PHYS11 CH:17 When Light Reveals Its Waves

Diffraction, Interference, and the Hidden Structure of Reality

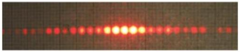
Mr. Gullo

December 2025

Outline

The Mystery of the Rainbow Disc

(a)



(b)

Figure: CD showing rainbow colors from white light

The Mystery of the Rainbow Disc

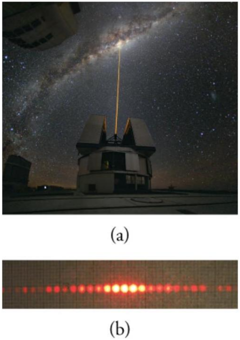


Figure: CD showing rainbow colors from white light

How does straw-colored plastic produce a rainbow?

The Dual Identity

Light behaves as both:

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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

$$\boxed{c = f\lambda}$$

Speed equals frequency times wavelength

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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

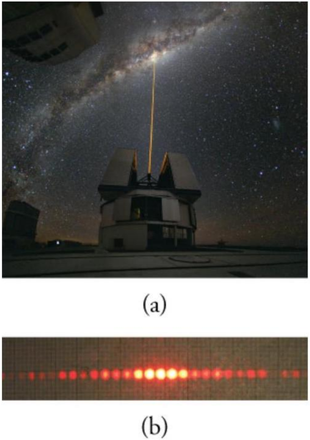

Figure: Laser beam as ray (straight line) and wave (interference pattern after slits)

17.1 Water Waves Show the Way

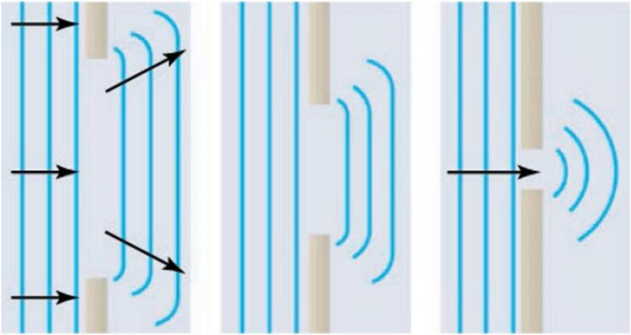

Figure: Water waves passing through gaps in rocks

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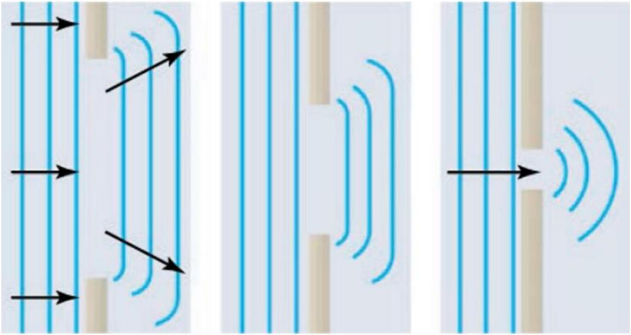

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Key observation: Gap width similar to wavelength causes interference pattern

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Real-World: Light in Water

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

17.1 Huygens's Principle

Nature's Rule for Wave Propagation

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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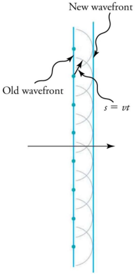

Figure: Wavefront emitting semicircular wavelets

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Answer: Wavelength compared to opening size

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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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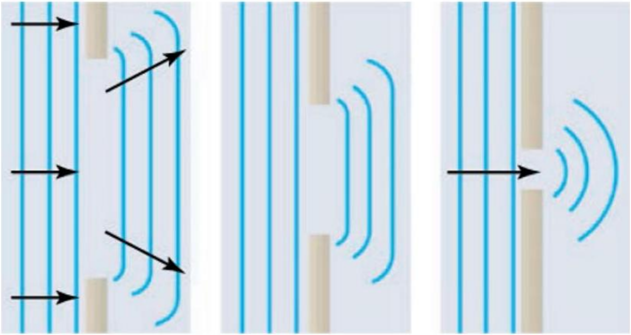

