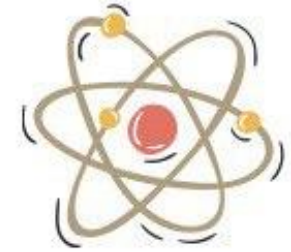


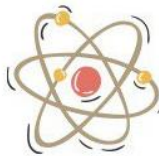
EOT – Term 1 – Part 1

Grade 11 Advanced

Inspire



SIMPLE PHYSICS
With Ms. Hoda



1	Define quantities of light like luminous flux and illuminance, specifying their SI units. Apply the equation for illuminance of a point source to numerical problems. Define luminous intensity, specifying its SI units. Relate luminous intensity to illuminance.	Student Textbook	5-9
		Figure 7	7
		PRACTICE Problems 3 & 4	9

Quantity of Light

If you were to have a flashlight shone at you from across the room, what factors would determine how bright that light would appear to you? Three main factors determine the brightness: the quantity of light the flashlight produces, the distance between the lightbulb and your eye, and the angle at which the light rays hit your eye. In this lesson, you will read about the first two of these factors.

Luminous flux With the ray model of light, a source that is brighter produces more light rays than a less bright source. Imagine again a single lightbulb sending rays in nearly all directions. How could you capture all the light it emits? You would need to construct a surface that completely encloses the bulb, as in **Figure 5**. The rate at which the bulb, a luminous source, produces light energy is called the **luminous flux** (P) and is measured in lumens (lm). The total amount of light that strikes the surface in a given unit of time depends only on the luminous flux of the source.

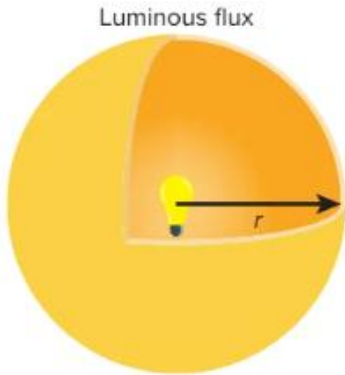


Figure 5 Luminous flux is the rate at which light rays are emitted from a luminous source.

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.

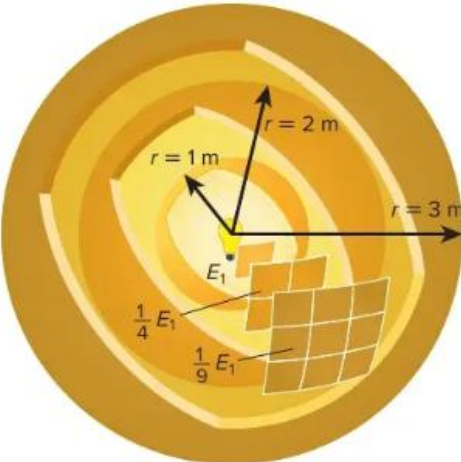
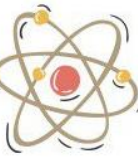


Figure 6 Illuminance (E) is the quantity of light that strikes a surface. As the distance from the luminous source (r) increases, E decreases. E depends on the inverse of r squared.

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



1	Define quantities of light like luminous flux and illuminance, specifying their SI units. Apply the equation for illuminance of a point source to numerical problems. Define luminous intensity, specifying its SI units. Relate luminous intensity to illuminance.	Student Textbook	5-9
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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 m² 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.

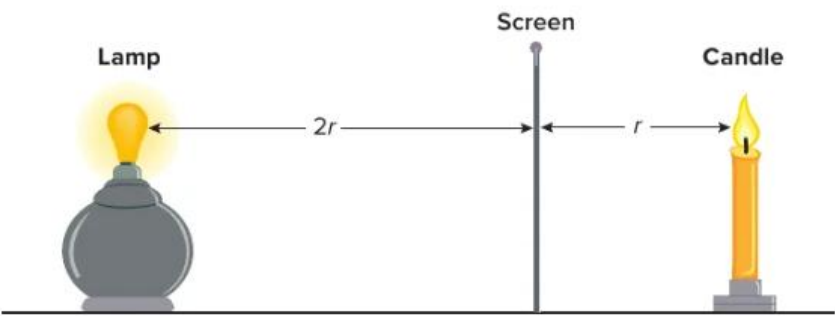


Figure 7 For the lightbulb and the candle to provide the same illuminance to the screen, the luminous intensity of the lightbulb is four times that of the candle.

