# Studio Optics

Department of Physics
Fall 2006

# Studio Optics

Welcome to Studio Optics.  The purpose of Studio Optics is two-fold:

1. To teach optics in a phenomenological manner.  The bulk of our understanding of optics is phenomenological, i.e. based on observation and experiment.  Ray optics, mirrors and lenses, telescopes, microscopes, and other imaging devices, polarization, and interference and diffraction were all well understood and used before the electromagnetic theory of light was espoused by Maxwell.  It is important that you view optics as phenomena that can be understood and applied as such to numerous applications.  Ultimately, with other courses in the theory of optics and/or electromagnetic theory, you can complete your knowledge of optics with this important theoretical foundation.  But, in fact, this is not necessary for a significant and useful understanding of optics.

2. To develop a pragmatic, hands-on ability for optics.  In Studio Optics you will not only read about optics, you will not only work optics problems, you will actually do optics.  You will see and experience many of the marvelous effects and results yourself.  It is important that you gain this knowledge in much the same way the original discoverers did, by hands-on investigation.  In this way an extremely important goal is achieved: intuition for optics.

Our method in Studio Optics will be to interweave lecture and experimentation during the time period of the class.  Hence a class might start out with brief lecture on ray optics for lenses and then turn you loose with some lenses to demonstrate to yourself what you just learned in the lecture.  This could then be followed by a lecture/demo combination regarding telescopes and microscopes, and etc.  Assigned homework will usually be problems which will revisit these topics. Nothing like “pete and repete” to learn a topic.

This Studio manual contains over 40 lab-demos. They are written with brevity; definitely non-cookbook.  They suggest what to do; it’s up to you to figure out what to do and then do it. Keep a good notebook, complete but economical in style.  Record what you see and measure.  Show all your work; never erase.

For the intellectually curious, this should be a great class! I wish you success in your study of this exciting and intuitive subject.

Chris Sorensen
University Distinguished Professor
August, 2006

**Acknowledgements.** This work was supported by NSF grant DUE054667 with a matching portion from Kansas State University. My Co-PI's on this grant were Zhenghu Chang, Brett DePaola, Bruce Law and Sanjay Rebello. Wang He, Andrew Jones, Dyan Jones, and Hao Yan assisted in the development of the lab-demos. Andrew Jones also drew the illustrations.

## Studio Optics

### 1. The Method of Complex Amplitudes

Pick a cosine and sine function with the same wave length and similar, but not necessarily the same, amplitudes. Plot them by hand on the same graph. Add them point by point on this graph to find their sum and determine the function that describes this sum, a new wave.

Represent the two functions as vectors (phasors). Add them vectorial, convert this to an algebraic function and compare to the graphical results above.

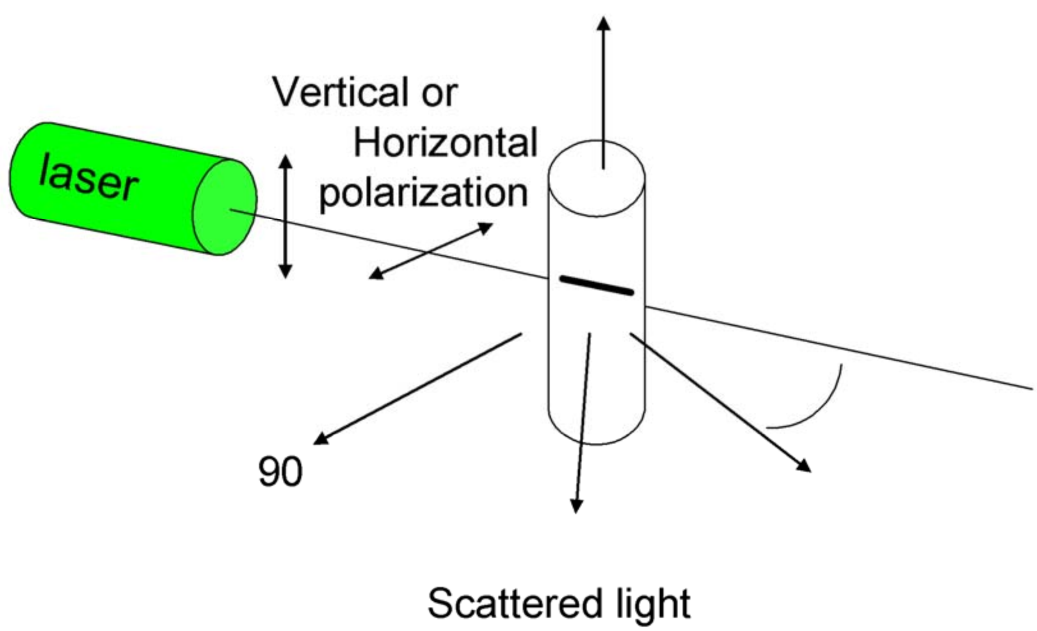
### 2. Fourier Series

Get on the internet and find a site that demonstrates Fourier Series to create functions such as square waves, saw tooth waves, and square pulses. Sketch some of these in your lab book. Note the inverse relationship between real space and reciprocal space ("k-space").

### 3. Light Scattering

Fill a test tube at least halfway with a suspension of scattering particles. Hold the test tube vertically on a support (e.g., a ring stand) and direct a horizontal laser beam with vertical polarization straight into tube and its suspension. Observe the scattered light intensity at all angles from the forward direction in the horizontal plane. Also observe the scattered intensity from directly above, looking down into the tube. Measure the polarization direction of the scattered light in these directions as well.

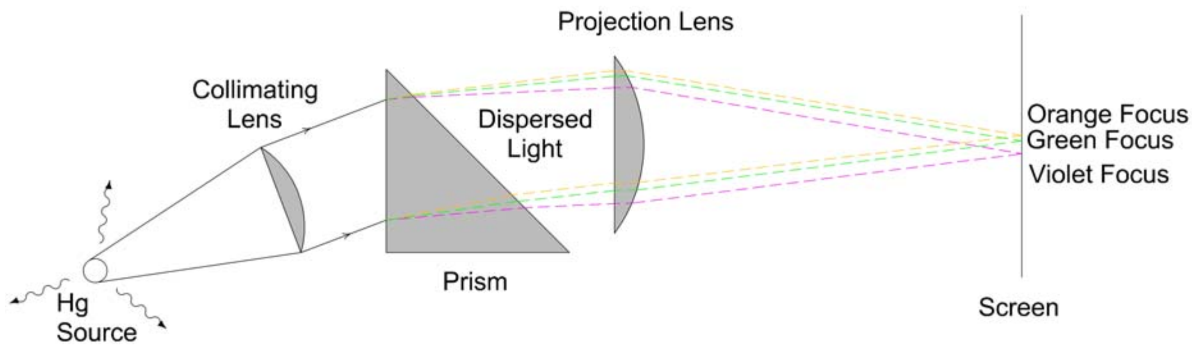
Repeat these observations for horizontally polarized incident light. Explain your observations



## 4. Dispersion

Use a mercury vapor discharge lamp as a light source. Collimate this light (i.e., put it at the focal point of a lens so that the light that comes out of the lens is plane parallel) and direct the collimated beam through a $45^o$ corner of a $45\text{-}45\text{-}90^o$ prism. After the light refracts through the prism, use a long focal length lens to collect it and form images of the lamp on a distant (2-3 meters) screen or wall. Due to dispersion several lamp images will form, one for each wavelength line of the mercury source. Measure the refraction angle for each image. Plot these versus wavelength. According to the Cauchy relation, how should you plot these $(\theta,\lambda)$ data to get a straight line plot? Do it and verify the Cauchy relation.

