## Experiment 15: The Diffraction Grating

Diffraction gratings are used to make very accurate measurements of the wavelength of light. In theory, they function much the same as two slit apertures (see Experiment 9). However, a diffraction grating has many slits, rather than two, and the slits are very closely spaced. By using closely spaced slits, the light is diffracted to large angles, and measurements can be made more accurately. In spreading out the available light to large angles, however, brightness is lost. By using many slits, many sources of light are provided, and brightness is preserved.

In this experiment you will use a diffraction grating to determine the range of wavelengths for each of the colors in the visible spectrum.

EQUIPMENT NEEDED: Optics Bench, Light Source, Ray Table Base, Component Holder, Diffraction Scale, Diffraction Plate, Diffraction Grating, Slit Mask. Perform in a well lighted room.


Equipment Setup
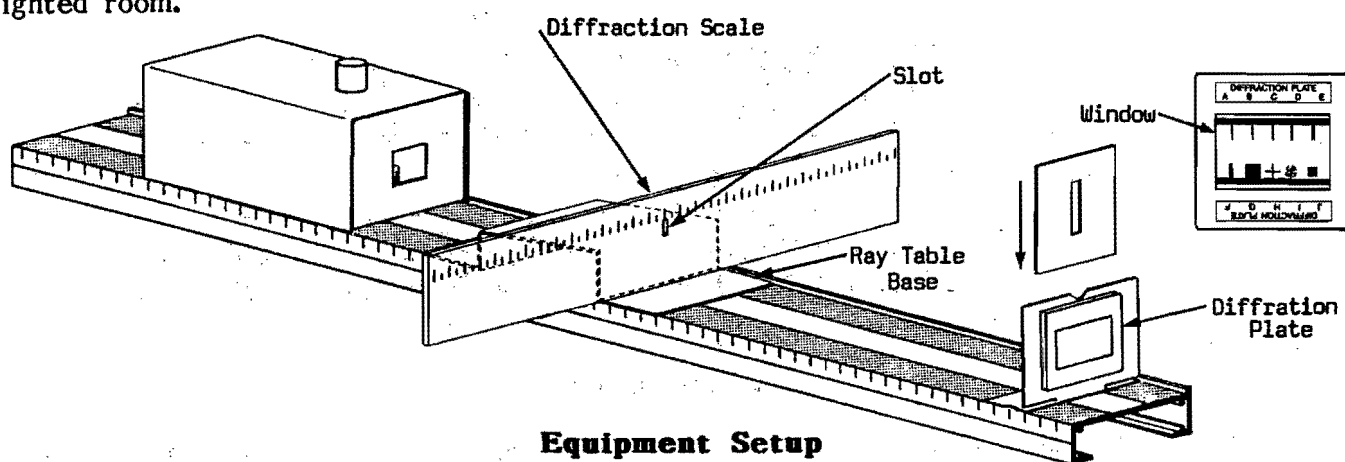
Arrange the equipment as shown above. When looking through the Diffraction Plate window, the filament of the Light Source must be directly visible through the slot in the Diffraction Plate. Look through each of the double slit patterns (Patterns D, E, and F) of the Diffraction Plate at the filament of the Light Source. Qualitatively, compare the spacing of the interference maxima for the different patterns.

1. How does the spacing of the maxima relate to the spacing of the slits on the Diffraction Plate (compare patterns of equal slit width, but different slit spacing)?

   _____.

2. Look through the 10-slit pattern (Pattern G) at the filament. What effect does the larger number of slits have on the diffraction pattern?

   _____.

Remove the Diffraction Plate and the Slit Mask and replace them with the Diffraction Grating. Look through the grating and observe the first order spectrum. Using the diagram below to identify the variables, fill in the data in the following table. Review Experiment 9, if necessary, to determine the calculations needed to calculate $\lambda[1]$ and $\lambda[2]$, the range of wavelengths corresponding to each particular color of light.

slit spacing = 5276 slits/cm

Diffraction Scale →

Diffraction Grating

retina of
your eye
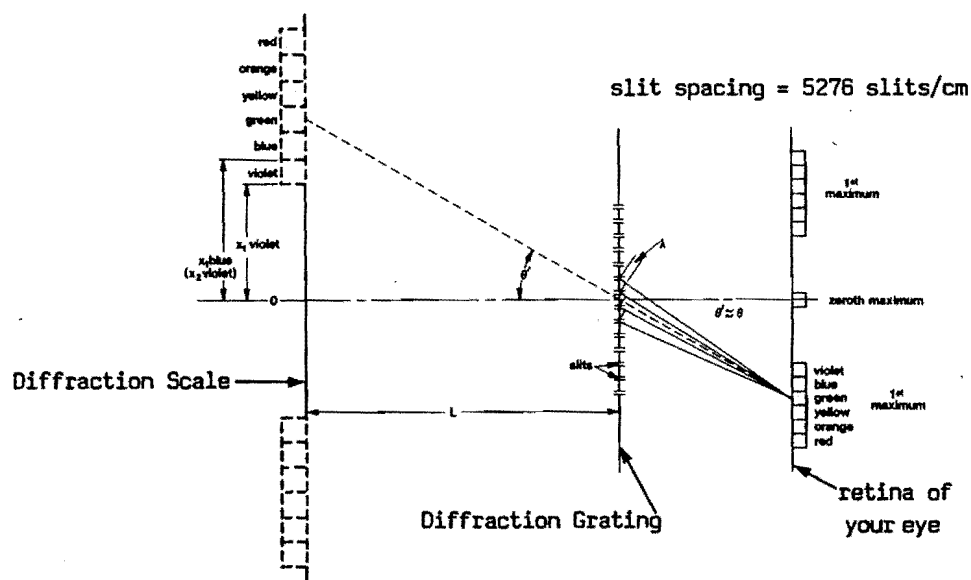
Measurements with the Diffraction Grating

	a	L	X1	X2	λ [1]	λ [2]
VIOLET						
BLUE						
GREEN						
YELLOW						
ORANGE						
RED						

Compare your results with those of other students, or with textbook values.

