



Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
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Crystals: More Than Meets the Eye

Curriculum Unit 89.06.07
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It is the purpose of this unit to acquaint the student with the intriguing world of crystals, their structure, formation, and uses.

Most students when confronted with a well-formed quartz crystal, or a purple fluorite, or a polished geode, literally jump about demanding to know “Who made this?” and “How did they make this?”. And the subject of diamonds and other gems is avariciously attended to with wide eyes and listening ears. Since the actual atomic structure can be drawn and modeled in a wide variety of mediums even the more humdrum aspects can be made inviting. And the chemical concoctions that can result in some homemade crystals bring out the white-coat scientist in even the most reluctant student. Many of the students own small personal calculators that are solar-powered, or have seen the advertisements in discount store circulars for solar powered exterior lighting. These objects provide a good jump-off point for discussions about crystals and technology.

My unit on crystals will be divided into three categories covering three areas of study. The first area will deal with the actual structure of crystals beginning with a look at the atom, some simple atomic drawings (Bohr models) of elements, and a study of the periodic table of the elements. Next we will look at compounds and their bonds. This will lead to the understanding of how crystals “look” and the shapes they can take. Within this section we will draw and construct in three dimensions paper models of six of the basic crystal shapes. We will also grow some of our own crystals in the laboratory.

The second major heading in my unit will focus on minerals. We will learn about the characteristics of a mineral: the chemical composition, mineral color, luster, cleavage, hardness (and how this property is related to crystal structure), and specific gravity. The characteristics of minerals lend themselves nicely to a mineral identification lab., and a lab. on specific gravity of minerals and selected rock samples. Some of the other topics in this section will include a study of the various forms of quartz; gems, especially diamonds; the formation of mineral crystals—by igneous, sedimentary, and metamorphic processes; and some stories of famous (or infamous) gems.

The final section of this unit will delve into the uses for crystals which modern technology has fostered, specifically solar cells, transistors, and liquid crystals.

The unit is designed for the middle school age level, specifically for the eighth grade Earth Science curriculum. In the two years that I have used this curriculum unit with my eighth grade classes I have amplified or omitted sections depending on the interest and abilities of the various classes. In this way I have been able to use the

unit with students that range in ability from very high to very low.

Throughout this paper I am indebted to the teaching and guidance of Dr. Werner Wolf and to the following books and sources:

On the topic of crystal growth and structure: Alan Holden and Phylis Morrison, *Crystals and Crystal Growing*; and Elizabeth Woods, *Crystals—A Handbook for School Teachers*.

On the topic of quartz and related minerals: Cornelius Hurlbut, *Minerals and Man*.

On the topic of gemstones, natural and man made: Cornelius Hurlbut, *Minerals and Man*; Joel Arem, *Man-made Crystals*; and Paul O'Neil, *Gemstones*.

On the topic of liquid crystals: Frederick Kahn in *Physics Today*; and Glenn Brown and Peter Crocker in *C&EN*.

On the topic of solar cells and semi-conductors: Bruce Chalmers in *Scientific American*; and Christopher Swan, *Suncell; Energy, Economy, and Photovoltaics*.

I. Atoms, Elements, and Compounds

The building blocks of all things are the tiny atoms that make up the many elements which we can see on the periodic table. The minerals we will be studying are made of these elements or combinations of elements called *compounds*. The basic atom is composed of positively-charged *protons*, negatively-charged *electrons*, and *neutrons*, which have no electrical charge at all. Protons and neutrons are located in the nucleus of a cell and have almost the same mass which is measured by a special unit called the *atomic mass unit*, or *amu*. A single proton or a single neutron has a mass of about one amu. The electron has a much smaller mass, only 1/1836 amu. There are always the same number of protons as electrons, and therefore the same number of positive charges as negative charges are found in the neutral atom.

A. The Bohr Model

Although our best understanding of the atom tells us that the electrons are in constant and rapid motion around the nucleus and the exact location of any electron cannot be known, we can by experimental means determine the most probable locations of electrons and establish energy levels or shells which we can use to help us understand the relations of atoms. In 1913 a Danish Scientist, Niels Bohr, developed a model that can be used by children to understand the way atoms combine into compounds. This model is called the Bohr model and shows a central nucleus with the protons and neutrons either drawn in or simply enumerated. Around this central core are the shells or energy levels. These levels are sometimes referred to as the K, L, M, N, O shells or alternatively, the first, second, third, fourth, fifth, energy levels. Each of these levels has a specific number of electrons it can maximally hold. The degree to which these shells are filled determines how readily it will combine with other elements and in what proportion.

Figure 1 illustrates a specific labelling technique that is quite easy to use with children and facilitates accuracy. Since the shells fill using definite laws and patterns involving energy, they are predictable. Beyond the element calcium, however, the laws become quite complex and need extensive explanation and understanding of subshells. It is wise, therefore, to limit the Bohr model drawing to that point at this grade

level. Some periodic tables give the number of electrons in the energy levels as part of the information in the block for each element. By looking at this data, some of the students might come up with partial explanations for the building of these shells. In the absence of such data it is sufficient to declare the numbers 2 and 8 “magic numbers” and let them build the smaller atoms.

(figure available in print form)

After drawing out a few, or many, of the Bohr models the children will notice that some of the models have an outer shell that only needs one or two more electrons to be filled, and that others have one or two electrons that seem to hang awkwardly by themselves in their outer shell. These conditions can of course be used to develop an understanding of the terms *metal* and non- *metal* . Since the children can “see” the electrons they can judge their availability for donating or receiving. This technique makes easy work of explaining compounds and their chemical formulas. It also aids in the explanation of ionic and covalent bonding.

B. Ionic Bonding

By drawing a Bohr model of sodium we can see that its K and L shells are filled and the one remaining electron is by itself in the outer M shell. It will take very little energy to coax that electron away from its atom, leaving only ten electrons with ten negative charges to balance with the eleven protons with their eleven positive charges. When this happens we will have an ion with a +1 charge. In the same way if we draw a shell that has seven electrons, one short of that “magic number” eight. In this case the chlorine atom would be very happy (anthropomorphically speaking) to grab another electron and fill that shell. In doing so the chlorine atom now would have seventeen protons and eighteen electrons, resulting in a net charge on the atom of -1. This would be a negative ion. When two elements come together in this way we refer to it as an ionic bond. The opposing charges on the two ions cause them to be attracted together.

