EOT – 2025-2026
GRADE 12 ADV
TERM 1
INSPIRE

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MCQ

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MCQ

1	**Define quantities of light like luminous flux and illuminance, specifying their SI units.**	**Student Textbook**	**5,6**

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.

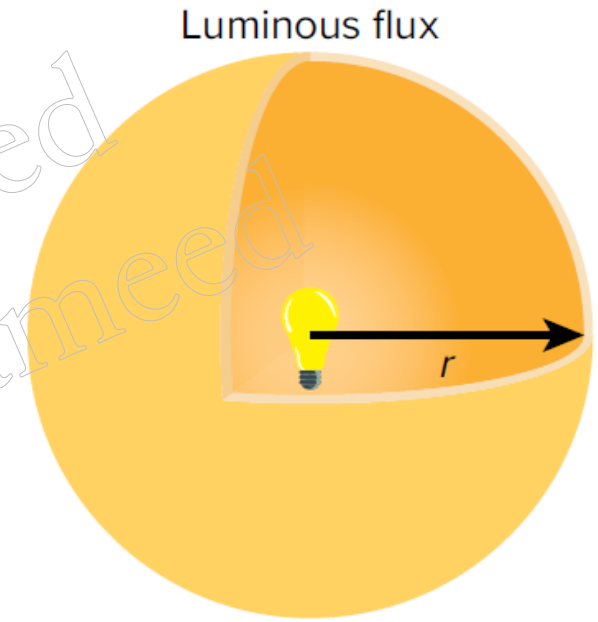


Figure 5 Luminous flux is the rate at which light rays are emitted from a luminous source.

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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.

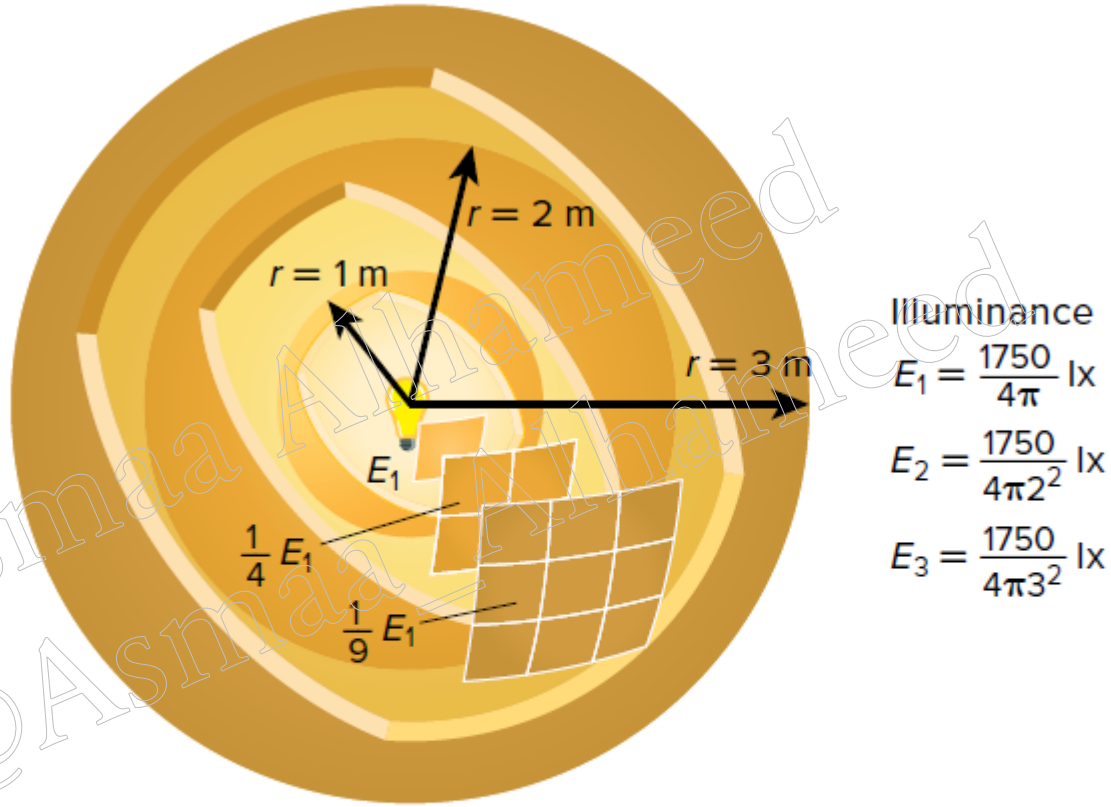


Figure 6 Illuminance (E) is the quantity of light that strikes a surface. As the distance from the luminous source (r) increases, E decreases. E depends on the inverse of r squared.

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 $\frac{1750\text{ lm}}{4\pi\text{ m}^2} = 139$ lx. This mathematical relationship means that at a distance of 1.00 m from the bulb, 139 lm strikes each square meter.

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Practice problems:

1.What is the SI unit of luminous flux?
a) Candela
b) Lux
c) Lumen
d) Watt

2.The illuminance on a surface is measured in:
a) Lumens
b) Candelas
c) Lux
d) Joules

3.Which quantity describes the total light power emitted by a source?
a) Luminous Intensity
b) Illuminance
c) Luminous Flux
d) Wavelength

Answers:

1.c) Lumen

2.c) Lux

3.c) Luminous Flux

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2	**Define diffraction as the bending of a wave as it passes the edge of a barrier.**	**Student Textbook**	**12**

Diffraction and the Wave Model

In 1665 Italian scientist Francesco Maria Grimaldi observed that the edges of shadows are not perfectly sharp. He introduced a narrow beam of light into a dark room and held a rod in front of the light such that it cast a shadow on a white surface. The shadow cast by the rod was wider than the shadow should have been if light traveled in a straight line past the edges of the rod. Grimaldi also noted that the shadow was bordered by colored bands. He determined that both of these observations could be explained if light bent slightly. He called the bending of light as it passes the edge of a barrier **diffraction.**

Huygens' principle In 1678 Dutch scientist Christiaan Huygens used a wave model to explain diffraction. According to Huygens' principle, all the points of a wavefront of light can be thought of as new sources of smaller waves. These smaller waves, or wavelets, expand in every direction and are in step with one another. A flat, or plane, wavefront of light consists of an infinite number of point sources in a line. **Figure 12** illustrates Huygen's principle.

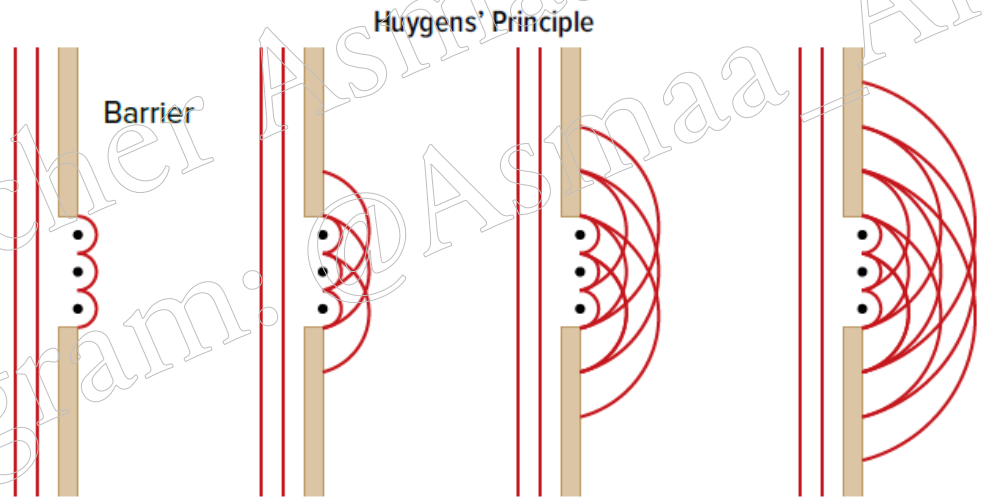


Figure 12 Huygens' wavelets combine to form a straight wavefront, except at the edges of the wave. The wavelets spread out in a circular manner when a barrier creates an edge.

As a wavefront passes by an edge, the edge cuts the wavefront such that each circular wavelet generated by each Huygens' point will propagate as a circular wave in the region where the original wavefront was bent. This wave model explained the diffraction Grimaldi.

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Practice problems:

1) Diffraction is best described as:
a) The change in wave speed in a new medium.
b) The bending of a wave as it passes the edge of a barrier.
c) The superposition of two waves meeting.
d) The change in frequency due to motion.

2) Which phenomenon occurs when a water wave spreads out after passing through a narrow opening in a barrier?
a) Refraction
b) Reflection
c) Diffraction
d) Dispersion

3) The bending of light around the edge of an obstacle is an example of:
a) Reflection
b) Refraction
c) Diffraction
d) Polarization

Answers:
1. b) The bending of a wave as it passes the edge of a barrier.
2. c) Diffraction
3. c) Diffraction

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3	-Describe that the colour of light is related to its wavelength and frequency. -Describe primary and secondary pigments and the effects of mixing pigments or dyes.	Student Textbook	13-15

Color

In 1666 Newton performed experiments on the colors produced when a narrow beam of sunlight passed through a glass prism, as shown in **Figure 13.** Newton called the ordered arrangement of colors a spectrum. Using his later-disproved corpuscle (or particle) model of light, he thought that particles of light interacted with some unevenness in the glass to produce the spectrum.

To test this assumption, Newton allowed the spectrum from one prism to fall on a second prism. If the spectrum was caused by irregularities in the glass, he reasoned that the second prism would increase the spread in colors. Instead, the second prism reversed the spreading of colors and recombined them to form white light. After more experiments, Newton concluded that white light is composed of colors and that a property of the glass other than unevenness caused the light to separate into colors.

Different wavelengths

Can the wave model of light explain Newton's observations? For light to be a wave, it must have wavelength and frequency. The work of Grimaldi, Huygens, Newton, and others suggested that the color of light is related to wavelength. Visible light falls within the range of wavelengths from about 400 nm (4.00×10^{-7} m) to 700 nm (7.00×10^{-7} m), as shown in **Figure 13.** The longest visible wavelengths are seen as red light and the shortest as violet.

As white light crosses the boundary from air into glass and back into air in **Figure 13,** its wave nature causes each different color of light to be bent at a different angle. The shorter the wavelength, the more the light is bent. This unequal bending of the different colors causes the white light to be spread into a spectrum.

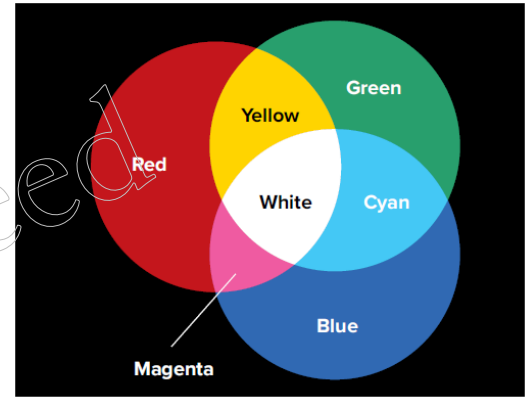


Figure 14 Red, green, and blue light, the primary colors, combine in pairs to produce yellow, cyan, or magenta light. The region where these three colors overlap on the screen appears white.

Color by addition of light

White light can be formed from colored light in a variety of ways. For example, when the correct intensities of red, green, and blue light are projected onto a white screen, as in **Figure 14,** white light is formed. This is called the additive color process, which is used in many television screens. A television screen uses three colors—red, green, and blue. Combinations of these produce the colors you see.

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The correct intensities of red, green, and blue light appear on a screen as white light when combined. Because of this phenomenon, they are called the **primary colors** of light. The primary colors can be mixed in pairs to form three additional colors, as shown in **Figure 14.** Red and green light together produce yellow light, blue and green light produce cyan, and red and blue light produce magenta. The colors yellow, cyan, and magenta are called secondary colors. A **secondary color** is a combination of two primary colors. Note that these are slightly different from the primary and secondary colors you might have learned in art class; the reasons for this will be explained later in this module.

As shown in **Figure 14**, yellow light can be made from red light and green light. If yellow light and blue light are projected onto a white screen with the correct intensities, the surface will appear to be white. **Complementary colors** are two colors of light that can be combined to produce white light. Thus, yellow is a complementary color of blue, and vice versa, because the two colors of light combine to make white light. In the same way, cyan and red are complementary colors. Magenta and green are the other pair of complementary colors. A practical application of this is that yellowish laundry can be whitened with a bluing agent added to detergent.

Color by subtraction of light

As you learned in the first lesson of this module, objects can reflect and transmit light. They also can absorb light. The color of an object depends on the wavelengths present in the light that illuminates the object. The color also depends on which wavelengths are absorbed by the object and which wavelengths are reflected. The natural existence or artificial placement of dyes in the material of an object, or pigments on its surface, gives the object color.

Dyes

You are probably familiar with dyes that are used to color cloth. Dyes can be made from plant or insect extracts. For example, purple dye can be extracted from the berries of a black mulberry tree. The saffron crocus is a source of yellow dye. One type of red dye is extracted from an insect called a cochineal. A dye is a molecule that absorbs certain wavelengths of light and transmits or reflects others. When light is absorbed, its energy is transferred to the object that it strikes and is transformed into other forms of energy. A red shirt is red because the dyes in it reflect mostly red light to our eyes. When white light falls on the red object shown in **Figure 15**, the dye molecules in the object absorb most of the blue and green light and reflect mostly red light. When only blue light falls on the red object, very little light is reflected and the object appears to be almost black.



Figure 15 The colors of objects we see are determined by which wavelengths of light are absorbed and which are reflected.

Explain *why the die that is yellow in the white light appears red in red light.*

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Pigments The difference between a dye and a pigment is that pigments usually are made of crushed minerals rather than plant or insect extracts. For example, hematite produces a red pigment, and blue pigment can be obtained from azurite. Pigment particles can be seen with a microscope. A pigment that absorbs only one primary color and reflects two from white light is called a **primary pigment.** Yellow pigment absorbs blue light and reflects red and green light. Yellow, cyan, and magenta are the colors of primary pigments.

A pigment that absorbs two primary colors and reflects one color is called a **secondary pigment.** The colors of secondary pigments are red (which absorbs green and blue light), green (which absorbs red and blue light), and blue (which absorbs red and green light). Note that the primary pigment colors are these secondary colors of light. In the same way, the secondary pigment colors are light's primary colors.

The primary and secondary pigments are shown in **Figure 16.** When the primary pigments yellow and cyan are mixed, the yellow absorbs blue light and the cyan absorbs red light. **Figure 16** shows yellow and cyan combining to make green pigment. When yellow pigment is mixed with the secondary pigment blue, which absorbs green and red light, all the primary colors are absorbed, and the result is black. Yellow and blue are complementary pigments. Cyan and red, as well as magenta and green, are also complementary pigments.

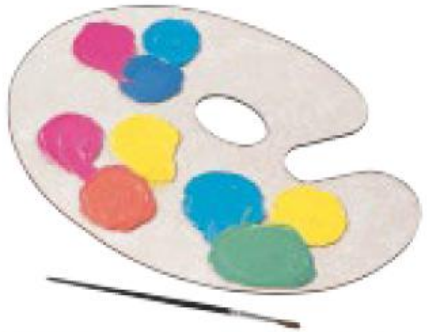


Figure 16 Magenta, cyan, and yellow are the primary pigments. Secondary pigments, red, green, and blue, are produced from mixing the primary pigments in pairs.

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Practice problems:

1) The property of light that primarily determines its color is:
a) Its amplitude
b) Its speed
c) Its wavelength and frequency
d) Its intensity

2) Which color of visible light has the longest wavelength?
a) Violet
b) Blue
c) Red
d) Green

3) A light wave with a high frequency will have a:
a) Long wavelength and appear red
b) Short wavelength and appear blue
c) Long wavelength and appear blue
d) Short wavelength and appear red

Answers:
1. c) Its wavelength and frequency
2. c) Red
3. b) Short wavelength and appear blue

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Practice problems:

4) Cyan, magenta, and yellow are known as:
a) Primary colors of light
b) Secondary colors of light
c) Primary pigments
d) Tertiary pigments

5) Mixing the primary pigments cyan and yellow will produce:
a) Red
b) Blue
c) Green
d) White

6) A magenta pigment absorbs:
a) Red light
b) Green light
c) Blue light
d) Cyan light

Answers:
4. b) Secondary colors of light
5. c) Green
6. b) Green light

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4	**Apply Malus's law to light filtered by polarizer and analyser filters.**	**Student Textbook Physics Challenge**	**16,17 18**

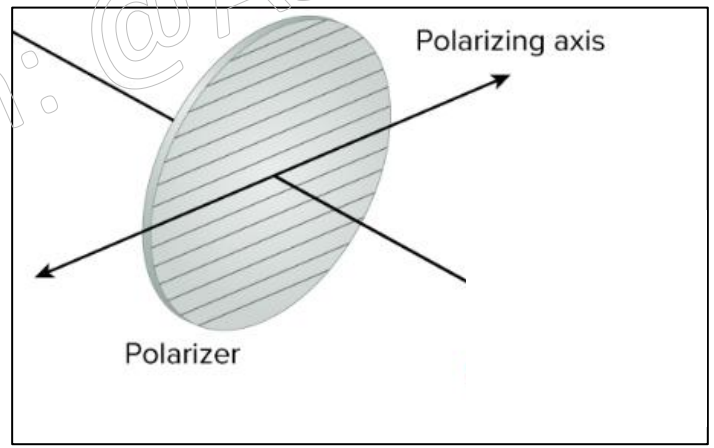
Polarization of Light



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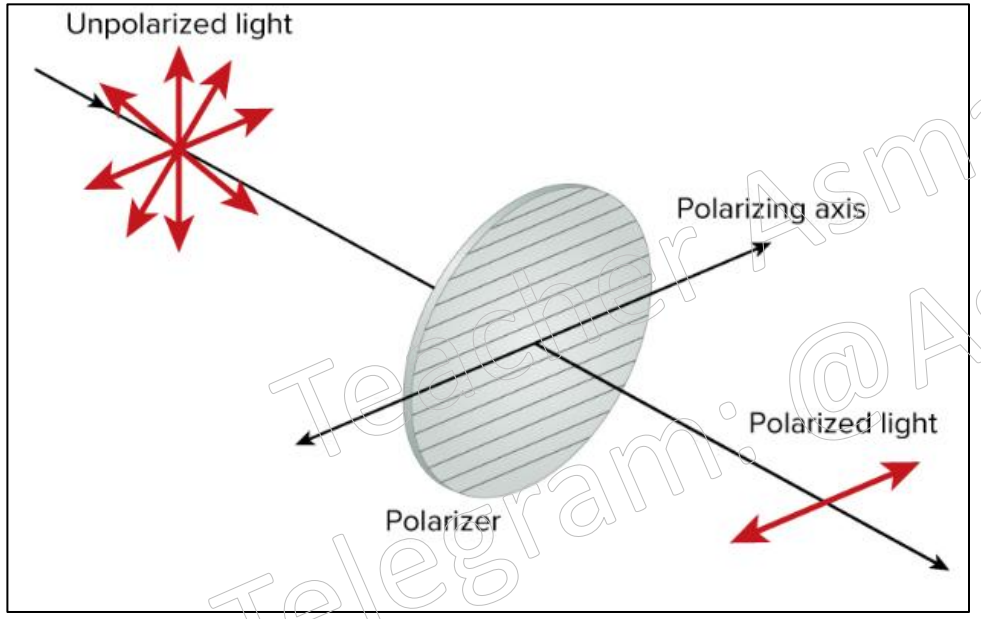
Polarization of Light

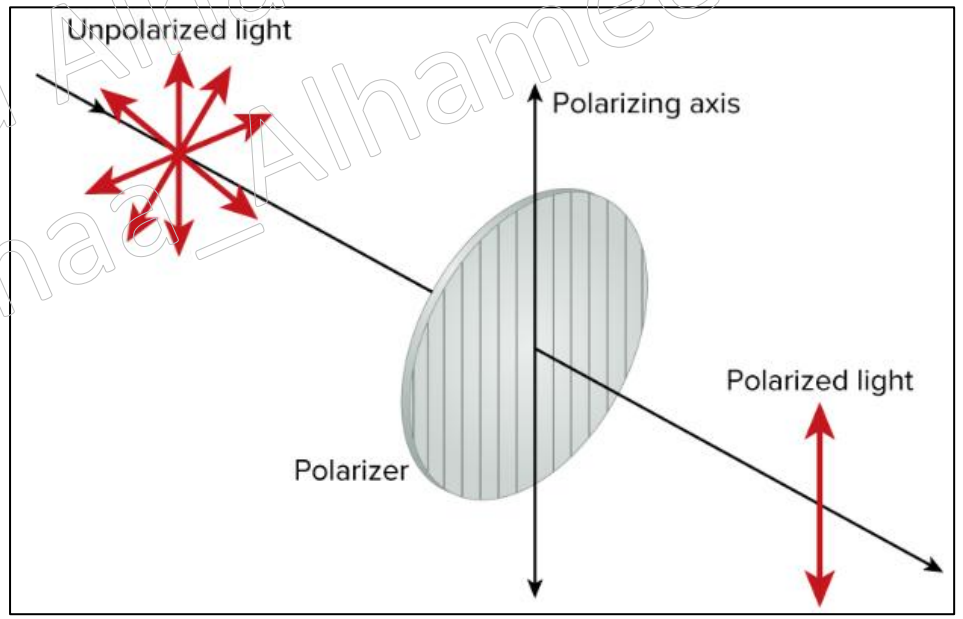
- **Polarization** is the production of light with a specific pattern of oscillation.
- When the electric field of a light wave oscillates in random directions, the light is nonpolarized.
- The lines in the polarizer represent a polarizing axis. The light with the portion of the electric field that oscillates parallel to the polarizing axis passes through, while the light with the portion of the electric field that oscillates perpendicular to the axis is absorbed.