3. Are your results in complete agreement? Can you account for any discrepancies?

4. What advantages are there in using wavelength rather than color to characterize visible light?

Experiment 16:   Single Slit Diffraction

If you look closely at a two slit interference pattern, you will notice that the intensity of the fringes varies. This variation in intensity forms an interference pattern of its own that is independent of the number of slits or the separation between the slits. In fact, two slits are not required to see this pattern; it can be seen most clearly when light passes through a single, narrow slit.

In this experiment you will compare the single slit diffraction pattern with the double slit pattern, and then use the single slit pattern to measure the wavelengths of red, green, and blue light.

EQUIPMENT NEEDED: Optical Bench, Light Source, Ray Table Base, Diffraction Scale, Component Holder, Diffraction Plate.   Perform in a well lighted room.
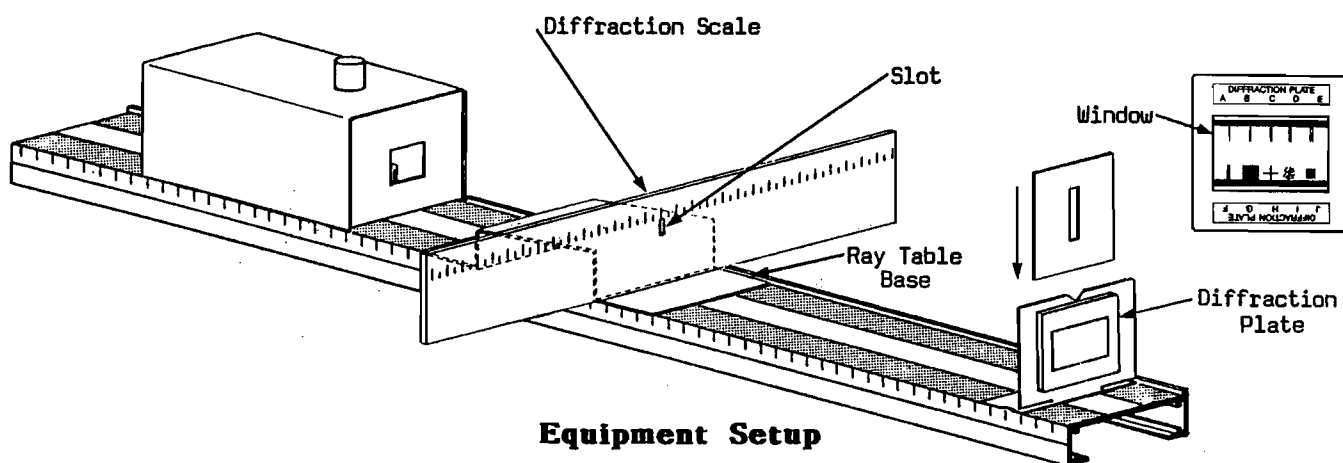
Equipment Setup

Setup the equipment as shown above. Look through each of the three single slit apertures in the Diffraction Plate (Patterns A, B, and C). Examine the diffraction patterns with and without color filters over the aperture of the Light Source.

1. How does the spacing between fringes vary with the width of the slit?

Compare the single slit patterns with the double slit patterns.

2. How does a double slit interference pattern differ from a single slit pattern (compare patterns of equal slit widths)?

The single slit pattern can be explained using Huygen's theory. When a plane wave front strikes the slit, each point on the slit acts as a point source of light. The Figure below shows a point P, far from the slit, where the distance AP = BP + λ. Since light from point A travels one wavelength farther than light from point B, the light from these two points is in phase at point P. But light reaching point P from the points in between A and B will vary in phase through a full 360°. For any point from which light reaches point P at a

42

particular phase, there will be a point from which light arrives in the exact opposite phase. Because of this, there is complete cancellation at point P, and a minima (dark fringe) will be seen at that point.

In the Figure, point P is at an angle θ from the slit, far enough away such that AP and BP are very nearly parallel. As shown, angle ABC = θ, also. Therefore w sin θ = λ; where w is the width of the slit (AB). A similar argument can be used to show that a minima will be found at any angle such that w sin θ = nλ, where n is any integer.

