Unit 2

Composition of Earth

In the setting Sun, the giant monolith called Uluru by the Aborigines of the Northern Territory of Australia glows a fiery red. Uluru, also known as Ayers Rock, is 2.5 km long, 1.6 km wide, and oval in shape. This rock is a conglomerate, a type of sedimentary rock composed of large, rounded chunks of rocks and minerals. Uluru is a solitary rock that rises nearly 350 m above the surrounding desert plain. How did such a huge sedimentary rock form in a desert? In this unit, you will explore the geologic forces that formed Uluru and also shape rocks and minerals.

Unit Contents

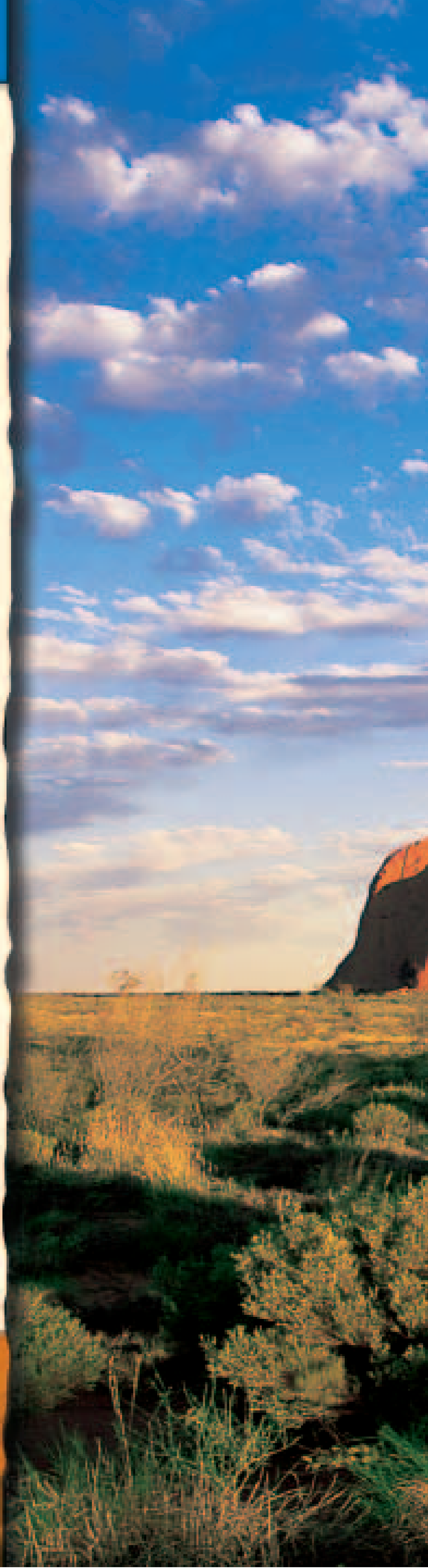
3 Matter and Atomic Structure

4 Minerals

5 Igneous Rocks

6 Sedimentary and Metamorphic Rocks

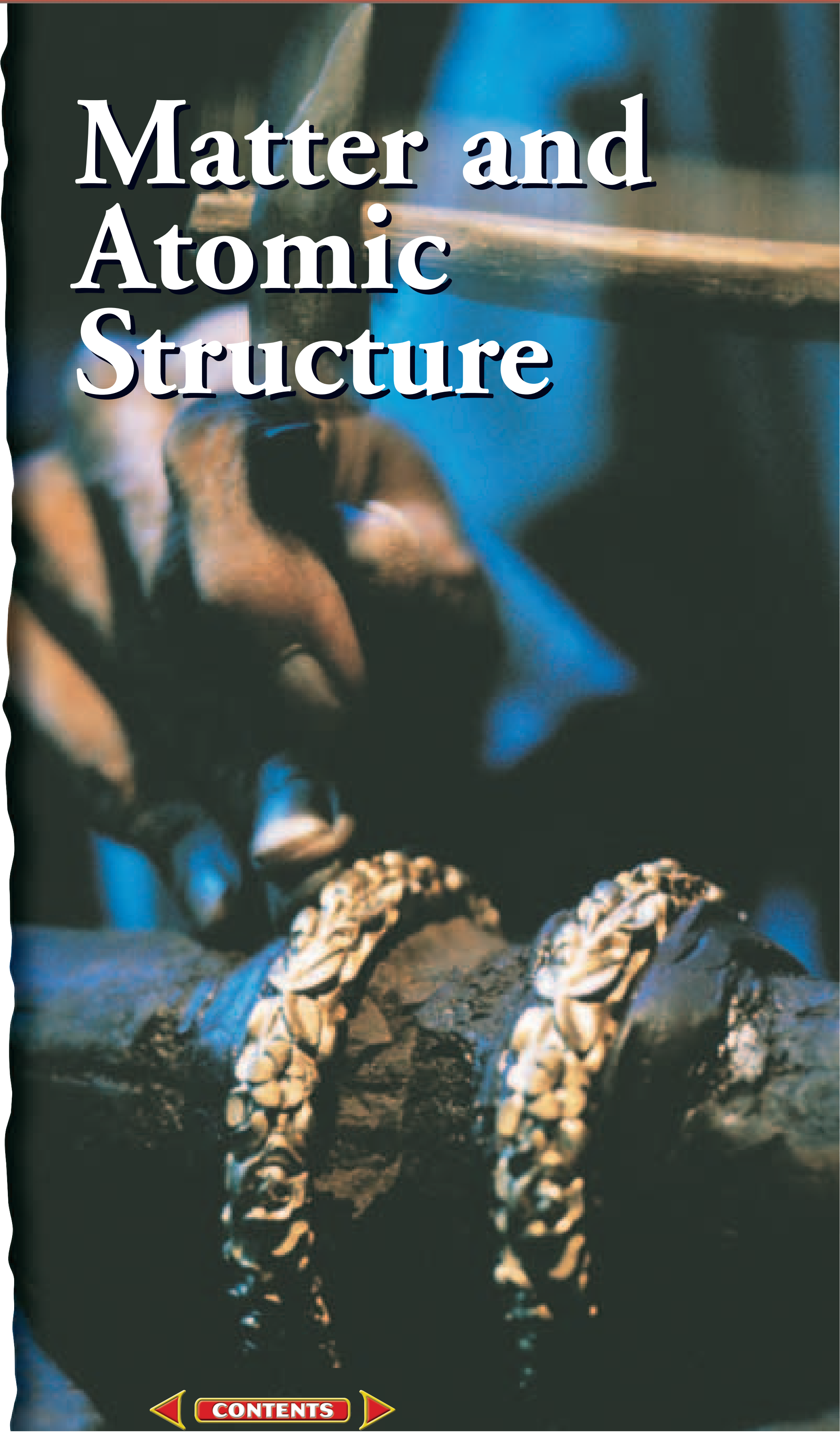
Go to the National Geographic Expedition on page 870 to learn more about topics that are connected to this unit.




Ayers Rock, Australia

Chapter 3

Matter and Atomic Structure



What You'll Learn

- What the basic structures are of the elements that make up Earth.
- How atoms interact to form compounds.
- What states of matter occur on Earth.

Why It's Important

Earth consists of many elements and compounds. Understanding how rocks and minerals form requires a basic knowledge of chemistry, the science of matter.

Earth Science Online

To find out more about matter and atomic structure, visit the Earth Science Web Site at earthgeu.com

Discovery Lab

Fortified Cereals

Advertisements for breakfast cereals often indicate that they are fortified with substances that increase their nutritional value. In this activity, you will identify one substance that is added to cereals.

1. Tape a small strong magnet to the eraser end of a pencil.
2. Pour a sample of dry, fortified cereal into a small plastic bag. Smooth the bag as you close it.
3. Using a rolling pin, thoroughly crush the cereal in the plastic bag.
4. Pour the crushed cereal into a 250-mL glass beaker. Add 150 mL of tap water to the beaker.
5. Using the pencil-magnet stirrer, stir the cereal/water mixture for 10 minutes, stirring slowly for the last minute.
6. Remove the stirrer from the mixture and examine the magnet end of the stirrer with a hand lens.

Observe In your science journal, describe what you see on the end of the pencil stirrer. Study the cereal box to determine what the substance on the magnet might be.

SECTION 3.1 What are elements?

OBJECTIVES

- **Describe** *the particles within atoms and the structure of atoms.*
- **Relate** *the energy levels of atoms to the chemical properties of elements.*
- **Define** *the concept of isotopes.*

VOCABULARY

element
atom
nucleus
proton
neutron
atomic number
mass number
electron
energy level
valence electron
isotope
atomic mass
radioactivity

When a jewelry designer plans a new piece, he or she often chooses to work in gold. Gold is soft and easy to work with. It can be molded, hammered, sculpted, or made into wire. But whatever shape the jewelry takes, the gold remains the same. Gold is a type of matter. The jewelry designer also is made up of matter. The physical world that surrounds you and all living things are composed of matter. What exactly is matter? Matter is anything that has volume and mass. On Earth, matter usually can be found as a solid, liquid, or gas.

