PHYS11 CH:17 When Light Reveals Its Waves

Diffraction, Interference, and the Hidden Structure of Reality

Mr. Gullo

December 2025

Outline

The Mystery of the Rainbow Disc

Figure: CD showing rainbow colors from white light

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How does straw-colored plastic produce a rainbow?

The Dual Identity

Light behaves as both:

- **Ray:** Travels in straight lines, reflects, refracts

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What Your Eyes Miss

You see light's ray behavior every day. Its wave behavior is hidden - until objects become tiny.

Learning Objectives

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

- **17.1:** Explain wave behavior of light, including diffraction and interference

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- **17.1:** Calculate wavelength of light using two-slit interference data

17.1 The Source Code of Light

Nature's Law for Light

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Speed equals frequency times wavelength

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- Speed: $c = 3.00 \times 10^8$ m/s (constant)

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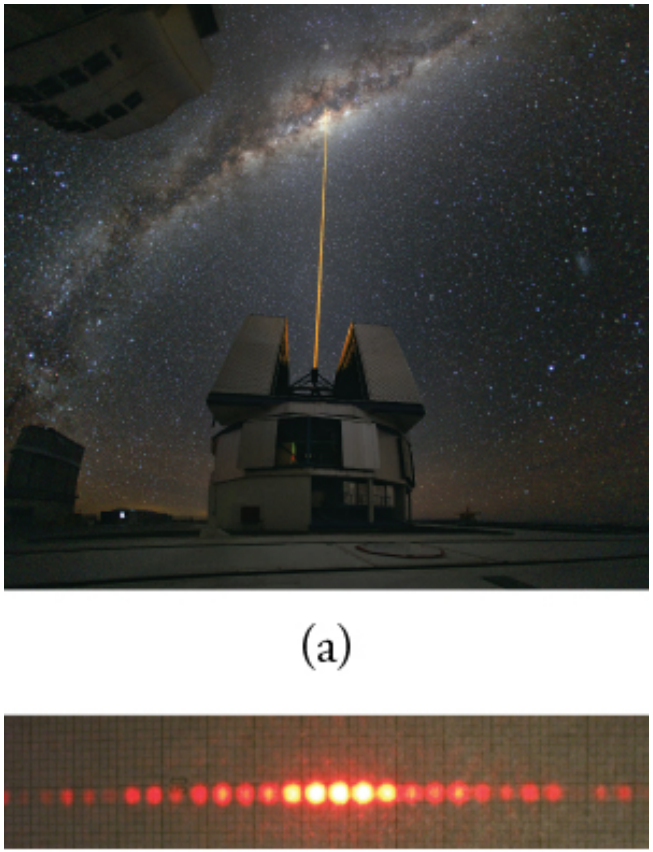
For visible light in vacuum:

- Speed: $c = 3.00 \times 10^8$ m/s (constant)
- Wavelength: $\lambda = 380$ to 750 nm
- Frequency: $f = 4.0 \times 10^{14}$ to 7.9×10^{14} Hz

17.1 Light as Both Ray and Wave



(a)

(b)

Figure: Laser beam as ray (straight line) and wave (interference pattern after slits)

17.1 Water Waves Show the Way

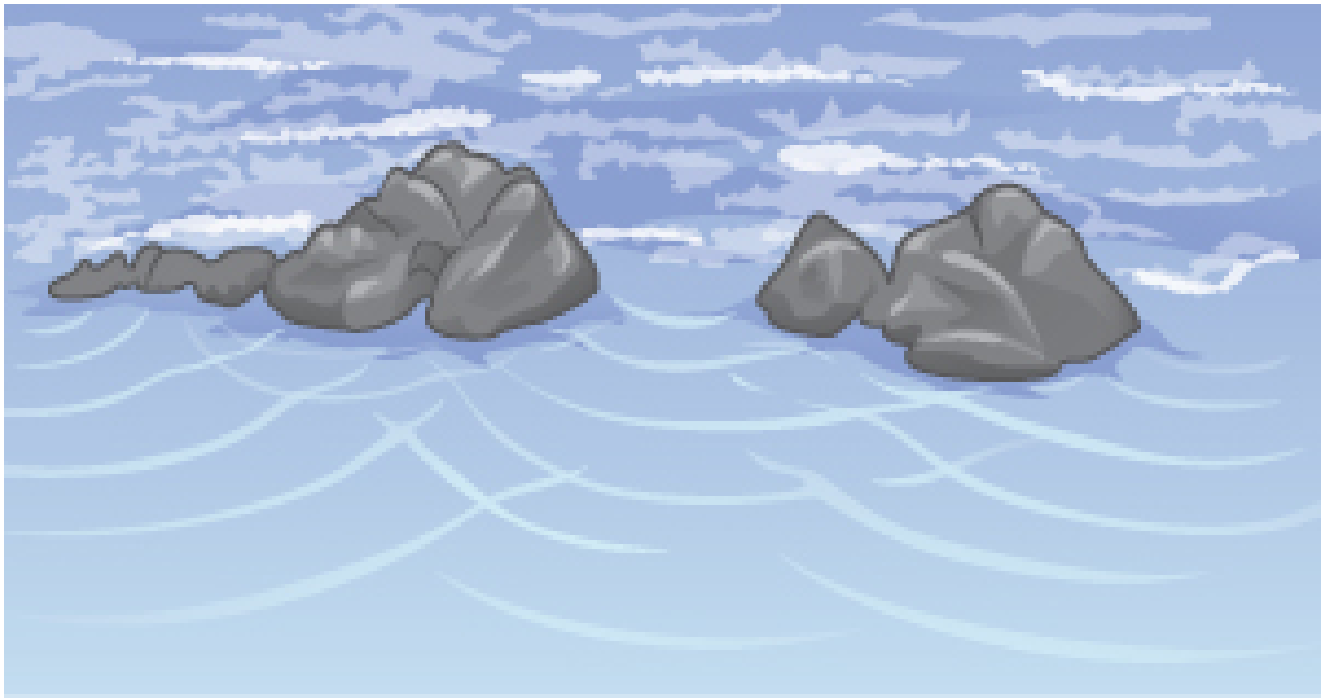


Figure: Water waves passing through gaps in rocks

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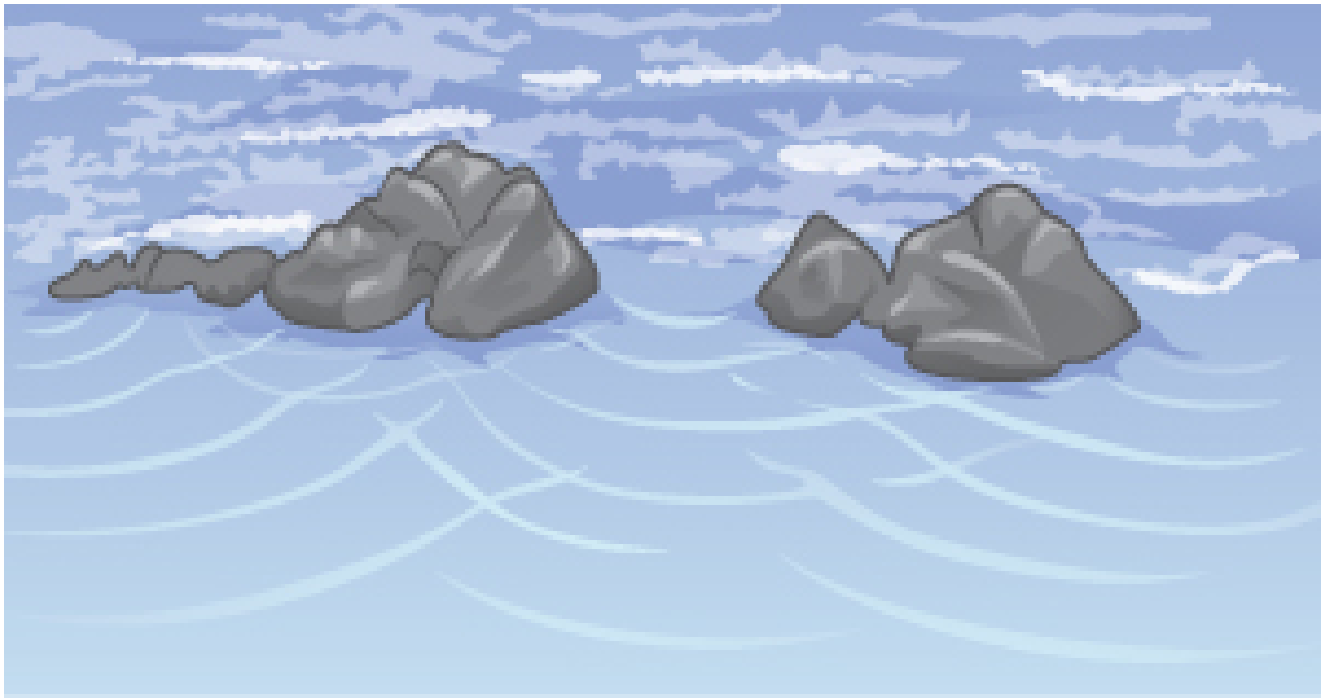

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Key observation: Gap width similar to wavelength causes interference pattern

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Real-World: Light in Water

Water has $n = 1.333$, so visible wavelengths compress to 285-570 nm

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Every point on a wavefront is a source of wavelets that spread forward at wave speed. New wavefront is tangent to all wavelets.

