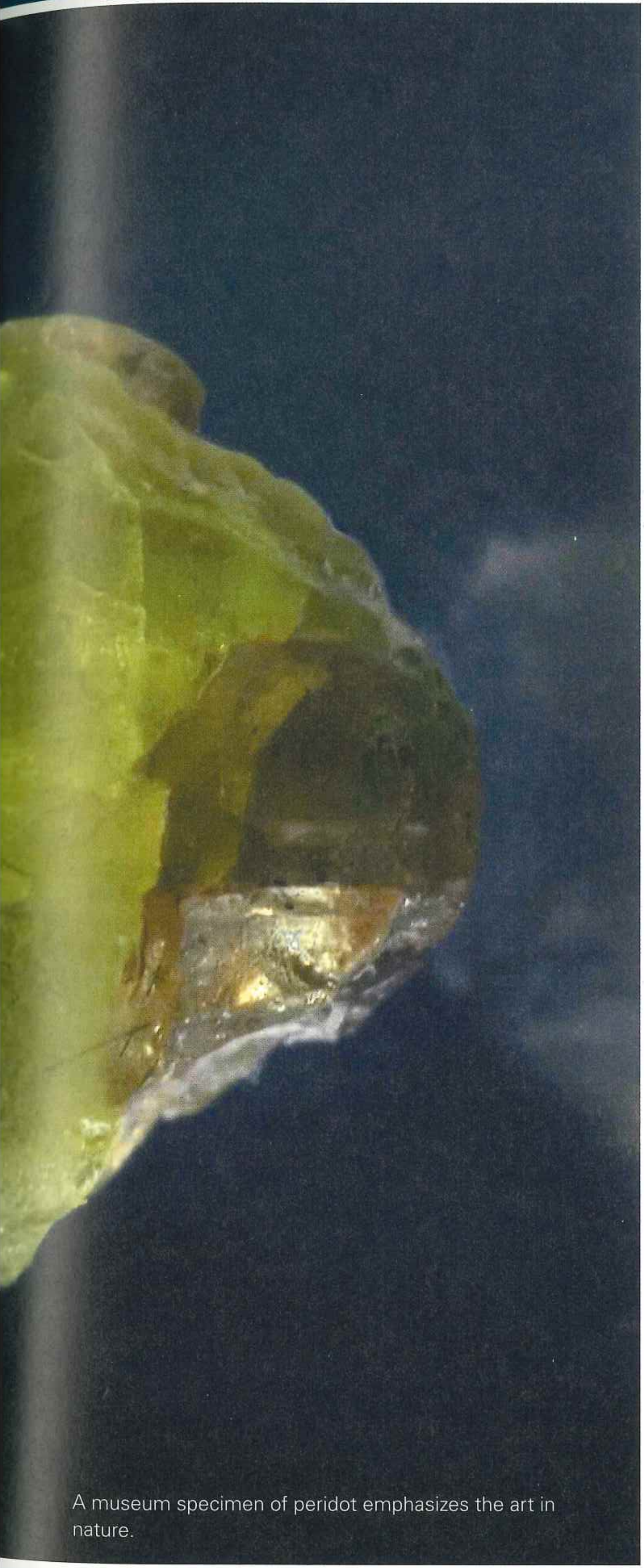


A museum specimen of peridot emphasizes the art in nature.

## Chapter Objectives

**By the end of this chapter, you should know . . .**

- the special meaning of the word "mineral" when used in a geologic context.
- how to organize the thousands of different minerals into just a few classes based on the chemicals the minerals contain.
- which minerals are the most common ones on Earth, and thus serve as the main building blocks of this planet.
- how to identify common mineral specimens.
- why we consider some minerals to be "gems" and how the shiny facets of gems in jewelry can be produced.

> *I died a mineral, and became a plant. I died as plant and rose to animal, I died as animal and I was Man. Why should I fear?*
>
> —Jalal-Uddin Rumi
> (Persian mystic and poet, 1207–1273)

## 3.1 Introduction

Zabargad Island rises barren and brown above the Red Sea, about 70 km off the coast of southern Egypt. Nothing grows on Zabargad, except for scruffy grass and a few shrubs, so no one lives there now. But in ancient times, many workers toiled on this 5-square-km patch of desert, gradually chipping their way into the side of its highest hill. They were searching for glassy green, pea-sized pieces of peridot, a prized gem. Carefully polished peridots were worn as jewelry by ancient Egyptians. Eventually, some of the gems appeared in Europe, set into crowns and scepters. These peridots now glitter behind glass cases in museums, millennia after first being pried free from the Earth, and perhaps 10 million years after first being formed by the bonding together of still more ancient atoms.

Peridot is the gem version of olivine, one of about 4,000 minerals that have been identified on Earth so far. Mineralogists, people who specialize in the study of minerals, discover 50 to 100 new minerals every year. Each different mineral has a name. Some names come from Latin, Greek, German, or English words describing a certain characteristic; some honor a person; some indicate the place where the mineral was first recognized; and some reflect a particular element in the mineral. Some names (quartz, calcite) may be familiar, whereas others (olivine, biotite) may be less so. Although the vast majority of mineral types are rare, forming only under special conditions, many are quite common and occur in a variety of rock types at Earth's surface

Why study minerals? Without exaggeration, we can say that *minerals are the building blocks of our planet.* To a geologist, almost any study of Earth materials depends on an understanding of minerals, for minerals make up most of the rocks and sediments comprising the Earth and its landscapes. Minerals are also important from a practical standpoint (see Chapter 12). Industrial minerals serve as the raw materials for manufacturing chemicals, concrete, and wallboard. Ore minerals are the source of valuable metals like copper and gold and provide energy resources like uranium (**Fig. 3.1a, b**). And particularly beautiful forms of minerals—gems—delight the eye in jewelry. Unfortunately, though, some minerals pose environmental hazards. No wonder **mineralogy**, the study of minerals, fascinates professionals and amateurs alike.

In this chapter, we begin by presenting the geologic definition of a mineral, and look at how minerals grow. Then, we discuss the main characteristics that enable us to identify specific samples. Finally, we describe the basic scheme that mineralogists use to classify minerals. This chapter assumes that you understand the fundamental concepts of matter and energy, especially the nature of atoms, molecules, and chemical bonds. If you are rusty on these topics, please study **Box 3.1**.

## 3.2 What Is a Mineral?

To a geologist, a **mineral** is a naturally occurring solid, formed by geologic processes, that has a crystalline structure and a definable chemical composition. Almost all minerals are inorganic. Let's pull apart this mouthful of a definition and examine its meaning in detail.

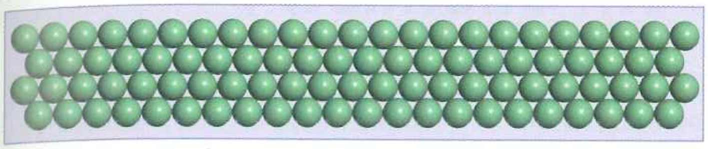
- *Naturally occurring*: True minerals are formed in nature, not in factories. We need to emphasize this point because in recent decades, industrial chemists have learned how to synthesize materials that have characteristics virtually identical to those of real minerals. These materials are not minerals in a geologic sense, though they are referred to in the commercial world as synthetic minerals.
- *Formed by geologic processes*: Traditionally, this phrase implied processes, such as solidification of molten rock or direct precipitation from a water solution, that did not involve living organisms. Increasingly, however, geologists recognize that life is an integral part of the Earth System. So, some geologists consider solid, crystalline materials produced by organisms to be minerals too. To avoid confusion, the term "biogenic mineral" may be used when discussing such materials.
- *Solid*: A solid is a state of matter that can maintain its shape indefinitely, and thus will not conform to the shape of its container. Liquids (such as oil or water) and gases (such as air) are not minerals (see Box 3.1).
- *Crystalline structure*: The atoms that make up a mineral are not distributed randomly and cannot move around easily. Rather, they are fixed in a specific, orderly pattern. A material in which atoms are fixed in an orderly pattern is called a crystalline solid.
- *Definable chemical composition*: This simply means that it is possible to write a chemical formula for a mineral (see Box 3.1). Some minerals contain only one element, but most are compounds of two or more elements. For example, diamond and graphite have the formula C, because they consist entirely of carbon. Quartz has the formula $SiO_2$—it contains the elements silicon and oxygen in the proportion of one silicon atom for every two oxygen atoms. Calcite has the formula $CaCO_3$, meaning it consists of a calcium ($Ca^+$) ion and a carbonate ($CO_3^-$) ion. Some formulas are more complicated: for example, the formula for biotite is $K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$.
- *Inorganic*: Organic chemicals are molecules containing some carbon-hydrogen bonds. Sugar ($C_{12}H_{22}O_{11}$), for example,

**FIGURE 3.1** Copper ore contains minerals that serve as a source of copper metal.

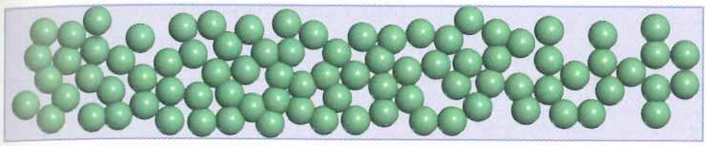
**(a)** Malachite is a mineral contained in copper ore [$Cu_2(CO_3)(OH)_2$]; it contains copper plus other chemicals.

**(b)** The copper for pots is produced by processing ore minerals.

**FIGURE 3.2** The nature of crystalline and noncrystalline materials.



**(a)** This quartz crystal contains an orderly arrangement of atoms. The arrangement resembles scaffolding.



**(b)** Atoms in noncrystalline solids, such as glass, are not orderly.

is an organic chemical. *Almost all minerals are inorganic.* Thus, sugar and protein are not minerals. But, we have to add the qualifier "almost all" because mineralogists do consider about 30 organic substances formed by "the action of geologic processes on organic materials" to be minerals. Examples include the crystals that grow in ancient deposits of bat guano.

With these definitions in mind, we can make an important distinction between minerals and **glass**. Both minerals and glass are solids, in that they can retain their shape indefinitely. But a mineral is crystalline, and glass is not. Whereas atoms, ions, or molecules in a mineral are ordered into a crystal lattice, like soldiers standing in formation, those in a glass are arranged in a semi-chaotic way, like people at a party, in small clusters or chains that are neither oriented in the same way nor spaced at regular intervals (**Fig. 3.2a, b**).