ELEMENTS

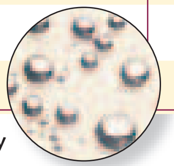
All matter—that is, everything on Earth and beyond—is made of substances called elements. An **element** is a substance that cannot be broken down into simpler substances by physical or chemical means. For example, gold is still gold whether it has been melted, pulled into wire, hammered into a thin sheet, or divided into small particles.

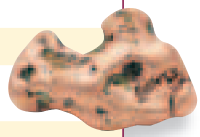
Ninety-two elements occur naturally on Earth and in the stars. Other elements have been produced in laboratory experiments. Each element is identified by a one-, two-, or three-letter abbreviation known as a chemical symbol. For example, the symbol H represents

Element	Symbol	Element	Symbol	Element	Symbol
Hydrogen	H	Helium	He	Lithium	Li
Beryllium	Be	Boron	B	Carbon	C
Nitrogen	N	Oxygen	O	Fluorine	F
Neon	Ne	Sodium	Na	Magnesium	Mg
Aluminum	Al	Silicon	Si	Phosphorus	P
Sulfur	S	Chlorine	Cl	Argon	Ar
Potassium	K	Calcium	Ca	Gold	Au
Silver	Ag	Mercury	Hg	Copper	Cu

Table 3-1 Chemical Symbols of Some Elements


Sulfur


Mercury


Copper

the element hydrogen, C represents carbon, and O represents oxygen. Elements known in ancient times, such as gold and mercury, have symbols that reflect their Latin origins. For example, gold is identified by the symbol Au, for its Latin name, *aurum.* The chemical symbols of some elements are shown in ***Table 3-1.***

Elements are Made of Atoms

Each element has distinct characteristics. You've already learned some of the characteristics of the element gold. Aluminum has different characteristics from gold, but both aluminum and gold are elements that are made up of atoms. An **atom** is the smallest particle of an element that has all of the characteristics of that element.

All atoms consist of even smaller particles: protons, neutrons, and electrons. The center of an atom is called the nucleus (*plural,* nuclei). A **nucleus** of an atom is made up of protons and neutrons. A **proton** (p^+) is a tiny particle that has mass and a positive electrical charge. A **neutron** (n^0) is a particle with about the same mass as a proton, but it is electrically neutral; that is, it has no electrical charge. All atomic nuclei have a positive charge because they are composed of protons with positive electrical charges and neutrons that have no electrical charges.

The number of protons and neutrons in different atoms varies widely. The lightest of all atoms is the hydrogen atom, which has only one proton in its nucleus. The heaviest naturally occurring atoms are those of uranium. Uranium-238 has 92 protons and 146 neutrons in its nucleus. The number of protons in an atom's nucleus is its **atomic number.** The combined number of protons and neutrons is its **mass number.** For example, the atomic number of uranium is 92 and its mass number is 238 (92 + 146). The atomic numbers and mass

Earth Science Online

Topic: Elements
To find out more about the elements, visit the Earth Science Web Site at earthgeu.com

Activity: Choose three elements. Design a chart that describes how each element was discovered, and its common uses.

numbers of 14 naturally occurring elements are shown in ***Table 3-2.*** You can explore the elements that you can find in your classroom in the *MiniLab* on this page. For a complete list of the elements arranged according to their chemical properties, see the Periodic Table of the Elements in *Appendix G* on page 917.

Surrounding the nucleus of an atom are smaller particles called electrons. An **electron** (e^-) has little mass, but it has a negative electrical charge that is exactly the same magnitude as the positive charge of a proton. An atom has an equal number of protons and electrons; thus, the electrical charge of an electron cancels the positive charge of a proton to produce an atom that has no overall charge.

Have you ever let a jawbreaker melt in your mouth? It may have started out as a large, red sphere, but as it melted, you may have observed layers of yellow, green, blue, and so on, until you reached the candy center. If you think of a jawbreaker's candy center as the nucleus of an atom, you can think of the various colored layers as the energy levels where electrons can be found. An **energy level** represents the area in an atom where an electron is most likely to be found.

MiniLab

Identifying Elements

Describe Most substances on Earth occur in the form of chemical compounds. Around your classroom, there are numerous objects or substances that consist mostly of a single element.

Procedure

1. Name three of these objects and the three different elements of which they are made.
2. List the atomic numbers of these elements and describe some of their properties.

Article	Element	Atomic Number	Properties

Analyze and Conclude

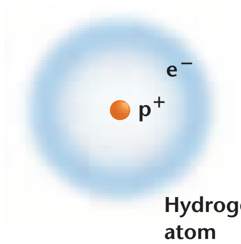
1. Matter can be solid, liquid, or gaseous. Give one example of a solid, liquid, and gaseous object or substance.
2. How does a liquid differ from a solid? How does a gas differ from a liquid?

Table 3-2 Atomic Structure of 14 Elements

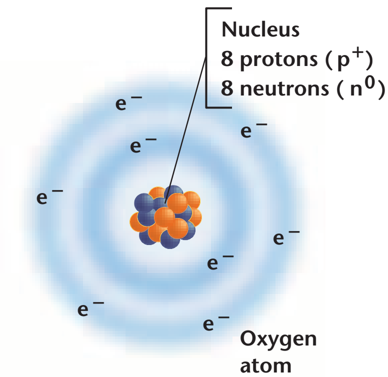
Element	Symbol	Atomic Number	Mass Number	Element	Symbol	Atomic Number	Mass Number
Hydrogen	H	1	1	Calcium	Ca	20	40
Helium	He	2	4	Iron	Fe	26	56
Oxygen	O	8	16	Sulfur	S	16	32
Carbon	C	6	12	Sodium	Na	11	23
Neon	Ne	10	20	Chlorine	Cl	17	35
Nitrogen	N	7	14	Potassium	K	19	39
Magnesium	Mg	12	24	Argon	Ar	18	40

Figure 3-1 shows models of several atoms with their energy levels represented as cloudlike regions. Notice that the volume of an atom is mostly empty space. Because the electrons have little mass, the *mass* of an atom depends mostly upon the number of protons and neutrons in its nucleus. However, the *size* of an atom depends upon the number and arrangement of its electrons. You can explore how electrons can be used to produce images of objects in the *Science & Technology* feature at the end of this chapter.

Figure 3-1 Electrons move around the nucleus of an atom.



A Hydrogen has just one proton in its nucleus and one electron in its innermost energy level.

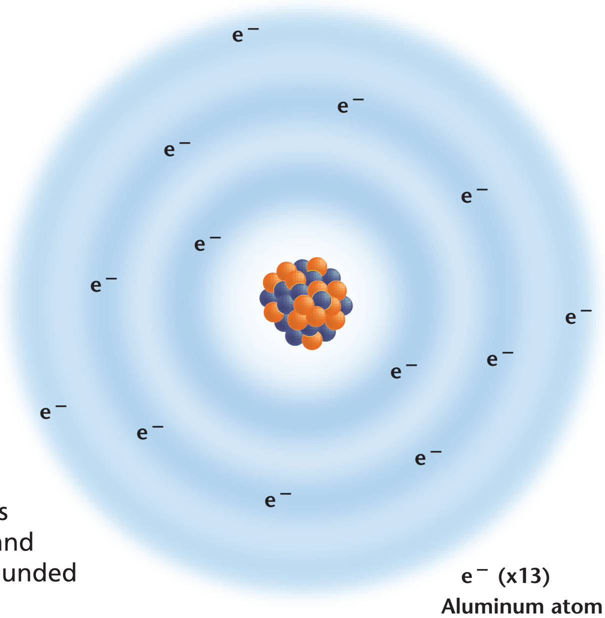


B Oxygen has eight protons and eight neutrons in its nucleus. Two electrons fill the innermost energy level; six electrons are found in the second energy level.

Electrons In Energy Levels

Study ***Figure 3-1.*** Note that electrons are distributed over one or more energy levels in a predictable pattern. Each energy level can hold only a limited number of electrons. For example, the smallest, innermost energy level can hold only two electrons, as illustrated by the oxygen atom shown in ***Figure 3-1B.*** The second energy level is larger, and it can hold up to eight electrons. The third energy level is larger still; it can hold up to 18 electrons. The fourth energy level can hold up to 32 electrons. Depending upon the element, an atom may have electrons in as many as seven energy levels surrounding its nucleus.

Electrons tend to occupy the lowest available energy level. For example, the aluminum (Al) atom in ***Figure 3-1C*** has 13 protons in its nucleus and 13 electrons in its energy levels. The first energy level in an aluminum atom is filled by two electrons. The second energy level is also filled, by eight electrons. The third energy level has only three electrons, so it is not filled.



C An aluminum atom has a nucleus that is composed of 13 protons and 13 neutrons. The nucleus is surrounded by 13 electrons.

