

PHYS11 CH:16 How Light Bends Reality

Mirrors, Refraction, and Lenses

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December 2025

Outline

- 1 Introduction
- 2 Reflection
- 3 Refraction
- 4 Lenses
- 5 Summary

What if you could see yourself
standing behind a solid wall?

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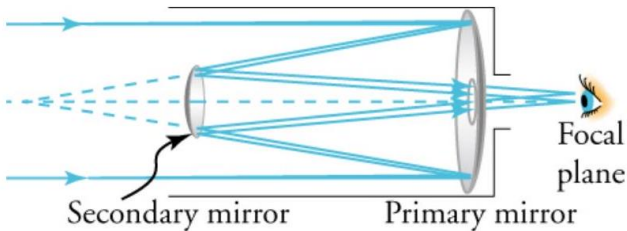
Mirrors create images where nothing exists. Your brain is fooled.

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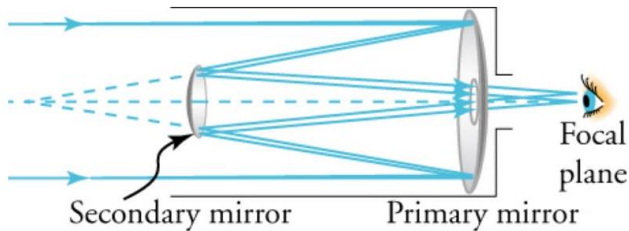
Mirrors create images where nothing exists. Your brain is fooled.

Yet cameras capture the same illusion. This is geometric optics.

Alice Through the Looking Glass

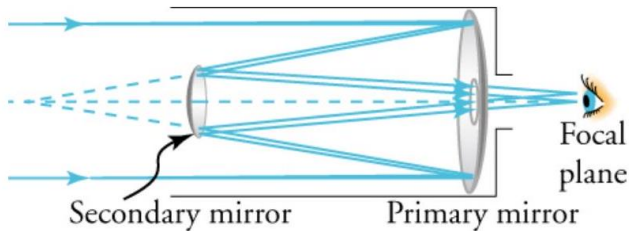


Alice Through the Looking Glass



In Lewis Carroll's story, Alice steps through a mirror into a virtual world.

Alice Through the Looking Glass



In Lewis Carroll's story, Alice steps through a mirror into a virtual world. Today we explore the optical meaning of real versus virtual.

Definition: Geometric Optics

When light interacts with objects much larger than its wavelength, it behaves like rays traveling in straight lines.

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Light as rays:

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When light interacts with objects much larger than its wavelength, it behaves like rays traveling in straight lines.

Light as rays:

- Travels in straight lines through a medium
- Changes direction at boundaries
- Predictable using geometry and trigonometry

Learning Objectives

By the end of this section, you will be able to:

- **16.1:** Explain reflection from mirrors and describe image formation

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- **16.1:** Apply ray diagrams to predict image locations
- **16.1:** Perform calculations using the law of reflection and curved mirror equations

16.1 Three Paths for Light

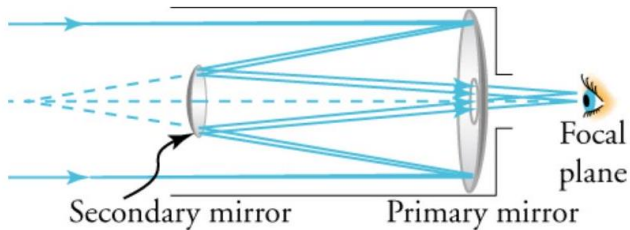


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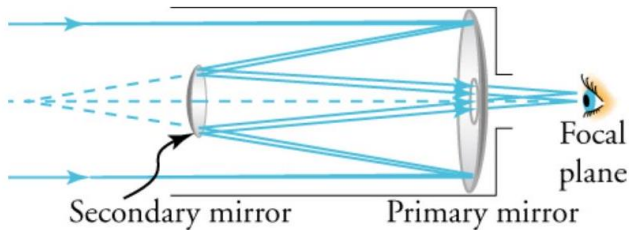


Light can travel: (a) through empty space, (b) through media, or (c) by reflection.

