

The following laboratories were developed by Catherine Crouch at Swarthmore College for Physics 4L (Electricity, Magnetism, and Optics with Biomedical Applications) drawing on problem-solving laboratories from the University of Minnesota (Kenneth and Patricia Heller), as well as other resources noted on the individual laboratories.

I am happy for others to use these laboratories; I would appreciate it if you notify me (ccrouch1@swarthmore.edu) that you are using them so that I know where they have spread. Please also share any feedback you have on how to improve them!

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LABORATORY 1:

REFLECTION AND REFRACTION

In this lab and the next, you will carry out multiple short experiments designed to solve problems related to the formation of optical images. Most of us have a great deal of experience with the formation of optical images: they can be formed by flat or curved mirrors, water surfaces, movie projectors, telescopes, and many other devices. We can see because the cornea and a flexible lens in each eyeball form images on our retinas (sometimes with the aid of "corrective lenses," in the form of contacts or eyeglasses). This laboratory should help you understand some of your daily experiences with images with the concept of light rays that travel from sources or illuminated objects in straight lines.

In the first laboratory, you will look carefully at how rays of light reflect and refract from surfaces, and begin to examine how images form with single lenses. This will give you the building blocks for the second lab, in which you will examine the formation of images by multiple lenses.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Use the concept of index of refraction to explain how light rays change their paths at boundaries.
- Describe the propagation of light through transparent objects and from mirrors in terms of ray diagrams.
- Explain the basic principle behind light guiding in optical fibers for instruments such as endoscopes.
- Describe how light travels through single convex lenses using ray diagrams and use the thin lens equation to relate the positions of the image and the object to the focal length of the lens.

PREPARATION:

Complete the "Prediction" and "Warmup" questions for **each of the two laboratory problems**. (If you are feeling uncertain about these questions, you may find it helpful to review Wolfson Chapter 30 and section 31.2.) Leave several blank pages in your lab notebook between the prelab material for Problem 1 and that for Problem 2.

Before coming to lab you should be able to:

- Use Snell's Law to calculate the angle of refraction of a light ray at a boundary between transparent materials.
- Use trigonometry and the properties of similar triangles to calculate unknown angles.

PROBLEM #1: TOTAL INTERNAL REFLECTION

Suppose you are part of a team designing a new endoscope at a medical device company. To do so, among other things, you need to know the index of refraction of the two types of glass to be used in the optical fiber bundle that carries the images of the interior of the patient's body to a video camera. Your job is to devise a method for measure the index of refraction of the materials provided, making use of total internal reflection, as that is the key physical process at work in optical fibers.

EQUIPMENT

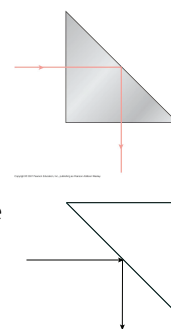
For this problem, you will be provided with a laser ray box (an object that produces narrow rays of red light), several transparent blocks, graph paper, a ruler, and a protractor for measuring angles.

PREDICTION

Based on information about indices of refraction for plastics (polystyrene is a plastic) and glass provided in Wolfson, give a range of values within which you expect your measured index of refraction to fall.

WARM-UP

1. Consider light totally internally reflected by a prism, as shown in the upper figure, and assume the angles at the corners of the prism are both 45° . What can you say from this figure about the index of refraction of the glass?
2. Could total internal reflection happen as shown in the lower figure, assuming that the index of refraction of the glass is in the range provided in Wolfson Table 30.1? Why or why not?



EXPLORATION

The laser ray box has a magnetic base. Anchor the laser ray box in place by positioning it on the steel plate clamped to the lab table. Place the bracket mask on the laser ray box so that just one ray emerges, and tape a sheet of graph paper down to the lab table so that the ray travels along one of the lines. (You may want to tape more than one sheet down eventually, depending on what measurements you end up doing.) Place different transparent blocks in the path of the ray and find one that is simple to orient so that you can observe total internal reflection.

Based on your observations, plan a strategy to measure the index of refraction of one of the blocks by means of total internal reflection. As part of your strategy, identify which shape of block and what positioning will enable the most accurate measurement. (There is more than one workable strategy, so if you and your lab partner disagree, discuss your ideas — you may all be on the right track!)

Please only use pencil when tracing around the transparent blocks, and try not to get pencil marks on them. If you do, please ask your lab instructor for wet towels to clean them up afterward.