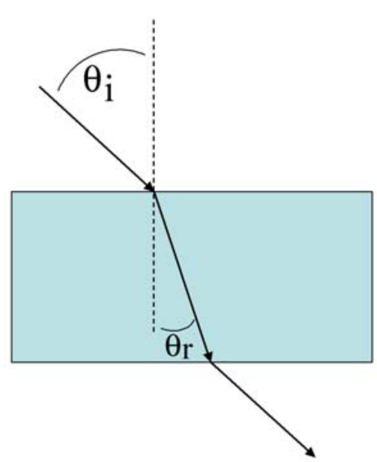
Dispersion




## 5. Refraction

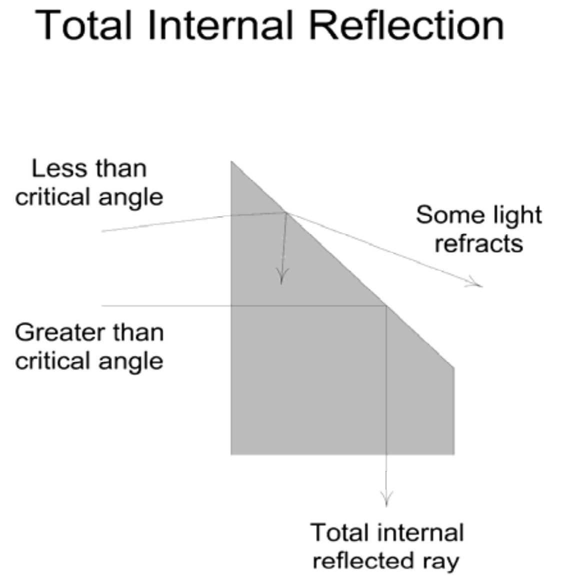
Use the Basic Optics Light Source to shine rays at various angles (a few or more) from the normal into a glass or plastic slab (there is an acrylic rhomb in the Ray Optics Kit). Measure incident and the refracted angles, verify Snell's Law (a graph would be nice), and measure the refractive index of the material. Try this in the small angle approximation, $\sin\theta \simeq \theta$, and see if this affects the determination of the refractive index.

Refraction



### 6. Total Internal Reflection

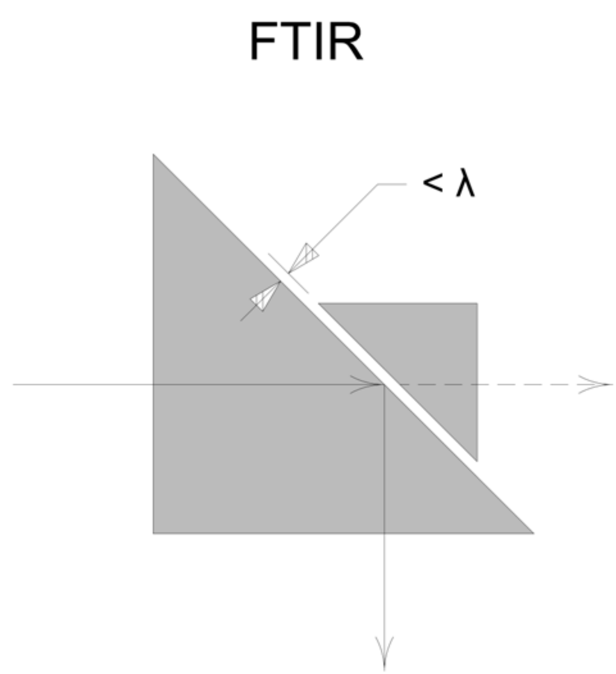
Shine a single beam from the Optics Light Source into the acrylic rhomb of the Ray Optics Kit so that it can possibly internally reflect from the 45° face. Vary the angle to observe reflection and refraction from this interface and, when the incident angle is large enough, total internal reflection. Note the relative intensity of these rays as a function of angle.




### 7. Frustrated Total Internal Reflection

Using a right angle prism and a laser, set up a system displaying Total Internal Reflection (TIR) with a 90° reflection off the prism hypotenuse. Attempt to frustrate the TIR by squeezing another prism against the hypotenuse. How successful is this? Next, place a drop of water on the second prism and again squeeze against the first. Explain what happens and how it differs from the first case.

Repeat the previous experiment, this time pressing the convex side of a short focal length positive lens against the prism hypotenuse. Which method of FTIR is the easiest? Which has the best results? Think about how close a second surface has to be to frustrate TIR and explain.

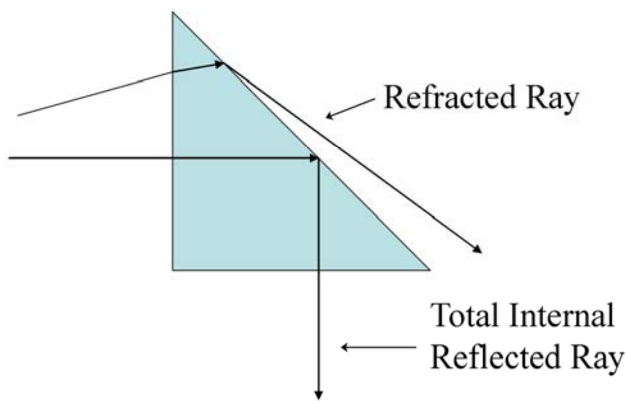


## 8. The Prism

A common 45°-45°-90° prism has a number of important applications which you want to be familiar with.

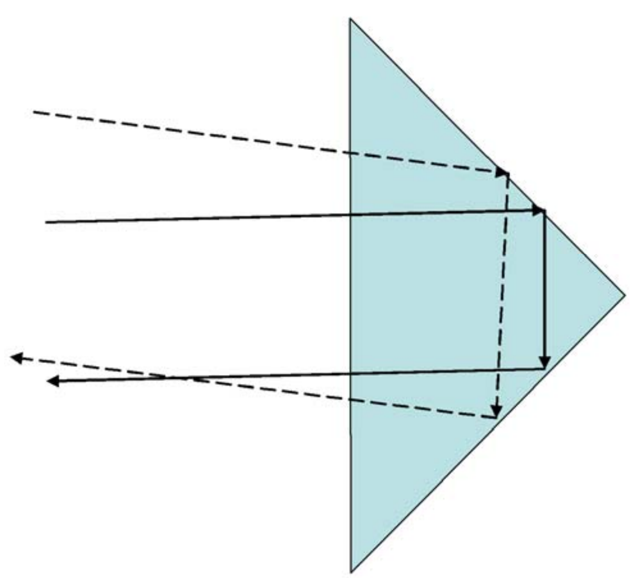
a) 90° deviation. Shine a laser beam perpendicularly into one face toward the hypotenuses as drawn. Light is totally reflected from the clear glass hypotenuse. Look through it this way too and notice the limits of total internal reflection. Also notice the left-right reversal viewing a printed page.

Prisms - right angle reflection

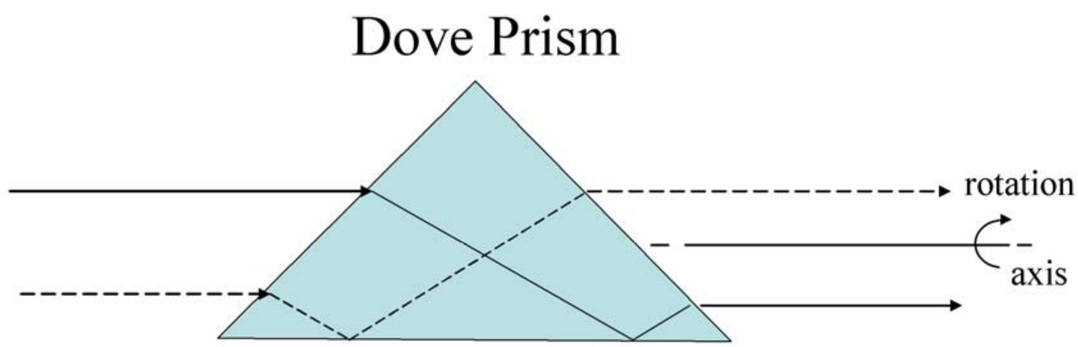



b) 180° deviation. Shine a laser beam into the hypotenuse toward the 90° corner. Look into this corner too. Move from side to side. Notice the beam is always exactly retroreflected. Again there are limits. Hold a printed page under your nose and look at this reflection through this corner. Where is the reversal?

