MINERALS AND LIGHT

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INTRODUCTION

When light strikes the surface of a substance, it is split into three parts that are: (1) transmitted through the substance; (2) reflected off the surface; and (3) absorbed by the substance. See Figure 1. How much of the light in each of the categories is determined by the nature of the substance. Substances that allow some light to be transmitted through them are said to be translucent or transparent; those that allow no light to pass through are opaque. When we worked to identify minerals in previous labs, two of the important properties we used were luster and color. Both of these properties have to do with the way a mineral interacts with light; in determining them we consider only the *reflected* light.

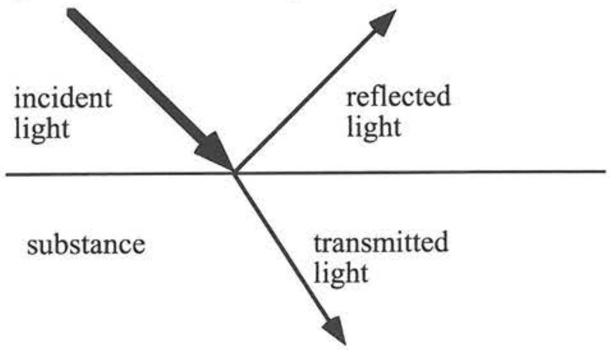

Figure 1. Light is split into three components: transmitted, reflected, and absorbed. (Absorbed light energy is transferred to atoms of the substance and is not shown here.)

Though many minerals are opaque, such as pyrite and graphite, even more are translucent. Today, we will examine translucent minerals (and some other substances) and observe the light *transmitted* by them.

POLARIZED LIGHT

Normal light, whether it comes from the sun or a light bulb, can be considered to vibrate rapidly at right angles to the path it travels. Usually, the vibration takes place in all directions perpendicular to the ray path simultaneously; or the vibration direction is spiralling so fast that it might as well be going in all directions. However, polarized light is light that is constrained to vibrate in only one direction. See Figure 2.

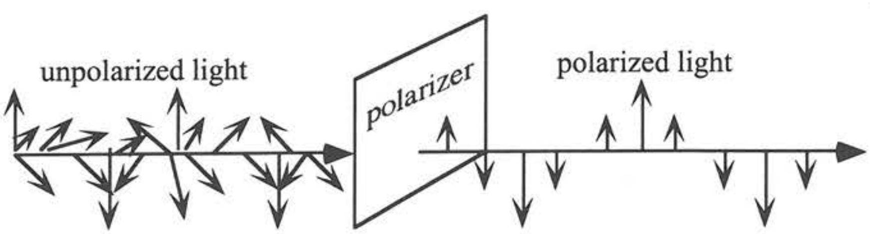

Figure 2. Polarization of light. Light ray is moving from left to right. Arrows indicate vibration direction and magnitude. The polarized light vibrates only in the plane of the page, while the unpolarized light vibrates in all possible directions at 90° to the ray.

One way to help visualize this is to take a strip of an index card and pretend it is a light ray. The long dimension of the card is the direction of a light ray's path; the short dimension shows the vibration of the light ray. When light is polarized it is as if all the possible light rays traveling in a given direction were filtered so that they all vibrate parallel to one another. This can be shown by using a comb to represent a polarizer; the card (vibrating light ray) can only pass through if it is parallel to the teeth of the comb. A polarizing filter does the same thing with unpolarized light: light is polarized in one direction (which we call the "vibration direction") as it passes through the filter, so that all rays are vibrating parallel to one another.

Polarization by reflection

We frequently encounter another type of polarized light, especially on a sunny day when the sun is low in the sky. When light rays reflect off a flat surface, they are partly polarized in a direction parallel to the surface. The shinier and smoother the surface, the stronger the polarization. This is the reason that our eyes are affected by reflected glare off road surfaces, the hood of our car, the surface of a lake, or a snow-covered field.

• What is the direction of polarization for all of these surfaces?

You can observe this type of polarization in the lab by moving to a position from which you see reflected glare (preferably from sunlight) off a clean smooth lab bench.

• Using a small polarizing filter that has been marked with its direction of polarization, determine the direction of polarization of the reflected light.

Because so much of the glare is vibrating the same way, manufacturers of sunglasses have devised a means of eliminating it. They do so by using polarizing filters in the lenses of the sunglasses.

