PHYS11 CH:16 How Light Bends Reality

Mirrors, Refraction, and Lenses

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December 2025

Outline

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

The Illusion

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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

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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.

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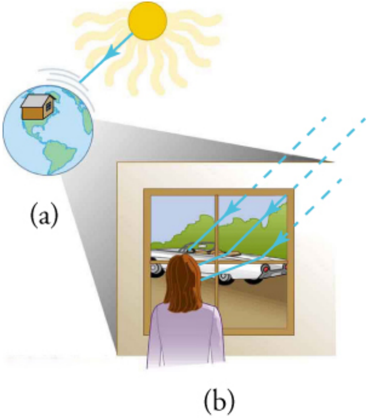
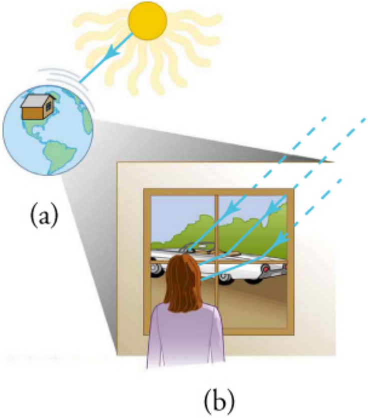
- **16.1:** Apply ray diagrams to predict image locations
- **16.1:** Perform calculations using the law of reflection and curved mirror equations

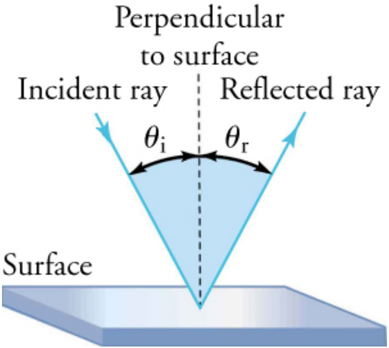

(a)
(b)

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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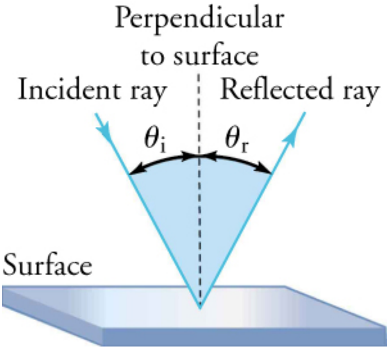
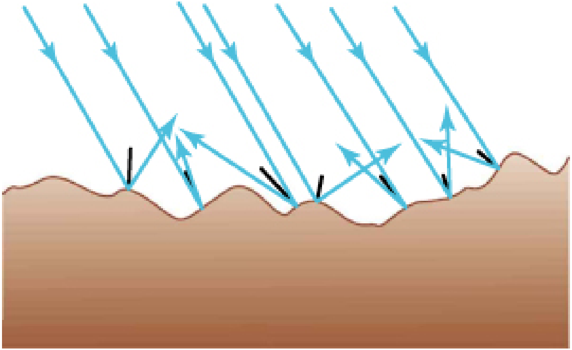


Universal Law: The Mirror's Rule

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

$\angle$*Angleofreflectionequals*$\angle$*angleofincidence*.

16.1 Smooth vs Rough Surfaces



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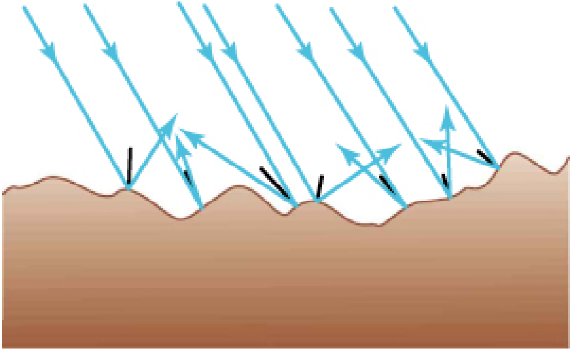