Prism Retroreflection

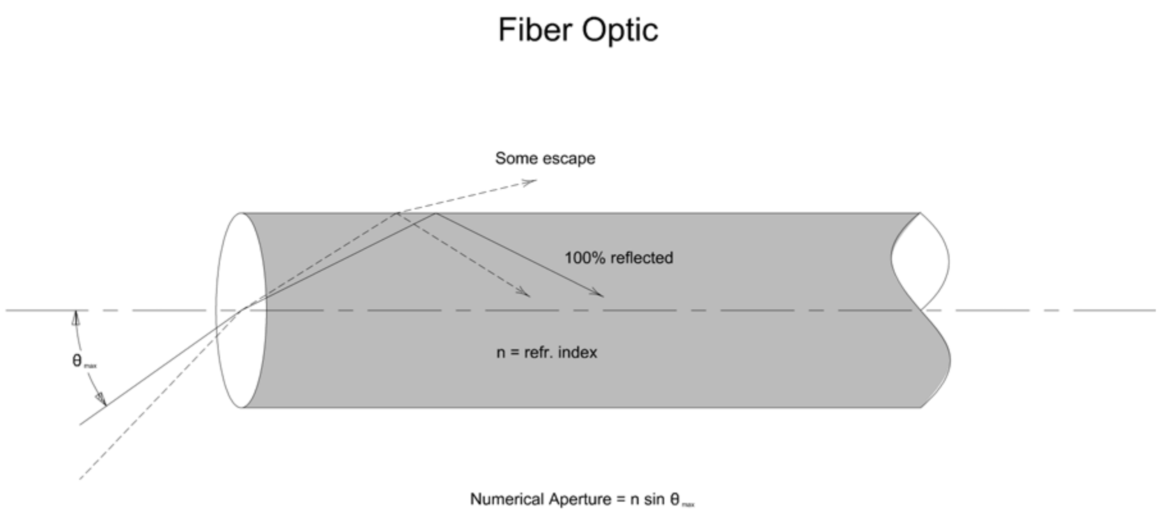


c) Dove prism. Look through the prism along a direction parallel to the hypotenuse as drawn. Rotate the prism about an axis through the prism, parallel to the hypotenuse. What happens? Explain with a ray diagram.



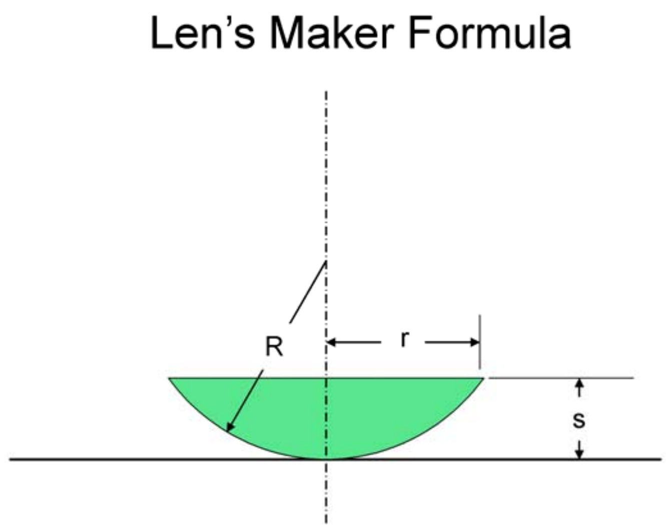

**9. Fibers**

Shine a laser beam into the wall of the cylinder and see it become trapped in the wall. Mess around with the optical fibers.



## 10. Lens Maker's Formula-1

- Measure the diameter of a lens and the sagitta of each curved surface as defined in the diagram.
- Derive a relationship between the sagitta, s, lens radius r, and radius of curvature R (see diagram).
- Use the Lens Maker's Formula to calculate the lens focal length. You will have to make an intelligent guess at the lens's index of refraction.
- Measure the focal length of the lens and then use all these data to calculate the index of refraction of the lens via the Lens Maker's Formula.




## 11. Lens Maker's Formula-2

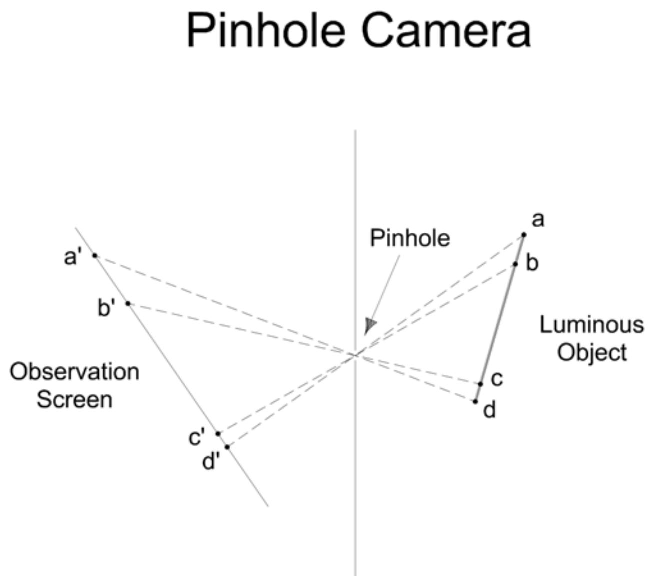
We usually think of convex lenses as positive, i.e., converging, lenses. However, place a convex lens in a medium of the same index of refraction, and its focal length becomes infinite. Place it in a medium with a greater index of refraction, and it becomes divergent with a negative focal length! This is all described by the Lens Maker's Formula and you can demonstrate it with the hollow lens in the Ray Optics Kit with the Optics Light Source. You will have to fill the storage tray with water.

## 12. Ray Optics

Use the Basic Optics Light Source to create three or five parallel beams of light. Project these beams toward the lens and mirror cross sections in the Ray Optics Kit to see how refraction and reflection can cause either convergence or divergence of rays hence focal points. Draw each case and label the focal point.

**13. Pinhole Camera**

Poke a hole in a sheet of cardboard (e.g., the back of a tablet) with a sharp object (a pencil or pen will do). In a dark room hold this between a lamp and an observation screen. You should be able to see an inverted image of the lamp on the screen. Move the arrangement around. Determine the depth of field. Determine the magnification. Notice that very unusual views of three dimensional objects can be obtained. Record and explain your results.




**14. Lenses**

Set up a luminous object (the Basic Optics Light Source has a nice one), a lens, and an observation screen.

- Form an image of the object on the screen using a positive lens. Measure the image and object distances. Compare to the paraxial formula. Vary your object distances from much greater than the focal length f to twice the focal length (the “2f point,” an important point of symmetry) to f. Close than f, what happens? Draw a ray diagram and show consistency with both the calculation and the measurement for your situations. Measure the image and object size and compare to calculation and your ray diagram.
- Mess around with a negative lens. Can you form a real image? Can you ever magnify (enlarge) with such a lens?