(figure available in print form)

C. Covalent Bonding

Next we will draw out an oxygen atom. In this case we can see that its outer shell has six electrons, two short of the “magic number” eight. And if we draw a hydrogen atom we can see that it has one electron in its outer shell, half of what it needs to fulfill the “magic” two count. From this we could deduce that by bringing in another hydrogen atom we can combine the three atoms into H₂O, and each atom’s outermost shell would be filled. This is the basis for an understanding of *covalent bonds* , in which atoms come together and share electrons in their outer shells. The electron clouds overlap and the electrons circle both atoms.

(figure available in print form)

The bonds of compounds can influence some substances’ physical properties. And bonds exist not just between individual atoms but also throughout a crystal. We can look at two forms of the element carbon for an example. Graphite is a slippery black solid, the bonds form sheets of carbon which slide loosely over one another. Diamond on the other hand is a hard, clear crystal with tight tetrahedral bonding that holds the carbon atoms of diamonds securely in place. The difference can be seen below in the illustration.

(figure available in print form)

Further investigation of the importance of chemical bonds can be accomplished by a study of sugar and salt crystals. By comparing melting points and ease of crushing some simple inferences can be made about their bonds. Directions for this experiment are to be found in Appendix 1, Activity 1.

II. Crystals and Crystal Systems

A. Unit Cells

When atoms or molecules are lined up in an orderly arrangement and connected by bonds, and these atoms or molecules have a repeating pattern, we can then say this material is a crystalline substance. The smallest subdivision of a crystal is a unit cell. It is a regular pattern of atoms held together by electrical forces or bonds. These unit cells are far too minute to be seen individual but can be combined together in incredibly large numbers to form visible shapes. As an example of the staggeringly large numbers of unit cells we are talking about we can take as an example sodium chloride, table salt. One typical salt grain has about 5.6×10^{18} unit cells. (Each salt unit cell is composed of four atoms of sodium and four atoms of chlorine.) ¹

B. Crystal Systems

When the unit cells group together they leave no empty spaces between themselves. This results in a limited number of crystal systems that can form. These systems can be grouped as follows: ²

1. Isometric or cubic — three edges of equal length and at right angles to one another.
2. Tetragonal — three edges at right angles but only two edges of equal length.
3. Orthorhombic — three edges at right angles but all edges of different lengths.
4. Monoclinic — two edges at right angle, the other angle not; and all edges of different lengths.
5. Triclinic — all three edges of different lengths and all angles not at right angles.
6. Hexagonal — two edges are equal and make angles of 60 to 120 degrees with each other. The third edge is at right angles to them and of different length.

Two activities which can be used with the students are to be found in Appendix 1 listed within Activity 2. The first is a simple introduction to the various crystal shapes by drawing them and identifying their title. The second activity applicable to crystal shapes using the diagrams given there. In doing so, the student can in very concrete terms understand the variety of angles and lengths involved.

C. Growing Crystals

Once the student has a basic understanding of what a crystal is, he or she is often anxious to create some crystals of his or her own. This provides a natural opportunity to introduce some new terms which they will use in their laboratory experiences.

Since most of their crystals will be formed by solution the student needs to add the words *solute*, *solvent*, and *solution* to his vocabulary. The solute is the substance being dissolved and the solvent is the substance doing the dissolving. A solvent can hold in solution just so much of the solute. At this point we say the solution is

saturated. If there is less solute in the solution than it would ideally hold we would then say it is an unsaturated solution. And in some cases such as when we heat the solvent we can continue to add solute and it will dissolve. When the heat source is removed and the solution's temperature falls the extra solute may remain in solution. This fragile situation is called supersaturation and is the basis for our crystal growth experiments.

Solubility , or the amount of solute which can be dissolved in the solvent, is affected by a number of factors, one of which is the temperature of the solvent. Generally speaking we increase solubility of solid solute when we increase the temperature of the solvent. (This is not true of the solubility of gases in a solvent as is witnessed by anyone who has sipped a glass of warm, flat soda.) In Appendix 2 there are some solubility figures which the student can use to set up graphs of solubility curves.

Crystal growth is a very orderly and regulated process. A crystal grows from the solution with the atoms of the compound being added according to a very specific pattern. If there is not enough space for the crystal to grow unhindered it will increase only until it meets something which gets in its way and then stop. Often many small crystals begin forming at the same time, and they grow until their edges meet at varying angles. They do not join to form a single large crystal but rather remain a jumble of small individual crystals forming a *polycrystalline* mass. The adjoining faces of the crystals are called the *grain boundaries* . These boundaries are particularly evident in metals which have formed by fairly rapid cooling of the molten form. During the cooling process innumerable small crystals form and grow until they bump into a neighboring crystal.

Crystals can form from the cooling or evaporation of solutions, or from the cooling of molten solid, or the cooling of vaporized substances. In Appendix 3 you will find a number of experimental techniques for demonstrating crystal growth and for student participation in crystal growing.

D. Impurities ³

While the regularity and order of crystals have been stressed thus far, it is important to note that this order can be disturbed. Generally the cause is the inclusion of an impurity. Sometimes this is the result of a crystal forming around a foreign particle. This can usually be detected by microscopic examination. But other times it is actually an invasion by an atom with approximately the same size and shape as the host crystal, and the pattern is not disrupted. This is called a *mixed crystal* . The classic example of this is alum which is composed of potassium sulfate and aluminum sulfate in a one to one proportion. A similar compound is chrome alum, in which you find potassium sulfate combined with chromium sulfate.

Many crystals in nature demonstrate this mixed crystal condition in the replacement of aluminum by chromium or sometimes iron. Rubies are a good example of this, being composed of aluminum oxide with chromium replacing some of the aluminum, and also sapphires which replace the aluminum with titanium and iron.

In some cases a slightly different atomic substance can enter a crystal but only in small quantities. This is called a *substitutional impurity* . A most relevant example of this is substitution of phosphorus or boron atoms in silicon crystals. These "impure" compounds are used to make transistors for electronic instruments.

