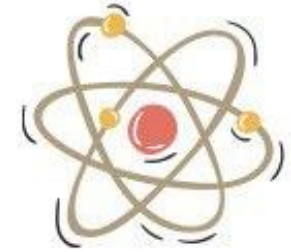


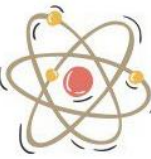
EOT – Term 1 – Part 1

Grade 12 Advanced

Inspire



SIMPLE PHYSICS
With Ms. Hoda



Illuminance Once you know the quantity of light being emitted by a luminous source, you can determine the amount of illumination the source provides to an object, such as a book. The luminous flux falling on a given surface area at any instant is called **illuminance** (E). It is measured in lux (lx), which is equivalent to lumens per square meter (lm/m^2). In this module, we assume, for simplification, that all light sources are point sources.

Consider the setup shown in **Figure 6**. The luminous flux of the source is 1750 lm (typical of a 26-W compact fluorescent bulb). What is the illuminance of the sphere's inside surface at $r = 1$ m? Because all the bulb's luminous flux strikes the surface, divide the luminous flux by the surface area of the sphere, $4\pi r^2$. The surface area is $4\pi(1.00 \text{ m})^2 = 4\pi \text{ m}^2$, so the illuminance is $\frac{1750 \text{ lm}}{4\pi \text{ m}^2} = 139 \text{ lx}$. This mathematical relationship means that at a distance of 1.00 m from the bulb, 139 lm strikes each square meter.

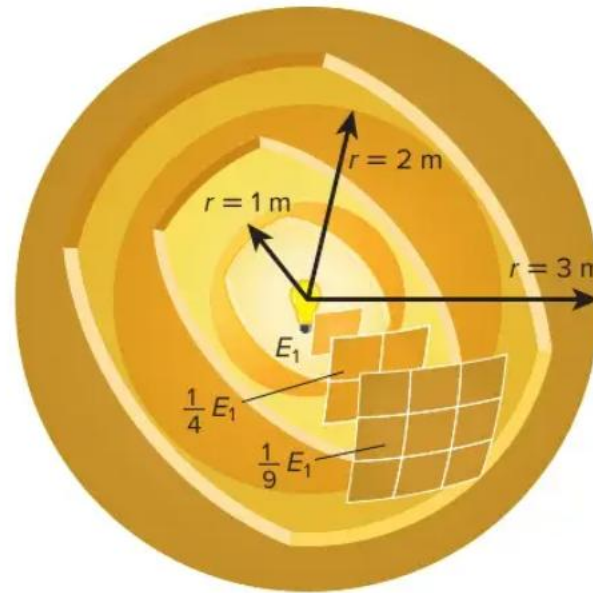
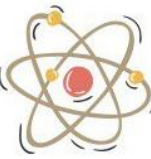


Figure 6 Illuminance (E) is the quantity of light that strikes a surface. As the distance from the luminous source (r) increases, E decreases. E depends on the inverse of r squared.

$$\begin{aligned}\text{Illuminance} \\ E_1 &= \frac{1750}{4\pi} \text{ lx} \\ E_2 &= \frac{1750}{4\pi 2^2} \text{ lx} \\ E_3 &= \frac{1750}{4\pi 3^2} \text{ lx}\end{aligned}$$



Luminous intensity Some luminous sources are specified in candelas (cd). A candela is not a measure of luminous flux but of luminous intensity. The luminous intensity of a point source is the luminous flux that falls on 1 m^2 of the inside of a 1-m-radius sphere, so luminous intensity is luminous flux divided by 4π . A bulb with 1750 lm of flux has an intensity of $\frac{1750 \text{ lm}}{4\pi} = 139 \text{ cd}$.

In **Figure 7**, the lightbulb is twice as far away from the screen as the candle. For the bulb to provide the same illuminance on its side of the screen as the candle does on the candle side of the screen, the bulb would have to be four times brighter than the candle. The lightbulb's luminous intensity, therefore, would have to be four times the candle's luminous intensity. If both sources in **Figure 7** had the same luminous intensity, the source at $2r$ would only provide one-quarter the illuminance to the screen. This is consistent with the inverse-square relationship we just developed.



Get It?

Describe what luminous intensity is a measure of and what its relationship is to illuminance.

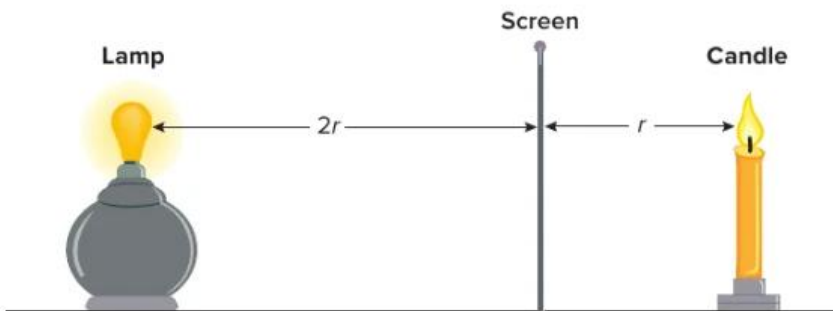


Figure 7 For the lightbulb and the candle to provide the same illuminance to the screen, the luminous intensity of the lightbulb is four times that of the candle.

Surface Illumination

Think again about the scenario in which a flashlight is shining at you from across the room. If the bulb has a small luminous intensity, the light will not be very bright. To increase the brightness, you could use a brighter bulb, thereby increasing the luminous flux, or you could move so that your eyes are closer to the light, decreasing the distance between the light source and your eyes. Following the simplification that we are treating all light sources as point sources, the illuminance and distance will follow the inverse-square relationship. In this case, and in all the cases we will deal with in this book, the illuminance caused by a point light source is represented by the following equation.

