

2

Matter and Minerals

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- 2.1** List the main characteristics that an Earth material must possess to be considered a mineral and describe each.
- 2.2** Compare and contrast the three primary particles contained in atoms.
- 2.3** Distinguish among ionic bonds, covalent bonds, and metallic bonds.
- 2.4** List and describe the properties that are used in mineral identification.
- 2.5** List the common silicate and nonsilicate minerals and describe the characteristics of each group.
- 2.6** Discuss Earth's natural resources in terms of renewability. Differentiate between mineral resources and ore deposits.

The Cave of Crystals, Chihuahua, Mexico, contains giant gypsum crystals, some of the largest natural crystals ever found.

(Photo by Carsten Peter/Speleoresearch & Films/National Geographic Stock/Getty Images)

Earth's crust and oceans are home to a wide variety of useful and essential minerals. Most people are familiar with the common uses of many basic metals, including aluminum in beverage cans, copper in electrical wiring, and gold and silver in jewelry. But some people are not aware that pencil "lead" contains the greasy-feeling mineral graphite and that bath powders and many cosmetics contain the mineral talc. Moreover, many do not know that dentists use drill bits impregnated with diamonds to drill through tooth enamel or that the common mineral quartz is the

source of silicon for computer chips. In fact, practically every manufactured product contains materials obtained from minerals.

In addition to rocks and minerals having economic uses, all the processes that geologists study are in some way dependent on the properties of these basic Earth materials. Events such as volcanic eruptions, mountain building, weathering and erosion, and even earthquakes involve rocks and minerals. Consequently, a basic knowledge of Earth materials is essential to understanding all geologic phenomena.

2.1 MINERALS: BUILDING BLOCKS OF ROCK

List the main characteristics that an Earth material must possess to be considered a mineral and describe each.

We begin our discussion of Earth materials with an overview of **mineralogy** (*mineral* = mineral, *ology* = the study of) because minerals are the building blocks of rocks. In addition, humans have used minerals for both practical and decorative purposes for thousands of years (**FIGURE 2.1**). Flint and chert were the first minerals to be mined; they were fashioned into weapons and cutting tools. Egyptians began mining gold, silver, and copper as early as 3700 B.C. By 2200 B.C., humans had discovered how to combine copper with tin to make bronze, a strong, hard alloy. Later, a process was developed to extract iron from minerals such as hematite—a discovery that marked the decline of the Bronze Age. During the Middle Ages, mining of a variety of minerals became common, and the impetus for the formal study of minerals was in place.

The term *mineral* is used in several different ways. For example, those concerned with health and fitness extol the benefits of vitamins and minerals. The mining industry typically uses the word to refer to anything taken out of the ground, such as coal, iron ore, or sand and gravel. The guessing game known as *Twenty Questions* usually begins with the question "Is it animal, vegetable, or mineral?" What criteria do geologists use to determine whether something is a mineral?

Defining a Mineral

Geologists define **mineral** as *any naturally occurring inorganic solid that possesses an orderly crystalline structure and a definite chemical composition that allows for some variation*. Thus, Earth materials that are classified as minerals exhibit the following characteristics:

1. **Naturally occurring.** Minerals form through natural geologic processes. Synthetic materials—meaning those produced in a laboratory or by human intervention—are not considered minerals.
2. **Generally inorganic.** Inorganic crystalline solids, such as ordinary table salt (halite), that are found naturally in the ground are considered minerals. (Organic compounds, on the other hand, are generally not. Sugar, a crystalline solid like salt but that comes from sugarcane or sugar beets, is a common example of such an organic compound.) Many marine animals secrete inorganic compounds, such as calcium carbonate (calcite), in the form of shells and coral reefs. If these materials are buried and become part of the rock record, geologists consider them minerals.
3. **Solid substance.** Only solid crystalline substances are considered minerals. Ice (frozen water) fits this criterion and is considered a mineral, whereas liquid water and water vapor do not. The exception is mercury,

FIGURE 2.1 Quartz Crystals Well-developed quartz crystals found near Hot Springs, Arkansas. (Photo by BOL/TH FOTO/AGE fotostock)



which is found in its liquid form in nature.

4. Orderly crystalline structure.

Minerals are crystalline substances, which means their atoms (ions) are arranged in an orderly, repetitive manner (FIGURE 2.2). This orderly packing of atoms is reflected in regularly shaped objects called *crystals*. Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.

5. Definite chemical composition that allows for some variation.

Minerals are chemical compounds having compositions that can be expressed by a chemical formula. For example, the common mineral quartz has the formula SiO_2 , which indicates that quartz consists of silicon (Si) and oxygen (O) atoms, in a ratio of one-to-two. This proportion of silicon to oxygen is true for any sample of pure quartz, regardless of its origin. However, the compositions of some minerals vary *within specific, well-defined limits*. This occurs because certain elements can substitute for others of similar size without changing the mineral's internal structure.

What Is a Rock?

In contrast to minerals, rocks are more loosely defined. Simply, a **rock** is any solid mass of mineral, or mineral-like, matter that occurs naturally as part of our planet. Most rocks, like the sample of granite shown in FIGURE 2.3, occur as aggregates of several different minerals. The term *aggregate* implies that the minerals are joined in such a way that their individual properties are retained. Note that the different minerals that make up granite can be easily identified. However, some rocks are composed almost entirely of one mineral. A common example is the sedimentary rock *limestone*, which is an impure mass of the mineral calcite.

In addition, some rocks are composed of nonmineral matter. These include the volcanic rocks *obsidian* and *pumice*, which are noncrystalline glassy substances, and *coal*, which consists of solid organic debris.

Although this chapter deals primarily with the nature of minerals, keep in mind that most rocks are aggregates of minerals. Because the properties of rocks are determined

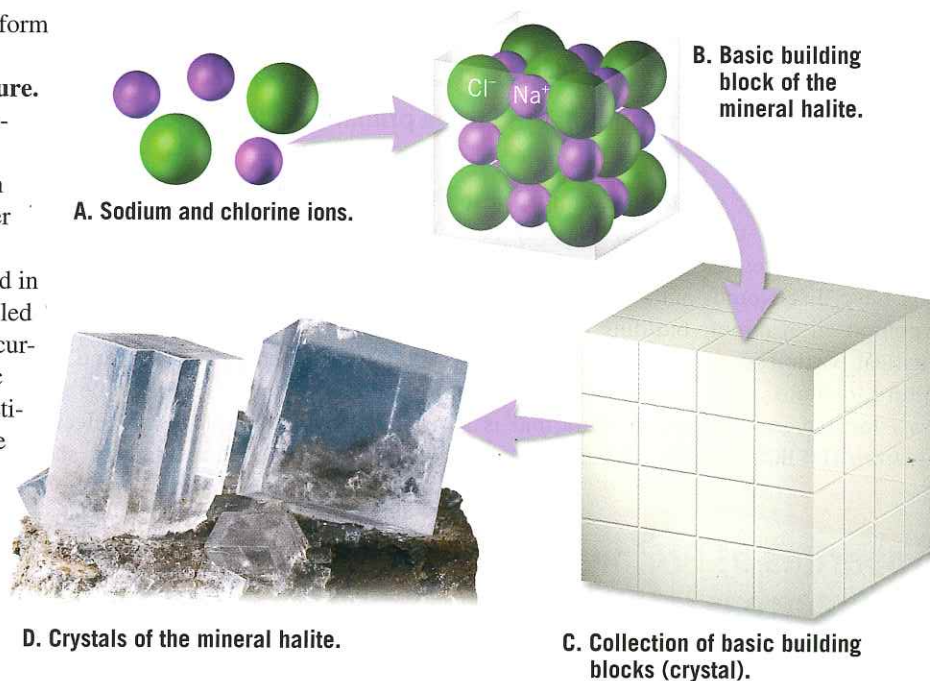


FIGURE 2.2 Arrangement of Sodium and Chloride Ions in the Mineral Halite

The arrangement of atoms (ions) into basic building blocks that have a cubic shape results in regularly shaped cubic crystals.

(Photo by Dennis Tasa)



SmartFigure 2.3 Most Rocks Are Aggregates of Minerals

Shown here is a hand sample of the igneous rock granite and three of its major constituent minerals.

(Photos by E. J. Tarbuck)



largely by the chemical composition and crystalline structure of the minerals contained within them, we will first consider these Earth materials.

2.1 CONCEPT CHECKS

- 1 List five characteristics an Earth material must have in order to be considered a mineral.
- 2 Based on the definition of *mineral*, which of the following materials are not classified as minerals and why: gold, water, synthetic diamonds, ice, and wood?
- 3 Define the term *rock*. How do rocks differ from minerals?

2.2 ATOMS: BUILDING BLOCKS OF MINERALS

Compare and contrast the three primary particles contained in atoms.

When minerals are carefully examined, even under optical microscopes, the innumerable tiny particles of their internal structures are not visible. Nevertheless, scientists have discovered that all matter, including minerals, is composed of minute building blocks called **atoms**—the smallest particles that cannot be chemically split. Atoms, in turn, contain even smaller particles—*protons* and *neutrons* located in a central **nucleus** that is surrounded by *electrons* (FIGURE 2.4).

Properties of Protons, Neutrons, and Electrons

Protons and **neutrons** are very dense particles with almost identical masses. By contrast, **electrons** have a negligible mass, about 1/2000 that of a proton. To illustrate this

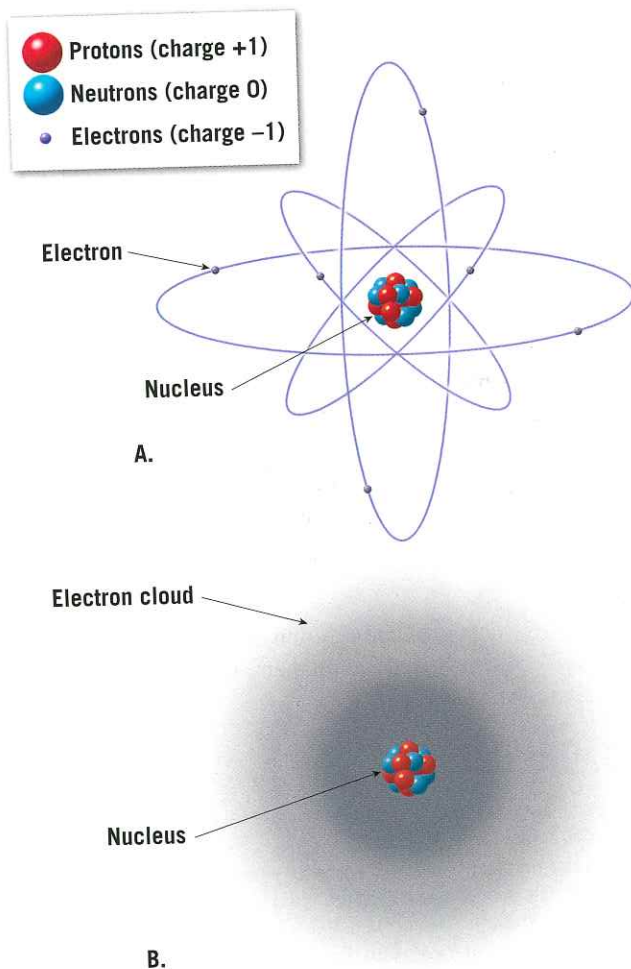
difference, assume that on a scale where a proton has the mass of a baseball, an electron has the mass of a single grain of rice.

Both protons and electrons share a fundamental property called *electrical charge*. Protons have an electrical charge of +1, and electrons have a charge of -1. Neutrons, as the name suggests, have no charge. The charges of protons and electrons are equal in magnitude but opposite in polarity, so when these two particles are paired, the charges cancel each other out. Since matter typically contains equal numbers of positively charged protons and negatively charged electrons, most substances are electrically neutral.

In illustrations, electrons are sometimes shown orbiting the nucleus in a manner that resembles the planets of our solar system orbiting the Sun (see Figure 2.4A). However, electrons do not actually behave this way. A more realistic depiction shows electrons as a cloud of negative charges surrounding the nucleus (see Figure 2.4B). Studies of the arrangements of electrons show that they move about the nucleus in regions called *principal shells*, each with an associated energy level. In addition, each shell can hold a specific number of electrons, with the outermost shell generally containing **valence electrons** that interact with other atoms to form chemical bonds.