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.

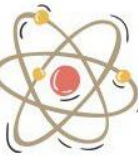
Point-Source Illuminance

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.



1	Define quantities of light like luminous flux and illuminance, specifying their SI units. Apply the equation for illuminance of a point source to numerical problems. Define luminous intensity, specifying its SI units. Relate luminous intensity to illuminance.	Student Textbook	5-9
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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 **Unknown**

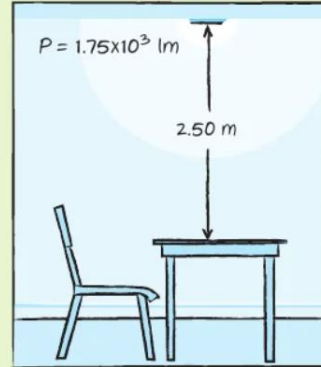
$$P = 1.75 \times 10^3 \text{ lm} \quad E = ?$$

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

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.

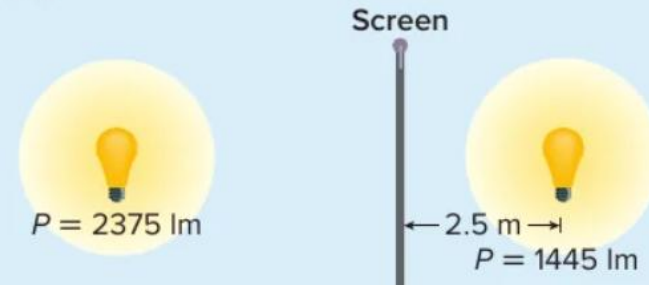
$$\begin{aligned}
 E &= \frac{P}{4\pi r^2} \\
 &= \frac{1.75 \times 10^3 \text{ lm}}{4\pi(2.50 \text{ m})^2} \quad \text{Substitute } P = 1.75 \times 10^3 \text{ lm, } r = 2.50 \text{ m} \\
 &= 22.3 \text{ lm/m}^2 \\
 &= 22.3 \text{ lx}
 \end{aligned}$$

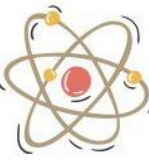


3 EVALUATE THE ANSWER

- 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.

- A 64-cd point source of light is 3.0 m away from a painting. What is the illumination on the painting in lux?
- 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?





2	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. Define magnification as the ratio of the image height to the object height. Calculate the magnification produced by a spherical mirror. Draw a ray diagram to find the image of an object formed by a convex mirror and determine the properties of the formed image	Student Textbook	38-40
		EXAMPLE Problem 3	42

