PHYS11 CH:16 How Light Bends Reality

Mirrors, Refraction, and Lenses

Mr. Gullo

December 2025

Outline

The Illusion

What if you could see yourself

standing behind a solid wall?

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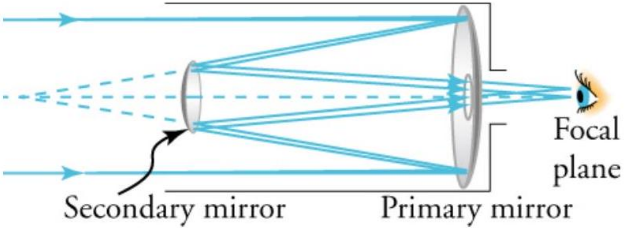
Mirrors create images where nothing exists. Your brain is fooled.

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

Alice Through the Looking Glass



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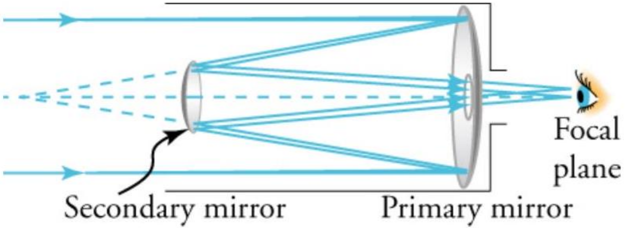

In Lewis Carroll's story, Alice steps through a mirror into a virtual world.

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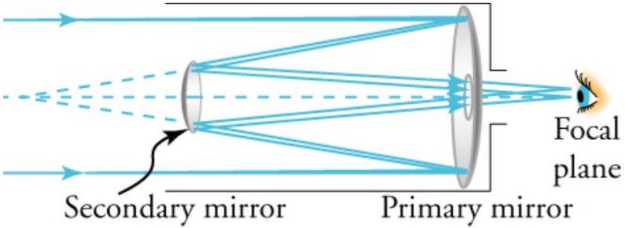

In Lewis Carroll's story, Alice steps through a mirror into a virtual world. Today we explore the optical meaning of real versus virtual.

Geometric Optics

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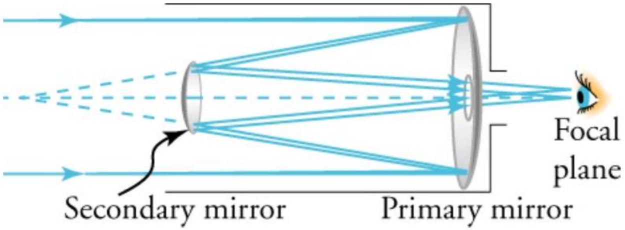
- **16.1:** Apply ray diagrams to predict image locations
- **16.1:** Perform calculations using the law of reflection and curved mirror equations

16.1 Three Paths for Light

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

16.1 The Law of Reflection



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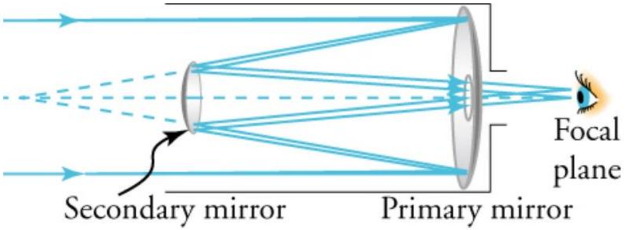
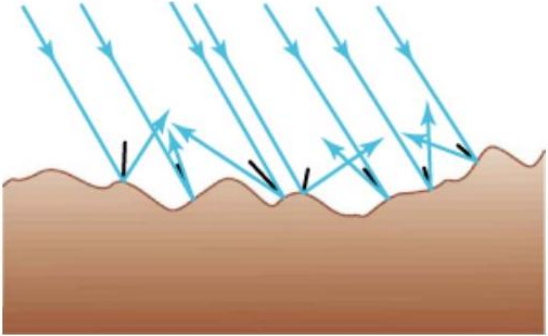


Universal Law: The Mirror's Rule

$$\boxed{\theta_r = \theta_i}$$

Angle of reflection equals angle of incidence.

