SECTION 9

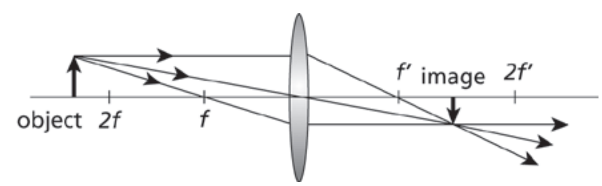
Effect of Lenses on Light

Section Overview

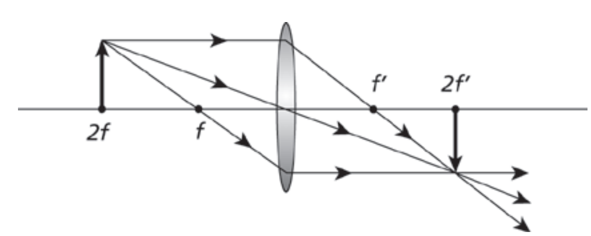
Students observe the real image made by a convex lens and how its size and position change as the object distance changes. They point a convex lens at a distant object and describe the image projected by the lens on a screen. They measure and record the object and image distance and note that the image distance is nearly equal to the focal length. Students then explore images of a light bulb on a screen, formed by the convex lens mounted at the same height as a light bulb. They record the image appearance (size and orientation), distance from the lens to the screen, and the object distance in a table. Students cut an arrow-shaped hole in a card and project the arrow's image on a screen. An arrow is also marked on a transparent sheet of plastic and then projected on a wall to illustrate how large images may be formed. The variations in the size of projected images helps students to prepare for their light show, and understand how a lens is able to project a sharp image of an object on a screen by focusing it at a distance close to the focal length of the lens.

Background Information

A light bulb sends out light in all directions. If a few of these rays pass through a convex lens (and if the light bulb is outside the focal point of the lens), the lens bends light to make a real image. One ray enters the lens parallel to its axis, so this ray is refracted through the focus (focal point, *F*). The focal point is also the position of the image if the object is extremely distant. The other ray goes through the center of the lens. If the lens is thin, this ray maintains its original direction, since the front and back of the lens are parallel right at the center. Where these two rays meet is the location of the image of the arrowhead. The image is upside down. Also, the image is smaller than the object and is located between *f* and 2*f* (*f* is the focal length) from the lens. The object is beyond 2*f*.



Notice that the object and image could be interchanged, without changing the ray diagram. When the object is close to the lens, the image is far away and larger than the object. When the image is close to the lens, the object is far away and larger than the image. The object and image can be equidistant from the lens, when each is located at 2*f*, as in the diagram below. In this symmetrical arrangement, the object is the same size as the image.



Crucial Physics

- A convex lens can produce a real image.
- For incident rays parallel to the axis of a convex lens, the rays will converge on the other side of the lens at the focal point. The distance between the (center of the) lens and the focal point is the focal length of the lens.
- The focal length, image distance, and object distance for a lens are related by

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}.$$

Learning Outcomes	Location in the Section	Evidence of Understanding
Observe real images formed by a convex lens.	***Investigate*** Step 2	Students observe images on a file card when they point a convex lens at a window or at another distant object.
Project a slide using a lens.	***Investigate*** Step 9	Students create a small slide and project it at different positions between the light bulb and screen.
Relate image size and position to object size and position and the properties of your lens.	***Investigate*** Steps 6–9 ***Physics Talk***	Students collect data to relate image size and position size to object size and position using a convex lens. Students read how real and virtual images are formed in relation to size and distance of the object using a convex lens.

Section 9 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks	1 per group	
Scissors	1 per group	
Light bulb socket with switch and 40W bulb	1 per group	
Posterboard, 11″ x 14″, white screen	1 per group	
Convex lens 10 cm focal point	1 per group	
Convex lens 20 cm focal point	1 per group	
Light source for optical bench with battery holder	1 per group	
Optical bench apparatus	1 per group	
Overhead transparencies	1 per group	
Wood block to raise light source	3 per group	
AA alkaline battery	1 per group	
Card, unlined index, 3″ x 5″ pkg 100		1 per class
Access to an electrical outlet*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and one-half periods or 65 minutes for students to complete the *Investigate* portion of this section.

Teacher Preparation

- Assemble the required material.
- Darken the room as much as possible so students can see the images easily. Using additional curtains, if available, to darken the room is helpful.
- Have students set up their equipment at right angles to one another to minimize the effect of a neighboring light source on their equipment.
- If you use 110-V light bulbs, be sure there are no exposed wires. Use the kind of sockets that have the wiring connections inside a plastic or ceramic cover. If the socket is ceramic, then the connections are probably exposed underneath. Screw each ceramic socket down to a piece of wood, so the wiring is safely out of reach.
- If the room has no windows, determine the focal length of the lenses beforehand.

Safety Requirements

- Review light bulb safety from *Section 5*.
- Do not use lenses with chipped edges.
- Students should not use the Sun to find the focal length of the lens. The focal spot is very bright and should not be stared at for an extended period.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks		1 per class
Scissors		1 per class
Light bulb socket with switch and 40W bulb		1 per class
Posterboard, 11″ x 14″, white screen		1 per class
Convex lens 10 cm focal point		1 per class
Convex lens 20 cm focal point		1 per class
Light source for optical bench with battery holder		1 per class
Optical bench apparatus		1 per class
Overhead transparencies		1 per class
Wood block to raise light source		1 per class
AA alkaline battery		1 per class
Card, unlined index, 3″ x 5″ pkg 100		1 per class
Access to an electrical outlet*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow one class period or 45 minutes to complete the *Investigate* portion of this section as a whole-class investigation.

Teacher Preparation

- Note the teacher preparation for *Plan A*.
- If a large lens is available, use this in place of the student lenses. Large lenses may be available from old overhead projectors. These lenses typically have long focal lengths. Test out the available equipment to see if it can accommodate a lens of this size.
- Have the equipment set up in a position easily seen by the class.
- Prepare a transparency of a sample data table for students to record in their logs, and to record the data taken during the *Investigate*. A student volunteer recording the data on transparency on an overhead projector is suggested.

Safety Requirements

- Review light bulb safety from *Section 5*.
- Do not use lenses with chipped edges.
- Do not use the Sun to find the focal length of the lens. The focal spot is very bright and should not be stared at for an extended period.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Learning a new concept from inquiry	***Investigate***	**Augmentation** • This high-interest investigation may be very motivating for students who often exhibit behavior issues during class. However, these same students often have reading comprehension and focus issues that make it difficult to follow a series of written directions. In small groups or as one large group, ask students to read the *Physics Essential Questions* prior to completing this *Investigate.* This may help students become engaged in the investigation. • Ask students to create a list of questions they may have about lenses and what they already know. This information could be used to guide their inquiry and possibly modify the *Investigate.* • Divide this investigation into organized stations through which students can rotate to complete each of the tasks. (Station 1: *Steps, 1-3*. Station 2: *Steps, 4-6*. Station 3: *Steps, 7-9*.) Debrief the main points of the first nine steps as a large group. Then students could work in groups of two or three to complete *Steps 10-12*, with more independence.
Creating a table without a model	***Investigate*** Steps 5 and 6	**Augmentation** • Students should be prompted to create the data table before they begin completing trials. Ask students to create a table based on the description in *Steps 5* and *6*. Then give them five minutes to complete this task. Circulate to make sure that students are creating tables that can be used to record the necessary data. • Some students may still need to be prompted with directions or a model to create a data table. This table requires three columns and at least 5 rows. The appearance/size description column needs to be wider than the other two columns. • Teach students how to independently figure out the number of rows and columns to include in their tables. **Accommodation** • Provide students with a blank table to tape into their logs and complete.
Conceptualizing images formed by lenses in real-life objects	***Physics Talk***	**Augmentation** • Provide students with opportunities to look at objects using binoculars, microscopes, magnifying glasses, telescopes, cameras, and so on. Ask them to write descriptions of the images they view with these real-life lenses. This common experience could anchor all the lens investigations in this chapter. • Show students examples of the same object viewed through a microscope, a camera, a projector, and so on. Ask students to describe the differences they notice in the images.
Differentiating real and virtual images	***Physics Talk*** ***Checking Up*** Question 3	**Augmentation** • Students with reading comprehension and executive-function issues may struggle to synthesize information from inquiry-based investigations. Provide direct instruction to teach the properties of real and virtual images. • Ask students to work with a partner and create a two-column list of the properties for both real and virtual images.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension	***Investigate*** Steps 4 and 5	Check students' understanding of the words "qualitatively" and "quantitatively." They should know that how sharp or fuzzy the image is, for example, is a qualitative description of the image. Quantitative, by contrast, describes characteristics that can be measured, such as the size of the image, or its distance from the lens.
Comprehension	***Investigate*** Step 4	Look at students' drawings to check for proper arrangements of lens, light source, and screen for each image (smaller than, same size as, and larger than light source).
Comprehension	***Investigate*** Steps 5 and 6	Check that image size and distance are correctly recorded for the object distance, and that images are correctly recorded as upside-down or right-side-up for the arrangement. Ask students if they notice a relationship between image size and object size. Also ask students to record any patterns relating object distance, image distance, and image size. Encourage them to give explanations in their own words.
Comprehension	***Investigate*** Step 10	Check students' *Active Physics* logs for correct representation of the directions given in *Step 10*.
Understanding equations	***Investigate*** Step 12	The mathematical relationship $1/f = 1/d_o + 1/d_i$ applies to lenses as well as to mirrors. Be sure students remember and can state the relationship in words: The inverse of the focal length for a lens equals the inverse of the object distance plus the inverse of the image distance.
Comprehension	***Physics Talk***	Be sure students are able to set up conditions that produce no image and conditions that produce an upright, virtual image.
Using mnemonics	***Physics Talk*** ***Physics Words***	Rays that pass through a convex lens (a lens thicker in the middle) converge on the far side of the lens. Help students remember this by having them focus on the "v": Rays conVerge when they pass through a conVex lens.
Comprehension	***Active Physics Plus***	Collaborate with students' math teachers to determine what level of comprehension students have with geometry, including interpreting and working with ray and angle diagrams, and algebra.
Comprehension	***What Do You Think Now?***	Hold a class discussion about the question, "How is a lens able to project movies or take photographs?" Encourage ELL students to participate orally in the discussion, and be sure all students know what they need to know to proceed with the *Chapter Challenge*.