16.1 The Law of Reflection



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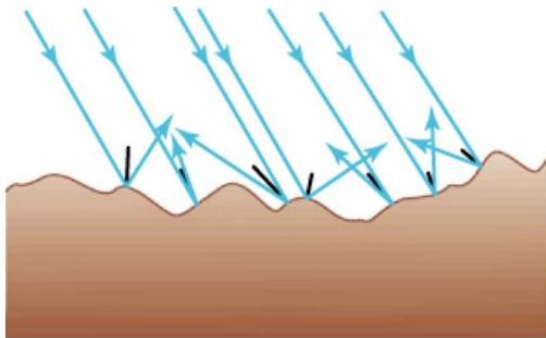


Universal Law: The Mirror's Rule

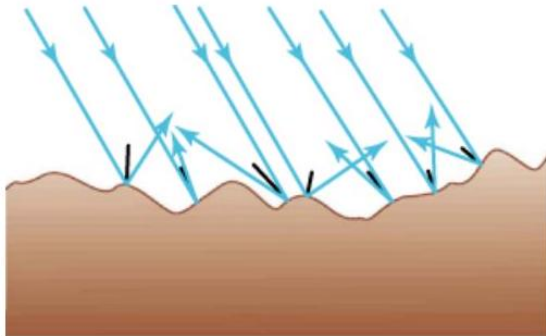
$$\theta_r = \theta_i$$

Angle of reflection equals angle of incidence.

16.1 Smooth vs Rough Surfaces

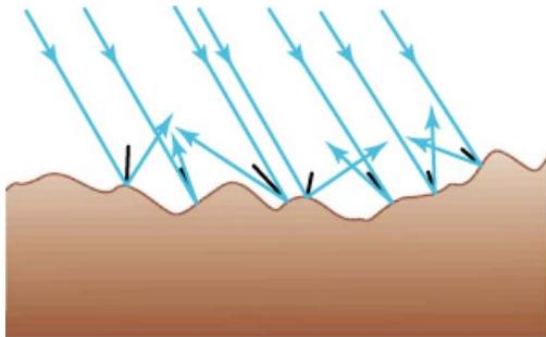


16.1 Smooth vs Rough Surfaces



Smooth surface: Specular reflection - rays reflect at same angle

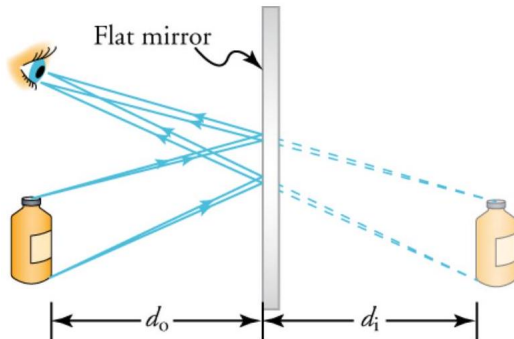
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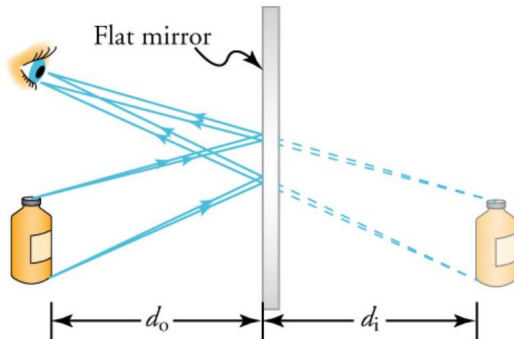
Smooth surface: Specular reflection - rays reflect at same angle

Rough surface: Diffuse reflection - rays scatter in many directions

16.1 Virtual Images in Plane Mirrors



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Definition: Virtual Image

An image formed when light rays *appear* to diverge from a point without actually doing so.

16.1 Curved Mirrors

The Mental Model

Concave: Caves inward (like a spoon bowl)

Convex: Curves outward (like a spoon back)

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The Mental Model

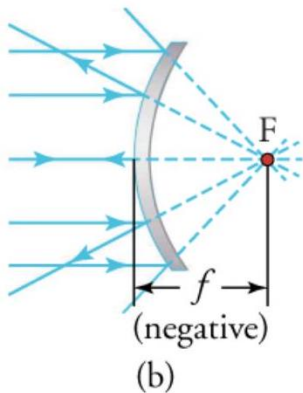
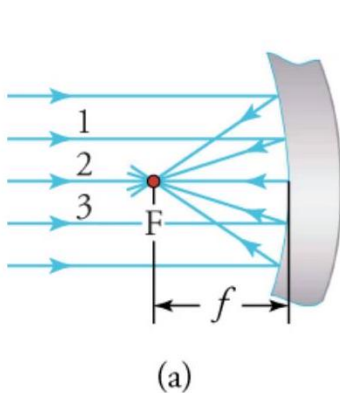
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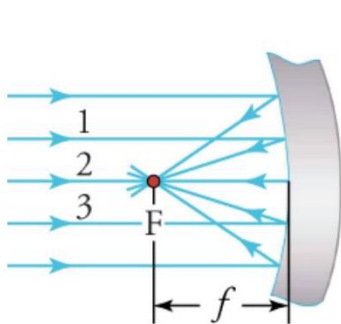
Focal point (F): Where parallel rays converge or appear to converge