Most of the atoms in the universe (except hydrogen and helium) were created inside massive stars by nuclear fusion and released into interstellar space during hot, fiery supernova explosions. As this ejected material cooled, the newly formed nuclei attracted electrons to complete their atomic structure. At the temperatures found at Earth's surface, all free atoms (those not bonded to other atoms) have a full complement of electrons—one for each proton in the nucleus.

FIGURE 2.4 Two Models of an Atom **A.** Simplified view of an atom consisting of a central nucleus composed of protons and neutrons encircled by high-speed electrons. **B.** This model of an atom shows spherically shaped electron clouds (shells) surrounding a central nucleus. The nucleus contains virtually all of the mass of the atom. The remainder of the atom is the space occupied by negatively charged electrons. (The relative sizes of the nuclei shown are greatly exaggerated.)



Elements: Defined by Their Number of Protons

The simplest atoms have only 1 proton in their nuclei, whereas others have more than 100. The number of protons in the nucleus of an atom, called the **atomic number**, determines its chemical nature. All atoms with the same number of protons have the same chemical and physical properties. Together, a group of the same kind of atoms is called an **element**. There are about 90 naturally occurring elements, and several more have been synthesized in the laboratory. You are probably familiar with the names of many elements, including carbon, nitrogen, and oxygen. All carbon atoms have six protons, whereas all nitrogen

Tendency to lose outermost electrons to uncover full outer shell

Tendency to fill outer shell by sharing electrons

Tendency to gain electrons to make full outer shell

Noble gases are inert because outer shell is full

Vertical columns contain elements with similar properties.

Step-like line divides metals from nonmetals.

Tendency to lose electrons

Atomic number

Symbol of element

Atomic weight

Name of element

1 H 1.0080 Hydrogen																	2 He 4.003 Helium
I A	II A											III A	IV A	V A	VI A	VII A	VIII A
3 Li 6.939 Lithium	4 Be 9.012 Beryllium											5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.9994 Oxygen	9 F 18.998 Fluorine	10 Ne 20.183 Neon
11 Na 22.990 Sodium	12 Mg 24.31 Magnesium	III B	IV B	V B	VI B	VII B	VIII B		IB	II B	13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.974 Phosphorus	16 S 32.064 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon	
19 K 39.102 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.90 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.71 Nickel	29 Cu 63.54 Copper	30 Zn 65.37 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.909 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (99) Technetium	44 Ru 101.1 Ruthenium	45 Rh 102.90 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.40 Cadmium	49 In 114.82 Indium	50 Sn 118.69 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.30 Xenon
55 Cs 132.91 Cesium	56 Ba 137.34 Barium	#57 TO #71	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.2 Rhenium	76 Os 190.2 Osmium	77 Ir 192.2 Iridium	78 Pt 195.09 Platinum	79 Au 197.0 Gold	80 Hg 200.59 Mercury	81 Tl 204.37 Thallium	82 Pb 207.19 Lead	83 Bi 208.98 Bismuth	84 Po (210) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra 226.05 Radium	#89 TO #103	57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (147) Promethium	62 Sm 150.35 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.92 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
			89 Ac (227) Actinium	90 Th 232.04 Thorium	91 Pa (231) Protactinium	92 U 238.03 Uranium	93 Np (237) Neptunium	94 Pu (242) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (249) Berkelium	98 Cf (251) Californium	99 Es (254) Einsteinium	100 Fm (253) Fermium	101 Md (256) Mendelevium	102 No (254) Nobelium	103 Lw (257) Lawrencium

Metals

Metalloids

Nonmetals

Lanthanide series

Actinide series

FIGURE 2.5 Periodic Table of the Elements

atoms have seven protons, and all oxygen atoms have eight protons.

Elements are organized so that those with similar properties line up in columns, referred to as groups. This arrangement, called the **periodic table**, is shown in **FIGURE 2.5**. Each element has been assigned a one- or two-letter symbol. The atomic numbers and masses for each element are also shown on the periodic table.

Atoms of the naturally occurring elements are the basic building blocks of Earth's minerals. Most elements join with atoms of other elements to form **chemical compounds**. Therefore, most minerals are chemical compounds composed of atoms of two or more elements. These include the minerals quartz (SiO_2), halite (NaCl), and calcite (CaCO_3). However, a few minerals, such as native copper, diamonds, sulfur, and gold, are made entirely of atoms of only one element (**FIGURE 2.6**).



A. Gold on quartz

B. Sulfur

C. Copper

FIGURE 2.6 These Are among the Few Minerals That Are Composed of a Single Element (Photos by Dennis Tasa)

2.2 CONCEPT CHECKS

- 1 List the three main particles of an atom and explain how they differ from one another.
- 2 Make a simple sketch of an atom and label its three main particles.
- 3 What is the significance of valence electrons?

Gold

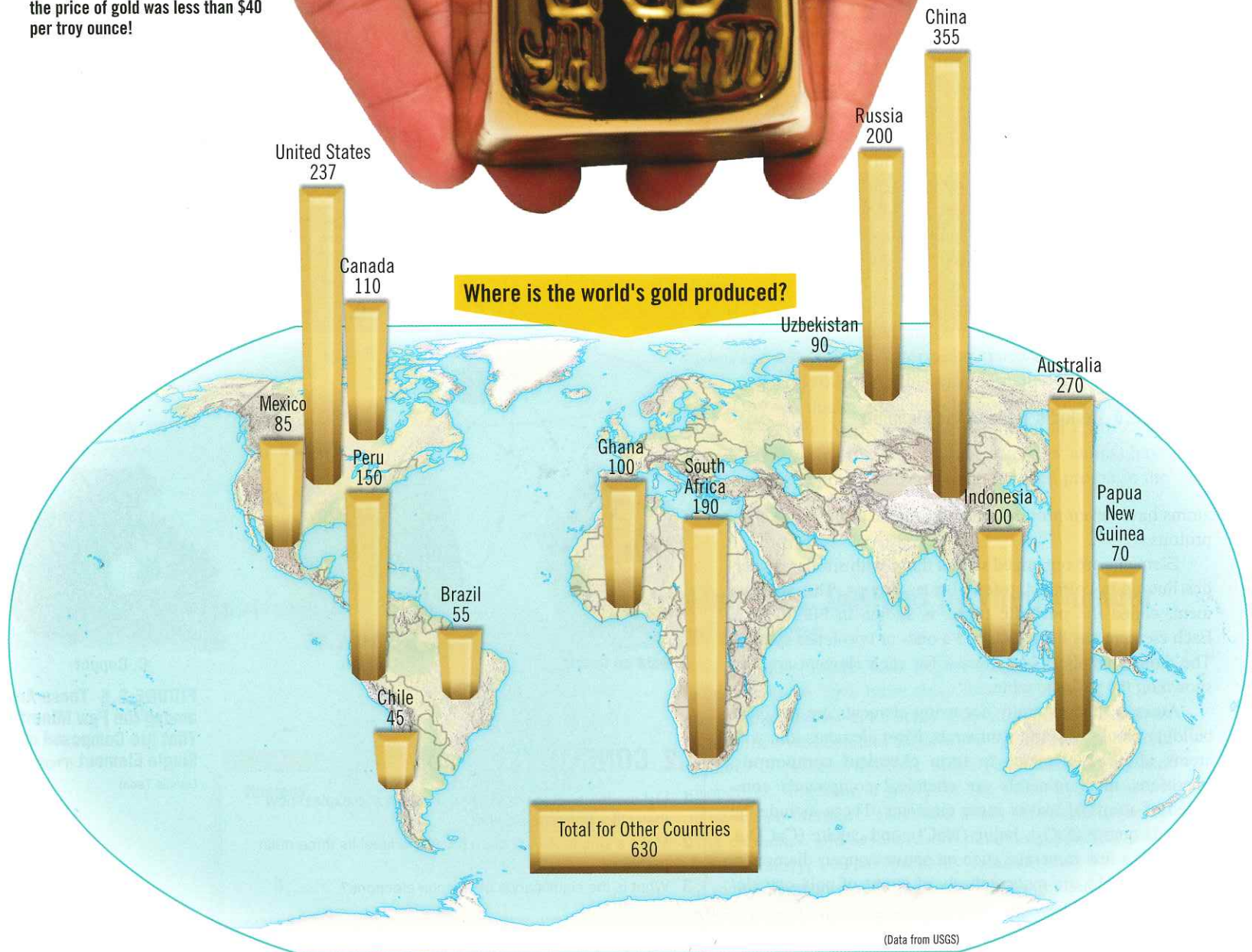
Gold has been treasured since long before recorded history for its beauty. Even today, its most common use is in jewelry.

How valuable is gold?

In early 2013, the value of one troy ounce of gold was about US\$1,677. Based on that value, a 1000-gram (32-ounce) bar of gold, like the one shown, was worth \$53,664. In 1970, the price of gold was less than \$40 per troy ounce!

\$53,664

Where is the world's gold produced?



(Data from USGS)

Native gold

Because gold does not easily react with other elements, it often occurs as a native element in nuggets found in stream deposits or as grains in igneous rocks.



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What are the uses of gold?

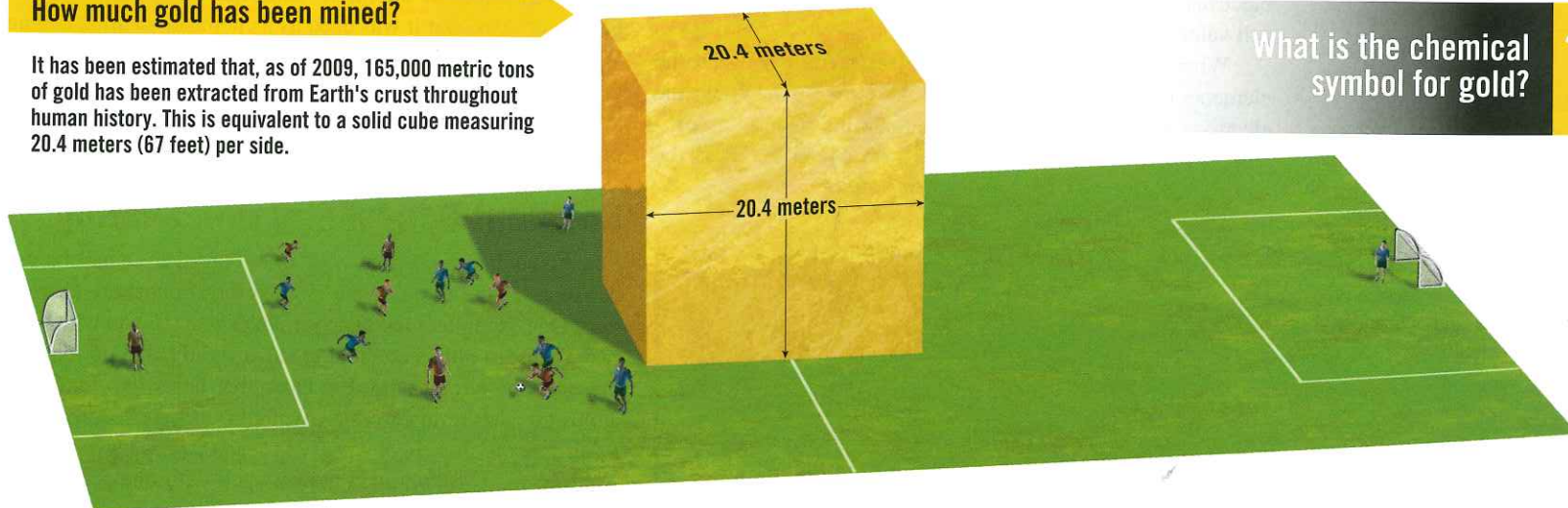
About 50% of gold is used in jewelry. Another 40% is used for currency and investment, and about 10% is used in industry, including electronic devices such as cell phones and televisions. Gold is also used in gourmet foods and cocktails as a decorative ingredient. Because metallic gold is one of the least reactive materials, it has no taste, provides no nutritional value, and leaves the human body unaltered.