Sometimes a different kind of impurity enters a crystal. These foreign atoms may be very small compared to the host substance and fit in between the orderly arranged host atoms. If the host substance has a generous size pattern the invading atoms could be as large as the host atoms themselves. The additional atoms are called *interstitial impurities* . A well known example of this is carbon and iron, which makes steel.

A third kind of defect could be called a *vacancy*. This results from very rapid crystal growth during which some of the atomic sites are simply not filled. The milky or veiled appearance of home-grown crystals, however, is caused by very large openings called voids. It generally occurs when the evaporation of solvent proceeds too rapidly and incomplete crystallization happens. The white coloration is caused by the presence of a liquid solution that is trapped in the open spaces of the crystal. Vacancies on the other hand are far too small to be visible.

(figure available in print form)

III. Minerals

A. Definitions

What is a mineral? What makes it unique? These are questions that can be used to open up the subject to the student. They will often confuse the term with “rock” or think only of the more valuable forms such as rubies or diamonds. They may also want to include coal because they have heard it called a mineral resource, or pearls since they seem to fit in with the other gems. So a discussion of just what a mineral is would be in order.

Minerals are natural substances that are inorganic and not the result of any living process, therefore ruling out coal, oil, or pearls. It must also have a specific chemical formula, made up of atoms in a definite ratio. In addition the atoms must have a definite and specific arrangement in space. It is because of these characteristics that minerals have unique properties which can be used to differentiate them from one another.

B. Terms of Identification

Some of a mineral’s properties are easily determined by simple visual examination: crystal shape, color, and luster. The beginning student will generally try to identify a mineral by its color first. In the case of some minerals this may be successful—malacite is always green, zaurite is always blue, etc. But for most minerals the surface color can vary tremendously depending on impurities included in the crystal structure.

Many minerals are made up primarily of elements which impart no strong color of their own and only minute amounts of a coloring agent can have striking results. Some color guidelines are: red may indicate the presence of chromium or hematite, green can indicate chlorite or chromium, and blue can indicate the presence of titanium or titanium and iron. The presence of copper ions can result in shades of green or blue and manganese can result in shades of red. It is sometimes helpful to determine the color of a mineral’s streak by rubbing the sample on an unglazed porcelain streak plate. This powdered residue is often more accurate in indicating true color and many mineral identification handbooks include a list of streak colors.

Hardness of a mineral is shown by its resistance to being scratched. This is related to the crystal structure in that the more tightly bonded the atoms the harder the surface resistance to being etched will be. Diamond is the hardest mineral but is not readily available for student experimentation. corundum is the next step down and it inexpensively available. In 1812 Friedrich Mohs devised a rough scale of hardness that is invaluable in mineral identification. Diamond at number 10 is the hardest, and talc at number 1 is the softest. The intervals between the numbers are not equal, however, and the difference between corundum at 9 and diamond at 10

is greater than the entire range of 1 to 9!

Mohs Scale of Mineral Hardness

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite
6. Feldspar
7. Quartz
8. Topaz
9. Corundum
10. Diamond

Cleavage is a reflection of the electrical forces acting between the atoms which result in the crystal breaking along atomic planes that are parallel to crystal faces. The children are asked to look for these flat faces and simply to indicate whether the mineral has “good” cleavage or instead breaks with rather raggedy edges and is therefore declared to be fractured. Or if the student has already looked at crystal shape pictures and constructed paper models of them, they can try naming the crystal system it belongs to.

(figure available in print form)

Luster is that mineral property which indicates the way light is reflected from the surface of the sample. Some luster terms are: glassy, metallic, greasy, pearly, or satin-like. These are all terms the students are familiar with and can also be used in conjunction with an identification manual.

Another means of identifying minerals is *specific gravity*. This measurement can be the most helpful identifying characteristic of all as it is apt to be the most reliable. The students can have a very interesting lab built around this property. Directions for this lab are in Appendix 1, Activity 4.

The story of Archimedes and his quest for a way to determine the value of the king’s crown is a sure-fire attention-getter to start the lesson. According to the legend, in about 250 B.C. Archimedes was given the task of determining if a crown belonging to King Hiero was pure gold or only an alloy of gold and silver. It is said that upon easing into his tub the bath water spilled over the edge and it came to him that the volume of water lost was the same as the volume of his body, and he could use the same technique to determine the volume

of the crown. Since it was known that gold and silver have different densities, the only thing that would remain would be to take an accurate measure of the weight of the crown and divide this by the volume of the crown. The resulting density figure could be compared with the density of gold, and the truth would be known. It is said that with this revelation, Archimedes leaped from his bath and ran, forgetting the state of his undress, through the streets of Syracuse in Sicily exclaiming, “Eureka! — I have found it!” on his way to the palace! A sad footnote to the story is that the crown was indeed not the pure gold it had been portrayed as, and the unfortunate merchant met an uncomfortable end. Or so they say.

Carried one step further, the concept of specific gravity is based on the physical law that an object immersed in water loses as much weight as an equivalent volume of water would weigh. With a spring balance and a water pan the students can determine the specific gravity of a variety of minerals. Experience has shown that fairly large specimens will give the best results. See Appendix 1 for directions for labs on this and related topics; Activities 4, 5, and 6.

IV. The Quartz Family

A. Characteristics

Once the student has become familiar with some of the characteristics of minerals in general it is time to focus in on some specific examples. Quartz is a good one with which to work as samples of a variety of forms are easily obtainable and have the all-important virtues of both durability and beauty. Quartz is at position 7 on the Mohs scale which means that it is one of the hardest common minerals. It crystallizes from the molten state at rather high temperatures but also can be deposited on the ocean floor at only a few degrees above zero. It forms very beautiful crystals that can be used as gem stones and is the source of crystals used for technical purposes. It is also the major ingredient in sand. Flint is a historically important form of quartz due to its use in the early weapons used by man to hunt wild game.