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Polarization of Light

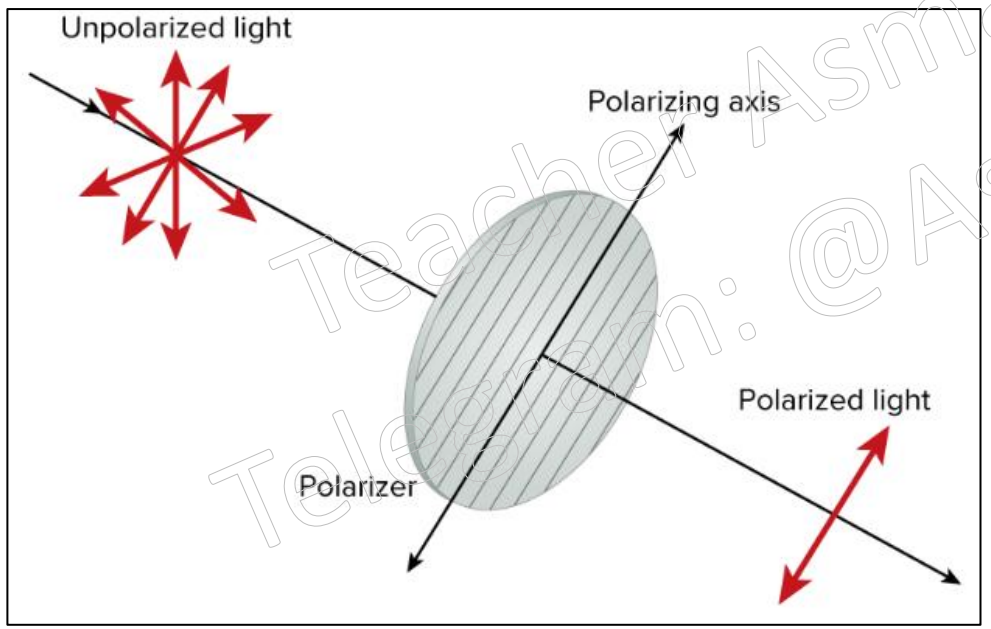


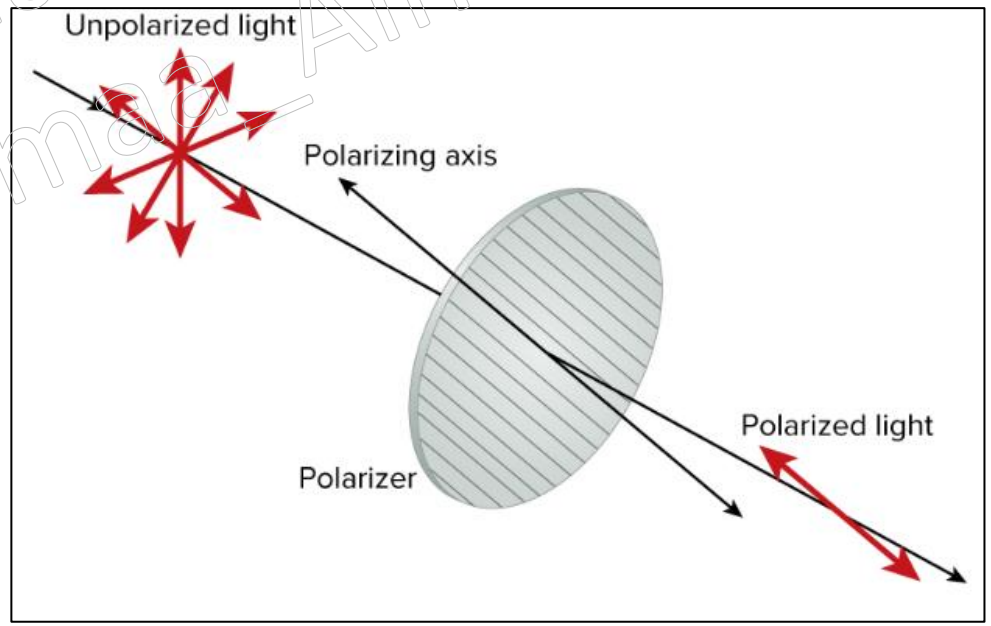


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Polarization of Light

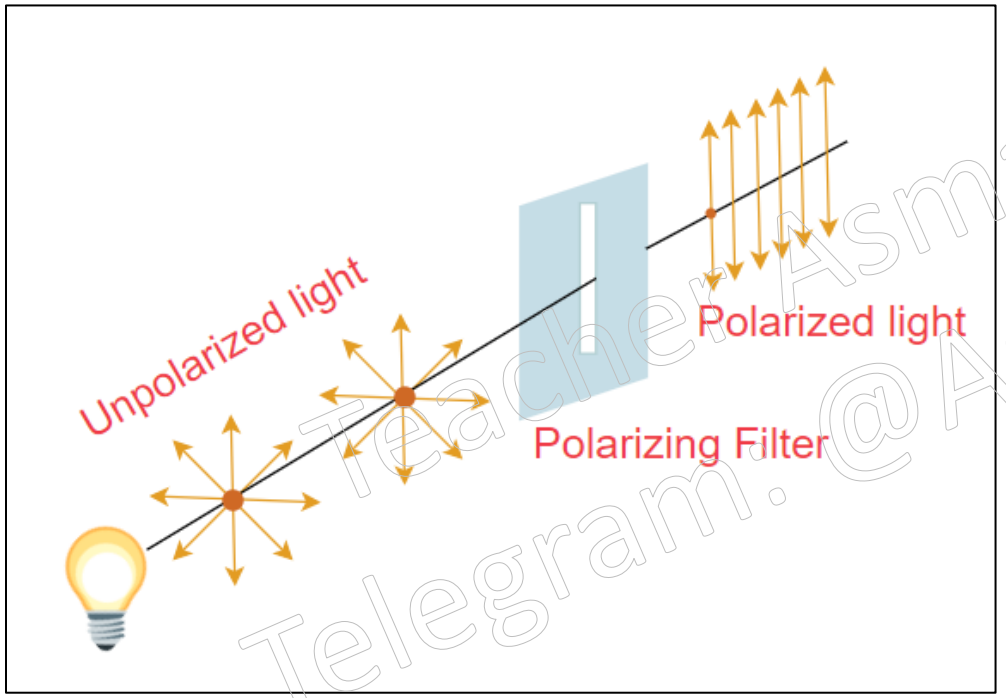
- If a polarizer is placed in a beam of nonpolarized light, only the components of the waves in the same direction as the polarizing axis can pass through.
- As a result, half of the total light passes through, reducing the intensity of the light by half.

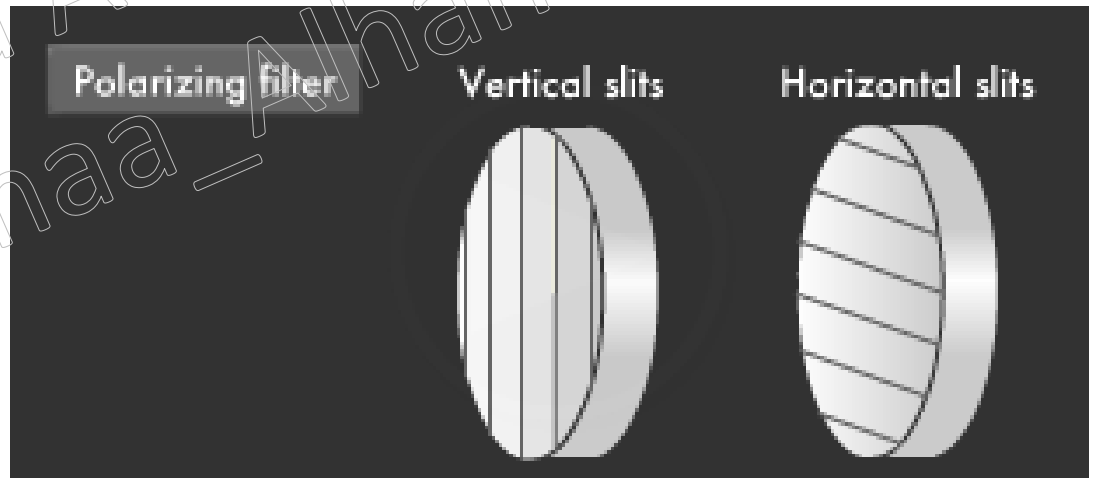




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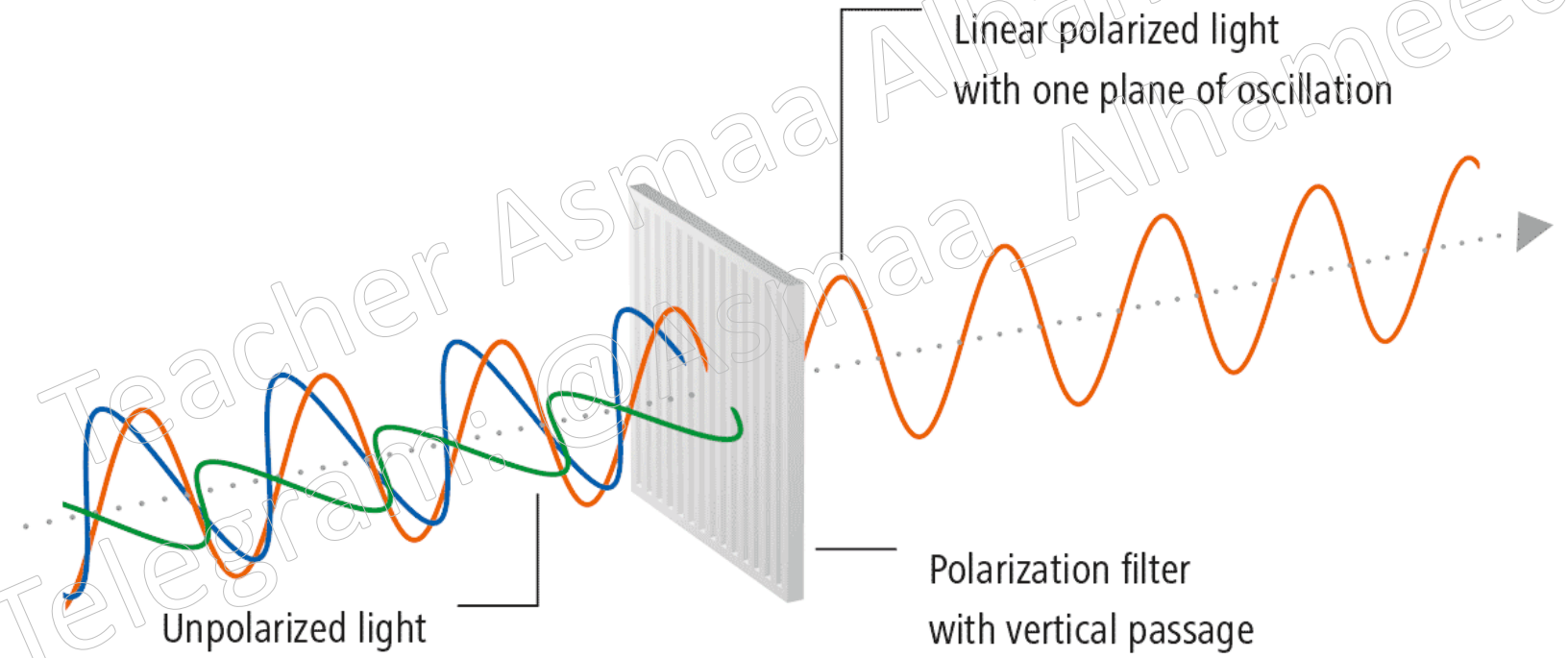
Polarization of Light





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Polarization of Light



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Polarization of Light

- Polarization can also occur when light is reflected, such as from a sheet of glass or from a road.
- Polarized reflected light causes glare. Polarizing sunglasses reduce glare from the polarized light reflected off roads.
- Photographers can use polarizing filters over camera lenses to block reflected light.





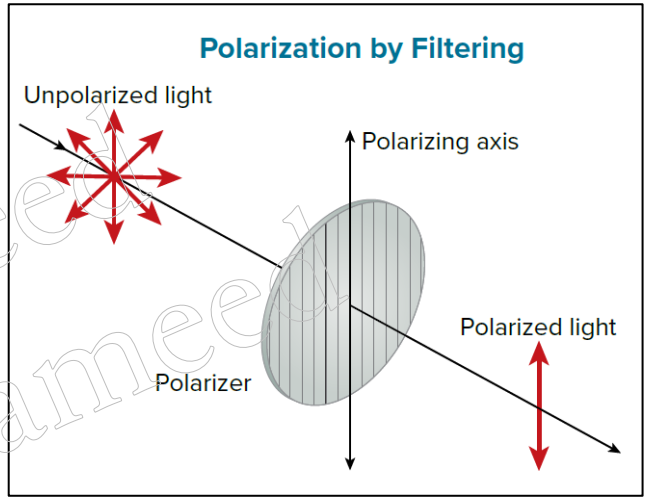


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Polarization of Light

Have you ever looked at light reflected off a road through polarizing sunglasses? If you rotate the glasses, the road first appears to be dark, then light, and then dark again. Light from a lamp, however, changes very little as the glasses are rotated. Why is there a difference? Normal lamp-light is not polarized. However, the light that is coming from the road is reflected and has become polarized. **Polarization** is the production of light with a specific pattern of oscillation.

Recall that light behaves as a transverse wave. For waves on a rope, the oscillating medium is the rope. For light waves, the oscillating medium is the electric field. When this electric field oscillates in random directions, the light is nonpolarized. How can you filter nonpolarized light so that whatever passes through the filter is polarized light?



Polarization by filtering

The lines in the polarizer in **Figure 18** represent a polarizing axis. The light with the portion of the electric field that oscillates parallel to these lines passes through. The light with the portion of the electric field that oscillates perpendicular to these lines is absorbed. If a polarizer is placed in a beam of nonpolarized light, only the components of the waves in the same direction as the polarizing axis can pass through. As a result, half of the total light passes through, reducing the intensity of the light by half.

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Polarization by reflection

When you look through a polarizing filter at the light reflected by a sheet of glass and rotate the filter, you will see the light brighten and dim. The light is partially polarized parallel to the plane of the glass when it is reflected. Polarized reflected light causes glare. Polarizing sunglasses reduce glare from the polarized light reflected off roads. Photographers can use polarizing filters over camera lenses to block reflected light. This result is shown in **Figure 19.**

Malus's law

Suppose you produce polarized light with a polarizing filter. What would happen if you place a second polarizing filter in the path of the polarized light? If the polarizing axis of the second filter is parallel to that of the first, the light will pass through. If the polarizing axis of the second filter is perpendicular to that of the first, no light will pass through, as shown in **Figure 20.**

If the light intensity after the first polarizing filter is I_1 and the intensity after the second filter is I_2, how can you control I_2? I_2 depends only on I_1 and the angle between the axes of the filters, θ. If θ is 0, I_2 equals I_1; if θ is 90°, all of the light is blocked, resulting in I_2 being 0. This indicates that the intensity might depend on the cosine of θ. The actual relationship is a that of a cosine squared. The law that explains the reduction of light intensity as light passes through a second polarizing filter is **Malus's law.**

Malus's Law

The intensity of light coming out of a second polarizing filter is equal to the intensity of polarized light coming out of a first polarizing filter multiplied by the cosine, squared, of the angle between the polarizing axes of the two filters.

$$I_2 = I_1 \cos^2 \theta$$



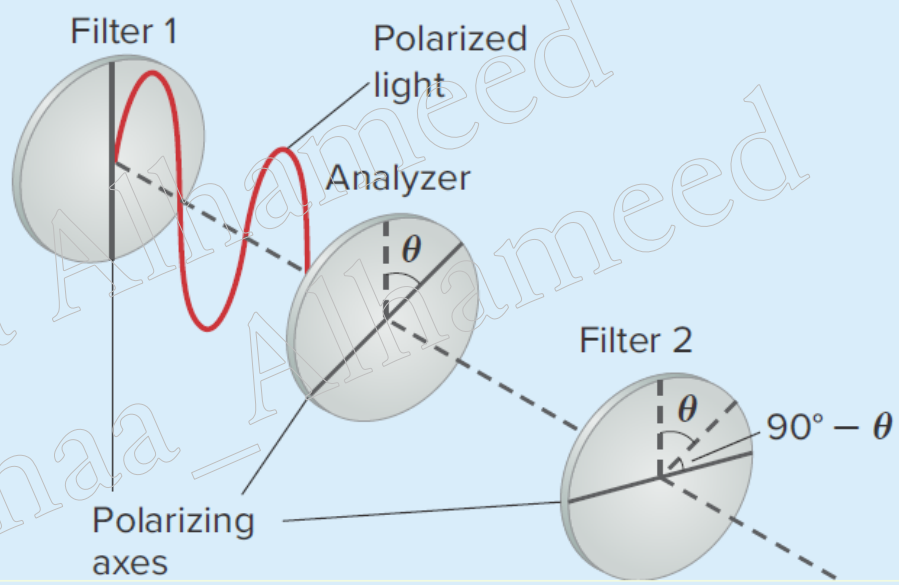
Figure 19 Glare is light that has been polarized by reflection. Photographers use polarizing filters to reduce glare.

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PHYSICS Challenge

You place an analyzer filter between the two cross-polarized filters, such that its polarizing axis is not parallel to either of the two filters, as shown in the figure to the right.

1. You observe that some light passes through filter 2, though no light passed through filter 2 before you inserted the analyzer filter. Why does this happen?
2. The analyzer filter is placed at an angle of θ relative to the polarizing axis of filter 1. Derive an equation for the intensity of light coming out of filter 2 compared to the intensity of light coming out of filter 1.



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Practice problems:

1) According to Malus's Law, if the angle between the transmission axes of a polarizer and an analyzer is 0°, the intensity of transmitted light is:

a) Zero
b) Minimum
c) Maximum
d) Half the original intensity

2) Unpolarized light of intensity I_o passes through a single polarizer. The intensity of the transmitted light is:

a) I_o
b) $I_o/2$
c) $I_o/4$
d) Zero

3) Polarized light of intensity I passes through an analyzer rotated at 60° from the polarizer's axis. What is the final intensity? (Malus's Law: $I = I_o\cos^2\theta$)

a) I
b) I/2
c) I/4
d) I/8

Answers:

1. c) Maximum
2. b) $I_o/2$
3. c) I/4

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5	**-Apply mathematical equations to calculate unknown physical quantities (wavelengths, frequencies, or speeds) when light waves are doppler shifted based on the relative speed of the observer and the light source.**	**Student Textbook Practice problems**	**20**

Speed, Wavelength, and Frequency of Light

As you have learned, the source of a wave determines that wave's frequency (f), and the medium and the frequency together determine the wavelength (λ) of a wave. Because light has wave properties, the same mathematical models used to describe waves in general can be used to describe light. For light of a given frequency traveling through a vacuum, wavelength is a function of the speed of light (c), which can be written as $\lambda_o = c/f$. The development of the laser in the 1960s provided new ways to measure the speed of light. The frequency of light can be measured with extreme precision using lasers and the time standard of atomic clocks. Measurements of wavelengths of light, however, are much less precise.

All colors of light travel at c in a vacuum, though the wavelengths are different. Since $\lambda_o = c/f$, once the frequency of a light wave in a vacuum is measured, the wavelength can be determined.

Relative motion and light What happens if a light source travels toward you or you move toward the source? You have learned that the frequency of a sound heard by a listener changes if either the source or the listener of the sound is moving. The same is true for light. However, when you consider the velocities of a sound source and the observer, you are really considering each one's velocity relative to the medium through which the sound travels. This is not the case for light.

Get It?

Explain how the wavelength, frequency, and speed of light are mathematically related.

The Doppler effect The nature of light waves is such that they are not vibrations of the particles of a medium. The Doppler effect for light can involve only the relative velocity between the source and the observer. Remember that the only factors in the Doppler effect are the velocity components along the axis between the source and the observer, as shown in **Figure 21** on the next page.

Doppler effect for light problems can be simplified by considering axial relative speeds that are much less than the speed of light ($v << c$). This simplification is used to develop the equation for the observed light frequency (f_{obs}), shown below.

Observed Light Frequency

The observed frequency of light from a source is equal to the actual frequency of the light generated by the source, times the quantity 1 plus the relative speed along the axis, divided by the speed of light, between the source and the observer if they are moving toward each other, or 1 minus the relative speed, divided by the speed of light, if they are moving away from each other.

$$F_{obs} = f\left(1 \pm \frac{v}{c}\right)$$

Applications Most applications of the Doppler effect for light are in astronomy, where phenomena are discussed more in terms of wavelength. Using the relationship $\lambda = c/f$ and the $v << c$ simplification, the following equation describes the Doppler shift ($\Delta\lambda$), the difference between the observed and the actual wavelengths.

Doppler Shift

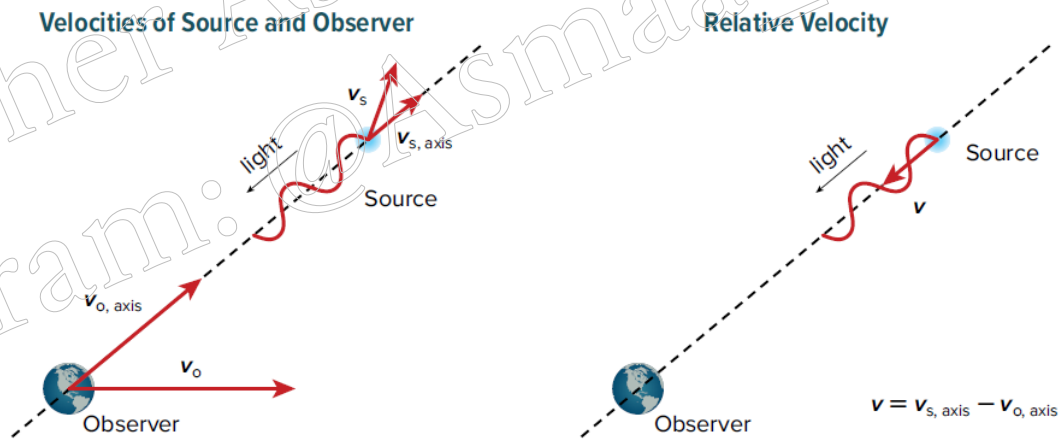
The difference between the observed wavelength of light and the actual wavelength of light generated by a source is equal to the actual wavelength of light generated by the source, times the relative speed of the source and observer, divided by the speed of light.

$$(\lambda_{obs} - \lambda) = \Delta\lambda = \pm\left(\frac{v}{c}\right)\lambda$$

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A positive change in wavelength occurs when the relative velocity of the source is away from the observer. In this case, the observed wavelength is longer than the original wavelength. The light appears closer to the red end of the spectrum than it normally would. We say this light is red shifted. A negative change in wavelength occurs when the relative velocity of the source is in a direction toward the observer. In this case, the observed wavelength is shorter than the original wavelength. This is known as a blue shift.