Smooth surface: Specular reflection - rays reflect at same angle

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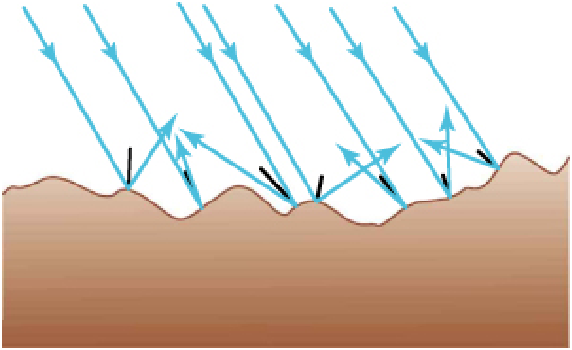
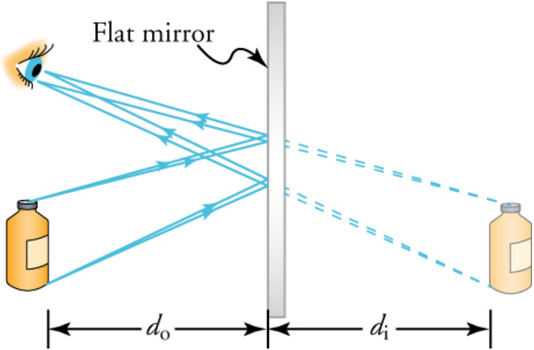
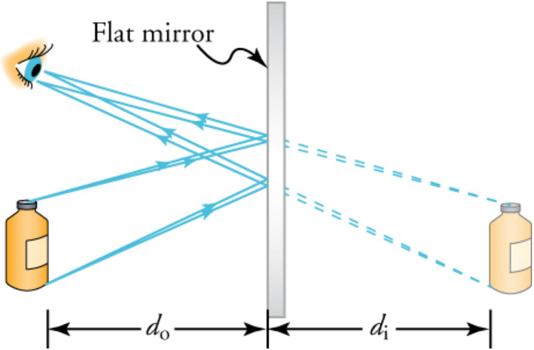


Smooth surface: Specular reflection - rays reflect at same angle
Rough surface: Diffuse reflection - rays scatter in many directions


Flat mirror
d_o
d_i

16.1 Virtual Images in Plane Mirrors



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)

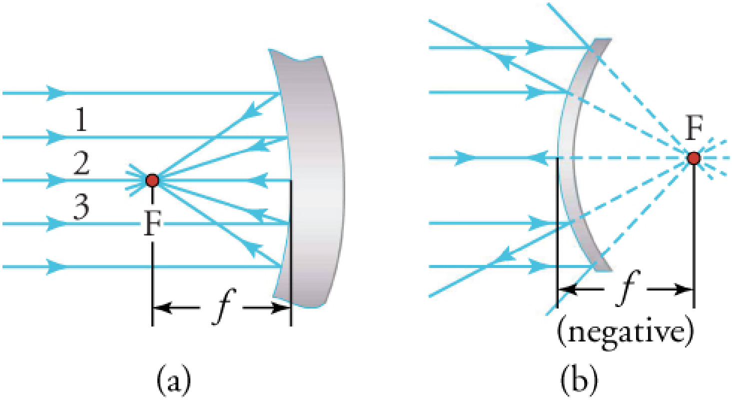
16.1 Curved Mirrors

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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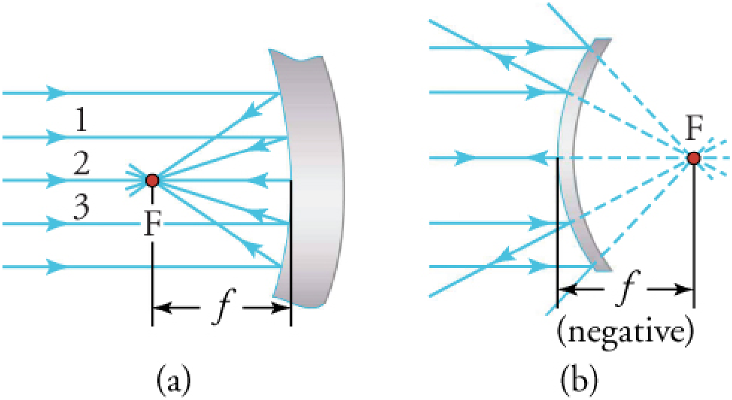
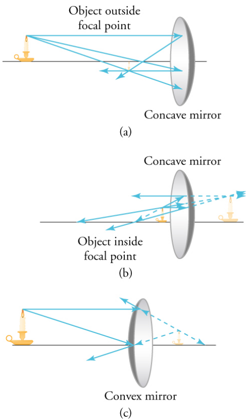


Concave: rays **converge** (f positive). Convex: rays **diverge** (f negative).