If you ever need to figure out whether a substance is a mineral or not, just check it against the criteria listed above. Is motor oil a mineral? No—it's an organic liquid. Is table salt a mineral? Yes—it's a solid crystalline compound with the formula NaCl. Is the hard material making up the shell of an oyster considered to be a mineral? Microscopic examination of an oyster shell reveals that it consists of calcite, so it can be called a biogenic mineral. Is rock candy a mineral? No. Even though it is solid and crystalline, it's made by people and it consists of sugar (an organic chemical).

**id you ever wonder . . .**
s rock candy a mineral?

**Take-Home Message**

**Minerals are solids with a crystalline structure (an orderly arrangement of atoms inside) and a definable chemical formula. They form by natural processes in the Earth System.**

## 3.3 Beauty in Patterns: Crystals and Their Structure

### What Is a Crystal?

The word crystal brings to mind sparkling chandeliers, elegant wine goblets, and shiny jewels. But, as is the case with the word mineral, geologists have a more precise definition. A **crystal** is a single, continuous (that is, uninterrupted) piece of a crystalline solid, typically bounded by flat surfaces, called **crystal faces**, that grow naturally as the mineral forms. The word comes from the Greek *krystallos*, meaning ice. Many crystals have beautiful shapes that look like they belong in the pages of a geometry book. The angle between two adjacent crystal faces of one specimen is identical to the angle between the corresponding faces of another specimen. For example, a perfectly formed quartz crystal looks like an obelisk (**Fig. 3.3a, b**); the angle between the faces of the columnar part of a quartz crystal is always exactly 120°. This rule, discovered by one of the first geologists, Nicolas Steno (1638–1686) of Denmark, holds regardless of whether the whole crystal is big or small and regardless of whether all of the faces are the same size. Crystals come in a great variety of shapes, including cubes, trapezoids, pyramids, octahedrons, hexagonal columns, blades, needles, columns, and obelisks (**Fig. 3.3c**).

Because crystals have a regular geometric form, people have always considered them to be special, perhaps even a source of magical powers. For example, shamans of some cultures relied on talismans or amulets made of crystals, which supposedly brought power to their wearer or warded off evil spirits. Scientists have concluded, however, that crystals have no effect on health or mood. For millennia, crystals have inspired awe because of the way they sparkle, but such behavior is simply a consequence of how crystal structures interact with light.

### Looking Inside Crystals

What makes crystals have regular geometric forms? This problem was the focus of study for centuries. An answer finally came from the work of a German physicist, Max von Laue, in 1912. He showed that an X-ray beam passing through a crystal breaks up into many tiny beams to create a pattern of dots on a screen (**Fig. 3.4a**). Physicists refer to this phenomenon as diffraction; it occurs when waves interact with regularly spaced objects whose spacing is close to the wavelength of the waves—you can see diffraction of ocean waves when they pass through gaps in a seawall. Von Laue concluded that, for a crystal to

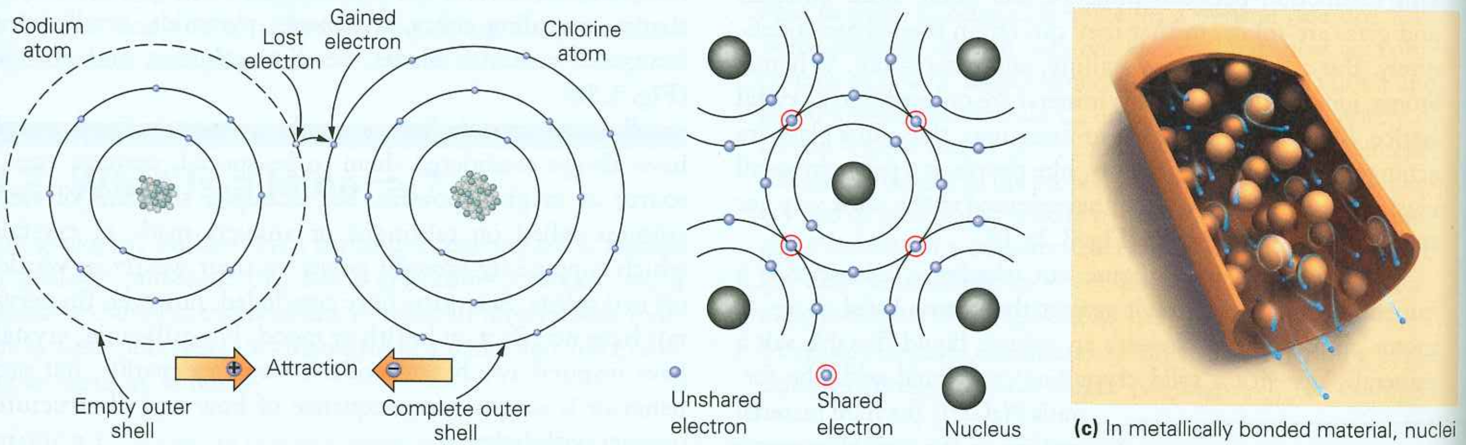
**BOX 3.1** **CONSIDER THIS ...**

# Some Basic Concepts from Chemistry

To describe minerals, we need to use several terms from chemistry. To avoid confusion, terms are listed in an order that permits each successive term to utilize previous terms.

- *Element:* A pure substance that cannot be separated into other materials.
- *Atom:* The smallest piece of an element that retains the characteristics of the element. An atom consists of a nucleus surrounded by a cloud of orbiting electrons; the nucleus is made up of protons and neutrons (except in hydrogen, whose nucleus contains only one proton and no neutrons). Electrons have a negative charge, protons have a positive charge, and neutrons have a neutral charge. An atom that has the same number of electrons as protons is said to be neutral, in that it does not have an overall electrical charge.
- *Atomic number:* The number of protons in an atom of an element.
- *Atomic weight:* Approximately the number of protons plus neutrons in an atom of an element.
- *Ion:* An atom that is not neutral. An ion that has an excess negative charge (because it has more electrons than protons) is an *anion,* whereas an ion that has an excess positive charge (because it has more protons than electrons) is a *cation.* We indicate the charge with a superscript. For example, $Cl^-$ has a single excess electron; $Fe^{2+}$ is missing two electrons.
- *Chemical bond:* An attractive force that holds two or more atoms together (**Fig. Bx3.1a–c**). For example, *covalent bonds* form when atoms share electrons. *Ionic bonds* form when a cation and anion (ions with opposite charges) get close together and attract each other. In materials with *metallic bonds,* some of the electrons can move freely.
- *Molecule:* Two or more atoms bonded together. The atoms may be of the same element or of different elements.
- *Compound:* A pure substance that can be subdivided into two or more elements. The smallest piece of a compound that retains the characteristics of the compound is a molecule.

**FIGURE Bx3.1** Examples of states of matter and chemical bonds.



**(a)** An ionic bond forms between a positive ion of sodium ($Na^+$) and chloride ($Cl^-$), a negative ion of chlorine produces halite NaCl, when sodium gives up one electron to chloride, so that both have filled shells.

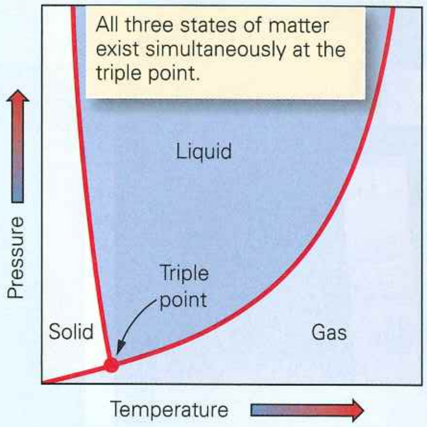
**(b)** Covalent bonds form when carbon atoms share electrons so that all have filled electron shells.

**(c)** In metallically bonded material, nuclei and their inner shells of electrons float in a "sea" of free electrons. The electrons stream through the metal if there is an electrical current.

cause diffraction, atoms within it must be regularly spaced and the spacing must be comparable to the wavelength of X-rays. Eventually, Von Laue and others learned how to use X-ray diffraction patterns as a basis for defining the specific arrangement of atoms in crystals. This arrangement defines the **crystal structure** of a mineral.

If you've ever examined wallpaper, you've seen an example of a pattern (**Fig. 3.4b**). Crystal structures contain one of nature's most spectacular examples of such a pattern. In crystals, the pattern is defined by the regular spacing of atoms and, if the crystal contains more than one element, by the regular alternation of atoms (**Fig. 3.4c**). (Mineralogists refer to a 3-D geometry of points representing this pattern as a lattice.) The pattern of atoms in a crystal may control the shape of a crystal. For example, if atoms in a crystal pack into the shape of a cube, the crystal may have faces that intersect at 90° angles—galena (PbS) and halite (NaCl) have such a cubic shape. Because of the pattern of atoms in a crystal structure, the structure has

- *State of matter:* The form of a substance, which reflects the degree to which the atoms or molecules comprising the matter are bonded together. **Figure Bx3.1d–f** defines three of the states—solid, liquid, and gas. There are more bonds in a solid than in a liquid, and more in a liquid than in a gas. Which state exists at a given location depends on pressure and temperature, as indicated by a phase diagram (**Fig. Bx3.1g**). A fourth state, plasma, exists only at very high temperatures.
- *Chemical:* A general name used for a pure substance (either an element or a compound).
- *Chemical formula:* A shorthand recipe that itemizes the various elements in a chemical and specifies their relative proportions. For example, the formula for water, $H_2O$, indicates that water consists of molecules in which two hydrogens bond to one oxygen.
- *Chemical reaction:* A process that involves the breaking or forming of chemical bonds. Chemical reactions can break molecules apart or create new molecules and/or isolated atoms.
- *Mixture:* A combination of two or more elements or compounds that can be separated without a chemical reaction. For example, a cereal composed of bran flakes and raisins is a mixture—you can separate the raisins from the flakes without destroying either.
- *Solution:* A type of material in which one chemical (the solute) dissolves in another (the solvent). In solutions, a solute may separate into ions during the process. For example, when salt (NaCl) dissolves in water, it separates into sodium ($Na^+$) and chloride ($Cl^-$) ions. In a solution, atoms or molecules of the solvent surround atoms, ions, or molecules of the solute.
- *Precipitate:* A compound that forms when ions in liquid solution join together to create a solid that settles out of the solution; (verb) the process of forming solid grains by separation and settling from a solution. For example, when saltwater evaporates, solid salt crystals precipitate.



