Optical Properties of Gem Substances

Educational objective: This exercise, unit 7 in the above syllabus, will introduce students to skills and equipment that will continue to be used throughout the following modules. You should attempt to master these skills and the use of the equipment. The student should become familiar with the equipment, its application to solving gem problems, its proper use, and the precautions necessary to ensure both the safety of the student and the equipment.
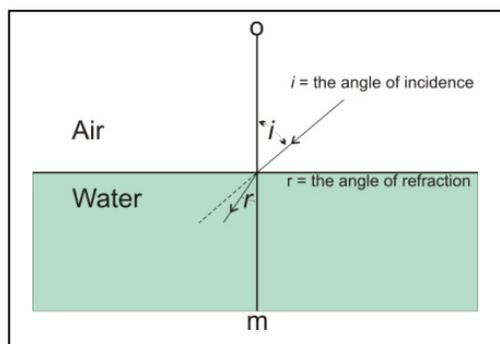
This lab may take up to two full meetings. Depending on equipment availability and time one or two setups for each experiment may be present. For each lab experiment, the student group will consist of 2 students. Groups are requested to make a 5 to 10 minute presentation using the digital Elmo overhead projector or a series of digital images (as in previous labs). There are some guiding questions for each exercise, but your overall grade is based on your presentation and discussion ensuing from it, plus observations of your behavior and preparedness in the lab. Images for your presentation are available in a "lab library" of images that you can pick and choose from as you see fit. The order in which the experiments will be presented does not have to correspond with the order they are presented here.

1. Refraction and the critical angle.

<u>Objectives.</u> To observe the change in light's path as it moves from one substance to another, record the angle of incidence and refraction, see total internal reflection, attempt to measure the critical angle, and learn about refractive index.

<u>Materials used.</u>   Either a laser pointer or a thin slit of light made using an intense light source, a piece of glass (ground on one side so that it causes the beam of light to be visible), large sheets of white paper, markers, or wax pencils, protractors, a glass of water, and a spoon.

Figure 1. An incident light beam enters the water at an angle of 40° (i) and is refracted so that $r = 28.9^o$ (redrawn from Kraus and Slawson, 1947).

<u>Discussion.</u> **Refraction** is a phenomenon that occurs when waves are bent. Light waves bend on moving from one substance to another. Light in a vacuum moves at a given speed (**c = 186,262 miles or 299,792 kilometers per second**; that is its velocity [V]). When light enters a denser medium, say water, it slows and it bends. This is familiar to all of us who have looked at the appearance of a spoon in a glass of water. This abrupt change in the position or angle of the spoon occurs because optically water is denser than air, and it bends on crossing from water to air. Water slows the light by about a third compared to its velocity in air. The change is velocity is related to a physical property called the **index of refractive** (n).

Snell's Law states that $n_i \sin i = n_r \sin r$

Where n_i and n_r are indices of refraction of the two, such as air and water. i is the angle of incidence and r is the angle of refraction. This relationship is shown for air and water in Figure 1. Air or a vacuum are given a refractive index of 1.

n (index of refraction) $= V$ (air)$/V'$(water)$=\sin i/\sin r = 1.333$

The optically denser the medium the more it bends the light beam on entering from a less dense medium. The angle of bending is toward the normal (O-M) in Figure 1.

We will use a piece of glass (instead of water) and a beam of light to observe the bending of light as it moves from air into the denser glass; when it leaves the denser glass it will also bend. Also, observe a

glass of water with a spoon in it. Move the spoon in the glass. When the spoon handle is vertical, straight up and down, is there any refraction of the spoon? What would happen if a ray of light came directly up or down the line "O-M" (the normal) in Figure 1?

1) Work with the beam on a horizontal surface on a sheet of paper. With a protractor set up the angle of incidence as in Figure 1. Make a normal line, o-m, and then choose an **angle of incidence** to that normal. Draw a line with extra length so that it continues past where you will put the glass. Mark the glass to air interface on the line (mark as point A). Mark the point where you would expect the light beam to exit if the glass did not refract the beam as B (dashed line in Figure 1). Put the piece of glass in place. Line up the beam to meet the air to glass interface along the line you have chosen.

You may be surprised what you observe. Turn on your light or laser pointer.
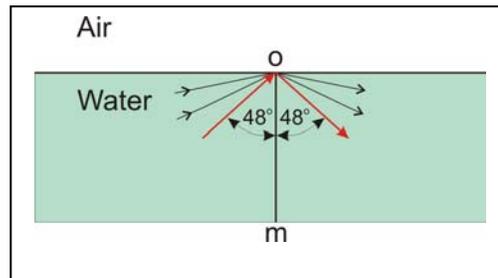
First record your angle of incidence, $i =$_____.

Now draw on the glass (use a marker or wax pencil that can be erased later) and mark on the paper where the refracted beam meets the back end of the glass block (point C).   Did the line of the incident beam change from the first line you drew without the glass present?

Measure the angle MAC; it is the angle of refraction.
Record several angles of incidence and refraction.

A) $i =$_____. $r =$_____.   B) $i =$_____. $r =$_____.
C) $i =$_____. $r =$_____.

Figure 2. The critical angle of water is 48° measured from the normal, om, any ray striking at the critical angle is reflected at the water to air interface and does not leave (red arrow). As well, rays striking at greater than the critical angle are totally internally reflected.

Now that you have moved the incident beam through a range of angles, you should have seen a very interesting phenomenon. The beam, rather than exiting the block of glass at the back was reflected back. The angle at which the beam no longer exits the back of the glass block, but is instead reflected back into the glass is called the **critical angle.**

In a gemstone, the critical angle is the angle at which rays of light attempting to pass from the stone into air (a less dense substance) are first totally reflected back into the gemstone (denser medium) in Figure 2. The critical angle is mearsured from the normal to the air-water interface, om in Figure 2. The inferface in gemology is the gem to air interface. When a ray of light enters a gem and strikes a face of the gem's interior at greater than the critical angle, no refracted ray escapes, thus the reflected ray does not lose intensity. This may not seem like such an exciting thing at first, but it a key element of cutting gemstones. Take a look at Figure 3.

A beam of light striking the inside surface of a stone at any angle greater than the critical angle cannot leave the stone and is totally reflected back into the stone. The higher the refractive index of the gemstone, the smaller will be the critical angle. Diamond has a critical angle of about 24°; any light ray striking at an angle greater than that (to the perpendicular; shown for two ray traces in Figure 3) will be totally internally reflected.

Quartz with an index of refraction of 1.55 has a critical angle of about 40° and thus a lot less of the light entering the crown is likely to be internally reflected back to the top surface of the gem.
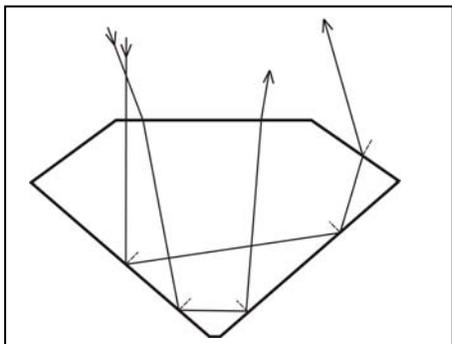
Figure 3. Light entering a brilliant cut diamond from the crown also exits from the crown. The light experiences total internal reflection because it impinges on the facets at an angle greater than the critical angle.

