8.03
Take-home Experiments

Contents

1. Influence of mass on the damping of a pendulum
2. Coupled oscillators, resonance, and normal modes
3. Vibrating string: resonance in a continuous system
   3A. Capillary waves
   3B. Polarization of light
4. Scattering of light
5. Reflection of light: the Fresnel equations
   5A. Liquid prism
   5B. Moire pattern simulation of interference phenomena
6. Thin-film interference, dry
7. Thin-film interference, wet
8. Diffraction of light
9. Transmission grating
10. Wavelength of light

Prepared by Thomas Greytak
Modified by Jacqueline Hewitt
Take-Home Experiment #1

INFLUENCE OF MASS ON THE DAMPING OF A PENDULUM

Objective The period of a simple pendulum is independent of its mass. The principal damping mechanism is the resistance that air offers to the motion of the swinging object. That resistance depends on the shape of the object, but not its mass. Hence, one might expect that the decay time of the pendulum would also be independent of its mass. You will discover here that this is not the case. You will also learn why.

Experiment Use the 10 ounce weight and the braided fishing line to construct a pendulum of length about 1 to 1.5 meters. Make sure that the suspension point is rigid, so that its motion does not provide a source of damping. Slice the foam sphere in half and scoop out a cavity inside just large enough to enclose the weight. Put the sphere around the weight and secure it with a band of Scotch tape around the equator.

Find a way of mounting the plastic ruler behind the pendulum so that it can be used to indicate the deflection of the string (it is harder to measure the deflection of the bottom or the edge of the sphere). Release the pendulum from an initial amplitude of about 15 cm. Measure the period. You may try a number of successive measurements of the time it takes to go through 20 oscillation to estimate how accurately you can measure the period. You do not need an accurate measurement for this experiment, but it is an interesting
exercise. Now the important measurement. Determine how long it takes the pendulum to change its amplitude by a factor of one half.

Now change weights and carry out the same measurements. Use one of the 1.5 oz weights this time. Thread the line through the hole and jam it in place with a wooden peg. This way the length of the pendulum can be made quite close to that used previously. Replace the sphere, using some cotton or tissue paper to fill the rest of the cavity so that the weight does not move relative to the sphere. Now the damping time should be noticeably shorter than was the case with the heavier weight.

**Discussion**  The force on the object due to air friction is modeled as \( F_{\text{friction}} = -b \dot{x} \). The constant \( b \) depends on such factors as the geometry of the object and the viscosity of air. It does not depend on the mass of the object. For small amplitude oscillations, \( F_{\text{restoring}} = -mg(x/\ell) \). Putting these forces into the equation of motion gives

\[
F_{\text{total}} = -mg(x/\ell) - b \dot{x} = m \ddot{x}.
\]

Recall that the damping time is \( \tau = 1/\gamma = m/b \). Thus, the damping time is proportional to the mass.

If the above explanation satisfied you, perhaps you should consider majoring in math instead of physics. Let's try again. If one moves an object a distance \( dx \) against an applied force \( F \), an energy \( dE = -Fd\) is transferred to the system supplying the force. In the case of the damping of the pendulum, \( F = -b \dot{x} \) and \( dE \) is supplied to the air in the form of an increase in the kinetic energy of the molecules. Since energy is conserved, the pendulum's energy decreases by an amount \( dE = b \dot{x} dx \). The energy lost per cycle, \( \Delta E \), is the integral of this quantity over one cycle of the pendulum. One does not have to do the integral analytically to understand the result. The path for \( dx \) is uniquely determined by the maximum amplitude of the swing, \( x_{\text{max}} \). The velocity, \( \dot{x} \), is uniquely determined for the entire path if one knows, in addition to \( x_{\text{max}} \), the frequency \( \omega \). Thus for all oscillations with the same \( x_{\text{max}} \) and \( \omega \), \( \Delta E \) will be the same. This energy loss per cycle does not depend on the mass.

Now consider the average total energy, \( E_{\text{total}} \), that the pendulum has when its maximum excursion is \( x_{\text{max}} \). This is easiest to determine at the end of the swing when all the energy is potential and is equal to \( mgh \). Notice that this quantity is linearly dependent on mass. The height, \( h \), above the stationary position depends only on \( x_{\text{max}} \) and \( \ell \): \( h \approx \frac{1}{2} x_{\text{max}}^2 / \ell \). To summarize, the energy lost per cycle is independent of the mass; the average energy during that cycle is directly proportional to the mass. Thus, all other things being equal, the damping rate, which is proportional to \( \Delta E / E_{\text{total}} \), is inversely proportional to the mass. \( \tau \) would then be proportional to the mass.

**Questions**

1. What is the relation between \( \tau \) discussed above and the time you measured, \( t_{1/2} \), that it takes for the amplitude to decrease by a factor of 2? (Answer: \( t_{1/2} = (2\ln 2)\tau \))
2. How is an infinitesimal fractional change in the period related to an infinitesimal fractional change in the length? (Answer: \( \frac{dT}{T} = \frac{1}{2} \frac{d\ell}{\ell} \))

3. How well, fractionally, could you determine the period \( T \)? How accurately, in cm, would you have to reposition the mass to set \( T \) to the same value within your experimental ability to determine \( T \)?

4. What was the \( Q \) of the oscillator in each case?

5. Damping causes the actual frequency \( \omega_f \) to fall below the undamped frequency \( \omega_0 \). Should you be able to measure this frequency (or period) shift when you change to the lighter mass?

6. Were your damping times proportional to the mass? If they were not, do you think the discrepancy is due to the measurement accuracy or to other sources of damping?
Take-Home Experiment #2

COUPLED OSCILLATORS, RESONANCE, AND NORMAL MODES

Objective  A system of coupled oscillators that is easy to construct and adjust is used to demonstrate the concepts of resonance and normal modes.

Experiment  Use the braided fishing line to rig a horizontal string under moderate to heavy tension between two secure end posts. Aim for a free length of about 30 cm. The legs of a desk chair work well as the end posts. Tie two lengths of line, each about 30 cm, to the horizontal string and let them hang vertically. Position them symmetrically about the center of the horizontal string. Slip a 1.5 oz weight onto each vertical string; secure it near the free end by jamming a wooden plug in the hole.

Displace one weight about 10 cm in a direction perpendicular to the horizontal string and let it go. If the two pendulums have the same length, they have the same frequency and we say they are in resonance with each other. Under these circumstances, the energy should slowly shift away from the first mass into the second. After a while the second mass will be swinging and the first will have come temporarily to rest. Then the energy will shift back again to the first. See how close you can come to this ideal situation by adjusting the position of the mass on the second string. Try changing the tension in the horizontal string. How does the tension effect the time it takes for the energy to shift from one mass to the other?
Change the position of one of the weights by about a cm and do the experiment again. Now the two pendulums are no longer exactly resonant with each other. Only a fraction of the energy in the first pendulum ever gets transferred to the second. The first mass never comes to rest. Explore the effect of successively larger detunings. Describe briefly.

Change the positions of the masses back to a resonant condition. A normal mode of a set of coupled variables is defined as pattern of motion of the system as a whole in which the relative amplitude of the variables is independent of time. All the variables oscillate at the same frequency, they differ only in maximum amplitude and in relative phase. Figure out and try to excite the two normal modes associated with motion of the two weights perpendicular to the string. Were you successful?

Now try three coupled masses. Careful adjustment is necessary to get the most pleasing results. Use the ruler to center one vertical string between the supports and to position the other two strings equal distances to the left and right of the center. When positioning the 1.5 oz. weights to attain equal uncoupled frequencies, note that the point where the center vertical string is attached to the horizontal one is somewhat lower than where the other two vertical strings are attached. Thus, to get equal pendulum lengths, the center mass will be a corresponding distance below the two outboard masses.