Point-Source Illuminance

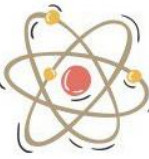
If an object is illuminated by a point source of light, then the illuminance at the object is equal to the luminous flux of the light source divided by the surface area of the sphere whose radius is equal to the distance the object is from the light source.

$$E = \frac{P}{4\pi r^2}$$

Remember that the luminous flux of the light source is spreading out in all directions, so only some fraction of the luminous flux is available to illuminate the object. Use of this equation is valid only if the light from the luminous source strikes perpendicular to the surface it is illuminating. It is also only valid if the luminous source is small enough or far enough away to be considered a point source. Thus, the equation does not give accurate values of illuminance for long fluorescent lamps or lightbulbs that are close to the surfaces they illuminate.

Engineers who design lighting systems must understand how the light will be used. If an even illumination is needed to prevent dark areas, the common practice is to evenly space normal lights over the area to be illuminated, as was most likely done with the lights in your classroom. Because such light sources do not produce truly uniform light, however, engineers also design special light sources that control the spread of the light, such that they produce even illuminations over large surface areas. For safety reasons, this is extremely important for automobile headlights, as in **Figure 8**. Automobile engineers must consider these factors when designing headlights.

Real-World F
Illuminated Mi
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 In addition, the
 sources are an i



EXAMPLE Problem 1

ILLUMINATION OF A SURFACE What is the illuminance on your desktop if it is lit by a 1750-lm lamp that is 2.50 m above your desk?

1 ANALYZE AND SKETCH THE PROBLEM

- Assume the lightbulb is the point source.
- Diagram the position of the bulb and the desktop. Label P and r .

Known

$$P = 1.75 \times 10^3 \text{ lm}$$

$$r = 2.50 \text{ m}$$

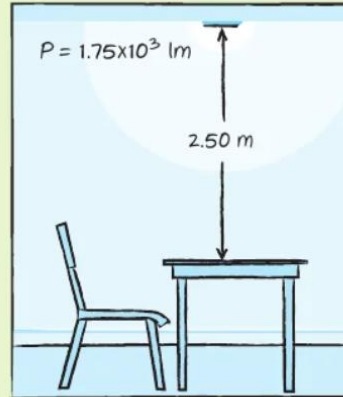
Unknown

$$E = ?$$

2 SOLVE FOR THE UNKNOWN

The surface is perpendicular to the direction in which the light ray is traveling, so you can use the point-source illuminance equation.

$$\begin{aligned}
 E &= \frac{P}{4\pi r^2} \\
 &= \frac{1.75 \times 10^3 \text{ lm}}{4\pi(2.50 \text{ m})^2} \quad \text{Substitute } P = 1.75 \times 10^3 \text{ lm, } r = 2.50 \text{ m} \\
 &= 22.3 \text{ lm/m}^2 \\
 &= 22.3 \text{ lx}
 \end{aligned}$$

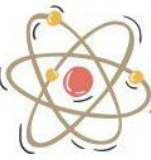


3 EVALUATE THE ANSWER

- **Are the units correct?** The units of luminance are $\text{lm/m}^2 = \text{lx}$, which the answer agrees with.
- **Do the signs make sense?** All quantities are positive, as they should be.
- **Is the magnitude realistic?** Illuminance from an 1800-lm lamp at a distance of 2 m is about 20 lx.

PRACTICE Problems

1. A lamp is moved from 30 cm to 90 cm above the pages of a book. Compare the illumination on the book before and after the lamp is moved.
2. Draw a graph of the illuminance produced by a lamp with a luminous flux of 2275 lm at distances from 0.50 m and 5.0 m.



3. A 64-cd point source of light is 3.0 m away from a painting. What is the illumination on the painting in lux?
4. A screen is placed between two lamps so that they illuminate the screen equally, as shown in **Figure 9**. The first lamp emits a luminous flux of 1445 lm and is 2.5 m from the screen. What is the distance of the second lamp from the screen if the luminous flux is 2375 lm?

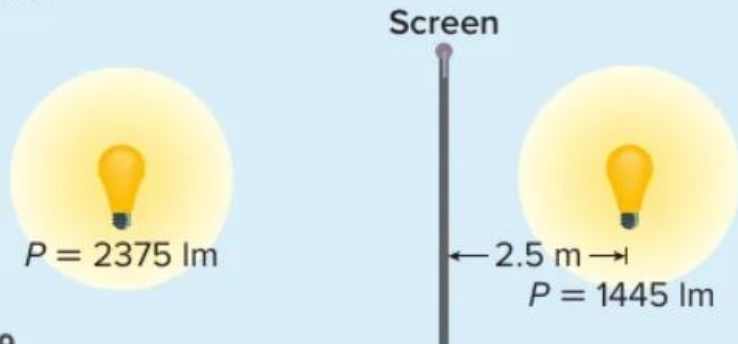
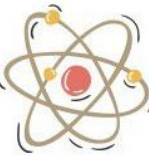


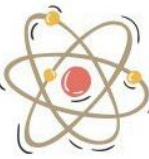
Figure 9

- Apply the equation for illuminance of a point source to numerical problems.
- Relate luminous intensity to illuminance.



ADDITIONAL PRACTICE

- What is the illumination on a surface that is 3.0 m below a 150-W incandescent lamp that emits a luminous flux of 2275 lm?
- A public school law requires a minimum illuminance of 160 lx at the surface of each student's desk. An architect's specifications call for classroom lights to be located 2.0 m above the desks. What is the minimum luminous flux that the lights must produce?
- CHALLENGE** Your local public library is planning to remodel the computer lab. The contractors have purchased fluorescent lamps with a rated luminous flux of 1750 lm. The desired illumination on the keyboard surfaces is 175 lx. Assume a single lamp illuminates each keyboard. What distance above the surface should the lights be placed to achieve the desired illumination? If the contractors had also already purchased fixtures to hold the lights that when installed would be 1.5 m above the keyboard surface, would the desired illuminance be achieved? If not, would the illuminance be greater or less than desired? What change in the lamp's luminous flux would be required to achieve the desired illuminance?



