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 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 parts**, 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 in your textbook 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

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PART 1:
MAGNIFICATION AND WORKING DISTANCE

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.

WARM-UP

1. How should you position a convex lens near a bright object in order to form a real image? Answer this with 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).

2. If you move the lens slightly 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. In this lab you will place a lens at several different distances from an object and measure the corresponding object and image positions. How could you **graph** these measurements (of s_o and s_i) to determine the focal length of the lens from the graph?

[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. (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 at the same time.

1. **Focal length:** Use the approach you described in Warmup #4 to find the focal length of the convex lens labeled "+100 mm" from a suitable graph. <u>Your graph should have at least 5 data points and you should also provide a neat table of your data in your lab book.</u>

Experimental tips: Keep the position of the light source fixed, and use 5 different positions of the lens. Obtain some data for which the image is larger than the object and some for which it is smaller.

2. **Magnification:** As you measure the image and object distances, also measure the heights of the object and image. <u>Include the heights and the magnification of the image calculated from them in your data table. Check whether your data are consistent with the expected relationship between these quantities and *M* either with a graph or with statistical analysis of your table of data.</u> (Confirm your approach with your lab instructor.)

Experimental tips: Measure the size of a 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.

Present your data clearly in your lab notebook and comment on it. Your discussion of your data should always evaluate how well it compares to your predictions and the models. For this lab, you should the following questions in the process of discussing your data:

- 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 the 10 cm lens in agreement?
- Do the measured and calculated values of magnification agree within uncertainty?
- Explain any discrepancies between your predictions and your measurements.

CHANGING OBJECTIVES

3. Keeping the light source position fixed, position the +200 mm lens and screen so that the image 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 object and image distances, and measure and record the magnification of the image.

4. Remove the +200 mm lens and place the +100 mm lens on the optical bench in an appropriate position to cast a sharply focused image on the screen **without moving the screen or the light source**. (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. Record the object and image distances and the magnification of the image with the +100 mm lens.

5. Look at the compound microscope nearest 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

Summarize your findings from the lab including addressing the following questions:

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:
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.

PART 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.

GOAL

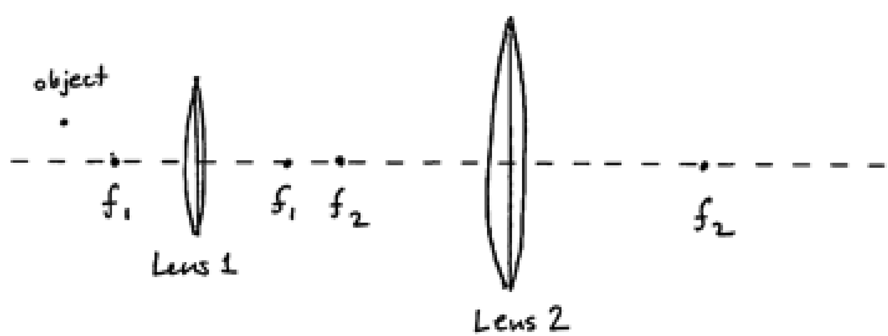
To construct two different types of microscope, one that produces a real image on a screen and one that produces a virtual image that must be viewed through the eyepiece lens.

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[3]

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. There is a copy of this diagram posted on the course web site. Print out a copy of the diagram, and on it 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. Tape this into your lab notebook.



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 viewed 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 viewed on a screen?

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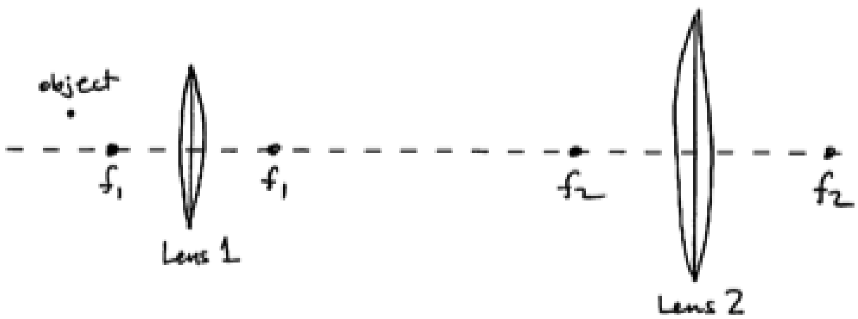
[3] Questions 1 and 3 inspired by *Tutorials in Introductory Physics*, McDermott, Shaffer, and the University of Washington Physics Education Group, "Convex Lenses" homework, p. HW-140 (Prentice Hall, 2003).

3. The diagram provided below shows another possible arrangement of a small object and two thin convex lenses. On a copy of 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. Tape this into your notebook.



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 viewed 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 viewed on a screen?

5. Practically speaking, you want to keep the microscope compact. If you have available to you a +6 cm lens, a +10 cm lens, and a +20 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? Keep in mind your findings in the previous part of the lab.