We can calculate the critical angle in air, i, using the formula $\sin i = 1/n$ where n equals the refractive index of the substance. You will have some homework problems to calculate the value of i for several gemstones. As you can see from Figure 1, the critical angle will have an impact on the angular relationships and the cutting of various gems, depending on their refractive indices.

Use your setup to directly measure the critical angle of the glass block (i_{glass}). Though this setup is not ideal, since we do not know the exact refractive index of the glass (n_{glass}), we cannot use a calculation in this case.

i_{glass} =_____ Now that you have i_{glass} you should be able to calculate n_{glass} =_____ using the formula above.

What were some of the problems you experienced in making your measurements? Explain.

Prepare an explanation of how this behavior of light might help make a properly cut stone appear better than a poorly cut stone. Also explain how you can measure the critical angle and calculate refractive index from it.

2. Dispersion of light and gemstones

Objectives. The objective is to learn about dispersion and how it is important to gemstones.

Materials used. Glass prisms, slit lamps (either slide projectors or fiber optic lamps), diamond simulants, cubic zirconium, Moissanite, YAG, strontium titanate, synthetic rutile, colorless spinel, as available.

Discussion. Visible light is part of the electromagnetic spectrum. We are most familiar with white light and, as you know, it is the result of a mixture of colors (wavelengths) of light (Figure 4). But what is the significance of this on how gems look and how they are cut?

Monochromatic light is light of a single wavelength (color) or in our everyday world, a light bulb that produces a narrow spectrum of mainly one color, such as a low pressure sodium street lamp (a yellow color). The world would be dull if everything were monochromatic (literally one color!). Since it is a single wavelength, monochromatic light cannot be dispersed by a prism or partly absorbed by a filter. Whatever monochromatic light wavelength illuminates a substance is the only color you will see.
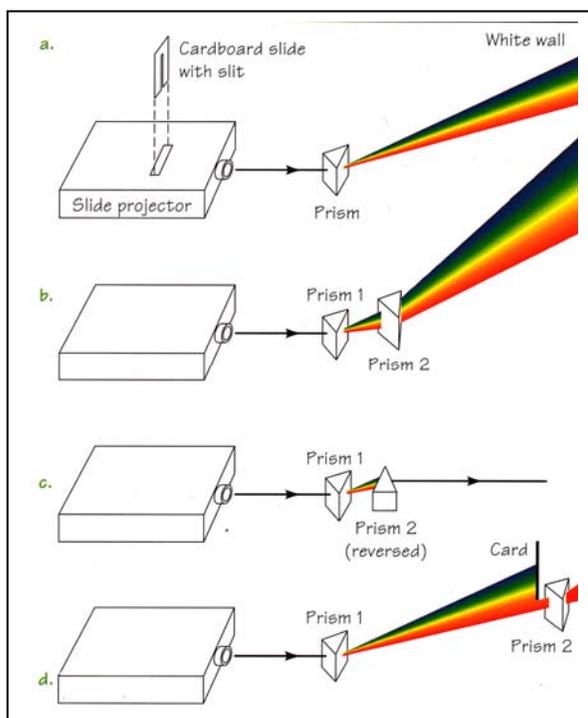
Figure 4. Setup for dispersion using prisms. From Nassau (1997).

Dispersion itself is a complicated physical property of materials. Sir **Isaac Newton** (1642 to 1727) used dispersive prisms (AD 1665), much as you will do, to prove that what we think of as white light is actually a mixture of all colors of the visible spectrum. Dispersion of white light creates a rainbow. In gemology, dispersion of a material is the difference in refractive index (n) between the extreme visible wavelengths of red (n_b) and violet (n_g) in the substance under consideration. That is n_b-n_g= **dispersion**.

Gems and other objects in life, such as the glass prisms we will use today, can disperse white light into a spectrum of colors (like a rainbow). In gems, we call these different colors leaving the stone its fire. Fire is a critical part of a diamond's appearance. Any diamond simulant should display similar fire.

Procedures.

First set up the prism and light source as in Figure 4a (Nassau, 1997).

1) Draw (with provided color pencils) the spectrum in the provided space (Figure 5).

**Figure 5.** Draw spectrum with color pencils

2) What are the extreme colors (left and right sides)?

3) How can the acronym ROYGBiV be used to remember the spectrum (The i is lower case because it stands for indigo [a dark blue] that is hard to distinguish from blue.)?

_____   _____   _____   _____   _____   indigo   _____

4) Using a second prism, could you succeed in getting the light spread more Figure 4b or to recombine as in Figure 4c?

5) Can you decide which color of light was deviated (bent) most in the prism? Which was bent least? Draw the extremes in Figure 6 below. That is, try to draw the approximate angle of deviation (Θ, the Greek letter "theta") for the extreme colors, most and least bent. Indicate the colors by labeling or using the appropriate color pencil.
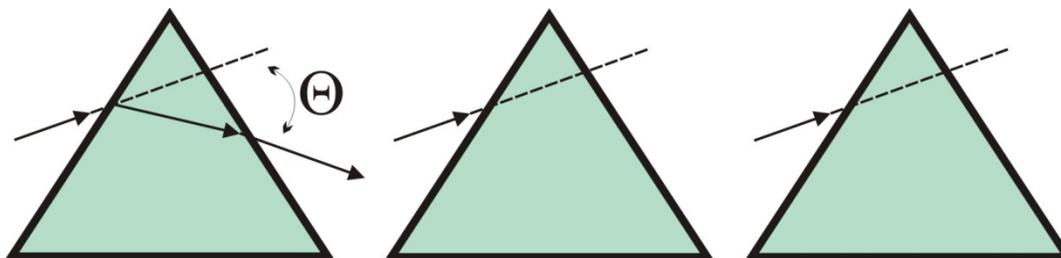
Figure 6. Illustrate the approximate angular deviation of the light leaving the glass prism for the two extreme colors in the created spectrum. This angular deviation is related to dispersion.

6) Look at the gems you were supplied. Shine light on them and vary the angle of the gems. Order them based on most to least displayed fire (dispersion). Record your results.

7) Now compare diamond simulants of the same type (for instance cubic zirconias) and as close in size

as possible. Compare different cuts, such as princess, marquise, and round brilliant cuts. Are some cuts of the same stone showing more fire? What about comparing similar sizes of the same stone, with slightly differing angles of faceting; is the quantity of fire the same?

Prepare a discussion of dispersion. Describe both how you observed it and the results of contrasting gemstones of different types and of the same type with different cuts.

3. Double refraction with calcite

<u>Objectives.</u> To observe double refraction in calcite and understand light behavior in anisotropic crystals.

<u>Materials needed.</u> At your station, you will find pieces of optical calcite (cleavage rhombs), a polarizing filter (gray plastic sheet), magnifier, cardboard, and **polariscope**. Be careful not to scratch the filter or calcite!

<u>Discussion.</u> Calcite is a mineral that, though rarely used as gemstone, has great value in optical experiments and devices. It is highly anisotropic and light's speed in the crystal varies with direction. You will see the dramatic way light behaves in a calcite crystal. Other anisotropic crystals in general also show this behavior but not to such a great extent.