**(g)** The state of matter depends on pressure and temperature, as depicted in this graph, called a phase diagram.

**(d)** A solid retains its shape regardless of the size of the container.

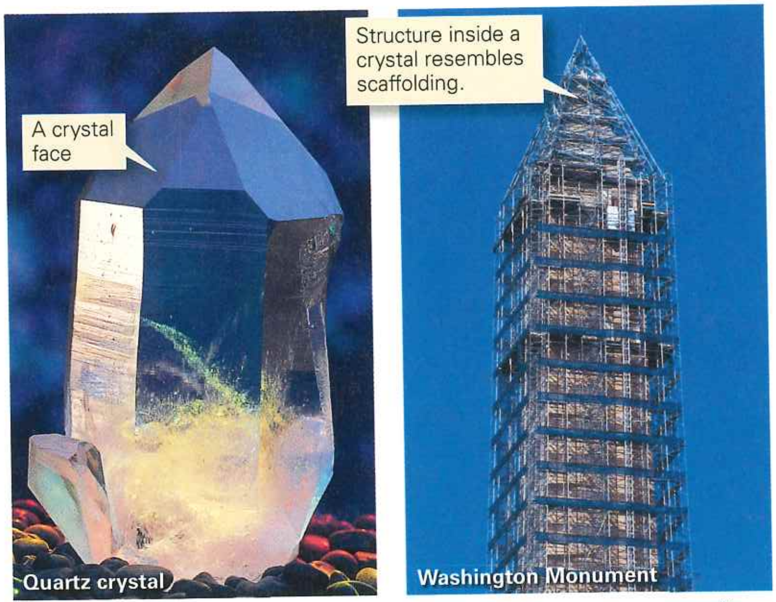
**(e)** A liquid conforms to the shape of the container, so its density does not change when the shape of the container changes.

**(f)** A gas expands to fill whatever volume it occupies, so its density changes if the volume changes.

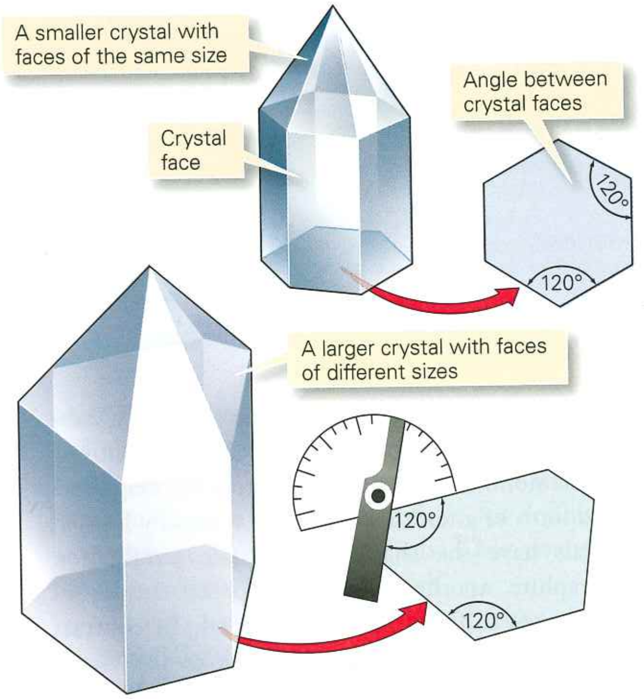
symmetry, meaning that the shape of one part of the structure is the mirror image of the shape of a neighboring part. For example, if you were to cut a halite crystal or a water crystal (snowflake) in half, and place the half against a mirror, it would look whole again (**Fig. 3.4d**).

To illustrate crystal structures, we look at a few examples. Halite (rock salt) consists of oppositely charged ions that stick together because opposite charges attract. In halite, six chloride ($Cl^-$) ions surround each sodium ($Na^+$) ion, producing an overall arrangement of atoms that defines the shape of a cube (**Fig. 3.5a, b**). Diamond, by contrast, is a mineral made entirely of carbon. In diamond, each atom bonds to four neighbors arranged in the form of a tetrahedron; some naturally formed diamond crystals have the shape of a double tetrahedron (**Fig. 3.5c**). Graphite, another mineral composed entirely of carbon, behaves very differently from diamond. In contrast to diamond, graphite is so soft that we use it as the "lead" in a pencil; when a pencil moves across paper, tiny flakes of graphite peel off the pencil point and adhere to the paper. This behavior occurs because the carbon atoms in graphite are not arranged in tetrahedra, but rather occur in sheets (**Fig. 3.5d**). The sheets are bonded to each other by weak bonds and thus can separate from each other easily. Of note, two different minerals (such as diamond and graphite) that have the same composition but different crystal structures are **polymorphs**.

**FIGURE 3.3** Some characteristics of crystals.



**(a)** A quartz crystal can resemble an obelisk. Inside, atoms are arranged in a specific geometric pattern, like the joint points in scaffolding.



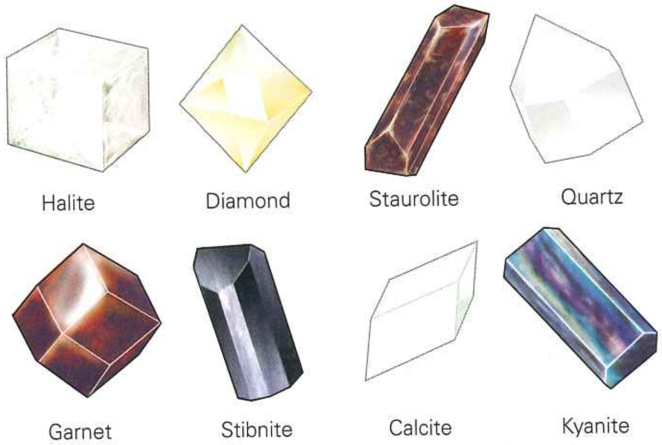
**(b)** Regardless of specimen size, the angle between two adjacent crystal faces is consistent in a particular mineral.

## The Formation and Destruction of Minerals

New mineral crystals can form in five ways. First, they can form by the solidification of a melt, meaning the freezing of a liquid to form a solid. For example, ice crystals, a type of mineral, are made by solidifying water, and many different minerals form by solidifying molten rock. Second, they can form by precipitation from a solution, meaning that atoms, molecules, or ions dissolved in water bond together and separate out of the water. Salt crystals, for example, precipitate when you evaporate salt water (see Box 3.1). Third, they can form by solid-state diffusion, the movement of atoms or ions through a solid to arrange into a new crystal structure, a process that takes place very slowly. For example, garnets grow by diffusion in solid rock. Fourth, minerals can form at interfaces between the physical and biological components of the Earth System by a process called biomineralization. This occurs when living organisms cause minerals to precipitate either within or on their bodies, or immediately adjacent to their bodies. For example, clams and other shelled organisms extract ions from water to produce mineral shells. Fifth, minerals can precipitate directly from a gas. This process typically occurs around volcanic vents or around geysers, for at such locations volcanic gases or steam enter the atmosphere and cool abruptly. Some of the bright yellow sulfur deposits found in volcanic regions form in this way.

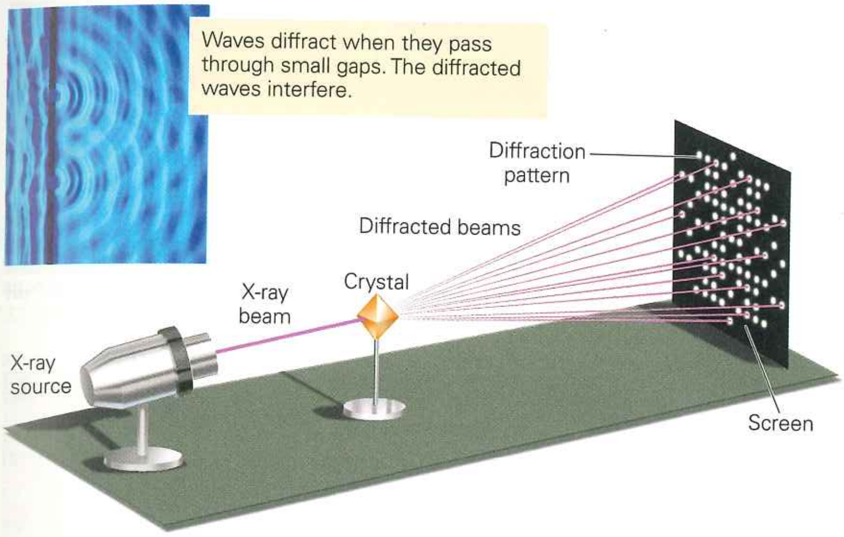
The first step in forming a crystal is the chance formation of a seed, or an extremely small crystal (**Fig. 3.6a**). Once the seed exists, other atoms in the surrounding material attach themselves to the face of the seed. As the crystal grows, crystal faces move outward but maintain the same orientation (**Fig. 3.6b**). The youngest part of the crystal is at its outer edge.

In the case of crystals formed by the solidification of a melt, atoms begin to attach to the seed when the melt becomes so cool that thermal vibrations can no longer break apart the

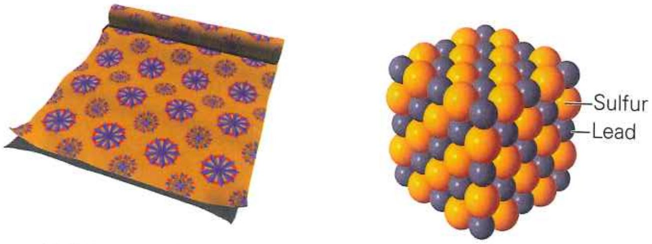


**(c)** Crystals come in a variety of shapes, including cubes, prisms, blades, and pyramids.

**FIGURE 3.4** Patterns and symmetry in minerals.

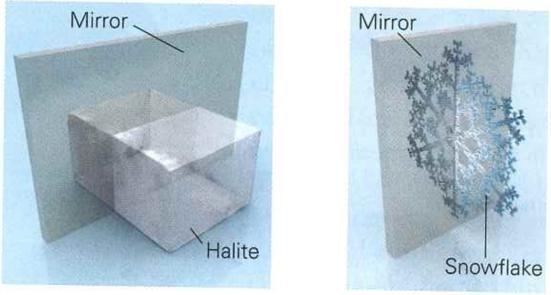


**(a)** Diffraction of an X-ray beam passing through a crystal produces a pattern of bright spots on a screen. The spots are due to interference of overlapping light waves.