• What is the direction of polarization of polarized sunglass lenses?

Now, imagine yourself, early on a summer evening, driving a car in a large city along a busy street lined by skyscrapers. The fronts of the skyscrapers are covered with huge sheets of plate glass. The street bends so that the low-angled light from the sun suddenly reflects off the buildings and nearly blinds you. You have your polarizing sunglasses in your pocket.

• How do you avoid an accident?

Polarization by minerals

Is reflection off a surface the only way that polarization can occur? No, in fact the polarizing filters, and polarizing sunglass lenses, polarize light by absorbing the light that is not vibrating in the "correct" direction. But we're not here to talk about sunglasses. What do translucent minerals do to the light that is transmitted through them?

In the next part of this exercise, we will use a clear rhombic piece of the mineral calcite. PLEASE TREAT THIS SPECIMEN CAREFULLY! Although most translucent minerals interact with light in the same way as calcite, we use calcite because the effects are much easier to see.

• Place the calcite rhomb on this paper directly over these words. Describe what you see.

• Now, using your small polarizing filter, test the vibration direction of the light associated with the images you see through the calcite. You can describe the polarization direction(s) by relating it(them) to the shape of the calcite, noting that the rhombus has two acute angles and two obtuse angles. Draw a sketch to show the top view of the rhomb and the polarization direction(s).

ISOTROPISM AND ANISOTROPISM

What you have just observed is the phenomenon of "double refraction." Minerals such as calcite actually split transmitted light rays in two! And you have discovered that the two rays actually are polarized in different directions (at 90° to each other) by the calcite. Substances that behave this way are said to be optically anisotropic. Isotropic substances, on the other hand, do not split light in two.

What determines whether a substance will be isotropic or anisotropic? It has to do with the arrangement of atoms; for a mineral, it's the crystal structure. If the atoms are arranged in the same way in all directions in a substance, it is isotropic; but if the arrangement is different in different directions, it is anisotropic. As an example, look at the crystal structure models of fluorite and muscovite.

- Would you expect these minerals to be isotropic or anisotropic?

Isotropic materials do not change the vibration of light that goes through them. An easy way to determine whether a substance is isotropic or anisotropic is to make use of polarized light. Use one polarizing filter on each side of a material to be tested, and set their polarization directions at right angles to each other. (This is called viewing under crossed polars.) If all you see is darkness (extinction), regardless of the orientation of the material being tested, then that material is isotropic. If you see light, it is anisotropic.

- Use a portable light box fixed with a large polarizing filter for the rest of this exercise. One student should hold a second polarizing filter above the first. Check to be sure the two filters are at right angles by getting them at the darkest (extinction) position. Now test each of the materials by holding them between the two polarizers. When testing a material, try rotating it a bit, and if it shows some transmitted light, turn it until it is at its brightest. Remember, if it remains dark, it is isotropic (I). If light comes through, it is anisotropic (A). BE SURE TO KEEP THE POLARIZERS' VIBRATION DIRECTIONS AT EXACTLY 90° TO EACH OTHER.

TABLE 1. OPTICAL CHARACTER OF SOME TRANSLUCENT MATERIALS

substance	**I/A**	**substance**	**I/A**	**substance**	**I/A**
air		cellophane tape		muscovite	
water		bubble wrap		halite	
cellophane		glass		gypsum	
plastic wrap		quartz		ice (be quick!)	
baggie		fluorite			

Notice the minerals in Table 1. Fluorite and halite belong to the isometric crystal system. In the isometric crystal system, atoms are arranged in the same way along the x, y, and z (a_1, a_2, a_3) directions. As it turns out, of all the non-opaque minerals, those belonging to the isometric system are isotropic, while those belonging to other crystal systems are all anisotropic. If you have done some work on crystallography or symmetry, you should see a relationship between the symmetry of a mineral and its optical behavior as well.

- Can you explain why water and glass behave the way they do?

INTERFERENCE COLORS AND THE COLOR CHART

You probably noticed that some of the anisotropic materials showed different colors when you viewed them through crossed polars. These colors, called interference colors, have nothing to do with the actual colors of the materials. What causes interference colors?

Remember how the calcite split the light into two rays with different vibration directions? Well, something more is going on: the two rays actually travel at different velocities through the calcite! By the time the slower ray reaches the end of the mineral, it lags behind the faster ray by a certain distance. It is this lag distance (also referred to as *retardation*) that determines what interference color you see. The difference in velocity between the two rays is a property of each specific mineral (usually expressed as *birefringence*).

