3.1 Calcite crystals on purple-blue fluorite. From the Annabel Lee Mine, Cave-in-Rock Mining District, southern Illinois, USA

3 Mineral Properties

KEY CONCEPTS
Mineral names derive from mineral appearance, composition, provenance, and many other things. Many are named after well-known mineralogists.

A mineral’s common appearance (its habit) includes both crystal shape and the way that multiple mineral crystals may grow together.

Mineral crystals have shapes related to the arrangements of atoms within them.

We typically use physical properties such as luster, color, diaphaneity, crystal shape, streak, hardness, and cleavage to identify and distinguish different minerals.

Other properties, including magnetism and reaction to hydrochloric acid are sometimes diagnostic.

### 3.1 Naming Minerals

Mineral names are based on mineral appearance, mineral chemistry, where the mineral is found, a famous scientist, or anything else deemed important by a mineral’s discoverer. The Commission on New Minerals and New Mineral Names of the International Mineralogical Association reviews proposed new names and descriptions and judges their appropriateness. The Commission also occasionally discredits old names. Absolute identification and classification of minerals require knowledge of their composition and atomic structure. Mineralogists must include such information when they submit names to the Commission for approval.
Determining mineral composition and structure may require time and equipment unavailable to most mineralogists or to mineralogy students. Fortunately, we can use other methods to tell minerals apart. Differences in composition and structure lead to differences in appearance and in many other mineral properties useful for identification. For example, the mineral halite, shown here in Figure 3.2, is most easily identified by its cubic, often clear crystals, by its softness, and by its salty taste.

Most of the properties discussed in this book fall into two general groups: hand specimen properties, which are easily determined using typical mineral samples, and optical properties, which we can only see with specially prepared slides and a polarizing light microscope, also called a petrographic microscope. This chapter reviews hand specimen properties and discusses their use in identification. We cover optical properties in the next chapter.

3.2 Mineral Identification

Give a mineral specimen to a nongeologist and ask them to describe it. Generally, they mention the appearance, especially color, first. With a little prodding, they may go on to describe the shape and nature of visible crystals. For example, they might describe the pyrite crystals in Figure 3.3 as metallic, having a gold color, and forming cubic crystals. They might describe the rose quartz in Figure 3.4 as hard, pinkish, glassy, and partially transparent.
3.3 Pyrite cubes in sandstone

3.4 Rose quartz on top of clear quartz

**Metallic** and **glassy** are terms describing **luster**. Gold, clear, and **pinkish** describe **color**. Transparent describes **diaphaneity**. **Cubic** describes **crystal shape**, a property related to **symmetry**. These four properties (luster, color, diaphaneity, and shape) are basic for mineral identification. Other properties including **streak** (the color of a mineral when powdered), the way a mineral breaks (**cleavage, parting, fracture**), and **hardness** are also common keys to identification. Still, other properties can be important for specific minerals.

Given a single property, for example **luster**, we can sort minerals into groups. In the case of luster, we usually start by dividing minerals into those that are **metallic** and those that are **nonmetallic**. The pyrite seen above is metallic. The quartz is nonmetallic. There are, however, many metallic and many nonmetallic minerals; other properties must be considered if minerals are to be identified correctly. Nonmetallic minerals can, for instance, be divided further based on more subtle luster differences.

Ultimately, we can identify minerals by name or at least place them into small groups based on their properties. It is tempting, then, to come up with a standard list of properties that we should evaluate when identifying minerals. However, most mineralogists know that, depending on the sample and circumstances, some properties are more important than others. Rather than going through a long list or filling out a
standard table, experienced mineralogists focus on the properties that are most exceptional or unique. Sometimes, a single property, such as strong effervescence by hydrochloric acid (diagnostic of calcite), may serve for mineral identification. And, being magnetic usually identifies magnetite. (Metallic iron in meteorites is also magnetic.) At first, mineral identification may seem tedious, but with a little experience, it is possible to find shortcuts to make the process more efficient.

3.3 Crystal Shape

To most people, a crystal is a sparkling gem-like solid with well-formed faces and a geometric shape. For many scientists, including all mineralogists, crystal and crystalline also refer to any solid compound having an ordered, repetitive, atomic structure, which may or may not result in crystal faces.
and a gemmy appearance.

We use the term “crystal” in both ways. When a mineralogist refers to a garnet crystal, the reference may be to a dodecahedron, a twelve-sided crystal with diamond-shaped faces like the drawing seen in Figure 3.5 and the real garnet next to it in Figure 3.6. We describe crystals, such as the well-formed garnet crystal with well-developed faces, as being euhedral.

![3.7 Anhedral garnet crystal](image)

On the other hand, petrologists and mineralogists may refer to crystals of garnet in a rock. The crystals may not have any smooth faces at all. The garnet seen in the photo here, which was picked out of garnet gneiss (a metamorphic rock), lacks crystal faces entirely. If no faces are visible, as in this photograph, the crystal is anhedral. Those crystals that fall between euhedral and anhedral are called subhedral.

![3.8 The atomic arrangement in](image)
the garnet almandine

Mineral crystals always have an ordered arrangement of atoms within them, but the crystals may not be geometrically shaped or smooth on the outside. All garnet crystals, for example, have the same highly ordered arrangement of atoms shown in this ball and stick drawing (Figure 3.8), but only some garnet crystals have visible crystal faces. In fact, most natural garnet is anhedral or, perhaps, subhedral. So, the garnet in the photo above is typical.

With just a few exceptions, all minerals are crystalline, but perfectly formed crystals with flat faces are relatively rare. Nonetheless, because crystal shape reflects the crystal’s atomic arrangement, when faces on a mineral are fully or partially developed, crystal shape can be a powerful identification tool. When no faces are visible, we must rely on other properties to identify a mineral.

3.3.1 Crystal Forms

Mineralogists use the term form to refer to a group of identically shaped faces on a crystal. The faces of a form are related by crystal symmetry and have identical chemical and
physical properties. If a crystal contains only one form, all crystal faces are the same size and shape. Euclidean garnet crystals, for example, generally have one form consisting of 12 identical diamond-shaped faces like the dodecahedron in Figure 3.5, earlier in this chapter. (Some garnet crystals, such as the one depicted at the bottom of Figure 3.9, however, contain a different form called a traphezoahedron.)

The drawings in Figure 3.9 show common forms for six different minerals. Different samples of the same mineral may crystallize with different forms, but those shown here are typical. Like most garnet crystals, chabazite crystals generally contain only one form, typically six identical nearly (but not quite) square faces. Five of the drawings show crystals with more than one form. In the ilmenite, corundum, vesuvianite and datolite drawings, the different forms have distinctive different shapes. In the gehlenite drawing, all faces are rectangular but not all are the same size. The gehlenite crystal contains three forms (three pairs of identical rectangular faces) with different sizes.

### 3.3.2 Mineral Habit

3.10 Blocky halite
3.11 fibrous actinolite
3.12 reticulated cerussite
The photos above (Figure 3.16) show examples of different mineral habits. Habit, a property closely related to crystal shape, includes shape and size of crystal faces, how forms combine, how well developed different forms are, and the way multiple crystals grow together. Habit, thus, is the characteristic appearance a mineral can have. The photos in Figure 3.16 show some contrasting examples.

