SECTION 7

Curved Mirrors

Section Overview

In this section, students investigate curved mirrors. Students begin by shining parallel light beams at curved mirrors to record the pattern of reflection on a sheet of lined paper. From these patterns, students verify that the rules of reflection hold true for curved mirrors. They note that a convex mirror causes light rays to diverge, and a concave mirror will bring light rays together at a point. Students find the virtual focal length and the location of the virtual focal point for the convex lens by extending reflected rays on the part of paper behind the mirror.

For the concave lens, the students identify the point where the reflected rays converge to locate the focal point, and measure the mirror's focal length. Using a small light bulb and a concave mirror, students project the light bulb's image on an index card and measure the image distance for a series of different object distances. They draw a graph of the image distance vs. the object distance and describe the relationship between the two. Students then estimate the focal length of a concave mirror by forming an image of an object far away from the mirror. They locate its image, and record the focal length. In addition, they investigate what happens when the object distance is less than the focal length. Finally, students explore what happens to the size of the virtual image formed by a convex mirror as the object distance is changed, and they record their observations in their logs.

Background Information

A good starting point for thinking about the curved mirror is the plane mirror. The plane mirror makes a virtual image, which has the same orientation as the original object. You say that the image is erect. Now imagine the mirror is bowed out to make a convex mirror. How does the image change? The light rays show that the image is still behind the mirror, so the image is still virtual. Moreover, the image is reduced in size, since parallel rays are reflected away from one another after striking the mirror. Unlike a plane mirror where the reflected rays are parallel, these light rays will appear to converge behind the mirror to form a virtual focal point, yielding a reduced size image. Also, the image is closer to the mirror than the object's distance from the mirror. Students measure and label the focal point. The more sharply the mirror is curved, the shorter its focal length and the more the virtual image is reduced in size compared to the object.

Students often confuse the focal point with the location of the image. In principle, the image is located at the focal point only if the object is infinitely far away. In practice, if the object is many focal lengths from the mirror, the image is almost at the focal point. It might be helpful to encourage the students to use the words "focal point" rather than "focus" because "focus" is used as a verb (focus the camera, focus your attention, and so on) and as an adjective (the picture is in focus). In scientific literature, focal point is more commonly used than focus.

Now imagine bending the plane mirror inward, to make a concave mirror. As incident parallel rays now reflect in toward the mirror axis, a real image is formed and an object appears magnified when it is within twice the focal length of the mirror. When the object is within a focal length of the mirror, the image is a virtual image. For such object positions, the image is further from the mirror than is the object. If the object is outside the focal length, the reflected rays cross, so a real image is formed, as shown in the drawings in the *Physics Talk*. This image can be seen on a card or a screen. It can, of course, also be seen by looking at the mirror from a position beyond the image distance, rather than on a card, and this is the basis of the famous "floating coin" illusion made by two parabolic mirrors fastened together. The virtual images formed when the object is inside the focal length can only be seen when looking at the mirror. The concave mirror is exactly similar to the convex lens. The convex lens magnifies an object when it is extremely close or, otherwise, produces a real image. The equation that describes the position of images formed by lenses (the lens equation) also describes the location of the image and object for mirrors:

$1/f = 1/d_o + 1/d_i$.

Image formation in curved mirrors, including the mathematical description of the equation above, are exactly similar to image formation in lenses.

Crucial Physics

- A convex mirror produces a virtual image, which seems to be behind the mirror.
- A concave mirror can produce a real image (visible on a screen, for example).
- The focal point of a concave mirror is the location at which incident rays of light parallel to the mirror's axis converge. The focal length is the distance between the mirror and the focal point.
- The focal length, f, the object distance $d_{o,}$ and the image distance d_i are related by

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

Learning Outcomes	Location in the Section	Evidence of Understanding
Identify the focal point and the focal length of a curved mirror.	***Investigate*** Steps 9-10	Students extend the reflected rays backward to the focal point where they meet. They identify the focal point and measure and record the focal length.
Observe virtual images in a convex mirror.	***Investigate*** Steps 1 and 17	Students record descriptions of their image when viewed in a convex mirror.
Observe real and virtual images in a concave mirror.	***Investigate*** Steps 10, 14, 16	Students observe real images of a light source that when focused on an index card are inverted. Students note that the virtual images formed are not inverted relative to the object.
Measure and graph image distance vs. object distance for a concave mirror.	***Investigate*** Step 15	Students measure and graph the image distance and object distance for different object locations for a concave mirror.

Section 7 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks	1 per group	
Ruler, metric, in./cm	1 per group	
Light bulb socket with switch and 40W bulb	1 per group	
Clear glass rod 4″- 8″	1 per group	
Laser pointer - class 2	1 per group	
Plastic rod holder	1 per group	
Cylindrical mirror	1 per group	
Graph paper, pkg 50		1 per class
Card, unlined index, 3″ x 5″ pkg 100		1 per class
Access to an electrical outlet*	1 per group	
Paper*	1 per group	

*Additional items needed not supplied

Time Requirement

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

Teacher Preparation

- Assemble the required material.
- Make copies of the Object and Image Distance Table following *Step 14.a)* in the *Investigate* of the *Student Edition* for students use.
- 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.
- The first part of this *Investigate* is designed for use with cylindrical mirrors, and the second part is designed for concave and convex mirrors. The concave and convex mirror may be used for the first part if cylindrical mirrors are not available.
- If you do not have cylindrical mirrors available, you can construct them from polyester film placed over a cardboard cylindrical section. Use large-diameter (about 10-cm) mailing tubes to make the forms for the mirrors used in the ray tracing.
- If a light bench apparatus is available, it may be used for *Steps 14* and *15*.
- Have students set up their equipment at right angles to one another to minimize the effect of a neighboring light source on their equipment.
- Demonstrate to students how an in-focus image (or the best approximation available with your equipment) appears to help them recognize when the image is in focus.

Safety Requirements

- Review safety requirements for lasers from *Section 6*.
- Review light bulb safety from *Section 5*.
- If any glass mirrors should break, immediately remove the pieces, being careful to avoid handling the broken glass.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks	1 per group	
Ruler, metric, in./cm	1 per group	
Light bulb socket with switch and 40W bulb	1 per group	
Clear glass rod 4″- 8″	1 per group	
Laser pointer - Class 2	1 per group	
Plastic rod holder	1 per group	
Cylindrical mirror	1 per group	
Graph paper, pkg 50		1 per class
Card, unlined index, 3″ x 5″ pkg 100		1 per class
Access to an electrical outlet*	1 per group	
Paper*	1 per group	

*Additional items needed not supplied

Time Requirement

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

Teacher Preparation

- Assemble the required material.
- Make a copy of the Object and Image Distance Table following *Step 14.a)* in the *Investigate* of the *Student Edition* students use.
- 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.
- The first part of this *Investigate* is designed for use with cylindrical mirrors, and the second part is designed for concave and convex mirrors. The concave and convex mirror may be used for the first part if cylindrical mirrors are not available.
- If you do not have cylindrical mirrors available, you can construct them from polyester film placed over a cardboard cylindrical section. Use large-diameter (about 10 cm) mailing tubes to make the forms for the mirrors used in the ray tracing.
- If a light bench apparatus is available, it may be used for *Steps 14* and *15*.
- Have students set up their equipment at right angles to one another to minimize the effect of a neighboring light source on their equipment.
- Demonstrate to students how an in-focus image (or the best approximation available with your equipment) appears to help them recognize when the image is in focus.