Focal length (f): Distance from mirror to focal point

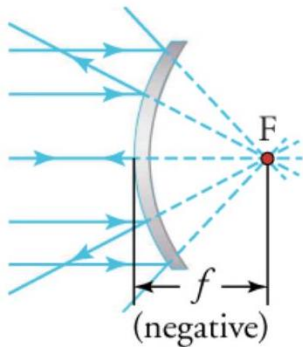
16.1 Concave vs Convex Focal Points



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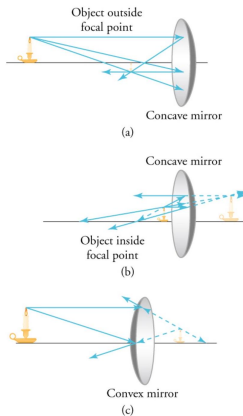
(a)



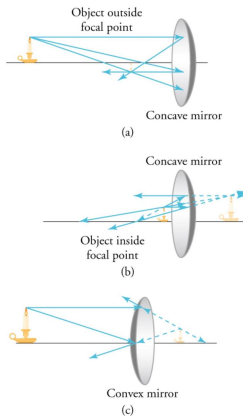
(b)

Concave: rays **converge** (f positive). Convex: rays **diverge** (f negative).

16.1 Concave Mirror Image Formation

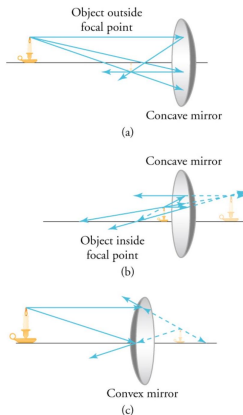


16.1 Concave Mirror Image Formation



Object beyond F: Real, inverted image

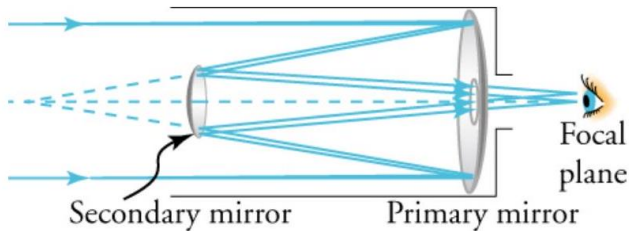
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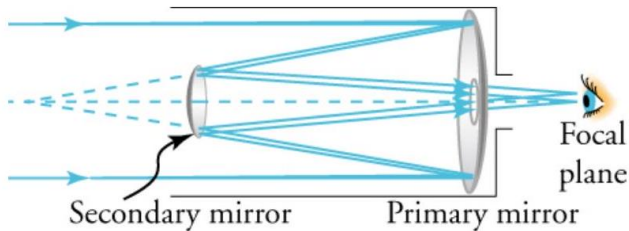
Object beyond F : Real, inverted image

Object inside F : Virtual, upright, magnified image

16.1 Applications: Car Headlights

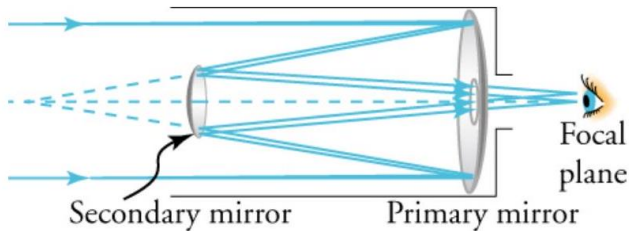


16.1 Applications: Car Headlights



Parabolic concave mirror: Bulb at focal point \rightarrow parallel rays exit

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Parabolic concave mirror: Bulb at focal point \rightarrow parallel rays exit
Same principle: spotlights, solar collectors, satellite dishes

16.1 Applications: Security Mirrors



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Convex mirrors: Create smaller, upright images \rightarrow wider field of view

16.1 Mirror Equations

Universal Laws: The Source Code

Lens/Mirror equation:

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Radius of curvature:

$$R = 2f$$

16.1 Sign Conventions

The Paradox: What Negative Means

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The Paradox: What Negative Means

- Negative $d_i \rightarrow$ virtual image
- Negative $h_i \rightarrow$ inverted image
- Concave: f positive; Convex: f negative

Key insight: Signs tell you where and how the image appears.

