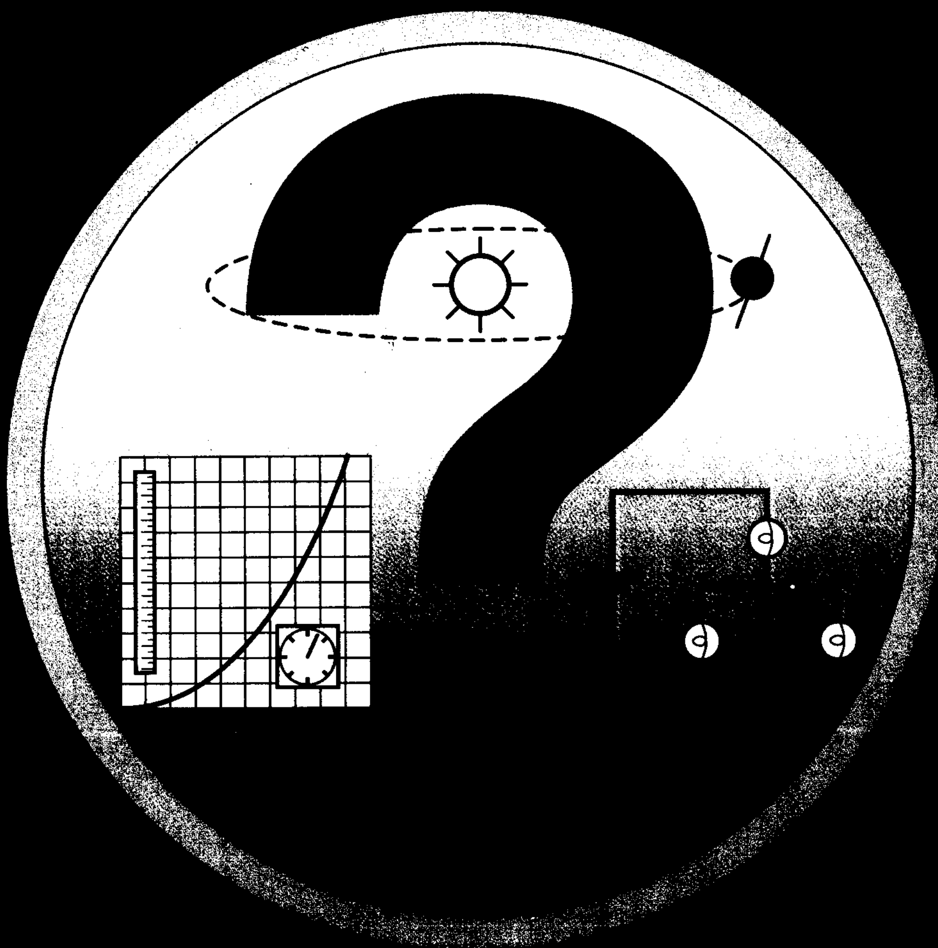
PHYSICS BY INQUIRY

Volume II



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and the
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Part A: Plane mirrors and images

In Part A of *Light and Optics,* we study how light reflects from mirrors. From our observations, we construct a model that enables us to account for the formation of images in plane mirrors.

Section 1. Introduction to reflection

Experiment 1.1

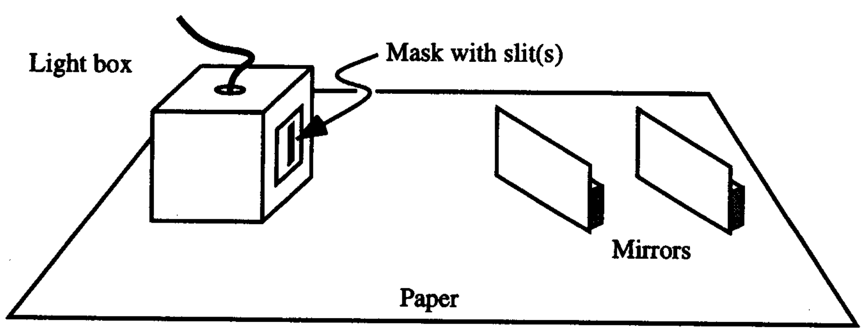
This experiment should be performed in a darkened room.

Obtain a light box. (A light box is a box that has a bulb inside it and a small hole over which a mask can be placed.) Make two masks by cutting vertical slits approximately 50 mm by 3 mm in black construction paper. One mask should have one slit; the other should have two slits approximately 10 mm apart.

A. Place the light box on a large sheet of paper. Put the two masks on the light box, one at a time, and describe your observations.

   What do you think would be the effect of changing the width of a slit in a mask? Make a new mask with a different slit width and check your answer.

B. Obtain two mirrors. Use blocks of wood or other objects to hold the mirrors upright as shown.



(1) Use the mask with a single slit to produce a beam of light. Examine the effect of putting one or both mirrors in the path of a beam of light. Describe your observations.

   Describe the path of the light when the beam is aimed (a) at an angle toward the mirror and (b) straight toward the mirror.

(2) Place the two-slit mask on the light box.

Is it possible to make the two beams cross using only one mirror? If so, draw a sketch that illustrates your answer.

(3) Place the single-slit mask on the light box and turn off the light. Make an *X* on the paper in a location that is not directly in front of the slit.

Decide where you need to place one or both mirrors so that the beam will pass over the *X*. Talk to a staff member if you need additional equipment. Explain how you determined your answer.

Turn on the light box and check your answer.

(4) Ask your partner to look away while you place one or two mirrors in the path of a beam of light. Mark the resulting path on the sheet of paper, then remove the mirrors and turn off the light box.

Ask your partner to predict where to place the mirrors in order to have the light follow your marked path.

Turn on the light box and check your partner's answer. Switch roles with your partner and repeat part (4).

Experiment 1.2

Place single-slit mask on the light box and put a mirror in the beam. Draw a line along the front of the mirror to mark its location.

A. Aim the beam so it reaches the mirror at an angle.

Use a ruler to mark the path of the light both toward and away from the mirror by drawing a line along the center of the beam.

Use a protractor to measure the angle at which the beam strikes the mirror and the angle at which it leaves the mirror.

How do the two angles compare?

B. Move the light box so that the beam strikes the mirror at a different angle and repeat part A.

C. Summarize your observations in this experiment as a rule describing how to predict the path of a beam of light that is aimed at a mirror.

Is your rule true for all angles or only for certain angles?

Does your rule describe the behavior of each edge of the beam as well as the center of the beam?

✔ Check your rule with a staff member.

We call the beam that strikes the mirror the *incident* beam. The beam that leaves the mirror is called the *reflected* beam.

Experiment 1.3

This experiment should be performed in a darkened room.

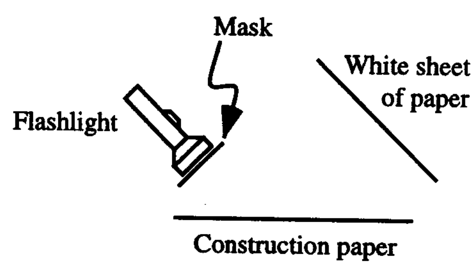
You will need colored construction paper, white paper, a mirror, a flashlight, and a mask for the flashlight. Make the mask by cutting a small slit (approximately 25 mm by 5 mm) in an index card or other thick piece of paper. Tape the mask to the front of the flashlight.

A. Shine the masked flashlight onto various flat surfaces, including colored pieces of construction paper.

Describe what you observe as you vary the angle between the flashlight and the surfaces.

Compare what happens when you shine the flashlight on various types of surfaces, such as dark-colored surfaces, light-colored surfaces, rough surfaces, and smooth surfaces.

B. Place a white sheet of construction paper flat on the table and hold a white sheet of paper near it as shown. Aim the flashlight at the construction paper, not the paper you are holding.



How does the appearance of the paper that you are holding change as the light is turned on and off?

How might you account for your observations?

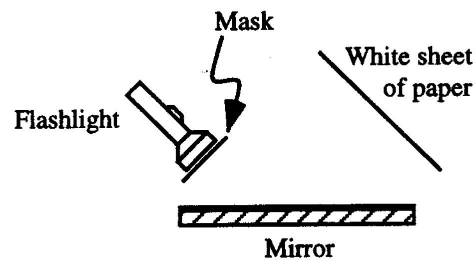
Replace the white construction paper with red construction paper. Does this change affect the appearance of the sheet that you are holding?

C. Repeat part B using several other colors of construction paper.

How does the color of the construction paper affect what you see on the white paper you are holding? How can you account for your observations?

D. Imagine that the construction paper in part B were replaced by a mirror.

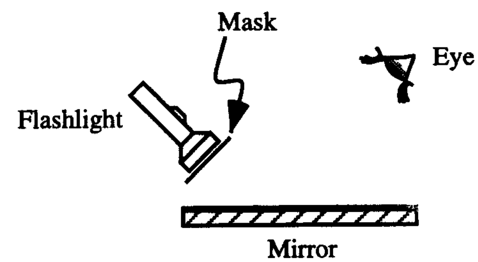
Predict whether this change would affect what you see on the paper that you are holding. Explain.



Discuss your prediction with your partner, then check your answer.

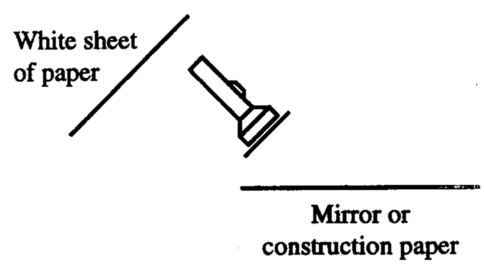
Suppose that you removed the white sheet of paper and placed your eye where the paper had been located.

Predict what you would see if you were to look toward the mirror in this case. Explain.



Discuss your prediction with your partner, then check your answer.

E. Imagine that you were to place the sheet of white paper at the location shown at right.



What would you see on the white sheet of paper if the flashlight were aimed at:

(1) a mirror?

(2) construction paper?

Discuss your predictions with your partner, then check your predictions.

F. Compare and contrast how light is reflected by mirrored surfaces and by non-mirrored surfaces.

Recall the rule that you wrote in Experiment 1.2 to predict the path of a beam of light that is aimed toward a mirror.

Does this rule also describe the behavior of a light beam that is reflected by a non-mirrored surface? Explain your reasoning.

✔ Discuss your results with a staff member.

Exercise 1.4

A. Consider the following statement made by a student:

"At night it is dark, but during the day it is bright because the sun lights up objects. When objects are lit up I can see them."

Do you agree with the statement by this student? Would you change the statement in any way to make it more complete? Base your answer on your findings from the preceding experiments.

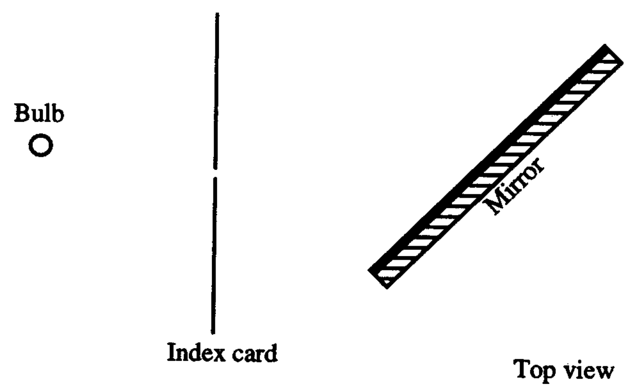
B. Summarize the conditions necessary for you to be able to see an object.

✔ Check your reasoning with a staff member.

Experiment 1.5

For this experiment you will need a mirror, a small bulb, an index card (or other piece of heavy paper), a nail, and a large sheet of white paper.

Cut a narrow slit (2–3 mm wide) in the index card. Then, on the large sheet of paper, set up the lighted bulb, slit, and mirror as shown.



A. Describe the path of the light through the slit. Sketch the path on the paper. Show the beams that are incident on and reflected from the mirror. Draw arrow heads to indicate the direction the light travels.

Where must you place your eye to see the light bulb in the mirror?

The bulb that you see in the mirror is called the *image* of the bulb.

B. Replace the bulb by a nail at the same location.

Where must you place your eye to see the image of the nail?

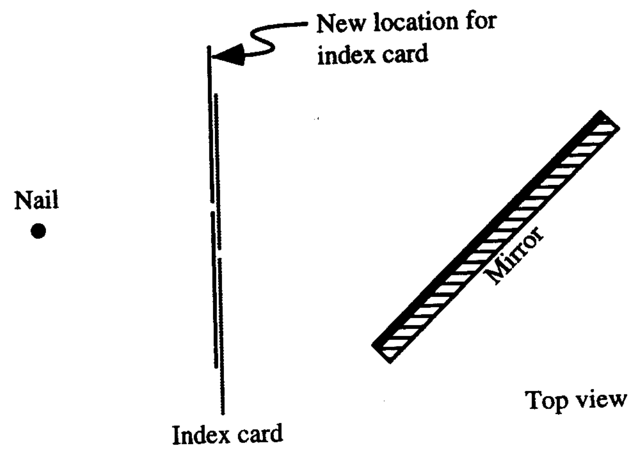
Describe the path that light takes from the nail to your eye.

How does the line that you drew in part A compare to the path of the light from the nail to your eye in part B?

C. Move the index card to a new location as shown.

Predict where you must place your eye to see the image of the nail. Explain.

Check your prediction. On the paper, mark the path that light takes from the nail to your eye. Draw arrow heads to indicate the direction the light travels along the path.



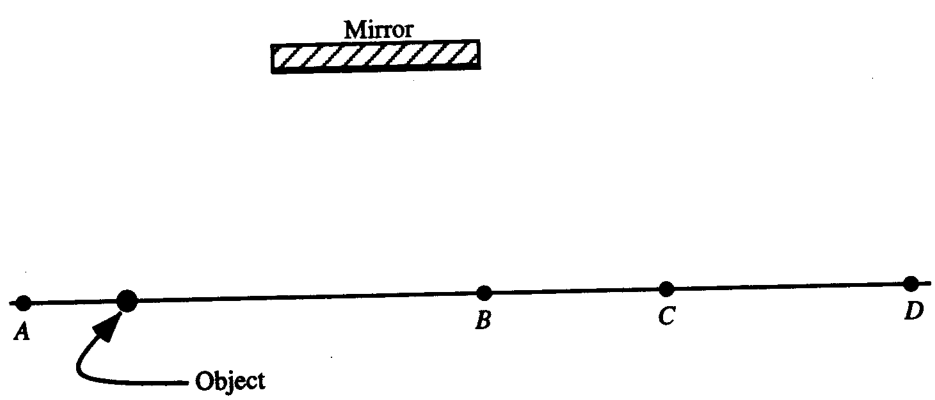
D. Remove the index card. Find the region in which you must place your eye in order to see the image of the nail. Draw lines on the paper to show the path of the light from the bulb to your eye at the extreme limits of the range.

In the preceding experiment, you drew lines with arrow heads (——>——) to indicate the path of light. These lines are called *rays*. A diagram in which rays are used is called a *ray diagram*.

Exercise 1.6

The diagram below shows an object near a mirror. An observer is free to walk along the line in front of the mirror.

A. From which of the lettered points along the line could the observer see the image of the object? Explain.



B. For each point from which the observer can see the image, indicate the direction in which the observer must look in order to see the image.

Experiment 1.7

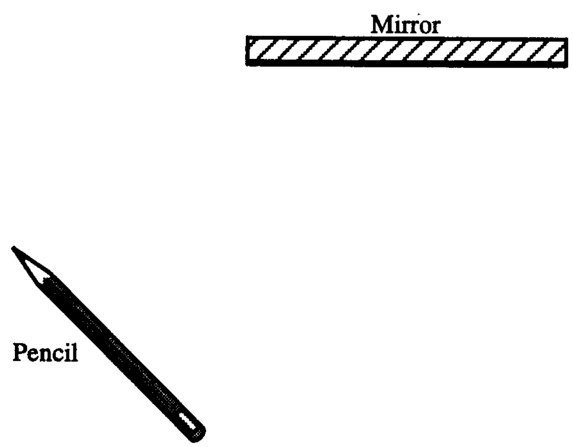
Ask a staff member to show you the demonstration for this experiment.

A. Write a description of the demonstration in your notebook. Record your predictions.

B. Observe the demonstration. Use a ray diagram to account for your observations.

Exercise 1.8

Consider a pencil near a mirror as shown in the top view diagram below.



A. Indicate the region in front of the mirror where an observer could see:

(1) the image of the tip of the pencil

(2) the image of the eraser

(3) the entire image of the pencil

B. Choose a point from which the observer could see the entire image of the pencil. Indicate the directions in which that observer would have to look to see:

(1) the image of the tip

(2) the image of the eraser

C. Place a mirror on your ray diagram and check your results for parts A and B. (If necessary, use paper to mask a larger mirror to make it the correct size.)

✔ Discuss this experiment with a staff member.

Section 2. Image formation in a plane mirror

In this section, we investigate image formation in a plane mirror. We develop techniques that can be used to determine the location and size of an image.

Experiment 2.1

A. Close one eye and place your open eye at table level. Have your partner drop a small piece of paper (1 cm by 1 cm) onto the table.

   Hold your finger above the table and then move your finger until you think it is directly above the piece of paper. Move your finger straight down and see if it was actually directly above the paper.

   Try this procedure several times, with your partner dropping the piece of paper at different locations. Keep your open eye at table level. After several tries, switch roles with your partner.

      Were you and your partner consistently able to locate the piece of paper?

      How can your account for the fact that when your finger misses the piece of paper, your finger is in front of the paper or behind it, but not to the left or right of the paper?

B. Try to develop a strategy that allows you to consistently locate the piece of paper with your finger.

Experiment 2.2

A. Have your partner hold two pencils one above the other about one meter in front of you. Then have your partner move one pencil about 15 cm closer to you.

   Close one eye, then move your head so that one pencil appears to be directly above the other. Now move your head from side to side. Describe what you observe.

B. Again, close one eye and move your head so that the pencils appear one directly above the other.

      If you move your head to the right, which pencil appears to be on the right: the one closer to you or farther from you?

      If instead you move your head to the left, which pencil appears to be on the left: the one closer to you or farther from you?

C. Have your partner move the pencils closer together.

How does this change affect what you observe when you move your head from side to side?

Have your partner place the two pencils one above the other.

How does this change affect what you observe when you move your head from side to side?

In the previous experiment, you observed that there is an apparent change in the relative location of the two pencils when you move your head from side to side. This effect is said to be due to *parallax.*

Experiment 2.3

A. Describe how you can use parallax to determine which of two objects is closer to you. Draw a ray diagram to illustrate your answer.

How must the two objects be located relative to one another if you observe no effect of parallax when you move your head from side to side?

B. Explain how you could use parallax in Experiment 2.1 to tell whether your finger is (1) directly over the piece of paper, (2) in front of the piece of paper, or (3) behind the piece of paper.

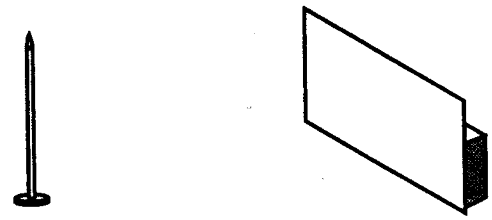
Repeat Experiment 2.1 and test the method that you have devised.

C. Have your partner hold two pencils in front of you as in part A of Experiment 2.2. Close one eye and use the method of parallax to direct your partner as to which direction to move the upper pencil until it is directly above the lower pencil.

✔ Discuss your reasoning with a staff member.

Experiment 2.4

Obtain two identical nails and a mirror that is shorter than the nails. Place one nail upright on a sheet of paper about 10 cm in front of the mirror. We will call this nail the "object nail."



A. Place your head so that you can see the image of the object nail. Then move your head from side to side. Describe what you observe.

Where does the image appear to be located? Does the image stay in the same location or does it change location as you move your head? If there is a single location, mark that location on the paper. If the image location depends on where you place your eye, mark several locations of the image for several different eye locations.

B. Place your head so that you can see the image of the object nail. Apply the strategy for using parallax that you developed in Experiment 2.3 to place the second nail at the location of the image of the object nail. Mark this location on the paper.

Move your head to a new location and repeat the procedure in part B.

Is there a unique location where all observers would agree that the image is located (provided they can see an image)? Check your answer experimentally.

C. Two students discuss the image of a nail in a mirror:

Student 1: *"The location of the nail's image changes as I move my head. When I move to the left, the image moves to the left side of the mirror. When I move to the right, it moves to the right side of the mirror. The image location is changing."*

Student 2: *"Your observations tell you that the image isn't located on the surface of the mirror. The image acts like it is behind the mirror. Since the image seems to follow you, as compared to the mirror, the image must be behind the mirror."*

Do you agree with student 1, student 2, or neither? Explain your reasoning.

✔ Discuss this experiment with a staff member.

In Experiment 2.3, you developed a strategy for finding the location of an object using the effect of parallax. In Experiment 2.4, you applied your method to find the location of an image. We refer to the process of using parallax to determine the location of an image as the *method of parallax* or *locating an image by parallax.*

In the following experiments, we determine the location of an image by another technique called *ray tracing.* This technique is based on our model for light in which we envision light as being emitted in all directions by luminous objects, such as light bulbs, or as being reflected in all directions by non-luminous objects, such as nails or pins.

Experiment 2.5

Secure a sheet of paper to a piece of corrugated cardboard. Stand a nail on its head at one end of the paper.

A. Place your head at table level at the other end of the paper from the nail. Close one eye and look at the nail.

Push two pins into the cardboard so that, from your location, they appear to be in line with the nail.

The two pins determine your line of sight to the nail. Use a ruler to draw your line of sight to the nail.

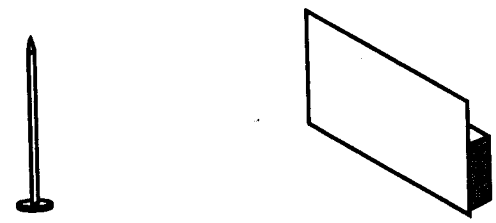
Do you determine your line of sight more accurately by placing the pins close together or far apart?

Repeat the procedure above to mark lines of sight from three other vantage points, then remove the nail.

How can you use the lines of sight that you drew to determine where the nail was located?

What is the smallest number of lines of sight necessary to determine the location of an object?

B. Turn the paper over (or obtain a fresh sheet). Place a mirror and nail on top of the paper as shown at right. Draw a line on the paper to mark the location of the mirror.



(1) Place your head near the surface of the table and look at the image of the nail. Push two pins into the cardboard so that, from your location, they appear to be in line with the image of the nail. Use a ruler to draw your line of sight to the image.

Can you tell the location of the image from the single line of sight that you have drawn? Explain.

Repeat the procedure above from several different eye locations.

How can you use the lines of sight that you drew to determine the location of the image of the nail?

Would *all* observers who can see the image of the nail agree on its location? Explain.

(2) Use the method of parallax to determine the location of the image of the nail.

Does the method of parallax yield the same image location as you found in part (1) above?

(3) Discuss how the methods in part (1) and part (2) for determining image location are related.

C. Move the nail and use the method developed above to find the new location of the image. Repeat for several different nail locations including: a location close to the mirror, a location far from the mirror, and a location off to the side of the mirror. Use a different sheet of paper for each case.

