

Waves Sound and Physical Optics

Follow the original lesson progression: traveling waves and graphs, electromagnetic waves, boundary behavior, polarization, Doppler, superposition, standing waves, then diffraction and interference. Keep the side-by-side comparisons that prevent separate memorization.

TEACHING ROUTE

The explanations follow the original lesson sequence. Connections, analogies and worked reasoning remain together. Syllabus additions appear beside the ideas they support.

Lesson group	Focus
Traveling waves	Particle motion, graphs, EM spectrum and boundaries
Combining waves	Doppler, superposition, beats and standing modes
Physical optics	Diffraction first; double slit, grating, then single-slit minima
Thin films and review	Count reflection phase changes, compare cases, then practice

Predict first, draw the situation, then calculate. Use the class questions for discussion and the chapter review for independent practice. Unless stated otherwise, numerical examples use idealized models and the assumptions given on the page.

Source keys N01, N02, and so on refer to the original PDF files listed near the end of this chapter. Source page numbers count PDF pages. CED means the supplied 2026 AP Physics 2 Course and Exam Description.

What travels when a wave travels?

A pulse is one localized disturbance; a periodic wave repeats. In the ideal wave model, the disturbance and energy travel while medium particles oscillate around equilibrium rather than being carried from source to receiver. A mechanical wave requires a medium; an electromagnetic wave does not.

Type	Disturbance relative to propagation	Example
Transverse	Perpendicular	Displacement of a stretched string; electric field of light.
Longitudinal	Parallel	Sound in air: pressure/density compressions and rarefactions.

RELATIONSHIP AND CONDITIONS

String-wave speed: $v = \sqrt{F_T/\mu}$, where $\mu = m/L$

For a fixed medium, wave speed depends primarily on the medium's properties, not on the source frequency.

Tension F_T supplies a restoring influence; linear density μ supplies inertia. Increasing tension speeds up disturbances, while increasing mass per length slows them down. Sound speed in a gas generally increases with absolute temperature for fixed composition. In the usual linear model, changing how hard a source oscillates changes amplitude rather than wave speed.

Worked example

A string has mass 0.020 kg over 2.0 m, so $\mu = 0.010$ kg/m. Under 40 N tension, $v = \sqrt{(40/0.010)} = \mathbf{63.2}$ m/s. Quadrupling the tension doubles speed; quadrupling μ halves it.

Teaching check

A floating marker moves up and down as a small water wave passes. The pattern travels across the water; the marker's repeated motion is not the wave's propagation speed. Real fluids can also have currents, which are a separate motion.

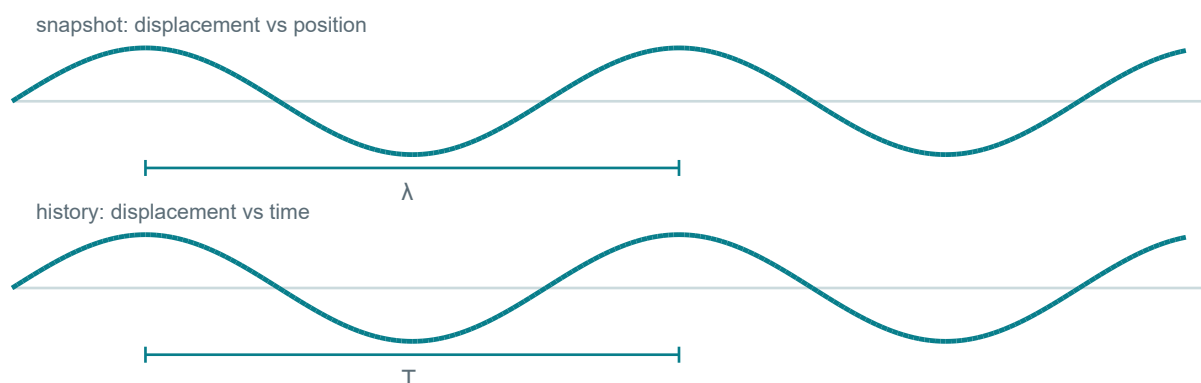
Read a wave graph before using it

RELATIONSHIP AND CONDITIONS

$$f = 1/T; v = f\lambda$$

A sinusoidal history at one location: $y(t) = A \cos(2\pi t/T + \phi)$

A snapshot at one time: $y(x) = A \cos(2\pi x/\lambda + \phi)$.



Top: a snapshot gives wavelength from a distance interval. Bottom: a time record gives period from a time interval. A crest-to-trough interval is half a cycle, not a whole cycle.

Amplitude A is the largest displacement from equilibrium. Wavelength λ is the distance between neighboring points in the same phase, such as crest to crest. Period T is the time between successive repetitions at one point. Frequency determines pitch for sound; amplitude is associated with loudness. The vertical axis of a sound graph may be pressure variation rather than particle displacement.

Worked example

A wave repeats every 0.020 s and has crests 0.80 m apart. $f = 50 \text{ Hz}$ and $v = 40 \text{ m/s}$. If its amplitude doubles while the linear medium is unchanged, neither f nor v must change. The energy transport increases.

Extension: $y(x,t) = A \cos(kx - \omega t + \phi)$ travels in $+x$; replacing $-\omega t$ by $+\omega t$ reverses travel direction. Here $k = 2\pi/\lambda$ and $\omega = 2\pi f$. A snapshot alone generally does not tell which way the wave travels.

Electromagnetic waves and the spectrum

A plane electromagnetic wave consists of oscillating electric and magnetic fields, mutually perpendicular and perpendicular to the direction of propagation. In vacuum, all electromagnetic wavelengths travel at $c \approx 3.00 \times 10^8$ m/s. Different colors do not have different vacuum speeds.

RELATIONSHIP AND CONDITIONS

In vacuum: $c = f\lambda$

Order from longest wavelength / lowest frequency to shortest wavelength / highest frequency:

radio → **microwave** → **infrared** → **visible** → **ultraviolet** → **X-ray** → **gamma ray**

Visible ordering	Relative wavelength	Relative frequency
Red → orange → yellow → green → blue → violet	Decreases along the sequence	Increases along the sequence

Worked example

A radio wave has $f = 1.00 \times 10^8$ Hz. $\lambda = c/f = \mathbf{3.00\text{ m}}$. Green light with vacuum wavelength 500 nm has frequency $\mathbf{6.00 \times 10^{14}\text{ Hz}}$. Their frequencies differ enormously, but both travel at c in vacuum.

Wavefronts join points of equal phase. Plane waves have planar wavefronts and parallel rays perpendicular to those fronts in a uniform isotropic medium. A point source can instead produce approximately spherical fronts. Far from a small source, a small portion of a spherical front can be approximated as planar.

Exact category boundary wavelengths are not required by the supplied CED. Memorize the ordering and qualitative scale, not a table of arbitrary dividing values. In a material, speed depends on refractive index and may depend on frequency; that is dispersion, covered in geometric optics.