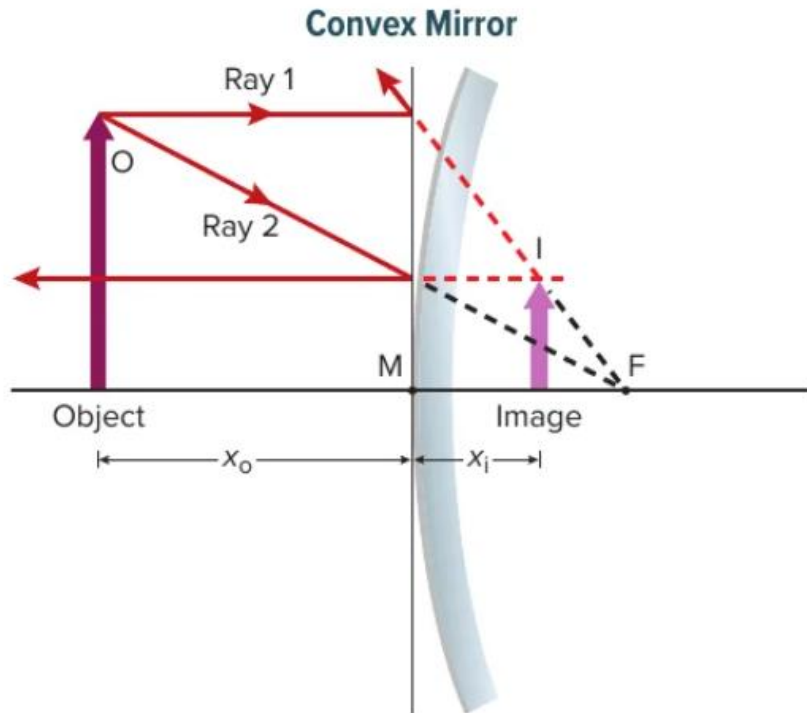


Figure 15 Convex mirrors form images that are virtual, upright, and smaller than the object.

Magnification

The magnification of an object by a spherical mirror, defined as the image height divided by the object height, is equal to the negative of the image position, divided by the object position.

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

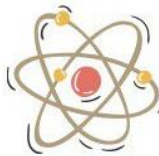
Mirror Equation

The reciprocal of the focal length of a spherical mirror is equal to the sum of the reciprocals of the image position and the object position.

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

Negative values When virtual images are formed, the image position (x_i) has a negative value, indicating that it is located behind the mirror. For concave mirrors, a virtual image only forms when the object is between a concave mirror and the focal point. The focal point is in front of the mirror and the focal length has a positive value. For convex mirrors, the focal point is always behind the mirror, and the focal length has a negative value.

Remember that the mirror equation is only approximately correct. In reality, light coming from an object toward a mirror is diverging, so not all of the light is close to or parallel to the axis. When the mirror diameter is large relative to the radius of curvature to minimize spherical aberration, this equation predicts image properties more precisely.



2	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. Define magnification as the ratio of the image height to the object height. Calculate the magnification produced by a spherical mirror. Draw a ray diagram to find the image of an object formed by a convex mirror and determine the properties of the formed image	Student Textbook	38-40
		EXAMPLE Problem 3	42

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

$$h_o = 2.0\text{ m}$$

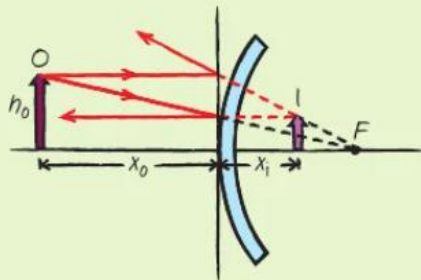
$$x_o = 5.0\text{ m}$$

$$f = -0.50\text{ m}$$

Unknown

$$x_i = ?$$

$$h_i = ?$$



2 SOLVE FOR THE UNKNOWN

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

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

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

$$= \frac{(-0.50\text{ m})(5.0\text{ m})}{5.0\text{ m} - (-0.50\text{ m})} \quad \text{Substitute } f = -0.50\text{ m}, x_o = 5.0\text{ m}.$$

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

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

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

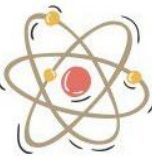
$$h_i = \frac{-x_i h_o}{x_o}$$

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

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

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.



3	State and apply Snell's law of refraction. Define the critical angle as the angle of incidence at which the refracted light ray lies along the boundary of the two mediums. Calculate the critical angle using Snell's law. Describe total internal reflection and the conditions under which total internal reflection takes place.	Student Textbook	44-48
		Figure 21	48

Light and Boundaries

Recall that when light crosses a boundary between two mediums, it bends. You might be familiar with this phenomenon already. Have you ever looked down through the water of a swimming pool and thought the water looked shallower than it was? This strange appearance is due to the bending of light at the boundaries between two mediums, or refraction.

