

# PHYS11 CH:16 How Light Bends Reality

## Mirrors, Refraction, and Lenses

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# 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



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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.

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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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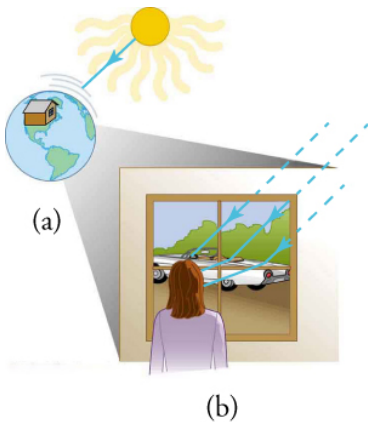
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- **16.1:** Apply ray diagrams to predict image locations

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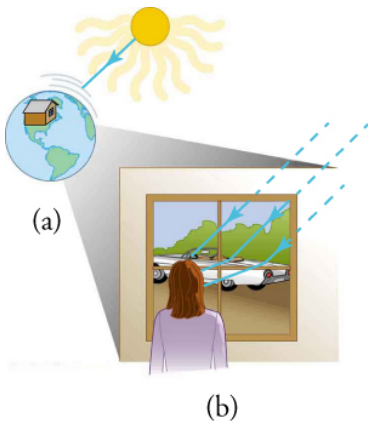
By the end of this section, you will be able to:

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

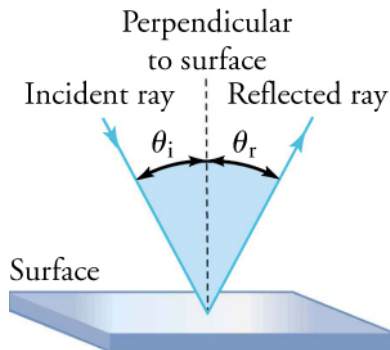


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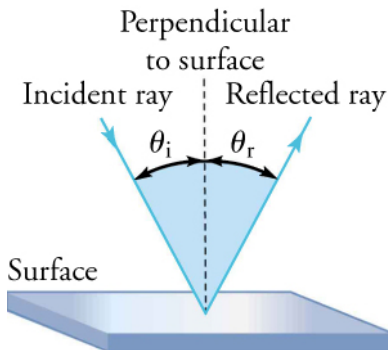


Light can travel: (a) through empty space, (b) through media, or (c) by reflection.

# 16.1 The Law of Reflection



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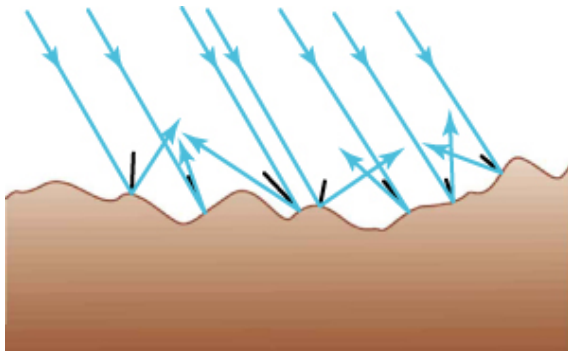


Universal Law: The Mirror's Rule

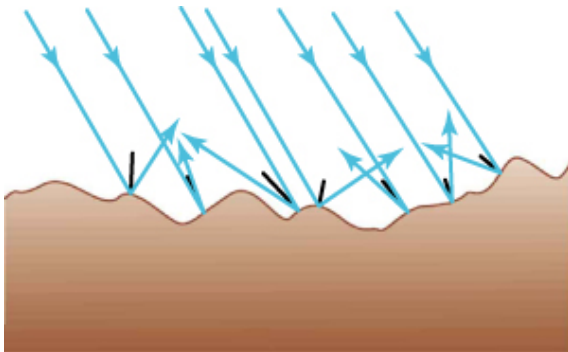
$$\theta_r = \theta_i$$

Angle of reflection equals angle of incidence.

