Optics Experiments for Advanced Physics Lab

Paolina Doleva   Dr. David Gore

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Contents

1 Abstract

The Physics, Computer Science, and Engineering (PCSE) department at Christopher Newport University (CNU) gives students the choice to enroll in accompanying laboratory courses that follow along lectures with the same topics. This serves as an opportunity to apply the knowledge and theory learned in class to a hands-on experience. However, the highest laboratory course for the Applied Physics major is PHYS202L, even though the University Physics series includes a PHYS303 course; hence the motivation behind designing and testing a lab for the third installment of the introductory courses. Successfully creating an outline and testing the experiments will provide the department and its students with an additional lab course in order to ensure that students are left with a solid foundation of physics and be prepared to apply the skills from the lectures and labs to the intermediate and advanced courses. In order to provide a set of instructions to students, a lab handout was written for each experiment. Furthermore, the handouts test students' understanding of concepts before and after each experiment. An analysis of the results and performance of each student shows that this project successfully provides a set of lab experiments to be included in a PHYS303 lab course.

2 Introduction

The design for this project was created with the intention to improve students' understanding of theory, the ability to take data, and the ability to address any unexpected results and solutions to those results. If students are given the option to practice theory outside of class, they will be able to understand the theory by incorporating observations and results from the experiment. Additionally, they will be able to further apply the skills acquired to intermediate and advanced physics. For each of the three experiments available, students will be asked to conduct five trials. The trials will rely on different variables to be changed. Conducting multiple trials will also aid in minimizing the uncertainty, which interferes with results. Additionally, students will use multiple media and sources. In the case that a student finds an incorrect measurement, they will be able to trace it back and record the trial at which an issue might have occurred. Then, the student will take into account any obstacles and will be able to recommend a solution.

3 Theory

3.1 Laser Interferometry

In the late 1800's, Albert Michelson invented a device called a Michelson interferometer which was used in an experiment conducted by him and Edward Morley. The device, shown in Fig. 1, consists of two perpendicular arms with a beam splitter at the intersection and a mirror at the end of each arm. The purpose of the experiment was to determine whether the Earth was traveling through something called the ether and whether light propagated that medium which caused a speed change. If that were the case, the fringe pattern observed with the interferometer would be affected. This means that after rotating the device by 90°, the fringes would shift if the speed was not constant and if light took longer to travel over one arm than the other. However, the experiment showed that the speed of light is constant regardless of the source.

There are two different types of interference which causes the fringe patterns mentioned above. The left side of Fig. 2 shows constructive interference, which happens when two waves are in-phase, meaning that the frequencies of the waves are the same. In this type of interference, the amplitude of the final wave is the sum of the amplitudes of the two original waves. Bright fringes like those in Fig. 3 display this scenario. In contrast, destructive interference is when two waves are out of phase by 180°. The amplitude of the final wave results in being zero and the fringes appear to be dark. For this project, a micrometer is used to change the distance of mirror M1.

Laser interferometry is used for many different purposes, but during this project, the focus will be calculating the wavelength of the laser beam. To do that, students look at the change in distance in one of the mirrors, defined as Δd. However, the setup used in the experiments requires additional calculations due to the rod that is being used to move the plate on which the device is built. Fig. 4 displays the equipment.

In order to calculate the distance, one must look at the change in angle made by the rod. By using trigonometry, the change in angle becomes

$$\Delta\theta = \frac{\Delta y}{130.2} \tag{1}$$

where Δy is the change made by a micrometer. It is important to note that the micrometer reading has units of tenths of an inch. See Appendix **??** for more information on how to read a micrometer.

Using the arc length of a section, one can derive the relationship between the total change in distance and the change in angle

$$\Delta d = r\Delta\theta = r\frac{\Delta y}{130.2} \tag{2}$$

where r is the radius of the rod, $r = 2.595$ mm.

To measure the wavelength of light, one can use the distance previously calculated, d, of mirror M1, which would cause the fringes to change from dark to bright by a whole number, m.

$$\lambda = \frac{2\Delta d}{\Delta m} \tag{3}$$

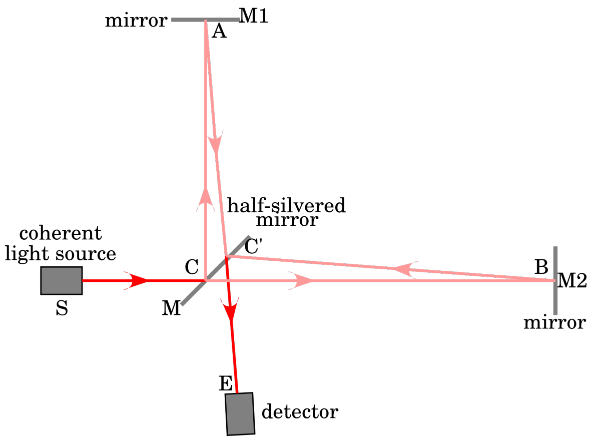

Figure 1: A diagram of a light ray going through water.