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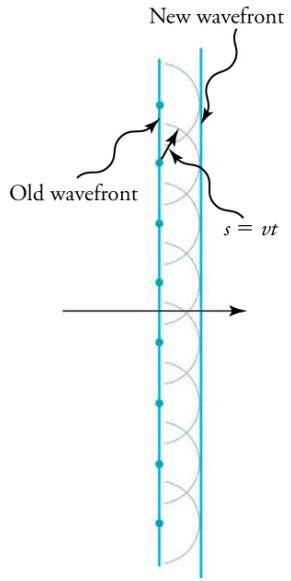

Figure: Wavefront emitting semicircular wavelets

17.1 The Bending of Light

The Mental Model

Sound bends around doorways. Light seems to travel straight. Why?

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The Paradox

Light DOES bend - but only around objects comparable to its wavelength

17.1 Diffraction Revealed

Nature's Definition

Diffraction: Bending of wave around edges of opening or obstacle

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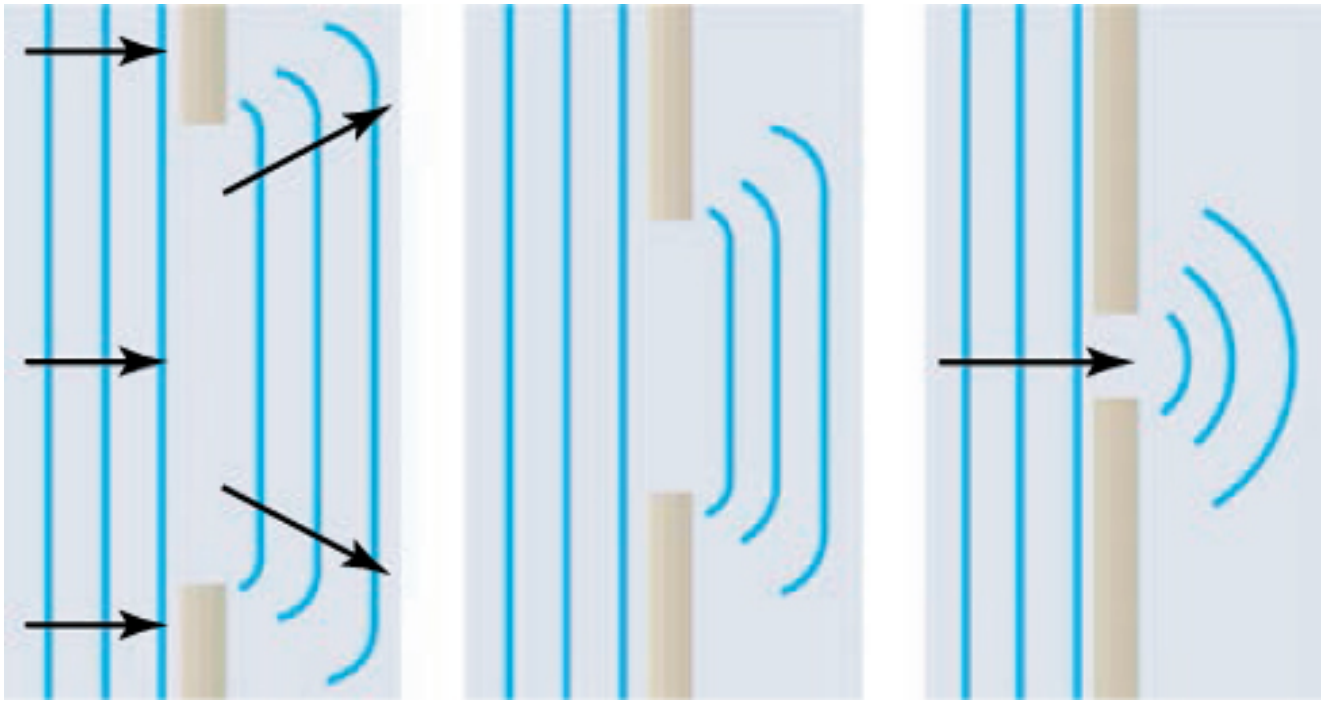

Figure: Huygens's principle applied to slit - edges bend

17.1 Ocean Waves Through Reef

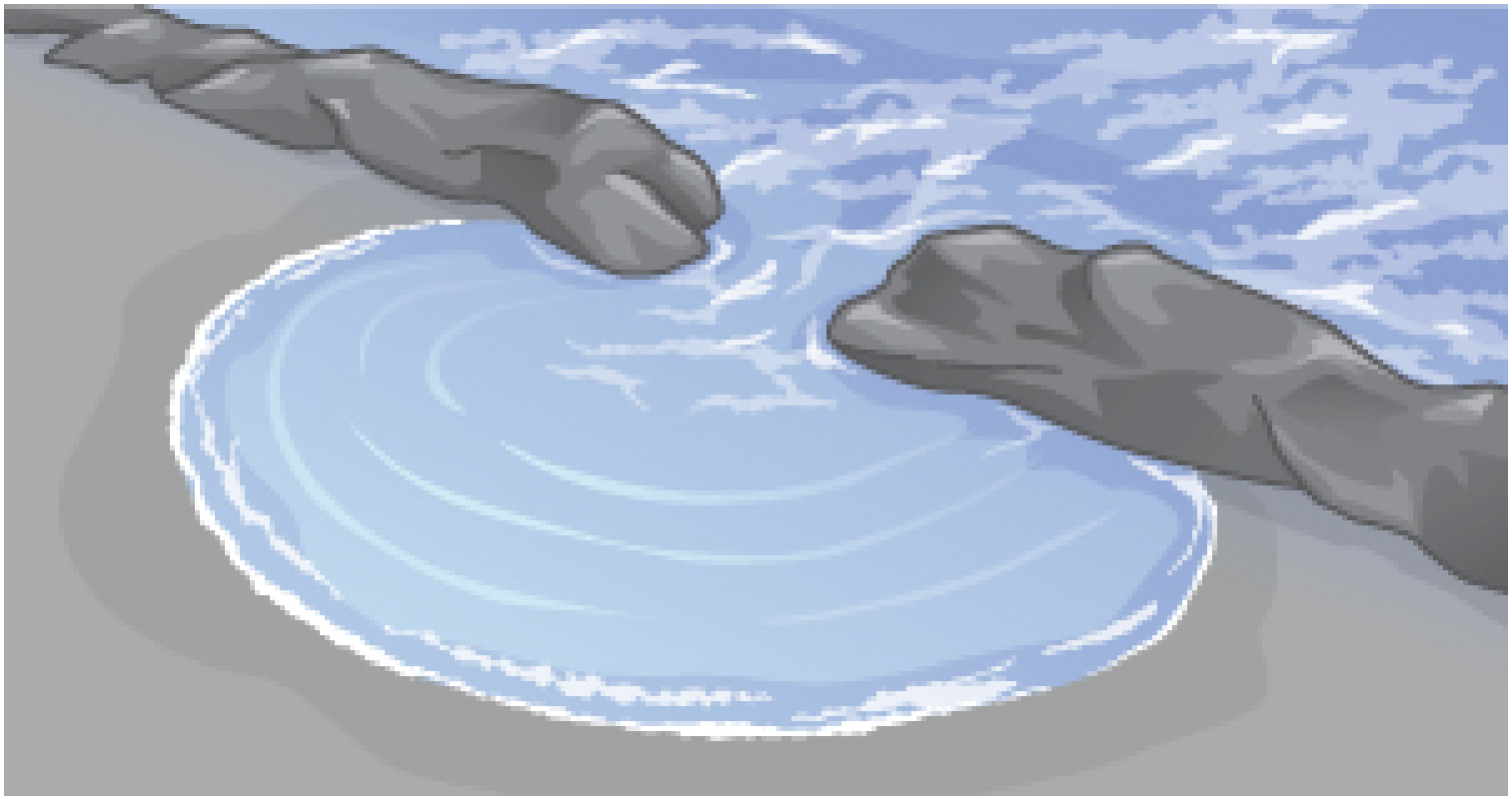

Figure: Ocean waves diffracting through opening - visible interference pattern

17.1 Young's Revolutionary Experiment

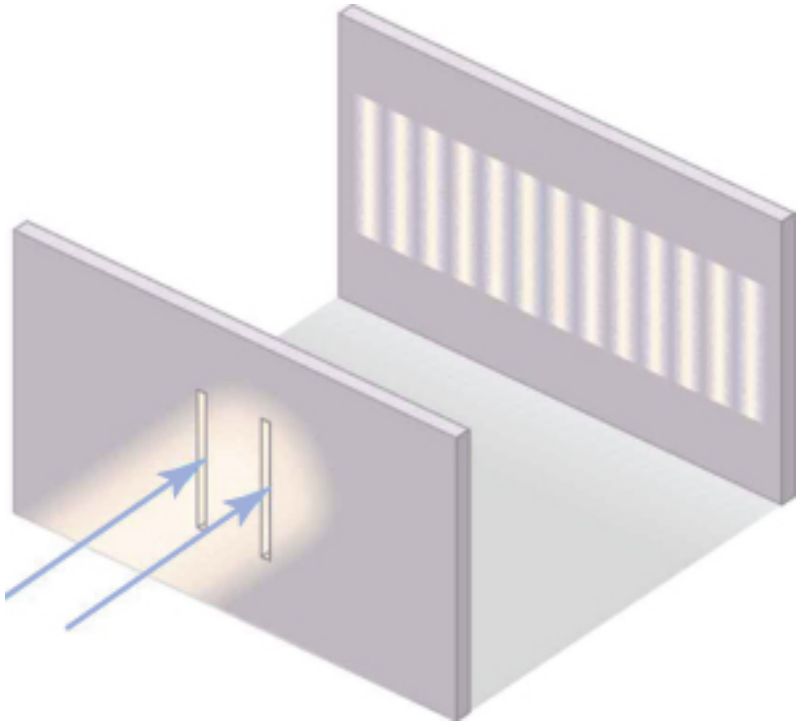

Figure: Double-slit experiment setup (1801)

