Matter and Minerals

CHAPTER

3

Crystals of Beryl (blueish-green), Feldspar (white), and Quartz (clear). (Photo by Jeff Scovil)

Earth's crust and oceans are the source of 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 drill bits impregnated with diamonds are employed by dentists 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. As the mineral requirements of modern society grow, the need to locate the additional supplies of useful minerals also grows, becoming more challenging as well.

In addition to the economic uses of rocks and minerals, all of the processes studied by geologists 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 the understanding of all geologic phenomena.

FIGURE 3.1 The Coronation Crown of England, made of solid gold and set with 444 gemstones. Known as the St. Edward's Crown, the stones were reset in 1911. (Photo by Tim Graham/Getty Images)

Minerals: Building Blocks of Rocks

Minerals: Building Blocks of Rocks
▸ **Introduction**

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, minerals have been employed by humans for both useful and decorative purposes for thousands of years (Figure 3.1). The first minerals mined were flint and chert, which people fashioned into weapons and cutting tools. As early as 3700 B.C., Egyptians began mining gold, silver, and copper; and by 2200 B.C. humans discovered how to combine copper with tin to make bronze, a tough, hard alloy. The Bronze Age began its decline when the ability to extract iron from minerals such as hematite was discovered. By about 800 B.C., iron-working technology had advanced to the point that weapons and many everyday objects were made of iron rather than copper, bronze, or wood. During the Middle Ages, mining of a variety of minerals was common throughout Europe 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 when referring 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?

Geologists define a **mineral** as *any naturally occurring inorganic solid that possesses an orderly crystalline structure and a well-defined chemical composition.* Thus, those Earth materials that are classified as minerals exhibit the following characteristics:

1. **Naturally occurring.** Minerals form by natural, geologic processes. Consequently, synthetic diamonds and rubies, as well as a variety of other useful materials produced in a laboratory, are not considered minerals.
2. **Solid substance.** Minerals are solids within the temperature ranges normally experienced at Earth's surface. Thus, ice (frozen water) is considered a mineral, whereas liquid water and water vapor are not.
3. **Orderly crystalline structure.** Minerals are crystalline substances, which means their atoms are arranged in an orderly, repetitive manner. This orderly packing of atoms is reflected in the regularly shaped objects we call crystals (Figure 3.2). Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.
4. **Well-defined chemical composition.** Most minerals are chemical compounds having compositions that are given by their chemical formulas. The mineral pyrite (FeS_2), for example, consists of one iron (Fe) atom, for every two sulfur (S) atoms. In nature, however, it is not uncommon for some atoms within a crystal structure to be replaced by others of similar size without changing the internal structure or properties of that mineral. Therefore, the chemical compositions of minerals may vary, but they *vary within specific, well-defined limits.*
5. **Generally inorganic.** Inorganic crystalline solids, as exemplified by 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 which comes from sugarcane or sugar beets, is a common example of such an organic compound. However, many marine animals secrete inorganic compounds, such as calcium carbonate (calcite), in the form of shells and coral reefs. These materials are considered minerals by most geologists.

FIGURE 3.2 Collection of well-developed quartz crystals found near Hot Springs, Arkansas. (Photo by Jeff Scovil)

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. A few rocks are composed almost entirely of one mineral. A common example is the sedimentary rock *limestone,* which consists of impure masses of the mineral calcite. However, most rocks, like the common rock granite shown in Figure 3.3, occur as aggregates of several kinds of minerals. Here, the term *aggregate* implies that the minerals are joined in such a way that the properties of each mineral are retained. Note that you can easily identify the mineral constituents of the granite in Figure 3.3.

A few 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 (see Box 3.1).

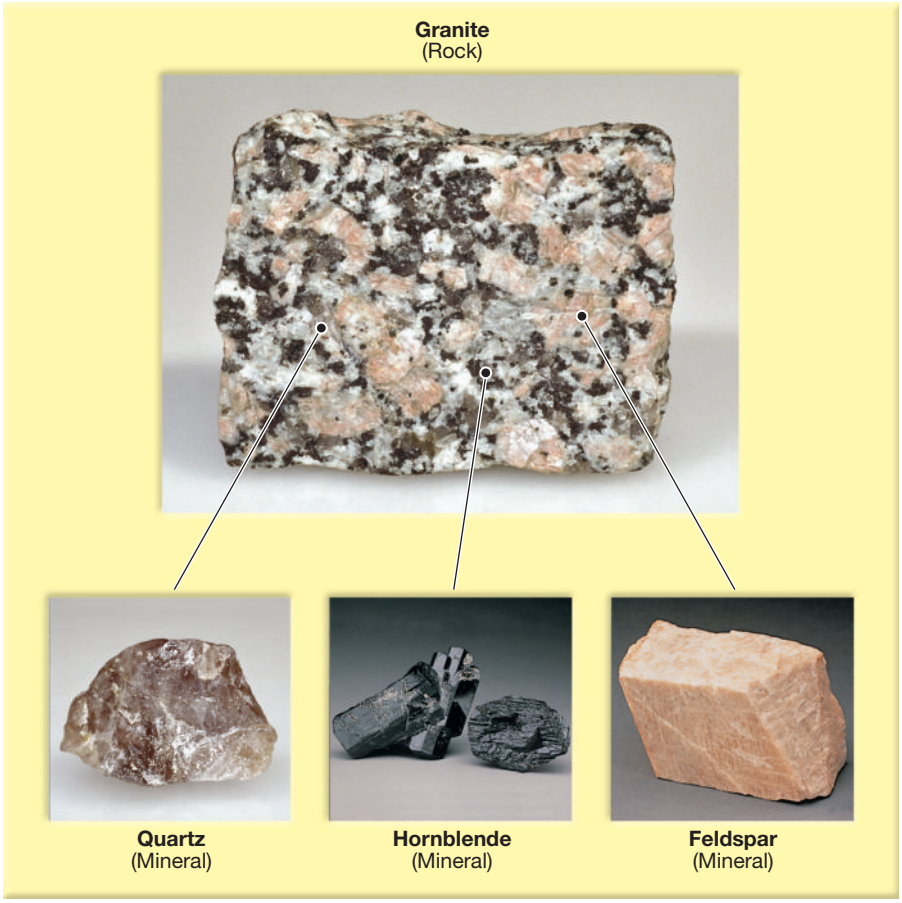


FIGURE 3.3 Most rocks are aggregates of two or more minerals.

BOX 3.1 ▸ PEOPLE AND THE ENVIRONMENT

Making Glass from Minerals

Many everyday objects are made of glass, including windowpanes, jars and bottles, and the lenses of some eyeglasses. People have been making glass for at least 2000 years. Glass is manufactured by melting naturally occurring materials and cooling the liquid quickly before the atoms have time to arrange themselves into an orderly crystalline form. (This is the same way that natural glass, called *obsidian*, is generated from lava.)

It is possible to produce glass from a variety of materials, but the primary ingredient (75 percent) of most commercially produced glass is the mineral quartz (SiO_2). Lesser amounts of the minerals calcite (calcium carbonate) and trona (sodium carbonate) are added to the mix. These materials lower the melting temperature and improve the workability of the molten glass.

In the United States, high-quality quartz (usually quartz sandstone) and calcite (limestone) are readily available in many areas. Trona, on the other hand, is mined almost exclusively in the Green River area of southwestern Wyoming. In addition to its use in making glass, trona is used in making detergents, paper, and even baking soda.

Manufacturers can change the properties of glass by adding minor amounts of several other ingredients (Figure 3.A). Coloring agents include iron sulfide (amber), selenium (pink), cobalt oxide (blue), and iron oxides (green, yellow, brown). The addition of lead imparts clarity and brilliance to glass and is therefore used in the manufacture of fine crystal tableware. Ovenware, such as Pyrex®, owes its heat resistance to boron, whereas aluminum makes glass resistant to weathering.

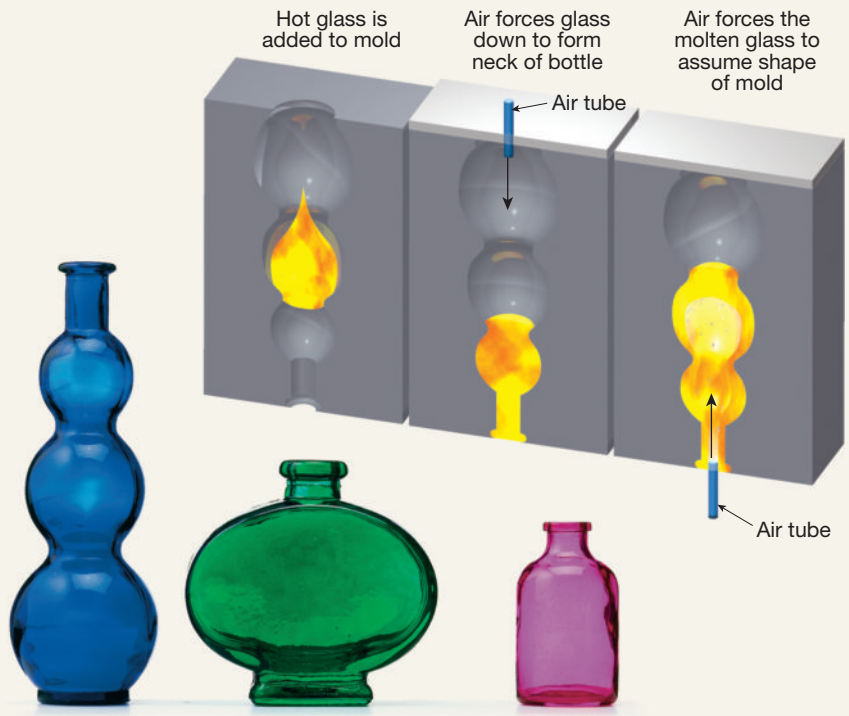


FIGURE 3.A Glass bottles are made by first pouring molten glass into a mold. Then air forces the molten glass to assume the shape of the mold. Metallic compounds are mixed with the raw ingredients to color the glass. (Photo by Guy Ryecart)

Students Sometimes Ask . . .

Are the minerals you talked about in class the same as those found in dietary supplements?

Not ordinarily. From a geologic perspective, a mineral must be a *naturally occurring* crystalline solid. Minerals found in dietary supplements are man-made inorganic compounds that contain *elements* needed to sustain life. These dietary minerals typically contain elements that are metals—calcium, potassium, phosphorus, magnesium, and iron—as well as trace amounts of a dozen other elements, such as copper, nickel, and vanadium. Although these two types of "minerals" are different, they are related. The source of the elements used to make dietary supplements is in fact the naturally occurring minerals of Earth's crust. It should also be noted that vitamins are *organic compounds* produced by living organisms, not *inorganic compounds*, such as minerals.

Although this chapter deals primarily with the nature of minerals, keep in mind that most rocks are simply aggregates of minerals. Because the properties of rocks are determined largely by the chemical composition and crystalline structure of the minerals contained within them, we will first consider these Earth materials. Then, in Chapters 4, 7, and 8 we will take a closer look at Earth's major rock groups.

Elements: Building Blocks of Minerals

You are probably familiar with the names of many elements, including copper, iron, oxygen, and carbon. An **element** is a substance that cannot be broken down into simpler substances by chemical or physical means. There are about 90 different elements found in nature, and consequently about 90 different kinds of atoms. In addition, scientists have succeeded in creating about 23 synthetic elements.

The elements can be organized into rows so that those with similar properties are in the same column. This arrangement,

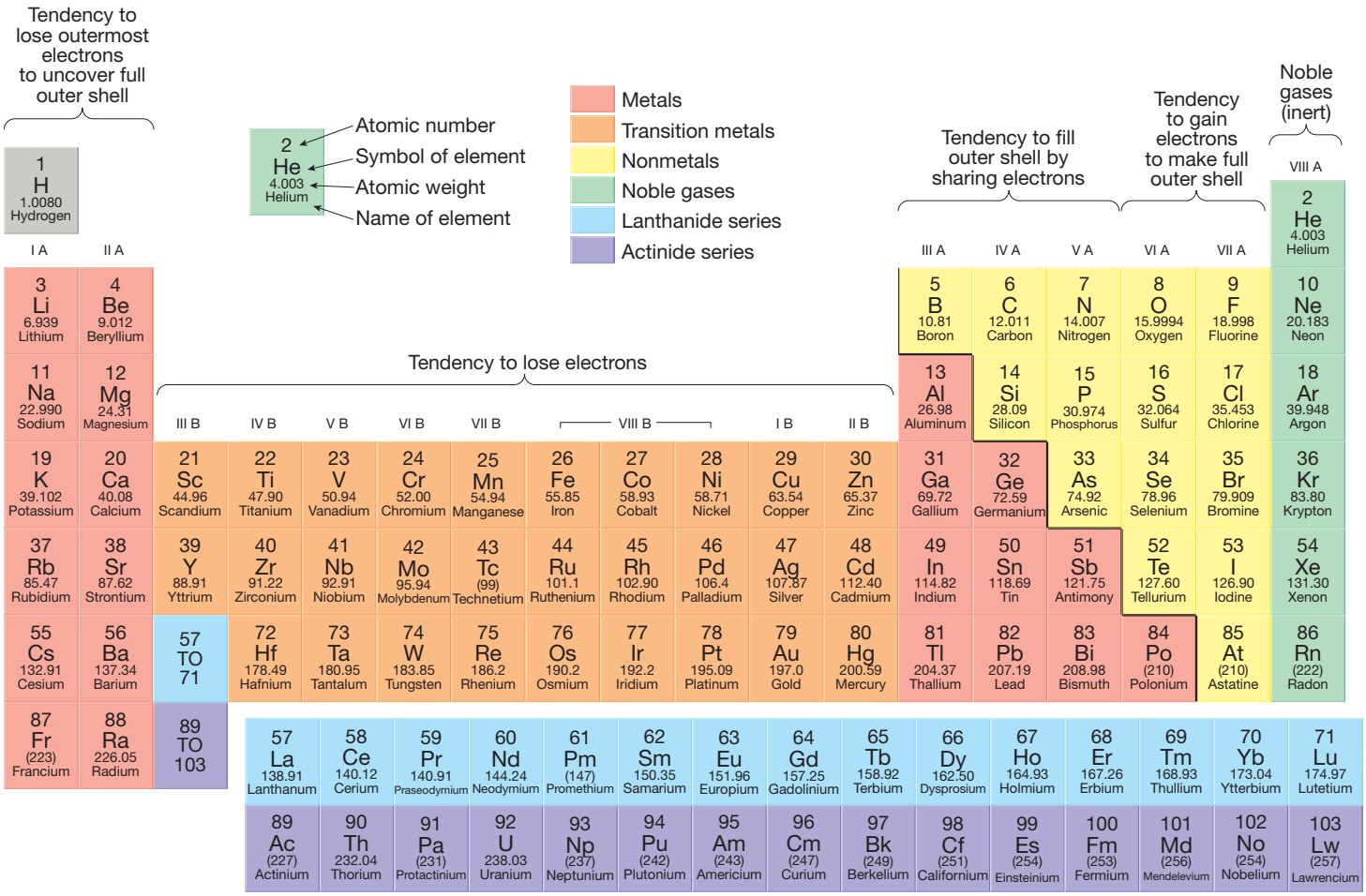


FIGURE 3.4 Periodic table of the elements.

called the **periodic table** is shown in Figure 3.4. Notice that symbols are used to provide a shorthand way of representing an element. Each element is also known by its atomic number, which is shown above each symbol on the periodic table.

Some elements, such as copper (number 29) and gold (number 79), exist in nature with single atoms as the basic unit. Thus, native copper and gold are minerals made entirely from one element. However, many elements are quite reactive and join together with atoms of one or more other elements to form **chemical compounds.** As a result, most minerals are chemical compounds consisting of two or more different elements.

To understand how elements combine to form compounds, we must first consider the atom. The **atom** (*a* = not, *tomos* = cut) is the smallest particle of matter that retains the essential characteristics of an element. It is this extremely small particle that does the combining.