Figure: Huygens's principle applied to slit - edges bend

17.1 Ocean Waves Through Reef

Figure: Ocean waves diffracting through opening - visible interference pattern

17.1 Young's Revolutionary Experiment

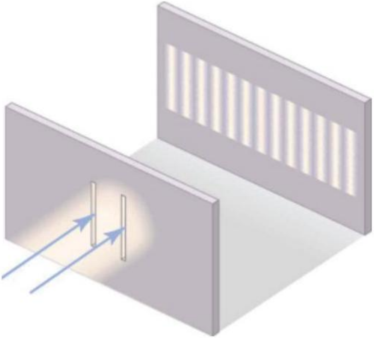

Figure: Double-slit experiment setup (1801)

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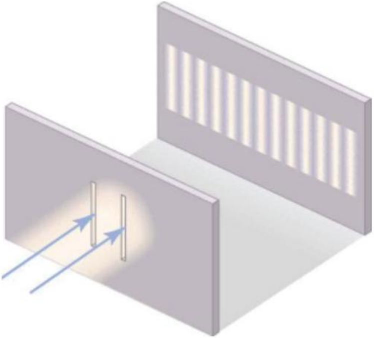

Figure: Double-slit experiment setup (1801)

Result: Vertical light and dark lines spread horizontally

17.1 The Interference Pattern

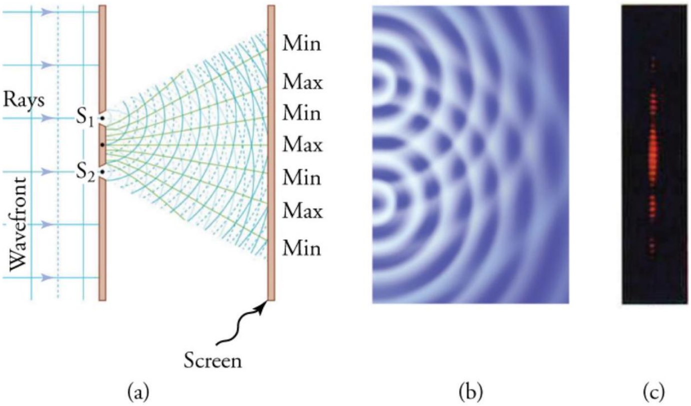

Figure: Double-slit interference: light diffracts from each slit, waves overlap and interfere

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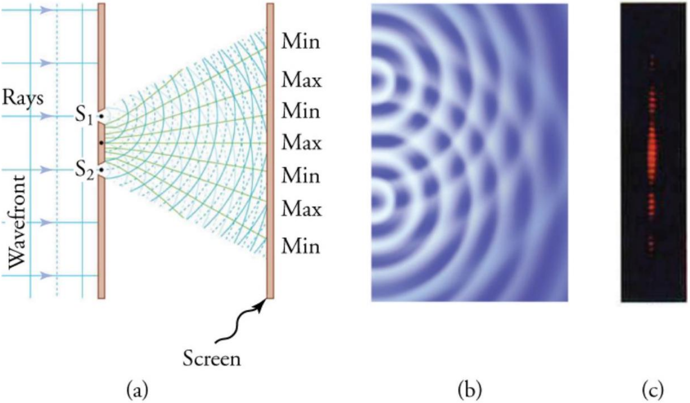

Figure: Double-slit interference: light diffracts from each slit, waves overlap and interfere

- **Constructive interference:** Crest meets crest → bright
- **Destructive interference:** Crest meets trough → dark

17.1 The Math of Double-Slit Interference

Universal Law: Constructive Interference

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

For $m = 0, \pm1, \pm2, \pm3, \ldots$ (order of maximum)

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Universal Law: Constructive Interference

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

For $m = 0, \pm1, \pm2, \pm3, \ldots$ (order of maximum)

Universal Law: Destructive Interference

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

For $m = 0, \pm1, \pm2, \ldots$ (order of minimum)