Link to Unit 15

Interference and polarization support the wave model. Photoelectric emission and Compton scattering require photon energy and momentum. These are complementary descriptions of light used for different observations.

Reflection, transmission and intensity

At a boundary, part of a wave can reflect and part transmit. A displacement pulse reflecting from a fixed end inverts; at a free end it does not. For strings under equal tension, reflection from a heavier, slower string is inverted; reflection toward a lighter, faster string is not. The transmitted displacement pulse is not inverted in the usual joined-string model.

RELATIONSHIP AND CONDITIONS

Across a stationary boundary: $f_1 = f_2$

Thus $\lambda_2/\lambda_1 = v_2/v_1$.

Intensity I = average power / area, measured in W/m^2 .

If a wave enters a slower medium, the wavelength decreases because the interface must keep oscillating at the driving frequency. The reflected wave remains in the original medium and keeps that medium's wave speed. Reduced transmitted amplitude can mean energy was reflected or absorbed; it does not mean the source frequency changed.

Worked example

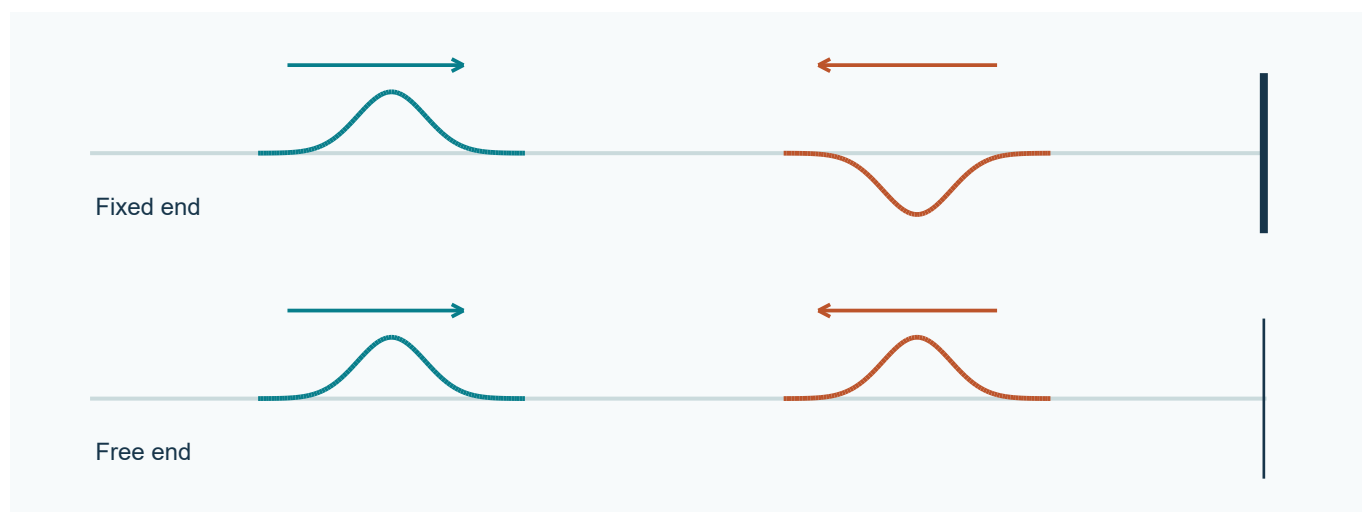
A 20 Hz wave travels at 8.0 m/s before a boundary and 5.0 m/s after it. Its wavelength changes from **0.40 m** to **0.25 m**; its frequency remains **20 Hz**.

For many linear waves at fixed frequency and medium, intensity is proportional to amplitude squared. Doubling amplitude then gives four times the intensity. For an isotropic point source without absorption, $I = P/(4\pi r^2)$, so doubling distance gives one quarter the intensity. These useful scaling extensions require their stated assumptions.

Energy needs a specified comparison

For a sinusoidal mechanical wave at fixed displacement amplitude and medium, increasing frequency increases energy transport. For electromagnetic waves at fixed field amplitude, classical intensity is set by field amplitude; photon energy separately increases with frequency. Avoid a blanket claim that frequency alone determines every wave's total energy.

The original boundary comparison: fixed, free, heavy, light



At a fixed end an upward incident displacement pulse returns inverted. At a free end it returns upright.

Boundary	Reflected displacement	Physical connection
Fixed endpoint	Inverted	Endpoint must stay at zero displacement
Free endpoint	Not inverted	Endpoint can move; transverse slope is zero in the ideal model
Light string $\rightarrow$ heavy string, equal tension	Inverted	Transmitted speed is smaller
Heavy string $\rightarrow$ light string, equal tension	Not inverted	Transmitted speed is larger

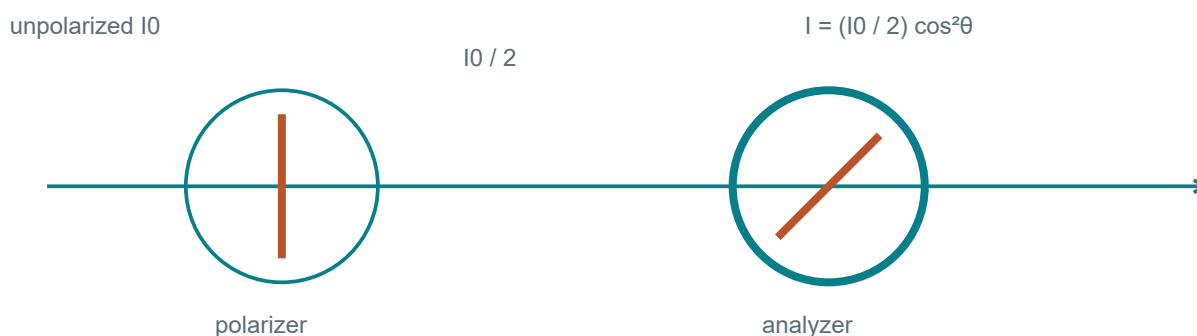
The source's heavy/light comparison refers to linear mass density, with the same tension. A transmitted wave in the joined-string model remains upright. Its wavelength changes with its speed; its frequency remains the source frequency.

PAUSE AND EXPLAIN

Does an inverted reflected pulse mean the wave's energy became negative? No. Inversion changes displacement sign and phase. Energy is still nonnegative and is distributed between reflected and transmitted waves.

Polarization isolates an oscillation direction

A transverse wave has possible oscillation directions perpendicular to travel. A polarizer selects a direction from them. Reflection and transmission at an interface can also preferentially select an oscillation direction; polarized sunglasses reduce glare associated with reflected light. An ideal longitudinal wave has no comparable transverse oscillation direction to select, so ordinary longitudinal sound cannot be polarized this way. Polarization of light is evidence that light is transverse.



After an ideal first polarizer, initially unpolarized light has half its original intensity. A second analyzer transmits the component aligned with its axis.