Safety Requirements

- Review safety requirements for lasers from *Section 6*.
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- If any glass mirrors should break, immediately remove the pieces, being careful to avoid handling the broken glass.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation And Accommodations
Understanding academic vocabulary	***Investigate*** Step 6	**Augmentation** • Students have heard the word "parallel" but may not remember the meaning well enough to apply the concept to making a series of parallel beams. Ask students to explain "parallel" in their own words or with a drawing. If no one in the class knows the meaning, show an example of parallel lines to stimulate prior knowledge and ask a student to explain the meaning.
Labeling a series of rays	***Investigate*** Steps 7 and 10	**Augmentation** • Students may struggle to differentiate the pairs of rays when there are several pairs on one drawing. Instruct students to use a different colored pencil to draw each pair of rays. Then students only have to label the incident and reflected rays. The pairs will be differentiated by color.
Copying a drawing	***Investigate*** Steps 9-10	**Augmentation** • If students use dark colors to mark the rays of light on their group paper, the students who struggle to draw diagrams could place the paper behind a page in their log and trace the rays. **Accommodation** • Provide a photocopy of the drawings for students to tape into their logs. • Allow a student to tape the original drawings into his or her log if all other students can copy the diagrams.
Extending reflected rays	***Investigate*** Step 9	**Augmentation** • Extending the reflected rays to locate the focal point may be a challenge for students with graphomotor issues, especially since some level of accuracy is required to gain understanding of this concept. Model how to extend a ray using a ruler. **Accommodation** • Pair students strategically to include a person who is able to draw accurate rays that can be extended to mark a focal point.
Creating a graph Interpreting a graph to understand an essential concept	***Investigate*** Step 15 ***Physics to Go*** Question 5	**Augmentation** • Make sure students know the difference between the *x*-axis and *y*-axis. • Many students do not recognize the patterns in numbers that make it possible to set up the scale for each axis. Use the board or an overhead to model the process for setting up the axes scales. Scaffold this graphing skill by providing opportunities for students to practice setting up axes scales as the main goal of the *Investigate*. • Check to make sure students have drawn an accurate graph before they begin making conclusions about the relationships. • Provide a few descriptions of possible relationships and ask students to choose the description that is supported by their graph. **Accommodation** • Give students a graph with both the *x*-axis and the *y*-axis labeled and scaled, and then ask students to graph their data. • Some students may need one-on-one or small group assistance to graph the data. • If students are unable to describe the relationship shown by the graph, guide them through the process of interpreting graphs by modeling a "think-aloud" to point out key features of a graph and to explain the thought processes used while interpreting a graph.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Research skills	***What Do You Think?***	Divide ELL students into three groups and assign each group a short research project: the Hale Telescope at Palomar Observatory, the Hubble Space Telescope, or fun-house mirrors. Have them write up a paragraph or two and present the information orally to the class.
Using mnemonics	***Investigate*** Steps 1 and 10	ELL students may benefit from associating the concave shape with the term “cave-in,” meaning “to fall in on itself.”
Comprehension	***Investigate*** Steps 9, 10, and 12	Check students’ work to be sure they have correctly determined the focal point and correctly labeled the focal length using the convex mirror. Do the same for the concave mirror. Students should now see that each reflected beam from the convex mirror moves *away from* the focal point and each reflected beam from the concave mirror moves *toward and through* the focal point.
Applying content	***Investigate*** Step 15	After students have written down the relationship between the image distance and the object distance, have them repeat the relationship to you orally. They should state an inverse relationship: As the object distance decreases, the image distance increases.
Vocabulary Comprehension Understanding concepts	***Physics Talk***	Be sure students are able to explain what a real image is and also what a virtual image is in terms of whether the image can be projected [real: yes; virtual: no] and whether the light rays pass through the image location [real: yes; virtual: no].
Understanding equations	***Active Physics Plus***	Give ELL students the mathematical relationship $1/f = 1/d_o + 1/d_i$ and have them explain it in words: The inverse of the focal length for the mirror equals the inverse of the object distance plus the inverse of the image distance.
Critical thinking	***What Do You Think Now?***	Have students revisit the brief presentations they made at the start of the section. Ask them to add any new thoughts and ideas they may have on why the mirrors in those three devices are curved. Hold a class discussion so students can share their thoughts through more speaking practice.
Vocabulary comprehension	***Reflecting on the Section and the Challenge***	Give ELL students the opportunity to infer the meaning of “pliable” from context as “bendable” or “flexible.”

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SECTION 7

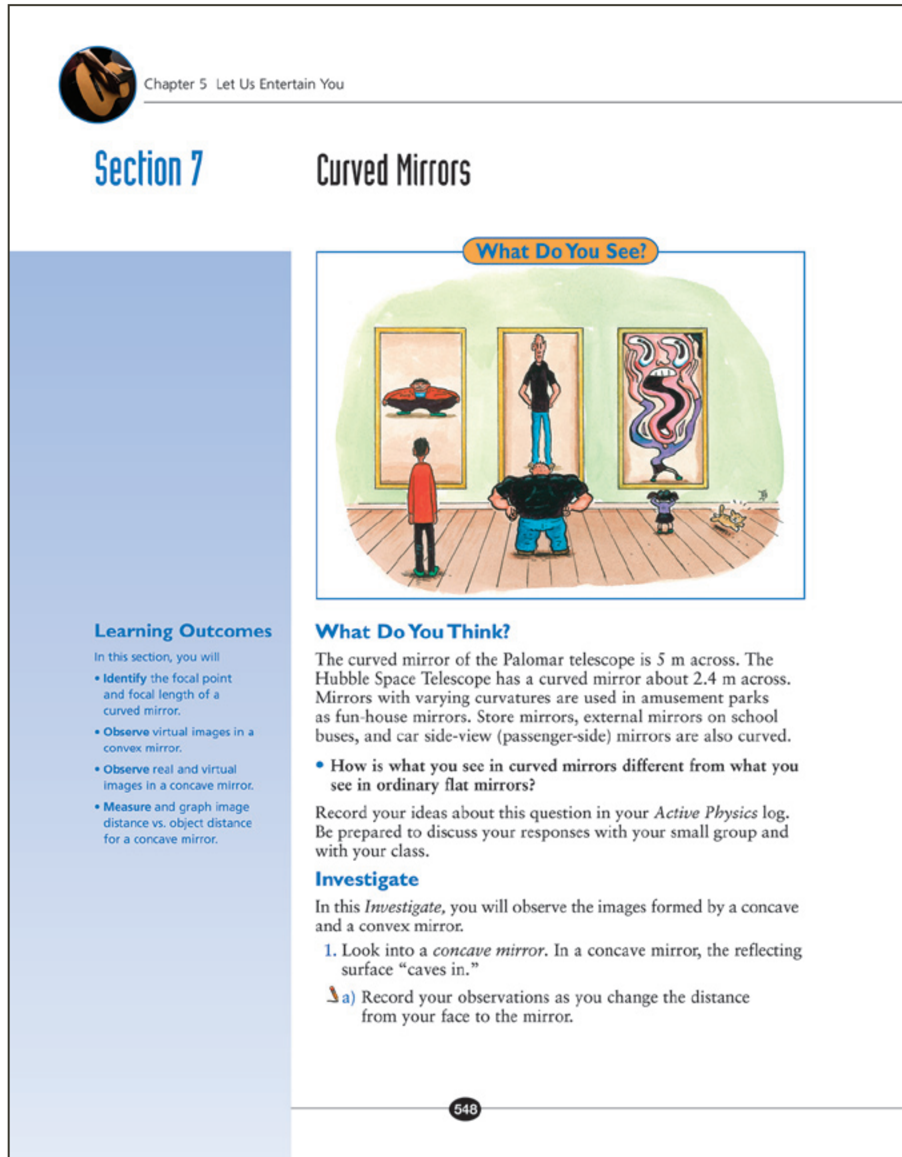
Teaching Suggestions and Sample Answers

What Do You See?

The *What Do You See?* illustration can be answered on many levels. This illustration offers a multi-layered perspective in one glance, and students will most likely comment on the different images on the wall. Use an overhead projector to magnify the illustration so that students can gain a sharper focus of each image. Tell students that each detail in this illustration points to the purpose of this section. Prompt students to distinguish between the different images on the wall. Point out that their reflections are significant and will eventually lead them to a better understanding of the topic.

What Do You Think?

Students will come up with varied answers. Encourage them to recall where they have seen curved mirrors and what differences they


Chapter 5 Let Us Entertain You

Section 7 Curved Mirrors

What Do You See?

Learning Outcomes

In this section, you will

- **Identify** the focal point and focal length of a curved mirror.
- **Observe** virtual images in a convex mirror.
- **Observe** real and virtual images in a concave mirror.
- **Measure** and graph image distance vs. object distance for a concave mirror.

What Do You Think?

The curved mirror of the Palomar telescope is 5 m across. The Hubble Space Telescope has a curved mirror about 2.4 m across. Mirrors with varying curvatures are used in amusement parks as fun-house mirrors. Store mirrors, external mirrors on school buses, and car side-view (passenger-side) mirrors are also curved.

- **How is what you see in curved mirrors different from what you see in ordinary flat mirrors?**

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

In this *Investigate,* you will observe the images formed by a concave and a convex mirror.

1. Look into a *concave mirror*. In a concave mirror, the reflecting surface "caves in."

   a) Record your observations as you change the distance from your face to the mirror.

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Students' Prior Conceptions

The experience that students gain in this section is a necessary intervention to help them differentiate between the location of real images and the location of the focal point.

1. **Students confuse clarity of an image with the position of a focal point for a curved mirror (i.e., where the image is in focus). They believe that the focal point of the mirror is the location of all of the clearly formed images.** This implies that the focal point is not a fixed entity but that it moves with the location of a clearly defined image. The *Investigate* in this section and explanatory observations are critical for students to test their predictions and to change what they believe about clarity of image and focal point. Emphasize the difference between the focal point, where parallel rays cross, and the image distance/position where nonparallel rays from the object converge.

observed between the images in curved mirrors and those in plain ones. If you bring a curved mirror to class, (for example a spoon), students will have a concrete example before them on which they can support their answers. Students should be prepared to talk about their responses with their group and with the class. You might also want to write their responses on the board to provide important points of discussion. Remind students to record their ideas in their *Active Physics* logs. This question gives you the opportunity to assess students' prior understanding of curved mirrors and later address their misconceptions. Accept all answers that are relevant, even though they may not be correct.

Investigate

1.a)

Students' observe that the image is upside down and that it gets larger as they move closer to the mirror. If the mirror is large enough (or has a long focal length), they may be able to bring their face inside the focal length, at which point their image will be right-side up, continuing to get smaller as they get closer to the mirror. The image may be larger or smaller, depending upon the distance from the mirror.