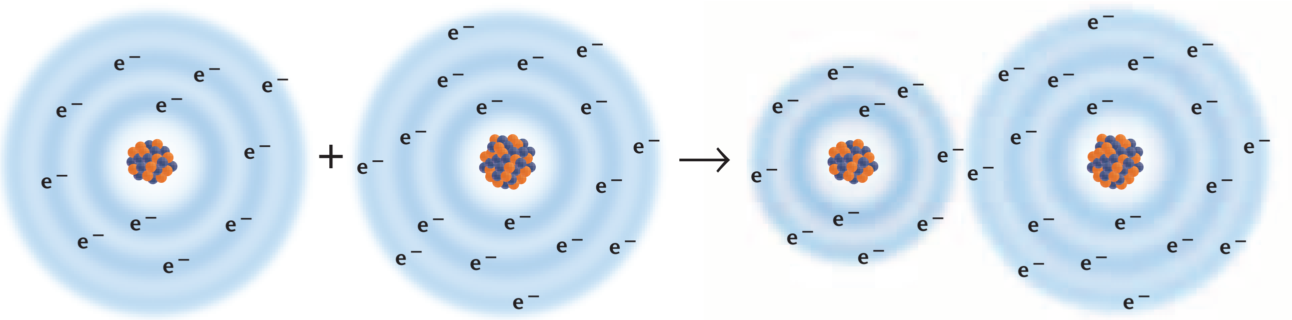


Figure 3-2 A sodium (Na) atom, with one valence electron, combines with a chlorine (Cl) atom, with seven valence electrons, to form a common substance, table salt (NaCl). The new substance forms when the sodium atom loses its valence electron to the chlorine atom.

The electrons in the outermost energy level determine the chemical behavior of the different elements. These outermost electrons are called **valence electrons.** Elements with the same number of valence electrons have similar chemical properties. For example, a sodium (Na) atom, with the atomic number 11, and a potassium (K) atom, with the atomic number 19, both have just one valence electron. Thus, both sodium and potassium are highly reactive metals, which means that they combine easily with other elements. ***Figure 3-2*** illustrates how the common substance table salt is formed when sodium combines with the element chlorine.

Elements such as helium (He), neon (Ne), and argon (Ar) are inert, which means that they do not easily combine with other elements. This is because they have full outermost energy levels. For example, a neon atom has ten electrons in its energy levels. The innermost energy level is filled with two electrons, and the second energy level, which is the outermost energy level, also is filled, with eight electrons. With a filled outermost energy level, neon is unlikely to combine chemically with other elements.

Isotopes

You have learned that all atoms of an element have the same number of protons. However, the number of neutrons in the nuclei of an element's atoms can vary. For example, all chlorine atoms have 17 protons in their nuclei, but they may have either 18 or 20 neutrons. This means that there are two types of chlorine atoms: one with a mass number of 35 (17 protons + 18 neutrons) and one with a mass number of 37 (17 protons + 20 neutrons). When atoms of the same

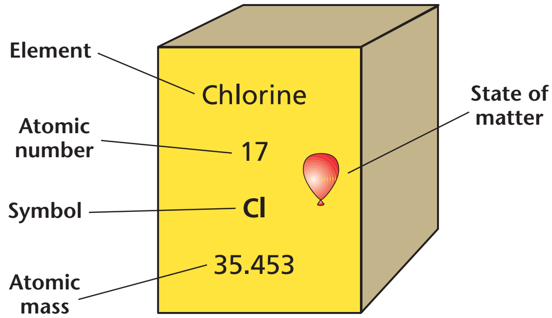


Figure 3-3 The Periodic Table of the Elements in *Appendix G* provides information about every element. Each block on the table gives the name of the element, its chemical symbol, its atomic number, its atomic mass, and the state of matter in which it is usually found. In this text, the gaseous state is represented by a balloon.

element have different mass numbers, they are known as **isotopes** of that element. The element chlorine has two isotopes: chlorine-35 and chlorine-37. Naturally occurring chlorine is a mixture of these two isotopes. Many elements are mixtures of isotopes. Because the number of electrons in an atom equals the number of protons, isotopes of an element have the same chemical properties.

If many elements are mixtures of isotopes, how do scientists know how many neutrons are found in an element's atoms? Scientists have measured the mass of atoms of elements and found an average atomic mass for each element. The **atomic mass** of an element is the average of the mass numbers of the isotopes of an element. For example, in ***Figure 3-3,*** note that the atomic mass of chlorine is 35.453. This number is the average of the mass numbers of the naturally occurring isotopes of chlorine-35 and chlorine-37.

The nuclei of some isotopes are unstable and release radiation. **Radioactivity** is the spontaneous process through which unstable nuclei emit radiation. During radioactive decay, a nucleus can lose protons and neutrons, change a proton to a neutron, or change a neutron to a proton. Because the number of protons in a nucleus identifies an element, decay changes the identity of an element. For example, the isotope uranium-238 decays over time into lead-206, so uranium originally present in a rock gradually and predictably is replaced by lead. By measuring the amount of uranium and lead in rocks, scientists can calculate their age. You will find out more about the radioactive dating of rocks in Chapter 21.

Using Math

Using Numbers As the radioactive isotope uranium-235 (atomic number 92) decays, it emits two protons and two neutrons. How many protons and neutrons are left in the nucleus after these neutrons and protons have been ejected? What is the atom's new atomic number? What is the name of this element?

What Elements are Most Abundant?

Astronomers have identified the two most abundant elements in the universe as hydrogen and helium. All other elements account for less than one percent of all atoms in the universe, as you can see in ***Figure 3-4A.*** Analyses of the composition of rocks and minerals on Earth indicate that the percentages of elements in Earth's crust

Abundance of Elements

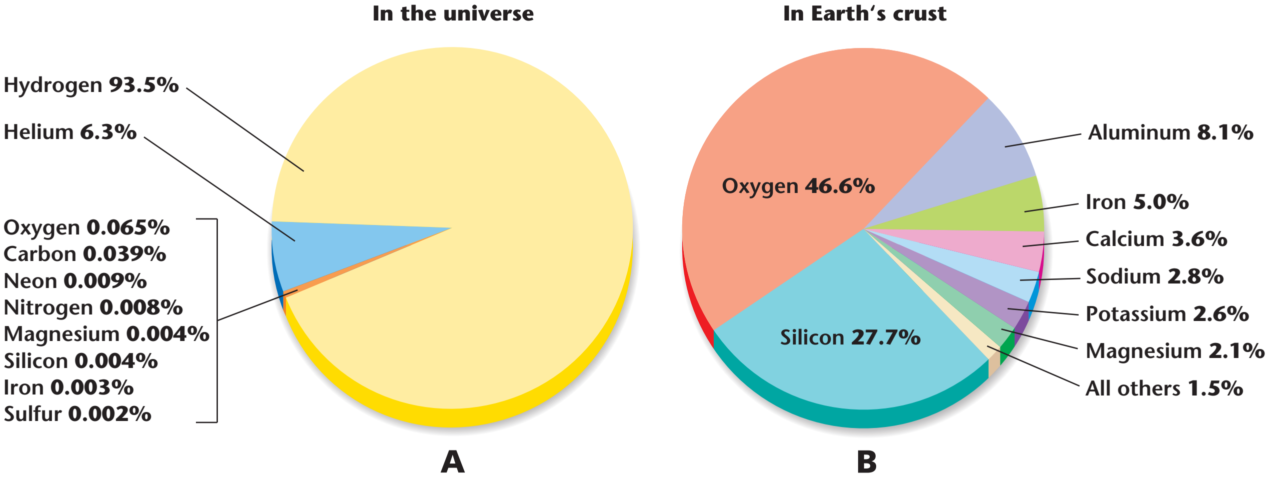


Figure 3-4 The most abundant elements in the universe are hydrogen and helium **(A).** The most abundant elements in Earth's crust are oxygen, silicon, and aluminum **(B).**

differ from the percentages in the universe. The circle graph in ***Figure 3-4B*** shows the percentages of elements in Earth's crust. Note that 98.5 percent of Earth's crust is made up of only eight elements, and that two elements, oxygen and silicon, account for almost 75 percent of the crust. This means that most of the rocks and minerals on Earth contain oxygen and silicon. You might wonder how rocks can contain oxygen, as you usually think of oxygen as a gas in the atmosphere. Oxygen is a reactive element that is mostly found in chemical combinations with other elements. In the next section, you'll learn how elements combine to form compounds.

Section Assessment

1. Name the three particles that make up an atom of an element and discuss their relative masses.
2. The elements magnesium and calcium have similar chemical properties. Explain why.
3. The atomic mass for the element carbon (C) is 12.011. Explain how this number indicates that carbon is a mixture of isotopes. What is the mass number of the most common, naturally occurring isotope of carbon?
4. **Thinking Critically** Oxygen is often found in chemical combinations with other elements, such as magnesium. Using the concepts of valence electrons and energy levels, explain why oxygen might combine easily with magnesium.

Skill Review

5. **Applying Concepts** The element copper (Cu) has 29 electrons. Draw a diagram of an atom of copper that shows the placement of its electrons in the correct energy levels and the number of protons it has. For more help, refer to the *Skill Handbook.*

SECTION 3.2 How Atoms Combine

OBJECTIVES

- **Describe** *the chemical bonds that unite atoms to form compounds.*
- **Relate** *the nature of chemical bonds that hold compounds together to the physical structures of compounds.*
- **Distinguish** *among different types of mixtures and solutions.*

VOCABULARY

compound
chemical bond
covalent bond
molecule
ion
ionic bond
chemical reaction
solution
acid
base

Can you identify the materials in ***Figure 3-5?*** The greenish gas in the flask is the element chlorine, which is poisonous. The solid, silvery metal is the element sodium, which also is toxic. Yet these two elements combine chemically to form the third material in the photograph: table salt. How can two toxic elements combine to form a material that you sprinkle on your french fries?