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How much gold has been mined?

It has been estimated that, as of 2009, 165,000 metric tons of gold has been extracted from Earth's crust throughout human history. This is equivalent to a solid cube measuring 20.4 meters (67 feet) per side.



What is the chemical symbol for gold?

?

2.3 WHY ATOMS BOND

Distinguish among ionic bonds, covalent bonds, and metallic bonds.

Except in a group of elements known as the noble gases, atoms bond to one another under the conditions (temperatures and pressures) that occur on Earth. Some atoms bond to form *ionic compounds*, some form *molecules*, and still others form *metallic substances*. Why does this happen? Experiments show that electrical forces hold atoms together and bond them to each other. These electrical attractions lower the total energy of the bonded atoms, which, in turn, generally makes them more stable. Consequently, atoms that are bonded in compounds tend to be more stable than atoms that are free (not bonded).

The Octet Rule and Chemical Bonds

As was noted earlier, valence (outer shell) electrons are generally involved in chemical bonding. FIGURE 2.7 shows a shorthand way of representing the number of valence electrons for selected elements in each group. Notice that the elements in Group I have one valence electron, those in Group II have two valence electrons, and so on, up to eight valence electrons in Group VIII.

The noble gases (except helium) have very stable electron arrangements with eight valence electrons and, therefore, tend to lack chemical reactivity. Many other atoms gain, lose, or share electrons during chemical reactions, ending up with electron arrangements of the noble gases. This observation led to a chemical guideline known as the **octet rule**: *Atoms tend to gain, lose, or share electrons until they are surrounded by eight valence electrons*. Although there are exceptions to the octet rule, it is a useful rule of thumb for understanding chemical bonding.

When an atom's outer shell does not contain eight electrons, it is likely to chemically bond to other atoms to fill its shell. A **chemical bond** is a transfer or sharing of electrons that allows each atom to attain a full valence shell of electrons. Some atoms do this by transferring all their valence electrons to other atoms so that an inner shell becomes the full valence shell.

When the valence electrons are transferred between the elements to form ions, the bond is an *ionic bond*. When the electrons are shared between the atoms, the bond is a *covalent bond*. When the valence electrons are shared among all the atoms in a substance, the bonding is *metallic*.

FIGURE 2.7 Dot Diagrams for Certain Elements Each dot represents a valence electron found in the outermost principal shell.

Electron Dot Diagrams for Some Representative Elements							
I	II	III	IV	V	VI	VII	VIII
H •							He ••
Li •	• Be •	• B •	• C •	• N •	• O •	• F •	• Ne ••
Na •	• Mg •	• Al •	• Si •	• P •	• S •	• Cl •	• Ar ••
K •	• Ca •	• Ga •	• Ge •	• As •	• Se •	• Br •	• Kr ••

Ionic Bonds: Electrons Transferred

Perhaps the easiest type of bond to visualize is the *ionic bond*, in which one atom gives up one or more of its valence electrons to another atom to form **ions**—*positively and negatively charged atoms*. The atom that loses electrons becomes a positive ion, and the atom that gains electrons becomes a negative ion. Oppositely charged ions are strongly attracted to one another and join to form ionic compounds.

Consider the ionic bonding that occurs between sodium (Na) and chlorine (Cl) to produce the solid ionic compound sodium chloride—the mineral halite (common table salt). Notice in FIGURE 2.8A that a sodium atom gives up its single valence electron to chlorine and, as a result, becomes a positively charged sodium ion. Chlorine, on the other hand, gains one electron and becomes a negatively charged chloride ion. We know that ions having unlike charges attract. Thus, an **ionic bond** is an attraction of oppositely charged ions to one another, producing an electrically neutral ionic compound.

FIGURE 2.8B illustrates the arrangement of sodium and chlorine ions in ordinary table salt. Notice that salt consists of alternating sodium and chlorine ions, positioned in such a manner that each positive ion is attracted to and surrounded on all sides by negative ions and vice versa. This arrangement maximizes the attraction between ions with opposite charges while minimizing the repulsion between ions with identical charges. Thus, ionic compounds consist of an orderly arrangement of oppositely charged ions assembled in a definite ratio that provides overall electrical neutrality.

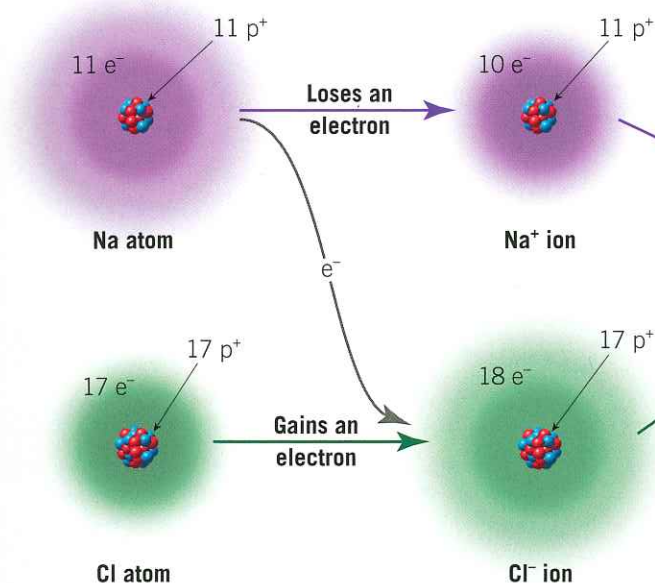
The properties of a chemical compound are dramatically different from the properties of the various elements comprising it. For example, sodium is a soft silvery metal that is extremely reactive and poisonous. If you were to consume even a small amount of elemental sodium, you would need immediate medical attention. Chlorine, a green poisonous gas, is so toxic that it was used as a chemical weapon during World War I. Together, however, these elements produce sodium chloride, a harmless flavor enhancer that we call table salt. Thus, when elements combine to form compounds, their properties change significantly.

Covalent Bonds: Electron Sharing

Sometimes the forces that hold atoms together cannot be understood on the basis of the attraction of oppositely charged ions. One example is the hydrogen molecule (H_2), in which the two hydrogen atoms are held together tightly, and no ions are present. The strong attractive force that holds two hydrogen atoms together results from a **covalent bond**, a *chemical bond formed by the sharing of a pair of electrons between atoms*.

Imagine two hydrogen atoms (each with one proton and one electron) approaching one another as shown in FIGURE 2.9. Once they meet, the electron configuration will change so that

A. The transfer of an electron from a sodium (Na) to a chlorine (Cl) atom leads to the formation of a Na^+ ion and a Cl^- ion.



B. The arrangement of Na^+ and Cl^- in the solid ionic compound sodium chloride (NaCl), table salt.

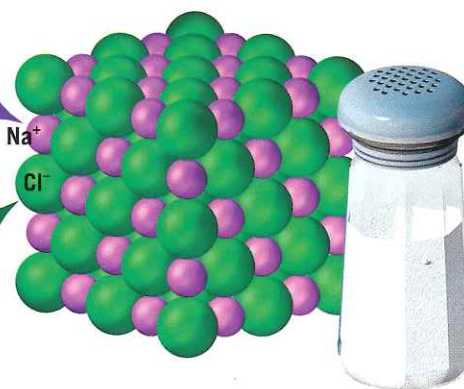


FIGURE 2.8 Formation of the Ionic Compound Sodium Chloride

both electrons will primarily occupy the space between the atoms. In other words, the two electrons are shared by both hydrogen atoms and are attracted simultaneously by the positive charge of the proton in the nucleus of each atom. Although hydrogen atoms do not form ions, the force that holds these atoms together arises from the attraction of oppositely charged particles—positively charged protons in the nuclei and negatively charged electrons that surround these nuclei.

Two hydrogen atoms combine to form a hydrogen molecule, held together by the attraction of oppositely charged particles—positively charged protons in each nucleus and negatively charged electrons that surround these nuclei.

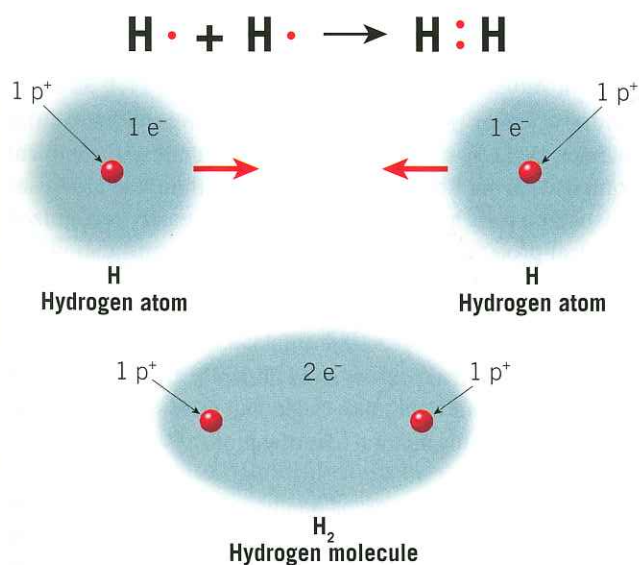


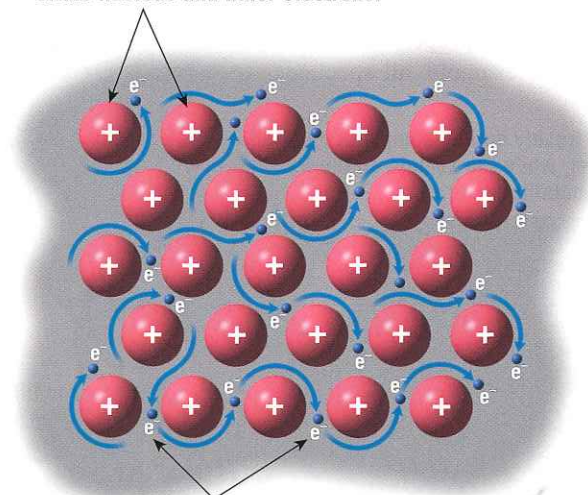
FIGURE 2.9 Covalent Bonding of Two Hydrogen Atoms (H) to Form a Hydrogen Molecule (H_2) When hydrogen atoms bond, the negatively charged electrons are shared by both hydrogen atoms and attracted simultaneously by the positive charge of the proton in the nucleus of each atom.

Metallic Bonds: Electrons Free to Move

A few minerals, such as native gold, silver, and copper, are made entirely of metal atoms that are packed tightly together in an orderly way. The bonding that holds these atoms together is the result of each atom contributing its valence electrons to a common pool of electrons that are free to move throughout the entire metallic structure. The contribution of one or more valence electrons leaves an array of positive ions immersed in a "sea" of valence electrons, as shown in **FIGURE 2.10**.

The attraction between the "sea" of negatively charged electrons and the positive ions produces the **metallic bonds** that give metals their unique properties. Metals are good conductors

A. The central core of each metallic atom, which has an overall positive charge, consists of the nucleus and inner electrons.



B. A "sea" of negatively charged outer electrons, that are free to move throughout the structure, surrounds the metallic atoms.

FIGURE 2.10 Metallic Bonds Metallic bonding is a result of each atom contributing its valence electrons to a common pool of electrons that are free to move throughout the entire metallic structure. The attraction between the "sea" of negatively charged electrons and the positive ions produces the metallic bonds that give metals their unique properties.

EYE ON EARTH



The accompanying image is of the world's largest open-pit gold mine, located near Kalgoorlie, Australia. Known as the Super Pit, it originally consisted of a number of small underground mines that were consolidated into a single open-pit mine. Each year, about 28 tons of gold are extracted from the 15 million tons of rock that are shattered by blasting and then transported to the surface.

QUESTION 1 Calculate the average percentage of gold extracted from the rock removed each year from the Super Pit.

QUESTION 2 What is one environmental advantage that underground mining has over open-pit mining?

QUESTION 3 If you had been employed at this mine, what change in working conditions would you have seen as it evolved from an underground mine to an open-pit mine?

McPHOTO/AGE Fotostock



of electricity because the valence electrons are free to move from one atom to another. Metals are also *malleable*, which means they can be hammered into thin sheets, and *ductile*, which means they can be drawn into thin wires. By contrast, ionic and covalent solids tend to be brittle and fracture when stress is applied. Consider the difference between dropping a metal frying pan and a ceramic plate onto a concrete floor.