The most useful terms describing habit are self-explanatory. Common ones used to describe the habit of single crystals include *equant* (equidimensional), *acicular* (needlelike), *tabular*, and *bladed*. These and other terms are defined below.

<table>
<thead>
<tr>
<th>Terms Used to Describe Shapes of Individual Crystals (With Example Minerals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>equant</td>
</tr>
<tr>
<td>blocky</td>
</tr>
<tr>
<td>acicular</td>
</tr>
</tbody>
</table>
tabular or platy | appearing to be a plates or a thick sheet (gypsum, graphite)
capillary or filiform | hairlike or threadlike (serpentine, millerite)
bladed | elongated and flattened in one direction (kyanite, wollastonite)
prismatic or columnar | elongated with faces parallel to a common direction (apatite, beryl)
foliated or micaceous | easily split into sheets (muscovite, biotite)

For describing an assembly of multiple crystals, we use terms such as massive, granular, radiating, and fibrous. We list and define these terms and others in this table:

<table>
<thead>
<tr>
<th>Terms Used to Describe Properties of Crystal Aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>massive</td>
</tr>
<tr>
<td>granular</td>
</tr>
<tr>
<td>radiating or divergent</td>
</tr>
<tr>
<td>fibrous</td>
</tr>
<tr>
<td>stalactitic</td>
</tr>
<tr>
<td>lamellar or tabular</td>
</tr>
<tr>
<td>stellated</td>
</tr>
<tr>
<td>plumose</td>
</tr>
<tr>
<td>arborescent or dendritic</td>
</tr>
<tr>
<td>reticulated or latticelike</td>
</tr>
<tr>
<td>colloform or globular</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>botryoidal</td>
</tr>
<tr>
<td>reniform</td>
</tr>
<tr>
<td>mammillary</td>
</tr>
<tr>
<td>drusy</td>
</tr>
<tr>
<td>elliptic or pisolitic</td>
</tr>
</tbody>
</table>

Unfortunately, although museum specimens and pictures of minerals in textbooks often show distinctive shapes and habits, most mineral samples do not. Small anhedral crystals without flat faces, or massive aggregates of many small crystals, are typical, sometimes rendering shape and habit of little use for identification. Additional complications arise because some minerals, for example calcite, have different crystal shapes or habits, depending on how they grow. Nonetheless, shape and habit reflect the internal arrangement of atoms in a crystal and, when visible, can be important diagnostic properties. For example, the movie makers blew it in the 1995 movie Congo. See the Box 3-1 below.

**Box 3-1 What’s Wrong With This Picture?**

3.19 A bogus diamond in the movie Congo

In the 1995 movie Congo, an exploration team goes to Africa to seek large, flawless diamonds. When the diamonds are shown, the movie immediately loses credibility with mineralogists because the crystals are hexagonal prisms (long crystals with a hexagonal cross section). Mineralogists know that diamond crystals can never be hexagonal prisms. The photo shows actor Timothy Curry holding a quartz crystal, not a diamond crystal.
For additional views of many different mineral habits with a discussion, go the video linked below. It does a good job of defining many of the terms used to describe different habits that are listed in the tables above:

Video 3-2: Examples of mineral habits (10 minutes)

Asbestos mineral have, for a long time, been known for posing health risks because of their habits. The box below discusses these minerals and risks.
Box 3-2  Asbestiform Minerals and Health Risks

3.20 Chrysotile mineral specimen

We use the term asbestiform to describe a mineral habit characterized by small, strong, and flexible fibers, equivalent to hairs or whiskers. Asbestos is a commercial name for any marketable asbestiform mineral. For legal and regulatory purposes, however, the US Environmental Protection Agency has developed a more restrictive definition and defines asbestos as being fibrous varieties of one of six specific minerals. Other countries have similar legal definitions.

Mineralogists have described many asbestiform mineral varieties, but most are rare and only a few are produced for sale. The photo seen in Figure 3.20 shows "white asbestos," composed of the mineral chrysotile. Chrysotile, which accounts for about 95% of the commercial asbestos market, is a member of the serpentine mineral group. It is a widespread but minor mineral in many altered ultramafic rocks.

3.21 Scanning electron microscope image of chrysotile fibers

Some commercial asbestos is composed of crocidolite ("blue asbestos") or amosite ("brown asbestos"), varieties of the amphiboles riebeckite and grunerite, respectively. Other minerals that may be asbestiform include other amphiboles (anthophyllite, tremolite, actinolite), clays (sepiolite, palygorskite), and some members of the zeolite mineral group.

Historically, asbestos has had many uses. Since around 1880, it has been mined in large quantities because it is tough, flexible, and fire and chemical resistant. Between 1900 and 1986, builders sprayed asbestos on walls, ceilings, and pipes in many buildings in the United States. Industries have used asbestos in brake linings, roof shingles, and other applications. Unfortunately, asbestos easily crumbles to make a fine dust that people can inhale. Fibers can become embedded in lung tissue and cause asbestosis (a chronic breathing disorder that may be fatal), lung cancer, or mesothelioma (another form of cancer). For the most part, epidemiologists have documented these diseases only in workers exposed to high levels of asbestos over long times.

In 1907 health workers reported the first asbestos-related diseases, but it was not until around 1960 that the threat posed by asbestos was accepted as serious. In 1974 the Environmental Protection Agency (EPA) banned asbestos for most commercial use in the United States, and soon afterward launched a vigorous program to remove asbestos from commercial structures. However, American companies still ship many products containing asbestos to developing countries. Despite the ban and efforts to eliminate asbestos from our environment, it is still common in many buildings and as a component in urban dust.

Click on the arrow below to be taken to a video that shows some spectacular images of crystals that have different crystal habits. This video is one of many produced by the Envisioning Chemistry Project.
3.4 Mineral Appearance

3.4.1 Luster

Luster refers to the general appearance or sheen of a mineral. It refers to the way in which a mineral reflects light.

For a very good discussion, with examples, of many different mineral lusters, watch the video linked below:

▶️ Video 3-3: Examples of mineral lusters (7 minutes)

3.4.1.1 Metallic and Submetallic Lusters

Minerals that have the shiny appearance of polished metal are said to have a metallic luster. Some could be used as mirrors. Well-crystallized pyrite is a good example. Other commonly metallic minerals include chalcopyrite (CuFeS₂), bornite (Cu₅FeS₄), native copper (Cu), native gold (Au), hematite (Fe₂O₃), and magnetite (Fe₃O₄). The photo seen here (Figure 3.22) shows metallic stibnite (Sb₂S₃). The crystal cluster is almost a meter across! Most of minerals with a metallic luster are sulfides, oxides, or native elements.
Minerals that do not appear metallic have a *nonmetallic* luster. Those that appear only partially metallic are called *submetallic*. The chalcopyrite (CuFeS$_2$; gold-bronze color) seen in this photo is metallic, the minor dark grey sphalerite (ZnS) in the photo might be considered submetallic, and the hard-to-pick-out fluorite (CaF$_2$) (semi-clear and white) is nonmetallic. Other commonly submetallic minerals include, cinnabar (HgS), and cuprite (Cu$_2$O).