Review the two slit interference experiment. Notice the similarity between the equations for single and double slit patterns. To measure the wavelength of light, use the same techniques you used in the two slit experiment (θ = arctan X/L). Use your data to fill in the following table, then perform the calculations shown to determine the wavelength of Red, Green, and Blue Light.
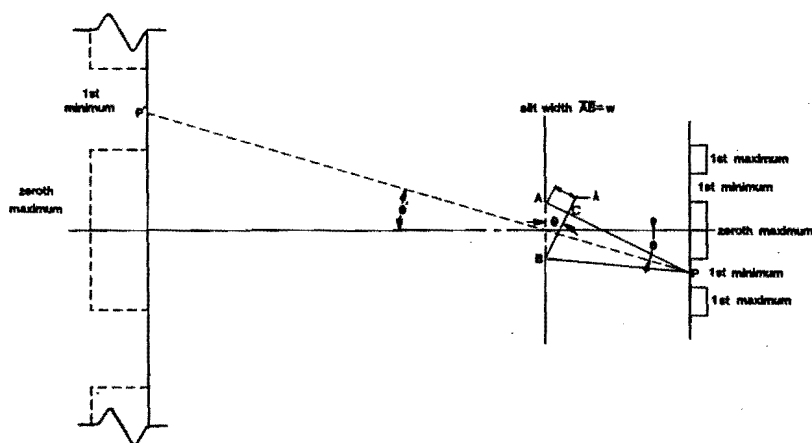
Geometry of Single Slit Diffraction

DATA					CALCULATIONS	
Color	n	w	X	L	arctan X/L	sin (arctan X/L) = λ
RED						
GREEN						
BLUE						

3. If the width of the slit, a, were less than the wavelength of the light being used, how many maxima would you expect to see in the single slit diffraction pattern? Why?

43

Experiment 17: General Diffraction

The simplest diffraction patterns are produced by narrow slits. However, any aperture, or collection of apertures, will produce a diffraction pattern if the dimensions of the apertures are of the same order of magnitude as the wavelength of visible light.

The diffraction pattern created by a particular aperture can be determined quantitatively using Huygen's principle. Simply treat each aperture as a collection of point sources of light (small, closely packed points will give the best approximation of the diffraction pattern). At any position on your viewing screen, determine the phase of the light contributed by each point on the aperture. Finally, use the superposition principle to sum the contributions from all the points on the aperture.

Of course, you must perform this same calculation for each point on your viewing screen to determine the complete diffraction pattern—a time consuming task! In this experiment the approach will be more qualitative. You will use your knowledge of diffraction patterns formed by slits to understand the patterns formed by more complicated apertures.

EQUIPMENT NEEDED: Optics Bench, Light Source, Component Holders (2), Variable Aperture, Diffraction Plate.

ADDITIONAL EQUIPMENT NEEDED: Black Construction Paper, pin.
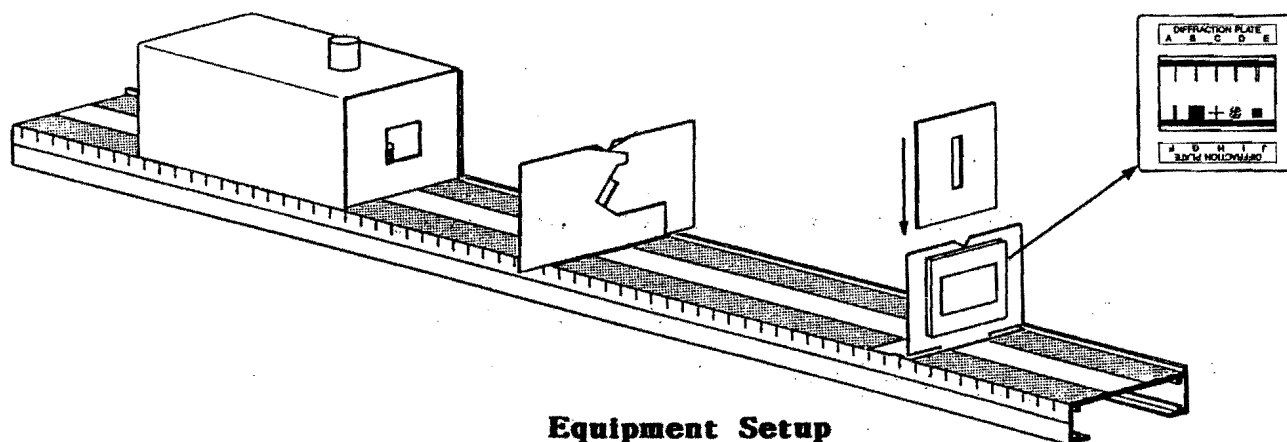
Equipment Setup

Setup the equipment as shown above. Begin with the Variable Aperture fully open. Looking through the Diffraction Plate at the Light Source filament, examine the diffraction patterns formed by Patterns H, I, and J.

While looking through Pattern H, slowly close the Variable Aperture. Repeat this with Patterns I and J.

1. What effect does aperture size have on the clarity of the diffraction patterns?

_____

_____

2. What affect does aperture size have on the brightness of the diffraction patterns?

_____.

Adjust the Variable Aperture to maximize the brightness and clarity of the pattern. Place a color filter over the Light Source Aperture.

3. In what way does the color filter simplify the diffraction patterns that are formed?

_____.

CROSSED SLITS

Examine the diffraction pattern formed by aperture H, the crossed slits. Slowly rotate the Diffraction Plate so first one slit is vertical, then the other.

1. Describe the diffraction pattern in terms of the patterns formed by each individual slit.

_____

_____.

RANDOM ARRAY OF CIRCULAR APERTURES

Examine the diffraction pattern formed by aperture I, the random array of circular apertures. The pattern is similar to that formed by diffraction through a single circular aperture. To verify this, use a pin to poke a small hole in a piece of black construction paper. Look at the Light Source filament through this hole. In the pattern formed by the random array, the patterns from all the circular apertures are superposed, so the combined diffraction pattern is brighter.

In the random array, smaller circles are used than you can produce with a pin.

1. What effect does the smaller diameter of the circles have on the diffraction pattern?

_____.

In observing single slit diffraction, you found that the narrower the slit, the greater the separation between the fringes in the diffraction pattern. This is generally true. For any aperture, diffraction effects are most pronounced in a direction parallel with the smallest dimension of the aperture.