**(b)** The repetition of a flower motif on wallpaper.

**(c)** The repetition of alternating sulfur and lead atoms in the mineral galena (PbS).



**(d)** Minerals display symmetry. One-half of a crystal is a mirror image of the other.

attraction between the seed and the atoms in the melt. Crystals formed by precipitation from a solution develop when the solution becomes saturated, meaning the number of dissolved ions per unit volume of solution becomes so great that they can get close enough to each other to bond together.

As crystals grow, they develop their particular crystal shape, based on the geometry of their internal structure. The shape is defined by the relative dimensions of the crystal (needle-like, sheet-like, etc.) and the angles between crystal faces. Typically, the growth of minerals is restricted in one or more directions, because existing crystals act as obstacles. In such cases, minerals grow to fill the space that is available, and their shape is controlled by the shape of their surroundings. Minerals without well-formed crystal faces are anhedral grains (**Fig. 3.6c**). If a mineral's growth is unimpeded so that it displays well-formed crystal faces, then it is a euhedral crystal. The surface crystals of a **geode**, a mineral-lined cavity in rock, may be euhedral (**Fig. 3.6d**).

A mineral can be destroyed by melting, dissolving, or some other chemical reaction. Melting involves heating a mineral to a temperature at which thermal vibration of the atoms or ions in the lattice break the chemical bonds holding them to the lattice. The atoms or ions then separate, either individually or in small groups, to move around again freely. Dissolution occurs when you immerse a mineral in a solvent, such as water. Atoms or ions then separate from the crystal face and are surrounded by solvent molecules. Chemical reactions can destroy a mineral when it comes in contact with reactive materials. For example, iron-bearing minerals react with air and water to form rust. The action of microbes in the environment can also destroy minerals. In effect, some microbes can "eat" certain minerals; the microbes use the energy stored in the chemical bonds that hold the atoms of the mineral together as their source of energy for metabolism.

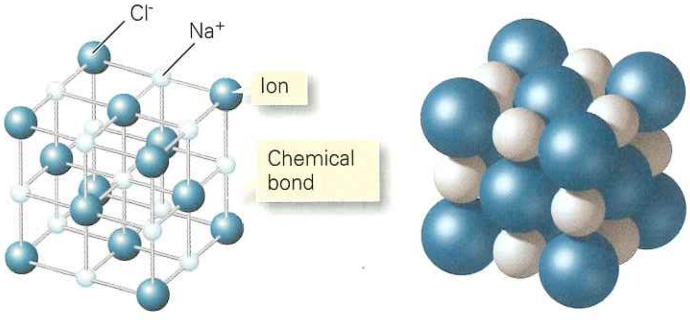
### Take-Home Message

**The crystal structure of minerals is defined by a regular geometric arrangement of atoms that has symmetry. Minerals can form by solidification of a melt, by precipitation from a water solution or a gas, or by rearrangement of atoms in a solid.**

## 3.4 How Can You Tell One Mineral From Another?

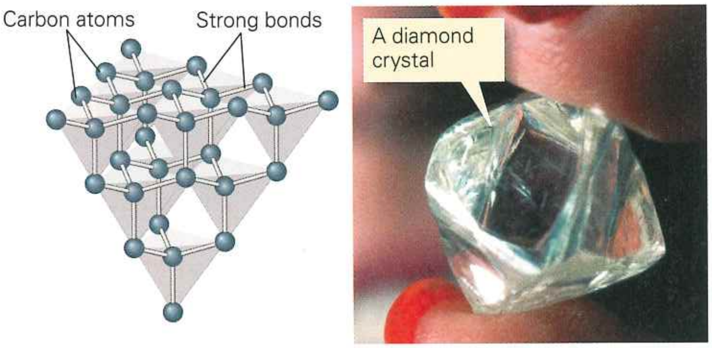
Amateur and professional mineralogists get a kick out of recognizing minerals. They might hover around a display case in a museum and name specimens without bothering to look at the labels. How do they do it? The trick lies in learning to recognize the basic physical properties (visual and material characteristics) that distinguish one mineral from another. Some physical properties, such as shape and color, can be seen from a distance. Others, such as hardness and magnetization, can be determined only by handling the specimen or by performing an identification test on it. Identification tests include scratching the mineral by another object, placing it near a magnet, weighing it, tasting it, or placing a drop of acid on it. Let's examine some of the physical properties most commonly used in basic mineral identification.

**FIGURE 3.5** The nature of crystalline structure in minerals. The arrangement of atoms can be portrayed by a ball-and-stick model, or by a packed-ball model.

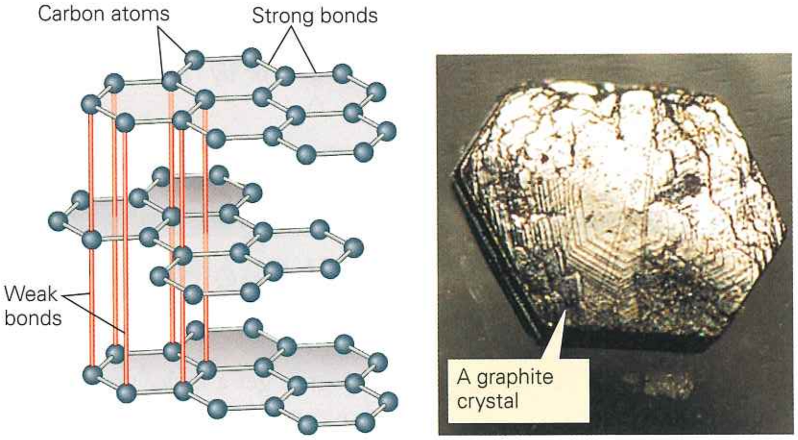


**(a)** In a ball-and-stick model of halite, the balls are ions, and the sticks are chemical bonds.

**(b)** This packed-ball model gives a better sense of how ions fit together in crystal.



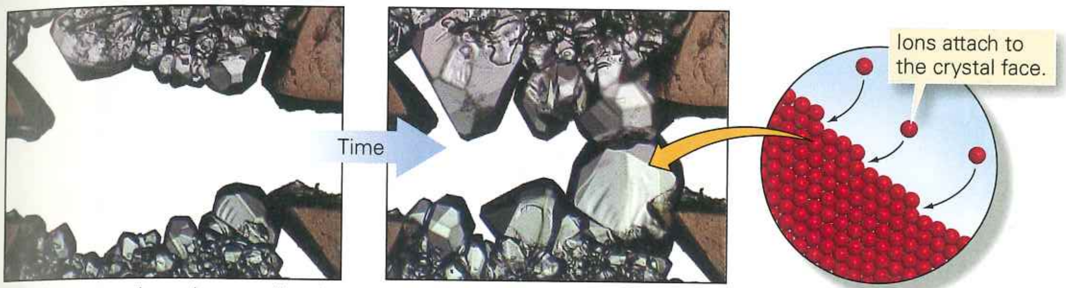
**(c)** In a diamond, carbon atoms are arranged in tetrahedra. All of the bonds are strong.



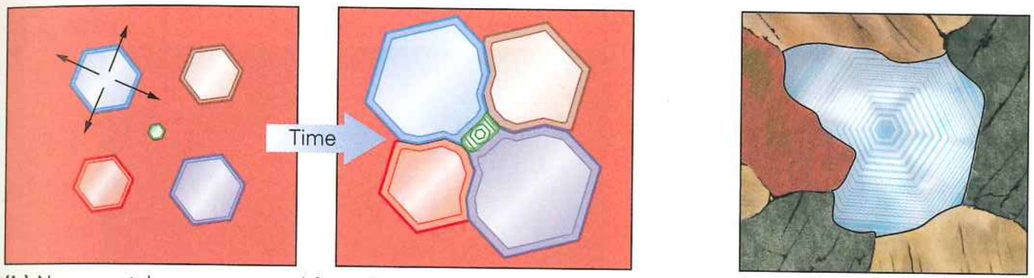
**(d)** Graphite consists of carbon atoms arranged in hexagonal sheets. The sheets are connected by weak bonds.

- *Color*: **Color** results from the way a mineral interacts with light. Sunlight contains the whole spectrum of colors; each color has a different wavelength. A mineral absorbs certain wavelengths, so the color you see when looking at a specimen represents the wavelengths the mineral does not absorb. Certain minerals always have the same color, but many display a range of colors (**Fig. 3.7a**). Color variations in a mineral are due to the presence of impurities. For example, trace amounts of iron may give quartz a reddish color.
- *Streak*: The **streak** of a mineral refers to the color of a powder produced by pulverizing the mineral. You can obtain a streak by scraping the mineral against an unglazed ceramic plate (**Fig. 3.7b**). The color of a mineral powder tends to be less variable than the color of a whole crystal, and thus provides a fairly reliable clue to a mineral's identity. Calcite, for example, always yields a white streak even though pieces of calcite may be white, pink, or clear.
- *Luster*: **Luster** refers to the way a mineral surface scatters light. Geoscientists describe luster by comparing the appearance of the mineral with the appearance of a familiar substance. For example, minerals that look like metal have a metallic luster, whereas those that do not have a nonmetallic luster—the adjectives are self-explanatory (**Fig. 3.7c, d**). Terms used for types of nonmetallic luster include silky, glassy, satiny, resinous, pearly, or earthy.
- *Hardness*: **Hardness** is a measure of the relative ability of a mineral to resist scratching, and it therefore represents the resistance of bonds in the crystal structure to being broken. The atoms or ions in crystals of a hard mineral are more strongly bonded than those in a soft mineral. Hard minerals can scratch soft minerals, but soft minerals cannot scratch hard ones. Diamond, the hardest mineral known, can scratch most anything, which is why it is used to cut glass. In the early 1800s, a mineralogist named Friedrich Mohs listed some minerals in sequence of relative hardness; a mineral with a hardness of 5 can scratch all minerals with a hardness of 5 or less. This list, the **Mohs hardness scale**, helps in mineral identification. To make the scale easy to use, common items such as your fingernail, a penny, or a glass plate have been added (**Table. 3.1**).
- *Specific gravity*: **Specific gravity** represents the density of a mineral, as represented by the ratio between the weight of a volume of the mineral and the weight of an equal volume of water at 4°C. For example, one cubic centimeter of quartz has a weight of 2.65 grams, whereas one cubic centimeter of water has a weight of 1.00 gram. Thus, the specific gravity of quartz is 2.65. In practice, you can develop a "feel" for specific gravity by hefting minerals in your hands. A piece of galena (lead ore) feels heavier than a similar-sized piece of quartz.
- *Crystal habit*: The **crystal habit** of a mineral refers to the shape of a single crystal with well-formed crystal faces, or to the character of an aggregate of many well-formed crystals that grew together as a group (**Fig. 3.7e**). The habit depends on the internal arrangement of atoms in the crystal. A description of habit generally includes adjectives that