17.1 Path Difference Geometry

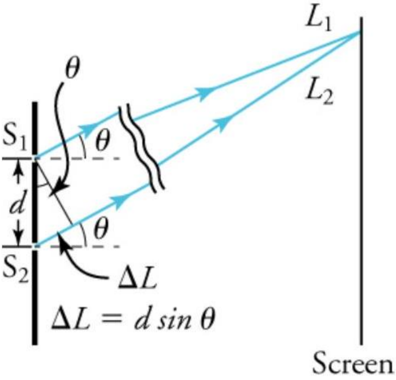

Figure: Path difference $\Delta L = d \sin \theta$

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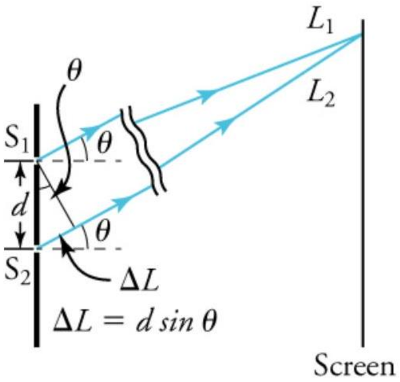

Figure: Path difference $\Delta L = d \sin\theta$

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

17.1 Intensity Pattern

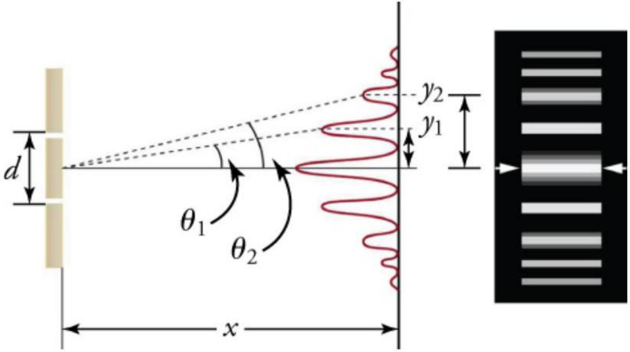

Figure: Intensity decreases with angle from center

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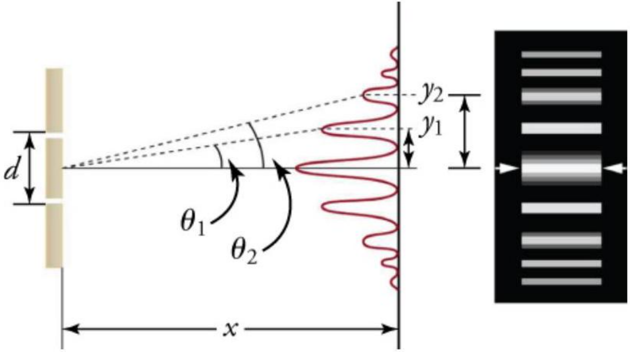

Figure: Intensity decreases with angle from center

Observation: Central maximum brightest, intensity falls off to sides

17.1 Single-Slit Diffraction

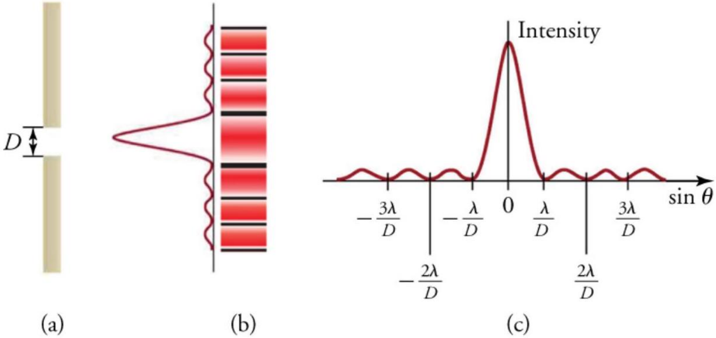

Figure: Single slit produces wider central maximum with dimmer side maxima

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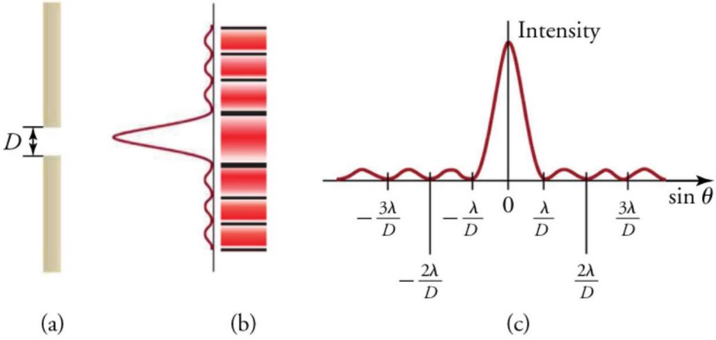