There is one other factor that affects interference colors. Here's an analogy that may help. Assume there are two runners competing in a race; neither runner ever gets tired, so they each run at a constant speed, but one runs faster than the other.

- For these two runners, what will determine the lag distance between them at the end of a race?

- How does this relate to the discussion on interference colors?

Examine the interference color chart. Notice there is a specific sequence of interference colors, going from black to gray and white at the left end of the chart, out to yellow, orange, red, blue, and so forth, and becoming more washed-out and pastel in appearance toward the right. (Actually there is no right end to the chart, but the colors would fade to a whitish hue so that the colors would be indistinguishable.)

- Where have you seen these colors before? (Hint: If you said a rainbow, you're wrong! Think again!)

Each of the colors on the chart corresponds to a specific lag distance between the fast and slow rays; the units are nannometers (nm; 1 nm = 1×10^{-9} m or 1×10^{-6} mm). Look at a few of the anisotropic substances again, and see if you can match their interference colors.

- Tape a piece of cellophane tape to a glass slide and determine its lag distance and interference color, referring to the color chart.

- Now assume that the velocity difference between the two rays for the cellophane tape is 0.004 (no units). Determine the thickness of the cellophane tape using the simple formula:
  lag distance = (thickness) x (velocity difference)

INTERFERENCE COLORS AND STRAIN

When a translucent substance is deformed, bent, or heated, its optical properties commonly change. In fact, isotropic materials can become anisotropic when they are strained. Certain plastics and glasses are tested for strain using cross-polarized light. The higher the interference color, the greater the strain. Engineers use this technique to show where a material might break. As an example, take the plastic baggie and stretch it diagonally. Pull hard until it begins to tear.

- Describe what you see when the baggie is viewed between crossed polars.

- For another example, take the molded piece of clear plastic (a plastic box divider) and examine it between crossed polars. Where is the strain the greatest? Draw a sketch.

COMPENSATION

Let's return to the runner analogy.

• Suppose we doubled the length of the race. What would happen to the lag distance?

• What would happen if you doubled the thickness of the tape? Try it! Describe what you see. You may want to add on more layers of tape, in stair-step fashion, making a sort of "wedge" of tape.

• What do you think would happen if you put a strip of tape on at right angles to the first? If you like the track analogy, this would be like a two-lap relay race where the fast runner hands off to a slow runner, and the slow runner hands off to a fast runner. What would be the lag distance at the end of the race?

• Try it with the tape and describe what happens.

With cellophane tape, and all other anisotropic substances, the fast ray and slow ray have a specific relationship to the atomic structure of the substance. For example, in the tape, the slow ray vibrates parallel to the long dimension of the tape, and the fast ray vibrates across the width of the tape. When you place one strip of tape on top of another in the same orientation, the lag distances (and interference colors) are added; when you place them at right angles, they subtract.

Using a glass slide with one strip of tape, you can determine the fast and slow directions of other substances, merely by seeing if the interference colors add or subtract. If they add, then the fast direction of the tape is parallel to the fast direction of the tested substance; if they subtract, the fast direction of the tape is parallel to the slow direction of the tested substance.

THIN SECTIONS AND THE POLARIZING MICROSCOPE

Some minerals are opaque, some are isotropic, and many are anisotropic. Furthermore, many minerals may have their own "natural" color. But all anisotropic minerals have a specific velocity difference, and therefore show a characteristic range of interference colors. Because these properties are so useful in identifying minerals, geologists use a special microscope with built-in polarizing filters. They also use thin sections of rock. These are prepared by cutting a slice of rock, gluing it to a glass slide, and grinding it down to a thickness of 0.03 mm. By making the thickness the same for all minerals in the rock, the interference colors that you see will be determined only by the velocity difference of each specific mineral.

Examine your thin section. Before inserting the upper polarizer, first find an opaque mineral. Opaque minerals appear black no matter how they are oriented. All the minerals that are not black are translucent. Now find an isotropic mineral. These will not allow light to pass through when viewed between crossed polars, so if you insert the upper polarizer, and a grain turns black, and stays black as it is rotated (along with the microscope stage), then it is isotropic. All the other minerals are anisotropic minerals, and you should be able to determine some of the interference colors. Do you see why this type of microscope is so useful to geologists?