The central region of an atom is called the **nucleus.** The nucleus contains protons and neutrons. **Protons** are very dense particles with positive electrical charges. **Neutrons** have the same mass as a proton but lack an electrical charge.

Orbiting the nucleus are **electrons,** which have negative electrical charges. For convenience, we sometimes diagram atoms to show the electrons orbiting the nucleus, like the orderly orbiting of the planets around the Sun (Figure 3.5A). However, electrons move in a less predictable way than planets. As a result, they create a sphere-shaped negative zone around the nucleus. A more realistic picture of the positions of electrons can be obtained by envisioning a cloud of negatively charged electrons surrounding the nucleus (Figure 3.5B).

Studies of electron configurations predict that individual electrons move within regions around the nucleus called **principal shells,** or **energy levels.** Furthermore, each of these shells can hold a specific number of electrons, with the outermost principal shell containing the **valence electrons.** Valence electrons are important because, as you will see later, they are involved in chemical bonding.

Some atoms have only a single proton in their nuclei, while others contain more than 100 protons. The number of protons in the nucleus of an atom is called the **atomic number.** For example, all atoms with six protons are carbon atoms; hence, the atomic number of carbon is 6. Likewise, every atom with eight protons is an oxygen atom.

Atoms in their natural state also have the same number of electrons as protons, so the atomic number also equals the

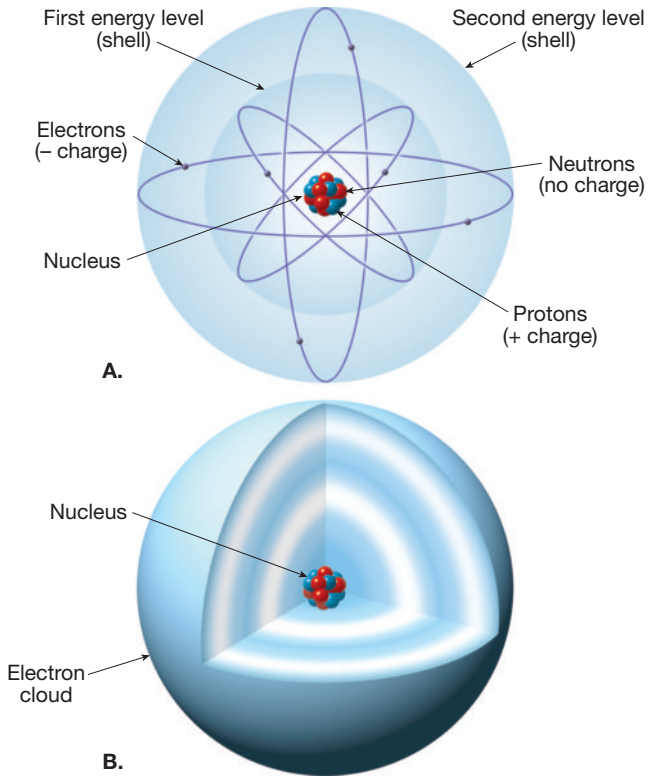


FIGURE 3.5 Two models of the atom. **A.** A very simplified view of the atom, which consists of a central nucleus, consisting of protons and neutrons, encircled by high-speed electrons. **B.** Another model of the atoms showing spherically shaped electron clouds (energy level shells). Note that these models are not drawn to scale. Electrons are minuscule in size compared to protons and neutrons, and the relative space between the nucleus and electron shells is much greater than illustrated.

number of electrons surrounding the nucleus. Therefore, carbon has six electrons to match its six protons, and oxygen has eight electrons to match its eight protons. Neutrons have no charge, so the positive charge of the protons is exactly balanced by the negative charge of the electrons. Consequently, atoms in the natural state are neutral electrically and have no overall electrical charge.

Why Atoms Bond

Why do elements join together to form compounds? From experimentation it has been learned that the forces holding the atoms together are electrical. Further, it is known that chemical bonding results in a change in the electron configuration of the bonded atoms. As we noted earlier, it is the valence electrons (outer-shell electrons) that are generally involved in chemical bonding. Figure 3.6 shows a shorthand way of representing the number of electrons in the outer principal shell (valence electrons). Notice that the elements in group I have one valence electron, those in group II have two, and so forth up to group VIII, which has eight valence electrons.

Other than the first shell, which can hold a maximum of two electrons, *a stable configuration occurs when the valence shell contains eight electrons.* Only the noble gases, such as neon and argon, have a complete outermost principal shell. Hence, the noble gases are the least chemically reactive and are designated as "inert."

When an atom's outermost shell does not contain the maximum number of electrons (eight), the atom is likely to chemically bond with one or more other atoms. A *chemical bond* is the sharing or transfer of electrons to attain a stable electron configuration among the bonding atoms. If the electrons are transferred, the bond is an *ionic bond.* If the electrons are shared, the bond is called a *covalent bond.* In either case, the bonding atoms get stable electron configurations, which usually consist of eight electrons in the outer shell.

Ionic Bonds: Electrons Transferred

Perhaps the easiest type of bond to visualize is an **ionic bond.** In ionic bonding, one or more valence electrons are transferred from one atom to another. Simply, one atom gives up its valence electrons, and the other uses them to complete its outer shell. A common example of ionic bonding is sodium (Na) and chlorine (Cl) joining to produce sodium chloride (common table salt). This is shown in Figure 3.7A. Notice that sodium gives up its single valence electron to chlorine. As a result, sodium achieves a stable configuration having eight electrons in its outermost shell. By acquiring the electron that sodium loses, chlorine—which has seven valence electrons—gains the eighth electron needed to complete its outermost shell. Thus, through the transfer of a single electron, both the sodium and chlorine atoms have acquired a stable electron configuration.

Once electron transfer takes place, atoms are no longer electrically neutral. By giving up one electron, a neutral sodium atom becomes *positively charged* (11 protons/10 electrons). Similarly, by acquiring one electron, the neutral chlorine atom becomes *negatively charged* (17 protons/18 electrons). Atoms which have an electrical charge because of the unequal numbers of electrons and protons, are called **ions.** Atoms that pick up extra electrons and become negatively charged are called *anions,* whereas atoms that lose electrons and become positively charged are called *cations.*

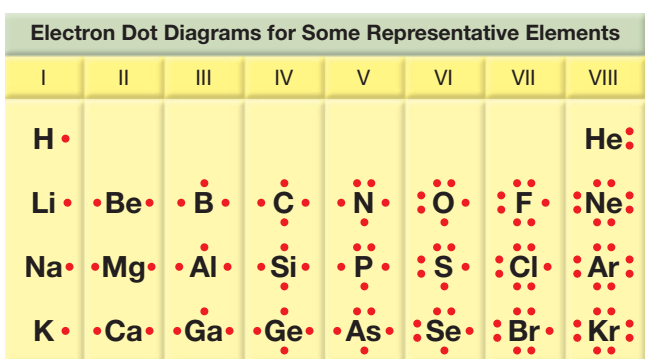


FIGURE 3.6 Dot diagrams for some representative elements. Each dot represents a valence electron found in the outermost principal shell.

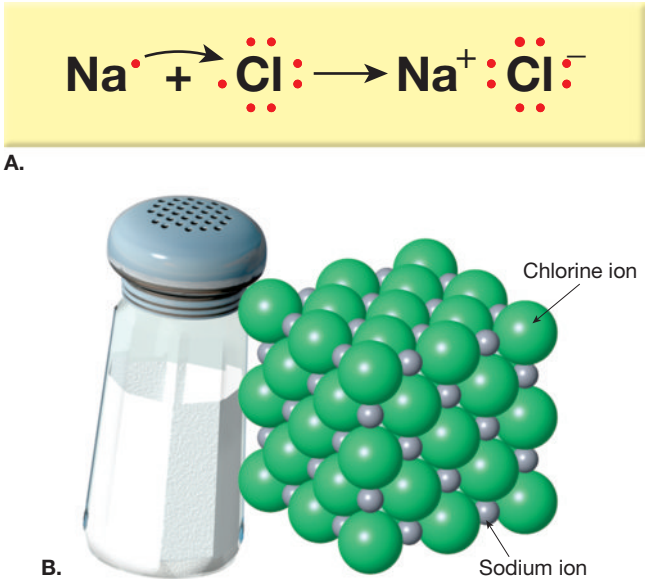


FIGURE 3.7 Chemical bonding of sodium chloride (table salt). **A.** Through the transfer of one electron in the outer shell of a sodium atom to the outer shell of a chlorine atom, the sodium becomes a positive ion (cation) and chlorine a negative ion (anion). **B.** Diagram illustrating the arrangement of sodium and chlorine ions in table salt.

We know that ions with like charges repel, and those with unlike charges attract. Thus, an *ionic bond* is the attraction of oppositely charged ions to one another, producing an electrically neutral compound. Figure 3.7B 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 unlike charges while minimizing the repulsion between ions with like 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 elements comprising it. For example, sodium, a soft, silvery metal, 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 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. When elements combine to form compounds, their properties change dramatically.

Covalent Bonds: Electrons Shared

Not all atoms combine by transferring electrons to form ions. Some atoms *share* electrons. For example, the gaseous elements oxygen (O_2), hydrogen (H_2), and chlorine (Cl_2) exist as stable molecules consisting of two atoms bonded together, without a complete transfer of electrons.

Figure 3.8 illustrates the sharing of a pair of electrons between two chlorine atoms to form a molecule of chlorine gas (Cl_2). By overlapping their outer shells, these chlorine atoms share a pair of electrons. Thus, each chlorine atom has acquired, through cooperative action, the needed eight electrons to complete its outer shell. The bond produced by the sharing of electrons is called a **covalent bond.**

A common analogy may help you visualize a covalent bond. Imagine two people at opposite ends of a dimly lit room, each reading under a separate lamp. By moving the lamps to the center of the room, they are able to combine their light sources so each can see better. Just as the overlapping light beams meld, the shared electrons that provide the "electrical glue" in covalent bonds are indistinguishable from each other. The most common mineral group, the silicates, contains the element silicon, which readily forms covalent bonds with oxygen.

Other Bonds

As you might suspect, many chemical bonds are actually hybrids. They consist to some degree of electron sharing, as in covalent bonding, and to some degree of electron transfer,

Students Sometimes Ask . . .

What's the difference between a carrot, a karat, and a carat?

Like many words in English, *carrot, karat,* and *carat* have the same sound but have different meanings. Such words are called *homonyms* (*homo* = same, *nym* = name). A *carrot* is the familiar orange crunchy vegetable, and *karat* and *carat* have to do with gold and gems, respectively. (Both *karat* and *carat* derive from the Greek word *keration* = carob bean, which early Greeks used as a weight standard.)

Karat is a term used to indicate the purity of gold, with 24 karats representing pure gold. Gold less than 24 karats is an alloy (mixture) of gold and another metal, usually copper or silver. For example, 14-karat gold contains 14 parts of gold (by weight) mixed with 10 parts of other metals.

Carat is a unit of weight used for precious gems such as diamonds, emeralds, and rubies. The size of a carat has varied throughout history, but early in the twentieth century it was standardized at 200 milligrams (0.2 gram, or 0.007 ounce). For example, a typical diamond on an engagement ring might range from one half to one carat, and the famous Hope Diamond at the Smithsonian Institution is 45.52 carats.

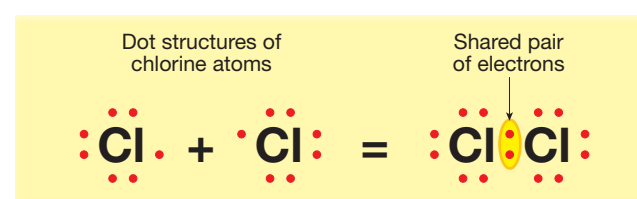


FIGURE 3.8 Dot diagrams used to illustrate the sharing of electrons between two chlorine atoms to form a chlorine molecule. Notice that by sharing a pair of electrons, both chlorine atoms achieve a full outer shell (8 electrons).

as in ionic bonding. For example, silicate minerals are composed of silicon and oxygen atoms that are joined together by bonds that display characteristics of both ionic and covalent bonds. These basic building blocks are, in turn, ionically bonded to metallic ions, producing a great variety of electrically neutral chemical compounds.

Another chemical bond exists in which valence electrons are free to migrate from one ion to another. The mobile valence electrons serve as the electrical glue. This type of electron sharing is found in metals such as copper, gold, aluminum, and silver and is called **metallic bonding.** Metallic bonding accounts for the high electrical conductivity of metals, the ease with which metals are shaped, and numerous other special properties of metals.

Isotopes and Radioactive Decay

Subatomic particles are so incredibly small that a special unit, called an *atomic mass unit,* was devised to express their mass. A proton or a neutron has a mass just slightly more than one atomic mass unit, whereas an electron is only about one two-thousandth of an atomic mass unit. Thus, although electrons play an active role in chemical reactions, they do not contribute significantly to the mass of an atom.

The **mass number** of an atom is simply the total of its neutrons and protons. Atoms of the same element always have the same number of protons. But the number of neutrons for atoms of the same element can vary. Atoms with the same number of protons but different numbers of neutrons are **isotopes** of that element. Isotopes of the same element are labeled by placing the mass number after the element's name or symbol.

For example, carbon has three well-known isotopes. One has a mass number of 12 (carbon-12), another has a mass number of 13 (carbon-13), and the third, carbon-14, has a mass number of 14. Since all atoms of the same element have the same number of protons, and carbon has six, carbon-12 also has *six neutrons* to give it a mass number of 12. Likewise, carbon-14 has six protons plus *eight neutrons* to give it a mass number of 14.

In chemical behavior, all isotopes of the same element are nearly identical. To distinguish among them is like trying to differentiate identical twins, with one being slightly heavier. Because isotopes of an element react the same chemically, different isotopes can become parts of the same mineral. For example, when the mineral calcite forms from calcium, carbon, and oxygen, some of its carbon atoms are carbon-12 and some are carbon-14.

The nuclei of most atoms are stable. However, many elements do have isotopes in which the nuclei are unstable. "Unstable" means that the isotopes disintegrate through a process called **radioactive decay.** Radioactive decay occurs when the forces that bind the nucleus are not strong enough.

During radioactive decay, unstable atoms radiate energy and emit particles. Some of this energy powers the movements of Earth's crust and upper mantle. The rates at which unstable atoms decay are measurable. Therefore, certain radioactive atoms can be used to determine the ages of fossils, rocks, and minerals. A discussion of radioactive decay and its applications in dating past geologic events is found in Chapter 9.

Crystals and Crystallization

Many people associate the word crystal with delicate water or wine goblets or, perhaps glassy objects with smooth sides and gem-like shapes. Mineralogists, on the other hand, use the term **crystal** or **crystalline** in reference to *any natural solid with an ordered, repetitive, atomic structure.*

By this definition, crystals may or may not have smooth-sided faces. The specimen shown in Figure 3.2, for example, exhibits the characteristic crystal form we associate with the mineral quartz—a six-sided prismatic shape with pyramidal ends. However, the quartz crystals in the sample of granite shown in Figure 3.3 do not display well-defined faces. Crystals that exhibit perfect geometric shapes with smooth faces are called *euhedral,* as opposed to crystals with irregular surfaces, which are known as *anhedral.* All minerals are crystalline, but those with well-developed faces are relatively uncommon.

How Do Minerals Form?

Minerals form through the process of **crystallization,** in which the constituent molecules, or ions, chemically bond to form an orderly internal structure. Perhaps the most familiar type of crystallization results when an aqueous (water) solution containing dissolved ions evaporates. As you might expect, the concentration of dissolved material increases as water is removed during evaporation. Once saturation occurs, the atoms bond together to form solid crystalline substances that precipitate from (settle out of) the solution. Inland bodies of salty water such as the Dead Sea or the Great Salt Lake often precipitate the minerals halite, sylvite, gypsum, and other soluble salts. Worldwide, extensive sedimentary rock layers, some exceeding 300 meters (1000 feet) in thickness, provide evidence of ancient seas that have long since evaporated (see Figure 3.35, p. 97).