In 1880 the Curies discovered another peculiar property of quartz while studying the electrical conductivity of crystalline bodies. They discovered that pressure on plates of quartz caused a deflection of the needle on a sensitive electrometer. This is called the piezoelectric effect. It occurs when the crystal is squeezed slightly out of shape and then springs back. This shape change actually affects the crystal at the atomic level causing a movement of ions, with their attendant electric charges. This motion of the electrically charged particles constitutes flow of electrons, or electricity. This particular characteristic is now used to control and stabilize the frequency of a radio transmitter or to regulate watches. ⁴

B. Types of Quartz

Probably the most familiar form of quartz is the clear, colorless form known as *rock crystal*. These crystals can range in size from the most minute to the gigantic; one from Brazil weighed in at 5.5 tons! This clear material has been used far back into history for carved goblets, bowls, and other objects.

Another form of quartz known and valued for its beauty is *amethyst*. This mineral is almost pure SiO₂ with only a trace of iron. As the amount of iron increases, so does the intensity of the violet color, so it is believed to be the coloring agent. According to folklore the amethyst gives its wearer great power, increased intelligence, and strength.

Smoky quartz does not differ from clear quartz in chemical composition. In fact when it is heated to very high temperatures the “smoky” color vanishes, and it looks identical to clear crystalline quartz. The color can be restored by treating the crystal with a beam of x-ray radiation. Scientists believe that the color of smoky quartz is a result of natural radiation in the earth.

Agate is a common form of quartz which does not have any external evidence of its crystal nature. The extremely tiny crystalline particles are so intergrown that they appear smoothly mixed. Agate is used decoratively and as jewelry, especially in the onyx form. ⁵

A form of quartz that is unique and appears to be most “un-quartz like” is the *opal*. It contains a rather large percentage of water, ranging from four to twenty percent. And a complex internal structure of microscopic silica fitted together in a lattice-pattern results in diffraction of the light hitting it, forming rainbows of brilliant color as the gem is rotated. Opal is a low-pressure and low-temperature mineral and is formed at the earth’s surface by deposition from ground water or by the evaporation of *hydrothermal*, or hot water, springs as they rise to the surface and cool leaving opal mineral behind. Because of the rather large amount of water present in opal, it tends to be relatively soft (5.5 to 6.5) and low in specific gravity. These qualities limit its use as a gem, and it is usually found mounted in pendants and pins where the stone is relatively protected. ⁶

V. Gems

A. Diamonds

Of all the gems diamonds seem to hold a special fascination for both children and adults. Perhaps this is due to all the adventuresome stories seen in movies and on television or perhaps it stems from a vague understanding of the tremendous forces that create diamonds and the vexing inability of man with his modern technology to duplicate this feat completely.

Man is not at a total loss in this field. Currently we are producing some 44,000 pounds for industrial use annually by a process developed by H. Tracy Hall for the General Electric Research Labs in the early 1950s. His process involved a mixture of graphite powder and an iron compound placed in a hydraulic press. This press was able to generate a force of more than 1.5 million pounds per square inch! To that was added an electrical current which heated the mix to over 4,800 degrees Fahrenheit. From this was produced low quality diamond grit used widely for industrial purposes as an abrasive.

Gem quality diamonds are another story. Instead of the less expensive carbon sources which are used in the manufacture of industrial diamonds, the feed material for gem quality diamonds is the industrial grit, and the pressure and temperatures must be maintained for long periods of time, up to a week. From this we can obtain gem quality diamonds of up to one carat, but unfortunately the cost of manufacture is higher than the present cost of mining the natural stones. ⁷

Natural diamonds are thought to be formed deep within the earth, probably 90 to 120 miles down within the upper regions of the mantle. Here pressures of 975,000 pounds per square inch and temperatures of at least 2,700 degrees Fahrenheit may cause carbon atoms to crystallize into tetrahedral shapes of great strength. Diamond is more resistant to scratching than any other mineral, only another diamond can mark it. It is resistant to acids and alkalis. It is brilliant and has very high dispersive qualities which result in the flashes of

light reflecting from the cut stone. *Dispersion* is the ability of a substance to separate white light into its component colors just as a prism or water droplets forming a rainbow. It also has a relatively high specific gravity, 3.5, which results in it being found in *placer deposits*, those areas in stream beds where heavy and often valuable particles settle out and collect in quantity.

Diamonds were first found in India and for thousands of years this was the only source. They were not mined but rather found in stream gravel and alluvial deposits. Some famous stones from India with fascinating histories are the Koh-i-nor and the Great Mogul. In the early 1700s diamonds were discovered in Brazil. Men panning for gold found clear pebbles that were later recognized as diamonds! Many of these South American gems were shipped to India to be sold in their markets to Europeans. As India's sources began to dry up, Brazil became more acceptable in the world's eyes as a diamond source. And so for a while Brazil was the principal producer of diamonds. Even today many fine gemstones come from there.

The most extraordinary diamond finds have occurred only within the last one hundred years or so. In 1866 a Boer farmer's son found a shiny pebble on a river bank in South Africa. It turned out to be a 21.5 carat diamond! Adventurers from all over the world descended on the site turning it into a free-for-all not unlike the American gold rush. Diamonds were recovered from the river bank, the surface soil, deeper "yellow ground," and finally at depths of fifty to sixty feet, the "blue ground." This rock is the original matrix which the diamonds formed in more than 15 million years ago. Diamonds have also been found beneath the beach sand at the mouth of the Orange River and now mining is being done in the Atlantic Ocean in that area. ⁸

Very few diamonds have been found elsewhere in the world. An occasional gem has been found in the American midwest in glacial deposits or in dunes. And in Arkansas some have been found in their rock matrix similar to the blue ground of South Africa. They have also been found in the Soviet Union, but not much is known about these.