Displace and release the center weight. Watch the energy flow away into the outboard masses and then (hopefully) return. Displace and release one of the outer masses. The evolution of the system is now more complex because of the lack of symmetry. But the same general result should be observed. The energy flows away from the perturbed mass and eventually returns.

While the system is tuned to resonance, try to figure out and then excite the three normal modes associated with motion of the weights perpendicular to horizontal string. It will
be harder to excite the modes with three masses than it was with two because the initial displacements for two of the modes require specific amplitude ratios which are hard to obtain by eye. Sketch the three modes you expect. Did you find them?

Finally, examine the effect of moving away from the complete resonant situation. Change the length of one pendulum. Excite that one and see how much of the energy gets coupled out. Excite one of the two equal length pendulums and see where the energy migrates. Make all three lengths different. Now what happens when any one of the pendulums is initially excited?
Take-Home Experiment #3

VIBRATING STRING: RESONANCE IN A CONTINUOUS SYSTEM

Objective  The normal modes of continuous systems are usually displayed by sweeping the frequency at which the system is driven through the fixed resonant frequency of the mode. Variable frequency oscillators are common laboratory instruments, but are somewhat expensive. In this experiment the drive frequency is held fixed at an easily obtainable value. It is the resonant frequency of the normal mode which is swept by changing a parameter of the system.

Experiment  Use the double sided masking tape to secure the pulley block at the edge of a table or desk as shown above. Tie one end of the clear nylon fishing line (280 yards weigh 1/4 pound) to the 10 ounce (nominal) lead weight. Tie the other end to the screw eye in the drive block leaving about 115 centimeters of line between the two knots. Position the drive block on the desk and hold it in place with something heavy (a pile of textbooks works well). Guide the line over the pulley so the lead weight hangs vertically. Use some Scotch tape to attach a wire brad to the under side of the line (see detail above) about one centimeter out from the knot at the drive block. Connect the AC power supply to the solenoid. Place the solenoid under the wire brad and shim it up until it is only a millimeter or two below the brad.

Start with the lead weight suspended just off the floor. You should have no more than 20 cm of line between the pulley and drive block. Plug in the power supply. Slowly draw back the drive block while watching the line. When the line starts to vibrate, adjust the position of the solenoid to get the maximum amplitude. Now adjust the position of the drive block to find the exact line length for this resonance. Measure the length between drive block knot and the top of the pulley.
Observe the mode pattern on the string. Is the mode linearly polarized (in other words, is the deflection of the string in one direction only)? Can you change this by changing the position of the solenoid relative to the wire brad? Does the vibrating line look any different under fluorescent (gas discharge) light than under a tungsten (filament) source? Why does the image of the line look brightest at the ends of its swing?

Measure how far you can displace the line length $\Delta L$ on either side of its resonant length $L_o$ before the amplitude of vibration falls to about half of its resonant value (obviously, this is not going to be a precision measurement). Disconnect the power supply from the solenoid and estimate how long it takes for the amplitude of vibration to drop by a half.

Finally, draw the block further back and see if you can find any other resonant modes. Measure the corresponding resonant line lengths.

Questions

1. Which direction will the wire brad move when the electric current runs clockwise through the solenoid as viewed from above the string? Which direction will it move when the current runs counter clockwise? What is the frequency of the current in the solenoid? What is the frequency at which the line is driven?

2. What is the shortest length $L_o$ at which you should find resonance behavior? At what other lengths should you find resonance? [Note: one yard = 0.914 meters, one pound = 0.453 kilograms, and one ounce = 0.0283 kilograms.]

3. How is an infinitesimal fractional change in the length of the line related to an infinitesimal fractional change in the resonant frequency? (Answer: $dL/L = -d\nu/\nu$)

4. For a simple driven damped harmonic oscillator, how far does one have to move away from the resonant frequency in order to see the amplitude of the response drop to one half of its resonant amplitude. Assume light damping and express your answer in terms of $\nu_o$ and $Q$. (Answer: $\Delta \nu = \pm \sqrt{3/4} \nu_o / Q$)

5. Use the results of 3. and 4. together with your observations to estimate the $Q$ of the first resonance.

6. How long should the vibration take to decay to half its amplitude after the drive is shut off? Compare this with your observation. (Answer: $t_{1/2} = \frac{\ln 2}{\pi \nu_o} Q$)
Objective Wave motion on the surface of a liquid is a complex but practical topic. We will investigate just one aspect of the problem, short wavelength oscillations on the surface of a deep fluid. They are called capillary waves, or sometimes just ripples. Under these conditions the restoring force originates in the surface tension and the dispersion relation is given by

$$\omega(k) = (\sigma k^3/\rho)^{1/2}$$

where $\sigma$ is the surface tension of the liquid-vapor interface and $\rho$ is the liquid density. In this experiment you will drive a water-air interface at a fixed frequency and measure the wavelength of the resulting standing wave. From this you can determine the surface tension of water.

Experiment Obtain a half gallon milk or juice carton that has an approximately rectangular cross section. The walls should be quite flexible. Cut off the carton cleanly at a height of about 10 centimeters above its base. Wash the inside and rinse thoroughly to remove any possible soap film. Cut one of the popsicle sticks so that it is about 3 centimeters shorter than the width of the side of the carton. Use the double sided tape to mount it about one centimeter below the open edge as shown below. Use another piece of double sided tape to attach the small magnet to the center of the wooden stick.
Fill the carton with water. Place it under a broad light source in such a way that the water surface acts as a mirror. Connect the solenoid to the 12 volt transformer and bring it near the magnet. Observe the various patterns created on the surface. You may notice that the nature of the standing waves seems to change markedly if the drive is too strong. It is the weaker drive that we need here. Do not expect to see a set of perfectly uniform and parallel standing waves. Rather, aim to set up a pattern for which you will be able to count the number of wave crests across the width of the surface in a reliable fashion. You may find that the pattern can be simplified somewhat by taping another popsicle stick as a stiffener across the outside of the facing carton edge and overfilling the carton slightly so that the surface of the film is above the edge of the carton (stabilized by surface tension).

What happens to the direction of force on the magnet when the direction of current flow in the solenoid is reversed? What is the frequency of the capillary waves being excited? How does this differ from the frequency at which you drove the string in a previous experiment?

On one complete cycle (wavelength) of a plane wave on the surface, how many locations are there that would reflect light from a distant source to your eye? Count the number of wavelengths from one side to the other in your standing wave patterns, measure the carton width, and thus determine the wavelength of the capillary waves at this frequency.

Use the dispersion relation above to derive a relation between the wavelength \( \lambda \) and the frequency \( v \):

\[
\lambda = \left[ \frac{2\pi \sigma}{\rho v^2} \right]^{1/3} .
\]

Use your measurements to determine a value for the surface tension of water. The accepted value is \( \sigma = 73 \text{ dynes/cm} \) at a temperature of 20\( ^\circ \text{C} \).

You can use the magnet and solenoid to drive capillary waves in other containers. Try a plastic cup with a circular opening (no need for the popsicle stick here). Can you get a change from the weak to strong drive patterns in this geometry?
3B - POLARIZATION OF LIGHT

Objective In this experiment you will investigate the various polarization states of light with the help of polarizers and retardation plates.

Experiments

Polarizers The polarizers in your kit are made from a Polaroid material. You can read about Polaroid materials in the textbook. The material is shipped with a thin plastic protective sheet on each side. Check to see that these have been removed from your Polaroids. The easy axis of the material, along which the electric field has the least attenuation, should be parallel to the short edge of your rectangular pieces. How can you test to see that this is indeed the orientation for your Polaroids? As you do the following experiments think about how the outcome would change if the easy axis of the Polaroids were at some other angle to the edge.