Attempt: Security Mirror

The Challenge (3 min, silent)

A person stands 6.0 m from a convex security mirror. The virtual image appears 1.0 m behind the mirror.

Given:

- $d_o = 6.0$ m
- $d_i = -1.0$ m (virtual)

Find: Focal length f

Can you decode the mirror's geometry? Work silently.

Compare: Mirror Strategy

Turn and talk (2 min):

- 1 Which equation did you choose? Why?
- 2 What sign did you use for d_i ? Why negative?
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Reveal: Mirror Math

Self-correct in a different color:

Equation: Lens/mirror equation

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

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Check: Negative f confirms convex mirror!

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- **16.2:** Describe the index of refraction and explain total internal reflection
- **16.2:** Perform calculations using Snell's law

16.2 The Mystery of the Bent Pencil

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Light changes direction when moving between air and water.

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Light changes direction when moving between air and water.

This is refraction - the bending of light at boundaries.

16.2 Why Light Bends

The Mental Model: Lawnmower Analogy

- Lawnmower from sidewalk to grass: right wheel slows first, mower turns

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The Mental Model: Lawnmower Analogy

- Lawnmower from sidewalk to grass: right wheel slows first, mower turns
- Light from air to glass: slows down, bends toward normal
- Light from glass to air: speeds up, bends away from normal

16.2 Index of Refraction

Nature's Speed Limit Code

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

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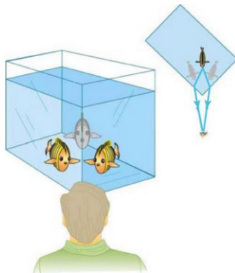
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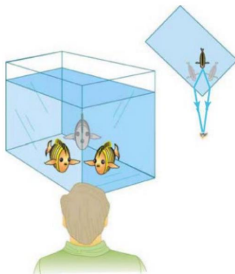
- n = index of refraction (dimensionless)
- $c = 3.00 \times 10^8$ m/s (speed of light in vacuum)
- v = speed of light in the material

Because $c > v$ always, $n \geq 1$ always.

16.2 Snell's Law



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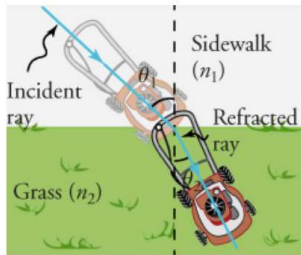


Universal Law: The Bending Rule

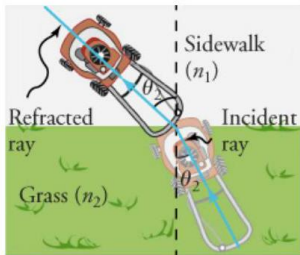
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

This predicts exactly how light bends at any boundary.

16.2 Dispersion: Rainbows

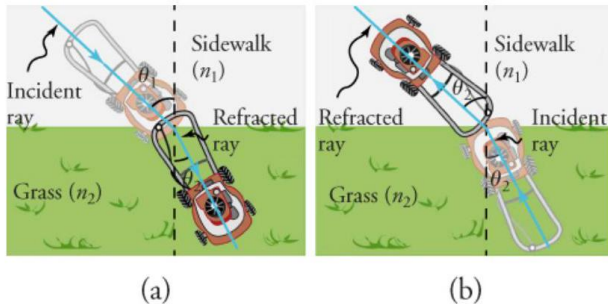


(a)



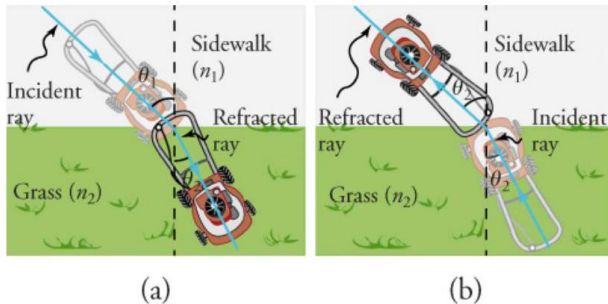
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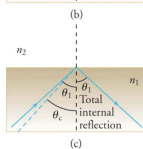
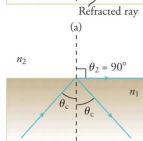
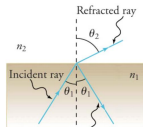
Dispersion: Index of refraction varies slightly with wavelength

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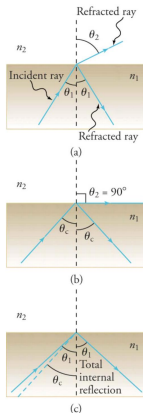


Dispersion: Index of refraction varies slightly with wavelength
White light separates into colors: red bends least, violet bends most

16.2 Total Internal Reflection



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When $\theta_1 > \theta_c$, **all** light reflects back - no refraction!