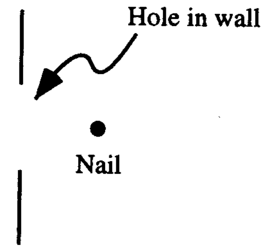
D. Based on your observations, describe the relationship between the object location, the image location, and the location of the mirror.

You will need the sheets of paper from part C for the next experiment.

Experiment 2.6

A. For this part of the experiment, use one of the sheets of paper from part C of Experiment 2.5. For each of your eye locations in that experiment, draw a ray that shows the entire path of light from the object nail to your eye. Base your rays on the lines of sight that you drew to the image of the nail. Draw an arrow head on each line segment to show the direction of the light.

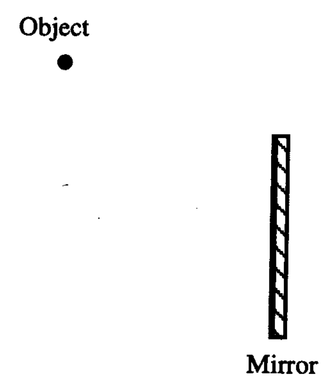
B. Imagine that several observers are looking through a hole in the wall at a nail.



Draw several rays from the nail to various observers. Use arrow heads to indicate the direction of the light.

C. Compare your ray diagrams for parts A and B above. Discuss how the two situations are similar. In particular, to which feature in Experiment 2.5 would the nail correspond? To what would the hole in the wall correspond?

D. An object is placed near a mirror as shown.



(1) On the diagram, draw a *solid line* to represent one ray of light from the object to the mirror. Show the path of the reflected light also. (Use a protractor to find the reflected ray.)

If you looked back along the reflected ray, what would you see?

What can you tell about the location of the image from the single ray you have drawn?

Does a single ray *alone* give you enough information to determine the location of an image?

(2) Repeat part (1) for a second ray from the object to the mirror.

Describe how to use the two rays you have drawn to determine the image location. Show the image location on your diagram.

Note: When extending a ray behind a mirror, it is conventional to use a *dashed line*, rather than a solid line. This helps distinguish between a path that light actually took and a path that light *appears* to have taken.

What is the smallest number of rays you must draw when using a ray diagram to locate the image of an object?

✔ Discuss your results with a staff member.

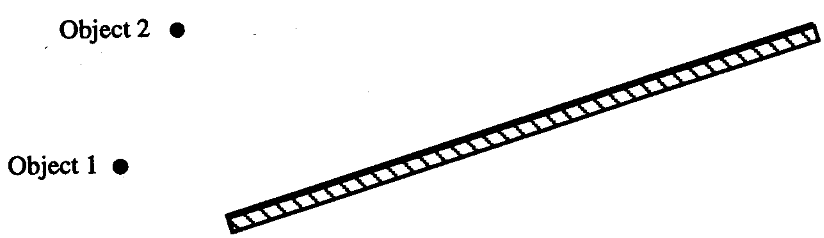
In this course, when you are asked to use ray tracing to determine the location of an image, always draw at least two rays. Use a solid line *with an arrow head* (——>——) to represent the actual path of a ray of light. Use a dashed line (- - - - - - - -) to extend a ray behind a mirror to indicate a path that light only *appears* to take.

Exercise 2.7

As you may have noticed in your experiments thus far, the image of an object in a plane mirror is located as far behind the mirror as the object is in front. Use geometry to prove this fact. (*Hint:* Start with a ray diagram that shows the location of an image and look for similar triangles. You may find it necessary to draw additional lines or rays.)

Exercise 2.8

A. Draw a ray diagram to determine the location of the image of each of the two objects in the diagram below.



B. Determine the region in which you could stand and see the images of both objects at the same time.

C. Describe how you could use a ray diagram to determine the location of the image of an extended object, such as a pencil or brick.

Exercise 2.9

Draw a ray diagram to find the location of the image of the nail shown in the side view diagram below.

Experiment 2.10

Obtain a half-silvered mirror and two identical cylinders (e.g., cans or batteries). Examine the half-silvered mirror and describe how it differs from a standard mirror.

A. Place one cylinder (the "object cylinder") in front of the mirror. While looking at the image of the cylinder, move the cylinder away from the mirror.

   How is the size of the image affected by moving the cylinder away from the mirror?

B. Return the object cylinder to its original position in front of the mirror. Use the method of parallax to place the second cylinder at the location of the image of the object cylinder.

   How does the size of the image compare to the size of the object cylinder? Explain your reasoning.

   Move the object cylinder farther away from the mirror and repeat the experiment.

   Is the size of the image still the same as it was before? Explain how you can tell.

C. Try to resolve any conflict in your answers to parts A and B.

✔ Check your reasoning with a staff member.

Experiment 2.11

A. Imagine that you are looking at yourself in a mirror mounted on a wall. From where you stand, you are able to see from the top of your head down to the top of your shoulders.

Suppose you were to back away from the mirror. Would the amount of your body that you see in the mirror increase, decrease, or stay the same? Explain. Include a diagram as part of your explanation.

B. What is the minimum size mirror you need to view your entire body? Draw a ray diagram that supports your answer.

(1) Does moving closer to or farther from the mirror change how much of yourself is visible in the mirror?

(2) Does moving closer to or farther from the mirror change the size of your image?

(3) Imagine that your eyes were at the top of your head. Would your answers to parts (1) and (2) above be different in this case?

Draw ray diagrams to justify your answers to the questions above.

C. If possible, perform an experiment to test your answers to the questions above.

D. Does moving closer to or farther from a mirror change how much of the room is visible in the mirror? Draw a ray diagram(s) that supports your answer.

✔ Check your diagrams and your reasoning with a staff member.

Exercise 2.12

Discuss how the size of an object compares to the size of its image in a plane mirror. Describe how, if at all, the size of the image would change if (1) the object were moved farther away from the mirror, or (2) you, the observer, were to move farther away from the mirror.

Section 3. Multiple images

Experiment 3.1

Obtain two mirrors and a small object, such as a coin.

How many images of the coin can you see using only one mirror?

How many images can you see using two mirrors?

Examine the ways in which you can use two mirrors to make more than one image. As you work , try to think of questions and attempt to answer them by designing and performing experiments.

As part of your explorations, try to answer the following questions:

What is the greatest number of images of the coin that you can make? How are the mirrors arranged to do this?

Can you arrange the two mirrors so that there are only two images of the coin? If so, how should the mirrors be arranged?

Does the number of images that you see depend on where you place your eye? Is this true for all arrangements of the mirrors?

Are all of the images identical to one another and to the coin? Describe any differences you see.

Can you make two images overlap so that they appear to be a single image? Can you do this when the two overlapping images are identical? Can you do this when the two overlapping images are different? How many images would you say that there are in each case?

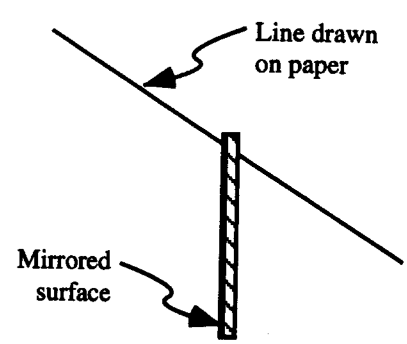
Can you make an even number of images? Can you make an odd number of images?

How many images can you see if the mirrors are placed parallel to each other but on opposite sides of the coin?

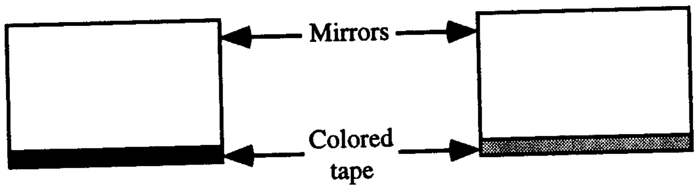
Experiment 3.2

A. The top view diagram at right shows a line drawn on a piece of paper and a mirror placed on top of the line. Draw a sketch that shows what you think you would see in the mirror.

Obtain a mirror and check your prediction.



B. Place a narrow piece of tape along the bottom edge of each of two mirrors as shown below. Make each of the tapes a different color in order to be able to tell the mirrors apart.



Stand the mirrors upright on a piece of paper with the taped edges on the bottom. Place the mirrors side-by-side along the 0°–180° line on a sheet of polar graph paper. Slowly rotate the mirrors so that the angle between them is a little less than 180°. Describe what you observe.

How does what you see in the mirrors relate to what you observed in part A?

C. Slowly decrease the angle between the mirrors, keeping the junction of the mirrors centered on the paper.

What happens when the angle between the mirrors reaches 90°?

What happens when the angle becomes a little less than 90°?

Continue to decrease the angle. Describe your observations.

D. Set up the mirrors so that you can see at least two images of each mirror. On another piece of polar graph paper, draw a diagram that shows the arrangement of the mirrors and the images.

On the diagram, indicate which angles are equal.

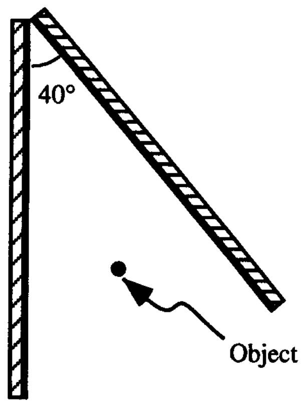
Is it possible to arrange the mirrors so that all the adjacent angles in your diagram are equal? Describe the arrangement(s) of the mirrors for which this would happen.

E. In the situation that you sketched in part D, are there any images that appear to be the image of another image?

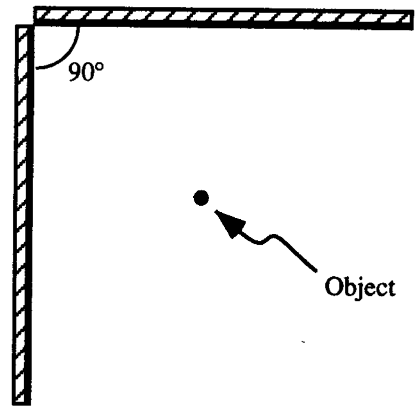
If so, how can you use the idea of an "image of an image" to account for all of the images of each mirror?

Experiment 3.3

A. Each of the diagrams below shows two mirrors held at an angle. Using a straightedge and protractor, copy each of the diagrams onto a separate sheet of paper.



(1)



(2)

The idea of an "image of an image" can be used to predict the number of images and the image locations. Apply this idea in each case above to:

- Determine the number of images of the mirrors and their locations.
- Determine the number of images of the object and their locations.

Imagine that one of the mirrors in each figure were removed. Predict which image(s) you would still see and which image(s) would vanish.

Check your predictions. If a prediction was incorrect, try to resolve the conflict before continuing.

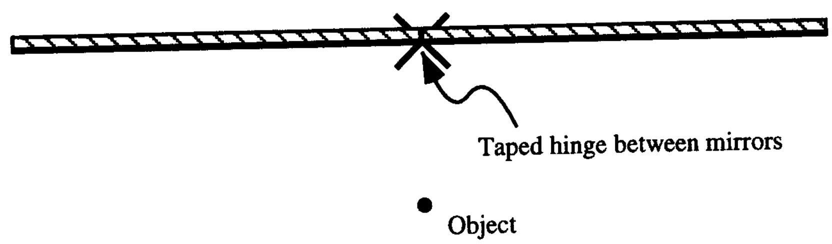
B. In your own words, describe the approach that you used in part A to determine the number of images and the image locations. Your description should be sufficiently clear that someone else could read it and apply it to a new situation.

✔ Check your answers for this experiment with a staff member.

Experiment 3.4

Remove the tape from the mirrors you used in the preceding experiment. Place the mirrors in contact face-to-face. Tape one edge of the mirrors together so that when they are opened, the mirrors are held together.

On a separate sheet of paper, draw an *X* and a dot as shown in the diagram below. Place the mirrors on the paper with the hinge between the mirrors on the *X* as shown.



In this experiment, we *qualitatively* examine how the angle between the mirrors affects what you see in the mirrors.

A. Gradually close the mirrors, all the while keeping the hinge on the *X* and keeping the object midway between the mirrors.

Describe what you observe as the mirrors are closed. Notice how the number of images of the object changes.

B. On the paper beneath the mirrors, mark the locations of the mirrors when there is one image, two images, three images, and so on.

In which case is the number of images more sensitive to a small change in the angle between the mirrors: when the angle is large or when the angle is small?

C. For certain angles between the mirrors, both the object and one of the images lie on the bisector of the angle formed by the mirrors. In this case we call the image a *central image*.

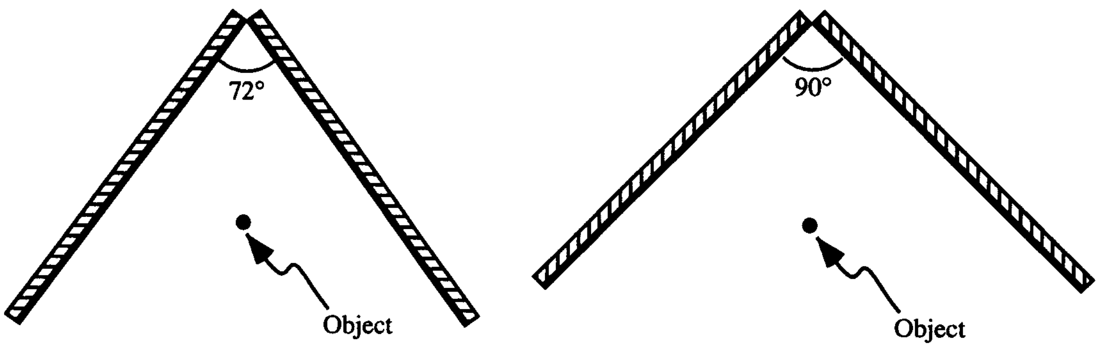
For which angles is there a central image?

What is distinctive about the number and arrangement of images when there is a central image?

✔ Check your results with a staff member.

Experiment 3.5

Copy each of the diagrams below onto a separate sheet of paper. Use a straight-edge and a protractor.



(1) (2)

Arrange two mirrors and an object (e.g., a nail) as shown in each of the diagrams. For each case, answer the following questions.

A. Use the method of parallax to find the locations of the all the images of the object. Mark these image locations on your diagram.

   How would you characterize the arrangement of the images?

B. Find the locations of the images of the mirrors. Mark these locations on your diagram.

   Indicate which images of the mirrors can be seen in each mirror. (Are there any that can be seen in both mirrors?)

   How would you characterize the locations of the images of the mirrors in each figure?

C. For each figure, how are the locations of the images of the mirrors related to the locations of the images of the object?

Experiment 3.6

In this experiment, we determine a mathematical relationship between the number of image locations and the angle between the mirrors.

Place two mirrors along the 0°–180° line of a sheet of polar graph paper. The hinge between the mirrors should be at the center of the paper. Put a pin on the 90° line. Slowly close the mirrors, keeping the pin in the center between the mirrors.

A. Make the measurements necessary to complete the table below. Note that in some cases, there is a range of angles for which a given number of images are visible. For the purpose of this experiment, you should pick a single angle to represent each range. The following questions can help you decide on a criterion for picking a particular angle.

(1) For which of the cases listed in the table does a single mirror angle correspond to a particular number of images?

How is the arrangement of images similar for these cases?

(2) For each case in which a range of angles corresponds to a particular number of images, is there a single angle that results in a similar arrangement of images as in (1) above?

What criterion might you use to pick one specific angle to characterize a range of angles? What reason can you give for choosing that particular angle rather than some other angle?

Mirror angle (given as a single angle)	Number of image locations
	1
	2
	3
	4
	5
	6
	7
	8
	9
	10

B. Use the data above and your diagrams in Experiments 3.3 and 3.5 to infer a mathematical relationship between the number of image locations and the corresponding angle between the mirrors.

✔ Check your reasoning with a staff member.

Experiment 3.7

A. An object is placed on the bisector of the angle between two mirrors. Three images result. The images and the object are equally spaced.

What is the angle between the mirrors? Explain.

Draw a diagram showing two mirrors with the appropriate angle between them. Use ray tracing to determine the image locations.

Is there a central image in this case? If so, how many times is a light ray reflected in producing the central image?

How many times is a light ray reflected in producing each of the other images?

B. At what angle should the mirrors be placed so that there are two images of the object, and the images and object are equally spaced?

Use ray tracing to determine the location of the images.

Use your ray diagram to explain why there is not a third image.

Experiment 3.8

Find a coin that has a head engraved on one side of it.

Does the coin show the left or the right side of the person's head?

Stand the coin upright in front of a single mirror so that the image of the head is upright. Which side of the person's head do you see on the image?

The image of the head is said to be a "mirror image" or a *perverted* image.

Experiment 3.9

A. Place a hinged set of mirrors on the 0°–180° line of a piece of polar graph paper. Place a coin on the 90° line in front of the mirrors. As you close the mirrors note whether the emerging central image is perverted. Record the pattern of perverted images and non-perverted images for several cases, including some with a central image and some for equally spaced images without a central image. Describe this pattern in words.

B. Describe the relationship between the number of times a light ray is reflected in producing an image and whether or not that image is perverted.

✔ Check your answers with a staff member.

Part B: Lenses, curved mirrors, and images

In Part B of *Light and Optics,* we study the behavior of light as it passes from one material to another, such as from air to glass or from air to water. We develop a technique for drawing ray diagrams that enables us to determine the location and size of an image formed by a lens. We extend the model to account for the images formed by curved mirrors and apply it in constructing optical instruments, such as a simple telescope and microscope.

Section 4. Introduction to refraction

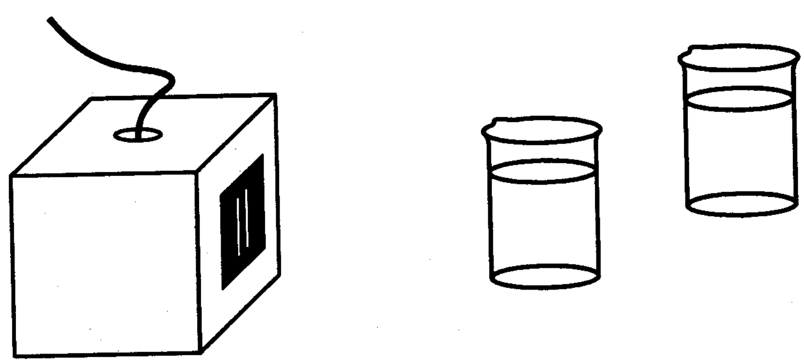
Experiment 4.1

This experiment should be performed in a darkened room.

A. Obtain a light box and two clear glass beakers. Fill the beakers with water to a level that is higher than the slits of the light box.

Place the light box and beakers on a large sheet of white paper. Turn on the light box and explore what happens when one or both of the beakers are placed into a beam of light.

Describe some of your observations, both in diagrams and in words. Ask a staff member for assistance if you need additional materials for further explorations.



On the white paper and in your notebook, record several arrangements of the beakers and light beams. Try both single and double beams.

If you can see the path of a beam through the water, record that also. If you cannot see the path, can you infer it based on where the light entered and exited the beaker?

B. As part of your explorations, try to answer the following questions:

Does light follow a straight path in water the way it does in air?

How does the path of a beam that passes through a beaker of water differ from the path through an empty beaker?

Can you use a single beaker of water to make the beam bend:

(1) left then left again?

(2) left then right?

(3) right then right again?

(4) only once either left or right?

(5) not at all?

Describe how to place a beaker of water to produce (1) the largest overall bend in a beam and (2) the smallest overall bend in a beam.

Does changing the liquid in the beaker affect the behavior of the light? If so, how? Try various liquids. In each case decide whether the effect is greater than or less than it is with water.

C. On the basis of your observations, would you say that it is the glass from which the beaker is made or the liquid in the beaker that is responsible for the bend in the beam? Explain.

D. Describe in words what happens to a beam when it strikes a beaker of water at various angles.

Experiment 4.2

Repeat Experiment 4.1 using containers with straight sides rather than curved sides. Record your observations.

Compare and contrast your results with the results of Experiment 4.1. How is the behavior of light similar for the two types of containers, and how is it different?

✔ Check your results from Experiments 4.1 and 4.2 with a staff member.

We call the bending of light when it passes from one material to another (e.g., from air to water) *refraction*. This word comes from the Latin *refringere, refractus:* to break off. We say that light *refracts* in passing from one material to another. The beam in the second material is called the *transmitted* or *refracted* beam. As you may have observed, often light is both transmitted and reflected at the boundary between two materials.

Exercise 4.3

The beam inside a beaker may be considered as both a transmitted beam and an incident beam: it is the transmitted beam where light enters the beaker and it is the incident beam where light leaves the beaker.

Examine several of your diagrams from Experiments 4.1 and 4.2. For each diagram, identify the incident, transmitted, and reflected beams. Clearly label the beams that are both incident and transmitted beams.

Experiment 4.4

A. Obtain two flat sheets of glass, one thick and one thin (e.g., a microscope slide and a piece of window glass).

Place each piece of glass, in turn, into a beam of light and examine the effect on the beam. Try various orientations of the glass. Sketch diagrams to record your observations.

Does one of the pieces of glass seem to affect the beam to a greater extent? If so, which one? Describe the experiment(s) that allow you to determine your answer.

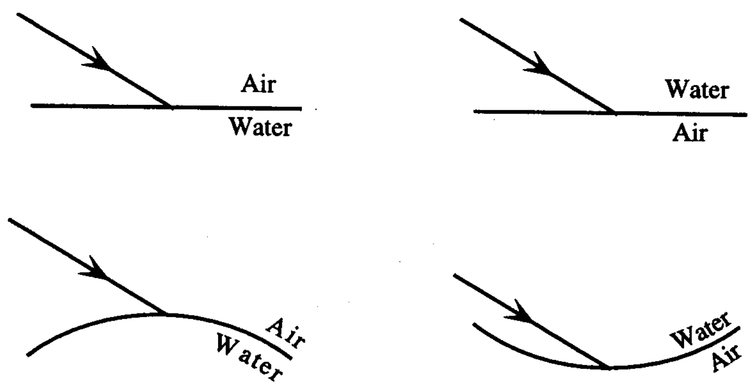
B. In Experiment 4.1 you examined the path of light through a beaker of water. You determined whether the glass from which a beaker is made plays a large role in refracting light.

Are your observations in part A above consistent with your conclusion in Experiment 4.1? Explain.

Exercise 4.5

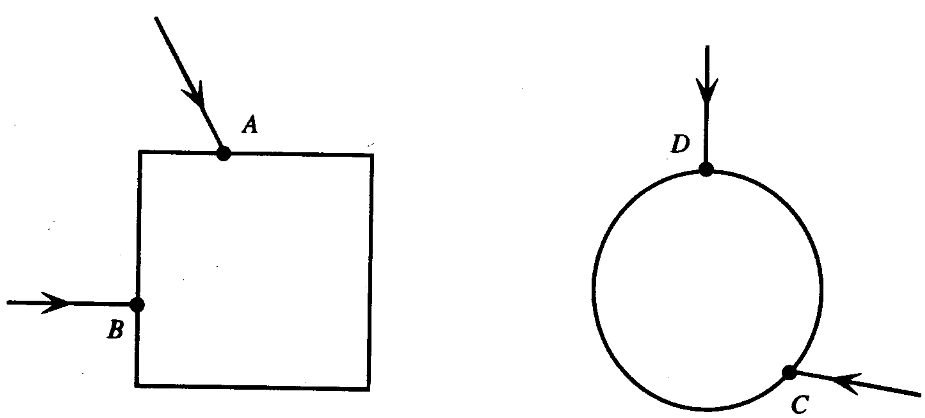
In each top view diagram below, the path of a beam of light is shown incident on the side of a transparent container of water. Only part of each container is shown.

