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Objectives

- **Recognize** situations in which refraction will occur.
- **Identify** which direction light will bend when it passes from one medium to another.
- **Solve** problems using Snell's law.

Refraction of Light

- The bending of light as it travels from one medium to another is call **refraction**.
- As a light ray travels from one medium into another medium where its speed is different, the light ray will change its direction unless it travels along the normal.

Refraction

End Of Slide

Refraction of Light, *continued*

- Refraction can be explained in terms of the wave model of light.
- The speed of light in a vacuum, *c*, is an important constant used by physicists.
- Inside of other mediums, such as air, glass, or water, the speed of light is different and is usually less than *c.*

End Of Slide

Wave Model of Refraction

End Of Slide

The Law of Refraction

- The **index of refraction** for a substance is the ratio of the speed of light in a vacuum to the speed of light in that substance.

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

$$\text{index of refraction} = \frac{\text{speed of light in a vacuum}}{\text{speed of light in medium}}$$

Indices of Refraction for Various Substances

Solids at 20°C	*n*
Cubic zirconia	2.20
Diamond	2.419
Fluorite	1.434
Fused quartz	1.458
Glass, crown	1.52
Glass, flint	1.66
Ice (at 0°C)	1.309
Polystyrene	1.49
Sodium chloride	1.544
Zircon	1.923

Liquids at 20°C	*n*
Benzene	1.501
Carbon disulfide	1.628
Carbon tetrachloride	1.461
Ethyl alcohol	1.361
Glycerine	1.473
Water	1.333

Gases at 0°C, 1 atm	*n*
Air	1.000 293
Carbon dioxide	1.000 450

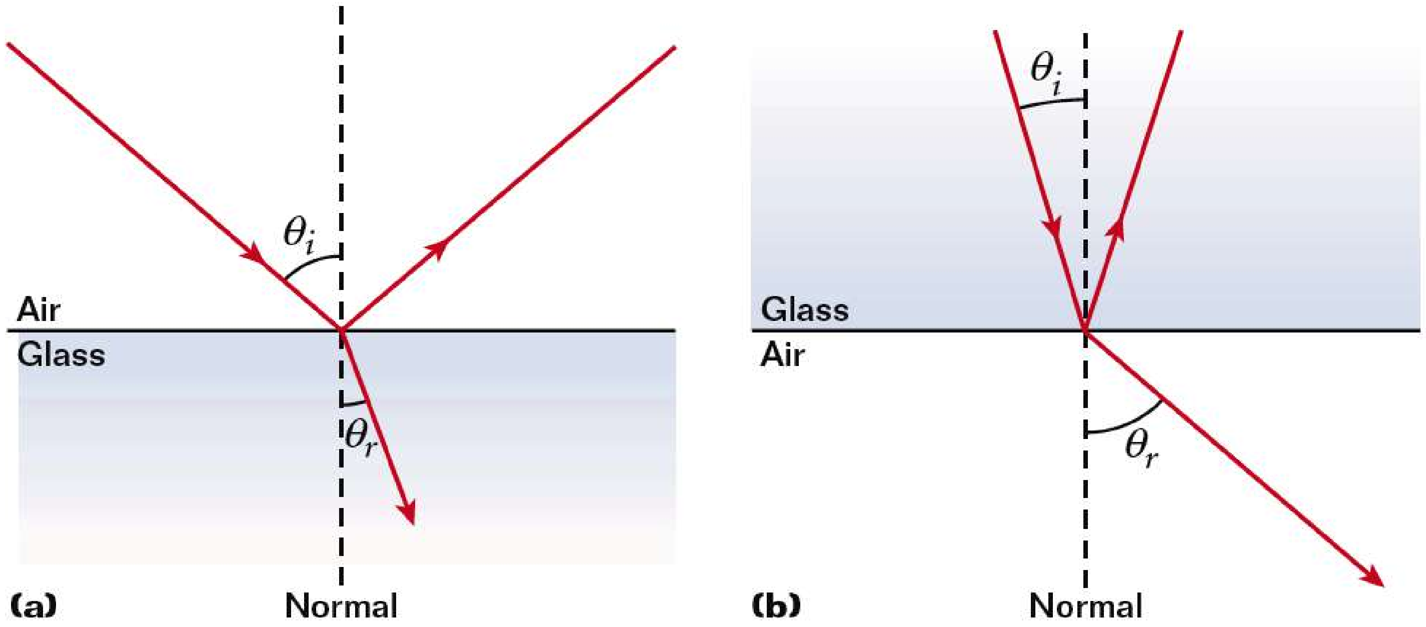
*measured with light of vacuum wavelength = 589 nm

The Law of Refraction, *continued*

- When light passes from a medium with a smaller index of refraction to one with a larger index of refraction (like from air to glass), the ray bends toward the normal.

- When light passes from a medium with a larger index of refraction to one with a smaller index of refraction (like from glass to air), the ray bends away from the normal.

Refraction



The Law of Refraction, *continued*

- Objects appear to be in different positions due to refraction.

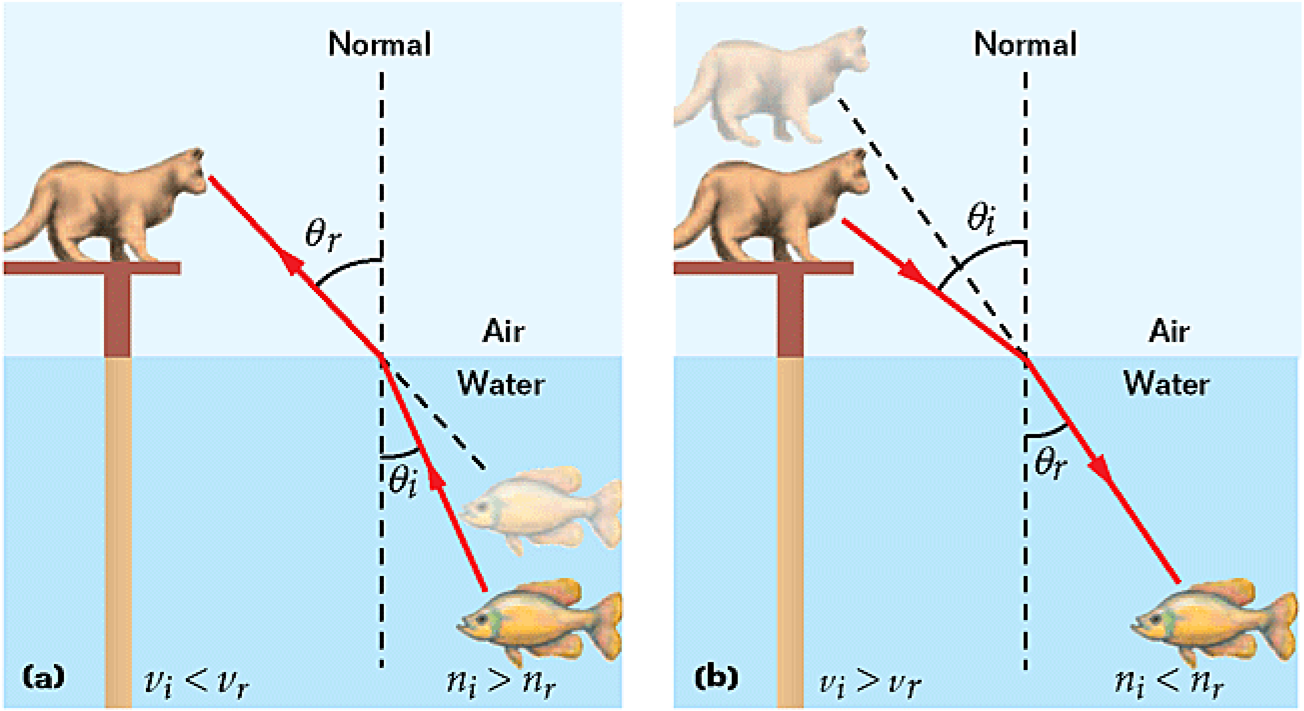
- Snell's Law determines the angle of refraction.

$$n_i \sin\theta_i = n_r \sin\theta_r$$

index of refraction of first medium × sine of the angle of incidence =

index of refraction of second medium × sine of the angle of refraction

Image Position for Objects in Different Media



Sample Problem

Snell's Law

A light ray of wavelength 589 nm (produced by a sodium lamp) traveling through air strikes a smooth, flat slab of crown glass at an angle of 30.0º to the normal. Find the angle of refraction, θ_r.