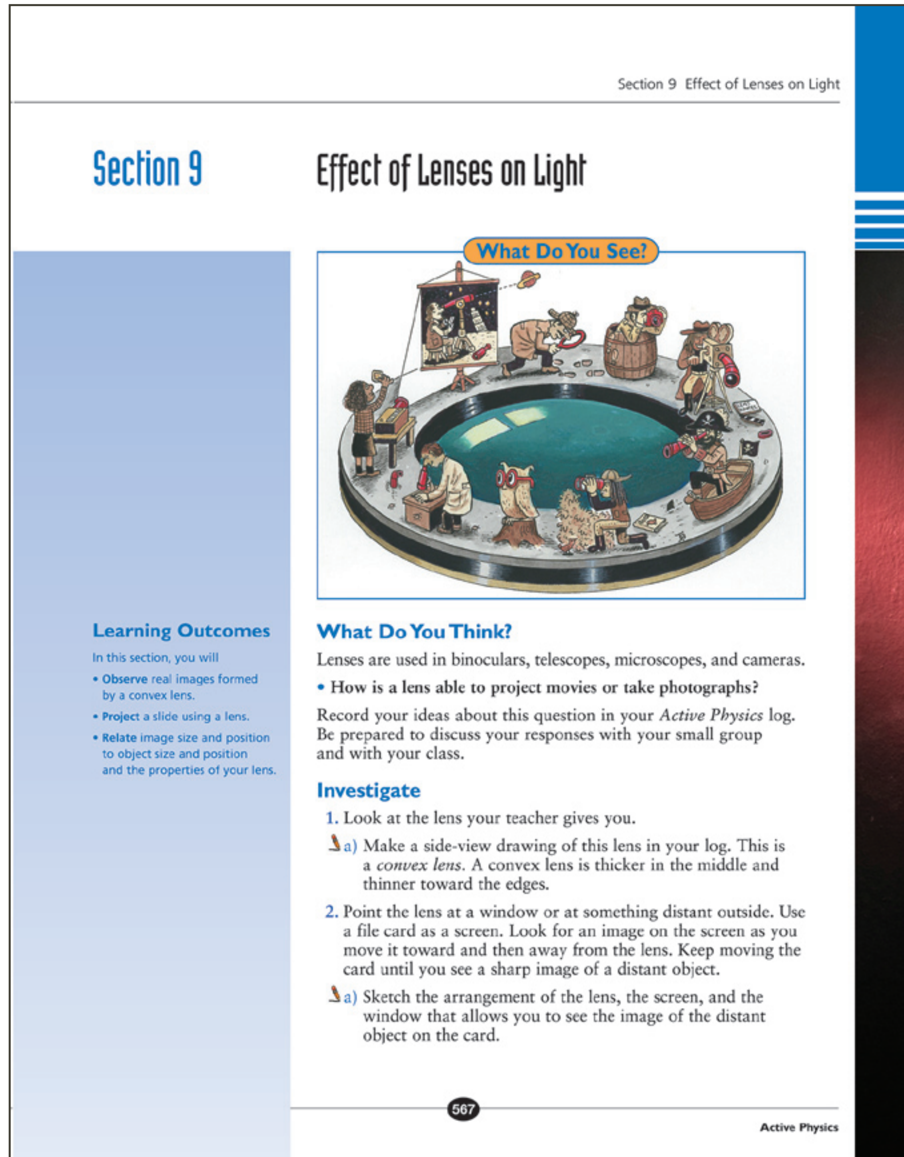
CHAPTER 5

SECTION 9

Teaching Suggestions and Sample Answers

What Do You See?

The *What Do You See?* illustration renders an array of images. Students are presented with a range of possibilities that relate to lenses. Use a color overhead of the illustration to focus on each aspect of the illustration. Direct students attention to the artists' intention of showing lenses being used in different ways. Ask them to notice the connection between this illustration and the *What Do You Think?* question. Elicit their responses and try to determine what students already know about lenses. Regardless of whether their responses demonstrate an understanding, encourage them to participate freely in a discussion.



Section 9 Effect of Lenses on Light

Section 9 Effect of Lenses on Light

What Do You See?

Learning Outcomes

In this section, you will

- **Observe** real images formed by a convex lens.
- **Project** a slide using a lens.
- **Relate** image size and position to object size and position and the properties of your lens.

What Do You Think?

Lenses are used in binoculars, telescopes, microscopes, and cameras.

- **How is a lens able to project movies or take photographs?**

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and with your class.

Investigate

1. Look at the lens your teacher gives you.
   a) Make a side-view drawing of this lens in your log. This is a *convex lens*. A convex lens is thicker in the middle and thinner toward the edges.
2. Point the lens at a window or at something distant outside. Use a file card as a screen. Look for an image on the screen as you move it toward and then away from the lens. Keep moving the card until you see a sharp image of a distant object.
   a) Sketch the arrangement of the lens, the screen, and the window that allows you to see the image of the distant object on the card.

567

Active Physics

Students' Prior Conceptions

This section allows the student to revisit models. They observe how light behaves and extend their understanding to how light interacts with the surfaces of lenses. They also observe how light refracts as it passes through the lens to form real and virtual images. Their predictions may be more in tune with scientific explanations for this section, now that they have experienced a scientific model of refraction. Students can make predictions about what they think, and evaluate their prior conceptions to elaborate on what they have learned. They should ask, "Why should I care?" not only because they may choose to use *Inputs* from this section in their design of their sound and light show, but also because their model for ray optics and the effect of lenses influences their daily lives on a continuous basis.

1. **Students believe that the focal point of a lens is the location of clearly formed images.** This prior conception is connected to the alternative ideas students hold on the formation of clearly defined images with curved mirrors. Students do not believe that the focal point is defined by the geometry of the lens as with the geometry of the curved mirrors. Model building and ray diagrams enable students to see that the focal point is not the same thing as the locations of various clearly defined images.
2. **Students do not believe that the distance between the lens and the screen affects the sharpness of the image because they hold the previous prior conception to be true.** Students are confused by the fact that the image can be located in space and clearly defined without being "on" the

What Do You Think?

Many students may have cell phones with the ability to take pictures. Ask them whether they know what is needed to take the photographs, or if they have information on the lenses used in cell phones. Encourage students to draw ray diagrams as they answer the question in this section. The diagrams will help them focus and generate meaningful responses. Tell your students that all relevant answers will be accepted at this stage. Have a discussion with the whole class or divide them into groups so that ideas can be shared to generate a stimulating discussion. Consider asking students to think of any equipment with lenses they might have used and how they were able to get a better focus of what they were trying to project or see through a lens.

What Do You Think?

A Physicist's Response

The lens does all these things by bending light, a process called refraction. Without refraction, cameras could take only pinhole images with light coming through only a tiny opening. The images would be very dim. But by bending light, the lens can direct all the light that strikes the lens onto the proper place in the image, so the light opening is larger and the image is far brighter than a pinhole image.

To make a real image, a lens must be convex. If you make a ray diagram of a light beam passing through a convex lens, you will see that the light bends toward the lens axis as it enters the glass and then again toward the axis as it leaves the glass. The result is that the ray can be part of an image, which is located near the axis.

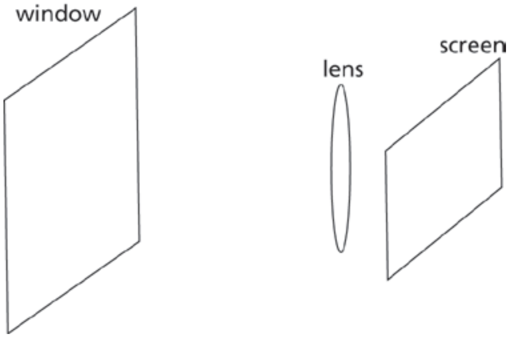
Investigate

1.a)

Students' drawings should look like the one below.