2.3 CONCEPT CHECKS

- 1 What is the difference between an atom and an ion?
- 2 What occurs in an atom to produce a positive ion? A negative ion?
- 3 Briefly distinguish among ionic, covalent, and metallic bonding and describe the role that electrons play in each.

2.4 PROPERTIES OF A MINERAL

List and describe the properties that are used in mineral identification.

Minerals have definite crystalline structures and chemical compositions that give them unique sets of physical and chemical properties shared by all samples of that mineral. For example, all specimens of halite have the same

hardness, have the same density, and break in a similar manner. Because a mineral's internal structure and chemical composition are difficult to determine without the aid of sophisticated tests and equipment, the more easily recognized physical properties are frequently used in identification.

FIGURE 2.11 Metallic versus Submetallic Luster

(Photo courtesy of E. J. Tarbuck)

The freshly broken sample of galena (right) displays a metallic luster, while the sample on the left is tarnished and has a submetallic luster.



Optical Properties

Of the many optical properties of minerals, their luster, their ability to transmit light, their color, and their streak are most frequently used for mineral identification.

Luster The appearance or quality of light reflected from the surface of a mineral is known as **luster**. Minerals that have the appearance of metals, regardless of color, are said to have a *metallic luster* (FIGURE 2.11). Some metallic minerals, such as native copper and galena, develop a dull coating, or tarnish, when exposed to the atmosphere. Because they



A. Fluorite

B. Quartz

SmartFigure 2.12 Color Variations in Minerals

Some minerals, such as fluorite and quartz, occur in a variety of colors. (Photo A by Dennis Tasa; photo B by E. J. Tarbuck)



are not as shiny as samples with freshly broken surfaces, these samples are often said to exhibit a *submetallic luster*.

Most minerals have a *nonmetallic luster* and are described using adjectives such as *vitreous* or *glassy*. Other nonmetallic minerals are described as having a *dull*, or *earthy*, luster (a dull appearance like soil) or a *pearly luster* (such as a pearl or the inside of a clamshell). Still others exhibit a *silky luster* (like satin cloth) or a *greasy luster* (as though coated in oil).

Ability to Transmit Light Another optical property used in the identification of minerals is the ability to transmit light. When no light is transmitted, the mineral is described as *opaque*; when light, but not an image, is transmitted through a mineral sample, the mineral is said to be *translucent*. When both light and an image are visible through the sample, the mineral is described as *transparent*.

Color Although **color** is generally the most conspicuous characteristic of any mineral, it is considered a diagnostic property of only a few minerals. Slight impurities in the common mineral quartz, for example, give it a variety of tints, including pink, purple, yellow, white, gray, and even black (FIGURE 2.12). Other minerals, such as tourmaline, also exhibit a variety of hues, with multiple colors sometimes occurring in the same sample. Thus, the use of color as a means of identification is often ambiguous or even misleading.

Streak The color of a mineral in powdered form, called **streak**, is often useful in identification. A mineral's streak is obtained by rubbing the mineral across a *streak plate* (a piece of unglazed porcelain) and observing the color of the mark it leaves (FIGURE 2.13). Although the color of a mineral may vary from sample to sample, its streak is usually consistent in color.

Streak can also help distinguish between minerals with metallic luster and those with nonmetallic luster. Metallic minerals generally have a dense, dark streak, whereas minerals with nonmetallic luster typically have a light-colored streak.

It should be noted that not all minerals produce a streak when rubbed across a streak plate. For example, the mineral

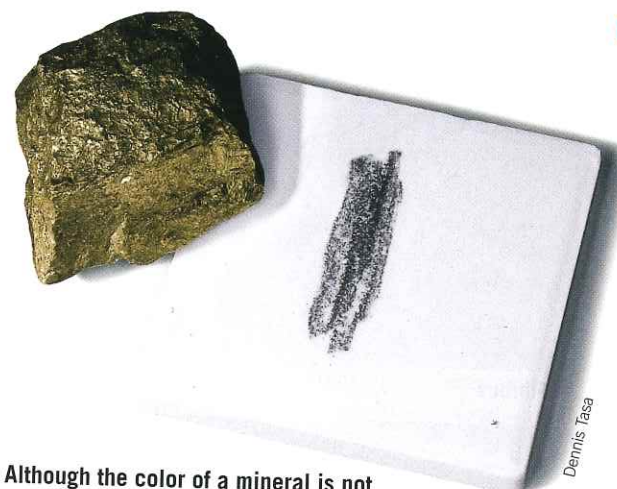


FIGURE 2.13 Streak

Although the color of a mineral is not always helpful in identification, the streak, which is the color of the powdered mineral, can be very useful.

quartz is harder than a porcelain streak plate. Therefore, no streak is observed for quartz.

Crystal Shape, or Habit

Mineralogists use the term **crystal shape**, or **habit**, to refer to the common or characteristic shape of individual crystals or aggregates of crystals. Some minerals tend to grow equally in all three dimensions, whereas others tend to be elongated in one direction or flattened if growth in one dimension is suppressed. A few minerals have crystals that exhibit regular polygons that are helpful in their identification. For example, magnetite crystals sometimes occur as octahedrons, garnets often form dodecahedrons, and halite and fluorite crystals tend to grow as cubes or near cubes. While minerals tend to have one common crystal shape, a few have two or more characteristic crystal shapes, such as the pyrite samples shown in FIGURE 2.14.

In addition, some mineral samples consist of numerous intergrown crystals that exhibit characteristic shapes that



FIGURE 2.14 Common Crystal Shapes of Pyrite

Although most minerals exhibit only one common crystal shape, some, such as pyrite, have two or more characteristic habits.

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SmartFigure 2.15 Common Crystal Habits A. Thin, rounded crystals that break into fibers. B. Elongated crystals that are flattened in one direction. C. Minerals that have stripes or bands of different color or texture. D. Groups of crystals that are shaped like cubes.



A. Fibrous



B. Bladed



C. Banded



D. Cubic crystals

are useful for identification. Terms commonly used to describe these and other crystal habits include *equant* (equidimensional), *bladed*, *fibrous*, *tabular*, *prismatic*, *platy*, *blocky*, *banded*, *granular*, and *botryoidal*. Some of these habits are pictured in **FIGURE 2.15**.

Mineral Strength

How easily minerals break or deform under stress is determined by the type and strength of the chemical bonds that hold the crystals together. Mineralogists use terms including *tenacity*, *hardness*, *cleavage*, and *fracture* to describe mineral strength and how minerals break when stress is applied.

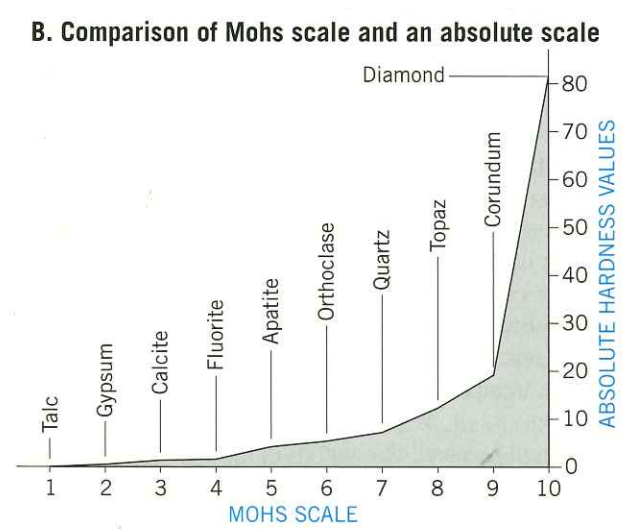
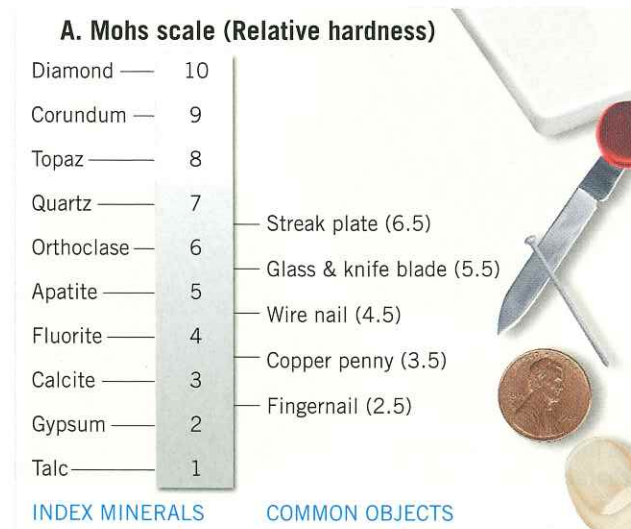
These include a human fingernail, which has a hardness of about 2.5, a copper penny (3.5), and a piece of glass (5.5). The mineral gypsum, which has a hardness of 2, can be easily scratched with a fingernail. On the other hand, the mineral calcite, which has a hardness of 3, will scratch a fingernail but will not scratch glass. Quartz, one of the hardest common minerals, will easily scratch glass. Diamonds, hardest of all, scratch anything, including other diamonds.

Cleavage In the crystal structure of many minerals, some atomic bonds are weaker than others. It is along these weak bonds that minerals tend to break when they are stressed. **Cleavage** (*kleiben* = carve) is the tendency of a mineral to break (cleave)

Hardness One of the most useful diagnostic properties is **hardness**, a measure of the resistance of a mineral to abrasion or scratching. This property can be determined by rubbing a mineral of unknown hardness against one of known hardness or vice versa. A numerical value of hardness can be obtained by using the **Mohs scale** of hardness, which consists of 10 minerals arranged in order from 1 (softest) to 10 (hardest), as shown in **FIGURE 2.16A**. It should be noted that the Mohs scale is a relative ranking, and it does not imply that mineral number 2, gypsum, is twice as hard as mineral 1, talc. In fact, gypsum is only slightly harder than talc, as **FIGURE 2.16B** indicates.

In the laboratory, other common objects can be used to determine the hardness of a

SmartFigure 2.16 Hardness Scales A. The Mohs scale of hardness, showing the hardness of some common objects. B. Relationship between the Mohs relative hardness scale and an absolute hardness scale.



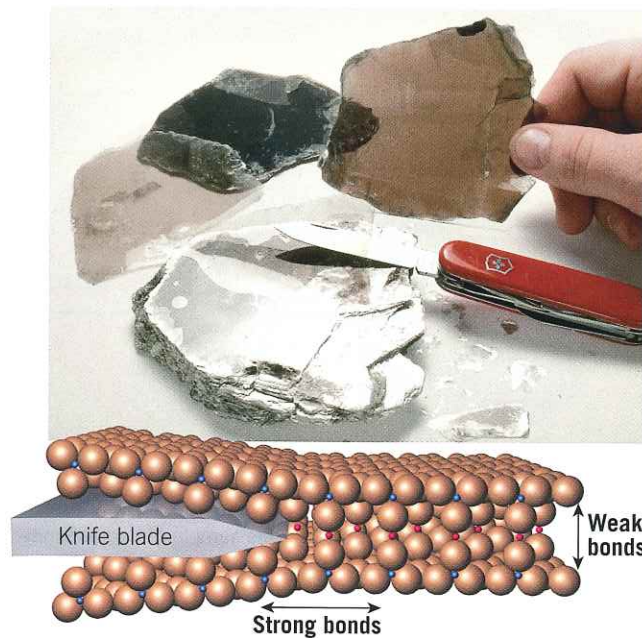


FIGURE 2.17 Micas Exhibit Perfect Cleavage The thin sheets shown here exhibit one plane of cleavage. (Photo by Chip Clark/Fundamental Photographs, NYC)

along planes of weak bonding. Not all minerals have cleavage, but those that do can be identified by the relatively smooth, flat surfaces that are produced when the mineral is broken.

The simplest type of cleavage is exhibited by the micas (**FIGURE 2.17**). Because these minerals have very weak bonds in one direction, they cleave to form thin, flat sheets. Some minerals have excellent cleavage in one, two, three, or more directions,

whereas others exhibit fair or poor cleavage, and still others have no cleavage at all. When minerals break evenly in more than one direction, cleavage is described by the *number of cleavage directions and the angle(s) at which they meet* (**FIGURE 2.18**).