MEASUREMENT

Find the index of refraction of one of the transparent blocks using the strategy devised in the previous part. As part of this measurement, make any measurements needed to determine the uncertainty in your measured value.

Then find the index of refraction of that same block using Snell's law ($n_1 \sin \theta_1 = n_2 \sin \theta_2$) rather than total internal reflection. (Hint: it is easier to measure large angles accurately.)

In your lab notebook, be sure to include a description of the measurement strategy you used and diagrams showing how you performed each measurement, and any calculations involved in obtaining the index of refraction from your experimental data.

ANALYSIS

Determine the uncertainties in your two values of the index of refraction.

Do your two values of the index of refraction of the block (one obtained with total internal reflection, one with Snell's Law) agree within uncertainty?

CONCLUSION

Which method do you think determines the index of refraction more accurately? Are these values consistent with the range of values you predicted before lab?

PROBLEM #2: EXPLORING FOCUSING

In this problem, the goal is to make qualitative observations and gain practice with how light rays are focused. The lab manual will guide you through the type of observations you are to make, but you should also feel free to experiment — to ask your own questions and try things out. You will do some measurements and some pencil and paper exercises, and use some computer animations.

EQUIPMENT

You will use a laser ray box, two “lenses” (lens-shaped blocks of transparent material) and a mirror to use with the laser ray box, graph paper, a clear acrylic box to hold water, a protractor, and a ruler.

PREDICTION

If a lens is placed in water, will it bend the light rays more or less sharply than if it is surrounded by air?

EXPLORATION

To explore how parallel rays of light travel through lenses: Set up the laser ray box as in the previous problem, positioning the mask so that three beams are visible. Tape down the graph paper so that the beams are parallel to the lines on the paper. Place the converging (teardrop-shaped) lens on the graph paper, frosted side down, and position it so that the center beam goes through the center of the lens, and the rays are parallel to the axis of the lens.

How will you know if the rays are parallel to the axis? The best way to tell is if the center beam reflects directly back on itself from the lens (your instructor can show this to you).

Q1. Why does the center beam reflect directly back on itself when the rays are parallel to the axis and the center beam is passing through the center of the lens? (A sketch may help explain this.)

Trace the outline of the lens and the paths taken by the beams that pass through the lens on the graph paper, then tape this graph paper into your lab notebook. (Do not trace the beams that reflect back from the lens.)

Q2. Measure and record the focal length of your lens. Observing how the beams are refracted by the lens, is the index of refraction of the lens material greater or less than that of air?

On a new sheet of graph paper, trace the lens outline and the beam paths. Remove the lens and place the clear acrylic box over the graph paper where you had the lens before. Put in enough water so that the lens will be almost but not quite covered with water, put the lens down over its original position, and observe how the beams are focused by the lens in the water.

Q3. Does the focus occur at the same place when the lens is in the water? If not, is the focus closer to or farther away from the lens? How does your observation compare to your prediction? Explain your observation.

Finally, remove the box of water, prepare a fresh sheet of graph paper, and position the diverging (hourglass-shaped) lens on the paper so that the beams are parallel to the axis and the center beam passes through the center. Trace the outline of the lens and the paths taken by the beams that pass through the lens (ignore the reflected beams). Put this graph paper in your notebook also.

Q4. Do the beams ever meet at a single point? Show on your tracing the focal point of the diverging lens and measure the focal length.

IMAGES WITH CONVEX LENSES

In this part of the lab, you will qualitatively examine image formation with convex lenses with a simulation, with actual lenses, and by drawing ray diagrams. Use the simulation, the equipment, and drawings in whatever order you find most helpful. Examine three cases:

1. The object is at a distance from the lens greater than twice the focal length f ($2f < s_o$.)
2. The object is at a distance greater than f but less than $2f$ ($f < s_o < 2f$)
3. The object is at a distance less than the focal length ($s_o < f$).

Use the simulation to observe the paths taken by light rays from the object through a convex lens for these three cases. You may want to experiment with the following options offered by the simulation:

- The simulation allows you to select “no rays,” “marginal rays,” “principal rays,” or “many rays”. The most useful views are “principal rays” and “many rays.”
- The focal points of the lens are marked with an “x” on the optical axis. Dragging either the focal point or the lens with the mouse will move both focal points and the lens together. To change the focal length of the lens, you must change the value of either “curvature radius” or “index of refraction” with the sliders at the top.
- To see when a virtual image forms, you must check “virtual image” at the top right. (Think about under what circumstances you expect to find a virtual image rather than a real image.)
- To see rays from more than one point in an image, check “second point” at the left.