2.a)

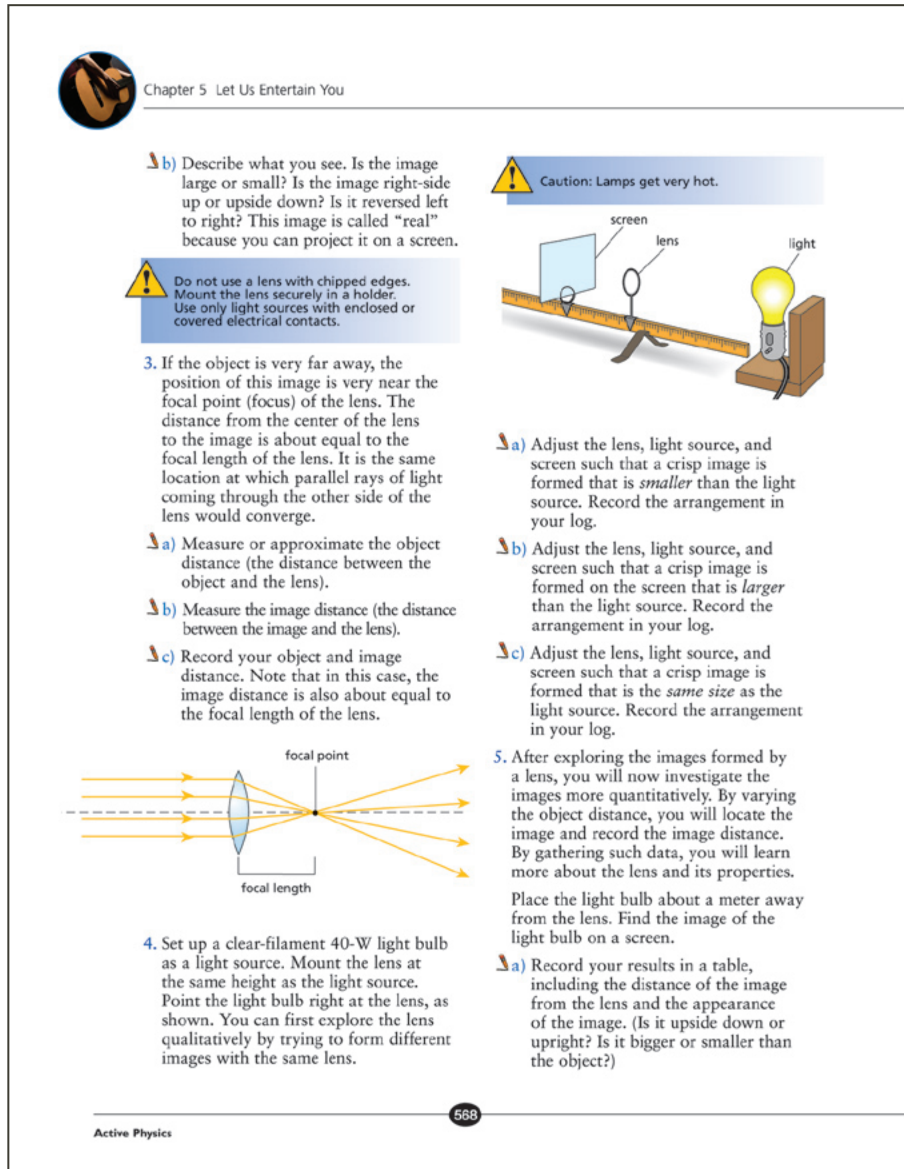
Students' drawings should look like the one below.



CHAPTER 5

focal point. Understanding this section is crucial to students gathering evidence to refute this preconception and to modifying it. Listen carefully to student "output" and to the language used to explain the phenomena.

3. **Students reject the idea that each object point on an object emits a single ray that carries all of the information about the corresponding image point.** Observing real images formed by a lens and relating image size and position to the property of the lens are important. An interesting extension of *Section 9* is to take a piece of a lens that is broken (or to cover most of a lens with an opaque material) and demonstrate the formation of identical images with this fragment of lens as with the whole lens. You may ask students how this happens and lead them to predict that other rays of light coming from the same source must be traveling in space to interact with the lens and form the same image.



b) Describe what you see. Is the image large or small? Is the image right-side up or upside down? Is it reversed left to right? This image is called "real" because you can project it on a screen.

Do not use a lens with chipped edges. Mount the lens securely in a holder. Use only light sources with enclosed or covered electrical contacts.

3. If the object is very far away, the position of this image is very near the focal point (focus) of the lens. The distance from the center of the lens to the image is about equal to the focal length of the lens. It is the same location at which parallel rays of light coming through the other side of the lens would converge.

a) Measure or approximate the object distance (the distance between the object and the lens).

b) Measure the image distance (the distance between the image and the lens).

c) Record your object and image distance. Note that in this case, the image distance is also about equal to the focal length of the lens.

4. Set up a clear-filament 40-W light bulb as a light source. Mount the lens at the same height as the light source. Point the light bulb right at the lens, as shown. You can first explore the lens qualitatively by trying to form different images with the same lens.

Caution: Lamps get very hot.

a) Adjust the lens, light source, and screen such that a crisp image is formed that is *smaller* than the light source. Record the arrangement in your log.

b) Adjust the lens, light source, and screen such that a crisp image is formed on the screen that is *larger* than the light source. Record the arrangement in your log.

c) Adjust the lens, light source, and screen such that a crisp image is formed that is the *same size* as the light source. Record the arrangement in your log.

5. After exploring the images formed by a lens, you will now investigate the images more quantitatively. By varying the object distance, you will locate the image and record the image distance. By gathering such data, you will learn more about the lens and its properties.

Place the light bulb about a meter away from the lens. Find the image of the light bulb on a screen.

a) Record your results in a table, including the distance of the image from the lens and the appearance of the image. (Is it upside down or upright? Is it bigger or smaller than the object?)

2.b)

The image is upside down (inverted), and on the opposite side of the lens from the object. The image will be smaller than the object, and reversed from left to right.

3.a)

Students measure the distance between the lens and the screen when the image is in focus. This is approximately equal to the focal length of the lens. Lenses typically come in multiples of 5 cm for focal length up to approximately 30 cm.

3.b)

Students measure the image distance, which is also the focal length in this case.

3.c)

Students record the image distance, and will probably approximate the object distance.

4.a)

A crisp image that is smaller than the light source will occur when the object is away from the lens by twice its focal length.

4.b)

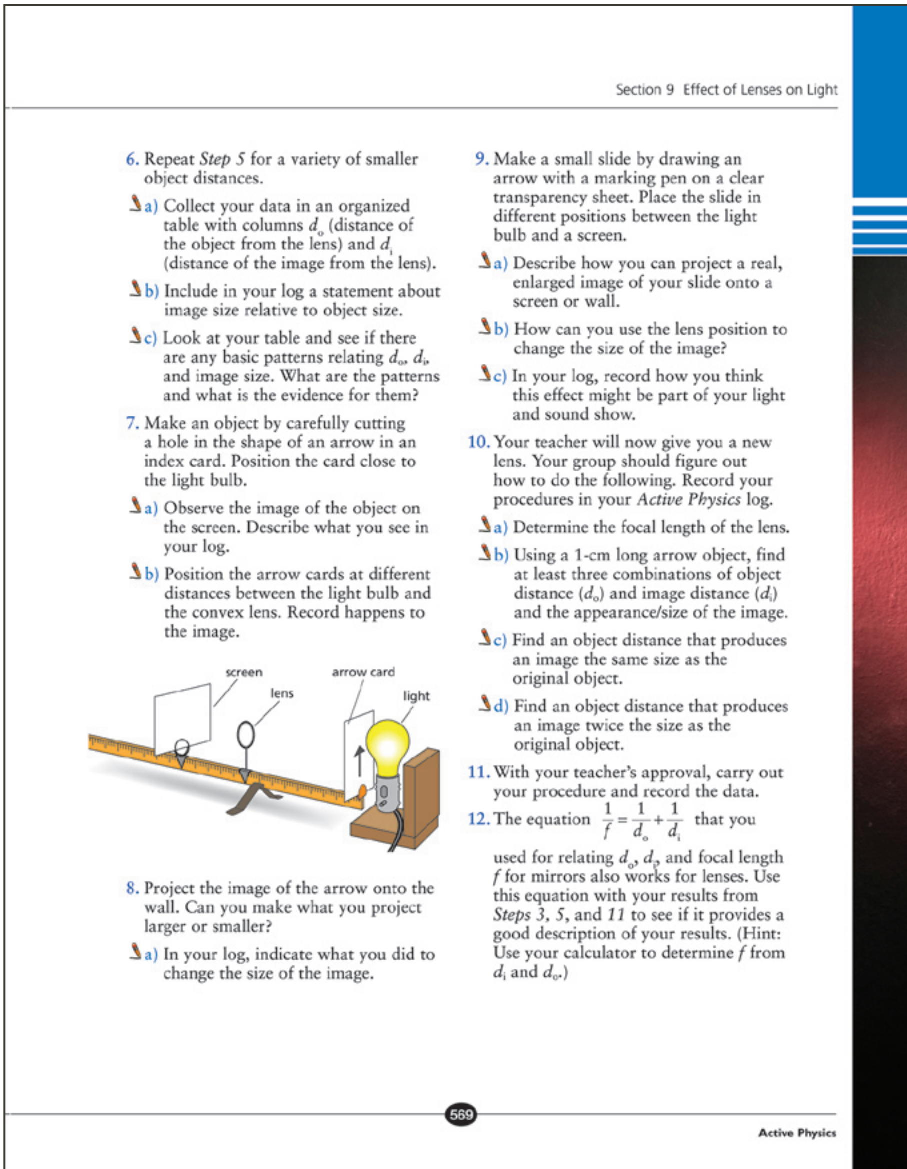
A crisp image that is larger than the light source may be difficult to form since the light bulb is a large extended object. Have students focus on the filament of the bulb. This larger image will occur when the object is between one focal length and two focal lengths away from the lens.

4.c)

An image that is the same size as the object is formed when the object is at a distance of exactly twice the focal length of the lens. This is an alternative method to find the focal length of the lens.

5.a)

Students record the object and image distances in a table that has columns for object distance, image distance, whether the image is inverted or upright, and whether the image is smaller or larger than the object.



6. Repeat *Step 5* for a variety of smaller object distances.

a) Collect your data in an organized table with columns d_o (distance of the object from the lens) and d_i (distance of the image from the lens).

b) Include in your log a statement about image size relative to object size.

c) Look at your table and see if there are any basic patterns relating d_o, d_i, and image size. What are the patterns and what is the evidence for them?

7. Make an object by carefully cutting a hole in the shape of an arrow in an index card. Position the card close to the light bulb.

a) Observe the image of the object on the screen. Describe what you see in your log.

b) Position the arrow cards at different distances between the light bulb and the convex lens. Record happens to the image.

8. Project the image of the arrow onto the wall. Can you make what you project larger or smaller?

a) In your log, indicate what you did to change the size of the image.