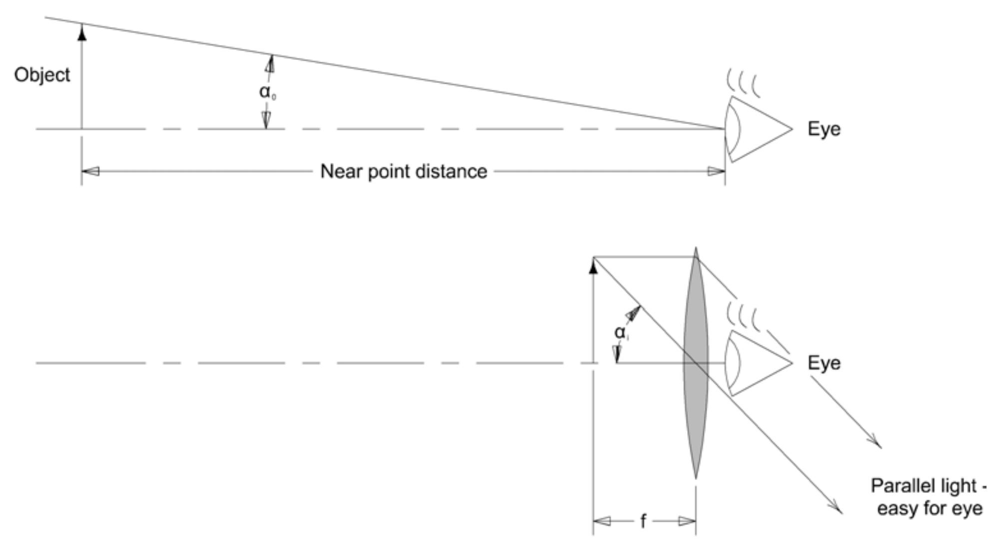
**15. Mirrors**

- Use a concave mirror to form a real image of a distant object. Reverse this, that is, hold a luminous object close to, but greater than f from, the mirror and project an enlarged image on a screen (or wall) far away. Draw a ray diagram to explain your observations. Compare to the paraxial formula.
- Hold the concave mirror close (less than the focal length, f) to your eye to form an image (real or virtual?) of your eye (i.e., look into the mirror). Now move it back until it is one radius of curvature (R=2f) from your eye. Next go further away. Describe and explain what you see with varying distance.
- Mess around with a convex mirror at various distances. Can it ever form a real, enlarged image?

**16. The Magnifier**

- Use a positive lens with a focal length of ca. 5 cm. Hold this close to your eye and then bring an object, e.g., a printed page up to the lens until you can view the magnified virtual image of this object through the lens. How far is the object from your eye/the lens?
- Now remove the lens and hold the object at a distance from your eye so that you can see it comfortably. Measure this distance.
- From these data calculate the apparent magnification.
- Mess around with some other focal lengths.

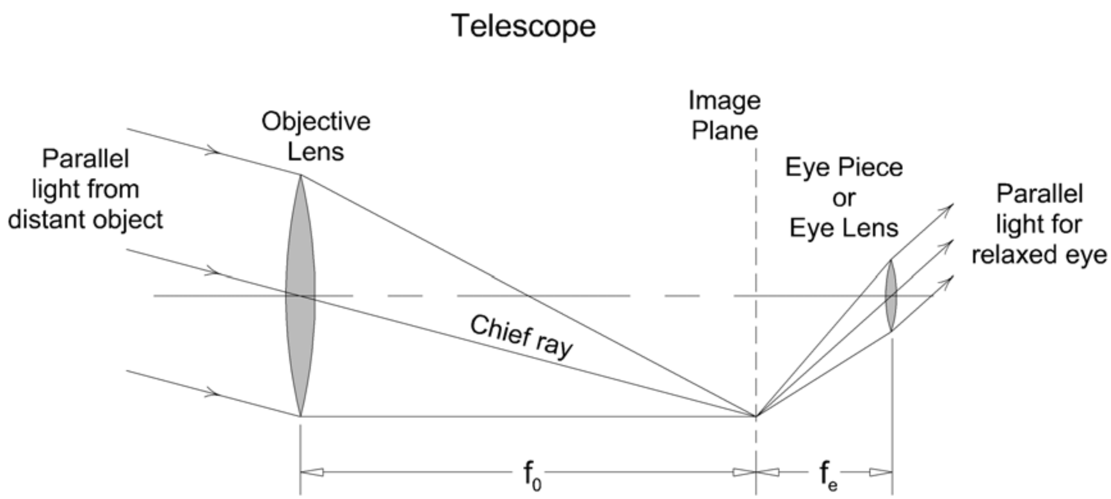
The Magnifier




$$\text{Apparent Magnification} \cong \frac{\alpha_i}{\alpha_o} = \frac{\text{near dist.}}{f}$$

## 17. Telescopes

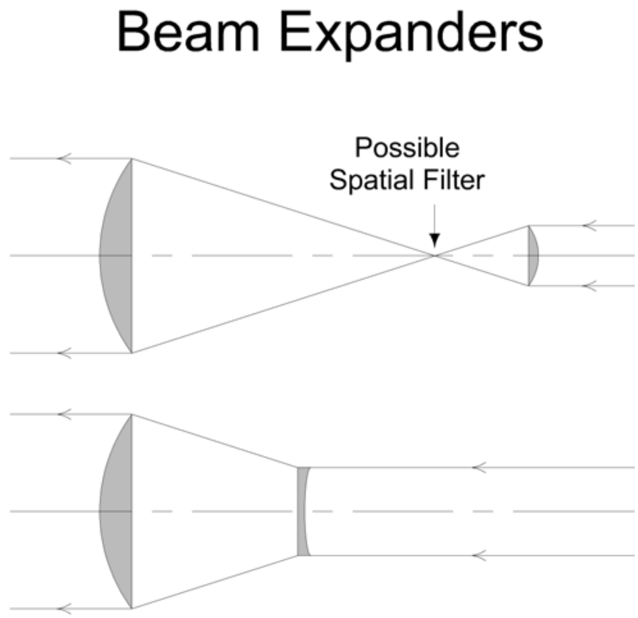
Make a telescope using two positive lenses. A focal ratio of about 5 to 1 works well for this demo. Test your telescope by looking at a distant object. What is the lens separation for a distant object? Verify that the final image is inverted. Calculate the magnification of your telescope. Estimate the experimental magnification by looking through your microscope with one eye, looking at the object with your other and allowing your eyes to relax – your brain will overlap the images. Measure the magnification using the clear aperture and the exit pupil. Change the orientation of the lenses and see which leads to the least image distortion. Why do things look smaller when you look the “wrong way” through your telescope?




A Galilean telescope uses an eye lens with a negative focal length. Make one. Is the image erect or inverted? What is the spacing between the lenses when focused at infinity? Compare this to the telescope with two positive lenses. Also compare both telescopes’ fields of view.

### 18. The Beam Expander

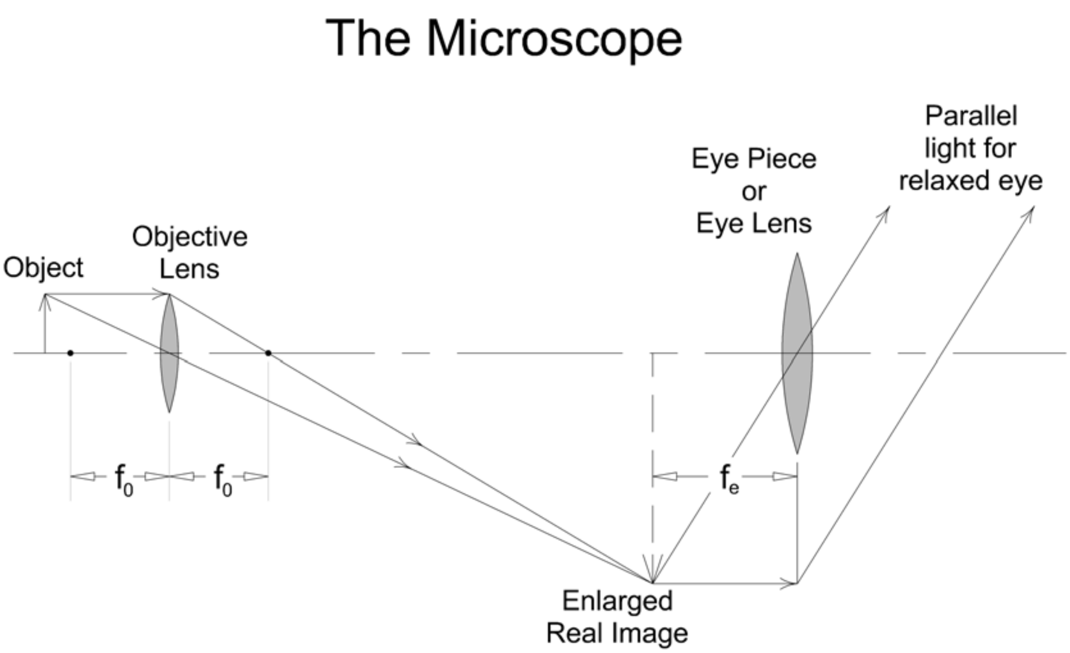
A telescope can be used to expand, i.e., increase the radius of, a laser beam. To do this shine the laser into the eye lens of a telescope, with either a positive or negative eye lens. The beam will be emitted out the objective lens expanded by the ratio of focal lengths, i.e., the magnification. With a positive eye lens a small aperture can be placed at the common focal point between the two lenses to clean up off axis stray light. This is often called a spatial filter. Try this with various small apertures, 1 mm and less, and describe the quality (uniformity) of the expanded beam.