RELATIONSHIP AND CONDITIONS

Useful quantitative extension:

Initially unpolarized light through an ideal polarizer: $I_1 = I_0 / 2$

Linearly polarized light through an analyzer: $I = I_{in} \cos^2 \theta$ (Malus's law).

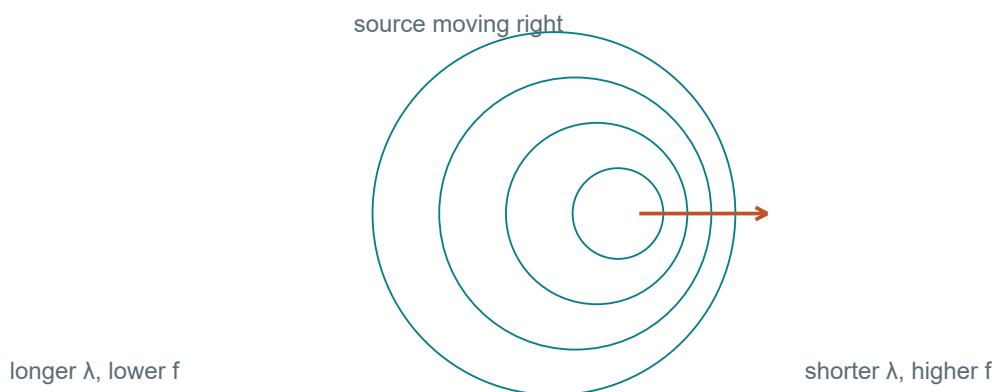
Parallel transmission axes give the greatest transmission from the first polarizer; perpendicular axes block it in the ideal model. Inserting a third polarizer at an intermediate angle between crossed polarizers can permit light through: the polarization direction is changed in stages. This is not ordinary light “bending around” the second polarizer.

Worked extension

Unpolarized light of intensity 80 W/m^2 passes through an ideal polarizer and an analyzer at 60° . First $I = 40 \text{ W/m}^2$; then $I = 40 \cos^2 60^\circ = 10 \text{ W/m}^2$. Applying the $1/2$ factor again at the second filter would be wrong because its input is already polarized.

The supplied CED requires the polarization concept and its connection to intensity reduction. Malus's-law calculations are included to support the original polarization notes, and are labeled here as an extension.

The Doppler effect



The moving source emits successive wavefronts from different positions. Fronts crowd ahead and spread behind. The source does not increase the wave speed in a stationary medium.

If source and observer approach one another along the relevant line of sight, the observed frequency is higher than the source's rest frequency. If they separate, it is lower. A greater approach/recession speed produces a larger shift in the usual subsonic sound situations. With equal source and observer velocities along the same line through a still medium, there is no frequency shift.

For a moving sound source, the spacing of emitted fronts in the medium changes. For an observer moving through an otherwise unchanged wave pattern, fronts are encountered at a different rate. These mechanisms differ, although both can alter observed pitch. A source traveling sideways need not produce the same shift as a source approaching head-on; use the motion along the observation direction.

Predict without an equation

An ambulance approaches, passes and recedes. Before passing its sound is higher in pitch than the rest tone; afterward it is lower. The source's emitted frequency can remain constant. The observed pitch change is not evidence that the siren itself slowed its oscillation.

Extension for one-dimensional sound in a still medium: $f_{\text{obs}} = f_{\text{source}} (v + v_{\text{observer, toward}}) / (v - v_{\text{source, toward}})$. The velocities are signed relative to the medium with the named toward directions. This formula is not the light Doppler formula and is not required for the supplied AP Physics 2 topic.

Source motion and observer motion: keep the two pictures

Situation in a still medium	What changes?	What stays fixed?
Source approaches stationary observer	Wavefront spacing ahead gets shorter	Sound speed relative to the medium
Source recedes	Wavefront spacing behind gets longer	Source oscillation frequency can stay fixed
Observer approaches stationary source	Fronts encountered more rapidly	Wavefront spacing in the medium
Observer recedes	Fronts encountered less rapidly	Wavefront spacing in the medium

RELATIONSHIP AND CONDITIONS

Observed frequency = rate at which wavefronts are encountered

The original notes use $f = \text{speed}/\text{spacing}$ in both pictures. For a moving observer, the speed in that encounter-rate reasoning is the relative speed of wavefronts past the observer. It is not a change in the sound speed measured relative to the air.

CLASSROOM PREDICTION

A listener runs toward a stationary loudspeaker. Are the physical wavefronts compressed in the air? No. The listener crosses the unchanged fronts faster. This distinguishes the observer case from the moving-source case.

The CED requires qualitative Doppler reasoning. Quantitative sound formulas are a labeled extension, and must not be applied to light.

Superposition, path difference and beats

RELATIONSHIP AND CONDITIONS

Net displacement: $y_{\text{net}} = y_1 + y_2 + \dots$

For two in-phase sources: constructive when $\Delta r = m\lambda$; destructive when $\Delta r = (m + \frac{1}{2})\lambda$.

Beat frequency: $f_{\text{beat}} = |f_1 - f_2|$.

Add signed displacements, not intensities, to find the instantaneous resulting disturbance. Equal displacements in the same direction reinforce; equal opposite displacements cancel. Pulses continue through one another after overlap in a linear medium. Temporary cancellation does not annihilate the waves or violate energy conservation.

Stable interference requires a stable relative phase, often obtained by splitting one source. The path-difference rules above assume the sources start in phase; an additional phase difference shifts the constructive/destructive conditions. Complete destructive interference also requires equal amplitudes at the observation point.

Worked example: two speakers

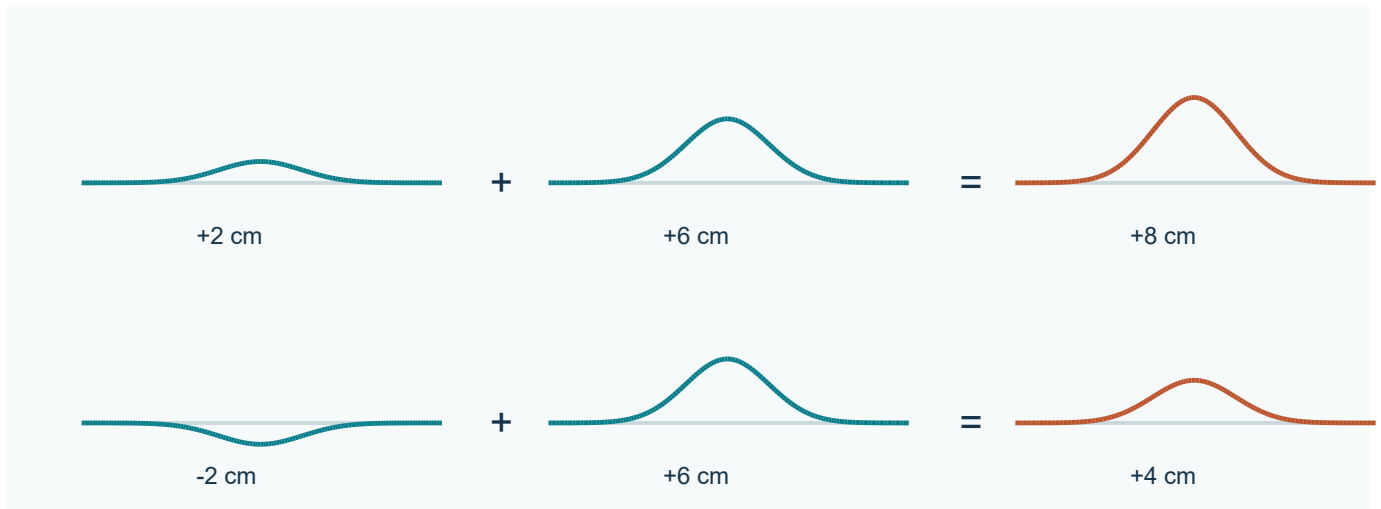
In-phase speakers emit sound of wavelength 0.40 m. At a point with path difference 0.80 m, $\Delta r = 2\lambda$, so interference is **constructive**. At a point with path difference 0.60 m, $\Delta r = 1.5\lambda$, so it is **destructive** in the equal-amplitude idealization.