Draw the following ray diagrams (and answer the accompanying questions) in your lab notebook. Each lab partner should do these individually but you should feel free to discuss them as you go.

1. Draw a fairly large sketch, showing a convex lens and a source of light (bright object) that has a defined top and bottom. Also indicate on your sketch the optical axis and the focal points of the lens. Place the source farther away from the lens than the focal point.
2. Sketch the paths of two light rays (one ray parallel to the axis and one ray through the center of the lens) from the top of the light source to the lens, and continue the sketch for each ray on the other side of the lens. Do you expect an image to form in this situation? If so, indicate the position of the image in your sketch. Where should you position the screen in order to see the image? Is the image right side up (“upright”) or upside down (“inverted”)?
3. Do the same as in 1 and 2, but placing the light source at one of the lens's focal points. Do you expect an image to form in this situation, and if so, where? Can you cast this image on a screen? Is it upright or inverted?
4. Do the same as in 1 and 2, but placing the light source closer to the lens than its focal point. Do you expect an image to form in this situation, and if so, where? Can you cast this image on a screen? Is it upright or inverted?
5. Does the image produced by a lens always form in the focal plane? If not, under what circumstances does the image form in the focal plane?

Use the 10 cm focal length lens, light source, and screen to examine image formation in all three cases.. (You may find it useful to go back and forth between drawing the ray diagrams and duplicating the same conditions with the apparatus.) Here are a couple of things to try; think about how each relates to the ray diagrams.

Position the lens relative the source in such a way that you cannot cast an image of the source on the screen, but you can see a magnified image of the source if you look through the lens toward the source. (Note that you can't put your eye too close to the lens, for reasons we'll discuss in class....)

PROBLEM #2: EXPLORING FOCUSING

Find an arrangement with which the image forms in the focal plane of the lens. (This is also a way to easily confirm that the focal length of the lens is about 10 cm.) If you need help coming up with a strategy, talk to your lab instructor.

Hints for using the optical equipment to form images:

Position the light source, the convex lens, and a screen on the optics bench. The light source will serve as your object; keep its position fixed. Check that the light source is aligned with the principal axis of the lens (it will be if both are mounted correctly on the optical bench). Adjust the position of the lens and screen so that a focused image appears on the screen.

Move the source slightly toward and away from the lens, each time adjusting the screen's position to show a crisp image. (There will be some range of distances over which there will be an image visible, and depending on the lens and its position relative to the source, you may be able to move the screen some distance over which the quality of focus of the image does not appear to change. Do your best to identify the location of the sharpest focus but expect that there will be some uncertainty.) Does the direction in which you have to move the screen match your responses to the warm-up questions?

LABORATORY 2: OPTICAL INSTRUMENTS

In this lab, you will continue solving problems related to the formation of optical images. In the first problem, you will examine image formation by a single lens; in the second and third problems, you will examine image formation by systems of two lenses, in which the image formed by the first lens serves as the object for the second lens. Although state-of-the-art optical instruments such as microscopes typically involve many lenses, the essentials of how they work can be understood with just two lenses.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Describe features of real optical systems in terms of ray diagrams.
- Use the concepts of real and virtual images, as well as real and virtual objects, to explain features of optical systems.
- Explain the eye's function in human perception of images.

PREPARATION:

Complete the Warmup and Prediction questions for each of the three problems, leaving space in your lab notebook between each for your measurements. You can do them on separate paper and then tape them into your notebook as you go so that you will have an appropriate amount of space. As you go, review Chapter 31 of Wolfson if needed.

Before coming to lab you should be able to:

- Use the thin lens equation to calculate the relationship between object position, image position, and the focal length of the lens.
- Draw a ray diagram to locate the image formed by an object and either a convex or a concave lens.
- Use the geometrical properties of similar triangles to find unknown quantities

PROBLEM #1: MAGNIFICATION AND WORKING DISTANCE

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When imaging small objects with a microscope, typically microscopists begin by examining the object (usually called the sample) with relatively low magnification, because it is easier to locate the region of interest of the sample at low magnification, and then increase the magnification. The strategy that microscopists have developed for doing so is to equip microscopes with more than one objective lens (typically two or three). These lenses are mounted on a rotating turret so that they can be exchanged without disturbing the sample.