9. Make a small slide by drawing an arrow with a marking pen on a clear transparency sheet. Place the slide in different positions between the light bulb and a screen.

a) Describe how you can project a real, enlarged image of your slide onto a screen or wall.

b) How can you use the lens position to change the size of the image?

c) In your log, record how you think this effect might be part of your light and sound show.

10. Your teacher will now give you a new lens. Your group should figure out how to do the following. Record your procedures in your *Active Physics* log.

a) Determine the focal length of the lens.

b) Using a 1-cm long arrow object, find at least three combinations of object distance (d_o) and image distance (d_i) and the appearance/size of the image.

c) Find an object distance that produces an image the same size as the original object.

d) Find an object distance that produces an image twice the size as the original object.

11. With your teacher's approval, carry out your procedure and record the data.

12. The equation $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ that you used for relating d_o, d_i, and focal length f for mirrors also works for lenses. Use this equation with your results from *Steps 3, 5,* and *11* to see if it provides a good description of your results. (Hint: Use your calculator to determine f from d_i and d_o.)

6.a)

Students collect data for a series of points closer to the lens up to about 1.3 times the lens's focal length.

6.b)

Students should record that the image is smaller than the object until the object reaches twice the focal length. After getting closer to the lens than twice the focal length, the image size becomes rapidly larger, until the object distance reaches the focal length and the image disappears.

6.c)

As the object moves toward the lens, the image moves away from the lens and gets larger.

7.a)

Students should see a bright arrow on the screen.

7.b)

By moving the arrow back and forth to the right place, the edge of the arrow can be seen sharply. It might help to cover the arrow opening with waxed paper. The waxed paper will diffuse the light, so the image formed will be that of the arrow and not of the light source seen directly. If the card is not directly between the lens and the light source, students may see the image of the light source.

8.a)

The size of the image can be varied by moving the arrow closer to or further away from the lens. The arrow now becomes the object and behaves as the object did in the previous step.

9.a)

By having the slide close to the lens (but not inside the focal length) and the image far away, students can make the image considerably larger than the arrow. By changing the distance between the arrow and the lens (and then adjusting the distance from the lens to the screen to get a sharp image), students can control the size of the image.

9.b)

You can change the size of what you see on the wall by changing the distance between the lens and the slide. If students move the lens closer to the slide and refocus by moving the lens and slide together, relative to the screen until the image is sharp, the size of the image will be larger.

CHAPTER 5

9.c)

Students record their ideas about projecting images for use in their sound and light show. In the show, they can project slides on the wall and change the size of the projected image

10.

Students repeat the procedures for a convex lens with a different focal length.

Make sure the focal lengths of the two lenses are significantly different.

10.a)

The focal length is found by focusing on a distant object.

10.b)

Students should choose one value well beyond twice the focal length, one near twice the focal length, and one between the focal length and twice the focal length.

10.c)

Students should locate where the object size and image sizes are equal. This will be when the object distance is twice the focal length.

10.d)

The image size is twice the object size when the image distance is twice the object distance.

11.

Students first measure the focal length of the new lens, and then find and record the image position for three different object positions. Students record the image size relative to the object size (smaller, larger or the same), and whether or not the image is inverted. They find the object position that produces an image that is the same size as the object (at the $2f$ position), and the object position that produces an image double the size of the object (at $1.5f$).

12.

Students should plug in some values of object distance and image distance from the steps listed to see if the values they calculate for the focal length match their measured value. Since their focal length was only approximate (and probably slightly too large), expect some variation from the accepted value in their calculations.

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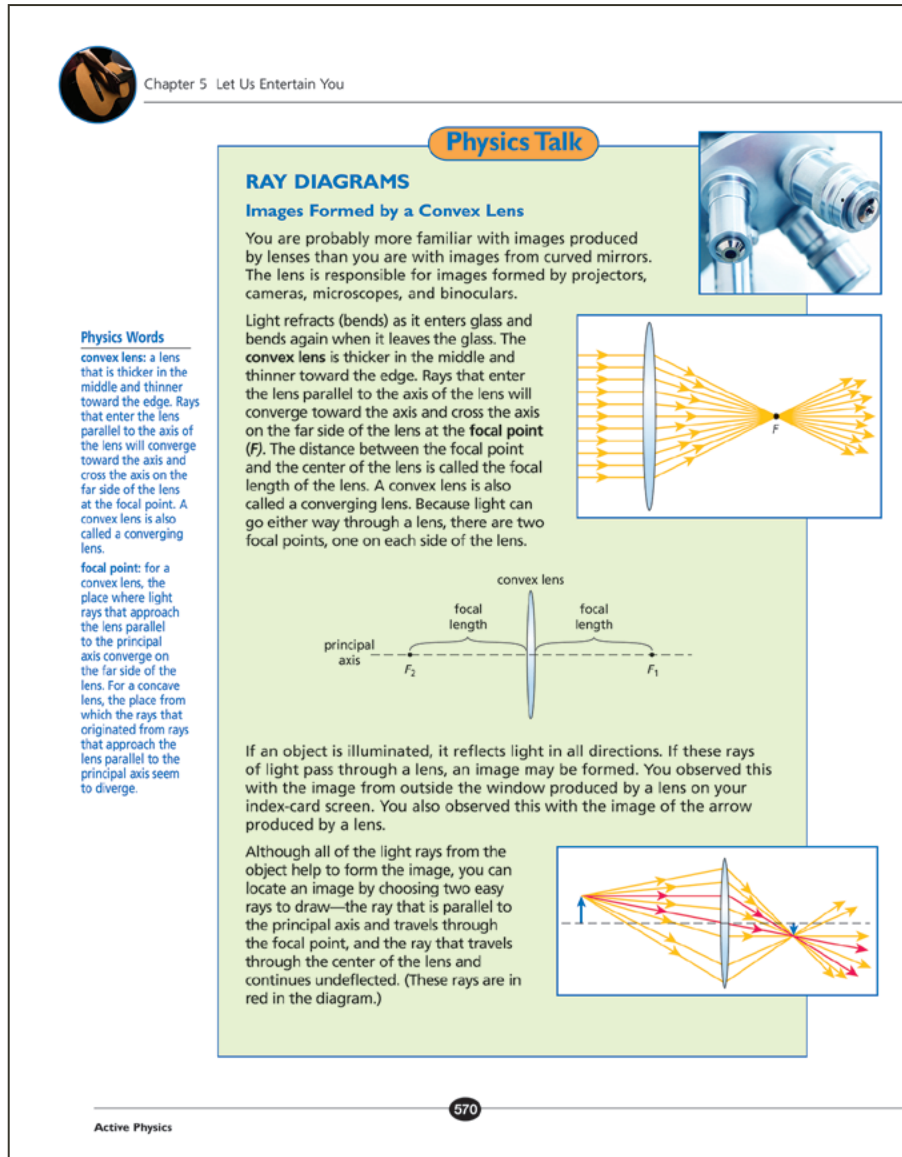
Physics Talk

Students read about the images formed by a convex lens. The first diagram in the *Physics Talk* illustrates that rays parallel to the principal axis converge at the focal point, *F*. There are two focal points because light can pass through the lens from either side. Students are shown that only two principal rays are needed to locate the images formed by lenses, all the light rays from an object that pass through the lens are brought together at the same point to form the image in focus.

Point out how the two main rays are reversible. A light ray parallel to the principal axis that passes through the focal point after leaving the lens can also pass through the focal point, strike the lens, and emerge parallel to the principal axis. A light ray passing through the lens center continues in the same direction and is clearly reversible. Drawing the ray diagrams in their logs will help students to see how rays pass through the center of the lens, and those that enter the lens parallel to the principal axis form an image.

By varying the object distance, students see how changing the distance changes the size and position of an image.

In a discussion, point out how the deflection of light rays by a lens is used as a technique to capture images of various sizes. Consider listing different technical devices and asking students to write a brief explanation on where the object and image are located relative to one another for the device to capture the appropriate image. Highlight how a magnifying glass forms a virtual image. You might want to ask students how eyeglasses change an image, and whether that image is real or virtual.



Chapter 5 Let Us Entertain You

Physics Talk

RAY DIAGRAMS

Images Formed by a Convex Lens

You are probably more familiar with images produced by lenses than you are with images from curved mirrors. The lens is responsible for images formed by projectors, cameras, microscopes, and binoculars.

Light refracts (bends) as it enters glass and bends again when it leaves the glass. The **convex lens** is thicker in the middle and thinner toward the edge. Rays that enter the lens parallel to the axis of the lens will converge toward the axis and cross the axis on the far side of the lens at the **focal point** (*F*). The distance between the focal point and the center of the lens is called the focal length of the lens. A convex lens is also called a converging lens. Because light can go either way through a lens, there are two focal points, one on each side of the lens.

If an object is illuminated, it reflects light in all directions. If these rays of light pass through a lens, an image may be formed. You observed this with the image from outside the window produced by a lens on your index-card screen. You also observed this with the image of the arrow produced by a lens.

Although all of the light rays from the object help to form the image, you can locate an image by choosing two easy rays to draw—the ray that is parallel to the principal axis and travels through the focal point, and the ray that travels through the center of the lens and continues undeflected. (These rays are in red in the diagram.)