Worked example: tuning with beats

A 256 Hz tuning fork and a nearby unknown fork produce 4 beats/s. The unknown frequency could be **252 Hz or 260 Hz**. If slightly lowering the unknown frequency reduces the beat rate, it started above 256 Hz. Beat rate alone does not determine which side of the reference it lies on.

Beats are slow amplitude variations caused by nearby frequencies repeatedly moving into and out of phase. The rapid oscillation remains near their mean frequency. Counting every positive and negative envelope extremum as a separate audible beat would double-count the beat rate.

The original pulse sums: add displacement point by point



At complete overlap, $+2\text{ cm}$ and $+6\text{ cm}$ give $+8\text{ cm}$; -2 cm and $+6\text{ cm}$ give $+4\text{ cm}$.

The operation is an algebraic sum of displacements at the same position and time. After overlap, each ideal linear pulse continues in its original direction and with its original shape. A smaller temporary resultant does not mean one pulse has permanently lost height.

RELATIONSHIP AND CONDITIONS

Same sign: $+2\text{ cm} + 6\text{ cm} = +8\text{ cm}$

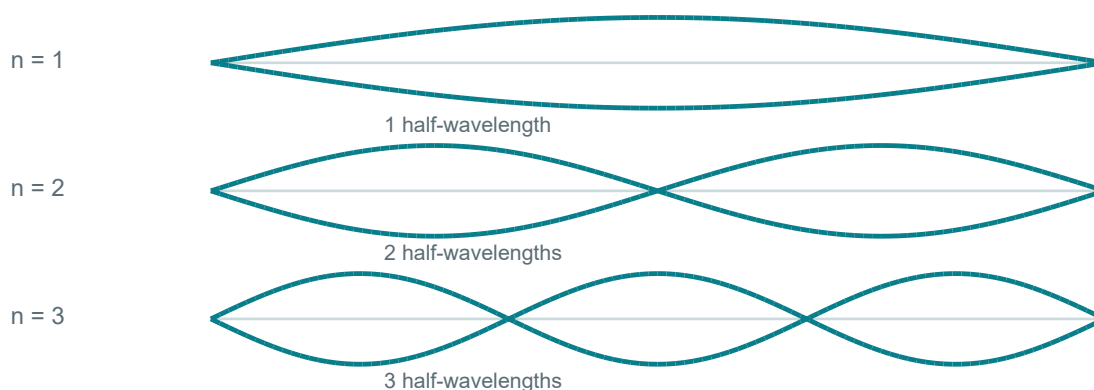
Opposite signs: $-2\text{ cm} + 6\text{ cm} = +4\text{ cm}$

For in-phase periodic sources, compare total path lengths to the observation point. Paths of 6λ and 7λ arrive in phase; paths of 6λ and 6.5λ arrive half a cycle apart. It is the difference, not the absolute length of either path, that determines the relative phase.

PAUSE AND EXPLAIN

Two equal opposite pulses momentarily make a flat string. Has energy disappeared? No. At that instant energy can be in the medium's motion even when its displacement is zero.

Standing waves on strings



For a string fixed at both ends, n counts half-wavelength segments. Two curves show opposite extreme shapes; every point between nodes also passes through equilibrium.

RELATIONSHIP AND CONDITIONS

Fixed-fixed string: $L = n\lambda_n/2$, $\lambda_n = 2L/n$

$f_n = nv/(2L)$, $n = 1, 2, 3, \dots$

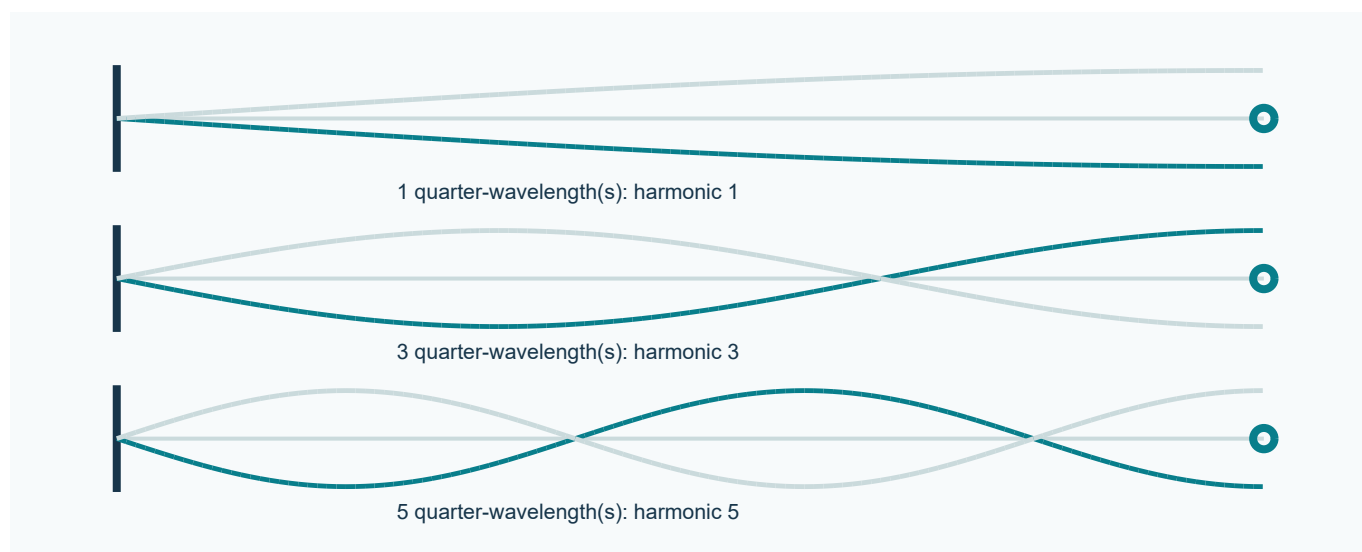
A standing wave forms from equal-frequency waves traveling in opposite directions. A node stays at zero displacement. An antinode has the largest oscillation amplitude; it is not permanently at its maximum displacement. Neighboring nodes are $\lambda/2$ apart; a node and its nearest antinode are $\lambda/4$ apart.