COMPOUNDS

Table salt is a common substance. However, table salt is not an element, but a compound. A **compound** is a substance that is composed of atoms of two or more different elements that are chemically combined. Water is another example of a compound, because it is composed of two elements, hydrogen and oxygen. Most compounds have totally different properties from the elements of which they are composed. For example, both oxygen and hydrogen are gases at room temperature, but in combination they form water, a liquid.

For most elements, an atom is chemically stable when its outermost energy level is full. We know this is true because the most stable elements are the gases helium, neon, and argon. A state of stability is achieved by other elements through **chemical bonds,** which are the forces that hold the elements together in a compound.

Covalent Bonds One way in which atoms fill their outermost energy levels is by sharing electrons. For example, two hydrogen atoms can combine with each other by sharing electrons. Individual atoms of hydrogen each have just one electron. Each atom becomes more stable when it shares its electron with another hydrogen atom so that each atom has two electrons in its outermost energy level. How do these two atoms stay together? The nucleus of each atom has one proton with a positive charge, and the two positively charged protons attract the two negatively charged electrons. This attraction of two atoms for a shared pair of electrons that holds the atoms together is called a **covalent bond.**

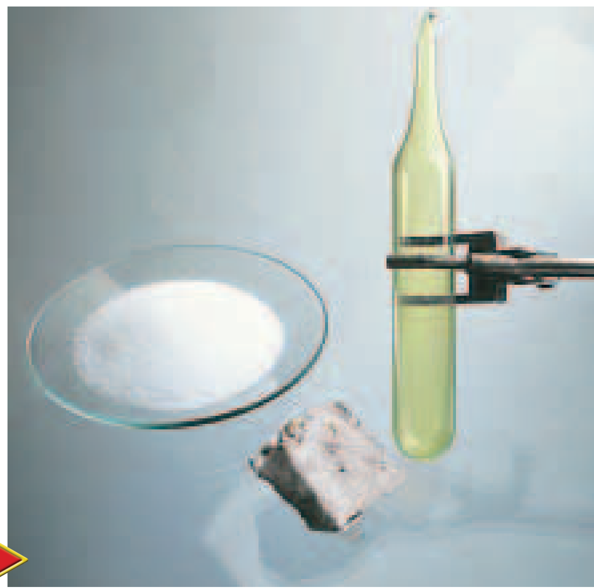


Figure 3-5 Two elements, sodium and chlorine, combine chemically to form table salt, a compound also known as halite.

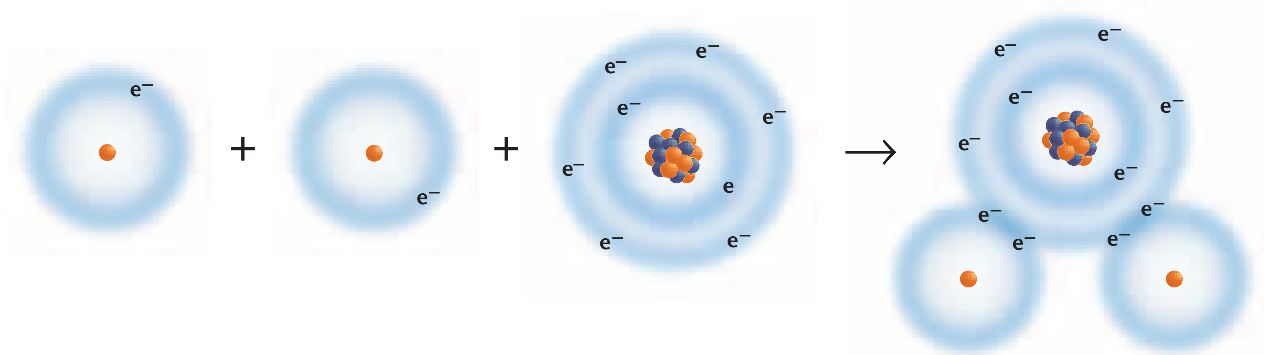


Figure 3-6 A water molecule forms when two hydrogen atoms share electrons with one oxygen atom by covalent bonding.

A **molecule** is composed of two or more atoms held together by covalent bonds. Molecules have no overall electrical charge because the total number of electrons equals the total number of protons. Molecules are represented in chemistry by chemical formulas that include the symbol for each element followed by a subscript number that stands for the number of atoms of that element in the molecule. If there is only one atom of an element, no subscript number follows the symbol. The chemical formula for hydrogen gas is written H_2 because two atoms of hydrogen make up one molecule of hydrogen gas. Water is an example of a compound whose atoms are held together by covalent bonds, as illustrated in ***Figure 3-6.*** The chemical formula for a water molecule is H_2O because, in this molecule, two atoms of hydrogen are combined with one atom of oxygen. A compound comprised of molecules is called a molecular compound.

Polar Molecules Although water molecules are held together by covalent bonds, the atoms do not share electrons equally. As shown in ***Figure 3-7,*** the shared electrons in a water molecule are attracted

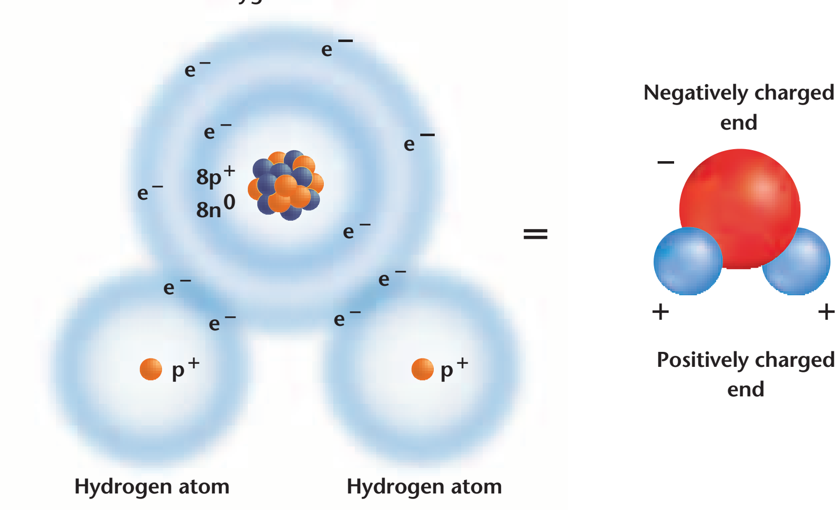


Figure 3-7 At one end of a water molecule, the hydrogen atoms have a positive charge, while at the opposite end, the oxygen atom has a negative charge.

more strongly by the oxygen atom than by the hydrogen atoms. As a result, the electrons spend more time near the oxygen atom than they do near the hydrogen atoms. When atoms in a covalent bond do not share electrons equally, they form polar bonds. A polar bond has a positive end and a negative end. The overall shape of a molecule indicates whether it is polar.

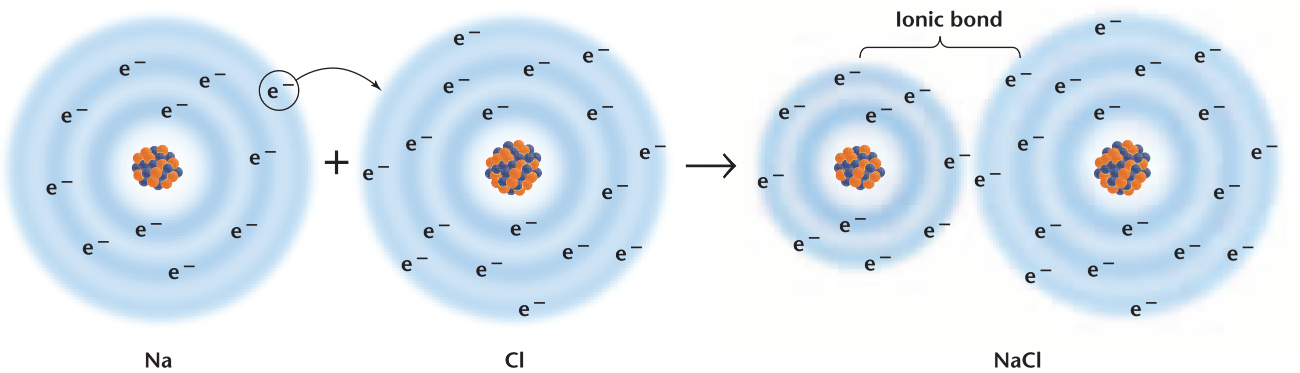
Ions

Not all atoms bond by sharing electrons. Sometimes, atoms gain or lose electrons from their outermost energy levels. An atom that gains or loses an electron is a charged particle called an **ion.** In general, an atom in which the outermost energy level is less than half-full—that is, it has fewer than four valence electrons—tends to lose its valence electrons. When an atom loses its valence electrons, it becomes positively charged. In chemistry, a positive ion is indicated by a superscript plus sign. For example, a sodium ion is represented by Na^+. If an ion results from the loss of more than one electron, the number of electrons lost is placed before the plus sign. A magnesium ion, which forms when a magnesium atom has lost two electrons, is thus represented by Mg^{2+}.