### 19. The Microscope

Build a microscope using two positive lenses. A focal ratio of 1 to 1 works well. Calculate the theoretical magnification then estimate the experimental magnification by looking through your microscope with one eye, looking at the object with your other and allowing your eyes to relax – your brain will overlap the images.

Given two lenses, how can you change the overall magnification?



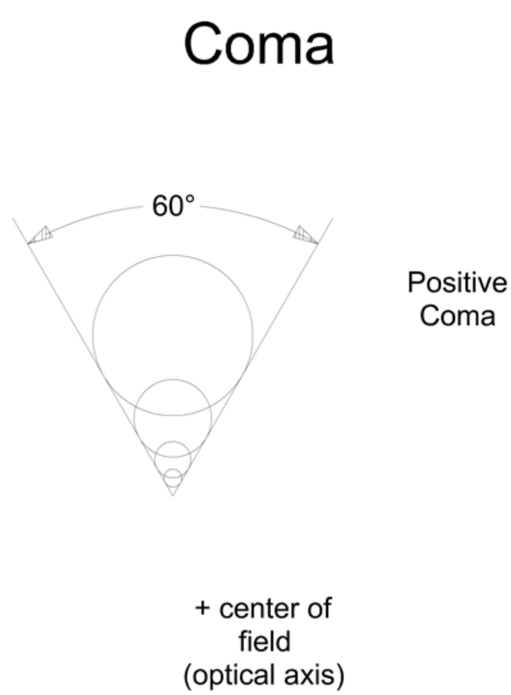
**20. Coma-1**

Use the Basic Optics Light Source and the positive lens shape from the Ray Optics Kit. Shine five rays through the lens and note the focus. Now severely tilt the lens relative to the incident rays and notice how the focus is no longer point-like. This is coma. Sketch this and compare to diagrams in your text.

**21. Coma-2**

Set up a telescope with a meniscus objective lens. Make a “star field” (sheet metal with numerous small holes and a color filter illuminated by a light box). Focus your telescope on the star field. Compare the star images across the field of view, center to edge. Look to the edge of the field and note the visible comatic aberration, or simply, coma. Sketch what you see.

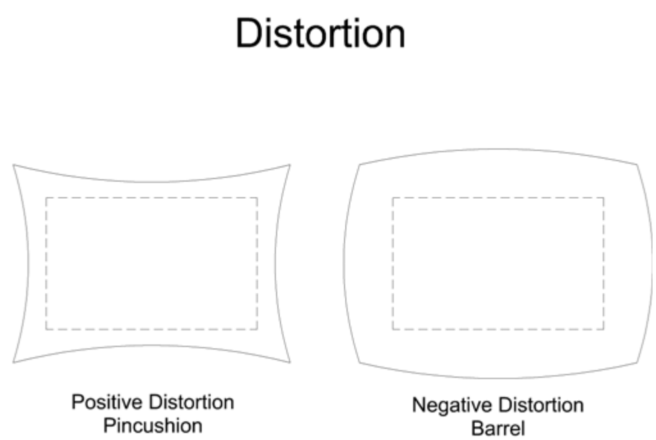
Turn the meniscus lens around, this will change the lens’ shape factor, sketch and note any changes that occur with the coma. Next, replace the meniscus with a plano convex lens and repeat. Qualitatively describe the change in coma as a function of the orientation and shape of a lens.



## 22. Distortion

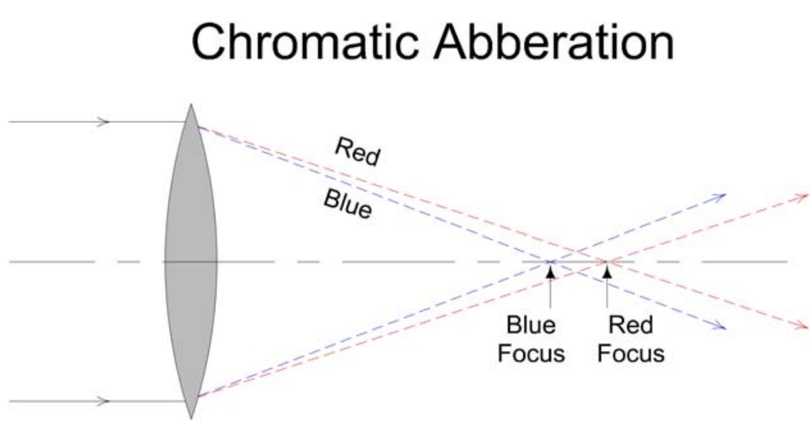
Look at the virtual image of a piece of graph paper through a variety of different lenses in each direction (orientation, which changes the lens' shape factor) and sketch and describe any distortion you see. Qualitatively describe what types of lenses and orientations (shape factors) create the two types of distortion.

Project the real image of a small piece of graph paper onto a screen. This works best for a short focal length lens maintaining a magnification of about one (at the "2f point") and graph paper with bold lines. Experiment with the placement of a stop at different locations along the optical axis on both the image and object sides. Sketch and describe what you seen in terms of distortion and explain.




## 23. Chromatic Aberration

Set up the "star field" in front of a light box and view it with a simple telescope. Notice the chromatic aberration. Set a single pinhole in front of the light box. Adjust the focus of your telescope to focus the red image and then the blue image of the hole. What can you do to change the amount of chromatic aberration? What can you do to eliminate it?



## 24. Polarization in Nature

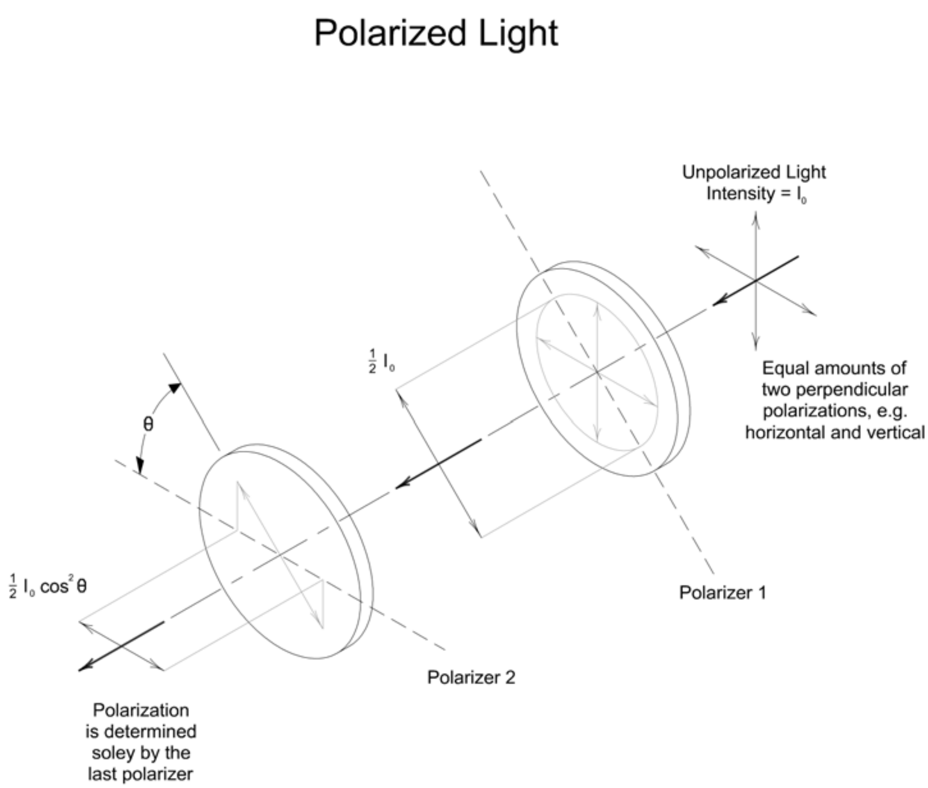
Use a sheet polarizer to check the polarization of natural light sources. Hold the polarizer in front of your eye and rotate it back and forth through 90° as you look at:

- Room lights,
- Light reflected from the tile floor, the optical table, and your finger nails.
- Light from the blue sky at various angles from the sun,
- Light from clouds.
- Electronic devices with liquid crystal displays.