Minerals can also precipitate from slowly moving groundwater where they fill fractures and voids in rocks. One interesting example, called a *geode,* is a somewhat spherical shaped body with inward-projecting crystals (Figure 3.9). Geodes often contain spectacular crystals of quartz, calcite, or other minerals.

A decrease in temperature may also initiate crystallization, as in the growth of ice from liquid water. Likewise, the crystallization of igneous minerals from molten magma, although more complicated, is similar to water freezing. When magma is very hot, the atoms are very mobile; but when the molten material cools, the atoms slow and begin to combine. Crystallization of a magma body generates igneous rocks that consist of a mosaic of intergrown crystals that lack well-developed faces (see Figure 3.3, p. 73).

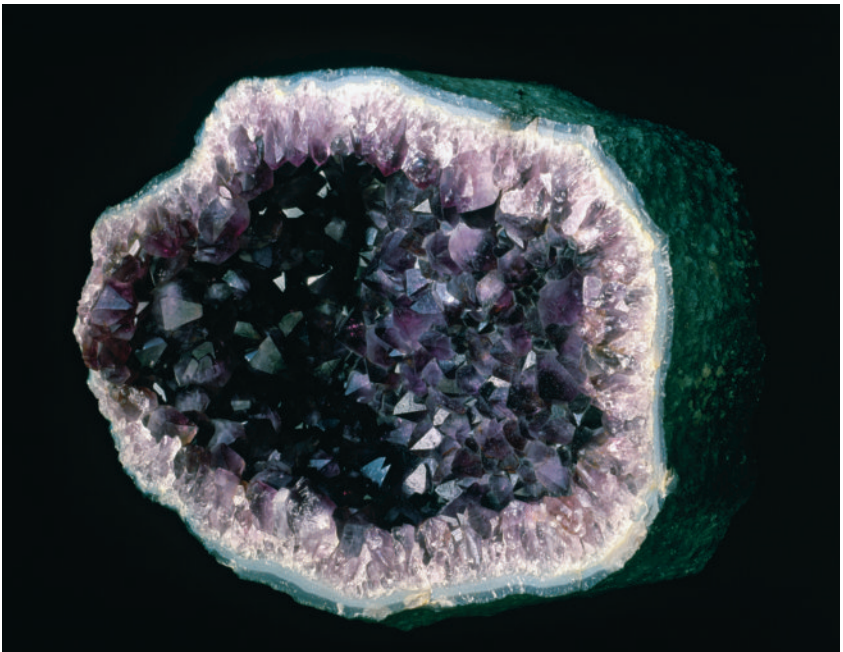
Students Sometimes Ask . . .

According to the textbook, thick beds of halite and gypsum formed when ancient seas evaporated. Has this happened in the recent past?

Yes. During the past 6 million years, the Mediterranean Sea may have dried up and then refilled several times. When 65 percent of seawater evaporates, the mineral gypsum begins to precipitate, meaning it comes out of solution and settles to the bottom. When 90 percent of the water is gone, halite crystals form, followed by salts of potassium and magnesium. Deep-sea drilling in the Mediterranean has encountered the presence of thick beds of gypsum and salt deposits (mostly halite) sitting one atop the other to a maximum depth of 2 kilometers (1.2 miles). These deposits are inferred to have resulted from tectonic events that periodically closed and reopened the connection between the Atlantic Ocean and the Mediterranean Sea (the modern-day Straits of Gibraltar) over the past several million years. During periods when the Mediterranean was cut off from the Atlantic, the warm and dry climate in this region caused the Mediterranean to nearly evaporate. Then, when the connection to the Atlantic was opened, the Mediterranean basin would refill with seawater of normal salinity. This cycle was repeated over and over again, producing the layers of gypsum and salt found on the Mediterranean seafloor.

Metamorphic processes, which typically occur where temperatures and pressures are high, can also generate new minerals (see Box 3.2). Under these extreme conditions, weathered mineral matter or preexisting minerals are recrystallized into new minerals that tend to exhibit larger grain sizes than the parent material. For example, the metamorphism of mudstones, which are made of minute clay minerals, generates rocks that contain minerals such as mica, quartz, and garnet (see Figure 3.34, p. 94).

FIGURE 3.9 Geode partially filled with amethyst, a purple variety of quartz, Brazil. (Photo by Jeff Scovil)



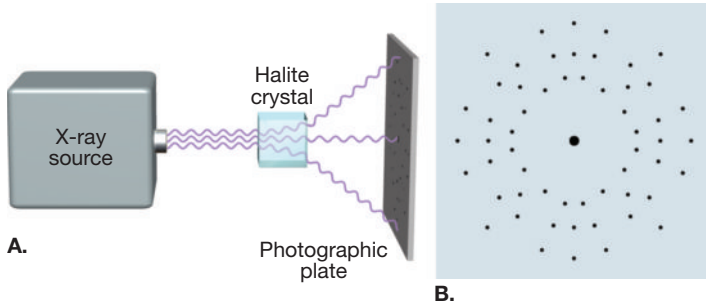


FIGURE 3.10 The principle of X-ray diffraction. **A.** When a parallel beam of X rays pass through a crystal, they are diffracted (scattered) in such a way as to produce a pattern of dark spots on a photographic plate. **B.** The diffraction pattern shown is for the mineral halite (NaCl).

The crystallization of minerals occurs in other ways as well. Sulfur deposits are often found near volcanic vents where crystals are deposited directly from hot, sulfur-rich vapors. This mechanism is similar to how snowflakes form—water vapor is deposited as ice crystals without ever entering the liquid phase. Organisms, such as microscopic bacteria, are also responsible for initiating the crystallization of substantial quantities of mineral matter. For example, the mineral pyrite (FeS_2), when found in shale and coal beds, is typically generated by the action of sulfate-reducing bacteria. In addition, mollusks (clams) and other marine invertebrates secrete shells composed of the carbonate minerals calcite and aragonite. The remains of these shells are major components of many limestone beds.

Crystal Structures

The smooth faces and symmetry possessed by well-developed crystals are manifestations of the orderly packing of atoms or molecules that constitute a mineral's internal structure. Although this relationship between crystallization and atomic structure had been proposed much earlier, experimental verification did not occur until 1912 when it was discovered that X rays are diffracted (scattered) by crystals. One X-ray diffraction technique emits a parallel beam of X rays that pass through a crystal and expose a sheet of photographic film on the far side (Figure 3.10A). This is similar to how medical and dental X-ray images are produced. Here, the beam interacts with atoms and is diffracted in a manner that produces a pattern of dark spots on the film (Figure 3.10B). The diffraction pattern produced is a function of the spacing and distribution of atoms in the crystal, and is unique to each mineral. Hence, X-ray diffraction is an important tool for mineral identification.

With the development of X-ray diffraction techniques, mineralogists were able to directly investigate the internal structures of minerals. What followed was the discovery that minerals have highly ordered atomic arrangements that can be described as spherical atoms, or ions, held together by ionic, covalent, or metallic bonds. Native metals that are

BOX 3.2 ▸ PEOPLE AND THE ENVIRONMENT

Asbestos: What Are the Risks?

Once considered safe enough to use in toothpaste, asbestos became one of the most feared contaminants on Earth. The asbestos panic in the United States began in 1986 when the Environmental Protection Agency (EPA) instituted the Asbestos Hazard Emergency Response Act. It required inspection of all public and private schools for asbestos. This brought asbestos to public attention and raised parental fears that children could contract asbestos-related cancers because of high levels of airborne fibers in schools.

What is Asbestos?

Asbestos is a commercial term applied to a variety of silicate minerals that readily separate into thin, strong fibers that are highly flexible, heat resistant, and relatively inert (Figure 3.B). These properties make asbestos a desirable material for the manufacture of a wide variety of products, including insulation, fireproof fabrics, cement, floor tiles, and car-brake linings. In addition, wall coatings rich in asbestos fibers were used extensively during the U.S. building boom of the 1950s and early 1960s.

The mineral *chrysotile*, marketed as "white asbestos," belongs to the serpentine mineral group and accounts for the vast majority of asbestos sold commercially. All other forms of asbestos are amphiboles and constitute less than 10 percent of asbestos used commercially. The two most common amphibole asbestos minerals are informally called "brown" and "blue" asbestos, respectively.

Exposure and Risk

Health concerns about asbestos stem largely from claims of high death rates among asbestos miners attributed to asbestosis (lung scarring from asbestos fiber inhalation), mesothelioma (cancer of chest and abdominal cavity), and lung cancer. The degree of concern created by these claims is demonstrated by the growth of an entire industry built around asbestos removal from buildings.

The stiff, straight fibers of brown and blue (amphibole) asbestos are known to readily pierce, and remain lodged in, the linings of human lungs. The fibers are physically and chemically stable and are not broken down in the human body. These forms of asbestos are therefore a genuine cause for concern. White asbestos, however, being a different mineral, has different properties. The curly fibers of white asbestos are readily expelled from the lungs and, if they are not expelled, can dissolve within a year.

The U.S. Geological Survey has taken the position that the risks from the most widely used form of asbestos (chrysotile or "white asbestos") are minimal to non-existent. They cite studies of miners of white asbestos in northern Italy that show mortality rates from mesothelioma and lung cancer differ very little from the general public. Another study was conducted on people living in the area of Thetford Mines, Quebec, once the largest chrysotile mine in the world. For many years there were no dust controls, so these people were exposed to extremely high levels of airborne asbestos. Nevertheless, they exhibited normal levels of the diseases thought to be associated with asbestos exposure.

Despite the fact that more than 90 percent of all asbestos used commercially is white asbestos, a number of countries have moved to ban the use of asbestos in many applications, because the different mineral forms of asbestos are not distinguished. Very little of this once exalted mineral is presently used in the United States. Perhaps future studies will determine whether the asbestos panic, in which billions of dollars have been spent on testing and removal, was warranted or not.

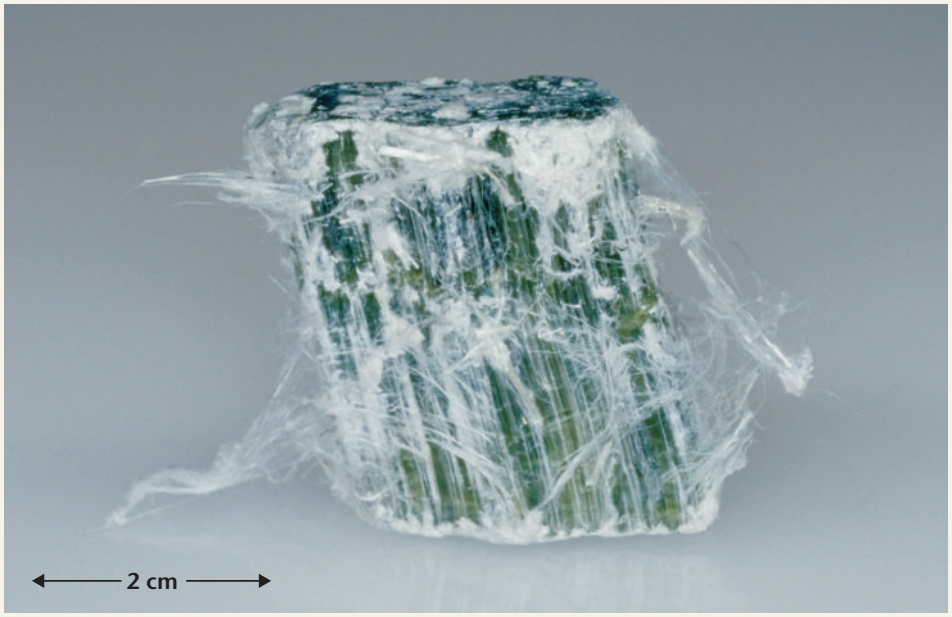


FIGURE 3.B Chrysotile asbestos. This sample is a fibrous form of the mineral serpentine. (Photo by E. J. Tarbuck)

composed of only one element, such as gold and silver, consist of atoms that are packed together in a rather simple three-dimensional network that minimizes voids. Imagine a group of same-sized cannon balls in which the layers are stacked so that the spheres in one layer nestle in the hollows between spheres in the adjacent layers.

The atomic arrangement in most minerals is more complicated than those of native metals, because they consist of various sized positive and negative ions. Figure 3.11 illustrates the relative sizes of some of the most common ions found in minerals. Notice that anions, which are atoms that gain electrons, tend to be larger than cations, which lose electrons.

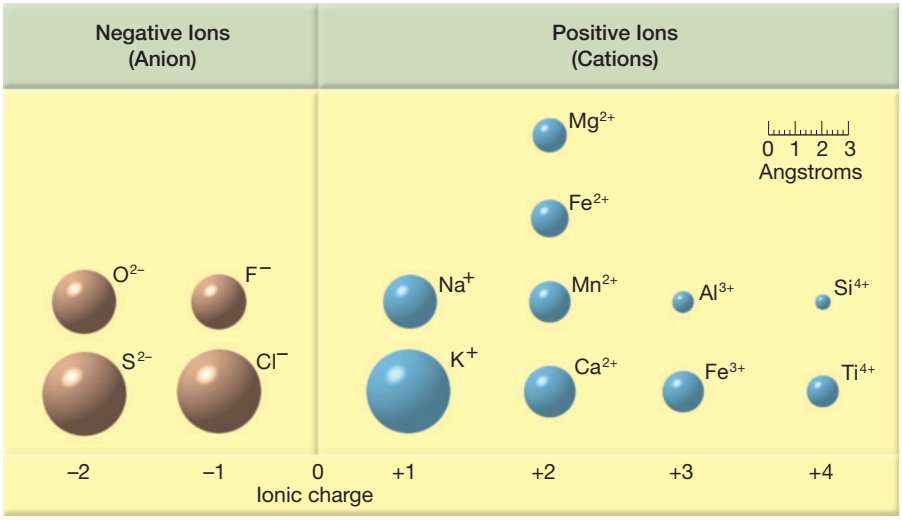


FIGURE 3.11 The relative sizes and ionic charges of various cations and anions commonly found in minerals. Ionic radii are usually expressed in angstroms (1 angstrom equals 10^{-8} cm).

Other things being equal, minerals containing large cations are typically less dense than those in which the cations are small. For example, the density of sylvite (KCl), which contains the relatively large potassium cation, is less than half that of pyrrhotite (FeS), even though their molecular weights are similar. This does not hold true for large cations that have very high atomic weights.

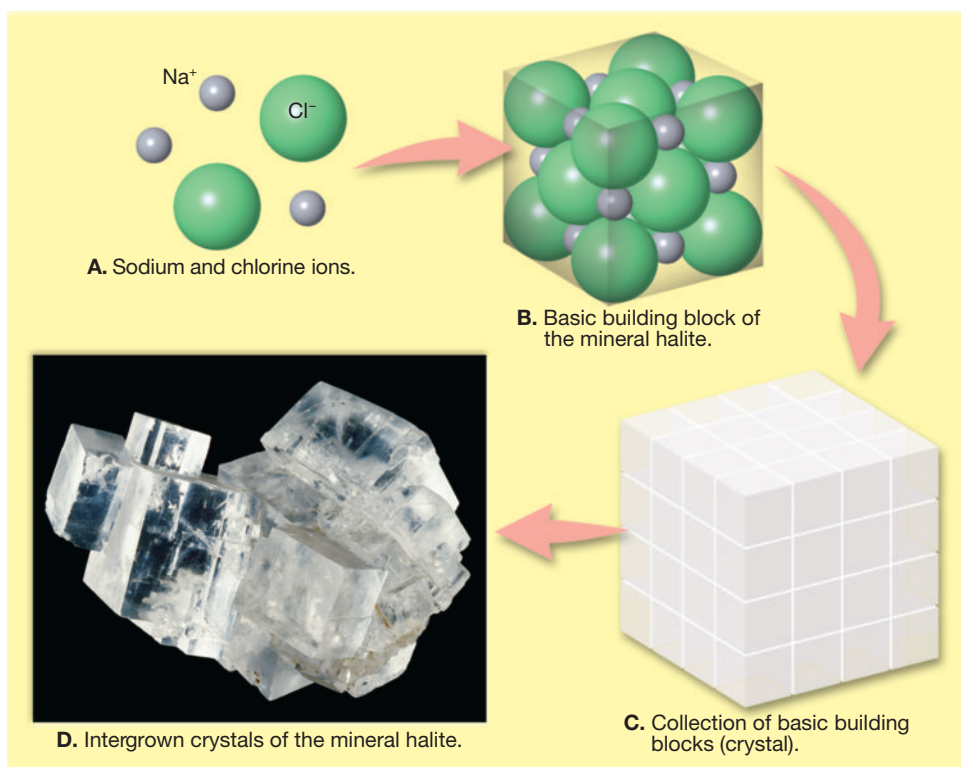
Most crystal structures can be considered three-dimensional arrays of large spheres (anions) with small spheres (cations) located in the spaces between them, so the positive and negative charges cancel each other out. Consider the mineral halite (NaCl), which has a relatively simple framework composed of an equal number of positively charged sodium ions and negatively charged chlorine ions. Because anions repel anions, and cations repel cations, ions of similar charge are spaced as far apart from each other as possible. Consequently, in the mineral halite, each sodium ion (Na^{1+}) is surrounded on all sides by chlorine ions (Cl^{1-}) and vice versa (Figure 3.12). This particular packing arrangement results in basic building blocks, called *unit cells,* that have cubic shapes. As shown in Figure 3.12C, these cubic unit cells combine to form cubic-shaped halite crystals. Salt crystals, including the ones that come out of a salt shaker, are often perfect cubes.