Sample Problem, *continued*

Snell's Law

Given: θ_i = 30.0º n_i = 1.00 n_r = 1.52

Unknown: θ_r = ?

Use the equation for Snell's law.

$$n_i \sin\theta_i = n_r \sin\theta_r$$

$$\theta_r = \sin^{1}\left[\frac{n_i}{n_r}(\sin\theta_i)\right] = \sin^{1}\left[\frac{1.00}{1.52}(\sin 30.0^\circ)\right]$$

$$\boxed{\theta_r = 19.2^\circ}$$

End Of Slide

Objectives

- **Use** ray diagrams to find the position of an image produced by a converging or diverging lens, and identify the image as real or virtual.
- **Solve** problems using the thin-lens equation.
- **Calculate** the magnification of lenses.
- **Describe** the positioning of lenses in compound microscopes and refracting telescopes.

Types of Lenses

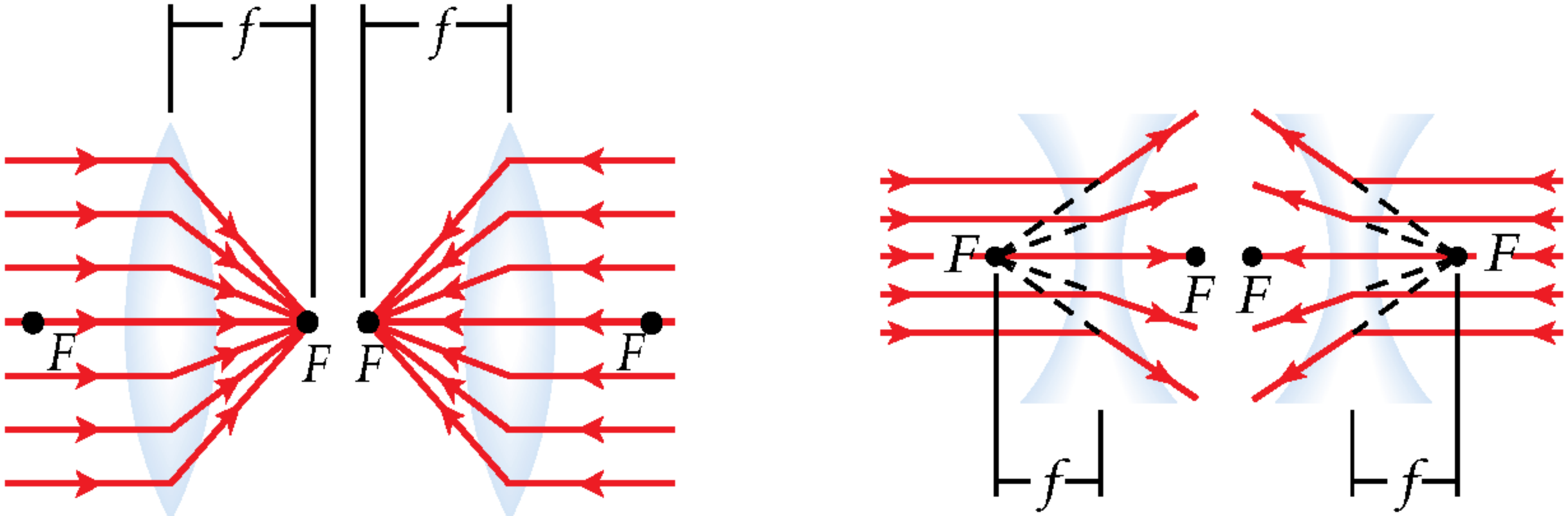
- A **lens** is a transparent object that refracts light rays such that they (to) converge or diverge to create an image.
- A lens that is thicker in the middle than it is at the rim is an example of a *converging* lens.
- A lens that is thinner in the middle than at the rim is an example of a *diverging* lens.

Converging and Diverging Lenses

Types of Lenses, *continued*

- The focal point is the location where the image of an object at an infinite distance from a converging lens if focused.
- Lenses have a focal point on each side of the lens.
- The distance from the focal point to the center of the lens is called the *focal length, f.*

Lenses and Focal Length



Focal Length for Converging and Diverging Lenses

Types of Lenses, *continued*

- Ray diagrams (path of light through a lens) of thin-lens systems help identify image height and location.

- Rules for drawing reference rays

Ray	From object to lens	From *converging* lens to image	From *diverging* lens to image
Parallel ray	parallel to principal axis	passes through focal point, *F*	directed away from focal point, *F*
Central ray	to the center of the lens	from the center of the lens	from the center of the lens
Focal ray	passes through focal point, *F*	parallel to principal axis	parallel to principal axis

Characteristics of Lenses

- Converging lenses can produce real or virtual images of real objects.
- The image produced by a converging lens is real and inverted when the object is outside the focal point.
- The image produced by a converging lens is virtual and upright when the object is inside the focal point.

Ray Tracing for a Converging Lens

End Of Slide

Characteristics of Lenses, *continued*

- Diverging lenses produce virtual images from real objects.

- The image created by a diverging lens is always a virtual, smaller image.

End Of Slide

Ray Tracing for a Diverging Lens

The Thin-Lens Equation and Magnification

- The equation that relates object and image distances for a lens is call the *thin-lens equation*.
- It is derived using the assumption that the lens is very thin.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

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

The Thin-Lens Equation and Magnification, *continued*

- Magnification of a lens depends on object and image distances.

$$M = \frac{h'}{h} = \frac{q}{p}$$

$$\text{magnification} = \frac{\text{image height}}{\text{object height}} = \frac{\text{distance from image to lens}}{\text{distance from object to lens}}$$

End Of Slide

The Thin-Lens Equation and Magnification, *continued*

- If close attention is given to the sign conventions defined in the table, then the magnification will describe the image's size and orientation.

	+	−
p	object in front of the lens	object in back of the lens
q	image in back of the lens	image in front of the lens
f	converging lens	diverging lens

End Of Slide

Sample Problem

Lenses

An object is placed 30.0 cm in front of a converging lens and then 12.5 cm in front of a diverging lens. Both lenses have a focal length of 10.0 cm. For both cases, find the image distance and the magnification. Describe the images.

End Of Slide

Sample Problem, *continued*

Lenses

1. Define

Given: $f_{converging}$ = 10.0 cm $f_{diverging}$ = –10.0 cm

$p_{converging}$ = 30.0 cm $p_{diverging}$ = 12.5 cm

Unknown: $q_{converging}$ = ? $q_{diverging}$ = ? $M_{converging}$ = ? $M_{diverging}$ = ?