2. Use the above generalization to explain the symmetry of the diffraction pattern formed by a circular aperture.

_____.

45

SQUARE ARRAY OF CIRCULAR APERTURES

Examine the diffraction pattern formed by aperture J, the square array of circular apertures.

1. How is this pattern similar to that formed by the random array? How is it different?

_____

_____

_____

Each circular aperture in the array forms a circular diffraction pattern with maxima and minima appearing at different radii. However, the regularity of the array causes there to be interference between the patterns formed by the individual circles. This is analogous to the way in which the double slit interference pattern creates maxima and minima that are superimposed on the single slit patterns created by the individual slits.

2. On a separate sheet of paper, draw the diffraction pattern you would expect if there were no interference between the patterns from the different holes (as in the random array). Clearly indicate the maxima and the minima.

3. To understand the interference that takes place, consider the array of points as if it were actually a collection of parallel slits, such as those shown in Figures (a), (b), and (c) below. Draw the diffraction patterns that would be created by each of these collections of parallel slits. Clearly label the maxima and minima.
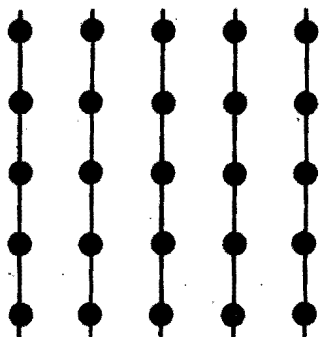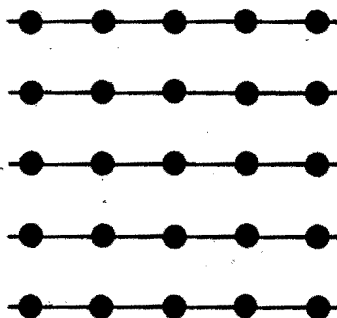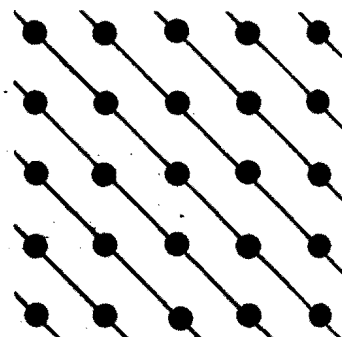
| (a) | (b) | (c) |

Square Array Interference

4. Your drawing from step 2 shows where the light is diffracted to from each individual circular aperture. To approximate the effect of interference between circular apertures, superimpose a copy of one of your interference patterns from step 3 over your drawing from step 2. Only where maxima overlap, will there be maxima in the combined pattern. Repeat this procedure for each of your interference drawings.

OPTICAL INSTRUMENTS

Experiment 18: Introduction

The design of high quality optical instruments can be quite complex, involving compound lenses and intricate lens coatings. But the complexity arises primarily from the need to reduce the effects of spherical and chromatic aberation (see Experiment 14). Understanding the basic principles of standard optical instruments is not complex. It requires only an understanding of the Fundamental Lens Equation:

$$1/d_o + 1/d_i = 1/f;$$

for which the magnification of the image is given by the equation:

$$m = -d_i/d_o.$$

In Experiments 19-22, you will use the above equations to investigate the workings of a Projector, a Magnifier, a Telescope, and a Compound Microscope. Before beginning, however, it is useful to understand certain generalities that can be made with regard to these equations.

Use the equations to complete the table on the following page. Show the location (d_i) and magnification (m) of the image, and whether the image is real or virtual, inverted or uninverted. Notice that d_o is given in units of f. Your calculated value for d_i will therefore also be in units of f.

- -

After completing the table, use it to answer the following questions. In each question, assume that $f > 0$ (as for a converging lens). A negative value for d_i indicates that the image is virtual.

1. For what range of d_o values is the image virtual and magnified?

   _____.

2. For what range of d_o values is the image real and magnified?

   _____.

3. For what range of d_o values is the image real and reduced in size?

   _____.

4. For what range of d_o values can the image be focused onto a viewing screen?

   _____.

Table of Object/Image Relationships:
Using the Fundamental Lens Equation

d_o	d_i	m	REAL/VIRTUAL	INVERTED/UNINVERTED
0				
f/16				
f/8				
f/4				
f/2				
3f/4				
7f/8				
15f/16				
f				
17f/16				
9f/8				
5f/4				
3f/2				
7f/4				
15f/8				
31f/16				
2f				
33f/16				
17f/8				
9f/4				
5f/2				
11f/4				
23f/8				
3f				
5f				
10f				
100f				