Because the speed of light is constant, when the wavelength is red shifted, the observed frequency is lower than the original due to the inverse relationship between the two variables. When light is blue shifted, the observed frequency is higher.



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16. Oxygen can be made to produce light with a wavelength of 513 nm. What is the frequency of this light?

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17. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a frequency of 6.16×10^{14} Hz. What frequency of light from that hydrogen atom would be observed by an astronomer on Earth?

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18. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a wavelength of 486 nm. What wavelength would be observed on Earth from that hydrogen atom?

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19. CHALLENGE An astronomer is looking at the spectrum of a galaxy and finds that it has an oxygen spectral line of 525 nm, while the laboratory value is measured at 513 nm. Calculate how fast the galaxy would be moving toward or away from Earth and how you know.

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Practice problems:

1) A distant galaxy emits light with a rest wavelength of 500 nm. An observer on Earth measures this wavelength to be 505 nm. What can be concluded about the galaxy's motion relative to Earth?

a) It is moving toward Earth at 0.01c.
b) It is moving away from Earth at 0.01c.
c) It is moving toward Earth at 0.02c.
d) It is moving away from Earth at 0.02c.

2) A spaceship is moving toward a stationary star at 0.1c. If the star emits light of frequency 6.0×10^{14} Hz, what frequency does the spaceship observe? (Use the Doppler formula for light)

a) 5.4×10^{14} Hz
b) 6.0×10^{14} Hz
c) 6.6×10^{14} Hz
d) 7.2×10^{14} Hz

3) A police radar gun uses the Doppler effect to measure the speed of a car. If the reflected microwave has a frequency shift of +1500 Hz from the transmitted frequency of 10.5 GHz, how fast is the car moving toward the radar gun? (Assume speed of light $c = 3 \times 10^8$ m/s)

a) 15 m/s
b) 21.4 m/s
c) 30 m/s
d) 42.8 m/s

Answers:
1. b) It is moving away from Earth at 0.01c.
2. c) 6.6×10^{14} Hz
3. b) 21.4 m/s

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6	**-Apply the law of reflection in drawing ray diagrams and solving numerical problems.**	**Student Textbook Example problem1 Practice problems**	**29,30 31**

The Law of Reflection

Figure 2 shows a light ray striking a reflecting surface. The normal is an imaginary line that is perpendicular to a surface at the location where light strikes the surface. The incident ray, the reflected ray, and the normal are in the same plane, which is perpendicular to the surface. Although light travels in three dimensions, the reflection of light is planar (two-dimensional). Planar relationships are known as the law of reflection.

Law of Reflection

The angle that a reflected ray makes as measured from the normal to a reflective surface equals the angle that the incident ray makes as measured from the same normal.

$$\theta_r = \theta_i$$

Wave model We can describe this law in terms of the wave model of light. **Figure 3** shows a wavefront of light approaching a surface. The wavefront is perpendicular to the light ray. As each point along the wavefront reaches the surface, it reflects off that surface. Because all points are traveling at the same speed, they all travel the same total distance in the same time. Thus, the wavefront as a whole leaves the surface at an angle equal to its incident angle. Note that the wavelength of the light does not affect this process. The surface reflects red, green, and blue light all in the same direction.

Smooth surfaces Consider the light rays shown on the left in **Figure 4** on the next page. All the rays reflect off the surface parallel to one another. This occurs only if the reflecting surface is not rough on the scale of the wavelength of the light. We consider such a surface to be

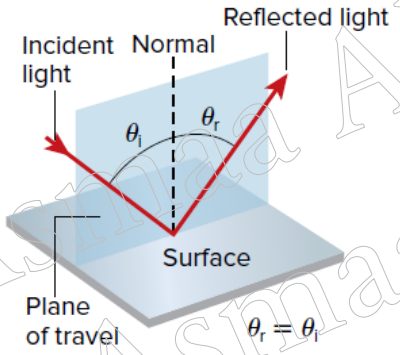
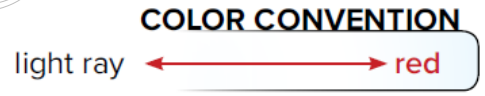


Figure 2 Reflecting light waves have an angle of reflection in the same plane as and equal to the angle of incidence.



smooth. A smooth surface, such as a mirror, produces **specular reflection,** in which parallel light rays reflect in parallel.

Rough surfaces What happens when light strikes a sheet of paper? A sheet of paper might appear smooth, but on the scale of the wavelength of light, paper is actually quite rough. The right side of **Figure 4** shows light rays reflecting off a sheet of paper. All of the light rays are parallel before they strike the surface, but the reflected rays are not parallel, as shown. This scattering of light off a rough surface is called **diffuse reflection.**

The law of reflection applies to smooth and rough surfaces. For a rough surface, the angle that each incident ray makes with the normal equals the angle that its reflected ray makes with the normal. On a microscopic scale, however, the normals to the surface locations are not parallel.

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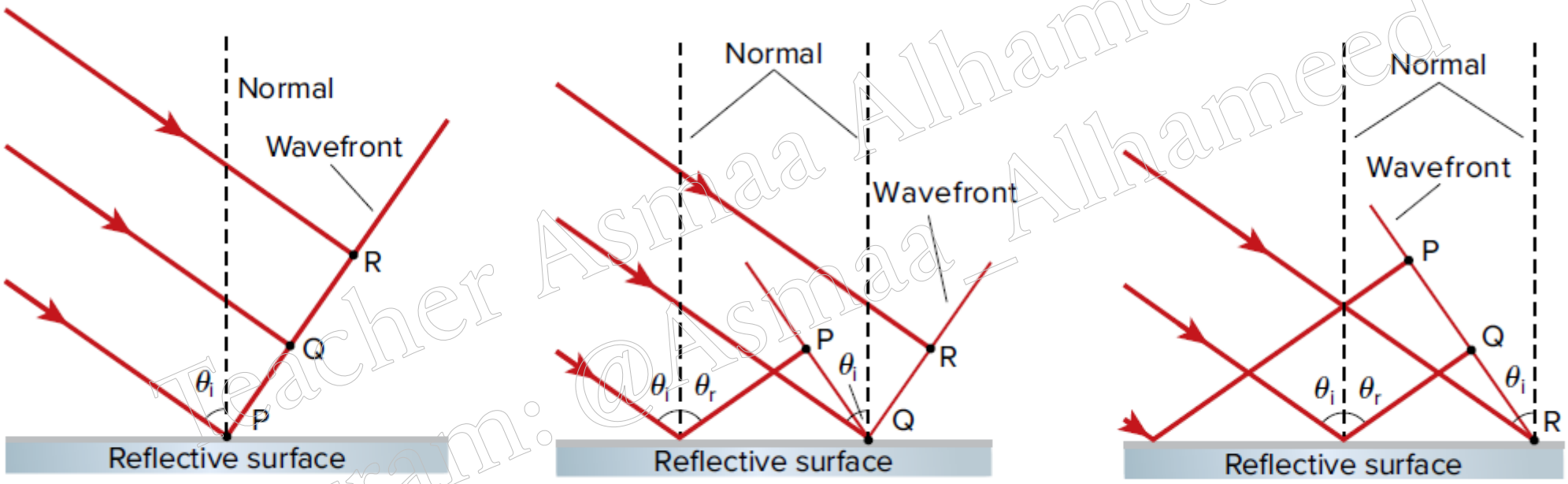


Figure 3 All parts of a wavefront reflect from a surface at the same angle. The angle of incidence equals the angle of reflection.

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Thus, the rough surface prevents the reflected rays from being parallel, so the reflected rays are scattered in different directions. With specular reflection, as with a mirror, you can see your face. But no matter how much light reflects off a wall or a sheet of paper, as shown in **Figure 4,** you will never be able to use them as mirrors.

Objects and Plane-Mirror Images

A **plane mirror,** such as a mirror we use to look into, is a flat, smooth surface from which light is reflected by specular reflection.

When studying illumination, an **object** is either a luminous source of light rays, such as a lightbulb, or an illuminated source of light rays, such as a person. For most of the light sources that you will study in this module, light spreads out from that source in all directions. A mirrored surface can reflect these light rays so an image is visible, as shown in **Figure 5.**

In **Figure 6** light reflects diffusely from all parts of the bird (the object). The girl sees the light that reflects into her eye. Because her brain processes this information as if the rays travel in a straight path, it seems to the girl as if the light follows the dashed lines. The light seems to have come from a point behind the mirror. Just as the rays diverge from the object, they also diverge from the image.

The combination of light rays reflected from the bird in **Figure 6** forms the **image** of the bird. It is a **virtual image,** a

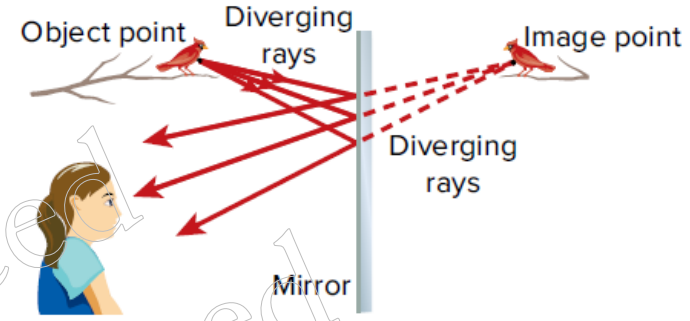


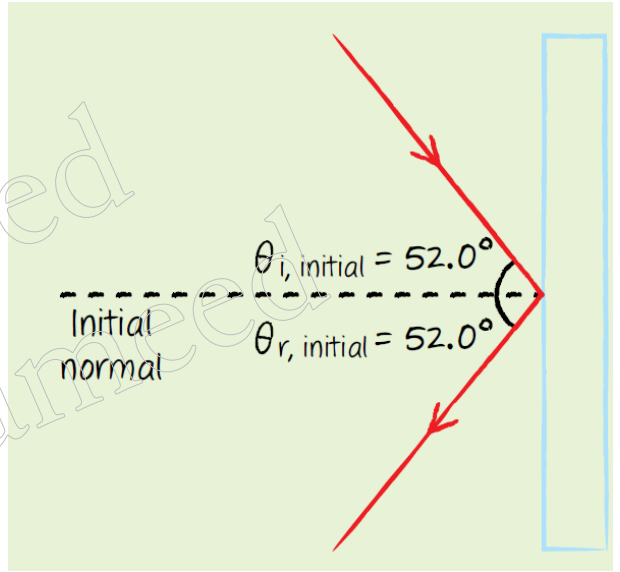
Figure 6 Rays that reflect from the bird disperse in many directions. Only a few that travel toward the mirror are shown. The image is located where multiple light rays from a point on an object seem to converge.

type of image formed by diverging light rays. A virtual image is always on the opposite side of the mirror from the object. The image is virtual because there are no light rays at the image location. Plane mirrors produce only virtual images.

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EXAMPLE Problem 1

CHANGING THE ANGLE OF INCIDENCE A light ray strikes a plane mirror at an angle of 52.0° to the normal. The mirror then rotates 35.0° around the point where the ray strikes the mirror so that the angle of incidence of the light ray decreases. The axis of rotation is perpendicular to the plane of the incident and the reflected rays. What is the angle between the initial and final reflected ray?



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1. Explain why the reflection of light off ground glass changes from diffuse to specular if you spill water on it.

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2. What is the angle of incidence of a light ray reflected off a plane mirror at an angle of 35° to the normal?

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3. Suppose the angle of incidence of a light ray is 42°.

a. What is the angle of reflection?
b. What is the angle the incident ray makes with the mirror?
c. What is the angle between the incident ray and the reflected ray?

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4. Light from a laser strikes a plane mirror at an angle of 38° to the normal. If the angle of incidence increases by 13°, what is the new angle of reflection?

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5. You position two plane mirrors at right angles to each other. A light ray strikes one mirror at an angle of 60° to the normal and reflects toward the second mirror. What is its angle of reflection off the second mirror?

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6. CHALLENGE You are asked to design a retro-reflector using two mirrors that will reflect a laser beam by 180° independent of the incident direction of the beam. What should be the angle between the two mirrors?

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Practice problems:

1) A light ray strikes a smooth, flat mirror with an angle of incidence of 35°. What is the angle between the reflected ray and the mirror's surface?
a) 35°
b) 55°
c) 70°
d) 90°

2) In a ray diagram showing reflection from a plane mirror, which statement is always true?
a) The incident ray, reflected ray, and normal all lie in different planes.
b) The angle of incidence is twice the angle of reflection.
c) The incident ray and reflected ray are perpendicular to each other.
d) The incident ray, reflected ray, and normal all lie in the same plane.

3) Two mirrors are placed at right angles to each other. A light ray strikes the first mirror at an angle of incidence of 25°. What is the angle of reflection from the second mirror?
a) 25°
b) 65°
c) 90°
d) 115°

Answers:
1. b) 55°
2. d) The incident ray, reflected ray, and normal all lie in the same plane.
3. b) 65°

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7	-Draw a ray diagram to locate the position of an image formed by a plane mirror, showing its properties. -Represent mathematically the relation between image position and object position, as well as the image height and object height for a plane mirror.	Student Textbook Check your progress	32,33 33

Properties of Plane-Mirror Images

Looking at yourself in a mirror, you can see that your image in the mirror appears to be the same distance behind the mirror as you are in front of the mirror. How could you test this? Place a ruler between you and the mirror. Where does the image touch the ruler? You see that your image is vertically oriented as you are, and it matches your size. This is where the expression *mirror image* originates.

Image position and height

The geometric model in **Figure 7** shows why the distances are the same. Two rays from point O at the tip of the candle strike the mirror at points P_1 and P_2. The mirror reflects both rays according to the law of reflection.

We can extend the reflected rays behind the mirror as sight lines (the dashed lines in the figure). These sight lines converge at point I, which is the image of point O. Ray 1, which strikes the mirror at an angle of incidence of 0°, reflects back on itself, so the sight line is at 90° to the mirror, just as ray 1 is. Ray 2 also reflects at an angle with respect to the normal equal to the angle of incidence, so the sight line is at the same angle to the mirror as ray 2.

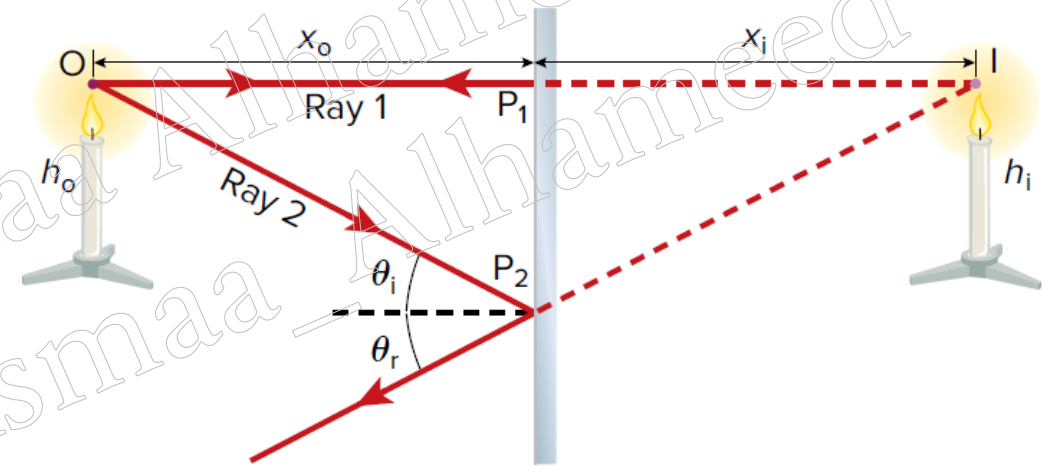


Figure 7 Reflected light rays from the candle (two rays are shown) strike the mirror. Some of those rays reach the viewer's eye. Sight lines (dashed lines) are drawn from where the rays reflect from the mirror to where they converge. The image is located where the sight lines converge.

Explain *why* $x_i = -x_o$.

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This geometric model reveals that line segments OP_1 and IP_1 are corresponding sides of two congruent triangles, ΔOP_1P_2 and ΔIP_1P_2. The object's position with respect to the mirror (x_o) has a magnitude equal to the length of $\overline{OP_1}$. The apparent position of the image with respect to the mirror, which is called the image position (x_i), has a magnitude equal to the length of $\overline{IP_1}$. If image position is negative, indicating that the image is virtual, the following is true.

Plane-Mirror Image Position

With a plane mirror, the image position is equal to the negative of the object position. The negative sign indicates that the image is behind the mirror (and therefore virtual).

$$x_i = -x_o$$

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You can draw more light rays from the object to the mirror to determine the size of the image. The sight lines of two rays originating from the bottom of the candle in **Figure 7** will converge at the bottom of the image. From the law of reflection and congruent-triangle geometry, we find the following is true of the object height (h_o) and image height (h_i) and any other dimension of the object and image.

Plane-Mirror Image Height

With a plane mirror, image height is equal to object height.

$$h_i = h_o$$

Image orientation A plane mirror produces an image with the same orientation as the object. If you stand upright, a plane mirror produces an image of you standing upright. If you do a headstand, the mirror shows you doing a headstand. However, the mirror gives a front-to-back reversal. You are looking face-to-face at the image of yourself.

Follow the sight lines in **Figure 8**. The image is behind the mirror such that the boy appears to be facing himself. When the boy extends his right hand, it appears as though the left hand of the image is extended, but from the boy's perspective, the hand that is extended is on his right-hand side. This happens because a plane mirror does not really reverse left and right. The mirror in **Figure 8** only reverses the boy's image such that it is facing in the opposite direction as the boy, or, in other words, it produces a front-to-back reversal.

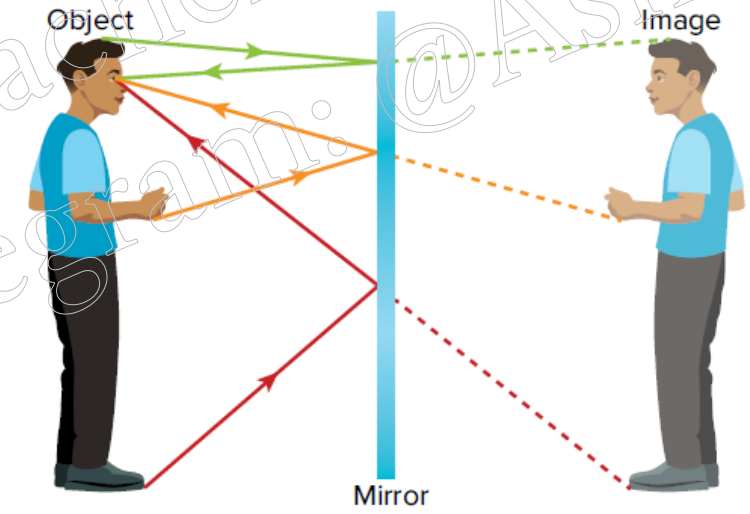


Figure 8 Viewed in a mirror, your height and distance from the mirror appear the same. There is, however, a difference. You are facing the opposite direction.

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7. **Reflection** A light ray strikes a flat, smooth, reflecting surface at an angle of 80° to the normal. What angle does the reflected ray make with the surface of the mirror?

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8. **Image Properties** A dog looks at its image, as shown in **Figure 9.** What are the position, height, and type of image?

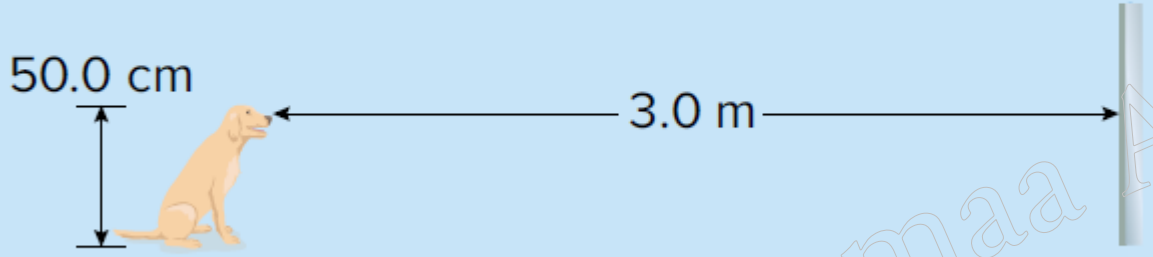


Figure 9

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9. **Law of Reflection** Explain how the law of reflection applies to diffuse reflection.

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10. **Image Diagram** A car is following another car along a straight road. The first car has a rear window tilted at 45° to the horizontal. Draw a ray diagram showing the position of the Sun that would cause sunlight to reflect into the eyes of the driver of the second car.

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11. **Critical Thinking** Explain how diffuse reflection of light off an object enables you to see that object from any angle.

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Practice problems:

1) When drawing a standard ray diagram for a plane mirror, where is the image of an object located?
a) In front of the mirror
b) Behind the mirror
c) At the surface of the mirror
d) At the center of curvature

2) Which of the following is a property of an image formed by a plane mirror?
a) It is always magnified.
b) It is always inverted relative to the object.
c) It is always virtual and erect.
d) It can be projected onto a screen.

3) In a ray diagram for a plane mirror, two rays from the top of an object are drawn. One ray strikes the mirror perpendicularly. What is the path of the second ray typically used?
a) A ray striking the mirror at the focal point.
b) A ray striking the mirror at an arbitrary angle, then reflecting according to the law of reflection.
c) A ray passing through the center of curvature.
d) A ray parallel to the principal axis.

Answers:
1. b) Behind the mirror
2. c) It is always virtual and erect.
3. b) A ray striking the mirror at an arbitrary angle, then reflecting according to the law of reflection.

