability of liquid water enables life to survive over much of the planet.

Density of Ice and Water

The melting point of water is 0° C. Below this temperature, water is a solid (ice). Unlike most chemical substances, water in a solid state has a lower density than water in a liquid state. This is because water expands when it freezes. Again, hydrogen bonding is the reason. Hydrogen bonds cause water molecules to line up less efficiently in ice than in liquid water. As a result, water molecules are spaced farther apart in ice, giving ice a lower density than liquid water. A substance with lower density floats on a substance with higher density. This explains why ice floats on liquid water, whereas many other solids sink to the bottom of liquid water.

In a large body of water, such as a lake or the ocean, the water with the greatest density always sinks to the bottom.

FIGURE 14.13

Droplets of dew cling to a spider web, demonstrating the tendency of water molecules to stick together because of hydrogen bonds.

Water is most dense at about 4° C. As a result, the water at the bottom of a lake or the ocean usually has temperature of about 4° C. In climates with cold winters, this layer of 4° C water insulates the bottom of a lake from freezing temperatures. Lake organisms such as fish can survive the winter by staying in this cold, but unfrozen, water at the bottom of the lake.

Solutions

Water is one of the most common ingredients in solutions. A **solution** is a homogeneous mixture composed of two or more substances. In a solution, one substance is dissolved in another substance, forming a mixture that has the same proportion of substances throughout. The dissolved substance in a solution is called the **solute**. The substance in which is it dissolved is called the **solvent**. An example of a solution in which water is the solvent is salt water. In this solution, a solid—sodium chloride—is the solute. In addition to a solid dissolved in a liquid, solutions can also form with solutes and solvents in other states of matter. Examples are given in **Table 1**.

TABLE 14.1: **Examples of Solutions**

Solvent	Gas	Liquid	Solid
Gas	Oxygen and other gases in nitrogen (air)		
Liquid	Carbon dioxide in water (carbonated water)	Ethanol (an alcohol) in water	Sodium chloride in water (salt water)
Solid	Hydrogen in metals	Mercury in silver and other metals (dental fillings)	Iron in carbon (steel)

(*Source:* http://en.wikipedia.org/wiki/Solute, *License:* Creative Commons)

The ability of a solute to dissolve in a particular solvent is called **solubility**. Many chemical substances are soluble in water. In fact, so many substances are soluble in water that water is called the universal solvent. Water is a strongly polar solvent, and polar solvents are better at dissolving polar solutes. Many organic compounds and other important biochemicals are polar, so they dissolve well in water. On the other hand, strongly polar solvents like water cannot dissolve strongly nonpolar solutes like oil. Did you ever try to mix oil and water? Even after being well shaken, the two substances quickly separate into distinct layers.

Acids and Bases

Water is the solvent in solutions called acids and bases. To understand acids and bases, it is important to know more

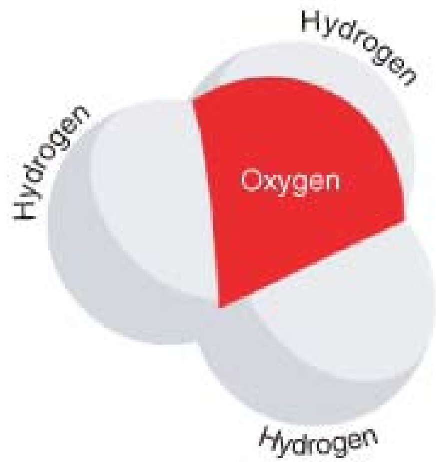

FIGURE 14.14
A hydronium ion has the chemical formula H_3O^+. The plus sign ($^+$) indicates that the ion is positively charged. How does this molecule differ from the water molecule in **Figure** ?

hydronium ion in pure water. This gives water a pH of 7. The hydronium ions in pure water are also balanced by hydroxide ions, so pure water is neutral (neither an acid nor a base).

Because pure water is neutral, any other solution with the same hydronium ion concentration and pH is also considered to be neutral. If a solution has a higher concentration of hydronium ions and lower pH than pure water, it is called an **acid**. If a solution has a lower concentration of hydronium ions and higher pH than pure water, it is called a **base**. Several acids and bases and their pH values are identified on the pH scale, which ranges from 0 to 14, in **Figure** below.

An introduction to acids and bases, *Acids and Bases Have Two Different Faces,* can be seen and heard at http://www.youtube.com/watch?v=zTLiJE-j1-I&feature=related (3:27).

MEDIA
Click image to the left for more content.