Worked example

A 0.80 m string has wave speed 120 m/s and fixed endpoints. Its fundamental is $f_1 = 120/(2 \times 0.80) = \mathbf{75 \text{ Hz}}$. The third harmonic is **225 Hz**, with $\lambda_3 = \mathbf{0.533 \text{ m}}$, three antinodes and four nodes including the ends.

Doubling string tension doubles neither frequency nor speed: both scale with $\sqrt{F_T}$ at fixed length and density. To double a given harmonic's frequency, quadruple tension. Shortening a string increases the harmonic frequencies because fewer wavelengths fit into a given length.

Mixed ends: the source's fixed-free sequence



A fixed end is a node and a free end an antinode. The first three allowed modes contain 1, 3 and 5 quarter-wavelengths.

RELATIONSHIP AND CONDITIONS

$$L = n\lambda/4; f_n = nv/(4L), n = 1, 3, 5, \dots$$

Build the diagrams by preserving the two endpoint conditions, then insert an extra half-wavelength for each new mode. The sequence is first, third, fifth, seventh harmonic. Calling the second allowed shape “second harmonic” gives the wrong frequency.

Example: $v = 80$ m/s and $L = 0.50$ m give $f_1 = 40$ Hz, followed by 120 Hz and 200 Hz. The spacings between successive allowed frequencies are 80 Hz, which is twice the fundamental.

TRANSFER THE PICTURE TO AIR COLUMNS

A closed pipe end is a displacement node; an open end is a displacement antinode. The same quarter-wave construction works. Pressure nodes and antinodes are opposite to displacement nodes and antinodes.

Standing sound waves and boundary conditions

Tube / string endpoints	Displacement condition	Allowed frequencies
Open-open tube	Antinodes at both open ends	$f_n = nv/(2L)$, all positive integers n
Closed-closed tube	Nodes at both closed ends	$f_n = nv/(2L)$, all positive integers n
Closed-open tube	Node at closed end; antinode at open end	$f_n = nv/(4L)$, $n = 1, 3, 5, \dots$
Fixed-free string	Node at fixed end; antinode at free end	Same odd-harmonic pattern as mixed tube ends

For sound in a tube, displacement and pressure boundary patterns are opposite: an open end is approximately a displacement antinode and pressure node; a closed rigid end is a displacement node and pressure antinode. First identify what quantity the diagram's vertical displacement represents. A pressure-wave sketch can look inverted relative to an air-displacement sketch without being wrong.

RELATIONSHIP AND CONDITIONS

Closed-open tube: fundamental $\lambda_1 = 4L$

Successive allowed resonances: $f_1, 3f_1, 5f_1, \dots$

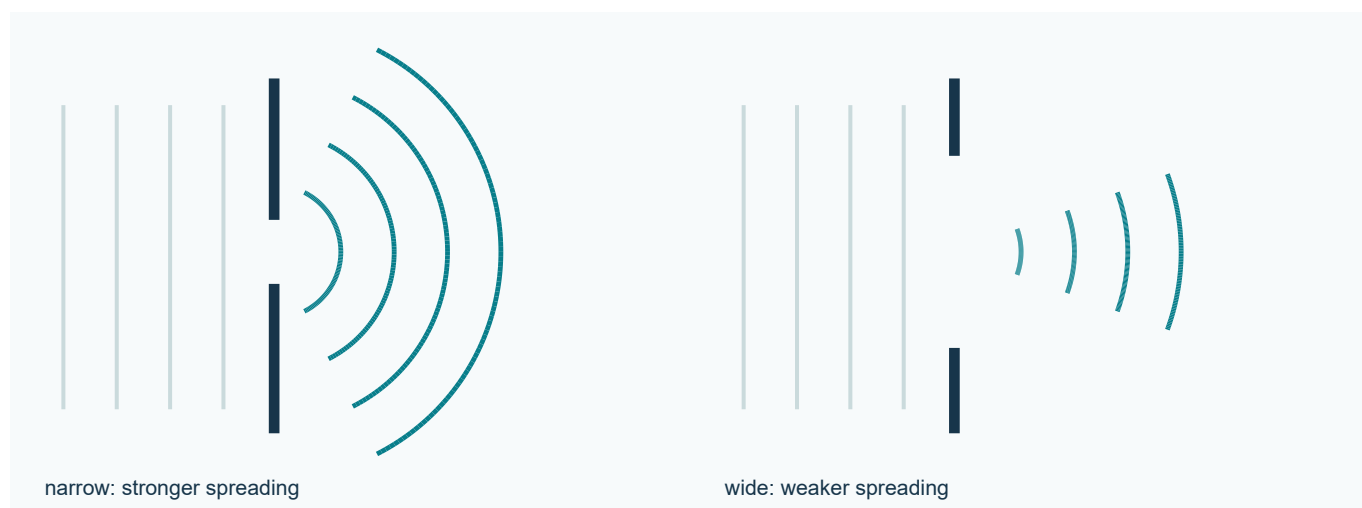
The second allowed mode is the third harmonic, not the second harmonic.

Worked example

A tube is closed at one end with $L = 0.25$ m, and sound speed is 340 m/s. Fundamental $f_1 = \mathbf{340\text{ Hz}}$; the next two ideal resonances are **1020 Hz** and **1700 Hz**. Opening the closed end changes the fundamental to **680 Hz**, with all integer harmonics allowed.

Real open tubes have a small end correction because the displacement antinode lies slightly beyond the physical opening. The ideal formulas ignore this unless information is supplied. Resonance measurements can test whether such a correction matters.

Diffraction before formulas: sound around a doorway



Schematic outgoing wavefronts and angular spreading. Circular curvature represents the same isotropic propagation speed. The aperture width relative to wavelength controls the angular range of appreciable intensity.

The original classroom picture places a sound source inside a room and a listener outside, away from a direct ray. Sound spreads around the doorway. With sound speed 330 m/s and frequency 300 Hz, $\lambda = v/f = 1.1$ m, comparable to a typical doorway width.

Visible light has a wavelength hundreds of nanometers long, far smaller than the doorway. Its spreading angle is correspondingly tiny. This explains why hearing around the door is easy while seeing the source directly through the wall is not.

RELATIONSHIP AND CONDITIONS

At fixed opening width: larger $\lambda \rightarrow$ more spreading

At fixed λ : narrower opening $\rightarrow$ more spreading

A CAREFUL QUALITATIVE STATEMENT

Diffraction does not suddenly switch on at one exact width. Its angular spread grows as the width-to-wavelength ratio decreases. Small transmitted power through a very small opening is a different issue from broad angular spreading.