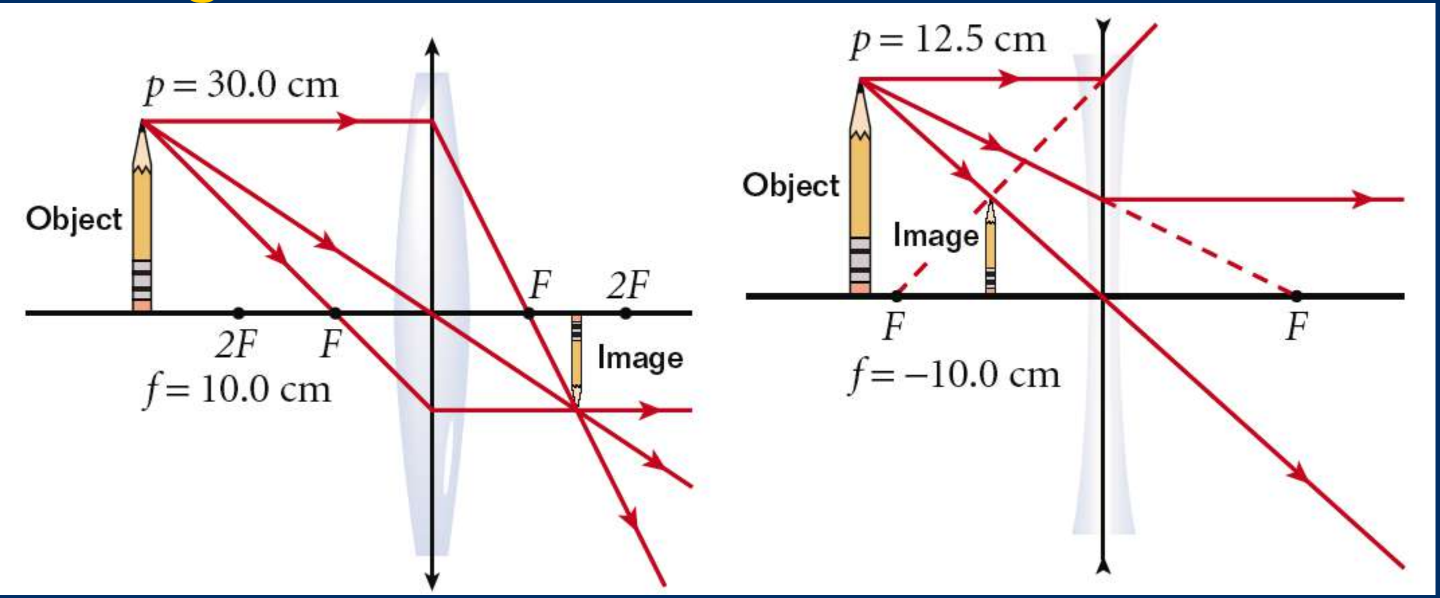
End Of Slide

Sample Problem, *continued*

Lenses

1. Define, *continued*

Diagrams:



Sample Problem, *continued*

Lenses

2. Plan

Choose an equation or situation: The thin-lens equation can be used to find the image distance, and the equation for magnification will serve to describe the size and orientation of the image.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \qquad M = -\frac{q}{p}$$

End Of Slide

Sample Problem, *continued*

Lenses

2. Plan, *continued*

Rearrange the equation to isolate the unknown:

$$\frac{1}{q} = \frac{1}{f} \quad \frac{1}{p}$$

End of Slide

Sample Problem, *continued*

Lenses

3. Calculate

For the converging lens:

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{10.0 \text{ cm}} - \frac{1}{30.0 \text{ cm}} = \frac{2}{30.0 \text{ cm}}$$

$$\boxed{q = 15.0 \text{ cm}}$$

$$M = -\frac{q}{p} = -\frac{15.0 \text{ cm}}{30.0 \text{ cm}}$$

$$\boxed{M = -0.500}$$

End Of Slide

Sample Problem, *continued*

Lenses

3. Calculate, *continued*

For the diverging lens:

$$\frac{1}{q} = \frac{1}{f} \quad \frac{1}{p} = \frac{1}{10.0\ \text{cm}} \quad \frac{1}{12.5\ \text{cm}} = \frac{22.5}{125\ \text{cm}}$$

$$\boxed{q = \quad 5.56\ \text{cm}}$$

$$M = \quad \frac{q}{p} = \frac{5.56\ \text{cm}}{12.5\ \text{cm}}$$

$$\boxed{M = 0.445}$$

End of Slide

Sample Problem, *continued*

Lenses

4. Evaluate

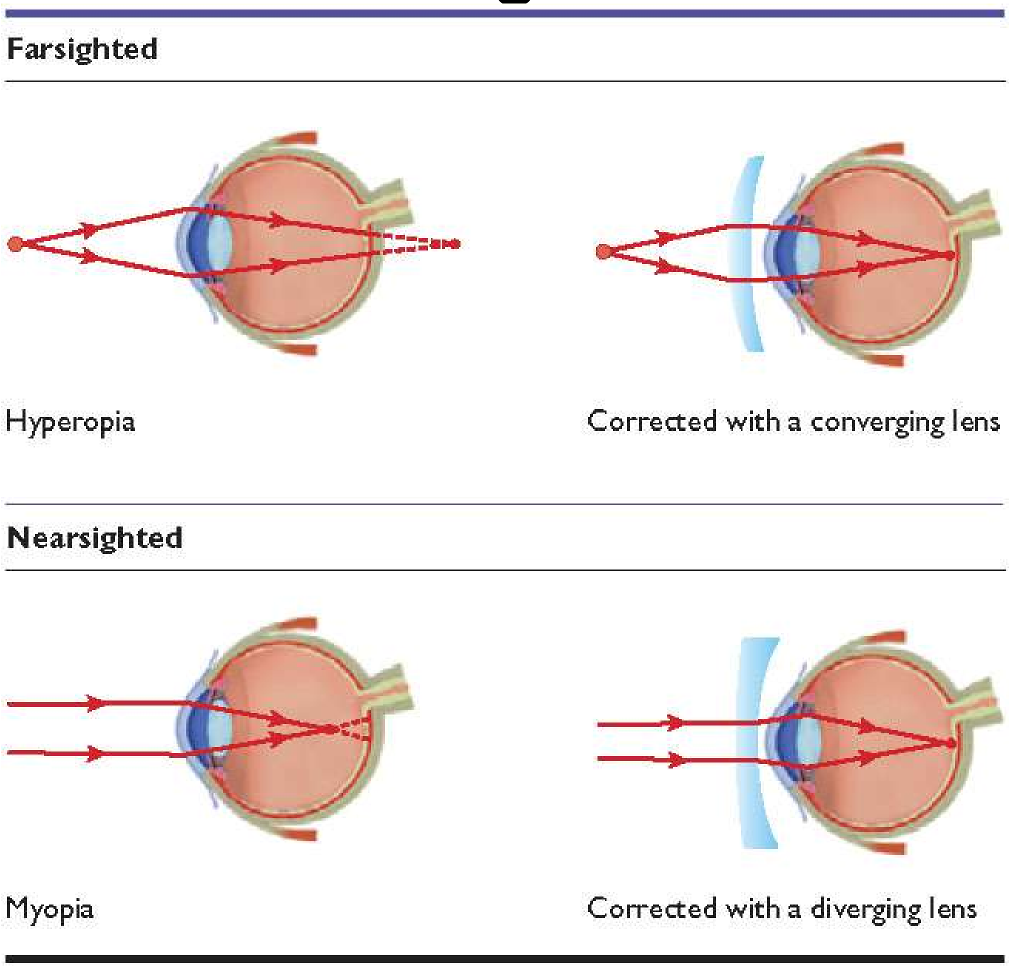
These values and signs for the converging lens indicate a real, inverted, smaller image. This is expected because the object distance is longer than twice the focal length of the converging lens. The values and signs for the diverging lens indicate a virtual, upright, smaller image formed inside the focal point. This is the only kind of image diverging lenses form.

Eyeglasses and Contact Lenses

- The transparent front of the eye, called the *cornea,* acts like a lens.
- The eye also contains a *crystalline lens,* that further refracts light toward the light-sensitive back of the eye, called the *retina.*
- Two conditions, *myopia and hyperopia,* occur when light is not focused properly retina. Converging and diverging lenses can be used to correct these conditions.