The pH scale is a negative logarithmic scale. Because the scale is negative, as the ion concentration increases, the pH value decreases. In other words, the more acidic the solution, the lower the pH value. Because the scale is logarithmic, each one-point change in pH reflects a ten-fold change in the hydronium ion concentration and acidity. For example, a solution with a pH of 6 is ten times as acidic as pure water with a pH of 7.

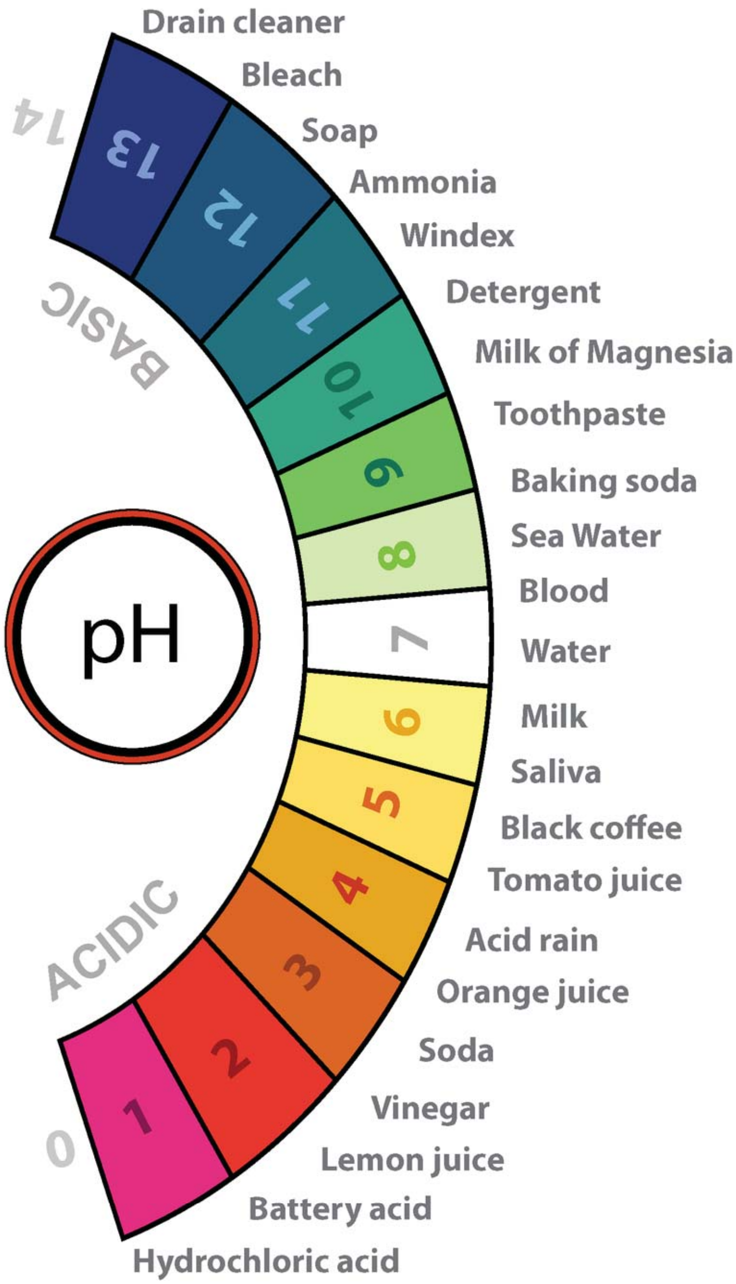

FIGURE 14.15

Acidity and the pH Scale. Water has a pH of 7, so this is the point of neutrality on the pH scale. Acids have a pH less than 7, and bases have a pH greater than 7. The approximate pHs of numerous substances is shown.

Acids

An acid can be defined as a hydrogen ion donor. The hydrogen ions bond with water molecules, leading to a higher concentration of hydronium ions than in pure water. For example, when hydrochloric acid (HCl) dissolves in pure water, it donates hydrogen ions (H^+) to water molecules, forming hydronium ions (H_3O^+) and chloride ions (Cl^-). This is represented by the chemical equation:

$HCl + H_2O \rightarrow Cl^- + H_3O^+$.

Strong acids can be harmful to organisms and damaging to materials. Acids have a sour taste and may sting or burn the skin. Testing solutions with litmus paper is an easy way to identify acids. Acids turn blue litmus paper red.