Using two polarizers, observe the transmission and extinction as one is rotated relative to the other throughout the full 360 degrees. For which end of the optical spectrum is the extinction the strongest? Check the consistency of the alignment of the easy axis with respect to an edge for your three polarizers by observing the orientation corresponding to maximum extinction. It is conceivable that some of them were not cut square to the easy axis.

Use one polarizer to search for sources of polarized light. First try primary light sources: light bulbs, fluorescent lamps, discharges, and flames. Examine the polarization of the blue sky, particularly in a direction directly overhead. What about clouds in the same position in the sky? Look for polarization in the light reflected from various objects: water, metallic surfaces, glass or plastic. The light reflected from book covers shows interesting polarization effects. Try looking at a digital watch and the display on a notebook computer through the Polaroid.

Insert a third polarizer between crossed polarizers and rotate it. Be sure you understand why you see transmitted light even though the first and last polarizer are crossed. In which direction is the easy axis of the center polarizer when the transmission is a maximum? Can you achieve a similar effect by having the third polarizer outside the two crossed ones?

Quarter Wave Plate The half and quarter wave plates in your kit are made of a birefringent plastic. The fast and slow axes should be parallel to the edges of the rectangular samples. The difference in the optical path lengths for the two orthogonal directions of incident polarization is 140 nanometers for the "quarter wave" material. For what color will this actually be a quarter wave plate? What fractional wave material will this be at either end of the visible spectrum, 400 and 700 nanometers?

Place the quarter wave plate between two polarizers. Hold the plate at various angles, θ, with respect to the first (polarizer) while rotating the second (analyzer)
through a full 360 degrees. For what values of $\theta$ can you achieve complete extinction? For what values of $\theta$ is the transmitted intensity least sensitive to the orientation of the analyzer? How should one set $\theta$ so that the polarizer and quarter wave plate produce circular polarization? linear polarization? elliptical polarization? Cross the polarizer and analyzer then rotate the quarter wave plate between them. At what angle $\theta$ is the transmission a maximum? Can you explain why this is so?

You should have noticed that the color of a white object being viewed through the stack changed slightly during the rotations carried out above. Why is that? Set up the polarizer and analyzer to produce circularly polarized light. Place various color filters in front of the stack and use the analyzer to determine how close the polarization is to circular. The apparent effect will be subtle since the eye tends to have a logarithmic response to intensity. It responds over many orders of magnitude, but has difficulty distinguishing small changes in absolute intensity.

Try the following coin trick. Place a silver coin on a piece of black paper. Hold the quarter wave plate and a Polaroid together with their edges rotated by 45°. Place the stack on the coin, plate side up. Now you see it. Place the stack on the coin, plate side down. Now you don’t. Why is this? Can you think of a way of using a Polaroid and a quarter wave plate to make an anti-glare filter to use with computer screens? If you can, don’t rush to patent it; someone else got there first.

**Half Wave Plate** Test the supposition that a half wave plate rotates the plane of polarization of linearly polarized light through an angle which is twice the angle one of its axes makes with the incident polarization. Try this with and without the color filters. The material used for these plates has a retardation of 280 nanometers.

**Make Your Own Wave Plates** It turns out that clear cellophane tape (it has to be glossy, but not all clear glossy tape is cellophane) and saran wrap develop birefringence during their manufacture. Put a piece of clear cellophane tape on a microscope slide and test it. The retardation should be of the order of a quarter or half wave. Try some of the saran wrap from your kit. Its retardation is less. It may take several layers to build up a quarter wave of retardation. Beware of Scotch Magic Tape. It is great stuff, but not for this application. The substrate is not very birefringent, and it depolarizes the light by scattering.

**Stress Birefringence** Plastics which may not naturally be birefringent can develop birefringence when stressed. The total path length difference through the sample can be 1000 nanometers or more, thus the effect on linearly polarized incident light can be much more wavelength dependent than you saw in the above experiments. This can lead to some very colorful displays. Set up two crossed polarizers separated by an inch or two. Taping them to the opposite covers of a thick textbook is one possibility. Now place various objects between them and look at the transmitted light. Try some of the following: drafting tools
such as triangles and French curves, hard plastic boxes such as CD and audio
tape cases, a clear plastic tape dispenser, a clear plastic picture frame, eyeglass
lenses, and stretched or crumpled plastic or cellophane sheet.
Take-Home Experiment #4

SCATTERING OF LIGHT

Objective In this experiment you will investigate the scattering of light by a collection of independent, isotropic, polarizable particles. You will be able to observe the frequency dependence of the scattering and the polarization of the scattered light. It is just this sort of scattering that produces the color and polarization of sky light, where the polarizable particles are the molecules that make up the atmosphere.

Experiment Obtain a half gallon milk or juice carton with flat, rectangular sides. Either plastic (translucent) or plastic covered cardboard (opaque) will do. Cut the carton off evenly at a height of about 6 inches above its base. Use a penny as a template to cut two circular holes in opposite vertical faces, centered about 2 inches from the top. Use the RTV to cement a microscope slide (oriented vertically) over each hole on the inside of the carton. Use enough RTV to ensure a water tight seal of the glass to the carton, but not so much that it squeezes out and obscures the resulting window. You may find it helpful to hold the slides in place with Scotch tape until the RTV has set (about 24 hours).

Fill the carton with clean, cold water to within about an inch of the top. Adjust the mini-maglite to produce a roughly parallel beam of light. Prop it up so that the beam goes in one window and out the other. Turn out the room lights and look down into the water from above. Apart from stray light at the windows, you should not be able to see the beam traversing the water. (It is possible that floating pieces of dust in the water may
be illuminated and give some indication of the beam path.)

Add a few drops of milk to the water and stir thoroughly. Continue adding milk by this process until you can distinguish the beam path by a faint glow in the water. The glow is caused by scattering of the light by the tiny droplets of milk which range from 1/2 to 2 microns in diameter. The light in the beam is traveling horizontally; the scattered light that reaches your eye is traveling vertically. Look at the scattered light carefully. What color does it appear to be? Look backwards through the exit window at the light which has traversed the water without scattering. What color does it appear to be?

Look at the scattered light thorough a polarizer. In which direction is it polarized? Why? Next put the polarizer in the flashlight beam before it enters the water. What happens to the intensity of the scattered light which you see from above when you rotate the polarizer? Why?

Repeat the above series of observations with higher and higher concentrations of milk. The character of the results should change when the probability becomes appreciable that the light which reaches your eye has been scattered more than once. Can you use the results in this case to explain the difference in color and polarization between clouds and the clear sky?
Take-Home Experiment #5

REFLECTION OF LIGHT: THE FRESNEL EQUATIONS

Objective The Fresnel equations describe the ratio of transmitted or reflected electric field to the incident electric field when electromagnetic radiation impinges on an interface between two different indices of refraction. The result depends on whether the incident electric field is parallel or perpendicular to the plane of incidence; thus there are four separate equations. The results are plotted as a function of the angle of incidence in the figure below. We will explore the physical meaning of these results by doing a simple experiment.
**Experiment** Clean one of the microscope slides. Find a room with a high ceiling and a ceiling light under which you can stand comfortably. Stand erect with a hand holding the slide at your side. With your arm pointing toward the floor use the slide as a mirror to view the ceiling light. You are looking at light reflected at near normal incidence ($\theta = 0$). Actually, you are looking at two images of the light, one reflected from the top surface of the slide and one from the bottom surface. Since the two surfaces are probably not exactly parallel to each other, you may be able to distinguish two different images of some sharp feature on the light fixture.