End Of Slide

Farsighted and Nearsighted



Combination of Thin Lenses

- An image formed by a lens can be used as the object for a second lens.
- *Compound microscopes* use two converging lenses. Greater magnification can be achieved by combining two or more lenses.
- Refracting telescopes also use two converging lenses.

Compound Light Microscope

Refracting Telescope

End Of Slide

Objectives

- **Predict** whether light will be refracted or undergo total internal reflection.
- **Recognize** atmospheric conditions that cause refraction.
- **Explain** dispersion and phenomena such as rainbows in terms of the relationship between the index of refraction and the wavelength.

Total Internal Reflection

- **Total internal reflection** can occur when light moves along a path from a medium with a *higher* index of refraction to one with a *lower* index of refraction.
- At the **critical angle,** refracted light makes an angle of 90º with the normal.
- Above the critical angle, total internal reflection occurs and light is completely reflected within a substance.

End of Slide

Total Internal Reflection, *continued*

- Snell's law can be used to find the critical angle.

$$\sin\theta_C = \frac{n_r}{n_i} \qquad \text{for } n_i > n_r$$

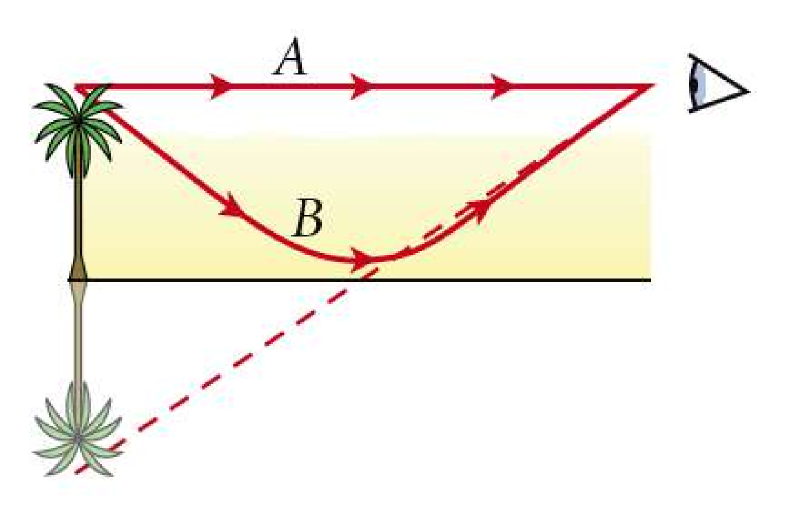
$$\text{sine}(\text{critical angle}) = \frac{\text{index of refraction of second medium}}{\text{index of refraction of first medium}}$$

- Total internal reflection occurs *only* if the index of refraction of the first medium is *greater than* the index of refraction of the second medium.

Total Internal Reflection

End Of Slide

Atmospheric Refraction

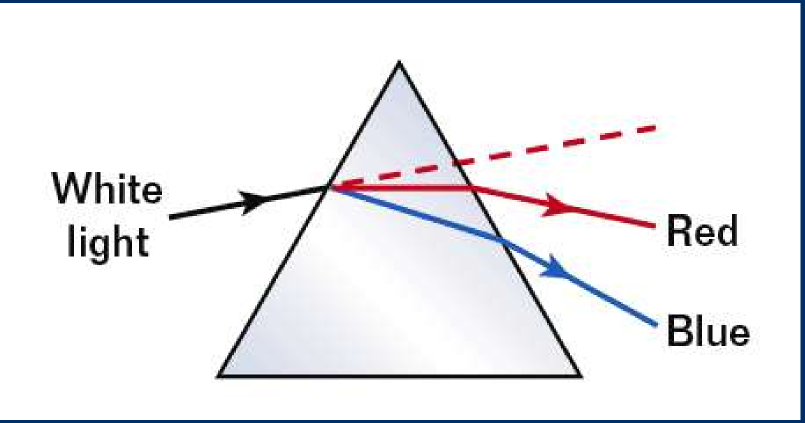


- Refracted light can create a mirage.
- A mirage is produced by the bending of light rays in the atmosphere where there are large temperature differences between the ground and the air.

Dispersion

- **Dispersion** is the process of separating polychromatic light into its component wavelengths.

- White light passed through a prism produces a *visible spectrum* through dispersion.



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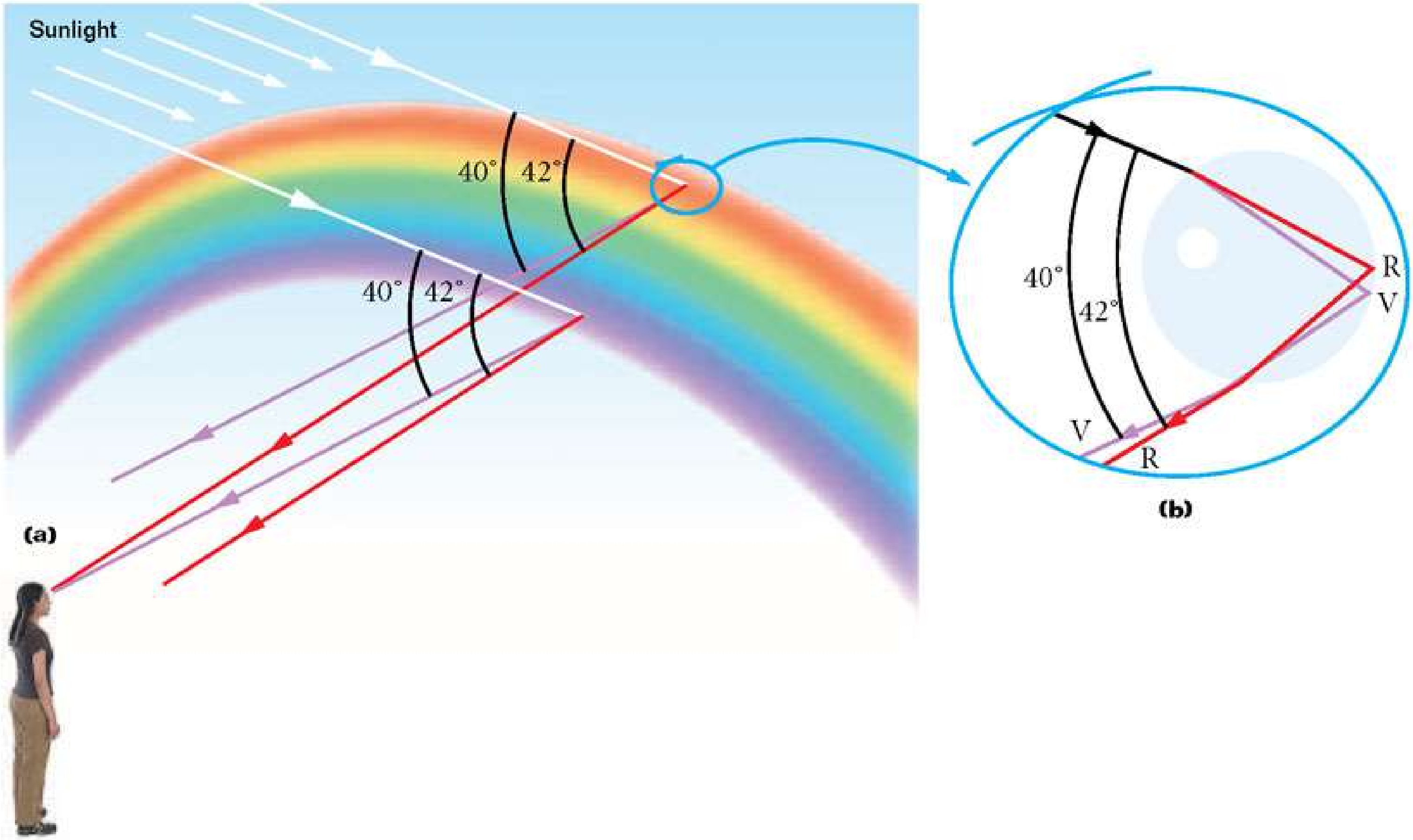
Dispersion of Light