B. Rubies and Sapphires

Two gems which are color variations of the same mineral, corundum, are ruby and sapphire. Rubies contain a small amount of chromium, and sapphires have titanium. They are very hard minerals, 9 on the Mohs scale, and have a high specific gravity, 4.0. This allows them to survive being washed great distances into alluvial placers. An interesting variation of these gems is the "star" form which results when needle-like impurities are aligned at angles of sixty degrees to each other during the formation of the stone. Unlike the highly organized and businesslike enterprises that mine diamonds, the mining of rubies and sapphires is a haphazard, sometimes dangerous endeavor. Most of the rubies come from Burma or Thailand and sapphires come from Sri Lanka, Australia, and surprisingly, Montana in the United States. Many of the stones travel rather dubious routes and are handled by smugglers and contraband dealers in open-air markets guarded by local police armed with automatic rifles. ⁹

C. Emeralds

Emeralds are quite different from their sister gems in that they are quite soft, only 7.5 on the Mohs scale. They are the green form of beryl, colored by the presence of chromium or vanadium. If rubies have wild tales to tell, emeralds out-do them every time.¹⁰ Like something out of an Indiana Jones story the history of emeralds includes torture, conquistadors, native slaves imprisoned in tunnels, and lost treasure maps. Both of the major emerald producing regions in Colombia have violent and greed-filled pasts and presents. One of the areas had to be closed down due to the astronomical numbers of murders and other crimes there. In addition to the problems created by the human element, the mines are plagued by mining-technique problems. The

preferred mode of obtaining the emeralds involves dynamiting the parent rock. Although this does speed up the rock removal process, it also fragments many of the emeralds crystals. As an example, the 632 carat Patricia emerald was uncovered by a dynamite blast which also destroyed what appeared to be an even larger stone! Although emeralds are quite soft as gems go, they are often mined from alluvial deposits. The places they are found, however, are never far from their source or else they would be very eroded. Colombian stones are taken directly from the parent rock. Other countries which produce emeralds are Zimbabwe, Zambia, and Brazil. Their stones are considered, however, to be somewhat inferior in color or size. ¹⁰

D. The Origins of Mineral Crystals

Although the geologic processes which produce minerals, gems, or otherwise, vary in their specifics, there are some generalities to their origins. Like all rocks they form by either igneous, sedimentary, or metamorphic means. *Igneous* formations would include diamonds, rubies, sapphires, topaz, and garnet. These form when magma wells up through cracks and fissures and is trapped in molten pockets. There, water, dissolved gases, and rare elements combine and crystals begin to grow as the molten mass slowly cools. The rock it forms is a mixture of minerals called pegmatite characterized by its large chunks or crystals. With just the right chemicals present and just the right ambient conditions this pegmatite will hold precious gems.

Sedimentary formations may contain gems with two separate histories. Some of the sedimentary rocks hold crystals that were formed elsewhere and then were moved by erosional forces to sediment basins where they became part of the deposit. Other gems were formed when groundwater seeped down through the volcanic ash or other sediments dissolving minerals and moving them into pockets. Opal and turquoise are examples of this type of gem.

When tectonic processes, volcanic activity, or deep burial subject rock to great heat and pressure, *metamorphic* forms may result. The partial melting of the parent rock allows specific minerals to escape and move to areas where they concentrate into gems. Examples are garnets, which can be found here in Connecticut, and the famous Burmese rubies and sapphires.

E. Geodes

Geodes are hollow balls of mineral with numerous well-developed crystals lining the walls of the interior. The formation of geodes is not well understood and there are several theories that attempt to explain these unusual shapes. Some geologists feel that they are merely hollow spaces formed by gas bubbles trapped in molten rock when it cooled. This would allow space for the projecting crystals to form but does not explain the ease with which the geode separates from the host rock. Other geologists think the round shape was originally formed as a concretion which later eroded away leaving a hollow space in which crystals grew. Still other researchers put forth a rather complicated geologic scenario involving a hollow of undetermined origin, its filling with fluids, including a gelatinous silica layer which provides a semipermeable membrane for osmotic movement of water into and out of the open space, and as a final step the dehydration of the gel and the subsequent formation of crystals from mineral rich waters that leak into the opening through cracks.

Displaying geodes to the students is an extremely valuable tool as it is obvious to the group that the individual perfectly formed crystals could not have been carved out by man. This idea of the human manufacture of crystals, especially the particularly beautiful quartz or pyrite crystals, is quite common among students at this grade level.

VI. Crystals and Modern Technology

A. Introduction

Crystals have been valued by man throughout history as building materials or ornamental objects. Today they are further valued as technological materials. Solar cells and semiconductors are two recent developments based on the unique properties of certain crystals. Liquid crystals are another source of exciting possibilities for the future.

B. Solar Cells

Solar cells are perhaps the most familiar to the student, as many of them own solar-powered calculators, or have seen the solar panels on various space vehicles. Inexpensive solar toys are available for student assembly which emphasize the rather simple nature of their operation. The energy produced by the solar cell is also called *photovoltaic energy*. The solar cell is made of silicon which has been infused with an impurity such as boron. Silicon has a strongly bonded tetragonal crystal with pairs of shared electrons uniting it to its four neighbors. When the boron is added as a substitutional impurity (see section II D) it will share its three valence electrons with three of its silicon neighbors but is lacking a fourth electron to share with the fourth silicon neighbor. This absence of an electron is called a hole. So the addition of boron results in a “hole” which is considered to be a positive charge. Next we diffuse a very thin layer of phosphorus into the top of the boron silicon. Phosphorus is different from boron in that it has five valence electrons, one more than it needs to join into the stable bonding with silicon. So this extra electron is free to move among the electron shells, in some cases filling in boron holes, but usually resulting in an excess of electrons moving around. These are called *conduction electrons*. The silicon region with holes is called the “p-type layer” and the region with the excess of conduction electrons is called the “n-type layer.” ¹¹

(figure available in print form)

As the conduction electrons move in to fill in the holes, a peculiar thing happens. The boron atoms which take up the electrons in their holes now become negative ions! And the phosphorous which has given the conduction electron up now becomes a positive ion! This results in a boundary called the *p-n junction* where holes with their positive charge and electrons with their negative charge are repelled by the charged ions that set them loose. So the excess conduction electrons are unable to move across the boundary to fill in the holes. This results in electrons building up in the n-type layer and holes will collect in the p-type layer.

(figure available in print form)

Electrons move toward the p-type side and holes (positive) move toward the n-type side until a dynamic equilibrium is reached. Ionized boron repels further movement of electrons and ionized phosphorus repels further movement of holes (positives).