An atom in which the outermost energy level is more than half-full—that is, it has more than four valence electrons—tends to fill its outermost energy level by adding one or more needed electrons. Such an atom forms a negative ion. By including additional electrons, negative ions, such as O^{2-} and Cl^-, tend to be larger than positive ions. If the outermost energy level is exactly half-full, an atom may form either a positive or negative ion.

Some compounds contain ions made up of covalently bonded atoms. Two such compounds that are important in forming the materials at Earth's surface are silicate ions (SiO_4^{4-}) and carbonate ions (CO_3^{2-}).

Figure 3-8 The positive charge of a sodium ion attracts the negative charge of a chlorine ion. The two ions are held together by an ionic bond. Note that the negative chlorine ion is slightly larger than the positive sodium ion.



Ionic Bonds As you might expect, positive and negative ions attract each other. The attractive force between two ions of opposite charge is known as an **ionic bond.** ***Figure 3-8*** illustrates an ionic bond between a positive ion of sodium and a negative ion of chlorine. Common table salt (NaCl) consists of equal numbers of sodium (Na^+) ions and chlorine (Cl^-) ions. Note that positive ions are always written first in chemical formulas.

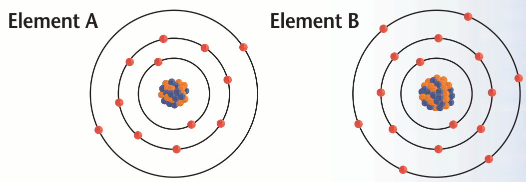
Within the compound NaCl, there are as many positive as negative ions; therefore, the positive charge on the sodium ion cancels the negative charge on the chloride ion, and the net electrical charge of the compound NaCl is zero. Magnesium and oxygen ions combine in a similar manner to form the compound magnesium oxide (MgO), one of the most common compounds on Earth. Compounds formed by ionic bonding are known as ionic compounds. You can determine if elements form ionic compounds in the *Problem-Solving Lab* on this page.

Other ionic compounds have different proportions of ions. For example, oxygen and sodium ions combine in the ratio shown by the chemical formula for sodium monoxide, Na_2O, in which there are two sodium ions to each oxygen ion. With any other ratio of sodium ions and oxygen ions, the electrical charges wouldn't cancel, as you can prove by adding up the ionic charges.

Problem-Solving Lab

Interpreting Scientific Illustrations

Forming compounds Many atoms gain or lose electrons in order to have eight electrons in the outermost energy level. In the diagram, energy levels are indicated by the circles around the nucleus of each element. The colored spheres in the energy levels represent electrons, and the spheres in the nucleus represent protons and neutrons.



Analysis

1. What is the name and symbol of element A?
2. What is the name and symbol of element B?
3. How many electrons are present in atoms of element A? Element B?

Thinking Critically

4. Can these elements form ions? If so, how many protons would be present in the nuclei of these ions? What would be the electrical charges (magnitude and sign) and chemical symbols of these ions?
5. Can these two elements form a compound? If so, what is the chemical formula of the compound?

METALLIC BONDS

Most compounds on Earth are held together by ionic or covalent bonds, or by a combination of these two types of bonds. However, there are other types of bonds. In metals, for example, the valence electrons are shared by all the atoms, not just by adjacent atoms, as in covalent compounds. You could think of a metal as a group of positive ions floating in a sea of negative electrons. The positive ions of the metal are held together by the negative electrons between them. This type of bond, known as a metallic bond, allows metals to conduct electricity because the electrons can move freely throughout the entire solid metal.

CHEMICAL REACTIONS

You have learned that atoms gain, lose, or share electrons to become more stable, and that these atoms form compounds. Sometimes, compounds break down into simpler substances. The change of one or more substances into other substances is called a **chemical reaction.** Chemical reactions are described by chemical equations. For example, water is formed by the chemical reaction between hydrogen gas (H_2) and oxygen gas (O_2). The formation of water can be described by the following equation.

$$2H_2 + O_2 \rightarrow 2H_2O$$

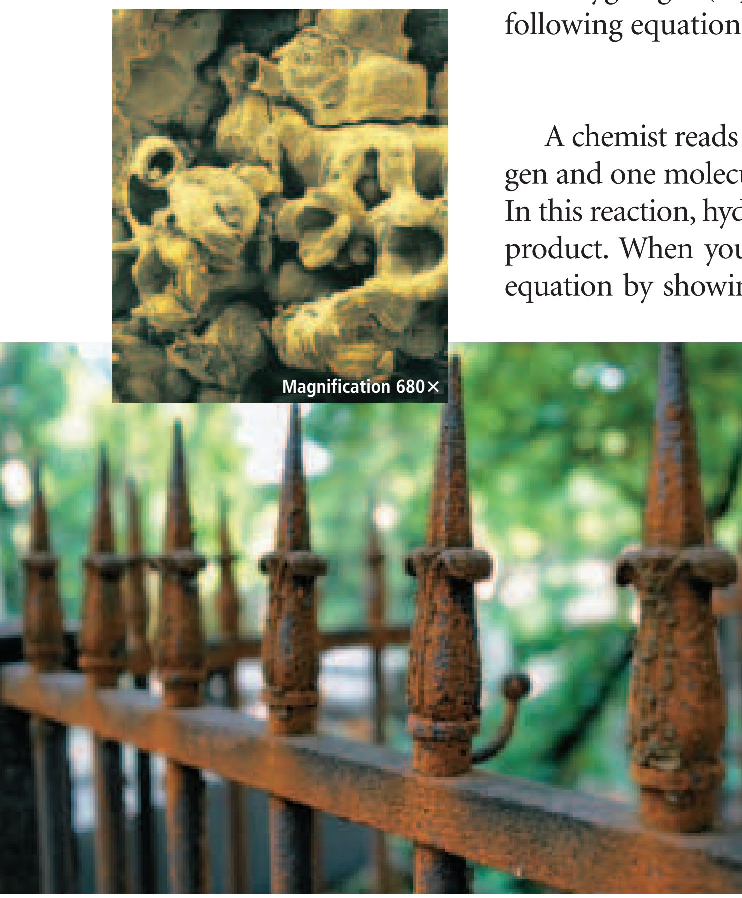
A chemist reads this chemical equation as "Two molecules of hydrogen and one molecule of oxygen react to yield two molecules of water." In this reaction, hydrogen and oxygen are the reactants, and water is the product. When you write a chemical equation, you must balance the equation by showing an equal number of atoms for each element on each side of the equation. This is because the same amount of matter is present both before and after the reaction. Note that there are four hydrogen atoms on each side of the above equation ($2 + 2 = 4$). There are also two oxygen atoms on each side of the reaction.

Another example of a chemical reaction, one that takes place between iron (Fe) and oxygen (O), is represented by the following chemical equation.

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

This reaction forms the mineral hematite, an important iron ore. You may be more familiar with another form of this compound shown in ***Figure 3-9***—rust!

Figure 3-9 Rust, shown magnified in the top photo, forms on metals that contain iron when they are exposed to moist air.



Mixtures and Solutions

Unlike a compound, in which the constituent atoms combine and lose their identities, a *mixture* is a combination of two or more components that retain their identities. When a mixture's components are easily recognizable, it is called a heterogeneous mixture. For example, soil, as shown in ***Figure 3-10A,*** is a heterogeneous mixture because its components are still recognizable: bits of minerals such as quartz and feldspar, clay particles, fragments of plants, and so on. In contrast, in a homogeneous mixture, the component particles cannot be distinguished, even though they still retain their original properties. Brewed coffee is an example of a homogeneous mixture, which is also called a **solution.**

A solution may be liquid, gaseous, or solid. Seawater is a liquid solution consisting of water molecules and ions of many elements that exist on Earth. You will investigate liquid solutions in the *GeoLab* at the end of this chapter. Magma is also a liquid solution; it is composed of ions representing all atoms that were present in the crystals of the rock before it melted. Air is a solution of gases, mostly nitrogen and oxygen molecules together with other atoms and molecules. Metal alloys, such as bronze and brass, are also solutions. Bronze is a homogeneous mixture of copper and tin atoms; brass is a similar mixture of copper and zinc atoms. Such solid homogeneous mixtures are called *solid solutions.* You will learn more about solid solutions in Chapters 4 and 5.