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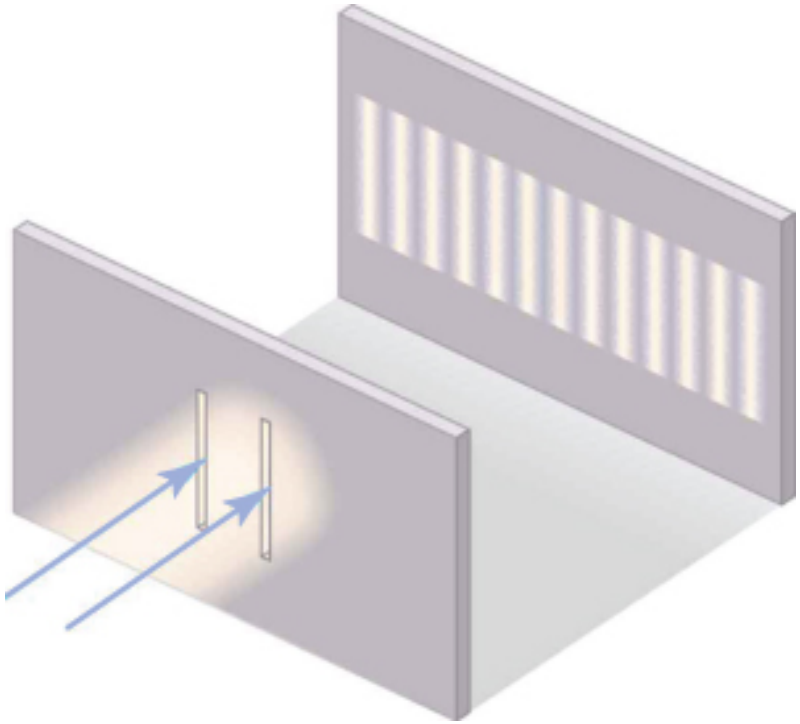

Figure: Double-slit experiment setup (1801)

Result: Vertical light and dark lines spread horizontally

17.1 The Interference Pattern

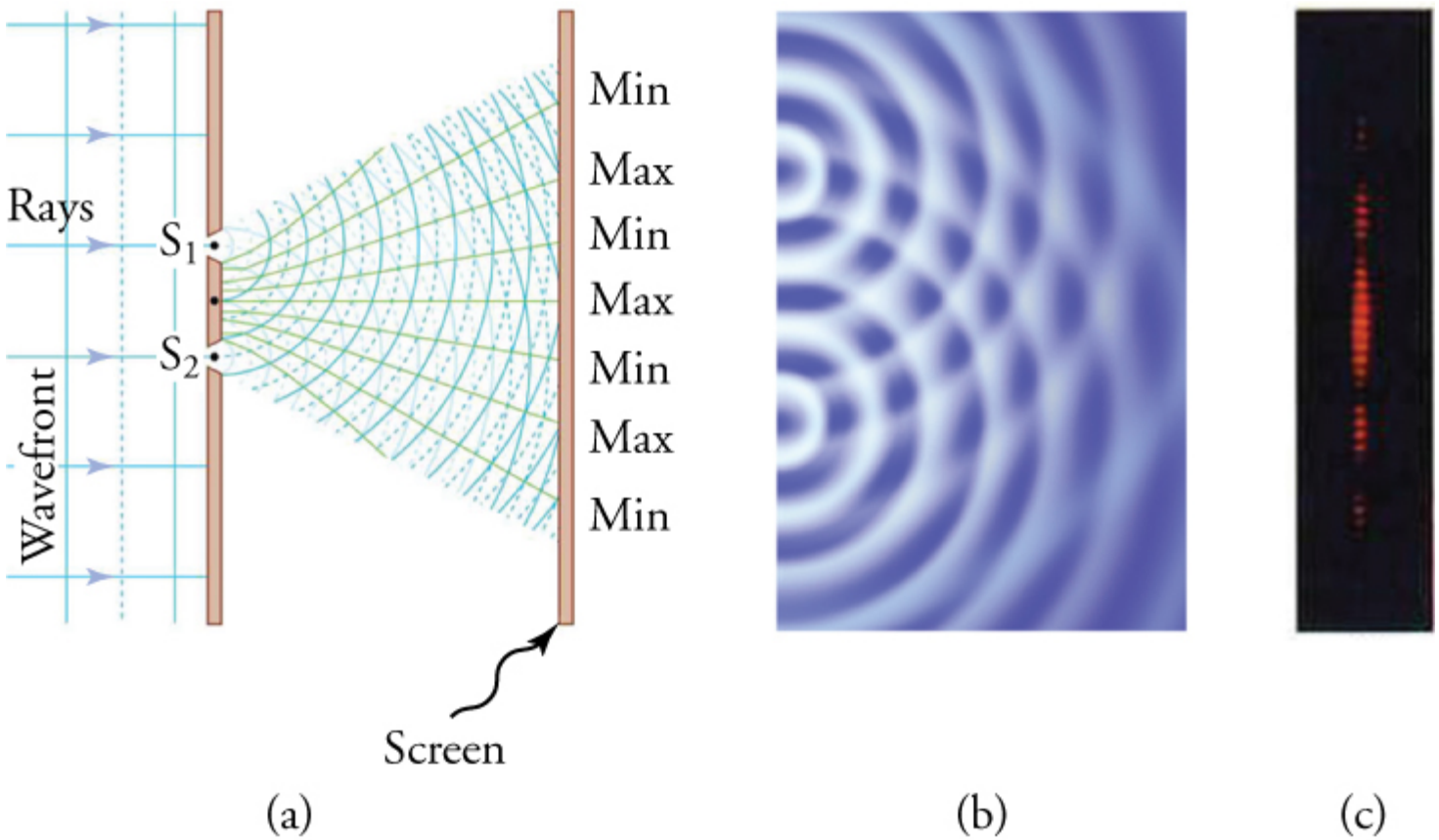

Figure: Double-slit interference: light diffracts from each slit, waves overlap and interfere

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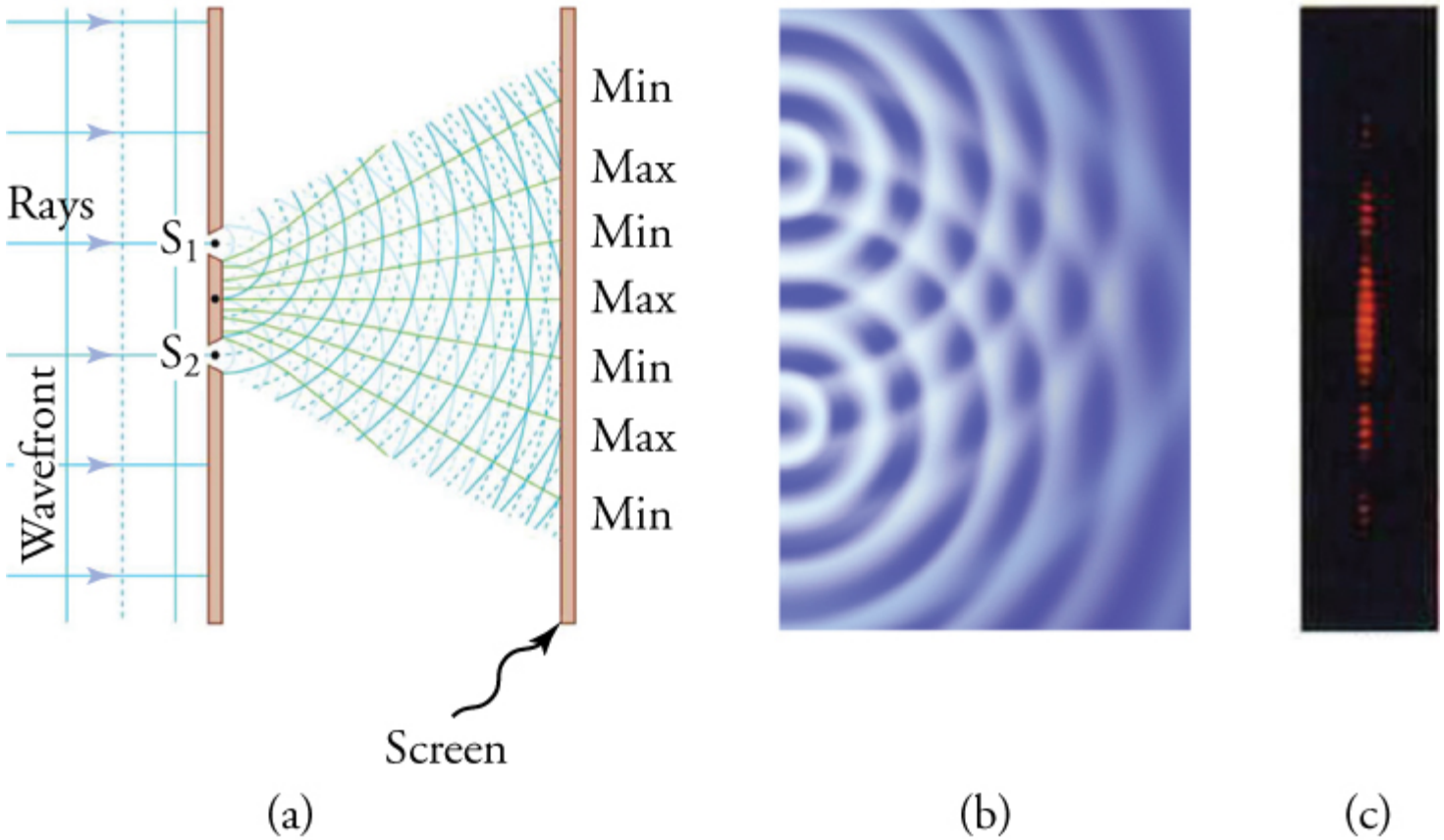