**FIGURE 3.6** The growth of crystals.

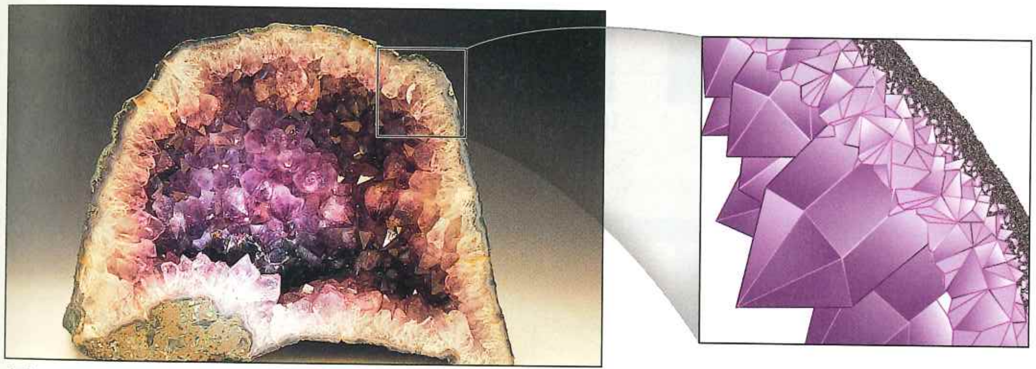


**(a)** New crystals nucleate and begin to precipitate out of a water solution. As time progresses, they grow into the open space.



**(b)** New crystals grow outward from the central seed. As time passes, they maintain their shape until they interfere with each other.

**(c)** A crystal growing in a confined space will be anhedral.



**(d)** A geode from Brazil consists of purple quartz crystals (amethyst) that grew from the wall into the center. The enlargement sketch indicates that the crystals are euhedral.

highlight the shape of the crystal. For example, crystals that are roughly the same length in all directions are called equant or blocky, those that are much longer in one dimension than in others are columnar or needle-like, those shaped like sheets of paper are platy, and those shaped like knives are bladed.

- *Special properties*: Some minerals have distinctive properties that readily distinguish them from other minerals. For example, calcite ($CaCO_3$) reacts with dilute hydrochloric acid (HCl) to produce carbon dioxide ($CO_2$) gas (**Fig. 3.7f**). Dolomite ($CaMg[CO_3]_2$) also reacts with acid, but not as strongly. Graphite makes a gray mark on paper, magnetite attracts a magnet (**Fig. 3.7g**), halite tastes salty, and plagioclase has striations (thin parallel corrugations or stripes) on its surface.

- *Fracture and cleavage*: Different minerals fracture (break) in different ways, depending on the internal arrangement of atoms. If a mineral breaks to form distinct planar surfaces that have a specific orientation in relation to the crystal structure, then we say that the mineral has **cleavage** and we refer to each surface as a cleavage plane. Cleavage forms in directions where the bonds holding atoms together in the crystal are the weakest (**Fig. 3.8a–e**). Some minerals have one direction of cleavage. For example, mica has very weak bonds in one direction but strong bonds in the other two directions. Thus, it easily splits into parallel sheets; the surface of each sheet is a cleavage plane. Other minerals have two or three directions of cleavage that intersect at a specific angle. For example, halite has three sets of cleavage planes that intersect at right angles, so halite crystals break into little cubes. Materials that have no cleavage at all (because bonding is equally strong in all directions) break either by forming irregular fractures or by forming conchoidal fractures (**Fig. 3.8f**). **Conchoidal fractures** are smoothly curving, clamshell-shaped surfaces; they typically form in glass. Cleavage planes are sometimes hard to distinguish from crystal faces (**Fig. 3.8g**).

## Take-Home Message

**The characteristics of minerals (such as color, streak, luster, crystal shape, hardness, specific gravity, cleavage, magnetism, and reaction with acid) are a manifestation of the crystal structure and chemical composition of minerals.**

**FIGURE 3.7** Physical characteristics of minerals.

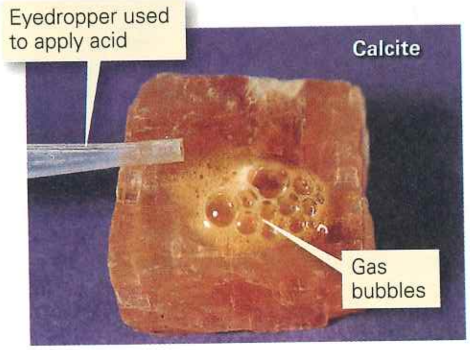
**(a)** Color is diagnostic of some minerals, but not all. For example, quartz can come in many colors.

**(b)** To obtain the streak of a mineral, rub it against a porcelain plate. The streak consists of mineral powder.

**(c)** Pyrite has a metallic luster because it gleams like metal.

**(d)** Feldspar has a nonmetallic luster.

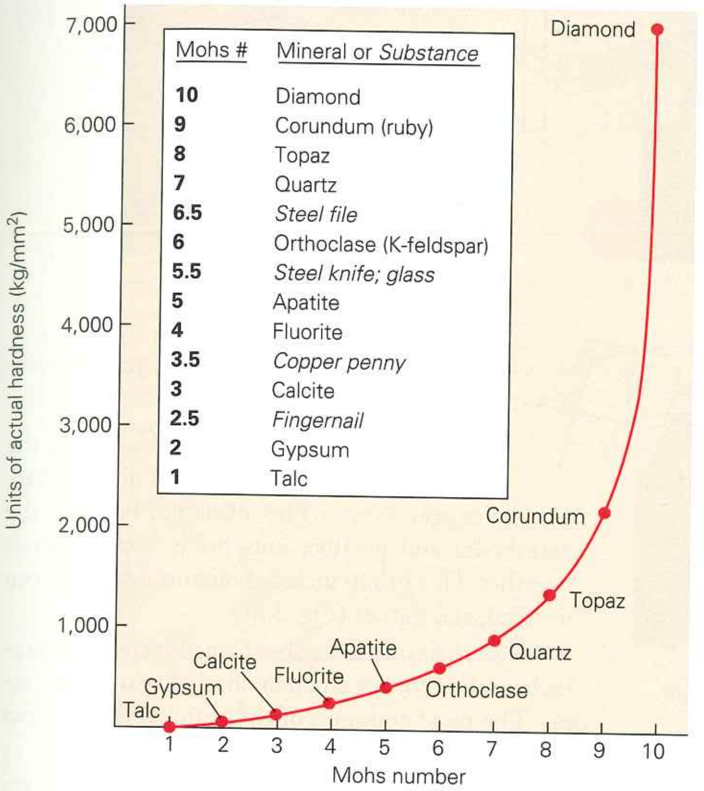
**(e)** Crystal habit refers to the shape or character of the crystal. The blue kyanite crystals on the left are bladed, and the chrysotile on the right is fibrous.



**(f)** Calcite reacts with hydrochloric acid to produce carbon dioxide gas.

**(g)** Magnetite is magnetic.

**TABLE 3.1** Mohs hardness scale. Mohs' numbers are relative—in reality, diamond is 3.5 times harder than corundum, as the graph shows.



| Mohs # | Mineral or *Substance* |
|---|---|
| **10** | Diamond |
| **9** | Corundum (ruby) |
| **8** | Topaz |
| **7** | Quartz |
| **6.5** | *Steel file* |
| **6** | Orthoclase (K-feldspar) |
| **5.5** | *Steel knife; glass* |
| **5** | Apatite |
| **4** | Fluorite |
| **3.5** | *Copper penny* |
| **3** | Calcite |
| **2.5** | *Fingernail* |
| **2** | Gypsum |
| **1** | Talc |

## 3.5 Organizing Our Knowledge: Mineral Classification

The 4,000 known minerals can be separated into a small number of groups, or mineral classes. You may think, "Why bother?" Classification schemes are useful because they help organize information and streamline discussion. Biologists, for example, classify animals into groups based on how they feed their young and on the architecture of their skeletons, and botanists classify plants according to the way they reproduce and by the shape of their leaves. In the case of minerals, a good means of classification eluded researchers until it became possible to determine the chemical makeup of minerals. A Swedish chemist, Baron Jöns Jacob Berzelius (1779–1848), analyzed minerals and noted chemical similarities among many of them. Berzelius, along with his students, established that most minerals can be classified by specifying the principal anion (negative ion) or anionic group (negative molecule) within the mineral (see Box 3.1). We now take a look at principal mineral classes, focusing especially on silicates, the class that constitutes most of the rock in the Earth.

### The Mineral Classes

Mineralogists distinguish several principal classes of minerals. Here are some of the major ones.