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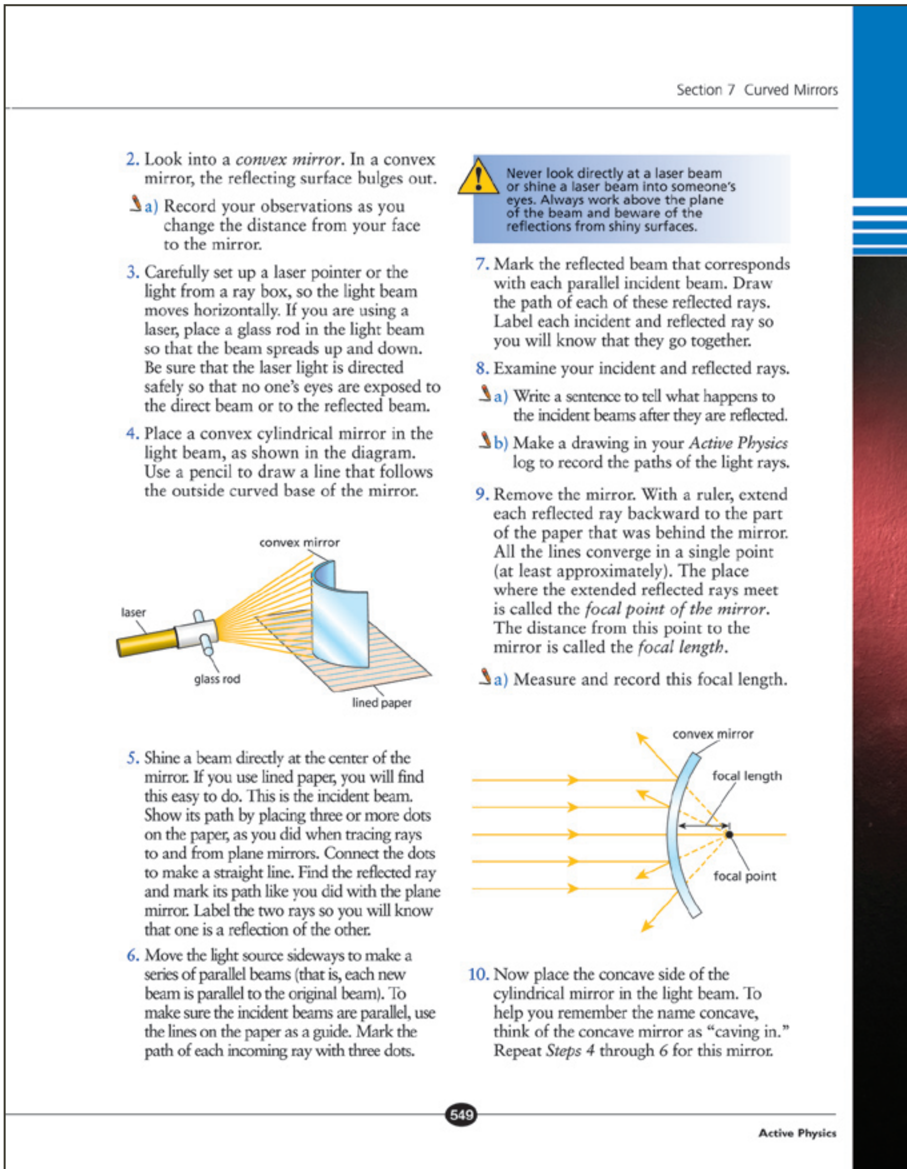
What Do You Think?

A Physicist's Response

The image in a flat mirror has the same proportions as the object. To explain this observation, recall that the reflected image is the same distance behind the mirror as the object is in front, and on a line from the object perpendicular to the mirror. A displacement of the object produces an equal displacement of the image, so the proportions are preserved. But in a curved mirror, this proportionality is lost. The ray diagrams following *Question 10* in the *Investigate* as well as the ones in the *Physics Talk* show how curved mirrors reflect a parallel beam of light. Imagine standing close to these mirrors and looking at the image of the distant object. Because the image is seen along the extension of the reflected light rays, the concave mirror makes the object look larger (in the direction of the curvature) and the convex mirror makes the image look smaller. Images seen in concave mirrors can be real if the object is located outside the focal point of the mirror. The image will be virtual if the object is between the focal point and the concave mirror. For convex mirrors, the images are always virtual and always smaller than the original object.

NOTES



Section 7 Curved Mirrors

2. Look into a *convex mirror*. In a convex mirror, the reflecting surface bulges out.

a) Record your observations as you change the distance from your face to the mirror.

3. Carefully set up a laser pointer or the light from a ray box, so the light beam moves horizontally. If you are using a laser, place a glass rod in the light beam so that the beam spreads up and down. Be sure that the laser light is directed safely so that no one's eyes are exposed to the direct beam or to the reflected beam.

4. Place a convex cylindrical mirror in the light beam, as shown in the diagram. Use a pencil to draw a line that follows the outside curved base of the mirror.

5. Shine a beam directly at the center of the mirror. If you use lined paper, you will find this easy to do. This is the incident beam. Show its path by placing three or more dots on the paper, as you did when tracing rays to and from plane mirrors. Connect the dots to make a straight line. Find the reflected ray and mark its path like you did with the plane mirror. Label the two rays so you will know that one is a reflection of the other.

6. Move the light source sideways to make a series of parallel beams (that is, each new beam is parallel to the original beam). To make sure the incident beams are parallel, use the lines on the paper as a guide. Mark the path of each incoming ray with three dots.

Never look directly at a laser beam or shine a laser beam into someone's eyes. Always work above the plane of the beam and beware of the reflections from shiny surfaces.

7. Mark the reflected beam that corresponds with each parallel incident beam. Draw the path of each of these reflected rays. Label each incident and reflected ray so you will know that they go together.

8. Examine your incident and reflected rays.

a) Write a sentence to tell what happens to the incident beams after they are reflected.

b) Make a drawing in your *Active Physics* log to record the paths of the light rays.

9. Remove the mirror. With a ruler, extend each reflected ray backward to the part of the paper that was behind the mirror. All the lines converge in a single point (at least approximately). The place where the extended reflected rays meet is called the *focal point of the mirror*. The distance from this point to the mirror is called the *focal length*.

a) Measure and record this focal length.

10. Now place the concave side of the cylindrical mirror in the light beam. To help you remember the name concave, think of the concave mirror as "caving in." Repeat *Steps 4* through *6* for this mirror.

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Active Physics

2.a)

Students should record their image is right-side up and that it gets larger as they move toward the mirror, but is always reduced in size relative to the object (their face).

3.

Place the glass rod in the laser beam as you did in *Section 6, Step 4* of the *Investigate*.

4.

Students should use a cylindrical convex mirror for this step of the *Investigate*.

5.

Students should mark the path of incident and reflected rays as they did in *Section 6, Step 7* of the *Investigate*.

6.

It may be easier to pull the paper sideways to move the mirror and keep the light source stationary, instead of moving the light source. Students mark the path of each incoming ray with three dots.

7.

Students mark the incident and reflected rays as in *Section 6, Step 9* of the *Investigate*.

8.a)

After reflecting from the convex mirror, the parallel, incident beams spread apart.

8.b)

Students' drawings should resemble the one below *Investigate Step 9.a)* of this section in the *Student Edition*.

9.a)

After students extend the rays behind the mirror, they may find that the rays may not meet at exactly the same place, but students should get the general idea. Students should measure and record the distance between the mirror and this focal point. (Actually, a virtual focal point because the light rays do not really meet there.)

10.a)

For this part, students should use the concave side of the cylindrical mirror.

After reflecting from the concave mirror, the parallel beams come together at approximately a single point.

10.b)

Students drawings should appear similar to the one for this step in the *Student Edition*.

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10.c)

If students used the same mirror for both the convex and concave mirror, the focal lengths should be approximately the same because the two sides have the same magnitude of curvature.

11.

Students should note that the reflected beam moves back along the parallel lines.

12.a)

Convex mirrors cause parallel light rays to diverge. Concave mirrors cause parallel light rays to converge.

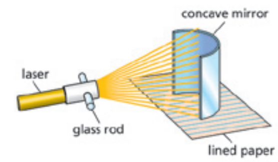
13.

For this part, students should use a "spherical" concave mirror, such as a cosmetics mirror.

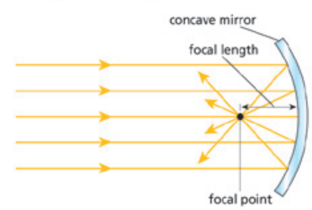
14.a)

Students may need help in finding the image. Look for the brightest and clearest image (in focus) where the rays converge. They should record both the distance from the mirror to the bulb and the distance from the mirror to the position where the image appears clearest on the card.

5-7a Blackline Master



a) Is it true that all the reflected light beams from the concave mirror converge in a single point (at least approximately)?



b) Make a drawing in your *Active Physics* log to record the path of the light.

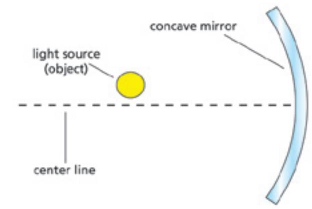
c) Measure and record the focal length.

11. Now that you have located the focal point, move the laser back along the parallel lines as before. As you move the laser, you will notice that the reflected beam always moves through the focal point.

12. How do concave and convex mirrors reflect light differently?

a) Record your answer in your log.