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Practice problems:

4) If an object is placed 4 meters in front of a plane mirror, where is the image located relative to the mirror?
a) 2 meters behind the mirror
b) 4 meters in front of the mirror
c) 4 meters behind the mirror
d) 8 meters behind the mirror

5) What is the mathematical relationship between the image height (h_i) and the object height (h_o) for a plane mirror?
a) $h_i > h_o$
b) $h_i < h_o$
c) $h_i = h_o$
d) $h_i = 2h_o$

6) An object is 1.8 meters tall and stands 3 meters from a plane mirror. What is the distance between the object and its image?
a) 3 meters
b) 4.8 meters
c) 6 meters
d) 7.8 meters

Answers:
4. c) 4 meters behind the mirror
5. c) $h_i = h_o$
6. c) 6 meters

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8	**-Describe defects in concave mirrors, such as curved aberration, and how they can be corrected.** **-List some of the uses of concave and mirrors**	**Student Textbook**	**35** **39**

Properties of Curved Spherical Mirrors

Move a metal spoon toward and away from your face. Look at your image on both sides of the spoon. Your image may appear larger or smaller, or it may even be inverted. The properties of curved mirrors, such as a metal spoon, and the images that they form depend on the shape of the mirror and the object's position.

The way that a spherical mirror reflects light depends on its curve. **Figure 10** shows two spherical mirrors and some important points and distances for understanding how they form images. A spherical mirror is shaped as if it were a section of a hollow sphere. The mirror (M) has the same geometric center (C) as a sphere of radius *r*. The distance *r* is also called the radius of curvature.

The straight line that includes line segment CM is called the **principal axis,** or line perpendicular to the mirror's surface that divides the mirror in half.

Focal point Light rays from the Sun to Earth are almost parallel because the Sun is so far away. When you point the principal axis of a concave mirror toward the Sun, all the rays reflect through a point. You can locate this point by moving a sheet of paper toward and away from the mirror until the smallest and sharpest spot of sunlight is focused on the paper. This spot is the mirror's **focal point,** which is the point at which incident light rays that are parallel to the principal axis converge after reflecting from the mirror. This is point F.

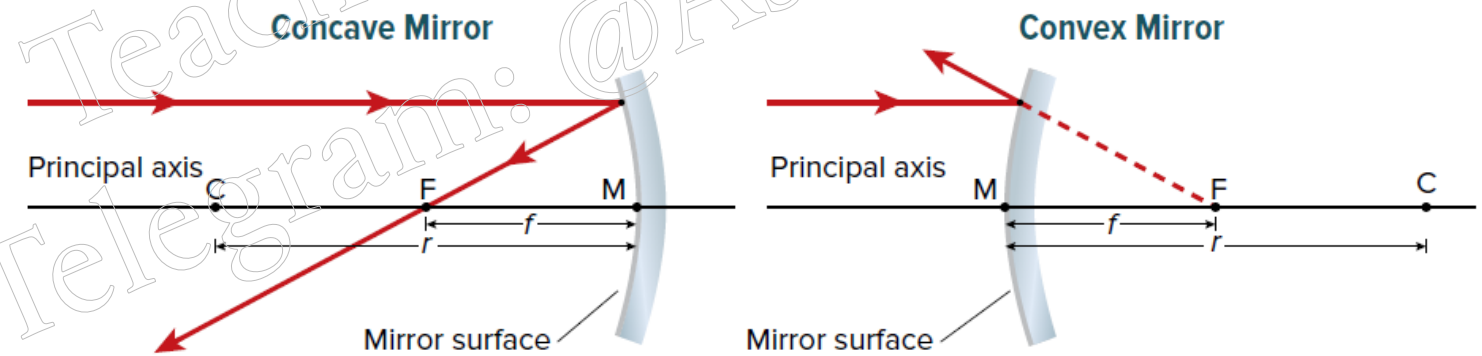


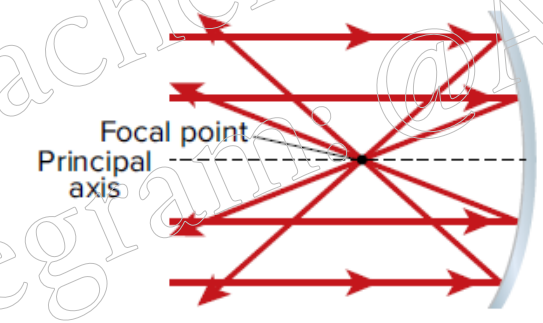
Figure 10 For concave and convex mirrors, the distance from M to F (the focal point) is half the distance from M to C.

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For the mirror on the left in **Figure 10**, a ray parallel to the principal axis is reflected and crosses the principal axis at point F. Note that the distance from M to F is half the distance from M to C. The **focal length** (f) is the distance between the mirror and the focal point and can be expressed as $f = \frac{r}{2}$.

Concave mirrors

The inside surface of a shiny metal spoon acts as a concave mirror. A **concave mirror,** such as the one on the left in **Figure 10**, has an inwardly curving reflective surface, the edges of which curve toward the observer. Incident light rays parallel to the principal axis are reflected and intersect the principal axis at point F. The focal length is positive for a concave mirror because it is a point of converging rays. Rays reflected from concave mirrors are parallel, as shown in **Figure 11**. Concave mirrors are placed in car headlights. It is a concave mirror that allows the light from a spotlight to be focused into a spot.



Light rays parallel to the principal axis reflect off a concave mirror and converge at the focal point.



A lightbulb is placed at the focal point of a concave mirror. The parallel reflected rays are evident in this flashlight beam.

Figure 11 Rays traced from the focal point to a concave mirror reflect off the surface as parallel rays.

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Defects in Concave Mirrors

In diagramming rays, you used a vertical line to represent the mirror. In reality, light rays reflect off the mirror itself, as shown in **Figure 17.** Only parallel rays that are close to the principal axis reflect through the focal point. Other rays converge at points closer to the mirror. This defect, called **spherical aberration,** occurs because the light rays do not all converge at the focal point, which makes an image look fuzzy.

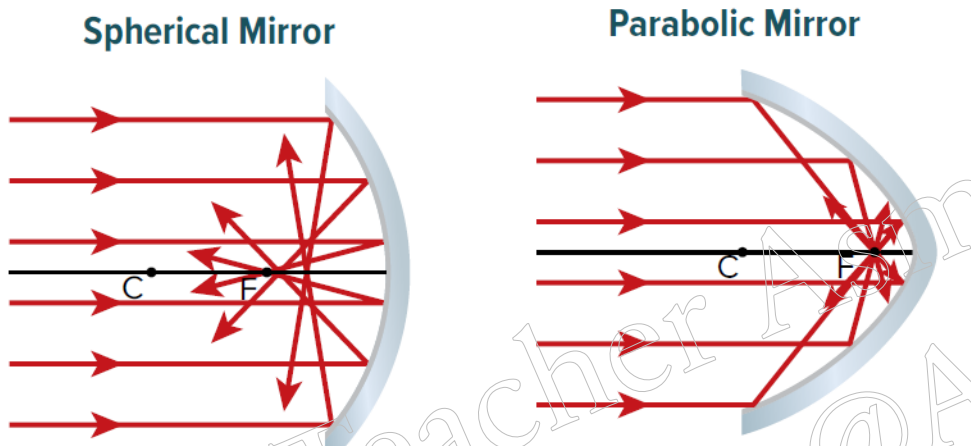


Figure 17 Spherical aberration occurs for spherical mirrors but does not occur for parabolic mirrors.

A mirror ground to the shape of a parabola, as in **Figure 17,** suffers no spherical aberration. Large, parabolic glass mirrors are expensive to manufacture; so, many telescopes use spherical mirrors and smaller, specially designed secondary mirrors or lenses to correct for spherical aberration.



Figure 16 Images from convex mirrors are smaller than the object. This increases the field of view and decreases the driver's blind spot.

Explain *why a warning stating that objects in a convex side-view mirror are closer than they appear may be useful.*

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Uses of concave mirrors:

Everyday & Household

- **Shaving/Makeup Mirrors:** Produce a magnified, upright image for seeing fine details.
- **Torches & Headlights:** Bulb at focus creates a strong, parallel beam of light.
- **Solar Cookers:** Concentrate sunlight to a focal point to generate high heat for cooking.

Scientific & Medical

- **Telescopes:** Large mirrors collect and focus light from distant stars to form images.
- **Dental/ENT Mirrors:** Illuminate and provide a magnified view of body cavities.
- **Microscopes:** Used as a condenser to focus light onto the specimen.

Industrial & Other

- **Solar Power Plants:** Huge arrays of mirrors concentrate sunlight to heat a fluid and generate electricity.
- **Satellite Dishes:** Use the same principle to collect and focus weak radio signals from satellites.

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Practice problems:

1) What is the primary cause of spherical aberration in a concave spherical mirror?
a) Different colors of light focus at different points
b) Marginal rays focus at a different point than paraxial rays
c) The mirror absorbs too much light
d) The image becomes magnified unevenly

2) How can spherical aberration in concave mirrors be corrected?
a) By using a parabolic mirror instead of a spherical one
b) By placing a convex lens in front of the mirror
c) By silvering the mirror surface
d) By increasing the mirror's focal length

3) Which statement best describes spherical aberration?
a) Light rays parallel to the principal axis converge at a single point
b) The mirror produces multiple images of a single object
c) The mirror focuses parallel rays to different points, creating a blurred image
d) The mirror changes the color of the reflected light

Answers:
1. b) Marginal rays focus at a different point than paraxial rays
2. a) By using a parabolic mirror instead of a spherical one
3. c) The mirror focuses parallel rays to different points, creating a blurred image

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Practice problems:

4) Which application typically uses a concave mirror?
a) Car side-view mirrors
b) Security mirrors in stores
c) Shaving/makeup mirrors
d) Rear-view mirrors in vehicles

5) Where would you most commonly find a convex mirror being used?
a) In astronomical telescopes
b) In dental examination tools
c) In vehicle side-view mirrors
d) In flashlight reflectors

6) What makes concave mirrors suitable for use in solar cookers?
a) They create virtual, erect images
b) They provide a wide field of view
c) They diverge light rays
d) They converge sunlight to a focal point

Answers:
4. c) Shaving/makeup mirrors
5. c) In vehicle side-view mirrors
6. d) They converge sunlight to a focal point

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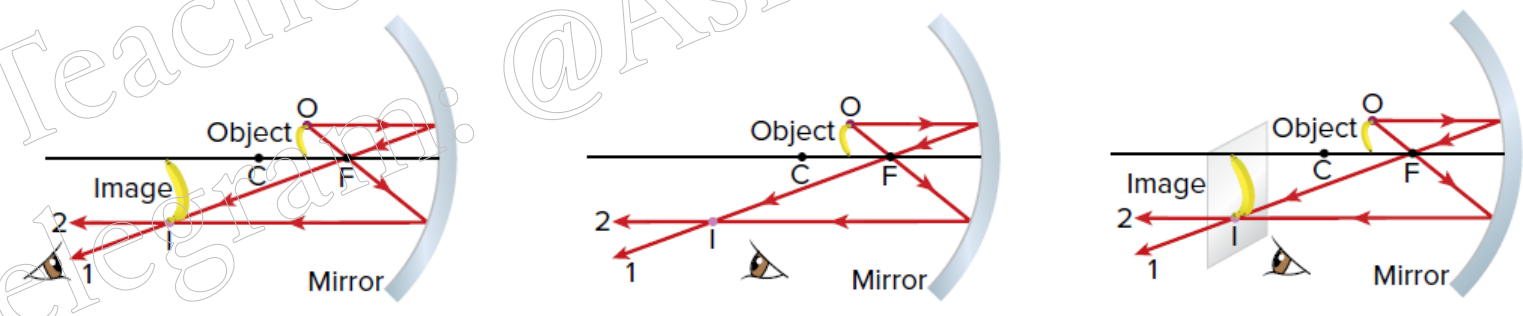
9	**-Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image.**	**Student Textbook**	**36-38**

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.



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.

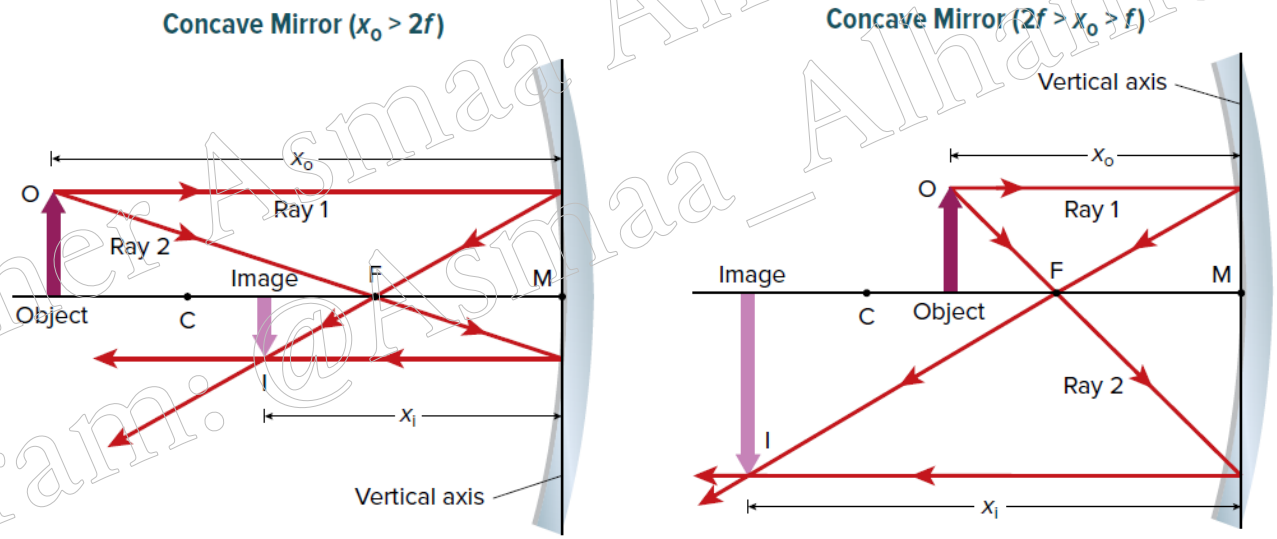
The image can be seen when projected on a white opaque screen.

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

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Real Images with Concave Mirrors

You can often simplify ray diagrams by using simple, one-dimensional objects, such as the arrow shown in **Figure 13** on the next page. A spherical concave mirror produces an inverted real image if the object position (x_o) is greater than twice the focal length (f). The object is then beyond the center of curvature (C). If the object is placed between the center of curvature and the focal point, as shown on the right in **Figure 13**, the image is again real and inverted. The size of the image is now greater than the size of the object.



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

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

Figure 13 The type of image depends on the object's distance from the mirror. A real, inverted image is formed in both situations shown here. Remember that f, the focal length, is the distance from M to F.

Diagram *how other points on the image are formed.*

COLOR CONVENTION

Object	magenta
Image	lilac
Light ray	red

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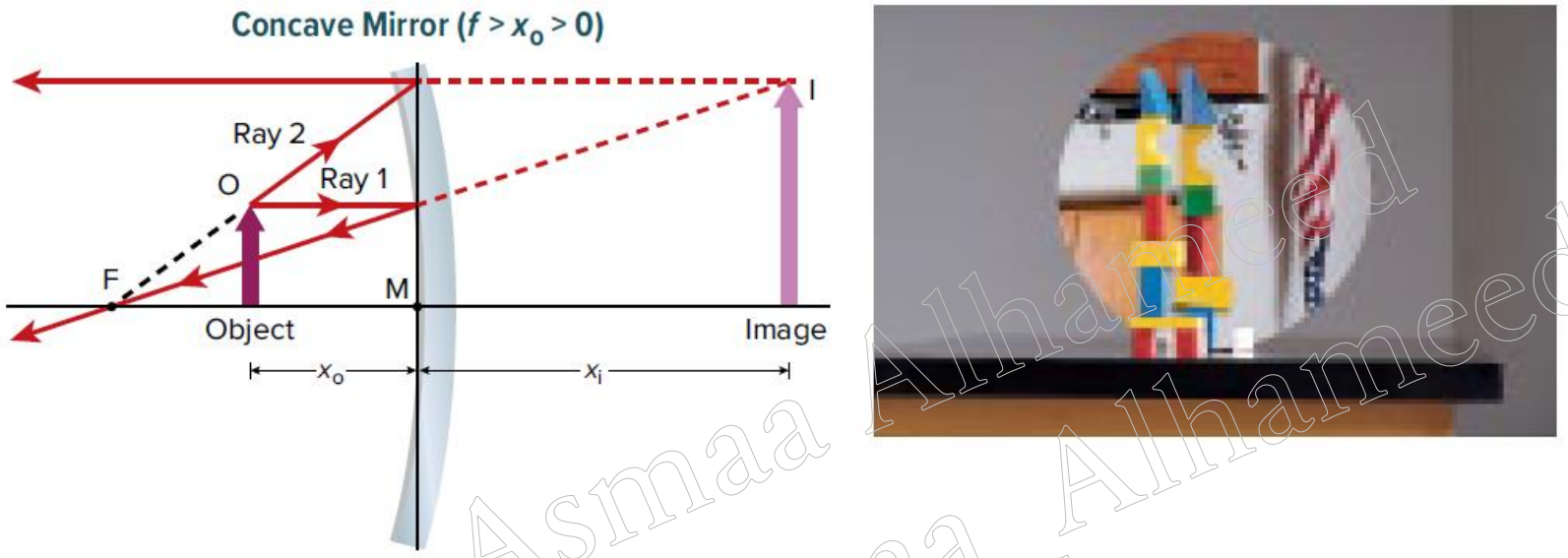


Figure 14 A virtual, upright, enlarged image is formed when an object, such as the block tower on the right, is placed between the focal point and the surface of a concave mirror.

Consider *the cause of the appearance of the other images in the mirror.*

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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.

Get It?

Explain how you can determine whether an image is virtual.

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.

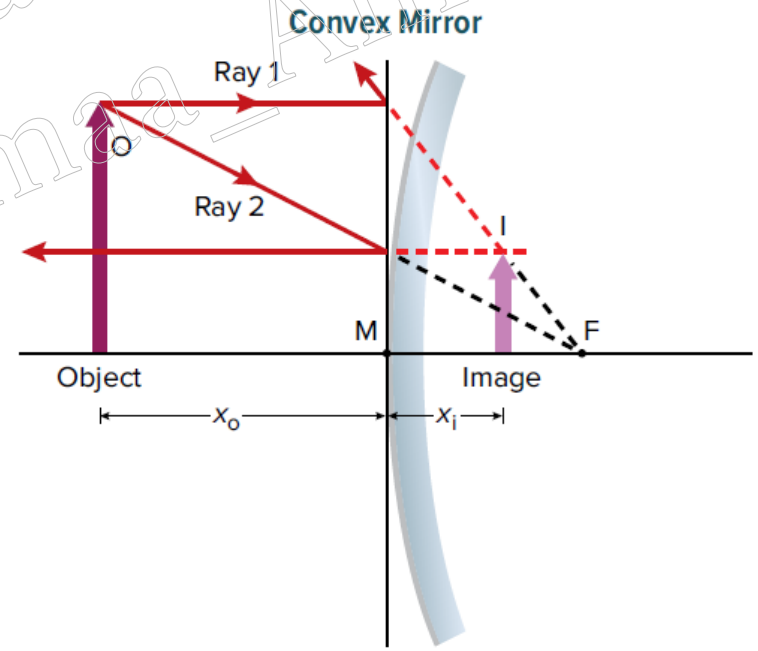


Figure 15 Convex mirrors form images that are virtual, upright, and smaller than the object.

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A sight line extends from the point where ray 1 strikes the principle plane through F. Ray 2 approaches the mirror on a path that, if extended behind the mirror, would pass through F. The reflected part of ray 2 and its sight line are parallel to the principal axis. The two reflected rays diverge. However, the sight lines intersect behind the mirror. The point where they intersect is the location of the image. An image produced by a convex mirror is a virtual image that is upright and smaller than the object.

Field of view It might seem that convex mirrors would have little use because the images they form are smaller than the objects. This property of convex mirrors, however, does have practical uses. By forming smaller images, convex mirrors enlarge the area that an observer sees, which is called the field of view. Also, the image is visible from a large range of angles; thus, the field of view is visible from a wide perspective.

Because of the increased field of view, convex mirrors are used in cars as passenger-side rearview mirrors, as shown in **Figure 16.** However, because the reduced image size makes the objects appear farther away than they really are, there is often a warning on passenger-side rearview mirrors of cars stating that objects may be closer than they appear.

PROBLEM-SOLVING STRATEGIES

Using Ray Diagrams to Locate Images Produced by Spherical Mirrors

Use the following strategies for curved spherical-mirror problems. Refer to **Figure 13,** as well as **Figure 14** and **Figure 15** on the next page.

1. Using lined or graph paper, draw the principal axis of the mirror as a horizontal line from the left side to the right side of your paper, leaving six blank lines above and six blank lines below.
2. Place points and labels on the principal axis for the object, C, and F as follows:
   a. If the mirror is concave and the object is beyond C away from the mirror, place the mirror at the right side of the page, the object at the left side of the page, and make C and F to scale.
   b. If the mirror is concave and the object is between C and F, place the mirror at the right side of the page, C at the center of the paper, F halfway between the mirror and C, and the object to scale.
   c. For any other situation, place the mirror in the center of the page, the object or F (whichever is the greater distance from the mirror) at the left side of the page, and the other to scale.
3. To represent the mirror, draw a vertical line at the mirror point that extends for 12 lines. This is the mirror's principal plane.
4. Draw the object as an arrow, and label its top O. For concave mirrors, objects inside of C should not be higher than three lines. For all other situations, the objects should be six lines high. The scale for the height of the object will be different from the scale along the principal axis.
5. Draw ray 1, the parallel ray. It is parallel to the principal axis, reflects off the principal plane, and passes through F.
6. Draw ray 2, the focus ray. It passes through F, reflects off the principal plane, and is reflected parallel to the principal axis.
7. If reflected rays 1 and 2 diverge from each other, then extend the sight lines behind the mirror as dashed lines.
8. The image is located where rays 1 and 2 or their sight lines cross after reflection. For either case, label the point of intersection I. Draw the image as a perpendicular arrow from the principal axis to I.