16.1 Smooth vs Rough Surfaces



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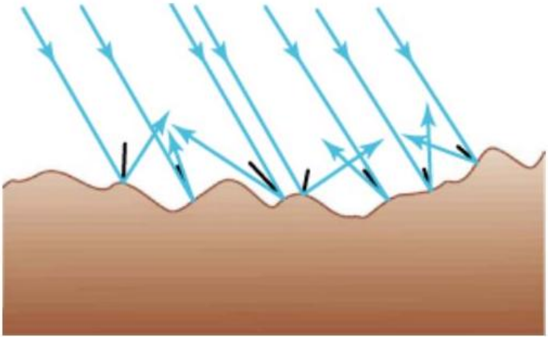

Smooth surface: Specular reflection - rays reflect at same angle

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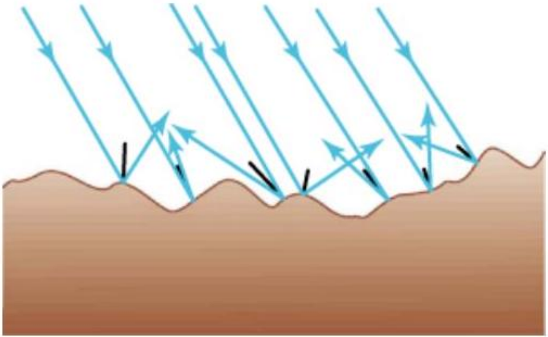
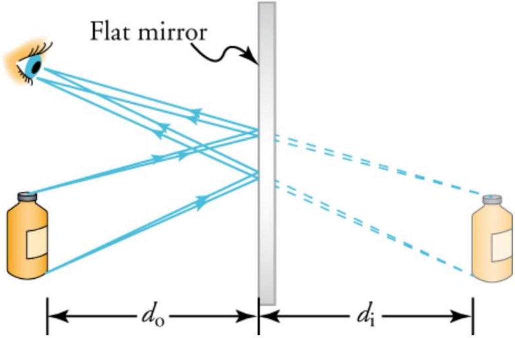


Smooth surface: Specular reflection - rays reflect at same angle
Rough surface: Diffuse reflection - rays scatter in many directions

16.1 Virtual Images in Plane Mirrors



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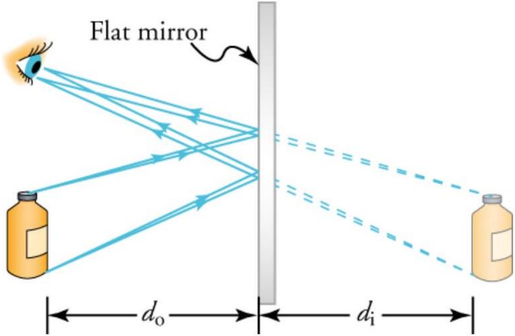


Definition: Virtual Image

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

The Mental Model

Concave: Caves inward (like a spoon bowl)
Convex: Curves outward (like a spoon back)

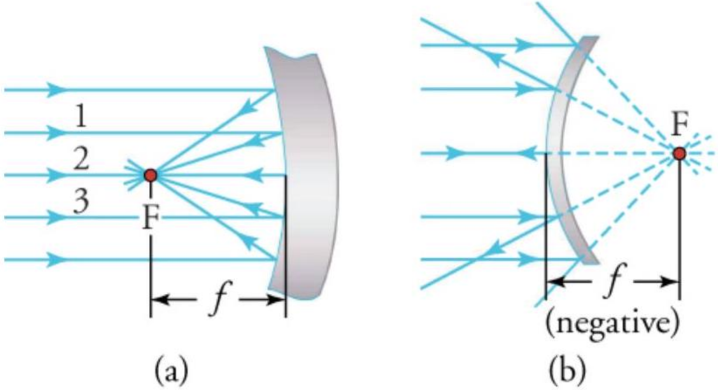
16.1 Curved Mirrors

The Mental Model

Concave: Caves inward (like a spoon bowl)
Convex: Curves outward (like a spoon back)