When changing objectives to change magnification, the position of the sample and the position of the image must stay the same. However, the position of the lens can change, so the distance from the sample to the lens (which microscopists call the “working distance”¹), and the distance from the image to the lens, can change.

Suppose you are designing a set of objective lenses for a new microscope. To do so, you need to understand the relationship between the focal length of the lens, the magnification that can be achieved with that lens, and the distance between the lens and the sample that is needed to achieve that magnification. To study this in a simple system first, you will model the objective as a single lens. Keep in mind that the position of the sample and the position of the image are fixed, but you can change where the objective is placed along the optical axis.

PREDICTION

The objective lens of a microscope must form a real image in order for it to be viewed by the eyepiece (if you’re curious about why, think about it, and discuss with your instructor). Where should the objective lens be placed relative to the sample to form a highly magnified real image?

WARM-UP

1. How should you position a convex lens near a bright object in order to form a real image? To answer this, construct a ray diagram: Draw the lens and its axis, label the lens's focal points, draw the object, construct two principal rays from the object, and using those rays, indicate the position of the image. (It’s convenient to represent the object with an arrow as in Wolfson).
2. If you move the lens farther away from the object, does the image move closer to or farther from the lens? Does the image get smaller or larger? Construct a ray diagram and answer these questions based on your results. Be sure to keep the focal length of the lens the same.
3. If the focal length is constant and the object distance increases slightly, what does the lens equation suggest about whether the image distance should increase or decrease? Is this consistent with your answer to (2)?
4. How could you determine the focal length of a lens from a graph of $1/(\text{distance from object to lens})$ vs. $1/(\text{distance from lens to image})$?

¹ If the object is a biological specimen that is mounted on a glass microscope slide and sealed with a cover slip, the working distance is defined as the distance from the objective lens to the surface of the cover slip.

EQUIPMENT

For this problem, you will be provided with an optical bench, a set of convex lenses in lens holders, a light source with a crosshair pattern on it, a white screen, and digital calipers to measure sizes (your lab instructor can show you how to use these when you are ready). There is also a compound microscope at your lab station that you will look at after you make your measurements on the lenses.

EXPLORATION

Estimate the focal length of each convex lens experimentally using a light source that is much more distant than the focal length of each lens. (Where should light from a very distant object be focused?) Confirm that your estimate matches the value on the sticker on the lens holder.

Position the light source, the convex lens, and a screen on the optics bench. The light source will serve as your object; keep its position fixed. Check that the light source is aligned with the principal axis of the lens (it will be if both are mounted correctly on the optical bench). Adjust the position of the lens and screen so that a focused image appears on the screen.

Move the lens slightly toward and away from the light source, each time adjusting the screen's position to show a crisp image. (There will be some range of distances over which there will be an image visible, and depending on the lens and its position relative to the source, you may be able to move the screen some distance over which the quality of focus of the image does not appear to change. Do your best to identify the location of the sharpest focus but expect that there will be some uncertainty.)

Do your observations confirm your answer to Warmup #2?

DETERMINING FOCAL LENGTH AND MAGNIFICATION

Read over the procedures for measuring focal length and magnification before you begin, as these measurements can be made in parallel.

1. **Focal length:** Carefully determine the focal length of the convex lens labeled "+100 mm," by recording the positions of the image, lens and light source for at least five distances between the lens and the light source, and using the strategy suggested in Warmup 4.

Experimental tips: Keep the position of the light source fixed, but move the screen as needed when you move the lens to view the image. Obtain some data for which the image is larger than the object and some for which the image is smaller.

2. **Magnification:** As you measure the image and lens positions, also measure the magnification of the image. Tabulate the measured magnification along with the positions and compare it to the magnification you calculate from the object and image distances. **For one measurement**, also determine uncertainties in the measured and calculated values of magnification. Do the measured and calculated values agree within uncertainty?

Experimental tips: Measure the size of a suitable feature in the image with the digital calipers. Select a feature large enough that you can measure it accurately, but not so large that it will be distorted in the more highly magnified images. You may wish to measure different features for different magnifications.

3. Once you have finished measurements 1 and 2 for the +100 mm lens, determine the focal length of the +200 mm lens.

CHANGING LENSES

4. Position the lens and screen so that the image with the +200 mm lens is as large as practical while still well focused. (You will find that as the images get especially large, it is hard to focus them well.) When you have a sharp large image, record the distance of the +200 mm lens to the source and to the screen, and the magnification of the image.