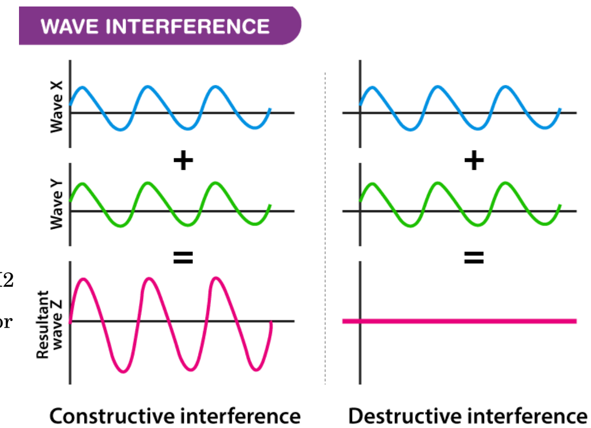

Figure 2: A diagram of a light ray going through water.

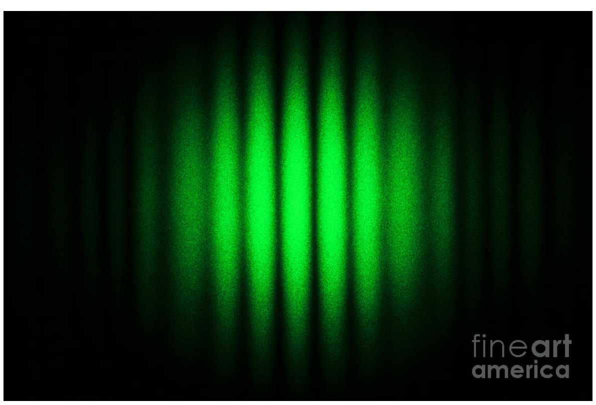

Figure 3: A diagram of a light ray going through water.

3.2 Gradient Index of Refraction (GRIN)

A refractive index gradient is the rate of change of the index perpendicular to the optical axis with respect to the distance in a material. For instance, the human eye's crystalline lens has a refractive index which varies from $n = 1.386$ to $n = 1.406$, making it a gradient index of refraction. It also depends on the density of the material; the denser the medium is, the higher the index of refraction becomes. For a lens, the GRIN can be modeled mathematically,

$$n = n_o \left[1 - \frac{Ar^2}{2}\right] \tag{4}$$

where n is the index at a radius r away from the optical axis, n_0 is the index of the optical axis, and A is the gradient constant.

Furthermore, Fermat's principle of least time also applies in this scenario. In simple terms, Fermat showed that out of all possible paths, light will take the one that requires the shortest amount of time.

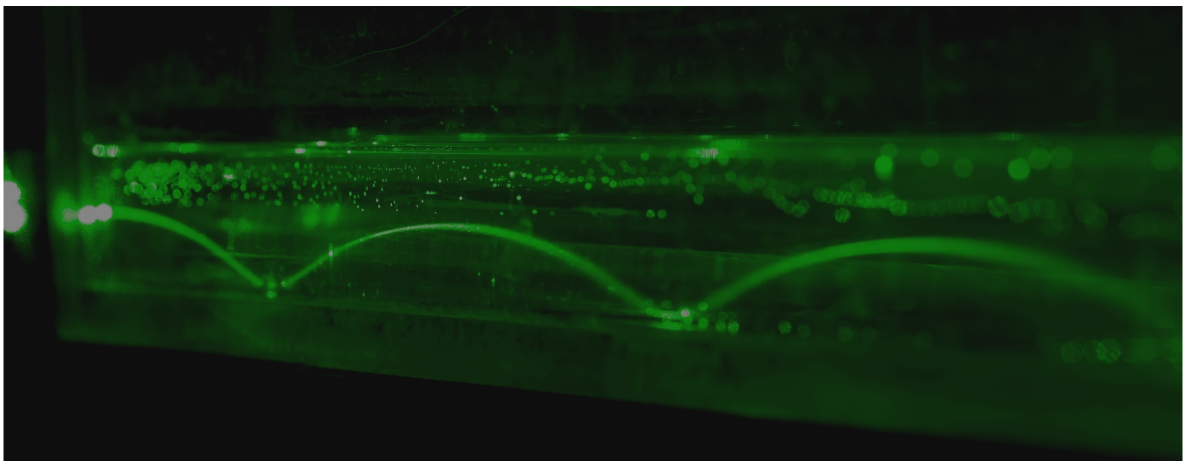

Figure 4: Corn syrup and water experiment.