Check Your Progress

8. **Light** What evidence have you observed that light travels in a straight line?
9. **Light Properties** Why might you choose a window shade that is translucent? Opaque?
10. **Illuminance** Does one lightbulb provide more or less illuminance than two identical lightbulbs at twice the distance? Explain.
11. **Luminous Intensity** Two lamps illuminate a screen equally from distances shown in **Figure 11**. If Lamp A is rated 75 cd, what is Lamp B rated?

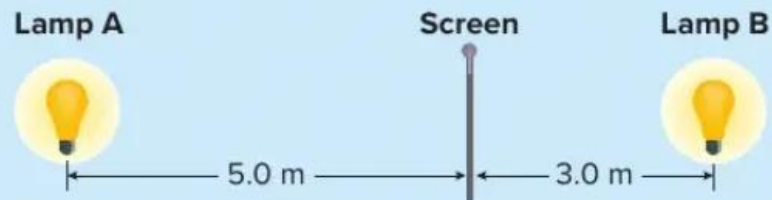
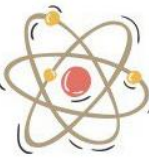


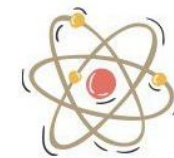
Figure 11

- Apply the equation for illuminance of a point source to numerical problems.
- Relate luminous intensity to illuminance.



12. **Distance of a Light Source** A lightbulb illuminating your computer keyboard provides only half the illuminance that it should. If it is currently 1.0 m away, how far should it be to provide the correct illuminance?
13. **Light and Sound Travel** How far does light travel in the time it takes sound to travel 1 cm in air at 20°C?
14. **Distance of Light Travel** The distance to the Moon can be found with the help of mirrors left on the Moon by astronauts. A pulse of light is sent to the Moon and returns to Earth in 2.562 s. Using the defined value for the speed of light to the same precision, calculate the distance from Earth to the Moon.
15. **Critical Thinking** The correct time taken for light to cross Earth's orbit is 16.5 min, and the diameter of Earth's orbit is 2.98×10^{11} m. Calculate the speed of light using Roemer's method. Does this method appear to be accurate? Why or why not?

- Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image.
- Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances.
- Calculate the magnification produced by a spherical mirror.



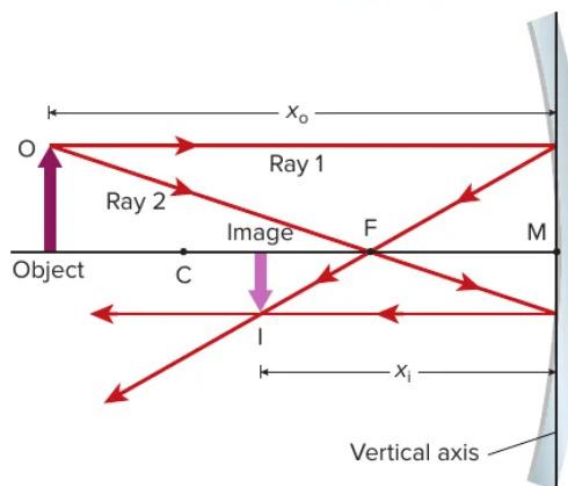
Ray Diagrams for Curved Mirrors

Ray diagrams give you a visual representation of images formed by a curved mirror, depending on where the object is placed in relation to the focal point.

Figure 12 shows rays reflected from a concave mirror converging at the point I , where an image is located. The converging light rays form a **real image** that is inverted and larger than the object. You can see the image floating in space if you place your eye so that the rays that form the image fall on your eye, as in **Figure 12**. You must face a direction that allows the light rays coming from the image to enter your eyes, however. You cannot look at the image from behind. If you were to place a piece of paper or a movie screen at this point, the image would appear on the screen, as shown on the right in **Figure 12**. You cannot project virtual images on a screen, since they are not formed by converging light rays.

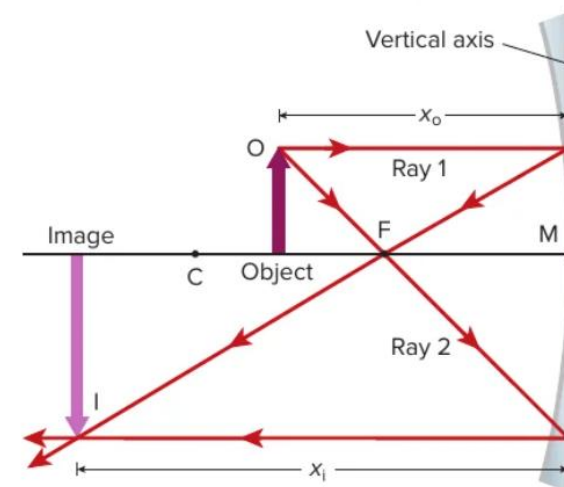
In **Figure 12**, if the object is beyond point C , the absolute value of the magnification for the real image is less than 1. This means that the image is smaller than the object. If the object is placed between point C and point F , the absolute value of the magnification is greater than 1, which means the image is larger than the object.

Concave Mirror ($x_o > 2f$)

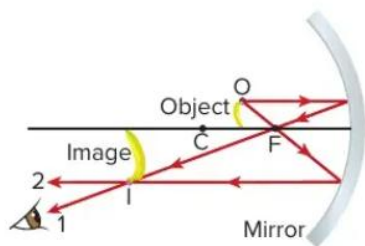


The image is reduced for an object located a distance greater than $2f$ from the mirror.

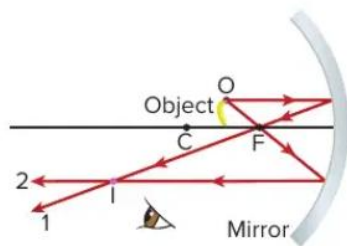
Concave Mirror ($2f > x_o > f$)



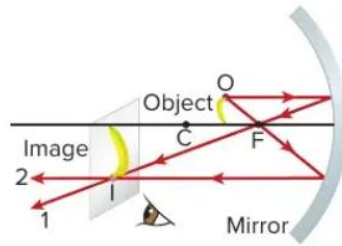
The image is enlarged for an object between f and $2f$.