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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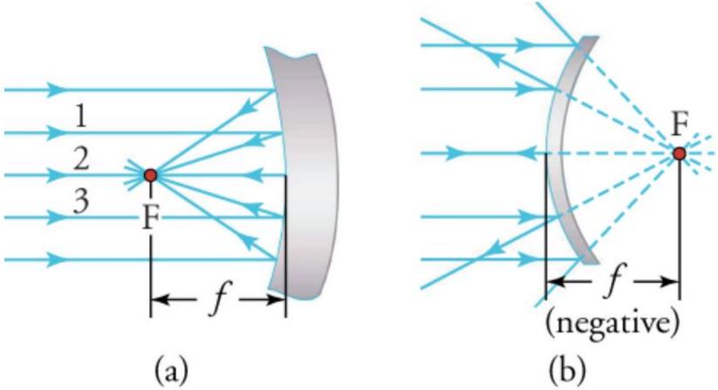
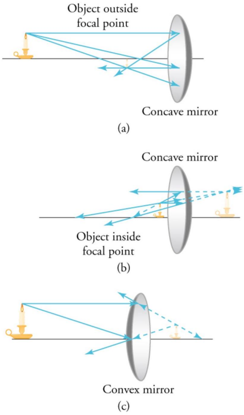


Concave: rays **converge** (f positive). Convex: rays **diverge** (f negative).

16.1 Concave Mirror Image Formation



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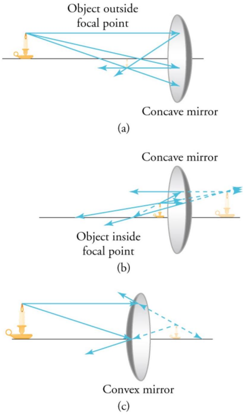

Object beyond F: Real, inverted image

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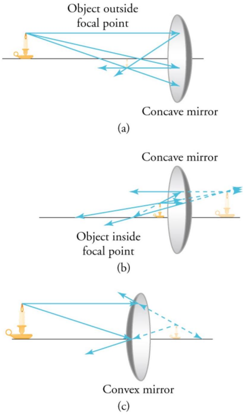
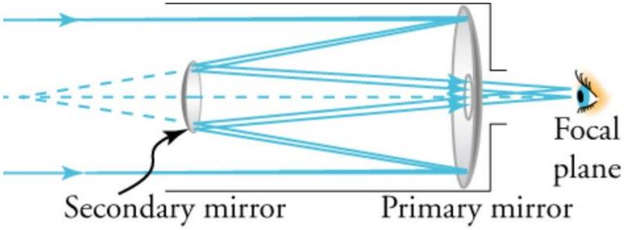


Object beyond F: Real, inverted image
Object inside F: Virtual, upright, magnified image

16.1 Applications: Car Headlights



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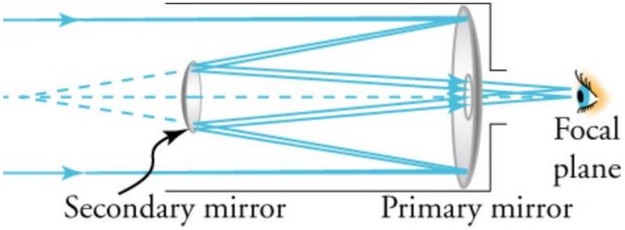

Parabolic concave mirror: Bulb at focal point → parallel rays exit

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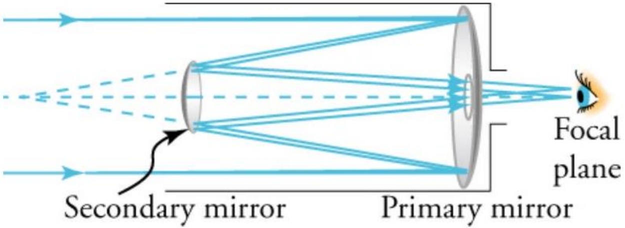

Parabolic concave mirror: Bulb at focal point → parallel rays exit
Same principle: spotlights, solar collectors, satellite dishes

16.1 Applications: Security Mirrors

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:

$$R = 2f$$

The Paradox: What Negative Means

- Negative $d_i \rightarrow$ virtual image

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16.1 Sign Conventions

The Paradox: What Negative Means

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- Concave: f positive; Convex: f negative

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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?
3. How did you rearrange to solve for f?

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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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Substitute: $d_i = -1.0$ m, $d_o = 6.0$ m

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Check: Negative f confirms convex mirror!

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- **16.2:** Explain refraction at media boundaries and predict light paths

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

Why does a pencil appear broken
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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.