Estimate the angles of maximum polarization effects and compare.

## 25. Polarized Light

- Look through two polarizers and rotate one relative to the other to qualitatively demonstrate the $\cos^2\theta$ functionality (the Law of Malus).
- Cross two polarizers, i.e., arrange them so that their optical axes are perpendicular and hence no light is transmitted. Now place a third polarizer between the two crossed polarizer and rotate its optical axis. Determine and graph both the transmitted intensity and polarization as a function of the orientation of the third polarizer?



**26. Birefringence of Calcite Crystals**

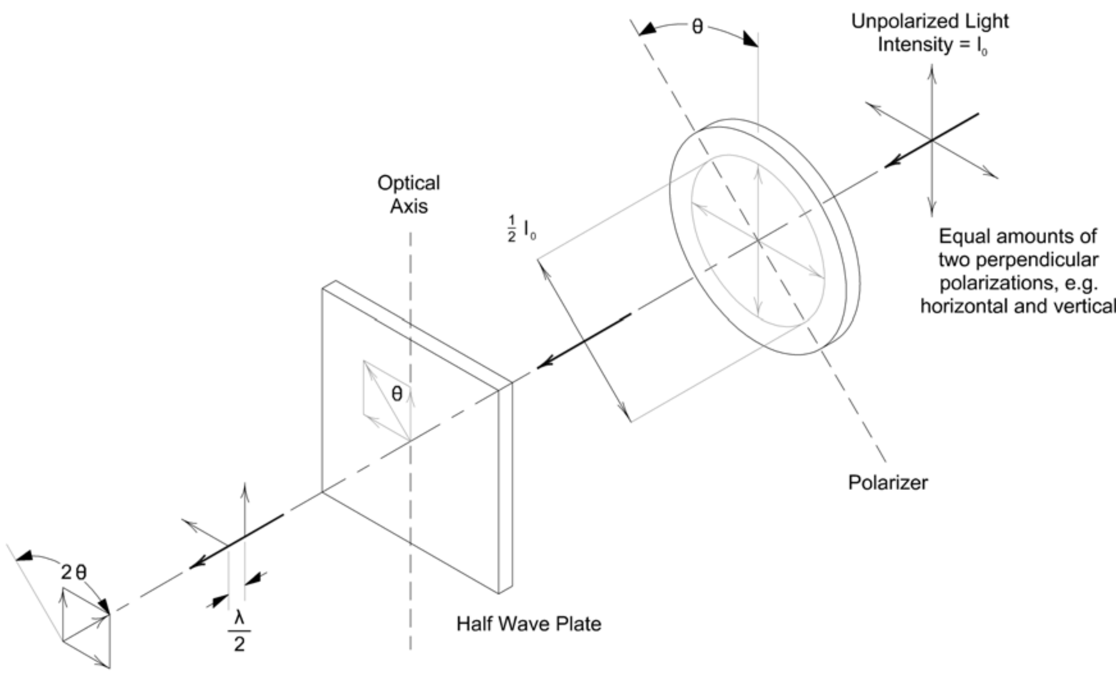
Mark a dot or an x on a piece of paper.

- Place a calcite crystal over it and note the double image.
- Rotate the crystal, describe what happens.
- Use polarizers to determine the polarization of the two images and the rotation effects.

**27. Half Wave Plate**

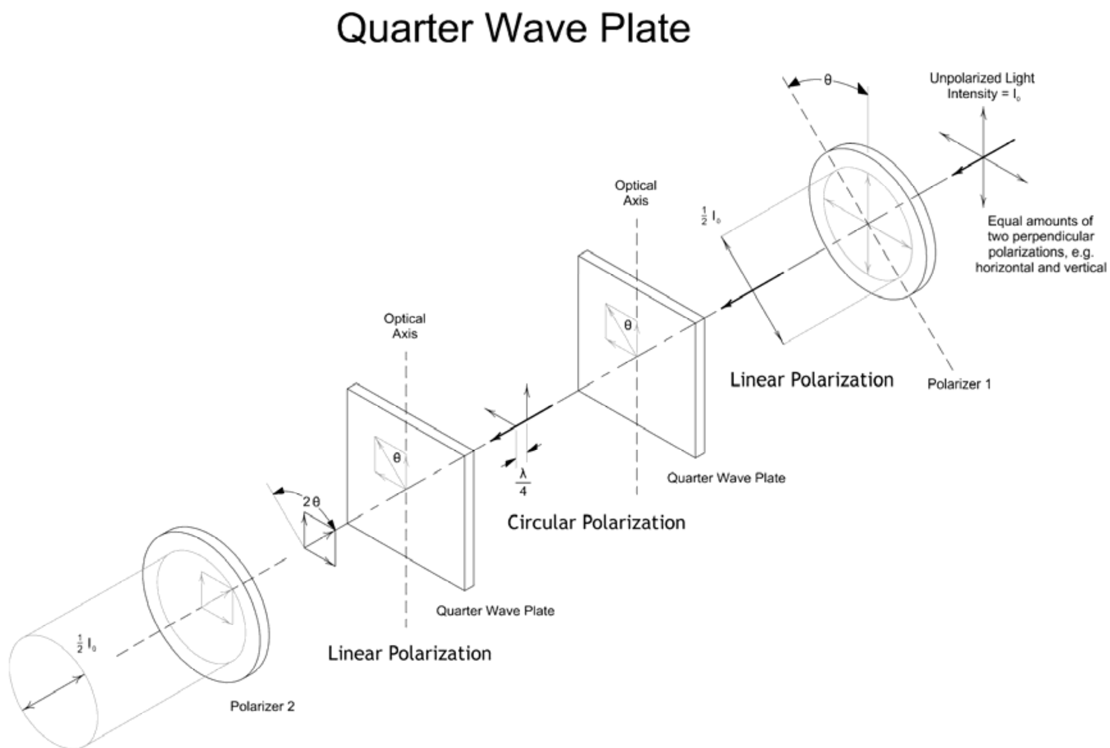
Place a λ/2 plate in a polarized laser beam and determine the transmitted polarization as a function of the incident polarization and the orientation of the optical axis of the λ/2 plate.

Half Wave Plate



**28. Circular Polarization**

Set up a laser with vertical polarization (you might have to "calibrate" against a known polarizer or even reflection off the tile floor). Use a $\lambda / 4$ plate to create both left and right handed circularly polarized light. Observe and graph the transmission of the circularly polarized light through a linear polarizer at various angles. How can you prove with other polarizers and wave plates that you have circularly polarized light? Reflect the light and show that the handedness is reversed.




