2–1 The Nature of Matter

Life depends on chemistry. When you eat food or inhale oxygen, your body uses these materials in chemical reactions that keep you alive. Just as buildings are made from bricks, steel, glass, and wood, living things are made from chemical compounds. If the first task of an architect is to understand building materials, then the first job of a biologist is to understand the chemistry of life.

Guide for Reading

Key Concepts
- What three subatomic particles make up atoms?
- How are all of the isotopes of an element similar?
- What are the two main types of chemical bonds?

Vocabulary
atom
nucleus
electron
element
isotope
compound
ionic bond
ion
covalent bond
molecule
van der Waals forces

Reading Strategy: Using Prior Knowledge Before you read, write down what you already know about atoms, elements, and compounds. As you read, note the main new concepts you learn.

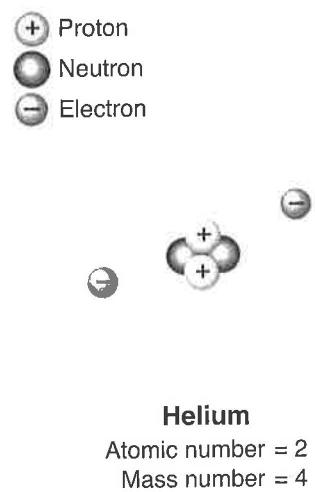
Atoms

The study of chemistry begins with the basic unit of matter, the **atom.** The Greek word *atomos,* which means "unable to be cut," was first used to refer to matter by the Greek philosopher Democritus nearly 2500 years ago. Democritus asked a simple question: If you take an object like a stick of chalk and break it in half, are both halves still chalk? The answer, of course, is yes. But what happens if you go on? Suppose you break it in half again and again and again. Can you continue to divide without limit, or does there come a point at which you cannot divide the fragment of chalk without changing it into something else? Democritus thought that there had to be a limit. He called the smallest fragment the atom, a name scientists still use today.

Atoms are incredibly small. Placed side by side, 100 million atoms would make a row only about 1 centimeter long—about the width of your little finger! Despite its extremely small size, an atom contains subatomic particles that are even smaller.

Figure 2–1 shows the subatomic particles in a helium atom. **The subatomic particles that make up atoms are protons, neutrons, and electrons.** Protons and neutrons have about the same mass. However, protons are positively charged particles (+) and neutrons carry no charge. Their name is a reminder that they are neutral particles. Strong forces bind protons and neutrons together to form the **nucleus,** which is at the center of the atom.

The **electron** is a negatively charged particle (–) with 1/1840 the mass of a proton. Electrons are in constant motion in the space surrounding the nucleus. They are attracted to the positively charged nucleus but remain outside the nucleus because of the energy of their motion. Because atoms have equal numbers of electrons and protons, and because these subatomic particles have equal but opposite charges, atoms are neutral.



▶ **Figure 2–1 Helium atoms contain protons, neutrons, and electrons.** The positively charged protons and uncharged neutrons are bound together in the dense nucleus, while the negatively charged electrons move in the space around the nucleus.