Figure: Double-slit interference: light diffracts from each slit, waves overlap and interfere

- **Constructive interference:** Crest meets crest $\rightarrow$ bright
- **Destructive interference:** Crest meets trough $\rightarrow$ dark

17.1 The Math of Double-Slit Interference

Universal Law: Constructive Interference

$$\boxed{d \sin \angle\theta = m\lambda}$$

For $m = 0, \pm 1, \pm 2, \pm 3, \ldots$ (order of maximum)

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$$\boxed{d \sin \angle\theta = m\lambda}$$

For $m = 0, \pm 1, \pm 2, \pm 3, \ldots$ (order of maximum)

Universal Law: Destructive Interference

$$\boxed{d \sin \angle\theta = \left(m + \frac{1}{2}\right) \lambda}$$

For $m = 0, \pm 1, \pm 2, \ldots$ (order of minimum)

17.1 Path Difference Geometry

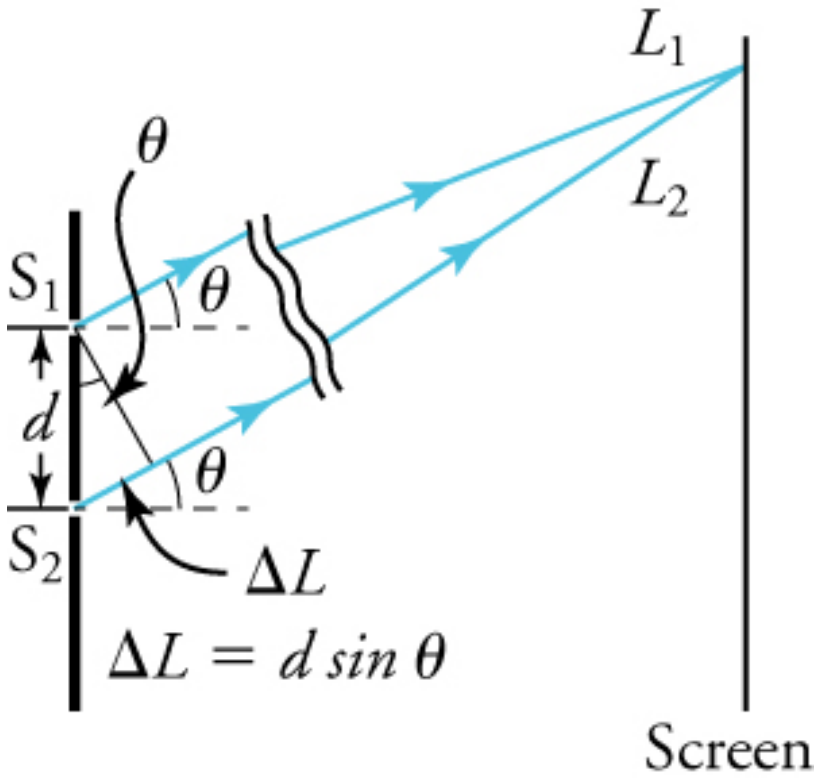

Figure: Path difference $\Delta L = d \sin \angle\theta$

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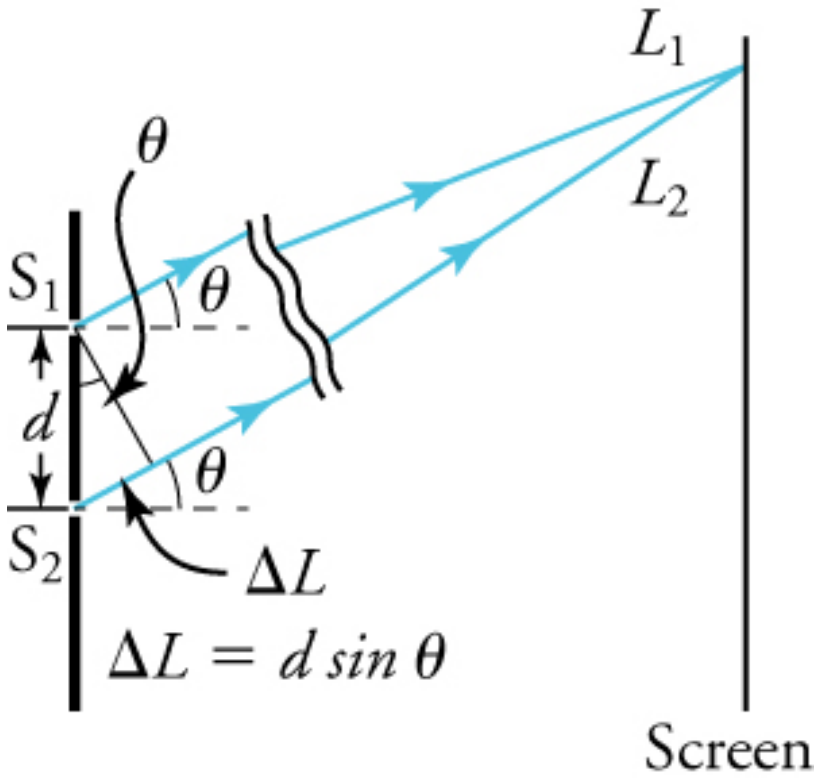

Figure: Path difference $\Delta L = d \sin \angle\theta$

Key insight: Waves start in phase, end in or out of phase depending on path difference