16.2 Critical Angle

The Escape Threshold

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

for $n_1 > n_2$

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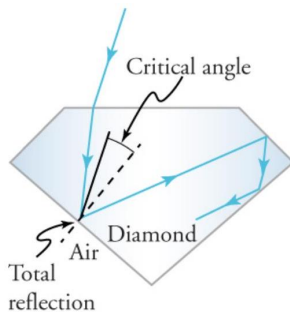
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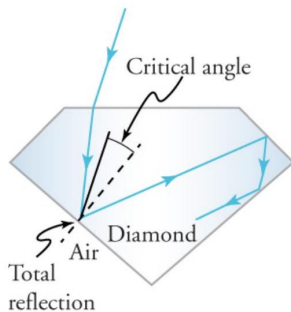
Example: Water to air

$$\theta_c = \sin^{-1}(1.00/1.33) = 48.6^\circ$$

16.2 Applications: Diamonds

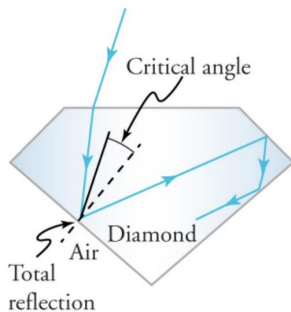


16.2 Applications: Diamonds



Diamond critical angle: only 24.4° !

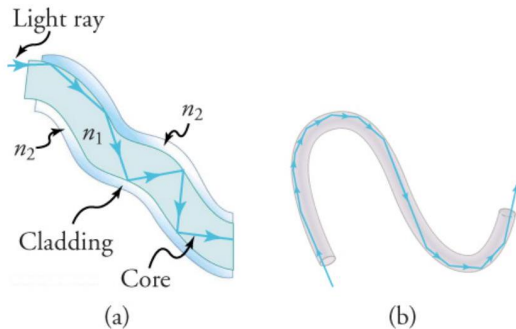
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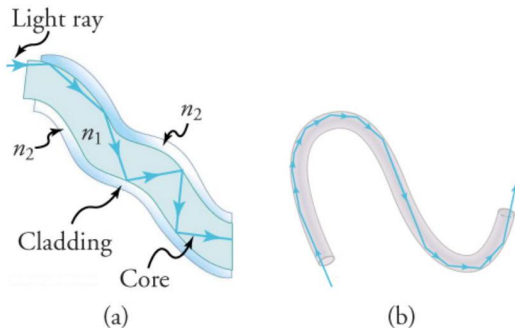
Diamond critical angle: only 24.4° !

Light enters easily but struggles to exit \rightarrow sparkle!

16.2 Applications: Fiber Optics



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Total internal reflection in thin fibers:

- Light enters at large angle
- Reflects repeatedly inside fiber
- Carries signals around corners!

Attempt: Light Bending Through Glass

The Challenge (3 min, silent)

Light enters glass ($n = 1.50$) from air ($n = 1.00$) at 45.0° to the normal.

Given:

- $n_1 = 1.00$ (air)
- $n_2 = 1.50$ (glass)
- $\theta_1 = 45.0^\circ$

Find: Angle of refraction θ_2

Can you predict the bend? Work silently.

Compare: Refraction Strategy

Turn and talk (2 min):

- 1 Which law did you use?
- 2 How did you rearrange for θ_2 ?
- 3 Did you use arcsine? Why?

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Reveal: Snell's Law Solution

Self-correct in a different color:

Snell's Law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

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

Substitute: $\sin \theta_2 = \frac{(1.00)(\sin 45.0^\circ)}{1.50} = \frac{0.707}{1.50}$

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$$\theta_2 = \sin^{-1}(0.471) = 28.1^\circ$$

Check: Light bends toward normal entering denser medium!

Learning Objectives

By the end of this section, you will be able to:

- **16.3:** Describe image formation by convex and concave lenses

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- **16.3:** Describe image formation by convex and concave lenses
- **16.3:** Explain how the human eye works using geometric optics
- **16.3:** Perform calculations using the thin-lens equation

16.3 The Power to Focus Sunlight

What if you could concentrate sunlight
to ignite paper?

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A converging lens bends all parallel rays to one focal point.

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Enough concentrated light energy = fire!