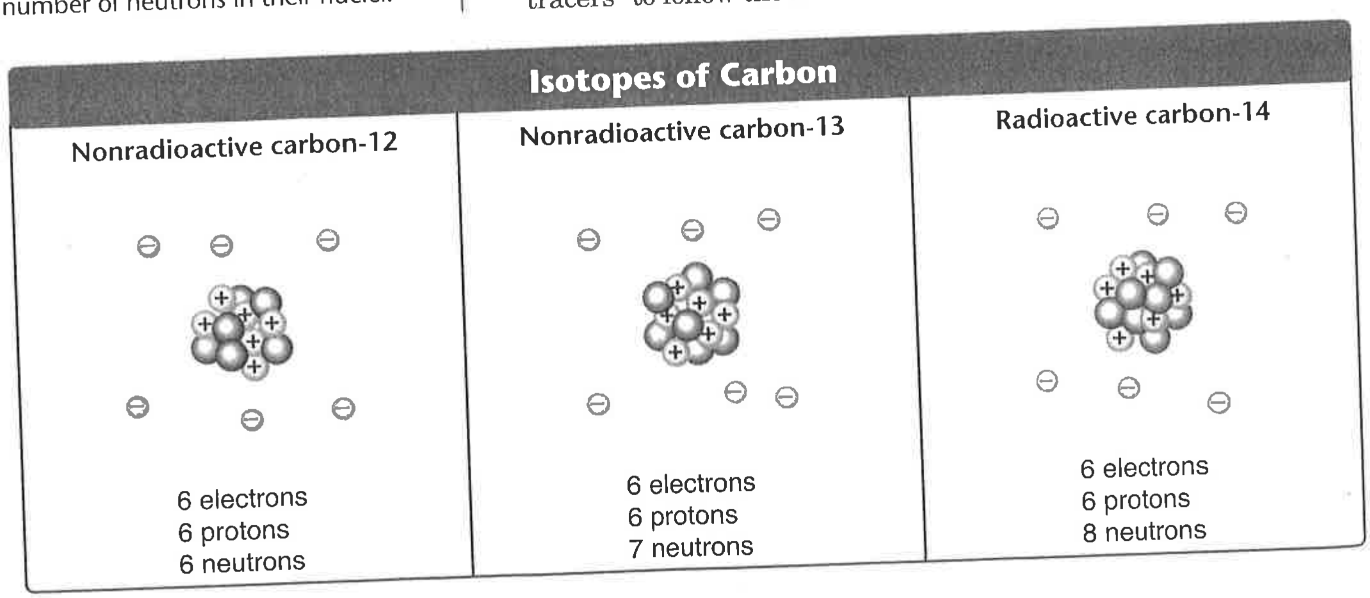
Elements and Isotopes

A chemical **element** is a pure substance that consists entirely of one type of atom. More than 100 elements are known, but only about two dozen are commonly found in living organisms. Elements are represented by a one- or two-letter symbol. C, for example, stands for carbon, H for hydrogen, and Na for sodium. The number of protons in an atom of an element is the element's atomic number. Carbon's atomic number is 6, meaning that each atom of carbon has six protons and, consequently, six electrons. See Appendix G, The Periodic Table, which shows the elements.

Isotopes Atoms of an element can have different numbers of neutrons. For example, some atoms of carbon have six neutrons, some have seven, and a few have eight. Atoms of the same element that differ in the number of neutrons they contain are known as **isotopes.** The sum of the protons and neutrons in the nucleus of an atom is called its mass number. Isotopes are identified by their mass numbers. **Figure 2–2** shows the subatomic composition of carbon-12, carbon-13, and carbon-14 atoms. The weighted average of the masses of an element's isotopes is called its atomic mass. "Weighted" means that the abundance of each isotope in nature is considered when the average is calculated. **Because they have the same number of electrons, all isotopes of an element have the same chemical properties.**

Radioactive Isotopes Some isotopes are radioactive, meaning that their nuclei are unstable and break down at a constant rate over time. The radiation these isotopes give off can be dangerous, but radioactive isotopes have a number of important scientific and practical uses.

Geologists can determine the ages of rocks and fossils by analyzing the isotopes found in them. Radiation from certain isotopes can be used to treat cancer and to kill bacteria that cause food to spoil. Radioactive isotopes can also be used as labels or "tracers" to follow the movements of substances within organisms.



▼ **Figure 2–2** **Because they have the same number of electrons, these isotopes of carbon have the same chemical properties.** The difference among the isotopes is the number of neutrons in their nuclei.

Careers in Biology

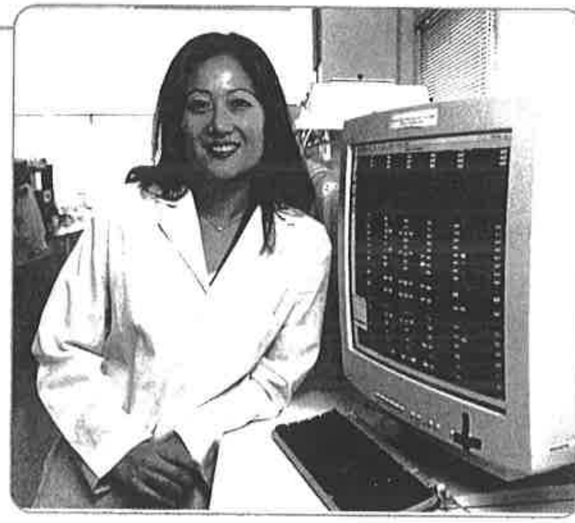
Forensic Scientist

Job Description: work as a forensic scientist for local, state, or federal investigative agencies in order to conduct scientific forensic examinations in criminal investigations