### 3.4.1.2 Nonmetallic Lusters

Mineralogists use many terms to describe *nonmetallic* lusters. The table below lists the most commonly used terms.

<table>
<thead>
<tr>
<th>luster</th>
<th>meaning</th>
<th>example minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>vitreous</td>
<td>having a glassy appearance</td>
<td>quartz, tourmaline</td>
</tr>
<tr>
<td>resinous</td>
<td>having the appearance of resin</td>
<td>sphalerite, sulfur</td>
</tr>
<tr>
<td>greasy</td>
<td>reflecting light to give a play of colors; similar to oil on water</td>
<td>chlorite, nepheline</td>
</tr>
<tr>
<td>silky</td>
<td>having surfaces appearing to be composed of fine fibers</td>
<td>chrysotile (asbestos), gypsum</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>adamantine</td>
<td>having a bright brilliant appearance similar to that of diamonds</td>
<td>diamond, cerussite</td>
</tr>
<tr>
<td>pearly</td>
<td>appearing iridescent, similar to pearls or some seashells</td>
<td>muscovite, talc</td>
</tr>
<tr>
<td>dull</td>
<td>not reflecting significant amounts of light or showing play of colors</td>
<td>kaolinite (clay), niter</td>
</tr>
</tbody>
</table>

**Vitreous Minerals**

Vitreous minerals are nonmetallic minerals that have a glassy appearance. The adjective is derived from the Latin *vitrium*, meaning glass. Quartz (SiO$_2$) is an excellent example. Calcite (CaCO$_3$), topaz (Al$_2$SiO$_4$F$_2$), and fluorite (CaF$_2$) are other minerals that may be vitreous. The two photos below show vitreous calcite and topaz.

![Vitreous calcite from the Pyrenees Mountains, France](image1)

![Vitreous topaz, Minas Gerais, Brazil](image2)

**Resinous Minerals**

Resinous minerals have a luster similar to violin resin or pine pitch. The most common mineral example is a resinous variety of sphalerite (ZnS) such as that shown in the photo below (Figure 3.26). Sphalerite, however, has other appearances. In fact, the name *sphalerite* is from the Greek
sphalereros which means deceiving or treacherous. This name refers to the many different appearances that sphalerite may have. Its luster can be metallic, submetallic, resinous or adamantine. Some samples are transparent with a vitreous luster.

![Image of dark metallic sphalerite with orange resinous sphalerite on top.](image)

The photo on the right above shows resinous amber, which is fossilized tree resin, with an insect inclusion. Amber, however, is a biomineral, not a true mineral.

**Greasy Minerals**

Greasy minerals show a *play of color* – color change with angle of view – that resembles grease or maybe fat. Examples are the opal and cordierite seen in the two photos below. Besides opal and cordierite, jadeite and a few other minerals sometimes have a greasy luster. However, this luster occurs most commonly in opal (a mineraloid) and in minerals that contain many small inclusions.
3.28 Opal (moss opal variety)  3.29 Cordierite from Madagascar

A good short discussion of play of color can be found at:
▶️ Video 3-4: Play of colors (5 minutes)

Silky, Fibrous, and Acicular Minerals

Silky minerals appear to have a parallel arrangement of fine fibers, sometimes giving them the luster of silk. Satin spar, in the photo on the left below, is a variety of gypsum (CaSO₄•2H₂O). It gets its name from its fibrous appearance and silky sheen.

3.30 Satin spar, a variety of gypsum, from Hot Springs County, Wyoming
3.31 Ulexite and TV-rock, from Kern County, north of Los Angeles

If fibers are coarse, we may describe a mineral as fibrous instead of silky. Ulexite, a hydrated borate mineral shown in the photo on the right above, is a classic example of a fibrous mineral. In the large photo, the acicular (needle-like) ulexite fibers are radiating from a cluster of blocky colemanite (a different borate mineral).
Mineral fibers occasionally display the same optical properties that characterize fiber optics – they transmit light. The inset in Figure 3.31 shows a variety of ulexite called TV-rock because it transmits images of what is behind it – in this case, writing. The fibers in this specimen cannot be seen but are all parallel and perpendicular to the page.

Adamantine Minerals

We use the term *adamantine* to describe crystals that sparkle or appear brilliant; *diamond* (C) is perhaps the best-known example. But, *Herkimer diamonds*, a variety of quartz (SiO₂) from Herkimer, New York can also be adamantine. The two photos below show a Herkimer diamond and a real diamond. Other minerals that are sometimes adamantine include *anglesite* (PbSO₄), *cerussite* (PbCO₃), and corundum (Al₂O₃). Some synthetic minerals, including *cubic zirconia* (ZrO₂) are also adamantine. All these natural and synthetic stones can have their sparkle enhanced with proper faceting.

Pearly Minerals

Pearly minerals show a *play of color* that resembles the luster of pearls. Light reflecting from pearly minerals may be white
or appear to have washed out rainbow colors. The play of colors is due to a layered atomic arrangement, so pearly minerals generally have excellent planar cleavage. The two photos below show pearly muscovite and talc. These minerals are somewhat dichroic, which means their colors change with angle of view. But, that property cannot be seen in standard photos.

![Pearly muscovite](image1.png) ![Pearly talc](image2.png)

**Dull and Earthy Minerals**

Dull minerals show no remarkable luster – because they have non-reflective surfaces. Kaolinite (Figure 3.36, below) is a good example – it is usually a fine-grained aggregate of small grains, white, and drab. Besides kaolinite, the other clay minerals, such as montmorillonite or illite, also have dull lusters.

We say that dull minerals are earthy if they have a brownish or reddish color resembling dirt. Common hematite is an excellent example (although some hematite may be metallic). The hematite seen in the photo below (Figure 3.37) can be described as being earthy, and Figure 3.14 showed another example of earthy hematite. Besides hematite, limonite and other metal oxides and hydroxides are commonly earthy.
3.36 Kaolinite from the Pyrenees

3.37 Hematite from New York

3.4.2 Diaphaneity

3.38 Iceland spar, a variety of calcite

Diaphaneity refers to a mineral’s ability to transmit light. For example, some minerals are transparent. When they are thick, a small amount of distortion may occur, but light passes relatively freely through them. Thus, we can see the clouds in the distance through the clear Iceland spar (calcite) crystal in Figure 3.38. Because it is so clear, Iceland spar has been used in some industrial applications. (Unfortunately, it is not very durable because calcite is very soft.) Very few minerals are as transparent as the calcite seen here. Thin sheets of muscovite and some quartz come
Minerals that do not transmit light as well as clear calcite may be *translucent*. Although it is not possible to see through them as with transparent minerals, if thin enough, translucent minerals transmit light. Both the whitish calcite and the darker colored orpiment in this photo (Figure 3.39) are translucent. Many other minerals exhibit this same property.