Sketch the approximate path of the beam in the second material. Using a dashed line, also draw the path that the beam would have taken had it continued without bending. Be sure that your rays are consistent with your observations. Make additional observations if necessary.



Exercise 4.6

A. Each of the top view diagrams below illustrates two rays of light incident on a container filled with water.



Make a sketch that shows the approximate directions of the corresponding transmitted rays. Draw the rays so that they are consistent with your prior observations.

B. Draw a line through point *A* that makes a 90° angle with the side of the container. Repeat for point *B*.

These lines are said to be *perpendicular* or *normal* to the container. Each line is called the *normal* to the container at the point it intersects the container.

Draw the normal at point *C* and at point *D* on the beaker. Explain what it means for a line to be normal to a curve.

Where do the lines that you drew normal to the circle at points *A, B, C,* and *D* intersect? Explain. Describe a simple method for drawing the normal to a circle at a given point.

C. Compare the path of each transmitted beam that you drew in part A with the path the beam would have taken if the container had been empty.

Does light bend "toward" or "away from" the normal when passing from air to water?

Does light bend in the same way for a flat or curved surface?

D. If you have not already done so, extend the transmitted rays in part A so that they reach another point on the container and pass from water back into air.

Does light bend "toward" or "away from" the normal when passing from water to air?

Does light bend in the same way for a flat or curved surface?

✔ Check your results with a staff member.

Experiment 4.7

In Section 1, you were instructed to draw directional arrows on the rays in your diagrams. Is it possible to tell the direction of a light ray from the path alone? Consider the following cases:

(1) a light ray in air
(2) a light ray reflected from a mirror
(3) a light ray refracted through two different materials

A. Design and perform experiments that allow you to check your responses. Are the results consistent with your answers above? Explain.

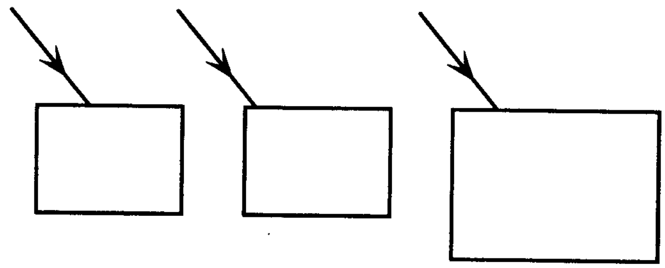
B. What generalization might you draw about the reversibility of a light ray? Explain.

✔ Discuss your results with a staff member.

Exercise 4.8

The top view diagrams below show beams of light incident on transparent containers of water. The beams are all incident on the containers at the same angle.

Sketch the transmitted beams in each case and show the direction of each beam when it passes back out of the containers into the air.



How do the directions of the beams inside the containers compare? Explain your reasoning.

How do the directions of the beams once they have left the containers compare? Explain your reasoning.

In each case, how does the direction of the beam that has exited the container compare to the direction of the beam incident on the container?

Obtain several containers of water and check your answers.

Experiment 4.9

A. Obtain a prism and place it into a beam from your light box. Try various orientations of the prism. Describe your observations.

Does the prism refract light? In your notebook, make a sketch of the path of the light through the prism.

B. Use a two-slit mask on your light box. Place a beaker of water into the beams and adjust the beaker so that the two beams cross.

Place a blue acetate over both slits and mark the point where the beams cross. Replace the blue acetate by a red acetate and again mark the intersection point of the beams.

Describe your observations.

What can you conclude about the amount by which red and blue light bend when passing from air to water? If they bend by different amounts, which bends more?

C. Discuss how your observations in part B can help you to account for your observations in part A. (You may also want to refer to the experiments on color in *Light and Color* in Volume I.)

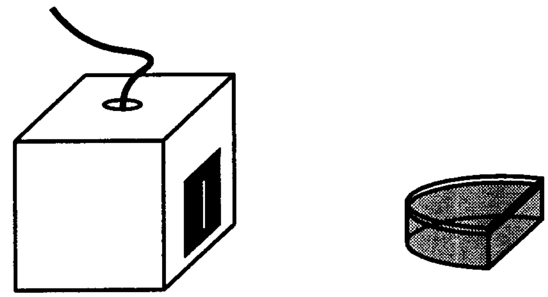
Section 5. Law of refraction: Snell's law

Experiment 5.1

This experiment should be performed in a darkened room.

Place a semi-cylindrical dish of water onto a sheet of paper, and aim a beam of light from a light box at the dish. (If necessary, raise the dish to the height of the slits.)

Use paper to block the part of the beam above the water surface.



A. View the dish from above and slowly rotate it through 360°. Describe your observations.

Make several sketches in your notebook for various configurations of the dish and incident beam. On your diagrams show not only the incident beam, but any reflected and transmitted beams.

B. For this part of the experiment, orient the dish so that the beam always strikes the flat side of the dish first.

(1) Examine what happens when the beam strikes the dish at different locations along the flat side and at different angles.

Sketch various arrangements of the dish and beam.

(2) Find orientations of the beam and dish in which the beam is first incident on the flat side of the dish and behaves as follows:

- the beam bends at both the flat side and the curved side of the dish
- the beam does not bend at either side of the dish
- the beam bends at the flat side of the dish, but not at the curved side
- the beam bends at the curved side of the dish, but not at the flat side

Record several examples of each case (unless a particular behavior occurs for only one orientation of the incident beam).

C. For this part of the experiment, orient the dish so that the beam always strikes the curved side of the dish first.

Examine what happens when the beam strikes the dish at different locations along the curved side and at different angles.

Sketch various arrangements of the dish and beam.

Compare your diagrams for parts B and C. Describe the similarities and differences.

D. Orient the dish so that the beam strikes the curved side of the dish first. Gradually rotate the dish, keeping the beam aimed at the same location on the curved side of the dish.

Find an orientation of the dish for which one of the incident beams (either the beam in air or the beam in water) produces no refracted beam, that is, the beam is entirely reflected. In your notebook, sketch this configuration of dish and light beams.

E. Rotate the dish so that the beam strikes the flat side of the dish first and repeat part D.

We use the term *angle of incidence* to refer to the angle between an incident beam and the normal to the surface. The term *angle of refraction* is used for the angle between the refracted beam and the normal. The *angle of reflection* is defined in a similar way. As you have already observed, for any two materials (e.g., air and water) the angle of refraction depends on the angle of incidence. Under certain conditions, there is no refracted beam and the beam is entirely reflected. This phenomenon is called *total internal reflection*.

In the remainder of this section we examine the relationship between the angle of incidence and the angle of refraction for light passing from one material to another.

Experiment 5.2

Devise and perform experiments to answer the following questions. Record your results in your notebook.

A. Can total internal reflection occur when a light beam in water is incident on air?

Can total internal reflection occur when a light beam in air is incident on water?

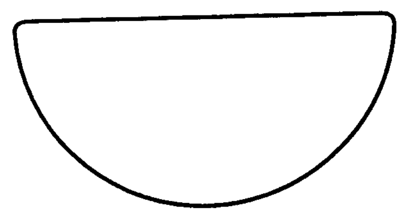
B. Does total internal reflection occur for a single angle of incidence or for a range of angles? Find the angle or range of angles.

✔ Check your results from Experiments 5.1 and 5.2 with a staff member.

Experiment 5.3

In this experiment we conduct a qualitative investigation of the relationship between the angle of incidence and the angle of refraction for a light beam that passes from air to water.

A. The top view diagram at right shows a semi-cylindrical dish of water. Sketch the path of a beam of light that strikes the flat side of the dish and passes through the dish without bending at either side of the dish.



Clearly label the angle of incidence and the angle of refraction for the beam at both the flat and the curved surfaces. (*Hint:* Recall from Exercise 4.6 your method for drawing the normal to a circle at any point on the circle.)

B. Aim a beam from your light box at a semi-circular dish of water at the angle you illustrated in part A.

Gradually increase the angle of incidence, keeping the beam aimed at the same point on the flat side of the dish.

Describe your observations.

As the angle of incidence increases, does the angle of refraction increase, decrease, or stay the same?

Experiment 5.4

In this experiment we conduct a quantitative investigation of the relationship between the angle of incidence and the angle of refraction for a light beam that passes from air to water.

A. Place a semi-cylindrical dish on a sheet of polar graph paper with the center of the flat side at the center of the paper. Arrange the light beam and dish as you did in part B of the preceding experiment. Concentrate on the incident and refracted beams at the flat side of the dish.

(1) If the angle of incidence is 0°, what is the angle of refraction?

(2) Aim the incident beam at the center of the flat side so that the angle of incidence is 10°. Measure and record the angle of refraction for this case.

When the angle of incidence is doubled to 20°, does the angle of refraction double? Check your answer experimentally.

(3) Double the angle of incidence twice more to 40° and 80°. Measure and record the angle of refraction each time.

Is the angle of refraction directly proportional to the angle of incidence for all angles of incidence? Explain your reasoning.

B. Vary the angle of incidence while keeping the incident beam aimed at the center of the flat side of the dish. Record each angle of incidence and the corresponding angle of refraction in the table at the right. Use angles of incidence ranging from 0° to 90° in increments of 10°.

Light passing from air to water

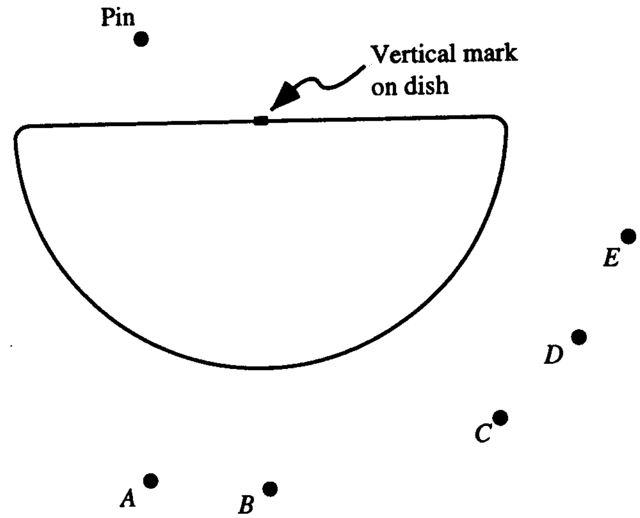
Angle of incidence	Angle of refraction
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______

In the following experiment, we investigate an alternative and more precise method of measuring the angles of incidence and refraction.

Experiment 5.5

There is a small vertical mark at the center of the flat side of the semi-cylindrical dish. We will use that mark in this experiment.

Suppose that a pin were placed upright near the dish of water as shown.



A. Imagine that you were to look at the pin through the water from each of the five locations labeled *A–E*.

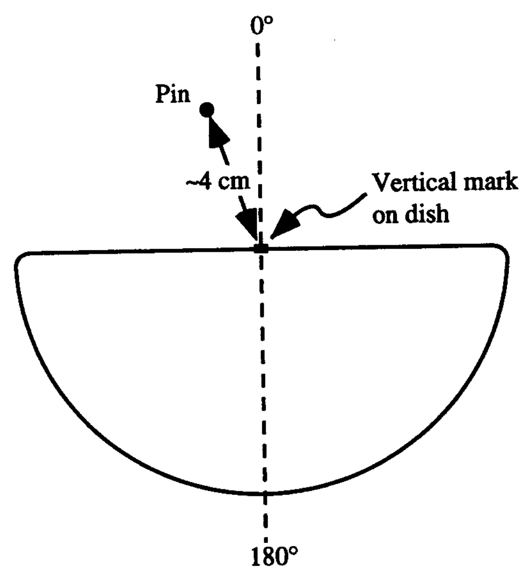
   From which locations, if any, do you think the vertical mark on the dish would appear to be in line with the pin? Explain your reasoning.

   Obtain a pin and check your predictions. Resolve any inconsistencies.

B. Secure a piece of polar graph paper to a piece of corrugated cardboard. Place the dish on the paper with the vertical mark on the dish at the center of the paper.

   Place a pin about 4 cm from the center of the dish and at an angle of 20° from the normal to the center of the flat side of the dish.

   Predict where you would place your eye so that you could look through the curved side of dish and see the pin in line with the vertical mark on the dish. (*Hint:* How could you use your results from Experiment 5.4 in making this prediction?)



   Check your prediction experimentally. Resolve any inconsistencies.

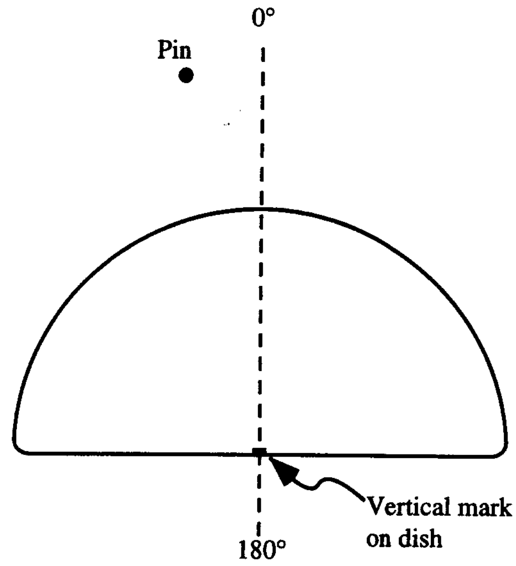
C. Use your results from part B to devise a simple method for determining the angle of refraction for a given angle of incidence.

   Check your method by comparing the results you obtain with this method to those that you obtained in Experiment 5.4.

✔ Check your results from Experiments 5.4 and 5.5 with a staff member.

Experiment 5.6

Reverse the orientation of the semi-cylindrical dish on the polar graph paper as shown at right.



A. Devise a method for using the equipment in Experiment 5.5 to measure the angle of refraction for various angles of incidence for light passing from water to air.

(*Hint:* How could you modify your method from part C of Experiment 5.5 to do this?)

Explain why your method gives correct values of these angles for light passing from water to air when the pin is in air, not in water.

B. Use the method you devised in part A to complete the table at right.

C. Compare the results you obtained in this experiment to those you obtained in Experiments 5.4 and 5.5. Describe any similarities and differences.

D. Earlier, you found that under certain circumstances light is totally internally reflected. Use your method from part A to find the range of angles for which total internal reflection occurs.

✔ Check your results from this experiment with a staff member.

Light passing from water to air

Angle of incidence	Angle of refraction
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______
______	______

Exercise 5.7

Suppose you were to use your data from Experiments 5.4 and 5.5 to graph angle of incidence versus angle of refraction for light passing from air to water.

Would you expect the graph to be a straight line? Explain.

Graph your data and check your prediction.

✔ Check your answers with a staff member.

Exercise 5.8

Your results so far indicate that the relationship between the angle of incidence and the angle of refraction is more complicated than just a linear one. Since we are dealing with angles, let us look for an algebraic relationship between these angles that involves trigonometric functions such as sin θ, cos θ, and tan θ.

A. Use your results from Experiments 5.4 and 5.5 to make a graph of sin θ_i versus sin θ_r, where θ_i represents the angle of incidence (in air) and θ_r represents the angle of refraction (in water). (Add additional columns to your table from Experiment 5.4 to help you make this graph.)

Should your graph go pass through the origin *(0,0)?* Explain.

Is the relationship between sin θ_i and sin θ_r linear? Explain how you can tell from your graph.

Determine the slope of the graph and write an equation that relates the slope, θ_r, and θ_i.

B. Repeat part A using the angles of incidence (in water) and angles of refraction (in air) that you listed in the table in Experiment 5.6.

How is the slope of the graph from part A related to the slope of the graph from part B?

✔ Check your answers with a staff member.

As your graphs suggest, there is a simple relationship between the sine of the angle of incidence and the sine of the angle of refraction for light that passes from one material to another. The slope of the graph of sin θ_i versus sin θ_r from part A of Exercise 5.8 is called the *index of refraction of water with respect to air.* This relationship is called the *law of refraction* or *Snell's Law.*

Experiment 5.9

A. Use the methods you have developed in this section to determine the index of refraction with respect to air of a substance other than water (e.g., glass, plastic, vegetable oil, corn syrup).

B. Describe how the index of refraction for light passing from one material to a second is related to the index of refraction for light passing from the second material to the first.

✔ Discuss your results with a staff member.

Section 6. Examples of refraction in everyday life

In this section, we investigate simple examples of refraction in everyday life. The emphasis is on relating ray diagrams to real world observations.

Experiment 6.1

Place a coin at the bottom of an empty can (or a beaker that has the sides covered so that you cannot see through them).

Look into the can at the coin while your partner slowly moves the can away from you until you no longer see the coin. Keep your head steady while your partner gently pours water into the can.

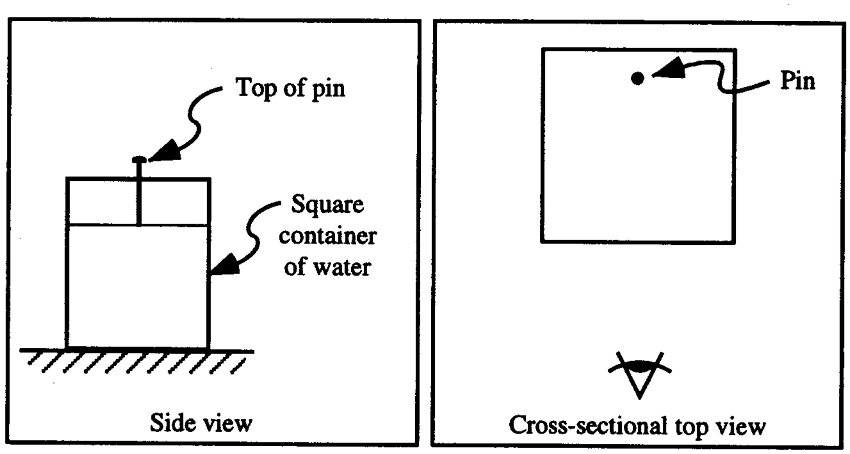
Describe your observations.

Sketch ray diagrams to illustrate how you were able to see the coin after the water was added, but not before.

In drawing a ray diagram, it is often necessary to show the location of an observer. In this module, we use the following symbol to show the observer: .

Experiment 6.2

A. A pin is held vertically at the back of a square clear container of water, as shown below. The portion of the pin below the surface of the water is not shown in the side view diagram.



On a separate piece of paper, make an enlargement of the top view diagram.

On the enlargement, sketch rays to *predict* where the bottom of the pin would *appear* to be located to the observer shown. For simplicity, assume that light passes directly from water to air.

Note: Do not try to draw a ray diagram in which the rays bend by exactly the correct amount. However, your diagram should be qualitatively correct.

On the basis of your ray diagram, would the bottom of the pin appear to be located closer, farther, or the same distance from the observer as the top of the pin? Explain your reasoning.

B. Set up the equipment and use the method of parallax to check your predictions.

Does your observation agree with your prediction? If not, how can you resolve the inconsistencies? Sketch a new ray diagram that is consistent with your observations.

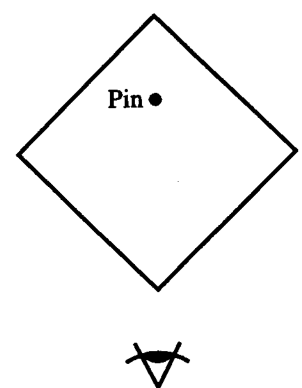
C. Check whether the assumption that light from the pin passes directly from water to air, is reasonable. In other words, we would like to see whether the plastic has a negligible effect on the path taken by the light.

Devise and perform an experiment that would allow you to test whether this assumption is valid.

D. Imagine that you were to look at the pin from the location shown at right.

Sketch a ray diagram to illustrate what you would see. (*Hint:* What would you see if the left side or the right side of the container were covered?)

Check your predictions. If your observations are in conflict with your predictions, try to resolve the inconsistencies. Sketch a new ray diagram to account for your observations.



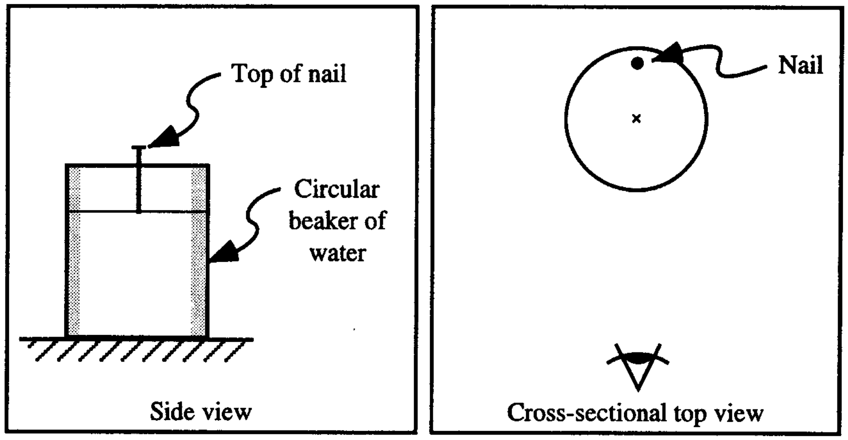
Cross-sectional top view

✔ Discuss your results with a staff member.

As you have observed, an object in water may appear to be in a different location to an observer out of the water. The place where the bottom of the pin appeared to be located is called the location of the image of the pin, or the *image location*.

Experiment 6.3

A. Suppose a nail were held vertically at the back of a circular beaker of water, as shown below. (The portion of the nail below the surface of the water is not shown in the side view diagram.)



On a separate piece of paper, make an enlargement of the top view diagram. Use a compass to draw an accurate circle.

Predict whether the image of the bottom of the nail is closer, farther, or the same distance from the observer as the top of the nail. Sketch a qualitatively correct ray diagram to support your prediction. Explain. (*Hint:* Treat the nail as a point source of light.)

Use parallax to place a second nail at the location of the image of the bottom of the nail, and check your predictions. If your prediction was incorrect, find your error.

B. Three students are discussing their results from part A:

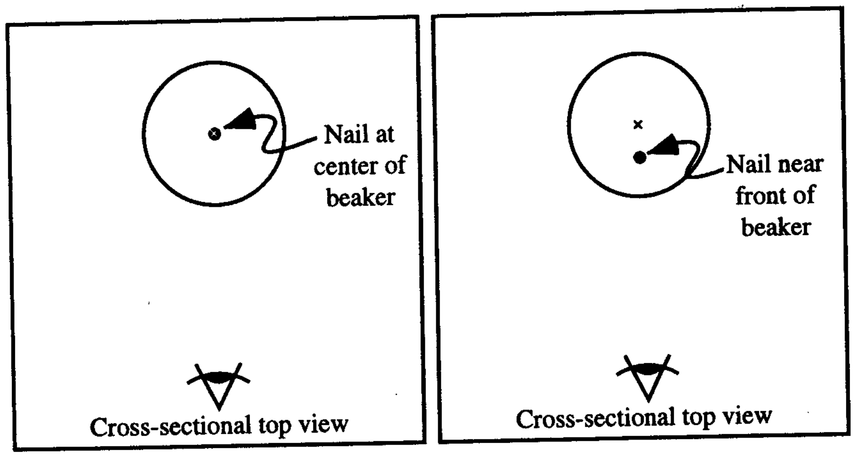
Student 1: *"I think the image is closer to me than the nail itself. The closer something is, the bigger it looks. Because the image of the nail appears larger than the nail itself, the image must be closer to me than the nail."*

Student 2: *"But when I used parallax to determine the location of the image of the nail, I found the image to be farther from me than the nail."*

Student 3: *"That doesn't make sense. If the image were farther from me than the nail, then how could I see the image? Wouldn't the nail block my view of the image?"*

Do you agree or disagree with each of these students? Discuss your reasoning with your partners.

