

CRYSTALS - A HANDBOOK FOR SCHOOL TEACHERS

Elizabeth A. Wood, 1972

Written for the Commission on Crystallographic Teaching of the
International Union of Crystallography

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I Preface to the 2002 Edition

The text of this edition is largely unchanged from that of the original 1972 edition; there has been a small amount of editing where materials are no longer considered safe for general use, *e.g.* the use of benzene as a solvent is no longer advocated due to its toxic and carcinogenic properties.

Readers outside the USA and Canada should be aware that the measurements (*e.g.* cup) used in the practical sections are based on American cooking measures, which are not quite the same as the equivalents used in British or other Commonwealth kitchens!

Users of “U.K.” or “British” English should be warned that spellings and usage in this document are “American” (*e.g.* “color” rather than “colour”, ‘Crystals Outside of Home’ rather than “Crystals Outside the Home”).

The original guide is available as an HTML document on the IUCr’s website (<http://www.iucr.org/iucr-top/comm/cteach/pamphlets/20/index.html>); there are translations (by native speakers) into several languages (currently (*i.e.* Autumn 2002) Arabic, Czech, Polish, Russian and Spanish).

Harry Powell
Cambridge, UK
November 2002

II Introduction

To the Teachers of Young Children Everywhere:

This booklet was produced for the Commission on Teaching of the International Union of Crystallography, which is an organization for the benefit of the science of crystallography throughout the World. It is not a trade union, but a group of people of all nations interested in crystals. Many teachers have found that children are interested in crystals. There are good reasons for the teacher to encourage this interest. Children can perform simple experiments with crystals and so get the feel of doing science themselves, the experience of watching something happen in their own experiments. Crystals are of interest to chemists, physicists, geologists, biologists and mathematicians. To study crystals is to be part of all these fields and to become aware that Nature is not separated into chemistry, physics, geology, and biology. Most teachers at the present time (the 1970s) did not learn about crystals when they were in school and college. The purpose of this booklet is to give them some background of understanding of crystals so that they can enjoy working with children who are interested in crystals. It is not a systematic course in crystallography. This would not be suitable. Those students who want to know that much about crystallography will take courses in crystallography at the university. It is a handbook for your enjoyment.

In this booklet, technical terms are avoided as much as possible, not to make it easier, but to avoid the pitfall of substituting **learning names** for **thinking** about what is going on. Children think they know why an apple falls because they have learned the word 'gravity', but our most competent scientists are puzzled by the way in which an apple and the Earth are drawn toward each other.

Most books on crystallography, the subject that deals with the study of crystals, emphasize the importance of symmetry in the classification of crystals. However, many of the crystals that children can grow themselves, or find in nature, have shapes that do not exhibit perfect symmetry, because the growing conditions were not the same all around the crystal. It takes a mature imagination and experience with some perfectly symmetrical crystals to imagine what such a crystal would have looked like if the growing conditions had been uniform.

Unless students can be convinced from their own observations that symmetry is really useful in classifying crystals, there is no merit in having them memorize the symmetry terms, since they have no meaning for them. The essence of science is observation and wonder, curiosity and the effort to satisfy that curiosity. Learning what others have found out is part of learning about science, but first we must see how scientists learn what they know about nature so that we may be convinced that their results are based on

repeatable experiments.

For these reasons this booklet does not deal with systematic crystallography, the classification of crystals according to their symmetry. It seeks to lay a firm foundation for later study of crystallography by encouraging observation and experimentation. Over a period of time, the students' observations will probably lead them to conclusions such as the following:

1. Under suitable conditions some kinds of solid matter form in shapes called **crystals**.

2. Crystals grow bigger by adding more layers of solid matter around their outsides.

3. Crystals form from solution when the solvent evaporates. Crystals form from the molten state when the liquid cools. Crystals form from warm invisible vapor when that vapor meets a cooler surface.

4. Crystals of different substances have different forms.

5. Crystals of different substances have different properties; that is, some are colored and some are not; some grow nicely and some do not; some have cleavage (to be discussed later) and some do not; some look bright between crossed polarizers (see section III-D) and some do not.

6. (for older students) There must be something orderly about the way a crystal forms that is responsible for its flat faces, its characteristic shape, and the way it affects light. This orderliness must be different for different substances.

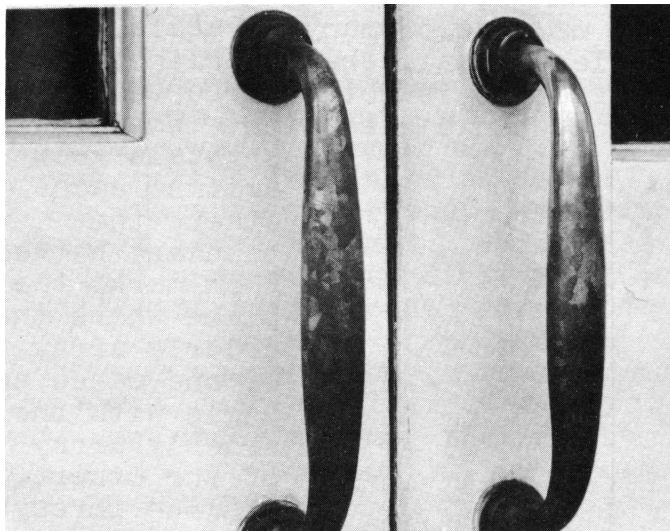
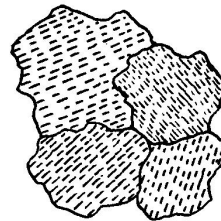
If your students have some conviction about such conclusions from their own observations, they will have a good foundation in the science of crystallography.

* * *

A crystal of a given substance or material shows plane faces always at the same angles to each other and has its other orderly properties because it is made up of atoms, ions, or molecules arranged in a very orderly way. This orderliness of structure is found in almost all solid matter, though some substances have a more orderly arrangement than others. Even in wood the molecules are arranged in good order along the fibers, though there is not much orderliness from one fiber to the next. Is wood, then, a crystal? It doesn't show shiny faces. Some crystallographers (people who study crystals) would say its fibers are crystals; some would not.

A substance that is made up of crystals is called a crystalline substance. Sometimes the word **polycrystalline** is used to indicate a substance made up of many crystals. In a single crystal, the orderliness of rows of atoms is not interrupted and does not change direction. When two crystals grow against each other, the boundary between them marks the place where the orderly array of one makes an angle with the orderly array of the other. A slice through four crystals with such boundaries is crudely suggested by this sketch. The solid lines represent boundaries between crystals (sometimes called grain boundaries). The dotted lines represent layers of atoms, ions, or molecules.

Many substances that we are familiar with are made of very orderly crystals that do not show their bright faces because neighboring crystals have grown against each other with irregular boundaries. Nearly all rocks are made up of crystals and the different kinds of crystals in a rock can often be distinguished from each other. Metal objects are made up of interlocking crystals. Sometimes their boundaries can be seen, as in the zinc coating on galvanized iron often used for pails (buckets) and garbage cans. Sometimes a brass door handle shows the boundaries between the crystals of which it is composed. A substance in which the atoms or ions or molecules are not arranged in



orderly rows is called a glass. Window glass is a familiar example. Volcanic glass, and some volcanic ash, is also glassy - not crystalline. There is a glassy kind of candy that is very brittle, usually made with nuts in it. It is made by cooling the melted sugar very quickly so that crystals do not have time

to grow before the fluid gets too stiff to allow the molecules to move about and take their proper positions to make a crystal. This suggests that other glasses may be formed by quick cooling. This is so of volcanic glass and of some manufactured glass too, although glass manufacturers have learned to produce mixtures that can be cooled at a convenient rate without crystallizing. In some very old glass, made before the art was well developed, crystals have begun to form as, over the years, the atoms have slowly migrated into orderly positions, drawn by their attraction for each other. There are no very old volcanic glasses, geologically speaking. In hundreds of thousands of years, the atoms have had time to get together to form crystals.