Note in the figure that at $\theta = 0$, $R_{\parallel}$ and $R_{\perp}$ have identical magnitudes of 0.2. Therefore each image has 4% of the incident intensity and the combined intensity is 8%. You should have no difficulty perceiving that the reflected image is weaker than that seen when looking directly at the ceiling light. You may wish to compare this reflection to that from a small mirror held in a similar position.

Slowly raise your arm in a circular arc in front of you. Simultaneously tilt the slide so that the ceiling light remains in view. You should see that the image reflected by the slide is getting brighter. When your arm is pointing almost at the light the image you see is reflected at grazing incidence; that is, $\theta$ is almost 90 degrees. In this position you should be able to compare the reflected and the direct image of the light. You should see that there is no apparent difference in the brightness of the two images. This corresponds to the right hand side of the graph where the magnitude of the electric field ratio for reflection goes to one. The clear glass slide becomes a perfect mirror near grazing incidence!

Repeat the above experiment using a polarizer near your eye. The Fresnel equations predict that at normal incidence and at grazing incidence the reflectivity will be independent of polarization. Test this first. Now sweep through the full range of angles with the easy axis of the polarizer horizontal. This corresponds to $R_{\perp}$ in the graph. The brightness of the reflected image should be a monotonically increasing function of $\theta$. Next hold the easy axis of the polarizer vertically. How does the brightness vary with angle now? Can you tell when you are at Brewster’s angle?

You can try to measure Brewster’s angle as follows. Determine a position on a wall of the room that is exactly at your shoulder height. While holding the slide directly under the light, find Brewster’s angle and then sight through the slide to a second position on the wall above the first. Measure the difference, $h$, between these two heights and the distance, $d$, of your feet from the wall. Prove to yourself that under these circumstances $\theta_B = \frac{1}{2}[90^\circ + \tan^{-1}(h/d)]$. See what value you get.

**Note:** *If you do not have easy access to a room with a high ceiling, you could try this experiment in a horizontal plane in your own room. Position a light source at eye level. You could use the mini-maglite as a source, but it is hard to judge the intensity of a bright small source. You can get around this problem by putting a handkerchief over the face of the flashlight.*
LIQUID PRISM

Objective In this experiment you will construct a hollow prism which can be filled with various liquids and used to study refraction.

Construction Note: The actual time necessary to make this prism is not very long; however, since the RTV requires up to 24 hours to set properly you should allow several days to complete the construction. Begin by cleaning four microscope slides. Place a piece of tape along one of the long sides of a slide so that about half the width of the tape is stuck to the face of the slide. Place the slide on a piece of notebook paper (to avoid a mess) with the tape next to the paper, sticky side up. See Figure A. Use two other slides as spacers as you stick a second slide to the tape, parallel to the first but separated from it by the two-slide-width gap. Be careful to make sure that the short edges of the two slides are aligned. Once the second slide is positioned and stuck down, you can remove the two spacer slides. Repeat this process to tape a third slide to the assembly, as shown in Figure B. Using a fine nozzle on the RTV tube, fill each of the two gaps between the taped slides with sealant.

Prepare several 3 inch lengths of tape and stick them by a small corner to some convenient spot within easy reach. Fold the three slides together so that they form an equilateral prism as shown in Figure C. Position the untaped edges so that they either just touch or are separated by a gap of about half of a millimeter. Make sure the long edges are parallel and that the short edges meet properly. You can maintain this alignment by putting tape across each open end of the prism (it does not adhere very well to the thin edges of the slides) and then folding the tape across the flat sides (where it does adhere well). Take the extra time to insure that the alignment is good and the tape has stabilized the structure. Put RTV along this third long edge of the prism. Make sure that the bead of sealant wets the entire exposed long edge of each slide. I have found that this is the most likely of the three edges to leak. Put your assembly aside and let the sealant set for about a day.

Remove the tape from the two long edges of the prism and inspect your work. Note any spots that might need touching up with more sealant. Put RTV on the three short sides at one end of the prism. Stick it down on a fourth slide as shown in Figure D. Put an extra bead of RTV around the base of the prism and touch up any spots that need it on the long edges. Put your completed assembly away for another day to set.

Fill your prism with water. Note where the leaks are occurring. Empty and dry the prism. Patch the leaks and put the prism aside again. Repeat until the prism is leak free.
Experiments Fill the prism with water. Using the geometry shown below, view
distant objects through the prism. The colors will be most pronounced around the
edge of bright objects. A clean spectrum can be obtained by using the mini-
maglite (with its reflector removed) as a source.

The amount the prism bends a light ray away from a straight path increases with
increasing index of refraction of the liquid. It is also known that for normal
materials, the index of refraction is an increasing function of the frequency of the
light. Hence, colors at the blue end of the spectrum will be bent (refracted)
further than colors at the red end. It is interesting to note that this is just the
opposite to what happens with a diffraction grating. With a grating, the lowest
frequency light gets deflected the most. But look carefully at the dispersed image
of the mini-maglite bulb. The blue end of the spectrum is closer to the apex of
the prism! You do not fully understand what is happening in the experiment
until you can explain this apparent contradiction.

Place the prism on a sunny window sill. If you can get the sun to shine directly
on the prism, you will be rewarded with a fine spectrum somewhere in your
room. Now where does the blue end of the spectrum fall?

Not only does blue light have a higher index of refraction than red in normal
materials, but the rate of change of the index with frequency is greater at that end
of the spectrum. You can see this for yourself with the set up shown on the next
page. Take the reflector off of the mini-maglite and use it as a stand. Find the
transmission grating and tape it to the edge of a convenient support so that its
center is about two inches lower than the bulb. Make sure the grating is oriented
to disperse the light in the vertical plane. With your eye where the prism is in
the figure, adjust the separation between the support and the mini-maglite so that
the center of the spectrum travels horizontally across the room. Position yourself
so that the spectrum appears as a colored vertical line. (By the way, which color
appears highest? Do you now understand why?) Now view the dispersed spec-
trum through the prism. If dn/d\(\lambda\) were roughly constant, the spectrum would
now simply appear tilted at some angle to the vertical. Instead, it has a pro-
nounced curvature which increases toward the blue end.
Different liquids have different dispersing power, which is not the same as saying that they have a higher average index of refraction. You should try different liquids in your prism. (Yes, I know, but beer is mainly water anyway.) One liquid which is clearly more dispersive than water is mineral oil. It can be found in most drug stores, usually in the laxative section. It makes a nice liquid to use if you plan to leave your prism on the window for the pretty effect it produces. The mineral oil does not evaporate as fast as water does, but it is a mess to clean up if it spills.
MOIRE PATTERN SIMULATION OF INTERFERENCE PHENOMENA

Objective The moiré patterns produced by overlapping sets of equally spaced concentric circles are used to demonstrate several important concepts associated with interference phenomena.

Experiment You should have three identical transparencies, each consisting of concentric circles of equal width, alternating between clear and black. Check to see that the transparencies are nearly identical by superposing one over another. The resulting pattern should look just like that of a single transparency. In this situation, the two transparencies are in-phase everywhere: clear overlapping clear, black overlapping black. Displace one transparency with respect to the other. Now there will be some regions in the resulting pattern where the two transparencies are still in-phase and the local pattern is that of alternating clear and black lines. But there will also be regions where the two transparencies are out-of-phase (clear overlapping black) and the local pattern is almost all black.