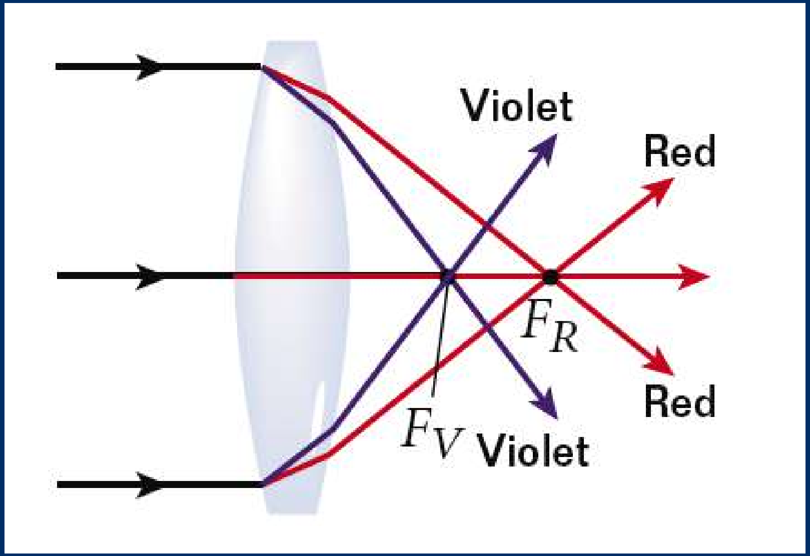
End Of Slide

Rainbows



Lens Aberrations

- **Chromatic aberration** is the focusing of different colors of light at different distances behind a lens.
- Chromatic aberration occurs because the index of refraction varies for different wavelengths of light.



Multiple Choice

1. How is light affected by an increase in the index of refraction?

A. Its frequency increases.

B. Its frequency decreases.

C. Its speed increases.

D. Its speed decreases.

Multiple Choice, *continued*

1. How is light affected by an increase in the index of refraction?

A. Its frequency increases.

B. Its frequency decreases.

C. Its speed increases.

D. Its speed decreases.

End Of Slide

Multiple Choice, *continued*

2. Which of the following conditions is not necessary for refraction to occur?

F. Both the incident and refracting substances must be transparent.

G. Both substances must have different indices of refraction.

H. The light must have only one wavelength.

J. The light must enter at an angle greater than 0° with respect to the normal.

Multiple Choice, *continued*

2. Which of the following conditions is not necessary for refraction to occur?

F. Both the incident and refracting substances must be transparent.

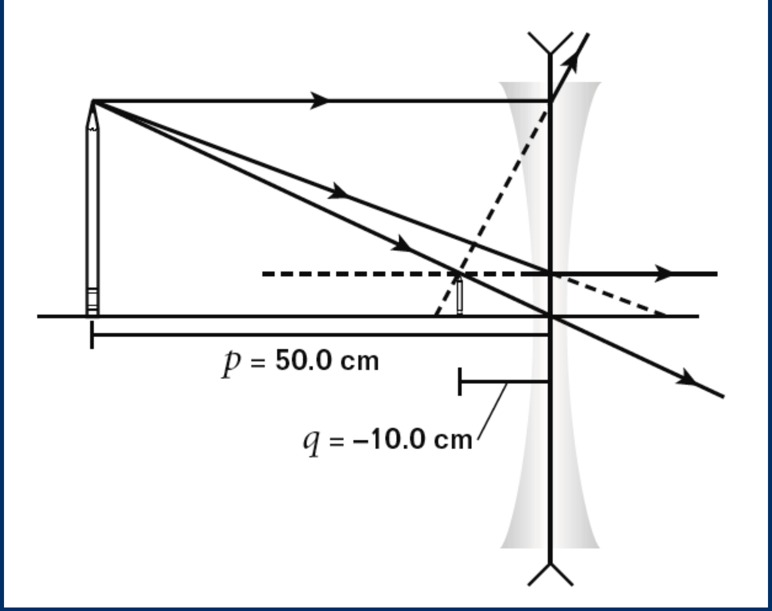
G. Both substances must have different indices of refraction.

H. The light must have only one wavelength.

J. The light must enter at an angle greater than 0° with respect to the normal.

Multiple Choice, *continued*

Use the ray diagram below to answer questions 3–4.



3. What is the focal length of the lens?

A. -12.5 cm

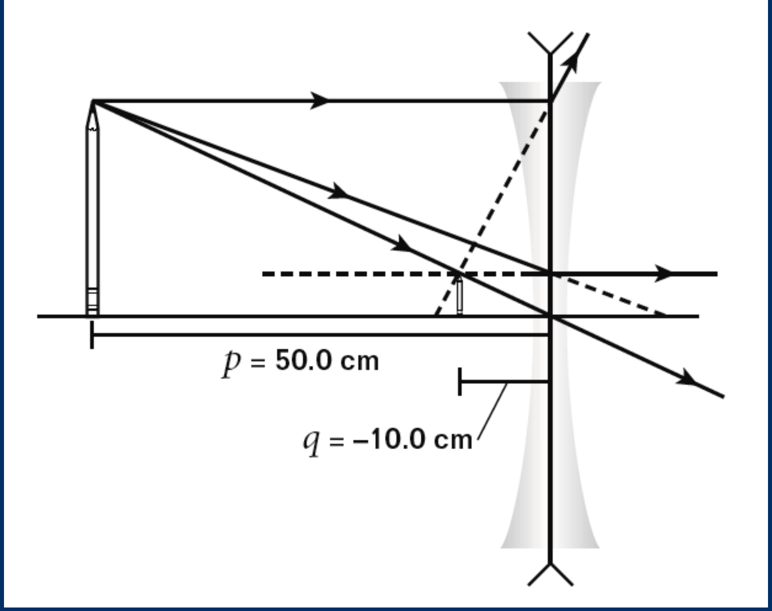
B. -8.33 cm

C. 8.33 cm

D. 12.5 cm

Multiple Choice, *continued*

Use the ray diagram below to answer questions 3–4.



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Multiple Choice, *continued*

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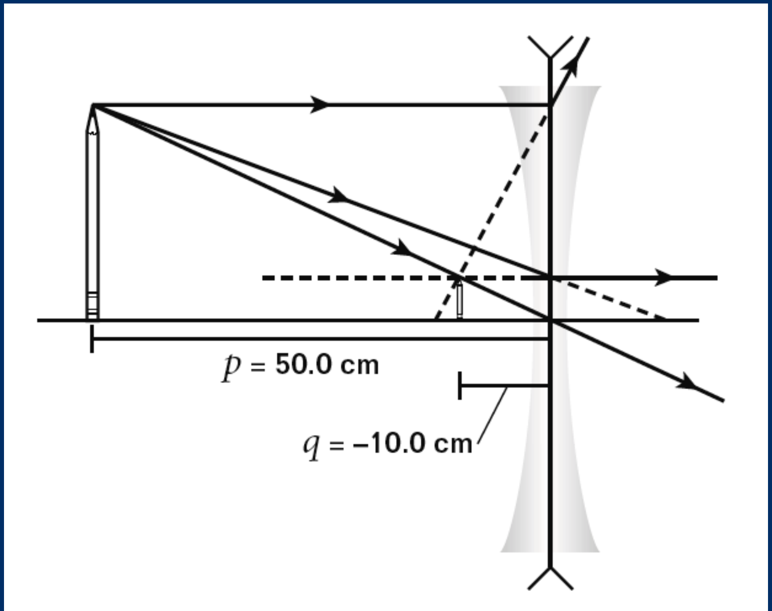