Young people learn best by doing, not by being told. The best way for a child to learn about crystals is by experience, not by having someone tell him about them. Let him observe and wonder and ask questions. Then perhaps you can help him seek answers to them. We will not even try to define the word **crystal** until we have had some experience with crystals. It is essential that you, the teacher, have these experiences yourself so that you can enjoy the discoveries with your students.

The rest of this handbook will be written as though for the students. If it teaches something that you already know, remember that it was written for all schools, everywhere in the World.

III Equipment and Materials

A. Essential Materials	Equipment
Salt (table salt, sodium chloride, NaCl)	Cup, glass or other container
Sugar (sucrose or saccharose, $C_{12}H_{22}O_{11}$)	Measuring cup (8 ounce; about 235 cm ³)
Water	Teaspoon Thread or thin string
B. Desirable Materials	Equipment
Borax ($Na_2B_4O_7 \cdot 7H_2O$)	Magnifying glass
Alum (ammonium alum $NH_4Al(SO_4)_2 \cdot 12H_2O$ or potassium alum, $KAl(SO_4)_2 \cdot 12H_2O$)	Tweezers or forceps Microscope slides (glass). The bottom of an overturned drinking glass can be used.
Copper sulfate (blue vitriol, $CuSO_4 \cdot 5H_2O$)	Candle or match flame
Epsom salt ($MgSO_4 \cdot 7H_2O$)	Source of heat to boil water Refrigerator or temperature below 0°C
Salol (phenyl salicylate, $HOC_6H_4COOC_6H_5$)	Two pieces of polarizing film, such as Polaroid
Bismuth (Bi)	
Naphthalene (moth flakes, $C_{10}H_8$)	

IV Crystals in Classroom and Home

A Growing Crystals from Solution

1 Salt (table salt, sodium chloride, NaCl)

We will begin with salt because everybody has it. While the salt experiment is going on, you can be getting together the materials for the later experiments.

a. Growing the crystals and observing their growth

Put 3 teaspoonfuls of salt into 1/3 cup of water.¹ Stir well. Most of the salt will dissolve, forming a solution of salt in water, but some will remain in the bottom of the container and the solution may appear cloudy. (Some producers of salt coat the salt grains with a harmless insoluble substance so that they will not stick together in damp weather. The following procedure is used to separate this and the undissolved salt, if any, from the salt solution.) Let the mixture stand over night. Next morning, the solution will appear clear. Pour the clear solution into a shallow glass or cup, being careful not to stir up any of the material from the bottom. (This process of separating a liquid from a solid, simply by pouring the liquid off, is called decanting.)

Discard the solid material. Let the clear solution stand, uncovered, for a few days. To keep the dust out, it may be well to place an overturned box over it.

A given amount of any **solvent**, such as water, can hold in solution just a certain amount of a particular substance. When it has this amount in solution, it is said to be a **saturated solution** of that substance. If it has less than that amount, it is **undersaturated**. In some cases, substances seem to need a nucleus - a tiny bit of crystal of their own kind - to cause the beginning of crystallization of the solid from the solution. In such cases, as a saturated solution stands, and the solvent evaporates, it may become **super-saturated**, containing in solution more than it would if it were in contact with crystalline material of the substance that it has in solution. In such cases, addition of the tiniest fragment of the **solute** (the dissolved substance) will cause **precipitation** of the excess solute in the bottom of the vessel.

When the first solid particles appear in the bottom of your salt solution, examine them with a magnifier. Try to pay attention to one particular particle and watch it change from day to day. If the vessel containing the solution is glass, you can place it over a piece of paper on which a marked circle helps you locate the particle you are watching. (A white crust may

¹ In a chemical laboratory, amounts would be given in grams. Here we use the measuring cup and the measuring teaspoon familiar to all cooks. An American cup holds 8 fluid ounces or approximately 236 milliliters; a British cup holds 10 fluid ounces or 284 milliliters. Both American and British teaspoons are closely equivalent to 5 milliliters.

form at the edge of the solution, where evaporation is rapid. We will discuss that later.) You may find that a strong light from the side helps your observations.

The particles gradually forming from solution are salt crystals. If you will watch the very early stages of their formation you will find that they look square. If you look at them from the side, you will see that they also look square, or perhaps rectangular. Their sides are very precisely at right angles to each other and stay that way as they grow.

Think about this! Out of that formless solution come these perfectly formed solid shapes, whether you are evaporating the solution in Spain or in Siberia, in Africa, America, or Australia, in a submarine or in an airplane. Dependably, the solid that comes out of salt solution forms little crystals with bright, shiny faces at right angles to each other. How do you suppose it does this?

Take one of the little crystals out of the container, with tweezers if you have them, and dry it off. You can put it in a box and keep it. It will not change, unless the weather is **very** damp. With extreme dampness, water from the air may gather on the crystal and dissolve it. Those left in the container continue to grow larger because, as the water evaporates, the salt that you dissolved in it has to come out of solution and it is added to the tiny salt crystals, making them bigger. As layer after layer is added, like layers of paint on a box, each flat face just progresses outward, staying precisely at right angles to its neighbors.

What happens when two crystals that are growing next to each other meet? Watch carefully and see. In most cases they grow together, irregularly, while their beautifully flat faces continue to grow outward on the free sides where they are not in contact with each other. When they have grown together for a while, pick them up with the tweezers. Can you tell where one crystal ends and the other begins? In some cases this is easy, in other cases not. Can you pull them apart?

As your solution evaporates further, many crystals will grow together in the bottom of the container. The white crust at the side is formed of just such crystals grown together but they are very very small. Where the evaporation was very rapid, many crystals started to grow at the same time and quickly met neighboring crystals so that none could grow large.

In the very small spaces between some of these crystals and between this crust of crystals and your container capillary action causes the solution to be drawn up the side of the container where it then evaporates rapidly and more white crust is formed.

How could you grow a bigger crystal that still had its perfect shape because it had not come in contact with a neighboring crystal? Try to answer this before reading further.

Here are two methods to try:

1. Since rapid evaporation caused many crystals to start growing at

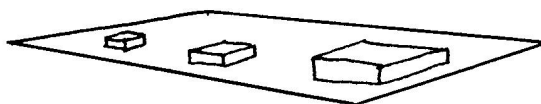
the same time, close to each other, perhaps we could cause fewer crystals to grow, farther apart, by preventing rapid evaporation. We could put a cover on the container - not a tight cover, that would stop the evaporation completely, but more of a cover than the overturned box. A piece of paper or cloth could be fastened over the top of the container with a rubber band to let evaporation proceed slowly.

2. We could take one good little crystal out, transfer the saturated solution to another container, and put that crystal back in again. Maybe it would be the only one to grow. A crystal used in this way is called a seed crystal. (Remember that any solution, clinging to the crystal you take out or to the tweezers or your fingers, is saturated. As it evaporates little crystals will grow rapidly in it and form additional seeds that will compete for material with the one that you want to grow. For this reason you should dry your crystal quickly on cleansing tissue or a clean handkerchief, and wash and dry the tweezers and your fingers.)

When a crystal grows, resting on a surface, the part next to the surface is deprived of additional material and cannot develop. To let a crystal develop on all sides, we must hang it from a thread in the solution. Tying a thread around a very small crystal is not easy. An alternative method is to cement the thread to the crystal with a tiny bit of the kind of cement that is used for mending plates. Let it dry over night before hanging the crystal in the saturated solution.

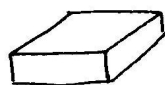
b. What to do with the crystals

1. An instructive exhibit could be made by taking out a series of crystals (with tweezers) at various stages of growth, and mounting them with a very small bit of glue or cement on a card or paper (perhaps black or dark colored). The sequence, from small to large, will show how the crystals keep the same shape as they grow larger.