<u>Procedure.</u> a) First, draw a dot on a piece of paper and place the rhomb over it (Figure 7). What do you see?

b) Can you make observations about the behavior of the dot when you vary the direction from which you view the dot through the calcite rhomb (try different rhomb faces)?   What happens when your rotate it? What about the depth of the dot? What happens if the rhomb is thicker (Try two rhombs of different thicknesses oriented the same way.)?

c) Now first use the polarizing filter and later the polariscope to make a few more observations. Find the alignment of the filter by the method explained earlier (using it to cut glare reflected from surfaces). Place a small label with an arrow showing the filter's orientation. Now look through the filter at the rhomb with a dot below it. What happens to the dot (rotate the filter; the rhomb)?

d) To further our study of the behavior of the dot, let's make a dot with the light from the polariscope. Poke a hole in the cardboard. Place the card over the light of the polariscope. You now see how many dots of light when you look through the polariscope? When you look through the rhomb placed over the light spot? Is the light entering and exiting the rhomb plane polarized? Does it become plane polarized in the crystal itself? How can you test this (hint: Go back to the paper experiment in a.)?
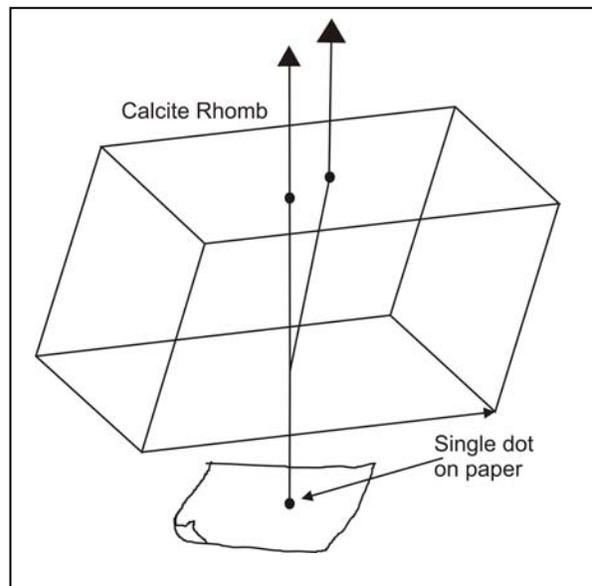
Figure 7. Calcite rhomb with a paper with a dot. Double refraction creates two dots exiting the rhomb from the top. Indicate the direction of vibration of the two rays exiting the rhomb. Also indicate the relative depths of the dots within the rhomb. Label the ray that does not rotate as *O.* Redrawn after Bloss (1961).

Rotate the top polarizing filter and study the behavior for a moment. How many degrees of rotation are necessary between seeing only one dot to completely extinguishing one of the light dots and seeing only the other? What do you see when the top polarizer is rotated approximately half that distance (start at seeing only one dot and rotate the filter 45°)?

Illustrate what happens in the rhomb (Figure 7). Can you illustrate the two rays and the directions in which the plane polarized light is vibrating in the paths in Figure 7?

Now repeat all your observations with first a transparent piece of halite and second a piece of glass. Are there any overlaps in behavior?

Prepare a discussion of your results and choose several illustrations to present to the class.

4. Using a refractometer

Objectives.   To become familiar with a gem refractometer, apply it to measure refractive index, observe the behavior of amorphous, isotropic, anisotropic, uniaxial, and biaxial substances with the refractometer.

Materials used. Gem refractometer, a monochromatic light source, gemstones, contact fluid, glass slides.

Discussion. A gem refractometer is an optical instrument that uses the critical angle of a gemstone (exercise 1 above which we saw above is related to the index of refraction of a gemstone) to illuminate a calibrated scale. In monochromatic light, darker and lighter zones of the scale meet at a boundary at the gemstone's refractive index (See Figure 8 below). This boundary is called the **shadow edge**. Since the refractive index of a substance is related to the wavelength of light used, a standard wavelength is used to measure refractive index. This wavelength referred to as the **sodium D line** is approximately 589 nm (**nm = a nanometer** or 10^{-9} meters [one billionth of a meter]). This **yellow light** can be produced by a light bulb, by using sodium in a flame (such as an alcohol lamp), or more commonly today by using either a yellow filter or a yellow light emitting diode (**LED**). You may have access to a sodium lamp or at least have seen one used for street lighting.

If white light is used in the refractometer, instead of sodium light, the line between light and dark is less distinct as light disperses into several colors while passing through the optical system of the refractometer. If white light is used, the refractive index reading should be taken at the boundary between where the green-colored fringe passes into the yellow fringe. If this fringe boundary is curved, choose the highest value along the curved boundary with the scale (Anderson and Jobbins, 1990).
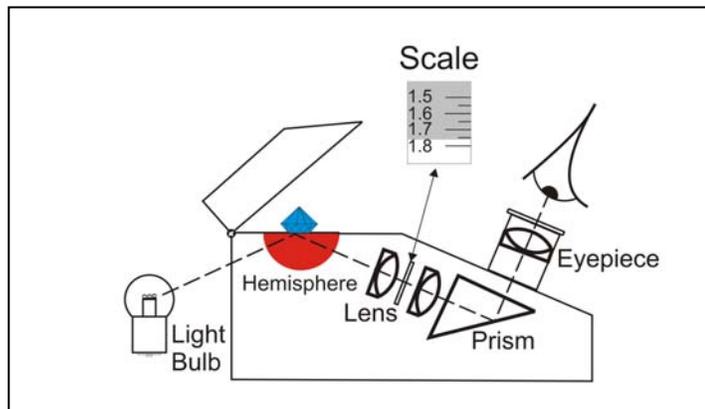
Figure 8. Refractometer. The gem is placed onto a drop of contact fluid on the hemisphere. In monochromatic light, the refractive index 1.75 is read from the scale in the eyepiece.

Your task will be to measure the refractive index of gemstones, but you must **be exceedingly cautious** to avoid damaging this instrument's optical prism.

Some gemstones you measure will have only one value on the refractometer and are called **isotropic**. These gem minerals are in the cubic crystal system or are amorphous (like glass). Some gemstones have more than one value for refractive index, depending on the direction light travels through the crystal; these gemstones are **anisotropic**. For the present exercise, we are most interested in the extreme values of these anisotropic gemstones, and we can find them by changing the position of the gemstone on the prism. However, this movement **must be done with caution** or the much harder gemstone will scratch or chip the soft and weak prism of the refractometer.

The results of careful measurement of refractive indices of gemstones are tabulated in the lab manual appendix and in most gemology textbooks. After you make the measurements required, try to find the possible gemstones in the appendix table or from a list of gemstones provided by your instructor.

Note that the index of refraction reported may vary for almost any gemstone through a range of values, because of differences in composition due to either impurities or natural substitutions of elements that change the optical properties of the gemstone. Two notorious gem minerals that vary in composition over a great range are **olivine** (gem mineral **peridot**) and **garnet**. Gem peridot can vary in its relative proportions of iron and magnesium. Though the internal arrangement of atoms, or structure, is the same the composition can vary from pure magnesian (Mg_2SiO_4) forsterite to pure iron (Fe_2SiO_4) fayalite and the chemical formula is often written as $(Mg, Fe)_2SiO_4$. Olivine is anisotropic and its RI can vary from 1.60-1.69 as can its specific gravity which varies from 3.2-4.3. The garnet group, all isotropic species, has a great deal of substitution and can have various colors and refractive indices (RI). Some of the members of the garnet group, such as the gem variety of andradite garnet called **demantoid** (RI: 1.85-1.89), have too high a RI to read on a normal gem refractometer. If the RI goes off the scale (beyond 1.81; the RI of the contact fluid) no reading is possible and the gemstone is said to have a **"negative"** reading.