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Practice problems:

1) For a concave mirror, an object is placed between the focal point (F) and the center of curvature (C). In a ray diagram, which describes the image formed?

a) Virtual, erect, and magnified
b) Real, inverted, and diminished
c) Real, inverted, and magnified
d) Virtual, erect, and diminished

2) When drawing a ray diagram for a convex mirror, where is the image always located?

a) Behind the mirror
b) Between F and C in front of the mirror
c) Beyond C in front of the mirror
d) At the focal point in front of the mirror

3) In a ray diagram for a concave mirror with the object placed beyond the center of curvature (C), one standard ray is drawn parallel to the principal axis. After reflection, this ray:

a) Passes through the focal point (F)
b) Appears to come from the focal point (F)
c) Reflects back parallel to the principal axis
d) Passes through the center of curvature (C)

Answers:

1. c) Real, inverted, and magnified
2. a) Behind the mirror
3. a) Passes through the focal point (F)

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10	**-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**	**Example problem2,3 Practice problems**	**41,42**

Calculating Image Position

We can use the spherical mirror model to develop a simple equation for spherical mirrors. You must use the paraxial ray approximation, which states that only rays that are close and almost parallel to the principal axis are used to form an image. Using this with the law of reflection leads to the mirror equation, relating the focal length (f), object position (x_o), and image position (x_i) of a spherical mirror.

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.

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

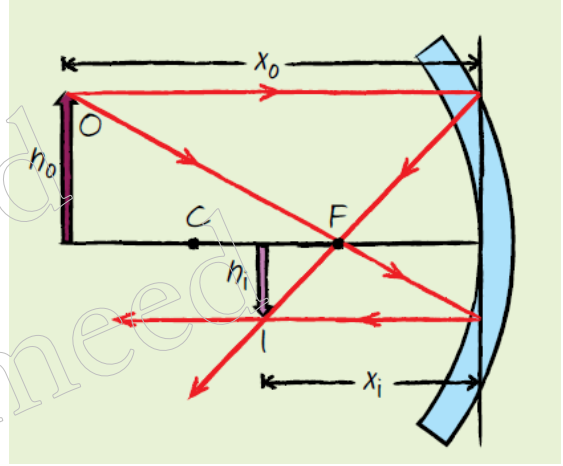
Negative values When virtual images are formed, the image position (x_i) has a negative value, indicating that it is located behind the mirror. For concave mirrors, a virtual image only forms when the object is between a concave mirror and the focal point. The focal point is in front of the mirror and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

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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?

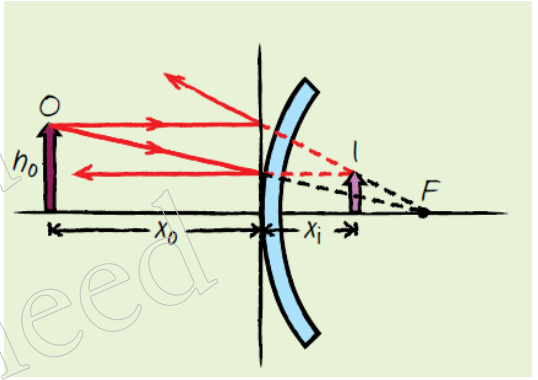


12. Use a ray diagram drawn to scale to solve Example Problem 2.

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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?



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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.

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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.

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.

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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?

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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.

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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?

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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?

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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.

a. What is the image's distance?

b. What is the focal length of the mirror?

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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.

a. What is the object's distance?

b. What focal length should be specified?

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11	**Infer the type, orientation, and size of an image from the magnitude and algebraic sign of magnification.**	**Student Textbook**	**35**

Magnification

Another property of a spherical mirror is **magnification** (m), which is the ratio of the image height to the object height.

The sign of the magnification tells you whether the image is upright or inverted. For virtual images such as those formed by convex mirrors, x_i is negative. This means m is positive. Note that virtual images are always upright, so the height is always positive.

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.

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



Get It?

Explain What does it mean if $m < 1$?

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Practice problems:

1) A spherical mirror produces an image with a magnification of -2.0. What can be concluded about the image?

a) Virtual, upright, and diminished
b) Virtual, upright, and magnified
c) Real, inverted, and diminished
d) Real, inverted, and magnified

2) What does a magnification value of +0.5 indicate about the image?

a) Real, inverted, and twice the size of the object
b) Virtual, upright, and half the size of the object
c) Real, upright, and half the size of the object
d) Virtual, inverted, and twice the size of the object

3) An optical system forms an image with a magnification of -0.8. Which statement correctly describes the image?

a) The image is virtual and larger than the object
b) The image is real and smaller than the object
c) The image is virtual and inverted
d) The image is real and upright

Answers:

1. d) Real, inverted, and magnified
2. b) Virtual, upright, and half the size of the object
3. b) The image is real and smaller than the object

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12	**Compare and contrast plane, concave, and convex mirrors regarding the properties of images formed and the algebraic**	**Student Textbook**	**43**

Mirror Comparison

Table 1 summarizes the properties of single-mirror systems with objects that are located on the principal axis of the mirror.

Notice that the single plane mirror and convex mirror produce only virtual images. A concave mirror produces real images when the object is father than the focal distance. A concave mirror produces virtual images when the object is closer than the focal distance. Plane mirrors give reflections on scale with the objects, and convex mirrors provide reduced images, expanding the field of view. A concave mirror acts as a magnifier when an object is within the focal length of the mirror.

A concave mirror enlarges and inverts the image when the object is between the focal length and the radius of curvature. Beyond the radius of curvature, a concave mirror produces a reduced, inverted image.

Table 1 Single-Mirror System Properties

Mirror Type	f	x_o	x_i	m	Image
Plane	∞	$x_o > 0$	$\lvert x_i \rvert = x_o$ (negative)	same size	virtual
Concave	+	$x_o > r$	$r > x_i > f$	reduced, inverted	real
		$r > x_o > f$	$x_i > r$	enlarged, inverted	real
		$f > x_o > 0$	$\lvert x_i \rvert > x_o$ (negative)	enlarged	virtual
Convex	—	$x_o > 0$	$\lvert f \rvert > \lvert x_i \rvert > 0$ (negative)	reduced	virtual

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Practice problems:

1) Which type of mirror can form a real, inverted image that is larger than the object?
a) Plane mirror
b) Concave mirror
c) Convex mirror
d) Both b and c

2) For which mirror type is the image always virtual, upright, and the same size as the object?
a) Plane mirror
b) Concave mirror
c) Convex mirror
d) Both a and c

3) Which statement about algebraic signs for image distance (v) is correct?
a) For convex mirrors, v is always positive
b) For concave mirrors forming real images, v is negative
c) For virtual images (all mirrors), v is positive
d) For virtual images (all mirrors), v is negative

Answers:
1. b) Concave mirror
2. a) Plane mirror
3. d) For virtual images (all mirrors), v is negative

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13	**Describe refraction of light (or a wave) as it crosses the boundary between two different mediums and represent that in a ray diagram.**	**Student Textbook**	**44,45**

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?

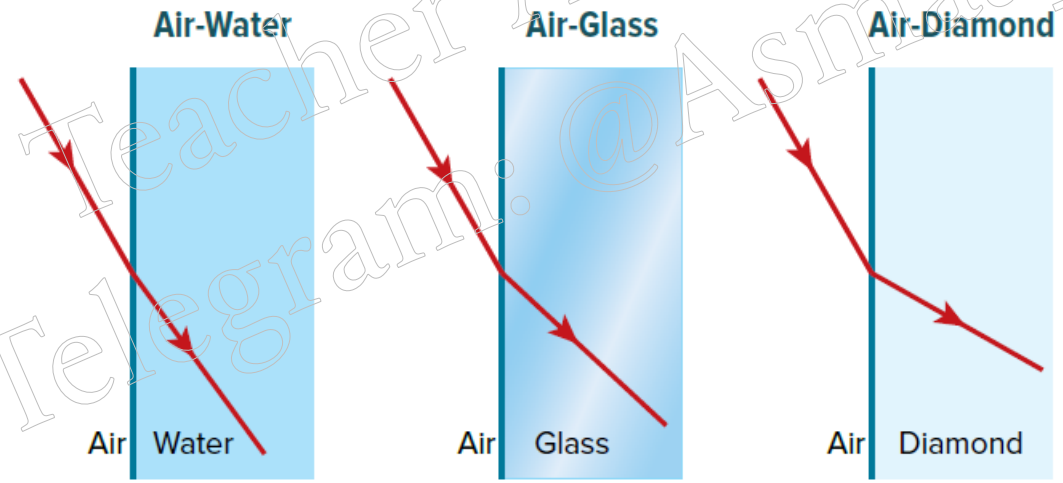


Figure 18 Light refracts as it crosses a boundary. The amount of refraction depends on the properties of the mediums. (Angles are not to scale.)

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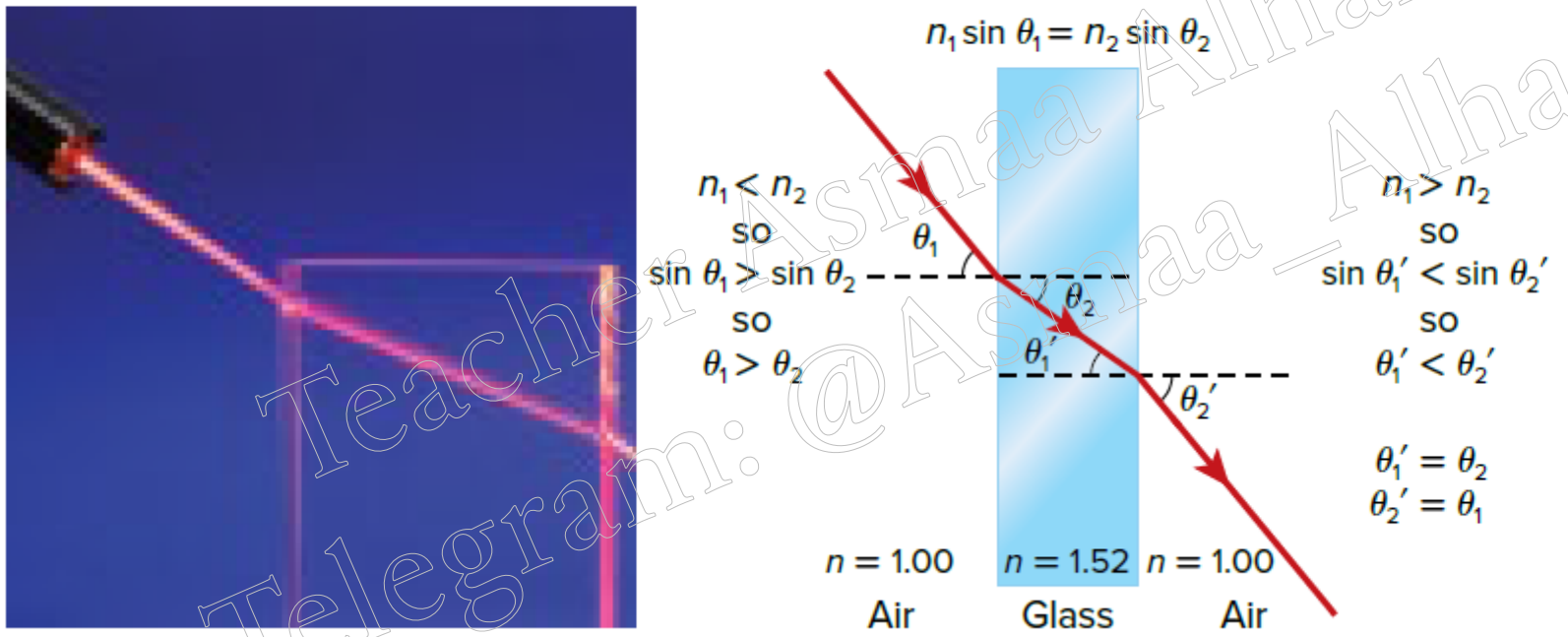


Figure 19 When light travels from air through glass and back to air, it refracts toward and then away from the normal.

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Practice problems:

1) What is the best description of refraction?
a) The bouncing of light off a surface
b) The bending of light as it passes from one medium to another
c) The spreading of light around obstacles
d) The change in light's speed in a vacuum

2)In a ray diagram showing light passing from air into glass, how does the ray behave at the boundary?
a) It bends away from the normal
b) It bends toward the normal
c) It continues straight without bending
d) It reflects back into the air

3) When drawing a refraction ray diagram, what must be included at the point where the ray crosses the boundary between two media?
a) A dotted line showing the original path
b) A label showing the wavelength change
c) A normal line perpendicular to the boundary
d) An arrow showing the speed increase

Answers:
1. b) The bending of light as it passes from one medium to another
2. b) It bends toward the normal
3. c) A normal line perpendicular to the boundary

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14	**-Define the index of refraction of a medium and relate it to the properties of the medium.**	**Student Textbook**	**45**

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.

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

We can use **Figure 19** and **Table 2** to show how Snell's law applies when light travels through a piece of glass with parallel surfaces, such as a windowpane. The light is refracted when it enters the glass and again when it leaves the glass. When light goes from air into glass, it travels from a medium with a lower n of 1.00 to a medium with a higher n of 1.52. The light bends toward the normal.

Traveling from glass to air, light moves from a medium with a higher n (1.52) to one with a lower n (1.00). The light is bent away from the normal. The relative values of n determine whether the light will bend toward or away from the normal. Note the direction of the ray when it leaves the glass. It is the same as before it struck the glass, $\theta_1 = \theta_2'$. This is because the boundaries are between the same two mediums.

Table 2 Indices of Refraction for Yellow Light ($\lambda = 589$ 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.

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We can use **Figure 19** and **Table 2** to show how Snell's law applies when light travels through a piece of glass with parallel surfaces, such as a windowpane. The light is refracted when it enters the glass and again when it leaves the glass. When light goes from air into glass, it travels from a medium with a lower n of 1.00 to a medium with a higher n of 1.52. The light bends toward the normal.

Traveling from glass to air, light moves from a medium with a higher n (1.52) to one with a lower n (1.00). The light is bent away from the normal. The relative values of n determine whether the light will bend toward or away from the normal. Note the direction of the ray when it leaves the glass. It is the same as before it struck the glass, $\theta_1 = \theta_2'$. This is because the boundaries are between the same two mediums.

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Practice problems:

1) How is the index of refraction (n) of a medium defined?
a) The speed of light in the medium multiplied by the speed of light in a vacuum
b) The speed of light in a vacuum divided by the speed of light in the medium
c) The wavelength of light in the medium divided by its wavelength in a vacuum
d) The frequency of light in the medium divided by its frequency in a vacuum

2) A medium with a higher index of refraction will cause light to:
a) Travel faster and bend less
b) Travel slower and bend more
c) Travel faster and bend more
d) Travel slower and bend less

3) Which material typically has the highest index of refraction?
a) Air
b) Water
c) Glass
d) Diamond

Answers:
1. b) The speed of light in a vacuum divided by the speed of light in the medium
2. b) Travel slower and bend more
3. d) Diamond

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15	-Describe some applications of total internal reflection -Explain some natural phenomena, such as the formation of mirage or rainbows or others, which involve optical phenomena like reflection, refraction, total internal reflection, or dispersion of light.	Student Textbook	48,49
16	Define dispersion and explain the dispersion of light through a prism.	Student Textbook	49,50

Total Internal Reflection

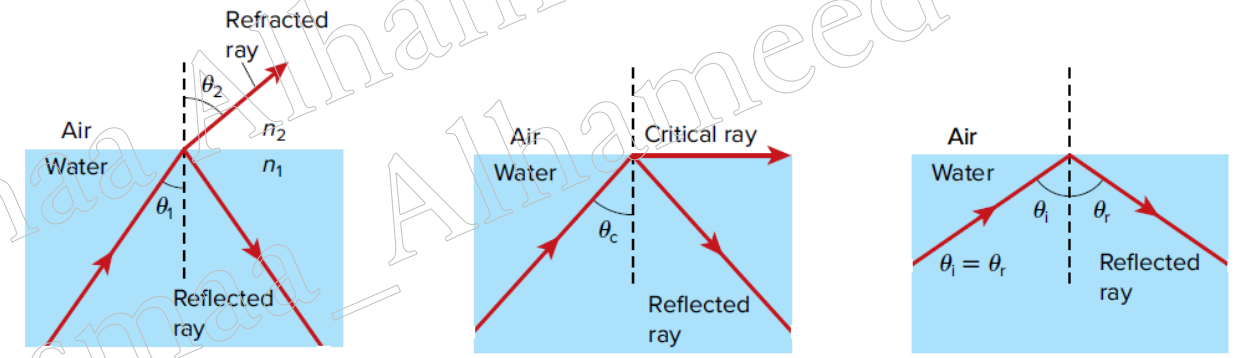
Recall that when light strikes a transparent boundary, some of the light is transmitted and some is reflected. As light travels from a medium of higher index of refraction to a medium of lower index of refraction, the angle of refraction is larger than the angle of incidence, as shown in **Figure 21.**

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.

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Mirages

On a hot summer day, you sometimes can see what appears to be the reflection of an oncoming vehicle in a pool of water as shown on the left in **Figure 22**. The pool, however, disappears as you approach it. This mirage is the result of the Sun heating the road. The speed of light and, therefore, the index of refraction, for a gaseous medium can change slightly with temperature. The hot road heats the air above it and produces a thermal layering of air, causing light traveling toward the road from the car to gradually bend upward. This makes the light appear to be coming from a reflection in a pool.

The diagram in **Figure 22** shows how this occurs. As light from a distant object travels downward toward the road, the index of refraction of the air decreases as the air gets hotter, but the temperature change is gradual. Recall that light wavefronts are comprised of Huygens' wavelets. In the case of a mirage, the Huygens' wavelets closer to the ground travel faster than those higher up, causing the wavefronts to gradually turn upward.

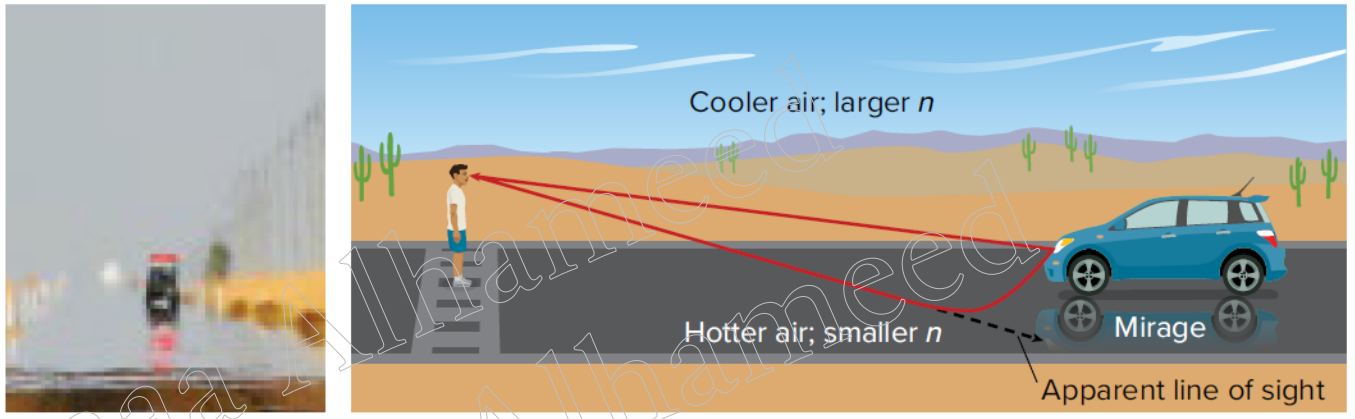


Figure 22 Light waves reflected from the vehicle on the road are refracted when the air near the surface of the road is hotter than the air above it.

Apply *Are the light waves traveling faster near the surface of the road or near the top of the vehicle?*

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Dispersion of Light

If you look carefully at the spectrum formed by light passing through the prism in **Figure 23**, you will notice that violet light is refracted more than red light. This occurs because the speed of violet light through glass is less than the speed of red light through glass. Violet light has a higher frequency than red light, which causes it to interact differently with the atoms of the glass. This results in glass having a slightly higher index of refraction for violet light than it has for red light. This separation of white light into a spectrum of colors is called **dispersion.**

The speed of light in a medium is determined by interactions between the light and the atoms that make up the medium. The speed of light and the index of refraction for a solid or liquid medium vary for different wavelengths of light.

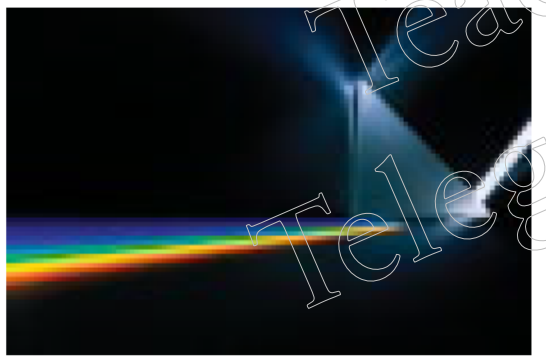


Figure 23 Dispersion through a prism occurs because the index of refraction varies with the wavelength of light.

Rainbows A rainbow is a spectrum formed when sunlight is dispersed by water droplets in the atmosphere. Sunlight that falls on a water droplet is refracted. Since each color has a different wavelength, it is refracted at a slightly different angle, as shown in **Figure 24** on the next page, resulting in dispersion. At the back surface of the droplet, some of the light undergoes internal reflection. On the way out of the droplet, the light once again is refracted and dispersed.

Although each droplet produces a complete spectrum, an observer positioned between the Sun and the rain will see only a certain wavelength of light from each droplet. The wavelength observed depends on the relative positions of the Sun, the droplet, and the observer, as shown in **Figure 24.**

Second-order rainbow Sometimes, you can see a faint second-order rainbow like the one shown in **Figure 25.** The second rainbow is outside of the first. It is also fainter and has the order of the colors reversed. Light rays that are reflected twice inside water droplets produce this effect.



Figure 25 Light reflected within raindrops can cause the appearance of a secondary rainbow.

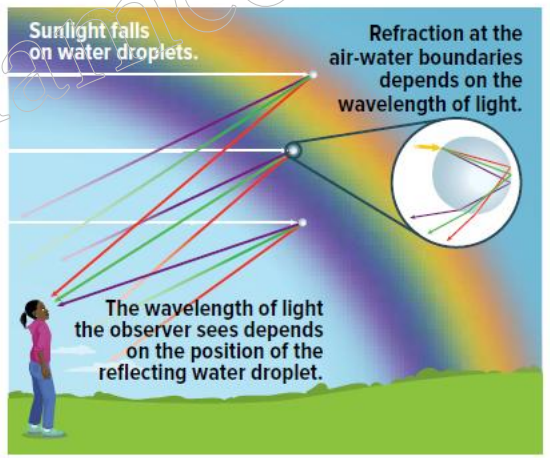


Figure 24 Light from the Sun is dispersed by water droplets to form rainbows. Because there are many droplets at various positions in the sky, a complete spectrum is visible.