When photons strike the solar cell, bonded electrons are bounced right out of their positions creating many more conduction n-electrons and holes on both sides of the junction. Since there are already so many electrons on the n-type side and so many holes on the p-type side, the additional new ones are only a tiny proportion; but by making new holes on the n-type side and new conduction electrons on the p-type side, the solar cell is unbalanced. The electrons from the p-type side move across the junction creating a flow of electrons, or electricity! This flow moves electrons out through the n-type layer onto a conductive wire grid which is connected to a circuit that is completed by an attachment to the p-type layer. ¹² Read more about this fascinating but complex topic in Chalmers’ article or Swan’s book.

(figure available in print form)

Solar cell circuit in which conduction electrons move toward the n-type crystal where they travel to the current collector on the surface of the cell and move through the external circuit to the p-type crystal area. ¹³

C. Transistors

Transistors are constructed of the same types of materials as described in the section on solar cells. These materials are called semi-conductors and when bonded together form a p-n junction which is influenced by the addition of a voltage differential placed across it rather than the effects of photons of sunlight. When these thin layers of semi-conductors are sandwiched together they make up a transistor which can be used to regulate the flow of electrons in circuits, detect and amplify radio signals, produce oscillations in transmitters, and act as digital switches. These tiny solids were the first electrical components in which materials with different electrical characteristics were physically joined by structural contact rather than by wires. ¹⁴

D. Liquid Crystals

Another interesting crystal technology involves a crystal which is not a solid. The melting point of a pure crystalline substance is very precise. And in some cases the crystalline properties of a solid crystal carry over into the liquid state. There are many compounds that will do this. Their atomic structure remains quite orderly even while taking on the other characteristics of typical liquids such as pouring or taking on the shape of its container. Selective reflection of white light into its various spectral components by these liquid crystals can be directed and controlled by thermal, acoustical, electrical, magnetic, and even mechanical means. Wrist watches and clocks whose numbers melt from one display into another are liquid crystals. Window glass can be made dim or clear depending on the intensity of the sunlight passing through. An exciting futuristic application of the liquid crystal would be flat plates or screens hung on walls which display television images.

The simplest or first generation display capability with a single electrical lead connected to a single picture element forms the seven-segment number displays as seen on clocks and watches. Second generation displays attaches four picture elements to one electrical lead and displays the seven segment numbers and also star-burst shapes which can form letters or numbers, useful for pocket calculators. ¹⁵

More complex wiring and liquid crystals with helical (spiral) axis positions can display 5-32 elements per electrical lead and are used for personal computers. The newest experimental versions are capable of producing TV picture displays on a flat substrate.

Liquid crystals are true liquids but also have some solid properties. Their internal order is very delicate and can be changed by a weak electrical field, magnetism, or even temperature variations. Noticeable optical effects are the result of re-arrangement of the molecules and the resulting changes in refraction (light-bending), reflection, absorption, scattering, or coloring of the visible light from their surface. Liquid crystals modify the ambient light rather than emit their own light and therefore require minimal amounts of power. A typical LCD (liquid crystal device) uses one microwatt per square centimeter of display area. ¹⁶

A very simplified diagram below shows the effect of an electric current on liquid crystal molecules. This change is visible due to its effect on light waves.

(figure available in print form)

Some liquid crystals are sensitive to temperature, and are used as a component in thermometers. They can be used in diagnostic tools to detect cancers, pulmonary disease, and vascular diseases. Their dramatic color variations are caused by an actual helical swing of 360 degrees by the molecules! The diagram below shows

this 360 degree re-orientation process. ¹⁷

(figure available in print form)

A uniform starting position for the crystals is vital to their usefulness. Liquid crystals can be aligned by “rubbing” of the substrate. Until recently this was poorly understood but used as a standard practice anyway. It is now known that the rubbing results in microgrooves which serve to orient the molecules. ¹⁸

Although liquid crystal technology has only recently been exploited by man for diagnostic tools, displays, new materials such as kevlar, and oil-recovery technology; nature has used these peculiar molecules in living systems right along. The structure of cell membranes and some tissues are liquid crystals. Hardening of the arteries is a result of the deposition of liquid crystals of cholesterol, cells involved in sickle cell anemia have liquid crystal structure, and on a brighter note, it may soon be possible to change the solid form of a gall stone into a liquid crystal form that can be flushed from the body. ¹⁹ For further information see the Brown or Kahn articles.

The technological development of crystals has taken off in this generation from semiconductors to transistors to integrated circuits to microchips. Always getting smaller but with vastly increased information handling abilities. They are the mainstay of the space and military industries, making possible the impossible in distant space travel, satellite technology, and weapons’ accuracy.

Solar cells are becoming more efficient and more common, and as our energy problems increase, student interest in solar technology has also increased. And the liquid crystals in our students’ watches and pocket calculators are just one more bit of technology waiting to be explained to our students.

There are many very helpful books and articles which can aid the reader in his or her understanding of these interesting, complex topics. Many of these have been listed in the bibliography, but I would like to specifically recommend the Holden book, *The Nature of Solids* , and the Chalmers article, “Photovoltaic Generation of Electricity,” as two excellent readings with which to begin. They will provide you with the information you will want to feel confident about teaching about crystal technology.

All of the books and articles that are specifically referred to in the text of this unit are available in book or reprint form at the Yale-New Haven Teachers Institute office on Wall Street, New Haven.

Appendix 1

Activity 1

Objective: *to observe the properties of two substances with different kinds of bonds.*

Materials:

three metal teaspoons

magnifying glass

matches

2 cm table salt

2 cm table sugar

folded paper towel hot pad

Procedure:

1. Rub a few grains of the salt and then the sugar between your fingers. Which one feels the sharpest or the roughest?
2. Examine with the magnifying glass a few grains of both salt and sugar. Describe the grain shape of each.
3. Put some of the salt in a spoon. Crush it with the other spoon. Do the same with some of the sugar. Which is the most difficult to crush?
4. Light a match or a candle. Hold the teaspoon of salt over the flame for ten seconds. Does it melt? Do the same with a teaspoon of sugar. Which substance appears to have the higher melting temperature?

Record all of your data in the chart below as you do each test.

Characteristics Table Salt Table Sugar

Roughness

Grain Shape

Hardness

Melting point

Questions:

1. Use your book to find out what kind of bonds salt and sugar have.
2. Which of these two substances appears to have the stronger bonds?