Procedure. To begin the exercise, first look at the bottle of contact fluid, make sure its lid is tightly screwed on. Return it in a similar manner. The contact fluid is a chemical that should be handled with care; it has a very high index of refraction, $n_D = 1.81$. Its constitution to develop this necessarily high RI makes it somewhat toxic and gives an obnoxious odor. **Wash your hands after use!** Also follow the instructions for cleaning the prism after you are finished testing the stones. Use a soft cloth or lens tissue to wipe excess RI fluid from the prism before returning the instrument to its case.

The stones we will use for our first tests today are attached to small wax rods (in later labs we will not use these); the rods make the stones easier to handle and to move on the refractometer prism. Before using a stone for testing, practice putting small drops of RI contact fluid onto the glass microscope slide provided. Try to make small drops, as tiny a drop as you can; remember only a tiny amount of contact fluid is necessary between the facet and the glass. Try putting a stone on a test drop; avoid air bubbles.

Look at the instructions for your refractometer; they will tell you where to put the drop. When you remove a stone from the refractometer, also be careful not to scratch the prism. Usually you slide the stone to the edge of the prism and remove it; that is why the stone must be clean before placing on the refractometer.

Then examine your first stone; make sure it is clean and free of dirt using your 10 X loupe. Then place a drop of contact RI fluid in the correct spot on the glass prism and carefully place the stone's table facet onto the drop and avoid catching bubbles of air under the stone. Turn on the refractometer light and take a look. You should see the shadow edge and scale as in Figure 8.

We will use only faceted stones today. Distribute the work so that you each test an equal number of stones.

First observe the stones from Box A; they should have blue wax sticks attached, but be careful not to rush

and to move the stones gently. These stones are supposed to all be isotropic and should have one shadow edge; but be careful, there may be an anisotropic stone mixed in by accident! Clean each stone of RI contact fluid after use with a soft cloth or lens paper. Repeat the procedure and record the results in the table below.

Box A.

When you finish with the Box A stones, make sure they are clean and neatly returned to their box.

Report the following for each stone, index of refraction (n_D) or negative reading and color in the table.

Stone #	RI of Isotropic Stones (n_D)	Color of Stones
1		
2		
3		
4		

Box B.

Box B contains anisotropic, **uniaxial** stones. Record the highest and lowest RI you find on rotating the stones. Using the sodium lamp, there should be two separate shadow edges, easily separated by viewing through the portion of Polaroid as it is also rotated, since these two rays are each polarized but perpendicularly to each other. Uniaxial stones on rotation will have two shadow edges. One shadow edge will not change, the other will move higher or lower on the eyepiece scale as you rotate the stone. Report the extreme reading of this moving shadow edge. If the stone is repositioned on another facet, it may be higher or lower than the one you just measured. When you are done, put an "O" for **"ordinary"** in the box next to the RI recorded for the shadow edge that does not move, and put an "E" for **"extraordinary"** in the box next to the value of the RI that varied with the orientation of the stone. The value "O" is the refractive index of the single ("uni") optic axis of these uniaxial gemstones.

Stone #	Lowest RI (n_D)	Highest RI (n_D)	Color of Stones
1			
2			

Box C.

Box C contains biaxial gemstones. These stones have two optic axes and both shadow edges will move when the stone is rotated on the refractometer while the shadow edge is viewed through polarizing filter, unless the stone is oriented with the optic axis coming perpendicularly through the stone's table facet, which is unlikely. Because the recording of the important maximum and minimum RI values, which occur at different gem orientations is difficult, only a couple of examples will be studied today. Record your results in the table below.

Stone #	Lowest RI (n_D)	Highest RI (n_D)	Color of Stones
1			
2			

Prepare a brief discussion of the 3 different types of stones you investigated. Explain any problems you encountered. Did you have a stone with a negative reading? If the stone is birefringent, (i.e. anisotropic) did you have more trouble with a particular stone than with others? For homework, you might consider the identification of stones that gave your measured results and list some further test you would like to do to verify your identifications. Also compare results for a green tourmaline to peridot; do they overlap in properties? How would you distinguish the two? List as many methods and differences as you can.

5. Anisotropism and Observing Interference Figures

Objectives. Optical anisotropism of materials will be investigated; amorphous, uniaxial, biaxial, and anomalous behavior will be observed in polarized light. Conoscopy will be used to study interference figures. The Michel-Lévy Interference color chart will be introduced. After this exercise students should be able to differentiate uniaxial and biaxial crystals by optical examination.

Materials used. Polariscopes, interference spheres, if available a polarizing or regular compound microscope with a convergent light condenser below the stage. Transparent amorphous objects such as molded plastic (disposable tape dispenser, etc.), several oriented mineral fragments, crystals and slices of tourmaline, quartz crystal, cleavage fragments of mica, halite, cubic zirconia, chalcedony, agate, other minerals and gemstones as available, a halved Ping Pong ball, and at least 2 polarizing filters.

Discussion. Gemstones, like all minerals, have a highly ordered internal arrangement of atoms, and this separates them from **amorphous** substances such as glass. When an amorphous (internally unordered) substance or a cubic system mineral is put between two polarizing filters (crossed polarizers) and illuminated, it remains dark on any rotation. Any material that is dark between polarizers, e.g. a polariscope, is said to be at **extinction**. When an **anisotropic** gemstone (member of any of the other 6 crystal systems) is placed between crossed polarizers, it may be at extinction or it may show progressively varying amounts of transmission as it is rotated, (i.e. light-dark-light-dark-, four times each per complete rotation) and perhaps even various colors due interference phenomena of the light waves caused by the uneven breaking of light on entering an anisotropic substance. The colors created by interference may be seen by reference to a **Michel-Lévy Interference Color Chart** provided by your instructor. You will soon see some of these colors by placing anisotropic materials between crossed polarizers on your **polariscope**. The colors are related to the retardation of the crystal being observed (how much the light is slowed) and the path length and direction the light travels through the crystal. Any substance that shows these colors is necessarily **birefringent** or anisotropic.

Rather than studying all of the optical phenomena (which are both beautiful and informative), we will concentrate on observing the general properties of anisotropism (see also Double refraction with calcite) and how what is called **conoscopic illumination** reveals a very informative property of the anisotropic crystal called the **interference figure**. When a cone of light (Figures 9 and 10) is used to illuminate a crystal between polarizers (conoscopic illumination), a very interesting and informative pattern of light and darkness called the interference figure is produced. The interference figure is only seen in certain orientations of the gemstone or crystal and sometimes is very difficult to spot.

Today, we will only look at very well-oriented crystals to make the observations easy at first. In later labs you may have to be very patient or **may in fact not be able to find the mineral's interference figure**, even if it is anisotropic. Your job is to observe things that are birefringent and to find and observe two types of interference figures and **report** their distinguishing feature.

Procedure. First examine the materials we will use today. Besides minerals to examine, we have some molded plastic objects (disposable tape dispenser, etc.) to show **stress and anomalous birefringence**. Different processes can create stress in some transparent amorphous objects and make them birefringent. Isotropic minerals, such as halite, could also show anomalous birefringence, but this is more unusual than in molded objects such as acrylic (Lucite). Keep this in mind however, because some isotropic gemstones such as diamonds and especially garnets may also behave anomalously.

Part 1. Examinations with the Polariscope of crystals and cut stones.

Be careful with the cut gemstones and mineral fragments not to scratch any glass parts of the equipment!