Each transparency can be used to represent a monochromatic wave spreading from a point source in two dimensions. The wavelength is the spacing between neighboring black lines; the phase of each wave at its source is the same. When waves are in-phase in some region they interfere constructively, resulting in an intensity maximum. Thus the in-phase condition pointed out above for the moiré pattern corresponds to peaks in the interference pattern of the associated waves. Waves exhibit destructive interference in regions where they are out-of-phase; in these regions the intensity pattern would have a minimum (actually a zero if the amplitudes were equal). Therefore the out-of-phase condition described above for the moiré pattern corresponds to minima in the interference pattern. You can now follow the loci of these interference maxima and minima as the sources are moved relative to each other.

Displace one transparency a number of "wavelengths" relative to a second. Observe that the loci of individual maxima and minima form hyperbolas. There is always an interference maximum along the perpendicular bisector of the line joining the two sources. We learned in class that the number of interference maxima for a geometry such as this is the integer part of 1 + (2d/λ) where d is the separation between the two sources. Verify this relation for several source separations of the two transparencies. [Suggestion: d/λ is most easily determined by looking at the relative shift of the transparencies at their largest (last) black circle.]

The location of an interference maximum can be changed by changing the relative phase with which the sources are driven, even if the source locations remain fixed. This is the principle behind phased array radar, where the radar beam can be swept in direction without changing the physical orientation of the antenna. Obviously we can not change the phase of the "sources" imprinted on the transparencies. However, we can simulate the effect at large distances from the sources by moving one of the sources perpendicular to the line joining them.
Separate two transparencies by a wavelength or two. This is most easily done by beginning with exact overlap and then displacing one relative to the other along the long axis of the sheets. Now hold this displacement fixed while displacing the sheets by small amounts along the short axis of the sheets. You should be able to sweep smoothly the angle that the principal interference maximum makes with the center of the "array". For equal transverse displacements (equal changes in relative source phase), how does the angular excursion depend on the source separation $d$? In other words, is the rate of change of angle with respect to phase a function of $d$?

Next try using three sources. This takes careful alignment of the transparencies, but the results are worth the effort. Displace two transparencies by some amount. A source separation $d = 4\lambda$ works well. Again count line displacement at the edge of the pattern to establish the shift. Now overlay a third transparency so that it has the same displacement (in the same direction) relative to the second. It will be displaced by $2d$ relative to the first transparency. Hold down all three at one edge while alternately lifting and returning the third transparency. Watch the interference pattern as you change from two to three sources. You should see that the principal maxima remain in the same location but become narrower. At the same time, secondary maxima appear between the principal maxima.

In the above experiment you changed the number of sources while keeping their separation, $d$, constant. Next, keep the width of the array constant while changing the number of sources. Remove the top transparency and replace it so that its center is located half way between the centers of the first two transparencies. Again study changes in the moiré pattern while folding back and returning the third transparency. You should see that the number of interference maxima remains the same, but the principal maxima become more widely spaced.
Take-Home Experiment #6

THIN FILM INTERFERENCE, DRY

Objective In this experiment and the next, you will investigate the two beam interference pattern that results when light is reflected at near normal incidence from thin films. The phenomena is not hard to see, and the mathematical derivation is not difficult to follow. However, a true understanding of what is happening only comes by examining a variety of examples.

Experiments

Two Microscope Slides Carefully wash two microscope slides and dry them with a relatively lint free material such as a fresh handkerchief. Align one on top of the other and squeeze them together at one end between your thumb and forefinger. Hold them in front of a dark background (such as the supplied black construction paper) and look at the light reflected by the slides from a broad tungsten (filament) light or from the sky (NOT the sun!). You should see that near your fingers the reflected image is crossed by several interference fringes. Toward the center of the slides, the interference pattern should disappear.

In this case the two interfering waves come from the glass-air and air-glass interfaces between the slides. The phase of the electric field is changed by 180 degrees at one of these reflections and is unchanged at the other. Thus if the separation between the plates was much less than the wavelength of light at a given point, there would be destructive interference between the two beams and the "air film" would be completely transparent at that point. [Note that there would still be reflections from the top of the upper slide and the bottom of the lower slide, so there would still be some reflected image from the assembly as a whole.]

As the air gap grows, there will be constructive interference at normal incidence for light of wavelength $\lambda$ when the width of the gap is equal to $(m + 1/2)\lambda/2$ for any non-negative integer $m$. For small gaps (of order 1000 angstroms) this relation is first satisfied for blue light, then yellow, then red as the gap increases. In this region the different thicknesses reflect different colors unequally, thus the reflected light appears colored. As the gap increases further, the interference maxima of different orders ($m$) overlap and the distinction between different colors is washed out. Eventually the average intensity just approaches that which one would get from the two interior interfaces individually. This is what is happening as you look toward the center of the side assembly. The same effect prevents one from seeing interference fringes from the two surfaces of a single slide, no matter how flat and parallel the surfaces may be.

Sometimes when one opens a new box of microscope slides they are so clean and lint free that several will stick together when removed from the box and interference fringes can be seen across the entire sandwich. It is hard to duplicate this condition after the slides have been handled.
Of course if the light were monochromatic one would see the interference fringes for any width gap, as long as the surfaces were sufficiently flat and parallel. Laser light which has been been sent through a diffuser to give it a distribution of angles and a finite spatial extent would provide such a source. Although we can not afford to provide each of you with a laser, you can see for yourself the effect of narrowing the spectral distribution of the light.

Perform the same experiment as above, but this time view the fringes through a colored filter. You should be able to see more fringes for the same configuration of the the slides with the filter than without. The fringes should be visible over a larger area of the slides, that is, out to wider gaps. The filter narrows the spectrum by a factor of three or four, so the fringes should be visible for gaps of up to about 5000 angstroms.

Now for a surprise. Repeat the experiment using a fluorescent light as a source. The fringes are visible over a much wider range than in either of the two previous cases. You know the light is not monochromatic because it appears white (the lighting engineers have gone to great pains to achieve that effect). In addition, you can see that your interference fringes are colored! As it turns out, the fluorescent lights have, in addition to a broad continuous spectrum, several bright and very narrow individual lines in the red, green and blue. It is these lines that dominate the interference pattern and allow fringes to be observed over a much larger range of gaps. You still can not see fringes from a single slide (thickness of about one millimeter) this way, but a microscope cover slip (thickness of about 0.15 millimeter) should exhibit fringes under a fluorescent light.

**Solid Thin Sheets** Try to see interference fringes with a single microscope cover slip under fluorescent light. Each fringe corresponds to a contour of constant thickness. In essence, you are seeing a topographic map of the cover slip. Try some other cover slips; some are flatter than others. Try the same experiment with daylight, then with daylight and a filter. Any luck?

Some transparent solid polymers can be made into very thin sheets which may be uniform enough to exhibit interference fringes. Find a sheet of such material and stretch it over the mouth of a cup or glass to achieve a flat, free standing film. We have supplied a sample of a common kitchen wrap; you should find and test other possibilities. First check to see if the surface smoothness is sufficient to allow you to observe a mirror like reflection of some fluorescent ceiling fixture. If the reflection is distorted on a small distance scale there is local surface roughness which will preclude observing fringes. With some luck you will see a mottled coloring of the reflection indicating interference but thickness variations on a medium scale. If you are fortunate enough to have found a very flat material you will see distinct interference contours, as was the case with the cover slips.

**Newton’s Rings** Any textbook discussing interference mentions Newton’s rings. This is the interference pattern seen in reflection when the spherical surface of a lens is resting on a flat uncoated glass surface. The phenomenon is identical to that which you observed with the two microscope slides. In this case, however, the interference pattern is a visually pleasing set of concentric rings. The text may have a photograph of the rings. The accompanying schematic diagram, a cross-section of the lens resting on the flat and the intervening air space, is guaranteed not to be in scale. The reason is that if the interference pattern is to be visible easily to the unaided eye, the radius of curvature of the lens must be very large.