4. What is true of the image formed by the lens?

F. real, inverted, and enlarged

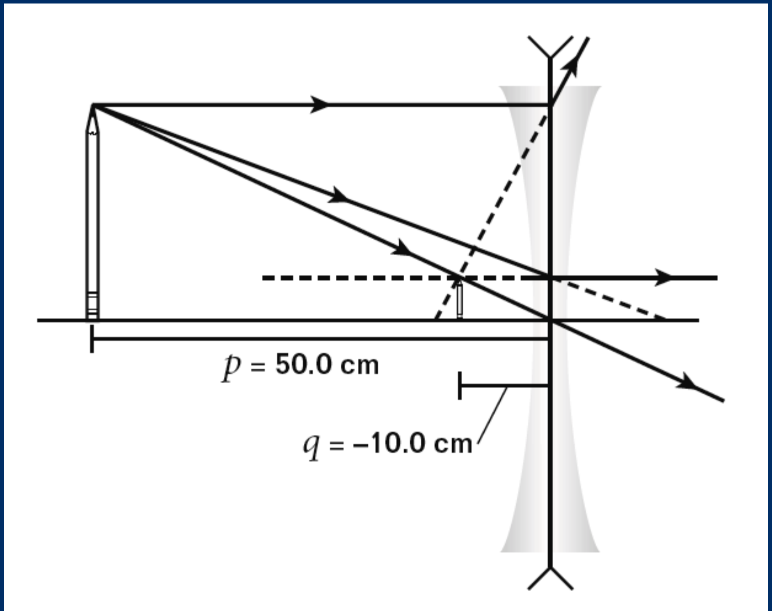
G. real, inverted, and diminished

H. virtual, upright, and enlarged

J. virtual, upright, and diminished

Multiple Choice, *continued*

Use the ray diagram below to answer questions 3–4.



4. What is true of the image formed by the lens?

F. real, inverted, and enlarged

G. real, inverted, and diminished

H. virtual, upright, and enlarged

J. virtual, upright, and diminished

Multiple Choice, *continued*

5. A block of flint glass with an index of refraction of 1.66 is immersed in oil with an index of refraction of 1.33. How does the critical angle for a refracted light ray in the glass vary from when the glass is surrounded by air?

A. It remains unchanged.

B. It increases.

C. It decreases.

D. No total internal reflection takes place when the glass is placed in the oil.

Multiple Choice, *continued*

5. A block of flint glass with an index of refraction of 1.66 is immersed in oil with an index of refraction of 1.33. How does the critical angle for a refracted light ray in the glass vary from when the glass is surrounded by air?

A. It remains unchanged.

B. It increases.

C. It decreases.

D. No total internal reflection takes place when the glass is placed in the oil.

Multiple Choice, *continued*

6. Which color of light is most refracted during dispersion by a prism?

F. red

G. yellow

H. green

J. violet

Multiple Choice, *continued*

6. Which color of light is most refracted during dispersion by a prism?

F. red

G. yellow

H. green

J. violet

Multiple Choice, *continued*

7. If an object in air is viewed from beneath the surface of water below, where does the object appear to be?

A. The object appears above its true position.

B. The object appears exactly at its true position.

C. The object appears below its true position.

D. The object cannot be viewed from beneath the water's surface.

Multiple Choice, *continued*

7. If an object in air is viewed from beneath the surface of water below, where does the object appear to be?

A. The object appears above its true position.

B. The object appears exactly at its true position.

C. The object appears below its true position.

D. The object cannot be viewed from beneath the water's surface.

Multiple Choice, *continued*

8. The phenomenon called "looming" is similar to a mirage, except that the inverted image appears above the object instead of below it.What must be true if looming is to occur?

F. The temperature of the air must increase with distance above the surface.

G. The temperature of the air must decrease with distance above the surface.

H. The mass of the air must increase with distance above the surface.

J. The mass of the air must increase with distance above the surface.

Multiple Choice, *continued*

8. The phenomenon called "looming" is similar to a mirage, except that the inverted image appears above the object instead of below it. What must be true if looming is to occur?

F. The temperature of the air must increase with distance above the surface.

G. The temperature of the air must decrease with distance above the surface.

H. The mass of the air must increase with distance above the surface.

J. The mass of the air must increase with distance above the surface.

Multiple Choice, *continued*

9. Light with a vacuum wavelength of 500.0 nm passes into benzene, which has an index of refraction of 1.5. What is the wavelength of the light within the benzene?

A. 0.0013 nm

B. 0.0030 nm

C. 330 nm

D. 750 nm

Multiple Choice, *continued*

9. Light with a vacuum wavelength of 500.0 nm passes into benzene, which has an index of refraction of 1.5. What is the wavelength of the light within the benzene?

A. 0.0013 nm

B. 0.0030 nm

C. 330 nm

D. 750 nm

Multiple Choice, *continued*

10. Which of the following is not a necessary condition for seeing a magnified image with a lens?

F. The object and image are on the same side of the lens.

G. The lens must be converging.

H. The observer must be placed within the focal length of the lens.

J. The object must be placed within the focal length of the lens.

Multiple Choice, *continued*

10. Which of the following is not a necessary condition for seeing a magnified image with a lens?

F. The object and image are on the same side of the lens.

G. The lens must be converging.

H. The observer must be placed within the focal length of the lens.

J. The object must be placed within the focal length of the lens.

End of Slide

Short Answer

11. In both microscopes and telescopes, at least two converging lenses are used: one for the objective and one for the eyepiece. These lenses must be positioned in such a way that the final image is virtual and very much enlarged. In terms of the focal points of the two lenses, how must the lenses be positioned?

Short Answer, *continued*

11. In both microscopes and telescopes, at least two converging lenses are used: one for the objective and one for the eyepiece. These lenses must be positioned in such a way that the final image is virtual and very much enlarged. In terms of the focal points of the two lenses, how must the lenses be positioned?

Answer: The focal point of the objective must lie within the focal point of the eyepiece.

End of Slide

Short Answer, *continued*

12. A beam of light passes from the fused quartz of a bottle (n = 1.46) into the ethyl alcohol (n = 1.36) that is contained inside the bottle. If the beam of the light inside the quartz makes an angle of 25.0° with respect to the normal of both substances, at what angle to the normal will the light enter the alcohol?

Short Answer, *continued*

12. A beam of light passes from the fused quartz of a bottle (n = 1.46) into the ethyl alcohol (n = 1.36) that is contained inside the bottle. If the beam of the light inside the quartz makes an angle of 25.0° with respect to the normal of both substances, at what angle to the normal will the light enter the alcohol?

Answer: 27.0°

Short Answer, *continued*

13. A layer of glycerine (n = 1.47) covers a zircon slab (n = 1.92). At what angle to the normal must a beam of light pass through the zircon toward the glycerine so that the light undergoes total internal reflection?

Short Answer, *continued*

13. A layer of glycerine (n = 1.47) covers a zircon slab (n = 1.92). At what angle to the normal must a beam of light pass through the zircon toward the glycerine so that the light undergoes total internal reflection?

Answer: 50.0º

Extended Response

14. Explain how light passing through raindrops is reflected and dispersed so that a rainbow is produced. Include in your explanation why the lower band of the rainbow is violet and the outer band is red.

Extended Response, *continued*

14. Explain how light passing through raindrops is reflected and dispersed so that a rainbow is produced. Include in your explanation why the lower band of the rainbow is violet and the outer band is red.