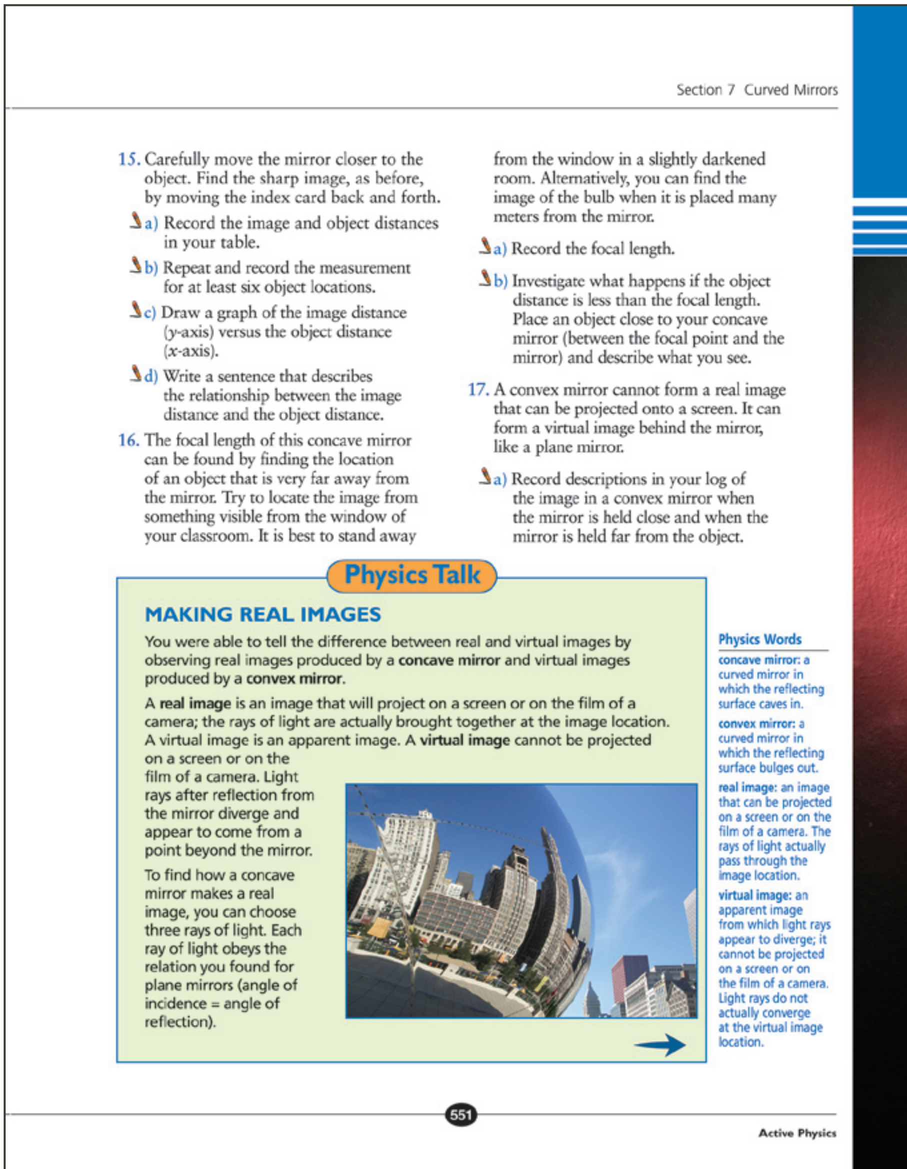
13. Now set up the concave spherical mirror as shown in the diagram. Use a 40-W light bulb as a light source. The light bulb will be called the "object." Carefully mount your mirror so its center is at the same height as the light source. Place the light source about a meter away from the mirror. Put the source slightly off the centerline, as shown.



14. Try to find the image of the light source on an index card. (You may need to move the light source a bit more to the side of the centerline so the index card does not block the light from hitting the mirror.) Move the card back and forth until the image is sharp. The image you found is called a *real image* because you are able to project it on a card or a screen. The images you saw in a flat mirror are not real images because they cannot be seen on a screen or card. Such images are called *virtual images*. Here, virtual means "not real." A virtual image is an apparent source of light rays. The light rays do not actually converge at a virtual image location.

a) Record the distance of the bulb from the reflecting surface of the concave mirror and of the focused image on the index card from the mirror. Put your results in the first line of a table like the one below.

Object distance (Distance of bulb from mirror)	Image distance (Distance of image from mirror)



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15. Carefully move the mirror closer to the object. Find the sharp image, as before, by moving the index card back and forth.

a) Record the image and object distances in your table.

b) Repeat and record the measurement for at least six object locations.

c) Draw a graph of the image distance (*y*-axis) versus the object distance (*x*-axis).

d) Write a sentence that describes the relationship between the image distance and the object distance.

16. The focal length of this concave mirror can be found by finding the location of an object that is very far away from the mirror. Try to locate the image from something visible from the window of your classroom. It is best to stand away from the window in a slightly darkened room. Alternatively, you can find the image of the bulb when it is placed many meters from the mirror.

a) Record the focal length.

b) Investigate what happens if the object distance is less than the focal length. Place an object close to your concave mirror (between the focal point and the mirror) and describe what you see.

17. A convex mirror cannot form a real image that can be projected onto a screen. It can form a virtual image behind the mirror, like a plane mirror.

a) Record descriptions in your log of the image in a convex mirror when the mirror is held close and when the mirror is held far from the object.

Physics Talk

MAKING REAL IMAGES

You were able to tell the difference between real and virtual images by observing real images produced by a **concave mirror** and virtual images produced by a **convex mirror**.

A **real image** is an image that will project on a screen or on the film of a camera; the rays of light are actually brought together at the image location. A virtual image is an apparent image. A **virtual image** cannot be projected on a screen or on the film of a camera. Light rays after reflection from the mirror diverge and appear to come from a point beyond the mirror.

To find how a concave mirror makes a real image, you can choose three rays of light. Each ray of light obeys the relation you found for plane mirrors (angle of incidence = angle of reflection).

Physics Words

concave mirror: a curved mirror in which the reflecting surface caves in.

convex mirror: a curved mirror in which the reflecting surface bulges out.

real image: an image that can be projected on a screen or on the film of a camera. The rays of light actually pass through the image location.

virtual image: an apparent image from which light rays appear to diverge; it cannot be projected on a screen or on the film of a camera. Light rays do not actually converge at the virtual image location.

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Active Physics

15.a)

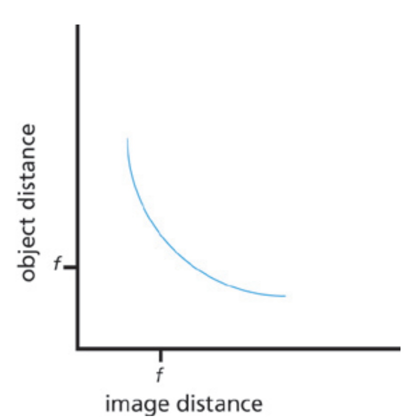
Students record object and image distances.

15.b)-c)

See sample data. Results depend on the curvature of the mirror.

Sample Data	
d_o (m)	d_i (m)
26.5	0.37
5.13	0.45
2.74	0.48
1.37	0.52
0.95	0.63
0.51	1.30

Students graphs should look similar to the following graph.



15.d)

As the object distance decreases, the image distance increases (and vice versa).

16.a)

Students locate the image of the distant object and record the distance from the mirror as approximately equal to the focal length.

16.b)

With the object distance less than the focal length, students will find that the image would appear to be enlarged and right-side up but located behind the mirror (like the image in a plane mirror). No image can be focused on the card since no real image is formed.

17.a)

Students should note that the image is always right-side up and smaller than the object. The closer the object gets to the mirror, the larger the image becomes.

Physics Talk

This section discusses the images formed by concave and convex mirrors, and how a real image is different from a virtual image. Ray diagrams show how real images are formed by curved mirrors, showing the path of incident and reflecting rays. The formation of virtual images is shown by extending reflected light rays behind the mirrors. Students read why a concave mirror produces both a real image and a virtual image, while a convex mirror produces only a virtual image. For real images formed by concave mirrors and virtual images formed by convex mirrors, students see that decreasing the