5. Remove the +200 mm lens and place the +100 mm lens on the optical bench in an appropriate position to cast an image on the screen **without moving the screen**. (This is like changing objectives on the microscope: you are keeping your sample and image in place, and changing lenses.) You should be able to estimate roughly where the +100 mm lens will need to go before placing it on the bench, based on your previous measurements and your prediction/warmup exercises. Record the distance of the +100 mm lens to the source and to the screen, and the magnification of the image with the +100 mm lens.

5. Look at the compound microscope at your lab station. The objectives are labeled with their magnification. For each objective, the lens is mounted at the very end of the barrel.² Which lens is closest to the sample position, the lowest magnification or the highest magnification lens? What does this suggest about which lens has the shortest focal length, the lowest or highest magnification?

CONCLUSION

For your measurements of focal length and magnification (1, 2, and 3):

Was your prediction consistent with the conditions under which you found the largest image? Was your work for warmups 1 and 2 consistent with your observations? Did your graphs used for calculating focal length have the shape you expected? Were the estimated and measured values for the focal length of each lens in agreement? Were the measured and calculated values of magnification in agreement? Explain any discrepancies between your predictions and your measurements.

Is the magnification of an optical system solely a property of the lens in the system, or are other factors important as well?

For the “changing objectives” measurement (4 and 5):

Which image is larger, the one formed with the +100 mm lens or the one formed with the +200 mm lens?

Which lens is closer to the object, the +100 mm lens or the +200 mm lens?

Are these observations consistent with your observations of the compound microscope?

² The objective actually consists of multiple lenses that fill most of the barrel, but for comparison to this simple model, you can consider the lens to be at the end of the barrel.

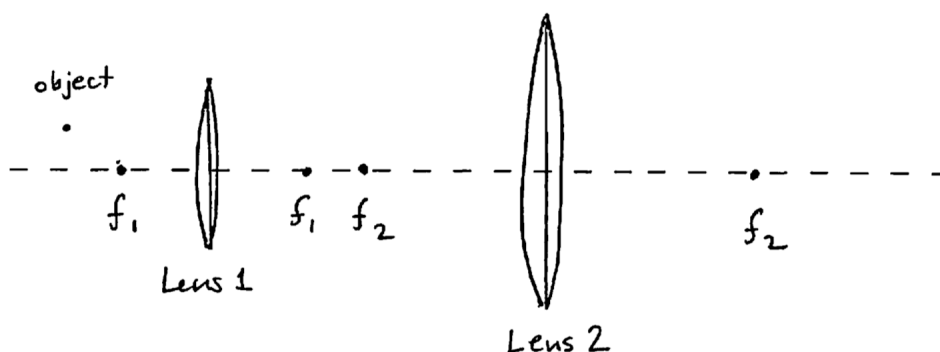
PROBLEM #1: MAGNIFICATION AND WORKING DISTANCE

PROBLEM #2: THE COMPOUND MICROSCOPE

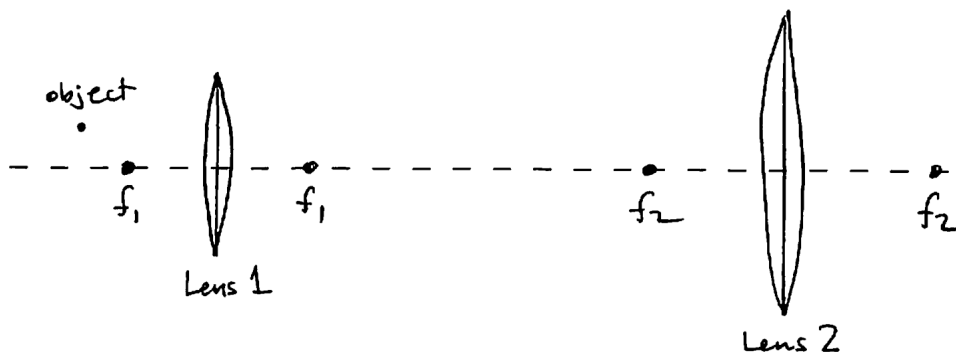
Suppose you have been hired to run the optical microscopy lab at the local hospital. On your first day at work, you discover that the microscopes in the lab, although of very high quality, are quite old and are not equipped to digitally capture the image on a CCD camera. You therefore go to the director of your division with a proposal to purchase new, suitably equipped microscopes. Your director frowns on seeing the amount of money required and says, “Just attach CCD cameras to an eyepiece in place of your eye.” Will this do the job, assuming you could find a way to attach the CCD cameras to the eyepieces? To figure this out, in this lab you will construct a simple model of a microscope.