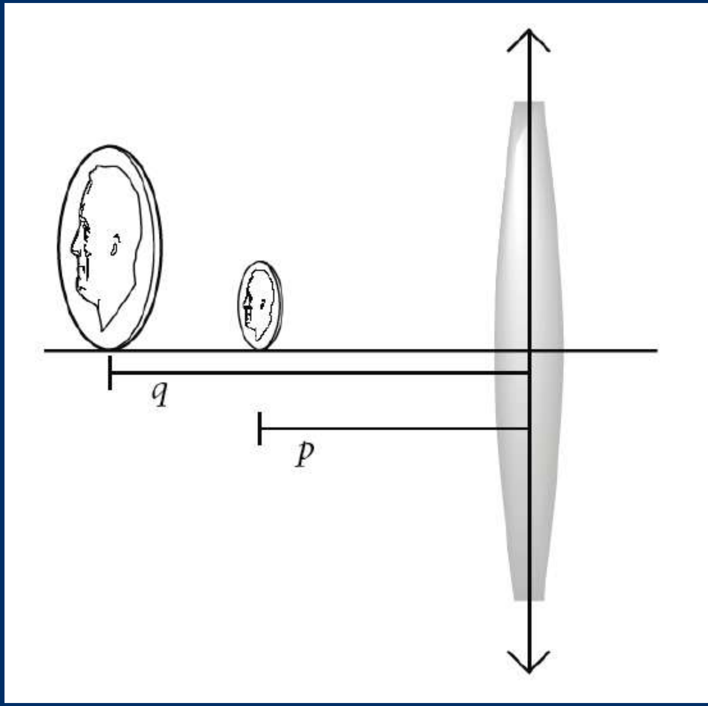
Answer: There are three effects—a refraction, a reflection, and then a final refraction. The light of each wavelength in the visible spectrum is refracted by a different amount: the red light undergoes the least amount of refraction, and the violet light undergoes the most. (*Answer continued on next slide.)*

Extended Response, *continued*

14. Answer *(continued):* At the far side of the raindrop, the light is internally reflected and undergoes refraction again when it leaves the front side of the raindrop. Because of the internal reflection, the final dispersion of the light is such that the violet light makes an angle of 40° with the incident ray, and the red light makes an angle of 42° with the incident ray. For an observer, the upper edge of the rainbow has the color of the light that bends farthest from the incident light, so the outer band of the rainbow is red. Similarly, the lower edge has the color of the light that bends least from the incident light, so the inner band is violet. The net effect is that the ray that is refracted the most ends up closest to the incident light, that is, the smallest angular displacement.

Extended Response, *continued*

Use the ray diagram below to answer questions

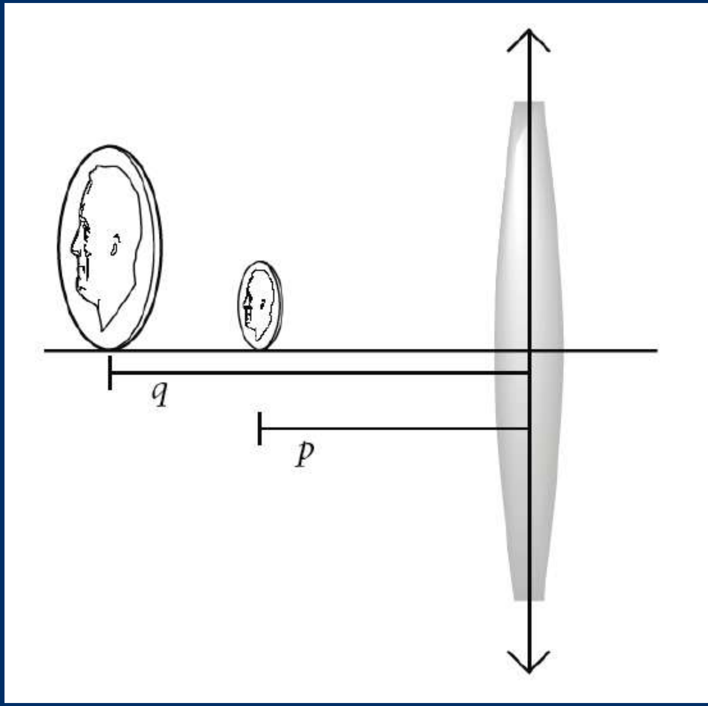


A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

15. What is the focal length of the lens?

Extended Response, *continued*

Use the ray diagram below to answer questions



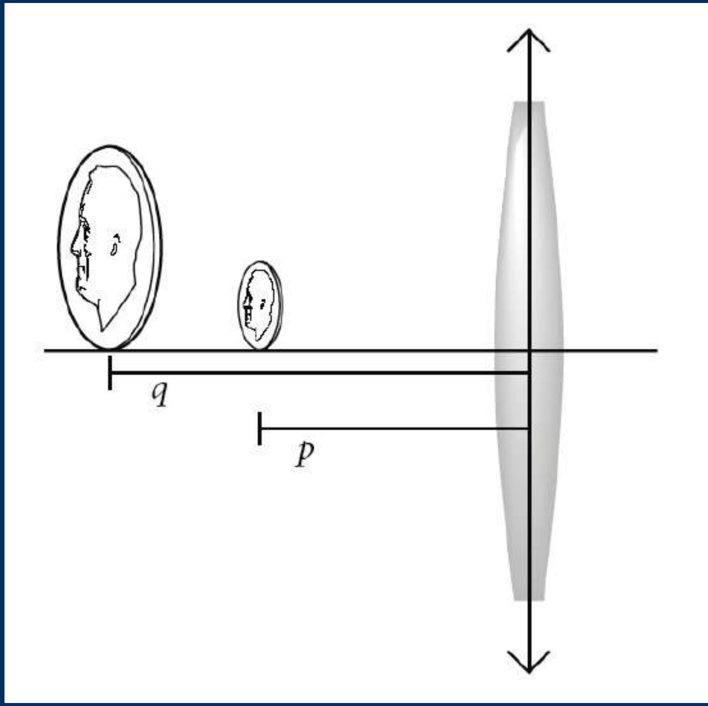
A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