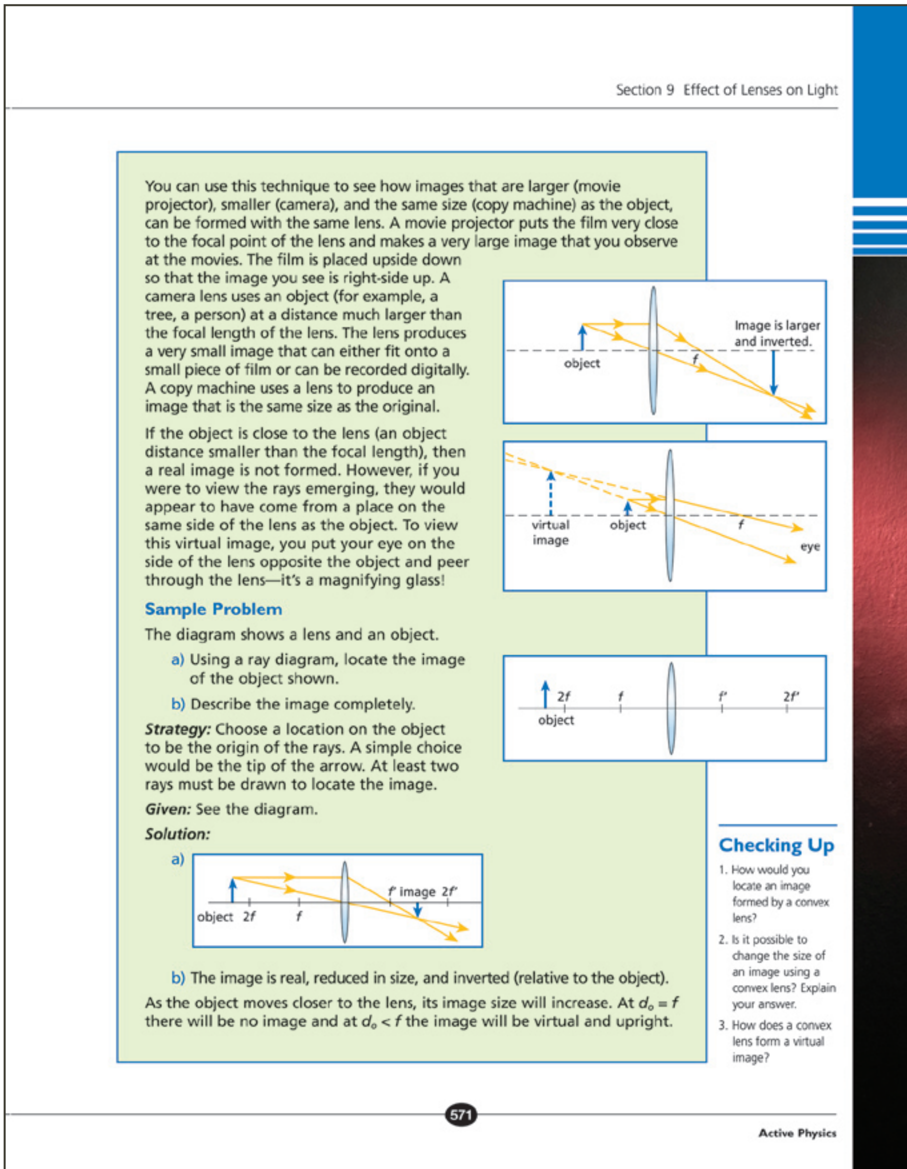
Physics Words

convex lens: a lens that is thicker in the middle and thinner toward the edge. Rays that enter the lens parallel to the axis of the lens will converge toward the axis and cross the axis on the far side of the lens at the focal point. A convex lens is also called a converging lens.

focal point: for a convex lens, the place where light rays that approach the lens parallel to the principal axis converge on the far side of the lens. For a concave lens, the place from which the rays that originated from rays that approach the lens parallel to the principal axis seem to diverge.

570

Active Physics


Section 9 Effect of Lenses on Light

You can use this technique to see how images that are larger (movie projector), smaller (camera), and the same size (copy machine) as the object, can be formed with the same lens. A movie projector puts the film very close to the focal point of the lens and makes a very large image that you observe at the movies. The film is placed upside down so that the image you see is right-side up. A camera lens uses an object (for example, a tree, a person) at a distance much larger than the focal length of the lens. The lens produces a very small image that can either fit onto a small piece of film or can be recorded digitally. A copy machine uses a lens to produce an image that is the same size as the original.

If the object is close to the lens (an object distance smaller than the focal length), then a real image is not formed. However, if you were to view the rays emerging, they would appear to have come from a place on the same side of the lens as the object. To view this virtual image, you put your eye on the side of the lens opposite the object and peer through the lens—it's a magnifying glass!

Sample Problem

The diagram shows a lens and an object.

a) Using a ray diagram, locate the image of the object shown.

b) Describe the image completely.

Strategy: Choose a location on the object to be the origin of the rays. A simple choice would be the tip of the arrow. At least two rays must be drawn to locate the image.

Given: See the diagram.

Solution:

a)

b) The image is real, reduced in size, and inverted (relative to the object).

As the object moves closer to the lens, its image size will increase. At $d_o = f$ there will be no image and at $d_o < f$ the image will be virtual and upright.

Checking Up

1. How would you locate an image formed by a convex lens?
2. Is it possible to change the size of an image using a convex lens? Explain your answer.
3. How does a convex lens form a virtual image?

571

Active Physics

5-9a **Blackline Master**

Checking Up

1.

You can locate the image by drawing the path of a ray that is parallel to the principal axis and the path of the ray which passes through the center of the lens. The image will be formed at the point at which the two rays meet. For an actual lens, you would move a screen until a crisp, sharp image is formed on the screen.

2.

It is possible to change the size of an image because the size of an image is determined by the distance of the object from the lens. As the object distance decreases, the size of the image increases.

3.

A convex lens forms a virtual image when the object distance is less than the focal length.

CHAPTER 5

Active Physics Plus

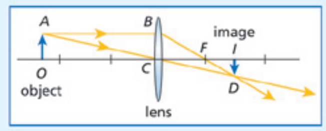
This exercise leads the students through a derivation of the lens equation using geometry. Students may need help in recalling the appropriate theorems from geometry. The algebra leading to the reciprocal form of the lens equation is also a bit tricky.

Chapter 5 Let Us Entertain You

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
••			

Geometry for the Lens Equation



By using some geometry and algebra and the diagram shown here, you can derive the lens equation

$$\frac{1}{d_o}+\frac{1}{d_i}=\frac{1}{f}.$$

Note that the object distance is given by $d_o=\overline{OC}$, the image distance is given by $d_i=\overline{CI}$, and the focal length (the distance from the lens to the focal point) is given by $f=\overline{CF}$. The object height is $h_o=\overline{AO}$ and the image height is $h_i=\overline{ID}$.

The figure above shows two representative light rays leaving the tip *A* of the object arrow on the left. The ray traveling from *A* to *B* is parallel to the principal axis of the lens and hence passes through the focal point *F* on the far side of the lens. The second ray passes through the center of the lens C and is not deviated (for a thin lens).

The two rays cross at point *D*, which is the location of the image of the tip of the arrow. It is a real image because the rays of light actually converge there. Also note that the tip of the arrow is in the reverse position on the opposite side of the lens so that the image will be inverted or upside down.

a) Opposite angles are equal. Hence, $\angle ACO=\angle ICD$.

b) Triangles *AOC* and *CID* are right triangles because the original arrow is perpendicular to the optic axis. Use geometry to show that the two triangles, *AOC* and *CID* are similar.

c) Since triangles *AOC* and *CID* are similar, use geometry to show that $\frac{\overline{AO}}{\overline{OC}}=\frac{\overline{ID}}{\overline{CI}}$ or in terms of object distance, object height, image distance, and image height $\frac{h_o}{d_o}=\frac{h_i}{d_i}$. (Note that this result can be rearranged to give the magnification expression $\frac{h_i}{h_o}=\frac{d_i}{d_o}$.)

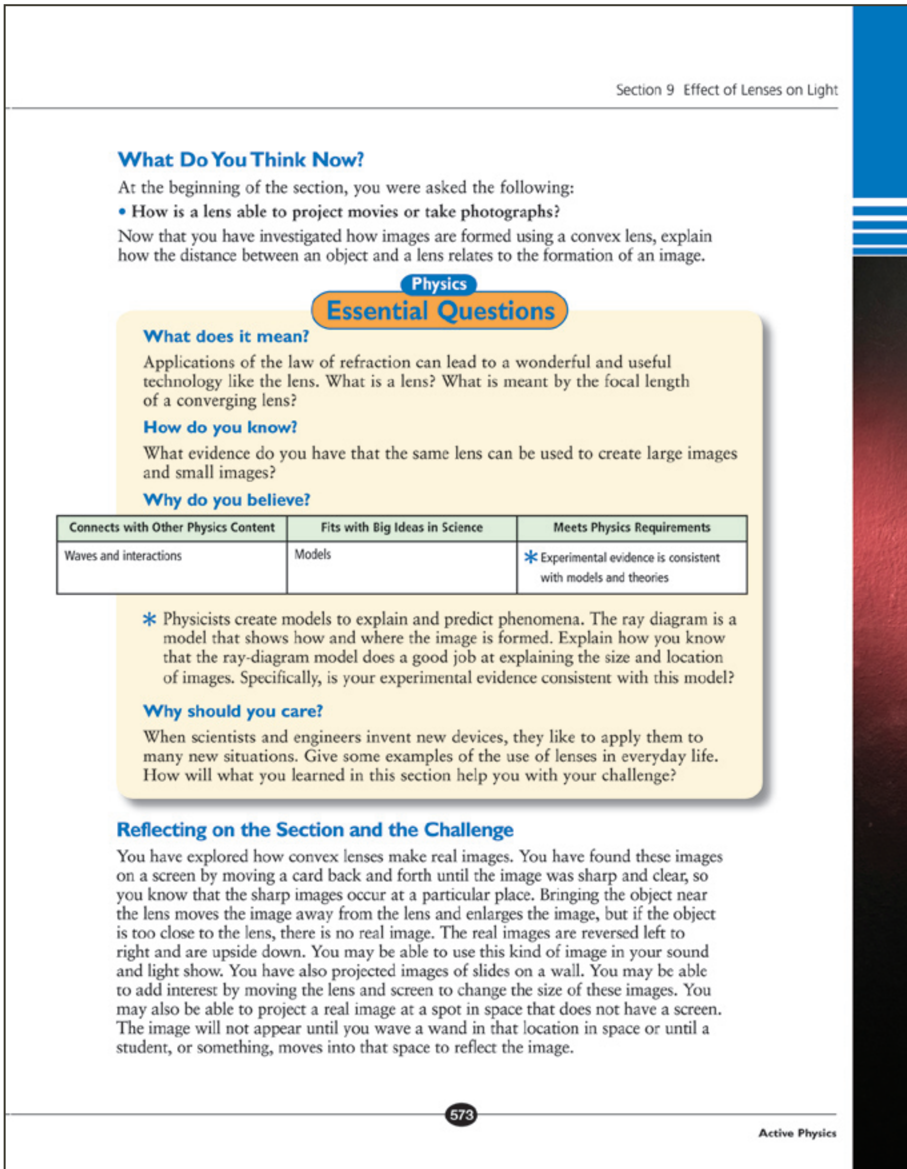
d) Triangles *BCF* and *FID* also are similar triangles. Use geometry to show that this is true.