Bases

A base can be defined as a hydrogen ion acceptor. It accepts hydrogen ions from hydronium ions, leading to a lower concentration of hydronium ions than in pure water. For example, when the base ammonia (NH_3) dissolves in pure water, it accepts hydrogen ions (H^+) from hydronium ions (H_3O^+) to form ammonium ions ($NH_4{}^+$) and hydroxide ions (OH^-). This is represented by the chemical equation:

$NH_3 + H_2O \rightarrow NH_4{}^+ + OH^-$.

Like strong acids, strong bases can be harmful to organisms and damaging to materials. Bases have a bitter taste and feel slimy to the touch. They can also burn the skin. Bases, like acids, can be identified with litmus paper. Bases turn red litmus paper blue.

Neutralization

What do you think would happen if you mixed an acid and a base? If you think the acid and base would "cancel each other out," you are right. When an acid and base react, they form a neutral solution of water and a salt (a molecule composed of a positive and negative ion). This type of reaction is called a **neutralization** reaction. For example, when the base sodium hydroxide (NaOH) and hydrochloric acid (HCl) react, they form a neutral solution of water and the salt sodium chloride (NaCl). This reaction is represented by the chemical equation:

$NaOH + HCl \rightarrow NaCl + H_2O$.

In this reaction, hydroxide ions (OH^-) from the base combine with hydrogen ions (H^+) from the acid to form water. The other ions in the solution (Na^+) and (Cl^-) combine to form sodium chloride.

Acids and Bases in Organisms

Enzymes are needed to speed up biochemical reactions. Most enzymes require a specific range of pH in order to do their job. For example, the enzyme pepsin, which helps break down proteins in the human stomach, requires a very acidic environment in order to function. Strong acid is secreted into the stomach, allowing pepsin to work. Once the contents of the stomach enter the small intestine, where most digestion occurs, the acid must be neutralized. This is because enzymes that work in the small intestine need a basic environment. An organ near the small intestine, called the pancreas, secretes bicarbonate ions ($HCO_3{}^-$) into the small intestine to neutralize the stomach acid.

Bicarbonate ions play an important role in neutralizing acids throughout the body. Bicarbonate ions are especially important for protecting tissues of the central nervous system from changes in pH. The central nervous system includes the brain, which is the body's control center. If pH deviates too far from normal, the central nervous system cannot function properly. This can have a drastic effect on the rest of the body.

Water and Life

Humans are composed of about 70 percent water (not counting water in body fat). This water is crucial for normal functioning of the body. Water's ability to dissolve most biologically significant compounds—from inorganic salts to large organic molecules—makes it a vital solvent inside organisms and cells.

Water is an essential part of most metabolic processes within organisms. **Metabolism** is the sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions). In anabolic reactions, water is generally removed from small molecules in order to make larger molecules. In catabolic reactions, water is used to break bonds in larger molecules in order to make smaller molecules.

Water is central to two related, fundamental metabolic reactions in organisms: photosynthesis (*Photosynthesis* chapter) and respiration (*Cellular Respiration* chapter). All organisms depend directly or indirectly on these two reactions.

- In photosynthesis, cells use the energy in sunlight to change water and carbon dioxide into glucose and oxygen. This is an anabolic reaction, represented by the chemical equation:

6 CO_2 + 6 H_2O + energy $\rightarrow$ $C_6H_{12}O_{6,}$ + 6 O_2.

- In cellular respiration, cells break down glucose in the presence of oxygen and release energy, water, and carbon dioxide. This is a catabolic reaction, represented by the chemical equation:

$C_6H_{12}O_6$ + 6 O_2 $\rightarrow$ 6 CO_2 + 6 H_2O + energy

Two other types of reactions that occur in organisms and involve water are dehydration and hydration reactions. A dehydration reaction occurs when molecules combine to form a single, larger molecule and also a molecule of water. (If some other small molecule is formed instead of water, the reaction is called by the more general term, condensation reaction.) It is a type of anabolic reaction. An example of a dehydration reaction is the formation of peptide bonds between amino acids in a polypeptide chain. When two amino acids bond together, a molecule of water is lost. This is shown in **Figure** 14.16.