C. Consider two other locations of the nail: at the center of the beaker and near the front of the beaker, as shown below.



For each of these cases:

(1) Predict whether the image of the bottom of the nail would appear closer to the observer, farther from the observer, or the same distance from the observer as the top of the nail.

(2) Sketch a qualitatively correct ray diagram that supports your prediction.

Check your predictions, and resolve any inconsistencies.

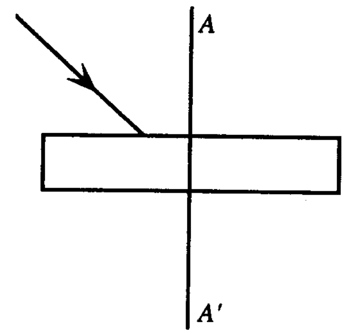
D. Describe how the location of the image of the nail changes as the nail is moved from the far side of the beaker to the near side of the beaker.

✔ Discuss your results with a staff member.

Section 7. Image formation by convex lenses

Exercise 7.1

A. At right is a diagram of a light ray incident on a thin rectangular plate of glass. The line *AA'* is perpendicular to the plate.

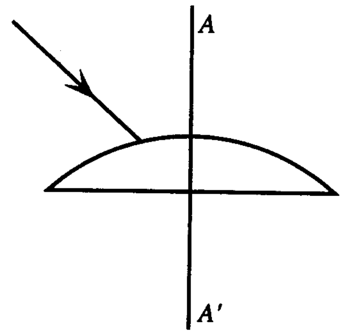


Sketch the continuation of the ray through the glass and into the air.

How does the angle between the emergent ray and *AA'* compare to that between the incident ray and *AA'*? Explain.

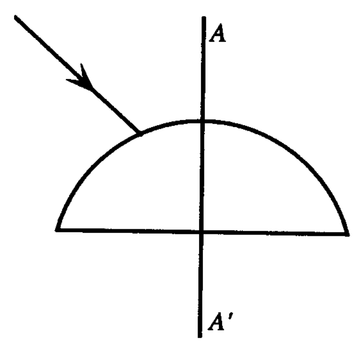
How would your answer change if the plate were thicker or thinner than the one shown above? Explain.

B. At right is a diagram of a light ray incident on a piece of glass with one spherical surface and one plane surface.



How does the angle between the emergent ray and *AA'* compare to that between the incident ray and *AA'* ? Explain.

C. Suppose that the spherical surface in the diagram in part B were replaced by a spherical surface with a smaller radius of curvature as shown below. The angle between the incident ray and *AA'* is the same as in part B.



How would the angle between the emergent ray and *AA'* compare to the corresponding angle in part B? Explain.

D. Suppose that the glass in part B were made of a type of glass with a greater index of refraction.

How would the angle between the emergent ray and *AA'* compare to the corresponding angle in part B? Explain.

E. What factors determine the ability of a piece of transparent material, such as glass, to change the direction of an incident ray? Explain your reasoning.

A *lens* is an optical device that refracts light. The pieces of glass in the previous experiment are examples. Lenses can be divided into two categories according to shape: *convex* and *concave*. Convex lenses have at least one surface that curves outward and are thicker in the middle than at the edges. In contrast, concave lenses have at least one surface that curves inward and are thinner in the middle than at the edges.

The lenses in parts B and C in Exercise 7.1 are called *plano-convex* lenses. Another common type of convex lens has both surfaces curved outward. These are called *double-convex* lenses. In this section, we investigate image formation by convex lenses in air.

Experiment 7.2

Obtain two convex lenses of different diameters.

A. Look at various objects through the lenses. Describe what you see. What factors affect what you see? (Possibilities might include the following: distance from the object to the lens, distance of the lens to your eye, etc.) Record your observations.

B. Look at a coin through the lens with the larger diameter. Hold the coin so it is upright when you are looking at it without the lens.

Where can you hold the lens so that the coin appears to be:

(1) upside down?

(2) right side up?

(3) larger than it is in real life?

(4) smaller than it is in real life?

(5) the same size as it is in real life?

C. Hold the lens fixed in place about 30 cm from your eye. Place a coin behind the lens and very close to it. Slowly move the coin as far from the lens as you can. Describe your observations in words and with sketches.

Repeat the procedure above for the other lens. Do you notice any differences between the two lenses?

D. Hold the coin at arm's length in front of you. Place the lens directly in front of the coin, then move it slowly toward your eye. Keep the coin fixed in place as you move the lens.

Describe your observations in words and with sketches.

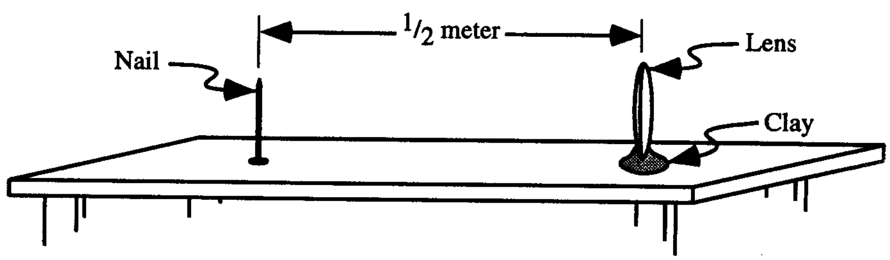
When we look at an object through a lens, we say that we are looking at an *image* of the object. In the preceding experiment, you found that the image can appear to be large or small. It can also appear to be right-side up *(erect)* or upside down *(inverted).* In the following experiments, we examine in more detail the image formed by a lens.

Experiment 7.3

For this experiment, you will need the larger diameter lens from the preceding experiment.

A. Use a piece of clay to support the lens on a table as shown. Place your eye about 30 cm from the lens and look through the lens at a nail placed about a half meter beyond the lens.

Describe your observations of the image of the nail.



Does the location of the image seem to differ from the actual location of the nail? Explain.

Based on your observations, would you say that the image of the nail is closer to you, farther from you, or the same distance from you as the nail? Explain how you can tell from your observations.

B. Obtain a second nail that is identical to the first. Use the method of parallax to place the second nail at the location of the image of the first nail.

Does the image appear to be larger or smaller than the nail appears without the lens?

Is the location of the image consistent with your answer in part A? If not, how can you resolve the inconsistencies? (*Hint:* Can you determine the location of the image solely on the basis of the size of the image?)

Remove the second nail.

C. Place the first nail about 5 cm from the lens. Look at the nail through the lens with your eye about 30 cm from the lens. Use the method of parallax to determine the location of the image.

Is the image closer to you, farther from you, or the same distance from you as the nail?

Does the image appear to be larger or smaller than the nail appears without the lens? Can you use the apparent size of the image as a clue as to whether the image is closer to you than the nail?

D. Turn the lens around. Does the location of the image depend on which side of the lens is toward the nail?

✔ Discuss this experiment with a staff member.

Experiment 7.4

Obtain several convex lenses of different sizes and shapes.

A. Hold a lens in one hand so that light from a brightly lit distant source (e.g., an illuminated building) passes through the lens and falls on a sheet of paper held in your other hand. Move the paper back and forth until a clear image of the object appears on the paper.

Describe the appearance of the image. Is it erect or inverted? Is it larger or smaller than the object?

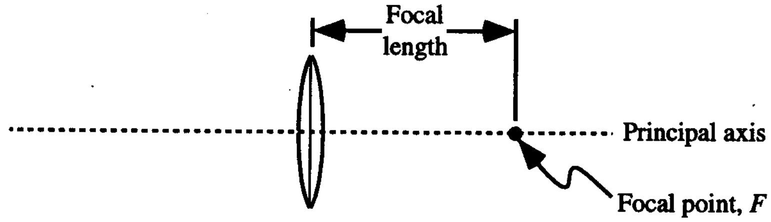
Turn the lens around. Describe what happens to the image.

Move the paper back and forth. Describe what happens to the image.

B. Repeat the process for each of the remaining lenses.

Describe the similarities and differences among the various lenses.

The line through the center of the lens and perpendicular to the plane of the lens is called the *principal axis.* (See the figure below.) The point of intersection of this axis and the image of a very distant object is called the *focal point.* The distance of the focal point from the center of the lens is called the *focal length.*



Experiment 7.5

For each lens that you used in the preceding experiment:

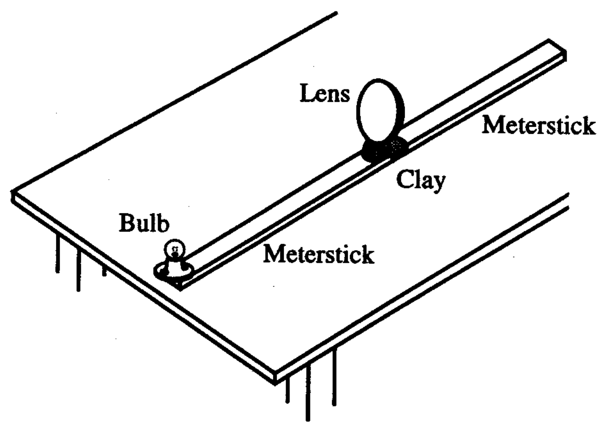
Is there a focal point on each side of the lens? If so, how does the focal length on one side of the lens compare with that on the other? Explain how you can tell from your observations.

It is customary to use a single symbol f to denote the focal length of a lens. Explain why two symbols, one for each focal point, are not necessary.

The image formed by the convex lens in the preceding experiment is called a *real image*. Such an image can be seen on a sheet of paper or a screen placed at the location of the image. A real image is different from the type of image formed by a plane mirror, which is called a *virtual image*. A virtual image cannot be seen on a screen placed at the location of the image.

Experiment 7.6

Place two meter sticks end-to-end on a table so that the zero markings are at the same point. Place the center of a lens above this point. Use a piece of clay as shown.



A. Find the focal points on each side of the lens and mark each of these points.

Describe the method you used to find the focal point.

B. Place a lighted bulb at the far end of one of the meter sticks.

Locate the image of the bulb by parallax. Also locate the image by using a piece of paper as a screen.

Compare the results of these two methods.

Describe the image and record your observations.

(1) Is it real or virtual?

(2) Is it erect or inverted?

(3) Does it appear to you to be larger, smaller, or the same size as the object?

(4) Is it on the same side of the lens as the object or on the opposite side?

(5) Note where the image is located relative to the lens and its focal points.

C. Repeat part B for each of following locations for the lighted bulb:

(1) at a distance between 1 m and $2f$ from the lens

(2) at a distance $2f$ from the lens

(3) at a distance between $2f$ and f from the lens

(4) at a distance f from the lens

(5) at a distance between f and $f/2$ from the lens

(6) at a distance $f/2$ from the lens

(7) at a distance less than $f/2$ from the lens

Do the two methods for determining the location of the image always work? If not, note which method fails and when it fails.

Place the lighted bulb as close to the lens as possible. Describe the image in this case. Record your observations.

D. Summarize your observations in words. If necessary, make additional observations to answer the following questions:

As an object is moved toward a lens from a large distance away, how does the location of the image vary?

As the object is moved toward the lens, how does the apparent size of the image vary?

For what range of object locations is the image erect? For what range of object locations is the image inverted?

Where must the object be located in order for the image to be on the same side of the lens as the object? Where must the object be located in order for the image to be on the opposite side of the lens as the object?

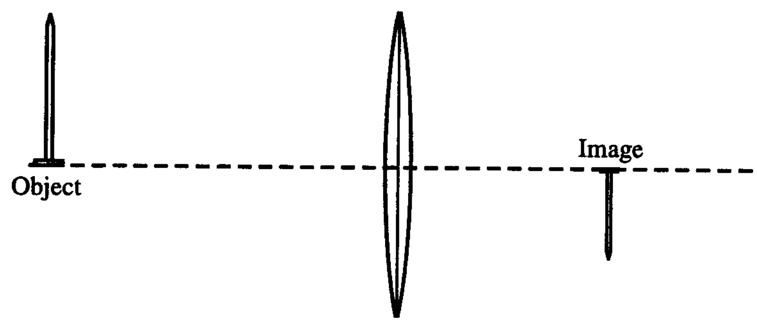
✔ Discuss this experiment with a staff member.

Section 8. Image formation and ray diagrams

In this section, we develop an algorithm, or a set of rules, for predicting the position and appearance of the image formed by a convex lens. This procedure, which is based on the tracing of light rays through a lens, is a powerful tool that we will apply and extend throughout our study of geometrical optics.

Exercise 8.1

The diagram below shows a nail near a convex lens. The image formed by the lens is shown on the diagram.



A. From the tip of the nail, draw several rays, some of which pass through the lens.

Show by a sketch how you can use these rays to account for the formation of the image of the tip of the nail. Explain.

B. Draw similar sketches for two other points on the nail.

C. Explain how you decided to draw the rays in the way that you did in parts A and B.

D. A convex lens is often called a *converging lens.*

Is this term appropriate? Explain why or why not.

Exercise 8.2

A lens is held at a very great distance from a tall building so that a clear image of the building is formed on a piece of paper. Consider two points on the building, *P* and *Q*. *P* is on the principal axis, *Q* is directly above it at the top of the building.

A. Draw a diagram that shows several rays from point *P* that reach the lens.

   How are these rays oriented with respect to one another and the principal axis? Explain.

   Where do these rays converge? Explain your reasoning.

B. On the diagram above, sketch some rays from point *Q* that reach the lens.

   How are these rays oriented with respect to one another? Explain.

   Where do these rays converge? Explain your reasoning.

The image of the building in the preceding exercise lies in the *focal plane* of the lens. This plane intersects the principal axis at the focal point and is perpendicular to the principal axis.

Experiment 8.3

A very small object is placed at the focal point of a convex lens. Where would you expect the image to be located?

Draw a diagram to illustrate your prediction. (*Hint:* Consider the effect of reversing the direction of light through a lens or a beaker of water. You did such an experiment in an earlier section on refraction.)

Set up the apparatus and check your prediction.

Exercise 8.4

Draw an enlarged side view diagram of a convex lens.

A. Draw a ray incident on the lens that passes through the center of the lens. The ray should be incident on the lens at an angle with the principal axis.

   How does the direction of the incident ray compare to the direction of the ray that emerges from the lens? Explain your reasoning.

B. Suppose that the lens that you drew were made much thinner. Use a diagram to justify the following statement:

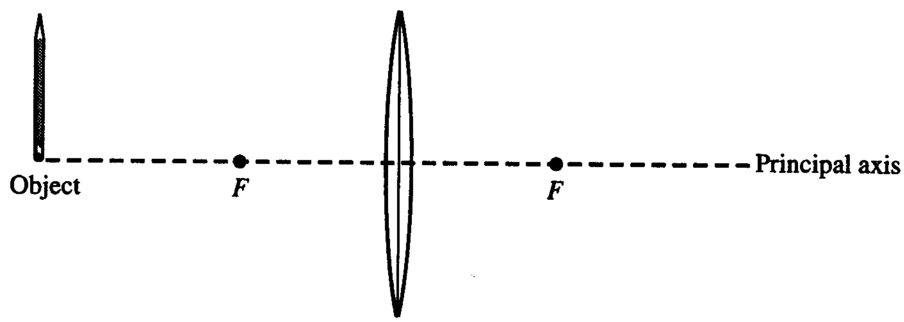
   The path of any ray passing through the center of a thin lens is essentially undeviated.

✔ Discuss Experiment 8.1 through Exercise 8.4 with a staff member.

The location of the image for any object can be found through the use of a ray diagram. Analysis of the preceding experiments and exercises suggests a method for tracing the path of light rays from a point on an object, through a lens, to a corresponding image point. Below, we apply this technique to the construction and interpretation of the image formed by a convex lens.

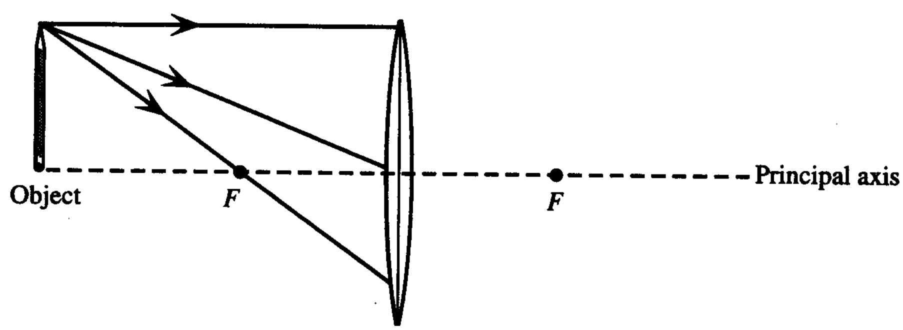
Exercise 8.5

In drawing a ray diagram for a lens, we begin by showing the lens, the principal axis, and the locations of the two focal points. A simple sketch of the object is then drawn at the proper distance from the center of the lens, usually on the left side of the lens.



As we found in Exercise 8.1, we can think of all the rays from a single point on the object that pass through the lens as converging at a single corresponding image point.

There are three special rays from each object point for which it is particularly easy to determine the path through the lens. These are shown in the following sketch. Copy this diagram in your notebook.



A. Do you expect these three rays to intersect after they pass through the lens? Explain.

Draw the continuation of each of these rays on the other side of the lens. In each case, explain your reasoning.

How would you interpret the intersection of these three rays?

These three rays, which are called *principal rays,* are only a few of the infinitely many that we might draw from one point on the object.

B. Choose another ray from the same point on the object. Continue that ray through the lens and out the other side. Explain how you were able to determine the direction of that ray after it passed through the lens.

In drawing a ray diagram for a thin lens, it is customary to treat rays either as being refracted all at once at the center of the lens or to treat the lens as a line with no thickness. Refraction actually takes place at the two surfaces.

C. Choose another point on the object and use the three principal rays from that point to determine the location of the corresponding point on the image.

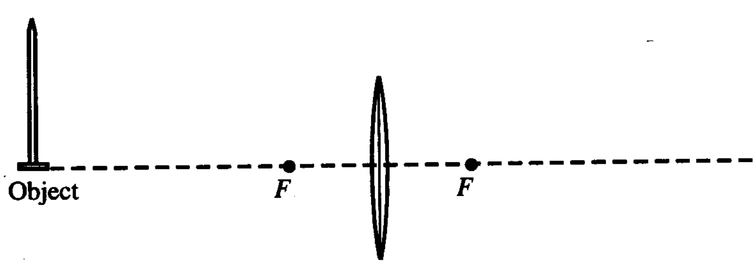
D. Consider a point on the object that lies on the principal axis. Where is the image of this point located? Explain.

E. Sketch the entire image at the appropriate location on your diagram.

✔ Discuss this exercise with a staff member.

Exercise 8.6

A nail is placed near a lens. The top of the nail is above the top of the lens, as shown in the diagram below.



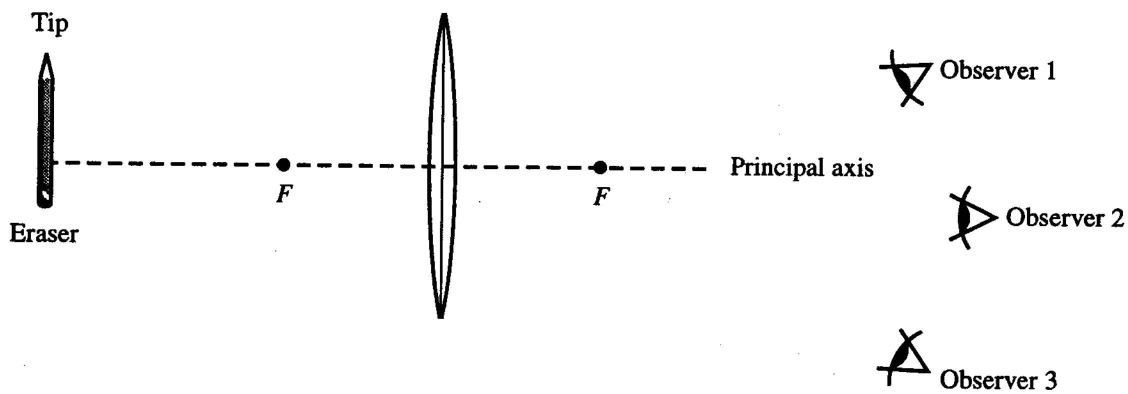
A. Will the lens form a complete image of the nail? Sketch a ray diagram to illustrate your answer.

B. How many of the principal rays must you draw to be able to locate an image? Explain.

Exercise 8.7

A pencil is placed near a converging lens of focal length *f*. Three observers are located as shown.

A. Draw a ray diagram in which you use the principal rays to determine the location of the image of the pencil.



B. Which observer(s) can see the image of the pencil tip? Explain.

C. Which observer(s) can see the image of the eraser? Explain.

D. Which observer(s) can see the entire image of the pencil? Explain.

E. Suppose that you were to place your eye at the location of an observer who can see the entire image of the pencil.

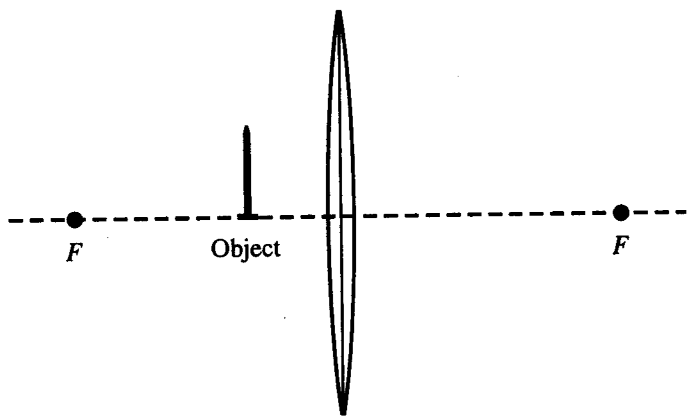
Which would *appear* to be larger to the observer: the image of the pencil (with the lens in place) or the pencil (with the lens removed)? Explain how you can tell from the ray diagram.

If you were to use a ruler to measure the length of the pencil and the length of the image, which would be larger? Explain how you can tell from the ray diagram.

✔ Discuss your reasoning with a staff member.

Exercise 8.8

In Exercise 8.5, we developed a procedure for drawing ray diagrams for situations in which a convex lens forms a real image. In this exercise, we extend this procedure to include the case that the image is virtual.



A. Copy this diagram in your notebook and draw the three principal rays from the tip of the nail to the lens.

Do these rays intersect on the right side of the lens?

Would an observer on the right side of the lens see an image? If so, where is the image located? (*Hint:* Consider your observations using convex lenses in Section 7.)

Explain how you would find the location of the image by using the principal rays. Recall that it is customary to use dashed lines to indicate the extension of a ray into a region in which the light does not pass.

B. Is the image erect or inverted? Is the image larger or smaller than the object? Explain how you can tell from the ray diagram.

Exercise 8.9

An object is placed near a lens along the principal axis.