16.3 Converging vs Diverging Lenses



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Convex (converging): Parallel rays converge to focal point (f positive)

16.3 Converging vs Diverging Lenses



Convex (converging): Parallel rays converge to focal point (f positive)
Concave (diverging): Parallel rays diverge from focal point (f negative)

16.3 Lens Power

The Focusing Strength

$$P = \frac{1}{f}$$

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Where:

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The Focusing Strength

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Where:

- P = power in diopters (D) or m^{-1}
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Shorter focal length = stronger lens = higher power

16.3 Ray Tracing Rules for Lenses

Converging lens:

- 1 Ray parallel to axis \rightarrow passes through far focal point

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- 2 Ray through center \rightarrow continues straight
- 3 Ray through near focal point \rightarrow exits parallel to axis

Diverging lens:

- 1 Ray parallel to axis \rightarrow appears from near focal point

16.3 Ray Tracing Rules for Lenses

Converging lens:

- 1 Ray parallel to axis \rightarrow passes through far focal point
- 2 Ray through center \rightarrow continues straight
- 3 Ray through near focal point \rightarrow exits parallel to axis

Diverging lens:

- 1 Ray parallel to axis \rightarrow appears from near focal point
- 2 Ray through center \rightarrow continues straight

16.3 Ray Tracing Rules for Lenses

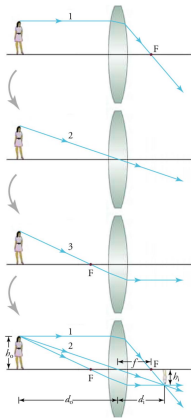
Converging lens:

- 1 Ray parallel to axis \rightarrow passes through far focal point
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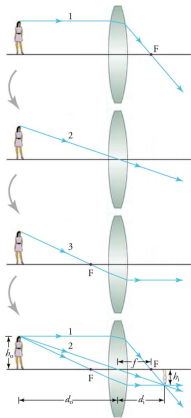
Diverging lens:

- 1 Ray parallel to axis \rightarrow appears from near focal point
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- 3 Ray toward far focal point \rightarrow exits parallel to axis

16.3 Converging Lens Image Formation

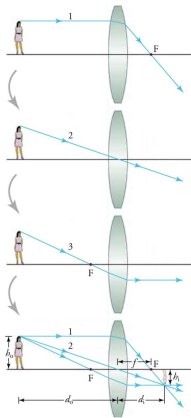


16.3 Converging Lens Image Formation



Object beyond f : Real, inverted image on far side

16.3 Converging Lens Image Formation



Object beyond f : Real, inverted image on far side

Object inside f : Virtual, upright, magnified image on near side

16.3 Thin Lens Equation

Same Equation as Mirrors

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

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

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$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

16.3 Thin Lens Equation

Same Equation as Mirrors

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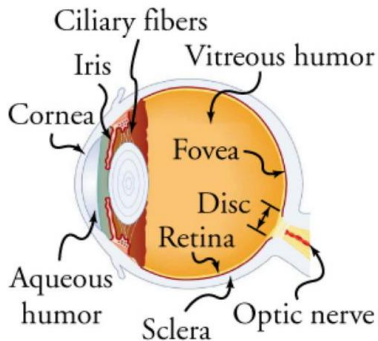
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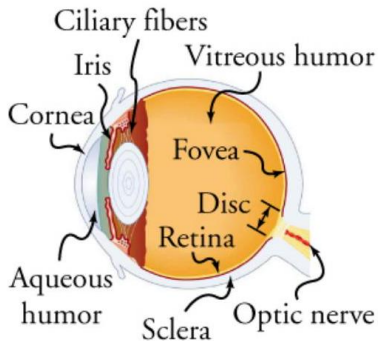
Sign conventions:

- Converging lens: f positive; Diverging lens: f negative
- Negative $d_i \rightarrow$ virtual image
- Negative $m \rightarrow$ inverted image

16.3 The Human Eye

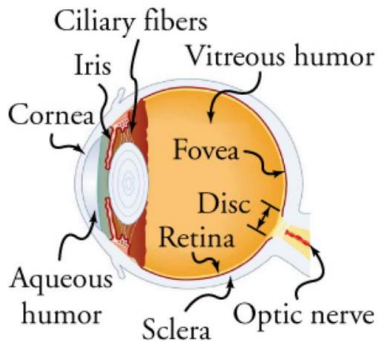


16.3 The Human Eye



Cornea and lens: Form real image on retina

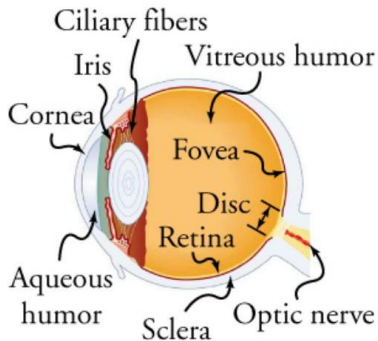
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Cornea and lens: Form real image on retina