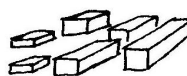


Try to avoid choosing a piece made up of more than one crystal, since this makes observation of the shape and comparison of the sizes more difficult.

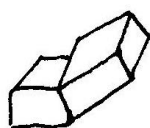
2. Break them. Tap a crystal lightly with a small hammer or the heavy handle of a knife or screwdriver or the bowl of a spoon. It will break along plane surfaces parallel to the plane faces that form the outside surface. These



This may break
into... these



may be broken into still smaller pieces, again with plane surfaces (that shine brightly in a strong light) parallel to the original ones. They may be broken anywhere at all. The surfaces will still be parallel to each other.



Two crystals

This tendency of a crystal to come apart along plane surfaces of a particular orientation is known as **cleavage**. Not all crystals show cleavage. Some just break like a piece of glass.

In salt, the cleavage planes are parallel to the growth faces, the faces that form the outer surfaces as the crystal grows. In crystals of some other substances, the cleavage planes are not parallel to the growth faces.

What is it that makes sodium chloride crystals grow in rectangular shapes and come apart along planes at right angles to each other? Crystallographers wondered and speculated about such questions for many years. Only in the twentieth century has the use of x-ray diffraction enabled us to find out how the arrangement of atoms and ions and molecules in crystals accounts for the way they grow and can be cleaved and for many other properties. The x rays do not cast shadows of the atoms as they do of the bones of the body. The atoms are too small for that. The x rays are scattered by the atoms, and by studying the directions in which they are scattered crystallographers learn how the crystals are put together.

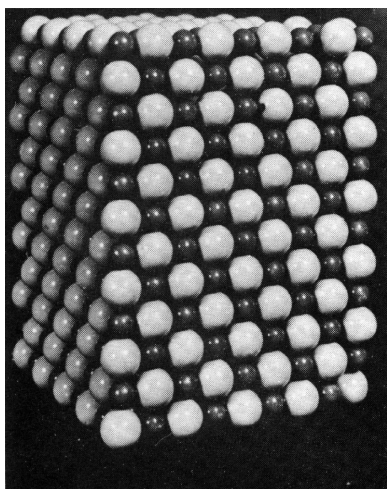
In sodium chloride, common table salt, they find that the sodium and chlorine ions alternate with each other, like this.

It would take 10^{17} blocks like this to make one cubic grain of salt 1 mm on each edge. That is 100,000,000,000,000,000. That's a hundred million times a thousand million. You would expect such an arrangement to build rectangular crystals. You might also expect that it would come apart most easily along those layers of sodium and chlorine ions.

Each crystal has its own characteristic arrangement of atoms, ions, or molecules which accounts for the shape in which it grows and for its other properties.

3. Keep a few of the best crystals in a small box or jar or envelope, for use in later experiments. (See experiments with polarized light, Section III-D.)

4. Place a crystal on a glass slide or other clean surface and place a large drop of water on it, watching it with a magnifier as it dissolves in the water.



The corners get rounded quickly because they have three faces exposed to the solvent. The edges get rounded somewhat less quickly because they have only two faces exposed to the solvent. If the crystal is rescued before it has dissolved completely, is dried with cleansing tissue or a clean handkerchief, and then placed again in the saturated salt solution, it will start to grow again, filling out the edges and corners and regaining its original shape!

5. You can use any of your crystals as seed crystals, to grow bigger crystals from a saturated solution of the same substance, but the smaller ones are better.

6. Use your crystals as source material to start over again from the beginning. They are now pure salt, without any insoluble coating.

c. Lessons from this section

An important lesson to be learned from this section is that a salt crystal grows by adding salt to itself from the water solution of salt that surrounds it and that it grows with flat shiny faces which are at right angles to each other, provided its growth is not obstructed. The fact that these crystals have cleavage indicates that, **within the crystal**, one direction is not like every other. The kind and arrangement of atoms, ions, or molecules in a crystal determine its shape and other properties.

Decanting has been used as a method of separating liquid from solid. Seeding has been used as a method of growing larger single crystals.

The fact that crystals growing from closely spaced nuclei cannot grow very large was observed in the growth of the white crust at the edge of the solution, a crust which spread as the solution crept up through it and under it by capillary action.

The manner in which solution of a cube-shaped solid progresses was observed.

2 Borax ($Na_2B_4O_7 \cdot 10H_2O$) in water

Although the third substance, sugar, is more readily available than borax, borax is placed second because it forms beautiful crystals so quickly. Borax is used as a cleaning agent, in washing clothes, and is sold in paper boxes, just as powdered soap is. It is harmful, if swallowed.

Borax is much more soluble in hot water than in cold water. This is not true of everything. Salt, for instance, is about as soluble in cold water as it is in hot water.

a. Growing the crystals and observing their growth

Add one teaspoonful of borax to 1/2 cup of very hot water, stirring the mixture until the borax has dissolved completely. After this has cooled, many beautiful little crystals will grow.

b. What to do with the crystals

The activities suggested for using the sodium chloride (salt) crystals are also suitable for the borax. Similar growth-stage exhibits could be made. It could be tested for cleavage. One crystal could be taken from the solution, dried, tied with a thread, and used for a seed to be suspended in a saturated solution. A solution with which growing crystals are in contact is certainly saturated. Otherwise they would dissolve. Therefore if such a solution is poured into another container, at the same temperature, (taken away from the several little crystals growing in it) it will deposit borax on a borax seed hung in it.

It is best to have the seed near the bottom of the container. The reason for this is as follows. The density of a saturated solution of almost anything is greater than that of an unsaturated solution. As borax is deposited on the crystal, the solution from which it is deposited becomes less dense and rises. The denser, saturated solution (weighing more, per unit volume) flows in to take its place and bring more material to the seed crystal. If the seed is close to the top of the solution, the less dense, unsaturated solution surrounds its upper end. Of course, right at the surface, where the solution is in contact with the air, evaporation results in crystallization. Seeds often form there, but can only develop on one side and are always, therefore, distorted in form.

Compare the shape of the borax crystals with that of the salt crystals.

Look at very small salt crystals and very small borax crystals between crossed polarizers (see section III-D), using a magnifier. The effect may be less obvious with large crystals having bright faces or inclusions which reflect the light.

Water molecules are among the invisible particles of which borax crystals are made. If borax crystals are kept in a warm dry place for a long time, some of the water will escape into the air. That part of the crystal that

has lost water falls apart into a powder. The little particles of the powder scatter the light and therefore look white. This process of losing water is called **dehydration**.

c. Lessons from this section

Some crystals, such as borax, grow faces that do not meet at right angles. Borax and salt have different shapes. Borax and salt have different effects on light, as indicated by their appearance between crossed polarizers. The two substances could be distinguished from each other by the **properties** which have been observed. They differ in solubility, crystal form, cleavage, and effect on light. It is clear, therefore, that when borax comes out of solution, it builds borax crystals in a different way from that in which the salt builds salt crystals when it comes out of solution.

3 Sugar (sucrose or saccharose, $C_{12}H_{22}O_{11}$) in water

a. Growing the crystals and observing their growth

Good sugar crystals are difficult to grow. Sugar in water forms a very viscous (thick, syrupy) liquid and the sugar molecules cannot move rapidly through it to join the other sugar molecules in the orderly arrangement that we call a crystal.

The secret of success is to keep the solution warm enough to promote the mobility of the molecules, but, at the same time, not to cause rapid evaporation at the surface that would cause the formation of a surface crust. To achieve these two results, proceed as follows.

Heat one cup of sugar and one-half cup of water gently, with constant stirring, until all the sugar dissolves and the solution is clear. Put this in a jar of the sort used for jams and jellies and put a cover on the jar, but do not screw it down tightly. The jar must be kept very warm for many days. It could be placed over the pilot light of a gas stove. Water evaporating from the surface condenses on the lid and drops back onto the surface, preventing the formation of a crust. A little water escapes, all the time, because the lid is not tight. Eventually crystals will grow with the beautiful form characteristic of table-sugar crystals. The growth continues slowly for a very long time.