## 16.1 Smooth vs Rough Surfaces

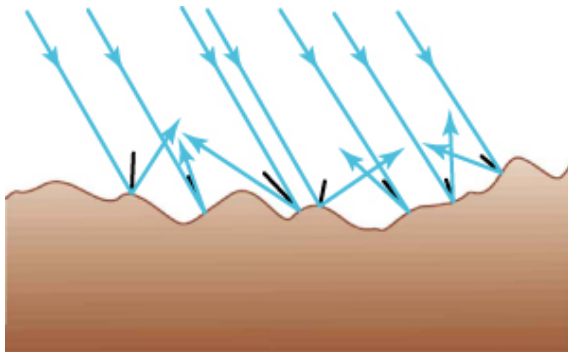


## 16.1 Smooth vs Rough Surfaces



**Smooth surface:** Specular reflection - rays reflect at same angle

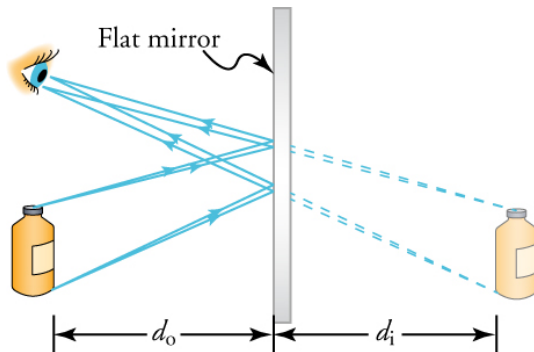
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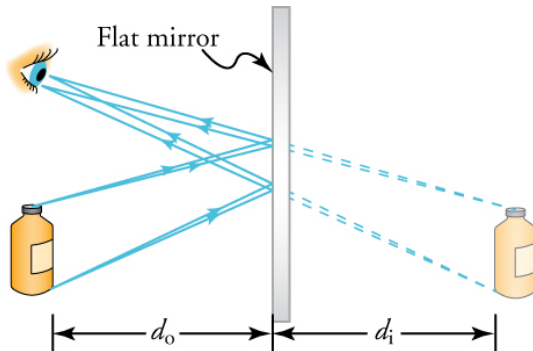
**Smooth surface:** Specular reflection - rays reflect at same angle

**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)

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## The Mental Model

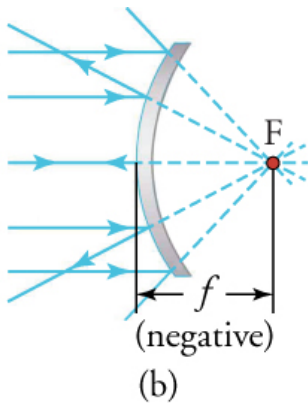
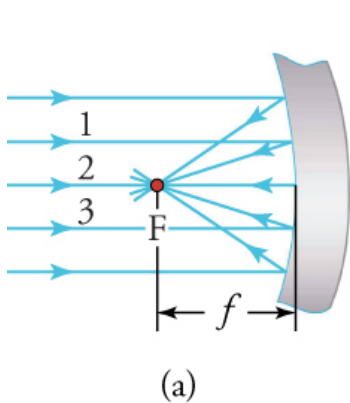
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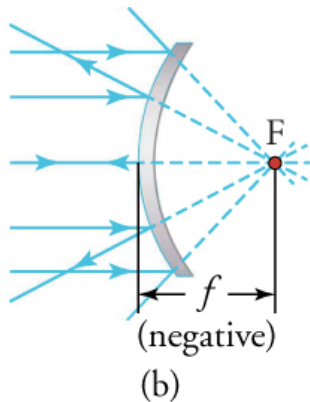
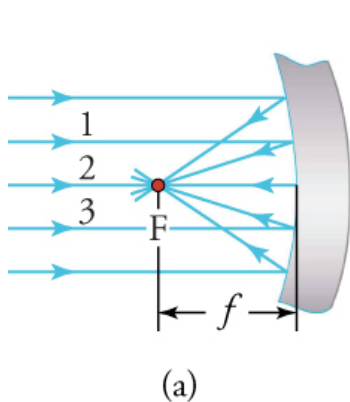
**Focal point (F):** Where parallel rays converge or appear to converge