Ciliary muscles: Change lens shape to adjust focal length

16.3 The Human Eye

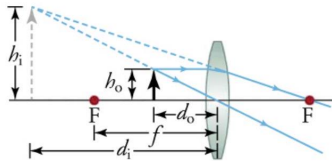


Cornea and lens: Form real image on retina

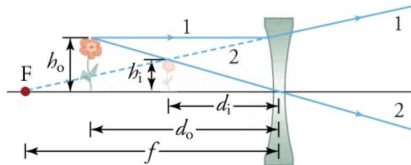
Ciliary muscles: Change lens shape to adjust focal length

Eye adjusts power to keep image distance constant for all object distances!

16.3 Vision Defects

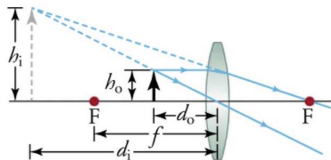


(a)

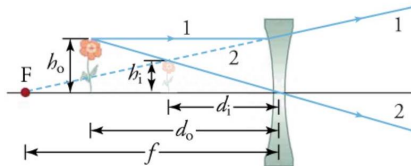


(b)

16.3 Vision Defects



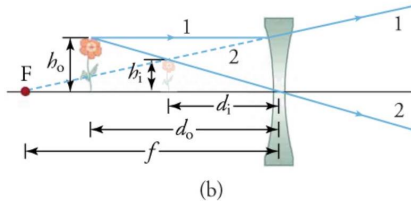
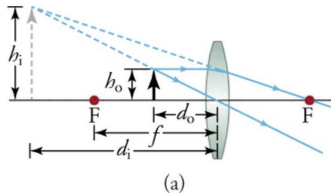
(a)



(b)

Nearsighted (myopia): Eye too strong, image forms in front of retina

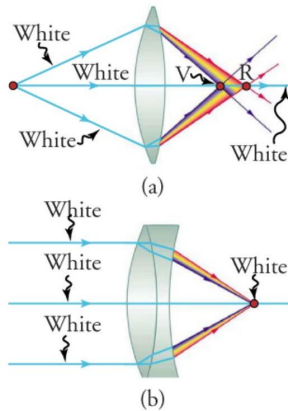
16.3 Vision Defects



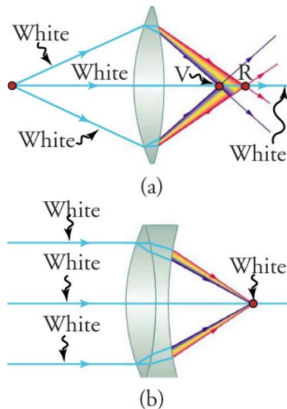
Nearsighted (myopia): Eye too strong, image forms in front of retina

Farsighted (hyperopia): Eye too weak, image forms behind retina

16.3 Correcting Vision Defects

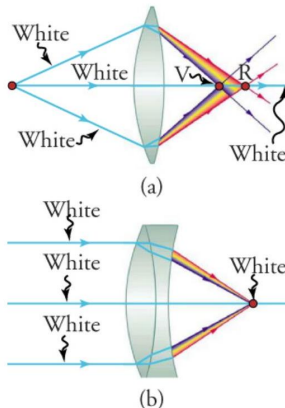


16.3 Correcting Vision Defects



Nearsighted: Diverging lens (concave) reduces power

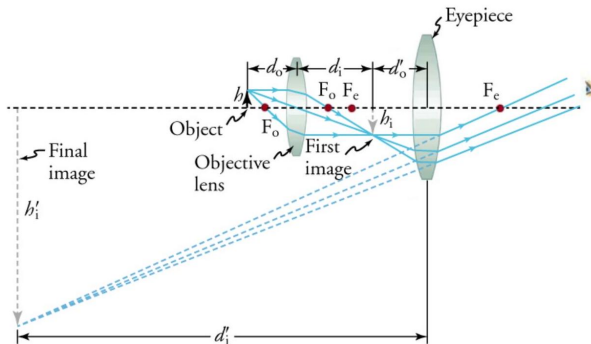
16.3 Correcting Vision Defects



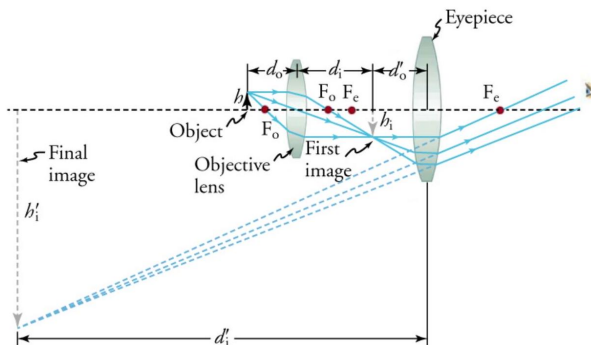
Nearsighted: Diverging lens (concave) reduces power