The basic building blocks of halite stack together in a regular manner, creating the whole crystal. In addition, the shape and symmetry of these building blocks relate to the shape and symmetry of the entire crystal.

Thus, despite the fact that natural crystals are rarely perfect, the angles between equivalent crystal faces of the same mineral are remarkably consistent. This observation was first made by Nicolas Steno in 1669. Steno found that the angles between adjacent prism faces of quartz crystals are 120 degrees, regardless of sample size, the size of the crystal faces, or where the crystals were collected (Figure 3.13). This observation is commonly called **Steno's Law,** or the **Law of Constancy of Interfacial Angles,** because it applies to all minerals. Steno's Law states that *angles between equivalent faces of crystals of the same mineral are always the same.* For this reason, **crystal shape** is frequently a valuable tool in mineral identification.

It is important to note, however, that minerals can be constructed of geometrically similar building blocks yet exhibit different external forms. For example, the minerals fluorite, magnetite, and garnet are all constructed of cubic unit cells. However, cubic cells can stick together to produce crystals of many shapes. Typically, fluorite crystals are cubes, while magnetite crystals are octahedrons, and garnets form dodecahedrons built up of many small cubes as shown in Figure 3.14. Because the building blocks are so small, the resulting crystal faces are smooth, flat surfaces.

FIGURE 3.12 This diagram illustrates the orderly arrangement of sodium and chloride ions in the mineral halite. The arrangement of atoms into basic building blocks having a cubic shape results in regularly shaped cubic crystals. (Photo by M. Claye/Jacana Scientific Control/Photo Researchers, Inc.)



Compositional Variations in Minerals

Using sophisticated analytical techniques, researchers discovered that the chemical composition of some minerals varies substantially from sample to sample. These compositional variations are possible because ions of similar size can substitute readily for one another without disrupting a mineral's internal framework. An analogy can be made with a bricklayer who builds a wall using bricks of different colors and materials. As long as the bricks are all the same size, the shape of the wall is unaffected; only its composition changes.

Let us consider the mineral olivine as an example of chemical variability. The chemical formula for olivine is $(Mg, Fe)_2SiO_4$, where the variable components magnesium and iron are shown in parentheses and separated by a comma. Notice in Figure 3.11 that the cations magnesium (Mg^{2+}) and iron (Fe^{2+}) are nearly the same size and have the same electrical charge. At one extreme, olivine may contain magnesium without any iron, or vice-versa—but most samples of olivine have some of both cations in their structure. Consequently, olivine can be thought of as having a range of combinations from fosterite (Mg_2SiO_4) at one end to fayalite (Fe_2SiO_4) at the other. Nevertheless, all specimens of olivine have the same internal structure and exhibit similar, but not identical, properties. For example, iron-rich olivines have a higher density than magnesium-rich specimens, a reflection of the greater atomic weight of iron as compared to magnesium.

In contrast to olivine, minerals such as quartz (SiO_2) and fluorite (CaF_2) tend to have chemical compositions that vary little from their chemical formulas. However, even these minerals contain extremely small amounts of other less common elements, referred to as *trace elements.* Although trace elements have little effect on most mineral properties, they can significantly influence a mineral's color.

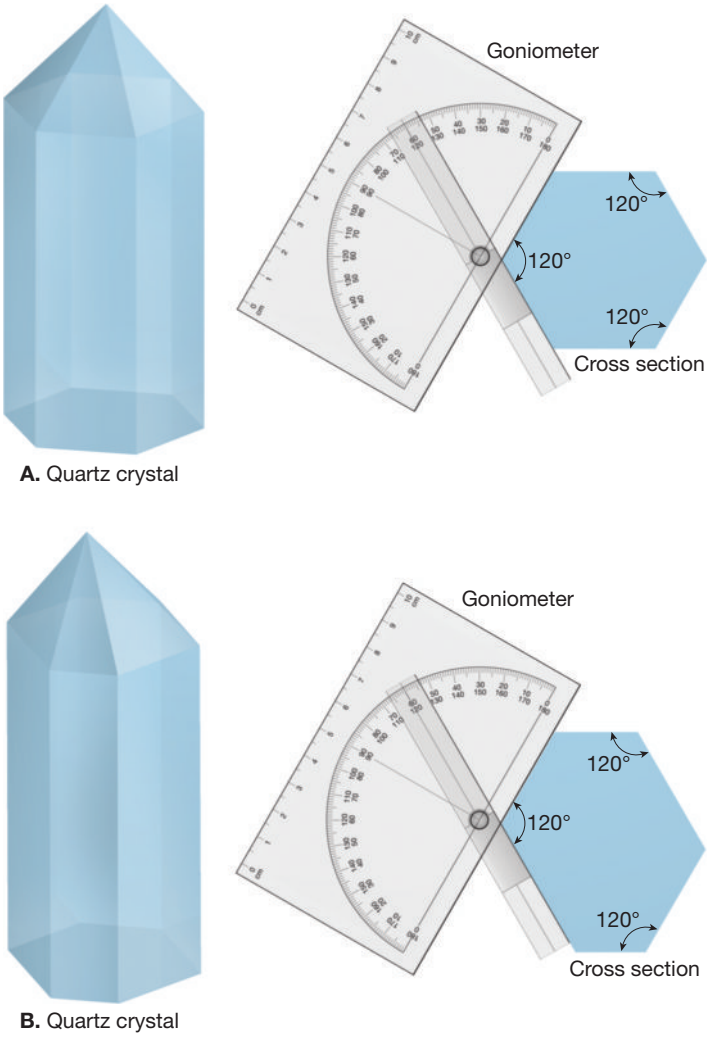


FIGURE 3.13 Illustration of Steno's Law. Because some faces of a crystal may grow larger than others, two crystals of the same mineral may *not* have identical shapes. Nevertheless, the angles between equivalent faces are remarkably consistent.

Structural Variations in Minerals

It is also common for two minerals with exactly the same chemical composition to have different internal structures and, hence. different external forms. Minerals of this type are called **polymorphs** (*poly* = many, *morph* = form). Graphite and diamonds are particularly good examples of polymorphism because they both consist exclusively of carbon atoms yet have drastically different properties. Graphite is the soft gray material of which pencil "lead" is made, whereas

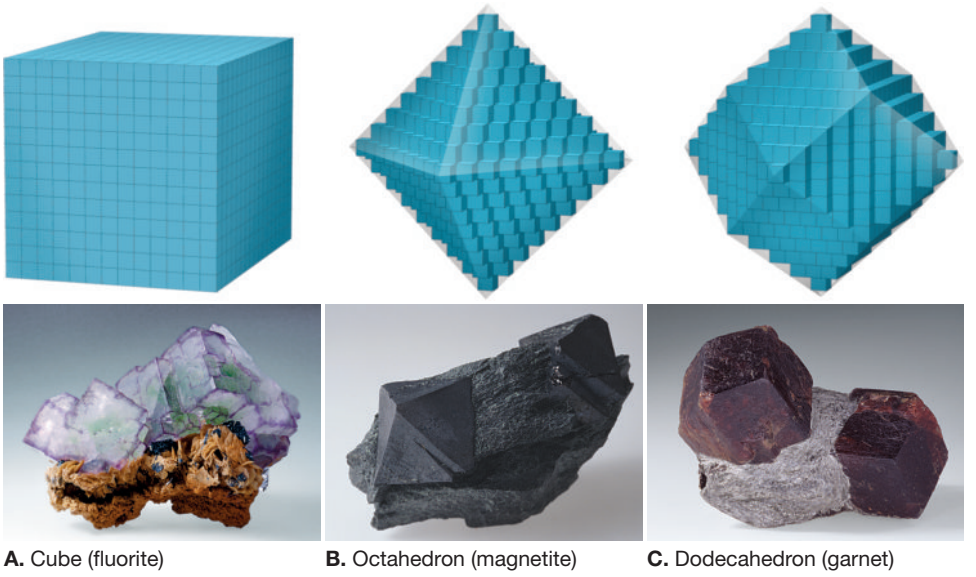


FIGURE 3.14 Cubic unit cells stack together in different ways to produce crystals that exhibit different shapes. Fluorite (**A**) tends to display cubic crystals, whereas magnetite crystals (**B**) are typically octahedrons, and garnets (**C**) usually occur as dodecahedrons. (Photos by Dennis Tasa)

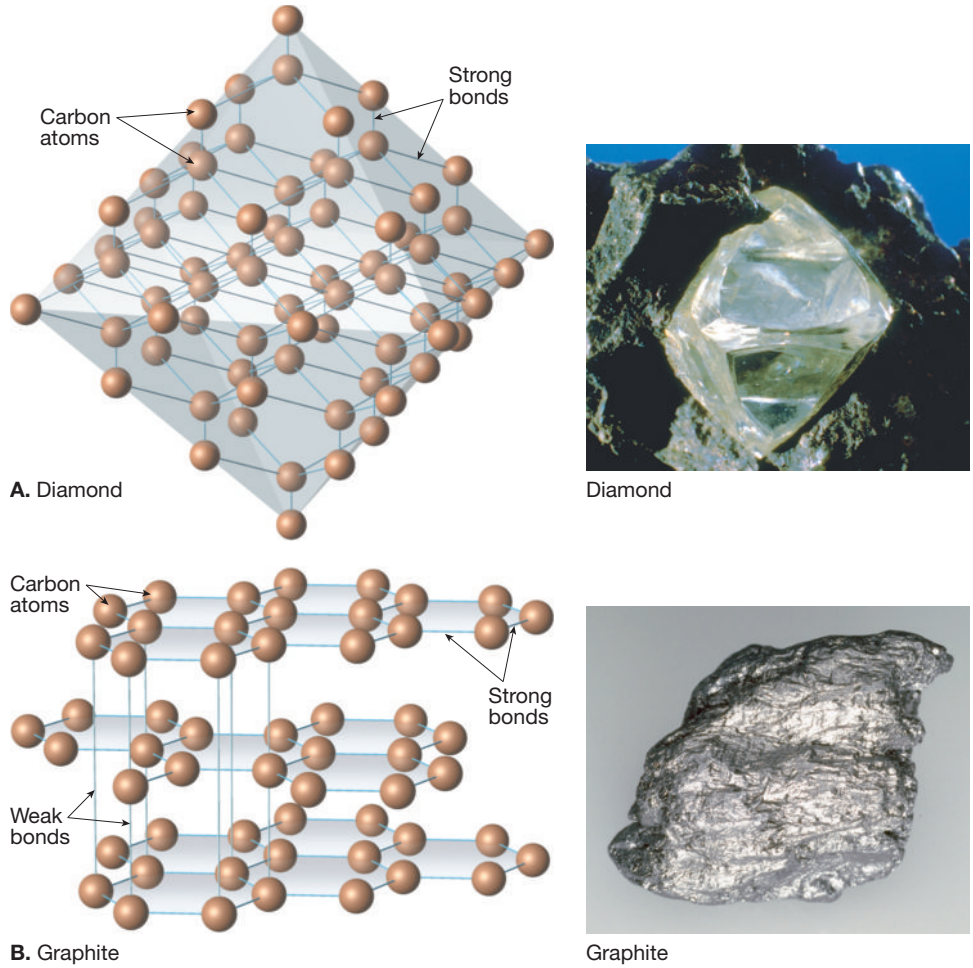


FIGURE 3.15 Comparing the structures of diamond and graphite. Both are natural substances with the same chemical composition—carbon atoms. Nevertheless, their internal structure and physical properties reflect the fact that each formed in a very different environment. **A.** All carbon atoms in diamond are covalently bonded into a compact, three-dimensional framework, which accounts for the extreme hardness of the mineral. **B.** In graphite the carbon atoms are bonded into sheets that are joined in a layered fashion by very weak electrical forces. These weak bonds allow the sheets of carbon to readily slide past each other, making graphite soft and slippery, and thus useful as a dry lubricant. (**A.** Photographer Dane Pendland, courtesy of Smithsonian Institution; **B.** E. J. Tarbuck)

diamond is the hardest known mineral. The differences between these minerals can be attributed to the condition under which they were formed. Diamonds form at depths approaching 200 kilometers (nearly 125 miles), where extreme pressures and temperatures produce the compact structure shown in Figure 3.15A. Graphite, on the other hand, forms under comparatively low pressures and consists of sheets of carbon atoms that are widely spaced and weakly bonded (Figure 3.15B). Because these carbon sheets will easily slide past one another, graphite has a greasy feel and makes an excellent lubricant.

Scientists have learned that by heating graphite under high pressure they can produce diamonds. Because synthetic diamonds often contain flaws, they are generally not gem quality. However, due to their hardness, they have many industrial uses. Further, because all diamonds form in environments of extreme pressures and temperatures, they are somewhat unstable at Earth's surface. Fortunately for jewelers, "diamonds are forever" because the rate at which they change to their more stable form, graphite, is infinitesimally slow.

Students Sometimes Ask . . .

Are there any artificial materials harder than diamonds?

Yes, but you won't be seeing them anytime soon. A hard form of carbon nitride (C_3N_4), described in 1989 and synthesized in a laboratory shortly thereafter, may be harder than diamond but hasn't been produced in large enough amounts for a proper test. In 1999, researchers discovered that a form of carbon made from fused spheres of 20 and 28 carbon atoms—relatives of the famous "buckyballs"—could also be as hard as a diamond. These materials are expensive to produce, so diamonds continue to be used as abrasives and in certain kinds of cutting tools. Synthetic diamonds, produced since 1955, are now widely used in these industrial applications.

Two other minerals with identical chemical compositions, calcium carbonate ($CaCO_3$), but different internal structures are calcite and aragonite. Calcite forms mainly through biochemical processes and is the major constituent of the sedimentary rock limestone. Aragonite, a less common polymorph of $CaCO_3$, is often deposited by hot springs and is an important constituent of pearls and the shells of some marine organisms. Because aragonite gradually changes to the more stable crystalline structure of calcite, it is rare in rocks older than 50 million years.

The transformation of one polymorph to another is called a *phase change.* In nature, certain minerals go through phase changes as they move from one environment to another. For example, when a slab of ocean crust composed of olivine-rich basalt is carried to great depths by a subducting plate, olivine changes to a more compact polymorph called spinel.

Physical Properties of Minerals

GEODe EARTH

Matter and Minerals
▸ **Physical Properties of Minerals**

Each mineral has a definite crystalline structure and chemical composition that give it a unique set of physical and chemical properties shared by all samples of that mineral.