The Mental Model: Lawnmower Analogy

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

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16.2 Why Light Bends

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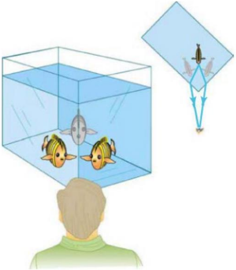
- $c = 3.00 \times 10^8$ m/s (speed of light in vacuum)
- $v =$ speed of light in the material

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

16.2 Snell's Law



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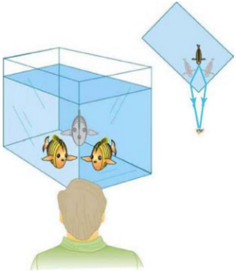
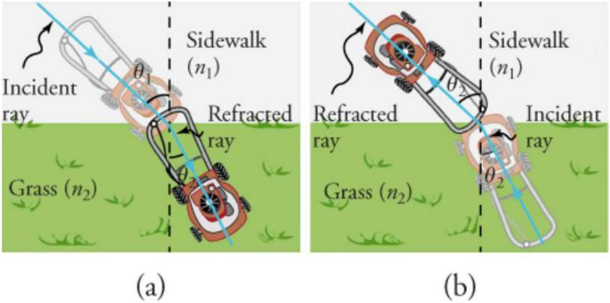


Universal Law: The Bending Rule

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

This predicts exactly how light bends at any boundary.

16.2 Dispersion: Rainbows



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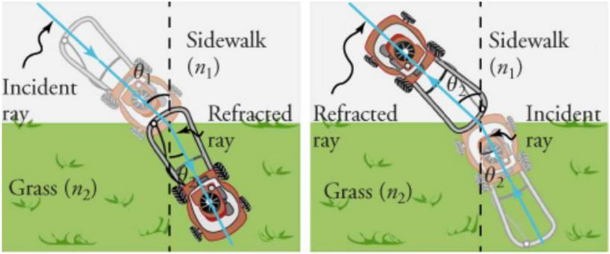

(a) (b)

Dispersion: Index of refraction varies slightly with wavelength

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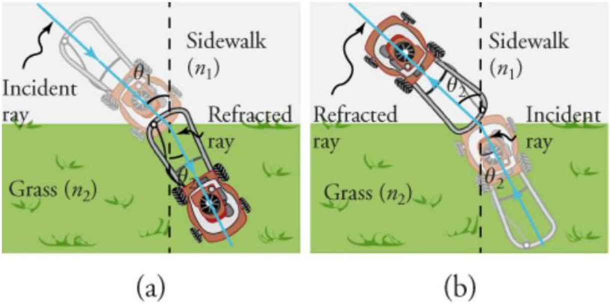
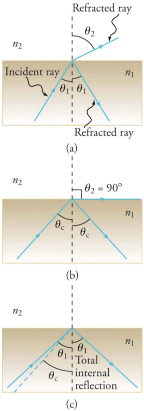


Dispersion: Index of refraction varies slightly with wavelength
White light separates into colors: red bends least, violet bends most

16.2 Total Internal Reflection



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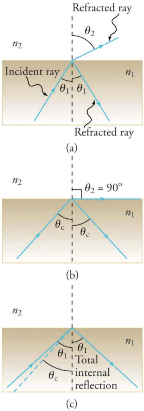

When $\theta_1 > \theta_c$, **all** light reflects back - no refraction!

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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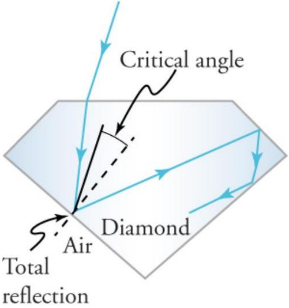
Example: Water to air
$\theta_c = \sin^{-1}(1.00/1.33) = 48.6$

16.2 Applications: Diamonds



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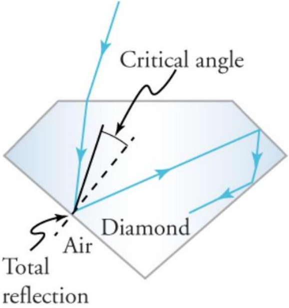

Diamond critical angle: only 24.4!