Refraction Observe the light rays in **Figure 18**. Identical rays of light start in air and pass into three different mediums: water, glass, and diamond. The light

rays hit the surface of each medium at the same angle and bend, or refract, as they cross the boundaries.

What difference do you notice between the three mediums shown? The light rays bend more when traveling from air to diamond than from air to water or air to glass. The amount of refraction depends on properties of the mediums that the light rays are traveling from and into.

What do you think the relationship is between the angle of the light as it crosses the boundary between mediums and refraction?

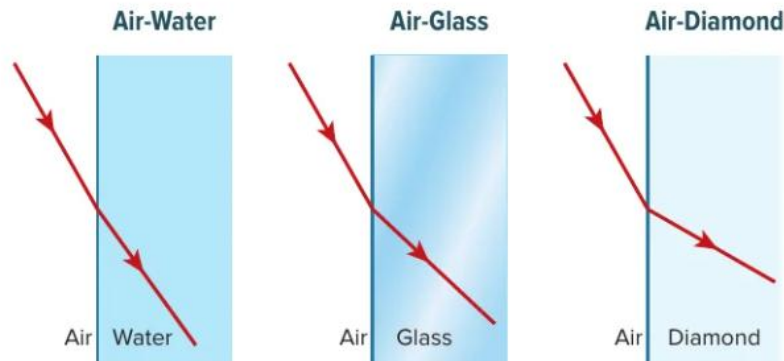


Figure 18 Light refracts as it crosses a boundary. The amount of refraction depends on the properties of the mediums. (Angles are not to scale.)

Snell's Law of Refraction

René Descartes and Willebrord Snell first studied refraction in the seventeenth century by shining a narrow beam of light onto a transparent medium, such as the glass shown in **Figure 19**. They measured two angles—the angle of incidence and the angle of refraction. The angle of incidence (θ_1) is the angle at which the light ray strikes the surface. The angle of refraction (θ_2) is the angle at which the transmitted light leaves the surface. Both angles are measured with respect to the normal.

Index of refraction Snell found that when light passes from air into a transparent medium, the sines of the angles are related. This **index of refraction** (n) determines the angle of refraction of light as it crosses the boundary between two mediums. Properties of the mediums light is traveling through determine indices of refraction. Values of n for several mediums are listed in **Table 2**.

Snell's Law of Refraction

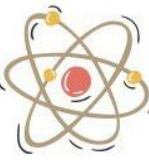
The product of the index of refraction of the first medium and the sine of the angle of incidence is equal to the product of the index of refraction of the second medium and the sine of the angle of refraction.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Table 2 Indices of Refraction for Yellow Light ($\lambda = 589 \text{ nm}$ in a vacuum)

Medium	n
Vacuum	1.00
Air	1.0003*
Water	1.33
Ethanol	1.36
Float glass	1.52
Quartz	1.54
Flint glass	1.62
Diamond	2.42

*The value given for air contains additional significant figures to distinguish it from that for a vacuum. Use a value of $n = 1.00$ for air in problems in this text.



3	State and apply Snell's law of refraction. Define the critical angle as the angle of incidence at which the refracted light ray lies along the boundary of the two mediums. Calculate the critical angle using Snell's law. Describe total internal reflection and the conditions under which total internal reflection takes place.	Student Textbook	44-48
		Figure 21	48

EXAMPLE Problem 4

ANGLE OF REFRACTION A beam of light in air hits a sheet of float glass at an angle of 30.0° . What is the angle of refraction of the light ray?

1 ANALYZE AND SKETCH THE PROBLEM

- Make a sketch of the air and float glass boundary.
- Draw the light ray and label θ_1 , θ_2 , n_1 , and n_2 .