EQUIPMENT

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

MEASUREMENTS

Overview of procedure: Begin by finding an approximate arrangement of the lenses that matches the design of each type of microscope and checking that it produces a magnified image as you expect. Then if you need to, adjust the positions of the lenses to improve the magnified image. Finally, record your arrangement with a careful diagram in your lab book.

Based on your work in the previous part of the lab, decide which lens you will use as the objective and which as the eyepiece in your model microscopes. Check your choice with your lab instructor.

Position the light source and the convex lens you chose for the objective on the bench. Find the image formed by the objective lens; this is the “first image”.

Place another convex lens (the “eyepiece”) on the bench in the proper position to produce a virtual magnified image of the first image. (Hint: this is the same as using the eyepiece lens as a magnifying glass to look at the first image.) If you aren’t sure how to do this, ask your lab instructor for help.

Look through the eyepiece lens, positioning your eye fairly close to the lens. Can you indeed see an image of the light source? (If not, adjust your microscope.) Is it inverted or upright? Does the image appear to be larger or smaller than the original source?

In your lab book, draw a neat diagram showing:
• the arrangement of the source, the lenses (labeled with focal lengths), and your eye
• all the measured distances between the parts
• the focal points of both lenses
• the images formed by each lens (note you will have to calculate the location of the final image; you will not be able to measure it)
• the distances from each lens to the image it forms
(You do not need to include rays unless you wish.)
Describe whether the final image is upright or inverted and estimate its magnification (it is not necessary to do this precisely).

Now adjust the microscope to project the final image on a screen. Draw a new diagram according to the same instructions for this arrangement. In addition, measure the magnification of the image on the screen, and record in your lab book whether it 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. Also answer the following in your lab book:
• 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?

CONCLUSION

For each of the two microscope designs, explain why the image formed by the eyepiece lens is real or virtual, based on the location of the image formed by the objective lens.

Which 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 made, and whether buying new microscopes is needed.

FOLLOW-UP: MICROSCOPE FOCUSING

Turn on the illumination for the compound microscope nearest your station, and place one of the samples provided 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 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 sample along the optical axis between the objective and the eyepiece,[4] while keeping the positions of the lenses fixed.

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?

[4] For some designs of microscope; others move the lens and keep the sample fixed.

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.

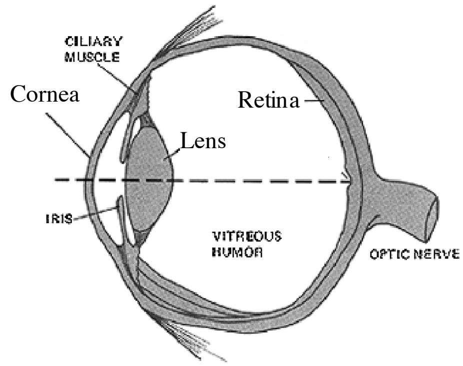
For this reason, microscopes are designed with ports to which the CCD camera can attach, so that the image produced by the objective will fall on the detector. (For a high-quality microscope equipped with what is called an "infinity-corrected objective", the story is a little more complicated and actually 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.

PART 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.

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 a ray diagram to show what happens to the image position if the object moves *much farther away* from the lens than in the previous case.

3. If a corrective lens were added, would it have to be convex or concave to produce a clear image on the "retina"?

4. Now consider what happens with corrective lenses. First draw a new ray diagram including only the object and the corrective lens to show the image that would be produced by *just the corrective lens*. Be sure your diagram is consistent with your answer to question 3.

   Then, use the *image* that would be produced by the corrective lens alone as the *object* to be imaged by the "eye" lens. Add the "eye" lens to your diagram and add rays showing the position of the final image, produced by the "eye" lens. This doesn't have to be to scale; draw the eye lens and its focal points however allows you to easily and clearly draw the rays.

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

If you were an opthalmologist 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. Instead the focal length of the corrective lens is determined by the equipment, and you adjust the distance from the corrective lens to the eye lens in order to produce a focused image.

Construct a model of the eye on the optics bench. Use the 10 cm 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, <u>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.</u>

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, in this case 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. You can only calculate the location of that image.

In this analysis, use your measurements with the ray diagram you drew in warmup 3 to determine the focal length of the corrective lens.

1. 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 first part of this lab) to determine the location of the object for the "eye" lens — namely, the image formed by the corrective lens.

2. 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?)

3. In a sentence or two, explain the meaning of the sign of the focal length of the corrective lens.

CONCLUSION

Compare your measured value of the focal length (with uncertainty) to the value on the sticker on the lens and discuss sources of error in the measurement. (Keep in mind that the value on the sticker has an uncertainty of about 10%.)

Based on your experience in this lab, do you think it is possible to measure the focal length of a diverging lens without using a second lens? If so, describe how you might do it; if not, explain why.