Activity 2

Objective: *to familiarize students with the shapes of crystals in their three dimensional forms.*

Materials:

pencil

crystal model outline sheets, 1 and 2

scissors

tape

drawing paper

Procedure:

1. Look at drawings of the six basic crystal shapes. Draw and label each one on drawing paper.
2. Using the outline sheet cut out each crystal pattern. Fold along the dotted lines and tape the edges. Identify each shape using your drawings done in part 1.

(figure available in print form)

(figure available in print form)

Activity 3

Objective: *to demonstrate in concrete fashion the relationship between atomic arrangement and crystal shape.*

Materials:

12 one inch size styrofoam balls

12 one-half inch size styrofoam balls

green crayons or paint

toothpicks

salt

magnifying glass

Procedure:

1. Color the large styrofoam balls green to represent chlorine atoms. The smaller size balls will represent sodium atoms.
2. Break a toothpick in half, push one end into the chlorine and the other end into the sodium. Do this to all the "atoms" you have. Now you have sodium chloride molecules.
3. Using the toothpick halves join one NaCl (sodium chloride) molecule to another, matching up sodium to chlorine each time, and at right angles to one another. They should be placed as tightly together as possible. Look at the diagram to get an idea of how it should look.
4. Sprinkle some of the salt grains on a dark surface and inspect them with the magnifying glass.

What shape are they? What is the chemical name for this compound?

(figure available in print form)

Questions:

1. What shape is the salt crystal?
2. What shape does the styrofoam ball model of the atoms have?
3. Is there a relationship between the answers to questions 1 and 2? Why?

Activity 4

Objective: *to understand the meaning of specific gravity by determining the specific gravities of several mineral samples experimentally.*

Materials:

thread or string

water

250 ml beaker

spring scale

mineral samples:

pyrite

quartzite

galena

others

Procedure:

1. Tie a twelve inch length of thread to the first sample, then tie the other end to the spring scale. Record the mass on the chart.
2. Fill the beaker about two-thirds full with the water. Submerge the sample in the water being

careful not to allow the mineral to touch the bottom or sides of the beaker. Record the mass on the chart.

3. Subtract the mass in water from the mass in air. This is the “loss of mass in water.” Record this on the chart.

4. The “loss of mass in water” amount is the same as the mass of water displaced. Enter this on the chart.

5. Use the formula below to calculate the specific gravity of your mineral.

$\text{Specific gravity} = \text{mass of the mineral in air} / \text{mass of the water displaced by the mineral}$

6. Repeat steps 1-5 for each of the samples available.

DATA CHART Pyrite Quartzite Galena Unknown Sample

mass in air

mass in water

loss of mass

in water

mass of water

displaced

specific gravity

Questions:

1. Pyrite is called fool’s gold. How can you tell it from real gold?
2. What is an alloy and how can you differentiate it from a pure sample?
3. Use the *Handbook of Physics and Chemistry* to find the material with the highest and lowest specific gravity.

Activity 5

Objective: *to determine density of solids using the direct measurement of the volume of the solid.*

Materials:

assortment of blocks:

pine

balsa wood

styrofoam

ceramic tile

steel plate

metric ruler

balance beam scale

Procedure:

1. Carefully measure the length, width, and thickness of the block using the metric ruler. Fill in the table below with your results.
2. Calculate the volume by multiplying the three numbers and enter the results in the designated space.
3. Use the balance beam scale to determine the mass of the block in grams. Enter the result in the designated space.
4. Calculate the density and record your answer.
Density = mass volume
5. Repeat the above procedure for all of the blocks and carefully record all of the measurements and results of calculations.

pine	balsa	styrofoam	tile	steel
bark wood			square plate	
length				
width				

thickness

volume

mass

density

Questions:

1. What is the definition of density?
2. Could you use this technique to determine the density of a toy soldier? Why?
3. Could you use this density formula to find the density of a steel ball? How?

Activity 6

Objective: *to determine the density of an irregularly-shaped solid using the displacement method.*

Materials:

balsa wood block

metal plate

small stone

metric ruler

thread

balance beam scale

graduated cylinder

250 ml. beaker of water

paper towels

Directions: *We have measured the density directly by using a ruler to find the volume of a regularly-shaped object. We can determine the density of an irregularly-shaped object using the displacement method. We will weigh the object on the scale to find mass; then we will use the graduated cylinder to find out how much water is displaced by the object when it is submerged. The amount of water displaced is the same as the volume of the object. Then we have only to put the numbers in our formula:*

Density = mass / volume

*Important Information:

one milliliter = one cubic centimeter

1 ml = 1 cm³

Procedure:

1. Weigh the three objects. Record the data on the chart below.
2. Fill the graduated cylinder to the 50 ml. line with water from your beaker.
3. Securely tie each object with a 30 cm. length of thread.
4. Submerge one of the objects in the graduated cylinder. Record the new water level on the chart below. Repeat for each object.
5. Subtract the first reading (50 ml.) from the second reading. This is the *volume displaced* , or the volume of the object.
6. Divide the mass by the volume to find the density. Remember 1 ml. = 1 cm.³

balsa wood metal plate stone
mass

second reading:

water and object

first reading

water only

volume displaced

density

Activity 7

Objective: *to develop skills in mineral identification using some characteristics of minerals.*

Materials:

mineral samples
penny

steel nail
hardened file
streak plate
compass
paper towels
lemon juice or dilute hydrochloric acid (Use acid *only* on samples kept at demonstration table — do *not* contaminate your samples at your desk.)

Procedure:

1. Read each mineral identification characteristic and use the suggested term or property to describe the mineral you are examining. Repeat for each mineral.
2. Characteristics:

Color: apparent external color: black, brown, gray-white, brownish-white, etc.

Luster: describes the shine or light-reflection from a mineral: metallic, pearly, greasy, glassy, silky.

Hardness: describes the resistance to scratching and is measured by the Mohs scale of hardness, #1 to #10, softest to hardest. To test hardness, scratch your sample with the following items in order. When a visible scratch is made (a dent in the rock), that is the hardness.