17.1 Intensity Pattern

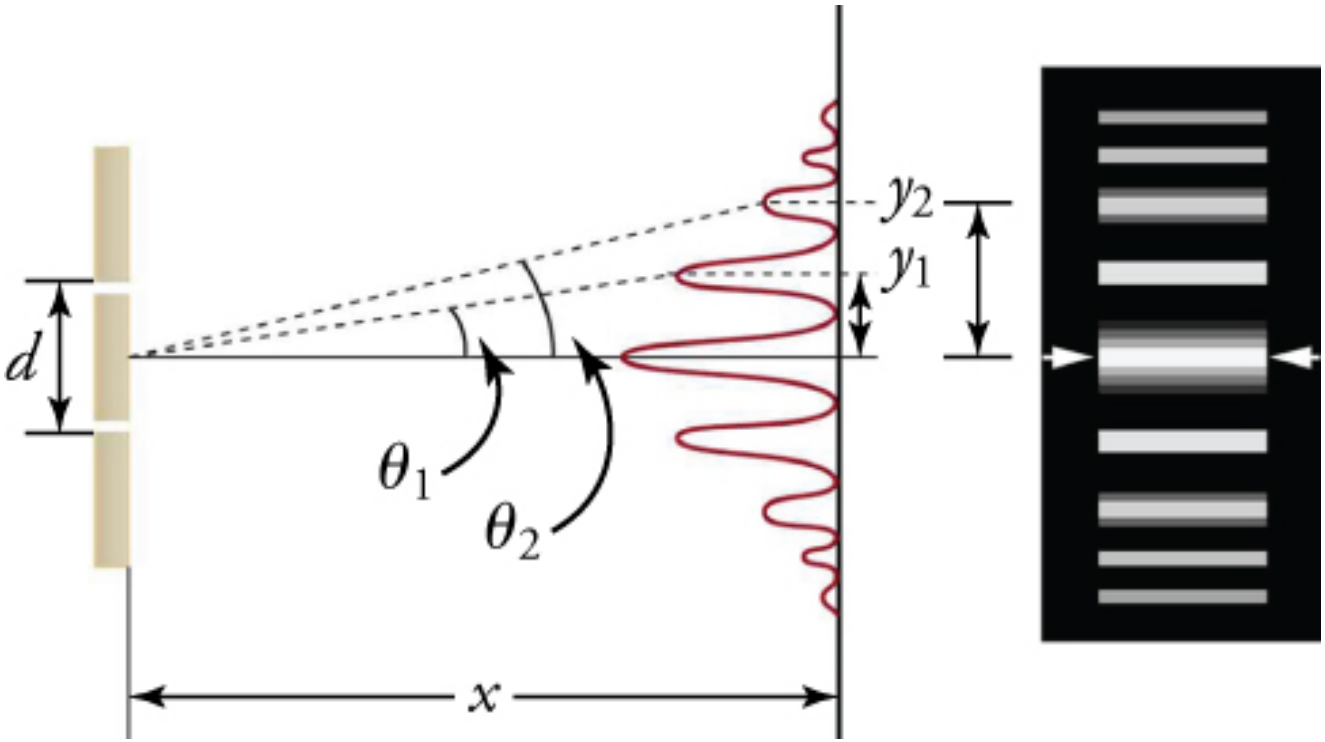

Figure: Intensity decreases with angle from center

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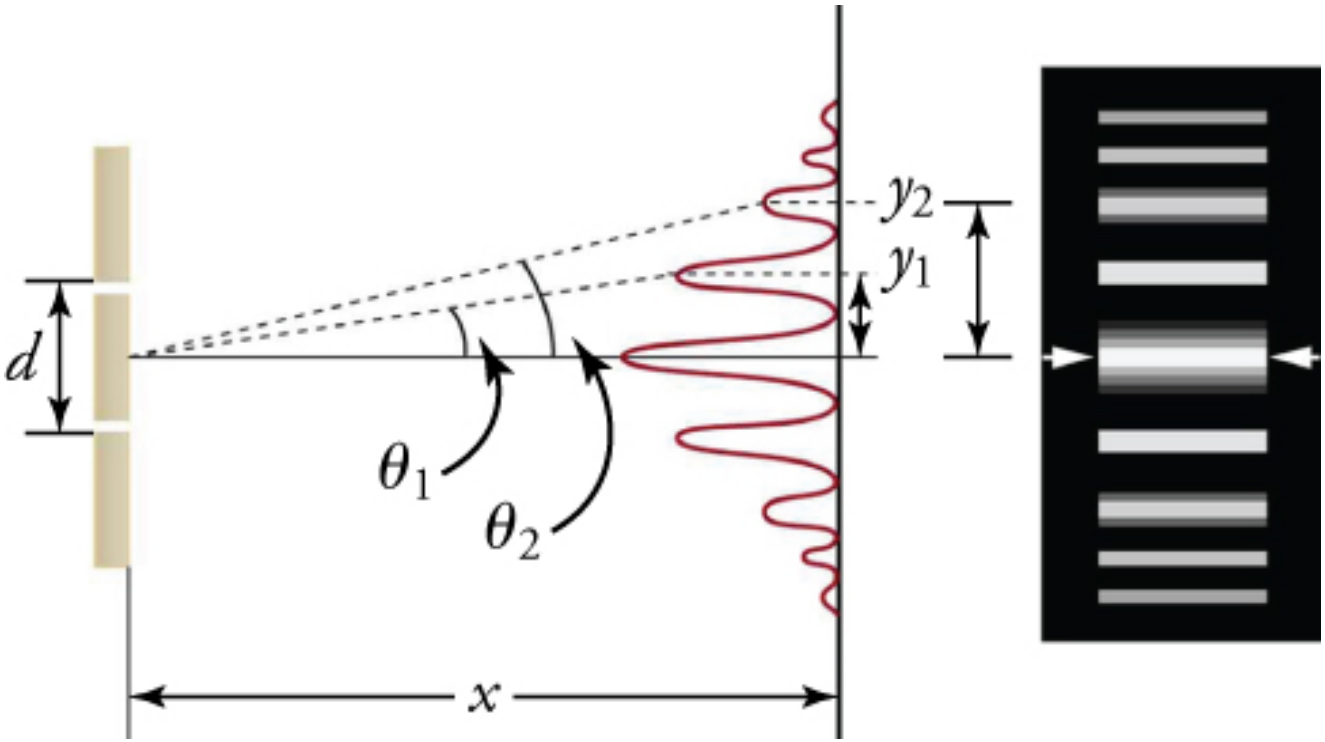

Figure: Intensity decreases with angle from center

Observation: Central maximum brightest, intensity falls off to sides

17.1 Single-Slit Diffraction

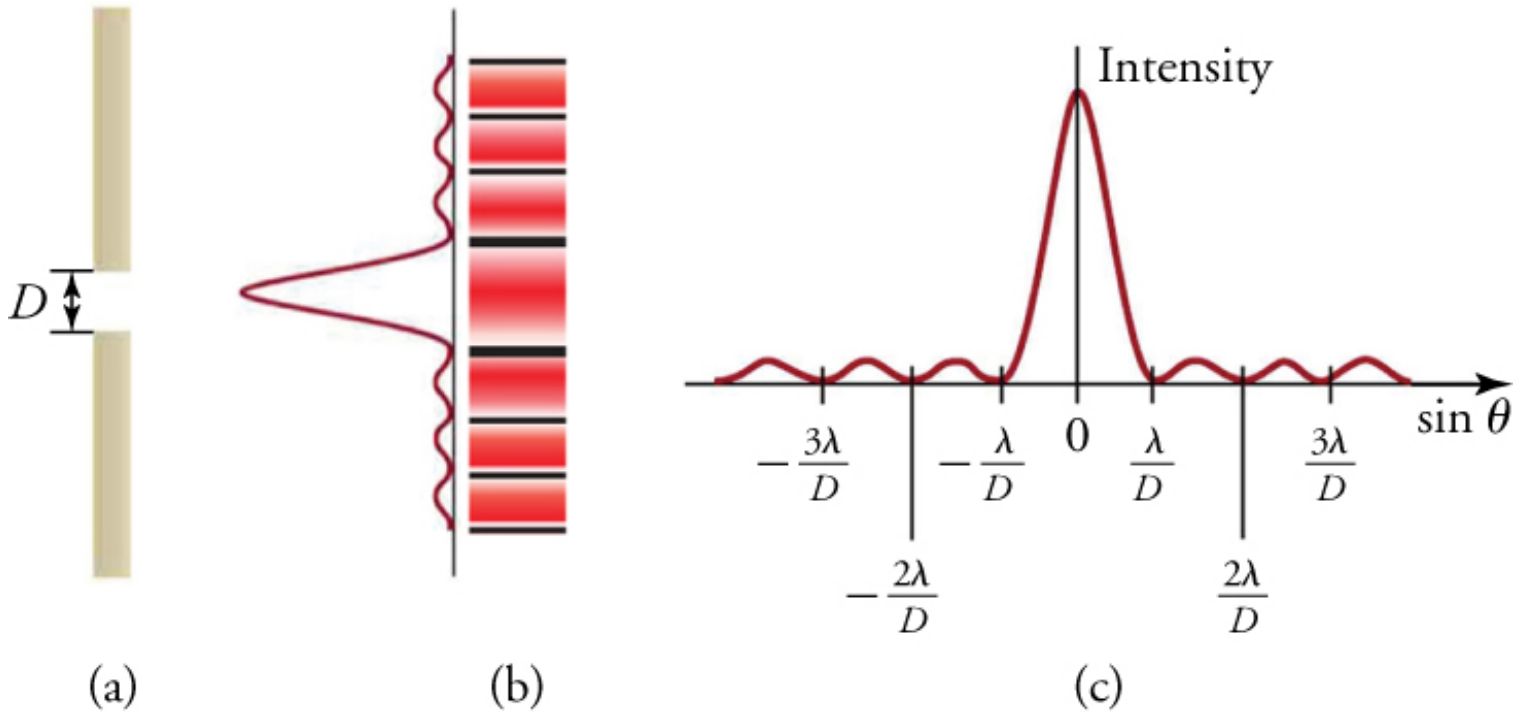

Figure: Single slit produces wider central maximum with dimmer side maxima

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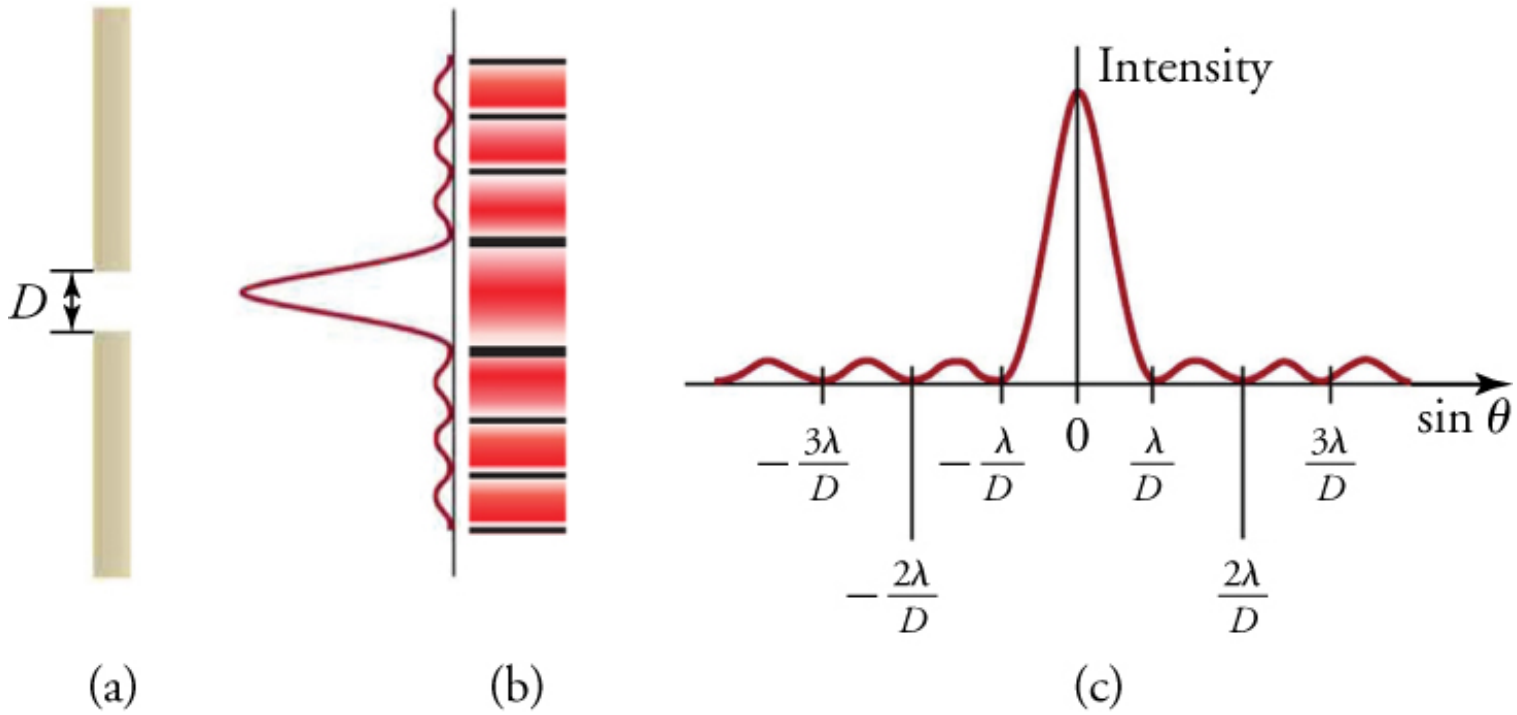