3.3 Image Formation

Image formation consists of light going through a lens or a mirror which then forms into an image that can be classified into two categories: real or virtual. For this project, convex and concave lenses are used to form the images. A convex lens, which has a positive focal length, is also known as a converging lens due to the converging of light when it passes through the lens. Typically this type of lens is used to focus an object and make it appear larger. If, however, the object is placed between the focal length and the lens, then it will appear virtual. A concave lens has a negative focal length and it is known as a diverging lens. This type of lens disperses the light rays and creates a diverging effect. Although it creates mostly virtual images, it is possible to have a real image formed.

The image equation is used to calculate the distances of the object or the image to the lens. Additionally, one can calculate the focal length of the lens.

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{5}$$

where d_o is the object distance and d_i is the image distance.

The height of an object can also help to calculate the magnification

$$M = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{6}$$

4 Methods

4.1 Experiment 1

The setup for this experiment includes a Michelson interferometer picture below. The interferometer consists of two mirrors on each arms and a beam splitter, and a compensator plate. Additionally, a helium-neon laser is used to provide the laser beam. A beam expander that consists of a convex and a concave lens is used to expand the laser beam in order to see the fringes better, and two lab jacks to place the laser on. To begin the run, students are asked to set the micrometer so that there is a bright fringe at the center of the paper. In order to display the interference pattern, students must adjust the two mirrors until they see the pattern shown in Fig. 3. Subsequently, students must record the number on the micrometer. Then, they must rotate the micrometer while counting 20, 30, and 40 fringes for each run of the experiment. After, students record the final distance. This is all of the measurements required to make calculations. After calculating the wavelength for each run, students are asked to get an average of the wavelength.

4.2 Experiment 2

To set up, a clear glass container is used, which contains 250 mL of water and 250 mL of corn syrup. The two liquids are left to separate for 6 to 12 hours. Additionally, the same helium-neon laser from experiment 1 is used, and an additional lab jack (making it a total of three lab jacks). After the the liquids have set, students place the laser perpendicular to the glass container. By raising and lowering the two lab jacks on which the laser sits on, students are able to visualize the behavior and path that the beam takes.

4.3 Experiment 3

To set up, students are asked to place the light source onto the optics bench on which a ruler in centimeters is provided. Then, students are asked to place each lens at a given distance. For each trial of the experiment, students are asked to move the object a given distance depending on the focal length of the lens. Before continuing, they are to measure the distance of the image and record the number, in addition to make observation about the structure of the image, i.e. is it present and upright?

5 Data

For experiment one, the following is a data table from one run of the experiment.

	Initial Position (in)	Final Position (in)	$\Delta y (mm)$	Fringes, m	Radius, r (mm)	$\Delta\theta$
Trial 1	0.614	0.602	0.012	20	2.595	0.00234
Trial 2	0.763	0.773	0.010	20	2.595	0.00195
Trial 3	0.710	0.723	0.013	20	2.595	0.002536
Trial 4	0.657	0.666	0.011	20	2.595	0.002146
Trial 5	0.698	0.71	0.012	20	2.595	0.002341

Table 1: Student 1 Data

	Δd	$\lambda (nm)$	% difference
Trial 1	0.00607	607.493	4.08
Trial 2	0.00506	506.244	22.22
Trial 3	0.006581	658.118	3.92
Trial 4	0.005569	556.869	12.765
Trial 5	0.006075	607.493	4.08

Table 2: Student 1 Data Continued

Following 5 trials of data taken for each run of the experiment, the average wavelength measurements came to be between 555 nm and 590 nm depending on the run, with a standard deviation of 57.72 nm and an average percent difference of 9.413%.