WARM-UP³

1. The diagram provided below shows an arrangement of a small object and two thin convex lenses analogous to that used in a typical compound microscope. On the diagram, construct rays showing the image formed by lens 1, then use that image as the object for lens 2 and construct rays showing the image formed by lens 2.



2. Think of lens 1 as the objective lens and lens 2 as the eyepiece lens of a microscope. Does the eyepiece lens form an image that could be projected on a screen? If so, where should the screen be placed? If not, is it possible to adjust lens 2 so that its image could be projected on a screen?
3. The diagram provided below shows another possible arrangement of a small object and two thin convex lenses. On the diagram, construct rays showing the image formed by lens 1, then use that image as the object for lens 2 and construct rays showing the image formed by lens 2.



³ Questions 1 and 3 inspired by *Tutorials in Introductory Physics*, McDermott, Shaffer, and the University of Washington Physics Education Group, “Convex Lenses” homework, p. HW-140 (Prentice Hall, 2003).

4. Think of lens 1 as the objective lens and lens 2 as the eyepiece lens of a microscope. Does the eyepiece lens form an image that could be projected on a screen? If so, where should the screen be placed? If not, is it possible to adjust lens 2 so that its image could be projected on a screen?
5. Practically speaking, you want to keep the microscope compact. If you have available to you a +100 cm lens, a +200 cm lens, and a +250 cm lens, which do you want to use for the objective lens to obtain maximum magnification, if you also want to keep the microscope as small as possible

EQUIPMENT

For this problem, you will be provided with an optical bench, a set of convex lenses in holders, a light source with a crosshair pattern, a screen, and a digital caliper for measuring image sizes.

EXPLORATION

Arrange an approximate model of a compound microscope before taking careful measurements. First, decide which lens you will use as the objective and which as the eyepiece to model the microscope, based on the focal lengths you determined in the previous problem. Discuss your choice briefly with your lab instructor.

Position the light source and the convex lens you chose for the objective on the bench. Verify that the principal axis of the lens is parallel to the bench and passes through the center of the source. Find the position of the image formed by the objective lens.

Place another convex lens (the “eyepiece”) in position so that the image formed by the objective lens is between the lenses and just inside the appropriate focal point of the eyepiece lens.

Look through the eyepiece lens, positioning your eye close to the lens. Can you see an image of the light source? Is it inverted or erect? Does it appear to be enlarged? Can you estimate how much the image is enlarged? How can you tell when you have achieved the conditions described in the warm-up questions for a compound microscope?

With the eyepiece in its current position, can the image formed by the eyepiece be projected onto a screen? Can you project the image onto a screen if you move the eyepiece lens?

MEASUREMENT

Position the light source and the objective lens on the optical bench and locate the image formed by the objective lens. Following the methods you developed in the exploration, adjust the position of the eyepiece lens until you have achieved the conditions necessary for a compound microscope, when viewing the image with your eye next to the eyepiece. Record the position of the source and the positions and focal lengths of the lenses. Qualitatively, does the image appear to be larger or smaller than the original source?

Now adjust the microscope to project the image on a screen. Record the position of the source, the positions and focal lengths of the lenses, and position and magnification of the image, and describe whether the image produced is upright or inverted.

Examine the compound microscope at your lab station, and identify each part that corresponds to the parts of your model microscope.

- Why would the designers choose to enclose the light path from the objective lens to the eyepieces with a solid box? (How might this improve the images you can see with the microscope?)
- Do you expect that this microscope produces a virtual image or a real image?

ANALYSIS

In your lab book, draw diagrams showing your recorded positions of the source and the lenses, and your eye or the screen, for the two arrangements of the microscope:

- 1) virtual image viewed by eye
- 2) real image cast on screen

On each diagram, mark the distances from the source to the objective lens, the objective lens to the eyepiece lens, and the eyepiece lens to the screen. Calculate where the image formed by the objective lens falls and mark it on the diagram. (You do not need to include rays unless you wish.) Also mark the focal points of the eyepiece lens on the diagrams. Use the location of the image formed by the objective lens to explain why the eyepiece lens forms either a real or a virtual image.

CONCLUSION

What design of a microscope is required to project the microscope's image onto the detector of a CCD camera? In the microscopes of the original problem, explain what modifications would need to be made, and whether an adequate case could be made for buying new microscopes.