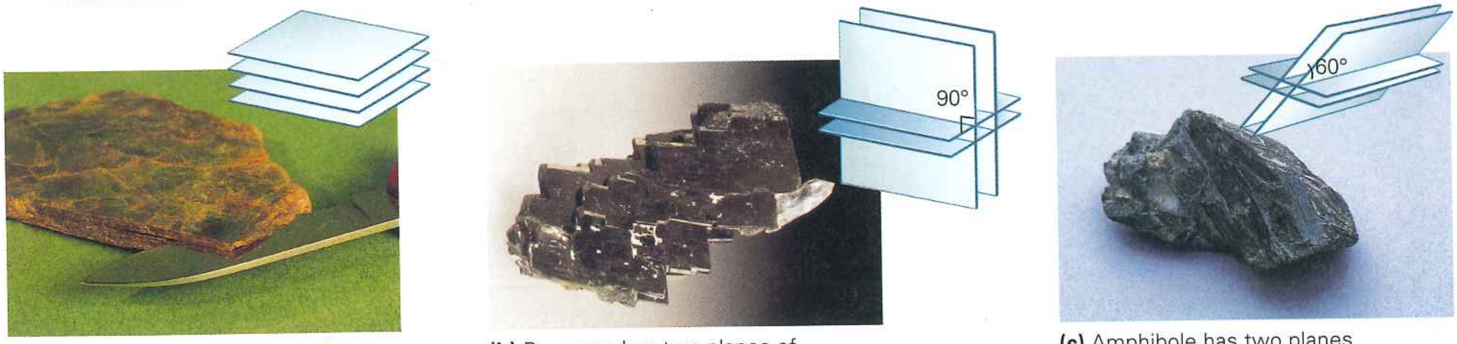
- *Silicates*: The fundamental component of most silicates in the Earth's crust is the $SiO_4^{4-}$ anionic group. A well-known example, quartz (Fig. 3.7a), has the formula $SiO_2$. We will learn more about silicates in the next section.
- *Oxides*: Oxides consist of metal cations bonded to oxygen anions. Typical oxide minerals include hematite ($Fe_2O_3$; Fig. 3.7b) and magnetite ($Fe_3O_4$; Fig. 3.7g).
- *Sulfides*: Sulfides consist of a metal cation bonded to a sulfide anion ($S^{2-}$). Examples include galena (PbS) and pyrite ($FeS_2$; Fig. 3.7c).
- *Sulfates*: Sulfates consist of a metal cation bonded to the $SO_4^{2-}$ anionic group. Many sulfates form by precipitation out of water at or near the Earth's surface. An example is gypsum ($CaSO_4 \cdot 2H_2O$).
- *Halides*: The anion in a halide is a halogen ion (such as chloride [$Cl^-$] or fluoride [$F^-$]), an element from the second column from the right in the periodic table (see Appendix). Halite, or rock salt (NaCl; Fig. 3.8d), and fluorite ($CaF_2$), a source of fluoride, are common examples.
- *Carbonates*: In **carbonates**, the molecule $CO_3^{2-}$ serves as the anionic group. Elements such as calcium or magnesium bond to this group. The two most common carbonates are calcite ($CaCO_3$; Fig. 3.8e) and dolomite ($CaMg[CO_3]_2$).
- *Native metals*: Native metals consist of pure masses of a single metal. The metal atoms are bonded by metallic bonds (see Box 3.1). Copper and gold, for example, may occur as native metals.

### Silicates: The Major Rock-Forming Minerals

Silicate minerals, or **silicates**, make up over 95% of the continental crust and almost 100% of the oceanic crust and of the Earth's mantle consist almost entirely of silicates. Thus, silicates are the most common minerals on Earth. As we've noted, silicates in the Earth's crust and upper mantle contain the $SiO_4^{4-}$ anionic group. In this group, four oxygen atoms surround a single silicon atom, thereby defining the corners of a tetrahedron, a pyramid-like shape with four triangular faces (**Fig. 3.9a**). We refer to this anionic group as the **silicon-oxygen tetrahedron** (or, informally, as the silica tetrahedron), and it acts, in effect, as the building block of silicate minerals.

Mineralogists distinguish among several groups of silicate minerals based on the way in which silica tetrahedra are arranged (**Fig. 3.9b**). The arrangement, in turn, determines the degree to which tetrahedra share oxygen atoms. Note that the number of shared oxygens determines the ratio of silicon (Si) to oxygen (O) in the mineral. Here are the groups, in

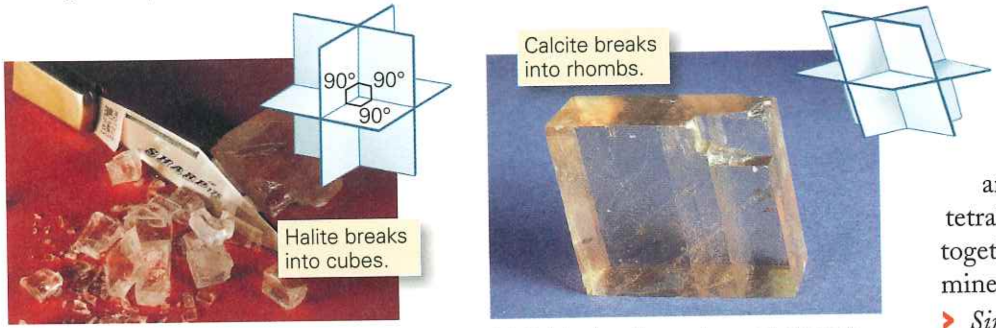
**FIGURE 3.8** The nature of mineral cleavage and fracture.



**(a)** Mica has one strong plane of cleavage and splits into sheets.

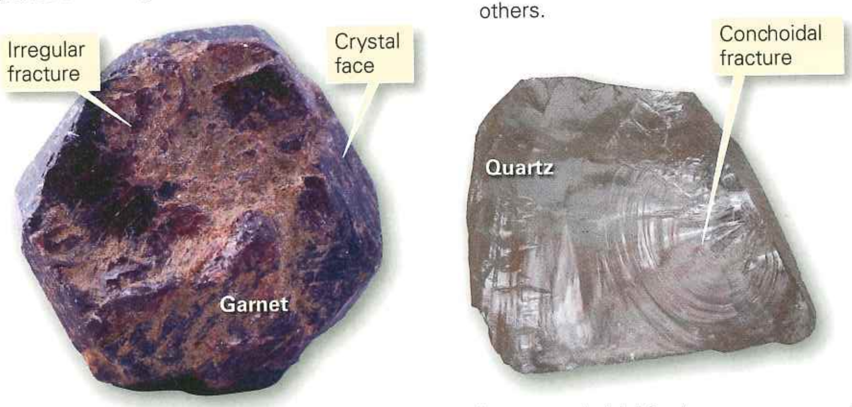
**(b)** Pyroxene has two planes of cleavage that intersect at 90°.

**(c)** Amphibole has two planes that intersect at 60°.

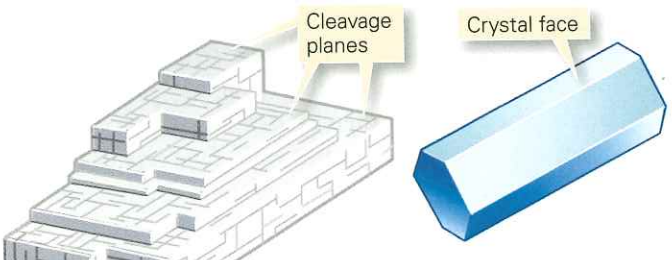


**(d)** Halite has three mutually perpendicular planes of cleavage.

**(e)** Calcite has three planes of cleavage, none of which are perpendicular to the others.



**(f)** Minerals without cleavage can develop irregular or conchoidal fractures.



**(g)** How do you distinguish between cleavage planes and crystal faces? Cleavage planes can be repeated, whereas a crystal face is a single surface.

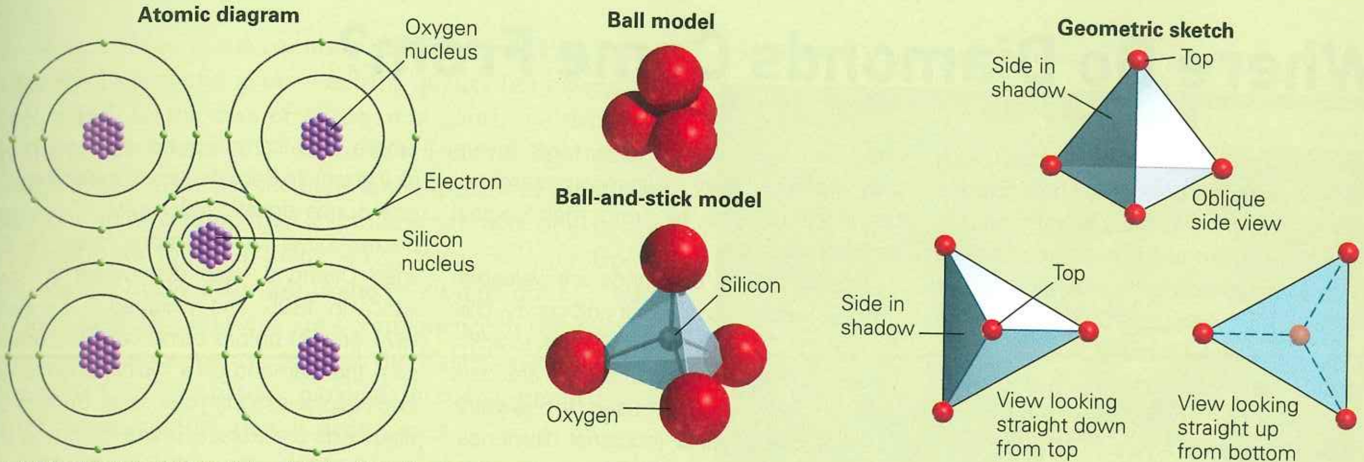
order from fewer shared oxygens to more shared oxygens:

- *Independent tetrahedra*: In this group, the tetrahedra are independent and do not share any oxygen atoms. The attraction between the tetrahedra and positive ions holds such minerals together. This group includes olivine, a glassy green mineral, and garnet (Fig. 3.8f).
- *Single chains*: In a single-chain silicate, the tetrahedra link to form a chain by sharing two oxygen atoms. The most common of the many different types of single-chain silicates are pyroxenes (Fig. 3.8b).
- *Double chains*: In a double-chain silicate, the tetrahedra link to form a double chain by sharing two or three oxygen atoms. Amphiboles are the most common type (Fig. 3.8c).
- *Sheet silicates*: The tetrahedra in this group share three oxygen atoms and therefore link to form two-dimensional sheets. Other ions and, in some cases, water molecules fit between the sheets in some sheet silicates. Because of their structure, sheet silicates have cleavage in one direction, and they occur in books of very thin sheets. In this group, we find micas (Fig. 3.8a) and clays. Clays occur only in extremely tiny flakes.
- *Framework silicates*: In a framework silicate, each tetrahedron shares all four oxygen atoms with its neighbors, forming a three-dimensional structure. Examples include feldspar and quartz. The two most common feldspars are plagioclase, which tends to be white, gray, or blue; and orthoclase (also called potassium feldspar, or K-feldspar), which tends to be pink (Fig. 3.7d).