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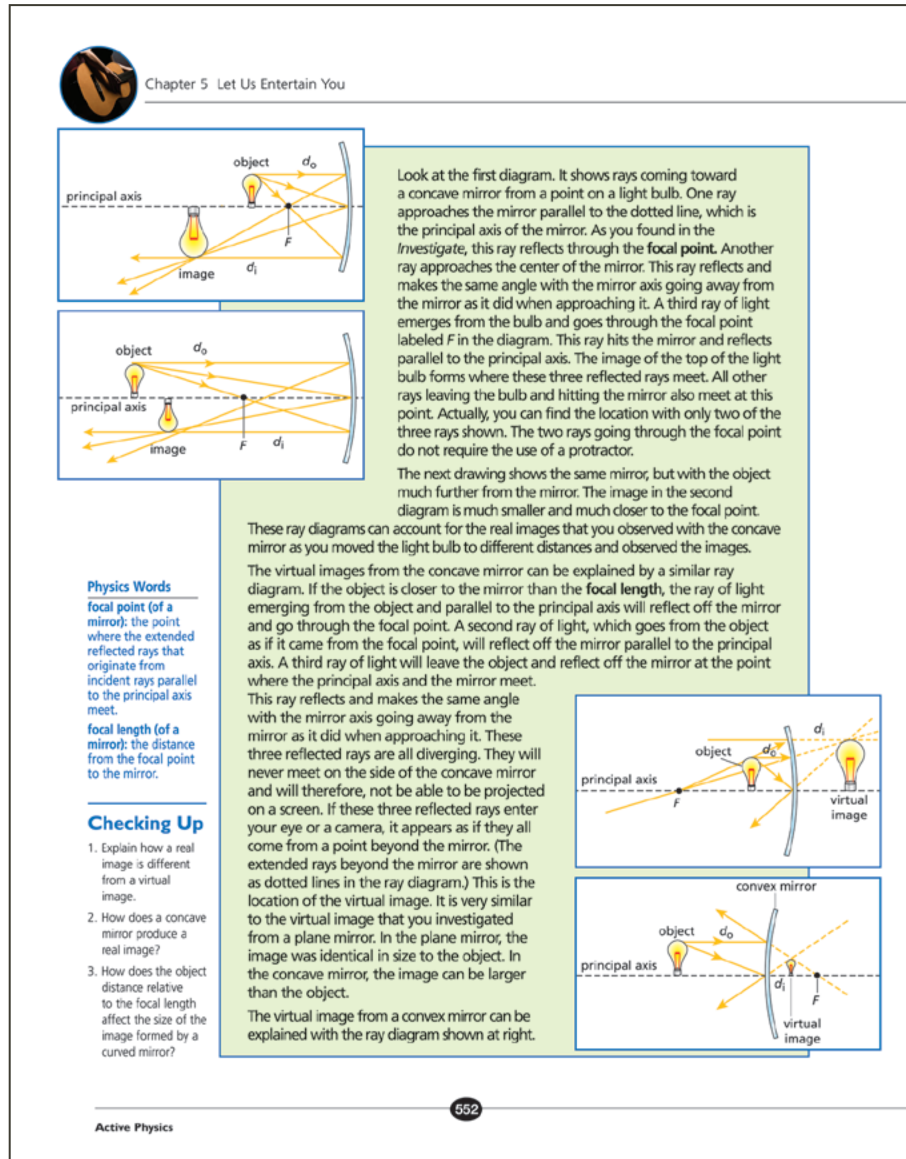
object distance increases the image distance and the size of the image. In contrast, the virtual images formed by concave mirrors become smaller and are closer to the mirror as the object distance is decreased.

Students are expected to note the general rules that govern the images formed by the mirrors. For concave mirrors, the image is always real when the object is outside the focal length, and virtual when inside the focal length. The real image decreases in size and distance from the mirror when the object moves away from the mirror, but the image is never closer to the mirror than the focal length. Virtual images formed by a concave mirror only occur when the object is inside the focal length. They are always larger than the object and decrease in size as the object moves toward the mirror.

Ask students to draw ray diagrams in which they change the position of the object in front of the mirror to trace the path of rays that converge or diverge from a reflecting surface to form a real or virtual image. Point out that convex mirrors only form virtual images that increase in size as the object distance decreases, and are always reduced in size relative to the object.

Consider asking students to give examples of concave and convex lenses that are used for practical purposes by doctors, drivers, and technicians. Find out if students understand how images formed by a concave mirror can be different from a plane mirror. Encourage students to write down the *Physics Words* in their *Active Physics* logs.


Chapter 5 Let Us Entertain You

Look at the first diagram. It shows rays coming toward a concave mirror from a point on a light bulb. One ray approaches the mirror parallel to the dotted line, which is the principal axis of the mirror. As you found in the *Investigate*, this ray reflects through the **focal point.** Another ray approaches the center of the mirror. This ray reflects and makes the same angle with the mirror axis going away from the mirror as it did when approaching it. A third ray of light emerges from the bulb and goes through the focal point labeled *F* in the diagram. This ray hits the mirror and reflects parallel to the principal axis. The image of the top of the light bulb forms where these three reflected rays meet. All other rays leaving the bulb and hitting the mirror also meet at this point. Actually, you can find the location with only two of the three rays shown. The two rays going through the focal point do not require the use of a protractor.

The next drawing shows the same mirror, but with the object much further from the mirror. The image in the second diagram is much smaller and much closer to the focal point.

These ray diagrams can account for the real images that you observed with the concave mirror as you moved the light bulb to different distances and observed the images.

The virtual images from the concave mirror can be explained by a similar ray diagram. If the object is closer to the mirror than the **focal length**, the ray of light emerging from the object and parallel to the principal axis will reflect off the mirror and go through the focal point. A second ray of light, which goes from the object as if it came from the focal point, will reflect off the mirror parallel to the principal axis. A third ray of light will leave the object and reflect off the mirror at the point where the principal axis and the mirror meet. This ray reflects and makes the same angle with the mirror axis going away from the mirror as it did when approaching it. These three reflected rays are all diverging. They will never meet on the side of the concave mirror and will therefore, not be able to be projected on a screen. If these three reflected rays enter your eye or a camera, it appears as if they all come from a point beyond the mirror. (The extended rays beyond the mirror are shown as dotted lines in the ray diagram.) This is the location of the virtual image. It is very similar to the virtual image that you investigated from a plane mirror. In the plane mirror, the image was identical in size to the object. In the concave mirror, the image can be larger than the object.

The virtual image from a convex mirror can be explained with the ray diagram shown at right.

Physics Words

focal point (of a mirror): the point where the extended reflected rays that originate from incident rays parallel to the principal axis meet.

focal length (of a mirror): the distance from the focal point to the mirror.

Checking Up

1. Explain how a real image is different from a virtual image.
2. How does a concave mirror produce a real image?
3. How does the object distance relative to the focal length affect the size of the image formed by a curved mirror?

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Active Physics

Checking Up

1.

A real image can be projected on a screen or on the film of a camera, while a virtual image cannot be projected on a screen or on the film of a camera.

2.

A concave mirror produces a real image by causing reflected incident rays of an object that are located outside the focal length of the mirror to converge at a point.

3.

In the case of a concave mirror, the size of an image decreases as the object distance increases. In a convex mirror, the size of an image increases as the object gets closer to mirror.

5-7b Blackline Master

5-7c Blackline Master

Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
•			

Is there an Equation to Relate Focal Length with Object and Image Distances?

A mathematical relation that describes focal length, object distance, and image distance for concave mirrors is

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

In mathematical symbols, the relationship is

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

where
f is the focal length of the mirror,
d_o is the object distance, and
d_i is the image distance.

You have measured d_o and d_i in the *Investigate*. Use the values from the log table in *Step 14* to calculate the sum of $\frac{1}{d_o}$ and $\frac{1}{d_i}$ for each pair of data.

1. Record your calculations in your log using a table like the following:

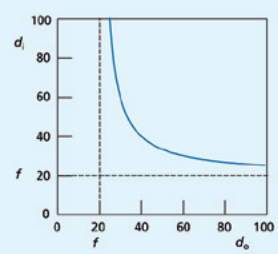
d_o	d_i	$\frac{1}{d_o}$	$\frac{1}{d_i}$	$\frac{1}{d_o}+\frac{1}{d_i}$	f

a) Are your sums approximately equal? If so, you have mathematically found the value of $1/f$ for the mirror you used. From that result, find the focal length.

As you have seen, the distances of the object and image and the focal length are related by the equation below.

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

Look at the graph of the equation that relates focal length, object distance, and image distance. Notice that as the object distance decreases, the image distance becomes very large. As the object distance increases, the image distance approaches the focal length (f).



The equation $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ can also be derived from this graph. You can attempt this derivation by recognizing that the graph is a hyperbola that has been shifted by a distance equal to the focal length in both the x- and y-axes.

Active Physics Plus

This exercise leads the students through the derivation of the relationship between the radius of curvature and the focal length of a spherical concave mirror. Students may need assistance in recalling the appropriate theorems from geometry.

1.a)

Using sample data from the *Investigate*, *Step 14*, and putting the values into the table gives the following data:

d_o	d_i	$1/d_o$	$1/d_i$	$1/d_o + 1/d_i$	$1/f$
26.5	0.37	0.037	2.70	2.74	2.74
5.13	0.45	0.194	2.22	2.41	2.41
2.74	0.48	0.365	2.08	2.45	2.45
1.37	0.52	0.73	1.92	2.65	2.43
0.51	1.30	1.96	0.77	2.73	2.73