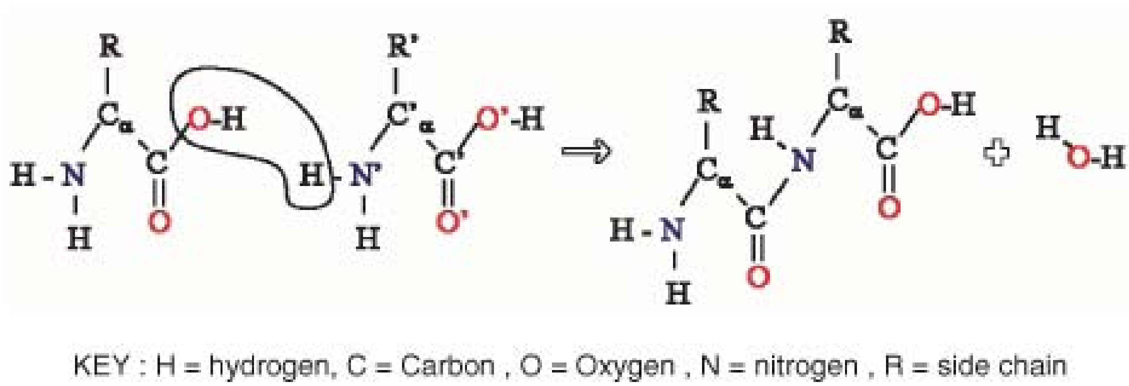

FIGURE 14.16

In this dehydration reaction, two amino acids form a peptide bond. A water molecule also forms.

A hydration reaction is the opposite of a dehydration reaction. A hydration reaction adds water to an organic molecule and breaks the large molecule into smaller molecules. Hydration reactions occur in an acidic water solution. An example of hydration reaction is the breaking of peptide bonds in polypeptides. A hydroxide ion (OH-) and a hydrogen ion (H+) (both from a water molecule) bond to the carbon atoms that formed the peptide bond. This breaks the peptide bond and results in two amino acids.

Water is essential for all of these important chemical reactions in organisms. As a result, virtually all life processes depend on water. Clearly, without water, life as we know it could not exist.

Lesson Summary

- Most of Earth's water is salt water located on the planet's surface. Water is constantly recycled through the water cycle.
- Water molecules are polar, so they form hydrogen bonds. This gives water unique properties, such as a relatively high boiling point.
- A solution is a homogeneous mixture in which a solute dissolves in a solvent. Water is a very common solvent, especially in organisms.
- The ion concentration of neutral, pure water gives water a pH of 7 and sets the standard for defining acids and bases. Acids have a pH lower than 7, and bases have a pH higher than 7.
- Water is essential for most life processes, including photosynthesis, cellular respiration, and other important chemical reactions that occur in organisms.

Review Questions

1. Where is most of Earth's water?
2. What is polarity, and why is water polar?
3. Define solution, and give an example of a solution.
4. What is the pH of a neutral solution? Why?
5. Draw a circle diagram to represent the water cycle. Identify the states of water and the processes in which water changes state throughout the cycle.
6. What type of reaction is represented by the chemical equation below? Defend your answer. $KOH + HCl \rightarrow KCl + H_2O$
7. Explain how hydrogen bonds cause molecules of liquid water to stick together.
8. Summarize how metabolism in organisms depends on water.

Further Reading / Supplemental Links

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- Robert A. Copeland, Enzymes: A Practical Introduction to Structure, Mechanisms, and Data Analysis. Wiley, 2000.
- Peter Swanson, Water: The Drop of Life. Cowles Creative Publishing, 2001.
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Vocabulary

acid
Solution with a higher hydronium ion concentration than pure water and a pH lower than 7.

acidity
Hydronium ion concentration of a solution.

base
Solution with a lower hydronium ion concentration than pure water and a pH higher than 7.

condensation
Process in which water vapor changes to water droplets, forming clouds or fog.

evaporation
Process in which liquid water changes into water vapor.

hydrogen bond
Bond that forms between a hydrogen atom in one molecule and a different atom in another molecule.

ion
Electrically charged atom or molecule.

metabolism
Sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions).

neutralization
Chemical reaction in which an acid and a base react to form a neutral solution of water and a salt.

pH
Measure of the acidity, or hydronium ion concentration, of a solution.

polarity
Difference in electrical charge between different parts of a molecule.

precipitation
Rain, snow, sleet, or other type of moisture that falls from clouds.

solubility
Ability of a solute to dissolve in a particular solvent.

solute
Substance in a solution that is dissolved by the other substance (the solvent).

solution
Homogeneous mixture in which one substance is dissolved in another.

solvent
Substance in a solution that dissolves the other substance (the solute).

sublimation
Process in which snow or ice changes directly into water vapor.

transpiration
Process in which plants give off water, most of which evaporates.

Points to Consider

Most life processes take place within cells. You probably know that cells are the microscopic building blocks of organisms.

- What do you think you would see if you could look inside a cell?
- What structures might you see?
- What processes might you observe?

14.3 References

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