# Experiment 19: The Projector
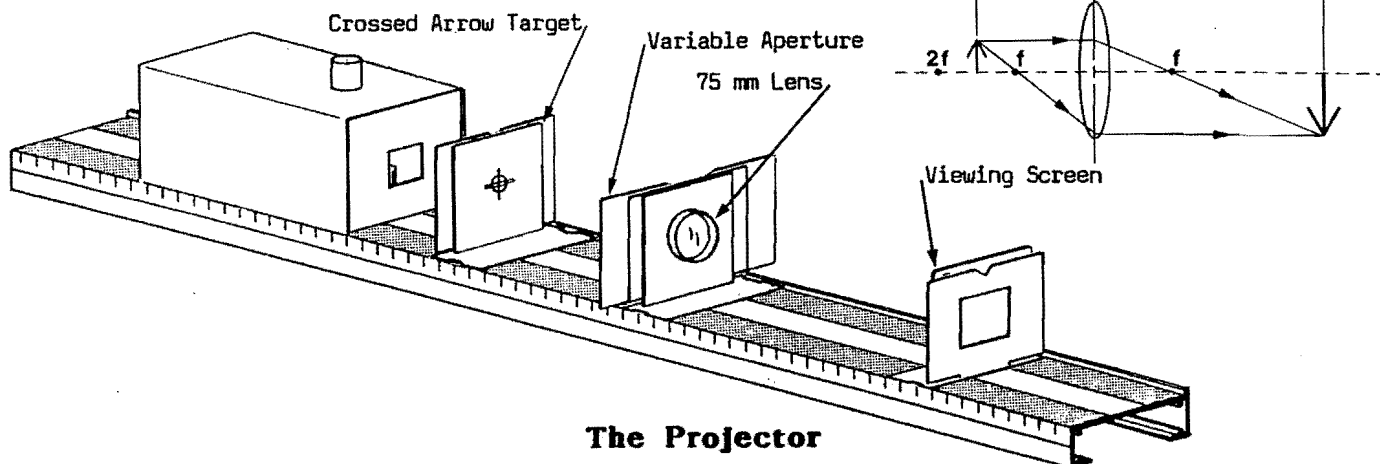
The Projector

When an object is located between **f** and **2f** of a converging lens, a real, inverted, magnified image is formed as shown above. If a viewing screen is placed at the location of the image, the image will be focused onto the screen. In this case the lens functions as a projector.

Setup a projector as shown. Try both the 75 and 150 mm converging lenses.

1. What happens to the image if d_o is less than **f**? Can the image still be focused onto the Viewing Screen? Why or why not?

   _____

2. What happens to the image if d_o is greater than 2**f**? Can the image now be focused onto the Viewing Screen? Why or why not?

   _____

3. Are there practical limits to the degree of magnification of the image? If so, what are they?

   _____

4. Is it possible, using a single lens, to project an image that is uninverted?

   _____

5. Can the image formed by a projector be viewed without using a viewing screen? If so, where must the observer be?

   _____

49

Experiment 20: The Magnifier
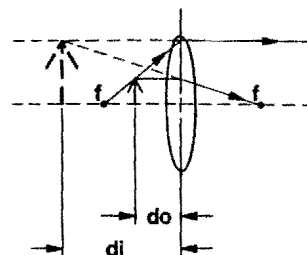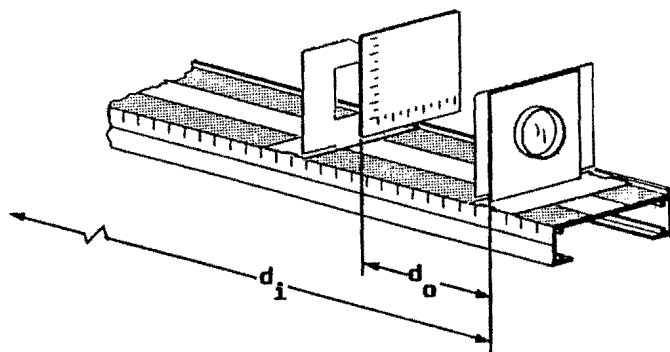
The Magnifier

When an object is located between a converging lens and its focal point, a virtual, magnified, uninverted image is formed. Since the image is not real, it can not be focused onto a screen. However, it can be viewed directly by an observer.

Setup a magnifier as shown above. Use first the 75 mm focal length lens, and then the 150 mm focal length lens. For each lens, adjust the distance between the object (the Viewing Screen) and the lens so the magnification is a maximum and the image is clearly focused.

Examine your table from Experiment 18.

1. Does the Fundamental Lens Equation place any limit on the magnification, m, that a lens can produce?

_____

2. Looking through the lenses, which lens seems to provide the greater magnification?

_____

Using each of the lenses as a magnifier, it should be clear that the magnification provided by a converging lens is not unlimited. This does not mean that the equation $m = -d_i/d_o$ is in error. This equation does give the correct ratio between the image size and the object size. However, image size is not the only important variable in determining the magnification of an optical system, such as a magnifier. Equally important is the distance between the observer and the image he is looking at. Just as a distant object appears smaller than the same object up close, an image viewed through an optical system appears larger if the image is close than if it is farther away.

50
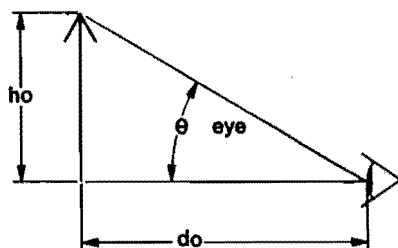
Angular Magnification

The illustration above shows an object of height h_o, a distance d_o from the observer. The size of the image on the retina of the observer is proportional to the angle θ_{eye}. For small angles, (the only angles for which the Fundamental Lens Equation holds), $\theta_{eye} = h_o/d_o$.

There is an important limitation to the magnitude of θ_{eye}. To see this, hold an object at arms length and move it slowly toward your eye (with one eye closed). There is a distance—the near point—at which the image begins to blur, because the rays entering your eye from the object are too divergent for your eye to focus. The near point differs for different people, but the average is approximately 25 cm. Therefore, $\theta_{eye\text{-}max} = h_o/25$ cm.