The sugar solution has the interesting property that it rotates the plane of polarized light (see section III-D). This rotation is different for different colors of light. When you hold the jar of sugar solution between crossed polarizers and look through it and the polarizers toward a white light, you will find that it does not look black, as the salt solution does, but colored. As you rotate either of the polarizers (in its own plane, as the hands of the clock rotate), keeping the other still, the color changes.

b. What to do with the crystals

All of the suggestions made under the headings of salt and borax are also applicable here. In addition, you can now compare the shape of a sugar crystal with that of a borax crystal and a salt crystal.

c. Lessons from this section

Sugar crystals differ in shape and ease of growth from salt, the other familiar substance on our dinner table. They also differ in shape and ease of growth from borax. When sugar comes out of solution, it must build the sugar crystal in a different way from that in which the salt crystals are built or that in which the borax crystals are built. Each substance has its own way of arranging the particles of the substance to form a crystal.

The particles that form a crystal must be free to move if they are to get together to form a crystal. The sugar solution is so viscous (thick, syrupy) that it slows down this motion and therefore sugar crystals are harder to grow than salt or borax crystals.

A water solution of sugar, unlike a water solution of salt or borax, rotates the plane of polarized light (see section III-D).

4 Alum [ammonium alum, $NH_4Al(SO_4)_2 \cdot 12H_2O$ or potassium alum, $KAl(SO_4)_2 \cdot 12H_2O$] in water

Alum crystals are easier to grow than salt crystals and much easier than sugar crystals. They have brightly reflecting faces and the smaller crystals sparkle attractively. Powdered alum is available in most drug stores (chemists', pharmacists'). It is used as an astringent and to reduce bleeding from small cuts.

a. Growing the crystals and observing their growth

Put 4 teaspoonfuls of alum powder in half a cup of hot water. Stir to aid solution. After some time, all of the powder will go into solution, which will then be clear.

Put a light cover, such as a piece of paper, over the container, to keep the dust out. As the water evaporates, beautiful alum crystals will appear.

Observe the crystals carefully and compare their shapes with those of other crystals. Are these clearer or less clear than the salt crystals? Note that alum, like borax, contains water (H_2O) as part of the composition of the crystal. It may be of interest to compare the appearance and ease of growth from water solution of those crystals that do contain water molecules in their composition and those that do not.

b. What to do with the crystals

1. Arrange a growth sequence exhibit, as in the salt case.
2. Break them. You will discover that, unlike salt, but like sugar, alum has no cleavage planes.

3. Keep some in a box or envelope, appropriately labeled, for use in later experiments.
4. Partially dissolve and regrow an alum crystal, as in b,4 of the salt experiment.
5. Hang a perfect little alum seed crystal in a saturated alum solution and grow a beauty.
6. Look at an alum crystal between crossed polarizers (section III-D2).

c. Lessons from this section

Alum crystals are unlike either salt crystals or sugar crystals in several ways. They grow large more quickly. They have a shape that differs from both salt and sugar. Like sugar crystals, but not like salt crystals, they do not show cleavage, but break irregularly. Like salt crystals, but not like sugar or borax crystals, they look dark between crossed polarizers.

5 Copper sulfate (blue vitriol, $CuSO_4 \cdot 5H_2O$) in water

POISONOUS

You may be able to get copper sulfate from a drug store (chemists', pharmacists'). It is used in some swimming pools to prevent plant growth, but is somewhat poisonous. Students should not be allowed to take any of it home. Wash your hands thoroughly after handling copper sulfate powder, solution, or crystals. (The powder is also made of very small crystals, but is mostly of the anhydrous copper sulfate, copper sulfate without water as part of its composition.)

a. Growing the crystals and observing their growth

Put 4 teaspoonfuls of copper sulfate powder into half a cup of hot water and stir until the solid has dissolved. As the solution evaporates, a crust of copper sulfate will creep up the side of the container and over the edge. Copper sulfate is even worse in this respect than the salt solution, so it would be a good idea to have the container standing on a dish or saucer.

When the solution has evaporated enough, bright blue crystals will start to grow. Study their shapes and watch them develop, day by day.

A very beautiful experiment can be performed by mixing alum powder and copper sulfate powder and dissolving the mixture (2 teaspoonfuls of each in half a cup of water, for example). The result is that the alum crystals grow as they did before, colorless, with their characteristic shape; and the copper sulfate crystals grow as they did before, bright blue, with their characteristic shape. They may meet and stick to each other; one may grow around another; but they don't **mix**. The orderly array in alum is not the same as the orderly array in copper sulfate and each substance builds its own kind of crystal.

b. What to do with the crystals

REMEMBER THAT COPPER SULFATE IS POISONOUS. It should not be given to young children. Older children should be repeatedly warned to wash their hands after handling it.

1. Crystals of various sizes may be mounted for display as previously grown crystals were.

2. Examine their shapes and compare them with the shapes of the alum, sugar, borax, and salt crystals.

3. Try to draw the edge-out-lines of each crystal grown so far. Drawing aids observation.

4. Try to cleave them. (Copper sulfate does not show cleavage.)

5. If kept for a very long time in a warm dry place, copper sulfate, like alum and borax, may become dehydrated.

6. The crust that forms on the side of the vessel consists mostly of the anhydrous form of copper sulfate. It can be collected and dissolved, just as the original powder was.

c. Lessons from this section

Again the comparison of the new crystals with the other crystals grown shows that each substance has its own form and properties, and this time a new property has been added - color.

If the mixture of alum and copper sulfate is tried, the added observation has been made that each substance adds on to its own crystals those particles that belong to the crystal that is being built and does not accept other particles that may be present that do not belong in the structure of that crystal.

6 Epsom Salt ($MgSO_4 \cdot 7H_2O$) in water

Epsom Salt is sold as a laxative and also for making a wet dressing to use on bruises, sprains, and insect bites. It is sold by nearly all drug stores (chemists', pharmacists').

a. Growing the crystals and observing them

Epsom salt is very soluble in water. You can dissolve about 6 teaspoonfuls in a quarter of a cup of hot water. Stir the solution for several minutes. If the salt does not all dissolve, add a very small amount of water and stir until the solution is clear.

The crystals grow as long needles, quite different in shape from those of table salt, borax, sugar, alum, or copper sulfate. Because the substance is so soluble, a drop of it contains enough to make a fine group of little crystals when it evaporates. If placed on a non-absorbing surface, such as glass, the surface of the drop becomes coated with crystals and further evaporation is hindered. It is better to place the drop on an absorbing surface such as

cardboard or rough paper. Observing the resulting little group of crystals with a magnifier is particularly rewarding.

b. What to do with the crystals

The needle shape of the little Epsom Salt crystals makes them easy to tie with thread. A little needle of Epsom Salt, hung in a saturated Epsom Salt solution will grow into a fine rod-shaped crystal.

Epsom Salt dehydrates faster than any of the other water-containing salts you have grown. The crystals will keep their shape, but the surface will look as though it had been painted with dull white paint. You can scrape the dehydrated surface material off and find the clear crystal that has not yet lost its water molecules underneath. You can convince yourself that the dull white substance lacks only the water to become the same as your originally grown crystals by dissolving some of it in a little water and letting the water evaporate.

Of all the hydrated crystals you have grown, alum holds its water most tightly. However, any of them can be made to give up its water in the heat from a match. Place a small crystal of each on a glass microscope slide or a bit of metal such as aluminum foil. Hold a lighted match beneath them. Each one will soon give off its water which will boil vigorously in the heat from the match. If you stop heating while there is still a lot of water present, many little crystals of the original substance will reform. However, if you continue heating until all the boiling stops (that is, until all the water has been driven off) the white, dehydrated substance will form.

c. Lessons from this section

Epsom Salt is very soluble in water.