16.1 Concave Mirror Image Formation



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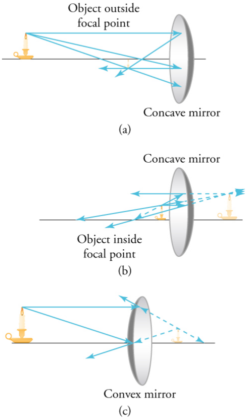

Object beyond F: Real, inverted image

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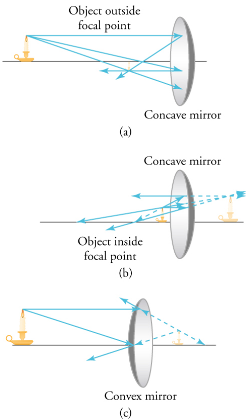
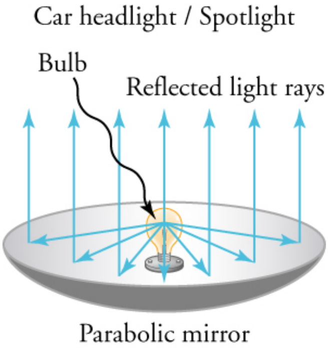


Object beyond F: Real, inverted image
Object inside F: Virtual, upright, magnified image

16.1 Applications: Car Headlights



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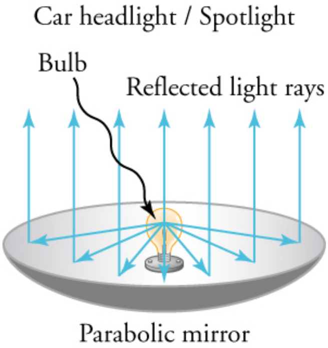

Parabolic concave mirror: Bulb at focal point $\rightarrow$ parallel rays exit

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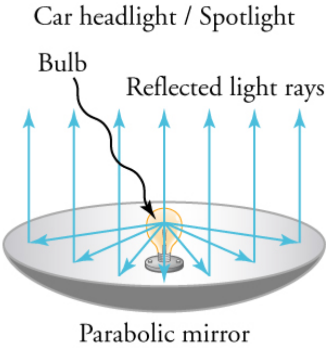

Parabolic concave mirror: Bulb at focal point $\rightarrow$ parallel rays exit
Same principle: spotlights, solar collectors, satellite dishes

16.1 Applications: Security Mirrors

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

Universal Laws: The Source Code

Lens/Mirror equation:

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

16.1 Mirror Equations

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Radius of curvature:

$$R = 2f$$

The Paradox: What Negative Means

- Negative $d_i \rightarrow$ virtual image

16.1 Sign Conventions

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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?
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!

Learning Objectives

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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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when placed in water?

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

16.2 Why Light Bends

The Mental Model: Lawnmower Analogy

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- Light from air to glass: slows down, bends toward normal

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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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Where:

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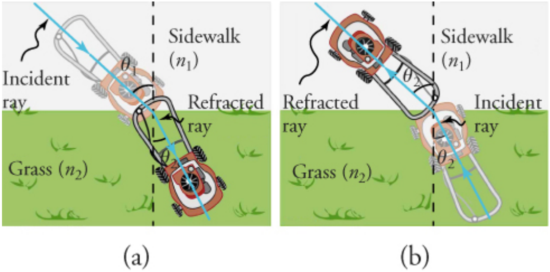
$$n = \frac{c}{v}$$

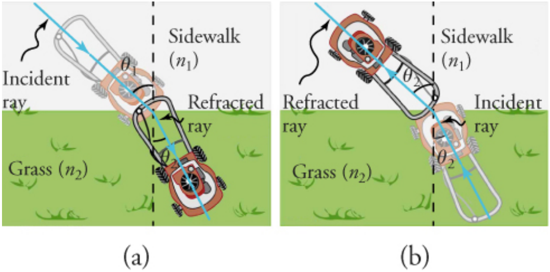
Where:

- 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



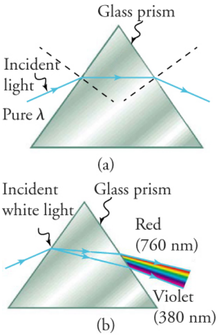


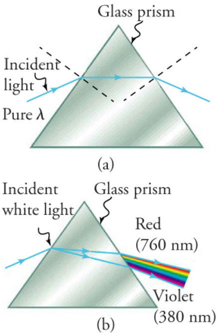
Universal Law: The Bending Rule

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

This predicts exactly how light bends at any boundary.

16.2 Dispersion: Rainbows





Dispersion: Index of refraction varies slightly with wavelength

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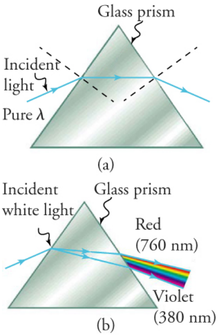
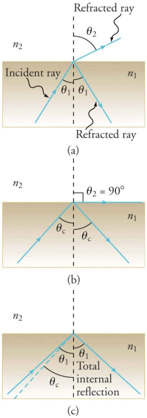


Dispersion: Index of refraction varies slightly with wavelength
White light separates into colors: red bends least, violet bends most

16.2 Total Internal Reflection



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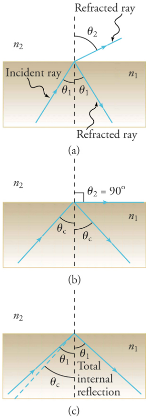


When $\angle\theta_1 > \angle\theta_c$, **all** light reflects back - no refraction!

The Escape Threshold

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

for $n_1 > n_2$

16.2 Critical Angle

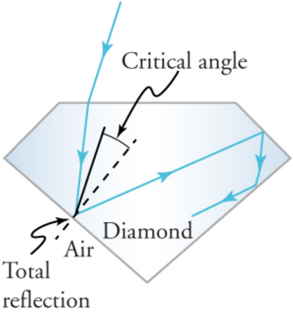
The Escape Threshold

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

for $n_1 > n_2$

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

16.2 Applications: Diamonds



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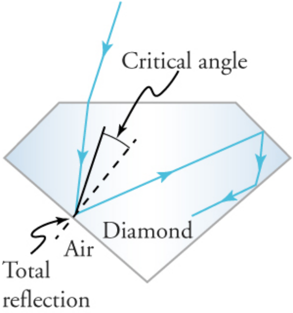
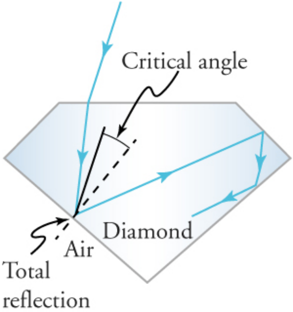
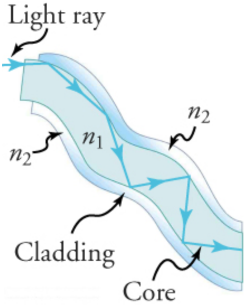


Diamond critical angle: only 24.4°!



Diamond critical angle: only 24.4°!
Light enters easily but struggles to exit $\rightarrow$ sparkle!

16.2 Applications: Fiber Optics



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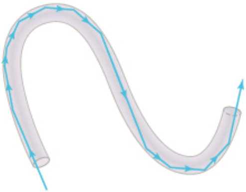

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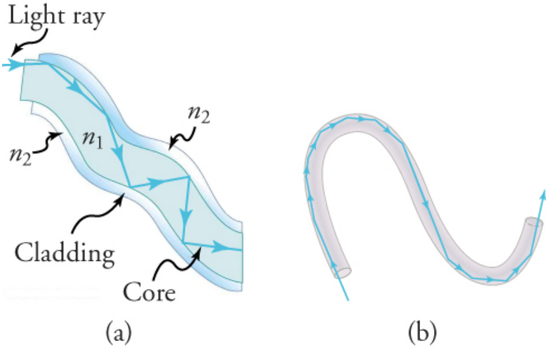

Total internal reflection in thin fibers:

- 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)
- $\angle\theta_1 = 45.0^\circ$

Find: $\angle Angle of refraction \angle\theta_2$

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 $\angle\theta_2$?
3. Did you use arcsine? Why?