Education: a bachelor's degree in science—biology, physics, chemistry, metallurgy; some states require several years of forensic laboratory experience

Skills: analytical, logical, computer literate, detail oriented, able to take meticulous notes and to prepare evidence for presentation in court as well as to testify as an expert witness

Highlights: have the opportunity to use logic and science to solve unique or unusual problems in criminal investigations and to work collaboratively with other scientists



Discovery Channel School

To find out more about forensic science, view the segment "History's Mystery: An Introduction to Forensic Science," on Videotape One.

Chemical Compounds

In nature, most elements are found combined with other elements in compounds. A chemical **compound** is a substance formed by the chemical combination of two or more elements in definite proportions. Scientists show the composition of compounds by a kind of shorthand known as a chemical formula. Water, which contains two atoms of hydrogen for each atom of oxygen, has the chemical formula H_2O. The formula for table salt, NaCl, indicates that the elements from which table salt forms—sodium and chlorine—combine in a 1 : 1 ratio.

The physical and chemical properties of a compound are usually very different from those of the elements from which it is formed. For example, hydrogen and oxygen, which are gases at room temperature, can combine explosively and form liquid water. Sodium is a silver-colored metal that is soft enough to cut with a knife. It reacts explosively with cold water. Chlorine is very reactive, too. It is a poisonous, greenish gas that was used to kill many soldiers in World War I. Sodium and chlorine combine to form sodium chloride (NaCl), or table salt. Sodium chloride is a white solid that dissolves easily in water. As you know, sodium chloride is not poisonous. In fact, it is essential for the survival of most living things.

✓ CHECKPOINT *What information is contained in a chemical formula?*

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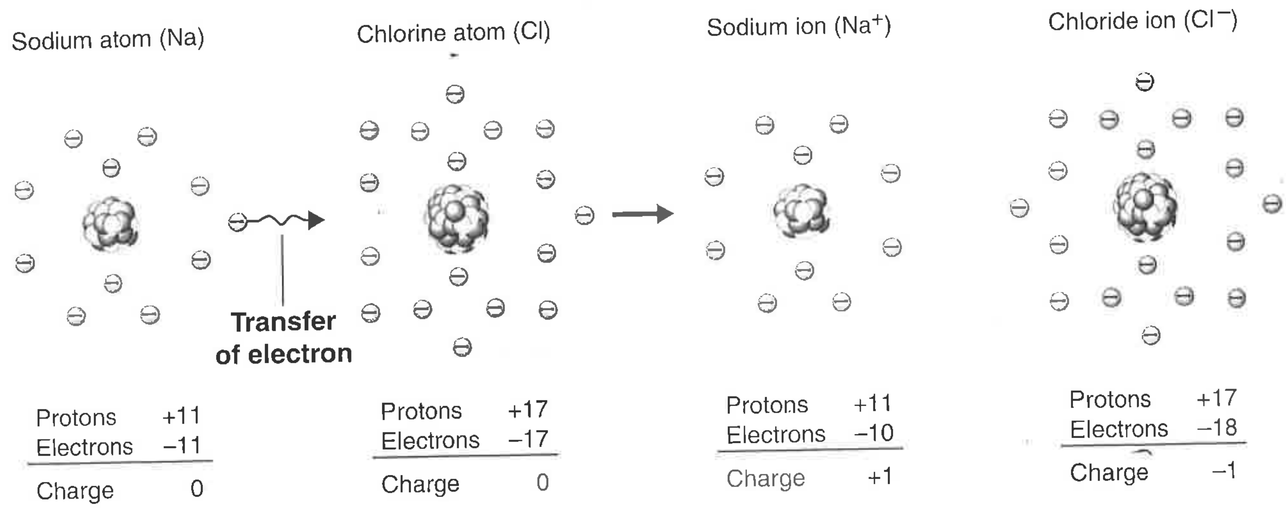


▲ **Figure 2–3 The chemical bond in which electrons are transferred from one atom to another is called an ionic bond.** The compound sodium chloride forms when sodium loses its valence electron to chlorine.