First use the polariscope to examine several gemstones and mineral fragments presented. Turn on the polariscope, make sure that the polarizing filters are completely crossed (darkest setting). Hold the samples between the two filters. Try all the stones.

a. Give a general report of what you observe. You are observing the materials between crossed polars. Look at a piece of halite provided (it is in the cubic system), look also at cut cubic zirconia, and several cut gemstones. How do the cut gemstones behave when they are rotated (some polariscopes have a rotating base; in others you must hold the gemstones and turn them).

b. Now try the glass interference sphere. Do you see any dark lines in it? These, lines if present, indicate stress. They are similar to isogyres that you will see in interference figures (next; Figure 9). Illustrate them below.

c. Now try the molded plastic tape dispenser. Remember it is not crystalline, but it may still be birefringent because of the stress of molding it. Compare your colors to the Michel-Lévy Interference Color Chart.   Which is more stressed, the interference sphere or the tape dispenser? Draw the appearance of the tape dispenser in polarized light with a colored pencil set.

d. Observe a polycrystalline gem, such as an agate or chalcedony. Does it ever go extinct? Why might it never become extinct? What does polycrystalline mean? Are all the crystals oriented the same way?

e. Lastly, place an elongate quartz crystal so that its axis is at first directly running across front of the polariscope (parallel to the lower polarizing filter's vibration direction). What is the amount of light that you observe through the polariscope? Now, turn the crystal by 45° degrees (ends pointing toward 1:30 and 7:30 or 4:30 and 10:30 on a clock face). Now illustrate both positions drawing the crystal inside the circle of a polariscope. You may also describe what happens when you rotate the crystal to different positions. Try it with several faceted and cabochon stones as well. Do some of them remain dark in any position? These may be amorphous or cubic crystals. What is the most common behavior during rotation of the minerals that display birefringence? Plan to present some generalized results from your observations.

Part 2. Observing interference figures.

In these experiment you will use the interference sphere (and a conoscopic microscope if available) to observe interference figures. We will observe a centered uniaxial interference figure, an off center interference figure, and a biaxial interference figure. You will be able to distinguish members of the tetragonal, hexagonal, and trigonal crystal systems that are uniaxial from member of the orthorhombic, monoclinic, and triclinic crystal systems that are biaxial. Distinguishing and seeing uniaxial and biaxial interference is important for gem and mineral identification. Although you could accomplish this with a refractometer, this more general analysis will help with rough material and with stones that are difficult to analyze with the refractometer.
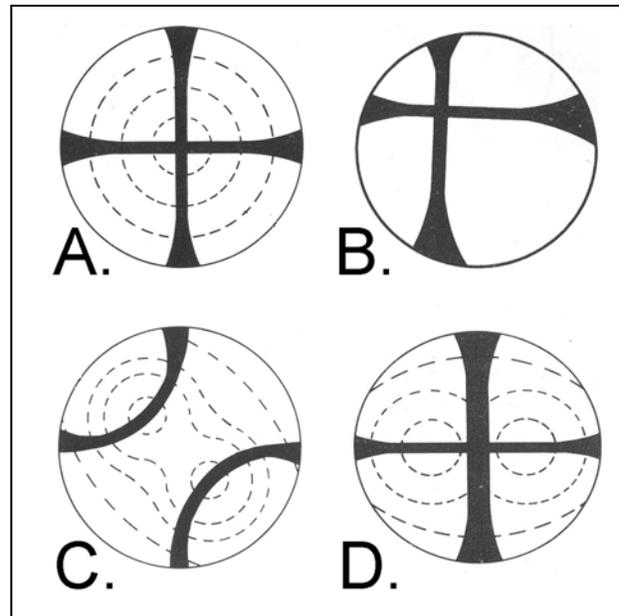
Uniaxial Interference Figure

A slice of tourmaline cut at 90° to the prism face (shield-shaped slice) is provided. You may receive other oriented uniaxial crystals. How does the slice behave when you look at it lying flat on the polariscope? Does it vary much in appearance when rotated on the polariscope?

Now take the interference sphere and place it close to the tourmaline slice. You should see a dark cross called an **isogyre** (like a Maltese cross) surrounded by rings of color called **isochromes**. You are seeing a uniaxial interference figure. If you have a stone holder and a holder for your interference sphere, you can take a good look. If not it is a little difficult to hold the sphere steady. This may be solved by the microscope technique we will use later.

Draw the interference figure with colored pencils, use Figure 9A as a model.

In the position you were just looking, you could see directly down the optic axis of the tourmaline crystal. Now tilt the tourmaline slice. Consider that a stone might be cut off of the axis you just observed. How does the interference figure change as you tilt it towards its side? Use Figure 9 to confirm the type of figure you are seeing. Figure 9 shows both a centered and an off-centered uniaxial interference figure. Using color pencils, draw the isochromes on Figure 9 (You may wish to use scrap paper first). Are the colors becoming more intense or washed out as you move away from the center of the figure. Look at the provided Michel-Lévy chart. Are you going to higher order colors toward the outside? Does this indicate anything about the amount of gem material the light is going through? Consider a solid cone of light illuminating the crystal. Draw it and consider the distances traversed by light coming straight up through the cone versus light on the edge of the cone traversing through the crystal or gemstone.

Figure 9. Interference figures. A and B show uniaxial figures. A is centered, B is off center. The isogyres are shown (cross shaped). Fill in the colors for the isochromes using color pencils. C and D show a biaxial interference figure, as can be seen in a sheet of mica. As the mica sheet is rotated on the polariscope, the isogyres, open in C will close together as in D. Observe this behavior. Illustrations from Shelly (1975).

Biaxial Interference Figure

Now take a sheet of muscovite or biotite mica, place it on the polariscope. Use the interference sphere in the same way. You will see a figure with two dark lines. As you turn the piece while it lies flat, the figure will change; Figure 9 shows it in two directions at 45° to each other. Use color pencils to fill in the colors on these illustrations. Now tilt the specimen. You will see a circular figure (somewhat like an eye) with a dark line through it. In this position, you are looking down one of the two optic axes (Since it is "bi" axial, it has two axis.). Draw this view as well.

A Microscope Using Conoscopic Projection

Set up the microscope as shown in Figure 10. If it is not a polarizing microscope, you will have to sandwich the crystal being observed between two sheets of polarizing film that are crossed (permitting no light to pass). To do this, make sure you know the vibration directions of the sheets and set them so that they are fully crossed. Once it is set, turn on the microscope lamp and place the half of the Ping Pong ball on top. We will refer to the Ping Pong half as a "Quirke hemisphere" (Quirke, 1937). Lower the lighting in the room. The interference figure should be projected on to the hemisphere. If it is too small, check the aperture diaphragm of the condenser, and you may lower or raise the condenser. Make sure

you can point out the isogyres, the color bands, and know which is a uniaxial and which is a biaxial figure. You will demonstrate this to the class.

If you are lucky enough to have a polarizing (petrographic) microscope, your instructor will show you how to set up the microscope to see the interference figures in it.

Does the Quirke Hemisphere give you a better sense of what is happening in the crystal?

Do you find it easier to understand than when you used the interference sphere?