Figure: Single slit produces wider central maximum with dimmer side maxima

Key difference: Central maximum is 6 times wider than side maxima

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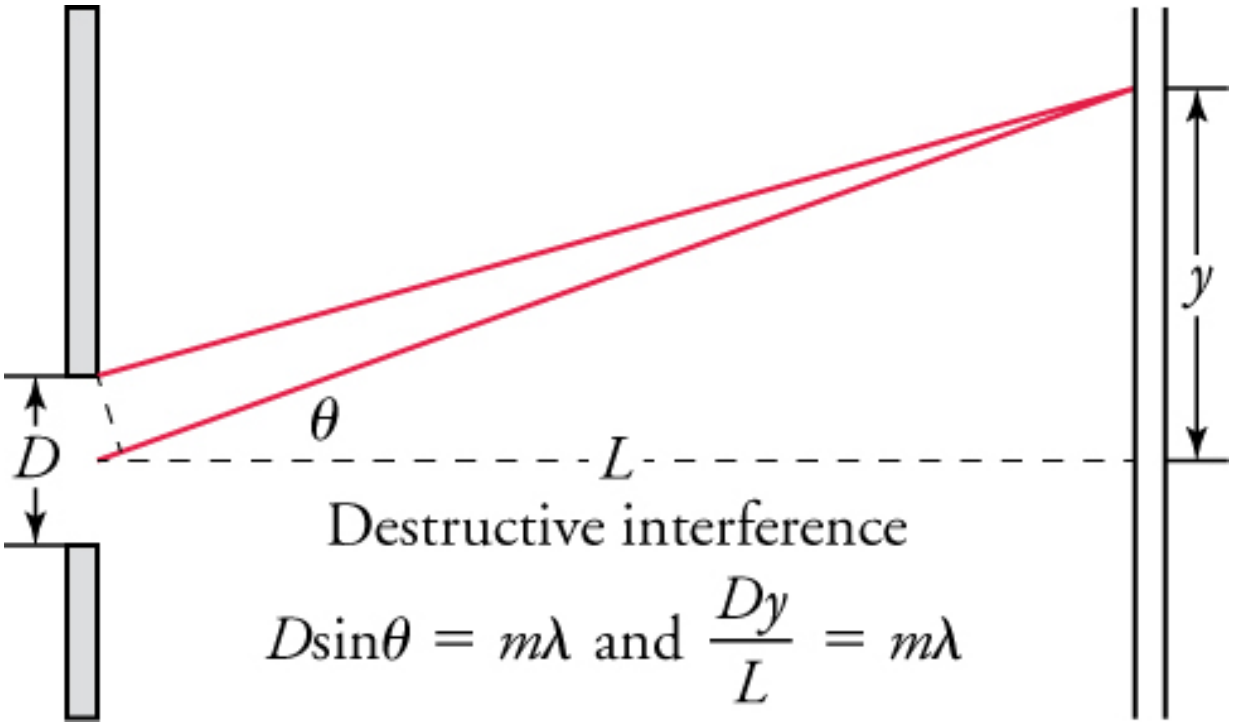

Figure: Ray diagram showing destructive interference for single slit

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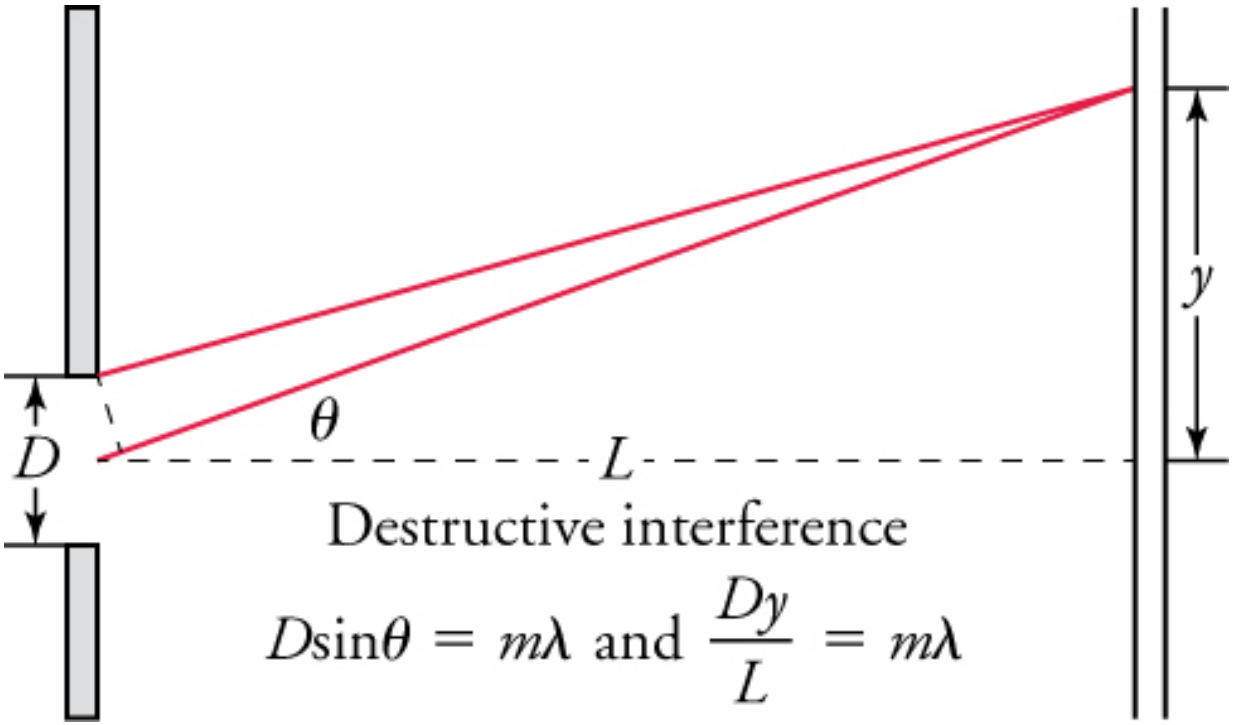

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Universal Law: Single-Slit Minima

$$\boxed{D \sin \angle\theta = m\lambda} \quad \text{or} \quad \boxed{\frac{Dy}{L} = m\lambda}$$

Attempt: Decoding the Double Slit

The Challenge (3 min, silent)

Light from a He-Ne laser passes through two slits separated by 0.0100 mm. The third bright line forms at angle 10.95° relative to incident beam.

Given:

- $d = 0.0100$ mm $= 1.00 \times 10^{-5}$ m
- $\angle\theta = 10.95°$
- $m = 3$ (third bright line)

Find: Wavelength λ in nm

Can you decode the wavelength? Work silently.

Compare: Double-Slit Strategy

Turn and talk (2 min):

1. Which equation did you choose for constructive interference?
2. How did you rearrange it to solve for λ?
3. What units did you get for wavelength?

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

Reveal: The Wavelength of Light

Self-correct in a different color:

Equation: $d \sin \angle\theta = m\lambda$

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Check: 633 nm is red light - wavelength of He-Ne laser. Perfect!

Attempt: Single-Slit Width

The Challenge (3 min, silent)

Visible light of wavelength 550 nm falls on single slit and produces second diffraction minimum at angle 45.0°.

Given:

- $\lambda = 550 \text{ nm} = 550 \times 10^{-9} \text{ m}$
- $\angle\theta = 45.0°$
- $m = 2$ (second minimum)

Find: Slit width D in micrometers

Can you decode the slit width? Work silently.

Compare: Single-Slit Strategy

Turn and talk (2 min):

1. What's the difference between single-slit and double-slit equations?
2. How did you solve for D?
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Check: Only few times wavelength - consistent with significant wave effects!