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

## 16.1 Concave vs Convex Focal Points

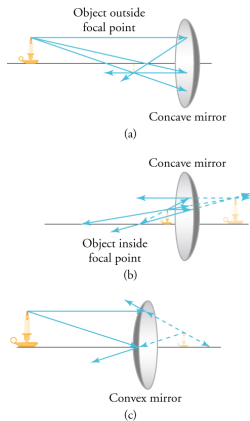


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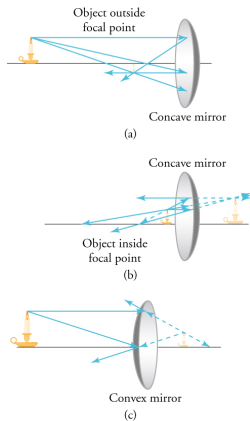


Concave: rays **converge** ( $f$  positive). Convex: rays **diverge** ( $f$  negative).

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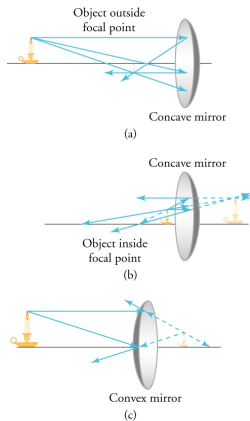


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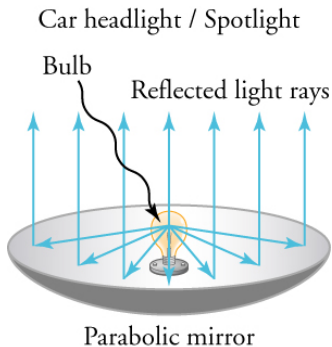
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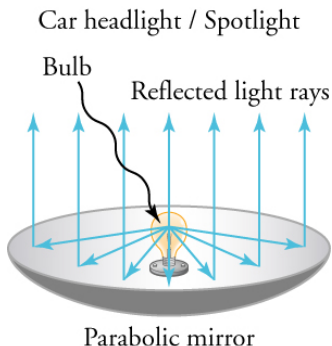
**Object beyond F:** Real, inverted image

**Object inside F:** Virtual, upright, magnified image

## 16.1 Applications: Car Headlights

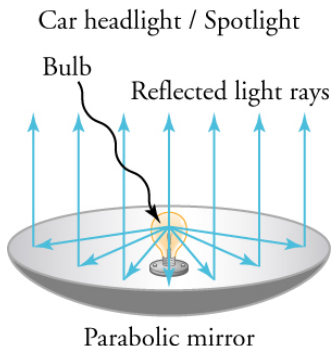


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**Parabolic concave mirror:** Bulb at focal point  $\rightarrow$  parallel rays exit  
Same principle: spotlights, solar collectors, satellite dishes

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

# 16.1 Mirror Equations

## Universal Laws: The Source Code

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**Radius of curvature:**

$$R = 2f$$

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## The Paradox: What Negative Means

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- Negative  $d_i \rightarrow$  virtual image
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- 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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**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.

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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- Light from glass to air: speeds up, bends away from normal

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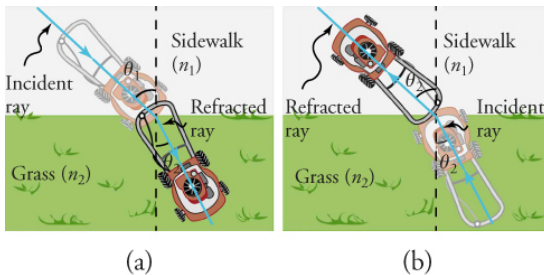
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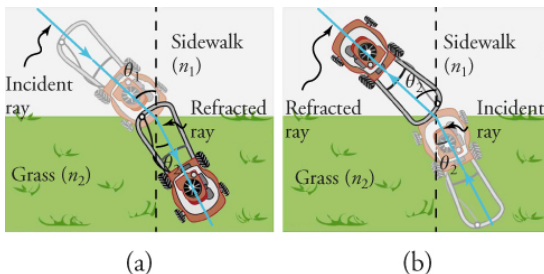
- $n$  = index of refraction (dimensionless)
- $c = 3.00 \times 10^8$  m/s (speed of light in vacuum)
- $v$  = speed of light in the material