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Reveal: Snell's Law Solution

Self-correct in a different color:

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

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

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

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

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

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

What if you could concentrate sunlight

to ignite paper?

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to ignite paper?

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

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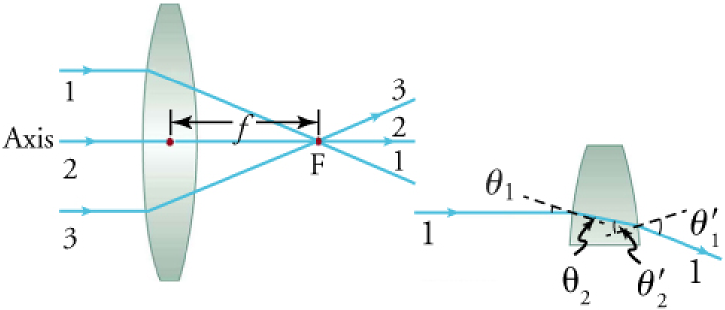
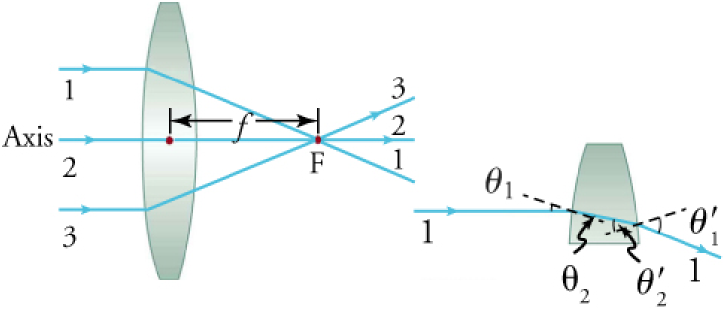
A converging lens bends all parallel rays to one focal point.

Enough concentrated light energy = fire!

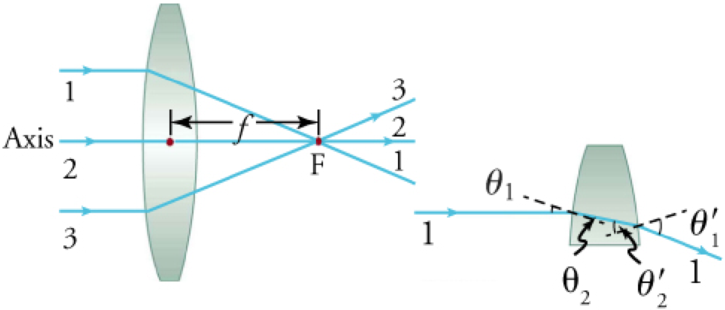
16.3 Converging vs Diverging Lenses





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:

- P = power in diopters (D) or m^{-1}

16.3 Lens Power

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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

16.3 Ray Tracing Rules for Lenses

Converging lens:

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

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 → passes through far focal point
2. Ray through center → continues straight
3. Ray through near focal point → exits parallel to axis

16.3 Ray Tracing Rules for Lenses

Converging lens:

1. Ray parallel to axis $\rightarrow$ passes through far focal point
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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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Converging lens:

1. Ray parallel to axis → passes through far focal point
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3. Ray through near focal point → exits parallel to axis

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1. Ray parallel to axis → appears from near focal point
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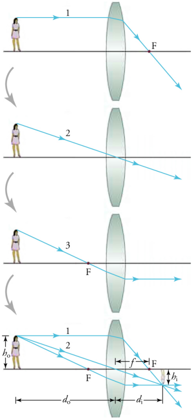
Converging lens:

1. Ray parallel to axis → passes through far focal point
2. Ray through center → continues straight
3. Ray through near focal point → exits parallel to axis