Known

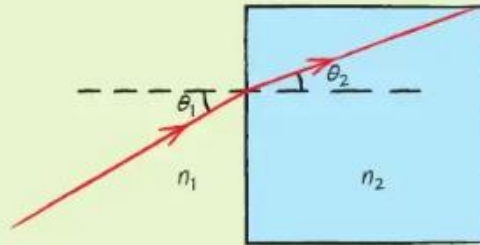
$$\theta_1 = 30.0^\circ$$

$$n_1 = 1.00$$

$$n_2 = 1.52$$

Unknown

$$\theta_2 = ?$$



2 SOLVE FOR THE ANGLE OF REFRACTION

Use Snell's law to solve for the sine of the angle of refraction.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

$$\sin \theta_2 = \left(\frac{n_1}{n_2} \right) \sin \theta_1$$

$$\theta_2 = \sin^{-1} \left(\left(\frac{n_1}{n_2} \right) \sin \theta_1 \right)$$

$$= \sin^{-1} \left(\left(\frac{1.00}{1.52} \right) \sin 30.0^\circ \right) \quad \text{Substitute } n_1 = 1.00, n_2 = 1.52, \theta_1 = 30.0^\circ.$$

$$= 19.2^\circ$$

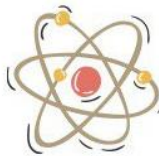
3 EVALUATE THE ANSWER

- **Does the answer make sense?** The light beam travels into a medium with a higher n . Therefore, θ_2 should be less than θ_1 .

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.

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



3	State and apply Snell's law of refraction. Define the critical angle as the angle of incidence at which the refracted light ray lies along the boundary of the two mediums. Calculate the critical angle using Snell's law. Describe total internal reflection and the conditions under which total internal reflection takes place.	Student Textbook	44-48
		Figure 21	48

Total Internal Reflection

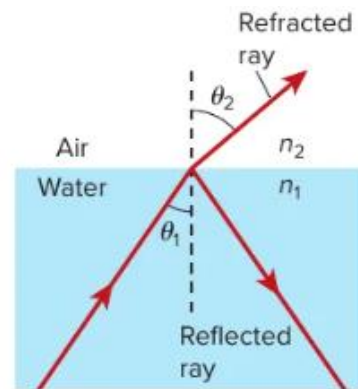
Recall that when light strikes a transparent boundary, some of the light is transmitted and some is reflected. As light travels from a medium of higher index of refraction to a medium of lower index of refraction, the angle of refraction is larger than the angle of incidence, as shown in **Figure 21**.

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.

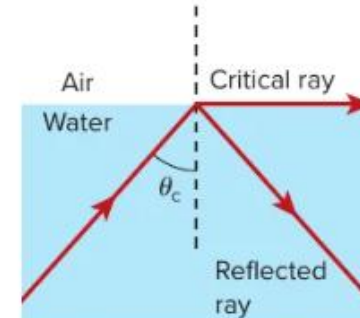
Total internal reflection occurs when light traveling from a region of a higher index of refraction to a region of a lower index of refraction strikes the boundary at an angle greater than θ_c such that all the light reflects back into the region of the higher index of refraction. This is shown in the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

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

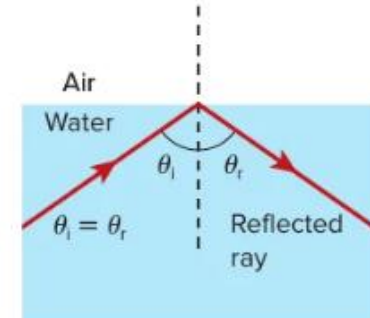
Total internal reflection causes some curious effects. Suppose you are looking up at the surface from under water in a pool. You might see an upside-down reflection of another nearby object that is also under water. You might see a reflection of the bottom of the pool itself. The surface of the water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

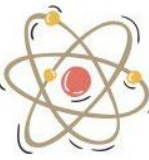


A ray refracted along the boundary of the medium forms the critical angle.