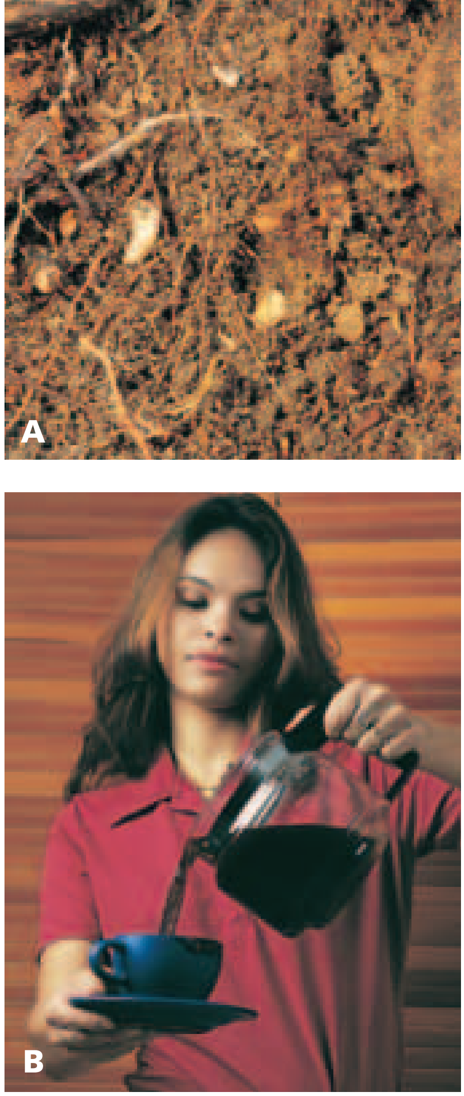


Figure 3-10 Soil is a heterogeneous mixture in which the component parts are easily recognizable **(A).** Coffee is a homogeneous mixture, called a solution, in which the component parts cannot be distinguished **(B).**

Acids and Bases Many chemical reactions that occur on Earth involve solutions called acids and bases. An **acid** is a solution containing a substance that produces hydrogen ions (H^+) in water. Recall that a hydrogen atom consists of one proton and one electron. When a hydrogen atom loses its electron, it becomes simply a proton. The most common acid in our environment is carbonic acid, which is produced when carbon dioxide is dissolved in water by the following reaction.

$$H_2O + CO_2 \longrightarrow H_2CO_3$$

Some of the carbonic acid molecules in the water dissociate, or break apart, into hydrogen ions and bicarbonate ions, as represented by the following equation.

$$H_2CO_3 \longrightarrow H^+ + HCO_3^-$$

These two equations play a major role in the dissolution and precipitation of limestone and the formation of caves, discussed in Chapter 10. Many of the reaction rates involved in geological

Environmental Connection

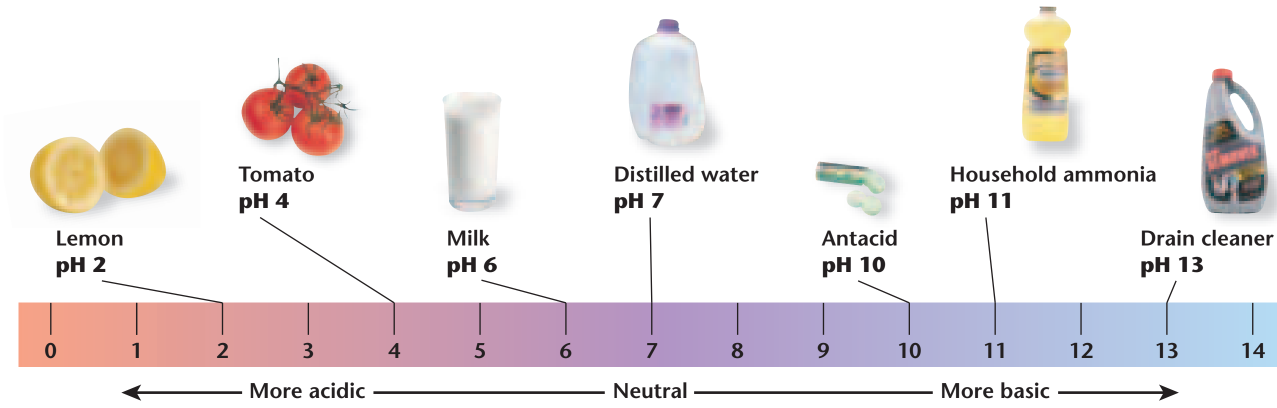


Figure 3-11 The pH values of some common substances are shown on this scale. Treated pH paper can be used to determine the acidity of a solution.

processes are exceedingly slow. For example, it may take thousands of years for the carbonic acid in groundwater to break down limestone to form a cave.

Bases produce hydroxide ions (OH^-) in solution. A base can neutralize an acid by combining with hydrogen ions of the acid to form water through the following reaction.

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

The pH scale measures the hydrogen and hydroxide ions in solutions, with 7 being neutral. A solution with a pH reading below 7 is considered to be acidic. The lower the number, the more acidic the solution is. A solution with a reading above 7 is considered to be basic. The higher the number, the more basic the solution is. Distilled water usually has a pH of 7, but rainwater is slightly acidic, having a pH of 5.0 to 5.6. The pH values of some common substances are shown in ***Figure 3-11.***

SECTION ASSESSMENT

1. What is the smallest unit of a molecular compound with the properties of that compound?
2. Why are negative ions usually larger than positive ions?
3. Explain why molecules held together by covalent bonds don't have electrical charges.
4. **Thinking Critically** Whole milk consists of microscopic fat globules suspended in a solution of nutrients. Is milk a homogeneous or a heterogeneous mixture? Explain.

SKILL REVIEW

5. **Predicting** What kind of bond forms between the nitrogen atoms and hydrogen atoms in ammonia (NH_3)? For more help, refer to the *Skill Handbook.*

earthgeu.com/self_check_quiz

SECTION 3.3

States of Matter

An iceberg floating in the ocean beneath a blue sky not only captures the beauty of nature, but it also illustrates three states of matter found on Earth. Matter may be solid, like the iceberg; liquid, like the ocean; or gaseous, like the water vapor in the air. But are these the only states in which matter can exist? At room temperature and standard atmospheric pressure, matter normally exists in one of these three states. However, there is another state of matter found on Earth, called plasma, which you will learn more about later in this section.

OBJECTIVES

- **Describe** *the states of matter on Earth.*
- **Explain** *the reasons that matter exists in these states.*
- **Relate** *the role of thermal energy to changes of state in matter.*

VOCABULARY

crystalline structure
glass
evaporation
sublimation
plasma
condensation

SOLIDS

What do ice crystals, table-salt crystals, and diamonds have in common? All of these substances are solids, and all of them form crystals. Solids are substances with densely packed particles, which may be ions, atoms, or molecules, depending upon the substance. The particles of a solid are arranged in a definite pattern; thus, a solid has both a definite shape and a definite volume. Most solids have a **crystalline structure,** in which the particles are arranged in regular geometric patterns, as illustrated in ***Figure 3-12.*** Crystals form symmetrical solid objects with flat faces and straight edges between faces. The angles between the faces depend upon the internal arrangement of the particles. For example, vanadium and quartz crystals look different from table-salt crystals because of the different internal arrangements of their particles. Magnesium, quartz, and many other substances have hexagonal crystals.

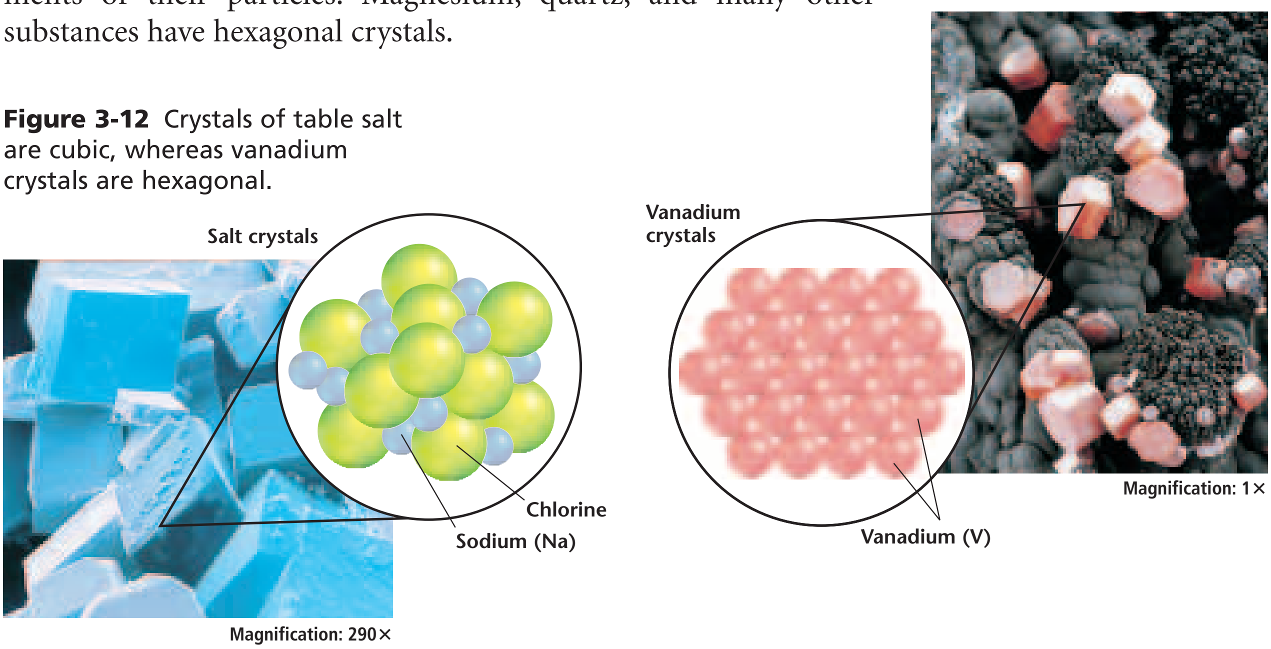


Figure 3-12 Crystals of table salt are cubic, whereas vanadium crystals are hexagonal.