Can you think of circumstances when you would rather use one method rather than the other? Explain.
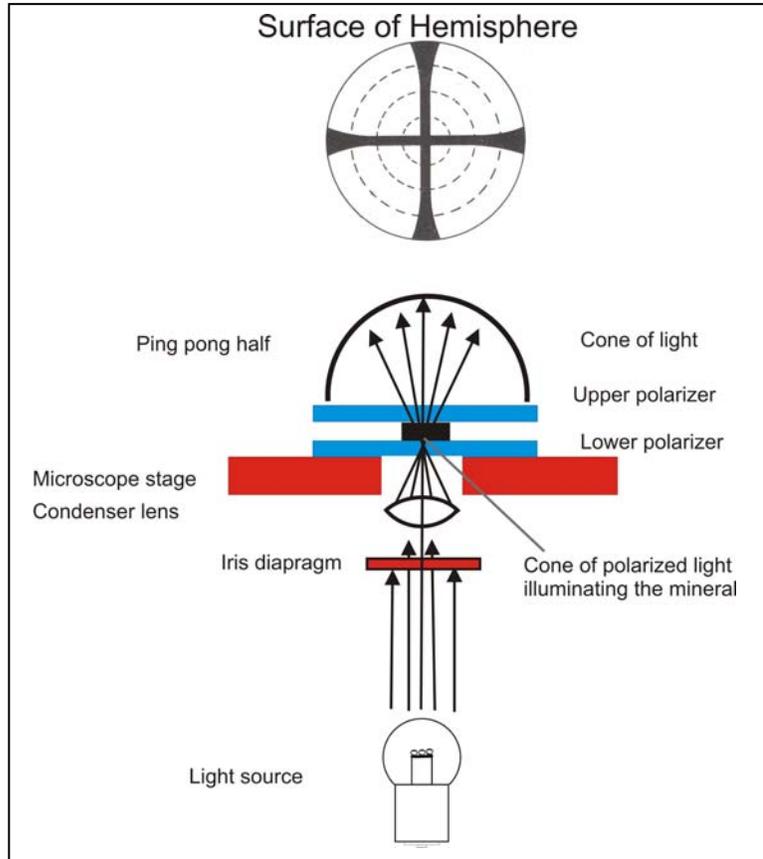
Figure 10. Illustration of the setup necessary to project an interference figure onto a Quirke hemisphere (Ping Pong ball half) using a microscope with a convergent condenser lens and a thick uniaxial mineral specimen (such as a tourmaline slice).

6. Using a dichroscope

Objectives. To observe and recognize pleochroism in it two forms, dichroism and trichroism. Discover how color varies with direction in crystals and to observe gemstones and consider their cutting.

Materials. Two types of dichroscopes (calcite prism and London dichroscope [polarizing film]), several dichroic gemstones such as ruby (natural and synthetic), ruby boule, synthetic alexandrite, synthetic and/or natural emerald, andalusite, cordierite, spodumene, tanzanite, tourmaline (faceted and natural prism). Fiber optics lamp or other strong lamp and tweezers or stone holders.

Discussion. A dichroscope is an optical instrument that allows gemologists to investigate color and a property called **pleochroism** in gemstones ("chroism" refers to color; "pleo" means more or many). The instrument can also tell you if a stone is birefringent. That means "two bendings," in this case of light entering the gemstone crystal. Any gemstone that shows two different colors in a dichroscope must be birefringent. It is producing two different rays that on passing through the gem experience different selective absorption of some wavelengths of the light used to illuminate the stone. Any gem that does not selectively absorb light differently in different directions will not exhibit dichroism whether it is birefringent or not.

A dichroscope can be made by using a calcite rhomb (see exercise 1 above) or using polarizing filters. Figure 11 illustrates a handheld calcite dichroscope, and you could make one yourself using some aluminum foil, a razor blade, and a piece of clear/colorless calcite (look at exercise 1 and consider how). The professional type illustrated has some glass prisms glued to the ends of the rhomb to maintain a straight line when light enters and leaves the rhomb. This makes it a little easier to use.
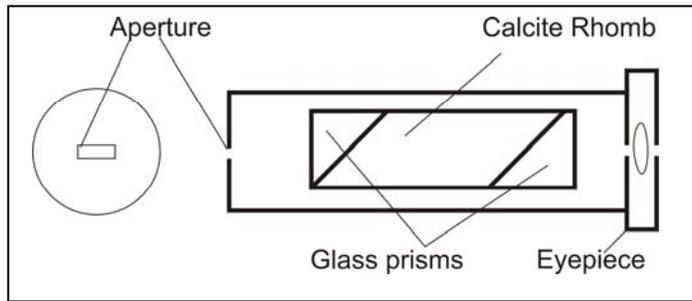
Figure 11. Calcite dichroscope (redrawn from Read, 1978). The calcite rhomb creates two images (double refraction) that are plain polarized at 90° to each other. This can show if there is selective absorption of color in either vibration direction.

Procedures. Step 1) Without using the dichroscope, look at the tourmaline crystal provided; tourmaline has such strong dichroism that you can see two colors if you look at light 1) transmitted parallel and 2) perpendicular to the prism faces. Selective absorption of some colors leads to the colors you see. A tourmaline crystal is a good example to look at because the two directions with the strongest color difference are at right angles to each other. In fact, tourmaline is often cut with respect to the directions just mentioned, so that the table facet is usually the lightest color and the edges or ends, of for example an emerald cut stone, appear darker. Try and observe this.

In the space below, illustrate a top and side view of the tourmaline crystal you examined. Using your own words, for example "salmon pink" or apple green" or if you are not familiar with the color, look at the Munsell Rock Color Chart (2009) and use their descriptive terminology.

Draw your tourmaline crystal (end and side view of prism):

Sometimes, however, when a stone is cut, as for example in a round shape, you will not have the mineral's axes arranged to the symmetry of the rough crystal. Certainly some rounded, alluvial pebbles could not easily be oriented with respect to the crystal's axes. If orientation of crystals was always easy, one would expect that every star sapphire would have the star perfectly oriented to have the star's rays meet in the exact center of the stone. This sadly is not the case, and few natural stars in stones are perfectly centered.

As we will see, the dichroscope could help you orient stones for cutting, but its main function is as a qualitative (non-numeric) means of reporting the stone's color character and whether is displays dichroism or even **trichroism** (3 separate colors).

Step 2. Take the dichroscope and examine it. Determine which end has the eyepiece (Figure 11). If an instruction booklet comes with it read it. There are two types of dichroscopes; the tube-shaped one is a **calcite dichroscope**. The one that looks like a folding loupe is a polarizing film type unit called a **London Dichroscope**. Try both; you may wish to make some comments on which was easier to use.

You have a box of six stones. Some are named, while others just have a number. Using a pair of locking

tweezers or spring loaded stone holder, examine the stones first with your unaided eye and loupe and then with the dichroscope. Use a fiber optics or other light to illuminate the stone. You want to send light through the stone and examine it with the dichroscope.

You may find the lighting is rather hard on your eyes and you may be squinting. One thing to help with this is to use a piece of provided Styrofoam to hold the tweezers or stone holder. Place the Styrofoam block on your lab bench, and use a pencil or the tweezers to punch a hole in the Styrofoam for holding the tweezers. Now move the flexible lamp; you will find the correct position to look at the stones with.

Move each stone, turn the holder, reset the stone in the holder. Record what changes in colors you can observe.

Sample ID	Color A	Color B	Color C	Overall color no dichroscope
Unknown A				
Unknown B				
Unknown C				
Synth. Faceted ruby				
Tourmaline crystal				
Rough ruby boule				

Things to consider. First, the synthetic faceted ruby and boule are very inexpensive to produce. The faceted synthetic ruby was cut from a similar boule. Does the faceted stone have the richest red when you use the dichroscope to look through the stone's table facet? Do you see any dichroism?