For example, quartz comes in many different colors but, unless very finely crystallized, it is generally translucent to some degree. Calcite, gypsum, topaz, and many micas, are often commonly translucent.
3.40 Molybdenite on quartz

Some minerals are neither transparent nor translucent, and are opaque instead. Opaque minerals do not transmit light unless the mineral is exceptionally thin. Most opaque minerals have metallic lusters and belong to the sulfide, oxide, or native element groups. This photo (Figure 3.40) shows a hexagonal flake of opaque molybdenite (MoS$_2$) on top of translucent quartz. Pyrite and magnetite are two more common examples of opaque minerals.

3.4.3 Color

Color is often used for quick identification of minerals. Sometimes, it can be diagnostic, but for many minerals it is ambiguous or even misleading. The deep red color of rubies may seem distinctive. Ruby is, however, just one variety of the mineral corundum. Sapphires are different colored varieties of the same mineral. The photos in Figure 3.41 show just a few of the many colors that corundum may have. To add to the confusion, other minerals, such as spinel or garnet, may have the same deep red color as ruby. Color is ambiguous because
many things can give a mineral its color.

Color is one of the most misunderstood mineral properties. It is easy to look at a ruby illuminated by white light and say it has a red color. If the ruby is illuminated by light of a different color, it may not appear red. Color, then, is not just a property of a mineral. It is instead the result we observe when light and a mineral interact. When we see that a mineral has color, what we are really observing is the color of the light that is being reflected or transmitted to our eye. Normal light, called white light, includes many different colors (wavelengths). When white light strikes a mineral surface, if all of the colors are reflected back to our eyes, the mineral will appear white. If none of the colors are reflected back to our eye, the mineral will appear black. Most minerals, like ruby, appear to have color because only one or a few wavelengths of light reflect and make it back to our eye. The other wavelengths are absorbed or transmitted by the mineral in some way.

3.42 Pyrite with minor hematite on dolomite

3.43 Chalcopyrite that is tarnishing

Metallic minerals, especially sulfides, tend to be constant in their coloration. So mineralogists commonly use color as a key tool for sulfide identification. However, metallic minerals easily tarnish, so we need a fresh surface to see the true color. The photos above show pyrite on top of dolomite (left photo) and chalcopyrite (right photo). The pyrite specimen also contains a few crystals of dark colored hematite.
Pyrite and chalcopyrite are both sulfides, but pyrite is FeS$_2$ and chalcopyrite has formula CuFeS$_2$. Both sulfides are quite common and color usually distinguishes one from the other – pyrite is more golden or brass colored, and chalcopyrite generally has a yellowish tint and sometimes appears a bit greenish. Notice that the chalcopyrite is tarnishing to an orangish color.

![Image of light purple amethyst and orangish citrine from Namibia](image)

3.44 Light purple amethyst and orangish citrine from Namibia

Color is often a poor property to use for identifying nonmetallic minerals because many things can cause minerals to have different colors. For example, quartz may be colorless, rosy (rose quartz), yellow (citrine), purple (amethyst), milky, smoky, or black. The photo seen here in Figure 3.44 contains both light purplish amethyst and orangish citrine.

The most significant control on color is a mineral’s chemical composition. Elements that give a mineral its color are called chromophores. It does not take large amounts of chromophores to color a mineral. Minor amounts, less than 0.1 wt% of transition metals such as iron and copper, may control a mineral’s color because electrons in the d-orbitals of transition metals are extremely efficient at absorbing certain visible wavelengths of light. The remaining wavelengths are
reflected and give minerals their color.

If the elements controlling the selective reflection of certain wavelengths are major components in a mineral, the mineral is *idiochromatic*, or “self-coloring.” Sphalerite (ZnS), for example, is an idiochromatic mineral. It changes from white to yellow to green to brown to black as its composition changes from pure ZnS to a mixture of ZnS and FeS. The two photos seen here are from the same mining district in New York but are different colors. Compare these with other photos of sphalerite earlier in this chapter (Figures 3.23 and 3.26). Sphalerite has a lot of different looks and colors!
Many copper minerals are idiochromatic and have green or blue coloration, while many manganese minerals are pinkish. These colors derive from selective absorption of certain colors by copper and manganese. Idiochromatic elements may have different effects in different minerals. Malachite and azurite, seen in the photo here (Figure 3.47), are both hydrated copper carbonates, but malachite is green and azurite is blue. In both minerals the color is due to copper.

Ruby and sapphire are examples of allochromatic varieties of corundum. In allochromatic minerals, minor or trace elements determine the color. Very small amounts of iron and titanium give sapphire a deep blue color. Small amounts of chromium give ruby and other gemstones deep red colors. Like the effects of idiochromatic elements, the effects of allochromatic elements may be different in different minerals. Allochromatic chromium is also responsible for the striking green color of emerald (a variety of the mineral beryl), chrome diopside, and some tourmalines.

Structural defects in minerals may also influence their color. Radiation damage gives quartz, for example, a purple, smoky, or black color. The purple color of many fluorites is caused by Frenkel defects (out of place ions in the atomic structure). Other causes of coloration include the oxidation or reduction of certain elements (especially iron), and the presence of minute inclusions of other minerals.

3.4.4 Streak
3.48 Red hematite streak

Although it would never occur to many people to check a mineral’s streak, streak is sometimes a key diagnostic property. It is not a useful property for identifying most silicates, but is especially useful for distinguishing oxide and sulfide minerals. The streak of a mineral is the color it has when finely powdered. For mineral identification, it is much more reliable than mineral color, and it is easy to determine. The usual method of determining streak is to rub the mineral against a ceramic streak plate or other piece of unglazed ceramic. Figure 3.48 shows a red streak from hematite, and the photo below (Figure 3.49) shows a yellow streak from sulfur. Mineralogists routinely use streak when identifying minerals, both in the laboratory and in the field, but it cannot be determined for minerals harder than the hardness of a streak plate.
Steak color is a good diagnostic property because when a mineral is finely powdered, structural and other nonchemical effects are minimized. Calcite, for example, comes in many different colors, but calcite’s streak is always white. Pyrite (fool’s gold) is yellow but has a dark-colored streak, as does chalcopyrite. Gold, which has a color similar to pyrite’s (in hand specimen), has a yellow-gold streak.

Streak can be extremely useful for telling dark-colored minerals apart, especially metallic ones. For example, hematite may be red, gray, or black in hand specimen and may or may not have a metallic luster. It always, however, has a diagnostic red streak that helps distinguish specular hematite from galena, or other kinds of hematite from similarly colored minerals.

Unfortunately, most minerals have a white or colorless streak. Yet, streak is a key property for identifying a small number of minerals. The table below lists some minerals that often have diagnostic streak colors.

<table>
<thead>
<tr>
<th>mineral</th>
<th>streak color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples of Minerals that Do Not Have a White Streak</td>
<td></td>
</tr>
</tbody>
</table>
3.4.5 Luminescence

Some minerals will emit light when they are activated by an energy form other than visible light. We call such an effect luminescence. Examples of luminescence include fluorescence, phosphorescence, and thermoluminescence.
clinohedrite, and calcite

This photo is a fluorescent specimen from the Franklin Mine in New Jersey. It is illuminated with short wavelength ultraviolet light and contains green willemite (Zn$_2$SiO$_4$), blue hardystonite (Ca$_2$ZnSi$_2$O$_7$), orange clinohedrite (CaZnSiO$_4$•H$_2$O), and minor red calcite (CaCO$_3$). Fluorescent minerals like the ones seen here give off visible light when they are struck by energy with wavelength shorter than visible light. If the visible emission continues after the energy source is turned off, the mineral is phosphorescent. Pectolite is an example of a phosphorescent mineral.