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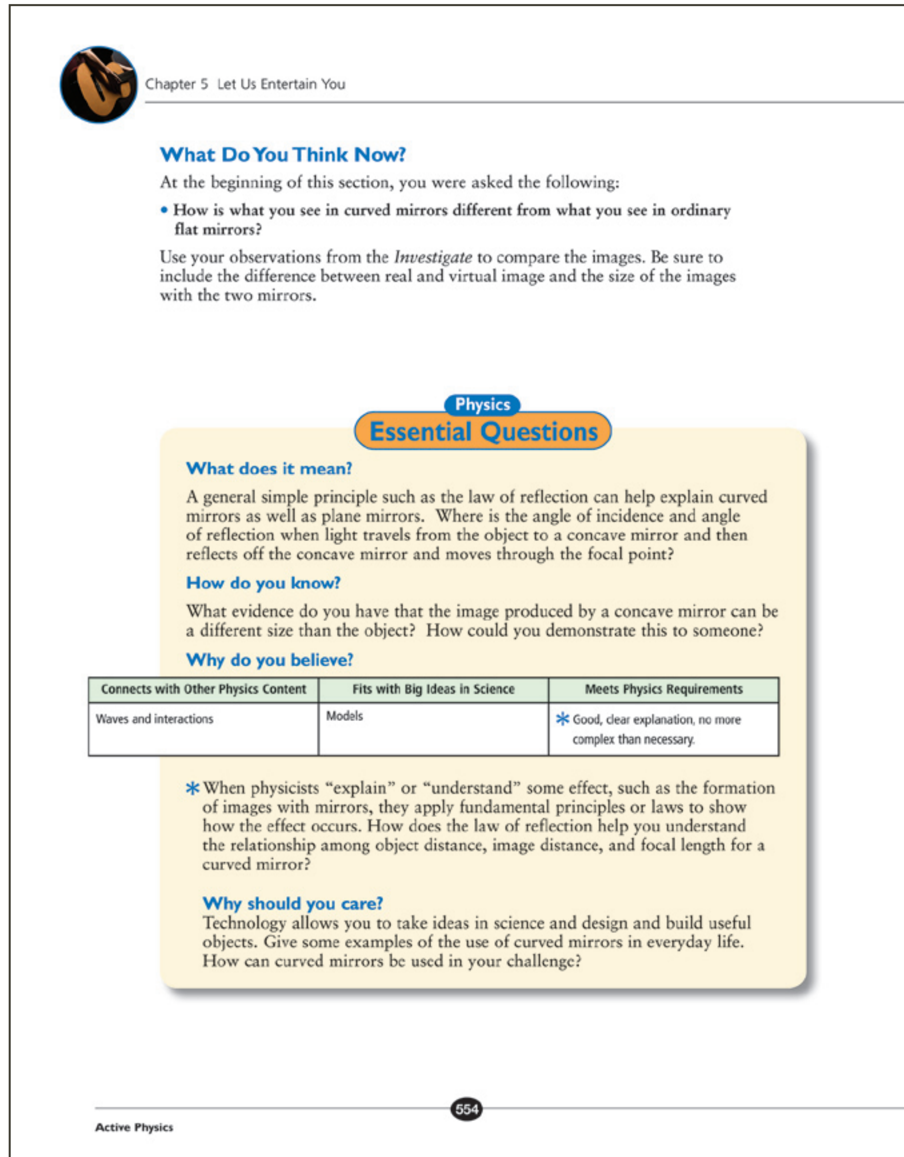
What Do You Think Now?

Make students revisit their responses in light of what they have learned. Consider sharing *A Physicist's Response* and how it explains the *What Do You Think?* question. Have students modify or change their answer in their *Active Physics* log. Encourage a discussion on how curved mirrors form images. Suggest the advantage of making a table where they can write the similarities and differences between different types of mirrors. This is also a good opportunity to revisit the *What Do You See?* illustration.

Reflecting on the Section and the Challenge

Students should now be able to recognize the relevance of curved mirrors to their sound and light show. The use of curved mirrors in producing images of different sizes could lead to an interesting discussion. You could have students make a list of all the possible scenarios where they could utilize their knowledge of


Chapter 5 Let Us Entertain You

What Do You Think Now?

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

- **How is what you see in curved mirrors different from what you see in ordinary flat mirrors?**

Use your observations from the *Investigate* to compare the images. Be sure to include the difference between real and virtual image and the size of the images with the two mirrors.

Physics **Essential Questions**

What does it mean?

A general simple principle such as the law of reflection can help explain curved mirrors as well as plane mirrors. Where is the angle of incidence and angle of reflection when light travels from the object to a concave mirror and then reflects off the concave mirror and moves through the focal point?

How do you know?

What evidence do you have that the image produced by a concave mirror can be a different size than the object? How could you demonstrate this to someone?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Waves and interactions	Models	* Good, clear explanation, no more complex than necessary.

*When physicists "explain" or "understand" some effect, such as the formation of images with mirrors, they apply fundamental principles or laws to show how the effect occurs. How does the law of reflection help you understand the relationship among object distance, image distance, and focal length for a curved mirror?

Why should you care?

Technology allows you to take ideas in science and design and build useful objects. Give some examples of the use of curved mirrors in everyday life. How can curved mirrors be used in your challenge?

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Physics Essential Questions

What does it mean?

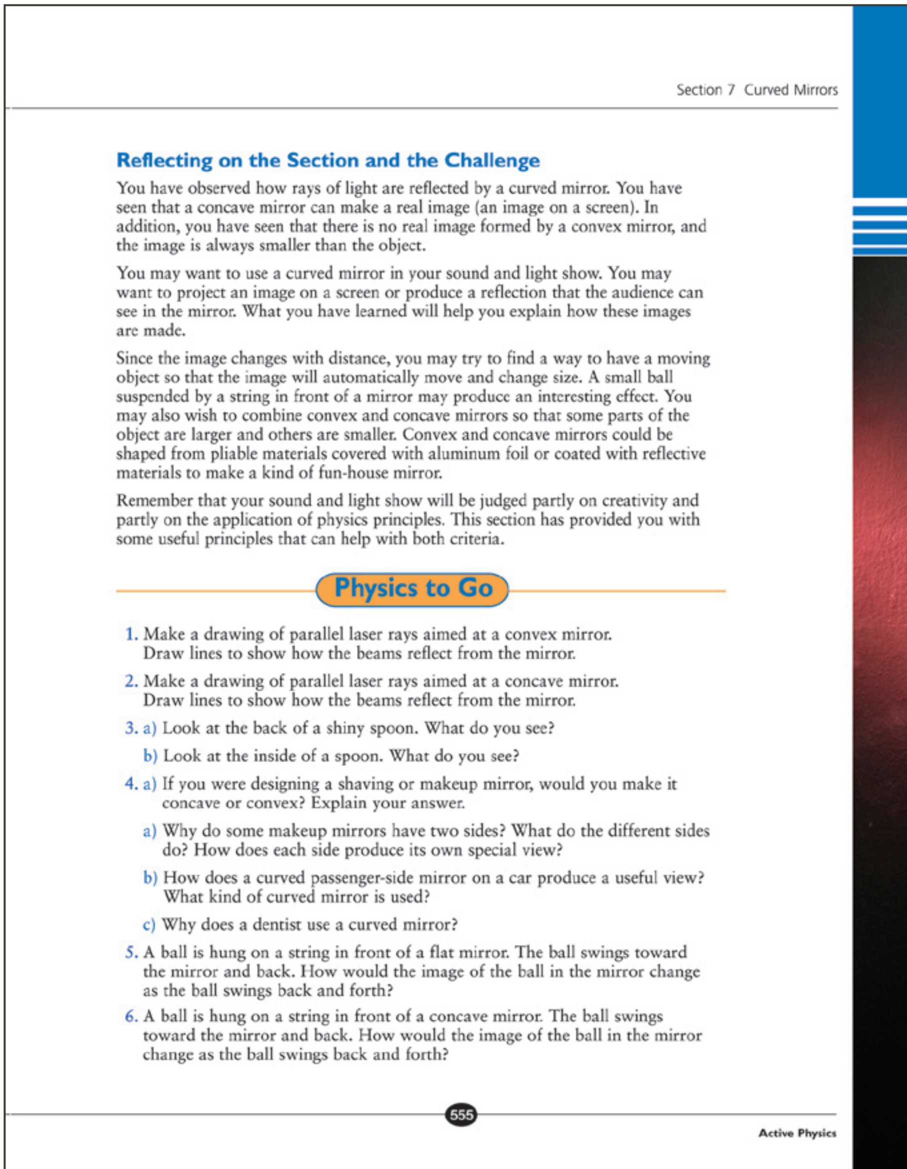
The angle of incidence is defined as the angle between the ray of light hitting the mirror and the normal line (the line that is perpendicular to the mirror). The angle of reflection is defined as the angle between the ray of light leaving the mirror after reflection and the normal line (the line that is perpendicular to the mirror). In a curved spherical mirror, the normal is along a radius of the sphere.

How do you know?

By using the same object and varying the distance between the object and the mirror, images of different sizes were created during the *Investigate* with concave and convex mirrors.

Why do you believe?

The law of reflection states that the angle of incidence equals the angle of reflection. By curving the mirror in such a way that all parallel rays of light reflect off the mirror and intersect at the focal point,



Reflecting on the Section and the Challenge

You have observed how rays of light are reflected by a curved mirror. You have seen that a concave mirror can make a real image (an image on a screen). In addition, you have seen that there is no real image formed by a convex mirror, and the image is always smaller than the object.

You may want to use a curved mirror in your sound and light show. You may want to project an image on a screen or produce a reflection that the audience can see in the mirror. What you have learned will help you explain how these images are made.

Since the image changes with distance, you may try to find a way to have a moving object so that the image will automatically move and change size. A small ball suspended by a string in front of a mirror may produce an interesting effect. You may also wish to combine convex and concave mirrors so that some parts of the object are larger and others are smaller. Convex and concave mirrors could be shaped from pliable materials covered with aluminum foil or coated with reflective materials to make a kind of fun-house mirror.

Remember that your sound and light show will be judged partly on creativity and partly on the application of physics principles. This section has provided you with some useful principles that can help with both criteria.