Each cleavage surface that has a different orientation is counted as a different direction of cleavage. For example, some minerals cleave to form six-sided cubes. Because cubes are defined by three different sets of parallel planes that intersect at 90-degree angles, cleavage is described as *three directions of cleavage that meet at 90 degrees*.

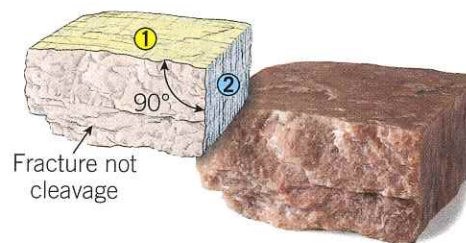
Do not confuse cleavage with crystal shape. When a mineral exhibits cleavage, it will break into pieces that all have the same geometry. By contrast, the smooth-sided quartz crystals shown in Figure 2.1 do not have cleavage. If broken, they fracture into shapes that do not resemble one another or the original crystals.

Fracture Minerals that have chemical bonds that are equally, or nearly equally, strong in all directions exhibit a property called **fracture**. When minerals fracture, most produce uneven surfaces and are described as exhibiting *irregular fracture*. However, some minerals, such as quartz, break into smooth, curved surfaces resembling broken glass. Such breaks are called *conchoidal fractures* (**FIGURE 2.19**). Still other minerals exhibit fractures that produce splinters or fibers that are referred to as *splintery fracture* and *fibrous fracture*, respectively.

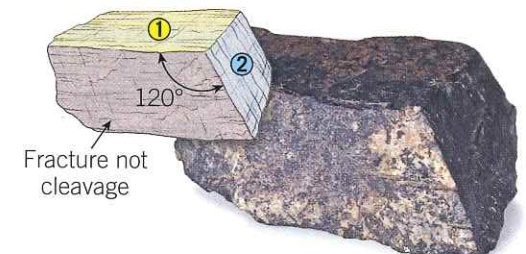
Tenacity The term **tenacity** describes a mineral's resistance to breaking, bending, cutting, or other forms of



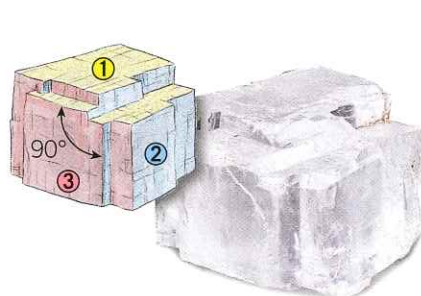
A. Cleavage in one direction.
Example: Muscovite



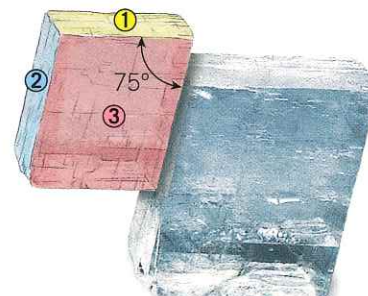
B. Cleavage in two directions at 90° angles.
Example: Feldspar



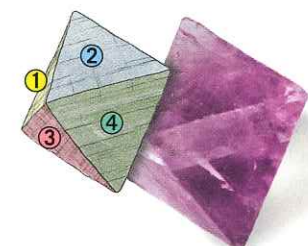
C. Cleavage in two directions not at 90° angles.
Example: Hornblende



D. Cleavage in three directions at 90° angles.
Example: Halite



E. Cleavage in three directions not at 90° angles.
Example: Calcite

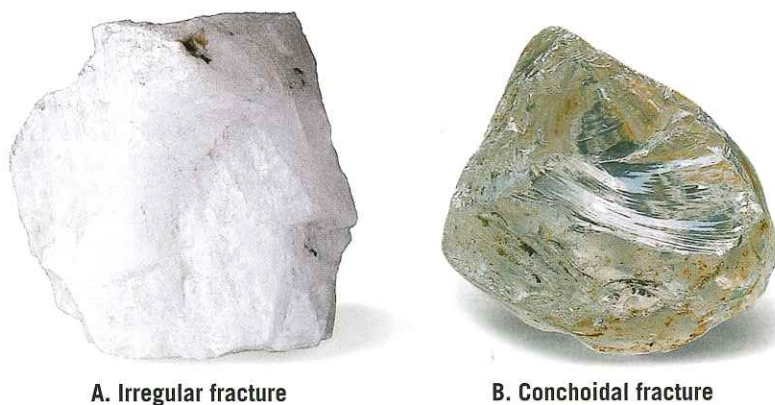


F. Cleavage in four directions.
Example: Fluorite



SmartFigure 2.18 Cleavage Directions Exhibited by Minerals (Photos by E. J. Tarbuck and Dennis Tasa)





A. Irregular fracture

B. Conchoidal fracture

FIGURE 2.19 Irregular versus Conchoidal Fracture (Photos by Dennis Tasa and E. J. Tarbuck)

deformation. Nonmetallic minerals, such as quartz and halite, tend to be *brittle* and fracture or exhibit cleavage when struck. By contrast, native metals such as copper and gold are *malleable*, and can be hammered into different shapes. In addition, minerals, including gypsum and talc, that can be cut into thin shavings are described as *sectile*. Still others, notably the micas, are *elastic* and will bend and snap back to their original shape after stress is released.

Density and Specific Gravity

Density, an important property of matter, is defined as mass per unit volume. Mineralogists often use a related measure called **specific gravity** to describe the density of minerals. Specific gravity is a number representing the ratio of a mineral's weight to the weight of an equal volume of water.

Most common minerals have a specific gravity between 2 and 3. For example, quartz has a specific gravity of 2.65. By contrast, some metallic minerals, such as pyrite, native copper, and magnetite, are more than twice as dense and thus have more than twice the specific gravity of quartz. Galena, an ore of lead, has a specific gravity of roughly 7.5, whereas the specific gravity of 24-karat gold is approximately 20.

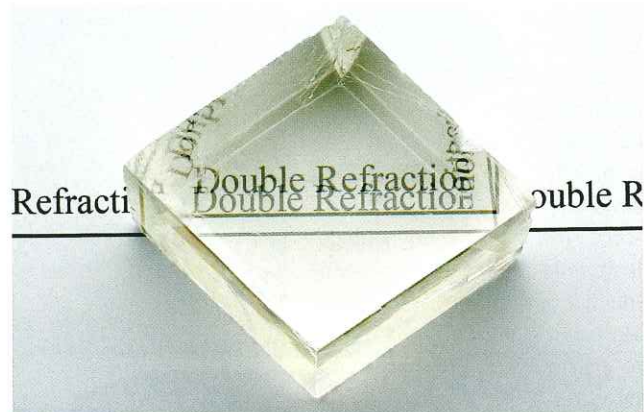
With a little practice, you can estimate the specific gravity of a mineral by hefting it in your hand. Does this mineral feel about as “heavy” as similar sized rocks you have handled? If the answer is “yes,” the specific gravity of the sample will likely be between 2.5 and 3.

Other Properties of Minerals

In addition to the properties discussed thus far, some minerals can be recognized by other distinctive properties. For example, halite is ordinary salt, so it can be quickly identified

**FIGURE 2.21 Calcite Reacting with a Weak Acid**

(Photo by Chip Clark/Fundamental Photographs, NYC)

**FIGURE 2.20 Double Refraction** This sample of calcite exhibits double refraction. (Photo by Chip Clark/Fundamental Photographs, NYC)

through taste. Talc and graphite both have distinctive feels: Talc feels soapy, and graphite feels greasy. Further, the streaks of many sulfur-bearing minerals smell like rotten eggs. A few minerals, such as magnetite (see Figure 2.31F), have a high iron content and can be picked up with a magnet, while some varieties (such as lodestone) are natural magnets and will pick up small iron-based objects such as pins and paper clips.

Moreover, some minerals exhibit special optical properties. For example, when a transparent piece of calcite is placed over printed text, the letters appear twice. This optical property is known as *double refraction* (FIGURE 2.20).

One very simple chemical test involves placing a drop of dilute hydrochloric acid from a dropper bottle onto a freshly broken mineral surface. Using this technique, certain minerals, called carbonates, will effervesce (fizz) as carbon dioxide gas is released (FIGURE 2.21). This test is especially useful in identifying the common carbonate mineral calcite.

2.4 CONCEPT CHECKS

- 1 Define *luster*.
- 2 Why is color not always a useful property in mineral identification? Give an example of a mineral that supports your answer.
- 3 What differentiates cleavage from fracture?
- 4 What do we mean when we refer to a mineral's *tenacity*? List three terms that describe tenacity.
- 5 What simple chemical test is useful in the identification of the mineral calcite?

2.5 MINERAL GROUPS

List the common silicate and nonsilicate minerals and describe the characteristics of each group.

More than 4000 minerals have been named, and several new ones are identified each year. Fortunately for students who are beginning to study minerals, no more than a few dozen are abundant! Collectively, these few make up most of the

rocks of Earth's crust and, as such, they are often referred to as the **rock-forming minerals**.

Although less abundant, many other minerals are used extensively in the manufacture of products and are called

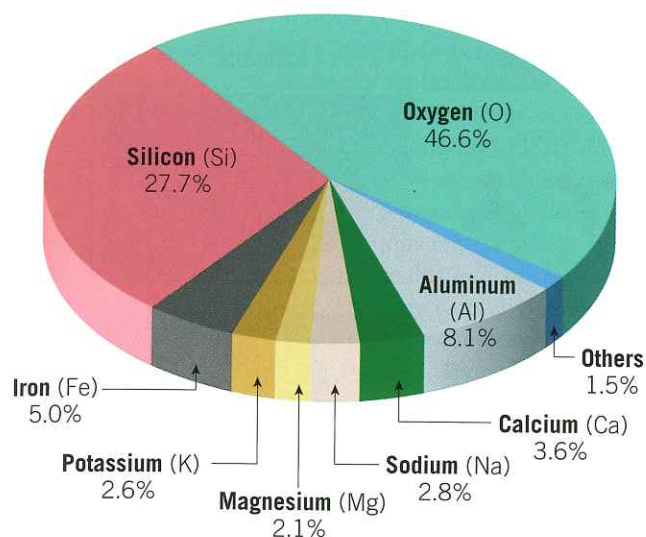


FIGURE 2.22 The Eight Most Abundant Elements in the Continental Crust

economic minerals. However, rock-forming minerals and economic minerals are not mutually exclusive groups. When found in large deposits, some rock-forming minerals are economically significant. One example is the mineral calcite, which is the primary component of the sedimentary rock limestone and has many uses, including being used in the production of cement.

It is worth noting that *only eight elements* make up the vast majority of the rock-forming minerals and represent more than 98 percent (by weight) of the continental crust (**FIGURE 2.22**). These elements, in order of abundance from most to least, are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). As shown in Figure 2.22, silicon and oxygen are by far the most common elements in Earth's crust. Furthermore, these two elements readily combine to form the basic “building block” for the most common mineral group, the **silicates**. More than 800 silicate minerals are known, and they account for more than 90 percent of Earth's crust.

Because other mineral groups are far less abundant in Earth's crust than the silicates, they are often grouped together under the heading **nonsilicates**. Although not as common as silicates, some nonsilicate minerals are very important economically. They provide us with iron and aluminum to build automobiles, gypsum for plaster and drywall for home construction, and copper wire that carries electricity and connects us to the Internet. Some common nonsilicate mineral groups include the carbonates, sulfates, and halides. In addition to their economic importance, these mineral groups include members that are major constituents in sediments and sedimentary rocks.