Thermoluminescent minerals, such as some tourmalines, give off visible light in response to heating. Some varieties of fluorite, calcite, and apatite also have this property.

3.4.6 Play of Colors

We discussed play of colors earlier in this chapter (for example the pearly luster that is sometimes exhibited by micas or talc) but it is worth returning to the topic to consider some special examples. When it enters some crystals, white light can be separated into individual wavelengths of varying intensities that are emitted in different directions. The effect is somewhat like the rainbows created when light is scattered by a glass prism. The play of colors in minerals is a form of light scattering due to very fine particles in the minerals or to textures of mineral surfaces. The two photos on the right below (Figures 3.52 and 3.54) show examples of opalescence (most notably exhibited by opals, but also by a variety of K-feldspar called moonstone).
The limonite photo above (Figure 3.51) displays iridescence, sometimes described as being similar to the colors on top of an oil slick. This play of colors commonly appears when metallic minerals such as bornite tarnish or, in this case, when limonite tarnishes. The fourth photo (bottom left, Figure 3.53) shows labradorite, a feldspar, displaying labradorescence. Labradorescence is a variety of iridescence.

Chatoyancy and asterism are two special scattering effects most easily seen in gemmy polished minerals, such as the two cabochons (gems that have been shaped and polished instead of faceted) and the polished tiger’s eye stone seen in the photos below.
Chatoyant minerals show a bright band of scattered light, often perpendicular to the long direction of a crystal. Such minerals are sometimes said to have a cat’s-eye (like the moonstone above) or tiger’s-eye (like the quartz above) appearance. The satin spar variety of gypsum is also chatoyant.

Asterism, a property sometimes visible in rubies, sapphires, garnets, and some other gems, refers to scattered light appearing as a “star.” The example shown above in (Figure 3.56 is a famous sapphire called the Star of India that is in the American Museum of Natural History in New York. It has spectacular asterism. Chatoyancy and asterism are caused by closely packed parallel fibers or inclusions of other minerals within a mineral crystal.

For some additional pretty examples of chatoyancy and asterism, see the video at:

▷ Video 3-5: Chatoyancy and asterism (3 minutes)

### 3.5 Strength and Breaking

The color and shape of minerals are obvious to anyone, but mineralogists note other, more subtle, properties too. Several relate to the strength of bonds that hold atoms in crystals together. These properties are especially reliable for mineral identification because they are not substantially affected by chemical impurities or defects in crystal structure.
3.5.1 Tenacity

The term *tenacity* refers to a mineral’s toughness and its resistance to breaking or deformation. Those that break, bend, or deform easily have little tenacity. In contrast, strong unbreakable minerals have great tenacity. The photo here shows samples of the gemstone *jade* shaped and polished to produce a figurine and a cabochon. Gemmy jade may be either of two kinds: *jadeite* (a pyroxene) or *nephrite* (a rock containing very fine-grained green amphibole). In either case, jade is one of the most tenacious natural materials known. It does not easily break or deform, even when under extreme stress. That is one reason, besides beauty, that it is prized as a gemstone.

The nature of its chemical bonds controls a mineral’s tenacity. Ionic bonding often leads to rigid, *brittle* minerals. Halite is an excellent example of a brittle mineral. It shatters into many small pieces when struck. Quartz, too, is brittle, although the bonding in quartz is only about half ionic. Many metallic minerals, such as native copper, are *malleable*, which means we can shape them with a hammer. Native copper is also *ductile*, which means we can stretch it out into
wire-like shapes. Other minerals, such as gypsum, are sectile, which means they can be cut into thin pieces with a knife.

Some minerals, including talc and chlorite, are flexible due to weak van der Waals and hydrogen bonds holding well-bonded layers of atoms together. When force is applied, slippage between layers allows bending. When pressure is released, they do not return to their original shape. Still other minerals, notably the micas, are elastic. They may be bent but resume their original shape after pressure is released if they were not too badly deformed. In micas and other elastic minerals, the bonds holding layers together are stronger than those in chlorite, clays, and other minerals with layered atomic arrangements.

Thus, we have a number of terms that we can use to describe mineral tenacity:

<table>
<thead>
<tr>
<th>Terms Used to Describe Tenacity</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>brittle</td>
<td>easily broken or powdered</td>
</tr>
<tr>
<td>malleable</td>
<td>capable of being hammered into different shapes</td>
</tr>
<tr>
<td>sectile</td>
<td>capable of being cut into shavings with a knife</td>
</tr>
<tr>
<td>ductile</td>
<td>capable of being drawn into a wire-like shape</td>
</tr>
<tr>
<td>flexible</td>
<td>capable of being bent into a different shape</td>
</tr>
<tr>
<td>elastic</td>
<td>a bendable mineral that returns to its original shape after release</td>
</tr>
</tbody>
</table>

3.5.2 Cleavage, Fracture, and Parting

Cleavage, fracture, and parting are three related terms that describe how a mineral crystal may break. The orientation and
manner of breaking provide important clues about crystal structure and can be keys to mineral identification. If breaking produces planar and smooth surfaces, oriented in a particular way relative to a crystal’s atomic arrangement, we say that the mineral has cleavage.

If a mineral cleaves along one particular plane, a nearly infinite number of parallel planes are equally prone to cleavage. This is because of the repetitive arrangement of atoms in crystal structures. The spacing between cleavage planes is the repeat distance of atoms, on the order of angstroms (1Å = 10^{-10} m) for mineral crystals. The whole set of planes, collectively referred to as a cleavage, represents planes of weak bonding in the crystal structure. If cleavage produces mineral fragments with distinctive shapes, we use geometric terms such as cubic, octahedral, rhombohedral, or prismatic to describe the cleavage when appropriate. Overall, the direction and angular relationships between cleavages give valuable hints about atomic arrangements.

The vast majority of minerals exhibit cleavage, but the nature of cleavage is highly variable, and some minerals cleave much more easily than others. We use general terms to describe the quality of a cleavage, including: perfect, imperfect, distinct, good, fair, and poor. Although some minerals exhibit no cleavage, many cleave in more than one direction, but the qualities of the different cleavages may not be the same.