15. What is the focal length of the lens?

Answer: 15 cm

Extended Response, *continued*

Use the ray diagram below to answer questions

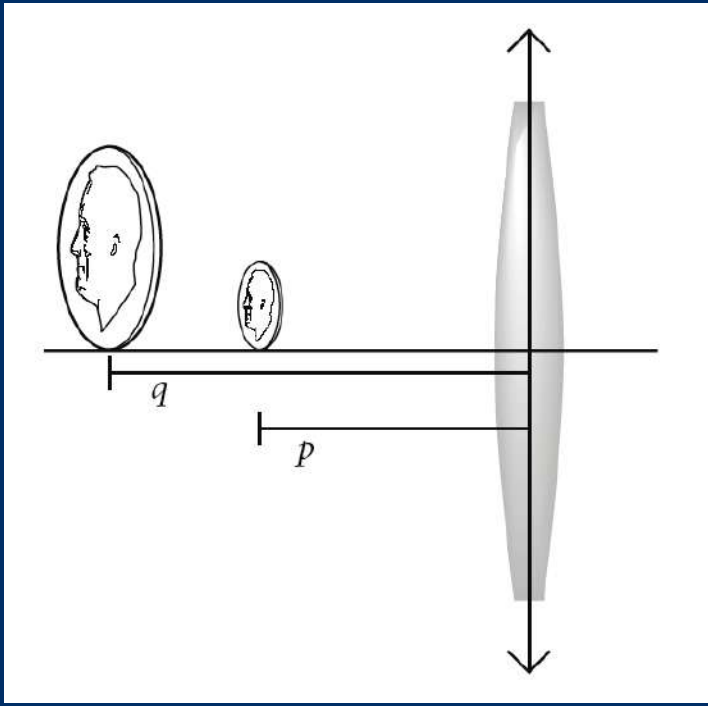


A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

16. What is the magnification of the coin's image?

Extended Response, *continued*

Use the ray diagram below to answer questions



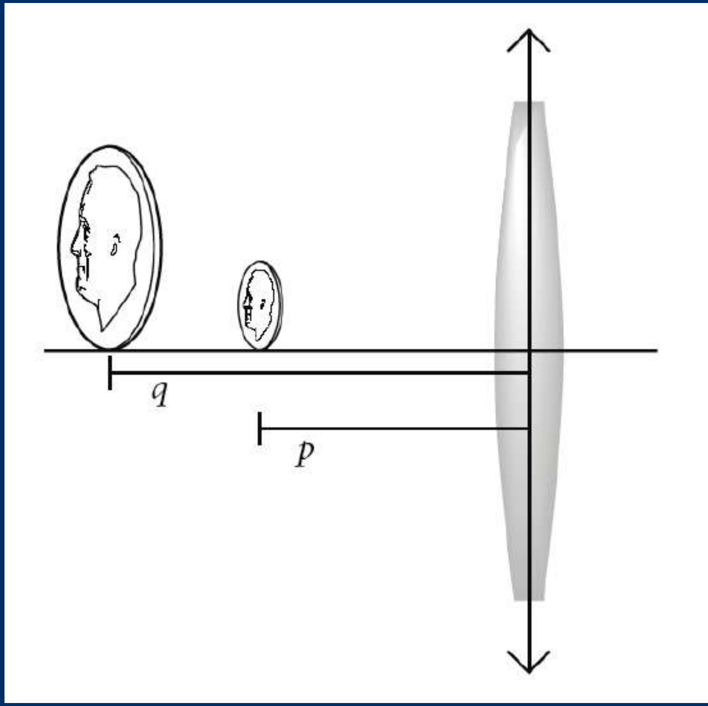
A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

16. What is the magnification of the coin's image?

Answer: 1.5

Extended Response, *continued*

Use the ray diagram below to answer questions

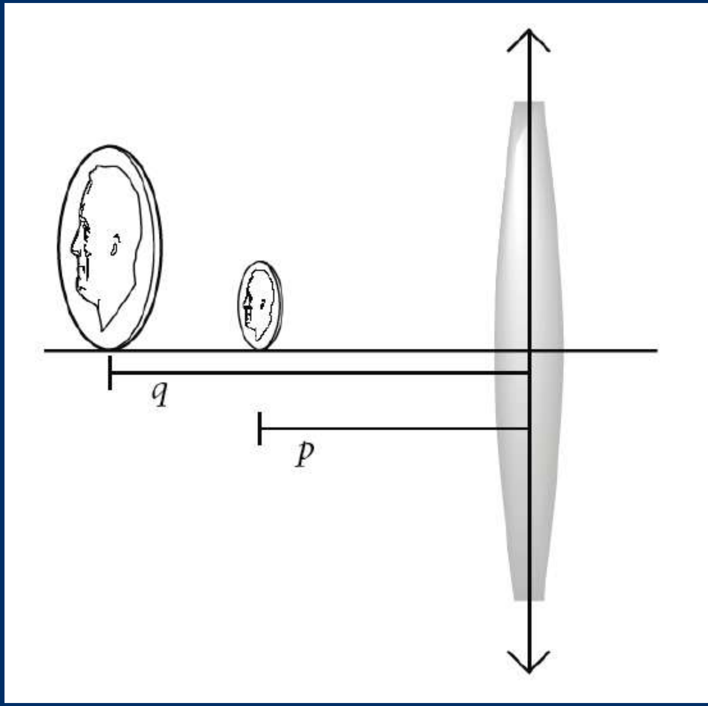


A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

17. If the coin has a diameter of 2.8 cm, what is the diameter of the coin's image?

Extended Response, *continued*

Use the ray diagram below to answer questions



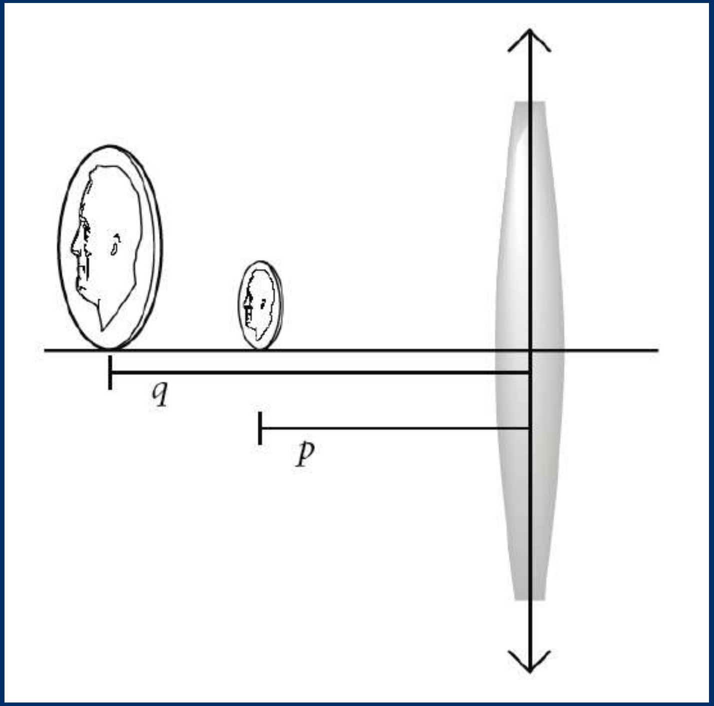
A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

17. If the coin has a diameter of 2.8 cm, what is the diameter of the coin's image?

Answer: 4.2 cm

Extended Response, *continued*

Use the ray diagram below to answer questions

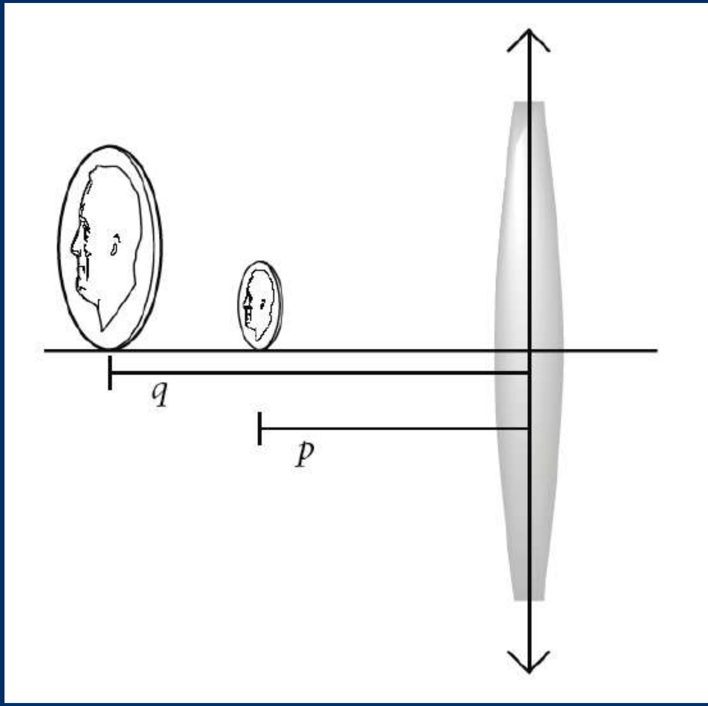


A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

18. Is the coin's image virtual or real? upright or inverted?

Extended Response, *continued*

Use the ray diagram below to answer questions



A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

18. Is the coin's image virtual or real? upright or inverted?

Answer: virtual; upright