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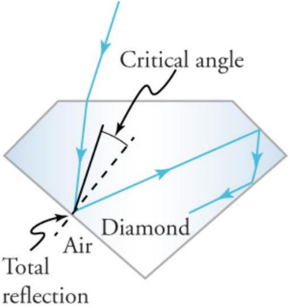
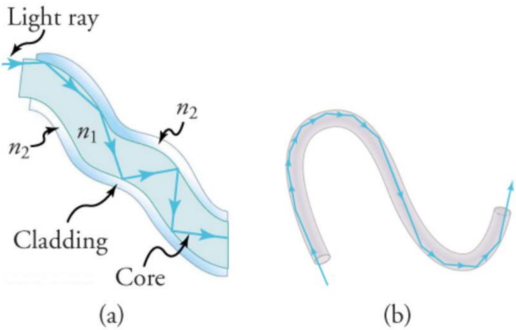


Diamond critical angle: only 24.4!

Light enters easily but struggles to exit → sparkle!

16.2 Applications: Fiber Optics



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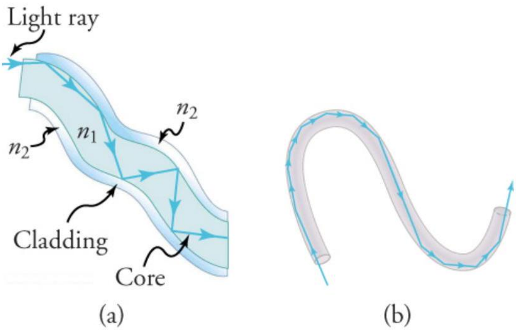

Total internal reflection in thin fibers:

- 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)
- $\theta_1 = 45.0$

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

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

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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:** Explain how the human eye works using geometric optics
- **16.3:** Perform calculations using the thin-lens equation

What if you could concentrate sunlight
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A converging lens bends all parallel rays to one focal point.

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

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

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

Where:

- P = power in diopters (D) or m^{-1}
- f = focal length in meters

Shorter focal length = stronger lens = higher power

Converging lens:

1. Ray parallel to axis $\rightarrow$ passes through far 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

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

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

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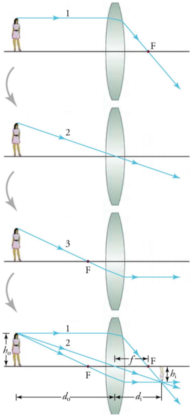
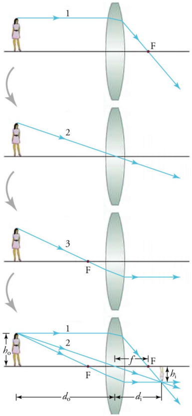
3. Ray toward far focal point $\rightarrow$ exits parallel to axis

16.3 Converging Lens Image Formation

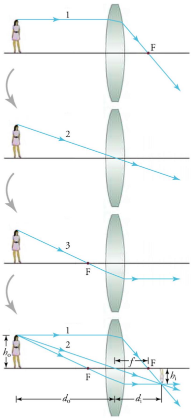


16.3 Converging Lens Image Formation



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

Same Equation as Mirrors

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

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

Magnification:

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

16.3 Thin Lens Equation

Same Equation as Mirrors

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

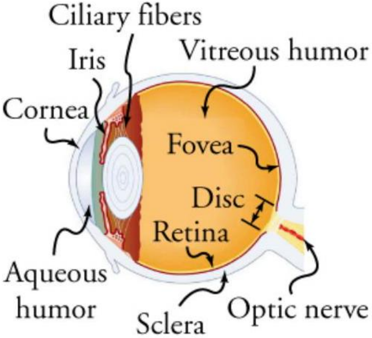
Magnification:

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

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



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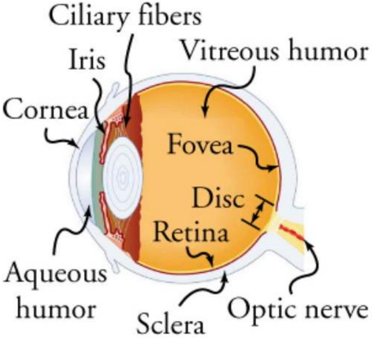