Some minerals contain only poorly developed cleavage. Others, like calcite, have perfect cleavage. Whether perfect or not, when present, cleavage can be a good property to help identify minerals. For example, some specimens of black pyroxene and hornblende may appear quite similar. But, pyroxenes have two cleavages at about 90° to each other, and hornblende has two cleavages at 60° to each other. Often we can see the cleavage angles in hand specimen, although sometimes it requires a hand lens.
Fracture is closely related to cleavage but is a general term that describes the way a mineral breaks or cracks in directions unrelated to weak atomic bonding. Minerals that are bonded with equal strength in all directions, such as quartz, have no cleavage, but instead fracture to form irregular surfaces. These minerals break along curved surfaces to form conchoidal fractures, similar to what happens when glass breaks. Figure 3.61 shows a sample of quartz displaying conchoidal fracture. Other kinds of fracture include even fracture, hackly fracture, splintery fracture, and others. The terms we use to describe fracture and cleavage are plentiful; the most commonly used terms are defined in the tables below.

<table>
<thead>
<tr>
<th>Terms Used to Describe Cleavage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>basal</strong></td>
</tr>
<tr>
<td>well developed planar cleavage in one direction only; also sometimes called “platy” (micas)</td>
</tr>
<tr>
<td><strong>cubic</strong></td>
</tr>
<tr>
<td>three cleavages at 90° to each other (galena)</td>
</tr>
<tr>
<td><strong>rhombohedral</strong></td>
</tr>
<tr>
<td>three cleavages not at 90° to each other (calcite)</td>
</tr>
<tr>
<td><strong>octahedral</strong></td>
</tr>
<tr>
<td>four cleavages that produce 8-sided cleavage fragments (fluorite)</td>
</tr>
<tr>
<td><strong>prismatic</strong></td>
</tr>
<tr>
<td>multiple directions of good cleavage all parallel to one direction in the crystal (tremolite)</td>
</tr>
<tr>
<td><strong>distinct</strong></td>
</tr>
<tr>
<td>cleavage is present but may not be manifested as perfectly smooth planes</td>
</tr>
</tbody>
</table>
indistinct | cleavage is present but neither smooth nor regular

| Terms Used to Describe Fracture (and example minerals) |
|-----------------|----------------------------------------------------------------------------------------------------------------|
| even            | breaking to produce smooth planar surfaces (halite)                                                                 |
| uneven / irregular | breaking to produce rough and irregular surfaces (rhodonite)                                                        |
| hackly          | fracturing to produce jagged surfaces and sharp edges (copper)                                                     |
| splintery       | forming sharp splinters (kyanite, pectolite)                                                                          |
| fibrous         | forming fibrous material (chrysotile, crocidolite)                                                                  |
| conchoidal      | breaking with curved surfaces as in the manner of glass (quartz)                                                      |

Micas, including muscovite and biotite, are the best examples of minerals with one excellent cleavage. The photo below (Figure 3.59) shows cleavage in biotite. Biotite can be easily broken into very thin sheets. Molybdenite, too, has only one direction of cleavage and breaks into sheets (see the molybdenite in Figure 3.40). The micas, molybdenite, and many other minerals that cleave into thick slabs or sheets have what we call **basal cleavage**.

3.59 Biotite

3.60 The atomic arrangement in micas
The ball and stick model in Figure 3.60 shows the atomic arrangement in micas. It is similar to the arrangement in all sheet silicates. The layered structure explains why micas cleave as they do. Micas cleave into sheets because the bonds to the potassium ions are very weak compared with all bonding in other directions.

3.62 K-feldspar

Feldspars, like the K-feldspar shown, have two cleavage directions. One is very good (meaning it is often easily observed) and the other better described as distinct (meaning it sometimes shows). The angle between the two feldspar cleavages is about 90°, which explains why the specimen in Figure 3.62 appears to have a square cross section. Cleavages in feldspar are, however, generally not as well developed as cleavages in minerals like mica and, so, may be hard to discern. Feldspars are typical – in ideal specimens the cleavages and angles between them can be easily seen. But, in many specimens, they cannot.
Albite is one of the most common feldspars. Click on this image for a 3-dimensional view.

The photo seen in Figure 3.36 shows albite, another kind of feldspar. Hints of cleavage can be seen, but it is not obvious how many cleavages are present or what their angular relationships are. But, if you click on the photo of albite, you will get to a 3-dimensional photograph that you can rotate so you see the cleavages. Look closely and you will see that the angle between cleavages is just about 90°.

Some minerals with two cleavages, such as kyanite, easily break into long splintery pieces. Anthophyllite, too, sometimes forms bladed crystals. The photos below show typical blue blades of kyanite and a cluster of bladed anthophyllite crystals.

Other minerals, including halite and calcite, have three directions of cleavage. The ball and stick model below shows the atomic arrangement in halite. Atoms are evenly spaced and all bonds are perpendicular. Consequently, halite has cubic...
cleavage — three directions of cleavage at 90° to each other. In the blue/gray halite crystal below, the cleavages created a cube, and additional cleavage traces can be seen as fine cracks. Figures 3.2 and 3.10 also show halite. The cleavage cannot be seen in Figure 3.2 but is very clear in Figure 3.10.

Like halite, calcite has three good cleavages. But, unlike halite, the cleavages are not perpendicular to each other. So calcite cleaves into shapes called rhombs. This photo shows a bunch of calcite cleavage fragments. Compare the shape of these fragments with the clear calcite shown in Figure 3.38. Besides calcite, dolomite and other carbonate minerals that belong to the rhombohedral carbonate group, cleave the same way. Some carbonates, such as aragonite and cerussite, however, are orthorhombic carbonates with three perpendicular
cleavages.

Euhedral fluorite crystals are typically cubes, but sometimes they are octahedra like those shown in Figure 3.69 below. Fluorite is the most common example of a mineral that has four perfect cleavages; the cleavage directions are parallel to the octahedral faces. Many fluorite cleavage fragments are perfect octahedra, and many cubic fluorite crystals are missing corners because of the mineral’s cleavage. All fluorite is essentially $\text{CaF}_2$, but color varies due to minor chemical impurities. Purple is the most common color, but the other hues in this figure are quite common too.

3.69 Fluorite

Click on the image below to explore a 3-dimensional model of cleavage in biotite, K-feldspar, and quartz. The biotite has perfect basal cleavage and the quartz shows conchoidal fracture. The feldspar cleavages is almost impossible to see.

3.70 Link to a 3-
dimensional sample with varying kinds of cleavage

Crystal faces and cleavage surfaces may be difficult to tell apart. In some minerals, principal cleavage directions are parallel to crystal faces, but in most they are not. A set of parallel fractures suggests a cleavage, but if only one flat surface is visible, there can be ambiguity. However, this problem is sometimes mitigated because crystal faces often display subtle effects of crystal growth. Twinning (oriented intergrowths of multiple crystals) and other striations (parallel lines on a face), growth rings or layers, pitting, and other imperfections often make a face less smooth than a cleavage plane, and give it lower reflectivity and a more drab luster.

The photo seen in Figure 3.71 is of a calcite crystal that shows visible striations on its crystal faces. The lines are artifacts of crystal growth and are not related to cleavage.
Some minerals exhibit *parting*, a type of breaking that is often quite similar to cleavage. Parting occurs when a mineral breaks along structural planes but, unlike cleavage, parting is not found in all samples of a particular mineral and does not repeat to form many parallel planes that are only a few angstroms apart. Several things can induce parting, perhaps most commonly it occurs because of twinning (when multiple crystals grow together and share atoms). Distinguishing parting from cleavage can, sometimes, be problematic.