The eye is positioned so that the rays that form the real image strike the eye, allowing the image to be seen.



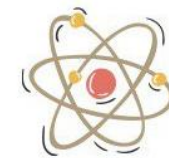
Rays from the object do not reach the eye, so the image cannot be seen from this position.



The image can be seen when projected on a white opaque screen.

Figure 12 Ray diagrams can be used to locate an image reflected from a curved mirror.

- Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image.
- Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances.
- Calculate the magnification produced by a spherical mirror.



Virtual Images with Concave Mirrors

You have seen that as an object approaches the focal point (F) of a concave mirror, the image moves farther away from the mirror. If the object is at the focal point, all reflected rays are parallel. They never meet, therefore, and the image is said to be at infinity, so the image could never be seen.

What happens if you move the object even closer to the mirror? The image is upright and behind the mirror. A concave mirror produces a virtual image if the object is located between the mirror and the focal point. This situation is shown in the ray diagram in **Figure 14**.

You draw two rays to locate the image of a point on an object. As before, you draw ray 1 parallel to the principal axis and then reflected through the focal point. Ray 2 is drawn as a line from the point on the object to the mirror, along a line defined by the focal point and the point on the object. At the mirror, ray 2 is reflected parallel to the principal axis. Note in **Figure 14** that ray 1 and ray 2 diverge as they leave the mirror, so there cannot be a real image. However, sight lines extended behind the mirror converge, showing that a virtual image forms behind the mirror. From the position of the point of convergence, you can see that the image is upright and larger than the object.

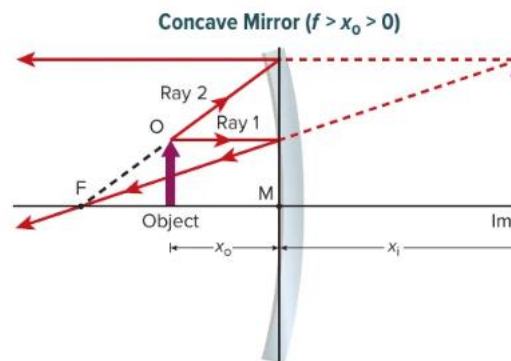


Figure 14 A virtual, upright, enlarged image is formed when an object is placed between the focal point and the surface of a concave mirror. Consider the cause of the appearance of the other images in the mirror.

Virtual Images with Convex Mirrors

Rays reflected from a convex mirror always diverge. Thus, convex mirrors form only virtual images. The ray diagram in **Figure 15** shows how a spherical convex mirror forms an image. The figure shows two rays, but remember that there is an infinite number of rays reflecting from the object. Ray 1 approaches the mirror parallel to the principal axis. Ray 1 reflects off the mirror following the line between F and the point where ray 1 strikes the principal plane.

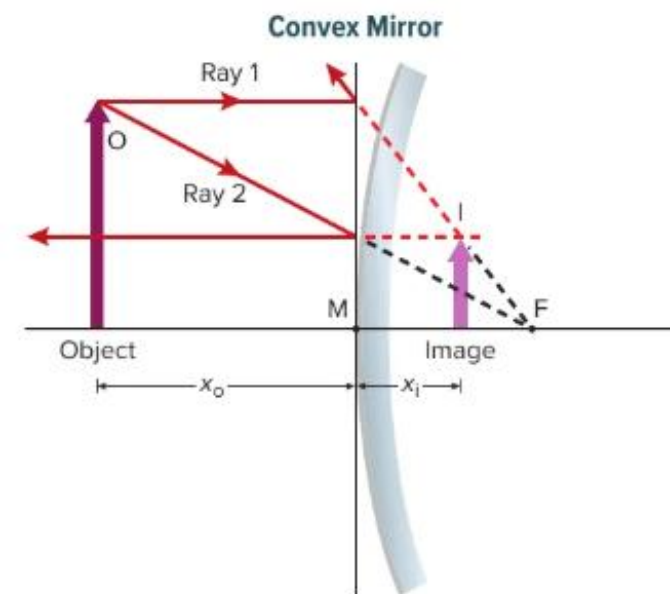
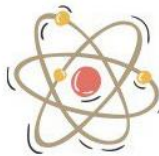


Figure 15 Convex mirrors form images that are virtual, upright, and smaller than the object.



22

- Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image.
- Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances.
- Calculate the magnification produced by a spherical mirror.

Student Textbook
Example problem 2,3
Practice problems

36-38
41,42

EXAMPLE Problem 2

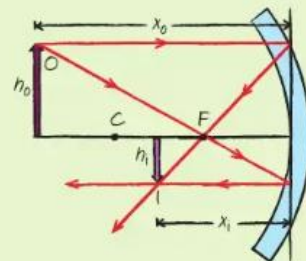
REAL IMAGE FORMATION BY A CONCAVE MIRROR A concave mirror has a radius of curvature of 20.0 cm. You place a 2.0-cm-tall object 30.0 cm from the mirror. What are the image position and image height?

1 ANALYZE AND SKETCH THE PROBLEM

- Draw a diagram with the object and the mirror.
- Draw two principal rays to locate the image in the diagram.

Known
 $h_o = 2.0 \text{ cm}$
 $x_o = 30.0 \text{ cm}$
 $r = 20.0 \text{ cm}$

Unknown
 $x_i = ?$
 $h_i = ?$



2 SOLVE FOR THE UNKNOWN

Focal length is half the radius of curvature.

$$f = \frac{r}{2}$$

$$= \frac{20.0 \text{ cm}}{2}$$

$$= 10.0 \text{ cm}$$

Substitute $r = 20.0 \text{ cm}$.