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

The diagnostic physical properties of minerals are those that can be determined by observation or by performing a simple test. The primary physical properties that are commonly used to identify hand samples are luster, color, streak, crystal shape (habit), tenacity, hardness, cleavage, fracture, and density or specific gravity. Secondary (or "special") properties that are exhibited by a limited number of minerals include magnetism, taste, feel, smell, double refraction, and chemical reaction to hydrochloric acid.

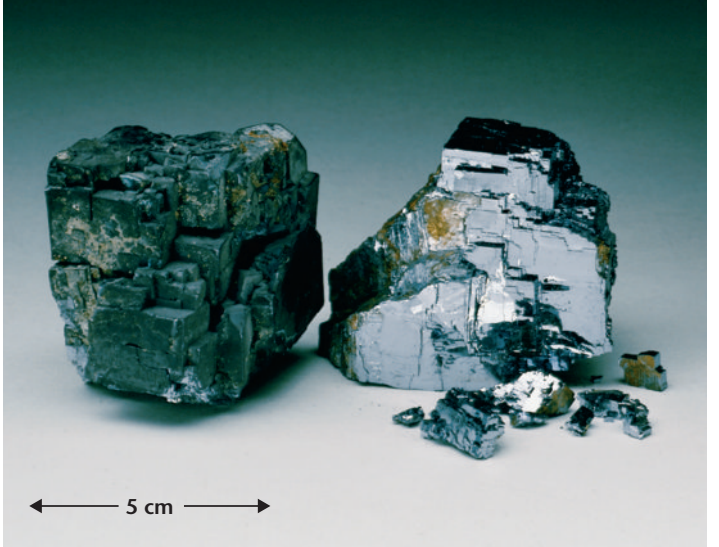


FIGURE 3.16 The freshly broken sample of galena (right) displays a metallic luster, while the sample on the left is tarnished and has a submetallic luster. (Photo courtesy of E. J. Tarbuck)

Optical Properties

Of the many optical properties of minerals, four—luster, the ability to transmit light, color, and 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 3.16). Some metallic minerals, such as native copper and galena, develop a dull coating or tarnish when exposed to the atmosphere. Because they 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 various 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).

The 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 it is said to be *translucent.* When 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 (see Figure 3.32, p. 93). 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 Although the color of a sample is not always helpful in identification, **streak**—the color of the powdered mineral—is often diagnostic. The streak is obtained by rubbing the mineral across a piece of unglazed porcelain, termed a *streak plate* and observing the color of the mark it leaves (Figure 3.17). Although the color of a mineral may vary from sample to sample, the streak usually does not.

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

It should be noted that not all minerals produce a streak when using a streak plate. For example, if the mineral is harder than the streak plate, no streak is observed.

Crystal Shape or Habit

Mineralogists use the term **habit** to refer to the common or characteristic shape of a crystal or aggregate of crystals. A few minerals exhibit somewhat regular polygons that are

FIGURE 3.17 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.

helpful in their identification. Recall that magnetite crystals sometimes occur as octahedrons, garnets often form dodecahedrons, and halite and fluorite crystals tend to grow as cubes or near cubes (see Figure 3.14). While most minerals have only one common habit, a few such as pyrite have two or more characteristic crystal shapes (Figure 3.18).

By contrast, some minerals rarely develop perfect geometric forms. Many of these do, however, develop a characteristic shape that is useful for identification. 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. Commonly used terms to describe these and other crystal habits include *equant* (equidimensional), *bladed, fibrous, tabular, prismatic, platy, blocky,* and *botryoidal* (Figure 3.19).

Mineral Strength

How easily minerals break or deform under stress relates to 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.

Tenacity The term **tenacity** describes a mineral's toughness, or its resistance to breaking or deforming. Minerals which are ionically bonded, such as fluorite and halite, tend to be *brittle* and shatter into small pieces when struck. By contrast, minerals with metallic bonds, such as native copper, are *malleable,* or easily hammered into different shapes. 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 the stress is released.

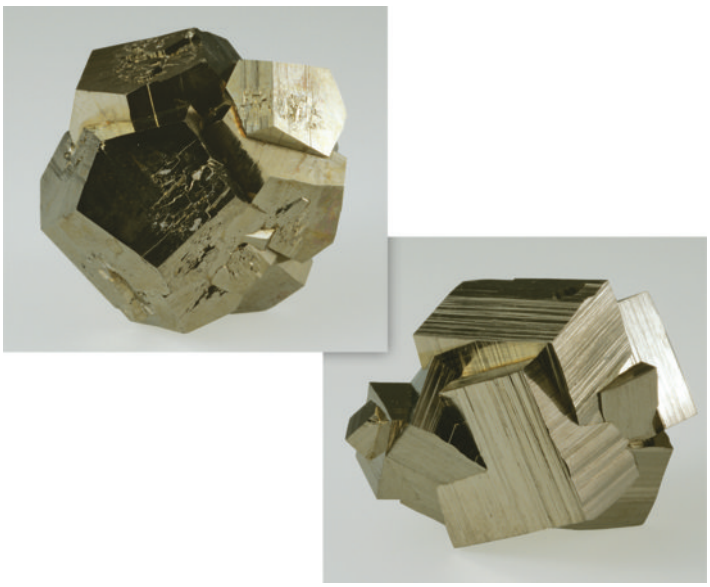


FIGURE 3.18 Although most minerals exhibit only one common crystal shape, some, such as pyrite, have two or more characteristic habits. (Photos by Dennis Tasa)

A. Bladed **B.** Prismatic

C. Banded **D.** Botryoidal

FIGURE 3.19 Some common crystal habits. **A.** *Bladed.* Elongated crystals that are flattened in one direction. **B.** *Prismatic.* Elongated crystals with faces that are parallel to a common direction. **C.** *Banded.* Minerals that have stripes or bands of different color or texture. **D.** *Botryoidal.* Groups of intergrown crystals resembling a bunch of grapes.

Hardness One of the most useful diagnostic properties is **hardness,** a measure of the resistance of a mineral to abrasion or scratching. This property is determined by rubbing a mineral of unknown hardness against one of known hardness, or vice versa. A numerical value of hardness can by 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 3.20A. 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 shown in Figure 3.20B.

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

Cleavage Some minerals have atomic structures that are not the same in every direction and chemical bonds that vary in strength. As a result, these minerals tend to break, so that the broken fragments are bounded by more or less flat, planar surfaces, a property called **cleavage** (*kleiben* = carve). Cleavage can be recognized by rotating a sample and looking for smooth, even surfaces that reflect light like a mirror. Note, however, that cleavage surfaces can occur in small, flat segments arranged in stair-step fashion.

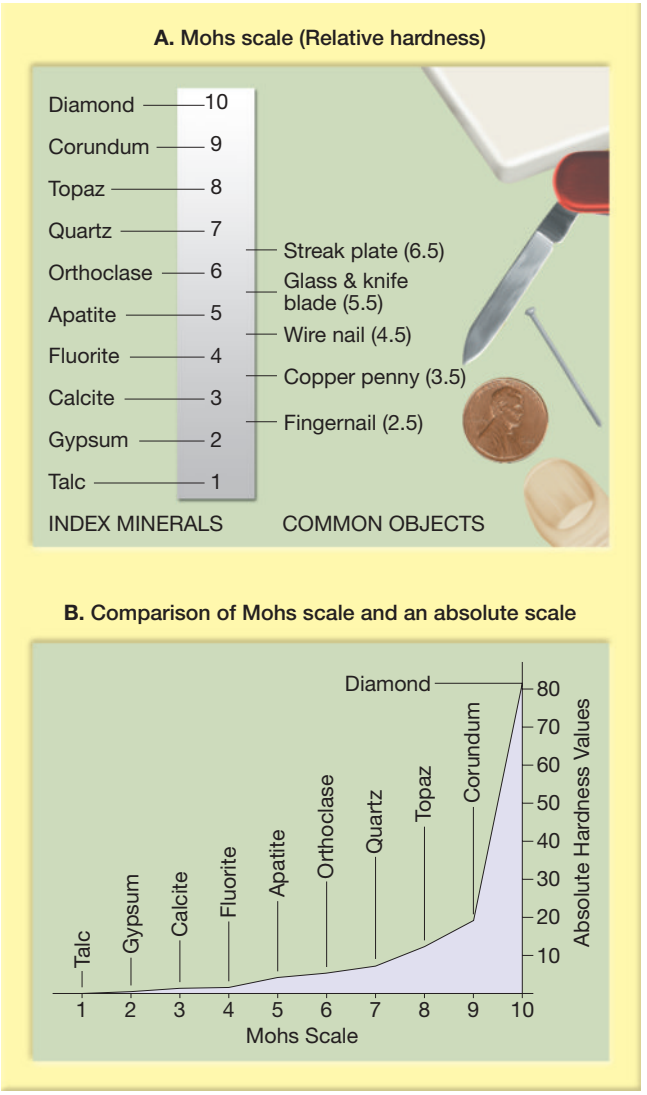


FIGURE 3.20 Hardness scales. **A.** Mohs scale of hardness, with the hardness of some common objects. **B.** Relationship between Mohs relative hardness scale and an absolute hardness scale.

The simplest type of cleavage is exhibited by the micas (Figure 3.21). Because the micas have much weaker bonds in one direction than in the others, they cleave to form thin, flat sheets. Some minerals have excellent cleavage in several 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 planes and the angle(s) at which they meet* (Figure 3.22).

Do not confuse cleavage with crystal shape. When a mineral exhibits cleavage, it will break into pieces that have the same geometry as each other. By contrast, the smooth-sided quartz crystals shown in Figure 3.2 do not have cleavage. If broken, they fracture into shapes that do not resemble each other or the original crystals.

Fracture Minerals that have structures that are equally, or nearly equally, strong in all directions **fracture** to form irregular surfaces. Those, such as quartz, that break into smooth curved surfaces resembling broken glass exhibit a *conchoidal fracture* (Figure 3.23). Others break into splinters or fibers, but most minerals display an irregular fracture.

FIGURE 3.21 The thin sheets shown here were produced by splitting a mica (muscovite) crystal parallel to its perfect cleavage. (Photo by Breck P. Kent)

Density and Specific Gravity

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

Most common rock-forming minerals have a specific gravity of 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 as quartz. Galena, which is 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. Ask yourself, 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 already discussed, some minerals can be recognized by other distinctive properties. For example, halite is ordinary salt, so it can be quickly identified through taste. Talc and graphite both have distinctive feels;

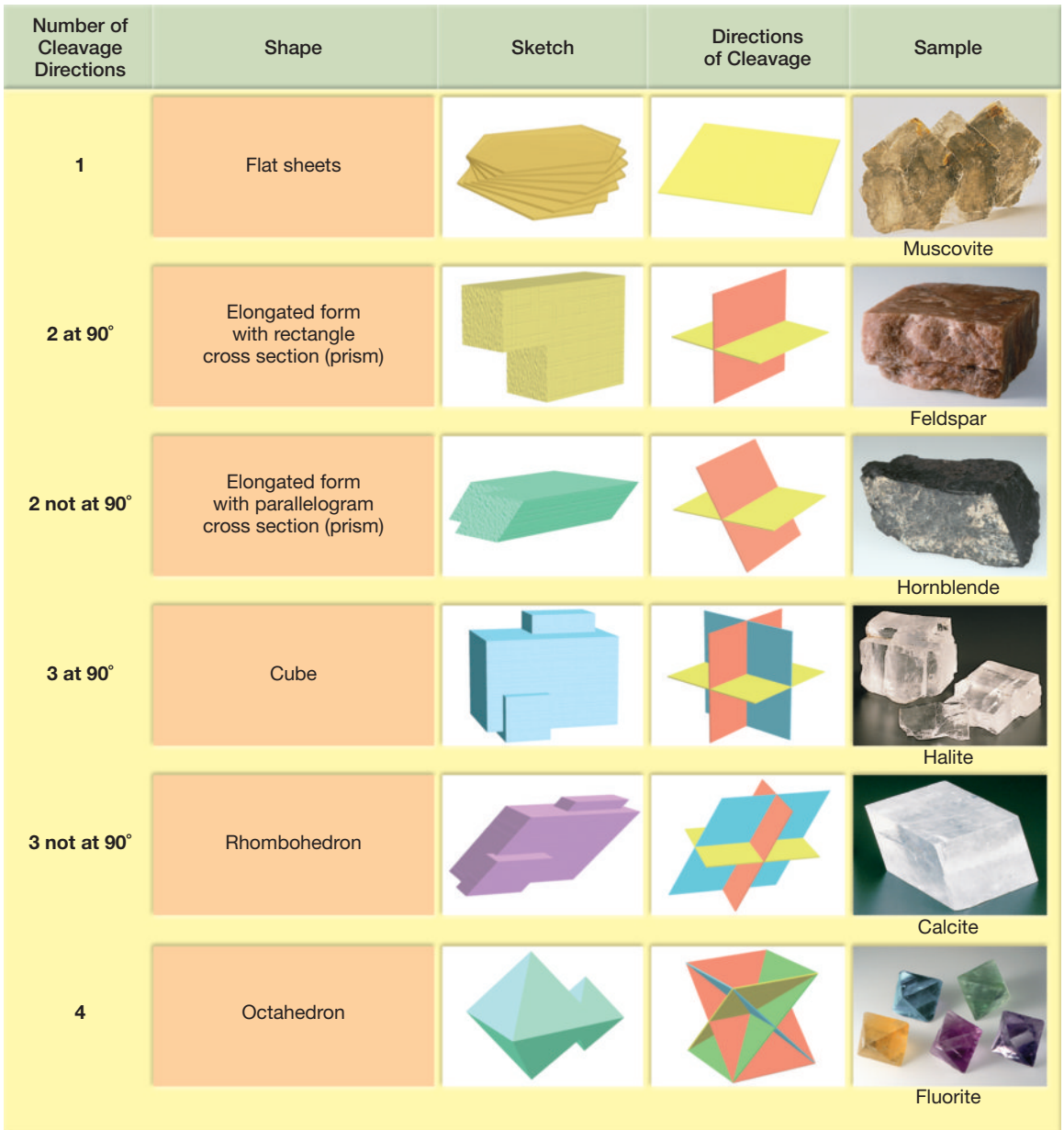


FIGURE 3.22 Common cleavage directions exhibited by minerals. (Photos by E. J. Tarbuck and Dennis Tasa)

talc feels soapy, and graphite feels greasy. Further, the streak of many sulfur-bearing minerals smells like rotten eggs. A few minerals, such as magnetite, have a high iron content and can be picked up with a magnet, while some varieties (lodestone) are natural magnets and will pick up small iron-based objects such as pins and paper clips (see Figure 3.36, p. 97).

Moreover, some minerals exhibit special optical properties. For example, when a transparent piece of calcite is placed over printed material, the letters appear twice. This optical property is known as *double refraction* (Figure 3.24).

One very simple chemical test involves placing a drop of dilute hydrochloric acid from a dropper bottle onto a freshly broken mineral surface. Certain minerals, called carbonates, will effervesce (fizz) as carbon dioxide gas is released (Figure 3.25). This test is especially useful in identifying the common carbonate mineral calcite.

How Are Minerals Named and Classified?

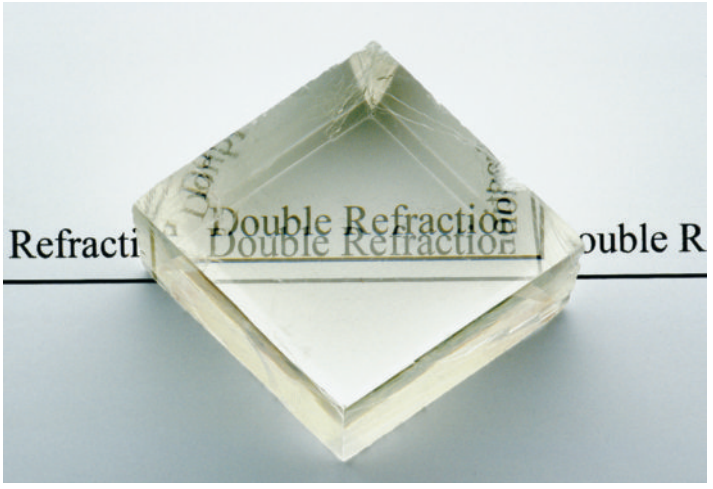
Nearly 4000 minerals have been named, and 30 to 50 new ones are identified each year. Fortunately, for students beginning their study of minerals, no more than a few dozen are abundant. Collectively, these few make up most of the rocks of Earth's crust and, as such, are often referred to as the *rock-forming minerals.*

FIGURE 3.23 Conchoidal fracture. The smooth curved surfaces result when minerals break in a glasslike manner. (Photo by E. J. Tarbuck)

Although less abundant, many other minerals are used extensively in the manufacture of products that drive our modern society and are called *economic minerals.* It should be noted that 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 the production of cement.