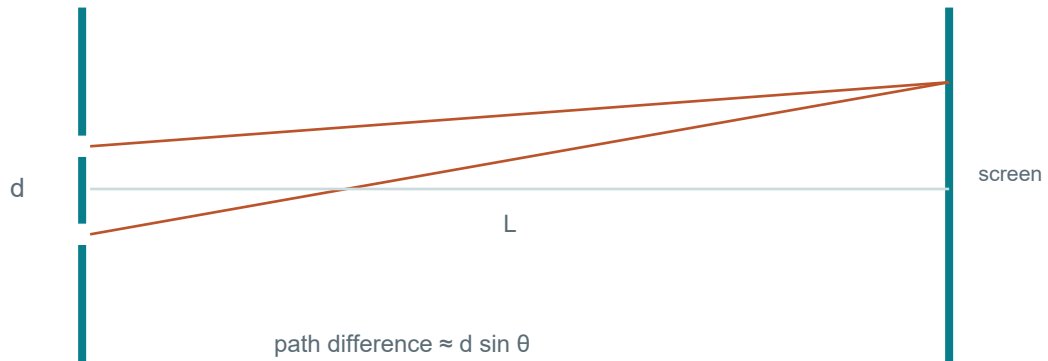
Young's double-slit interference

RELATIONSHIP AND CONDITIONS

Bright fringes: $d \sin \theta = m\lambda$, $m = 0, \pm 1, \pm 2, \dots$

Dark fringes for equal slits: $d \sin \theta = (m + \frac{1}{2})\lambda$

Small angles: $y_{\text{bright}} \approx m\lambda L/d$; fringe spacing $\Delta y \approx \lambda L/d$.



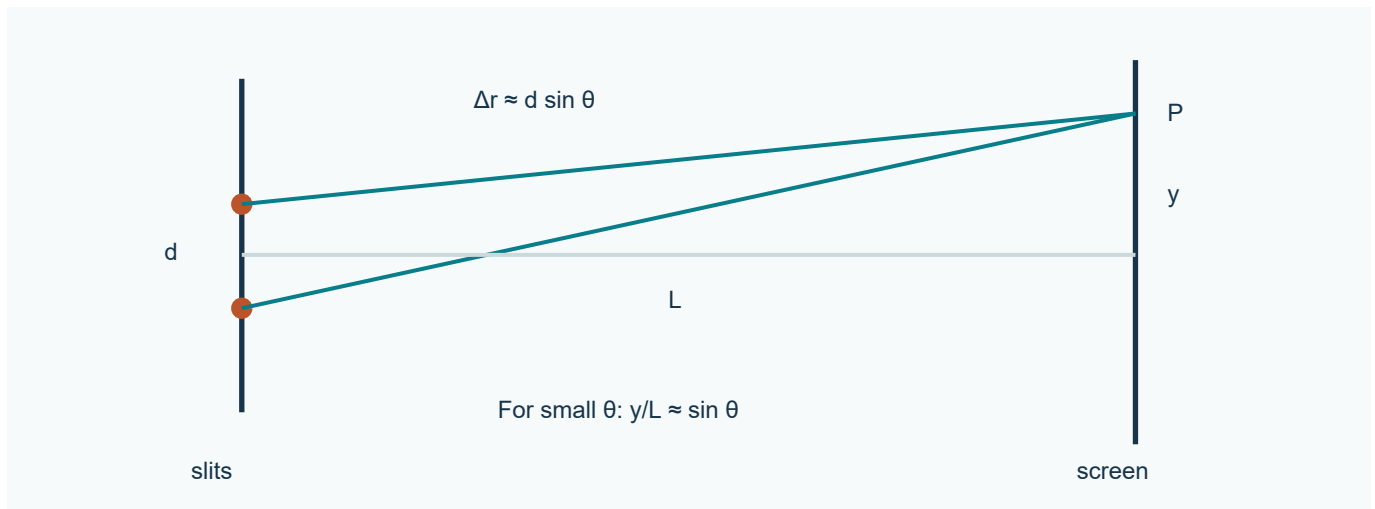
The two rays reach one point on the screen after traveling different distances. The screen displacement obeys $y = L \tan \theta$; replace $\tan \theta$ by $\sin \theta$ only for sufficiently small angles.

The central bright fringe is $m = 0$. The first dark fringe is a half-order path difference, not the first single-slit minimum. Increasing wavelength or screen distance widens the interference spacing; increasing slit separation narrows it. Approximately equal spacing applies near the center under the small-angle approximation, not to all angles.

Worked example

For $\lambda = 500 \text{ nm}$, $d = 0.25 \text{ mm}$ and $L = 2.0 \text{ m}$, $\Delta y = \mathbf{4.0 \text{ mm}}$. The second bright fringe is 8.0 mm from center; the first dark fringe is 2.0 mm from center. Halving d doubles all these near-center distances.

The original geometry: path difference to screen position



Use $\Delta r \approx d \sin \theta$ for a distant screen and $y = L \tan \theta$ for screen position. Only then decide whether a small-angle approximation is justified.

RELATIONSHIP AND CONDITIONS

Bright: $d \sin \theta = m\lambda$

Dark: $d \sin \theta = (m + \frac{1}{2})\lambda$

Small angle: $y_{\text{bright}} \approx m\lambda L/d$; $\Delta y \approx \lambda L/d$

Here d is slit separation, L is distance from the slit plane to the screen, and y is measured from the central maximum. The approximation $\sin \theta \approx \tan \theta$ is good near the center; its accuracy depends on the desired precision rather than on one absolute angle cutoff.

Change	Near-center spacing Δy
Double wavelength λ	Doubles
Double screen distance L	Doubles
Double slit separation d	Halves
Double d but keep the same spacing	Also double L , with λ fixed

PAUSE AND EXPLAIN

Blocking one finite-width slit removes two-slit interference. It leaves the broader single-slit diffraction pattern of the remaining opening, not necessarily uniform brightness.

Diffraction gratings and large angles

RELATIONSHIP AND CONDITIONS

Principal maxima: $d \sin \theta = m\lambda$

If the grating has N lines per meter, $d = 1/N$.

A possible order must satisfy $|m\lambda/d| \leq 1$.

A grating combines many evenly spaced openings. Their contributions reinforce strongly only near certain directions, creating narrower, sharper principal maxima than a two-slit arrangement of the same separation. For white light, $m = 0$ is white; in a given nonzero order, red has the larger angle than violet because its wavelength is longer.

Worked example

A grating has 500 lines/mm = 5.00×10^5 lines/m, so $d = \mathbf{2.00 \mu m}$. For $\lambda = 600$ nm in first order, $\sin \theta = 0.300$, giving $\theta = \mathbf{17.5^\circ}$. On a screen 1.0 m away, $y = L \tan \theta = \mathbf{0.314 \text{ m}}$. The small-angle estimate 0.300 m is already measurably different.