The fact is, with gem quality natural ruby, an effort is made to have the optic axis perpendicular to the table facet (or as close as possible) (Figure 12). This orientation displays the richest red color, with no dichroism, corresponding to the ordinary ray. Any deviation may bring extra yellowish color into the stone.
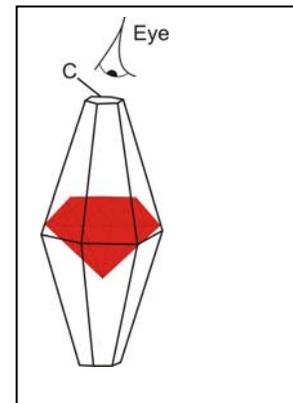
Now have a look at the boule; with this new information can you think of a reason(s) why a faceted stone might not be properly oriented? There are some important facts about rubies; both about their cutting and boule growth that are discussed in many textbooks; you may wish to investigate this further.

7. Using a Spectroscope

Objectives. Two types of spectroscopes will be used to obtain spectra of unknown gemstones and compare them to identified gemstone spectra. The differences of the two units and their spectra will become apparent. The difficulties and limitations of using a handheld spectroscope should be understood.

Figure 12. Faceted ruby properly oriented for best color inside corundum crystal.

Materials used. Diffraction and prism spectroscopes, fiber optics lamps or other sources of white light, unknown gemstones of various sizes.

Discussion. A spectroscope is a device that spreads light emanating from an object into its spectrum of

colors. You have seen this done with optical prisms, but it can also be done with a diffraction grating. A grating is made of very finely ruled lines, exactly like the lines on a compact disc (CD or DVD). You have seen the colors produced by reflected diffraction from the back of a CD. Both types of spectroscopes are effective for analyzing gemstones, but both have some limitations.
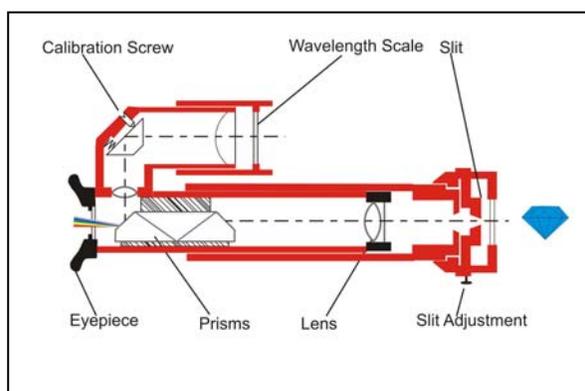
When analyzing gemstones, the gem acts as a filter that selectively absorbs portions of the spectrum (rainbow of colors) of light transmitted through it. This causes some wavelengths (colors) to be absent and creates dark lines, dark bands, and broad dark bands in some cases within the spectrum.

With the provided prism spectroscope (Figure 13), you have an additional calibrated scale that shows the wavelengths of light in the spectrum. These are usually calibrated in nanometers (nm; billionths of a meter). The visible spectrum has a range from 390 to 750 nm; you may see this on the scale. The scale has a separate window for illumination; the light from the gem comes in through a slit. There is a calibration screw for the wavelength scale; the 590 nm sodium D-line (monochromatic light from a sodium lamp) is used for calibration. You can check the calibration using a lamp from one of the refractometers (but this is not critical today).
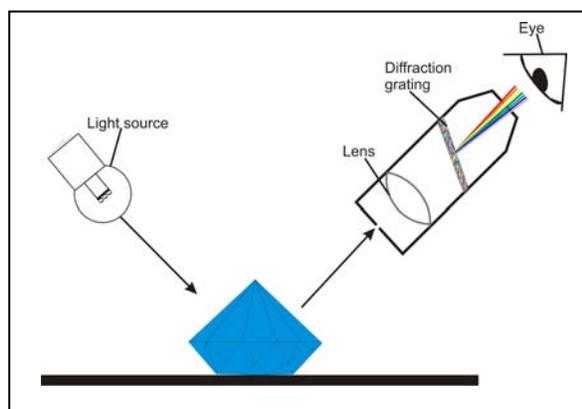
Warning! Your fingers should not touch the slit or the eyepiece. If the spectrum has horizontal streaks or seems otherwise distorted, contact your instructor.

Figure 13. Prism spectroscope with an extra tube for a wavelength scale. The gem is illuminated and light coming from it enters the stone. Do not adjust your spectroscope without consulting your instructor! Modified from Read (1978).

The spectroscope may be used to either acquire and compare unknown gemstones' spectra to known published spectra of gemstones illuminated with white light or to analyze properties of gemstones when they are illuminated with for instance ultraviolet light. Ultraviolet, visible, and infrared light are used in spectroscopy. They are often incorporated into analysis called Near IR, visible, or UV spectroscopy. All of these frequency ranges of the electromagnetic spectrum have value in gemology. For today, we will confine our study to visible spectra of gem materials.

Procedures. You will receive a box of unknown stones of various sizes. Test the stones with the spectroscope. You may use either the prism or the diffraction grating instrument. Try both. Try to use a setup in a manner similar to that illustrated in Figure 14. Use a nonreflecting black background such as a piece of velvet cloth. It is not easy to get good spectra, you may have to move the light and the gem around. If you have a fiber optics lamp, move the angle of illumination around, but try to keep it near 45 degree to the horizontal. You may also change the placement of your eye. Look at the stone from several angles; you may not see the whole spectrum at once, look at part, one of the extreme ends, then

Figure 14. Use of a diffraction spectroscope. You can use a similar set up with the prism spectroscope.

the other. Be careful not to look directly at the illumination source.

Look at the spectrum of one stone, and then compare it to the illustration in Figure 15. Though your spectrum is in color, the spectra shown in Figure 16 just use shading to show the absorption lines and bands. Can you use these for some of your identifications?

Is it more difficult to get the spectra of some stones? Is size a limiting factor?

What about remembering the position of lines and bands in the spectra? Is it hard to remember them and their position? Would it be better to draw the spectral lines and absorption areas onto a completed spectrum?

Sample #	Tentative identification	Color of stone in white light
1		
2		
3		
4		
5		
6		

Now that you have finished looking at your stones, take a look at some light sources and how their light looks through a spectroscope. Describe the following.

A) What do you see looking at fluorescent lights or computer screen?

B) Looking at a patch of blue or cloudy sky?

C) Looking at a sodium or LED monochromatic light source?

D) Looking a different colored surfaces or a black object?

Think about how these different light sources affect your perception of colors and the world.

Would a fluorescent lamp or monochromatic light be useful for looking at gemstone spectra? Explain.

Do you notice something different about the wavelength scales in Figures 15 & 16? Can you tell what type of spectroscope was used to make them?