Consider *whether it is possible for a rainbow to be close enough to touch.*

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Practice problems:

1) Which of the following devices operates primarily based on total internal reflection?
a) Convex lens
b) Plane mirror
c) Optical fiber
d) Concave mirror

2) In binoculars and single-lens reflex (SLR) cameras, what optical component is used to redirect light through 90 degrees using total internal reflection?
a) Concave lens
b) Prism
c) Diffraction grating
d) Convex mirror

3) Why are diamonds often cut to have many facets?
a) To decrease their refractive index
b) To maximize the light that undergoes total internal reflection, increasing brilliance
c) To minimize reflection and increase transparency
d) To spread light out and reduce its intensity

Answers:
1. c) Optical fiber
2. b) Prism
3. b) To maximize the light that undergoes total internal reflection, increasing brilliance

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Practice problems:

4) The formation of a rainbow primarily involves:
a) Reflection and diffraction only
b) Refraction and total internal reflection only
c) Refraction, dispersion, and internal reflection within water droplets
d) Polarization and interference of sunlight

5) A mirage, such as the appearance of water on a hot road, is caused by:
a) Reflection from a hot surface
b) Total internal reflection in cool air layers
c) The refraction of light in layers of air with different densities and temperatures
d) The dispersion of light into its component colors

6) The "green flash" sometimes seen just as the sun sets over the ocean is an atmospheric phenomenon caused primarily by:
a) Diffraction of sunlight
b) Refraction and dispersion of sunlight in the atmosphere
c) Total internal reflection in clouds
d) Polarization of light by water molecules

Answers:
4. c) Refraction, dispersion, and internal reflection within water droplets
5. c) The refraction of light in layers of air with different densities and temperatures
6. b) Refraction and dispersion of sunlight in the atmosphere

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17	**-Distinguish between a convex (converging) lens and a concave (diverging) lens. --Compare and contrast convex and concave lenses regarding the properties of images formed and the algebraic signs for different quantities involved.**	**Student Textbook Check your progress 50**	**51, 54 60**

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.

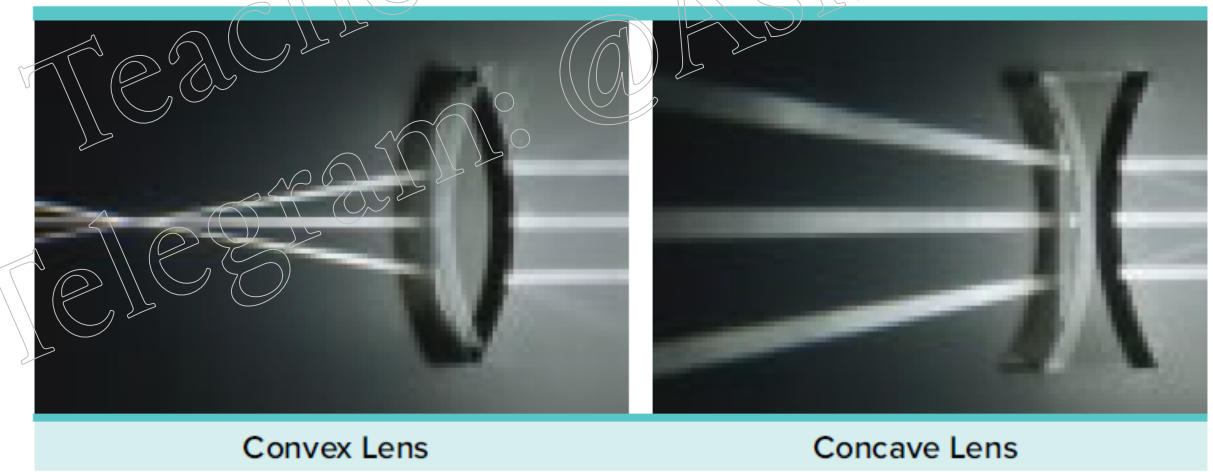


Figure 27 Convex lenses refract light so that the rays converge after passing through. The light passing through a concave lens does not meet at the focal point.

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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.

$x_o = 2f$ 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.

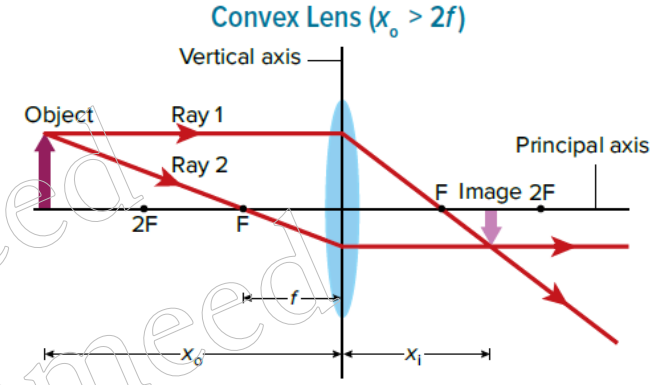


Figure 28 An object placed at a distance greater than twice the focal length from the lens will produce an image that is real, reduced in size, and inverted.

COLOR CONVENTION

Light ray	red
Object	magenta
Image	lilac

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$2f > x_o > f$ 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.

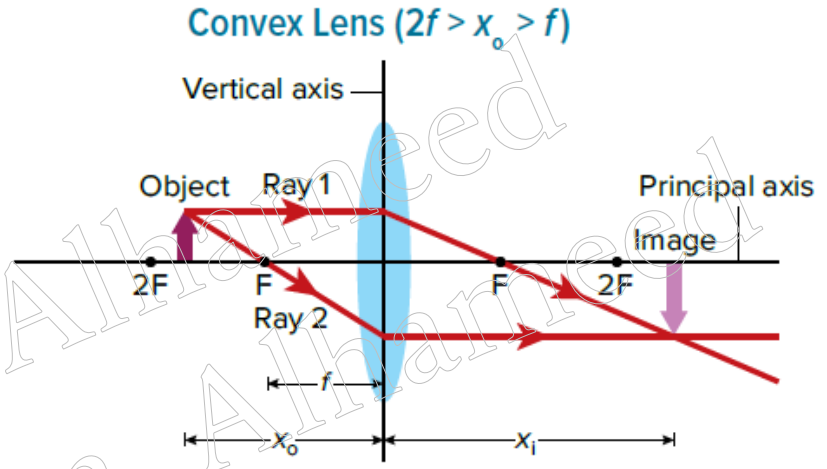


Figure 29 An object placed at a distance less than twice the focal length but greater than one focal length from the lens will produce an image that is real, enlarged, and inverted.

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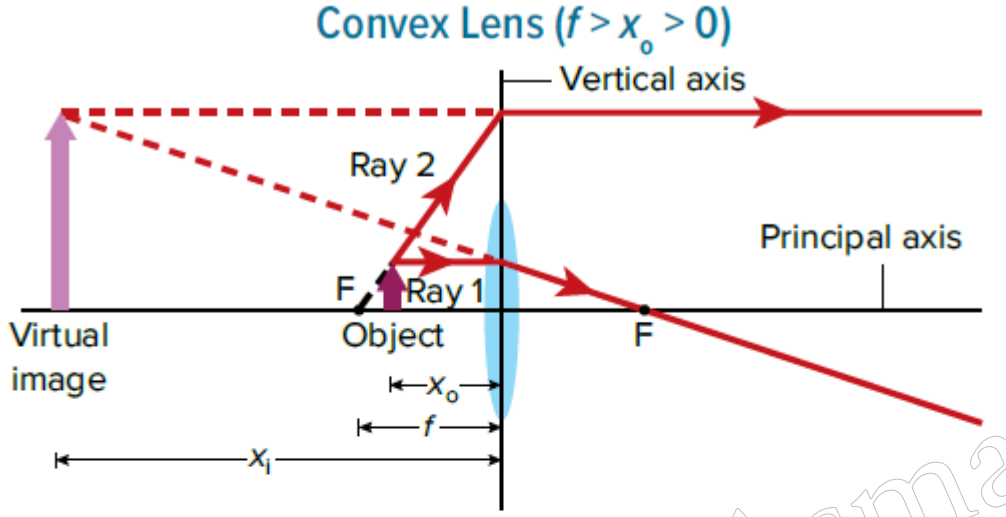


Figure 30 An object placed at a distance less than the focal length from the lens will produce an image that is virtual and enlarged.

Get It?

Classify an image as virtual or real based on the side of the lens it is on.

$f > x_o > 0$ **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.

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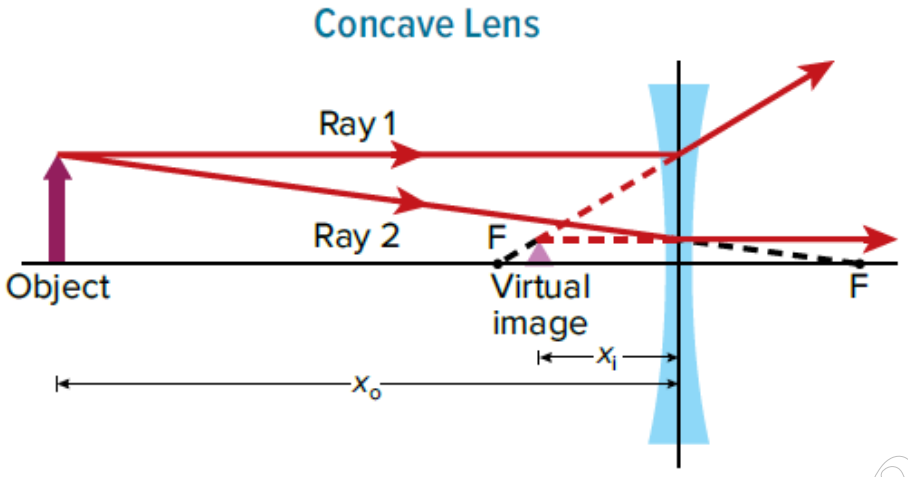


Figure 31 An object placed any distance from a concave lens will always produce an image that is virtual and reduced.

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.

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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
		$f > x_o > 0$	$\lvert x_i \rvert > x_o$ (negative)	enlarged	virtual
Concave	−	$x_o > 0$	$\lvert f \rvert > \lvert x_i \rvert > 0$ (negative)	reduced	virtual

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50. **Types of Lenses** The cross sections of four different thin lenses are shown in **Figure 38.**

a. Which of these lenses, if any, are convex, or converging, lenses?

b. Which of these lenses, if any, are concave, or diverging, lenses?

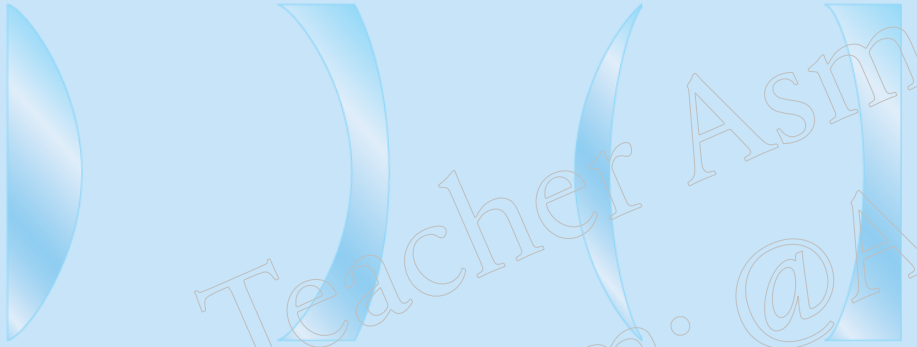


Figure 38

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18	**Explain defects in spherical lenses such as spherical aberration and chromatic aberration and how they can be corrected.**	**Student Textbook**	**56**

Defects of Spherical Lenses

Throughout this section, you have studied lenses that produce perfect images at specific positions. In reality, spherical lenses, just like spherical mirrors, have intrinsic defects that cause problems with the focus and color of images. Spherical lenses exhibit an aberration associated with their spherical design, just as mirrors do. In addition, the dispersion of light through a spherical lens causes an aberration that mirrors do not exhibit.

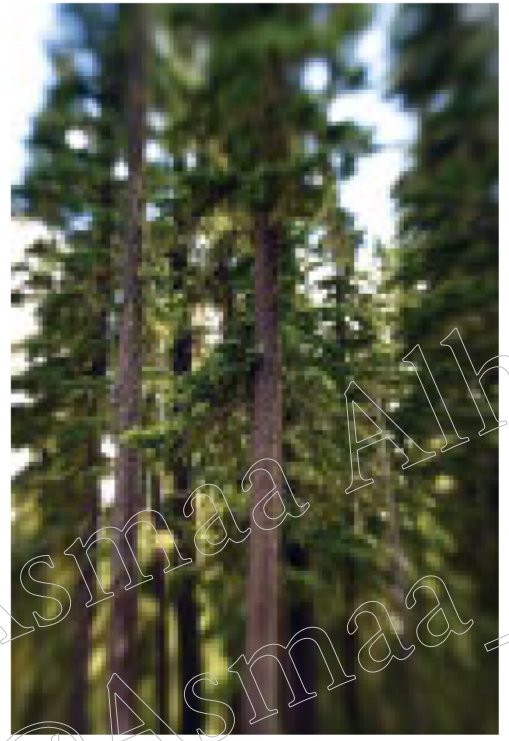


Figure 32 Spherical aberration from the camera lens blurs the edges of this image.

Spherical aberration The model you have used for drawing rays through spherical lenses suggests that all parallel rays focus at the same position. However, this is only an approximation. In reality, parallel rays that pass through the edges of a spherical lens focus at positions different from those of parallel rays that pass through the center. This inability of a spherical lens to focus all parallel rays to a single point is called spherical aberration. The effects are shown in **Figure 32.** In reality, most lenses have a slightly different shape to address this, but the spherical approximation works well enough for our purposes. In high-precision instruments, many lenses, often five or more, are used to form sharp, well-defined images.

Chromatic aberration Lenses have a second defect that mirrors do not have. Because the index of refraction of a medium depends on wavelength, different wavelengths of light are refracted at slightly different angles, as you can see on the right in **Figure 33.** Light that passes through a lens is slightly dispersed, especially near the edges, causing an effect called **chromatic aberration.** This is seen as an apparent ring of color around an object viewed through a lens, as shown on the left in **Figure 33.**

Chromatic aberration is always present when a single lens is used. However, this defect can be greatly reduced by an **achromatic lens,** which is a system of two or more lenses, such as a convex lens with a concave lens, that have different indices of refraction. A simple lens and an achromatic lens are shown in **Figure 33.** Both lenses disperse light, but the dispersion caused by the achromatic lens is less than the dispersion caused by the simple lens. The index of refraction of the achromatic lens is chosen so that the light will still converge at the desired location.

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Practice problems:

1) What is the primary cause of spherical aberration in a simple spherical lens?
a) Different colors of light focus at different points.
b) Marginal rays and paraxial rays focus at different points along the principal axis.
c) The lens material absorbs too much light.
d) The image becomes distorted due to lens curvature.

2) Chromatic aberration in lenses occurs because:
a) Light rays strike the edges of the lens at different angles.
b) The lens has an irregular surface.
c) The refractive index of the lens material varies with the wavelength of light.
d) The lens fails to reflect certain colors properly.

3) How can chromatic aberration in optical instruments be effectively corrected?
a) By using a lens with a shorter focal length.
b) By combining lenses made of different types of glass (an achromatic doublet).
c) By using a diaphragm to block marginal rays.
d) By silvering the surface of the lens.

Answers:
1. b) Marginal rays and paraxial rays focus at different points along the principal axis.
2. c) The refractive index of the lens material varies with the wavelength of light.
3. b) By combining lenses made of different types of glass (an achromatic doublet).

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19	-Define nearsightedness (Myopia) and farsightedness (Hyperopia). -Describe the formation of image in case of nearsightedness and farsightedness and how defects in vision are corrected using concave and convex lenses.	Student Textbook Check your progress 57	58 60

Lenses in Eyes

The concepts that you have learned for the refraction of light through lenses apply to almost every optical device, including the eye. The eye is a remarkable optical device. As shown in **Figure 34**, the eye is a fluid-filled, almost spherical vessel. Light that is emitted from or reflected off an object travels into the eye through the cornea and pupil. The light then passes through the lens and focuses onto the retina, which is at the back of the eye. Specialized cells on the retina absorb this light and send information about the image along the optic nerve to the brain.

BIOLOGY Connection Because of its name, you might assume that the lens of an eye is responsible for focusing light onto the retina. In fact, light entering the eye is primarily focused by the cornea, because the air-cornea boundary has the greater difference in indices of refraction. The lens is responsible for the fine focus that allows you to clearly see both distant and nearby objects.

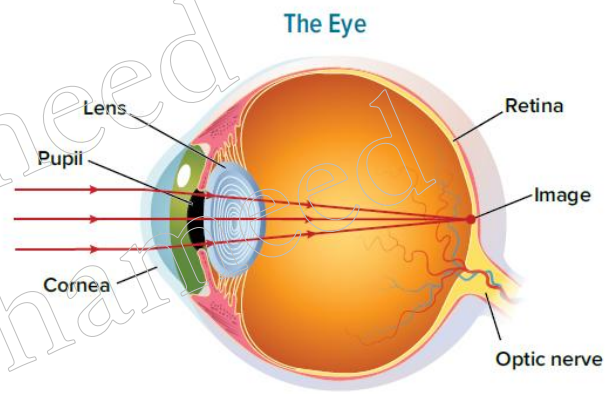


Figure 34 The cornea and the lens of your eye refract light that is reflected off every object you see.
Summarize *why most of the refraction occurs at the air-cornea boundary rather than at the lens.*

Get It?
Describe the roles of the cornea and the lens in your eye.

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The eye lens uses a process called accommodation. Muscles surrounding the lens can contract or relax, thereby changing the shape of the lens. This, in turn, changes the focal length of the eye. For a healthy eye, when the muscles are relaxed, the image of distant objects is focused on the retina. When the muscles contract, the focal length is shortened, and this allows images of closer objects to be focused on the retina.

Nearsightedness The eyes of many people focus images either in front of the retina or behind it. External lenses, such as eyeglasses and contact lenses, adjust the focal length and move images to the retina. **Figure 35** on the next page shows the condition of **nearsightedness,** also called myopia.

With myopia, the focal length of the eye is too short to focus light on the retina. Images are formed in front of the retina. As shown in **Figure 35,** concave lenses correct this by diverging light, thereby increasing images' distances from the lens, and forming images on the retina.

Farsightedness You also can see in **Figure 35** that **farsightedness,** also called hyperopia, is the condition in which the focal length of the eye is too long. Images are therefore not formed on the retina.

A similar result is caused by the increasing rigidity of the lenses in the eyes of people who are more than about 45 years old. Their muscles cannot shorten the focal length enough to focus images of close objects on the retina.

For either condition, convex lenses produce virtual images farther from the eye than the associated objects, as shown in **Figure 35.** The images then become the objects for the eye lens and can be focused on the retina, thereby correcting the condition.

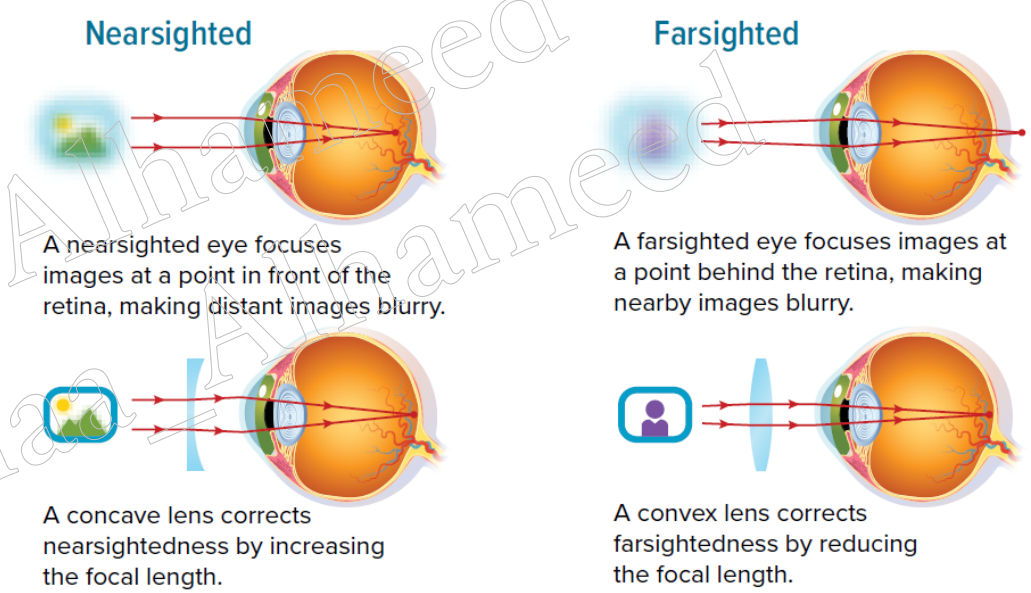


Figure 35 Objects at a distance are blurred for a nearsighted person. For a farsighted person, objects nearby are blurred.

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57. **Eyeglass Lenses** Which type of lens, convex or concave, should a nearsighted person use? Which type should a farsighted person use? See **Figure 40.** Explain.

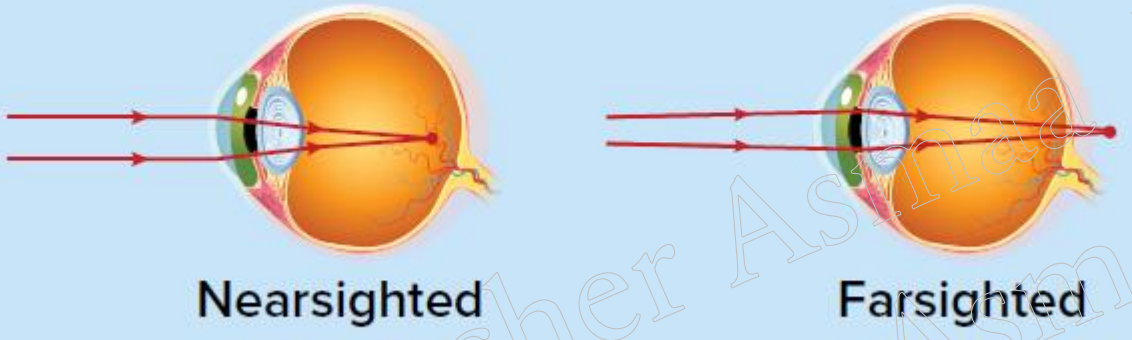


Figure 40

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Practice problems:

1) What is the primary cause of nearsightedness (Myopia)?
a) The eyeball is too short, causing the image to focus behind the retina.
b) The eyeball is too long, causing the image to focus in front of the retina.
c) The lens of the eye becomes too weak with age.
d) The cornea becomes irregularly shaped.