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_1 .



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
		PRACTICE Problems 46 & 47	55

Types of Lenses

Refraction of light can be quite useful. In 1303, French physician Bernard of Gordon wrote of using lenses to correct eyesight. Around 1610, Galileo discovered the four major moons of Jupiter using a telescope made with two lenses. Since that time, lenses have been used in instruments such as microscopes and cameras.

A **lens** is a piece of transparent material that focuses light and forms an image. Each of a lens's two faces might be either curved or flat. A lens that is thicker at the center than at the edges is called a **convex lens**, as shown on the left in **Figure 27**. When it is surrounded by material with a lower index of refraction, such as air, it refracts parallel light rays so that they all pass through a common point, called the focal point, after going

through the lens. For this reason, a convex lens is often called a converging lens.

A lens that is thinner in the middle than at the edges is called a **concave lens**, as shown on the right in **Figure 27**. When surrounded by material with a lower index of refraction, rays passing through it spread out, so it is often called a diverging lens.

You can determine the paths of rays passing through lenses using Snell's law. To simplify such problems, we assume that all refraction occurs at the principal plane, which passes through the center of the lens. This approximation, called the thin lens model, applies to all the lenses discussed in this module.

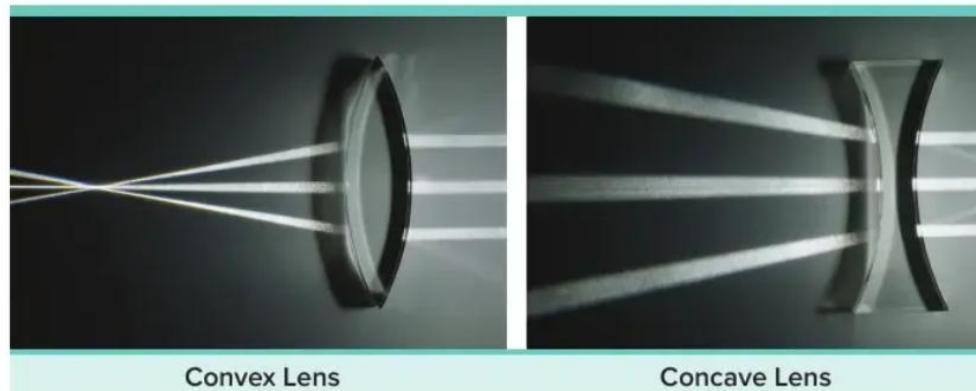
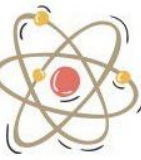


Figure 27 Convex lenses refract light so that the rays converge after passing through. The light passing through a concave lens does not meet at the focal point.



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
		PRACTICE Problems 46 & 47	55

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.

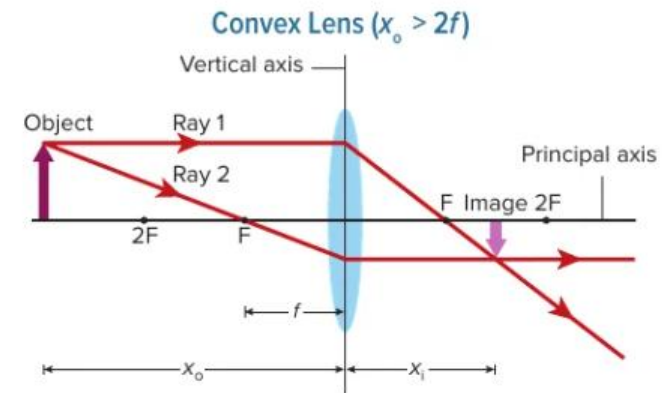
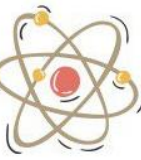


Figure 28 An object placed at a distance greater than twice the focal length from the lens will produce an image that is real, reduced in size, and inverted.