Chemical Bonds

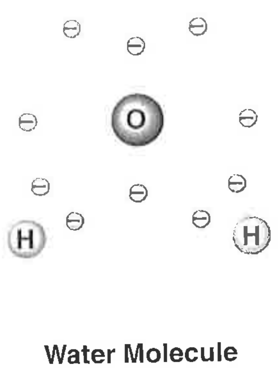
The atoms in compounds are held together by chemical bonds. Much of chemistry is devoted to understanding how and when chemical bonds form. Bond formation involves the electrons that surround each atomic nucleus. The electrons that are available to form bonds are called valence electrons. **The main types of chemical bonds are ionic bonds and covalent bonds.**

Ionic Bonds An **ionic bond** is formed when one or more electrons are transferred from one atom to another. Recall that atoms are electrically neutral because they have equal numbers of protons and electrons. An atom that loses electrons has a positive charge. An atom that gains electrons has a negative charge. These positively and negatively charged atoms are known as **ions.**

Figure 2–3 shows how ionic bonds form between sodium and chlorine in table salt. A sodium atom easily loses its one valence electron and becomes a sodium ion (Na^+). A chlorine atom easily gains an electron and becomes a chloride ion (Cl^-). In a salt crystal, there are trillions of sodium and chloride ions. These oppositely charged ions have a strong attraction. The attraction between oppositely charged ions is an ionic bond.

Covalent Bonds Sometimes electrons are shared by atoms instead of being transferred. What does it mean to "share" electrons? It means that the moving electrons actually travel in the orbitals of both atoms. A **covalent bond** forms when electrons are shared between atoms. When the atoms share two electrons, the bond is called a single covalent bond. Sometimes the atoms share four electrons and form a double bond. In a few cases, atoms can share six electrons and form a triple bond.

The structure that results when atoms are joined together by covalent bonds is called a molecule. The **molecule** is the smallest unit of most compounds. The diagram of a water molecule in **Figure 2–4** shows that each hydrogen atom forms a single covalent bond with the oxygen atom.



▲ **Figure 2–4 The chemical bond in which electrons are shared between atoms is called a covalent bond.** In a water molecule, each hydrogen atom shares two electrons with the oxygen atom.

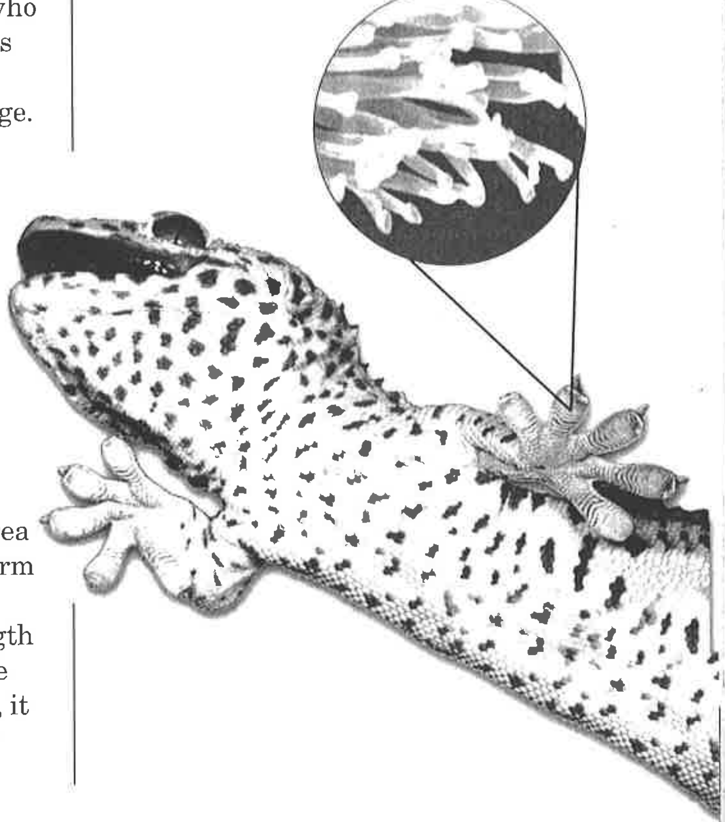
Van der Waals Forces Because of their structures, atoms of different elements do not all have the same ability to attract electrons. Some atoms have a stronger attraction for electrons than do other atoms. Therefore, when the atoms in a covalent bond share electrons, the sharing is not always equal. Even when the sharing is equal, the rapid movement of electrons can create regions on a molecule that have a tiny positive or negative charge.