Silicate Minerals

Each of the silicate minerals contains oxygen and silicon atoms. Except for a few silicate minerals such as quartz, most silicate minerals also contain one or more additional

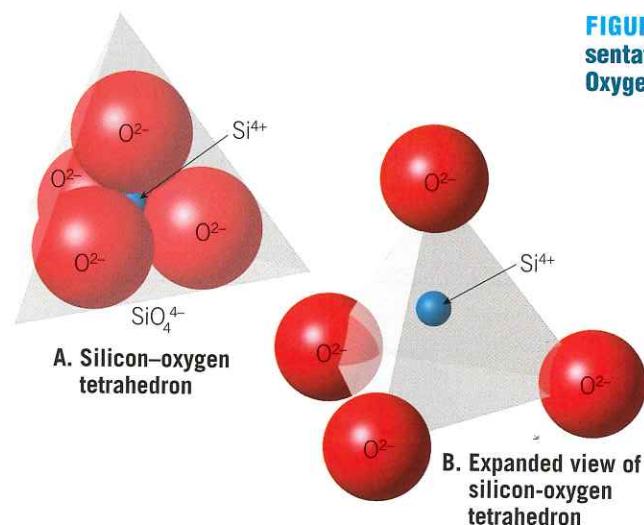


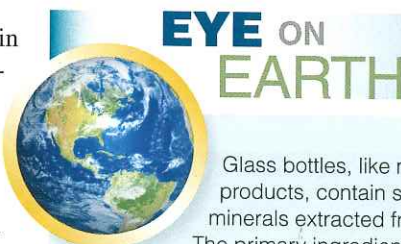
FIGURE 2.23 Two Representations of the Silicon–Oxygen Tetrahedron

elements in their crystalline structure. These elements give rise to the great variety of silicate minerals and their varied properties.

All silicates have the same fundamental building block, the **silicon–oxygen tetrahedron** (*tetra* = four, *hedra* = a base). This structure consists of four oxygen atoms surrounding a much smaller silicon atom, as shown in **FIGURE 2.23**. In some minerals, the tetrahedra are joined into chains, sheets, or three-dimensional networks by sharing oxygen atoms (**FIGURE 2.24**). These larger silicate structures are then connected to one another by other elements. The primary elements that join silicate structures are iron (Fe), magnesium (Mg), potassium (K), sodium (Na), and calcium (Ca).

Major groups of silicate minerals and common examples are given in Figure 2.24. The *feldspars* are by far the most plentiful group, comprising over 50 percent of Earth's crust. *Quartz*, the second-most-abundant mineral in the continental crust, is the only common mineral made completely of silicon and oxygen.

Notice in Figure 2.24 that each mineral *group* has a particular silicate *structure*. A relationship exists between this internal structure of a mineral and the *cleavage* it exhibits. Because



EYE ON EARTH

Glass bottles, like most other manufactured products, contain substances obtained from minerals extracted from Earth's crust and oceans. The primary ingredient in commercially produced glass bottles is the mineral quartz. Glass also contains lesser amounts of the mineral calcite. (Photo by Chris Brignell/Shutterstock)





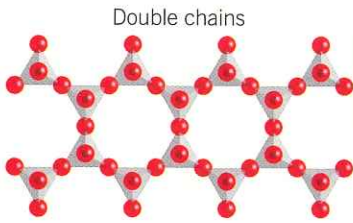

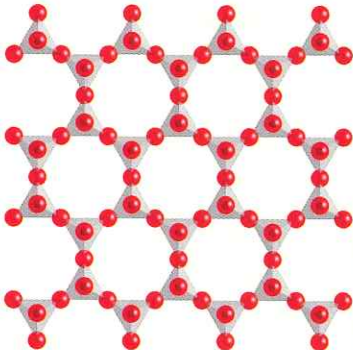


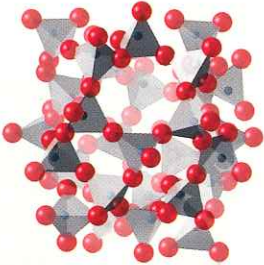
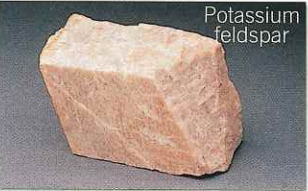

QUESTION 1 In what mineral group does quartz belong?

QUESTION 2 Glass beer bottles are usually clear, green, or brown. Based on what you know about how the mineral quartz is colored, what do glass manufacturers do to get green and brown bottles?

QUESTION 3 Why do you suppose some brewers start using brown bottles rather than the green bottles that were popular until the 1930s?



FIGURE 2.24 Common Silicate Minerals Note that the complexity of the silicate structure increases from the top of the chart to the bottom. (Photos by Dennis Tasa and E. J. Tarbuck)

Mineral/Formula	Cleavage	Silicate Structure	Example
Olivine group (Mg, Fe) ₂ SiO ₄	None	Single tetrahedra 	 Olivine
Pyroxene group (Augite) (Mg, Fe)SiO ₃	Two planes at 90°	Single chains 	 Augite
Amphibole group (Hornblende) Ca ₂ (Fe, Mg) ₅ Si ₈ O ₂₂ (OH) ₂	Two planes at 60° and 120°	Double chains 	 Hornblende
Micas	One plane	Sheets 	Biotite K(Mg, Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂  Biotite
Muscovite KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂  Muscovite			
Feldspars	Two planes at 90°	Three-dimensional networks 	Potassium feldspar (Orthoclase) KAlSi ₃ O ₈  Potassium feldspar
Plagioclase (Ca, Na)AlSi ₃ O ₈			Quartz SiO ₂  Quartz

the silicon–oxygen bonds are strong, silicate minerals tend to cleave between the silicon–oxygen structures rather than across them. For example, the micas have a sheet structure and thus tend to cleave into flat plates (see muscovite in Figure 2.18A). Quartz, which has equally strong silicon–oxygen bonds in all directions, has no cleavage but fractures instead.

How do silicate minerals form? Most of them crystallize from molten rock as it cools. This cooling can occur at or near Earth's surface (low temperature and pressure) or at great depths (high temperature and pressure). The *environment* during crystallization and the *chemical composition of the molten rock* mainly determine which minerals are produced.

For example, the silicate mineral olivine crystallizes at high temperatures (about 1200°C [2200°F]), whereas quartz crystallizes at much lower temperatures (about 700°C [1300°F]).

In addition, some silicate minerals form at Earth's surface from the weathered products of other silicate minerals. Clay minerals are an example. Still other silicate minerals are formed under the extreme pressures associated with mountain building. Each silicate mineral, therefore, has a structure and a chemical composition that *indicate the conditions under which it formed*. Thus, by carefully examining the mineral makeup of rocks, geologists can often determine the circumstances under which the rocks formed.

We will now examine some of the most common silicate minerals, which are divided into two major groups based on their chemical makeup.

Common Light Silicate Minerals The most common light silicate minerals are the feldspars, quartz, muscovite, and the clay minerals. Generally light in color and having a specific gravity of about 2.7, **light silicate minerals** contain varying amounts of aluminum, potassium, calcium, and sodium.

The most abundant mineral group, the *feldspars*, are found in many igneous, sedimentary, and metamorphic rocks (**FIGURE 2.25**). One group of feldspar minerals contains potassium ions in its crystalline structure and is referred to

Potassium Feldspar



A. Potassium feldspar crystal (orthoclase)



B. Potassium feldspar showing cleavage (orthoclase)

Plagioclase Feldspar



C. Sodium-rich plagioclase feldspar (albite)



D. Plagioclase feldspar showing striations (labradorite)

FIGURE 2.25 Feldspar Minerals A. Characteristic crystal form of potassium feldspar. B. Like this sample, most salmon-colored feldspar belongs to the potassium feldspar subgroup. C. Most sodium-rich plagioclase feldspar is light colored and has a porcelain luster. D. Calcium-rich plagioclase feldspar tends to be gray, blue-gray, or black in color. Labradorite, the variety shown here, exhibits striations on one of its crystal faces. (Photos by Dennis Tasa and E. J. Tarbuck)



A. Smoky quartz



B. Rose quartz



C. Milky quartz



D. Jasper

as *potassium feldspar*. The other group, called *plagioclase feldspar*, contains calcium and/or sodium ions (see Figure 2.25). All feldspar minerals have two directions of cleavage that meet at 90-degree angles and are relatively hard (6 on the Mohs scale). The only reliable way to physically differentiate the feldspars is to look for striations that are present on some cleavage surfaces of plagioclase feldspar (see Figure 2.25) but do not appear in potassium feldspar.

Quartz is a major constituent of many igneous, sedimentary, and metamorphic rocks. Found in a wide variety of colors (caused by impurities), quartz is quite hard (7 on the Mohs scale) and exhibits conchoidal fracture when broken (**FIGURE 2.26**). Pure quartz is clear, and if allowed to grow without interference, it will develop hexagonal crystals with pyramid-shaped ends (see Figure 2.1).

Another light silicate mineral, *muscovite*, is an abundant member of the mica family and has excellent cleavage in one direction. Muscovite is relatively soft (2.5 to 3 on the Mohs scale).

Clay minerals are light silicates that typically form as products of chemical weathering of igneous rocks. They make up much of the surface material we call soil, and nearly half of the volume of sedimentary rocks is composed of clay minerals. Kaolinite is a common clay mineral formed from the weathering of feldspar (**FIGURE 2.27**).



Dennis Tasa

FIGURE 2.26 Quartz Is One of the Most Common Minerals and Has Many Varieties A. Smoky quartz is commonly found in coarse-grained igneous rocks. B. Rose quartz owes its color to small amounts of titanium. C. Milky quartz often occurs in veins that occasionally contain gold. D. Jasper is a variety of quartz composed of minute crystals. (Photos by Dennis Tasa and E. J. Tarbuck)



Olivine-rich peridotite (variety dunite)

FIGURE 2.28 Olivine

Commonly black to olive green in color, olivine has a glassy luster and a granular appearance. Olivine is commonly found in the igneous rock basalt.

Common Dark Silicate Minerals The dark silicate minerals contain iron and magnesium in their crystalline structures and include the pyroxenes, amphiboles, olivine, biotite, and garnet. Iron gives the dark silicates their color and contributes to their high specific gravity, which is between 3.2 and 3.6, significantly greater than the specific gravity of the light silicate minerals.

Olivine is an important group of dark silicate minerals that are major constituents of dark-colored igneous rocks. Abundant in Earth's upper mantle, olivine is black to olive green in color, has a glassy luster, and often forms small crystals which gives it a granular appearance (FIGURE 2.28).

The *pyroxenes* are a group of dark silicate minerals that are important components of dark-colored igneous rocks. The most common member, *augite*, is a black, opaque mineral with two directions of cleavage that meet at nearly 90-degree angles (FIGURE 2.29A).

The *amphibole group*, the most common of which is *hornblende*, is usually dark green to black in color (FIGURE 2.29B). Except for its cleavage angles, which are about 60 degrees and 120 degrees, hornblende is very similar in appearance to augite. Found in igneous rocks, hornblende makes up the dark portion of otherwise light-colored rocks.

Biotite is the dark, iron-rich member of the mica family. Like other micas, biotite possesses a sheet structure that gives it excellent cleavage in one direction. Biotite's shiny appearance helps distinguish it from other dark silicate minerals. Like hornblende, biotite is a common constituent of most light-colored igneous rocks, including granite.

Another dark silicate is *garnet* (FIGURE 2.30). Much like olivine, garnet has a glassy luster, lacks cleavage, and exhibits conchoidal fracture. Although the colors of garnet are varied, the mineral is most often brown to deep red, and in transparent form, it is used as a gemstone.

FIGURE 2.29 Augite and Hornblende

These dark-colored silicate minerals are common constituents of a variety of igneous rocks.

(Photos by E. J. Tarbuck)



A. Augite



B. Hornblende

Important Nonsilicate Minerals

Nonsilicate minerals are typically divided into groups, based on the negatively charged ion or complex ion that the members have in common. For example, the *oxides* contain the negative oxygen ions (O^{2-}), which are bonded to one or more kinds of positive ions. Thus, within each mineral group, the basic structure and type of bonding is similar. As a result, the minerals in each group have similar physical properties that are useful in mineral identification.

Although the nonsilicates make up only about 8 percent of Earth's crust, some minerals, such as gypsum, calcite, and halite, occur as constituents in sedimentary rocks in significant amounts. Furthermore, many others are important economically. TABLE 2.1 lists some of the nonsilicate mineral groups and a few examples of each. A brief



FIGURE 2.30 Well-formed Garnet Crystal Garnets come in a variety of colors and are commonly found in mica-rich metamorphic rocks.