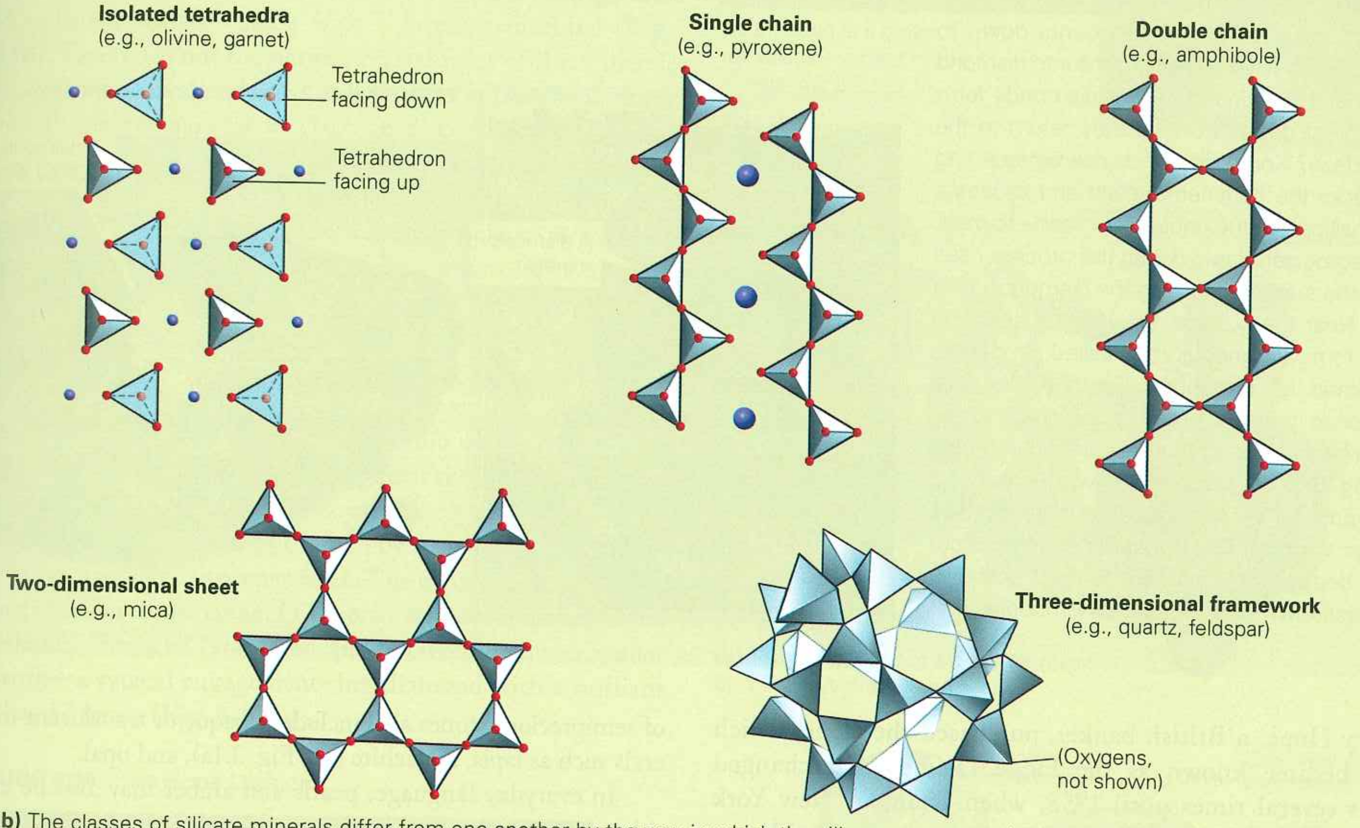
## Take-Home Message

**The 4,000 known minerals can be organized into a relatively small number of classes based on chemical makeup. Most minerals are silicates, which contain silicon-oxygen tetrahedral arranged in various ways.**

**FIGURE 3.9** The structure of silicate minerals.



**(a)** The fundamental building block of a silicate mineral is the silicon-oxygen tetrahedron. Oxygens occupy the corners of the tetrahedron, and silicon lies at the center. Geologists portray the tetrahedron in a number of different ways.



**(b)** The classes of silicate minerals differ from one another by the way in which the silicon-oxygen tetrahedra are linked. Where the tetrahedra link, they share an oxygen atom. Oxygen atoms are shown in red. Positive ions (not shown) occupy spaces between tetrahedra.

## 3.6 Something Precious—Gems!

Mystery and romance follow famous gems. Consider the stone now known as the Hope Diamond, recognized by name the world over (**Fig. 3.10**). No one knows who first dug it out of the ground (**Box 3.2**). Was it mined in the 1600s, or was it stolen off an ancient religious monument? What we do know is that in the 1600s, a French trader named Jean Baptiste Tavernier obtained a large (112.5 carats, where 1 carat = 200 milligrams), rare blue diamond in India, perhaps from a Hindu statue, and carried it back to France. King Louis XIV bought the diamond and had it fashioned into a jewel of 68 carats. This jewel vanished in 1762 during a burglary. Perhaps it was lost forever—perhaps not. In 1830, a 44.5-carat blue diamond mysteriously appeared on the jewel market for sale.

**Did you ever wonder . . .**
where diamonds come from and how they form?

**BOX 3.2** **CONSIDER THIS . . .**

# Where Do Diamonds Come From?

Diamonds consist of carbon, which typically accumulates only at or near Earth's surface. Experiments demonstrate that the pressures needed to form diamond are so extreme that, in nature, they generally occur only at depths of around 150 km below the Earth's surface. Nowadays, engineers can duplicate these conditions in the laboratory, so corporations manufacture several tons of synthetic diamonds a year.

How does carbon get down to depths of 150 km? Geologists speculate that subduction or collision carries carbon-containing rocks and sediments down to the depth where it transforms into diamond beneath continents. But if diamonds form at great depth, how do they return to the surface? Some diamonds rise when rifting cracks the continental crust and causes a small part of the underlying mantle to melt. Magma generated during this process rises to the surface, bringing the diamonds with it. Near the surface, the magma solidifies to form an igneous rock called kimberlite, named for Kimberley, South Africa. Diamonds brought up with the magma are embedded as crystals in solid kimberlite (**Fig. Bx3.2**). Much of the world's diamond supply comes from mines in this rock (**See For Yourself C**). But some sources occur in deposits of sediment formed from the breakdown and erosion of kimberlite that had been exposed at the surface. Rivers and glaciers may transport diamond-bearing sediments far from their original bedrock source.

Not all natural diamonds are valuable; the value depends on color and clarity. Diamonds that contain imperfections (cracks, or specks of other material), or are dark gray in color, are not used for jewelry. These stones, called industrial diamonds, are used as abrasives. Gem-quality diamonds come in a range of sizes. Jewelers measure the size of these gems in carats, where one carat equals 200 milligrams (0.2 gram). In English units of measurement, one ounce equals 142 carats. The largest diamond ever found, a stone called the Cullinan Diamond, was discovered in South Africa in 1905, and weighed 3,106 carats (621 grams) before being cut. By comparison, the diamond on a typical engagement ring weighs less than one carat. Gem-quality diamonds are actually more common than you might expect—suppliers stockpile the stones in order to avoid flooding the market and lowering the price.

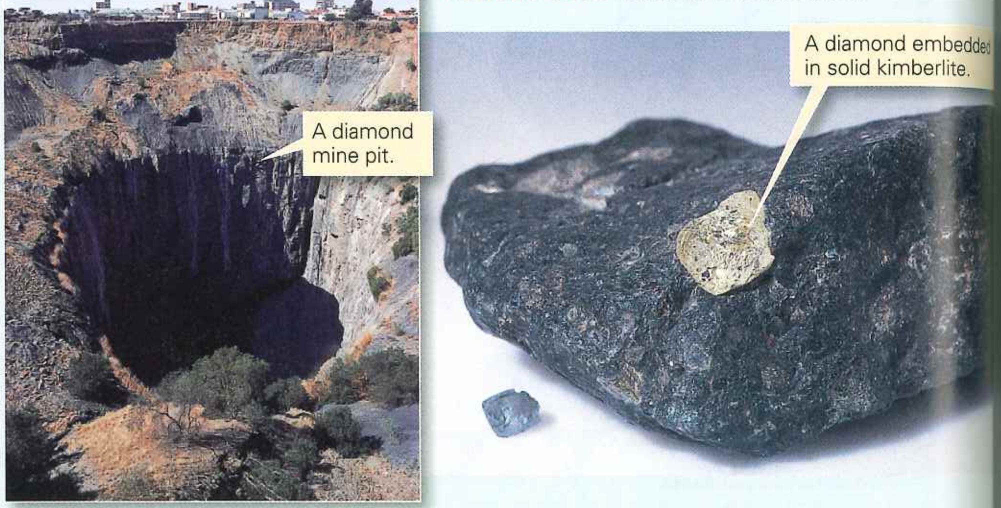


**FIGURE Bx3.2** Diamond occurrences.

Henry Hope, a British banker, purchased the stone, which then became known as the Hope Diamond. It changed hands several times until 1958, when a famous New York jeweler named Harry Winston donated it to the Smithsonian Institution in Washington, DC, where it now sits behind bulletproof glass in a heavily guarded display.

What makes stones such as the Hope Diamond so special that people risk life and fortune to obtain them? What is the difference between a gemstone, a gem, and any other mineral? A gemstone is a mineral that has special value because it is rare and people consider it beautiful. A **gem**, or jewel, is a finished stone ready to be set in jewelry. Jewelers distinguish between precious stones (such as diamond, ruby, sapphire, and emerald), which are particularly rare and expensive, and semiprecious stones (such as topaz, tourmaline, aquamarine, and garnet), which are less rare and less expensive. All the stones mentioned so far are transparent crystals, though most have some color. The category of semiprecious stones also includes opaque or translucent minerals such as lapis, malachite (see Fig. 3.1a), and opal.