From the discussion of the microscope slide experiment you should know that the center of the Newton’s rings, where the two glass surfaces are in contact, should be dark. It is not hard to derive the result that the
radius of the $m^{th}$ dark ring is given by $r_m = (m\lambda R)^{1/2}$. Here $R$ is the radius of the curved surface. From this one can see that if the radius of the first dark ring is to be 2 millimeters using light of 5000 angstrom wavelength, the radius of curvature must be 8 meters! A plano-convex lens of this radius of curvature would have a focal length of 16 meters. Such long focal lengths are primarily found in large refracting telescopes.

I have done the Newton's rings experiment with high quality laboratory lenses with focal lengths of about a meter. There are three problems: the radius of rings is quite small, the lenses have antireflection coatings so the contrast of the interference pattern is not what it might be, and the lenses are too expensive to use in take home experiments.

In this experiment we get around the above problems by using two inexpensive uncoated lenses. Find the lens with the largest focal length (the flattest one). Clean it carefully and put it curved surface down on a clean microscope slide. Place the slide under a light source so that you can expect to see interference fringes in reflection. You may be able to see a small black dot which indicates the center of the Newton's rings. Now take the other lens and use it as magnifying glass to inspect the ring pattern. In this way you should see a pattern that is as clear as those shown in books. As in the above experiments, see if you can resolve more rings (with larger diameters) if you use a colored filter or a fluorescent light.
Take-Home Experiment #7

THIN FILM INTERFERENCE, WET

Objective  In the previous experiment, “Thin Film Interference, Dry”, you investigated small scale, static interference phenomena. Here you will have a chance to study larger scale, dynamic phenomena.

Experiments

Chemical Films on Water  Fill the 5 inch diameter flower pot saucer with water. Open the sample bottle labeled Coleman fuel. Use the medicine dropper to place a small drop of Coleman fuel at the center of the water surface. Watch the interference pattern evolve using light at near normal incidence. Use both tungsten and fluorescent light. Try the filter.

Initially the film is so thick near its center that no fringes are visible. Is more or less light reflected from this bulk patch of Coleman fuel than from the surface of the surrounding water? What can you conclude about the index of refraction of Coleman fuel relative to that of water?

There is a gradient of film thickness near the edge of the floating patch and closely space fringes may be seen there. As time advances the patch thins and the fringes spread out over the entire patch. Eventually the entire patch disappears. The time that it takes for the Coleman fuel to disappear depends sensitively on the temperature of the water. Interesting effects can be created by allowing the drop to fall several inches before hitting the water.

What is actually happening to the Coleman fuel? One’s first thought is that it is all floating on the water and evaporating rapidly. On second thought, how can such a large amount of Coleman fuel form such a thin film? Transfer an equal amount of Coleman fuel to the surface of a clean microscope slide. Under these conditions it forms a macroscopic drop which takes a considerably longer time to disappear (blowing on it gently speeds up the process by increasing evaporation). Oil and water may be immiscible, but Coleman fuel and water are not. Evidently the Coleman fuel, or its major components, are dissolving in the water. Your nose, however, should tell you that evaporation also plays a role.

Try putting the kerosene or the Thin-x (an odorless paint thinner) on a fresh saucer of water. Far less of these materials is required to produce the thin films which give
interference fringes. Therefore in these cases it is more convenient to transfer the liquid with a toothpick than with the dropper. The physics is the same as above. The patterns will behave differently, however, since the properties of the added fluids differ.

**Discussion: The Parade of Colors** In the previous experiment “Thin Film Interference, Dry” we pointed out that as the film thickness increases from zero, interference maxima occur first for the blue, then for green and yellow, and finally for the red. This may tempt one to assume that the light reflected from the thinnest edge of our films should be blue, followed in succession by bands of green, yellow, and red as one goes through the first order of interference. Careful inspection of the thin edge of your chemical films will show that this is not the case. Indeed, the edge looks rather colorless, not unlike the reflection from a silvered mirror. The bands of distinct color seem to occur further inward, where the film is somewhat thicker.

The reason for this counter-intuitive result lies in two facts: the spectral resolution of two beam interference is not high and the visible spectrum spans only a relatively narrow range of wavelengths. The visible spectrum extends from about 400nm to 700nm, somewhat less than a factor of 2 in wavelength (or frequency). For the sake of this discussion let us identify the wavelength of blue as 440nm, green as 510nm and red as 660nm.

Consider a situation where a film thickness of zero gives rise to an interference minimum (for example the two microscope slides of the previous experiment or the Coleman fuel on water in this one) and assume the two reflected waves are of equal strength (almost exactly true for the slides, a fair approximation for the Coleman fuel). Let the film thickness be such that the green light experiences its first intensity maximum in reflection.

a) At that thickness, by what factor is the reflected intensity ratio smaller for the red than for the green? (answer: 0.88)

b) At that thickness, by what factor is the reflected intensity ratio smaller for the blue than for the green? (answer: 0.94)

From this one concludes that there will be little modification of the apparent color of a broad source upon reflection at the first order of interference. The apparent color is modified most when an $n^{th}$ order maximum for one wavelength is accompanied by $m^{th}$ order minima for neighboring wavelengths. But $n$ and $m$ must be modest or too many holes will be cut in the spectrum to make the effect resolvable by the eye. That is the case for thicker films where $n$ is of the order of 6 or more.

**Soap Films** Take the supplied sheet of artists’ sketch paper and cut it into quarters, each about 4.5” by 6”. Using the template on the next page as a guide, use the supplied razor blade to make bubble frames. Fold the top of a frame over the wooden dowel and secure it with two paper clips as shown in the illustration. Take two more paper clips and turn them into "S" hooks. After loading the frame with liquid you will need to hang it in a location where the reflection of a bright light (such as a desk lamp or ceiling fluorescent
fixture) can be viewed near normal incidence. You may want to rig a horizontal string for this purpose, or you may be able to use a wire clothes hanger. In any case make sure that the fluid that will drip from the bottom of the frame will not soak your textbooks or your roommate's bed.

Dump the contents of the bottle marked "bubble solution" into the plastic plate. Add ten bottle fulls of water to the plate and mix thoroughly. Dip the frame in the liquid to load it, then hang the frame for viewing. As the liquid drains to the bottom of the frame, the bubble stretched across the opening will thin from top to bottom. You should see a series of strongly colored horizontal bands. Eventually, the film across the top of the frame becomes so thin that it appears completely transparent. Under suitable conditions, the film can last ten minutes or more!

If the film thickness decreased smoothly with height, the apparent color of the reflected light would also change smoothly. The appearance, starting at the top, would be black (clear or transparent), silver (or mirror like as discussed above), and then a series of more distinct colors. The progression would be gradual with no sharp boundaries. Yet in this experiment a sharp boundary appears between the transparent region and an adjacent region of finite reflectivity. This suggests a step-like discontinuity in the thickness of the film, from some value larger than one quarter the wavelength of blue light to a value definitely less than a quarter of the blue wavelength. This is, in fact, exactly what is happening.

To understand the sudden change in film thickness upon draining, one must know something about the surface structure of the soap film. A soap or detergent contains large organic molecules with hydrophilic (water loving) and hydrophobic (water avoiding) ends. When mixed with water, these large molecules ionize. A monolayer of the ionized molecules coats the water-air interface as shown in the first figure; the remainder of the ions are dissolved in the bulk fluid. When a thin film is formed, two of these surface monolayers face each other across a gap filled with bulk fluid. This situation is shown in the second figure. When the width of the gap becomes comparable to the range of the Van Der Waals attraction between the surface monolayers, this geometry becomes unstable. The attractive interaction between the surface layers becomes strong enough to squeeze out the intervening bulk fluid. The surface monolayers snap together to a new equilibrium separation determined by the details of the intermolecular forces. The resulting film thickness profiles as a function of time are sketched in the third figure.