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

## 16.2 Snell's Law



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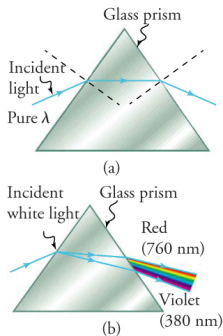


Universal Law: The Bending Rule

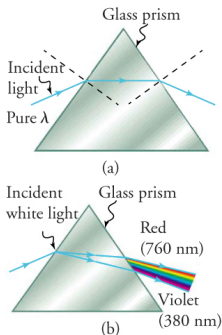
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

This predicts exactly how light bends at any boundary.

## 16.2 Dispersion: Rainbows

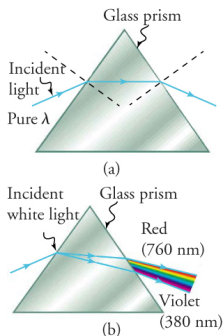


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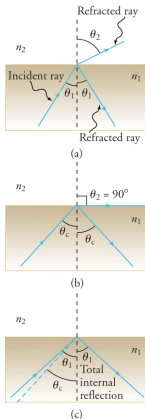
**Dispersion:** Index of refraction varies slightly with wavelength

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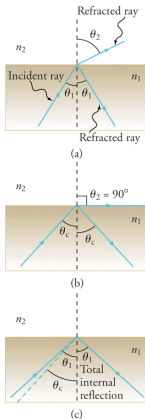


**Dispersion:** Index of refraction varies slightly with wavelength  
White light separates into colors: red bends least, violet bends most

## 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

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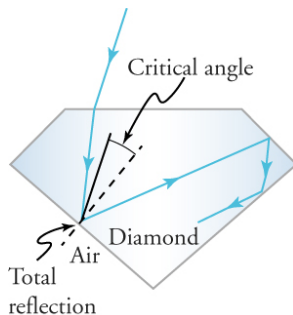
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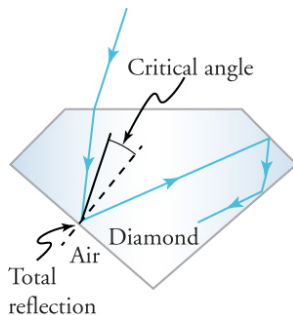
**Example:** Water to air

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

## 16.2 Applications: Diamonds

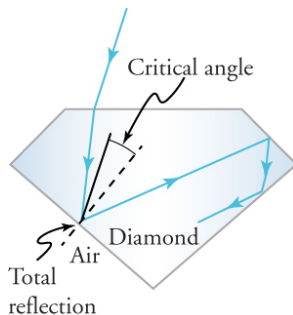


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Diamond critical angle: only  $24.4^\circ$ !

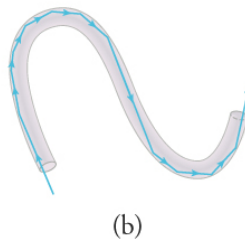
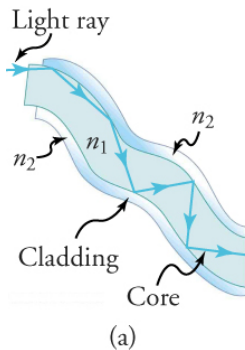
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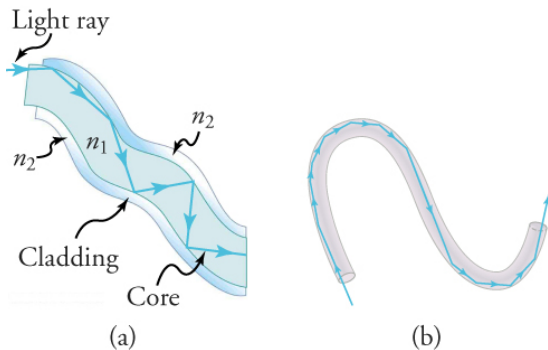
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Light enters easily but struggles to exit  $\rightarrow$  sparkle!