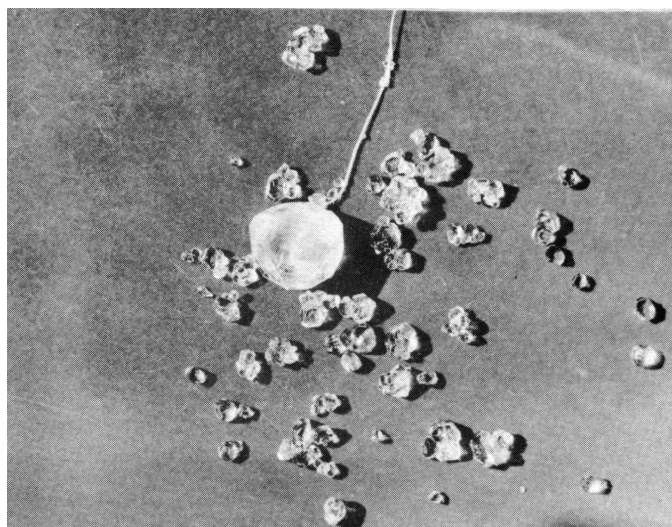
Like borax and alum and copper sulfate, Epsom Salt is made up partly of water and can become dehydrated.

When a substance is very soluble in water, a drop of the saturated solution contains a lot of the substance.

Now that you have grown several different kinds of crystals, you may wish to arrange an exhibit of them. Here is a photograph of some crystals of alum grown exactly as described in this handbook.

7 What else?

There may be other things that you could dissolve in water. Will they all form crystals when the water evaporates? No but you will not be sure about many of them until you try. 'Hypo', the substance that photographers use to 'fix' a film after it has been developed, will form good crystals from solution. So will Rochelle Salt. A recipe for growing large crystals of Rochelle Salt and some suggestions of interesting experiments to perform with them are



given in *Crystals and Crystal Growing* by Holden and Singer (see list of suggested reading at the end of this handbook).

B Crystals from the Melt (the molten condition of the same substance as the crystals)

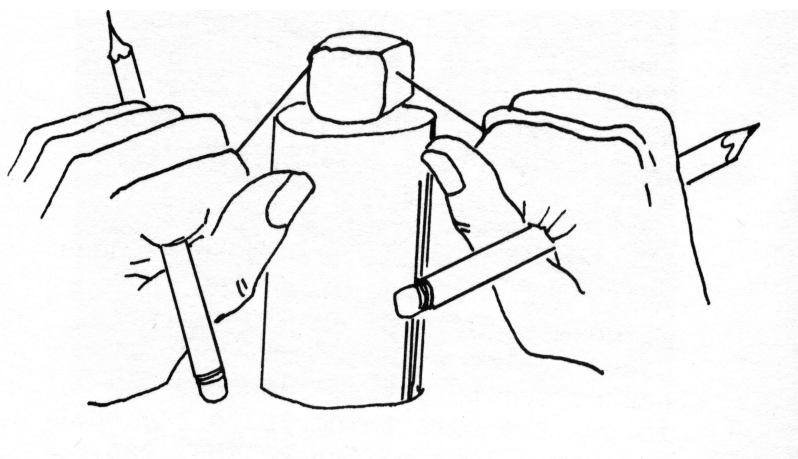
1 Ice (solid water, H_2O)

Ice is one of the few substances which changes its name when you melt it. Water is such a common substance that it is useful to have different names for the different ways in which it occurs: ice, snow, frost, dew, rain, steam, mist, cloud.

Ice is one of the few substances which shrinks when it melts. A given mass of ice takes up more space as ice than it does when it has melted to water. Another way to say the same thing is to say that a given volume of ice weighs less than the same volume of water. This is so because ice is less dense than water. Therefore it floats on water. If water freezes in a container that does not let it expand freely, the container may break.

Since water takes up less space than ice, you can make ice turn into water by exerting pressure on it. This is one of the reasons why ice is so slippery when you stand on it and skate on it. The pressure produces a thin film of water between you and the ice, which acts as a lubricant.

You can demonstrate the changing of ice into water by the application of pressure and its change back to ice by release of pressure with the following experiment. Place an ice cube on an overturned drinking glass. Tie both ends of a short piece of wire to pencils. Lay the wire across the top of the ice and pull down on the two ends of the wire, as shown in this diagram.



The wire will move downward through the ice. The ice melts below the wire, where it is under pressure, and refreezes above the wire, where the pressure is released.

a. Growing the crystals

One way to grow ice crystals is to place a pan of water in the freezing compartment of a household refrigerator, or out of doors if the temperature is well below 0°C . In about two hours (if the temperature is -10°C) some of the water will have turned to ice. Some of the crystals will have a long thin shape and they may be frozen together with other crystals. Lift them out of the pan and examine them. A good way to find the boundary between neighboring crystals is to view them between crossed polarizers (see section b, below).

Another way to grow ice crystals is to put a drop of water on a microscope slide or on the bottom of an overturned tumbler or any flat surface and place it in the freezer.

b. What to do with the crystals

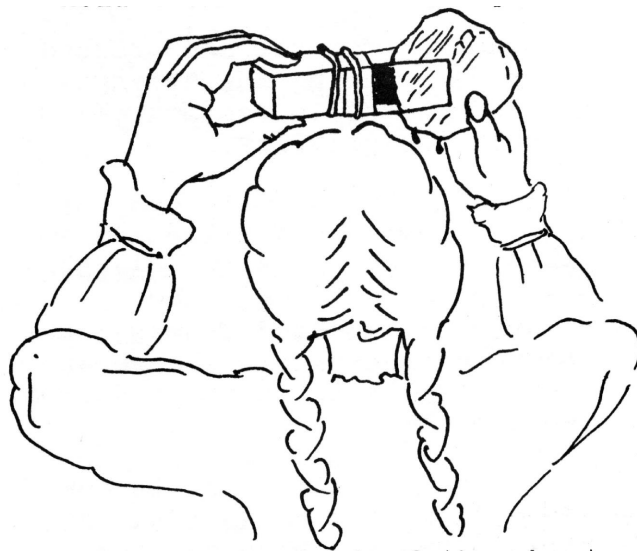
Examine them between crossed polarizers, using the arrangement suggested in section III-D to hold the polarizers.

If you have a small drop of water, frozen on a piece of glass, you can hold the glass horizontally, between the polarizers, lighted from below, and watch the colors change as the crystal gets thinner, during melting.

Rotate the slide in its own plane, like the hands of a watch, between the polarizers. Note that the crystals are dark in some positions, bright in others. A part that behaves the same throughout belongs to one crystal. Between it and another part that behaves differently is the crystal boundary. There may be a part that stays dark in all positions of rotation. This part

has its optic axis lined up in the direction in which you are looking. (See Reference number 3, Section V.) If you tilt the glass out of the plane of 'the face of the watch' this part will become light.

If you have a sheet of ice from the pan of water that is as thick as two or three millimeters, you have a chance to see something special between crossed polarizers. In order not to get the polarizers wet, hold them in a vertical plane.



Find a large part of the sheet of ice that stays dark when rotated in its own plane between crossed polarizers. Hold it close to the near polarizer and bring your eye up as close to the polarizer as possible. You will see a black cross on a gray background and if the ice is thick enough there will be a yellow ring around the cross and a red ring outside of that. This is known to optical crystallographers as an **interference figure**. (See Reference number 3, Section V.)

c. Lessons from this section

Crystals of ice can be grown from molten ice (that is, water).

The boundaries of crystals in a sheet of ice can be detected between crossed polarizers.