For many good examples of mineral fracture and cleavage, watch the video linked below:

▶️ Video 3-6: Examples of mineral fracture and cleavage (8 minutes)

A good additional perspective on cleavage can be found at:

▶️ Video 3-7: Mineral cleavage (5 minutes)

### 3.5.3 Hardness

*Hardness* is a mineral’s resistance to abrasion or scratching. We determine relative hardness (symbolized by $H$) using a scratch test: we try to scratch a surface of one mineral with an edge or corner of a second mineral. If a scratch or abrasion results, the first mineral is the softer. Absolute hardness is not quite the same as relative hardness. It is the measure of a material’s ability to resist permanent deformation. Although rarely done by mineralogists, values of absolute hardness may be determined in several ways; the easiest is to use an indenting tool similar to ones used to measure the hardness of steel. The indenting tool measures the force necessary to produce a permanent indentation in a flat surface.
This table gives the relative hardness scale that is used by mineralogists. Based on ten well-known minerals, it is called the Mohs Hardness Scale, named after Austrian mineralogist Friedrich Mohs who developed it in 1812. The Mohs scale ranks minerals by their ability to scratch each other. The Mohs scale is related to absolute hardness but does not measure the same thing because resistance to scratching depends on additional factors besides the force needed to make an indentation.

If we compare the Mohs hardness scale with absolute hardness, we find that the Mohs scale is not linear and is close to being exponential. The hardnesses of the softest minerals are more similar than the hardnesses of the four hardest ones (quartz, topaz, corundum, diamond). Gypsum (H = 2) is only slightly harder than talc (H = 1), but diamond (H = 10) has a hardness five times greater than corundum (H = 9).

We can estimate relative hardness by conducting scratch tests to compare the hardness of an unknown mineral to the minerals in the Mohs hardness scale. Many labs are equipped with boxes of reference minerals for this purpose.
Alternatively, we can approximate hardness by comparing mineral hardness with the hardness of a fingernail, penny, pocketknife, glass, or several other common objects – the most commonly used are listed in the table above. Figure 3.72 shows gypsum being scratched with a fingernail. Gypsum, one of the softest minerals known, has a hardness of 2 on the Mohs hardness scale; fingernails have a hardness of about 2½. A penny has hardness of 3½, iron has hardness of about 4½, a pocketknife has hardness of 5½, and a metal file has hardness of 6½.

Scratch tests are often straightforward, but there can be complications. Mineral specimens may be too small or too valuable to scratch. Large samples may consist of many grains loosely cemented together so that scratch tests are not possible. Other samples may cleave or fracture when we perform tests. In still other cases, the results of scratch tests may be ambiguous, especially if we try to scratch a mineral with one that has the same, or nearly the same, hardness.

Most minerals have hardness greater than 2 and less than 7. The tables below list some examples of relatively common minerals that fall outside this range.

<table>
<thead>
<tr>
<th>Hardest Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
</tr>
<tr>
<td>cordierite</td>
</tr>
<tr>
<td>quartz</td>
</tr>
<tr>
<td>andalusite</td>
</tr>
<tr>
<td>zircon</td>
</tr>
<tr>
<td>beryl</td>
</tr>
<tr>
<td>spinel</td>
</tr>
<tr>
<td>topaz</td>
</tr>
<tr>
<td>chrysoberyl</td>
</tr>
</tbody>
</table>
The hardness of a mineral relates to its weakest bond strength. So, because bonds are usually not the same in all directions in minerals, hardness may vary depending on the direction a mineral is scratched. In kyanite, for example, hardness varies from 4½ to 6½ depending on the direction of the scratch test. In most minerals, however, hardness is about the same in all directions. While the general relationship between hardness and bond strength is known, mineralogists have difficulty predicting hardness for complex atomic structures. For some simple ionic compounds, however, theoretical calculations match measurements well. Minerals with high density, highly charged ions, small ions, or covalent bonding tend to be hardest.
3.6 Density and Specific Gravity

3.73 Borax crystals from Boron, California

The Greek letter \( \rho \) (rho) symbolizes density. We usually give the density of a mineral in units of grams/cubic centimeter (gm/cm\(^3\)). Density varies slightly depending on pressure or temperature, but most minerals have values between 2 and 8 gm/cm\(^3\). Borax, shown in this photo, has density of about 1.8 gm/cm\(^3\), lower than all other common minerals.

The polymorphs diamond and graphite are both made of carbon (C), but due to differences in atomic arrangements, diamond has density of 3.5 gm/cm\(^3\), while graphite’s is 2.2 gm/cm\(^3\). Graphite forms under Earth surface conditions, but diamond, with its high density, only forms deep in Earth where pressures are great. The Laws of Thermodynamics tell us that high pressures favor dense minerals, which makes sense because at high pressure things are squeezed together.

Accurate determination of density can be difficult or impossible because it requires knowing the volume of a crystal – which can be difficult to measure with accuracy. A related property, specific gravity (\( G \)), is often used instead. Specific gravity (unitless) is the ratio of the mass of a mineral to the mass of an equal volume of water at 1 atm, and
because mass and weight are proportional, we normally determine specific gravity by comparing weights. If a mineral is at normal Earth surface conditions, density and specific gravity have about the same values.

3.74 Barite from Baia Sprie, Romania

Because specific gravity varies greatly between minerals, we can easily distinguish minerals with high, moderate, or low specific gravity simply by picking them up to see how heavy they feel. We use the term *heft* for estimations of $G$ made using this approach. H is sometimes very useful for mineral identification. For example, the mineral barite (BaSO$_4$), such as the example in Figure 3.74, sometimes exists as massive white material that is easily confused with feldspars. However, its great heft, easily discerned by picking it up, helps identify it. Similarly, we can distinguish cerussite (lead carbonate) from other carbonate minerals by its heft.

Specific gravity differences can also help in the separation of minerals. In the laboratory, researchers separate crushed rock into mineral components by “floating” samples in liquids of different specific gravities. In these *heavy liquids*, which are much denser than water, minerals separate as some float and others sink according to their specific gravities. In mining operations, ore minerals are often separated from valueless minerals by using gravity separation techniques that
depend on specific gravity differences. This occurs in natural systems, too. Placer gold deposits form when gold from weathered rock, because of its high specific gravity, concentrates in stream beds.

3.75 Gold nugget on quartz

The lightest minerals have specific gravities on the order of 1.8 to 2. They are mostly borates (such as borax), halides (e.g., halite), and sulfates (e.g., gypsum). Silicates (including quartz and all the other common rock-forming silicates) and carbonates (e.g., calcite or dolomite) range from about 2.5 to 3.5. Oxides and sulfides may have specific gravities as great as 7 or 8 but are highly variable. And, native metals (e.g., copper, silver, or gold) range up to 19 or 20. The photo in Figure 3.75 shows a gold nugget with quartz beneath it. It came from a placer. Gold has specific gravity of about 19.3 and quartz has specific gravity of 2.7.