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- **17.2:** Explain wave behaviors including diffraction, interference, and coherence
- **17.2:** Describe applications based on wave properties of light
- **17.2:** Perform calculations for diffraction gratings and resolution limits

17.2 The Birth of the Laser

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- Photon hits excited atom

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The Acronym

Light **A**mplification by **S**timulated **E**mission of **R**adiation

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- Eye surgery (minimal bleeding)
- Measure Earth-Moon distance
- Create holograms

17.2 Diffraction Gratings

Nature's Definition

Diffraction grating: Large number of evenly-spaced parallel slits

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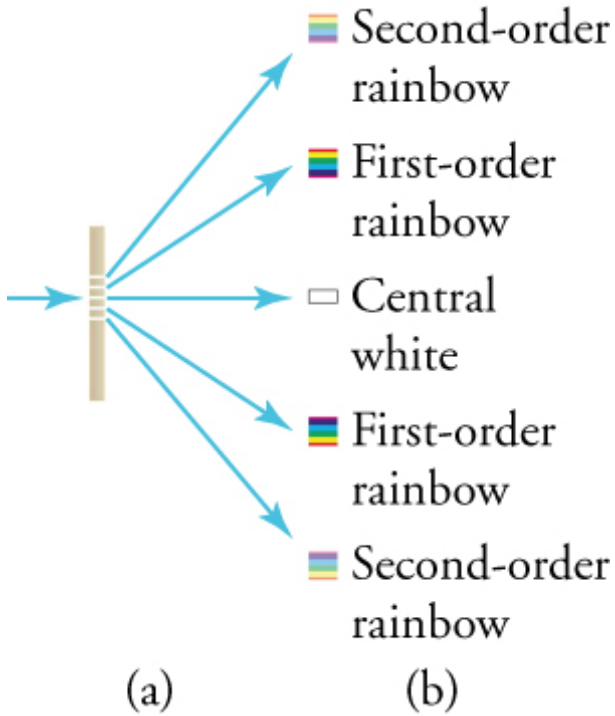

Figure: Light through grating produces sharper pattern than double slit

17.2 Natural Diffraction Gratings

(a) (b)

Figure: Australian opal and butterfly wings - natural reflection gratings

17.2 Grating vs Double Slit

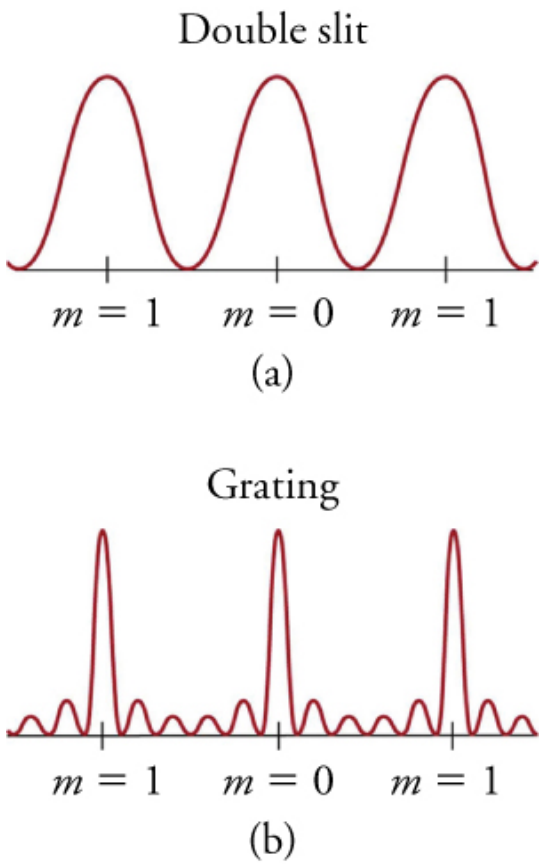

Figure: Intensity comparison: double slit (a) vs grating (b)

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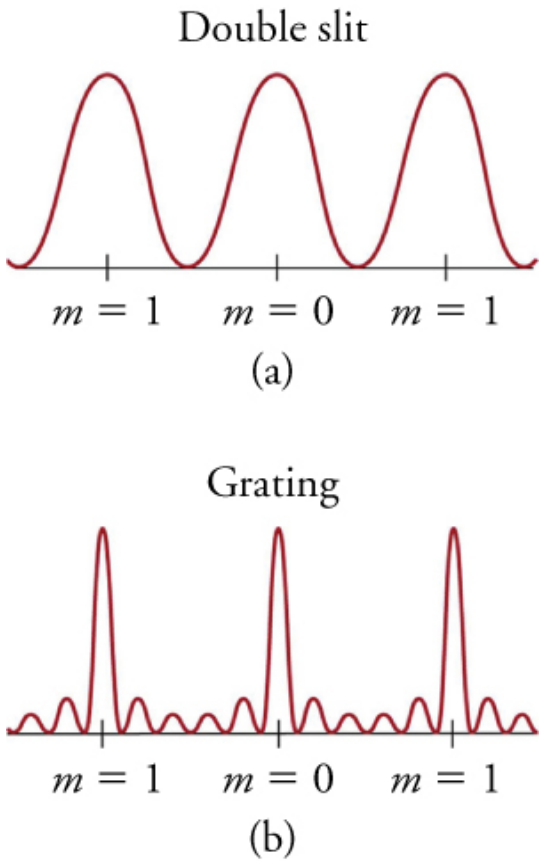

Figure: Intensity comparison: double slit (a) vs grating (b)

Key difference: More slits = narrower, brighter maxima

17.2 The CD as Diffraction Grating

Figure: CD holds data in spiral groove with 1,600 grooves per mm

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Figure: CD holds data in spiral groove with 1,600 grooves per mm

How it works:

- Grooves act as reflection grating
- Laser tracks along spiral
- Pits encode binary data (0s and 1s)
- Reflected beam goes to photodiode detector