When molecules are close together, a slight attraction can develop between the oppositely charged regions of nearby molecules. Chemists call such intermolecular forces of attraction **van der Waals forces,** after the scientist who discovered them. Although van der Waals forces are not as strong as ionic bonds or covalent bonds, they can hold molecules together, especially when the molecules are large.

People who keep geckos as pets have already seen van der Waals forces in action. These remarkable little lizards can climb up vertical surfaces, even smooth glass walls, and then hang on by a single toe despite the pull of gravity. How do they do it? No, they do not have some sort of glue on their feet and they don't have suction cups.

A gecko foot like the one shown in **Figure 2–5** is covered by as many as half a million tiny hairlike projections. Each projection is further divided into hundreds of tiny, flat-surfaced fibers. This design allows the gecko's foot to come in contact with an extremely large area of the wall at the molecular level. Van der Waals forces form between molecules on the surface of the gecko's foot and molecules on the surface of the wall. The combined strength of all the van der Waals forces allows the gecko to balance the pull of gravity. When the gecko needs to move its foot, it peels the foot off at an angle and reattaches it at another location on the wall.

▼ **Figure 2–5** Van der Waals forces help geckos to grip smooth, vertical surfaces. **Applying Concepts** *Which product(s) might be developed based on van der Waals forces? Explain.*



2–1 Section Assessment

1. **Key Concept** Describe the structure of an atom.
2. **Key Concept** Why do all isotopes of an element have the same chemical properties? In what way do isotopes of an element differ?
3. **Key Concept** What is a covalent bond? An ionic bond?
4. What is a compound? How are compounds related to molecules?
5. How do van der Waals forces hold molecules together?
6. **Critical Thinking Comparing and Contrasting** How are ionic bonds and van der Waals forces similar? How are they different?

Writing in Science

Writing an Article
Write an article for your school newspaper on forensic science as a career. Assume that you have already interviewed a forensic scientist who works for a law enforcement agency. The article should be about 500 words long. *Hint:* Consider the interests of your readers.

2–2 Properties of Water

Guide for Reading

Key Concepts
- Why are water molecules polar?
- What are acidic solutions? What are basic solutions?

Vocabulary
cohesion
adhesion
mixture
solution
solute
solvent
suspension
pH scale
acid
base
buffer

Reading Strategy: Using Visuals Before you read, preview **Figure 2–7** and **Figure 2–9.** As you read, note how these two figures are related.

After several days in space, one of the first astronauts to travel to the moon looked back longingly at Earth and marveled at its distant beauty. If there are other beings who have seen Earth, he said, they must surely call it "the blue planet." The astronaut was referring to the blue appearance of the water in the oceans, which cover three fourths of Earth's surface. Water is also the single most abundant compound in most living things.

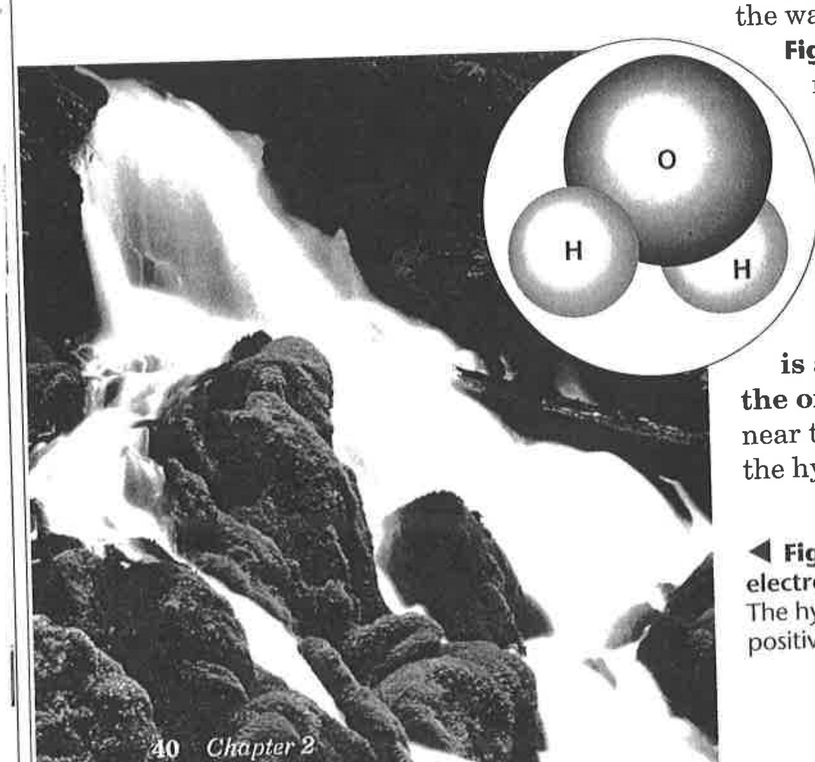
Water is one of the few compounds that is a liquid at the temperatures found over much of Earth's surface. Unlike most substances, water expands as it freezes. Thus, ice is less dense than liquid water, which explains why ice floats on the surface of lakes and rivers. If the ice sank to the bottom, the situation would be disastrous for fish and plant life in regions with cold winters, to say nothing of the sport of ice skating!