When using a magnifier, or any optical system for that matter, the apparent size of the image depends on the size and location of the image rather than the object, so $\theta_{mag} = h_i/d_i$. From the Fundamental Lens Equation $h_i = m\ h_o = (-d_i/d_o)\ h_o$. Therefore, ignoring the minus sign, $\theta_{mag} = h_o/d_o$, the same as without the magnifier.

However, using a magnifier, the object can be brought closer to the eye, so that d_o equals f, the focal point of the magnifying lens. In this case $_{mag} = h_o/f$. Therefore, the magnification (called the angular magnification) of the magnifier is calculated as $\theta_{mag}/\theta_{eye\text{-}max} = 25$ cm/f.

3. Calculate the angular magnification for the 75 mm and 150 mm focal length lenses. Are your calculated magnifications consistent with your answer to question 1?

_____

_____.

4. Would a converging lens with a 50 cm focal length be useful as a magnifier? Why or why not?

_____

_____.

Experiment 21:   The Telescope

Telescopes are used to obtain magnified images of distant objects.   As you can see by looking at your table from Experiment 18, the image of a distant object when viewed through a single converging lens will be focused nearly at the focal point of the lens.   This image will be real, inverted, and reduced in size.   In fact, the greater the distance of the object (with respect to f), the smaller the size of the image.

However, this reduced image is useful.   By viewing this image through a second converging lens—used as a magnifier--an enlarged image can be seen.
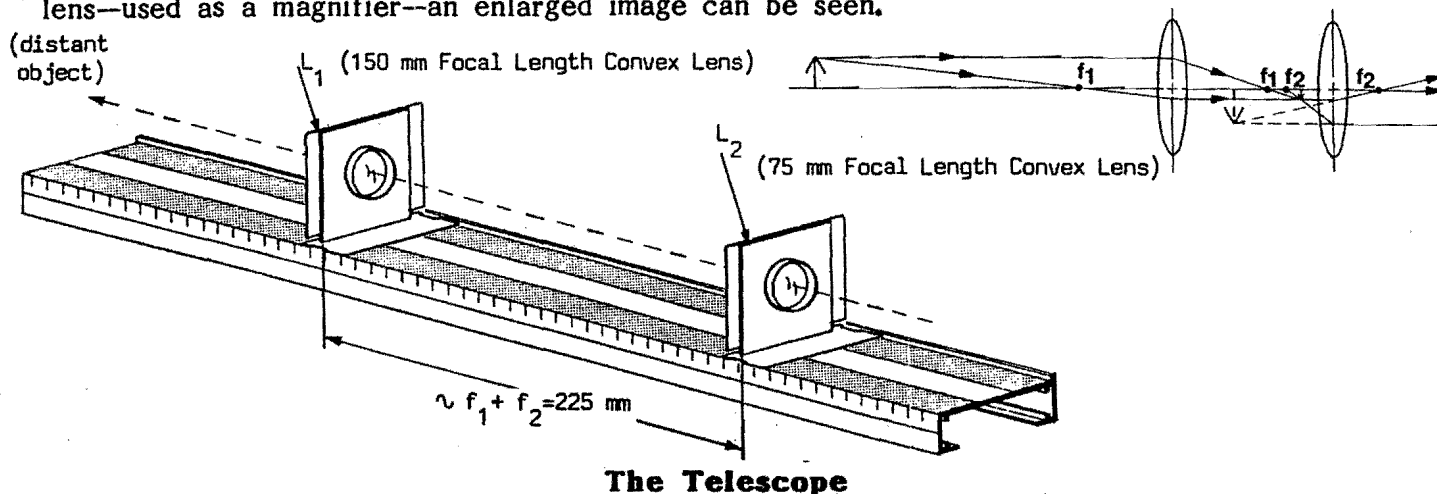
The Telescope

The illustration above shows the setup for a simple telescope.   The objective lens, L_1, creates a real, inverted image.   If the object is sufficiently far away, the image will be located approximately at f_1, the focal point of L_1.   The eyepiece, L_2, then acts as a magnifier, creating a magnified, virtual image which can be viewed by the observer.   For maximum magnification, L_2 is positioned so the virtual image is just slightly closer to it than its focal point, f_2.   Therefore, the distance between the objective lens and the eyepiece of a telescope, when viewing distant objects, is approximately $f_1 + f_2$.
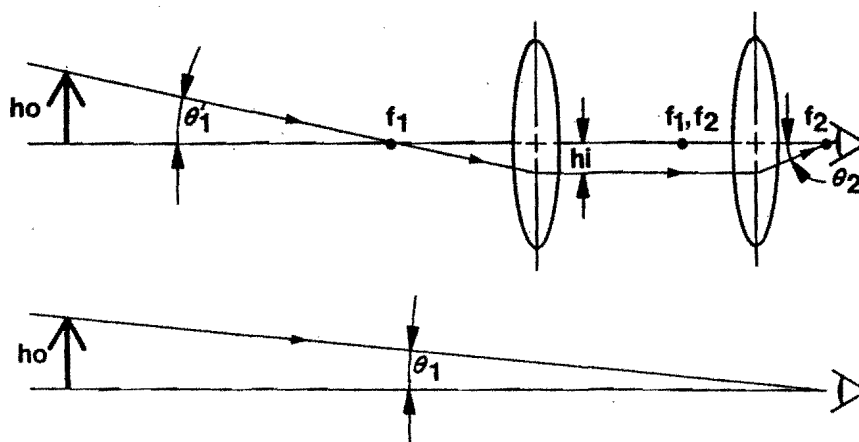
Telescope Magnification

The angular magnification (see Experiment 20: The Magnifier) for a telescope can be approximated by assuming the lenses are exactly $f_1 + f_2$ apart, as shown above.   The height of the object as seen with the naked eye is proportional to the angle θ_1.   If the distance from the object to the telescope is large--much larger than is shown in the

illustration-- $\theta_1 = \theta_1'$, to a good approximation. The ray shown in the illustration passes through the focal point of the objective lens, comes out parallel to the optical axis of the telescope, and is therefore refracted by the eyepiece through the focal point of the eyepiece. The angle θ_2 is proportional to the height of the image seen by the observer.