e) Since triangles *BCF* and *FID* are similar triangles, you can use geometry to prove that $\frac{\overline{BC}}{\overline{CF}}=\frac{\overline{ID}}{\overline{FI}}$ *or* $\frac{h_o}{f}=\frac{h_i}{(d_i-f)}$.

f) Use the magnification expression from *c)* with the result from *d)* to write $\frac{h_i}{h_o}=\frac{d_i}{d_o}=\frac{d_i-f}{f}=\frac{d_i}{f}-1$, where you broke up the last fraction into two parts to get $\frac{d_i}{d_o}=\frac{d_i}{f}-1$.

g) Divide both sides of the previous equation by d_i to show that $\frac{1}{d_o}=\frac{1}{f}-\frac{1}{d_o}$ or $\frac{1}{d_o}+\frac{1}{d_i}=\frac{1}{f}$, which is the lens equation.

572
Active Physics



What Do You Think Now?

At the beginning of the section, you were asked the following:

- **How is a lens able to project movies or take photographs?**

Now that you have investigated how images are formed using a convex lens, explain how the distance between an object and a lens relates to the formation of an image.

Physics Essential Questions

What does it mean?

Applications of the law of refraction can lead to a wonderful and useful technology like the lens. What is a lens? What is meant by the focal length of a converging lens?

How do you know?

What evidence do you have that the same lens can be used to create large images and small images?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Waves and interactions	Models	* Experimental evidence is consistent with models and theories

* Physicists create models to explain and predict phenomena. The ray diagram is a model that shows how and where the image is formed. Explain how you know that the ray-diagram model does a good job at explaining the size and location of images. Specifically, is your experimental evidence consistent with this model?

Why should you care?

When scientists and engineers invent new devices, they like to apply them to many new situations. Give some examples of the use of lenses in everyday life. How will what you learned in this section help you with your challenge?

Reflecting on the Section and the Challenge

You have explored how convex lenses make real images. You have found these images on a screen by moving a card back and forth until the image was sharp and clear, so you know that the sharp images occur at a particular place. Bringing the object near the lens moves the image away from the lens and enlarges the image, but if the object is too close to the lens, there is no real image. The real images are reversed left to right and are upside down. You may be able to use this kind of image in your sound and light show. You have also projected images of slides on a wall. You may be able to add interest by moving the lens and screen to change the size of these images. You may also be able to project a real image at a spot in space that does not have a screen. The image will not appear until you wave a wand in that location in space or until a student, or something, moves into that space to reflect the image.

What Do You Think Now?

Students should be able to talk about how projector lenses and camera lenses are used to make images and they should be able to refer to their observations for appropriate examples. Emphasize that people who are near-sighted can see things up close clearly, but distant objects are fuzzy. In effect, the focal length of their eyes' optical system (cornea and lens) is too short. They are prescribed diverging (concave) lenses to improve their vision. (The optometrist lists the focal length of a concave lens as a negative number.) For people who are "far-sighted," the situation is reversed: the focal length of their eyes' optical system is too long. Convex (converging) lenses are prescribed to correct their vision.

Reflecting on the Section and the Challenge

Students should find this section useful for improving the image quality in their sound and light show. Have them reflect on their

Physics Essential Questions

What does it mean?

A lens is a piece of transparent material that is shaped to let all rays of light parallel to the principal axis emerge on the other side of the material and intersect at a point called the focal point. The focal length is the distance between the center of a lens and its focal point.

How do you know?

In this section, an object was set up at different distances from the lens and images of varying sizes, both large and small, were observed on a screen.

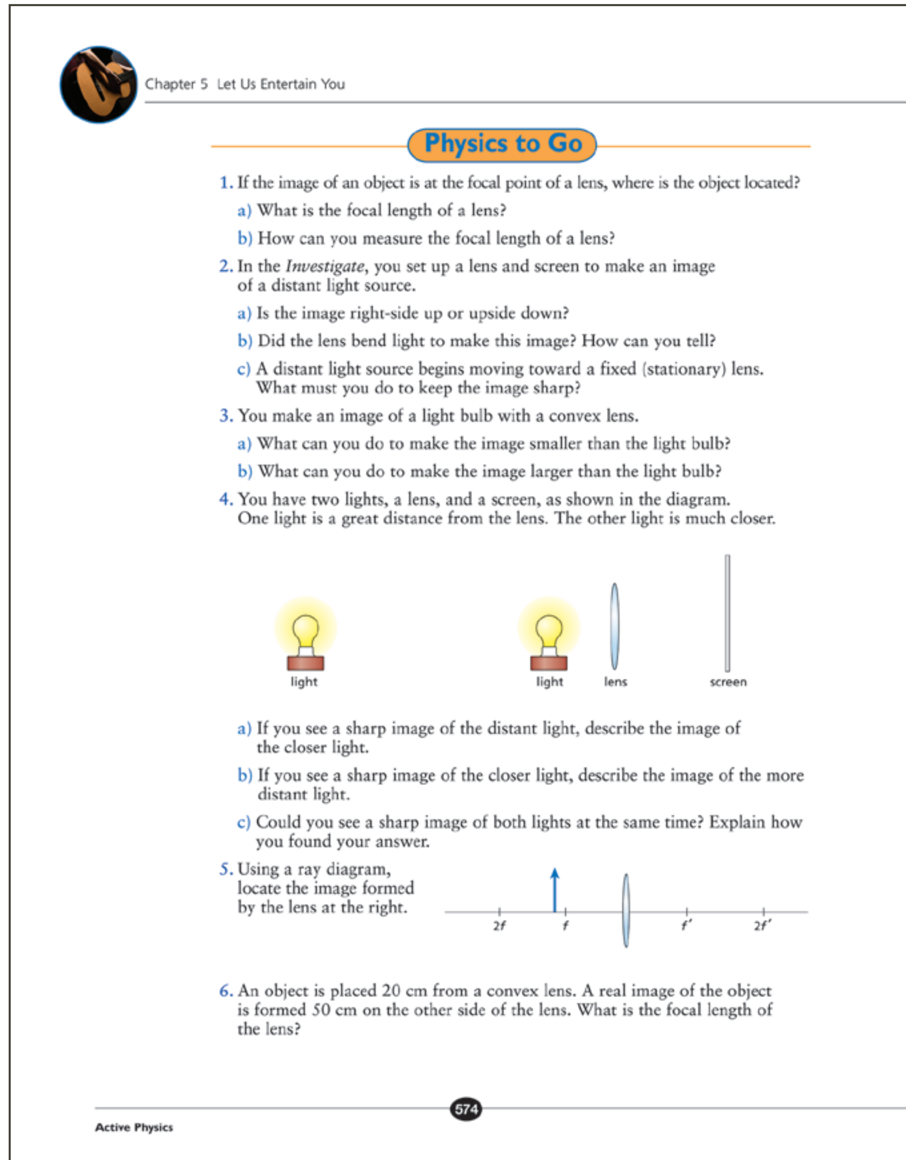
Why do you believe?

The location and size of the image as determined by experiments is identical to that predicted by the lens equation.

Why should you care?

Lenses are used to correct vision. They are used to project movies, and are also used in telescopes, microscopes and binoculars.

knowledge of convex lenses and how they can use and design instruments to aid them in their *Chapter Challenge*. Lead a discussion on how convex lenses can be used to reduce or enlarge an image. Ask students to read this section aloud and have them pause wherever you want to highlight a point or discuss its significance.


Chapter 5 Let Us Entertain You

Physics to Go

1. If the image of an object is at the focal point of a lens, where is the object located?
   a) What is the focal length of a lens?
   b) How can you measure the focal length of a lens?
2. In the *Investigate*, you set up a lens and screen to make an image of a distant light source.
   a) Is the image right-side up or upside down?
   b) Did the lens bend light to make this image? How can you tell?
   c) A distant light source begins moving toward a fixed (stationary) lens. What must you do to keep the image sharp?
3. You make an image of a light bulb with a convex lens.
   a) What can you do to make the image smaller than the light bulb?
   b) What can you do to make the image larger than the light bulb?
4. You have two lights, a lens, and a screen, as shown in the diagram. One light is a great distance from the lens. The other light is much closer.

   a) If you see a sharp image of the distant light, describe the image of the closer light.
   b) If you see a sharp image of the closer light, describe the image of the more distant light.
   c) Could you see a sharp image of both lights at the same time? Explain how you found your answer.
5. Using a ray diagram, locate the image formed by the lens at the right.

6. An object is placed 20 cm from a convex lens. A real image of the object is formed 50 cm on the other side of the lens. What is the focal length of the lens?

574

Active Physics

Physics to Go

1.

If the image of an object is located at the focal length of the lens, the object is very far away (technically at infinity).