FOLLOW-UP: MICROSCOPE FOCUSING

Turn on the illumination for the compound microscope at your station, and place one of the stage micrometers (microscope slides with ruler patterns) on the microscope stage. Even if you have previously used these microscopes (these are borrowed from the Biology 1 and 2 labs), unless you are a very experienced microscopist, ask your lab instructor to show you how to focus the microscope just to be sure to avoid damaging the objectives. Turning the focusing knob moves the objective lens along its optical axis, while keeping the position of the sample and the eyepiece fixed.

Position the lowest magnification objective above the sample and turn the focusing knob so that you can see a sharp image of the stage micrometer. Then hold a white index card by the eyepieces so that you can see the light coming out of the eyepieces. Is it possible to see an image on the card?

Starting with the lowest magnification objective, turn the focusing knob gently, to gain a sense of how rapidly the image goes in and out of focus. Then switch to the highest magnification. Does the focus disappear more or less rapidly at higher magnification?

How far the objective lens can be moved before the image goes out of focus depends on two properties of imaging systems known as depth of field and depth of focus, which we will not have time to study in great detail (though if you are a photographer you may already know about these).

The lenses we used in the model microscope have long focal lengths, in order to allow us to easily work with this equipment, and consequently have long depths of field and focus. On a real microscope, all the lenses involved have much shorter focal lengths and so the depth of field and focus are much shorter.

FOLLOW-UP NOTES ON DIGITAL MICROSCOPY

The following is optional additional information for those who are interested, but not required!

Modern microscopy is typically done using CCD cameras to record images. Unlike cameras for photography, ordinarily CCD cameras do not have lenses in front of the detector chip— the chip is simply protected with a transparent window. In addition, the size of the chip and the individual pixels of the CCD camera are such that the magnification provided by the microscope objective is the right amount of magnification; further magnification by a second lens would make the image too large for the chip.

For this reason, microscopes are designed with ports to which the CCD camera can attach, so that the image produced by the objective will fall on the detector. (For a high-quality microscope equipped with what is called an “infinity-corrected objective”, the story is a little more complicated and actually does involve a second lens which does not provide any further magnification, but for the purposes of understanding the basics, you can think of this as the image produced by the objective alone.) Then there is a mirror (or a prism operated in total internal reflection mode, as in last week’s lab) that can be positioned to direct the rays coming from the objective either toward the CCD camera or toward the eyepiece.

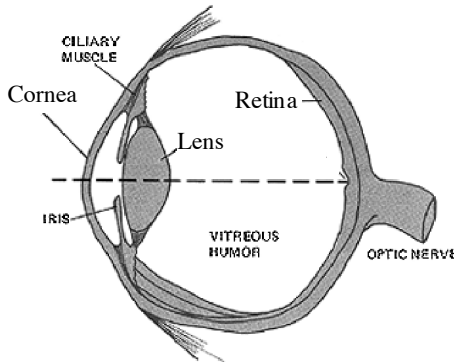
Before CCD cameras, microscopes were sometimes provided with so-called “photoeyepieces” which could produce a real image on the film plane in a photographic camera with the camera’s lens removed. A microscopist could thus view the sample looking through a normal eyepiece, then remove one eyepiece and replace it with a photoeyepiece with camera attached, and take a picture of the sample. So the director’s idea is not so crazy ... but has been rendered obsolete in most modern microscope technology.

PROBLEM #3:

THE EYE — COMPENSATING FOR AN ARTIFICIAL LENS

A diagram of a human eye is shown below. In an eye with normal vision, the *cornea* and the *lens* can project a focused image of objects at a wide range of distances (not shown in the diagram) on the *retina*. To achieve such flexibility, the *ciliary muscle* in the eye can slightly change the shape of the *lens* to adjust its focal length.

Image of a Human Eye



Your friend's grandmother has just had cataract surgery. During the surgery, the flexible *lens* in one of her eyes was removed, and was replaced with an artificial lens whose focal length cannot be adjusted. As a result, she can only see clear images of objects that are at a particular distance from her eyes, neither very close nor very distant. Your friend's grandmother has asked you to recommend a corrective lenses that will help her see distant objects clearly. (She already has good corrective lenses for seeing nearby objects.) Before making specific recommendations for a corrective lens, you and your group decide to work with a simplified model of her eye.

Your eye model will use a single convex lens to approximate the behavior of the inflexible lens and cornea, and a screen to take the place of the retina.