Use the relationship between focal length and object position to solve for image position.

$$\frac{1}{f} = \frac{1}{x_i} + \frac{1}{x_o}$$

$$x_i = \frac{fx_o}{x_o - f}$$

$$= \frac{(10.0 \text{ cm})(30.0 \text{ cm})}{30.0 \text{ cm} - 10.0 \text{ cm}}$$

$$= 15.0 \text{ cm (real image, in front of the mirror)}$$

Substitute $f = 10.0 \text{ cm}$, $x_o = 30.0 \text{ cm}$.

Use the relationship between object height and object and image position to solve for image height.

$$m \equiv \frac{h_i}{h_o} = \frac{-x_i}{x_o}$$

$$h_i = \frac{-x_i h_o}{x_o}$$

$$= -\frac{(15.0 \text{ cm})(2.0 \text{ cm})}{30.0 \text{ cm}}$$

$$= -1.0 \text{ cm (inverted, smaller image)}$$

Substitute $x_i = 15.0 \text{ cm}$, $h_o = 2.0 \text{ cm}$, $x_o = 30.0 \text{ cm}$.

3 EVALUATE THE ANSWER

- **Are the units correct?** All positions and heights are in centimeters.
- **Do the signs make sense?** Positive position and negative height agree with the drawing.

EXAMPLE Problem 3

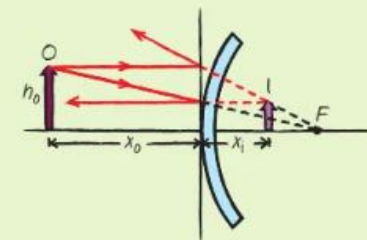
IMAGE IN A SECURITY MIRROR A convex security mirror in a warehouse has a -0.50-m focal length. A 2.0-m -tall forklift is 5.0 m from the mirror. What are the forklift's image position and image height?

1 ANALYZE AND SKETCH THE PROBLEM

- Draw a diagram with the mirror and the object.
- Draw two principal rays to locate the image in the diagram.

Known
 $h_o = 2.0 \text{ m}$
 $x_o = 5.0 \text{ m}$
 $f = -0.50 \text{ m}$

Unknown
 $x_i = ?$
 $h_i = ?$



2 SOLVE FOR THE UNKNOWN

Use the relationship between focal length and object position to solve for image position.

$$\frac{1}{f} = \frac{1}{x_i} + \frac{1}{x_o}$$

$$x_i = \frac{fx_o}{x_o - f}$$

$$= \frac{(-0.50 \text{ m})(5.0 \text{ m})}{5.0 \text{ m} - (-0.50 \text{ m})}$$

$$= -0.45 \text{ m (virtual image, behind the mirror)}$$

Substitute $f = -0.50 \text{ m}$, $x_o = 5.0 \text{ m}$.

Use the relationship between object height and object and image position to solve for image height.

$$m \equiv \frac{h_i}{h_o} = \frac{-x_i}{x_o}$$

$$h_i = \frac{-x_i h_o}{x_o}$$

$$= \frac{-(-0.45 \text{ m})(2.0 \text{ m})}{5.0 \text{ m}}$$

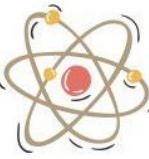
$$= 0.18 \text{ m (upright, smaller image)}$$

Substitute $x_i = -0.45 \text{ m}$, $h_o = 2.0 \text{ m}$, $x_o = 5.0 \text{ m}$.

3 EVALUATE THE ANSWER

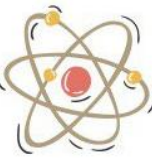
- **Are the units correct?** All positions and heights are in meters.
- **Do the signs make sense?** A negative position indicates a virtual image; a positive height indicates an image that is upright. These agree with the diagram.

22	-Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image. -Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances. -Calculate the magnification produced by a spherical mirror.	Student Textbook Example problem2,3 Practice problems	36-38 41,42
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PRACTICE Problems

12. Use a ray diagram drawn to scale to solve Example Problem 2.
13. You place an object 36.0 cm in front of a concave mirror with a 16.0-cm focal length. Determine the image position.
14. You place a 3.0-cm-tall object 20.0 cm from a 16.0-cm-radius concave mirror. Determine the image position and image height.



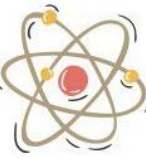
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ADDITIONAL PRACTICE

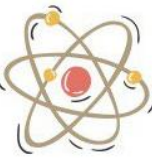
15. A concave mirror has a 7.0-cm focal length. You place a 2.4-cm-tall object 16.0 cm from the mirror. Determine the image height.
16. **CHALLENGE** You place an object near a concave mirror with a 10.0-cm focal length. The image is 3.0 cm tall, inverted, and 16.0 cm from the mirror. What are the object position and object height?

22	-Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image. -Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances. -Calculate the magnification produced by a spherical mirror.	Student Textbook Example problem 2,3 Practice problems	36-38 41,42
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PRACTICE Problems

17. You place an object 20.0 cm in front of a convex mirror with a -15.0 -cm focal length. Find the image position using both a scale diagram and the mirror equation.
18. A convex mirror has a focal length of -13.0 cm. You place a 6.0-cm diameter lightbulb 60.0 cm from that mirror. What are the lightbulb's image position and diameter?
19. A 7.6-cm-diameter ball is located 22.0 cm from a convex mirror with a radius of curvature of 60.0 cm. What are the ball's image position and diameter?

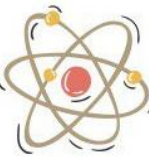


22	-Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image. -Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length and corresponding distances. -Calculate the magnification produced by a spherical mirror.	Student Textbook Example problem 2,3 Practice problems	36-38 41,42
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ADDITIONAL PRACTICE

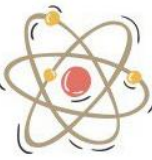
- 20.** A 1.8-m-tall girl stands 2.4 m from a store's security mirror. Her image appears to be 0.36 m tall.
- What is the image's distance?
 - What is the focal length of the mirror?
- 21. CHALLENGE** A convex mirror is needed to produce an image that is three-fourths the size of an object and located 24 cm behind the mirror.
- What is the object's distance?
 - What focal length should be specified?