A. For each of the following distances from the object to the lens, draw a ray diagram to determine the location of the image:

(1) greater than $2f$

(2) at $2f$

(3) between $2f$ and f

(4) at f

(5) between f and $f/2$

(6) at $f/2$

(7) less than $f/2$

B. For each case in part A:

Is the image erect or inverted?

Is the image real or virtual?

How does the size of the image compare to the size of the object?

Which would *appear* to be larger to an observer: the image of the object (with the lens in place) or the object (with the lens removed)? Explain how you can tell.

C. Compare your results for the image locations in part A with your observations in Experiment 7.6. Are they consistent? If not, resolve any discrepancies.

Experiment 8.10

In this experiment, be sure to make all predictions before performing the experiments. Draw ray diagrams to justify your predictions.

A lens, a bulb, and a screen are arranged as illustrated in the following diagram. The screen is at the location of the image of the bulb.

A. Predict what would happen to the image if the top half of the lens were covered by a mask. Explain your reasoning.

Does it matter on which side of the lens the mask is placed?

B. Predict what would happen to the image if a mask with a small hole in the center (smaller than the object) were placed in front of the lens.

How would your answer differ if:

- the hole were made larger than the object
- the hole were moved so it is not at the center of the lens

C. Perform each of the above experiments and check your predictions. If your predictions were incorrect, draw new ray diagrams that are consistent with what you observe.

Section 9. Image formation and the thin lens equation

In the preceding section, we introduced a diagrammatic representation that enables us to make predictions about the image formed by a thin lens. In this section, we develop an algebraic representation for the relationships among the distance of an object from a lens, the distance of an image from a lens, and the focal length of the lens.

In the algebraic analysis of image formation by a single lens, we use the following symbols.

> The symbol s represents the object distance measured from the center of the lens along the principal axis and the symbol s' represents the corresponding image distance from the center of the lens. The symbols F and f designate the focal point and focal length on the same side of the lens as the object, and the symbols F' and f' designate the focal point and focal length on the other side of the lens.

In developing an algebraic equation that relates the object distance and image distance, we need to establish an algebraic sign convention. We adopt the following convention.

> *Algebraic Sign Convention for object and image distances for a lens*
>
> The object distance, s, is considered positive. (The object is usually placed to the left of the lens.) The image distance, s', is considered positive when the image is on the opposite side of the lens from the object and negative when it is on the same side of the lens as the object. The focal length of a convex lens is considered positive.

Experiment 9.1

In this experiment, we develop a quantitative relationship between the object distance and the image distance for a convex lens. We repeat the procedure of Experiment 7.6, in which we made qualitative observations of how the distance of an object from a lens affects the image.

A. Place an object at a great distance from a convex lens. Record the values of s and s' in a table in your notebook.

   Move the object closer to the lens in several stages. (You may use the same locations for the object as you did in the Experiment 7.5.) For each location of the object, record the values of s and s'.

   Include an entry in your table for an image located at F'. What are the corresponding values of s and s'?

B. A convenient way to graph your results is to use new variables, x and x'. Let $x = s - f$, and $x' = s' - f'$.

What physical interpretation can you give to the variables x and x'?

Where is the object when x is positive, when x is negative and when x is zero? Where is the image when x' is positive, when x is negative, and when x is zero?

(1) Add two columns to your table, one for x and one for x'. Enter values for x and x' corresponding to each value of s and s' in your table.

(2) Graph x as a function of x'.

(3) As your graph indicates, the relationship between x and x' is clearly not linear. You might guess from your study of mathematics that the resultant curve is a hyperbola.

To test whether the curve is a hyperbola, plot a graph of x as a function of $1/x'$.

Is the relationship between x and $1/x'$ linear? Explain how you can tell from your graph.

Find the slope of the graph and call it κ.

Write an equation relating x, x', and κ.

The constant κ is related to the focal length, f. Make an educated guess as to this relationship, by considering the units of κ. Check your guess.

Write an equation relating x, x', and f.

✔ Check your reasoning with a staff member.

The equation that you derived in the preceding experiment is known as the Newtonian form of the thin lens equation. This form of the thin lens equation is seldom used. The Gaussian form, which is given in the following exercise, is more useful in practice.

Exercise 9.2

The Gaussian form of the thin lens equation is:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

A. Derive the Gaussian form of the thin lens equation from the Newtonian form.

B. Use your measurements from the preceding experiment to plot $1/s$ as a function of $1/s'$.

What is the shape of your graph?

What feature of the graph can you use to determine the focal length of the lens? Explain your reasoning.

The expressions that we have derived that relate object and image distances to the focal length of a lens are very useful for making predictions and designing simple optical instruments. It should be noted, however, that these equations apply only to thin lenses, in which the thickness of the lens is small compared to the other distances involved.

Exercise 9.3

A. Use the thin lens equation to find the image location, *s*, for an object placed at the following values of *s*: $s = 4f$, $2f$, $3f/2$, f, $3f/4$, $f/2$, $f/4$. Show your work in each case.

B. Not all of the values of s in part A result in a positive value for s'.

How would you interpret negative value for s'. How would you interpret the failure of the equation to yield a number for s'? (*Hint:* Draw on your experience in working with lenses in the laboratory and on your experience in drawing ray diagrams.)

Exercise 9.4

A. We now have three ways of finding the location of an image formed by a thin convex lens: by using parallax, by using a screen, and by using an equation.

Discuss which of the methods work for finding the image locations for each of the images in the preceding exercise. You have used the first two of these methods in Experiment 7.6.

If one of the methods fails for some of the object distances, discuss why that method fails.

B. Give an operational definition for a real image and for a virtual image. (You may need to refer to the discussion of operational definitions in *Properties of Matter* in Volume I.)

✔ Check your reasoning with a staff member.

Experiment 9.5

In this experiment, you will make several predictions. Record your predictions before performing any experiments. Explain your reasoning.

Suppose that a lighted bulb is placed about 2 meters from a convex lens. Imagine that you are looking at the bulb through the lens with your eye about 30 cm from the lens.

A. Predict what you would observe. Where would the image be located?

Predict what you would observe if a piece of plain white paper were placed at the location of the image.

Predict what you would observe if the paper were placed closer to the lens.

Predict what you would observe if the paper were moved to a location farther from the lens.

Perform the above experiments and record your observations. Try to resolve any discrepancies between your predictions and your observations.

Are your predictions and your observations consistent with the implications of the thin lens equation? Explain.

B. Predict what you would observe on a sheet of paper at the image location if the lens were removed.

How would what you would observe differ from what you observe when the lens is present?

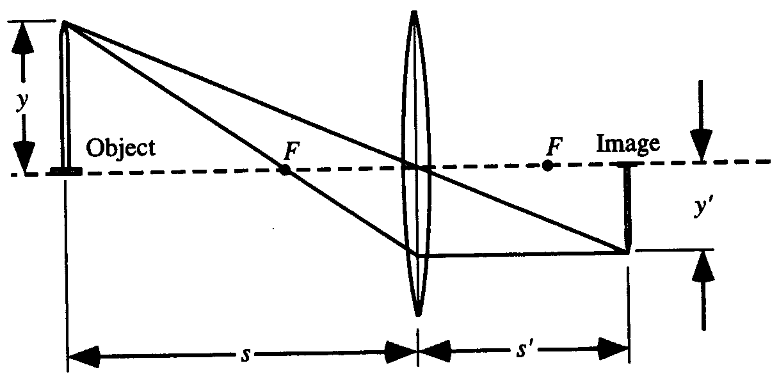
With the lens still removed, predict what will happen as the piece of paper is moved toward and away from the bulb. Explain your reasoning.

Perform the above experiments and record your observations. Try to resolve any discrepancies between your predictions and your observations.

Exercise 9.6

As illustrated below, the size of the image formed by a convex lens depends on the size and location of the object. We define the magnification, m, as the ratio of the height of the image, y', to the height of the object, y.

$$m = \frac{y'}{y}$$



A. Find the relative size of the image with respect to the object in terms of the image and object distances, s' and s. (*Hint:* Look for similar triangles in the diagram above.) Explain.

B. By convention, the magnification m of an inverted image is chosen to be negative. Note that this implies that y' is negative for inverted images, such as the real image above.

   Derive an expression for m in terms of s' and s that is consistent with this convention.

Experiment 9.7

Consider a convex lens of focal length f. Suppose that an object is placed at a distance less than f from the lens.

A. Is the magnification m positive or negative? Explain your reasoning.

B. Is the absolute value of the magnification greater than, equal to, or less than 1? Explain your reasoning.

C. Suppose that an observer who was originally located to the right of the image above moved further away from the lens.

   Would the magnification of the lens change? Explain.

   Would the size of the image as seen by that observer change? Would the size of the object as seen by that observer (with the lens removed) change? Explain.

✔ Check your results with a staff member.

Section 10. Image formation by concave lenses

In this section, we examine the behavior of concave lenses. Concave lenses have at least one surface that curves inward and are thinner in the middle than at the edge.

Experiment 10.1

Obtain two concave lenses of different diameters.

A. Look at various objects through the lenses. Describe what you see. What factors affect what you see? (Possibilities might include the following: distance from the object to the lens, distance of the lens to your eye, etc.) Record your observations.

B. Look at a coin through the lens with the larger diameter. Hold the coin so it is upright when you are looking at it without the lens.

Where, if at all, can you hold the lens so that the coin appears to be:

(1) upright?

(2) inverted?

(3) smaller than it is in real life?

(4) larger than it is in real life?

(5) the same size as it is in real life?

C. Hold the lens fixed in place about 20 cm from your eye. Place a coin behind the lens and very close to it. Slowly move the coin as far from the lens as you can. Describe your observations in words and with sketches.

Repeat the procedure above for the smaller lens. Do you notice any differences between the two lenses?

D. Hold the coin at arm's length in front of you. Place the lens directly in front of the coin, then move it slowly toward your eye. Keep the coin fixed in place as you move the lens.

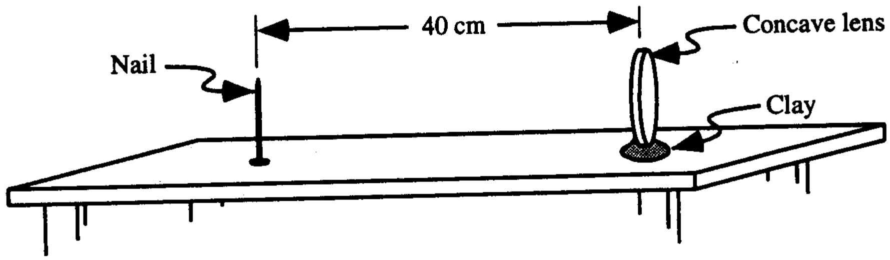
Describe your observations in words and with sketches.

Experiment 10.2

For this experiment, you will need the larger diameter lens from the preceding experiment.

A. Use a piece of clay to support the lens on a table as shown in the following diagram. Place your eye about 10 cm from the lens and look through the lens at a nail placed about 40 cm beyond the lens.

Describe your observations of the image of the nail.



Does the location of the image seem to differ from the actual location of the nail? Explain.

Based on your observations, would you say that the image of the nail is closer to you, farther from you, or the same distance from you as the nail? Explain how you can tell from your observations.

B. Obtain a second nail, identical to the first. Use the method of parallax to place the second nail at the location of the image of the first nail.

Does the image appear to be larger or smaller than the nail appears without the lens?

Is the image location consistent with your answer in part A? If not, how can you resolve the inconsistencies? (*Hint:* Can you determine the image location solely on the basis of the size of the image?)

Remove the second nail.

C. Place the first nail close to (but not touching) the lens. Look at the nail through the lens with your eye about 10 cm from the lens. Use the method of parallax to place the second nail at the location of the image.

Is the image closer to you, farther from you, or the same distance from you as the nail?

Does the image appear to be larger or smaller than the nail appears without the lens?

D. Reverse the lens. Does the location of the image depend on which side of the lens is toward the nail?

Experiment 10.3

Compare the behavior of concave and convex lenses. In particular:

- Is it possible to form both real and virtual images using either type of lens?
- Is it possible to form both erect and inverted images using either type of lens?

✔ Discuss Experiments 10.1 through Exercise 10.3 with a staff member.

Experiment 10.4

Obtain several concave lenses of different sizes and shapes.

A. Hold a lens in one hand so that light from a brightly lit source (e.g., an illuminated building) passes through the lens and falls on a sheet of paper held in your other hand. Try to place the paper at the image location.

Is it possible for an image of the distant object to appear on the paper? Explain how you can tell from your observations.

Would your answer above be different if you reversed the lens?

B. Repeat the process for each of the remaining lenses. Describe the similarities and differences of your results with various lenses.

C. On the basis of your observations, is the image formed by a concave lens of a distant object real or virtual?

In a previous section, we developed a method for determining the location of the focal point and focal length of a convex lens. The focal point is the point of intersection of the principal axis and the image of a very distant object. In the following experiment, we determine the focal length of a concave lens.

Experiment 10.5

Find the focal length for both sides of each lens from Experiment 10.4.

Is there a focal point on each side of the lens? If so, how does the focal length on one side of the lens compare with that on the other? Explain how you can tell from your observations.

It is customary to use a single symbol f to denote the focal length of a lens. Explain why two symbols, one for each focal point, are not necessary.

✔ Discuss Experiments 10.3 and 10.4 with a staff member.

For a convex lens, the image of a distant object is on the opposite side of the lens from the object. As you have seen, for a concave lens, the distant object and its image are both on the same side of the lens. The following sign convention is consistent with our observations and also with the sign convention for s and s'.

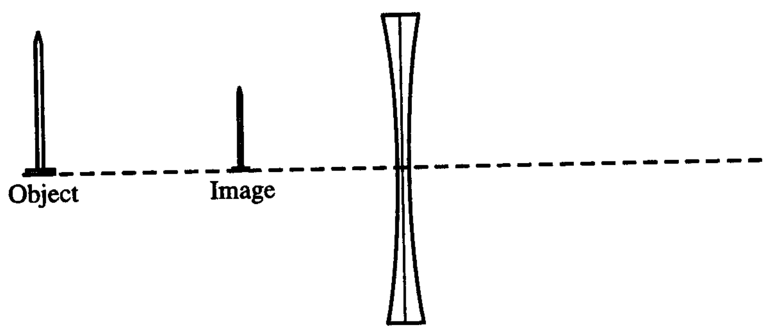
<u>*Algebraic sign convention for the focal length of a lens*</u>

When a distant object and its image are on opposite sides of the lens, the focal length is considered positive. (e.g., a convex lens)

When a distant object and its image are on the same side of the lens, the focal length is considered negative. (e.g., a concave lens)

Exercise 10.6

The diagram below shows a nail near a concave lens. The image formed by the lens is also shown.



A. From the tip of the nail, draw several rays. Some of the rays that you have drawn should pass through the lens.

Show with your sketch how you can use these rays to account for the formation of the image of the tip of the nail. Explain.

B. Draw similar sketches for two other points on the nail.

C. Explain how you decided to draw the rays in the way that you did in parts A and B.

D. A concave lens is often called a *diverging lens.*

Is this term appropriate? Explain why or why not.

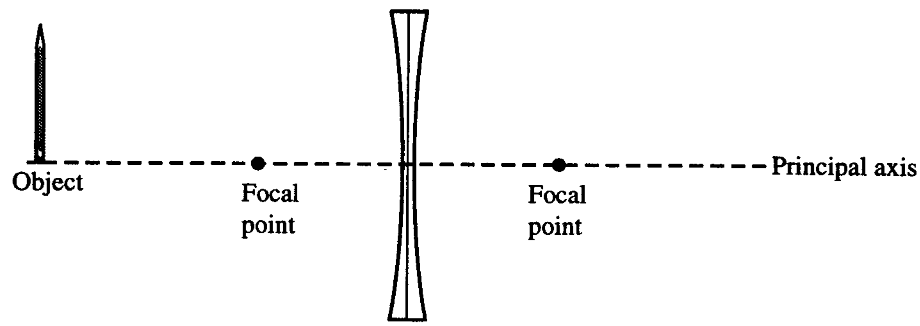
You have already used ray diagrams to determine the location of an image formed by a convex lens. Below, we apply this technique to the construction and interpretation of the image formed by a thin concave lens. Recall that a lens may be regarded as a thin lens if its thickness is small compared to the other distances involved.

Exercise 10.7

The diagram below shows a thin concave lens, the principal axis of the lens, an object, and the location of the two focal points.

As in Exercise 8.1, we can think of all the rays from a single point on the object that pass through the lens as appearing to originate from a single corresponding image point.

Copy the diagram below in your notebook.



A. On your diagram trace a ray parallel to the principal axis that extends from the tip of the object to the lens.

   How would you draw the continuation of this ray through the lens? Is your answer consistent with the idea that this is a diverging lens?

B. Trace another ray from the tip of the object that is directed toward the center of the lens.

   Does this ray change direction as it passes through the lens, assuming the lens is thin? Explain.

C. Determine where the image of the tip of the object is located. Explain your reasoning.

   Do the rays that you have drawn actually intersect at a point, or do they only appear to have passed through the same point? Explain.

D. Trace a third ray from the tip of the object that is initially directed toward the focal point on the far side of the lens.

   Continue the ray through the lens and out the other side. Explain how you determined the direction of the ray on the other side.

   How does the direction of the continuation of this ray compare to the orientation of the principal axis?

   The three rays that you have drawn are called *principal rays.* Although tracing principal rays is a convenient tool for determining the location of an image formed by a lens, these rays are only a few of the infinitely many that we might draw from one point on the object.

E. Trace a fourth ray from the tip of the object to the lens. Continue this ray through the lens and out the other side of the lens. Explain how you determined the direction in which this ray continues on the other side.

✔ Discuss your reasoning with a staff member.

Exercise 10.8

For this exercise you will need your ray diagram from the preceding exercise.

A. Choose a point on the object other than the tip of the object. On the ray diagram, trace rays from this point to determine where the image of this point is located. (You may want to use ink of a different color.) Explain the reasoning you used in determining your answer.

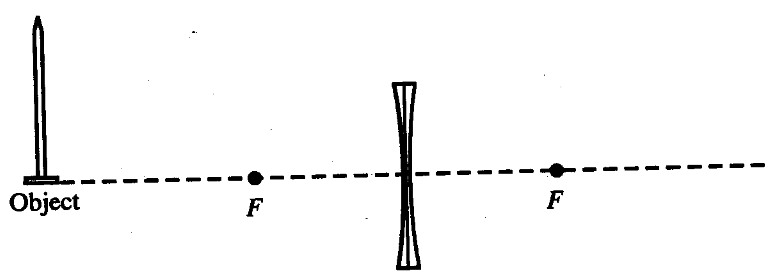
B. Consider a point on the object that lies on the principal axis. Trace rays to show where the image of this point is located.

C. Sketch the entire image of the object at the appropriate location on your diagram.

✔ Discuss your completed ray diagram with a staff member.

Exercise 10.9

A nail is placed near a converging lens as shown. The nail is taller than the lens.



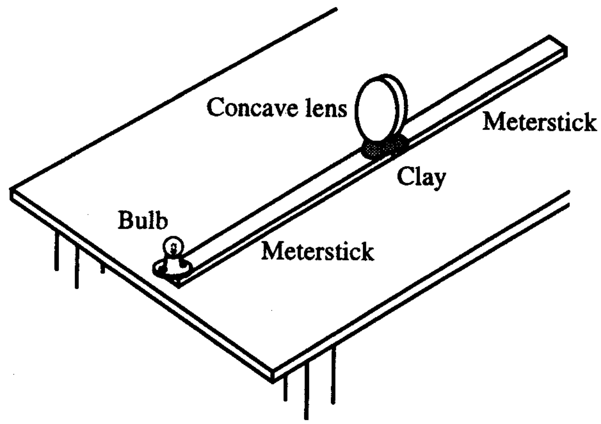
A. Will the lens form a complete image of the pencil? Sketch a ray diagram to illustrate your answer.

B. How many of the principal rays must you draw to be able to locate an image? Explain.

✔ Check your answers with a staff member.

We have used ray tracing techniques to predict the location of images formed by lenses. In the following experiments, we develop an alternative method.

Experiment 10.10



Place two meter sticks end-to-end on a table so that the zero markings are at the same point. Place the center of a concave lens above this point. Use a piece of clay as shown.

A. Find and mark the focal points of the lens.

B. Place a lighted bulb at the far end of one of the meter sticks.

Locate the image of the bulb by parallax.

Is it also possible to locate the image by using a piece of paper as a screen? Explain your reasoning.

Describe the image and record your observations.

(1) Is it real or virtual?
(2) Is it erect or inverted?
(3) Does it appear to you to be larger, smaller, or the same size as the object?
(4) Is it on the same side of the lens as the object or on the opposite side?
(5) Note where the image is located relative to the lens and its focal points.

C. Repeat part B for each of following locations for the lighted bulb:

(1) at a distance between 1 m and $2f$ from the lens
(2) at a distance $2f$ from the lens
(3) at a distance between $2f$ and f from the lens
(4) at a distance f from the lens
(5) at a distance between f and $\frac{f}{2}$ from the lens
(6) at a distance $\frac{f}{2}$ from the lens
(7) at a distance less than $\frac{f}{2}$ from the lens

Place the object as close to the lens as possible. Describe the image in this case. Record your observations.

D. Summarize your observations in words. If necessary, make additional observations to answer the following questions:

As an object is moved toward a concave lens from a large distance away, how does the location of the image change?

As the object is moved toward the concave lens, how does the apparent size of the image change?

For what range of object locations, if any, is the image erect? For what range of object locations, if any, is the image inverted?

Where, if anywhere, must the object be located in order for the image to be on the same side of the lens as the object? Where, if anywhere, must the object be located in order for the image to be on the opposite side of the lens as the object?

✔ Discuss your results with a staff member.

Exercise 10.11

An object is placed near a concave lens along the principal axis.

A. For each of the following distances from the object to the lens, draw a ray diagram to determine the location of the image:

(1) greater than $2f$

(2) at $2f$

(3) between $2f$ and f

(4) at f

(5) between f and $f/2$

(6) at $f/2$

(7) less than $f/2$

B. Compare your results for the image locations in part A with your observations in part C of Experiment 10.10. Are they consistent? If not, resolve any discrepancies.

C. For each case in part A:

Is the image erect or inverted?

How does the size of the image compare to the size of the object?

Which would *appear* to be larger to the observer: the image of the object (with the lens in place) or the object (with the lens removed)? Explain how you can tell.

In the following experiment, we develop an algebraic representation for the relationships among the object distance, the image distance and the focal length of a thin concave lens.

Experiment 10.12

Arrange two meter sticks end-to-end on a table in the same way as you did for Experiment 10.10. Place the center of a concave lens with a known focal length above the junction of the two meter sticks. Use clay to hold the lens upright.

In this experiment be sure to indicate the proper algebraic signs for s, s' and f. Refer to the sign conventions at the beginning of Section 9 and earlier in this section.

A. Place a lighted bulb at the far end of one of the metersticks. Measure the distance of the bulb from the lens.

Determine the corresponding image distance s'.

B. Move the object closer to the lens in small steps. For each location of the object, record the values of s and s' in a table.

Include an entry in your table for the location of the image of a very distant object. What is the value of s' in this case?

C. Use your measurements to plot $1/s$ as a function of $1/s'$. Describe the shape of the resulting graph.

Does the graph have a single value for the slope? If so, determine the slope of the graph.