The boundary between the black film and its thicker neighbor can be a dynamic one. If the film settles into a configuration where the boundary is relatively straight (horizontal) you should be able to excite waves on it by tapping the side of the bubble frame. Under other conditions, you may find that the boundary is turbulent. This situation can give rise to a fascinating visual display!
Surface structure of a soap solution.

Molecular structure of a typical soap film, containing anionic surfactant molecules plus metal ions and water molecules.

The cross-section of a typical simple mobile film with a height of 10 cm and cross-section of approximately 1 micron: (a) after 40 seconds; (b) after 120 seconds; (c) after 240 seconds.

Figures taken from *The Science of Soap Films and Soap Bubbles*, Cyril Isenberg (Tieto Ltd. 1978), also now available from Dover Books.
Template of a bubble frame. Make from heavy artists' sketch paper.
Suggestion for hanging completed bubble frame.
Take-Home Experiment #8

DIFFRACTION OF LIGHT

Objective In this experiment you will investigate simple diffraction phenomena by using the small filament of the mini-maglite to approximate a point source.

Experiments Unscrew the front 4 cm. long section of the mini-maglite (the part containing the reflector) and use it as a stand for the light. Press down on the ring around the bulb stem in order to turn the light off while you inspect the bulb (you may want to use one of the lenses from the Newton's Rings experiment as a magnifier). Note that the coiled filament forms an arch. You will want to orient the light so that you are looking at this arch from the side to obtain the smallest possible source width. This means that one of the two brown stripes (the wire leads) in the bulb stem should be facing you when you do the following experiments.

Single Slit Place the light as far away in a room as possible. It will help to dim the room lights and sit in a comfortable position. The conventional method of seeing the fringes is to make a slit in tin foil with a razor blade. Try it. Holding the foil close to your eye, look at the source. Try slits of different width.

Now try a more systematic approach. Tape two razor blades together in the same plane, facing each other with their blade edges nearly touching. The separation should be just perceptible at one end and a few tenths of a millimeter at the other. Look at the source through this variable width slit. Move the slit up and down in front of you eye to change the spacing of the fringes. See if the fringes appear more distinct, or if you can see more of them, when viewed through a colored filter.

Try to find a vernier caliper that you can use for a few minutes. View the source through the jaws as you slowly close them. Remember to hold the "slit" fairly close to your eye.

Airy Rings Use a pin to make round holes of various sizes in the tin foil. Hold the foil close to your eye and observe the circular ring pattern associated with the diffraction.

Rectangular Aperture To make a rectangular aperture use the double razor blade slit and a tin foil slit held together at right angles. Observe that the diffraction pattern rotates with the aperture. How does the pattern change if the two slits are not at right angles?

Double Slit Again the standard method is to make two parallel, closely spaced slits in
the tin foil. It takes some practice to get satisfactory results. I find it useful to use a ruler to make the slits, and then to do some adjusting of the position of the center strip afterward with the tip of the razor blade. One can also open the slit width somewhat by pulling on the foil perpendicular to the direction of the slits.

Another more controlled approach involves two taped razor blades again. This time make the the gap between the sharp edges a uniform width of several tenths of a millimeter. Take a length of fine wire and secure one end near the top of the gap, centered as well as possible. Leave the other end of the wire free so that you can move it to get the best centering in the gap half way down the slit as you view the distant source. Experiment with different blade gaps and wire sizes to get the most pleasing two slit diffraction pattern. Notice how the interference zeros (closely spaced) and the diffraction zeros (more widely spaced) change with the separation and width of the two slits.

**Multiple Slit Diffraction** View the source through a fine-toothed comb. What happens to the pattern as you change the angle of the comb relative to the line of sight (thus decreasing the effective spacing between the slits)? Can you find other common objects that can act as simple multiple slit arrays? What about a transparent ruler marked in millimeters?

**Two-dimensional Diffraction Grating** Now view the source through a piece of finely woven cloth. A handkerchief is one good candidate. Try several samples with different thread spacing. How does the diffraction pattern depend on the coarseness of the weave?
Take-Home Experiment #9

TRANSMISSION GRATING

Objective In this experiment you will explore both the behavior of an optical transmission grating and the nature of various light sources.

Experiments When using a transmission grating, light which is incident at a specific angle on one side of the grating is deflected by different angles on the other side depending on its frequency. If the incident light is coming from an extended source, then there is a distribution of incident angles. In order to resolve clearly two different lines in the source, the angular width of the source seen from the grating must be smaller than the difference in the angles by which the two lines are deflected. Thus, to obtain high resolution, one must use a source with narrow angular extent. A frosted 60 watt light bulb across a dorm room is not so good. A street light several blocks away is better. The filament of the mini-maglite viewed on edge is quite good.

The Grating Set up the mini-maglite as you did in the experiment on diffraction. Hold the grating close to your eye (with its plane perpendicular to the line of sight) and view the resulting spectra. Refer to figure A. You should see the 0th order image (no dispersion) straight ahead and two 1st order spectra (modest dispersion) displaced about 20 degrees to the left and right. You will find that you can view the 1st order spectra more easily if you translate the grating sideways so that the colored streak is centered in the slide frame and your new line of sight is 20 degrees to one side of the source (see figure B). By translating the grating further way from the line between you to the source (figure C) you should see the two 2nd order spectra (more dispersion but weaker), one on each side. Can you find 3rd order spectra?
Bring the grating back into line with the source and close to your eye so that you can see the 0th and 1st order spectra at the same time. What happens when you rotate the grating about the line of sight? What happens when you tilt the grating relative to the line of sight? Is the light in the 1st order spectra polarized? You would get a different result for the polarization if the spectra were generated by a metallic grating. Why do you think this might be the case?

**Continuous Spectra** Examine the spectrum of the mini-magLite. Notice that it has a smooth distribution of intensity throughout the range of colors that are visible. There are no sharp features which would indicate radiation from isolated atomic transitions. This is characteristic of incandescent sources, that is, those generated by heating a filament. Now that you know there are no lines to be missed by a smearing of the spectrum in angle, you may want to look at an ordinary light bulb with the grating. The spectrum will be taller now and the colors easier to appreciate. Examine the transmission characteristics of the colored filters by moving them in and out of your view of the spectrum. With the taller spectral image you could even have the top half unobscured while the filter covers the bottom half.

**Spectra with Atomic Lines** The best place to find line spectra is on the street at night. Look at the mercury vapor type of street lights (blue-green), the sodium vapor street lights (yellow) and the neon signs ("Buy Our Beer!"). These sources should consist of several prominent lines (characteristic of the atoms in the discharge or hot vapor) in addition to a continuous part. Back inside, find a fluorescent light. A fluorescent desk lamp is ideal. Make a cardboard mask with a thin slit cut into it. Tape the mask in front of the bulb. Explore the contention (made in the Thin Film Interference experiments) that there are several sharp lines in the spectrum. Do any of them occur as pairs?