1.a)

The focal length of the lens is the distance from the center of the lens to the point where light rays parallel to the principal axis of the lens are brought to focus.

1.b)

Focus on a small, distant object and locate the image position. The distance between the image and the lens is very close to the focal length. Alternatively, you may find the point where the object distance is equal to the image distance (twice the focal length), and divide by two to obtain the focal length.

2.a)

The image is upside down.

2.b)

The lens bends the light to form an image. You can tell by looking at the light concentrated at the focal point and see that it is all brought to a focus at that point. Alternatively, students could use a mist of smoke to see the light's path as a lens brings the light into focus.

2.c)

You can move the screen back from the lens.

3.a)

You can move the object away from the lens (more than twice the focal length away).

3.b)

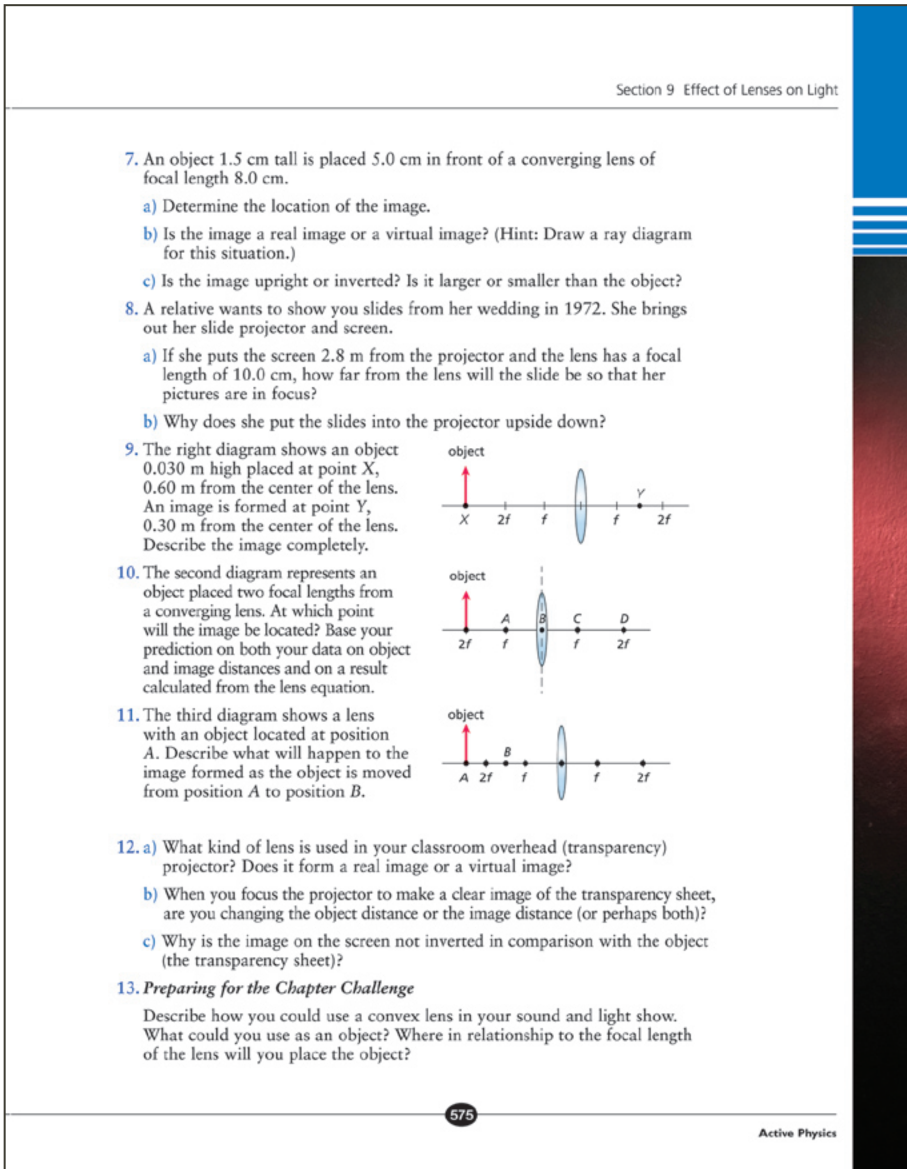
Bring the object close to the lens (closer than twice the focal length), but not less than the focal length for a real image.

4.a)

The image of the closer light is blurred.

4.b)

The image of the more distant light is blurred.



Section 9 Effect of Lenses on Light

7. An object 1.5 cm tall is placed 5.0 cm in front of a converging lens of focal length 8.0 cm.
   a) Determine the location of the image.
   b) Is the image a real image or a virtual image? (Hint: Draw a ray diagram for this situation.)
   c) Is the image upright or inverted? Is it larger or smaller than the object?
8. A relative wants to show you slides from her wedding in 1972. She brings out her slide projector and screen.
   a) If she puts the screen 2.8 m from the projector and the lens has a focal length of 10.0 cm, how far from the lens will the slide be so that her pictures are in focus?
   b) Why does she put the slides into the projector upside down?
9. The right diagram shows an object 0.030 m high placed at point *X*, 0.60 m from the center of the lens. An image is formed at point *Y*, 0.30 m from the center of the lens. Describe the image completely.
10. The second diagram represents an object placed two focal lengths from a converging lens. At which point will the image be located? Base your prediction on both your data on object and image distances and on a result calculated from the lens equation.
11. The third diagram shows a lens with an object located at position *A*. Describe what will happen to the image formed as the object is moved from position *A* to position *B*.
12. a) What kind of lens is used in your classroom overhead (transparency) projector? Does it form a real image or a virtual image?
   b) When you focus the projector to make a clear image of the transparency sheet, are you changing the object distance or the image distance (or perhaps both)?
   c) Why is the image on the screen not inverted in comparison with the object (the transparency sheet)?
13. ***Preparing for the Chapter Challenge***

   Describe how you could use a convex lens in your sound and light show. What could you use as an object? Where in relationship to the focal length of the lens will you place the object?

575

Active Physics

4.c)

A sharp image of both lights is not possible with a small, single, simple lens. This can be demonstrated with a ray diagram that shows the light rays from one source being brought into focus at some point, but the light rays from the other source not crossing in the same place as the first.

5.

Students should draw a ray diagram similar to the first diagram on the top in the *Physics Talk*.

6.

Given:
$d_o = 20$ cm; $d_i = 50$ cm.

Using the lens equation,

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

$$\frac{1}{20\text{ cm}} + \frac{1}{50\text{ cm}} = 0.07\text{ cm}^{-1}$$

Solving for the focal length gives you

$$\frac{1}{f} = 0.07\text{ cm}^{-1}\text{or } f = 14.3\text{ cm}.$$

7.a)

Object distance, $d_o = 5.0$ cm and focal length, $f = 8.0$ cm. Because the object is between the focal point and the lens, a virtual image will be formed. Using the lens equation to find d_i,

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \text{ or } \frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} =$$

$$\frac{1}{8.0\text{ cm}} - \frac{1}{5.0\text{ cm}} = -0.075\text{ cm}^{-1}$$

$$d_i = -13.3\text{ cm}.$$

7.b)

The image is virtual. The minus sign means that the image is a virtual image. A ray diagram of this case is shown in the second diagram from the top on the final page of the *Physics Talk* in this section.

7.c)

Because the image is virtual, it will be upright. The image distance is larger than the object distance, so the image will be larger than the object. The lens is being used as a magnifying glass.

8.a)

Apply the lens equation $1/f = 1/d_o + 1/d_i$ and rearrange it to find the object distance as follows:

CHAPTER 5

Given:
$d_i = 2.8$ m; $f = 0.1$ m

$1/d_o = 1/f - 1/d_i$
$1/d_o = 1/0.1 \text{ m} - 1/2.8 \text{ m}$
$1/d_o = 10 \text{ m}^{-1} - 0.357 \text{ m}^{-1}$
$1/d_o = 9.643 \text{ m}^{-1}$
Therefore, $d_o = 0.103$ m.

8.b)

She puts the slide upside down in the projector because she is forming a real image with a convex lens, and the image will be inverted relative to the slide. Therefore, the image on the screen will be seen with the picture's original orientation.

9.

The image is real, reduced in size, and inverted because the object distance is greater than twice the focal length.

10.

The image will be located at $2f$. Using the lens equation, you get $1/d_o + 1/d_i = 1/f$.

Since $1/2f + 1/d_i = 1/f$, solve for $1/d_i = 1/f - 1/2f = 1/2f$.

Therefore, $d_i = 2f$.

11.

As the object gets closer to the lens, the image will move further away and increase in size. The object and the image will be the same size when the object is located at $2f$. As the object moves closer to the lens from $2f$, the size of the image will be larger than the object.

12.a)

The overhead projector uses a convex lens and produces a real image of the transparency sheet on the screen.

12.b)

When you focus the projector, you are usually moving the lens relative to the object (the transparency sheet), so you are changing the object distance. If you move the projector relative to the screen, you are changing the image distance.

12.c)

The image is not inverted because the light reflects off a flat mirror on its way to the screen. The mirror introduces an inversion which compensates for the inversion produced by the convex lens. The transparency sheet is horizontal when the image is (usually) on a vertical surface, so comparing orientations is a bit tricky.

13.

Preparing for the Chapter Challenge

Students could use the convex lens to form images of their show on the screen, large enough for the whole class to see easily. Students could also use the lens to focus lights of different colors around the screen to add interest to other images.