Diverging lens:

1. Ray parallel to axis → appears from near focal point
2. Ray through center → continues straight
3. Ray toward far focal point → exits parallel to axis

16.3 Converging Lens Image Formation



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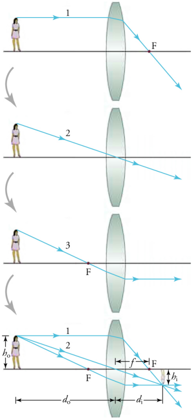
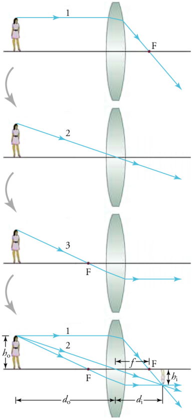


Object beyond f: Real, inverted image on far side

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

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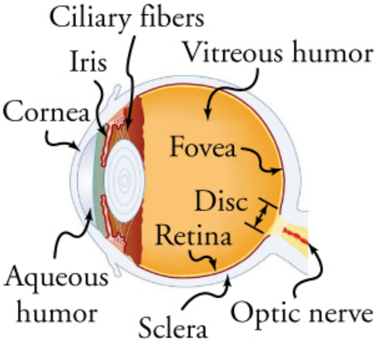
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

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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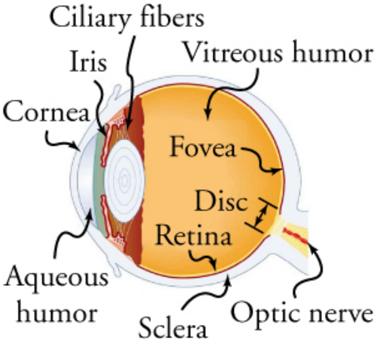

Cornea and lens: Form real image on retina

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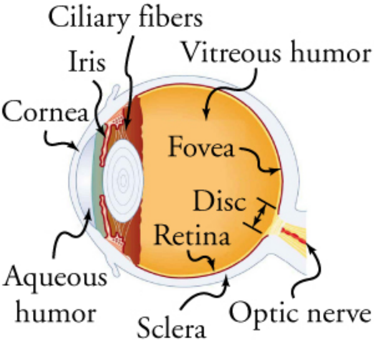

Cornea and lens: Form real image on retina
Ciliary muscles: Change lens shape to adjust focal length

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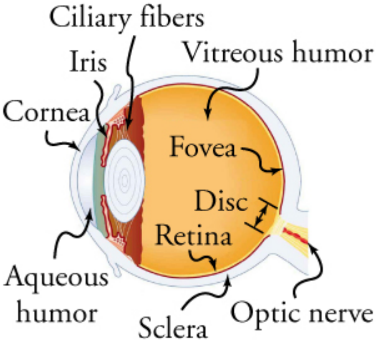
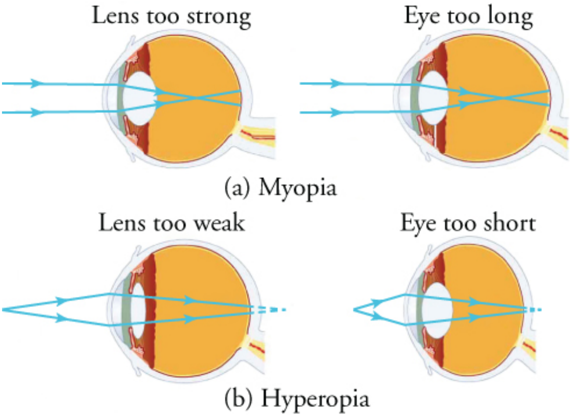


Cornea and lens: Form real image on retina
Ciliary muscles: Change lens shape to adjust focal length
Eye adjusts power to keep image distance constant for all object distances!