Figure: Single slit produces wider central maximum with dimmer side maxima

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

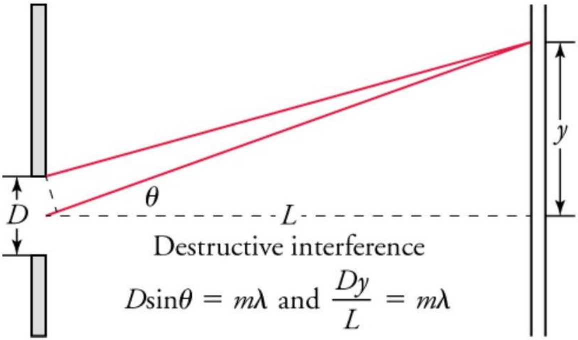

Figure: Ray diagram showing destructive interference for single slit

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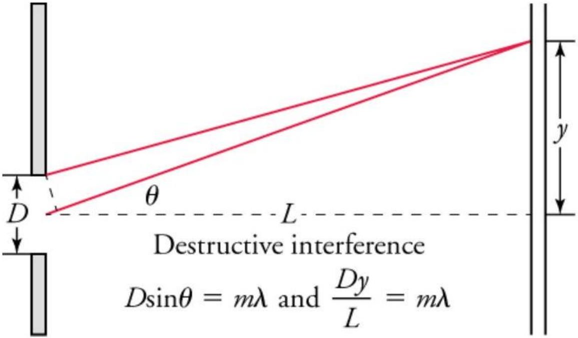

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Universal Law: Single-Slit Minima

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

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:

- $d = 0.0100 \text{ mm} = 1.00 \times 10^{-5} \text{ m}$
- $\theta = 10.95^\circ$
- $m = 3$ (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: $d \sin\theta = m\lambda$

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Substitute: $\lambda = \frac{(1.00\times10^{-5}\ \mathrm{m})(\sin 10.95^\circ)}{3}$

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$$\lambda = \frac{(1.00 \times 10^{-5})(0.190)}{3} = 6.33 \times 10^{-7}\ \text{m}$$

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$$\boxed{\lambda = 633\ \text{nm}}$$

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:

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

Find: Slit width D in micrometers

Can you decode the slit width? Work silently.

Turn and talk (2 min):

1. What's the difference between single-slit and double-slit equations?
2. How did you solve for D?
3. What units did you get?

Compare: Single-Slit Strategy

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Equation: $D \sin\theta = m\lambda$

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Self-correct in a different color:

Equation: $D \sin\theta = m\lambda$

Rearrange: $D = \frac{m\lambda}{\sin\theta}$

Reveal: The Narrow Slit

Self-correct in a different color:

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Rearrange: $D = \frac{m\lambda}{\sin\theta}$

Substitute: $D = \frac{2(550 \times 10^{-9}\ \text{m})}{\sin 45.0^\circ}$

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Rearrange: $D = \frac{m\lambda}{\sin\theta}$

Substitute: $D = \frac{2(550\times10^{-9}\text{ m})}{\sin 45.0^\circ}$

$$D = \frac{1100 \times 10^{-9}}{0.707} = 1.56 \times 10^{-6}\text{ m}$$

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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

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- Photon hits excited atom

17.2 The Birth of the Laser

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The Acronym

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

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Properties:

- Directional (doesn't spread much)

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- Create holograms

17.2 Diffraction Gratings

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Diffraction grating: Large number of evenly-spaced parallel slits

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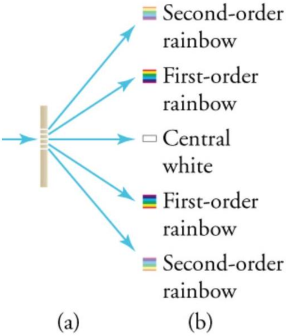