## 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  $45.0^\circ$  to the normal.

### Given:

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

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

*Can you predict the bend? Work silently.*

# Compare: Refraction Strategy

**Turn and talk (2 min):**

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**Check:** Light bends toward normal entering denser medium!

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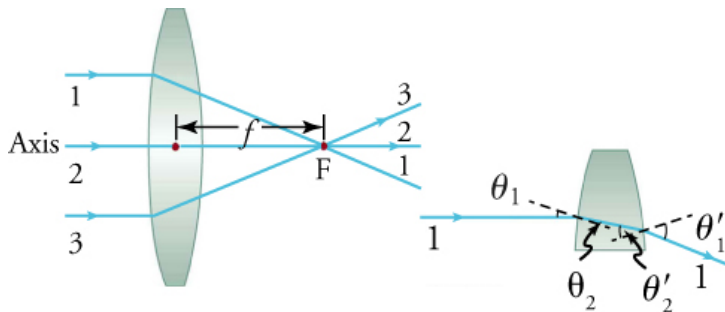
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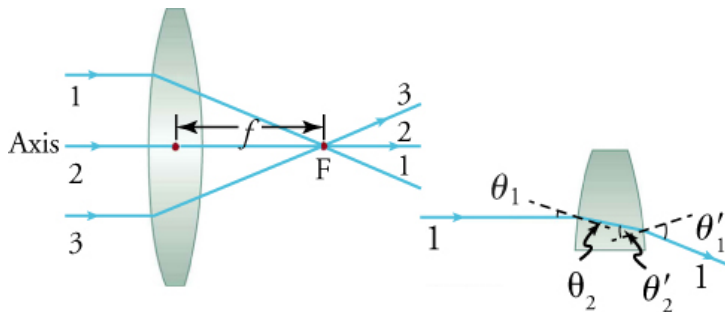
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Enough concentrated light energy = fire!

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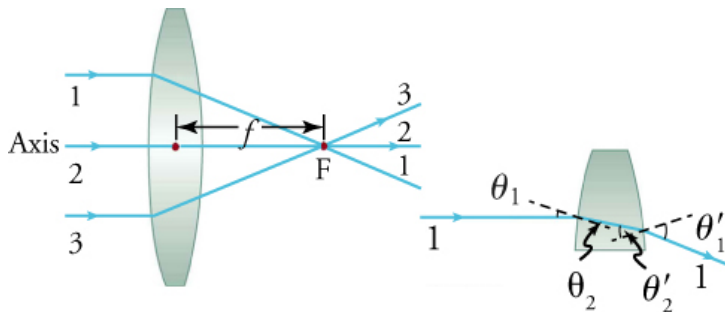


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## 16.3 Converging vs Diverging Lenses



**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  $\text{m}^{-1}$

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## 16.3 Lens Power

### The Focusing Strength

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

#### Where:

- $P$  = power in diopters (D) or  $\text{m}^{-1}$
- $f$  = 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

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### Converging lens:

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

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### Diverging lens:

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

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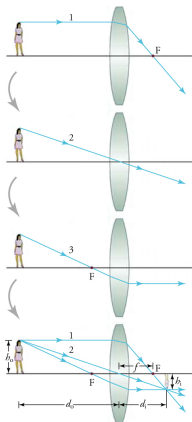
### Converging lens:

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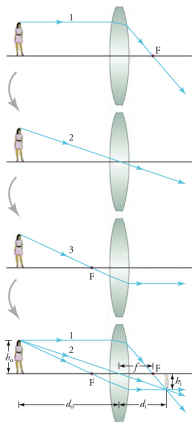
### Diverging lens:

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

## 16.3 Converging Lens Image Formation

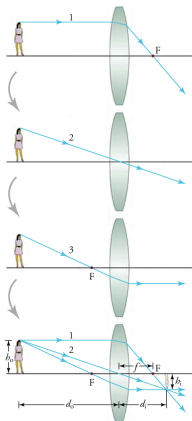


## 16.3 Converging Lens Image Formation



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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Same Equation as Mirrors

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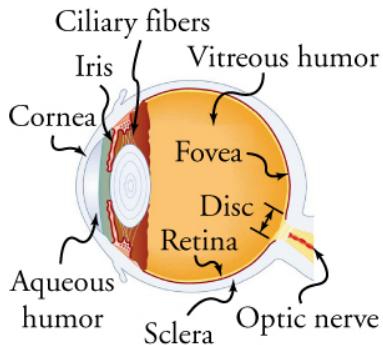
**Magnification:**

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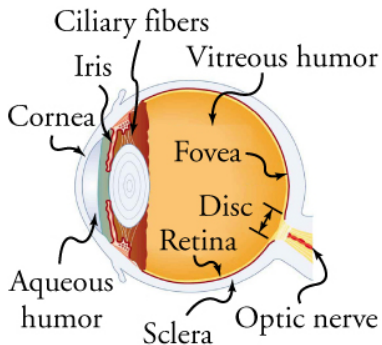
**Sign conventions:**

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

## 16.3 The Human Eye

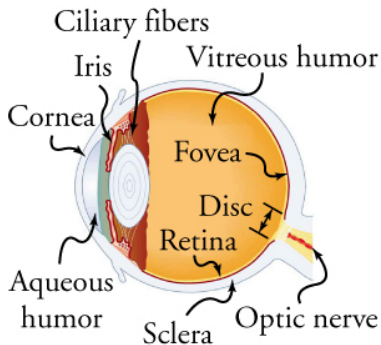


## 16.3 The Human Eye



**Cornea and lens:** Form real image on retina

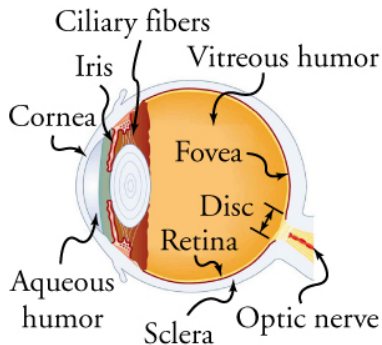
## 16.3 The Human Eye



**Cornea and lens:** Form real image on retina

**Ciliary muscles:** Change lens shape to adjust focal length

## 16.3 The Human Eye

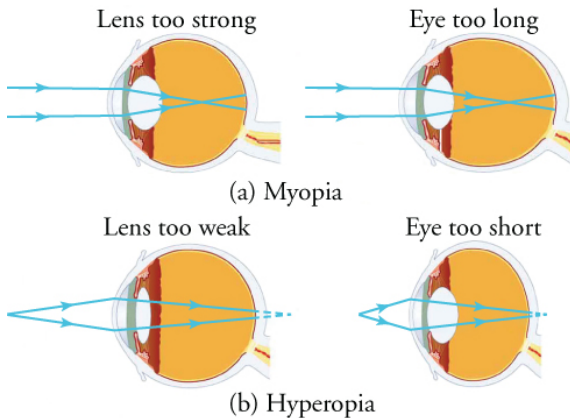


**Cornea and lens:** Form real image on retina

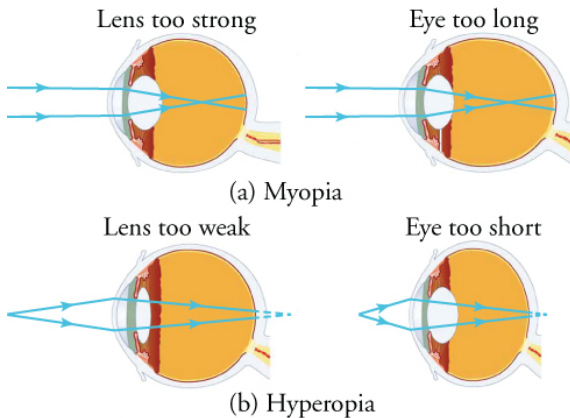
**Ciliary muscles:** Change lens shape to adjust focal length