Cornea and lens: Form real image on retina

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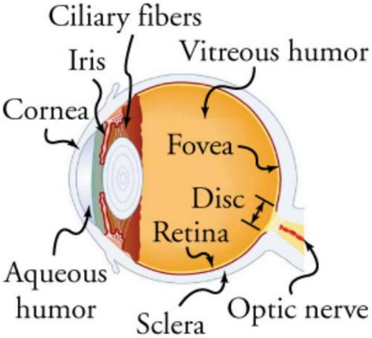
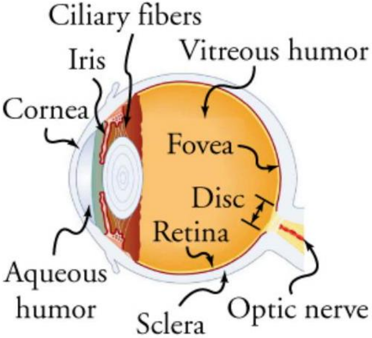


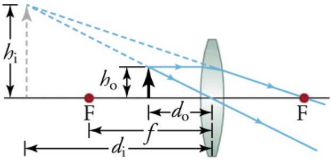
Cornea and lens: Form real image on retina
Ciliary muscles: Change lens shape to adjust focal length

16.3 The Human Eye

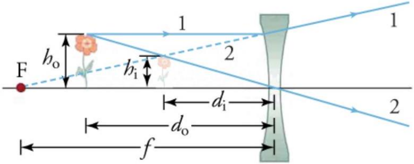


Cornea and lens: Form real image on retina
Ciliary muscles: Change lens shape to adjust focal length
Eye adjusts power to keep image distance constant for all object distances!

16.3 Vision Defects

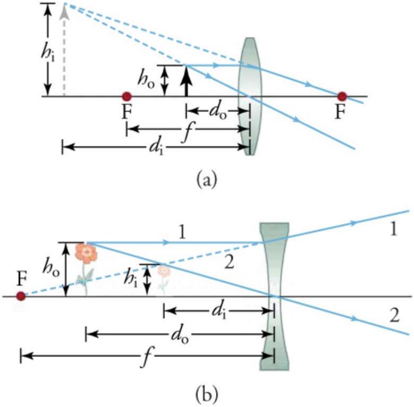


(a)

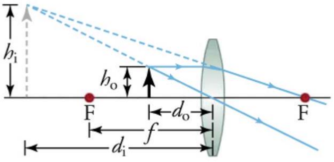


(b)

16.3 Vision Defects



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



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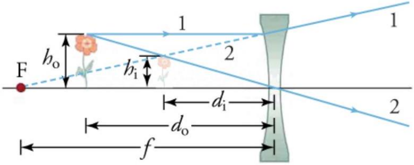
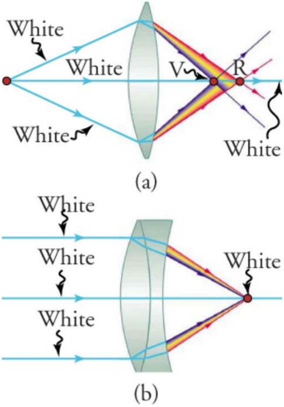
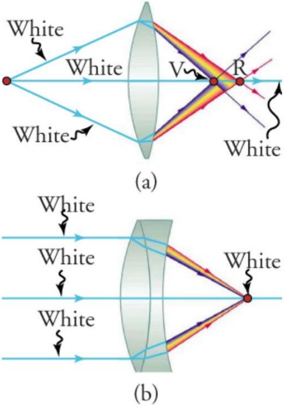


(b)

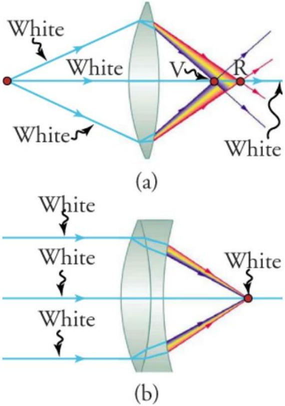
Nearsighted (myopia): Eye too strong, image forms in front of retina
Farsighted (hyperopia): Eye too weak, image forms behind retina