23	-Calculate the refractive index of a medium using a suitable mathematical representation ($n = c/v$). -State and apply Snell's law of refraction. -Calculate the critical angle using Snell's law.	Practice problems Student Textbook	46 47,48
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PRACTICE Problems

30. A laser beam in air enters ethanol at an angle of incidence of 37.0° . What is the angle of refraction?
31. As light travels from air into water, the angle of refraction is 25.0° to the normal. Find the angle of incidence.
32. Light in air enters a diamond facet at 45.0° . What is the angle of refraction?

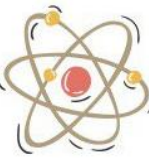


23	-Calculate the refractive index of a medium using a suitable mathematical representation ($n = c/v$). -State and apply Snell's law of refraction. -Calculate the critical angle using Snell's law.	Practice problems Student Textbook	46 47,48
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ADDITIONAL PRACTICE

- 33.** A block of unknown material is submerged in water. Light in the water enters the block at an angle of incidence of 31° . The angle of refraction of the light in the block is 27° . What is the index of refraction of the material of the block?
- 34. CHALLENGE** Light travels from air into another medium. The angle of incidence is 45.0° and the angle of refraction is 27.7° . What is the other medium?



23	-Calculate the refractive index of a medium using a suitable mathematical representation ($n = c/v$). -State and apply Snell's law of refraction. -Calculate the critical angle using Snell's law.	Practice problems Student Textbook	46 47,48
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$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

Snell's law also can be written as a ratio of the sines of the angles of incidence and refraction.

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{n_1}{n_2}$$

Using the transitive property of equality, the previous two equations lead to the following equation:

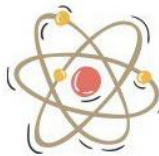
$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

In a vacuum, $n = 1.00$ and $v = c$. If either medium is a vacuum, then the equation is simplified to an equation that relates the index of refraction to the speed of light in a medium.

Index of Refraction

The index of refraction of a medium is equal to the speed of light in a vacuum divided by the speed of light in the medium.

$$n = \frac{c}{v}$$



- Calculate the refractive index of a medium using a suitable mathematical representation ($n = c/v$).
- State and apply Snell's law of refraction.
- Calculate the critical angle using Snell's law.

Total Internal Reflection

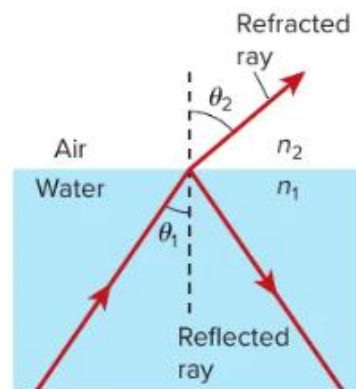
Recall that when light strikes a transparent boundary, some of the light is transmitted and some is reflected. As light travels from a medium of higher index of refraction to a medium of lower index of refraction, the angle of refraction is larger than the angle of incidence, as shown in **Figure 21**.

This leads to an interesting phenomenon. As the angle of incidence increases, the angle of refraction increases. At a certain angle of incidence known as the **critical angle** (θ_c), the refracted light ray lies along the boundary of the two mediums.

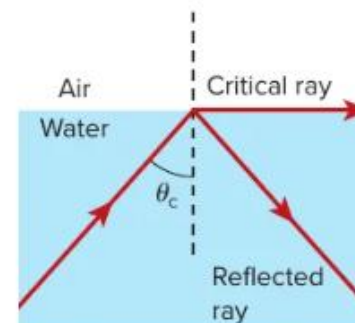
Total internal reflection occurs when light traveling from a region of a higher index of refraction to a region of a lower index of refraction strikes the boundary at an angle greater than θ_c such that all the light reflects back into the region of the higher index of refraction. This is shown in the third diagram of **Figure 21**. Using Snell's law and substituting $\theta_1 = \theta_c$, and $\sin \theta_2 = \sin 90.0^\circ = 1$:

$$\sin \theta_c = \frac{n_2}{n_1}$$

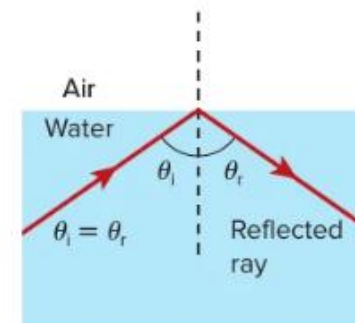
Total internal reflection causes some curious effects. Suppose you are looking up at the surface from under water in a pool. You might see an upside-down reflection of another nearby object that is also under water. You might see a reflection of the bottom of the pool itself. The surface of the water acts like a mirror, reflecting the image back into the water.



At an angle of incidence less than the critical angle, light is partially refracted and partially reflected.



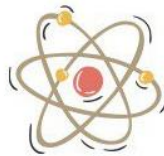
A ray refracted along the boundary of the medium forms the critical angle.



An angle of incidence greater than the critical angle results in total internal reflection, which follows the law of reflection.

Figure 21 Refraction and reflection of light traveling between mediums depend on the angle of incidence θ_i .

24	-Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image. -Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances -Calculate the magnification produced by a thin convex or concave lens.	Student Textbook Example problem5 Practice problems Check your progress 45,55,51,55,56	52,53 55 60
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Convex Lenses

To determine an image's location, we can use ray diagrams. In a ray diagram, as with mirrors you represent a few important rays to find out how a lens affects the light that passes through it. You can use any two rays to locate the image; with experience, you will learn that some rays are easier to draw and use than others.

In ray diagrams for convex lenses, x_o is the distance of the object from the lens and x_i is the distance of the image from the lens. In all ray diagrams in this module, the thin lens model is used. In this model, light refracts at the center of the lens rather than at the boundaries between air and the surface of the lens.