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

## 16.3 Vision Defects

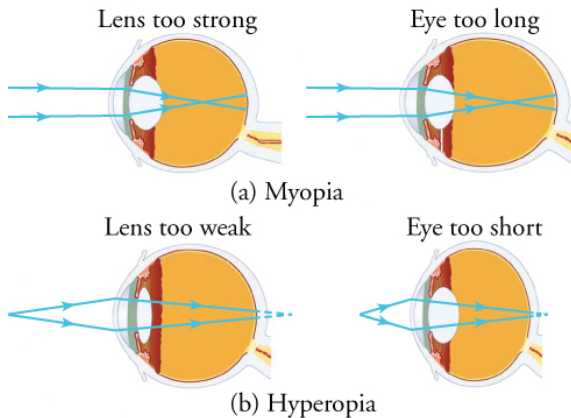


## 16.3 Vision Defects



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

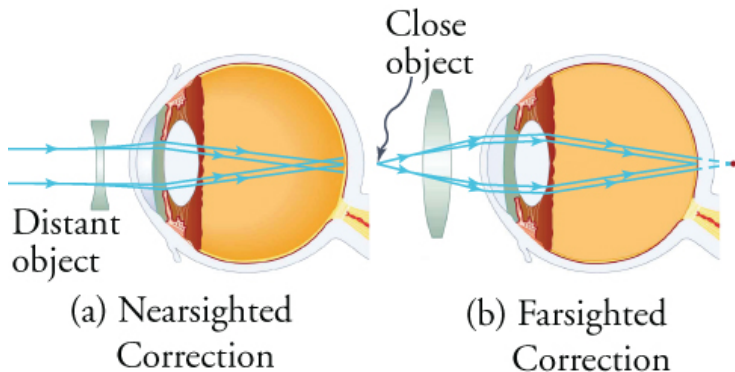
## 16.3 Vision Defects



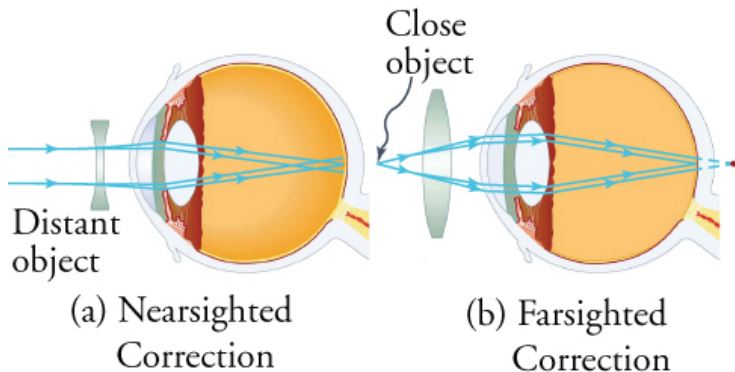
**Nearsighted (myopia):** Eye too strong, image forms in front of retina