2) A person with farsightedness (Hyperopia) has difficulty seeing:
a) Distant objects clearly
b) Both near and far objects
c) Near objects clearly
d) Objects in low light conditions

3) Which statement correctly describes hyperopia?
a) The focal point is in front of the retina
b) It is corrected using a diverging lens
c) The eyeball is typically shorter than normal
d) It improves naturally with age

Answers:
1. b) The eyeball is too long, causing the image to focus in front of the retina.
2. c) Near objects clearly
3. c) The eyeball is typically shorter than normal

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Practice problems:

4) In a myopic eye, where does the image of a distant object form?
a) On the retina
b) Behind the retina
c) In front of the retina
d) Not formed at all

5) What type of lens is used to correct hyperopia and why?
a) Concave lens to diverge light rays before they enter the eye
b) Convex lens to converge light rays before they enter the eye
c) Cylindrical lens to correct asymmetric curvature
d) Plane glass to reduce light intensity

6) How does a concave lens help correct myopia?
a) It converges light rays to move the focal point forward
b) It diverges light rays to move the focal point backward onto the retina
c) It magnifies the image to make it clearer
d) It reduces chromatic aberration in the eye

Answers:
4. c) In front of the retina
5. b) Convex lens to converge light rays before they enter the eye
6. b) It diverges light rays to move the focal point backward onto the retina

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20	**Describe the optical systems and formation of images in common optical instruments.**	**Student Textbook**	**59**

Refracting Telescopes

An astronomical refracting telescope uses lenses to magnify distant objects. **Figure 36** shows the optical system for a Keplerian telescope. Light from stars and other astronomical objects comes from so far away that the incoming rays can be considered parallel. These rays enter the objective convex lens, which focuses them as a real image at the focal point of the objective lens. The image is inverted compared to the object. This image then becomes the object for the convex lens of the eyepiece.

Notice that the eyepiece lens is positioned so that the focal point of the objective lens is between the eyepiece lens and its focal point. This means a virtual image is produced that is upright and larger than the first image. However, because the first image was already inverted, the final image is still inverted. For viewing astronomical objects, an image that is inverted is acceptable.

In a telescope, the convex lens of the eyepiece is almost always an achromatic lens. Recall that an achromatic lens is a combination of lenses that functions as one lens. The combination of lenses greatly reduces the peripheral colors that can form on images due to chromatic aberration.

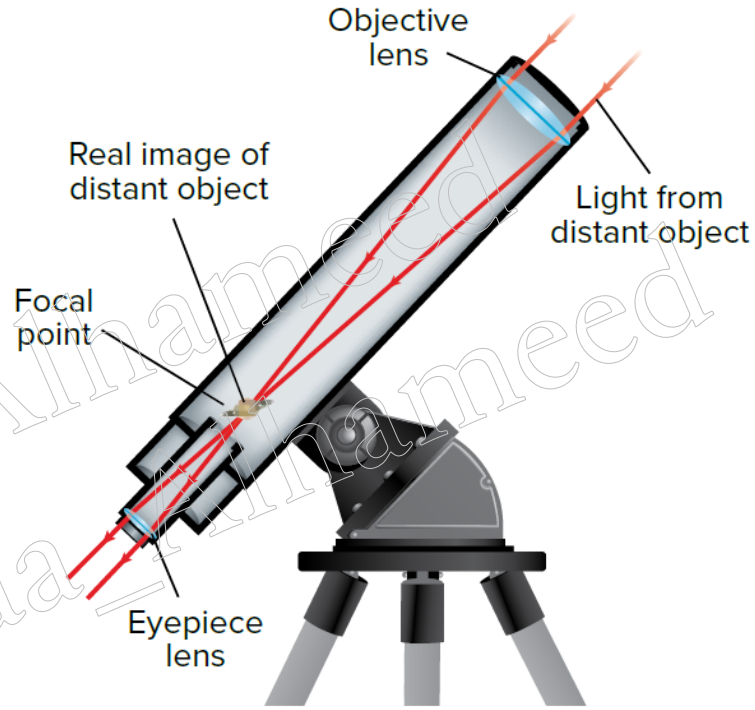


Figure 36 Light from distant objects is gathered by the objective lens and the eyepiece of a refracting telescope.

Evaluate *Why is an inverted image acceptable for viewing astronomical objects?*

Get It?

Explain how a refracting telescope works.

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Cameras

Figure 37 shows the optical system used in a single-lens reflex camera. As light enters the camera through the aperture, it passes through an achromatic lens. This lens system refracts the light much like a single convex lens would, forming an image that is inverted on the reflex mirror. The image is reflected upward to a prism that inverts and redirects the light to the viewfinder.

When the person holding the camera takes a photograph, he or she presses the shutter-release button, which briefly raises the mirror, as shown in **Figure 37**. The light, instead of being diverted upward to the prism, then travels along a straight path to form an image on the sensor.

The image sensor, which is often a charge-coupled device (CCD), captures a two-dimensional image that corresponds to the image projected onto it. The image information is collected on the photoactive region of the CCD as electric charge proportional to the light intensity. The CCD then processes the charge and transfers the information to a storage device.

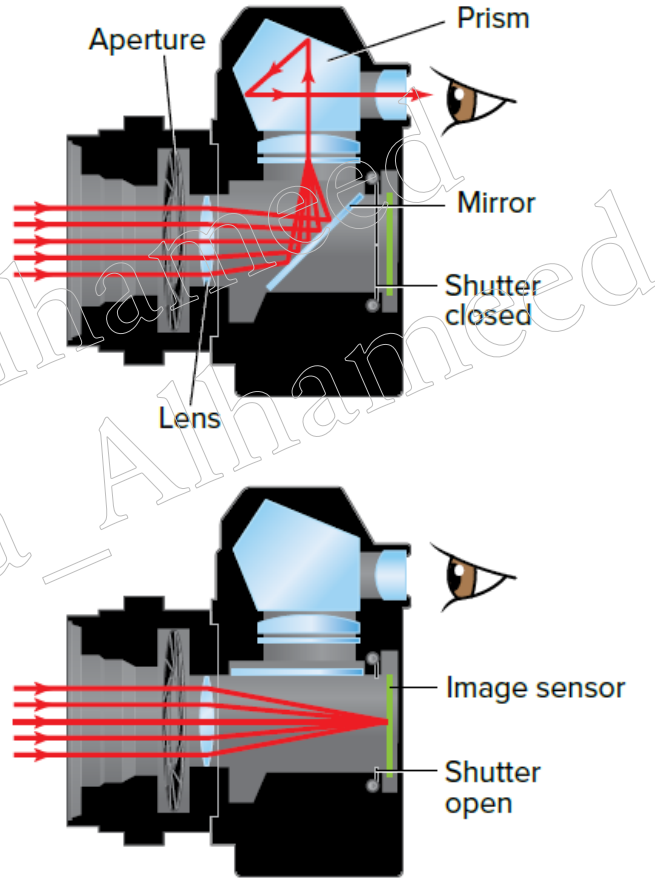


Figure 37 The lens of a camera can be adjusted to focus an image on the image sensor. When the shutter is closed, a mirror diverts the image to the viewer's eye.

Infer *Why would you want the shutter to be open longer when taking a photo in dim light?*

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Practice problems:

1) In a simple camera, what type of image is formed on the film or sensor?
a) Virtual, upright, and magnified
b) Real, inverted, and diminished
c) Virtual, inverted, and diminished
d) Real, upright, and magnified

2) What is the primary function of the eyepiece lens in a compound microscope?
a) To form a real, inverted image of the object
b) To magnify the real image formed by the objective lens
c) To reduce chromatic aberration in the system
d) To illuminate the specimen being viewed

3) In an astronomical refracting telescope, the final image seen by the eye is:
a) Real and inverted
b) Virtual and inverted
c) Real and upright
d) Virtual and upright

Answers:
1. b) Real, inverted, and diminished
2. b) To magnify the real image formed by the objective lens
3. b) Virtual and inverted

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21	-Apply the equation for illuminance of a point source to numerical problems. -Relate luminous intensity to illuminance.	Student Textbook Example problem1 Practice problems Check your progress	6-8 9 11
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
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
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

FRQ

21	-Apply the equation for illuminance of a point source to numerical problems. -Relate luminous intensity to illuminance.	Student Textbook Example problem1 Practice problems Check your progress	6-8 9 11

Iluminance

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.

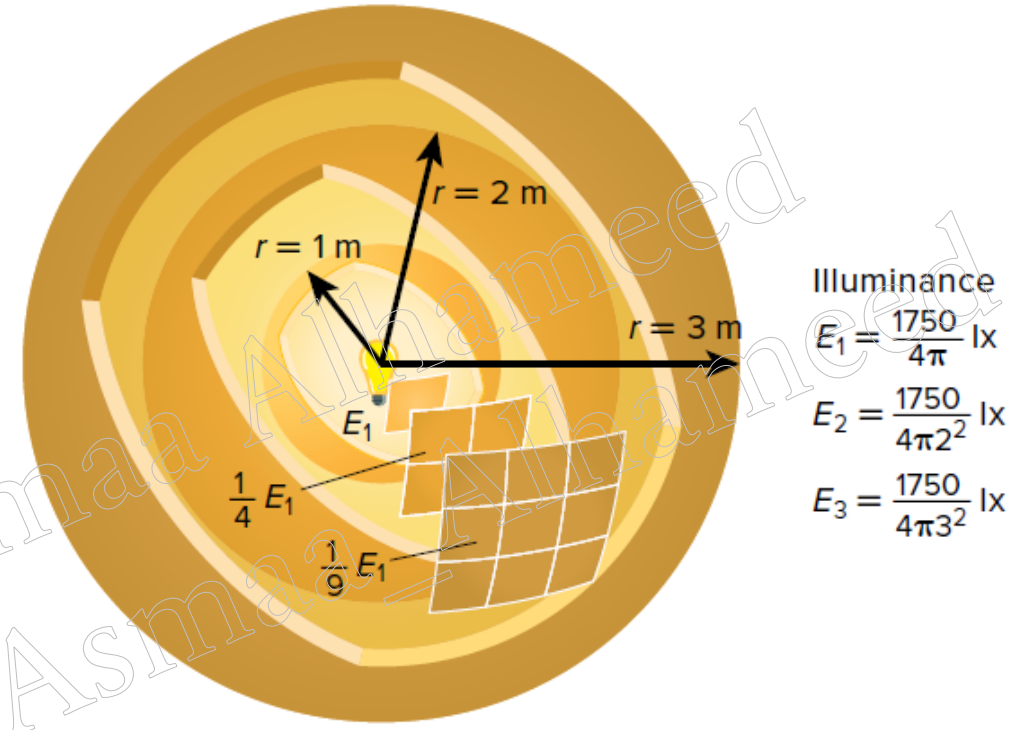


Figure 6 Illuminance (E) is the quantity of light that strikes a surface. As the distance from the luminous source (r) increases, E decreases. E depends on the inverse of r squared.

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 $\frac{1750\text{ lm}}{4\pi\text{ m}^2} = 139$ lx. This mathematical relationship means that at a distance of 1.00 m from the bulb, 139 lm strikes each square meter.

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Inverse-square relationship What if the sphere surrounding the lamp were larger? If the sphere's radius were 2.00 m, the luminous flux still would total 1750 lm because it only depends on the bulb. With a radius of 2.00 m, however, the area of the sphere would now be equal to $4\pi(2.00\text{ m})^2 = 16.0\pi\text{ m}^2$. The new area is four times larger than that of the 1.00-m sphere, as shown in **Figure 6.** The illuminance of the inside of the 2.00-m sphere is $\frac{1750\text{ lm}}{(160\pi\text{ m}^2)} = 34.8\text{ lx}$, so 34.8 lm strikes each square meter.

The illuminance on the inside surface of the 2.00-m sphere (E_2) is one-fourth the illuminance on the inside of the 1.00-m sphere. In the same way, the inside of a sphere with a 3.00-m radius has an illuminance only one-ninth $\left[\left(\frac{1}{3}\right)^2\right]$ as large as that of the 1.00-m sphere. **Figure 6** shows that the illuminance produced by a point source is proportional to $\frac{1}{r^2}$: an inverse-square relationship. In the case of the 3.00-m radius, only 15.5 lm strike each square meter inside the sphere. As the light rays spread out in straight lines in all directions from a point source, the number of light rays that illuminate a unit of area decreases as the square of the distance from the point source.

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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 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 $\frac{1750\ \text{lm}}{4\pi} = 139$ 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.

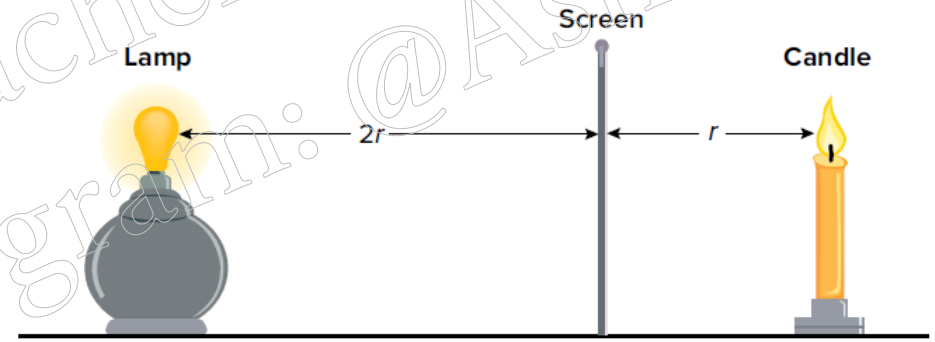


Figure 7 For the lightbulb and the candle to provide the same illuminance to the screen, the luminous intensity of the lightbulb is four times that of the candle.

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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.

Real-World Physics

Illuminated Minds

When deciding how to achieve the correct illuminance on students' desktops in a classroom, architects must consider the luminous flux of the lights as well as the distance of the lights above the desktops. In addition, the efficiencies of the light sources are an important economic factor.

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.

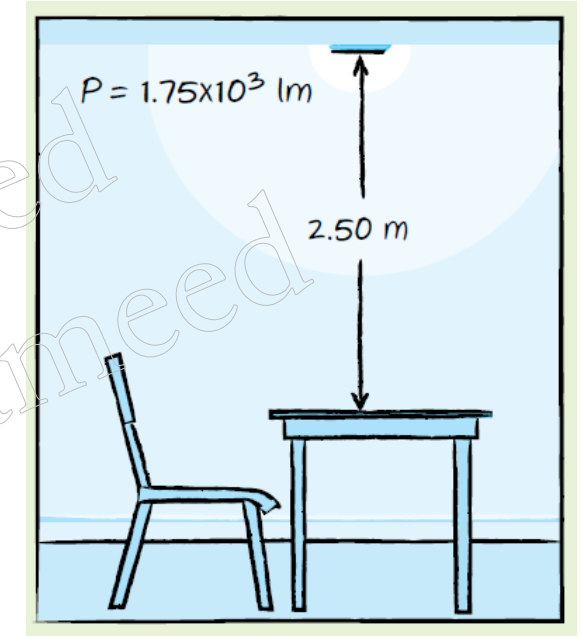
$$E = \frac{P}{4\pi r^2}$$

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.

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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?



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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.

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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.

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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?

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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?

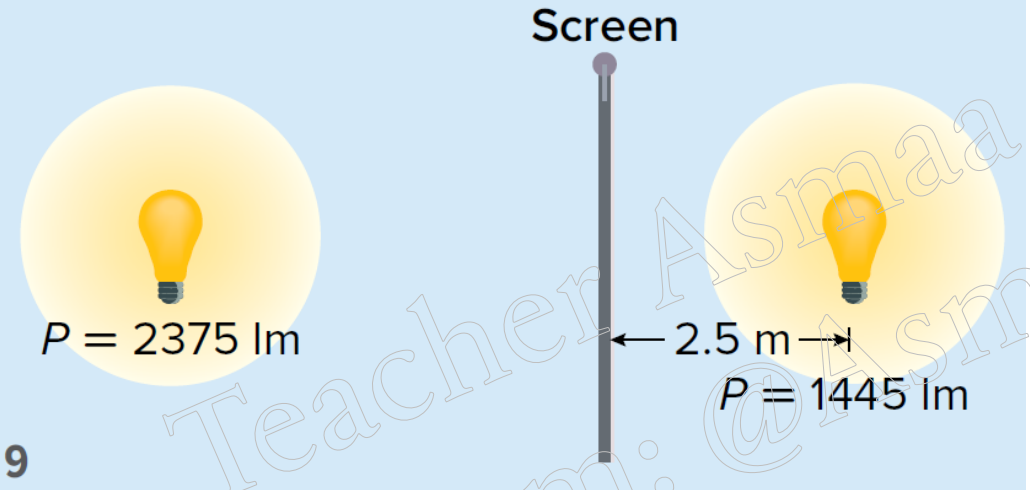


Figure 9

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5. 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?

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6. 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?

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7. **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?

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8. **Light** What evidence have you observed that light travels in a straight line?

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9. **Light Properties** Why might you choose a window shade that is translucent? Opaque?

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10. **Illuminance** Does one lightbulb provide more or less illuminance than two identical light-bulbs at twice the distance? Explain.

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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?

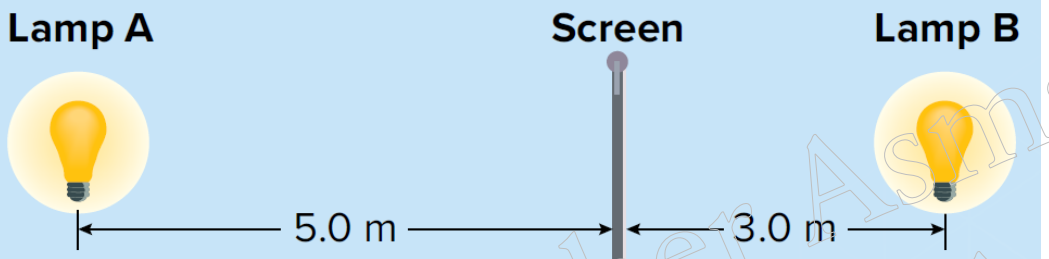


Figure 11

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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?

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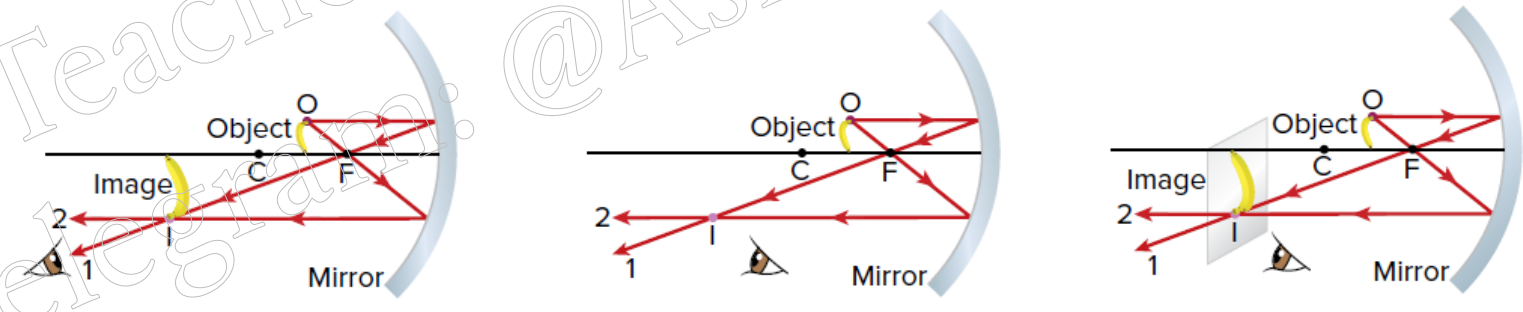
22	-Draw a ray diagram to find the image of an object formed by a curved mirror and determine the properties of the formed image. -Apply the mirror equation to calculate the image distance, the object distance, or the focal length of a spherical mirror using appropriate algebraic signs for focal length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

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.



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.

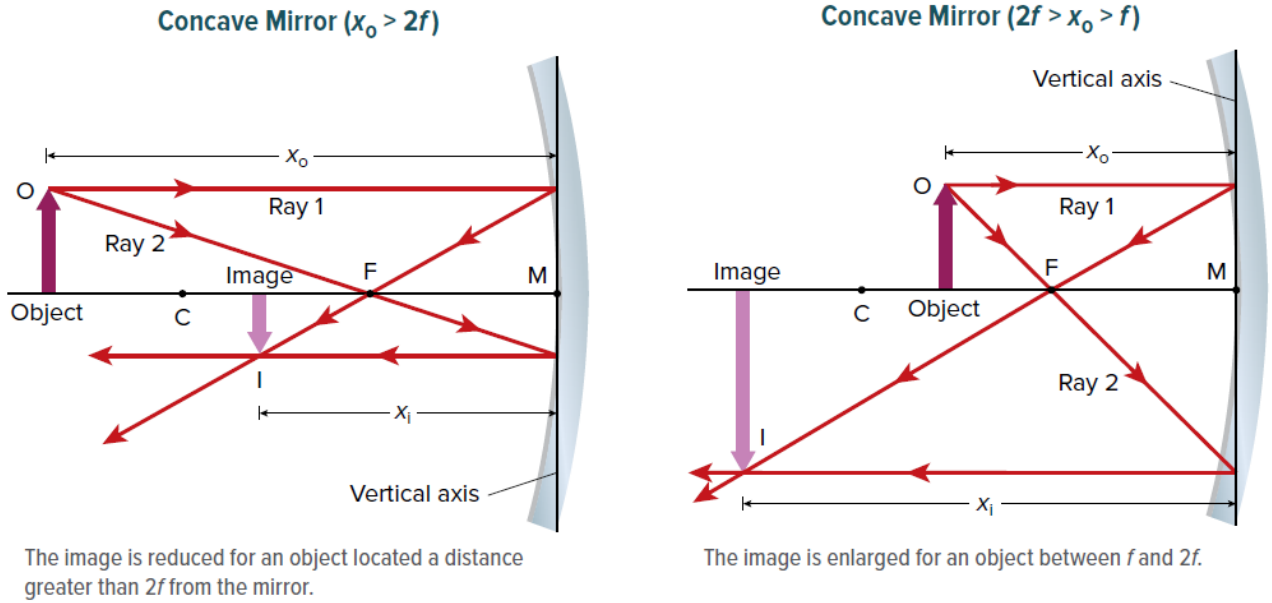
The image can be seen when projected on a white opaque screen.