The Water Molecule

Like all molecules, a water molecule (H_2O) is neutral. The positive charges on its 10 protons balance out the negative charges on its 10 electrons. However, there is more to the story.

Polarity With 8 protons in its nucleus, an oxygen atom has a much stronger attraction for electrons than does the hydrogen atom with a single proton in its nucleus. Thus, at any moment, there is a greater probability of finding the shared electrons near the oxygen atom than near the hydrogen atom. Because the water molecule has a bent shape, as shown in **Figure 2–6,** the oxygen atom is on one end of the molecule and the hydrogen atoms are on the other. As a result, the oxygen end of the molecule has a slight negative charge and the hydrogen end of the molecule has a slight positive charge.

A molecule in which the charges are unevenly distributed is called a polar molecule because the molecule is like a magnet with poles. **A water molecule is polar because there is an uneven distribution of electrons between the oxygen and hydrogen atoms.** The negative pole is near the oxygen atom and the positive pole is between the hydrogen atoms.



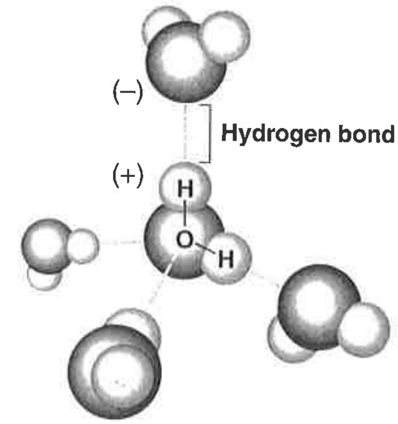
◀ **Figure 2–6 The unequal sharing of electrons causes the water molecule to be polar.** The hydrogen end of the molecule is slightly positive and the oxygen end is slightly negative.

Hydrogen Bonds Because of their partial positive and negative charges, polar molecules such as water can attract each other, as shown in **Figure 2–7.** The charges on a polar molecule are written in parentheses, (–) or (+), to show that they are weaker than the charges on ions such as Na^+ and Cl^-. The attraction between the hydrogen atom on one water molecule and the oxygen atom on another water molecule is an example of a hydrogen bond. Hydrogen bonds are not as strong as covalent or ionic bonds, but water's ability to form multiple hydrogen bonds is responsible for many of its special properties.

A single water molecule may be involved in as many as four hydrogen bonds at the same time. The ability of water to form multiple hydrogen bonds is responsible for many of water's properties. **Cohesion** is an attraction between molecules of the same substance. Because of hydrogen bonding, water is extremely cohesive. Water's cohesion causes molecules on the surface of water to be drawn inward, which is why drops of water form beads on a smooth surface. Cohesion also explains why some insects and spiders can walk on a pond's surface, as shown in **Figure 2–8.**

Adhesion is an attraction between molecules of different substances. Have you ever been told to read the volume in a graduated cylinder at eye level? The surface of the water in the graduated cylinder dips slightly in the center because the adhesion between water molecules and glass molecules is stronger than the cohesion between water molecules. Adhesion between water and glass also causes water to rise in a narrow tube against the force of gravity. This effect is called capillary action. Capillary action is one of the forces that draw water out of the roots of a plant and up into its stems and leaves. Cohesion holds the column of water together as it rises.