$x_o \geq 2f$ In Figure 28, rays are traced from an object located far from the lens. Ray 1 is parallel to the principal axis. It refracts and passes through the focal point (F) on the other side of the lens. Ray 2 passes through F on its way to the lens. After refraction, its path is parallel to the principal axis.

The two rays intersect at a point beyond F and locate the image. Rays selected from other points on the object converge at corresponding points to form the complete image. Note that this is a real image that is inverted and smaller compared to the object.

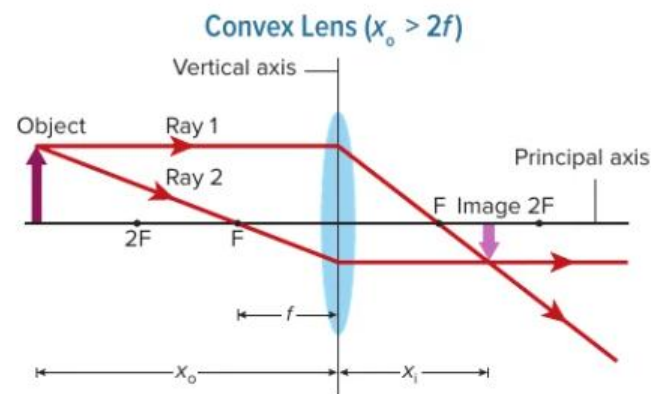
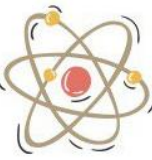


Figure 28 An object placed at a distance greater than twice the focal length from the lens will produce an image that is real, reduced in size, and inverted.

COLOR CONVENTION

Light ray		red
Object		magenta
Image		lilac



24	-Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image. -Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances -Calculate the magnification produced by a thin convex or concave lens.	Student Textbook Example problem5 Practice problems Check your progress 45,55,51,55,56	52,53 55 60
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$x_o = 2f$ If the object is placed at twice the focal length from the lens at the point $2F$, the diagram is similar. The image is real and is found at $2F$, but it is no longer reduced in size. Because of symmetry, the image and the object have the same size. Thus, you can conclude that if an object is more than twice the focal length from the lens, the image is smaller than the object.

$2f > x_o > f$ You can use **Figure 29** to locate the image of an object that is between F and $2F$ viewed through a convex lens. This is similar to the ray diagram for the object located at a distance greater than twice the focal length with the image and object interchanged. The direction of the rays would be reversed. In this case, the image is also real and inverted.

For an object placed between F and $2F$, the image is enlarged. When an object is placed at the focal point of a convex lens, ray diagrams cannot be drawn. The refracted rays will emerge in a parallel beam and no image will be seen.

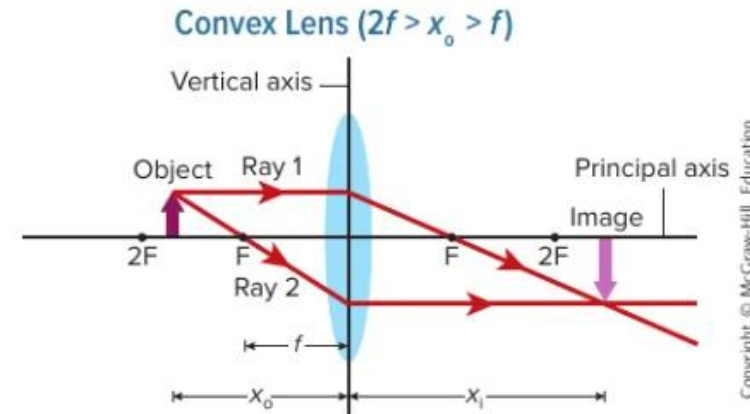
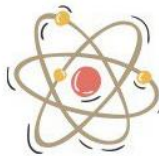


Figure 29 An object placed at a distance less than twice the focal length but greater than one focal length from the lens will produce an image that is real, enlarged, and inverted.



24	-Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image. -Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances -Calculate the magnification produced by a thin convex or concave lens.	Student Textbook Example problem5 Practice problems Check your progress 45,55,51,55,56	52,53 55 60
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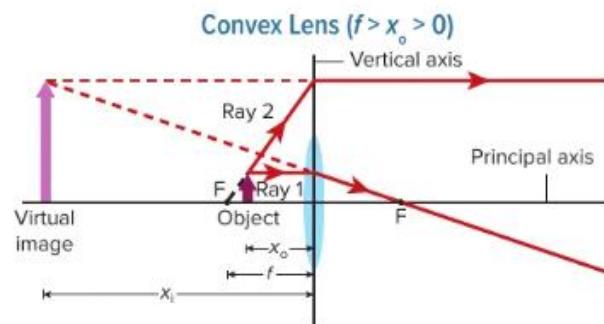


Figure 30 An object placed at a distance less than the focal length from the lens will produce an image that is virtual and enlarged.

$f > x_o > 0$ Figure 30 shows how a convex lens forms a virtual image. The object in this situation is located between F and the lens. Ray 1, as usual, approaches the lens parallel to the principal axis and is refracted through the focal point, F. Ray 2 travels from the tip of the object in the direction it would have if it had started at F on the object side of the lens. The dashed line from F to the object shows you how to draw ray 2. Ray 2 leaves the lens parallel to the principal axis. Ray 1 and ray 2 diverge as they leave the lens.

The reflection appears to an observer to come from a spot on the same side of the lens as the object. This is a virtual image that is upright and larger compared to the object. No real image is possible. Drawing sight lines for the two rays back to their apparent intersection locates the virtual image. Note that the actual image is formed by light that passes through the lens, but you can still determine the location of the image by drawing rays that do not have to pass through the lens.