Physics to Go

1. Make a drawing of parallel laser rays aimed at a convex mirror. Draw lines to show how the beams reflect from the mirror.
2. Make a drawing of parallel laser rays aimed at a concave mirror. Draw lines to show how the beams reflect from the mirror.
3. a) Look at the back of a shiny spoon. What do you see?
   b) Look at the inside of a spoon. What do you see?
4. a) If you were designing a shaving or makeup mirror, would you make it concave or convex? Explain your answer.
   a) Why do some makeup mirrors have two sides? What do the different sides do? How does each side produce its own special view?
   b) How does a curved passenger-side mirror on a car produce a useful view? What kind of curved mirror is used?
   c) Why does a dentist use a curved mirror?
5. A ball is hung on a string in front of a flat mirror. The ball swings toward the mirror and back. How would the image of the ball in the mirror change as the ball swings back and forth?
6. A ball is hung on a string in front of a concave mirror. The ball swings toward the mirror and back. How would the image of the ball in the mirror change as the ball swings back and forth?

curved mirrors to design scenarios for their sound and light show. This is a good time to have students pause and reflect on the new concepts they have learned in this section and how these concepts are linked together.

Physics to Go

1.

Students' drawings should be the same as the one below *Step 9* in the *Investigate*.

2.

Students' drawings should be the same as the one below *Step 10* in the *Investigate*.

3.a)

You see a right-side-up image of yourself and most of the room you are in. If you hold your finger very close to the spoon, you see a right-side up, reduced image. The back of the spoon is a convex mirror.

3.b)

You see an upside-down image of yourself. If you hold your finger very close to the spoon, you see a right-side-up, enlarged image. The curved depression of the spoon is a concave mirror.

CHAPTER 5

the images will have different properties than those of a plane mirror. The images can be real as well as virtual and can be larger and smaller than the object. By obeying the law of reflection, each light ray that leaves one point on the object after striking the mirror will reflect and converge at one point to form an image of that point on the object. It is the law of reflection that determines the location of the point where these light rays converge to form the image.

Why should you care?

Curved mirrors are used by dentists and in side- and rear-view mirrors of vehicles. They are also used in stores to see large areas of the store. Curved mirrors are often mounted on trees or posts near an entrance to driveways or alleyways with limited fields of view to allow a driver to see approaching vehicles. Curved mirrors can produce larger images for the light and sound show and/or can be used to distort images by bending the mirror in irregular ways.

4.a)

The mirror should be concave, so it can enlarge the area of the face that needs to be magnified. Make-up mirrors often have two sides—one side is a concave mirror to form an enlarged image, and the other side is a plane mirror. The plane mirror will allow the person looking into the mirror to see a normal view of the face (not enlarged). The concave mirror allows the viewer to see an enlarged virtual image of a smaller portion of their face.

4.b)

This curved mirror is convex. It provides a wide-angle view, so vehicles away to the side (called the blind spot) can be seen. But the image is smaller, so vehicles appear further behind than they actually are.

4.c)

A dentist uses a curved mirror to get a magnified view of the teeth.

5.

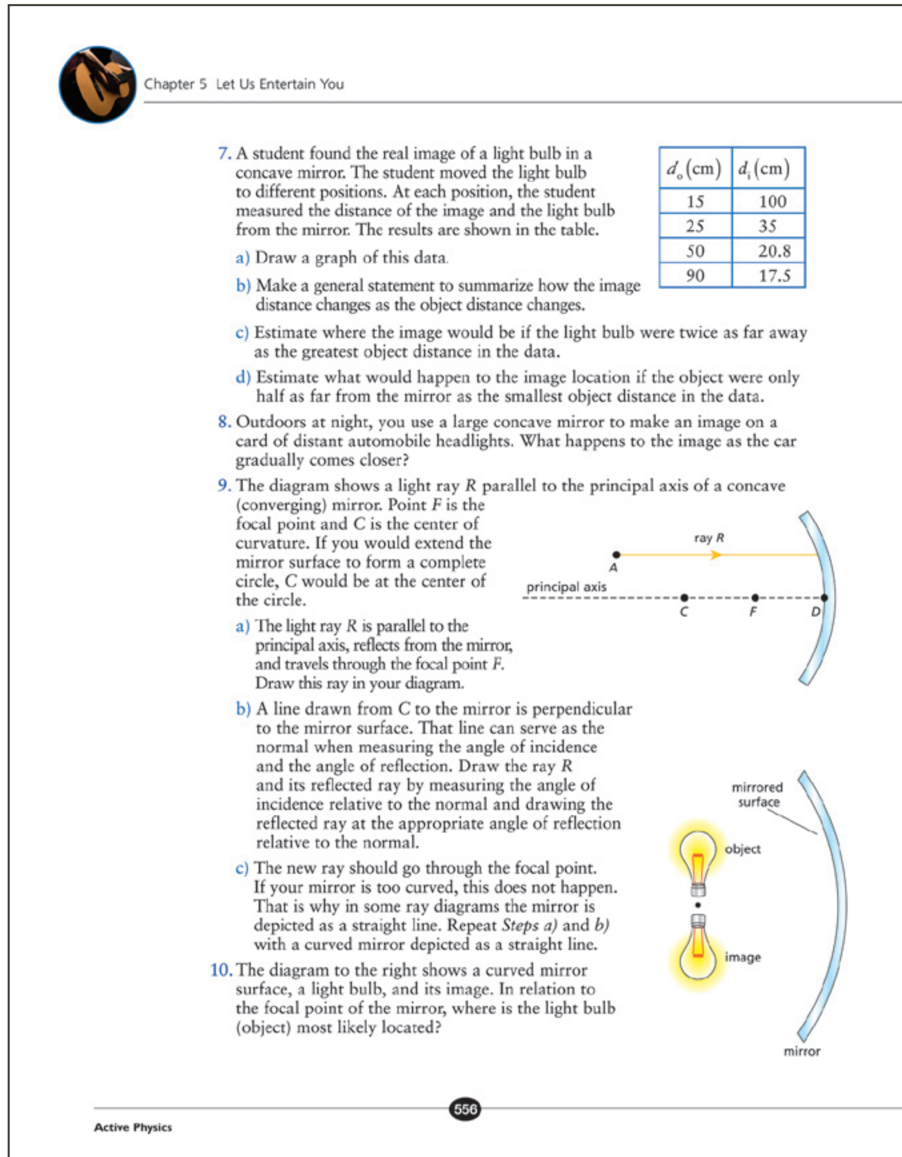
As the ball swings toward the mirror, the image also swings toward the mirror.

6.

The answer depends on whether or not the ball swings through the focal point of the mirror. If it does swing through the focal point, then while swinging in, the image goes from upside-down to right-side-up and gets magnified. At the focal point, the image fills the mirror.

7.a)

Students' graphs should look like the following:



7. A student found the real image of a light bulb in a concave mirror. The student moved the light bulb to different positions. At each position, the student measured the distance of the image and the light bulb from the mirror. The results are shown in the table.

d_o (cm)	d_i (cm)
15	100
25	35
50	20.8
90	17.5

a) Draw a graph of this data.

b) Make a general statement to summarize how the image distance changes as the object distance changes.

c) Estimate where the image would be if the light bulb were twice as far away as the greatest object distance in the data.

d) Estimate what would happen to the image location if the object were only half as far from the mirror as the smallest object distance in the data.

8. Outdoors at night, you use a large concave mirror to make an image on a card of distant automobile headlights. What happens to the image as the car gradually comes closer?

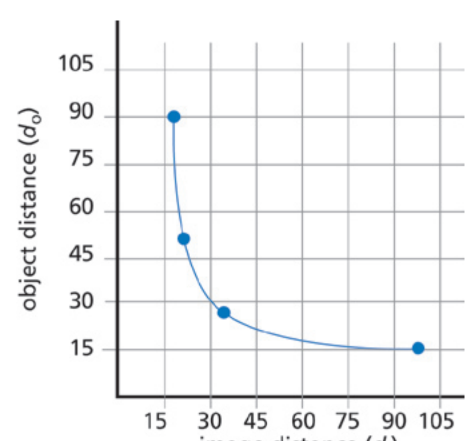
9. The diagram shows a light ray *R* parallel to the principal axis of a concave (converging) mirror. Point *F* is the focal point and *C* is the center of curvature. If you would extend the mirror surface to form a complete circle, *C* would be at the center of the circle.

a) The light ray *R* is parallel to the principal axis, reflects from the mirror, and travels through the focal point *F*. Draw this ray in your diagram.

b) A line drawn from *C* to the mirror is perpendicular to the mirror surface. That line can serve as the normal when measuring the angle of incidence and the angle of reflection. Draw the ray *R* and its reflected ray by measuring the angle of incidence relative to the normal and drawing the reflected ray at the appropriate angle of reflection relative to the normal.

c) The new ray should go through the focal point. If your mirror is too curved, this does not happen. That is why in some ray diagrams the mirror is depicted as a straight line. Repeat *Steps a)* and *b)* with a curved mirror depicted as a straight line.

10. The diagram to the right shows a curved mirror surface, a light bulb, and its image. In relation to the focal point of the mirror, where is the light bulb (object) most likely located?