Prepare a general discussion of the two types of spectroscopes, how you identified gemstones, and what else a spectroscope could be used for. If you have time consult a spectroscopy website on the Internet.
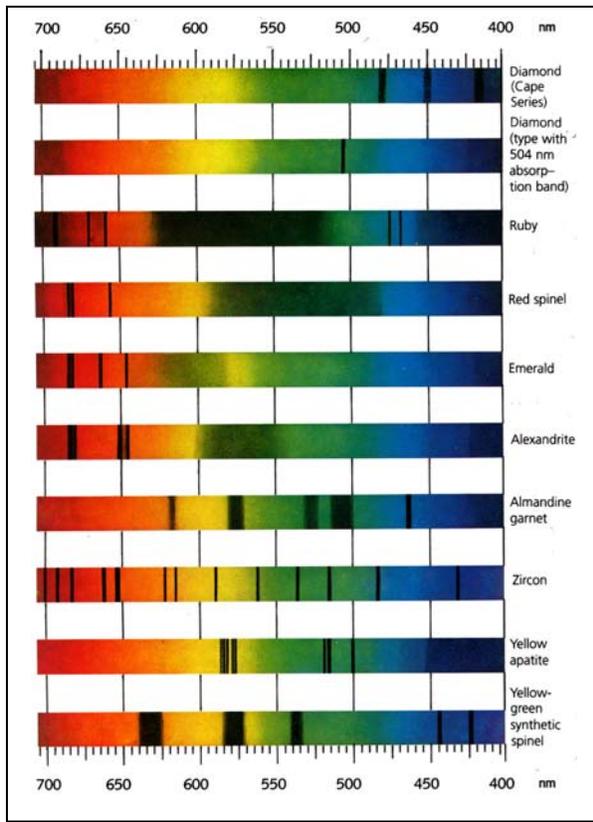
Figure 15. Gemstone spectra from Schumann (2006). Notice that the sharpness of lines and bands can vary. Compare to your samples.
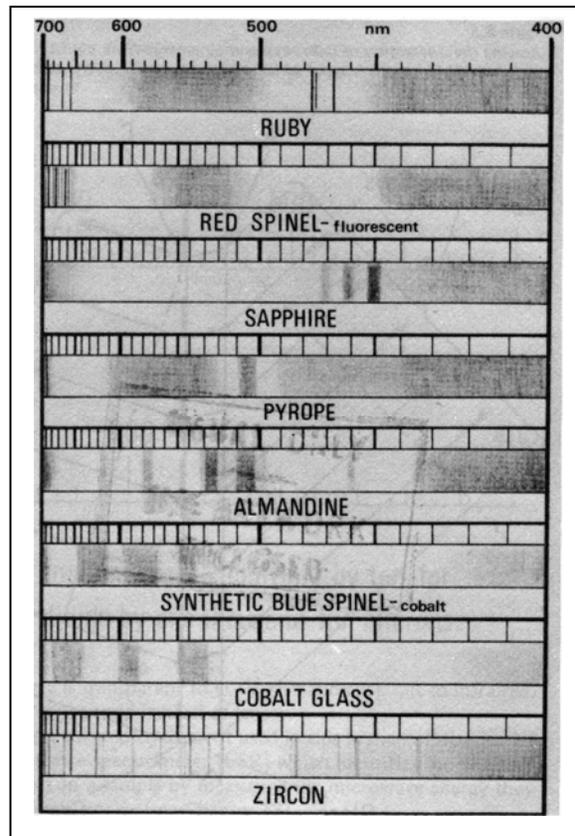
Figure 16. Gemstone spectra from Read (1978). These grayscale spectra are harder to use, but a wavelength scale is given along the top.

8. Light transmission and fluorescence of various gems

Objectives. Contrast the appearance of minerals in white light, to their appearance in ultraviolet light (UV). Understand how UV can help distinguish between gem and mineral materials.

Materials. UV lamp (or two lamps, short wave and long wave). UV safety goggle or glasses. **Anyone participating in the experiment must be wearing safety goggles!** A dark viewing box. Examples of minerals and gemstones.

Discussion.   Transmission of light means allowing it to pass through a substance. If light goes through a substance, it may be either transparent or translucent. Translucent means the light is diffused on entering the substance and you can't make out a sharp image on the other side of the substance (for example, when you look at a frosted light bulb you do not see the filament). Opaque means that light does not transmit through a substance. For instance, you do not get a sunburn through a glass window, so you could say window glass is opaque to ultraviolet light (discussed below).

Ultraviolet means "beyond violet." The light (It is better to say "radiation," since you can't see it, but most people often do say "light") is highly energetic and as you know from being outdoors, you can get burned by it. Sunlight has energetic UV rays; these rays can cause tissue damage (skin cancer and cataracts). But the precautions we use will not allow any real danger. Always use the viewing box and do not expose skin or eyes to direct rays from the lamps. Ultraviolet radiation is not visible to humans and can be characterized as having wavelengths between approximately 200 nm to 400 nm (A nm = a **nanometer**

and is one billionth of a meter in length.). UV radiation does not penetrate glass, or only to a very small degree, so we don't get sunburns sitting by a window. It will penetrate special glasses, some plastics, and the mineral quartz.

What we will see is that some minerals, when excited by UV, emit light in the visible spectrum. The light is called **fluorescence** if it is emitted only when the UV lamp is on. If light is still emitted when the lamp is shut off, you are seeing **phosphorescence** (This topic has been discussed in lecture.). Fluorescence can be very beautiful and useful, as for example in televisions and fluorescent light bulbs. Many mineral collectors specialize in beautiful fluorescent specimens. Interestingly, not all minerals of the same species, say all calcites, fluoresce. It is often a trace element included in the mineral that causes it. Some minerals such as ruby may behave just the opposite, and trace amounts of element such as iron (Fe) quench or inhibit the fluorescence (compare Burma rubies vs. Thai rubies).

Procedure. You are examining a tray containing various gem materials. You will observe their behavior in white light and using an ultraviolet lamp. A viewing box is prepared for the UV samples so that you can view them in a darkened space. Warning, all UV experiments should be done wearing safety goggles and the lamp should only be turned on when you have specimens in the box already.

Report the colors of the following specimens in white light and in their fluorescence. Also report if the specimens are transparent, translucent, or opaque in white light. You could check the transparency of minerals to ultraviolet light, but it is too dangerous with our present setup. After the experiments, you could consider a safe way to observe transparency to UV radiation.

Specimen name	Color (white light)	Color (UV light)	Transparent, translucent, opaque
Synth. blue spinel			
Natural sapphire			
Synth. ruby			
Synth. emerald			
Natural ruby			
Natural emerald			
Fluorite			
Calcite			
Willemite			
Plate glass			

Prepare a discussion of fluorescence. If you were prospecting at night, could you use fluorescence? How? Could you use UV light to do alluvial prospecting? How? What tests could you make to decide this?

Consider the 4 Cs of diamonds. What might be a problem caused by fluorescence in diamonds?

How would you describe the fluorescence of your specimens, vivid, dull, nonfluorescent? Explain.

Further Reading

Anderson, W., B. and Jobbins, A., E., 1990, Gem testing, 10th ed. Oxford: Butterworth-Heinemann, 390 p.

Bloss, F. D., 1961, An introduction to the methods of optical crystallography, New York, Holt, Rinehart, and Winston, 294 p.

Kraus, E. H. and Slawson, C. B.,1947, Gems and Gem Materials, 5th edition, McGraw-Hill Book Company, New York, 332 p.

Liddicoat, R. T., Jr., 1989, Handbook of gem identification: 12th edition, G.I.A., Santa Monica, California, 364 p.

Munsell, 2009, Rock Color Chart, Grand Rapids, Michigan, X-Rite, Inc.

Nassau, K., 1997, Experiments with color, New York, Franklin Watts, 128 p.

Quirke, T. T., 1937, Direct projection of optical figures, American Mineralogist, V. 22, no. 12 part 2, p. 12. (Accessed May 19, 2010), http://www.minsocam.org/ammin/AM22/AmMin_v22_n12_Pt_2.pdf

Read P.G., 1978, Gemmological Instruments *Their use and principles of operation*, London, Newnes-Butterworths, 227 p.

Schumann, W., 2006, Gemstones of the world, 3rd ed., New York, Sterling Publishing Co., 311p.

Shelley, D., 1975, Manual of optical mineralogy, Amsterdam, Elsevier Scientific Publishing. Co., 239 p.