2.5 — fingernail

3 — penny

4-5 — steel file

6 — hardened file

over 7 — may scratch a streak plate but leaves no color

Streak: Describes the color of the powdered mineral. The streak can have a different color from the external apparent color. It is determined by rubbing the sample firmly over the plate, the color on the plate is the streak. A mineral of hardness 7 or over will have no streak, but may scratch the plate instead.

Magnetism: minerals that are magnetic will cause a compass needle to spin.

Crystal structure: Use your paper crystal models to determine the crystal shape of your sample.

Acid test: put one or two drops of a weak acid on your sample (be sure to use the samples on the demonstration table). If the mineral bubbles and fizzes it contains carbonate. The gas being released is carbon dioxide.

Heft: refers to the weight per volume or size. Terms that could be used would be "heavy," "medium," or "light." These are only relative and imprecise terms but useful for comparing with specific gravity.

(figure available in print form)

Appendix 2

Problems

The solubility of a solute in a solvent generally, but not always, increases as temperature increases. You can set up a graph to show solubility by plotting the temperature horizontally and the gram mass of the solute vertically. Use the data below to find the solubility curve for each substance.

sodium nitrate

temperature (degrees Celsius)	solubility (grams/100 cc. water)
25	90
50	102
75	125
100	170

sodium chloride

temperature (degrees Celsius)	solubility (grams/100cc. water)
25	40
50	40
75	40
100	40

sodium sulfate

temperature (degrees Celsius)	solubility (grams/100cc. water)
25	55
50	50
75	45
100	41

potassium chloride

temperature (degrees Celsius)	solubility (grams/100cc. water)
25	35
50	42
75	50
100	58

sodium sulfate

temperature (degrees Celsius)	solubility (grams/100cc. water)
.70	4.71
10.25	9.21
15.65	14.07
24.90	27.67
27.65	34.05
30.20	41.78
31.95	47.98
33.50	49.39
38.15	48.47
44.85	47.49
60.10	45.22
75.05	43.59
89.85	42.67
101.90	42.18

Problems:

1. What is the solubility of sodium nitrate at 60 degrees Celsius?
2. What is the solubility of potassium chloride at 90 degrees Celsius?
3. What is the solubility of sodium sulfate at 50 degrees Celsius?
4. What is the solubility of sodium nitrate at 30 degrees Celsius?

Appendix 3

Growing Crystals

In this section you will find condensed directions for making crystals *from a solution* , *from a melt* , and *from a vapor* . You will find it very helpful to obtain Elizabeth Wood's book, *Crystals—A Handbook for School Teachers* , or the Alan Holden book, *Crystals and Crystal Growing* for trouble shooting or for more extensive examples and explanations. These books can be borrowed from the New Haven Teachers Institute office.

To grow crystals from an *alum solution* dissolve 4 teaspoons of alum powder in a half cup of hot water. Stir

until all of the powder dissolves. Cover the beaker with paper or cloth to keep the dust out and slow evaporation. Crystals will begin to form on the bottom of the container. It is important to keep your solution free from drafts or temperature changes. If your room has a widely varying temperature range, set the beaker in a large bucket of water, being careful not to get extra water in the beaker. The water will help prevent any rapid temperature changes.

When some good size crystals have formed, pour off and save the solution and carefully pick out the best crystals with tweezers. Dry the crystals and the tweezers well. Now pour the solution back into the beaker with the remaining crystal masses and gently reheat and redissolve the solute.

The next step is a real test of your dexterity! You must fasten the crystal to a thread, either by means of a slip knot or with a minuscule spot of glue (Duco cement is good). Suspend your hanging crystal “seed” in the cooled solution and cover the top. It is important to be sure there are no extraneous crystal grains on the sides of your crystal seed, on the thread, or in the container. Growth of your seed will be impeded by them. Again place the beaker in the water bath to control temperature during the growing time. This process would result in a single, large, well-formed crystal. ²⁰

Other substances which can form nice crystals are borax, salt, sugar, copper sulfate, and Epsom salts. The amount of solute will vary, but you can determine the appropriate amount by trial and error or by checking one of the books given above.

To grow crystals *from a melt*, obtain some *salol* (phenyl salicylate, $\text{HOC}_6\text{H}_4\text{COOC}_6\text{H}_5$) from a drugstore. Put a small amount on a glass slide or sheet of aluminum pie plate, and heat it with a candle. Since it melts at 42 degrees Celsius, you will not need much flame. As it cools, put a tiny grain of salol powder on the melted salol; this will act as a seed for the crystal to grow around. ²¹

To grow crystals from a vapor, obtain some naphthalene (moth-flakes, C_{10}H_8). CAUTION — NAPHTHALENE IS VERY FLAMMABLE AND MUST NOT BE HEATED NEAR AN OPEN FLAME! Woods suggests placing a few flakes in a tall glass jar and placing a loose cover (aluminum foil) on top. Place the base of the jar on a lighted 100 watt bulb, and soon you will see the rising vapor sublimating (changing from vapor to solid) onto the top sides of the container. This experiment should be done in a very well ventilated room, preferably within a vented hood.

²²

Notes

1. C. Hurlbut, *Minerals and Man*, 15.
2. *Ibid.*, 15.
3. A. Holden and P. Morrison, *Crystals and Crystal Growing*, 38-40.
4. *Ibid.*, 225-230.
5. Hurlbut, 242.
6. *Ibid.*, 248.
7. J. Arem, *Man-made Crystals*, 45.
8. C. Hurlbut, 212-216.
9. P. O’Neil, *Gemstones*, 82.

10. *Ibid .*, 88.
11. B. Chalmers, "Photovoltaic Generation of Electricity," 36.
12. C. Swan, Suncell; *Energy, Economy, Photovoltaics* , 56.
13. B. Chalmers, 38.
14. A. Holden, *Nature of Solids* , 216-218.
15. F. Kahn, "Molecular Physics of Liquid-Crystal Devices," 66.
16. *Ibid .*, 66.
17. G. Brown and P. Crooker, "Liquid Crystals," 32.
18. F. Kahn, 70.
19. G. Brown and P. Crooker, 36-37.
20. E. Woods, *Crystals-A Handbook for School Teachers* , 26.
21. *Ibid .*, 40.
22. *Ibid .*, 48.

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