(Photo by E. J. Tarbuck)

TABLE 2.1 Common Nonsilicate Mineral Groups

Mineral Groups (key ion[s] or element[s])	Mineral Name	Chemical Formula	Economic Use
Carbonates (CO_3^{2-})	Calcite	$CaCO_3$	Portland cement, lime
	Dolomite	$CaMg(CO_3)_2$	Portland cement, lime
Halides (Cl^{1-} , F^{1-} , Br^{1-})	Halite	$NaCl$	Common salt
	Fluorite	CaF_2	Used in steelmaking
	Sylvite	KCl	Fertilizer
Oxides (O^{2-})	Hematite	Fe_2O_3	Ore of iron, pigment
	Magnetite	Fe_3O_4	Ore of iron
	Corundum	Al_2O_3	Gemstone, abrasive
	Ice	H_2O	Solid form of water
Sulfides (S^{2-})	Galena	PbS	Ore of lead
	Sphalerite	ZnS	Ore of zinc
	Pyrite	FeS_2	Sulfuric acid production
	Chalcopyrite	$CuFeS_2$	Ore of copper
Sulfates (SO_4^{2-})	Cinnabar	HgS	Ore of mercury
	Gypsum	$CaSO_4 \cdot 2H_2O$	Plaster
	Anhydrite	$CaSO_4$	Plaster
Native elements (single elements)	Barite	$BaSO_4$	Drilling mud
	Gold	Au	Trade, jewelry
	Copper	Cu	Electrical conductor
	Diamond	C	Gemstone, abrasive
	Sulfur	S	Sulfa drugs, chemicals
	Graphite	C	Pencil lead, dry lubricant
	Silver	Ag	Jewelry, photography
	Platinum	Pt	Catalyst



FIGURE 2.31 Important Nonsilicate Minerals

(Photos by Dennis Tasa and E. J. Tarbuck)

discussion of a few of the most common nonsilicate minerals follows.

Some of the most common nonsilicate minerals belong to one of three classes of minerals: the carbonates (CO_3^{-2}), the sulfates (SO_4^{-2}), and the halides (Cl^{-1} , F^{-1} , Br^{-1}). The carbonate minerals are much simpler structurally than the silicates. These minerals are *calcite*, CaCO_3 (calcium carbonate), and *dolomite*, $\text{CaMg}(\text{CO}_3)_2$ (calcium/magnesium carbonate) (FIGURE 2.31A, B). Calcite and dolomite are usually found together as the primary constituents in the sedimentary rocks limestone and dolostone. When calcite is the dominant mineral, the rock is called *limestone*, whereas *dolostone* results from a predominance of dolomite. Limestone has many uses, including as road aggregate, as building stone, and as the main ingredient in Portland cement.

Two other nonsilicate minerals frequently found in sedimentary rocks are *halite* and *gypsum* (FIGURE 2.31C, D). Both minerals are commonly found in thick layers that are the last vestiges of ancient seas that have long since evaporated (FIGURE 2.32). Like limestone, both halite and gypsum are important nonmetallic resources. Halite is the mineral name for common table salt (NaCl). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which is calcium sulfate with water bound into the

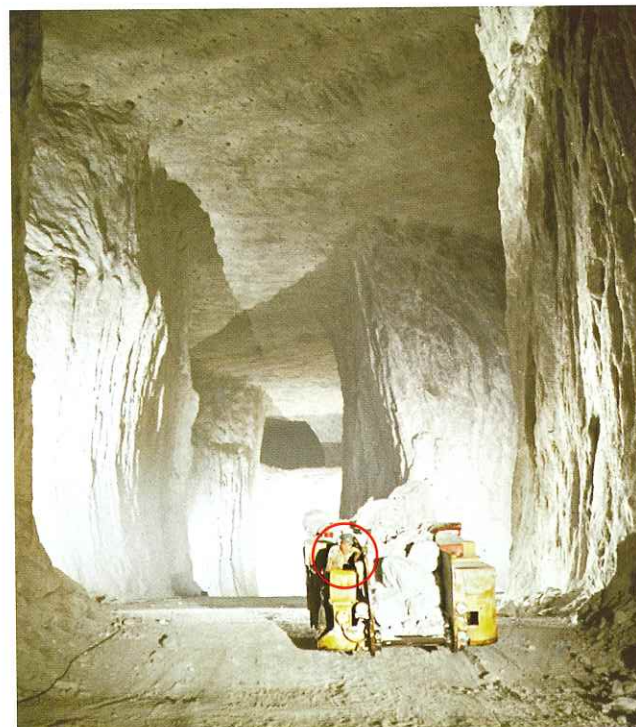


FIGURE 2.32 Thick Bed of Halite Exposed in an Underground Mine

Halite (salt) mine in Grand Saline, Texas. Note the person for scale. (Photo by Tom Bochsrer/Pearson Education)

structure, is the mineral of which plaster and other similar building materials are composed.

Most nonsilicate mineral classes contain members that are prized for their economic value. This includes the oxides, whose members *hematite* and *magnetite* are important ores of iron (see **FIGURE 2.31E, F**). Also significant are the sulfides, which are basically compounds of sulfur (S) and one or more metals. Examples of important sulfide minerals include galena (lead), sphalerite (zinc), and chalcopyrite (copper). In addition, native elements—including gold, silver, and carbon (diamonds)—plus a host of other nonsilicate minerals—fluorite (flux in making steel), corundum (gemstone, abrasive), and uraninite (a uranium source)—are important economically.

2.5 CONCEPT CHECKS

- 1 List the eight most common elements in Earth's crust, in order of abundance (most to least).
- 2 Explain the difference between the terms *silicon* and *silicate*.
- 3 Draw a sketch of the silicon–oxygen tetrahedron.
- 4 What is the most abundant mineral in Earth's crust?
- 5 List six common nonsilicate mineral groups. What key ion(s) or element(s) define each group?
- 6 What is the most common carbonate mineral?
- 7 List eight common nonsilicate minerals and their economic uses.

2.6 NATURAL RESOURCES Discuss Earth's natural resources in terms of renewability. Differentiate between mineral resources and ore deposits.

Earth's crust and oceans are the source of a wide variety of useful and valuable materials. From the first use of clay to make pottery nearly 10,000 years ago, the use of Earth materials has expanded and contributed to societies becoming more complex. Materials we extract from Earth are the basis of modern civilization. Mineral and energy resources from Earth's crust are the raw materials from which we make all the products we use.

Natural resources are typically grouped into broad categories according to their ability to be regenerated (renewable or nonrenewable) or their origin, or type. Here we will consider mineral resources. However, other indispensable natural resources exist, including air, water, and solar energy.

FIGURE 2.33 Solar Energy Is Renewable These solar collectors focus sunlight onto collection pipes filled with a fluid. The heat is used to make steam that drives turbines used to generate electricity. (Photo by Jim West/Alamy)

Renewable Versus Nonrenewable Resources

Resources classified as **renewable** can be replenished over relatively short time spans. Common examples are corn used

for food and for making ethanol, natural fibers such as cotton for clothing, and forest products for lumber and paper. Energy from flowing water, wind, and the Sun are also considered renewable (**FIGURE 2.33**).

By contrast, many other basic resources are classified as **nonrenewable**. Important metals such as iron, aluminum, and copper fall into this category, as do our most important fuels: oil, natural gas, and coal. Although these and other resources form continuously, the processes that create them are so slow that significant deposits take millions of years to accumulate. Thus, for all practical purposes, Earth contains fixed quantities of these substances. The present supplies will be depleted as they are mined or pumped from the ground. Although some nonrenewable resources, such as the aluminum we use for containers, can be recycled, others, such as the oil used for fuel, cannot.

Mineral Resources

Today, practically every manufactured product contains materials obtained from minerals. Table 2.1 lists some of the most economically important mineral groups. **Mineral resources** are those occurrences of useful minerals that are formed in such quantities that eventual extraction is reasonably certain. Mineral resources include deposits of metallic minerals that can be presently extracted profitably, as well as known deposits that are not yet economically or technologically recoverable. Materials used for such purposes as building stone, road aggregate, abrasives, ceramics, and fertilizers are not usually called mineral resources; rather, they are classified as industrial rocks and minerals.

An **ore deposit** is a naturally occurring concentration of one or more metallic minerals that can be extracted economically. In common usage, the term *ore* is also applied to some nonmetallic minerals such as fluorite and sulfur. Recall that more than



98 percent of Earth's crust is composed of only eight elements, and except for oxygen and silicon, all other elements make up a relatively small fraction of common crustal rocks (see Figure 2.22). Indeed, the natural concentrations of many elements are exceedingly small. A deposit containing the average concentration of an element such as gold has no economic value because the cost of extracting it greatly exceeds the value of the gold that could be recovered.

In order to have economic value, an ore deposit must be highly concentrated. For example, copper makes up about 0.0135 percent of the crust. For a deposit to be considered a copper ore, it must contain a concentration of copper that is about 100 times this amount, or 2.35 percent. Aluminum, on the other hand, represents 8.13 percent of the crust and can be extracted profitably when it is found in concentrations about four times that amount.

It is important to understand that due to economic or technological changes, a deposit may either become profitable to extract or lose its profitability. If the demand for a metal increases and its value rises sufficiently, the status of a previously unprofitable deposit can be upgraded from a mineral to an ore. Technological advances that allow a resource to be extracted more efficiently and, thus, more profitably than before may also trigger a change of status.

Conversely, changing economic factors can turn what was once a profitable ore deposit into an unprofitable mineral deposit. This situation was illustrated at the copper mining operation located at Bingham Canyon, Utah, one of the largest open-pit mines on Earth (FIGURE 2.34). Mining was halted there in 1985 because outmoded equipment had driven

the cost of extracting the copper beyond the current selling price. The mine owners responded by replacing an antiquated 1000-car railroad with more modern conveyor belts and dump trucks for efficiently transporting the ore and waste. The advanced equipment accounted for a cost reduction of nearly 30 percent, ultimately returning the copper mine operation to profitability. Today Bingham Canyon Mine produces about 25 percent of the refined copper in the United States.

Over the years, geologists have been keenly interested in learning how natural processes produce localized concentrations of essential minerals. One well-established fact is that occurrences of valuable mineral resources are closely related to the rock cycle. That is, the mechanisms that generate igneous, sedimentary, and metamorphic rocks, including the processes of weathering and erosion, play major roles in producing concentrated accumulations of useful elements.

Moreover, with the development of the theory of plate tectonics, geologists have added another tool for understanding the processes by which one rock is transformed into another. As these rock-forming processes are examined in the following chapters, we consider their role in producing some of our important mineral resources.

2.6 CONCEPT CHECKS

- 1 List three examples of renewable resources and three examples of nonrenewable resources.
- 2 Compare and contrast a *mineral resource* and an *ore deposit*.
- 3 Explain how a mineral deposit that previously could not be mined profitably might be upgraded to an ore deposit.

FIGURE 2.34 Aerial View of the Bingham Canyon Copper Mine Near Salt Lake City, Utah

Although the amount of copper in the rock is less than 0.5 percent, the huge volume of material removed and processed each day (over 250,000 tons) yields enough metal to be profitable. In addition to copper, this mine produces various amounts of gold, silver, and molybdenum. (Photo by Michael Collier)



Gemstones

Precious stones have been prized since antiquity. Although most gemstones are varieties of a particular mineral, misinformation abounds regarding gems and their mineral makeup.

Important Gemstones

Gemstones are classified in one of two categories: precious or semiprecious. Precious gems are rare and generally have hardnesses that exceed 9 on the Mohs scale. Therefore, they are more valuable and thus more expensive than semiprecious gems.