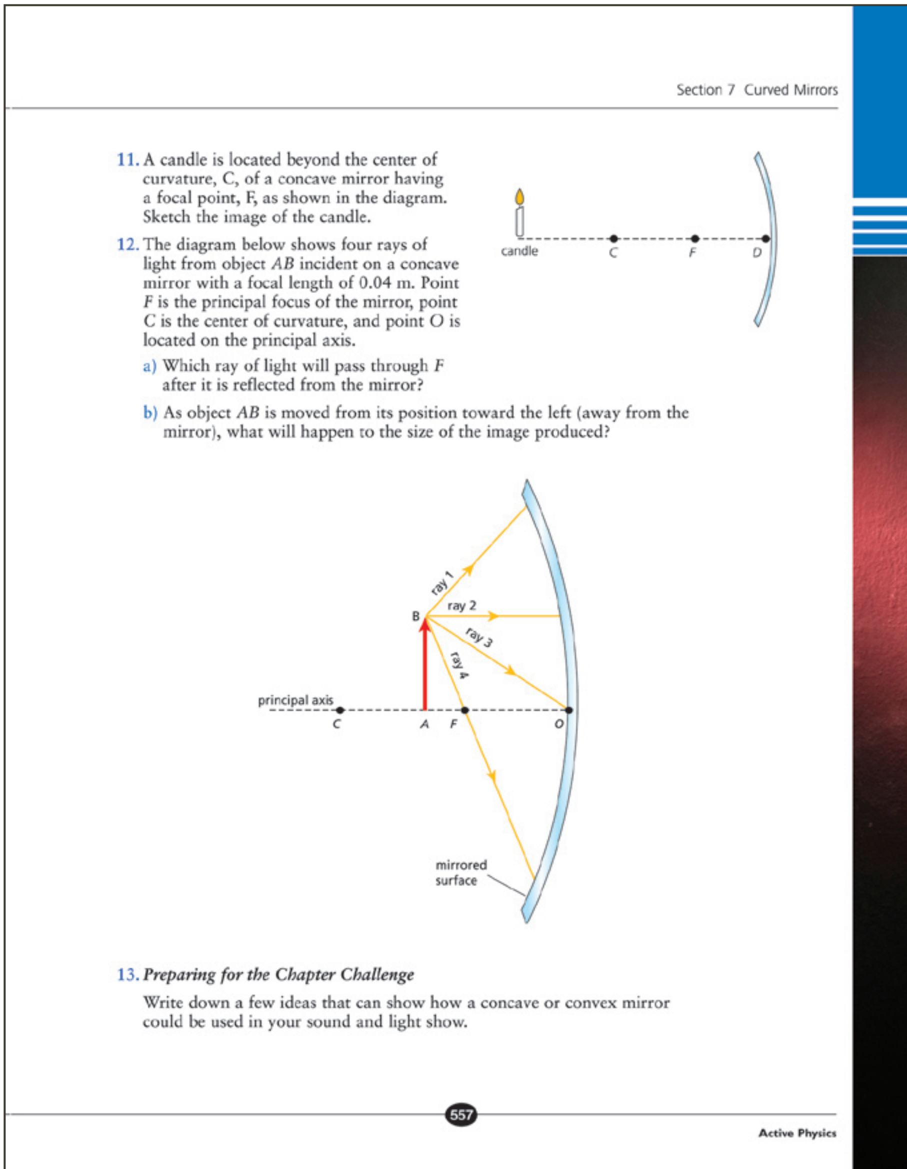


7.b)

As the object distance decreases, the image distance increases.

7.c)

When the object is very far away, the image distance is close to the focal length. Since 90 cm is already quite far away from the lens, the image formed is probably getting close to the focal length. Increasing the distance would bring the image even closer, so it



Section 7 Curved Mirrors

11. A candle is located beyond the center of curvature, C, of a concave mirror having a focal point, F, as shown in the diagram. Sketch the image of the candle.

12. The diagram below shows four rays of light from object *AB* incident on a concave mirror with a focal length of 0.04 m. Point *F* is the principal focus of the mirror, point C is the center of curvature, and point *O* is located on the principal axis.

a) Which ray of light will pass through *F* after it is reflected from the mirror?

b) As object *AB* is moved from its position toward the left (away from the mirror), what will happen to the size of the image produced?

13. ***Preparing for the Chapter Challenge***

Write down a few ideas that can show how a concave or convex mirror could be used in your sound and light show.

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Active Physics

might be located at perhaps 14.5 cm from the lens.

To check, use the equation $1/f = 1/d_o + 1/d_i$, and substitute in a set of values from the data table to find the focal length. Using $d_o = 25$ cm and $d_i = 35$ cm and inserting the values into the equation gives a focal length of 14.6 cm. Using different values from the data table gives slightly different values for the focal length, but this is the closest the image could be located to the lens.

7.d)

The smallest object distance is 15 cm, and the focal length of the mirror is about 13 cm (see *Step 7.c*)). If the smallest object distance were halved, the object would be within one focal length of the mirror, so there would be no real image. You could see a virtual image.

8.

The image gradually moves away from the mirror and becomes larger.

9.a)

A ray approaching the mirror parallel to the principal axis would be reflected from the mirror and cross the axis at the focal point. Students' diagrams should show this.

9.b)

Students should use a protractor to measure the angle of incidence of 19 degrees.

9.c)

Students repeat the measurements with a curved mirror.

10.

The object is most likely located at the center of curvature.

11.

Students sketch the image of the candle. Students' sketches should show an image of the candle that is inverted, located between *C* and *F*, and smaller than the object.

12.a)

The ray that is parallel to the principal axis will pass through *F*.

12.b)

The size of the image produced will get smaller.

13.

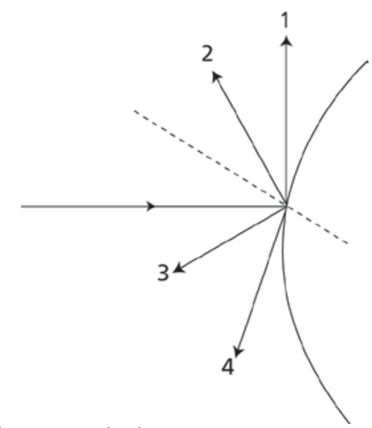
Preparing for the Chapter Challenge

Convex curved mirrors may be used to spread light out similar to a disco ball. Concave mirrors may be used to project an image of a light source onto a large screen.

SECTION 7 QUIZ

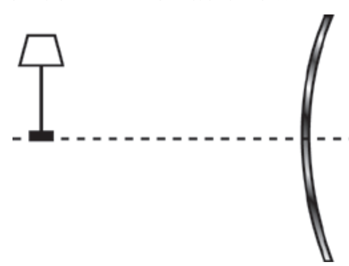
5-7d **Blackline Master**

1. The following diagram shows a light ray striking a convex mirror. The direction of the reflected ray will be

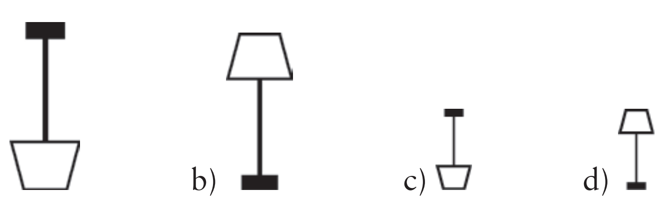


a) 1.
b) 2.
c) 3.
d) 4.

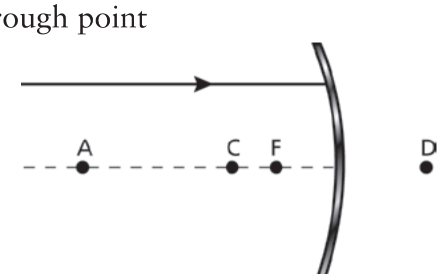
2. A lamp is placed in front of a convex mirror as shown in the diagram below.



Which diagram below best shows the size of the image of the lamp in the mirror?

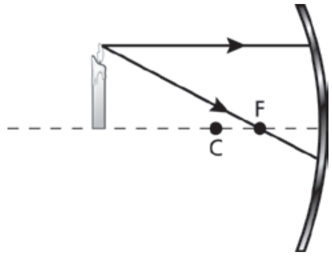


3. The diagram below shows a light ray striking a concave mirror parallel to the principal axis. Point C is the center of curvature of the mirror, and point F is the principal focus. The light ray will reflect through point



a) A.
b) F.
c) C.
d) D.

4. The diagram below shows a candle in front of a concave circular mirror. Two light rays originating from the same point on the candle strike the mirror as shown. After reflecting from the mirror, the light rays will



a) diverge to form a virtual image.

b) diverge to form a real image.

c) converge to form a virtual image.

d) converge to form a real image.

5. An object in front of a concave mirror forms a real image when the light rays are reflected from the mirror. As the object moves away from the mirror, the image will

a) still be real but become smaller.

b) still be real but become larger.

c) become virtual and become smaller.

d) become virtual and become larger.

SECTION 7 QUIZ ANSWERS

1. b) The angle of incidence also equals the angle of reflection for curved mirrors. The position of the perpendicular to the surface (marked by the dotted line) indicates the answer must be *b)*. Choice *a)* is for students who think that objects reflect at right angles, and choice *c)* is a distracter that would appear to go through the focus of a concave mirror.

2. d) Concave mirrors make objects appear smaller and right-side up. Although choice *c)* is smaller, it is inverted, and choices *a)* and *b)* are larger.

3. b) A light ray that strikes a concave spherical mirror parallel to the principal axis will reflect through the focal point. Choices *a)*, *c)*, and *d)* are simply distracters.

4. d) A concave spherical mirror will form a real image from converging light rays when the object is located a distance from the mirror greater than the focal length. Choice *b)* must be incorrect since light rays must converge to form a real image. Choices *a)* and *c)* are for virtual images, which only occur for a concave mirror when the object is inside the focal length.

5. a) Since the object has already formed a real image, it must be beyond the focal length. Moving away will then keep the object real (beyond the focal length), but make it smaller. Choices *c)* and *d)* could only occur if the object moved toward the mirror to inside the focal length.

CHAPTER 5