1. Using the illustration, calculate tan θ_1 and tan θ_2.

    tan θ_1 = tan θ_1' = _____ .

    tan θ_2 = _____ .

Assume that θ_1 and θ_2 are small, and therefore equal to tan θ_1 and tan θ_2, respectively.

2. Calculate the angular magnification of the telescope, θ_2/θ_1.

    Angular Magnification = _____ .

Setup a telescope using the 75 mm and 150 mm focal length lenses; the distance between the lenses should be approximately 225 mm. Using the 75mm lens as the eyepiece, look at some reasonably distant object. Adjust the distance between the lenses as needed to bring the object into sharp focus.

To measure the magnification, look with one eye through the telescope, and with the other eye look directly at the object. Compare the size of the two images. (If a meter stick is used as the object, fairly accurate measurements of magnification can be made.)

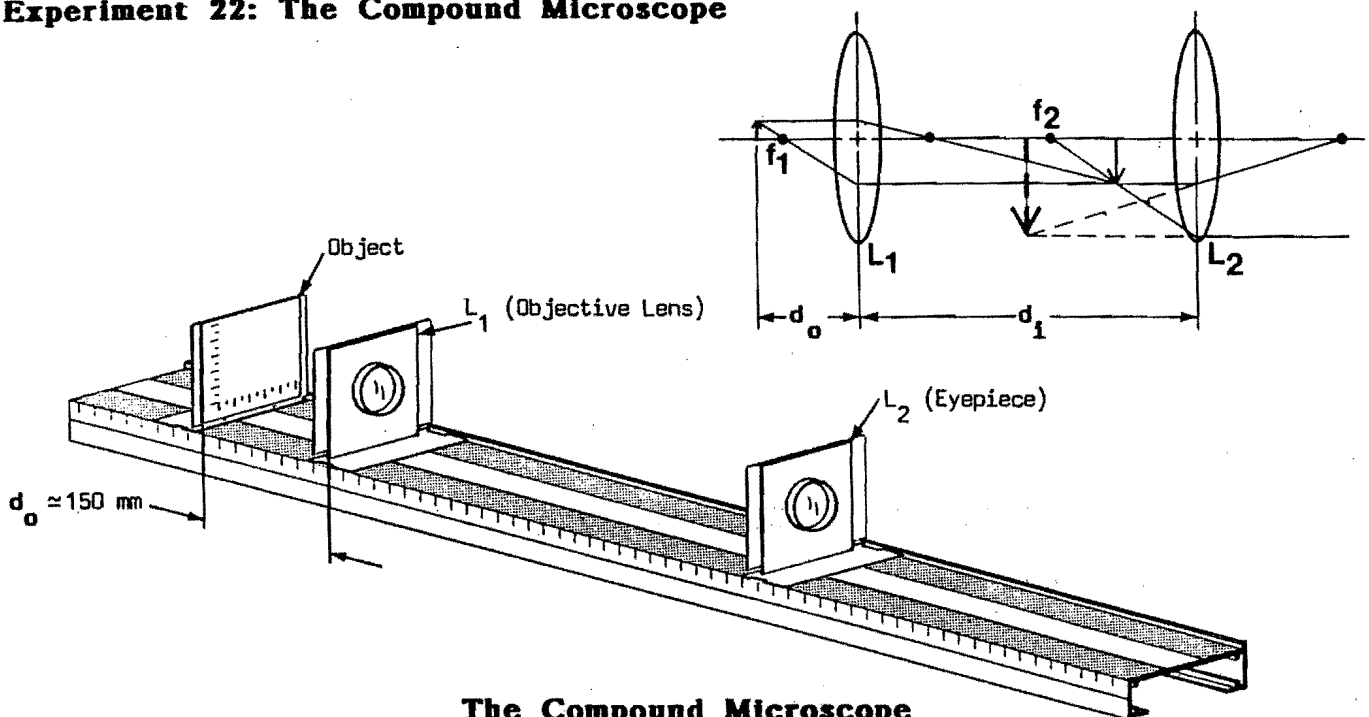3. What is the magnification of the telescope when using the 75 mm lens as the eyepiece?

    _____ .

4. What is the magnification of the telescope when using the 150 mm lens as the eyepiece and the 75 mm lens as the objective lens?

    _____ .

5. Are your answers to questions 3 and 4 in keeping with your answer to question 2?

    _____ .

Experiment 22: The Compound Microscope

The Compound Microscope

A compound microscope uses two lenses to provide greater magnification of near objects than is possible using a single lens as a magnifier. The setup is shown above. The objective lens, L_1, functions as a projector. The object is placed just beyond the focal point of L_1 so a real, magnified, inverted image is formed. The eyepiece, L_2, functions as a magnifier. It forms an enlarged virtual image of the real image projected by L_1.