16.3 Correcting Vision Defects



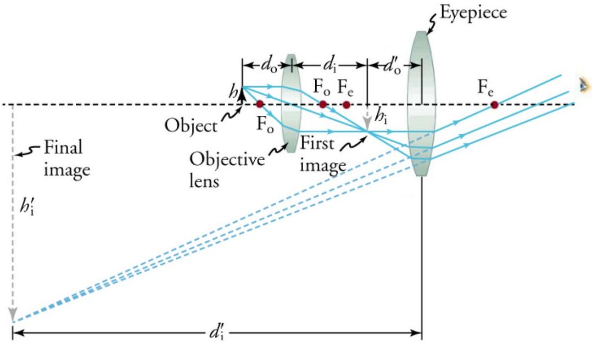


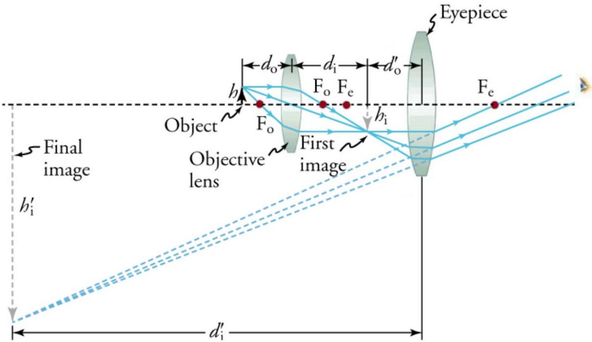
Nearsighted: Diverging lens (concave) reduces power



Nearsighted: Diverging lens (concave) reduces power
Farsighted: Converging lens (convex) increases power

16.3 Applications: Microscope

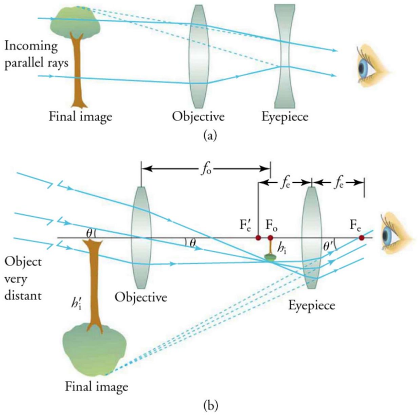




Two converging lenses:

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

16.3 Applications: Telescope



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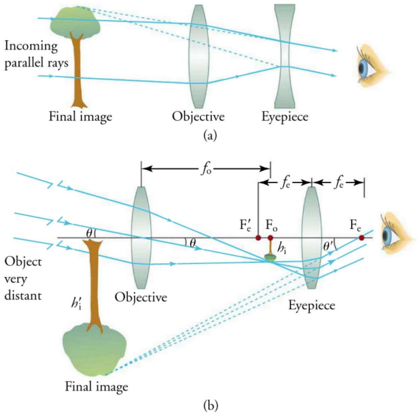

Galileo design: Convex objective + concave eyepiece = upright image

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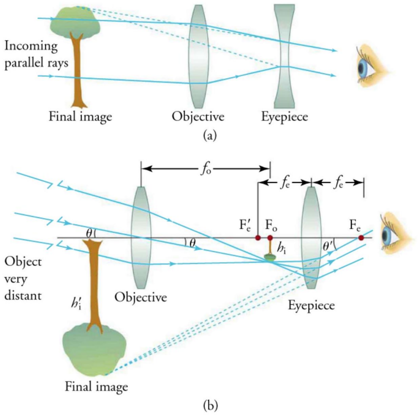

Galileo design: Convex objective + concave eyepiece = upright image
Astronomical: Two convex lenses = inverted image (doesn't matter for stars!)

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

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

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

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Check: This is a relatively powerful lens!

What You Now Know

The Revelations

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4. Total internal reflection traps light (fiber optics, diamonds)
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

$$\text{Law of Reflection:} \quad \theta_r = \theta_i \tag{1}$$

$$\text{Index of refraction:} \quad n = \frac{c}{v} \tag{2}$$

$$\text{Snell's Law:} \quad n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{3}$$

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

$$\text{Lens/Mirror:} \quad \frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o} \tag{5}$$

$$\text{Magnification:} \quad m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{6}$$

$$\text{Lens power:} \quad P = \frac{1}{f} \tag{7}$$

Homework

Complete the assigned problems

posted on the LMS