Determining what is or is not a mineral is in the hands of the International Mineralogical Association. Individuals who believe they have discovered a new mineral must apply to this organization with a detailed description of their findings. If confirmed, the discoverer is allowed to choose a name for the new mineral. Minerals have been named for people, locations where the mineral was discovered, appearance, and chemical composition. Although nearly 50 percent are named in honor of a person, rules prohibit naming a mineral after oneself.

FIGURE 3.24 Double refraction illustrated by the mineral calcite. (Photo by Chip Clark)



Classifying Minerals

Minerals are placed into categories in much the same way as plants and animals are classified by biologists. Mineralogists use the term *mineral species* for a collection of specimens that exhibit similar internal structures and chemical compositions. Some common mineral species include quartz, calcite, galena, and pyrite. However, just as individual plants and animals within a species differ somewhat from one another, so do most specimens within a mineral species.

Mineral species are usually assigned to a *mineral class* based on their anions, or anion complexes as shown in Table 3.1. Some of the important mineral classes include the silicates, (SiO_4^{4-}), carbonates (CO_3^{2-}), halides, (Cl^{1-}, F^{1-}, Br^{1-}), and sulfates (SO_4^{2-}). Minerals within each class tend to have similar internal structures and, hence, similar properties. For example, minerals that belong to the carbonate class react chemically with acid—albeit to varying degrees—and many exhibit rhombic cleavage. Furthermore, minerals within the same class are often found together in the same rock. The halides, for example, commonly occur together in evaporite deposits.

Mineral classes are further divided into *groups* (or, in some cases subclasses) based on similarities in atomic structures or compositions. For example, mineralogists group the feldspar minerals (orthoclase, albite, and anorthite) together because they all have similar internal structures. The minerals kyanite,

FIGURE 3.25 Calcite reacting with a weak acid. (Photo by Chip Clark)

TABLE 3.1 Major Mineral Classes

Class	Anion, Anion Complex, or Elements	Example (Mineral species)	Chemical Formula
silicates	$(SiO_4)^{4-}$	quartz	SiO_2
halides	Cl^-, F^-, Br^-, I^-	halite	NaCl
oxides	O^{2-}	corundum	Al_2O_3
hydroxides	$(OH)^-$	gibbsite	$Al(OH)_3$
carbonates	$(CO_3)^{2-}$	calcite	$CaCO_3$
nitrates	$(NO_3)^-$	nitratite	$NaNO_3$
sulfates	$(SO_4)^{2-}$	gypsum	$CaSO_4 \cdot 2H_2O$
phosphates	$(PO_4)^{3-}$	apatite	$Ca_5(PO_4)_3(OH, F, Cl)$
native elements	Cu, Ag, S	copper	Cu
sulfides	S^{2-}	pyrite	FeS_2

andalusite, and sillimanite are grouped together because they have the same chemical composition (Al_2SiO_5). Recall that minerals having the same composition, but different crystal structures are called *polymorphs.* Some common mineral groups include the feldspars, pyroxenes, amphiboles, micas, and olivine. Two members (species) of the mica group are biotite and muscovite. Although they have similar atomic structures, biotite contains iron and magnesium, which give it a greater density and darker appearance than muscovite.

Some mineral species are further subdivided into *mineral varieties.* For example, pure quartz (SiO_2) is colorless and transparent. However, when small amounts of aluminum are incorporated into its atomic structure, quartz appears quite dark, a variety called *smoky quartz. Amethyst,* another variety of quartz, owes its violet color to the presence of trace amounts of iron.

Major Mineral Classes

It is interesting to point out that only eight elements make up the bulk of rock-forming minerals and represent over 98 percent (by weight) of the continental crust (Figure 3.26). These elements, in order of abundance are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). As shown in Figure 3.26, silicon and oxygen are by far the most common elements in Earth's crust. Furthermore, these two elements readily combine to form the framework for the most dominant mineral class, the **silicates,** which account for more than 90 percent of Earth's crust. More than 800 species of silicate minerals are known.

Because other mineral classes are far less abundant than the silicates, they are often grouped together under the heading **nonsilicates.** Although not as common as the silicates, some nonsilicate minerals are very important economically. They provide us with the iron and aluminum to build our automobiles, gypsum for plaster and drywall to construct our homes, and copper for wire to carry electricity and connect us to the Internet. In addition to their economic importance, these mineral groups include members that are major constituents in sediments and sedimentary rocks.

We will first discuss the most common mineral class, the silicates, and then consider some of the prominent nonsilicate mineral groups.

The Silicates

Every silicate mineral contains the elements oxygen and silicon. Further, most contain one or more of the other common elements of Earth's crust. Together, these elements give rise to hundreds of minerals with a wide variety of properties, including hard quartz, soft talc, sheet-like mica, fibrous asbestos, green olivine and blood-red garnet.

The Silicon–Oxygen Tetrahedron

All silicate minerals have the same fundamental building block, the **silicon–oxygen tetrahedron.** This structure consists of four oxygen anions surrounding one comparatively small silicon cation, forming a tetrahedron—a pyramid shape with four identical faces (Figure 3.27). These tetrahedra are not chemical compounds, but rather complex anions (SiO_4^{4-}) having a net charge of –4. Because minerals must have a balanced charge, silicon-oxygen tetrahedra bond to other positively charged ions.

Specifically, each O^{2-} has one of its valence electrons balance by bonding with the Si^{4+} located at the center of the tetrahedron. The remaining –1 charge on each oxygen anion is available to bond with another cation, or with the silicon cation in an adjacent tetrahedron.

Independent Tetrahedra In nature, the simplest way for *independent tetrahedra* to become neutral compounds is through the addition of positively charged ions. For example, in the mineral olivine, magnesium (Mg^{2+}) and/or iron (Fe^{2+}) cations pack between larger independent SiO_4^{4-} units, forming a dense three-dimensional structure. Garnet, another

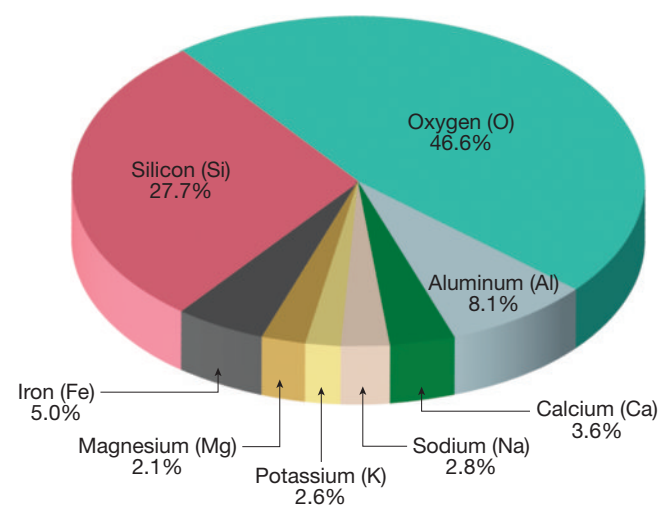


FIGURE 3.26 Relative abundance of the eight most abundant elements in the continental crust.

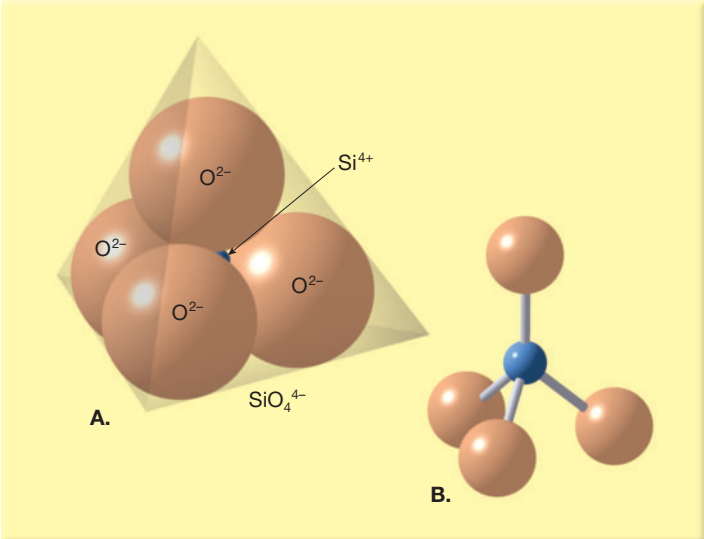


FIGURE 3.27 Two representations of the silicon–oxygen tetrahedron. **A.** The four large spheres represent oxygen ions, and the blue sphere represents a silicon ion. The spheres are drawn in proportion to the radii of the ions. **B.** An expanded view of the tetrahedron using rods to depict the bonds that connect the ions.

common silicate, is also composed of independent tetrahedra ionically bonded by cations. Both olivine and garnet form dense, hard, equidimensional crystals that lack cleavage.

Other Silicate Structures One reason for the great variety of silicate minerals is the ability of the silicate anion (SiO_4^{4-}) to link together in a variety of configurations. Vast numbers of tetrahedra connect to form *single chains, double chains,* or *sheet structures* as shown in Figure 3.28. This phenomenon, called *polymerization,* is achieved by the sharing of oxygen atoms between adjacent tetrahedra.

To understand how this sharing occurs, select one of the silicon ions (small blue spheres) near the middle of the single-chain structure shown in Figure 3.28. Notice that this silicon ion is completely surrounded by four larger oxygen ions (you are looking through one of the four to see the blue silicon ion). Also notice that, of the four oxygen ions, half are bonded to two silicon ions, whereas the other two are not shared in this manner. *It is the linkage across the shared oxygen ions that join the tetrahedra into a chain structure.* Now examine a silicon ion near the middle of the sheet structure and count the number of shared and unshared oxygen ions surrounding it. The sheet structure is the result of three of the four oxygen atoms being shared by adjacent tetrahedra.

Other silicate structures exist. In the most common of these, all four oxygen ions are shared and produce a complex three-dimensional framework. Each silicate framework forms the skeleton for a particular group of silicate minerals.

By now you can see that the ratio of oxygen ions to silicon ions differs in each of the silicate structures. In the independent tetrahedron, there are four oxygen ions for every silicon ion. In single chains, the oxygen-to-silicon ratio is 3:1, and in three-dimensional frameworks this ratio is 2:1. As more of the oxygen ions are shared, the percentage of silicon in the structure increases. Silicate minerals are, therefore, described as having a high or low silicon content based on their ratio of oxygen to silicon. This difference in silicon content is important, as we shall see in the chapter on igneous rocks.

Joining Silicate Structures

Except for quartz (SiO_2), the framework (chains, sheets, or three-dimensional networks) of most other silicate minerals has a net negative charge. Therefore, cations are required to bring the overall charge into balance and to serve as the "mortar" that holds these structures together. The cations that most often link silicate structures are iron (Fe^{2+}), magnesium (Mg^{2+}), potassium (K^{1+}), sodium (Na^{1+}), aluminum (Al^{3+}), and calcium (Ca^{2+}). These cations generally fit into spaces between unshared oxygen atoms that occupy the corners of the tetrahedra.

As a general rule, the partly covalent bonds between silicon and oxygen are stronger than the ionic bonds that hold one silicate framework to the next. Consequently, properties such as cleavage and, to some extent, the hardness of these minerals are controlled by the nature of the silicate framework. Quartz, which has only silicon–oxygen bonds, has great hardness and lacks cleavage, mainly because of equally strong bonds in all directions. By contrast, the sheet silicates, such as mica, have perfect cleavage in one direction and low hardness due to weak bonding between the sheet structures.

In addition, there tends to be a gradual decrease in density as the number of shared oxygens increases. For example, olivine and garnet, which are composed of independent tetrahedra (no sharing of oxygen atoms), tend to form quite compact structures having a specific gravity of about 3.2 to 4.4. By contrast, quartz and feldspar, which have a relatively open

Students Sometimes Ask . . .

Are these silicates the same materials used in silicon computer chips and silicone breast implants?

Not really, but all three contain the element silicon (Si). Further, the source of silicon for numerous products, including computer chips and breast implants, comes from silicate minerals. Pure silicon (without the oxygen that silicates have) is used to make computer chips, giving rise to the term "Silicon Valley" for the high-tech region of San Francisco, California's south bay area, where many of these devices are designed. Manufacturers of computer chips engrave silicon wafers with incredibly narrow conductive lines, squeezing millions of circuits into every fingernail-size chip.

Silicone—the material used in breast implants—is a silicon–oxygen polymer gel that feels rubbery and is water repellent, chemically inert, and stable at extreme temperatures. Although concern about the long-term safety of these implants limited their use after 1992, several studies have found no evidence linking them to various diseases.

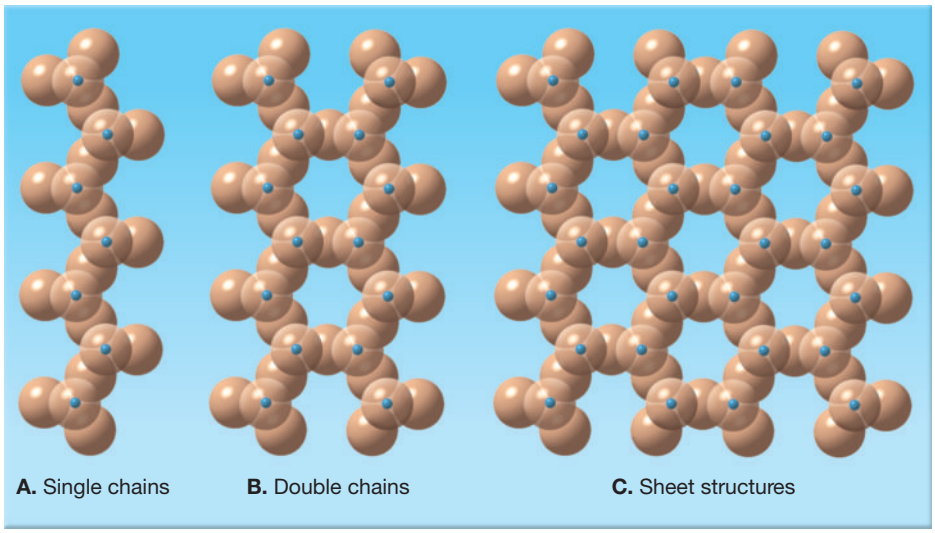


FIGURE 3.28 Three types of silicate structures. **A.** Single chains. **B.** Double chains. **C.** Sheet structures.

three-dimensional framework (complete sharing of oxygen atoms), have a specific gravity that is in the range of 2.6 to 2.8.

Recall that cations of approximately the same size are able to substitute freely for one another. For instance, the mineral olivine contains iron (Fe^{2+}) and magnesium (Mg^{2+}) ions that substitute for each other without altering that mineral's structure. This also holds true for some feldspars in which calcium and sodium cations occupy the same site in a crystal structure. In addition, aluminum (Al) often substitutes for silicon (Si) in silicon–oxygen tetrahedra.

Because most silicate structures will readily accommodate different cations at a given bonding site, individual specimens of a particular mineral may contain varying amounts of certain elements. As a result, many silicate minerals form a *mineral group* that exhibits a range of compositions between two end members. Some of the common mineral groups are given in Figure 3.29, and include the olivines, pyroxenes, amphiboles, micas, and feldspars.