16.3 Vision Defects



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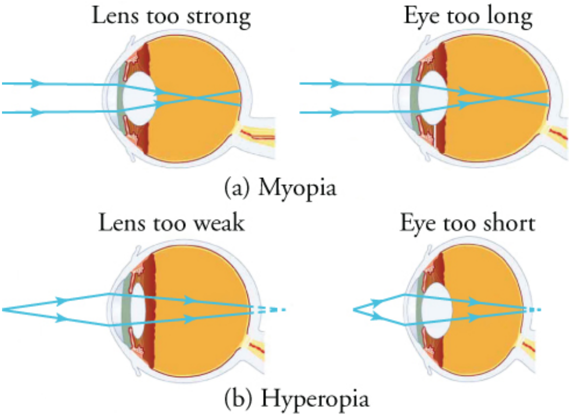
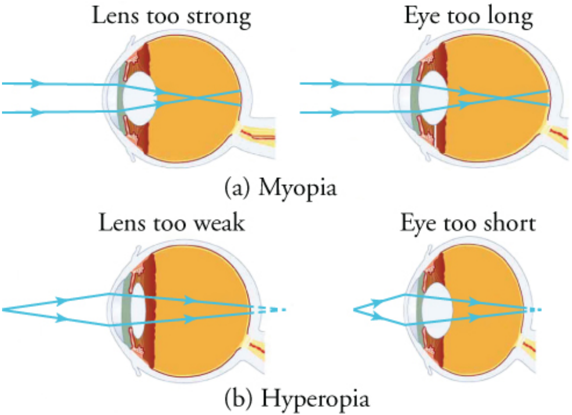


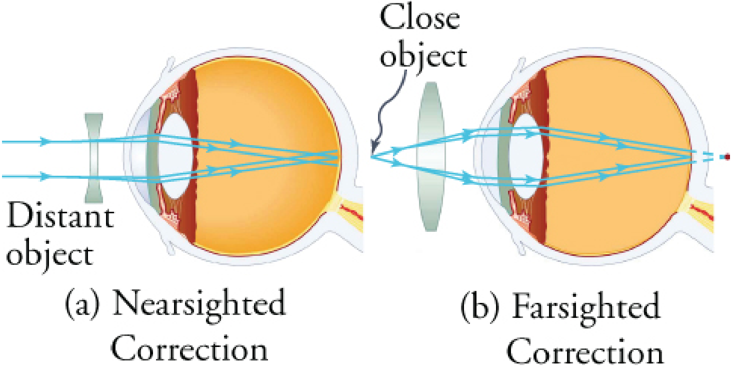
Nearsighted (myopia): Eye too strong, image forms in front of retina

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



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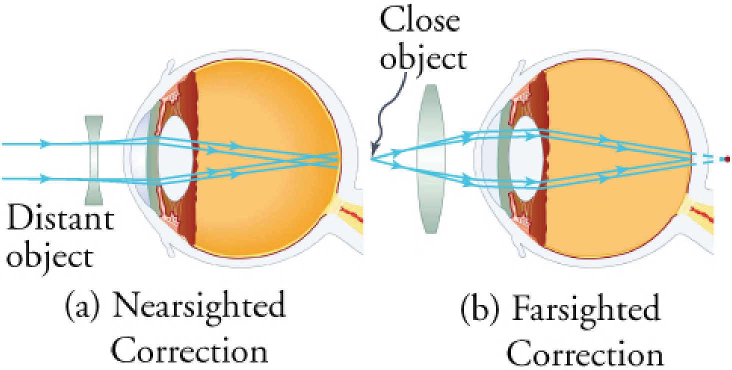
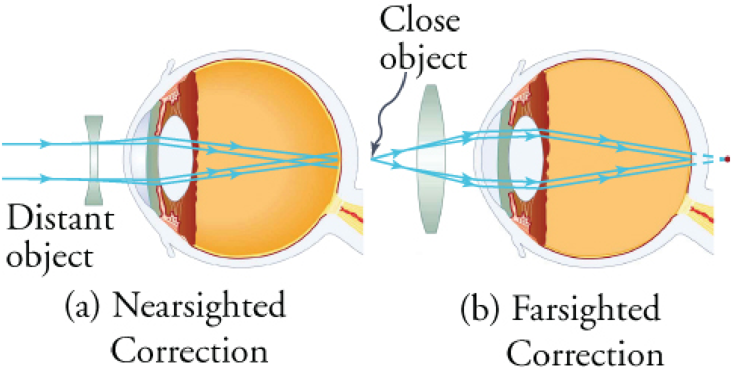