Figure: Light through grating produces sharper pattern than double slit

17.2 Natural Diffraction Gratings

(a) (b)

Figure: Australian opal and butterfly wings - natural reflection gratings

17.2 Grating vs Double Slit

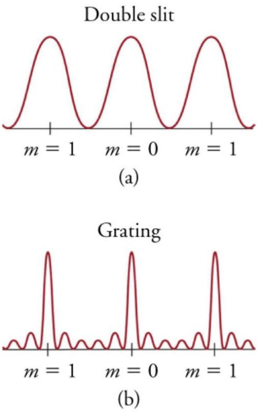

Figure: Intensity comparison: double slit (a) vs grating (b)

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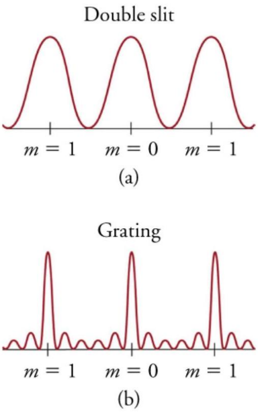

Figure: Intensity comparison: double slit (a) vs grating (b)

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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How it works:

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- Pits encode binary data (0s and 1s)
- Reflected beam goes to photodiode detector

Figure: Diffraction grating separates light into component wavelengths

17.2 Spectroscopes

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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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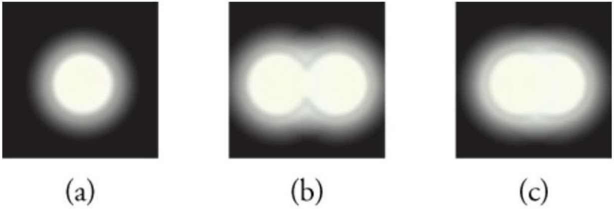

Figure: Light through circular aperture produces fuzzy spot with rings

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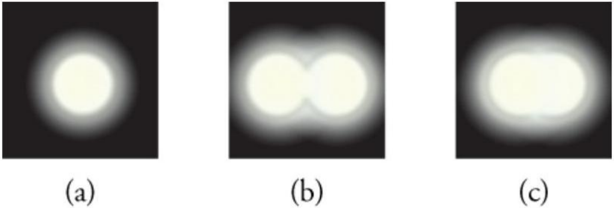

Figure: Light through circular aperture produces fuzzy spot with rings

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

Universal Law: Resolution Limit

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

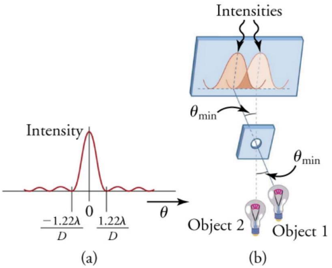

Figure: Rayleigh criterion for just-resolvable point sources

Universal Law: Resolution Limit

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

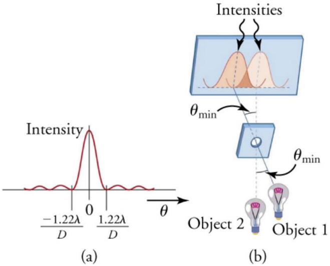

Figure: Rayleigh criterion for just-resolvable point sources

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

Diffraction limits:

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

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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?
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Name wheel: One pair share your reasoning.

Reveal: Light Slows and Compresses

Self-correct in a different color:

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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 θ 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, θ, and λ for grating?
3. How did you solve for θ?

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

Check: Small 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 θ 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?
3. How did you convert radians to degrees?

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Convert: $\theta = (7.72 \times 10^{-4})(57.3^\circ/\text{rad}) = \boxed{0.0442^\circ}$

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Convert: $\theta = (7.72 \times 10^{-4})(57.3^\circ/\text{rad}) = \boxed{0.0442^\circ}$
Check: Tiny spread - barely noticeable over short distances!

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7. Resolution fundamentally limited by wave nature: $\theta = 1.22\lambda/D$
8. Wavelength changes in media: $\lambda_n = \lambda/n$, but frequency constant

Key Equations

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

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

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

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

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

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

Homework

Complete the assigned problems

posted on the LMS