**29. Optical Activity - Qualitative**

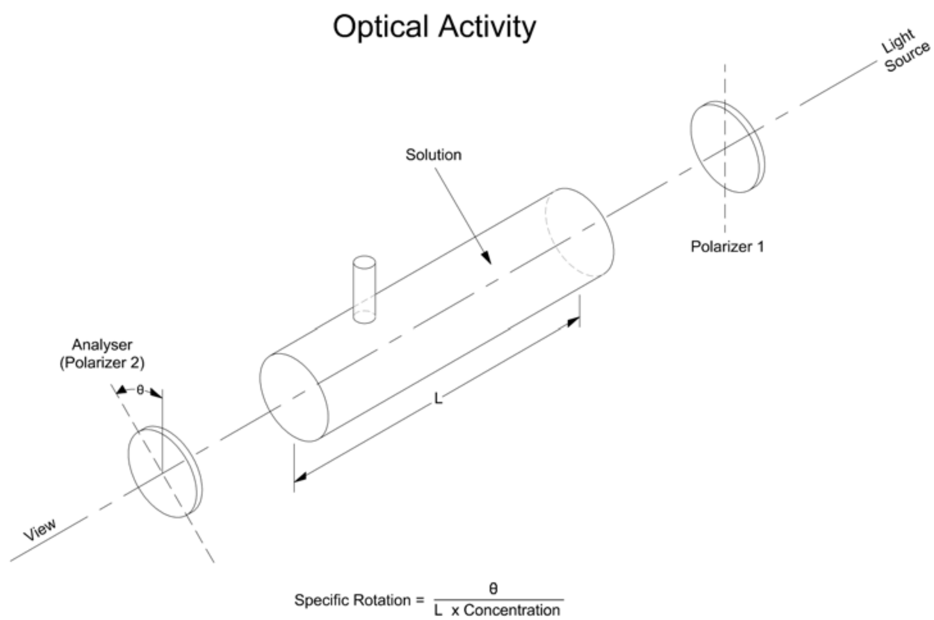
Partially fill a 250 ml. beaker with sugar syrup (e.g., Karo). Place a sheet polarizer on a light box, then this beaker on the polarizer. Look through a second polarizer at the beaker. Rotate the polarizer. Describe and explain your observations.

Repeat this with a variety of materials.

- pieces of plastic (bend them),
- plastic wrap (stretch it),
- plastic bags,
- crystals,
- scotch tape.

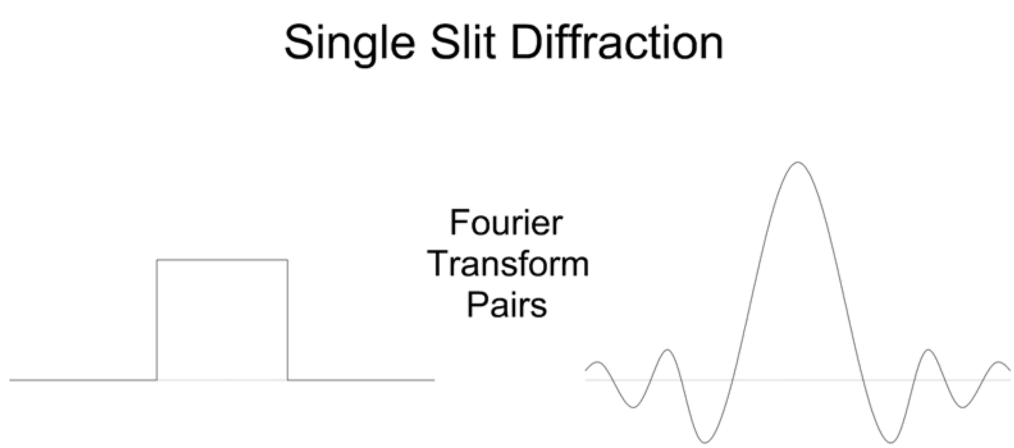
### 30. Optical Activity - Quantitative

Fill a sample tube with an aqueous sugar solution (e.g., Karo syrup, perhaps diluted). Place the sample tube horizontally between two polarizers, all coaxial. Place a quasi-monochromatic light source at one end and view through the other. Measure the angle of polarization rotation by comparing the polarization axes of the two polarizers. Do this as a function of sugar concentration. Graph the result. Determine the specific rotary power.




### 31. Single-Slit Fraunhofer Diffraction

Shine a laser onto a closed adjustable slit. Slowly open the slit until the interference pattern appears on a distant (~1 m) screen or wall. Observe and sketch how the pattern changes with varying widths, and qualitatively explain. Calculate the wavelength of the laser based on the interference pattern that appears and the width of the slit, and compare this to the known wavelength of the laser. (Use a magnifying glass and machinist's ruler to measure the slit width.) Note that you can also try to recreate the diffraction pattern by "squeezing" the laser beam with your thumb and index finger.



**32. Circular Aperture Diffraction**

Illuminate the circular apertures available in the Studio with a laser and project onto a screen that is at least 1m away (to achieve the Fraunhofer limit). Observe and sketch the diffraction pattern. Determine the wavelength of the laser from the measured aperture diameter (use a magnifying glass and machinists' ruler to measure the aperture diameter) and the angular size of the diffraction pattern and compare to the known value.

**33. Babinets' Principle**

Hold a thin fiber, e.g., a hair, thread, or thin wire, in a laser beam and observe and sketch the far field diffraction pattern. Compare this to single slit diffraction. Measure the diameter of your fibers. Compare to caliper measurements.

Shine the laser beam at small circular spots and observe and sketch the far field diffraction pattern. Compare this to circular aperature diffraction. Measure the spot diameter.

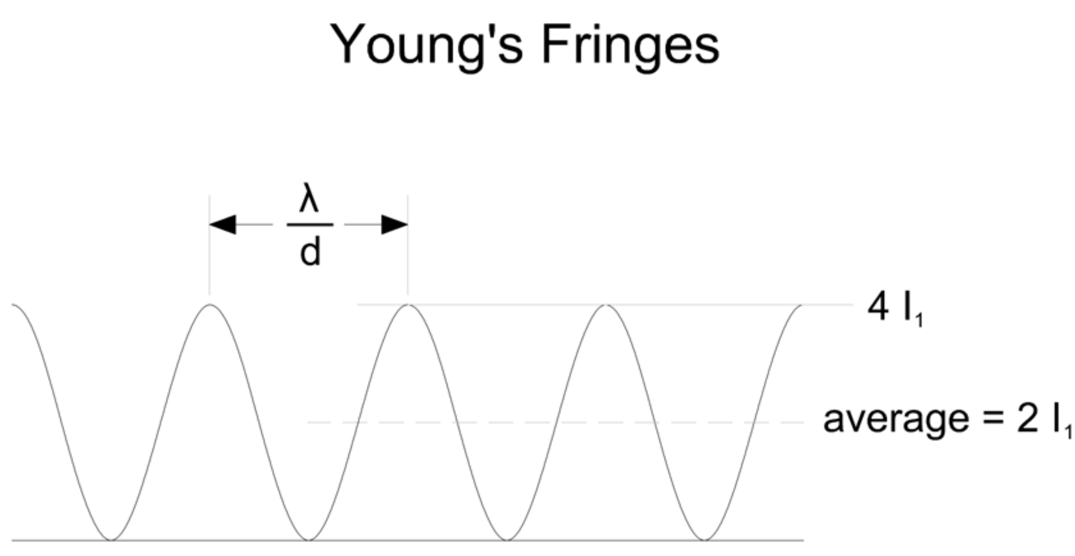
**34. Poisson's Spot**

Expand the beam of a laser by about an order of magnitude with a two-lens beam expander (telescope). Put a circular obstacle with a diameter of a few mm in the beam (the spherical head of a stick pin works well) to create a shadow on a screen or wall a few meters away. Look at the shadow and observe and sketch Poisson's spot. Experiment with the position of the spherical obstacle.

**35. The Double Slit**

Shine a laser at a double slit. Observe in the far field the interference pattern. Sketch the fringes and measure their angular spacing. Use slits of different spacing d. Verify the relation $\theta = \lambda / d$.