The real image projected by L_1 is magnified by an amount $m = -d_i/d_o$, as indicated by the Fundamental Lens Equation. That image is in turn magnified by the eyepiece by a factor of 25 cm/f (see Experiment 20: The Magnifier). The combined magnification is, therefore:

$$M = (-d_i/d_o) \ (25 \ cm/f).$$

Setup the microscope as shown above. Use the 75 mm focal length lens as the objective lens and the 150 mm focal length lens as the eyepiece. Begin with the objective lens approximately 150 mm away from the object (the Viewing Screen). Adjust the position of the eyepiece until you see a clearly focused image of the Viewing Screen scale.

1. Is the image magnified? How does the magnification compare to using the 75 mm focal length lens alone, as a simple magnifier?

_____

_____

While looking through the eyepiece, slowly move the objective lens closer to the Viewing Screen. Adjust the position of the eyepiece as needed to retain the best possible focus.

2. Why does the magnification increase as the objective lens is moved closer to the object?

_____

_____.

3. What focusing problems develop as the magnification increases?

_____

_____.

Use the Variable Aperture to restrict the path of light to the central regions of the objective lens. Vary the size of the aperture and observe the effects on focusing.

4. What effect does the aperture have on focusing?

_____

_____.

5. What effect does the aperture have on the brightness of the image?

_____.

6. What advantage would there be in using a 75 mm focal length lens as the eyepiece?

_____

_____.

LOCATING VIRTUAL IMAGES

Virtual images can be located using the Virtual Image Locators. The following procedure is for locating virtual images formed by a spherical mirror. The procedure for lenses is similar though, of course, both image locators are placed on the far side of the lens from the observer.
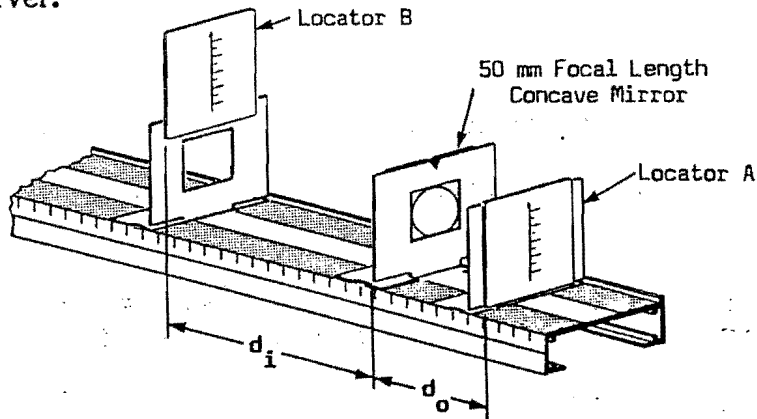
Setup for Locating a Virtual Image

Setup the equipment as shown above. Notice that the object must be between the mirror and its focal point, **f**, in order for a virtual image to be formed. Look through Locator A into the spherical mirror. Move your head from side to side, and notice how the image of the locator arrow moves.
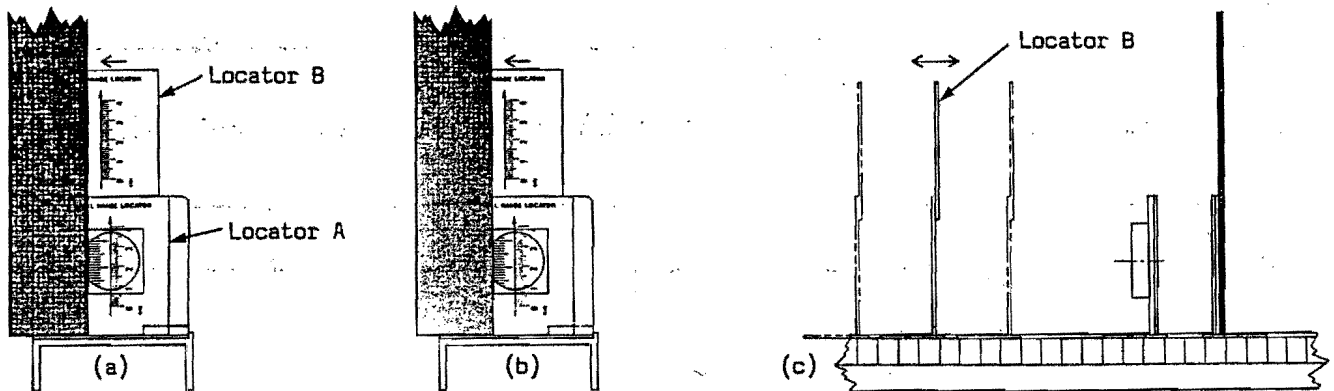
Locating a Virtual Image

Look through Locator A into the mirror, so your line of sight is at a slight angle from the optical axis of the mirror. Align a straightedge with the image of the locator arrow as shown in (a). Now adjust the position of Locator B until its arrow is aligned with the straightedge in your line of sight. Do this in two steps: (1) move the Locator laterally (perpendicular to the optical axis of the bench) to remove half the distance between the straightedge and the arrow as shown in (b); (2) move the Locator longitudinally (sliding the Component Holder along the optical axis of the bench) to complete the alignment as in (c).

Check to be sure that the image of the arrow of Locator A is aligned with the straightedge, and the straightedge is aligned with the arrow of Locator B.

Now move the straightedge to the other side of the arrow of Locator A and repeat the process. Continue changing the straightedge from side to side and aligning the locator arrows until the image of the arrow of Locator A and the arrow of Locator B remain aligned in your line of sight as you move your head from side to side. When this is the case, the arrow of Locator B is in the apparent position of the virtual image of the arrow of Locator A.