Common Silicate Minerals

Minerals: Building Blocks of Rocks
▸ Mineral Groups

The major silicate groups and common examples are given in Figure 3.29. The feldspars are by far the most plentiful silicate group, comprising more than 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.

Most silicate minerals form when molten rock cools and crystallizes. 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 determine to a large degree which minerals are produced. For example, the silicate mineral olivine crystallizes at high temperatures, whereas quartz crystallizes at much lower temperatures.

In addition, some silicate minerals form at Earth's surface from the weathered products of other silicate minerals. 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 constituents 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 we divide into two major groups on the basis of their chemical makeup.

The Light Silicates

The **light** (or **nonferromagnesian) silicates** are generally light in color and have a specific gravity of about 2.7, which is considerably less than the dark (ferromagnesian) silicates. These differences are mainly attributable to the presence or absence of iron and magnesium. The light silicates contain varying amounts of aluminum, potassium, calcium, and sodium rather than iron and magnesium.

Feldspar Group *Feldspar,* the most common mineral group, can form under a wide range of temperatures and pressures, a fact that partially accounts for its abundance (Figure 3.30). All of the feldspars have similar physical properties. They have two planes of cleavage meeting at or near 90-degree angles, are relatively hard (6 on the Mohs scale), and have a luster that ranges from glassy to pearly. As one component in a rock, feldspar crystals can be identified by their rectangular shape and rather smooth shiny faces (Figure 3.29).

Two different feldspar structures exist. One group of feldspar minerals contains potassium ions in its structure and is therefore referred to as *potassium feldspar.* (*Orthoclase* and *microcline* are common members of the potassium feldspar group.) The other group, called *plagioclase feldspar,* contains both sodium and calcium ions that freely substitute for one another depending on the environment during crystalization.

Potassium feldspar is usually light cream, salmon pink, or occasionally bluish-green in color. The plagioclase feldspars, on the other hand, range in color from white to medium gray. However, color should not be used to distinguish these groups. The only sure way to distinguish the feldspars physically is to look for a multitude of fine parallel lines, called *striations.* Striations are found on some cleavage planes of plagioclase feldspar but are not present on potassium feldspar (Figure 3.31).

Quartz *Quartz* is the only common silicate mineral consisting entirely of silicon and oxygen. As such, the term *silica* is

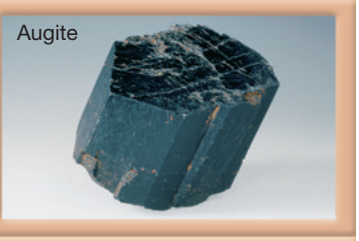
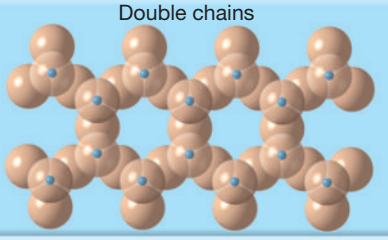
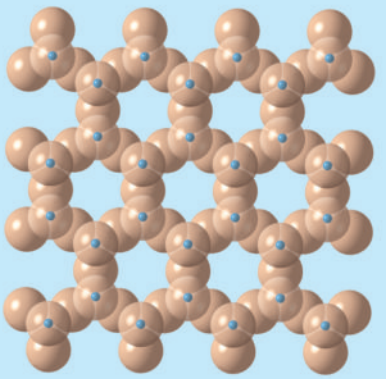
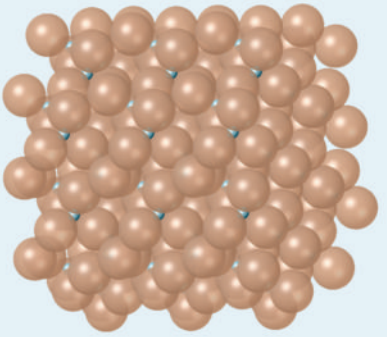
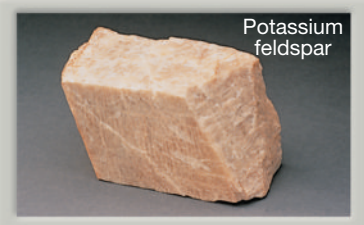
Mineral/Formula		Cleavage	Silicate Structure	Example
Olivine group $(Mg, Fe)_2SiO_4$		None	Independent tetrahedron 	 Olivine
Pyroxene group (Augite) $(Mg,Fe)SiO_3$		Two planes at right angles	Single chains 	 Augite
Amphibole group (Hornblende) $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$		Two planes at 60° and 120°	Double chains 	 Hornblend
Micas	Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	One plane	Sheets 	 Biotite
Micas	Muscovite $KAl_2(AlSi_3O_{10})(OH)_2$			 Muscovite
Feldspars	Potassium feldspar (Orthoclase) $KAlSi_3O_8$	Two planes at 90°	Three-dimensional networks 	 Potassium feldspar
Feldspars	Plagioclase feldspar $(Ca,Na)AlSi_3O_8$			
Quartz SiO_2		None		 Quartz

FIGURE 3.29 Common silicate minerals. Note that the complexity of the silicate structure increases down the chart. (Photos by Dennis Tasa and E. J. Tarbuck)

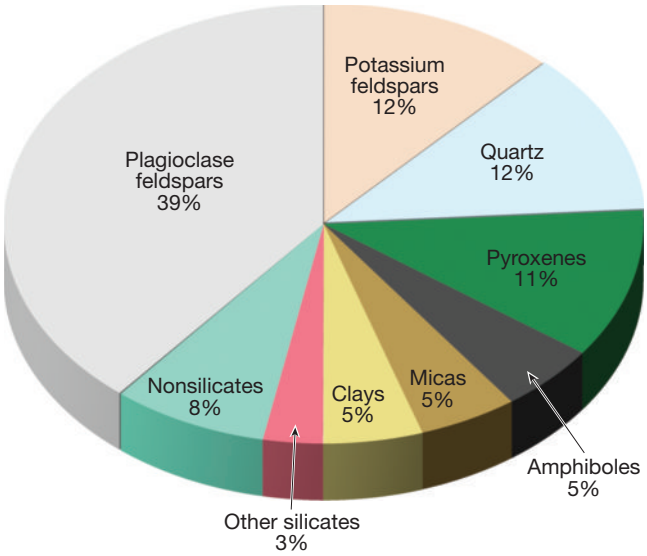
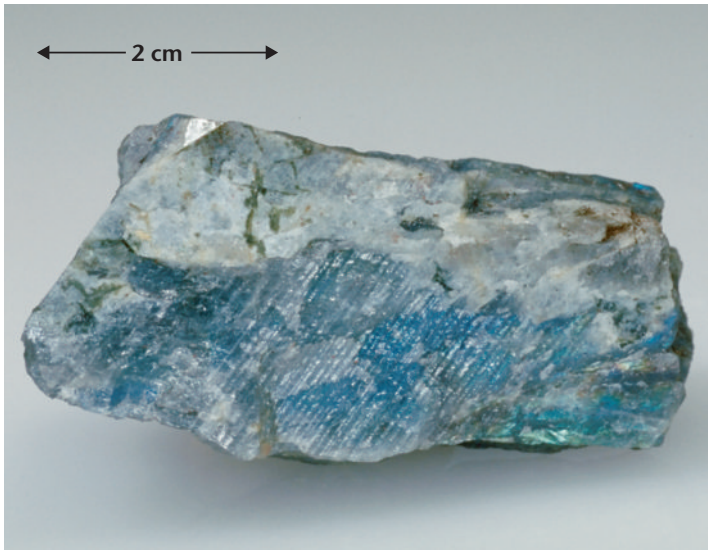


FIGURE 3.30 Estimated percentages (by volume) of the most common minerals in Earth's crust.

applied to quartz, which has the chemical formula SiO_2. Because the structure of quartz contains a ratio of two oxygen ions (O^{2-}) for every silicon ion (Si^{4+}), no other positive ions are needed to attain neutrality.

In quartz, a three-dimensional framework is developed through the complete sharing of oxygen by adjacent silicon atoms. Thus, all of the bonds in quartz are of the strong silicon–oxygen type. Consequently, quartz is hard, resistant to weathering, and does not have cleavage. When broken, quartz generally exhibits conchoidal fracture (See Figure 2.3). In a pure form, quartz is clear and, if allowed to grow without interference, will form hexagonal crystals that develop pyramid-shaped ends. However, like most other clear minerals, quartz is often colored by inclusions of various ions (impurities) and forms without developing good crystal faces. The most common varieties of quartz are milky (white), smoky (gray), rose (pink), amethyst (purple), and rock crystal (clear) (Figure 3.32).

FIGURE 3.31 These parallel lines, called striations, are a distinguishing characteristic of the plagioclase feldspars. (Photo by E. J. Tarbuck)



Muscovite *Muscovite* is a common member of the mica family. It is light in color and has a pearly luster. Like other micas, muscovite has excellent cleavage in one direction. In thin sheets, muscovite is clear, a property that accounts for its use as window "glass" during the Middle Ages. Because muscovite is very shiny, it can often be identified by the sparkle it gives a rock. If you have ever looked closely at beach sand, you may have seen the glimmering brilliance of the mica flakes scattered among the other sand grains.

Clay Minerals *Clay* is a term used to describe a variety of complex minerals that, like the micas, have a sheet structure. Unlike other common silicates, such as quartz and feldspar, clays do not form in igneous environments. Rather, most clay minerals originate as products of the chemical weathering of other silicate minerals. Thus, clay minerals make up a large percentage of the surface material we call soil. Because of the importance of soil in agriculture, and because of its role as a supporting material for buildings, clay minerals are extremely important to humans. In addition, clays account for nearly half the volume of sedimentary rocks.

Clay minerals are generally very fine grained, which makes identification difficult, unless studied microscopically. Their layered structure and weak bonding between layers give them a characteristic feel when wet. Clays are common in shales, mudstones, and other sedimentary rocks. Although clays are fine grained, they can form very thick beds or layers.

One of the most common clay minerals is *kaolinite,* which is used in the manufacture of fine chinaware and as a coating for high-gloss paper, such as that used in this textbook. Further, some clay minerals absorb large amounts of water, which allows them to swell to several times their normal size. These clays have been used commercially in a variety of ingenious ways, including as an additive to thicken milkshakes in fast-food restaurants.

FIGURE 3.32 Quartz. Some minerals, such as quartz, occur in a variety of colors. These samples include crystal quartz (colorless), amethyst (purple quartz), citrine (yellow quartz), and smoky quartz (gray to black). (Photo courtesy of E. J. Tarbuck)

The Dark Silicates

The **dark** (or **ferromagnesian**) **silicates** are those minerals containing ions of iron (iron = *ferro*) and/or magnesium in their structure. Because of their iron content, ferromagnesian silicates are dark in color and have a greater specific gravity, between 3.2 and 3.6, than nonferromagnesian silicates. The most common dark silicate minerals are olivine, the pyroxenes, the amphiboles, dark mica (biotite), and garnet.

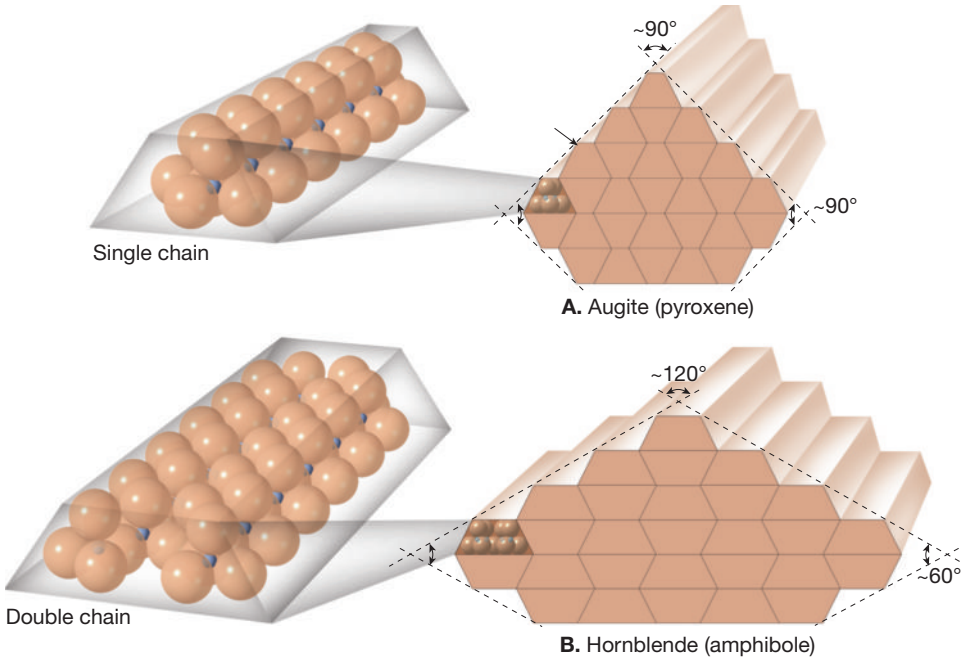


FIGURE 3.33 Cleavage angles for augite and hornblende. Because hornblende's double chains are more weakly bonded than augite's single chains, cleavage is better developed in hornblende.

Olivine Group *Olivine* is a family of high-temperature silicate minerals that are black to olive green in color and have a glassy luster and a conchoidal fracture (Figure 3.29). Rather than developing large crystals, olivine commonly forms small, rounded crystals that give rocks consisting largely of olivine a granular appearance. Olivine is composed of individual tetrahedra, which are bonded together by a mixture of iron and magnesium ions positioned so as to link the oxygen atoms and magnesium atoms together. Because the three-dimensional network generated in this fashion does not have its weak bonds aligned, olivine does not possess cleavage.

Pyroxene Group The *pyroxenes* are a group of complex minerals that are important components of Earth's mantle. The most common member, *augite,* is a black, opaque mineral with two directions of cleavage that meet at nearly a 90-degree angle (Figure 3.29). Its crystalline structure consists of single chains of tetrahedra bonded together by ions of iron and magnesium. Because the silicon–oxygen bonds are stronger than the bonds joining the silicate structures, augite cleaves parallel to the silicate chains, as shown in Figure 3.33. Augite is one of the dominant minerals in basalt, a common igneous rock of the oceanic crust and volcanic areas on the continents.

Amphibole Group *Hornblende* is the most common member of a chemically complex group of minerals called *amphiboles* (Figure 3.29). Hornblende is usually dark green to black in color, and except for its cleavage angles, which are about 60 degrees and 120 degrees, it is very similar in appearance to augite. The double chains of tetrahedra in the hornblende structure account for its particular cleavage (Figure 3.33). In a rock, hornblende often forms elongated crystals. This helps distinguish it from pyroxene, which forms rather blocky crystals. Hornblende is found in igneous rocks, where it often makes up the dark portion of an otherwise light-colored rock.

Biotite *Biotite* is the dark iron-rich member of the mica family (Figure 3.29). Like other micas, biotite possesses a sheet structure that gives it excellent cleavage in one direction. Biotite also has a shiny black appearance that helps distinguish it from the other dark ferromagnesian minerals. Like hornblende, biotite is a common constituent of igneous rocks, including the rock granite.

Garnet *Garnet* is similar to olivine in that its structure is composed of individual tetrahedra linked by metallic ions. Also like olivine, garnet has a glassy luster, lacks cleavage, and exhibits conchoidal fracture. Although the colors of garnet are varied, this mineral is most often brown to deep red. Garnet readily forms equidimensional crystals that are most commonly found in metamorphic rocks (Figure 3.34). When garnets are transparent, they may be used as gemstones.

FIGURE 3.34 A deep-red garnet crystal embedded in a light-colored, mica-rich metamorphic rock. (Photo by E. J. Tarbuck)

Students Sometimes Ask . . .

I've seen garnet sandpaper at the hardware store. Is it really made of garnets?