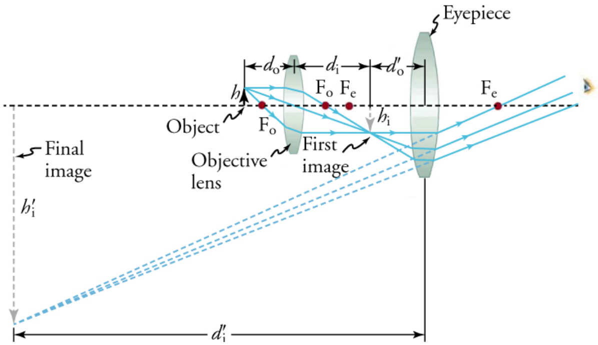
Nearsighted: Diverging lens (concave) reduces power

16.3 Correcting Vision Defects



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

16.3 Applications: Microscope



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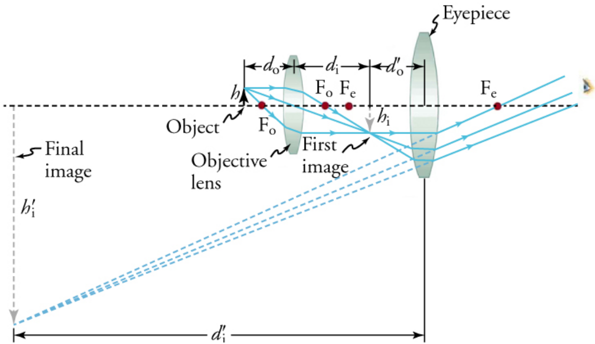
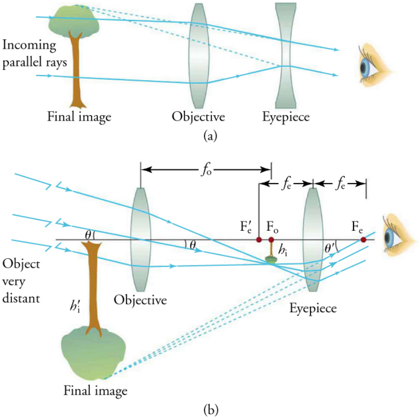


Two converging lenses:

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

16.3 Applications: Telescope



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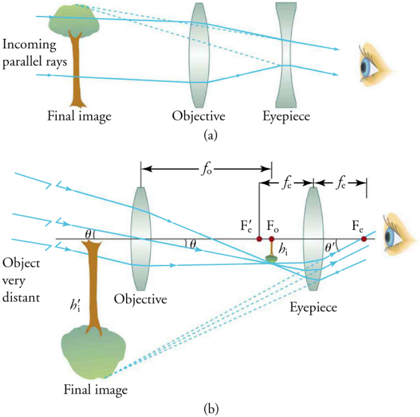
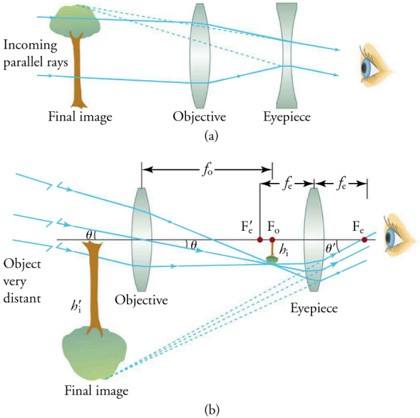


Galileo design: Convex objective + concave eyepiece = upright image

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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Turn and talk (2 min):

1. Which equation relates power and focal length?
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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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$$\boxed{P = 12.5\ \text{D}}$$

Check: This is a relatively powerful lens!

What You Now Know

The Revelations

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

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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

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

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

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

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

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

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

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

Homework

Complete the assigned problems

posted on the LMS

Temporary page!

LaTeX was unable to guess the total number of pages correctly. A
was some unprocessed data that should have been added to the
this extra page has been added to receive it.
If you rerun the document (without altering it) this surplus page
away, because LaTeX now knows how many pages to expect for t
document.