At which point does your graph intercept the vertical axis? How is the vertical intercept related to the focal length of the lens? Explain.

Is the algebraic sign that you determined for f from your graph consistent with the sign convention discussed in the text after Experiment 10.5?

D. Write an equation relating s, s', and f.

Compare the equation that you obtain for diverging lenses with the thin lens equation that you derived for converging lenses.

Can the same equation be used for both types of lenses? As part of your answer, discuss the critical importance of our conventions for the algebraic signs of s, s', and f.

✔ Discuss your results with a staff member.

Experiment 10.13

Use the thin lens equation to find the image distance, s', for an object located (1) very far from the lens, (2) at a distance $2f$ from the lens, (3) at a distance f from the lens, and (4) at a distance less than f from the lens.

Do your answers agree with your observations? If not, try to resolve any inconsistencies.

Section 11. Image formation by curved mirrors

Curved mirrors can be divided into two categories according to shape: convex and concave. The mirrored surface of a concave mirror curves inward and that of a convex mirror curves outward. As with a lens, we define the *principal axis* of a mirror as the line of symmetry for the curved surface. The point at which this line intersects the mirror is called the *vertex* of the mirror. The object distance, image distance, and focal length are measured from the vertex of the mirror.

In this section, we investigate image formation by curved mirrors, beginning with spherical concave mirrors.

Concave mirrors

Experiment 11.1

Obtain two concave mirrors of different diameters.

A. Look at various objects in the mirrors. Record your observations.

What factors affect what you see?

B. Hold a coin upright in front of the larger diameter mirror. Look at the image.

Where can you hold the mirrors so that the image is:

(1) upright?

(2) upside down?

(3) larger than it is in real life?

(4) smaller than it is in real life?

(5) the same size as it is in real life?

C. Hold the larger diameter concave mirror fixed in place at arm's length in front of you. Place a coin in front of the mirror and very close to it. Slowly move the coin toward your eye. Describe your observations in words and with sketches.

D. Does a concave mirror have a focal point? If so, are there one or two focal points? Explain how you can tell.

For your larger concave mirror, measure the distance from the vertex to the focal point(s).

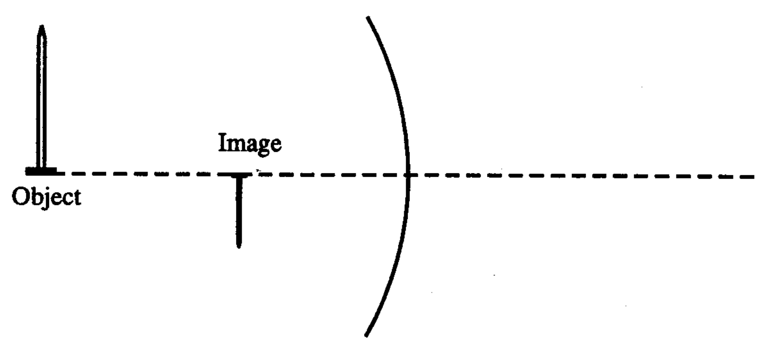
Is the image of a distant object formed by a concave mirror real or virtual? Explain how you can tell.

Is it possible to form both real and virtual images using a concave mirror?

Is it possible to form both erect and inverted images using a concave mirror?

Experiment 11.2

The diagram below shows an object held near a concave mirror. The image formed by the mirror is shown.



A. From the tip of the nail, draw several rays. Some of the rays that you have drawn should intersect the mirror.

Show with your sketch how you can use these rays to account for the formation of the image of the tip of the nail. Explain.

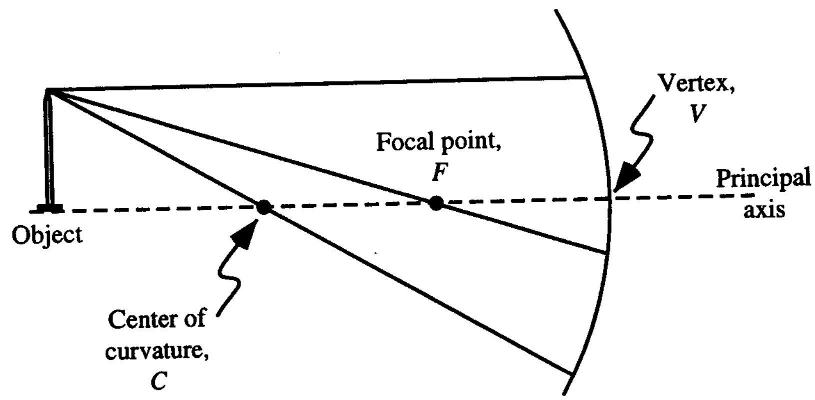
B. Draw similar sketches for two other points on the nail.

C. Explain how you decided to draw the rays in the way that you did in parts A and B.

Exercise 11.3

For a mirror, we can identify three principal rays that are analogous to those for a lens. These rays are shown below for the tip of a nail.

Copy the diagram in your notebook.



A. Do you expect these three rays to intersect after they are reflected from the mirror? Explain.

   Draw the continuation of each of these rays. Base your drawing on your knowledge of what you see when you look in a concave mirror. Explain your reasoning.

   How would you interpret the intersection of these three rays?

B. Draw the ray from the tip of the nail to the vertex *(V)* and show the reflected ray.

   You could have determined the direction of the reflected ray in two ways. Discuss both briefly.

C. How many of the four rays that you drew above are necessary in order to determine the image location? Explain.

D. Choose another point on the object and draw rays to determine the location of the corresponding point on the image.

E. Sketch the entire image at the appropriate location on your diagram.

✔ Discuss this exercise with a staff member.

Experiment 11.4

Obtain several concave mirrors of various radii of curvatures.

A. Perform an experiment that enables you to determine the location of the focal point for each mirror. Record the focal length and the radius of curvature for each mirror.

B. Plot a graph of focal length versus radius.

Determine the slope of the graph. Write an expression for the focal length in terms of the radius of curvature.

In working with lenses, we found that it was necessary to establish a sign convention in order to formulate an algebraic relationship between the object and image distance. The same is true for curved mirrors, however, the convention we adopt is different from that for lenses. The following is the convention that we use for mirrors in this module.

> *Algebraic sign convention for object and image distances for a curved mirror*
>
> The object distance, s, is considered positive. (The object is usually placed to the left of the mirror.) The image distance, s', is considered positive when the image is on the same side of the mirror as the object and negative when it is on the opposite side of the mirror as the object. The focal length of a concave mirror is considered positive.

Experiment 11.5

In Experiment 10.12, we found that the thin lens equation for convex lenses can also be applied to concave lenses. However, the proper choice of sign conventions is of critical importance.

In this experiment, we explore whether the same equation might also apply to a concave mirror by testing its validity at a few points.

A. Place a small object at the following locations:
   - at the focal point of the mirror
   - at the center of curvature of the mirror
   - at a great distance from the mirror

   In each case, determine the location of the image in terms of R, the radius of curvature of the mirror.

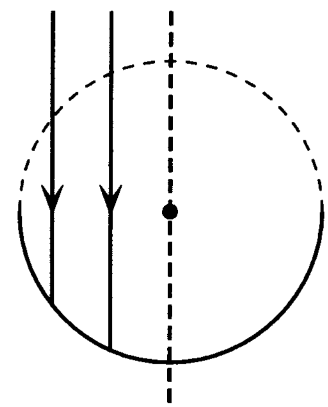
B. Check whether the object distances and image distances in part A are consistent with the thin lens equation.

C. If a large curved mirror is available, check additional object locations as well, such as $R = 3R/2$, $3R/4$, $R/2$, and $2R/3$.

Spherical aberration in concave mirrors

Experiment 11.6

Two rays of light from a distant source are incident on a mirror that consists of one-half of a sphere. The dashed line in the figure, which shows the entire surface of the sphere, is given for your convenience.



Draw an enlargement of the mirror on graph paper. Use a compass to draw an accurate semicircle.

A. Carefully draw the corresponding reflected rays. Base your construction on your knowledge of how light is reflected from a plane mirror. Use a ruler and a protractor.

   Do the reflected rays all pass through the same point?

B. Suppose that all the rays from a given point on an object to do not meet at a single point on the image. What effect would you expect this to have on the appearance of the image? Explain.

   Based on your observations in part A, would you expect a spherical mirror to have a well defined focal point? Explain.

   Suppose you were to paint over part of the mirror so that only light incident on the mirror near the principal axis is reflected. Would you expect the focal point to be better defined in this case? Explain. Draw a diagram to support your answer.

Spherical aberration is the term given to the failure of a spherical mirror or lens to form a sharp image of an object. For both, the effect is small for rays incident near the principal axis. In spite of this inherent shortcoming, most mirrors and lenses are spherical in shape since spherical surfaces are relatively easy to construct.

Experiment 11.7

A. Draw an accurate cross-section of a parabolic mirror on a piece of graph paper. Use your knowledge of the equation for a parabola as a guide.

   Draw several rays to convince yourself that a parabolic mirror reflects all the rays parallel to the principal axis so that they pass through a single point, the focus of the mirror.

B. Imagine that you were to place a small lighted bulb at the focus of a spherical mirror and another bulb at the focus of a parabolic mirror.

   Describe what would happen to the reflected light in both cases.

Convex mirrors

Experiment 11.8

A. Repeat Experiments 11.1 through 11.4 using convex mirrors instead of concave mirrors.

B. Compare the behavior of concave and convex mirrors. In particular:

   - Is it possible to form both real and virtual images using either type of mirror?
   - Is it possible to form both erect and inverted images using either type of mirror?

For a concave mirror, the image of a distant object is on the same side of the mirror as the object. For a convex mirror, a distant object and its image are on opposite sides of the mirror. The following sign convention is consistent with these observations and also with the sign convention for s and s' for curved mirrors.

Algebraic sign convention for the focal lengths of a curved mirror
When a distant object and its image are on opposite sides of the mirror, the focal length is considered positive. (e.g., a concave mirror)
When a distant object and the image are on the same side of the mirror, the focal length is considered negative. (e.g., a convex mirror)

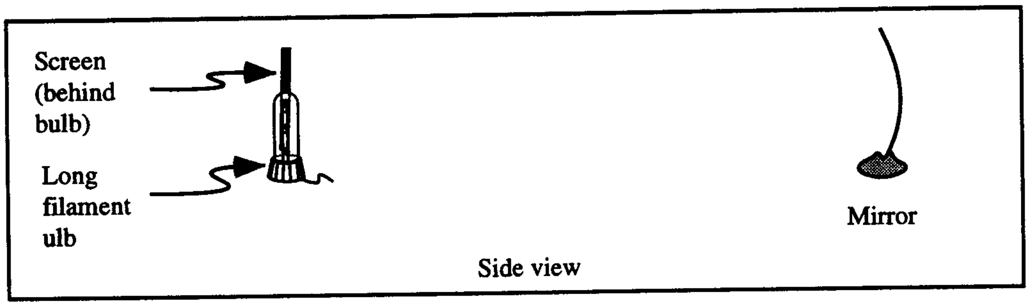
Experiment 11.9

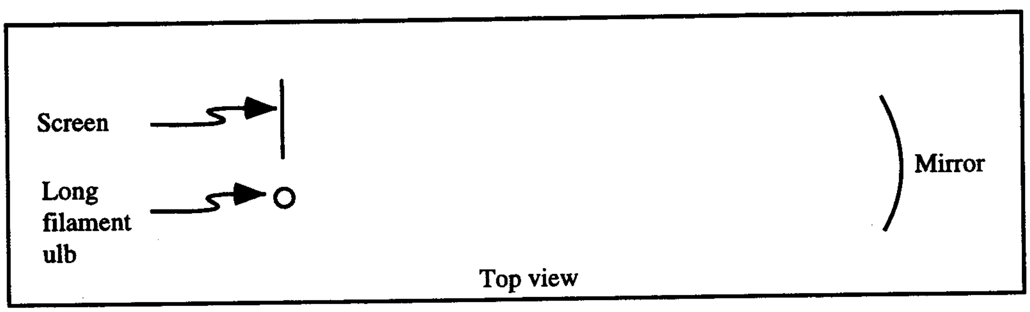
Explore whether the thin lens equation can be applied to convex mirrors. Perform the same test as in Experiment 11.5, using the same object locations as you did in that experiment.

Experiment 11.10

In this experiment, be sure to make all your predictions before performing the experiments. Draw ray diagrams to justify your predictions.

Place a screen next to a long filament bulb as shown in the diagram below. Place a concave mirror at the correct location to produce a sharp image of the bulb on the screen.





A. Predict what would happen to the image if the left half of the mirror were covered by a mask. Explain your reasoning.

B. Predict what would happen to the image if a mask with a small hole in the center (smaller than the object) were placed in front of the mirror.

   How would your answer change if:

   - the hole is made larger than the object
   - the hole is moved so it is not at the center of the mirror

C. Perform each of the above experiments and check your predictions. If your predictions were incorrect, draw new ray diagrams that are consistent with what you observe.

Section 12. Applications of geometrical optics

The phenomena of reflection and refraction are the basis of a number of optical instruments. In this section, we investigate several common optical instruments.

Experiment 12.1

Imagine that you wanted to spy on your neighbors who had erected a tall fence at your property line. How could you use two mirrors and a cardboard tube to create a *periscope,* a device that you could use to see over the fence?

Design and construct such a device.

Experiment 12.2

Obtain a plane mirror, a convex mirror, and a concave mirror. If needed, partially cover the mirrors so all three mirrored surfaces are the same size.

Hold each mirror one at a time in one hand at arm's length from you. Look at the images of objects behind you.

A. Which mirrors produce upright images?

Which mirrors produce images that appear larger than, smaller than, or the same size as the objects? Explain.

B. Is the extent of what you can see behind you (i.e., your field of view) different for the three mirrors? Explain.

C. Which type of mirror might be best suited for use as a *rear-view mirror?* Explain.

What sort of warning would you give drivers who use the mirror?

Experiment 12.3

A *magnifying glass* is a convex lens used to make an object appear larger than it is.

A. Use a convex lens as a magnifying glass.

Is the image erect or inverted? Is it real or virtual?

Does the lens make the object appear closer to you or farther from you? Use parallax to determine where the image is located.

B. Sketch a ray diagram to illustrate a lens used as a magnifying glass. The diagram need not be drawn to scale but should show the correct object and image locations with respect to the lens and its focal points.

Does a magnifying glass simply make objects appear closer? If not, what does it do?

✔ Discuss your answers with a staff member.

Exercise 12.4

In a *camera,* light from an object reaches a piece of film and exposes it.

A. Describe how to use a convex lens to make a simple camera. Does it matter whether the image is real or virtual?

Make a sketch showing the location of the convex lens, its focal points, the object and image locations, and the location of the film.

B. Imagine that you had just taken an in-focus photograph of a distant object. Would you need to adjust your camera to take a photograph of something much closer? If so, how? Explain.

Explain why in some photographs, certain objects are in focus while other objects are not.

C. Cameras use a shutter to control the length of time the film is exposed (e.g., 1/60th of a second). The more light that reaches a point on the film, the brighter the corresponding point on the photograph.

How would different exposure times affect the photograph?

When taking a photograph in a dim room, what would be an advantage of using a long exposure time?

When taking a photograph of a quickly moving object, why might you want to use a short exposure time?

D. In *Light and Color,* Volume I, you studied pinhole cameras. If you use a pinhole camera to take a photograph, where should you place the film?

If you have just used a pinhole camera to take a photograph of a distant object, do you need to adjust the camera to take a photograph of something much closer? If so, how would you adjust the camera?

In part B, it was noted that in some photographs, certain objects are in focus while other objects are not. Would this be true of a photograph taken by a pinhole camera?

Describe two ways that increasing the size of the hole in a pinhole camera would affect a photograph.

Why might a pinhole camera be more appropriate for taking pictures of stationary objects rather than moving objects?

E. Cameras typically include a *diaphragm* (an aperture or opening of adjustable size). This opening is near the lens between the lens and the film.

What would be the effect on the image of making the aperture larger or smaller?

Experiment 12.5

An eye can be modeled as a convex lens near a detector called the *retina*.

A. Would you expect a retina to detect real and virtual images equally well? If not, would you expect the lens in the eye to form real images or virtual images? Where do you think the images would be located?

B. In order to focus on objects that are at various distances, the focal length of the lens in the eye can change, while the distance between the lens and the retina is relatively unchanged.

How does this situation differ from that for a camera?

If you were to focus on something farther away than the words on this page, would the focal length of your lens increase or decrease? Draw ray diagrams to support your answer.

Estimate the focal length of the lens in your eye when you are viewing a distant object. (Assume the retina is at the back of the eyeball, and assume a reasonable diameter for the eyeball.)

C. Not everyone can focus on distant objects. In a *farsighted* eye, light from distant objects converges too far from the lens; in a *nearsighted* eye, too close.

Obtain a paper screen to represent a retina, a convex lens to represent a lens, and a lighted bulb to represent a distant object. Use these materials to illustrate a normal eye viewing a distant object.

Change your arrangement to illustrate: (1) a farsighted eye viewing a distant object and (2) a nearsighted eye viewing a distant object.

D. Do you think you would be able to correct farsightedness using glasses made from a convex lens? Test your answer by using the equipment from part C and a second convex lens.

Do you think you would be able to correct farsightedness using glasses made from a concave lens? Test your answer by using the equipment from part C and a concave lens.

E. Repeat part D, attempting to correct nearsightedness.

F. Describe an experiment you could perform to determine whether a pair of eyeglasses corrects for farsightedness or nearsightedness. If you or your partner wears eyeglasses, test your experiment.

Experiment 12.6

In this experiment, we construct a simple *telescope,* a device to magnify an object that is far from you.

A. Use a convex lens to form an image of a distant object, such as a window or lighted bulb.

Is the image erect or inverted? Is the image real or virtual?

B. Place a thin paper screen behind the lens so that an image of the object appears on the screen. Obtain a second convex lens with a smaller focal length than the first. Use the second lens as a magnifying glass to examine the back of the screen.

Remove the screen while you are looking at the image on the screen. Describe your observations.

Is the image that you see real or virtual? Is it erect or inverted?

In simple terms, what is the purpose of the second lens?

In simple terms, what is the purpose of the first lens?

C. Draw a ray diagram that illustrates the use of the two lenses as a telescope. Your diagram must include both lenses, however, you may find it easier to consider the lenses and images one at a time.

What would be one disadvantage of replacing the first lens by a lens with the same focal length, but with a smaller diameter?

Experiment 12.7

In this experiment, we construct a simple *microscope,* a device to magnify an object that is close to you.

A. How would you use two convex lenses to make a *microscope?*

Use two lenses of short focal length to construct such a device.

In simple terms, what is the purpose of each lens?

B. Draw a ray diagram that illustrates the use of the two lenses as a microscope. Your diagram must include both lenses, however, you may find it easier to consider the lenses and images one at a time.

✔ Discuss the preceding two experiments with a staff member.

Experiment 12.8

Obtain a plane mirror, a convex mirror, and a concave mirror. If needed, partially cover the mirrors so all three mirrored surfaces are the same size.

One at a time, place each mirror close to a small lighted bulb. Move the bulb toward and away from each mirror and record your observations.

Which mirror might be best suited for use in a *headlight?* Explain the important features of your design with words and using a sketch.

Experiment 12.9

Obtain a prism, a beaker of water, and a transparent sphere. Shine a very narrow beam of light through each of these objects onto a sheet of white paper. Record your observations.

A. For each of the materials you are using, does red light bend more than, less than, or the same amount as blue light? Explain how you can tell from your observations.

B. How are your observations of refraction of white light by the prism, water, and transparent sphere similar?

C. Construct a model for the appearance of a rainbow. (*Hints:* Have you seen a *rainbow* in the sky on (1) a sunny day, (2) a cloudy day, and (3) a rainy day? When you see a rainbow, what is the light source? What are the refracting objects?)

Exercise 12.10

In the preceding experiment you considered how the index of refraction of a material depends on the color of the incident light. In this exercise, we consider how this behavior affects the ability of a lens to focus light.

A. Consider an object a distance s from a convex lens. Imagine that the object is first illuminated by red light, and then by blue light.

   Will the image location change? If so, in which case will the image be closer to the lens? Explain your reasoning.

B. Repeat part A, considering a concave mirror instead of a lens.

C. Suppose that the object is now illuminated with white light and again placed in front of the lens.

   Would the image be located at a unique position or would it appear fuzzy? Explain your reasoning.

   This effect is called *chromatic aberration.*

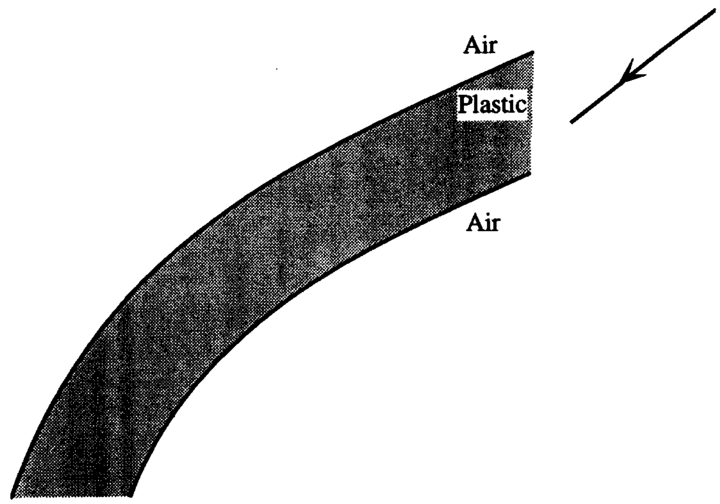
Experiment 12.11

A. Obtain an *optical fiber* (i.e., a long, thin, transparent strand of plastic or glass. Observe both ends of the fiber).

Place one end of the fiber close to a source of light. Keep the fiber straight. Describe the appearance of the other end of the fiber.

Keep one end of the fiber close to the source of light. Bend the fiber and describe the appearance of the other end.

B. To account for your observation that the direction of light appears to change, consider the enlargement of a section of the fiber below.



Continue the light ray that enters the fiber from the right until it reaches the plastic-air interface. Is the light ray reflected, transmitted, or both when it reaches this interface?

Sketch the light ray after it has reached the plastic-air interface and continue the path until the light leaves this section of the fiber.

Use the ideas from your drawing to account for the behavior of light in an optical fiber. Explain your reasoning.

C. This part of the experiment must be performed in a darkened room. Obtain a large funnel, a bright flashlight, a sheet of white paper, and either a sink or a bucket, and some water. Place your hand over the bottom of the funnel and fill the funnel with water. Hold the funnel so that the water will flow out at an angle rather than straight down. Aim the flashlight through the funnel as the water flows out onto a piece of white paper in the sink.

Note where the light beam hits the paper and compare it to where the light beam hits when the funnel is empty.

Use the ideas in part B to explain why the light hits the paper in different locations. Use a drawing in your explanation.