PREDICTION

If the artificial lens focuses well on objects that are a few meters away, but objects that are very far away are blurry, should the corrective lens that allows focusing on distant objects be concave (diverging) or convex (converging)?

WARM-UP

1. Sketch a ray diagram representing a surgically repaired eye with a convex lens, using an arrow as the object, and placing the object at a distance of roughly 3 times the focal length of the artificial lens. Assuming that this is the position at which the artificial lens can best focus, indicate the location of the retina for "seeing" an object at this distance.
2. Sketch ray diagrams to show what happens to the image position if the object moves *much farther away* from the lens than in the previous case. If a corrective lens were added, would it have to be convex or concave to project a clear image on the "retina"?

PROBLEM #3: ARTIFICIAL LENS

EQUIPMENT

For this problem, you will be provided with an optical bench, a set of lenses in holders, a light source with a measurement grating, and a screen.

EXPLORATION

Construct a simple model of the eye on the optics bench. Use the shortest focal length convex lens as your eye lens and the screen as the retina. Set up the lens and screen so that when the light source is about three focal lengths away from the lens, a focused image is formed, and you can leave the lens and screen in place and move the light source to anywhere from only about one focal length away from the lens to much more distant (8-10 focal lengths). (Ask your lab instructor to show you how to reposition the light source so that it remains properly aligned with the lenses.)

Without any corrective lens, demonstrate that the image of the source is out of focus when the source is a large distance away from the lens, clearly focused at a moderate distance (about three focal lengths), and out of focus at a short distance.

Now position the source far away from the lens and add a corrective lens between the source and the lens, so that you can focus the image of the source. (Was your prediction for the type of lens correct?) Note that if the image is very small, you can focus by making the outline of the bright square sharp, rather than by trying to focus the image of the crosshairs.

MEASUREMENT

With the lens and screen positioned as you found in the exploration, the light source far from the lens, and the corrective lens added to produce a focused image on the screen, draw a careful sketch of the arrangement of your model, and record the positions and focal lengths of each lens, and the positions of the light source and screen.

ANALYSIS

This analysis is challenging and may be time-consuming, so if you are running late and need to finish it after lab and have it checked off next week, that is fine!

Just as with the microscope, the image formed by the first lens (the corrective lens) serves as the object for the second lens (the eye lens). However, this situation is particularly counterintuitive because the image formed by a diverging lens is *virtual* rather than real. So, there is no place in this system where an intermediate real image forms — you can't cast the image formed by the first lens on a screen.

If you were an ophthalmologist treating a cataract patient, you would try different focal length lenses on the patient in order to identify the focal length that would allow the patient to see distant objects when that lens was worn in a pair of glasses — namely, when that lens is fixed at a particular distance from the patient's eye. However, in this lab we don't have a large supply of different focal length lenses, so instead the focal length of the corrective lens is determined by the equipment, and you find the distance for the corrective lens from the eye lens that produces a focused image.

PROBLEM #3: ARTIFICIAL LENS

In this analysis, you will use your measurements to determine the focal length of the corrective lens.

1. Draw a ray diagram to show the position of the image that would be produced by *just the corrective lens*.
2. Then, treat the *image* that would be produced by the corrective lens alone as the *object* to be imaged by the “eye” lens. Add rays to show the position of the final image, produced by the “eye” lens.
3. Now, to calculate the focal length of the corrective lens, work backward. Apply the thin lens equation to the image formed by the “eye” lens, and use your measurements (including your measured focal length for the “eye” lens from the beginning of this lab) to determine the location of the object for the “eye” lens — which, remember, is the image formed by the corrective lens.
4. Then, once you have determined the location of the image formed by the corrective lens, use that and the distance between the object and the corrective lens to determine the focal length of the corrective lens. (Be careful— what is the sign of the image distance for a virtual image?)
5. What does it mean if your equation predicts a corrective lens with a negative focal length? A positive focal length? An infinite focal length? Is each result possible? Could each of the three cases describe an actual lens?
6. How well does your measured value of the focal length compare to the value on the sticker on the lens? If there are discrepancies, what might be some of the sources of uncertainty in your measurement? (Keep in mind that the value on the sticker has an uncertainty of about 10%.)

CONCLUSION

What kind of lens was required to bring distant objects into focus? How close was your determined value of the focal length to the value listed on the sticker? Can you think of a way you could check the value of the focal length by a different measurement? If so, describe it.