For experiment 3, it is important to note that the images formed by a concave lens are only virtual images, meaning that students can not see those images on a screen; hence the actual data point taken for this scenario would be 0. For convex lens with focal length of 7.5 mm, the standard deviation ranges from 0.26 to 0.96, depending on the distance of the object moved. For convex lens with focal length of 15 mm, the standard deviation falls between 12 cm and 54.592 cm.

6 Discussion and Conclusions

Overall, this project has results that agree with the theory. The students who tested the experiments showed consistency and low percent differences. For experiment 1, the average wavelength is not ideal. Some of the reasons for this large error might come from the device itself. The silver coatings of the beam splitter could have started to wear off as the device has aged and could have affected the data. In addition, there could be friction caused under the plate that moves the second mirror that interferes with the measurement. For experiment 2 and 3, the trials show promising results in the sense that students are able to take accurate measurements.

In order to avoid the uncertainty in experiment 1, I would recommend building the interferometer on an optical bench. This will eliminate outside factors that can interfere with the mirrors' position, like accidentally leaning on the table which can result in movement of the device. Assembling the interferometer itself requires the same components that as the device used in this project, however, it requires more time available. Furthermore, experiment 3 would benefit from a longer than 1 meter optical bench. This will allow students to measure larger distance and better record measurements for the two-lens system. If I had more time, I would add a second part to experiment 3, which includes Snell's Law and further helps students visualize the refraction of light. This could be done by using glass blocks with different refractive indices ranging from $n = 1.5$ to $n = 1.7$.

References

[1] "Bouncing laser beam trough." [Online]. Available: https://www.vanderbilt.edu/physicsdemonstration/davesdemos/demonstrations/demo091.htm

[2] "Constructive and destructive interference." [Online]. Available: https://www.phys.uconn.edu/~gibson/Notes/Section5_2/Sec5_2.htm

[3] "Constructive interference." [Online]. Available: https://byjus.com/physics/constructive-interference/

[4] "Difference between convex and concave lens." [Online]. Available: https://keydifferences.com/difference-between-convex-and-concave-lens.html

[5] "Interference fringes." [Online]. Available: https://fineartamerica.com/featured/interference-fringes-giphotostock.html

[6] J. Evans, "Simple forms for equations of rays in gradient-index lenses," *American Journal of Physics - AMER J PHYS*, vol. 58, pp. 773–778, 08 1990.

[7] M. H. Weik, *refractive-index gradient*. Boston, MA: Springer US, 2001, pp. 1451–1451. [Online]. Available: https://doi.org/10.1007/1-4020-0613-6_15870

A Component Specifications

Experiment 1	**Experiment 2**	**Experiment 3**
Mirror, M1	Clear, glass container	Convex Lens (7.5 mm)
Mirror, M2	Lab Jacks (2)	Convex Lens (15 mm)
Beam Expander	250 mL Karo Syrup	Concave Lens (-15 mm)
Beam Splitter	250 mL Water	Light Source
Compensator Plate	HeNe Laser	Optics Bench
HeNe Laser		Object Screen
Viewing Screen		Viewing Screen

Table 3: Itemized list of components for each experiment.

B Lab Handouts

PHYS303 University Physics III: Lab Handout

Paolina Doleva

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Contents

1 Experiment I

Equipment

- Mirror, M1
- Mirror, M2
- "Beam Expander" Set-up (convex and concave lens)
- Beam Splitter
- Compensator Plate
- HeNe Laser
- Viewing/Observer Screen

Purpose

The purpose of this experiment is for students to understand conceptually and observe fringe patterns created by interference. In addition, students will be given the opportunity to calculate the wavelength, λ, of the light source and measure the phase change, ϕ, of the two light beams.

Background

In the late 1800's, Albert Michelson invented a device called an interferometer which was used in an experiment conducted by Michelson and Edward Morley. The device consists of two perpendicular arms with a beam splitter at the intersection and a mirror at the end of each arm. The purpose of the experiment was to determine whether the Earth was traveling through something called the ether and whether light propagated that medium which caused a speed change. If that were the case, the fringe pattern observed with the interferometer would be affected. This means that after rotating the device by 90°, the fringes would shift if the speed was not constant and if light took longer to travel over one arm than the other. However, the experiment showed that the speed of light is constant regardless of the source.

Theory

- **Constructive Interference** appears when two waves are in phase and whose amplitudes add up together, and cause bright fringes to appear.
- **Destructive Interference** appears when two waves are out of phase by 180° and whose resulting amplitude is zero, causing "dark" fringes to appear.