Yes, and it's one of many things at the hardware store that's made of minerals! Hard minerals such as garnet (Mohs hardness = 6.5 to 7.5) and corundum (hardness = 9) make good abrasives. The abundance and hardness of garnets make them suitable for producing abrasive wheels, polishing materials, non-skid surfaces, and in sandblasting applications. Alternatively, those minerals that have low numbers on the Mohs hardness scale are commonly used as lubricants. For example, another mineral found in hardware stores is graphite (hardness = 1), which is used as an industrial lubricant.

Important Nonsilicate Minerals

GEODe EARTH

Minerals: Building Blocks of Rocks
▸ **Mineral Groups**

Nonsilicate minerals are typically subdivided into *classes,* based on the anion (negatively charged ion) or complex anion that the members have in common (Table 3.2). For example, the *oxides* contain the negative oxygen ion (O^{2-}), which is bonded to one or more kinds of positive ions. Thus, within each mineral class, 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 3.2 lists some of the nonsilicate mineral classes and a few examples of each. A brief discussion of a few of the more 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. This mineral group is composed of the carbonate ion (CO_3^{2-}) and one or more kinds of anions. The two most common carbonate minerals are *calcite,* $CaCO_3$ (calcium carbonate), and *dolomite,* $CaMg(CO_3)_2$ (calcium/magnesium carbonate). Because these minerals are similar both physically and chemically, they are difficult to distinguish from each other. Both have a vitreous luster, a hardness between 3 and 4, and nearly perfect rhombic cleavage. They can, however, be distinguished by using dilute hydrochloric acid. Calcite reacts vigorously with this acid, whereas dolomite reacts much more slowly. 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.* Both minerals are commonly found in thick layers that are the last vestiges of ancient seas that have long since evaporated (Figure 3.35). Like limestone, both are important nonmetallic resources. Halite is the mineral name for common table salt (NaCl).

TABLE 3.2 Common Nonsilicate Mineral Classes

Mineral Groups (Key ions or elements)	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
	Cinnabar	HgS	Ore of mercury
Sulfates (SO_4^{2-})	Gypsum	$CaSO_4 \cdot 2\,H_2O$	Plaster
	Anhydrite	$CaSO_4$	Plaster
	Barite	$BaSO_4$	Drilling mud
Native elements (single elements)	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

BOX 3.3 ▸ UNDERSTANDING EARTH

Gemstones

Precious stones have been prized since antiquity. But misinformation abounds regarding gems and their mineral makeup. This stems partly from the ancient practice of grouping precious stones by color rather than mineral makeup. For example, *rubies* and red *spinels* are very similar in color, but they are completely different minerals. Classifying by color led to the more common spinels being passed off to royalty as rubies. Even today, with modern identification techniques, common *yellow quartz* is sometimes sold as the more valuable gemstone *topaz.*

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 (Figure 3.C). 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, and the gem is called *ruby.* Further, if a specimen is not suitable as a gem, it simply goes by the mineral name *corundum.* Because of its hardness, corundum that is not of gem quality is often crushed and sold as an abrasive.

To summarize, when corundum exhibits a red hue, it is called *ruby,* but if it exhibits any other color, the gem is called *sapphire.* Whereas corundum is the base mineral for two gems, quartz is the parent of more than a dozen gems. Table 3.A lists some well-known gemstones and their parent minerals.

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 (Figure 3.C). (One of the methods used to shape a gemstone is *cleaving,* the act of splitting the mineral along one of its planes of weakness, or cleavage.) Only those mineral specimens that are of such quality that they can command a price in excess of the cost of processing are considered gemstones.

Gemstones can be divided into two categories: precious and semiprecious. A *precious* gem has beauty, durability, and rarity, whereas a *semiprecious* gem generally has only one or two of these qualities. The gems traditionally in highest esteem are diamonds, rubies, sapphires, emeralds, and some varieties of opal (Table 3.A). All other gemstones are classified as semiprecious. However, large, high-quality specimens of semiprecious stones often command a very high price.

Today translucent stones with evenly tinted colors are preferred. The most favored hues are red, blue, green, purple, rose, and yellow. The most prized stones are pigeon-blood rubies, blue sapphires, grass-green emeralds, and canary-yellow diamonds. Colorless gems are generally less than desirable except for diamonds that display "flashes of color" known as *brilliance.*

The durability of a gem depends on its hardness; that is, its resistance to abrasion by objects normally encountered in everyday living. For good durability, gems should be as hard or harder than quartz as defined by the Mohs scale of hardness. One notable exception is opal, which is comparatively soft (hardness 5 to 6.5) and brittle. Opal's esteem comes from its "fire," which is a display of a variety of brilliant colors, including greens, blues, and reds.

It seems to be human nature to treasure that which is rare. In the case of gemstones, large, high-quality specimens are much rarer than smaller stones. Thus, large rubies, diamonds, and emeralds, which are rare in addition to being beautiful and durable, command the very highest prices.

Table 3.A Important Gemstones

Gem	Mineral Name	Prized Hues
Precious		
Diamond	Diamond	Colorless, yellows
Emerald	Beryl	Greens
Opal	Opal	Brilliant hues
Ruby	Corundum	Reds
Sapphire	Corundum	Blues
Semiprecious		
Alexandrite	Chrysoberyl	Variable
Amethyst	Quartz	Purples
Cat's-eye	Chrysoberyl	Yellows
Chalcedony	Quartz (agate)	Banded
Citrine	Quartz	Yellows
Garnet	Garnet	Reds, 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

FIGURE 3.C Australian sapphires showing variation in cuts and colors. (Photo by Fred Ward, Black Star)

FIGURE 3.35 Thick bed of halite (salt) at an underground mine in Grand Saline, Texas. (Photo by Tom Bochsler)

Students Sometimes Ask . . .

What is the largest diamond ever found?

Weighing in at 3106 carats (1.37 pounds), and mined in 1905 in South Africa, the Cullian diamond is the largest ever discovered. During the process of removing its flaws through cleaving, this enormous diamond was broken into nine fragments that were fashioned into gems. The largest of these is a 550.2 carat pear-shaped gem that was mounted in the British royal scepter. By comparison, the Hope diamond, perhaps the most-recognized gem in the world, was only about 112 carats when discovered. Having been cut at least twice, this fabulous 45.52 carat, blue diamond now resides in the National Museum of Natural History of the Smithsonian Institution.

A.

B.

FIGURE 3.36 Magnetite (**A**) and hematite (**B**) are both oxides and are both important ores of iron. (Photos by E. J. Tarbuck)

Gypsum ($CaSO_4 \cdot 2H_2O$), which is calcium sulfate with water bound into the 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 (Figure 3.36). 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.

Summary

- A *mineral* is any naturally occurring inorganic solid that possesses an orderly crystalline structure and a well-defined chemical composition. Most *rocks* are aggregates composed of two or more minerals.
- The building blocks of minerals are *elements.* An *atom* is the smallest particle of matter that still retains the characteristics of an element. Each atom has a *nucleus,* which contains *protons* (particles with positive electrical charges) and *neutrons* (particles with neutral electrical charges). Orbiting the nucleus of an atom in regions called *energy levels,* or *principal shells,* are *electrons,* which have negative electrical charges. The number of protons in an atom's nucleus determines its *atomic number* and the name of the element. An element is a large collection of electrically neutral atoms, all having the same atomic number.
- Atoms combine with each other to form more complex substances called *compounds.* Atoms bond together by either gaining, losing, or sharing electrons with other atoms. In *ionic bonding,* one or more electrons are transferred from one atom to another, giving the atoms a net positive or negative charge. The resulting electrically charged atoms are called *ions.* Ionic compounds consist of oppositely charged ions assembled in a regular, crystalline structure that allows for the maximum attraction of ions, given their sizes. Another type of bond, the *covalent bond,* is produced when atoms share electrons.

- *Isotopes* are variants of the same element but with a different *mass number* (the total number of neutrons plus protons found in an atom's nucleus). Some isotopes are unstable and disintegrate naturally through a process called *radioactivity.*
- Mineralogists use the term *crystal* or *crystalline* in reference to *any natural solid with an ordered, repetitive, atomic structure.* Minerals form through the process of *crystallization,* which occurs when material precipitates out of a solution, as magma cools and crystallizes, or in high-temperature and high-pressure metamorphic environments.
- The basic building blocks of minerals, called *unit cells,* consist of an array of cations and anions arranged so that the positive and negative charges cancel each other out. These unit cells stack together in a regular manner that relates to the shape and symmetry of a crystal. Thus, the *angles between equivalent faces of crystals of the same mineral are always the same,* an observation known as *Steno's Law.*
- The chemical composition of some minerals varies from sample to sample, because ions of similar size can substitute for one another. It is also common for two minerals with exactly the same chemical composition to have different internal structures, and hence, different external forms. Minerals of this type are called *polymorphs.*
- The properties of minerals include *crystal shape (habit), luster, color, streak, hardness, cleavage, fracture,* and *density* or *specific gravity.* In addition, a number of special physical and chemical properties (*taste, smell, elasticity, feel, magnetism, double refraction,* and *chemical reaction to hydrochloric acid*) are useful in identifying certain minerals. Each mineral has a unique set of properties that can be used for identification.
- Of the nearly 4000 minerals, no more than a few dozen make up most of the rocks of Earth's crust and, as such, are classified as rock-forming minerals. Eight elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium) make up the bulk of these minerals and represent over 98 percent (by weight) of Earth's continental crust.
- The most common mineral group is the *silicates.* All silicate minerals have the negatively charged *silicon–oxygen tetrahedron* as their fundamental building block. In some silicate minerals the tetrahedra are joined in chains (the pyroxene and amphibole groups); in others, the tetrahedra are arranged into sheets (the micas—biotite and muscovite), or three-dimensional networks (the feldspars and quartz). The tetrahedra and various silicate structures are often bonded together by the positive ions of iron, magnesium, potassium, sodium, aluminum, and calcium. Each silicate mineral has a structure and a chemical composition that indicates the conditions under which it formed.
- The *nonsilicate* mineral groups, which contain several economically important minerals, include the *oxides* (e.g., the mineral hematite, mined for iron), *sulfides* (e.g., the mineral sphalerite, mined for zinc, and the mineral galena, mined for lead), *sulfates, halides,* and *native elements* (e.g., gold and silver). The more common nonsilicate rock-forming minerals include the *carbonate minerals,* calcite and dolomite. Two other nonsilicate minerals frequently found in sedimentary rocks are halite and gypsum.

Review Questions

1. List five characteristics an Earth material should have in order to be considered a mineral.
2. Define the term *rock.*
3. List the three main particles of an atom and explain how they differ from one another.
4. If the number of electrons in a neutral atom is 35 and its mass number is 80, calculate the following:
   a. the number of protons
   b. the atomic number
   c. the number of neutrons
5. What is the significance of valence electrons?
6. Briefly distinguish between ionic and covalent bonding.
7. What occurs in an atom to produce a cation? An anion?
8. What is an isotope?
9. What do minerologists mean when they use the word *crystal*?
10. Describe three ways a mineral might form (crystallize).
11. What is Steno's Law?
12. What are polymorphs? How are they similar?
13. Why might it be difficult to identify a mineral by its color?
14. If you found a glassy-appearing mineral while rock hunting and had hopes that it was a diamond, what simple test might help you make a determination?
15. Explain the use of corundum as given in Table 3.2 (p. 95) in terms of the Mohs hardness scale.
16. Gold has a specific gravity of almost 20. If a 25-liter pail of water weighs 25 kilograms, how much would a 25-liter pail of gold weigh?
17. Explain the difference between the terms *silicon* and *silicate.*
18. What is meant when we refer to a mineral's tenacity? List three terms that describe tenacity.
19. On what basis are minerals placed in mineral classes?
20. Describe the silicon–oxygen tetrahedron.
21. What do ferromagnesian minerals have in common? List examples of ferromagnesian minerals.
22. What do muscovite and biotite have in common? How do they differ?
23. Should color be used to distinguish between orthoclase and plagioclase feldspar? What is the best means of distinguishing between these two types of feldspar?
24. Each of the following statements describes a silicate mineral or mineral group. In each case, provide the appropriate name:

a. the most common member of the amphibole group

b. the most common nonferromagnesian member of the mica family

c. the only silicate mineral made entirely of silicon and oxygen

d. a high-temperature silicate with a name that is based on its color

e. one that is characterized by striations

f. one that originates as a product of chemical weathering

25. What simple test can be used to distinguish calcite from dolomite?

Key Terms

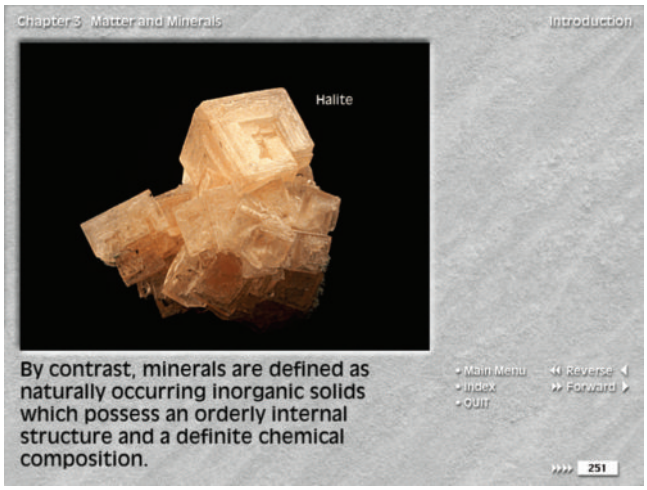
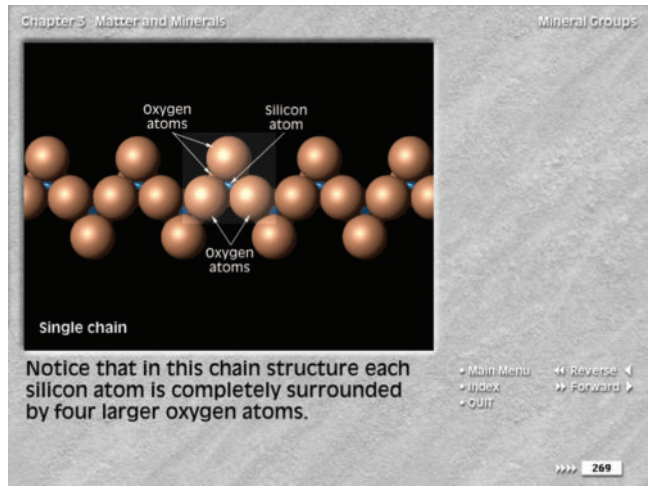
atom (p. 75)
atomic number (p. 75)
chemical compound (p. 75)
cleavage (p. 85)
color (p. 84)
Constancy of Interfacial Angles, Law of (p. 81)
covalent bond (p. 77)
crystal (p. 78)
crystalline (p. 78)
crystallization (p. 78)
crystal shape (p. 81)
dark silicates (p. 94)
density (p. 86)
electron (p. 75)
element (p. 75)
energy levels, or shells (p. 75)
ferromagnesian silicates (p. 94)
fracture (p. 86)
habit (p. 84)
hardness (p. 85)
ion (p. 76)
ionic bond (p. 76)
isotope (p. 78)
light silicates (p. 91)
luster (p. 84)
mass number (p. 78)
metallic bond (p. 78)
mineral (p. 72)
mineralogy (p. 72)
Mohs scale (p. 85)
neutron (p. 75)
nonferromagnesian silicates (p. 91)
nonsilicates (p. 89)
nucleus (p. 75)
periodic table (p. 75)
polymorph (p. 82)
principal shells (p. 75)
proton (p. 75)
radioactive decay (p. 78)
rock (p. 73)
silicate (p. 89)
silicon–oxygen tetrahedron (p. 89)
specific gravity (p. 86)
Steno's law (p. 81)
streak (p. 84)
tenacity (p. 85)
valence electron (p. 75)

Web Resources

The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

http://www.prenhall.com/tarbuck

GEODe: Earth

GEODe: Earth makes studying faster and more effective by reinforcing key concepts using animation, video, narration, interactive exercises and practice quizzes. A copy is included with every copy of *Earth.*