For that grating, $|m| \leq d/\lambda = 3.33$, so orders 0, ± 1 , ± 2 and ± 3 are geometrically possible. The actual visible intensity also depends on the individual-slit envelope and the apparatus. Increasing the number of illuminated slits sharpens peaks; changing their spacing changes the angles.

Use the correct unit conversion

“Lines per millimeter” is a density, not a spacing. Convert to lines per meter before taking its reciprocal, or use $d = (1 \text{ mm})/(\text{number of lines})$ with units carried explicitly.

Grating orders: overlap and the last visible maximum

The central order $m = 0$ has zero path difference for every wavelength, so white incident light gives a white central maximum. Within a nonzero order, longer wavelengths lie at larger angles. Higher orders can overlap across colors.

RELATIONSHIP AND CONDITIONS

Same angle: $m_1\lambda_1 = m_2\lambda_2$
An order exists only if $|m\lambda/d| \leq 1$.

Original overlap reasoning: second-order 660 nm light overlaps third-order light with $\lambda = 2(660)/3 = 440$ nm. The original 600 nm versus 400 nm sketch illustrates the same 2:3 relationship.

Counting example: if $d/\lambda = 3.7$, possible integer orders are 0, ± 1 , ± 2 , ± 3 : seven principal directions. Round the maximum order down. If an exact equality gives $\theta = 90^\circ$, that grazing order will not intersect an ordinary forward screen at finite distance.

WHAT MORE SLITS CHANGE

At fixed spacing d , adding illuminated slits makes principal peaks sharper. It does not move their ideal angular positions. Changing the line density changes d and therefore the positions.

Class question: a grating has 1000 lines/cm. Its spacing is 10^{-5} m. Do not confuse this with 1000 lines/mm, whose spacing is 10^{-6} m.

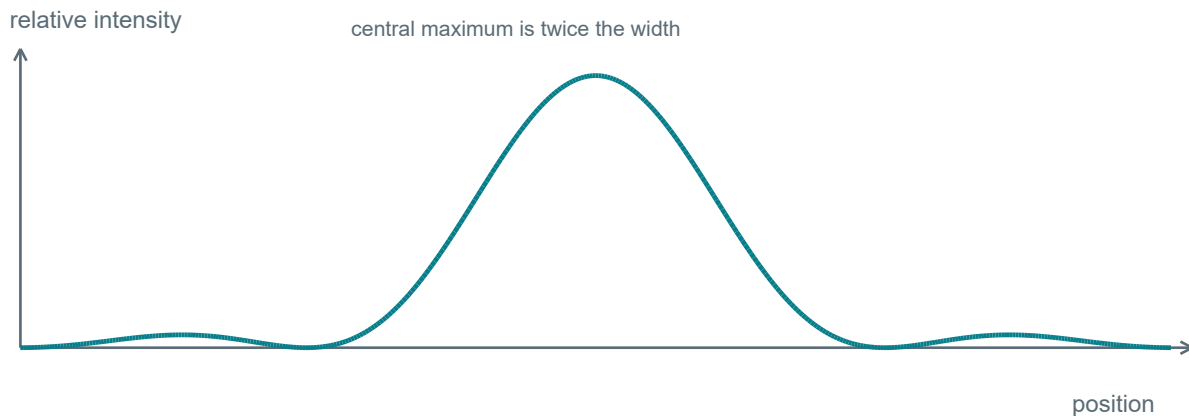
Single-slit diffraction

RELATIONSHIP AND CONDITIONS

Dark minima: $a \sin \theta = m\lambda$, $m = \pm 1, \pm 2, \dots$

Small angle: $y_{\min} \approx m\lambda L/a$

Central-maximum width $\approx 2\lambda L/a$ (between first minima).



A single slit creates a broad central bright maximum and weaker side maxima. The central maximum spans from the first minimum on one side to the first minimum on the other.

Diffraction is spreading around edges or through openings. It is especially noticeable when the opening is comparable to wavelength. A narrower slit creates a broader pattern. Contributions from different parts of the same slit interfere; dividing the slit into paired contributions explains why integer path differences across the full width produce dark minima rather than bright maxima.

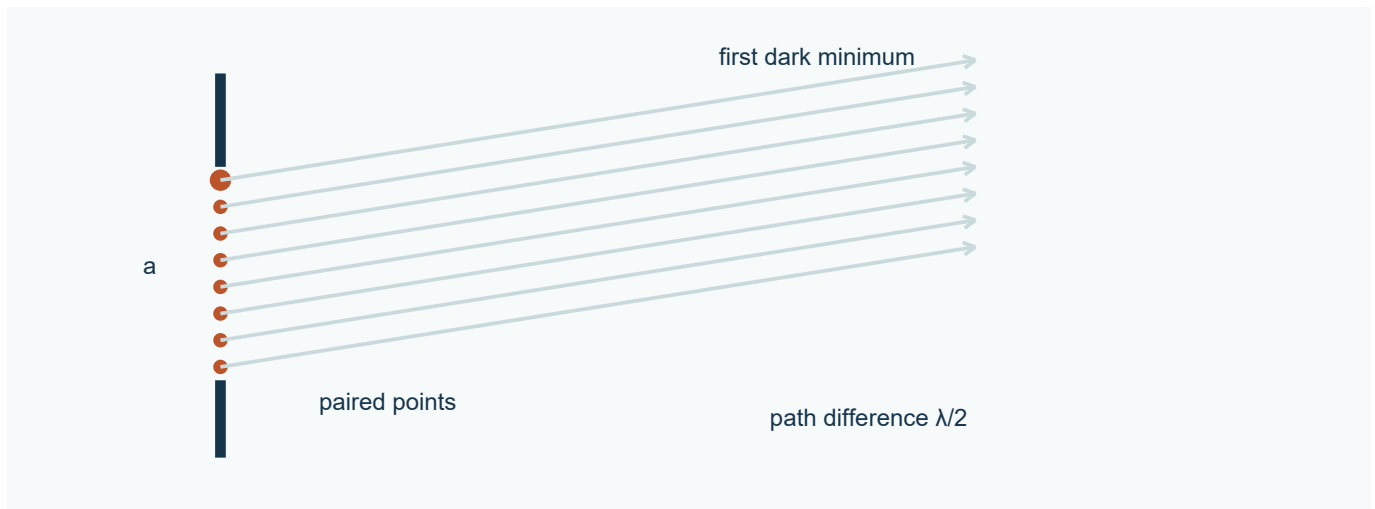
Worked example

For $\lambda = 600 \text{ nm}$, slit width $a = 0.10 \text{ mm}$ and screen distance $L = 2.0 \text{ m}$, the first minimum is $y = \lambda L/a = \mathbf{0.012 \text{ m}}$ from the center. The central bright maximum is therefore $\mathbf{0.024 \text{ m} = 2.4 \text{ cm wide}}$.