To measure the distance change in this set-up, we need to acknowledge the fact that there will be some change in θ. Fig. 1 shows a sketch of how to micrometer affects the distance change. Equations (1) and (2) show how to calculate the total distance change for mirror M2

$$\Delta\theta = \frac{\Delta y}{130.2} \tag{1}$$

where θ is the angle in degrees between the two rods and Δy is the micrometer reading in millimeters. Therefore, the total change in distance is

$$\Delta d = r\Delta\theta = r\frac{\Delta y}{130.2} \tag{2}$$

where r is in millimeters.

To measure the wavelength of light, we can use the distance previously calculated, d, of mirror M2, which would cause the fringes to change from dark to bright by a whole number, m. Thus we get the following equation

$$\lambda = \frac{2\Delta d}{\Delta m} \tag{3}$$

To measure the phase shift between the two light beams, we can use the following equation

$$\Phi = \phi' + 2k(d_1 - d_2) \tag{4}$$

where k is the wave number and defined as

$$k \equiv \frac{2\pi}{\lambda} \tag{5}$$

where λ is the wavelength of the light, d_1 and d_2 are the distances to each mirror, respectively.

Procedure

1. Set the interferometer on a flat surface, using Figure 2 as a guide.
2. Set the laser so that the light goes exactly through the middle of the beam splitter.
3. Set up the Observer Screen, and make sure that the two beams are exactly in the middle of the plate.
   (a) To do that, you need to adjust the tilt of M1 and M2 so that the reflected beams coincide with their incident paths and the two beam spots overlap (as close as possible) on the screen.
4. Start changing the distance between M2 and the beam splitter and count the number of fringes
   (a) The change in distance can be calculated using equation (4).
   (b) From there, you can calculate the new distance of M2.
5. Repeat Step (4) five times to get an average value and uncertainty.
6. Calculate the wavelength and phase shift.

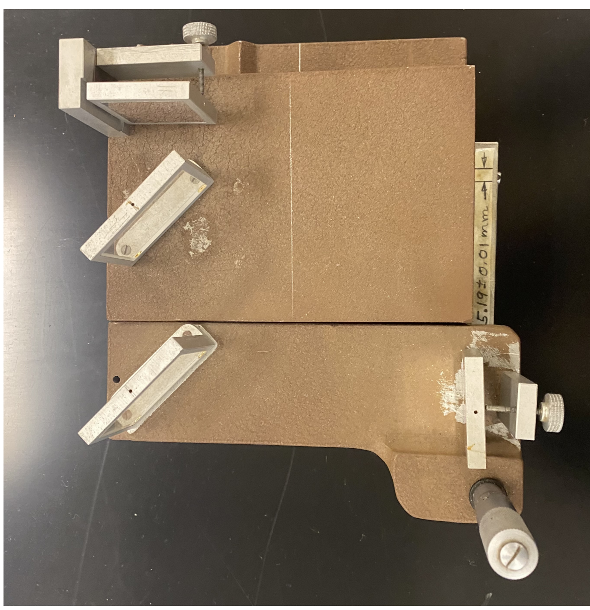

Figure 1: Side view of the Michelson Interferometer and the micrometer.

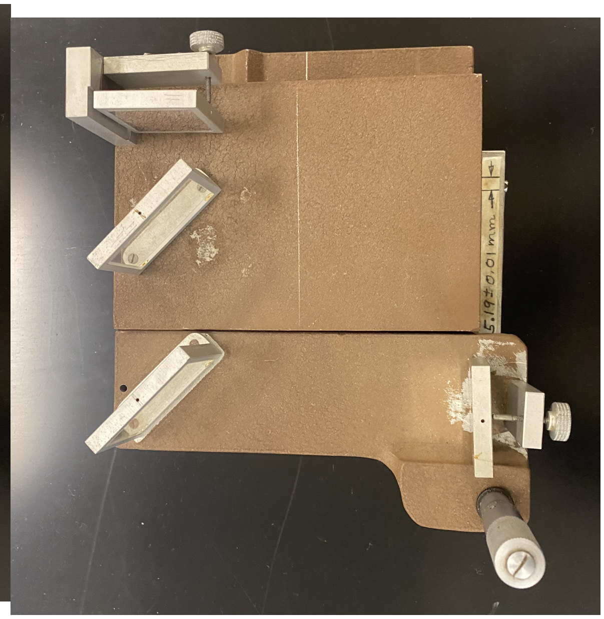

Figure 2: Top view of the Michelson Interferometer.