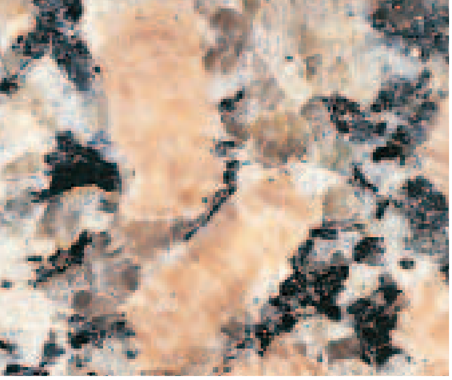


Figure 3-13 Granite, which is abundant in Earth's crust, is a mass of intergrown crystals.

Well-formed crystals are rare. When many crystals form in the same space at the same time, mutual interference prevents the formation of regular crystals with smooth boundaries. The result is a mass of intergrown crystals, called a polycrystalline solid. Most solid substances on Earth, including rocks, are polycrystalline materials. ***Figure 3-13*** shows the polycrystalline nature of the rock granite.

Some solid materials have no regular internal patterns. **Glasses** are solids that consist of densely packed atoms arranged at random. Glasses form when molten material is chilled so rapidly that atoms don't have enough time to arrange themselves into a regular pattern. These solids do not form crystals, or their crystals are so small that they cannot be seen. Window glass consists mostly of disordered silicon and oxygen with the chemical composition SiO_2.

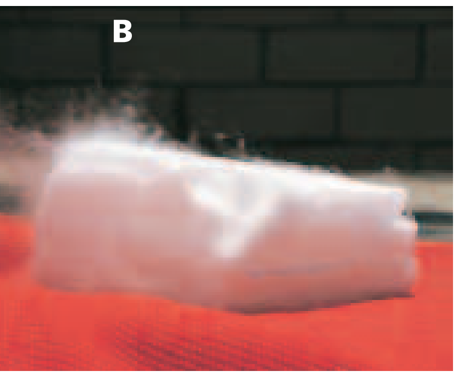
Liquids

At any temperature above absolute zero (−273°C), the atoms in solids vibrate. Because these vibrations increase with increasing temperature, they are called thermal vibrations. At the melting point of the material, these vibrations become sufficiently vigorous to break the forces holding the solid together. The particles can then slide past each other, and the substance becomes liquid. Liquids do not have their own shape; they take the shape of the container they are placed in, as you can see in ***Figure 3-14A.*** However, liquids do have definite volume.

Figure 3-14 Because the particles in liquids slide past each other, liquids have no definite shape **(A).** Dry ice, which is solid carbon dioxide (CO_2), sublimates from a solid directly into a gas **(B).**

A

B



Gases

The particles in liquids vibrate vigorously, and individual particles may gain sufficient energy to escape the liquid. This process of change from a liquid to a gas is called **evaporation,** or vaporization. When any liquid reaches its boiling point, it vaporizes quickly and becomes a gas. However, some evaporation takes place even below the boiling point. In fact, thermal vibrations can enable individual atoms or molecules to escape even from a solid. You may have noticed that even on winter days with temperatures below freezing, snow gradually disappears. This slow change of state from a solid, ice crystals, to a gas, water vapor, without an intermediate liquid state is called **sublimation,** as illustrated in ***Figure 3-14B.***

In gases, the particles are separated by relatively large distances and move about at extremely high speeds. Gas particles move independently of each other and travel randomly. They travel in one direction until they bump into another gas particle or the walls of a container. Gases, like liquids, have no definite shape. Gases also have no definite volume and can expand into any space available, unless they are restrained by a container or a force such as gravity. Earth's gravity keeps the gases in the atmosphere from escaping into space.

Plasma

When matter is heated to temperatures greater than 5000°C, the collisions between particles are so violent that electrons are knocked away from atoms. Such extremely high temperatures exist in stars, and, as a result, the gases of stars consist entirely of positive ions and free electrons. These hot, highly ionized, electrically conducting gases are called **plasmas.** ***Figure 3-15*** shows the plasma that forms the Sun's corona. You have seen matter in the plasma state if you have ever seen lightning or a neon sign. Both lightning and the matter inside a neon tube are in the plasma state.

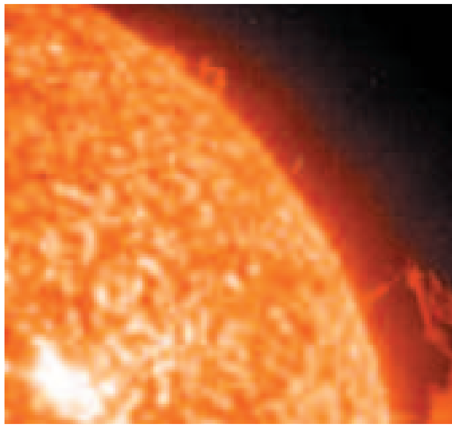


Figure 3-15 The corona around the Sun is formed from hot, glowing plasma.

Changes of State

Solids melt when they absorb thermal energy and their temperatures rise. When a liquid absorbs thermal energy from the environment, it evaporates. This actually has a cooling effect on the surrounding environment. What do you suppose happens when a liquid freezes? The same thermal energy is then released back into the environment. Finally, when a gas is cooled, it releases thermal energy in the process of **condensation,** the change from a gas to a liquid.

Conservation of Matter and Energy

The identity of matter can be changed through chemical reactions and nuclear processes, and its state can be changed under different thermal conditions. However, matter cannot be created or destroyed but can change from one form to another. This fundamental fact is called the law of conservation of matter. Like matter, energy cannot be created or destroyed but it can be changed from one form to another. This law of the conservation of energy is also called the first law of thermodynamics.

Section Assessment

1. What shape do salt crystals have? What determines the shape of a crystal?
2. Why is the puddle underneath a melting ice cube as cold as the ice cube itself?
3. Contrast what happens to thermal energy in evaporation and condensation.
4. **Thinking Critically** Water boils at 100°C at sea level. What do you think its boiling point would be if water molecules were not polar molecules?

Skill Review

5. **Concept Mapping** Use the following terms to construct a concept map to compare and contrast the three common states of matter. You may use some terms more than once. For more help, refer to the *Skill Handbook.*

definite shape · states of matter · solid · no definite shape · definite volume · liquid · gas · no definite volume

GeoLab

Salt Precipitation

Many rocks on Earth form from salts precipitating out of seawater. Salt ions precipitate when a salt solution becomes saturated. Solubility is the ability of a substance to dissolve in a solution. When a solution is saturated, no more of that substance can be dissolved. What is the effect of temperature and evaporation on salt precipitation? How do precipitation rates affect the size of crystals?

Preparation

Problem

Under what conditions do salt solutions become saturated and under what conditions does salt precipitate out of solution?

Materials

halite (sodium chloride)
250-mL glass beakers (2)
distilled water
plastic wrap
laboratory scale
hot plate
shallow glass baking dish
refrigerator
glass stirring rod

Objectives

In this GeoLab, you will:

- **Observe** salt dissolving and precipitating from a saturated salt solution.
- **Identify** the precipitated salt crystals.
- **Compare** the salt crystals that precipitate out under different conditions.
- **Hypothesize** why different conditions produce different results.

Safety Precautions

Always wear safety goggles and an apron in the lab. Wash your hands after handling salt solutions. Use care in handling hot solutions. Use protection handling hot glassware.

Procedure

1. Pour 150 mL of distilled water into a 250-mL glass beaker.
2. Measure 54 g of sodium chloride. Add the sodium chloride to the distilled water in the beaker and stir until only a few grains remain on the bottom of the beaker.
3. Place the beaker on the hot plate and turn the hot plate on. As the solution inside the beaker heats up, stir it until the last few grains of sodium chloride dissolve. The salt solution will then be saturated.
4. Pour 50 mL of the warm, saturated solution into the second 250-mL glass beaker. Cover this beaker with plastic wrap so that it forms a good seal. Put this beaker in the refrigerator.
5. Pour 50 mL of the saturated solution into the shallow glass baking dish. Place the dish on the hot plate and heat the salt solution until all the liquid evaporates. ***CAUTION:*** *The baking dish will be hot. Handle with care.*
6. Place the original beaker with 50 mL of the remaining solution on a shelf or windowsill. Do not cover the beaker.
7. Observe both beakers one day later. If crystals have not formed, wait another day to make your observations and conclusions.
8. Once crystals have formed in all three containers, observe the size and shape of the precipitated crystals. Describe your observations in your science journal.

Analyze

1. What is the shape of the precipitated crystals in the three containers? Does the shape of the crystals alone identify them as sodium chloride?
2. Why didn't all of the salt solution dissolve in step 2 above? How did heating affect the solubility of sodium chloride? Why did heating have the observed effect? Explain.
3. What effect does cooling have on the solubility of salt?
4. What happens when a salt solution evaporates? What effect does evaporation have on the solubility of salt?
5. Suppose you have two samples of volcanic rock of identical chemical composition but different crystal sizes. What conclusions can you make about the conditions under which each rock sample cooled?