Farsighted: Converging lens (convex) increases power

16.3 Applications: Microscope



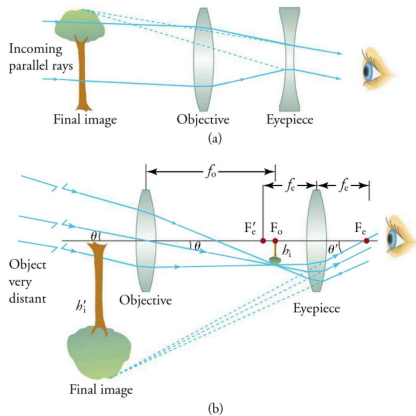
16.3 Applications: Microscope



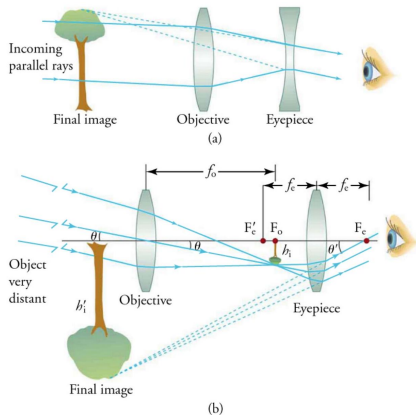
Two converging lenses:

- Objective: Creates magnified real image
- Eyepiece: Further magnifies that image

16.3 Applications: Telescope

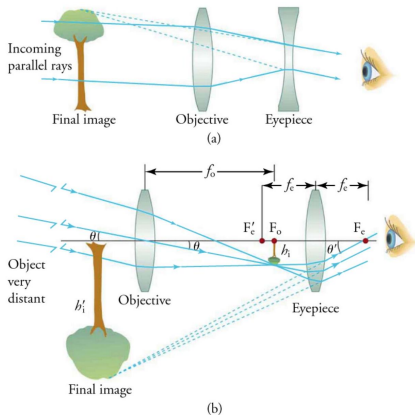


16.3 Applications: Telescope



Galileo design: Convex objective + concave eyepiece = upright image

16.3 Applications: Telescope



Galileo design: Convex objective + concave eyepiece = upright image

Astronomical: Two convex lenses = inverted image (doesn't matter for stars!)

Attempt: Magnifying Glass Power

The Challenge (3 min, silent)

A magnifying glass focuses sunlight to a bright spot 8.00 cm from the lens.

Given:

- $f = 8.00 \text{ cm} = 0.0800 \text{ m}$

Find: Power P in diopters

Can you calculate the lens strength? Work silently.

Compare: Power Strategy

Turn and talk (2 min):

- 1 Which equation relates power and focal length?
- 2 What units did you use for focal length?
- 3 Did you convert centimeters to meters?

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Name wheel: One pair share your approach (not your answer).

Reveal: Lens Power

Self-correct in a different color:

Given: $f = 8.00$ cm

Reveal: Lens Power

Self-correct in a different color:

Given: $f = 8.00$ cm

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Power equation: $P = \frac{1}{f}$

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$P = 12.5 \text{ D}$

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$$P = \frac{1}{0.0800 \text{ m}}$$

$$P = 12.5 \text{ D}$$

Check: This is a relatively powerful lens!

What You Now Know

The Revelations

- 1 Law of Reflection: $\theta_r = \theta_i$ (mirrors create virtual images)

What You Now Know

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- 5 Lenses use refraction to converge or diverge rays
- 6 Your eye is a variable-power converging lens
- 7 Same equations govern mirrors and lenses

Key Equations

Law of Reflection: $\theta_r = \theta_i$ (1)

Index of refraction: $n = \frac{c}{v}$ (2)

Snell's Law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$ (3)

Critical angle: $\theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right)$ (4)

Lens/Mirror: $\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$ (5)

Magnification: $m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$ (6)

Lens power: $P = \frac{1}{f}$ (7)

Complete the assigned problems
posted on the LMS