How to use the micrometer

The micrometer has two scales labeled the sleeve and the thimble. The sleeve is considered the primary scale while the thimble is the secondary scale. This micrometer has units of millimeters. To record the total reading, students must add the two numbers. An example reading is shown in Figure 3.

Post-Lab Questions

1. What is the purpose of the compensator plate in this set up?
2. Would you be able to calculate the index of refraction of the glass slide in this experiment? If not, what are some components you can add to help you measure the index?
3. What information about the two beams does the phase shift give us?
4. What would be the wave number be in this experiment?
5. What type of interference is seen on the observer screen?

2 Experiment II

2.1 Part I

Equipment

- Clear, glass container
- Lab Jacks (2)
- 250 mL of Karo Light Syrup
- 250 mL of water
- HeNe Laser

Purpose

The purpose of this experiment is for students to observe light following a continuous curve through a medium.

Background and Theory

In order to create the continuous path through the medium, we need to create a vertical mass density gradient and a refractive index gradient. The former describes the variation of density in two media, in this case the density of syrup and water are different. Density of syrup is higher than the density of water, which causes the former liquid to sit on top of the latter. The refractive index gradient refers to the change in the refractive index with respect to distance in the medium. An example of this would be the human eye, in which the refractive index varies in different layers of the lens.

Procedure

1. Set the glass container on top of the support jacks.
2. Pour the syrup on the bottom and then pour water on top. Wait for about 6 hours until the two liquids have set.
3. Prop the laser on one of the lab jacks and point perpendicular to the glass container.
4. Observe a continuous curve path caused by the reflected light from the mirror on the bottom of the trough.

2.2 Part II

Equipment

- Clear, glass container
- Lab Jacks (2)
- A pinch of powdered detergent
- 250 mL of water
- White light source

Purpose

The purpose of this experiment is to visualize and simulate scattering of blue light observed during red sunsets.

Background and Theory

During sunsets, light has to travel through a thicker amount of atmosphere because of how low on the horizon the sun sits. This causes blue light to be scattered and deflected several times before it reaches us. Therefore, there is more yellow and red light left. This experiment simulates that by creating a "thicker" medium that white light has to go through, causing scattering in blue light.

Procedure

Follow the same procedure as Part 1, but replace the Karo syrup with detergent and the HeNe laser with white light.

Post-Lab Questions

1. Explain why the path becomes a curve with this index of refraction gradient.
2. What derivation can be done to calculate the gradient index of refraction? (**Note:** Do not try to get the right answer but think creatively.)

3 Experiment III

Equipment

- Convex Lenses (7.5mm and 15mm)
- Concave Lens (-15mm)
- Light Source
- Optic Bench
- Object(Arrow) Screen
- Viewing/Observer Screen

Purpose

This experiment will let students observe image formation and the relationship given by the thin lens equation in addition to calculating the focal length of a thin lens.

Theory

To calculate the image distance, we can use the thin lens equation, which is

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{6}$$

where d_o will be given at the beginning of each trial of the experiment, d_i will be calculated, and f will be given. In addition, the height of the object and the image will be used to determine the magnification, which will be compared to the observations. To calculate the magnification,

$$M = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{7}$$

If the absolute value of the ratio is

- Greater than 1, then the image is magnified.
- Less than 1, then the image is diminished.
- Exactly equal to 1, then the there is no change.

Additional characteristics of images formed that might be useful

- Distant image (over 2F) creates a real, smaller, inverted image
- At 2F creates a real, full size, inverted
- Between 2F and F creates a real, bigger, inverted
- Between F and lens creates a virtual, bigger, upright

Procedure for each system

1. Set the object at the given distance
2. Set the observer screen on which the object will appear at the calculated distance of the object.
3. Set the object at the given distance.
4. Turn on the light source.
5. Measure the image distance.
6. Calculate the magnification. Does it match the observation?

Distances for each lens

- **f = 7.5mm:** 17 cm, 15 cm, 9 cm, 7.5 cm, 5.5 cm
- **f = 15mm:** 32 cm, 21.75 cm, 17,15 cm, 10 cm
- **f = -15mm:** 32 cm, 21.75 cm, 17,15 cm, 10 cm
- f_1 **= +7.5 mm,** f_2 **= -15 mm:** 17 cm, 15 cm, 9 cm, 7.5 cm, 5.5 cm; with a distance of 10 cm between the two lenses

Post-Lab Questions

1. Draw the ray diagrams for the distances that cause a virtual image to form for each lens.