Since water is more dense than ice, ice can be made to turn into water by the application of pressure. If the temperature is below 0°C , it will turn back into ice when the pressure is released. (Note that ice, like any solid, can be colder than its melting temperature. Many people seem to have the strange idea that ice is always at 0°C . When ice is freezing from water and there is still water present, its temperature is 0°C .)

2 Salol (phenyl salicylate, $\text{HOC}_6\text{H}_4\text{COOC}_6\text{H}_5$)

Salol is sold by drug stores (pharmacists', chemists') as medicine for intestinal disorders. It is not soluble in pure water, but it is soluble in ethyl alcohol. It melts at 42°C .

a. Growing the crystals and observing their growth

Put a little salol powder on some surface that can be heated from below with the flame of a match. A microscope slide, or other piece of glass, is the most satisfactory surface, but even a piece of aluminum foil will serve the purpose. The amount of the powder should be small, about the size of a pea. Heat it with a match flame from below, holding the match far enough away so that its flame does not blacken the glass with unburned carbon. Stop heating as soon as the salol melts.

You might expect the salol to become solid again as soon as the melt cooled to 42°C . This does not happen unless a seed crystal of solid salol is present. Since the salol powder is made up of tiny crystal fragments, a small grain of the powder will serve as a seed to start the crystallization when the liquid is cool enough.

If too much powder is added to the liquid, too many crystals will start to grow and will very soon interfere with each other's growth. Then you will not be able to see any of the beautifully straight boundaries that can be developed when a salol crystal grows, unhindered. The shape that salol crystals develop is like the diamond on playing cards. If you observe the growth with a magnifier, you can see these plates appear and grow larger, always keeping the same shape. Layer after layer of salol is being added at the rate of thousands of layers a second, all in such orderly array that the sides of the crystal stay perfectly straight and continue to make the same angles with the neighboring sides.

When growth has ceased, examine the mass of crystals closely with the magnifier. Most of them will not show their diamond-shaped outlines because they have met neighboring crystals and each has grown here and there around the other. If you turn the mass of crystals this way and that in a bright light, you will see the light reflected from their perfectly flat faces. The faces of crystals, built from the tiniest building blocks of matter, are the most perfectly flat surfaces physically possible - flatter than any surface that can be produced by polishing. The salol can be remelted and recrystallized repeatedly.

b. What to do with the crystals

Since salol is not sticky or corrosive or poisonous or harmful to clothing, a glass microscope slide with salol crystals frozen onto it can be carried in the pocket. If you prepare a slide with a larger mass of crystals at one end and a small bit at the other end, you can melt the larger mass while keeping

the smaller bit cool and solid. Then you can chip a tiny fragment of the smaller bit to use as a seed when you need it. Such a slide can be carried with you for demonstrating crystal growth to your friends.

If you get a thin film of melted salol between two glass microscope slides and keep them pressed tightly together until the salol solidifies (thus cementing the two slides together), you will have an even more exciting phenomenon to observe. First, observe your glass-salol-glass sandwich slide between crossed polarizers (see Section III-D). Rotate the slide, as the hands of the clock rotate, between the polarizers, keeping the polarizers crossed. If you do not see colors in the salol crystals, your film of salol is too thick. Remelt it and let it cool again, pressing the slides more tightly together this time.

Next, melt just a bit of the salol in the center of the sandwich slide. Stop heating just as the melting starts. Otherwise the whole layer of salol will melt and the glass slides will separate. Now observe the sandwich slide again between crossed polarizers. (**CAUTION:** Polarizing film is damaged by heat. Keep it away from the hot glass slide. The holder described in section III-D will help you do this.) The part that is liquid is black between crossed polarizers, but the salol crystals surrounding it are bright. With a magnifier, watch the bright blades of the salol crystals grow into the black area as the disorderly, tumbling particles of salol that make up the liquid fit into their orderly places to build the salol crystals.

c. Lessons from this section

Heat can cause the orderly solid to come apart into a disorderly liquid. The liquid looks like water, but it isn't, because it doesn't boil in a match flame's heat, and it turns into solid salol at a temperature much higher than that at which water turns into solid water, which is called ice.

A crystal can maintain its perfect shape and shiny faces while adding to itself thousands of layers of invisible particles a second.

Liquid salol is black between crossed polarizers, as glass and water are, but salol crystals are bright between crossed polarizers and show colors if they are thin enough.

Liquid salol will not form crystals (that is, will not turn into solid salol) unless given a seed crystal on which to start.

3 Bismuth (metallic element, Bi)

The metallic element, bismuth, melts at 271° C. Like water, it has the rare property of expanding when it changes to the solid form (crystallizes). You may be able to obtain bismuth from a chemical supply company or the chemistry department of a university.

a. Growing the crystals and observing their growth form

Melt the bismuth in an open pan. When it has all melted, remove the pan from the source of heat. As the pan cools, crystals of bismuth will form on its cooling inner surface. You may not be able to see them, but with large chemist's forceps you can feel them just below the surface of the opaque liquid. Lift them from the hot liquid with the forceps and carefully shake the excess liquid from them. The surfaces of bismuth crystals have many little steps.

b. What to do with the crystals

Turn the crystals this way and that in a bright beam of light, preferably one coming from some distance away. Notice that the surfaces of many of the steps reflect the light brightly at the same time. In order to do this, they must be making the same angle with the light beams, that is, they must be parallel with each other. They must all be formed by layers of the building blocks of the bismuth crystal that are parallel to each other in the orderly arrangement of the bismuth crystal. This tells you that the steps are not different crystals, but that they all belong to the same crystal. In a neighboring crystal, there will be a different set of stepped faces that reflect light at some other angle.

As you examine the bismuth crystals, you may see iridescence on their surfaces, as on peacock wings and soap bubbles. This is due to the presence of a thin film of bismuth oxide that sometimes forms on the surfaces of the crystals as they cool. It is so thin that the light goes through it to the surface of the bismuth crystal and is reflected there. On its way back, it joins the light that is being reflected from the surface of the oxide film. The two light beams interfere with each other. When this happens, some particular color of light will be canceled out of the white light beam which is made up of all the colors of the rainbow combined. When one color is subtracted, the light no longer remains white, but is colored. So the surfaces of the bismuth crystals may appear colored. A thin film of oil on water shows color in the same way. So do the peacock's wings and the soap bubble. Colors produced in this way are called interference colors.

c. Lessons from this section

A crystal face may be interrupted by a step and be the same single crystal on both sides of the step. It is the constancy of orientation that identifies a set of surfaces as all belonging to the same crystal.

Beams of white light reflecting from the two surfaces of a thin film may interfere and give colored light.

C Crystals from the Vapor (the gaseous condition of the same substance)

1 Ice

Ice sometimes forms directly from the vapor state out of doors. If the weather is very very cold and damp, frost may form on trees. Trees at high altitudes often show frost feathers. Ice may form on a very cold window glass in a house, from the water vapor that is in the house.

a. Growing the crystals and observing their growth

If the atmosphere in the room is humid enough, you may be able to induce ice crystals to grow from the vapor on the outside of a glass or metal container filled with crushed ice and alcohol. Stir the mixture vigorously from time to time. The crystals will not show fine faces, but you may see a tiny facet sparkle if you have a bright light on the frosty surface.

b. What to do with the crystals

Empty the glass and watch the frost melt. It did not come from liquid water; it came from gaseous water directly to the solid state. As it warms up, it changes to the liquid state. If you let the glass or metal container stand in the room for some time, the water will return to the gaseous state again; that is, it will evaporate.

c. Lessons from this section

Water vapor, which is water in the invisible gaseous state, is in the air around us. It can be induced to form on very cold surfaces as ice (or on less cold surfaces as water).