COLOR CONVENTION

Light ray		red
Object		magenta
Image		lilac



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
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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.

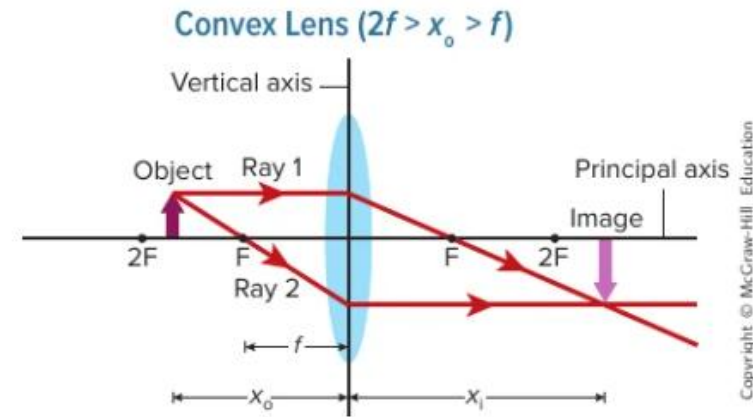
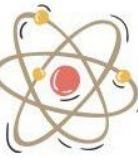


Figure 29 An object placed at a distance less than twice the focal length but greater than one focal length from the lens will produce an image that is real, enlarged, and inverted.



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
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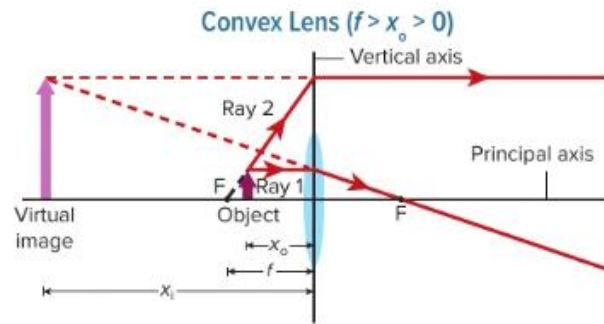


Figure 30 An object placed at a distance less than the focal length from the lens will produce an image that is virtual and enlarged.

$f > x_o > 0$ **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.

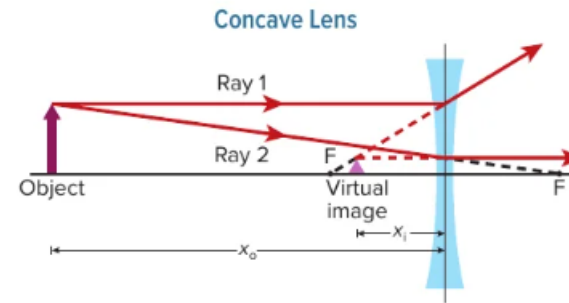


Figure 31 An object placed any distance from a concave lens will always produce an image that is virtual and reduced.

Concave Lenses

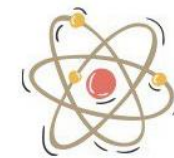
A concave lens causes all rays to diverge. **Figure 31** shows how a concave lens forms a virtual image. Ray 1 approaches the lens parallel to the principal axis. It leaves the lens along a line that extends back through the focal point on the object side of the lens. The focal point of a concave lens 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.



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
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Table 3 Properties of a Single Spherical Lens System

Lens Type	f	x_o	x_i	m	Image
Convex	+	$x_o > 2f$	$2f > x_i > f$	reduced, inverted	real
		$2f > x_o > f$	$x_i > 2f$	enlarged, inverted	real
		$f > x_o > 0$	$ x_i > x_o$ (negative)	enlarged	virtual
Concave	-	$x_o > 0$	$ f > x_i > 0$ (negative)	reduced	virtual

Lens Equations

Lenses can be constructed with a variety of shapes, but you will only consider thin lenses, with faces having spherical curvatures. Based on this model of thin spherical lenses, an equation has been developed that looks exactly like the one for spherical mirrors. For lenses, virtual images are always on the same side of the lens as the object, which means the image position is negative. Note that a concave lens produces only virtual images, whereas a convex lens can produce real images or virtual images.

and the orientation of the image formed by a spherical thin lens.