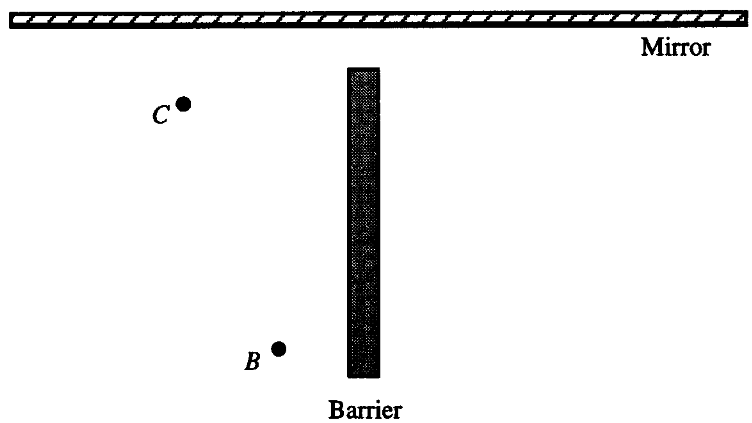
Supplementary problems for *Light and Optics*

Problem 1.1

A barrier is placed in front of, but not touching, a plane mirror. The barrier is perpendicular to the mirror. Suppose you have a flashlight that projects a narrow beam of light. A target is placed successively at positions *A, B,* and *C* on the left side of the barrier.

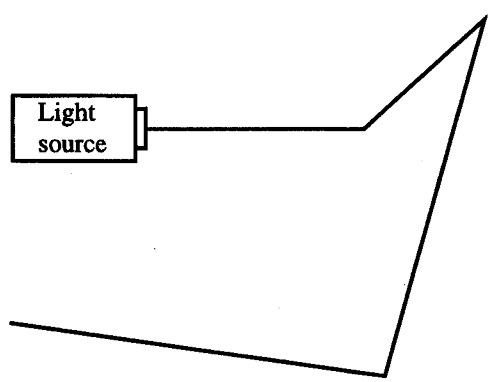
A. For target locations *A* and *B,* indicate a location on the right side of the barrier where the flashlight could be placed in order to hit the target with light. Explain how you determined these locations.

B. For target location *C,* determine the entire *region* on the right side of the barrier in which a flashlight could be placed in order to hit the target with light. Explain how you determined the region.



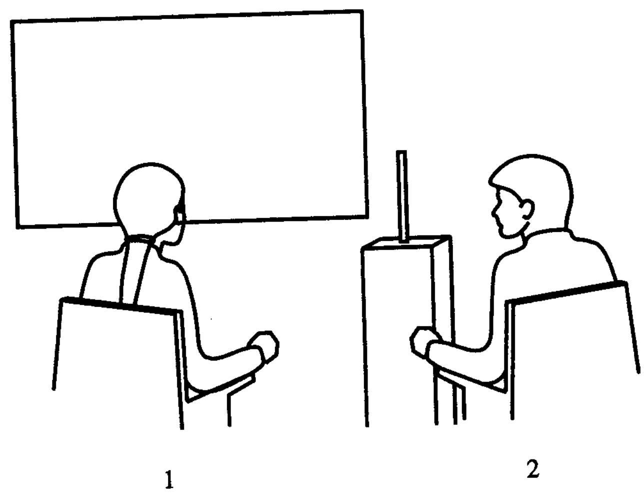
Problem 1.2

After class one day, you find a sheet of paper on the floor with the following drawing on it. Evidently, a student was doing an experiment that used mirrors and a light source, but the student apparently forgot to indicate the locations of the mirrors on the paper. On the diagram, indicate the locations and orientations of the mirrors and explain how you determined the arrangement of the mirrors used by the student.

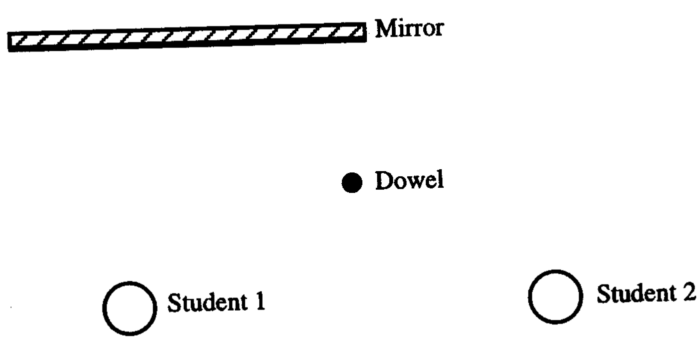


Problem 1.3

Two students are sitting near a wall from which hangs a covered mirror. In front of the mirror is a wooden dowel on a stand.



The diagram below is a top view representation of the situation pictured above.



A. In what order (left to right) will the following appear to student 1: his own image in the mirror, student 2's image, the dowel's image, and the dowel itself? If Student 1 can not see his image, student 2's image or the dowel's image, state that explicitly.

B. In what order (left to right) will the following appear to student 2: her own image in the mirror, student 1's image, the dowel's image, and the dowel itself? If Student 2 can not see her image, student 1's image or the dowel's image, state that explicitly.

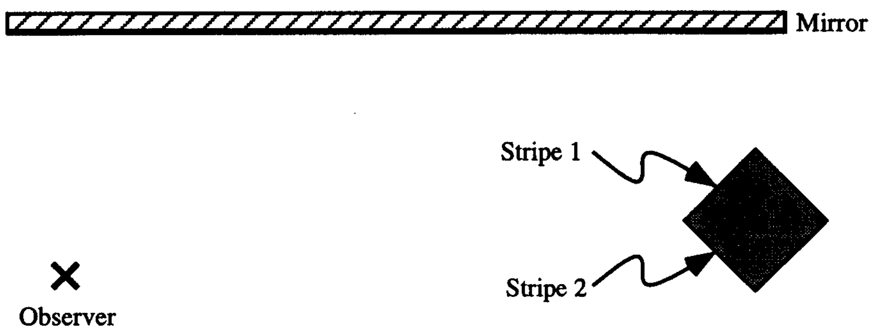
Problem 1.4

An observer and a cube are located in front of a large mirror as shown in the top view diagram below. The cube has a narrow stripe down the middle of two sides.

From the location shown, could the observer see:

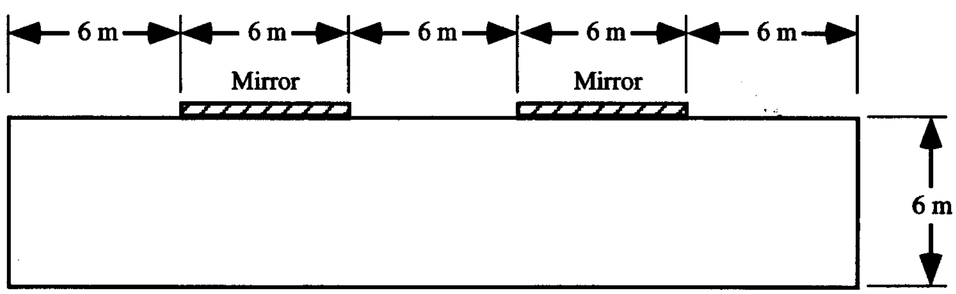
(1) the image in the mirror of stripe 1? Explain.

(2) the image in the mirror of stripe 2? Explain.



Problem 1.5

The ballroom shown below has two large mirrors mounted on the ceiling.



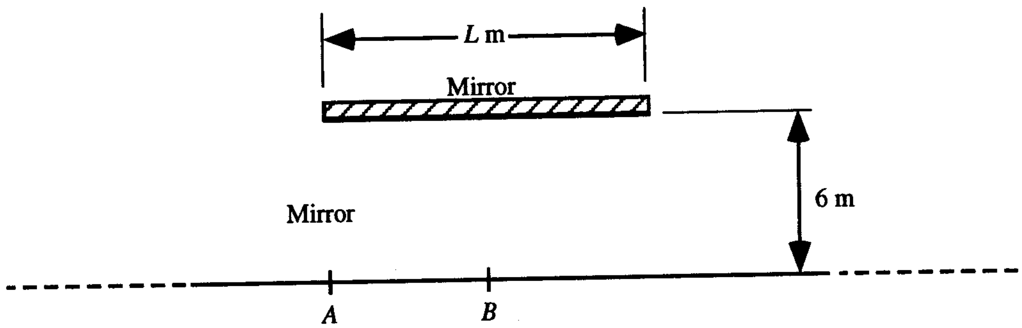
A. In what region of the floor could a small mouse be located so that when it looks at the mirrors it could see another mouse on the floor at either end of the room? Explain your reasoning.

B. Is there anywhere on the floor that a mouse could be located and see the entire ballroom floor in the mirrors? Again, explain your reasoning.

C. Would your answer to part B differ if the ceiling were higher, but the length of the room didn't change? Explain.

Problem 1.6

The line *AB* is parallel to the plane of a mirror. The mirror is 6 meters away from the line and is *L* meters long.



Explain your reasoning in each part of the question below.

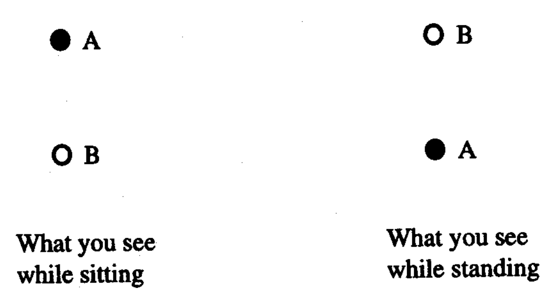
A. A man stands with his eyes at point *A*, directly under one end of the mirror,. How much of the line can he see in the mirror? If the man stands with his eyes at point *B*, under the center of the mirror, how much of the line can he see? In each case, express your answer in terms of *X*.

B. Does the man's location along the line affect how much of the line he is able to see?

C. How, if at all, would your answers to parts A and B differ if the mirror were moved so it is twice as far from the line?

Problem 2.1

When you are sitting in a chair, it appears to you that object A is above object B. When you stand up, object A appears to be below object B. Which of the two objects is farther away from you? Draw a diagram showing the locations of the two objects and your eye, and explain these observations.



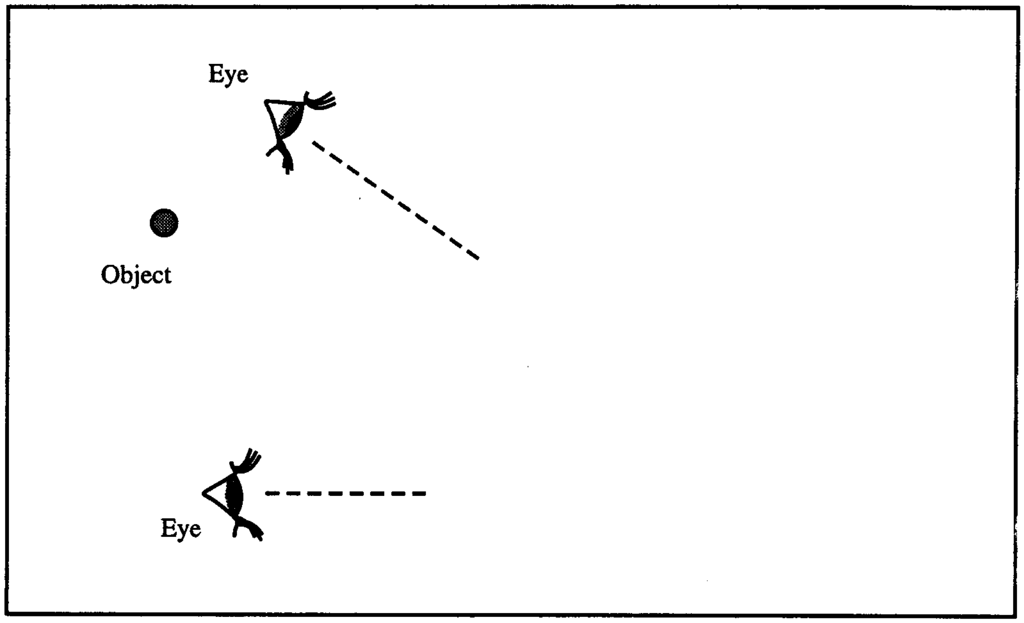
Problem 2.2

In each case below, you are given two lines of sight to the image of an object in a plane mirror. In addition, you are told where the object is.

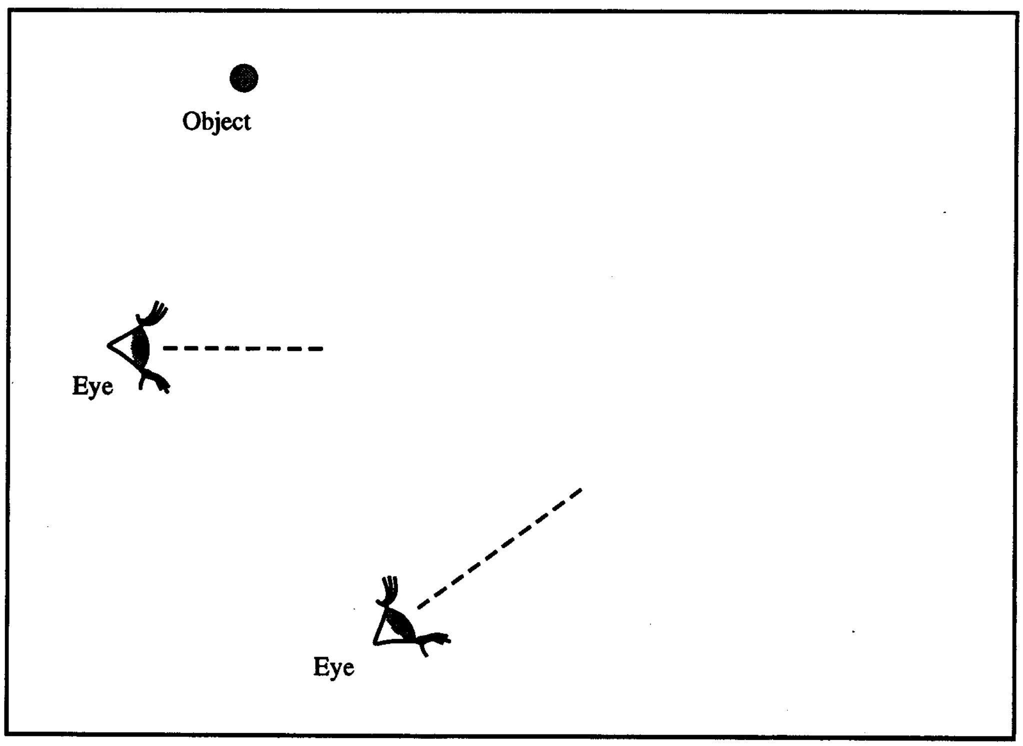
For each case determine whether this situation is possible. If so, draw the location and orientation of the mirror.

Explain how you reached your conclusions.

(1)

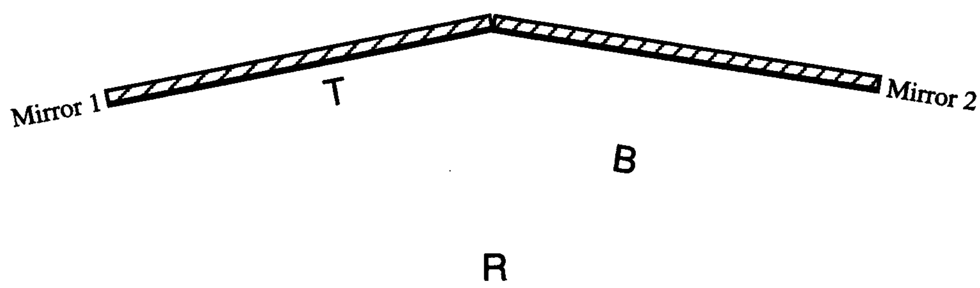


(2)



Problem 3.1

Two mirrors are placed at an angle of 160° as shown.



A. Using parallax, locate and draw the images of the letters *T, R,* and *B.* (Use real mirrors in this part.)

B. Give a detailed explanation of what you see. Identify each image as either a perverted or a non-perverted image. For each image, give the sequence of mirrors on which reflections occur.

C. Show some representative light rays that indicate how two of the images are formed. Pick a pair of rays that form an image after one reflection and another pair that form an image after two reflections (if there are any). You may select any single point on each object as the origin of the rays. Draw the rays carefully so that they clearly satisfy the law of reflection.

D. Is there a region in front of the mirrors that is "special" in terms of the number of images that are possible? If so, describe where that region is and tell why it is special.

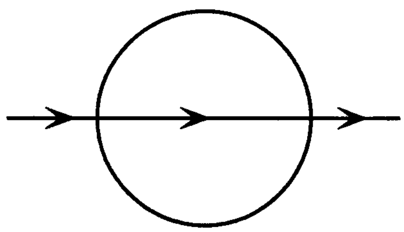
Problem 3.2

Show that for two mirrors at an angle of 90° to each other, a light ray that reflects off of both mirrors follows a path that is parallel to the incident ray.

Problem 4.1

The following are top view diagrams of a beaker of water. Some of the diagrams represent qualitatively correct paths for light through a beaker of water and some do not. Which diagrams have "flaws"? Briefly explain the flaw in each case.

(1)



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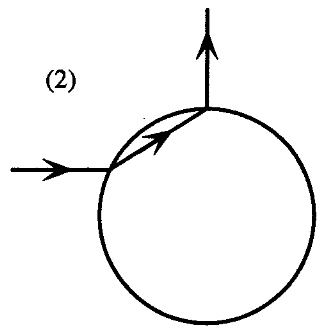
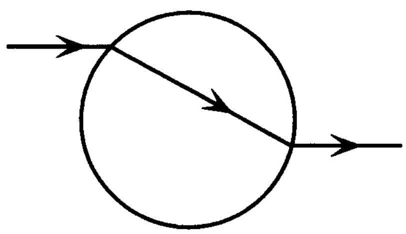


(3)



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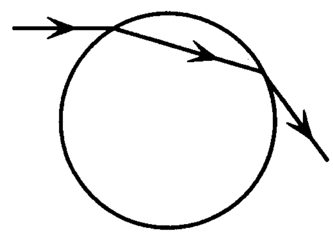

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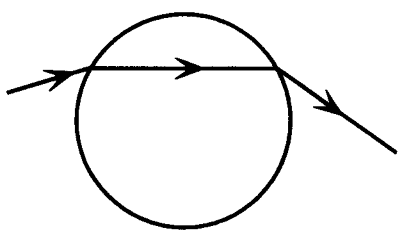
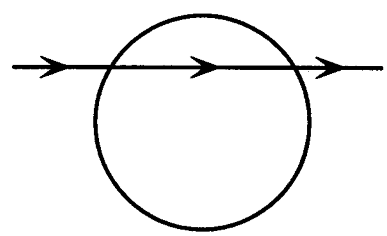


(6)



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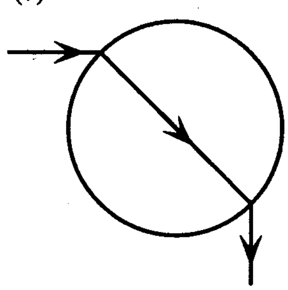

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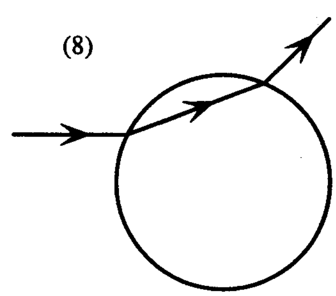
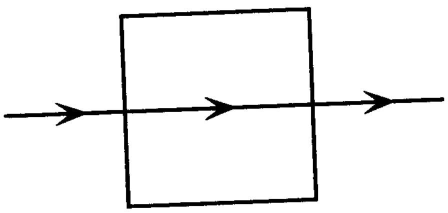


Problem 4.2

The following are top view diagrams of a container of water that has flat sides. Some of the diagrams represent qualitatively correct paths for light through the container of water and some do not. Which diagrams have "flaws"? Briefly explain the flaw in each case.

(1)



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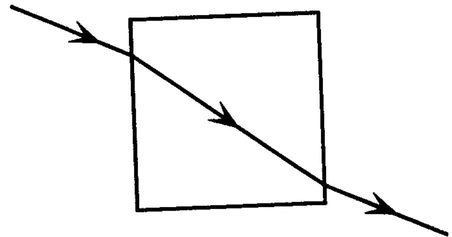

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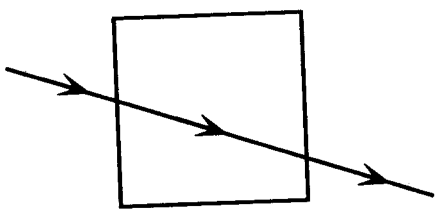

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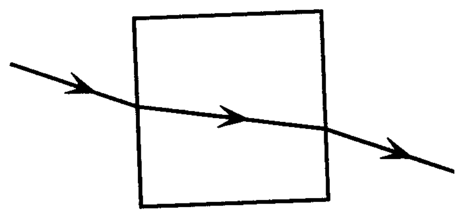

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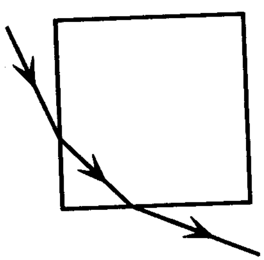

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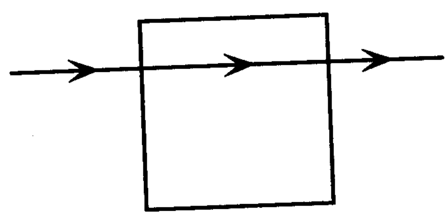

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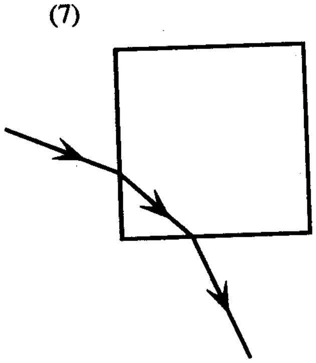

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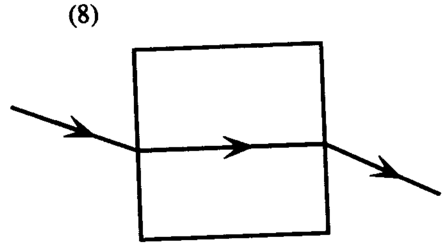


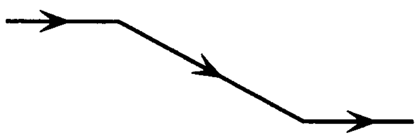
Problem 4.3

After class one day, you find a sheet of paper with the following drawings on it. On the table nearby, there is a light box and several containers of water. There are both round-bottomed beakers and square-bottomed plastic containers, but *no* semi-cylindrical containers. Evidently, a student was doing an experiment that used the containers of water and the light box, but the student apparently forgot to indicate the locations of the containers on the paper.

A. Draw an outline of each of the containers on the diagram for the student. (Your final diagrams should be *qualitatively* correct. You may find it helpful to read part B first.)