INTERFERENCE FIGURE DEMONSTRATION

If you have time, you may want to check this out: Take a flake of muscovite and set it on the microscope stage. Get it in focus, then cross the polars and switch to the highest power objective lens. Now following the instructor's guidance, obtain an interference figure. Surprised? What could possibly be the origin of this image?! Take a course in optical mineralogy and find out!

NOTES AND SUGGESTIONS FOR THE INSTRUCTOR

Optical Mineralogy and thin sections just blew me away when I first was exposed to them. (Of course that was the psychedelic 60's!) Because of my experience, I've always thought that we might attract a major or two if we introduced first-year students to interference colors and such. Therefore, this exercise is primarily intended to be used in an introductory (physical) geology class, perhaps for advanced students or as an extra credit project. It may also be appropriate as a brief introduction ("teaser"?) to optics in a mineralogy or optical class. If using this for more advanced students, remember to translate lag distance as retardation, and velocity difference as birefringence, if those are terms you want them to understand and remember.

The only significant expenses in setting this lab up are the light boxes and the polarizing film. Both are available from Edmund Scientific. The light boxes are small (12.5 in x 9.5 in) and expensive ($74), but we invested in 10 of them because I also plan to use this for schoolroom visits and science workshops. I'm sure there are less expensive alternatives. The polarizing film is about $38 for a huge (14" x 24") sheet. We cut these and inserted them on the light boxes, and had thin glass plates cut to cover and protect them. All can be secured neatly with the screws on the lids of the light boxes. Every team gets a light box and a small container with all the other "stuff" mentioned in the exercise, including an index-card "light ray" and a cheap comb.

It is nice to have an overhead projector handy so you can show the entire class some of these phenomena. (This can be done to as large a lecture class as you might have. It has been suggested that two polarizers with a big sheet of muscovite on an overhead can provide a motivational factor.) You will (or may) also want: polarizing sunglasses; large cleavage sheets of clean clear muscovite; good rhombs of iceland spar; interference color charts; thin sections of a rock with opaque, isotropic, and anisotropic minerals (preferably several anisotropic minerals each with distinct birefringence; a good thin section is a garnet-staurolite-white mica schist with fairly robust magnetite, ilmenite or graphite.) Please pass on your suggestions and comments.

The story about the sunlight polarized off the skyscrapers is true--it happened to me during the same semester that I was taking optical mineralogy. I had to drive to New York City to help move my sister from one apartment to another, and I was already nervous about driving in the city. I must have looked funny driving down the busy street with my head sideways and a big grin on my face. The incident really made me understand polarization better! I always recommend to my students that when they buy sunglasses, buy only polarizing sunglasses. They are so much more fun to play with (e.g. you can always see interference colors looking out an airplane window)!

Regarding the experiment using the clear calcite ("iceland spar"): I have seen so many references to the "strange" or "amazing" double refraction of calcite, that I am sure people treat it as an oddity. I think they should know that <u>all</u> anisotropic materials have double refraction, it's just that calcite has a really serious case of it. If you have ideas of good materials for determining isotropism and anisotropism, please pass them on. You could certainly use hair. In buying tape, buy the cheapest tape possible. Don't buy the "magic invisible" tape, it won't work. For ice, freeze water in a petri dish and quickly place it between crossed polars. Ice cubes don't work well.

In introducing the interference color chart, they will all think they recognize the colors of a rainbow. It is sometimes fun and effective to take them outside on a wet day to see an interference film on the asphalt. Soap bubbles or films and new (stuck together) glass slides are also good.

For the questions about the cellophane tape, I measured approximate refractive indices for my cheapo tape at about 1.532 parallel to the length and 1.528 perpendicular, so the birefringence was 0.004. You may need to modify this to suit your tape. If the retardation for one strip of tape is down in the 1° gray to white region, you may want to double or triple the thickness to get to a more distinctive interference color. This is a sort of procedure that even more advanced students should learn to apply. At the very least, they should get used to using something like this to tell 1° white from high-order white. By the way, with quartz wedges costing between $500 and $1,000 these days, I think everyone should be using homemade "tape wedges!" Incidentally, our tape turned out to be about twice as thick as a thin section!

The plastic box dividers were retrieved from damaged boxes used in mineral and rock labs in physical geology. They gave spectacular patterns of interference colors.