CHECKPOINT *How are cohesion and adhesion similar? Different?*



▲ **Figure 2–7** The illustration shows the hydrogen bonds that form between water molecules. **Applying Concepts** *Why are water molecules attracted to one another?*

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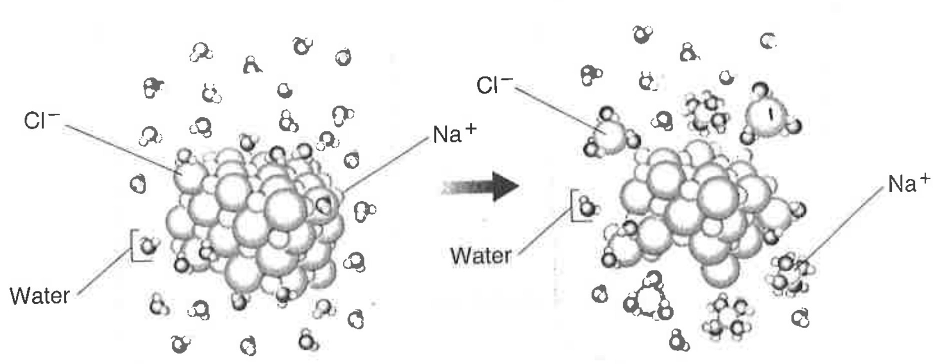
Solutions and Suspensions

Water is not always pure—it is often found as part of a mixture. A **mixture** is a material composed of two or more elements or compounds that are physically mixed together but not chemically combined. Salt and pepper stirred together constitute a mixture. So do sugar and sand. Earth's atmosphere is a mixture of gases. Living things are in part composed of mixtures involving water. Two types of mixtures that can be made with water are solutions and suspensions.

▶ **Figure 2–8** Cohesion is responsible for enabling this tarantula to rest on the water's surface. The strong attraction between water molecules produces a force sometimes called "surface tension," which can support very light objects, including this spider. **Observing** *How does the tarantula's physical structure help it to stay afloat?*

▶ **Figure 2–9** When an ionic compound such as sodium chloride is placed in water, water molecules surround and separate the positive and negative ions. **Interpreting Graphics** *What happens to the sodium ions and chloride ions in the solution?*



Quick Lab

Are foods acidic or basic?

Materials pH paper, samples of food, paper towel, scalpel, dropper pipette

Procedure

1. **Predicting** Predict whether most foods are acidic or basic.
2. If using a pH probe, see your teacher for instructions.
3. Tear off a small piece of pH paper for each sample you will test. Place these pieces on a paper towel.
4. Construct a data table in which you will record the name and pH of each food sample.
5. Use a scalpel to cut a piece off each solid. **CAUTION:** *Be careful not to cut yourself. Do not eat the food.* Touch the cut surface of each sample to a square of pH paper. Use a dropper pipette to place a drop of any liquid sample on a square of pH paper. Record the pH of each sample in your data table.

Analyze and Conclude

1. **Analyzing Data** Were most of the samples acidic or basic?
2. **Evaluating** Was your prediction correct?

Solutions If a crystal of table salt is placed in a glass of warm water, sodium and chloride ions on the surface of the crystal are attracted to the polar water molecules. Ions break away from the crystal and are surrounded by water molecules, as illustrated in **Figure 2–9.** The ions gradually become dispersed in the water, forming a type of mixture called a solution. All the components of a **solution** are evenly distributed throughout the solution. In a saltwater solution, table salt is the **solute**—the substance that is dissolved. Water is the **solvent**—the substance in which the solute dissolves. Water's polarity gives it the ability to dissolve both ionic compounds and other polar molecules, such as sugar. Without exaggeration, water is the greatest solvent on Earth.

Suspensions Some materials do not dissolve when placed in water but separate into pieces so small that they do not settle out. The movement of water molecules keeps the small particles suspended. Such mixtures of water and nondissolved material are known as **suspensions.** Some of the most important biological fluids are both solutions and suspensions. The blood that circulates through your body is mostly water, which contains many dissolved compounds. However, blood also contains cells and other undissolved particles that remain in suspension as the blood moves through the body.

Acids, Bases, and pH

A water molecule can react to form ions. This reaction can be summarized by a chemical equation in which double arrows are used to show that the reaction can occur in either direction.