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

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Real Images with Concave Mirrors

You can often simplify ray diagrams by using simple, one-dimensional objects, such as the arrow shown in **Figure 13** on the next page. A spherical concave mirror produces an inverted real image if the object position (x_o) is greater than twice the focal length (f). The object is then beyond the center of curvature (C). If the object is placed between the center of curvature and the focal point, as shown on the right in **Figure 13**, the image is again real and inverted. The size of the image is now greater than the size of the object.



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

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

Figure 13 The type of image depends on the object's distance from the mirror. A real, inverted image is formed in both situations shown here. Remember that f, the focal length, is the distance from M to F.

Diagram *how other points on the image are formed.*

COLOR CONVENTION

Object	magenta
Image	lilac
Light ray	red

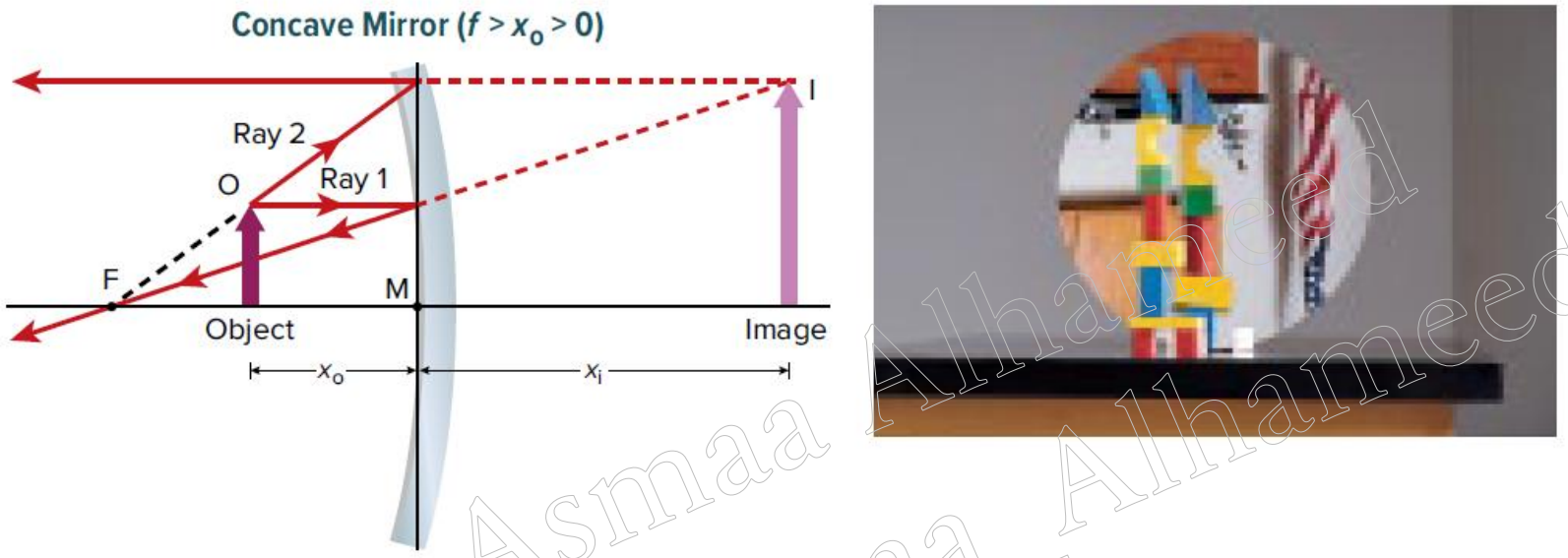


Figure 14 A virtual, upright, enlarged image is formed when an object, such as the block tower on the right, is placed between the focal point and the surface of a concave mirror.

Consider *the cause of the appearance of the other images in the mirror.*

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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.

Get It?

Explain how you can determine whether an image is virtual.

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.

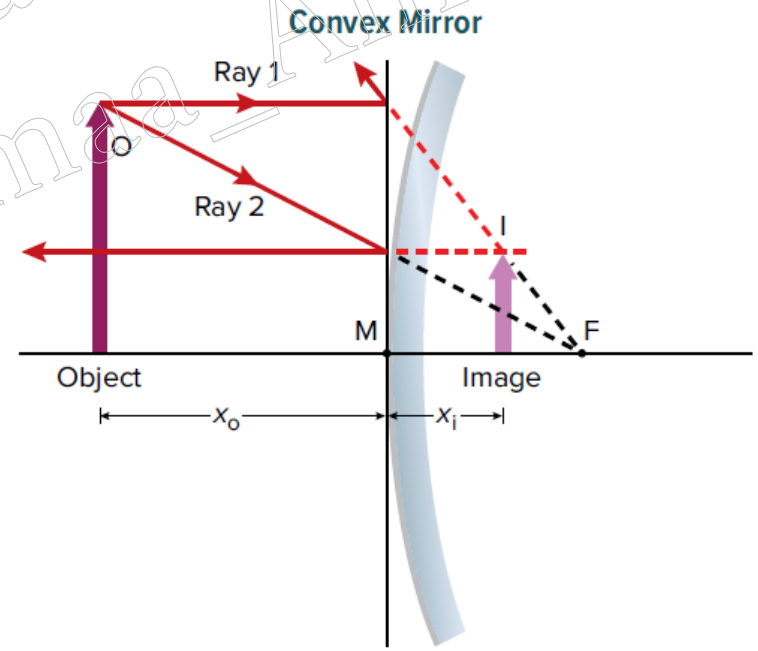


Figure 15 Convex mirrors form images that are virtual, upright, and smaller than the object.

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A sight line extends from the point where ray 1 strikes the principle plane through F. Ray 2 approaches the mirror on a path that, if extended behind the mirror, would pass through F. The reflected part of ray 2 and its sight line are parallel to the principal axis. The two reflected rays diverge. However, the sight lines intersect behind the mirror. The point where they intersect is the location of the image. An image produced by a convex mirror is a virtual image that is upright and smaller than the object.

Field of view It might seem that convex mirrors would have little use because the images they form are smaller than the objects. This property of convex mirrors, however, does have practical uses. By forming smaller images, convex mirrors enlarge the area that an observer sees, which is called the field of view. Also, the image is visible from a large range of angles; thus, the field of view is visible from a wide perspective.

Because of the increased field of view, convex mirrors are used in cars as passenger-side rearview mirrors, as shown in **Figure 16.** However, because the reduced image size makes the objects appear farther away than they really are, there is often a warning on passenger-side rearview mirrors of cars stating that objects may be closer than they appear.

PROBLEM-SOLVING STRATEGIES

Using Ray Diagrams to Locate Images Produced by Spherical Mirrors

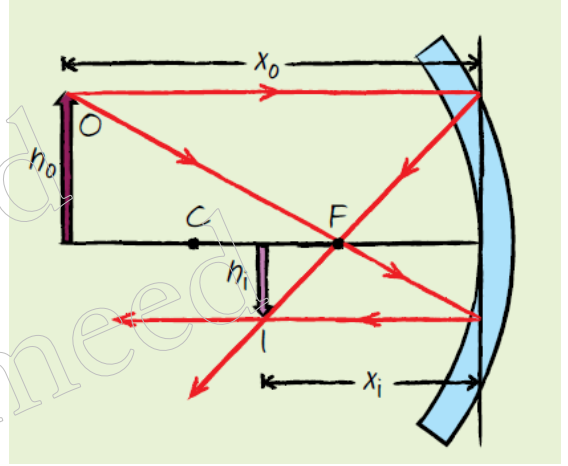
Use the following strategies for curved spherical-mirror problems. Refer to **Figure 13,** as well as **Figure 14** and **Figure 15** on the next page.

1. Using lined or graph paper, draw the principal axis of the mirror as a horizontal line from the left side to the right side of your paper, leaving six blank lines above and six blank lines below.
2. Place points and labels on the principal axis for the object, C, and F as follows:
   a. If the mirror is concave and the object is beyond C away from the mirror, place the mirror at the right side of the page, the object at the left side of the page, and make C and F to scale.
   b. If the mirror is concave and the object is between C and F, place the mirror at the right side of the page, C at the center of the paper, F halfway between the mirror and C, and the object to scale.
   c. For any other situation, place the mirror in the center of the page, the object or F (whichever is the greater distance from the mirror) at the left side of the page, and the other to scale.
3. To represent the mirror, draw a vertical line at the mirror point that extends for 12 lines. This is the mirror's principal plane.
4. Draw the object as an arrow, and label its top O. For concave mirrors, objects inside of C should not be higher than three lines. For all other situations, the objects should be six lines high. The scale for the height of the object will be different from the scale along the principal axis.
5. Draw ray 1, the parallel ray. It is parallel to the principal axis, reflects off the principal plane, and passes through F.
6. Draw ray 2, the focus ray. It passes through F, reflects off the principal plane, and is reflected parallel to the principal axis.
7. If reflected rays 1 and 2 diverge from each other, then extend the sight lines behind the mirror as dashed lines.
8. The image is located where rays 1 and 2 or their sight lines cross after reflection. For either case, label the point of intersection I. Draw the image as a perpendicular arrow from the principal axis to I.

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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?

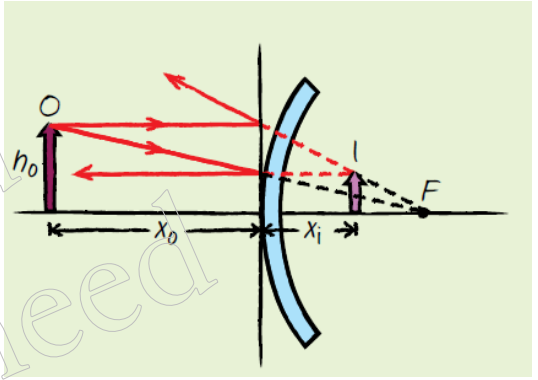


12. Use a ray diagram drawn to scale to solve Example Problem 2.

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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?



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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.

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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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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.

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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?

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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.

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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?

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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?

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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.

a. What is the image's distance?

b. What is the focal length of the mirror?

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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.

a. What is the object's distance?

b. What focal length should be specified?

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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**

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.

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

We can use **Figure 19** and **Table 2** to show how Snell's law applies when light travels through a piece of glass with parallel surfaces, such as a windowpane. The light is refracted when it enters the glass and again when it leaves the glass. When light goes from air into glass, it travels from a medium with a lower n of 1.00 to a medium with a higher n of 1.52. The light bends toward the normal.

Traveling from glass to air, light moves from a medium with a higher n (1.52) to one with a lower n (1.00). The light is bent away from the normal. The relative values of n determine whether the light will bend toward or away from the normal. Note the direction of the ray when it leaves the glass. It is the same as before it struck the glass, $\theta_1 = \theta_2'$. This is because the boundaries are between the same two mediums.

Table 2 Indices of Refraction for Yellow Light ($\lambda = 589$ 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.

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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.

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

This definition of the index of refraction can be used to find the wavelength of light in a medium. In a medium with an index of refraction n, the speed of light is given by $v = \frac{c}{n}$. The wavelength of the light in a vacuum is $\lambda_0 = \frac{c}{f}$. Solve for frequency, and substitute $f = \frac{c}{\lambda_0}$ and $v = \frac{c}{n}$ into $\lambda = \frac{v}{f}$.

$$\lambda = \frac{(c/n)}{(c/\lambda_0)} = \frac{\lambda_0}{n}$$

Note that the wavelength of light in a medium is smaller than its wavelength in a vacuum.

Get It?

Describe the relationship between the index of refraction and the speed of light in a medium.

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 $\sin \theta_2 = \sin 90.0° = 1$:

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

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30. A laser beam in air enters ethanol at an angle of incidence of 37.0°. What is the angle of refraction?

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31. As light travels from air into water, the angle of refraction is 25.0° to the normal. Find the angle of incidence.

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32. Light in air enters a diamond facet at 45.0°. What is the angle of refraction?

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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?

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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?

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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

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.

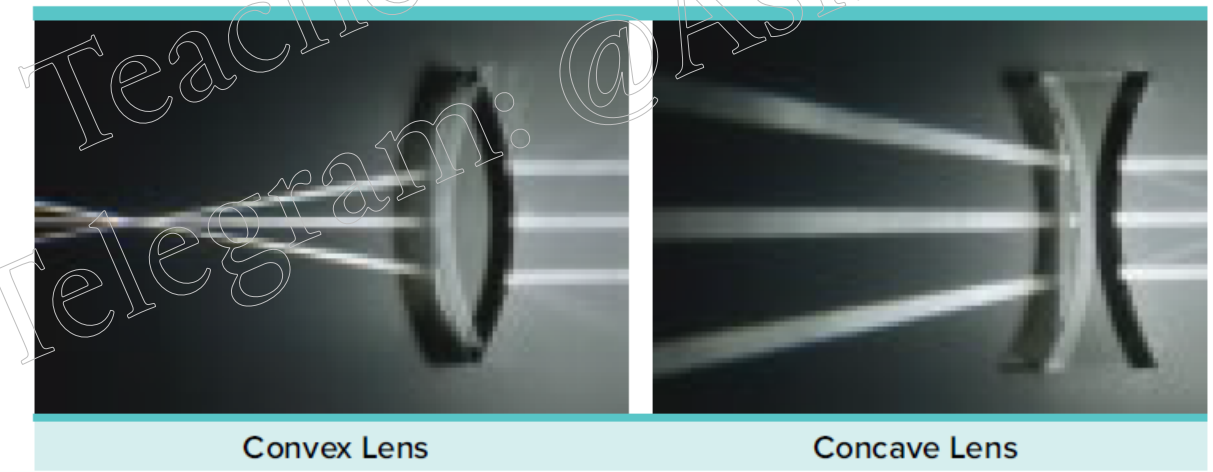


Figure 27 Convex lenses refract light so that the rays converge after passing through. The light passing through a concave lens does not meet at the focal point.

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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.

$x_o = 2f$ 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.

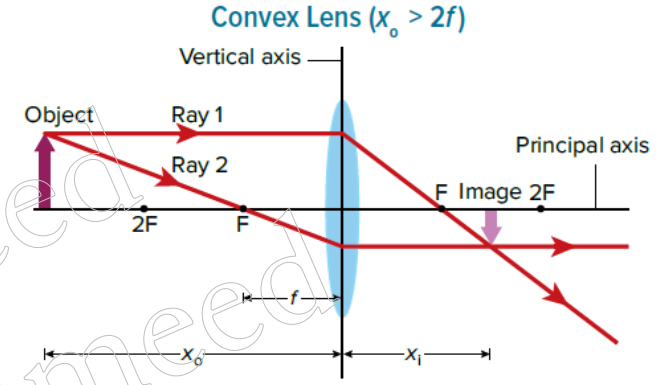


Figure 28 An object placed at a distance greater than twice the focal length from the lens will produce an image that is real, reduced in size, and inverted.

COLOR CONVENTION

Light ray	red
Object	magenta
Image	lilac

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$2f > x_o > f$ 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.

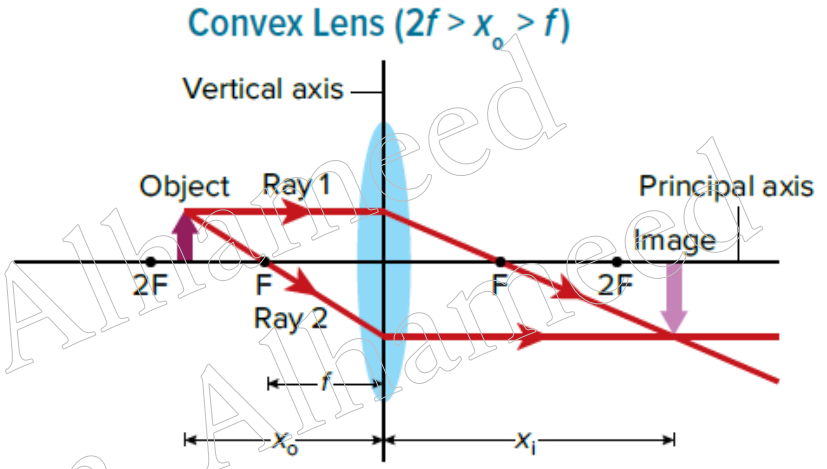


Figure 29 An object placed at a distance less than twice the focal length but greater than one focal length from the lens will produce an image that is real, enlarged, and inverted.

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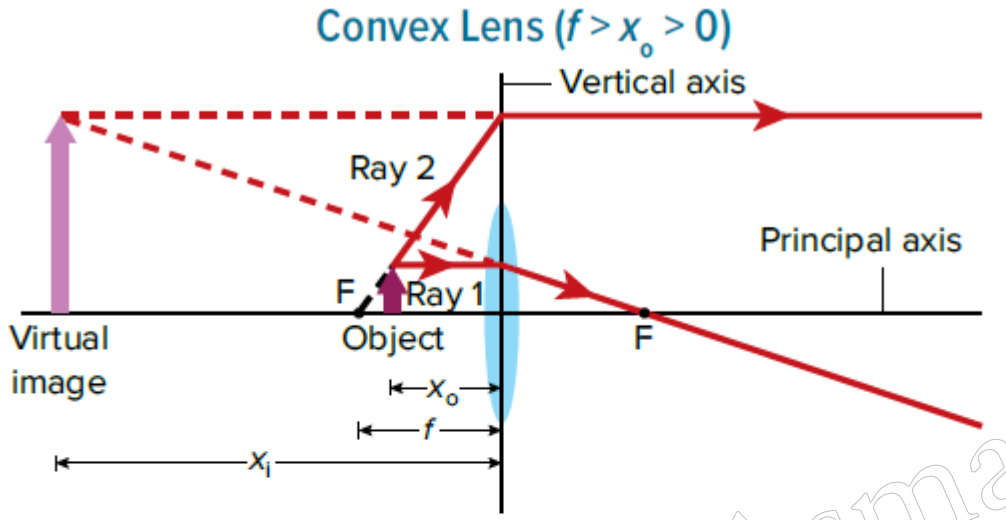


Figure 30 An object placed at a distance less than the focal length from the lens will produce an image that is virtual and enlarged.

Get It?

Classify an image as virtual or real based on the side of the lens it is on.

$f > x_o > 0$ **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.

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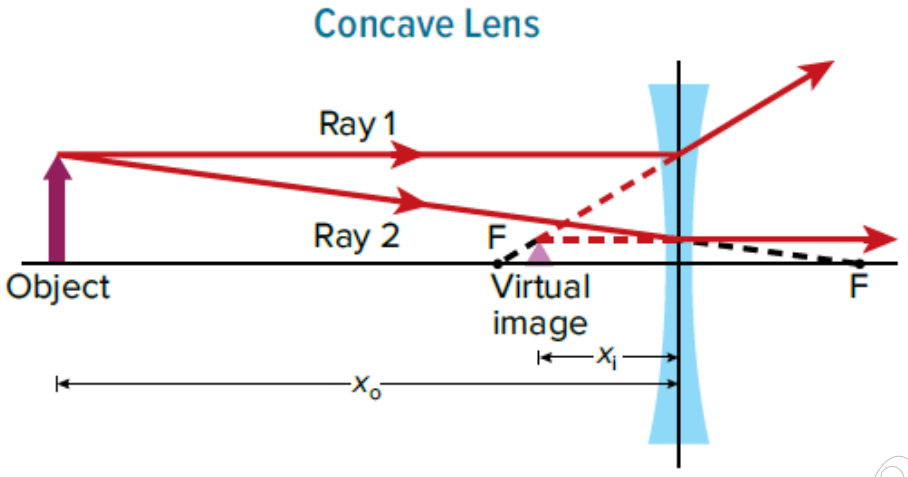


Figure 31 An object placed any distance from a concave lens will always produce an image that is virtual and reduced.

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.

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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 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.

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

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.

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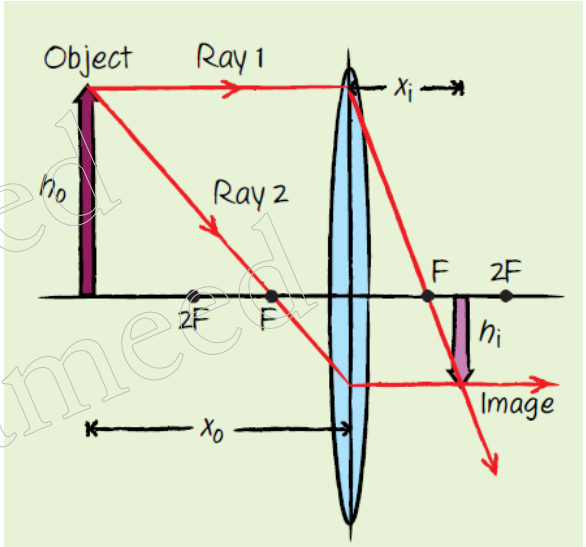
EXAMPLE Problem 5

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.

a. Where is the image?

b. If the object is 3.0 cm high, how tall is the image?

c. What is the orientation of the image?



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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?

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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?

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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.

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56. **Diverging Lens** A 6.5-cm-tall salt shaker is viewed through a diverging lens with a focal length of 5.0 cm.

a. If the shaker is 6.0 cm from the lens, what is the image distance from the lens? Is the image virtual or real?

b. What is the magnification? Is the image smaller or larger than the object?

c. 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?

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BEST OF LUCK IN THE FINAL EXAM!

Links for the group and files are in the description of the video

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