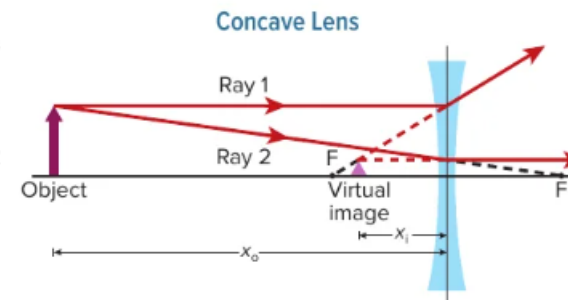


Figure 31 An object placed any distance from a concave lens will always produce an image that is virtual and reduced.

Concave Lenses

A concave lens causes all rays to diverge. **Figure 31** shows how a concave lens forms a virtual image. Ray 1 approaches the lens parallel to the principal axis. It leaves the lens along a line that extends back through the focal point on the object side of the lens. The focal point of a concave lens is found on the same side of the lens as the incoming light. Ray 2 approaches the lens as if it is going to pass through the focal point on the opposite side but leaves the lens parallel to the principal axis.

The sight lines of rays 1 and 2 intersect on the same side of the lens as the object. The image is located at the point from where the two rays appear to intersect, creating a virtual image. The image is upright and smaller than the object. This is true no matter how far from the lens the object is located. The focal length for a diverging lens is negative.



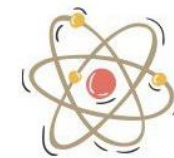
Get It?

Describe why a concave lens always produces a virtual image.

- Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image.
- Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances
- Calculate the magnification produced by a thin convex or concave lens.

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Practice problems
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60



EXAMPLE Problem 5

AN IMAGE FORMED BY A CONVEX LENS An object is placed 32.0 cm from a convex lens that has a focal length of 8.0 cm.

- Where is the image?
- If the object is 3.0 cm high, how tall is the image?
- What is the orientation of the image?

1 ANALYZE AND SKETCH THE PROBLEM

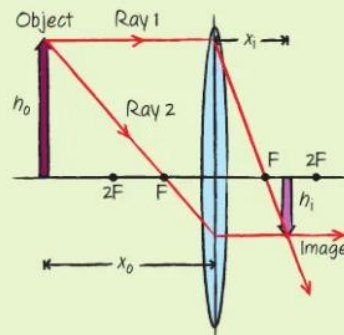
- Sketch the situation, locating the object and the lens.
- Draw the two principal rays.

Known

$x_o = 32.0$ cm
 $h_o = 3.0$ cm
 $f = 8.0$ cm

Unknown

$x_i = ?$
 $h_i = ?$



2 SOLVE FOR THE IMAGE POSITION AND HEIGHT

- Use the thin lens equation to determine x_i .

$$\frac{1}{f} = \frac{1}{x_i} + \frac{1}{x_o}$$

$$x_i = \frac{fx_o}{x_o - f}$$

$$= \frac{(8.0 \text{ cm})(32.0 \text{ cm})}{32.0 \text{ cm} - 8.0 \text{ cm}}$$

Substitute $f = 8.0$ cm, $x_o = 32.0$ cm.

$$= 11 \text{ cm (11 cm away from the lens on the side opposite the object)}$$

- Use the magnification equation to solve for image height.

$$m \equiv \frac{h_i}{h_o} = -\frac{x_i}{x_o}$$

$$h_i = -\frac{x_i h_o}{x_o}$$

$$= -\frac{(11 \text{ cm})(3.0 \text{ cm})}{32.0 \text{ cm}}$$

Substitute $x_i = 11$ cm, $h_o = 3.0$ cm, $x_o = 32.0$ cm.

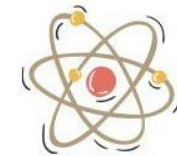
$$= -1.0 \text{ cm (1.0 cm tall)}$$

- The negative sign for the height in part **b** means the image is inverted.

3 EVALUATE THE ANSWER

- Are the units correct?** All are in centimeters.
- Do the signs make sense?** Image position is positive (real image), and image height is negative (inverted compared to the object), which make sense for a convex lens.

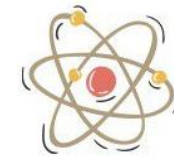
24	-Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image. -Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances -Calculate the magnification produced by a thin convex or concave lens.	Student Textbook Example problem5 Practice problems Check your progress 45,55,51,55,56	52,53 55 60
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PRACTICE Problems

- 43.** A 2.25-cm-tall object is 8.5 cm to the left of a convex lens whose focal length is 5.5 cm. Find the image position and height.
- 44.** An object near a convex lens produces a 1.8-cm-tall real image that is 10.4 cm from the lens and inverted. If the focal length of the lens is 6.8 cm, what are the object position and height?
- 45.** An object is placed to the left of a convex lens with a 25-mm focal length so that its image is the same size as the object. What are the image and object positions?

24	-Draw a ray to find the image of an object located at different distances from a lens and determine the location and properties of the formed image. -Apply the thin lens equation to calculate the image distance, the object distance, or the focal length of a convex or a concave lens using appropriate algebraic signs for focal length and corresponding distances -Calculate the magnification produced by a thin convex or concave lens.	Student Textbook Example problem5 Practice problems Check your progress 45,55,51,55,56	52,53 55 60
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51. **Image Position and Height** An object is placed 1.5 m from a convex lens with a focal length of 1.0 m. Use the thin lens equation to determine the distance of the image from the lens. If the object height is 2.0 m, what is the image height? Is the image real or virtual? Is the image inverted or upright?
55. **Image Position and Height** A 6.0-cm-tall object is placed 5.0 cm from a convex lens with a focal length of 4.0 cm. Draw a ray diagram to determine the image location and size. Confirm your results using the thin lens equation and the magnification equation.
56. **Diverging Lens** A 6.5-cm-tall salt shaker is viewed through a diverging lens with a focal length of 5.0 cm.
- If the shaker is 6.0 cm from the lens, what is the image distance from the lens? Is the image virtual or real?
 - What is the magnification? Is the image smaller or larger than the object?
 - The salt shaker is now 4 cm from the lens. What is the distance of the image from the lens? The magnification? Is the image now smaller or larger than the object?