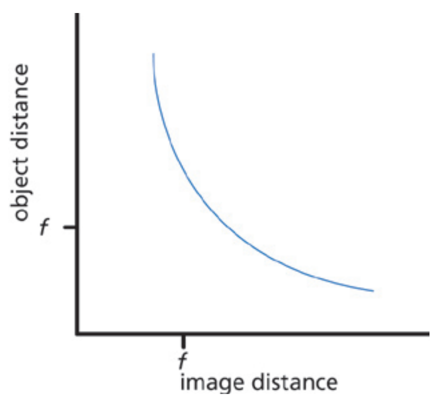
NOTES

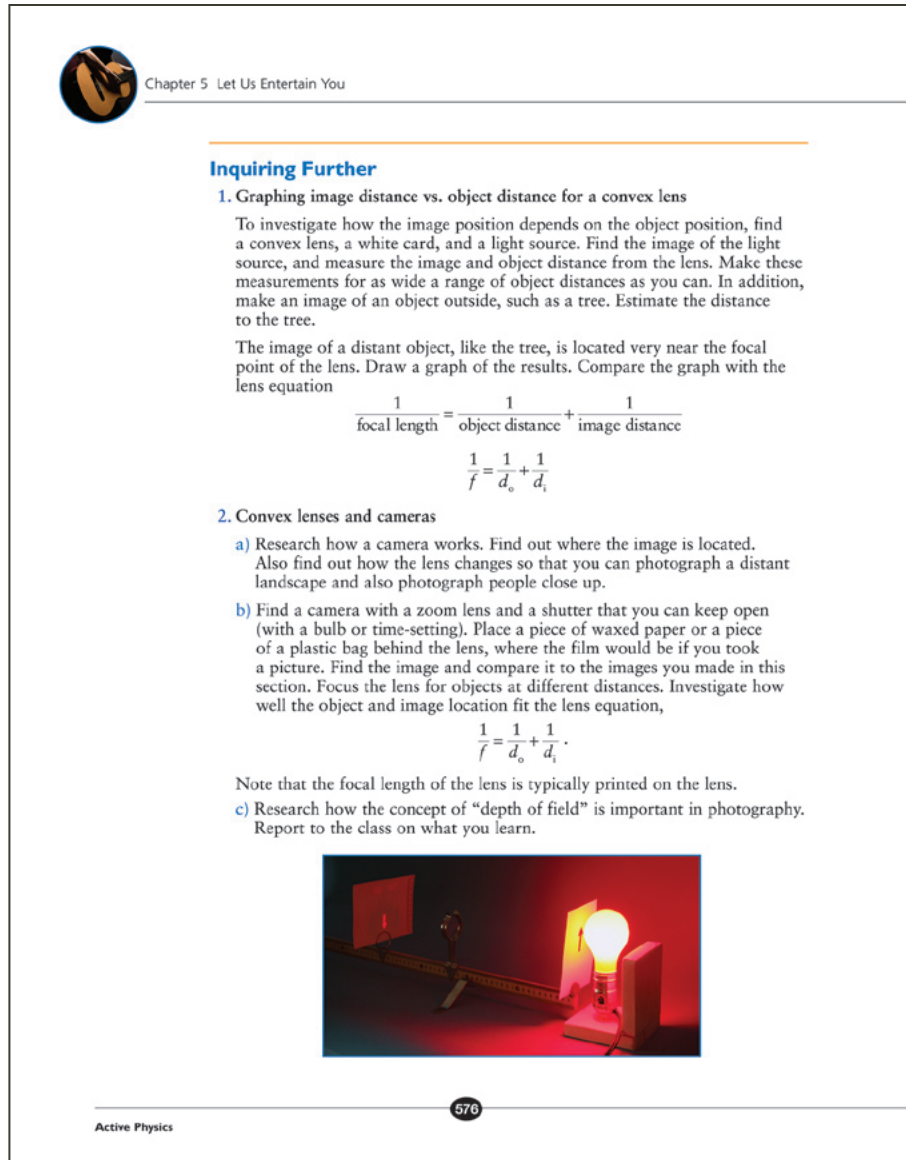
NOTES

Inquiring Further

1. Graphing image distance vs. object distance for a convex lens

To compare the graph with the equation, students can calculate $(1/d_o + 1/d_i)$ for each pair of images and object distances. If the values of $(1/d_o + 1/d_i)$ are approximately equal, then the equation shown describes their data (and they can calculate f). The graph of the data should resemble the one below.





Chapter 5 Let Us Entertain You

Inquiring Further

1. **Graphing image distance vs. object distance for a convex lens**

To investigate how the image position depends on the object position, find a convex lens, a white card, and a light source. Find the image of the light source, and measure the image and object distance from the lens. Make these measurements for as wide a range of object distances as you can. In addition, make an image of an object outside, such as a tree. Estimate the distance to the tree.

The image of a distant object, like the tree, is located very near the focal point of the lens. Draw a graph of the results. Compare the graph with the lens equation

$$\frac{1}{\text{focal length}} = \frac{1}{\text{object distance}} + \frac{1}{\text{image distance}}$$

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

2. **Convex lenses and cameras**

a) Research how a camera works. Find out where the image is located. Also find out how the lens changes so that you can photograph a distant landscape and also photograph people close up.

b) Find a camera with a zoom lens and a shutter that you can keep open (with a bulb or time-setting). Place a piece of waxed paper or a piece of a plastic bag behind the lens, where the film would be if you took a picture. Find the image and compare it to the images you made in this section. Focus the lens for objects at different distances. Investigate how well the object and image location fit the lens equation,

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}.$$

Note that the focal length of the lens is typically printed on the lens.

c) Research how the concept of "depth of field" is important in photography. Report to the class on what you learn.

Active Physics 576

2. Convex lenses and cameras

2.a)

The image formed by a camera is located on the film. In a camera, the lens moves further away from the film to produce a focused image of a close-up object. For producing focused images of more distant objects, the lens moves toward the film.

2.b)

The real image will lie on the wax paper.

2.c)

Depth of field is the range of object distances that will produce a sharp image. It depends on the lens's focal length, aperture size (f – number), and the object distance.

SECTION 9 QUIZ

5-9b **Blackline Master**

1. A copy machine makes images the same size as the object. To do this, where should the object be placed relative to the lens?

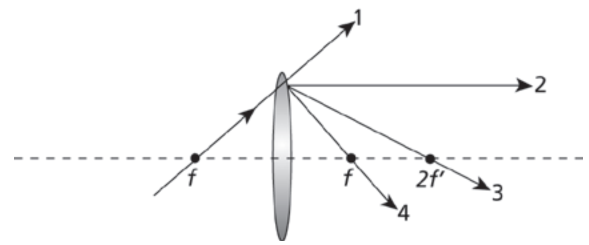
a) At the focal point (*f*).

b) Between the focal point and 2*f*.

c) At 2*f*.

d) Beyond 2*f*.

2. A light ray passes through the focal point of a lens as shown in the diagram below.



Which path will the light ray follow after passing through the lens?

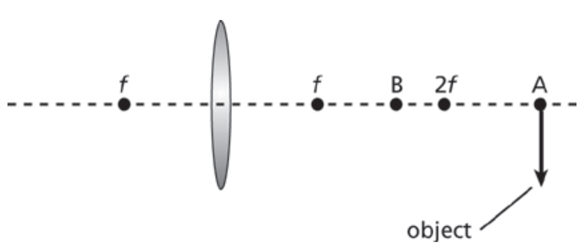
a) 1.

b) 2.

c) 3.

d) 4.

3. An object is located at position A as shown in the diagram below. As the object moves toward point B, what happens to the size and position of the image formed?



a) The image size increases and the image moves away from the lens.

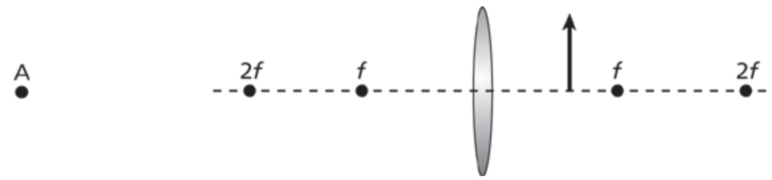
b) The image size decreases and the image moves away from the lens.

c) The image size increases and the image moves toward the lens.

d) The image size decreases and the image moves toward the lens.

CHAPTER 5

4. An object is placed in front of a convex lens as shown.



Which diagram below correctly describes the size and orientation of the image observed by a viewer in position A compared to the size of the object?

a) 

b) 

c) 

d) 

5. An object is placed at a distance greater than twice the focal length from a convex lens. Which statement below correctly describes the image formed of the object by the lens?

a) The image is virtual and larger than the object.

b) The image is real and larger than the object.

c) The image is virtual and larger than the object.

d) The image is real and smaller than the object.

SECTION 9 QUIZ ANSWERS

1 c) A convex lens forms an image equal to the object size when the image is placed at twice the focal length. Some students may think all images are formed at the focal point, which is choice *a)*. Closer to the focal length than 2*f*, choice *b)*, will produce an image larger than the object. Further away than twice the focal length, choice *d)*, will produce an image that is smaller.

2 b) A light that strikes a convex lens along a path parallel to the principal axis is refracted through the focal point, and one that follows the reverse path through the focal point will refract parallel to the principal axis. According to choice *a)*, the ray of light is not refracted.

3 a) When an object moves toward a convex lens from beyond the focal length, the image will increase in size and move away from the lens until the object reaches the focal length. Some students may think that the image size increases, as the object moves closer to the focal point, as in choice *c)*. Choices *b)* and *d)* are distracters that indicate a smaller image as the object moves closer, which should be clearly incorrect from the students' personal experience.

4 b) When inside the focal length, an object forms a virtual image that is always right-side-up, and in this case larger (the magnifying-glass case). According to choices *c)* and *d)* the images are inverted, so they must be real images, which can only be formed when the object is outside the focal length. According to choice *a)*, the image is smaller, defying the magnifying-glass concept.

5 d) The object size equals the image size when the object is at 2*f* and a real image is formed. Beyond 2*f*, the image formed will be smaller. Choices *a)* and *c)* are for virtual images, which are only formed inside the focal length, and choice *b)* is incorrect, since it makes the image larger.