GEM	MINERAL NAME	PRIZED HUES
PRECIOUS		
Diamond	Diamond	Colorless, pinks, blues
Emerald	Beryl	Greens
Ruby	Corundum	Reds
Sapphire	Corundum	Blues
Opal	Opal	Brilliant hues
SEMI-PRECIOUS		
Alexandrite	Chrysoberyl	Variable
Amethyst	Quartz	Purples
Cat's-eye	Chrysoberyl	Yellows
Chalcedony	Quartz (agate)	Banded
Citrine	Quartz	Yellows
Garnet	Garnet	Red, greens
Jade	Jadeite or nephrite	Greens
Moonstone	Feldspar	Transparent blues
Peridot	Olivine	Olive greens
Smoky quartz	Quartz	Browns
Spinel	Spinel	Reds
Topaz	Topaz	Purples, reds
Tourmaline	Tourmaline	Reds, blue-greens
Turquoise	Turquoise	Blues
Zircon	Zircon	Reds



Reuters

The Famous Hope Diamond

The deep-blue Hope Diamond is a 45.52-carat gem that is thought to have been cut from a much larger 115-carat stone discovered in India in the mid-1600s. The original 115-carat stone was cut into a smaller gem that became part of the crown jewels of France and was in the possession of King Louis XVI and Marie Antoinette before they attempted to escape France. Stolen during the French Revolution in 1792, the gem is thought to have been recut to its present size and shape. In the 1800s, it became part of the collection of Henry Hope (hence its name) and is on display at the Smithsonian in Washington, DC.

What Constitutes a Gemstone?

When found in their natural state, most gemstones are dull and would be passed over by most people as "just another rock." Gems must be cut and polished by experienced professionals before their true beauty is displayed. Cutting and polishing is accomplished using abrasive material, most often tiny fragments of diamonds that are embedded in a metal disk.



Shutterstock

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Why are diamonds used as an abrasive material to cut and polish gemstones?

Charles D. Winters/ Photo Researchers, Inc.

Naming Gemstones

Most precious stones are given names that differ from their parent mineral. For example, sapphire is one of two gems that are varieties of the same mineral, corundum. Trace elements can produce vivid sapphires of nearly every color. Tiny amounts of titanium and iron in corundum produce the most prized blue sapphires. When the mineral corundum contains a sufficient quantity of chromium, it exhibits a brilliant red color. This variety of corundum is called ruby.

Rubies, like sapphires, are varieties of the mineral corundum

Sapphires, showing variations of colors

Dorling Kindersley

Greg C. Grace/ Alamy

2 CONCEPTS IN REVIEW

Matter and Minerals

2.1 MINERALS: BUILDING BLOCKS OF ROCKS

List the main characteristics that an Earth material must possess to be considered a mineral and describe each.

KEY TERMS: mineralogy, mineral, rock

- In Earth science, the word *mineral* refers to naturally occurring inorganic solids that possess an orderly crystalline structure and a characteristic chemical composition. The study of minerals is mineralogy.
- Minerals are the building blocks of rocks. Rocks are naturally occurring masses of minerals or mineral-like matter, such as natural glass or organic material.

2.2 ATOMS: BUILDING BLOCKS OF MINERALS

Compare and contrast the three primary particles contained in atoms.

KEY TERMS: atom, nucleus, proton, neutron, electron, valence electron, atomic number, element, periodic table, chemical compound

- Minerals are composed of atoms of one or more elements. The atoms of any element consist of the same three basic ingredients: protons, neutrons, and electrons.
- The number of protons in an atom is its atomic number. For example, an oxygen atom has eight protons, so its atomic number is eight. Protons and neutrons are approximately the same size and mass, but while protons are positively charged, neutrons have no charge.
- Electrons are much smaller than both protons and neutrons, and they weigh about 2000 times less. Each electron has a negative charge, equal in magnitude to the positive charge of a proton. Electrons swarm around an atom's nucleus at a distance, in several distinctive energy levels called principal shells. The electrons in the outermost principal shell, called valence electrons, are important when one atom bonds with other atoms to form chemical compounds.
- Elements with similar numbers of valence electrons tend to behave in similar ways. The periodic table displays these similarities in its graphical arrangement of the elements.

Q Use the periodic table to identify these geologically important elements by their number of protons: (A) 14, (B) 6, (C) 13, (D) 17, and (E) 26.

2.3 WHY ATOMS BOND

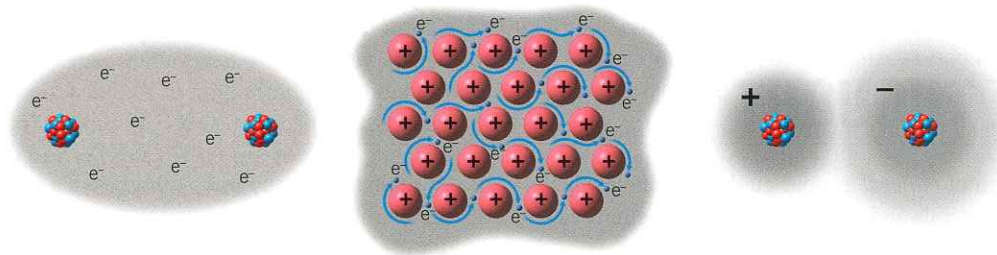
Distinguish among ionic bonds, covalent bonds, and metallic bonds.

KEY TERMS: octet rule, chemical bond, ion, ionic bond, covalent bond, metallic bond

- When atoms attract to other atoms, they can form chemical bonds, which generally involve the transfer or sharing of valence electrons. For most atoms, the most stable arrangement is to have eight electrons in the outermost principal shell. This idea is called the octet rule.

- Ionic bonds involve atoms of one element giving up electrons to atoms of another element, forming positively and negatively charged atoms called ions. Positively charged ions bond with negative ions to form ionic bonds.
- Covalent bonds involve the sharing of electrons between two adjacent atoms. The forces that holds these atoms together arises from the attraction of oppositely charged particles—protons in the nuclei and the electrons shared by the atoms.
- In metallic bonds, the sharing is more extensive: Electrons can freely move from one atom to the next throughout the entire mass.

Q Which of the situations in the diagram shows ionic bonding? What are its distinguishing characteristics?



2.4 PHYSICAL PROPERTIES OF MINERALS

List and describe the properties that are used in mineral identification.

KEY TERMS: luster, color, streak, crystal shape (habit), hardness, Mohs scale, cleavage, fracture, tenacity, density, specific gravity

- The composition and internal crystalline structure of a mineral give it specific physical properties. These properties can be used to tell minerals apart from each other and make minerals useful for specific human tasks.

- Luster is a mineral's ability to reflect light. The terms *transparent*, *translucent*, and *opaque* are used to describe the degree to which a mineral can transmit light. Color is an unreliable characteristic for identification, as slight impurities can "stain" minerals into misleading colors. A trustworthy characteristic is streak, the color of the powder generated by scraping a mineral against a porcelain streak plate.
- The shape that a crystal assumes as it grows is often useful for identification.
- Variations in the strength of chemical bonds give minerals properties such as tenacity (whether a mineral breaks in a brittle fashion or bends when stressed) and hardness (resistance to being scratched). Cleavage, the preferential breakage of a mineral along planes of weakly bonded atoms, is often useful in identifying minerals.
- The amount of matter packed into a given volume determines a mineral's density. To compare the density of minerals, mineralogists find it simplest to use a related property, specific gravity, which is the ratio between a mineral's density and the density of water.
- Other properties are diagnostic for certain minerals but rare in most others. A particular smell, taste, or feel; reaction to hydrochloric acid; magnetism; and double refraction are examples.



Quartz

Dennis Tasa



Calcite

Dennis Tasa

Q Research the minerals *quartz* and *calcite*. List three physical properties that may be used to distinguish one from the other.

2.5 MINERAL GROUPS

List the common silicate and nonsilicate minerals and describe the characteristics of each group.

KEY TERMS: rock-forming mineral, economic mineral, silicate, nonsilicate, silicon–oxygen tetrahedron, light silicate mineral, dark silicate mineral

- Silicate minerals have a basic building block in common: a small pyramid-shaped structure that consists of one silicon atom surrounded by four oxygen atoms. Because this structure has four sides, it is called the silicon–oxygen tetrahedron. Neighboring tetrahedra can share some of their oxygen atoms, causing them to develop long chains or sheet structures.
- Silicate minerals make up the most common mineral class on Earth. They are subdivided into minerals that contain iron and/or magnesium (dark silicates) and those that do not (light silicates). The light silicate minerals are generally light in color and have relatively low specific gravities. Feldspar, quartz, muscovite, and clay minerals are examples. The dark silicate minerals are generally dark in color and relatively dense. Olivine, pyroxene, amphibole, biotite, and garnet are examples.
- Nonsilicate minerals include oxides, which contain oxygen ions that bond to other elements (usually metals); carbonates, which have CO_3 as a critical part of their crystal structure; sulfates, which have SO_4 as their basic building block; and halides, which contain a nonmetal ion such as chlorine, bromine, or fluorine that bonds to a metal ion such as sodium or calcium.

2.6 NATURAL RESOURCES

Discuss Earth's natural resources in terms of renewability. Differentiate between mineral resources and ore deposits.

KEY TERMS: renewable, nonrenewable, mineral resource, ore deposit

- Resources are classified as renewable when they can be replenished over short time spans and nonrenewable when they can't.
- Ore deposits are naturally occurring concentrations of one or more metallic minerals that can be extracted economically using current technology. A mineral resource can be upgraded to an ore deposit if the price of the commodity increases sufficiently or when the cost of extraction decreases.

GIVE IT SOME THOUGHT

- Using the geologic definition of *mineral* as your guide, determine which of the items in this list are minerals and which are not. If something in this list is not a mineral, explain.

a. Gold nugget	d. Cubic zirconia	g. Glacial ice
b. Seawater	e. Obsidian	h. Amber
c. Quartz	f. Ruby	

Refer to the periodic table of the elements (see Figure 2.5) to help you answer Questions 2 and 3.
- Assume that the number of protons in a neutral atom is 92 and its mass number is 238.
 - What is the name of the element?
 - How many electrons does it have?
 - How many neutrons does it have?
- Which of the following elements is more likely to form chemical bonds: xenon (Xe) or sodium (Na)? Explain why.

4. Referring to the accompanying photos of five minerals, determine which of these specimens exhibit a metallic luster and which have a nonmetallic luster. (Photos by Dennis Tasa and E. J. Tarbuck)



A.



B.



C.



D.



E.

5. Gold has a specific gravity of almost 20. A 5-gallon bucket of water weighs 40 pounds. How much would a 5-gallon bucket of gold weigh?
6. Examine the accompanying photo of a mineral that has several smooth, flat surfaces that resulted when the specimen was broken.
- How many flat surfaces are present on this specimen?
 - How many different directions of cleavage does this specimen have?
 - Do the cleavage directions meet at 90-degree angles?



Cleaved sample

Dennis Tasa

7. Each of the following statements describes a silicate mineral or mineral group. In each case, provide the appropriate name.
- The most common member of the amphibole group
 - The most common light-colored member of the mica family
 - The only common silicate mineral made entirely of silicon and oxygen
 - A silicate mineral with a name that is based on its color
 - A silicate mineral that is characterized by striations
 - A silicate mineral that originates as a product of chemical weathering
8. What mineral property is illustrated in the accompanying photo?



Dennis Tasa

9. Do an Internet search to determine what minerals are extracted from the ground during the manufacture of the following products.
- Stainless steel utensils
 - Cat litter
 - Tums brand antacid tablets
 - Lithium batteries
 - Aluminum beverage cans
10. Most states have designated a state mineral, rock, or gemstone to promote interest in the state's natural resources. Describe your state mineral, rock, or gemstone and explain why it was selected. If your state does not have a state mineral, rock, or gemstone, complete the exercise by selecting one from a state adjacent to yours.

EXAMINING THE EARTH SYSTEM

1. Perhaps one of the most significant interrelationships between humans and the Earth system involves the extraction, refinement, and distribution of the planet's mineral wealth. To help you understand these associations, begin by thoroughly researching a mineral commodity that is mined in your local region or state. (You might find useful the information at the U.S. Geological Survey [USGS] Website: <http://minerals.er.usgs.gov/minerals/pubs/state/>.) What products are made from this mineral? Do you use any of these products? Describe the mining

and refining of the mineral and the local impact these processes have on each of Earth's spheres (atmosphere, hydrosphere, geosphere, and biosphere). Are any of the effects negative? If so, what, if anything, is being done to end or minimize the damage?

2. Referring to the mineral you described in Question 1, in your opinion does the environmental impact of extracting this mineral outweigh the benefits derived from its products?

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