17.2 Spectroscopes

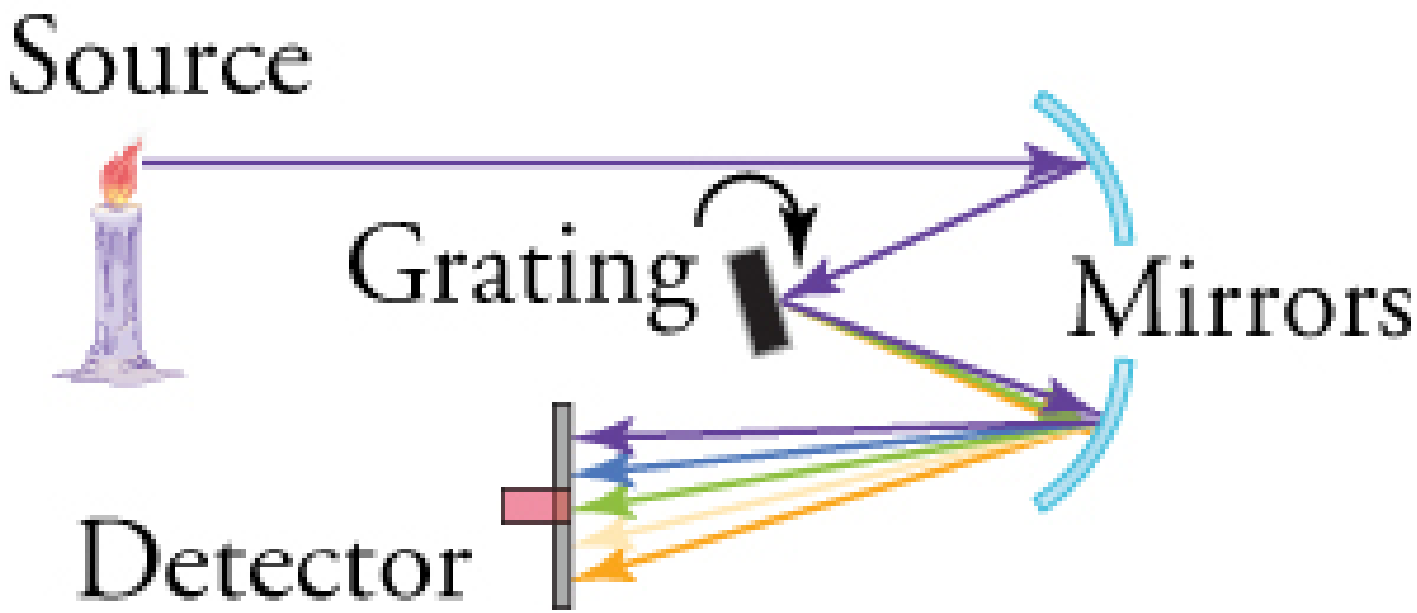

Figure: Diffraction grating separates light into component wavelengths

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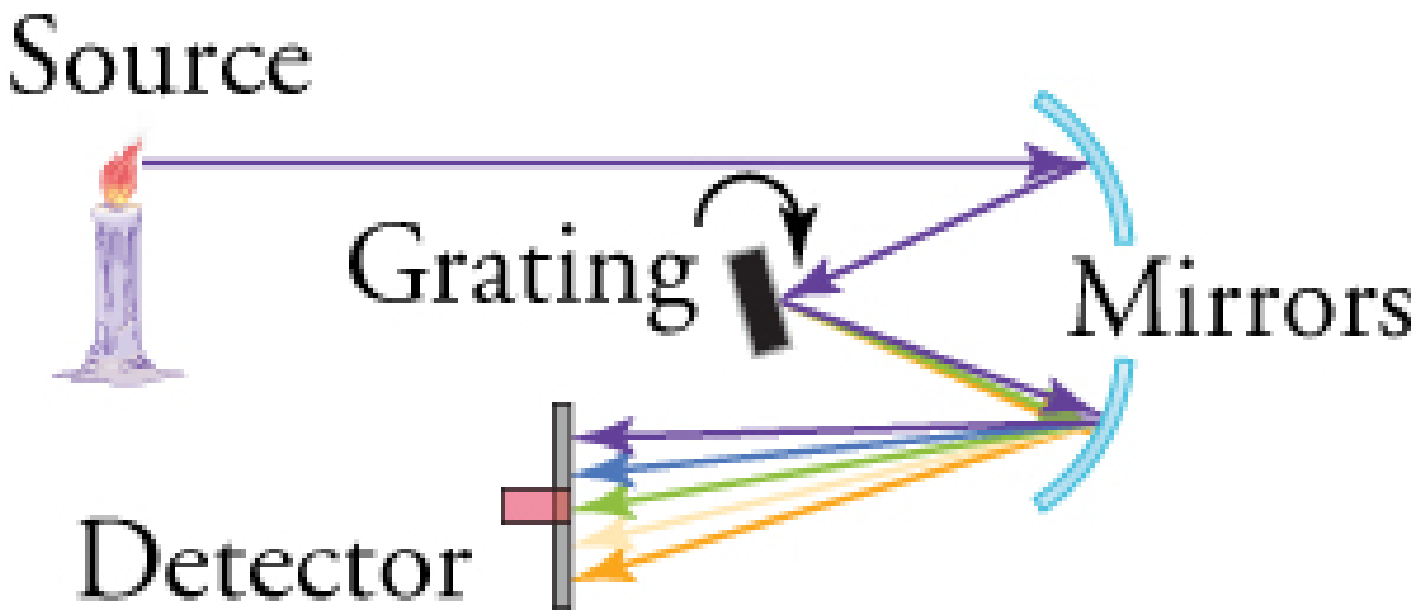

Figure: Diffraction grating separates light into component wavelengths

Uses:

- Identify chemical elements by spectrum
- Measure wavelengths of light from stars
- Analyze laser output

17.2 The Resolution Limit

Nature's Constraint

Diffraction limits detail we can observe in images

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Figure: Light through circular aperture produces fuzzy spot with rings

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The Paradox

Even perfect lens produces fuzzy images due to wave nature of light

17.2 The Rayleigh Criterion

Universal Law: Resolution Limit

Two images just resolvable when center of one diffraction pattern falls on first minimum of other

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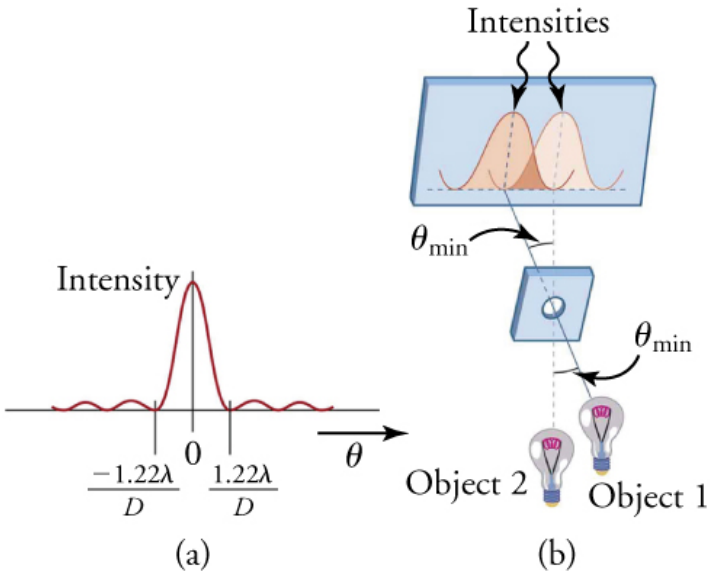

Figure: Rayleigh criterion for just-resolvable point sources

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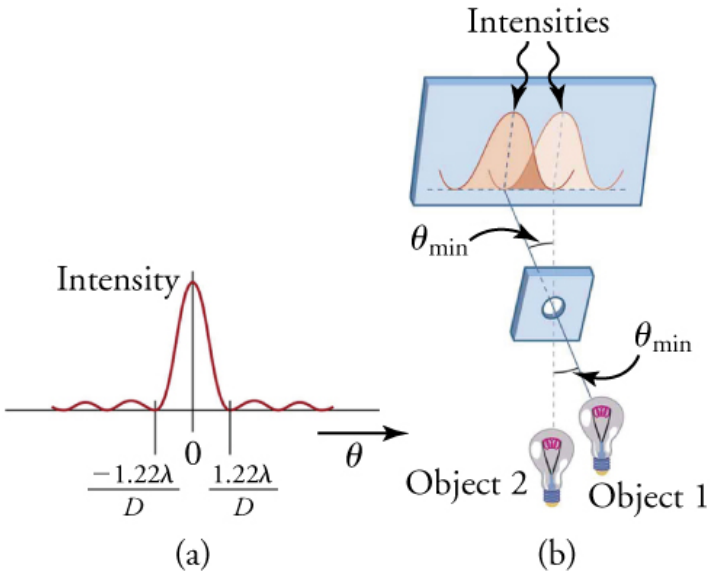

Figure: Rayleigh criterion for just-resolvable point sources

$$\angle\theta = 1.22\frac{\lambda}{D}$$

17.2 Real-World Limits

Diffraction limits:

- **Human eye:** Pupil diameter limits acuity

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- **Cameras:** Lens diameter affects sharpness

The Trade-off

Larger aperture = better resolution but heavier, more expensive

Attempt: Wavelength in Water

The Challenge (3 min, silent)

A monochromatic laser beam of green light with wavelength 550 nm in air enters water. Refractive index of water is 1.33.

Given:

- $\lambda = 550$ nm (in vacuum/air)
- $n = 1.33$ (water)

Find: Wavelength λ_n in water

Can you predict the wavelength shift? Work silently.

Compare: Medium Strategy

Turn and talk (2 min):

1. What happens to speed, wavelength, and frequency when light enters water?
2. Which equation relates wavelength in medium to wavelength in vacuum?
3. Does wavelength increase or decrease in water?

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Name wheel: One pair share your reasoning.

Reveal: Light Slows and Compresses

Self-correct in a different color:

Equation: $\lambda_n = \frac{\lambda}{n}$

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$$\boxed{\lambda_n = 414 \text{ nm}}$$

Check: Wavelength decreased ($550 \rightarrow 414$ nm). Color stays green because frequency constant!

Attempt: Diffraction Grating Angle

The Challenge (3 min, silent)

A diffraction grating has 2,000 lines per centimeter. Green light with wavelength 520 nm passes through.

Given:

- 2,000 lines/cm $\rightarrow$ $d = \frac{1\text{ cm}}{2000} = 5.00 \times 10^{-4}$ cm
- $\lambda = 520$ nm $= 520 \times 10^{-9}$ m
- $m = 1$ (first-order maximum)

Find: $\angle Angle \angle \theta$ for first-order maximum

Can you decode the angle? Work silently.

Compare: Grating Strategy

Turn and talk (2 min):

1. How did you calculate d from lines per cm?
2. Which equation relates d, $\angle\theta$, and λ for grating?
3. How did you solve for $\angle\theta$?

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$$\boxed{\angle\theta = 5.97^\circ}$$

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$$\boxed{\angle\theta = 5.97^\circ}$$

Check: Small $\angle angle - reasonable for first maximum$!

Attempt: Laser Beam Spread

The Challenge (3 min, silent)

A He-Ne laser beam (633 nm wavelength) is originally 1.00 mm in diameter.

Given:

- $\lambda = 633 \text{ nm} = 633 \times 10^{-9} \text{ m}$
- $D = 1.00 \text{ mm} = 1.00 \times 10^{-3} \text{ m}$

Find: Minimum angular spread $\angle\theta$ in radians and degrees

Can you predict the spreading? Work silently.

Compare: Beam Spread Strategy

Turn and talk (2 min):

1. Which equation gives minimum angular spread?
2. What does the diameter D represent?
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Check: Tiny spread - barely noticeable over short distances!

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5. Lasers produce coherent light via stimulated emission
6. Diffraction gratings separate wavelengths sharply
7. Resolution fundamentally limited by wave nature: $\angle\theta = 1.22\lambda/D$
8. Wavelength changes in media: $\lambda_n = \lambda/n$, but frequency constant

Key Equations

$$c = f\lambda \quad \text{(light in vacuum)} \tag{1}$$

$$\lambda_n = \frac{\lambda}{n} \quad \text{(wavelength in medium)} \tag{2}$$

$$d \sin \angle\theta = m\lambda \quad \text{(double-slit constructive)} \tag{3}$$

$$d \sin \angle\theta = \left(m + \frac{1}{2}\right)\lambda \quad \text{(double-slit destructive)} \tag{4}$$

$$D \sin \angle\theta = m\lambda \quad \text{(single-slit minima)} \tag{5}$$

$$\angle\theta = 1.22\frac{\lambda}{D} \quad \text{(Rayleigh criterion)} \tag{6}$$

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
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