Conclude & Apply

1. What are the sizes of the crystals in the different containers? Which container has the smallest crystals? Which crystals formed in the shortest time interval?
2. Why does salt precipitate from solution? How is crystal size related to precipitation rate?
3. Design an experiment to separate a heterogeneous mixture of different salts, such as NaCl and $MgCl_2$, into its components, by dissolving and precipitation.

Science & Technology

Magnification 33×

Extreme Magnification

Students from Malibu, California, to Atlanta, Georgia, are collecting bugs with more enthusiasm than usual. They are sending insects to a project called Bugscope. Bugscope workers use a scanning electron microscope (SEM) to take close-up photographs of these amazing animals. The photographs are then posted on the Internet. The photos provide detailed information about the structure and composition of matter in our world.

Electron Microscopy

Microscopes have been used by scientists to magnify objects since the 1600s. Traditional light microscopes, however, have limitations: they can magnify objects only up to 2000 times their size, and there is a limit to how clear these microscopes can make objects appear. In the early 1930s, German scientists developed a new type of microscope that could magnify objects 10 000 times their size. This microscope did not use light for the examination of objects; instead, it used a beam of high-energy electrons. Today, electron microscopes scan material to create detailed, three-dimensional, black-and-white images of objects that are magnified up to 100 000 times.

Applications

When a scanning electron microscope is used to examine an object, a beam of electrons is directed onto the object's surface. As scanning coils move the electron beam over the object in a gridlike pattern, the beam causes electrons to be knocked off the object's surface. An image is created on a fluorescent screen by the calculation of the number of electrons that are bounced off each spot on the object. Electron microscopes provide information about the properties of matter being examined, including its reactivity, strength, and reflectivity. Currently, scientists are using electron microscopes to further research in areas ranging from combating leukemia to searching for evidence of product tampering to developing better ways to process and store food.

Magnification 18×

Magnification 140×

Activity

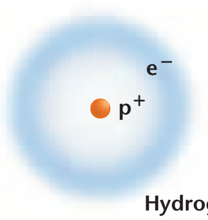
The photographs on this page are SEM images. What does each image represent? Go to earthgeu.com to find links to SEM images of solids and create an image gallery. Present your images, along with clues about their identities, to your classmates, and see how many they can identify.

Study Guide

Summary

SECTION 3.1

What are elements?



Hydrogen atom

Main Ideas

- The basic building blocks of matter are atoms. Atoms consist of protons, neutrons, and electrons.
- Protons have a positive electrical charge, electrons have a negative electrical charge, and neutrons are electrically neutral. Protons and neutrons make up the nucleus of an atom; electrons surround the nucleus in energy levels.
- An element is a substance consisting of atoms with a specific number of protons in their nuclei. Isotopes of an element differ by the number of neutrons in their nuclei. Many elements are mixtures of isotopes.
- The number of electrons in the outermost energy levels of atoms determines their chemical behavior. Elements with the same number of electrons in their outermost energy levels have similar chemical properties.

Vocabulary

atom (p. 54)
atomic mass (p. 58)
atomic number (p. 54)
electron (p. 55)
element (p. 53)
energy level (p. 55)
isotope (p. 58)
mass number (p. 54)
neutron (p. 54)
nucleus (p. 54)
proton (p. 54)
radioactivity (p. 58)
valence electron (p. 57)

SECTION 3.2

How Atoms Combine

Main Ideas

- Atoms of different elements combine to form compounds.
- Atoms held together by the sharing of electrons in covalent bonds form molecular compounds.
- Ions are electrically charged atoms or groups of atoms. Positive and negative ions attract each other and form ionic compounds.
- Acids are solutions containing hydrogen ions. Bases are solutions containing hydroxide ions. Acids and bases can neutralize each other.
- A mixture is a combination of components that retain their identities. A solution is a mixture in which the components can no longer be distinguished as separate. Solutions can be liquid, solid, gaseous, or combinations.

Vocabulary

acid (p. 65)
base (p. 66)
chemical bond (p. 60)
chemical reaction (p. 64)
compound (p. 60)
covalent bond (p. 60)
ion (p. 62)
ionic bond (p. 63)
molecule (p. 61)
solution (p. 65)

SECTION 3.3

States of Matter

Main Ideas

- Matter on Earth exists in three common physical states: solid, liquid, or gaseous. Matter in the universe includes plasma.
- Most solids have a crystalline structure.
- Liquids are densely packed arrangements of particles.
- Gases consist of widely separated, individual particles. Plasmas are hot, highly ionized, electrically conducting gases.
- Changes of state involve thermal energy.

Vocabulary

condensation (p. 69)
crystalline structure (p. 67)
evaporation (p. 68)
glass (p. 68)
plasma (p. 69)
sublimation (p. 68)

earthgeu.com/vocabulary_puzzlemaker

CHAPTER 3 Assessment

Understanding Main Ideas

1. What particles make up the nucleus of an atom?
   a. protons only **c.** neutrons and electrons
   b. neutrons only **d.** protons and neutrons

2. Which of these makes up an atom's mass number?
   a. number of protons **c.** neutrons and protons
   b. number of neutrons **d.** protons and electrons

3. Which is the average of the mass numbers of an element's isotopes?
   a. atomic number **c.** atomic mass
   b. energy levels **d.** valence electrons

4. What is the lightest of all the elements?
   a. helium **c.** hydrogen
   b. lithium **d.** magnesium

5. One of the isotopes of chlorine (atomic number 17) has a mass number of 35. How many neutrons does this isotope have in its nucleus?
   a. 17 **b.** 18 **c.** 35 **d.** 53

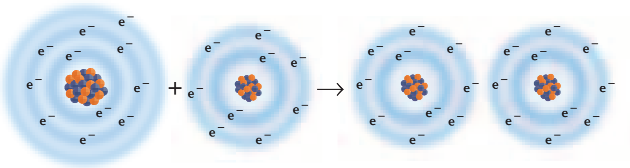
6. Which is NOT an element?
   a. hydrogen **c.** argon
   b. water **d.** uranium

7. What element is the final (nonradioactive) decay product of uranium?
   a. lead **c.** plutonium
   b. neon **d.** hydrogen

8. Many musical instruments are made of brass, which consists of copper and zinc atoms. What is brass an example of?
   a. an ionic compound **c.** a chemical reaction
   b. a solid solution **d.** a base

9. What are formed when sodium ions and chlorine ions combine to form NaCl?
   a. ionic bonds **c.** isotopes
   b. solid solutions **d.** covalent bonds

Use the following diagram to answer questions 10 and 11.



10. Write the chemical equation that the diagram represents.

11. Is the compound formed in the diagram a molecular compound or an ionic compound? Explain your answer.

12. What is the most abundant element in Earth's crust?
    a. hydrogen **c.** silicon
    b. uranium **d.** oxygen

13. Which chemical formula represents a polar molecule?
    a. MgO **b.** H_2O **c.** SiO_2 **d.** NaCl

14. If an atom gains electrons, what does it become?
    a. a positive ion **c.** a different element
    b. a negative ion **d.** a heavier isotope

15. What kind of ions characterize an acid?
    a. hydroxide ions **c.** oxygen ions
    b. hydrogen ions **d.** negative ions

16. Why do metals conduct electricity?

Test-Taking Tip

TERMS If a test question involves a term that you don't remember, see if you can figure out its meaning from the question. Sometimes standardized tests will give a definition or example right in the question.

Assessment

17. What happens to the thermal energy of a gas when it condenses and forms a liquid?
18. How are coffee and air chemically alike?
19. Explain the differences between a molecular compound and an ionic compound.
20. What is a molecule?

Applying Main Ideas

21. How many valence electrons do beryllium atoms (atomic number 4) have? Explain your answer.
22. Name two elements with chemical properties that are similar to those of sodium.
23. What is the charge on ions of fluorine (atomic number 9)?
24. List two elements that have ions with a 2+ charge.
25. What compound do the ions Al^{3+} and O^{2-} form?
26. Explain why the mass numbers of elements in the Periodic Table of Elements rarely are whole numbers.

Thinking Critically

27. Why don't gases such as neon and argon combine chemically with other elements?
28. Suppose you want to find out if the elements copper (atomic number 29) and sulfur (atomic number 16) could combine into a compound. How could you check this before you proceeded to do an experiment in the laboratory?

Standardized Test Practice

INTERPRETING DATA Use the table below to answer the following questions.

Atomic Structure

Element	Atomic Number	Atomic Mass
Beryllium	4	9.01
Calcium	20	40.08
Silicon	14	28.09
Scandium	21	44.96
Titanium	22	47.88
Zirconium	40	91.22

1. If titanium has 22 protons in its nucleus, how many neutrons are present in the nucleus of its most common isotope?
   a. 48 **c.** 60
   b. 26 **d.** 28

2. If the most common isotope of scandium has 24 neutrons in its nucleus, how many protons does scandium have?
   a. 66 **c.** 21
   b. 45 **d.** 13

3. If calcium's most common isotope has 20 neutrons in its nucleus, how many neutrons can be found in another naturally occurring isotope of calcium?
   a. 60 **c.** 30
   b. 41 **d.** 21

4. How many valence electrons does oxygen have?
   a. 2 **c.** 6
   b. 4 **d.** 9

5. Does silicon have any isotopes? Explain your answer.

earthgeu.com/standardized_test