In everyday language, pearls and amber may also be considered gemstones. Unlike diamonds and garnets, which form inorganically in rocks, pearls form in living oysters when the oyster extracts calcium and carbonate ions from water and precipitates them around an impurity, such as a sand grain, embedded in its body. Thus, pearls are a result of biomineralization. Most pearls used in jewelry today are "cultured" pearls, made by artificially introducing round sand grains into oysters in order to stimulate pearl production. Amber is also formed by organic processes—it consists of fossilized tree sap. But because amber consists of organic compounds that are not arranged in a crystal structure, it does not meet the definition of a mineral.

In some cases, gemstones are merely pretty and rare versions of more common minerals. For example, ruby is a special version of the common mineral corundum, and emerald is a special version of the common mineral beryl (**Fig. 3.11a**). As for the beauty of a gemstone, this quality lies basically in its color and, in the case of transparent gems, its "fire"—the way the mineral bends and internally reflects the light passing through it, and disperses the light into a spectrum. Fire makes a diamond sparkle more than a similarly cut piece of glass.

Gemstones form in many ways. Some solidify from a melt, some form by diffusion, some precipitate out of a water solution in cracks, and some are a consequence of the chemical interaction of rock with water near the Earth's surface. Many gems come from pegmatites, particularly coarse-grained rocks formed by the solidification of steamy melt.

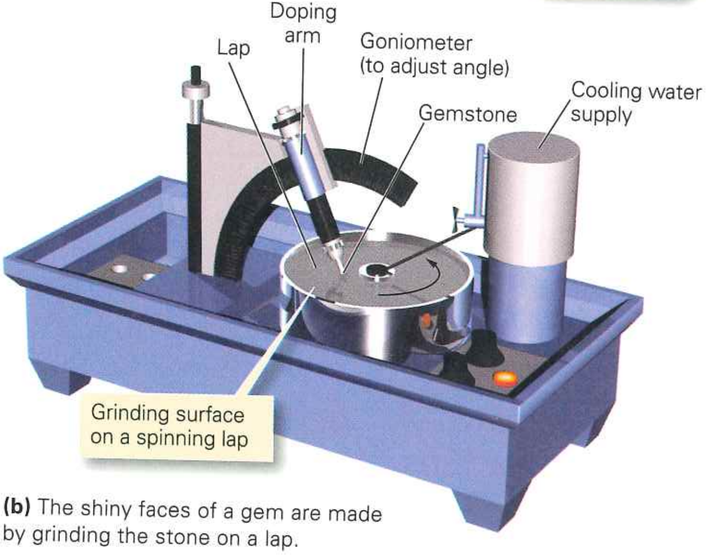
Most gems used in jewelry are "cut" stones, meaning that they are not raw crystals right from the ground, but rather have been faceted. The smooth **facets** on a gem are ground and polished surfaces made with a faceting machine (**Fig. 3.11b**). Facets are not the natural crystal faces of the mineral, nor are they cleavage planes, though gem cutters sometimes make the facets parallel to cleavage directions and will try to break a large gemstone into smaller pieces by splitting it on a cleavage plane. A faceting machine consists of a doping arm, a device that holds a stone in a specific orientation, and a lap, a rotating disk covered with a wet paste of grinding powder and water. The gem cutter fixes a gemstone to the end of the doping arm and positions the arm so that it holds the stone against the moving lap. The movement of the lap grinds a facet. When the facet is complete, the gem cutter rotates the arm by a specific angle, lowers the stone, and grinds another facet. The geometry of the facets defines the cut of the stone. Different cuts have names, such as "brilliant," "French," "star," and "pear." Grinding facets is a lot of work—a typical engagement-ring diamond with a brilliant cut has 57 facets (**Fig. 3.11c**)!

**Did you ever wonder . . .**
**how jewelers make the facets on a jewel?**

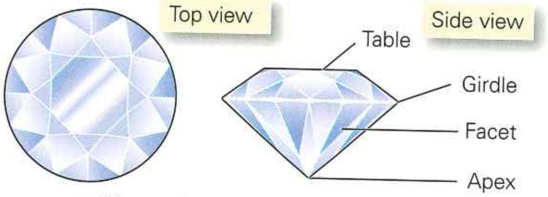
**FIGURE 3.10** The Hope Diamond.

**FIGURE 3.11** Cutting gemstones.

**(a)** Emerald is a green, transparent variety of the mineral beryl.



**(b)** The shiny faces of a gem are made by grinding the stone on a lap.



**(c)** There are many different "cuts" for a gem. Here we see the top and side views of a brilliant-cut diamond.

**Take-Home Message**

**Gemstones are particularly rare and beautiful minerals. The gems or jewels found in jewelry have been faceted using a lap—the facets are not natural crystal faces or cleavage surfaces. The fire of a jewel comes from the way it reflects light internally.**

# CHAPTER 3 REVIEW

## Chapter Summary

- Minerals are naturally occurring, solid substances, formed by geologic processes, with a definable chemical composition and an internal structure characterized by an orderly arrangement of atoms, ions, or molecules in a crystalline lattice. Most minerals are inorganic.
- Biogenic minerals are produced by organisms. The minerals in shells are an example of biomineralization.
- In the crystalline lattice of minerals, atoms occur in a specific pattern—one of nature's finest examples of ordering.
- Minerals can form by the solidification of a melt, precipitation from a water solution, diffusion through a solid, the metabolism of organisms, and precipitation from a gas.
- About 4,000 different types of minerals are known, each with a name and distinctive physical properties (such as color, streak, luster, hardness, specific gravity, crystal habit, cleavage, magnetism, and reactivity with acid).
- The unique physical properties of a mineral reflect its chemical composition and crystal structure. By observing these physical properties, you can identify minerals.
- The most convenient way to classify minerals is to group them according to their chemical composition. Mineral classes include silicates, oxides, sulfides, sulfates, halides, carbonates, and native metals.
- Silicate minerals are the most common minerals on Earth. The silicon-oxygen tetrahedron, a silicon atom surrounded by four oxygen atoms, serves as the fundamental building block of silicate minerals.
- Groups of silicate minerals are distinguished from each other by the ways in which the silicon-oxygen tetrahedra that constitute them are linked.
- Gemstones are minerals known for their beauty and rarity. The facets on cut gems used in jewelry are made by grinding and polishing the stones with a faceting machine.

## Key Terms

carbonate (p. 81)
cleavage (p. 79)
color (p. 78)
conchoidal fracture (p. 79)
crystal (p. 73)
crystal face (p. 73)
crystal habit (p. 78)
crystal structure (p. 74)
facet (p. 85)
gem (p. 84)
geode (p. 77)
glass (p. 73)
hardness (p. 78)
luster (p. 78)
mineral (p. 72)
mineralogy (p. 72)
Mohs hardness scale (p. 78)
polymorph (p. 76)
silicate (p. 81)
silicon-oxygen tetrahedron (p. 81)
specific gravity (p. 78)
streak (p. 78)

## Review Questions

1. What is a mineral, as geologists understand the term? How is this definition different from the everyday usage of the word?
2. Why is glass not a mineral?
3. Salt is a mineral, but the plastic making up an inexpensive pen is not. Why not?
4. Describe several ways that mineral crystals can form.
5. Why do some minerals occur as euhedral crystals, whereas others occur as anhedral grains?
6. List and define the principal physical properties used to identify a mineral. Which minerals react with acid to produce $CO_2$?
7. How can you determine the hardness of a mineral? What is the Mohs hardness scale?
8. How do you distinguish cleavage surfaces from crystal faces on a mineral? How does each type of surface form?
9. What is the prime characteristic that geologists use to separate minerals into classes?
10. What is a silicon-oxygen tetrahedron? What is the anionic group that occurs in carbonate minerals?
11. On what basis do mineralogists organize silicate minerals into distinct groups?
12. What is the relationship between the way in which silicon-oxygen tetrahedra bond in micas and the characteristic cleavage of micas?
13. Why are some minerals considered gemstones? How do you make the facets on a gem?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- A What a Geologist Sees exercise on identifying mineral properties.
- An Animation exercise on mineral growth.
- Problems that help students with mineral classification.

## On Further Thought

14. Compare the chemical formula of magnetite with that of biotite. Considering that iron is a relatively heavy element, which mineral has the greater specific gravity?
15. Imagine that you are given two milky white crystals, each about 2 cm across. You are told that one of the crystals is composed of plagioclase and the other of quartz. How can you determine which is which?
16. Could you use crushed calcite to grind facets on a diamond? Why or why not?

## SEE FOR YOURSELF C. . . Minerals

**Download** *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet C of our **Geotours Workbook**.

### Kimberley Diamond Mine

| | |
|---|---|
| Latitude | 28°44′17.06″S, |
| Longitude | 24°46′30.77″E |

The field of view shows part of the town of Kimberley, in South Africa. Looking down from 13 km, you can see an inactive diamond mine, which looks like a circular pit, and the tailings pile of excavated rock debris.

### Ekati Diamond Mine, Canada

| | |
|---|---|
| Latitude | 64°43′14.74″N, |
| Longitude | 110°37′32.76″W |

In this remote region, the landscape is largely untouched tundra. In the 1990s, prospectors found diamond pipes, and now the area contains small open-pit mines. Mining is difficult on the frozen ground.

### Mir Mine, Siberia

| | |
|---|---|
| Latitude | 62°31′40.77″N, |
| Longitude | 113°59′36.16″E |

Viewed from 4.2 km, we see an open pit (1.2 km across and 525 m deep) dug into kimberlite. In the 1960s, the mine produced 2,000 kg of diamonds per year. Mining continued underground after the pit closed in 2001.

### Diamantina, Brazil

| | |
|---|---|
| Latitude | 18°15′4.35″S, |
| Longitude | 43°34′57.21″W |

Independent miners excavated Precambrian sedimentary rocks by hand in this pit, viewed from 2.2 km. Diamonds occur as grains. They weathered out of kimberlite, then mixed in with sand and pebbles carried by rivers. The sediment later cemented into rock.