**Other Sources** Exercise your curiosity. Examine the spectra of other sources. Small neon bulbs are sometimes used as pilot lights in inexpensive electrical appliances such as plug strips and surge protectors. What about the flame from a candle, a gas burner? You could try seeding the flame with a chemical such as salt (sodium chloride). Remember the flame tests from chemistry lab?
SOMETHING OLD, SOMETHING NEW
MEASURING THE WAVELENGTH OF LIGHT WITH A CD AND A RULER

Objective Louis Alvarez was an experimental particle physicist who won the Nobel Prize for his development and use of the hydrogen bubble chamber. He was a versatile and imaginative scientist. Among other things, he "x-rayed" a pyramid (searching for hidden chambers) using cosmic rays. To the non-physicist, he is best known for the hypothesis, developed with his geophysicist son Walter, that the Cretaceous-Tertiary mass extinction (when the dinosaurs disappeared) was caused by an asteroid impact.

Alvarez published his first paper while an undergraduate at the University of Chicago (School Science and Math. 32, 89-91 (1932)). It showed how a student could use a phonograph record and a ruler to measure the wavelength of light. A copy of that original paper is attached. You could do that same experiment today. However, using modern materials, the experiment can be updated to give a much larger effect.

Experiment Read the Alvarez article. Note that the diffracted image was only displaced by about 4 degrees in the red (angle FCG in his figure). No problem using small angle approximations here, but the angle is inconveniently small. We will make the following modifications to the experiment:

a) Replace the record with a compact disk (CD). There is no need to break the CD. If you do not have one, you should be able to borrow one from a friend. The line separation is standard on CDs and corresponds to 6300 lines per centimeter.

b) Replace the lamp and shade with the mini-maglite from your kit. Focus the beam so that it is as narrow (parallel) as possible.

c) Arrange to deflect the image of the light horizontally instead of vertically. You will find that the deflection angle for the first order is quite sizable. Arranging the experiment in a horizontal plane will prove to be much easier under these circumstances.

Work on a flat, smooth, horizontal surface of a desk or table. Find a way to hold the CD vertically. One method would be to tuck it into the front lip of the cardboard transformer box and back it up with a wooden block as shown in the figure. Find a way to mount the mini-maglite horizontally so that its beam is horizontal and at the same height as the center of the CD.
Refer to the figure below. Shine the light beam on the CD at nearly grazing incidence from a distance of about two feet. You could start by having the CD bisect the beam. Then translate the CD sideways so that most of the beam is on the side of the CD you will be using. Now, keeping the leading edge of the CD in place, rotate it about that leading edge a small amount so that the beam illuminates the leading horizontal radius of the disk. Look back toward the source from behind the CD as shown (position 1). Use one eye only. If you have rotated the CD too much, you will see two distinct images of the source. The correct amount of rotation almost superimposes the two images.

Move your eye to position 2. You should see a bright spectrum of light. Notice that by moving your eye, you can place the red part of the spectrum just at the leading edge of the CD. At the same time, you can sight just in front of the leading edge on some distant object. Make that object a white target as shown in the figure. A white ruled pad set on edge makes a fine target, and you can number some of the resulting vertical lines. Make sure the target and the CD make a 90 degree angle with the front of the mini-mag light. Now sight from position 2 again to see where on the target your sight line falls when you see red at the edge of the CD. Determine the angle $\theta$ from your measurements of the distances $D$ and $d$. We continue to use the notation of Alvarez and let $n$ be the number of lines per unit length. Then the condition for the $N^{th}$ order of interference from the grating is

$$(n^{-1})(1 - \cos \theta) = N\lambda,$$

where $n^{-1}$ is the separation between the lines of the grating.

Determine the wavelength of red light, of blue light. Your main source of uncertainty should be your ability to identify the correct red or blue from the continuous visible spectrum you are using.
A SIMPLIFIED METHOD FOR THE DETERMINATION OF THE
WAVE LENGTH OF LIGHT.

BY LUIS ALVAREZ,

Chicago, Ill.

The wave length of light may be measured with the aim of a phonograph record, an electric light, and a meter stick. If the reflection of an electric light in the surface of a phonograph record is viewed at a large angle of incidence, it will be seen to be accompanied by several spectra. From measurements of the spectrum closest to the reflected image, the wave lengths of the various colors of the rainbow may be calculated. The record is used as a coarse diffraction grating, and a spectroscope is not needed.

A piece about two inches wide and as long as the grooved portion of the record is broken from the disk. On this piece, the grooves will be almost straight and parallel, as on a reflection grating. The only other piece of apparatus needed in the experiment is an electric bulb with some sort of reflector or shade attached to it. The reflector should be arranged to throw the beam horizontally, and with equal portions above and below the center of the bulb. The lamp is placed against a wall at a distance of five or ten meters from the observer. The latter should be seated directly behind some support for the record, such as the back of a chair. The record is held in the hand in a nearly horizontal position, and the eye is placed as close to it as possible, and directed downward. The record is held so that it may be rotated about a horizontal axis, which is perpendicular to the line joining the lamp with the observer. It is placed before only one eye; the other is used to determine the position of the spectrum on the wall in relation to the lamp. On looking into the record, a reflection of the lamp and its reflector will be seen. If a line joining the lamp and the record is in the surface of the latter, it will be impossible to see the image of the former. But in this case, the image of the upper edge of the shade will coincide with its lower edge, as seen with the other eye. The spectrum will still be seen plainly enough for the purposes of the experiment. Its position on the wall

Reprinted by permission from School Science and Mathematics.
below the lamp should be noted roughly, and a sheet of paper crossed with lines about an inch apart should be pinned on the wall so that the apparent position of the spectrum is on the paper. The lines should be numbered in large numbers for convenience in identification at a distance. Now, any color such as red, will be chosen on which to make the measurements. The record is held in the hand as described before, and steadied on the rest to prevent vibration. It is adjusted so that the image of the shade coincides with the shade as seen in the other eye. Now, the first spectrum will appear to be located on the wall behind the lamp, and the red portion of it will fall on one of the lines drawn on the paper, or between two of them. The particular line is noted by its number, and the distance from this line to the point directly in back of the center of the lamp is measured with a meter stick. The distance from the wall to the position occupied by the record is also measured. The number of grooves per centimeter is determined by using a low powered microscope, or by counting the number of revolutions necessary to move a needle a distance of one centimeter across the disk. Representing these three figures by \( d, D, \) and \( n \), respectively, the wavelength of red light is given by the relation: \( \text{wavelength} = \frac{d^2}{2nD^2} \) cm.

In this manner, the wavelength of any color may be determined.

Sample results obtained by using a small Victor Record, and a frosted electric light globe.
D = 762 cm.
n = 34.9 per cm.
d (green) = 46.5 cm.
d (red) = 52.5 cm.

Wavelengths

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>green</td>
<td>0.00005340 cm</td>
<td>0.00005200 cm</td>
</tr>
<tr>
<td>red</td>
<td>0.00005610 cm</td>
<td>0.00005680 cm</td>
</tr>
</tbody>
</table>

The derivation of the formula is given below. It is based on the wave theory of light, and Huygen's Principle. (See diagram.)

Distance between grooves = 1/n cm.
Path difference between SAF and SCF = AC - BC = \lambda, since first spectrum only is measured. (\lambda represents wavelength).

\[ AB/AC = d/D \]
\[ AB = d/Dn \]
\[ BC^2 = AC^2 - AB^2 = 1/n^2 - \frac{d^2/D^2}{n^2} = 1 - \frac{d^2/D^2}{n^2} \]
\[ BC = 1/n \cdot \sqrt{1 - d^2/D^2} \]
\[ AC - BC = \lambda = \frac{1}{n} \cdot \frac{1}{n} \cdot \sqrt{1 - d^2/D^2} = \frac{1}{n} \cdot \sqrt{1 - \frac{d^2}{D^2}} = \frac{1}{n} \cdot \frac{1}{n} \cdot \frac{1}{D} \cdot \sqrt{1 + \frac{2}{D^2}} \]

\[ \lambda = \frac{d^2}{2nD^4} \]