B. For each of the container locations that you indicated, can you be certain whether a student was using a container with curved sides or flat sides? Are there any that must be curved? Are there any that must be flat? Are there any that could be either? *If a container could be either type, show both possibilities on the diagram.*

(1)



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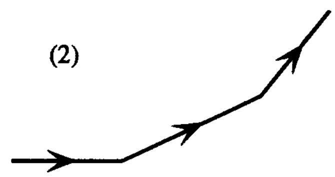

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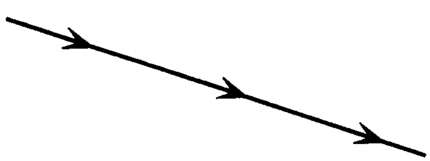

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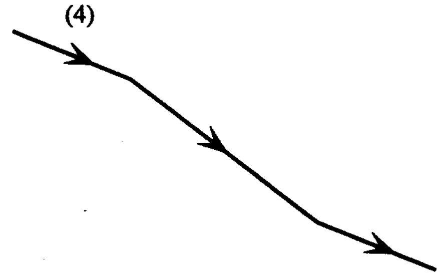

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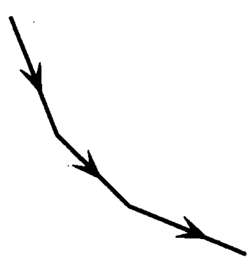

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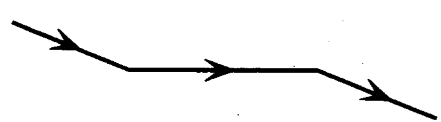
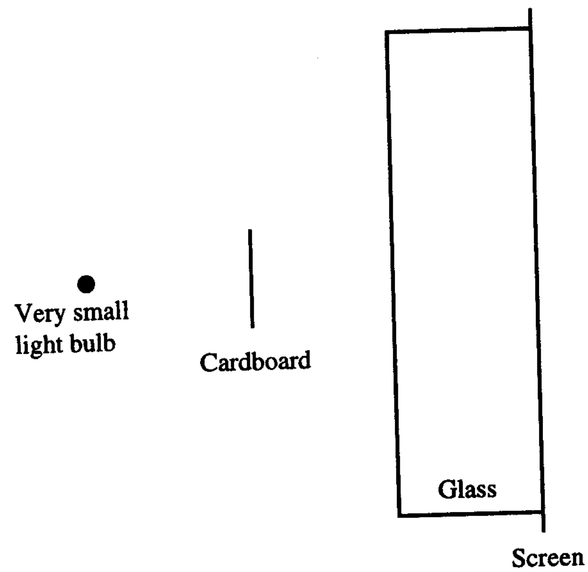


Problem 4.4

A piece of cardboard is placed between a very small light bulb and a screen. A block of glass is placed in front of the screen as shown in the side view diagram at right.

If the glass were *removed,* would the size of the shadow on the screen increase, decrease, or stay the same? Explain your reasoning, and support your answer with a clear, qualitatively correct ray diagram.



Problem 4.5

A. Is it possible to look into a mirror and see your friend's eyes, yet your friend cannot see your eyes? Explain.

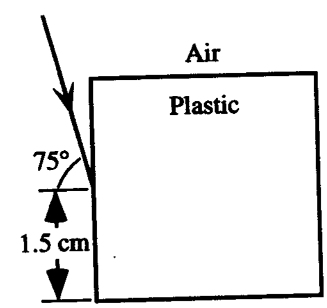
Does it matter if the light strikes several mirrors before reaching your eyes?

Does it matter if the light passes through one or more beakers filled with water?

B. Imagine that you are underwater, and your friend is out of the water. If you can see your friend's eyes, can your friend see your eyes? Explain.

Problem 5.1

A beam of light enters a plastic cube of side 3 cm from the center of the left side as shown in the diagram at right. The angle of incidence is 75°. The index of refraction of the plastic with respect to air is 1.5.

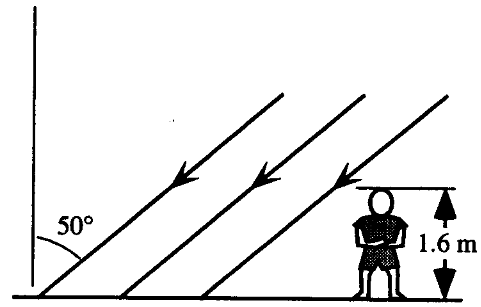


A. From which side of the cube will the ray emerge? Draw a diagram to support your answer.

B. At what angle will the ray emerge?

Problem 5.2

One day, a student determines that light from the sun strikes the ground at an angle of 50° from the vertical. The student is 1.6 m tall.



A. What is the length of the student's shadow? Explain.

B. The student then goes completely underwater on the bottom of the deep end of a large swimming pool. The surface of the pool is still and the bottom of the pool is level. What is the length of the student's shadow? Show your work.

Problem 5.3

Secure a water-resistant watch to your wrist and place in a sink of water so that the face of the watch is toward your eyes. Move your wrist so that the watch slowly rotates away from your face.

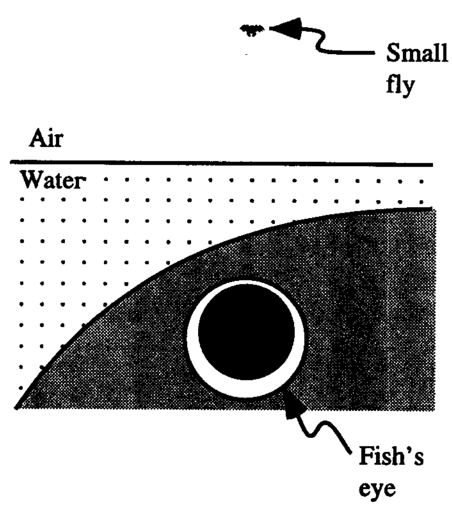
Is there an angle past which you can continue to see the face of the watch but you can no longer see the hands (or the digital display) of the watch?

How can you account for your observation? Draw a diagram to show the path of light rays from the hands (or the digital display) of the watch through the flat transparent face, through the water, to your eyes. How does your diagram change as the watch is rotated?

Is the index of refraction of the transparent face plate of the watch greater than, less than, or equal to that of water? Explain.

Problem 6.1

A hungry fish in a tank of water notices a small fly that is located directly above the fish's eye as shown at right. Draw a clear, qualitatively correct ray diagram that shows the apparent location of the fly *as seen by the fish* (i.e., the image location of the fly).

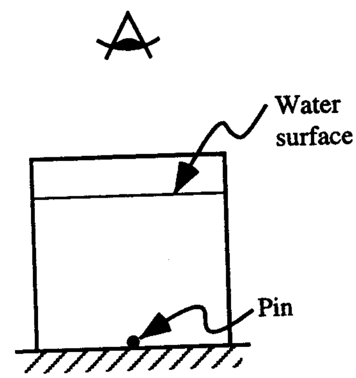


Problem 6.2

On an extended backpacking trip, you find that a bridge across a river has been washed out during a flash flood. The only way back to civilization is to wade across the river. How well can you judge depth of the river visually? Will you get wetter than you expect, not as wet as you might expect, or can you judge the depth of the river perfectly? Explain your reasoning and draw a ray diagram that supports your answer.

Problem 6.3

An observer is looking at a pin at the bottom of a container of water as shown in the side view diagram at right. Draw an *accurate* ray diagram to determine where the pin appears to be located to the observer (i.e., the image location). Use a protractor and a straightedge in drawing your diagram. Use the value that you determined for the index of refraction of water relative to air.



Side view

Problem 7.1

You have two convex lenses: one with focal length f and one with focal length $10f$. Which lens would you say is "stronger"? Explain your reasoning.

Problem 7.2

What are two simple ways you could use to estimate the focal length of a lens? Explain your reasoning.

Problem 7.3

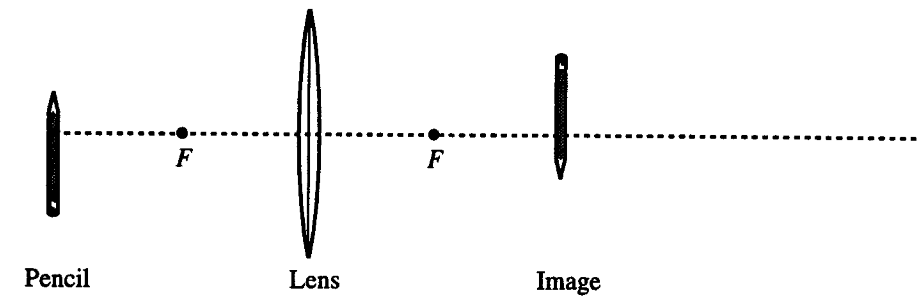
In Experiment 7.4, you observed that when a screen was placed at the image location, an image was formed on the screen. However, when the screen was moved toward or away from the lens, the image quickly disappeared.

A. Discuss how an image was formed on the screen when it was held at the image location. Include a ray diagram in your discussion.

B. Explain, both in words and with a ray diagram, the change in the image as the screen was moved.

Problem 8.1

A pencil is placed a distance $2f$ to the left of a convex lens, where f is the focal length of the lens. A student has found that the image is located $2f$ to the right of the lens, as shown in the scale diagram below.

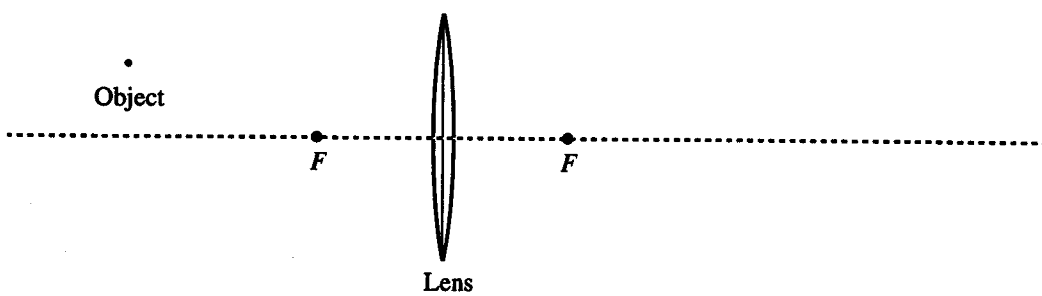


A. Determine the region where an observer's eye must be located in order to see the *entire* image of the pencil. Clearly label this region on your diagram.

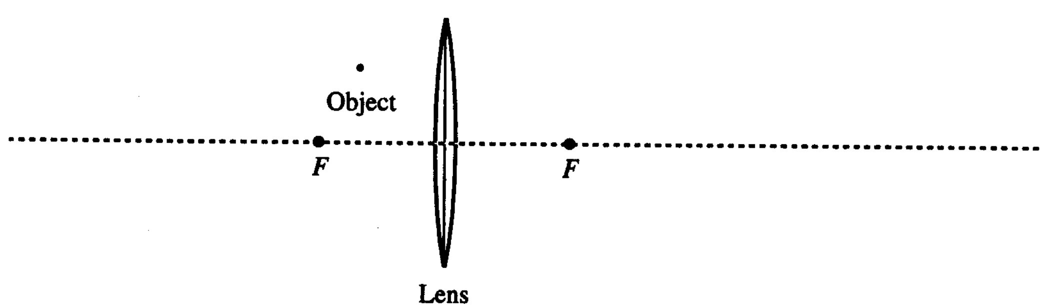
B. For an observer who can see the entire image, does the image *appear* longer than, shorter than, or the same length as the pencil would without the lens? Explain.

Problem 8.2

A. A small object is placed in front of a convex lens as shown below. Draw an accurate ray diagram using all principal rays to determine the location of the image. Explain how you determined the image location. Label each of the rays, and in words, explain how you decided to draw each ray in the way that you did.



B. Repeat part A for the object closer to the lens as shown below.



Problem 9.1

An object is placed in front of a convex lens. The focal length of the lens is 20 cm.

A. Suppose the object is 60 cm from the lens.

On a sheet of graph paper, draw a ray diagram to find the location of the image.

Use the thin lens equation to calculate the location of the image. Is your answer consistent with your ray diagram? If not, resolve any discrepancies

Is the image real or virtual? Explain.

B. Suppose the object is 10 cm from the lens.

On a sheet of graph paper, draw a ray diagram to find the location of the image.

Use the lens equation to calculate the location of the image. Is your answer consistent with your ray diagram? If not, resolve any discrepancies

Is the image real or virtual? Explain.

Problem 9.2

A light bulb is 100 cm from a screen. Suppose you have a convex lens with a focal length of 21 cm. At what location(s) between the bulb and the screen could you place the lens such that the image of the bulb would be on the screen? Show your work.

Problem 9.3

A student walks into a room and sees a lighted bulb 45 cm in front of a convex lens. He notices that there is a screen 90 cm from the lens with an image of the bulb on the screen.

A. Are the bulb and the screen on the same side or of the lens or on opposite sides of the lens? Explain.

B. Determine the value of the focal length of the lens.

C. Suppose the screen were moved 20 cm farther from the lens. Would you be able to position the bulb so that you could see a clear image of the bulb on the screen? If so, where? If not, why not? Explain.

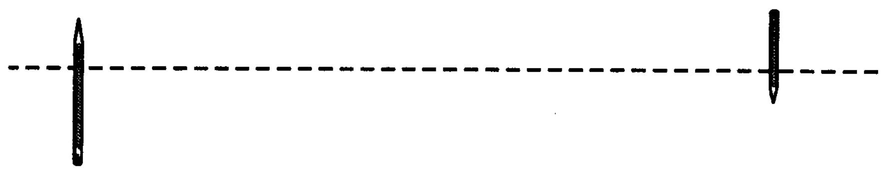
D. Suppose that instead the screen were moved 70 cm closer to the lens than its original position. Would you be able to position the bulb so that you could see a clear image of the bulb on the screen? If so, where? If not, why not? Explain.

Problem 9.4

In Exercise 9.6, you determined an expression for the magnification of a real inverted image formed by a convex lens. Does this expression hold for virtual images as well? If not, what is the expression in this case? Explain your reasoning, and support your answer with a ray diagram.

Problem 9.5

A convex lens is used to create a real image of a pencil. The locations of the pencil and its image are shown below. The lens, however, is not shown.

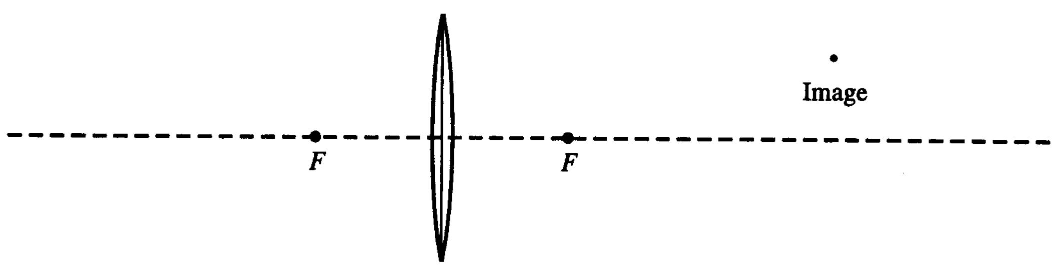


A. Where is the lens located? Explain how you determined your answer.

B. Where are the focal points of the lens located? Explain how you determined your answer.

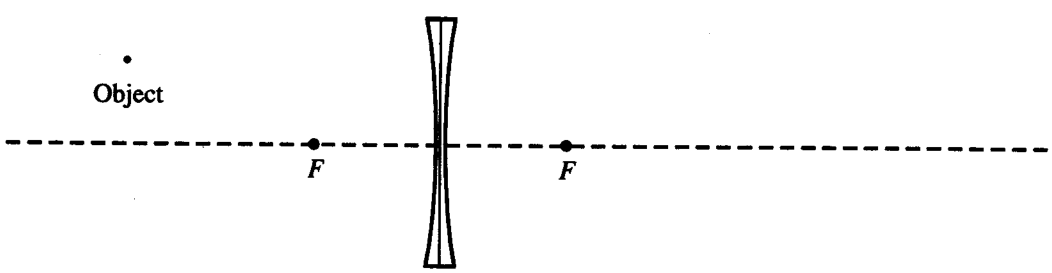
Problem 9.6

A convex lens is used to create a real image of a small object. The diagram below shows the locations of the lens, its focal points, and the image. Determine the location of the object. Explain how you determined your answer. Treat the object as a point source of light.



Problem 10.1

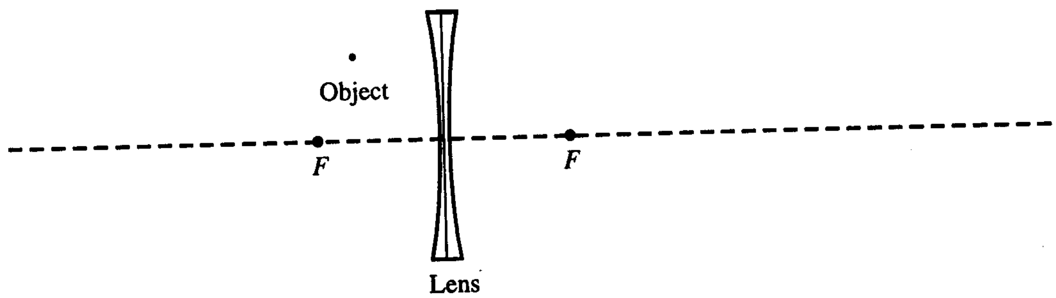
A. A small object is placed in front of a concave lens as shown below. Draw an accurate ray diagram to determine the location of the image. Label each of the rays, and in words, explain how you decided to draw each ray in the way that you did. Treat the object as a point source of light.



B. Repeat part A assuming the lens is replaced by a convex lens with the same magnitude focal length.

Problem 10.2

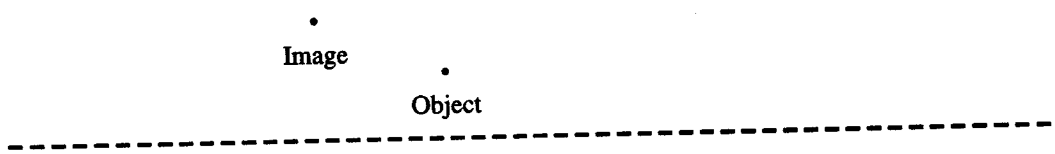
A. A small object is placed in front of a concave lens as shown below. Draw an accurate ray diagram to determine the location of the image. Label each of the rays, and in words, explain how you decided to draw each ray in the way that you did. Treat the object as a point source of light.



B. Repeat part A assuming the lens is replaced by a convex lens with the same magnitude focal length.

Problem 10.3

A. The diagram below shows a small object and its image, which is virtual. The principal axis of the lens is shown, however the lens is not. Treat the object as a point source of light.

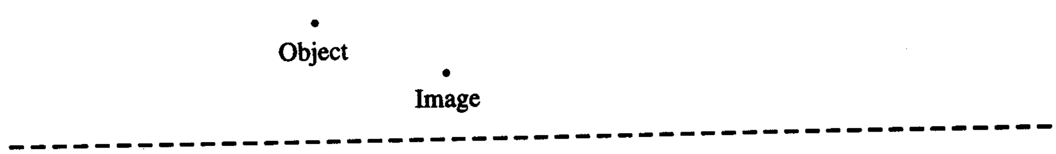


Is this situation possible?

If so: Is the lens concave, convex, or is either type possible? Determine the locations of the lens and its focal points. Explain how you determined your answers.

If not: Explain why not.

B. Suppose the object and image locations from part A were reversed.



Is this situation possible?

If so: Is the lens concave, convex, or is either type possible? Determine the locations of the lens and its focal points. Explain how you determined your answers.

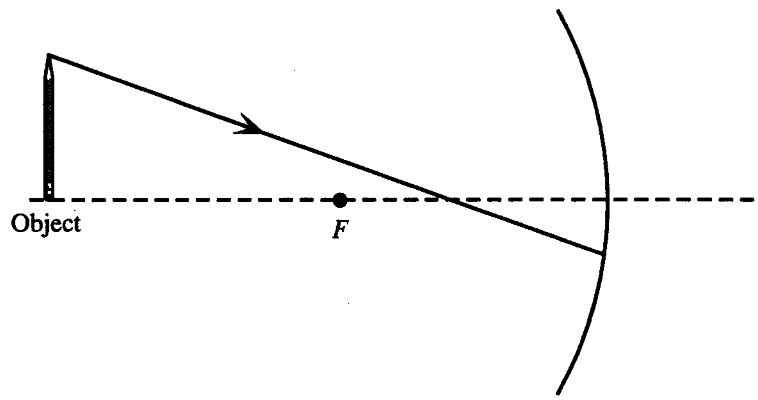
If not: Explain why not.

Problem 10.4

In Exercise 9.6, you determined an expression for the magnification of a real inverted image formed by a convex lens in terms of the object and image distances. Does this expression hold for images formed by concave lenses as well? If not, what is the expression in this case? Explain your reasoning, and support your answer with a ray diagram.

Problem 11.1

Consider the ray drawn incident on the mirror in the diagram below. Determine the continuation of the ray. Explain your reasoning.



Problem 11.2

A mirror placed to the right of a pencil is used to create a virtual image of it. The locations of the pencil and its image are shown below. The mirror, however, is not shown.

A. Is the mirror plane, convex, or concave? Explain how you determined your answer.

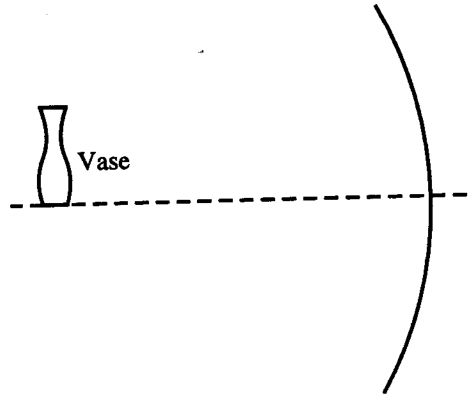
B. Where is the mirror located? Explain how you determined your answer.

Problem 11.3

In Exercise 9.6, you determined an expression for the magnification of a real inverted image formed by a convex lens in terms of the object and image distances. Does this expression hold for images formed by curved mirrors as well? If not, what is the expression in this case? Explain your reasoning, and support your answer with a ray diagram.

Problem 11.4

A flower and an empty vase are placed in front of a concave mirror. The flower is not shown in the diagram at right.



A. Where should the flower and the vase be placed so that the image of the flower is same size as the actual flower *and* the image of the flower is located in the actual vase as seen by an observer on the principal axis of the mirror? Draw a ray diagram to support your answer.

B. Determine the image and object distances in terms of the focal length of the mirror.

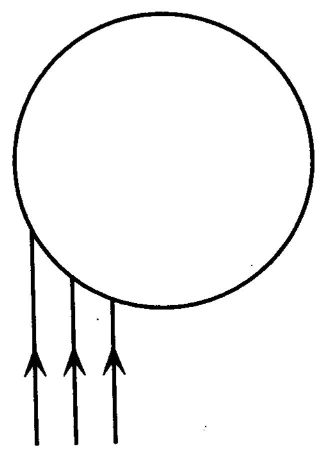
Problem 12.1

You have observed that if the angle of incidence of a beam of light striking a mirror takes on a very special value (i.e., zero), the beam is reflected so that it reverses its original direction. However this is only true for this one particular direction of the incident light.

It is possible to use several plane mirrors to design a *reflector,* a device that reverses the direction of any beam of light that strikes it—independent of the relative orientation of beam and reflector. Make a sketch of the reflector and draw ray diagrams to illustrate how it works. (*Hint:* This instrument is sometimes called a corner reflector.)

Problem 12.2

Consider a parallel beam of light of a given color striking a spherical water droplet as illustrated in the cross-sectional top view diagram at right. The index of refraction of water with respect to air is 1.33 for that color.



A. Continue each of the rays shown through and out of the droplet. Use a ruler and a protractor to draw an accurate diagram.

B. Suppose a student were looking at the droplet and the light source was behind her. Would she be able to see any of the emerging rays? Explain.

C. What would you expect the relative orientation of an observer, the sun, and rain drops to be during the appearance of a rainbow? Check your answer the next time you see a rainbow.