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

$$\text{water} \rightleftharpoons \text{hydrogen ion} + \text{hydroxide ion}$$

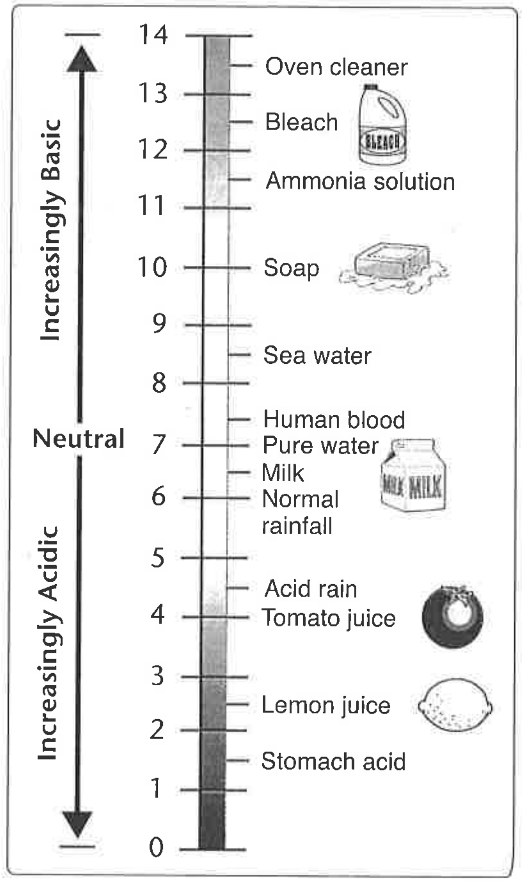
How often does this happen? In pure water, about 1 water molecule in 550 million reacts and forms ions. Because the number of positive hydrogen ions produced is equal to the number of negative hydroxide ions produced, water is neutral.

The pH Scale Chemists devised a measurement system called the **pH scale** to indicate the concentration of H^+ ions in solution. As **Figure 2–10** shows, the pH scale ranges from 0 to 14. At a pH of 7, the concentration of H^+ ions and OH^- ions is equal. Pure water has a pH of 7. Solutions with a pH below 7 are called acidic because they have more H^+ ions than OH^- ions. The lower the pH, the greater the acidity. Solutions with a pH above 7 are called basic because they have more OH^- ions than H^+ ions. The higher the pH, the more basic the solution. Each step on the pH scale represents a factor of 10. For example, a liter of a solution with a pH of 4 has 10 times as many H^+ ions as a liter of a solution with a pH of 5.

Acids Where do all those extra H^+ ions in a low-pH solution come from? They come from acids. An **acid** is any compound that forms H^+ ions in solution. **Acidic solutions contain higher concentrations of H^+ ions than pure water and have pH values below 7.** Strong acids tend to have pH values that range from 1 to 3. The hydrochloric acid produced by the stomach to help digest food is a strong acid.

Bases A **base** is a compound that produces hydroxide ions (OH^- ions) in solution. **Basic, or alkaline, solutions contain lower concentrations of H^+ ions than pure water and have pH values above 7.** Strong bases, such as lye, tend to have pH values ranging from 11 to 14.

Buffers The pH of the fluids within most cells in the human body must generally be kept between 6.5 and 7.5. If the pH is lower or higher, it will affect the chemical reactions that take place within the cells. Thus, controlling pH is important for maintaining homeostasis. One of the ways that the body controls pH is through dissolved compounds called buffers. **Buffers** are weak acids or bases that can react with strong acids or bases to prevent sharp, sudden changes in pH.



▲ **Figure 2–10 The concentration of H^+ ions determines whether solutions are acidic or basic.** The most acidic material on this pH scale is stomach acid. The most basic material on this scale is oven cleaner.

2–2 Section Assessment

1. **Key Concept** Use the structure of a water molecule to explain why it is polar.
2. **Key Concept** Compare acidic and basic solutions in terms of their H^+ ion and OH^- ion concentrations.
3. What is the difference between a solution and a suspension?
4. What does pH measure?
5. **Critical Thinking Predicting** The strong acid hydrogen fluoride (HF) can be dissolved in pure water. Will the pH of the solution be greater or less than 7?

Thinking Visually

Creating a Concept Map
Draw a concept map on the properties of water. Include the following terms in your concept map: hydrogen bonds, polarity, cohesion, adhesion, capillary action, and solvent.