2 Naphthalene (moth flakes, $C_{10}H_8$)

CAUTION: FLAMMABLE

This substance, which has long been used to protect woollen clothes from moths, should not be confused with several other substances more recently produced for the same purpose (for example, paradichlorbenzene). It is usually sold in a paper box and is in the form of large white flakes.

a. Growing the crystals and observing their growth

When naphthalene is gently heated, it goes directly into the vapor state. (Its melting point is 80°C .) Its strong tendency to change into the vapor state is one of the properties that make it useful in protecting clothes from moths. **IT IS VERY FLAMMABLE AND MUST NOT BE HEATED NEAR AN OPEN FLAME**

A convenient way to grow naphthalene crystals is as follows: Put a few flakes of naphthalene (half a teaspoonful) in the bottom of a tall glass jar. On top of the jar, lay a lid that is too big for it. A piece of aluminum foil or even a piece of paper would do. Do **not** screw a lid onto the jar that would trap the heated vapor in the jar. If you did this it might explode.

Rest the bottom of the jar on a lighted light bulb in a lamp. Very soon (with a 100-watt bulb) you will see little crystals start to form on the upper part of the jar, where the warm, invisible, naphthalene vapor is cooled and the attraction of the invisible particles of naphthalene for each other brings them together in the orderly arrangement of the naphthalene crystal.

Some may form in branching, feather-like groups of crystals that remind you of frost on a window glass. Some may form in very thin plates that show interference colors as light reflects from both of their surfaces, as from an oil film on water or a soap bubble. (See the section on bismuth.)

Naphthalene is not soluble in water or alcohol. If you wish to clean out the inside of the jar, you can do it with nail polish remover (which contains acetone). This is very flammable and somewhat toxic, so use it only with good ventilation and with a paper towel or tissue which is placed where it cannot catch fire afterward.

b. What to do with the crystals

The thin little naphthalene plates are very beautiful between crossed polarizers, viewed with a magnifier. The colors that some crystals show between crossed polarizers are not due to the reflection of light from two closely spaced surfaces, as are the soap-bubble colors. They result from the fact that, inside the crystal, light is broke up into two rays with different velocity. It is the interference between these two differently affected rays that produces the colors.

c. Lessons from this section

Other substances than water can be crystallized directly from the vapor state.

D Experiments with Polarized Light

1 The Nature of Polarized Light and the Means for Producing It

The concept of light that one uses in any particular situation depends on the situation. In what follows it will be convenient to think of light as having wave-like properties - as being a disturbance which moves forward with an oscillating motion like that of the waves of the sea. But we must think of the light waves as very very small, with the distance from crest to crest about

5/10,000 or one two-thousandth of a millimeter. (Two thousand of them across the head of a pin!)

Unlike the waves of the sea, the light waves do not just oscillate up and down. They oscillate from side to side in all directions that are at right angles to the direction in which the light is traveling. However, it is possible to pass the light through something that will only let through light that is oscillating in one particular plane. Light oscillating in one plane only is called **plane polarized light**, or often simply **polarized light**. The thing causing the **polarization** of the light is called a **polarizer**. There are several kinds of polarizers. Every smooth, non-metallic, surface that reflects light partially polarizes it. The polarized light from such a surface is oscillating parallel to the surface (and, of course, always at right angles to the direction in which the light is traveling). Probably the most convenient polarizer for studying crystals as described in this handbook is polarizing film. One brand that has been manufactured for many years is Polaroid, but there are others.

Such a film passes mostly light that is oscillating in a particular direction in the plane of the film. You can find out which direction this is, by using the film to view light reflected from a non-metallic smooth surface, such as a painted window sill. When the window sill looks darkest, as you view it through the film, the permitted oscillation direction for light passing through the film is vertical, at right angles to the window sill.

2 Crystals between Crossed Polarizers

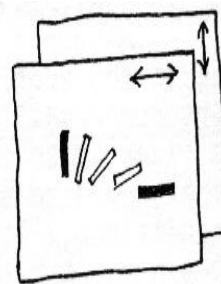
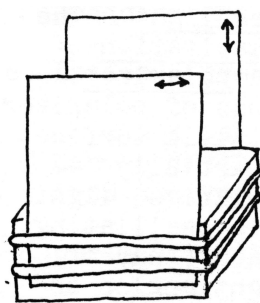
A convenient way to hold two polarizers for examining crystals is to place them on either side of a small box and hold them to the box with a rubber band.

The double-ended arrows in the sketch indicate the permitted oscillation direction for light passing through each polarizer. When the polarizers are arranged so that one of these directions is at right angles to the other, they are said to be 'crossed'. If the polarizers were perfect, no light could get through both of them when they are crossed. Without knowing the permitted direction of either one, you can arrange them in the crossed position by finding the orientation in which they appear darkest, when placed one behind the other.

A full discussion of crystals in polarized light is not appropriate for this handbook. The reader is referred to the list of references in Part V.

Specific observations concerning crystals mentioned in this handbook follow.

The crystals mentioned can be divided into two groups on the basis of their appearance between crossed polarizers.



Crystals that look dark in
any orientation

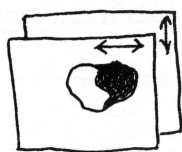
table salt
alum

Crystals that look bright in
most orientations

borax
sugar
copper sulfate
Epsom salt
ice
salol
naphthalene

It will be found that those that look bright in most orientations look dark in some orientations. Epsom Salt needles, for instance, look dark whenever their long edges are parallel to the permitted direction in either polarizer.

Any crystal that looks bright between crossed polarizers will appear colored if it is thin enough. When light passes through such a crystal, it is divided into two beams oscillating at right angles to each other. One of these has greater velocity than the other. When they come out of the crystal and pass through the second polarizer, they interfere with each other in a way similar to that of the two beams described in the section on bismuth crystals. Although the cause of the interference is different in this case, these colors are also called interference colors.



The polarizers are especially useful for determining whether a bit of matter consists of a single crystal or more than one crystal. A half-melted bit of ice may show no boundaries in regular light, but between crossed polarizers, you may find that part of it is dark in one position and the other part is dark in another position. Clearly, in such a case, it consists of two crystals.

3 Ice and mica

In the section on ice, an **interference figure** was described, a black cross on a gray background, that could be seen under favorable conditions. It is

not easy to see. One needs a rather thick piece of ice, with smooth surfaces, and an area that looks black in all orientations when the ice sheet is parallel to the plane of the polarizers.

A different interference figure, one with two ‘eyes’ instead of one, can be seen in a similar way with a large piece of mica between crossed polarizers. The eye of the observer must be as close to the mica as possible. Since mica does not damage the polarizers the way wet ice does, they may be held close against the mica on either side. If the whole sandwich is tilted this way and that way, at various angles to the line of sight, the two eyes will be discovered. A fuller discussion of interference figures is given in *Crystals and Light*, one of the references listed in Part V.

4 Sugar solutions

The fact that a crystal looks bright between crossed polarizers does not mean that it rotates the plane of polarized light. If it can be turned to some position in which it looks black, then it is not **optically active**. A sugar solution is optically active ... it rotates the plane of polarized light. This means that the oscillation direction of the light changes gradually, as though following a screw, as the light progresses through the solution.

If the sugar solution rotated the plane of polarization the same amount for all colors, then one could simply rotate the near polarizer, relative to the far one, by the right amount, and the solution would appear black between the adjusted polarizers. However, the plane of polarization of each different color of light is rotated by a different amount for a given length of path through the solution. Therefore, when the near polarizer is rotated by the right amount to be ‘crossed’ for one color, the other colors still come through. With a light source producing only one color, darkness can be achieved. With a piece of red or blue or yellow glass or plastic, you may be able to perform this experiment.

V Crystals Outside of Home and Classroom

A In Museums

1 Displays of Rocks and Minerals

Most museums have labeled specimens of rocks and minerals and some of them are very beautiful. **Minerals** are crystals that occur naturally in the Earth's crust. A trip to a museum would be a good introduction to the kind of crystals you may find out of doors.