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

## 16.3 Correcting Vision Defects

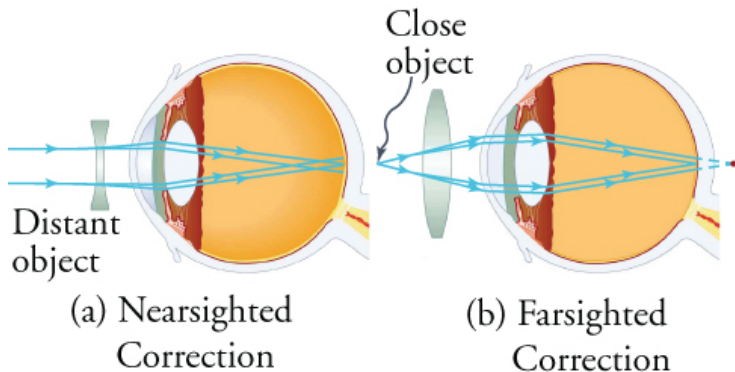


## 16.3 Correcting Vision Defects



**Nearsighted:** Diverging lens (concave) reduces power

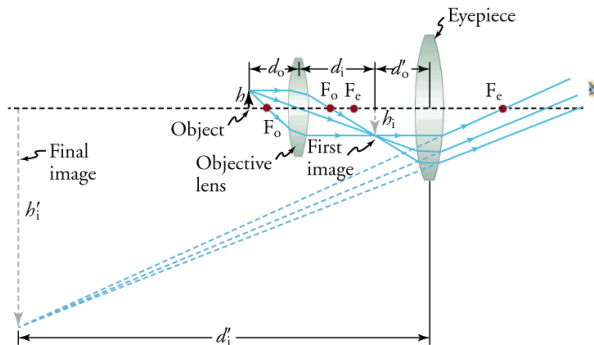
## 16.3 Correcting Vision Defects



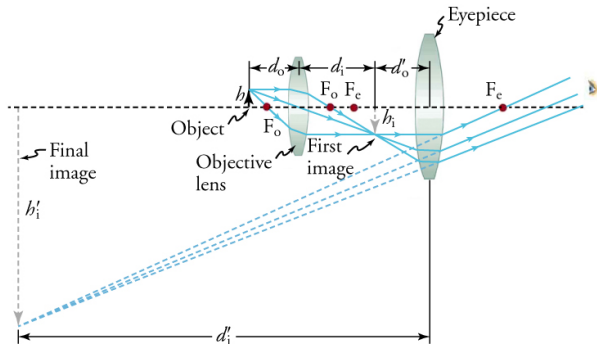
**Nearsighted:** Diverging lens (concave) reduces power

**Farsighted:** Converging lens (convex) increases power

## 16.3 Applications: Microscope



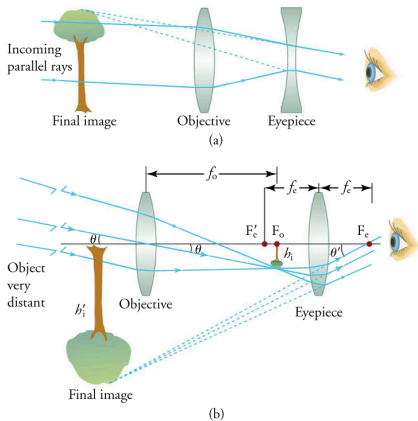
## 16.3 Applications: Microscope



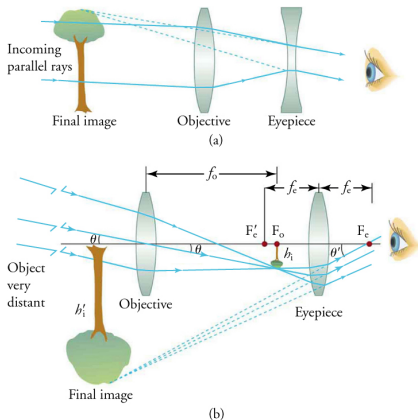
### Two converging lenses:

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

## 16.3 Applications: Telescope

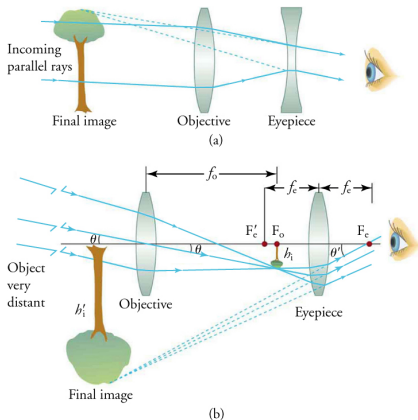


## 16.3 Applications: Telescope



**Galileo design:** Convex objective + concave eyepiece = upright image

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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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## Turn and talk (2 min):

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

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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)

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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