Repeat for constant spacing but different slit widths. Sketch and note how the double and single slit patterns convolve.



**36. Multiple Slit Interference**

Shine the laser at a series of two, three, four, etc. slits. Observe and sketch the diffraction patterns on a distant screen. Identify primary and secondary maxima. Determine their number, intensity (qualitative), spacing and width as a function of number of slits and the wavelength.

**37. Transmission Gratings**

Shine the laser at the multiple slit transmission grating with different slits (or lines) per length. Verify the grating equation.

Expand the laser with a beam expander. Shine this beam on the gratings. Note how the expanded beam yields sharper diffraction lines. Explain

Look through these gratings up close to your eye at a light source. Explain what you see. Compare to squinting your eyes and looking through your eye lashes.

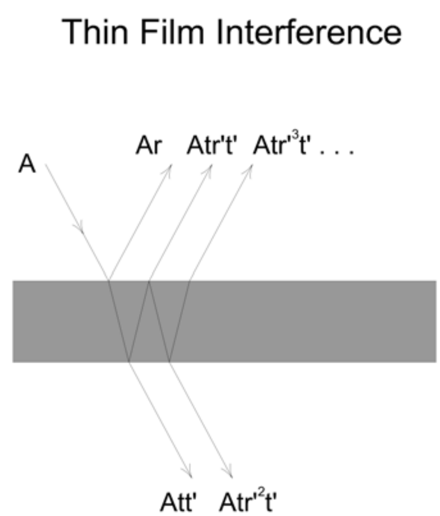
**38. The Diffraction Grating**

Reflect a laser off a diffraction grating. Describe the diffracted spot pattern. Measure the angles for each diffraction order. Find the wavelength of the light using these data, the specified grating lines per unit length, and the diffraction grating formula. Compare to the known wavelength.

Reflect a white light beam off the grating. Observe the spectrum. Measure the angle and calculate the wavelength at the limit of visibility at both the blue and red ends of the spectrum.

Shine a laser through a piece of woven material (e.g., a thin shirt). What do you see? What is the thread spacing?

**39. Thin Film Interference**




Clean two microscope slides with chem-wipes. Press them together with your fingers and look at the reflection of the overhead lights in them. You should see interference fringes. What color are they and why? What happens when you press harder? Why? Estimate the thickness of the air film between these slides based on your observations.

Suspend a soap film on a wire frame in a vertical plane and let it sit for a while (with preferably little air movement around it). Look for interference fringes. Record (draw) these fringes at various times after the initial suspension. What is the thickness of your film?

Blow some soap bubbles. What gives bubbles their iridescent color?

**40. Thin Film Interference with Optical Flats**

Carefully clean the surfaces of two optical flats and then lay one on top of the other so that their surfaces touch. Look for interference fringes when illuminated with a monochromatic light source, e.g., Hg lamp or laser beam expanded upon ground glass. Measure the relative flatness of the flats. Place a thin piece of shim at the edge between the surfaces to make an air wedge. By counting fringes, determine the thickness of the shim. As the spacing between the surfaces goes to zero, is the fringe dark or bright.

Repeat the shim experiment with water in the wedge between the plates. Use this to determine the refractive index of water. View the fringes as you press on the flats.

### 41. The Fabry-Perot Interferometer

Set up an optical cavity using two parallel mirror beam splitters. The simplest way to assure a parallel cavity is to align each beam splitter with the laser individually, and then combine them to make small adjustments. Experiment with the placement of a positive lens after the cavity to better project the image.

Demonstrate resonance in the cavity by adjusting the cavity length. This is very delicate.

Qualitatively measure the coherence length of the 532nm YAG-laser and the red laser pointer by varying the length of the cavity. Explain your results.

Look through the cavity at the diffuse Hg source to observe interference fringes. Estimate the fineness and qualitatively explain this value.

### 42. The Michelson Interferometer

Set up a Michelson interferometer using a mercury lamp as the light source. By looking through the beam splitter into the interferometer, align the mirrors so that interference fringes can be seen. This will happen when the images of the mirrors overlap.

Replace the Hg lamp with a laser. Don't look into the interferometer with the laser on! Allow an image to project onto a far screen or wall and again find the interference pattern. Experiment with the placement of a positive lens at the output side to better project the image.

The book (and many other sources) includes a compensator in their setup, though you have just shown it is not necessary. Explain why that compensator is used and its significance.

### 43. Crossover between Fresnel and Fraunhofer Diffraction—The Single Slit

Beam expand a laser with a simple telescope and then direct it at a narrow adjustable slit. View the Fraunhofer diffraction pattern on a far screen.

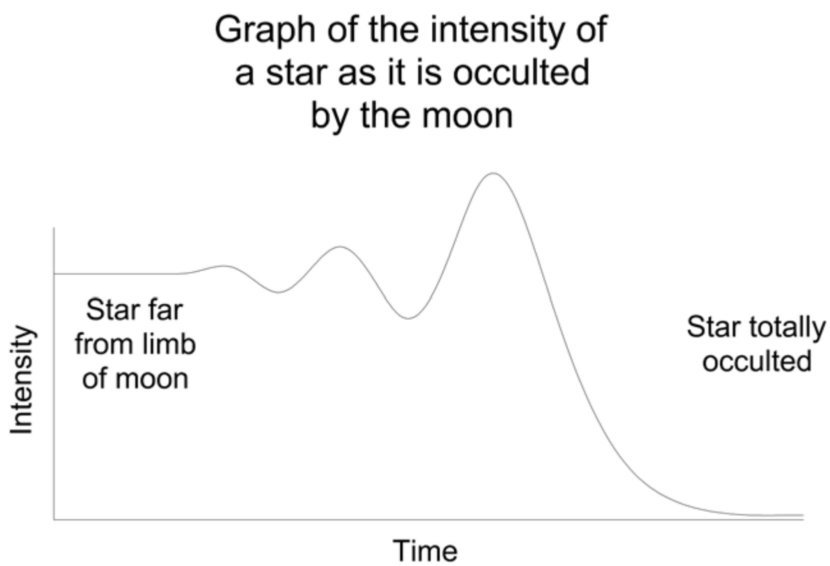
Change the width of the slit and watch the pattern evolve away from the Fraunhofer single slit diffraction pattern. Make a judgment when the Fraunhofer pattern is no longer present (i.e., when the Fresnel pattern begins). Do this for a variety of widths and screen distances. Use these data to determine a rule for approximately when the crossover occurs.

### 44. Crossover between Fresnel and Fraunhofer Diffraction—The Circular Aperture

Follow the procedure for the Single Slit Crossover (above) but for a circular aperture. Use an adjustable iris diaphragm. Since most irises won't close to smaller than ca. 1mm, the Fraunhofer limit might be hard to obtain.

**45. Fresnel Diffraction at a Straight Edge**

Beam expand a laser with a simple telescope and then partially intersect the beam with a straight edge. Observe and sketch the diffraction pattern on a distant screen or wall.




**46. Transverse Coherence**

Double slit diffraction is easy to observe with a laser because the laser has good transverse coherence across, perpendicular to, the beam. Van Cittert and Zernike showed that a normal incoherent source can achieve transverse coherence as the light propogates away from the source. The angle of transverse coherence is $\lambda / d$, where d is the width of the source. Coherence can be quantitatively measured by fringe visibility.

To study this transverse coherence and the Van Cittert-Zernike theorem set up a semimonochromatic (hence good longitudinal coherence) thermal source (nonlaser) such as a monochromatic mercury lamp. After that place an adjustable slit and then a few to several cm further a double slit. This will yield very little light so attempt of projection of fringe onto a screen may be futile. Instead use your eye as a projection lens and a screen by looking directly toward the lamp through the double thin single slit arrangement. Narrow the single slit until fringes are seen. At the rough width of fringe appearance record the slit width, double slit spacing and distance between the single and double slits. Compare these data to $\lambda / d$. Try this for different single-double slit spacings and vary this spacing to see when fringes appear and disappear.