Magnification

The magnification of an object by a spherical lens, defined as the image height divided by the object height, is equal to the negative of the image position divided by the object position.

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

Thin lens equation The **thin lens equation** relates the focal length of a spherical thin lens, the object position, and the image position.

Thin Lens Equation

The inverse of the focal length of a spherical lens is equal to the sum of the inverses of the image position and the object position.

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

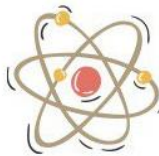
When solving problems for concave lenses using the thin lens equation, remember that the sign convention for focal length is different from that of convex lenses. This is because a concave lens is a divergent lens. If the focal point for a concave lens is 24 cm from the lens, you should use the value $f = -24$ cm in the thin lens equation. All images for a concave lens are virtual. Thus, if an image distance is given as 20 cm from the lens, then you should use $x_i = -20$ cm. The object position always will be positive.

Magnification A property of spherical thin lenses that measures how much larger or smaller the image is than the object is magnification. The magnification equation for spherical mirrors also can be used for spherical thin lenses. It is used to determine the height

Magnification gives information about the size and orientation of the image relative to the object. When the absolute value of a magnification is between zero and one, the image is smaller than the object. Magnifications with absolute values greater than one represent images that are larger than the objects. A negative magnification means the image is inverted compared to the object.

Using the equations for lenses It is important that you use the proper sign conventions when using these equations. **Table 3** shows a comparison of the image position, magnification (m), and type of image formed by single convex and concave lenses when an object is placed at various object positions (x_o) relative to the lens. For convex lenses, the object position relative to the focal point influences the image type.

Notice how this table is similar to **Table 1** in Lesson 1, the table for mirrors. As with mirrors, the distance from the principal plane of a lens to its focal point is the focal length (f). The focal length depends on the shape of the lens and the index of refraction of the lens material. Focal lengths, image positions, and image heights can be negative.



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
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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

$$x_o = 32.0 \text{ cm}$$

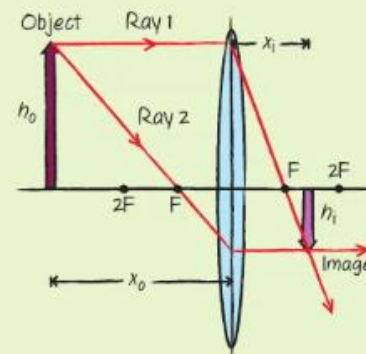
$$h_o = 3.0 \text{ cm}$$

$$f = 8.0 \text{ cm}$$

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 $f = 8.0 \text{ cm}$, $x_o = 32.0 \text{ cm}$.

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

- Use the magnification equation to solve for image height.

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

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

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

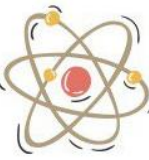
Substitute $x_i = 11 \text{ cm}$, $h_o = 3.0 \text{ cm}$, $x_o = 32.0 \text{ cm}$.

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

- 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.



4	Draw a ray diagram (using at least one light ray that is parallel to the principal axis and another ray that passes or appears to pass through the focal point) to find the image of an object located at different distances from a convex lens (greater than or equal twice the focal length, between the focal length and twice the focal length, and smaller than the focal length), 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.	Student Textbook	51-55
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- 46.** Calculate the image position and height of a 2.0-cm-tall object located 25 cm from a convex lens with a focal length of 5.0 cm. What is the orientation of the image?
- 47.** Use a scale ray diagram to find the image position of an object that is 30 cm to the left of a convex lens with a 10-cm focal length.