The specific gravity of a mineral depends, in part, on how its atoms are packed together within a crystal. For example, the left part of the table below lists the specific gravities for quartz and four other SiO₂ polymorphs. Stishovite, coesite, quartz, cristobalite, and tridymite all have different densities because they do not have the same atomic arrangements. The densest two – stishovite and coesite – are only found in very high pressure rocks or in meteorite impact craters.
Specific gravity also depends on composition. This can be demonstrated by looking at *isostructural minerals* – minerals with the same atomic arrangement but with different compositions. Consider the garnet group minerals for example. The table below lists names, compositions and specific gravities for seven garnets. The specific gravity values vary from 3.54 for pyrope to 4.33 for almandine, reflecting the atomic weights of the garnets’ elemental constituents. Two examples of garnet can be seen in Figures 3.6 and 3.7.

<table>
<thead>
<tr>
<th>Specific Gravities of Some Silica Polymorphs</th>
<th>mineral</th>
<th>formula</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>stishovite</td>
<td>SiO₂</td>
<td>4.35</td>
<td></td>
</tr>
<tr>
<td>coesite</td>
<td>SiO₂</td>
<td>3.01</td>
<td></td>
</tr>
<tr>
<td>quartz</td>
<td>SiO₂</td>
<td>2.65</td>
<td></td>
</tr>
<tr>
<td>cristobalite</td>
<td>SiO₂</td>
<td>2.32</td>
<td></td>
</tr>
<tr>
<td>tridymite</td>
<td>SiO₂</td>
<td>2.26</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specific Gravities of Some Garnet Minerals</th>
<th>mineral</th>
<th>formula</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>pyrope</td>
<td>Mg₃Al₂Si₃O₁₂</td>
<td>3.54</td>
<td></td>
</tr>
<tr>
<td>grossular</td>
<td>Ca₃Al₂Si₃O₁₂</td>
<td>3.56</td>
<td></td>
</tr>
<tr>
<td>uvarovite</td>
<td>Ca₃Cr₂Si₃O₁₂</td>
<td>3.80</td>
<td></td>
</tr>
<tr>
<td>andradite</td>
<td>Ca₃Fe₂Si₃O₁₂</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>spessartine</td>
<td>Mn₃Al₂Si₃O₁₂</td>
<td>4.19</td>
<td></td>
</tr>
<tr>
<td>almandine</td>
<td>Fe₃Al₂Si₃O₁₂</td>
<td>4.33</td>
<td></td>
</tr>
</tbody>
</table>
The photos in Figures 3.76 and 3.78 show a diamond crystal and a graphite crystal. Graphite and diamond are polymorphs – they have the same compositions but different atomic arrangements. Both minerals are made of carbon but they have different properties and appearances because the carbon atoms are arranged differently in the two minerals. The drawings in Figures 3.77 and 3.79 show how carbon atoms are arranged in each.

As shown in the atomic drawings, in diamond, each carbon atom is covalently bonded to four others, creating an overall cubic 3-dimensional network that has the same properties in all directions. In graphite, carbon atoms are covalently bonded to form sheets that contain interconnected 6-carbon rings; very weak van der Waals bonds hold the sheets together.

Diamond is a tenacious mineral that does not cleave easily. In contrast, graphite, because of its layered atomic arrangement, has excellent basal (planar) cleavage. Graphite has a hardness of 1½ and diamond has a hardness of 10. In diamond, all electrons are tied up in covalent bonds, so diamond does not conduct electricity. In graphite, there is a free electron associated with each carbon atom, so graphite conducts electricity well. Diamond has a denser structure than graphite – the specific gravity of diamond is about 3.5, and graphite’s is 2.1 to 2.3. Because of its high density, diamond only forms deep within Earth. This is true for all high density minerals – they only form where pressure is great.

3.7 Magnetism
Magnetism derives from a property called the magnetic moment that results from the spinning and orbiting of electrons. The sum of all the magnetic moments of all the atoms in a mineral gives it magnetism. There are different kinds of magnetism. Minerals may be ferromagnetic, diamagnetic, or paramagnetic.

In ferromagnetic minerals, the moments of a mineral’s electrons are aligned in a constructive way and the minerals have properties similar to those of metallic iron. Ferromagnetic minerals may be magnetized. Magnetite (Figure 3.80) and pyrrhotite are examples of ferromagnetic minerals, but magnetite is much more ferromagnetic than pyrrhotite.

Diamagnetic minerals exhibit little magnetic character overall but may be weakly repelled by a strong magnetic field. Pure feldspars, halite, and quartz all exhibit weak diamagnetism. An impure feldspar, however, may contain iron, which results in paramagnetism, which means it is attracted to a strong magnet. Other commonly paramagnetic minerals include garnet, hornblende, and many pyroxenes.
For routine mineral identification, only a few minerals – for practical purposes only magnetite – can be identified because of their magnetism. In the field, rocks that contain magnetite will attract a magnet. This sometimes help distinguish different rock formations. And, in the laboratory, subtle differences in the magnetic properties of minerals are routinely used to separate different minerals in crushed rock samples. Figure 3.81 shows a device used for this purpose. Magnetism, thus, can be an important property of minerals.

3.8 Electrical Properties

Electricity can be conducted if a mineral contains electrons
that can move throughout its structure. (See the discussion of diamond and graphite in Box 3-3.) So, minerals with metallic, or partially metallic bonds – like many sulfides – are good conductors. The native metals, such as copper, are the best examples. This photo (Figure 3.82) shows a “branch” of native copper with several small quartz crystals on it. The branch was extracted from a rock matrix. Sulfide minerals, because they commonly have partially metallic bonds, are also good conductors.

Small amounts of electrical conduction may also occur in minerals with defects or other imperfections in their structures. And, some minerals, while being unable to conduct electricity, may hold static charges for brief times. They may be charged by exposure to a strong electric field, a change in temperature, or an application of pressure. A mineral charged by temperature change is pyroelectric; a mineral charged by pressure change is piezoelectric. Because they are difficult to measure, however, electrical properties are not often used for mineral identification.

3.9 Reaction to Dilute Hydrochloric Acid

3.83 Hydrochloric acid effervescing on calcite
One chemical property, the reaction of minerals to dilute (5%) hydrochloric acid (HCl), is included here because it is diagnostic for calcite, one of the most common minerals of the Earth’s crust. Drops of dilute acid placed on coarse samples of calcite cause obvious bubbling or fizzing, called effervescence, seen in the photo here (Figure 3.83).

Dolomite, a closely related carbonate mineral, effervesces when finely powdered but not when coarse. Other carbonate minerals, such as smithsonite (ZnCO₃), aragonite (CaCO₃), and strontianite (SrCO₃), effervesce to different degrees. They are usually distinguished, however, by crystal form, color, and other properties. Although acid tests have limited use, most mineralogy labs are equipped with small bottles of HCl and eyedroppers to aid in carbonate identification. Many geologists carry a small bottle of dilute hydrochloric acid when they go in the field so they may distinguish between rocks that contain calcite and rocks that do not.

3.10 Additional Properties

Minerals possess many other properties (for example, solubility, radioactivity, or thermal conduction). Because they are of little use for mineral identification in most cases, we will not discuss them individually here.
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