2 The Museum Staff (suggestions for field trips)

The people on the museum staff may be able to suggest good places to go to look for crystals. The crystals in rocks commonly grow against each other and form irregular boundaries, but they are crystals, none the less. You should explain to the people in the museum that you are willing to collect the rock-forming minerals, without beautiful shining faces, as well as those with more perfect external form.

B Out of Doors (field trips)

If you live where there are big exposures of rock, you may find that it is igneous rock (crystallized from the molten condition), sedimentary rock (laid down by water), or metamorphic rock (changed by heat and pressure, though it began as one of the first two).

1. **Igneous rocks** that cooled slowly have large grains of minerals composing them because few crystals started to grow in them at the same time and each could grow big before meeting its neighbor. They were formed deep beneath the surface. (Giant crystals may form, however, when water-rich melts are injected into surface rocks and slow crystallization results from the large water content.) Minerals that commonly make up such rocks are: quartz (gray, glassy, no cleavage); feldspar (pink, white, or gray. Dull, with cleavage); mica (colorless, gray, or black. Perfect cleavage, peeling off in sheets); hornblende (black, short rods, inconspicuous cleavage, small grains). When molten rock cools quickly it is finer grained and then the various minerals are more difficult to distinguish, but the same minerals are still commonly found.

2. **Sedimentary rocks** are formed when layers of fragments, deposited by the streams and rivers that have carried them to the sea, are hardened into rock. These fragments originally came from the igneous rocks, so you might expect to find the same minerals again. However, feldspar and mica break up easily when tossed about by a river, and may also decompose chemically. Quartz is harder and does not have cleavage, so it stands the abrasion better. It is also chemically resistant. So it wins. Quartz is the

commonest mineral in the sedimentary rocks, sandstone and shale (finer-grained). The rivers also carry matter in solution. One of the commonest substances deposited from solution is calcium carbonate. When it becomes hardened into rock it is generally very fine-textured and light gray or nearly white. It is called limestone. The mineral that makes up limestone is called calcite. Calcite is also deposited from water in little white veins in various kinds of rock. It is easily identified by its perfect cleavage in three directions that causes it to break into little blocks. The sides of the blocks are not rectangular, like those of salt, but rhombic (the shape of a parallelogram).

3. **Metamorphic rocks** are formed from both igneous and sedimentary rocks by the action of heat and pressure, deep within the Earth, sometimes aided by solutions of various substances, migrating through the rocks. When limestone is metamorphosed, marble results. The calcite crystals become larger, some growing at the expense of others. Metamorphism of shale produces slate. Further metamorphism of slate produces schist, a rock full of mica that glistens in the sunlight.

4. **Boulders, pebbles, and sand.** If you live where you do not see any big rock masses exposed for you to study, pick up any small bits that you can find. Often they are dirty on the outside, and sometimes their surfaces have been changed by the weather. Break them open to find a fresh surface. Unless you live on the side of a volcano, all of the pieces you find will be crystalline, that is, they will be composed entirely of crystals, although these may be small and with irregular boundaries.

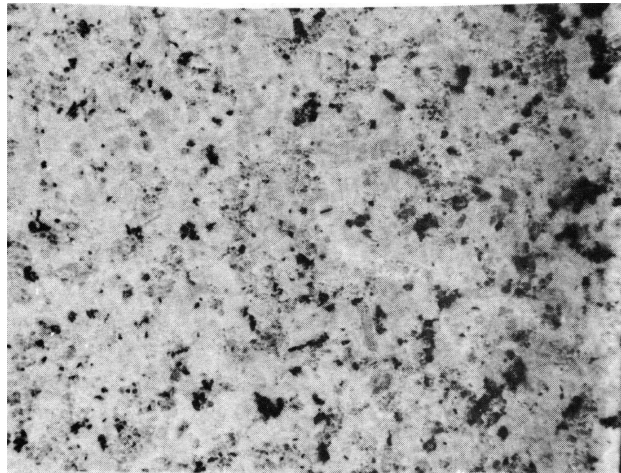
Giving names to the mineral grains in a rock is only part of the pleasure of studying rocks, and not as significant as examining the relationships among them. You may be able to tell whether the rock is igneous, sedimentary, or metamorphic. If it is an igneous rock, try to determine which mineral grains crystallized first, with the others having to form around them in the space that was left.

5. **Ice** is a crystalline solid that occurs naturally, without the aid of man, so it is properly called a mineral. Frost on the window glass looks like the feathery crystals of naphthalene. An icicle is sometimes made up almost entirely of a single ice crystal. Examine a clear one between crossed polarizers!

Perhaps the prettiest of all natural crystals is the one we have left for last - - the snowflake. If you live where it snows, take your magnifier out when a very fine snow is falling. Each flake may be a single crystal. (Big flakes are bunches of many crystals.) The variety of patterns of snow flakes has been a source of wonder and delight to all who enjoy observing the world about them. They probably result from the fact that the habit of growth of the little ice crystal is very sensitive to small changes in humidity and temperature. The great student of snowflakes, Ukichiro Nakaya, has found that he can produce various types of growth, at will, in the laboratory, by controlling the conditions of temperature and humidity under which the

little ice crystal is growing. In the turbulence of a snow storm, each crystal experiences many different changes of conditions during its period of growth. Two that are growing for a few seconds under the same conditions will soon be blown far apart and will continue their growth under different conditions. With such a constantly changing environment and such sensitivity to it, one might well expect such variety and such intricate beauty.

C At the Big Stores and Small Shops



Polished igneous rock showing white feldspar, grey quartz, and black mica

1 Decoration of buildings and counters

Many big stores use polished rock for trimming the outside of their buildings, and sometimes inside the store as well. Such polished surfaces cut through the crystals of which the rock is made. The boundary between one crystal and the next can easily be traced and the various crystal grains distinguished from each other. Usually the rock is made of no more than three different minerals, sometimes of only one. Marble (metamorphosed limestone) is made almost entirely of the mineral calcite. However, the marble most highly prized for decoration usually has inclusions of other substances in it that give it the streaks of color that add to its decorative effect.

If the polished surface happens to cut through a crystal at an orientation which does not differ much from that of its cleavage planes, the crystal may reflect the sunlight brightly if you happen to see it from a favorable angle. Look for the flashing cleavage planes of crystals as you walk past a polished-rock trimming on a building. All that part that reflects light at the same angle (that looks bright when you stand in one place) belongs to a single crystal.

2 Jewelry stores

Nearly all gem stones are single crystals. Exceptions are jade and cat's-eye, which are polycrystalline, and opal, which is not crystalline at all. Most gems are cut with many-sided surfaces, both on the top surface and on the bottom. Light reflects from the top facets, but also enters the gem and reflects back out again from the bottom surfaces. This gives the gem its brilliance, and great care is taken to cut the small surfaces at the most favorable angles to achieve this.

3 Drug stores (apothecaries, chemists' shops)

Several of the substances mentioned in this handbook are available at the drug store. If you tell your druggist of your interest in growing crystals, he may be able to supply you with other substances. Be sure to determine whether there is any danger in handling the substance.

VI References for Further Reading

Experience with crystals you have grown yourself or found in rocks may lead to further curiosity about them. Hundreds of books have been written on the subject of crystallography and you may want to look for them in your library. But a beginner is sometimes overwhelmed by being given too much information at once. The following list includes one book on growing crystals, one book on rocks and minerals, and one book on crystals between crossed polarizers. All three of these books contain information on the external symmetry of perfectly formed crystals, a symmetry that results from the symmetry of their orderly structure. Every crystal has that orderliness. You can provide, for many of them, the conditions favorable for displaying it as they grow in beautiful shapes, with brightly shining faces.

VII References

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VIII Acknowledgement

Special thanks to Jovanka Kink for scanning and correcting the original handbook (June 1993). Copyright ©1972, 2001 International Union of Crystallography