Two distinctions

Use slit **width** a here, not separation d between two slits. The single-slit minima are exact under the far-field model; side maxima are not exactly at half-integer orders. Different aperture shapes produce different diffraction patterns.

Why an integer order is dark for one slit



For the first minimum, divide the aperture into two equal halves. Each paired pair of points has path difference $\lambda/2$ and cancels.

RELATIONSHIP AND CONDITIONS

Full-aperture path difference: $a \sin \theta = \lambda$

Paired points separated by $a/2$: $(a/2) \sin \theta = \lambda/2$

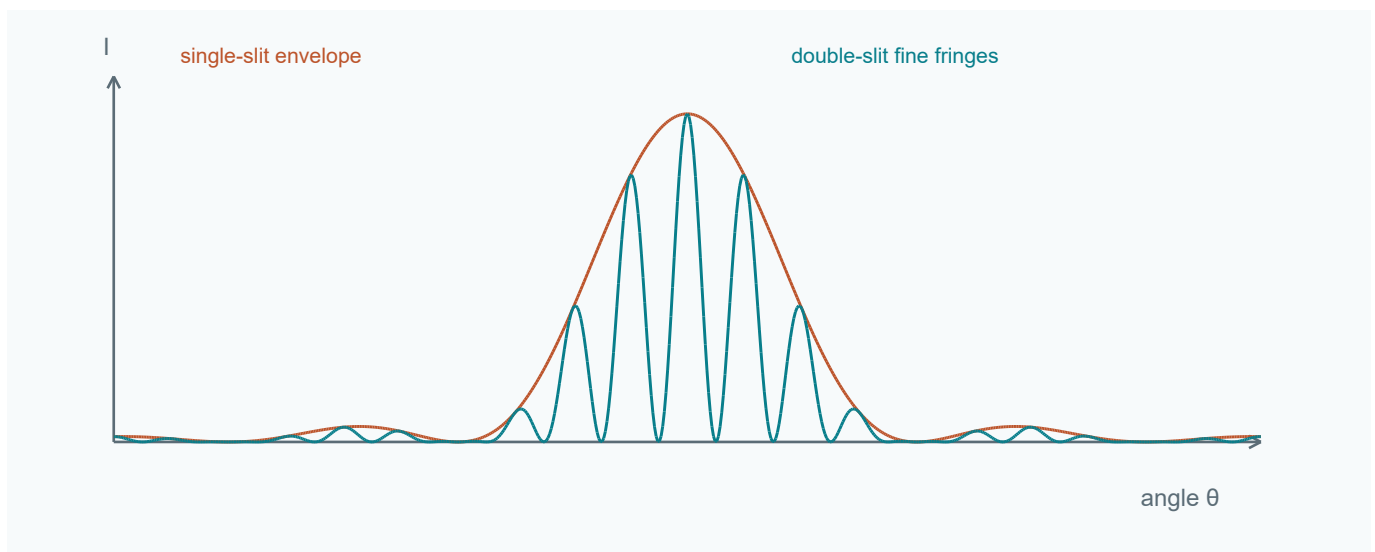
The crucial difference from two pointlike slits is that every point across the aperture contributes. Pair the top half with the bottom half at the first minimum. At the second minimum, divide into four equal strips and pair adjacent strips. The general dark conditions are $a \sin \theta = m\lambda$ for nonzero integer m .

At $\theta = 0$ all contributions start together and travel equal distances, so the center is bright. Never substitute $m = 0$ into the dark-minimum list. The central bright band reaches from $m = -1$ to $m = +1$ and is about twice as wide as a neighboring side band in the small-angle pattern.

PAIR THIS WITH DOUBLE SLITS

Double slit: integer $d \sin \theta / \lambda$ gives bright. Single slit: nonzero integer $a \sin \theta / \lambda$ gives dark. The integer alone is not enough; first identify the geometry and the quantity being canceled.

Finite slit width: the fine fringes sit inside an envelope



Fine spacing is controlled by separation d . The broad envelope is controlled by slit width a .

Finite-width slits also diffract individually. The rapidly spaced double-slit fringes lie inside a broad single-slit envelope. Slit separation d controls fine fringe spacing; slit width a controls envelope width. An interference maximum can be absent when it coincides with a diffraction minimum. This is why real patterns do not consist of equal-height bright fringes everywhere.

RELATIONSHIP AND CONDITIONS

Fine fringes: $d \sin \theta = m\lambda$

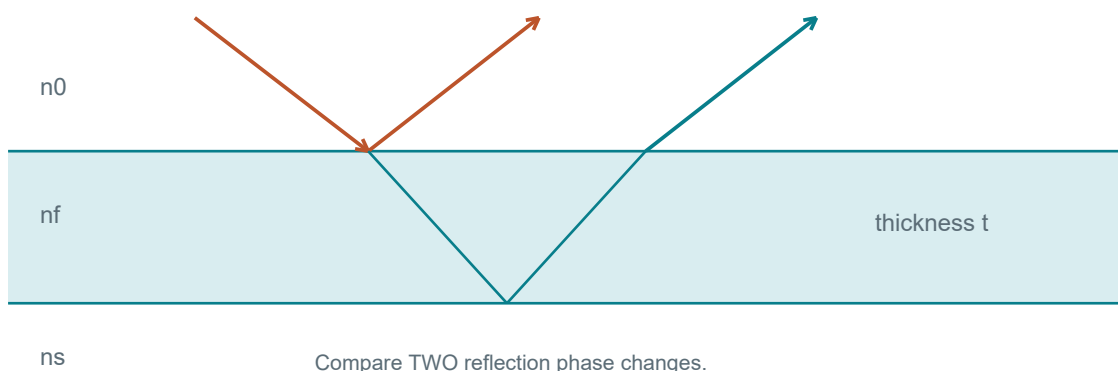
Envelope minima: $a \sin \theta = p\lambda$, $p = \pm 1, \pm 2, \dots$

Example: $d = 4a$. The $m = 4$ interference maximum satisfies $\sin \theta = 4\lambda/d = \lambda/a$ and coincides with the first envelope minimum. That order is missing. This does not change the slit separation or the spacing of the other fine fringes.

PAUSE AND EXPLAIN

Increase each slit's width while keeping their separation fixed. The broad central envelope becomes narrower; the near-center fine fringe spacing stays approximately the same.

Thin films: count phase reversals first



Two reflected rays interfere. One reflects at the top; the other enters the film, reflects at the bottom and leaves. Determine the index change at EACH reflecting interface. Rays are separated obliquely for visibility; the $2n_f t$ equations below use the normal-incidence limit.

For the ideal transparent nonabsorbing dielectric interfaces used here, reflection from lower to higher refractive index produces a 180° phase reversal. Reflection from higher to lower index does not. Transmission does not add that reflection phase reversal, although the wave accumulates phase as it travels through the film.

RELATIONSHIP AND CONDITIONS

Normal incidence: extra optical path = $2n_f t$

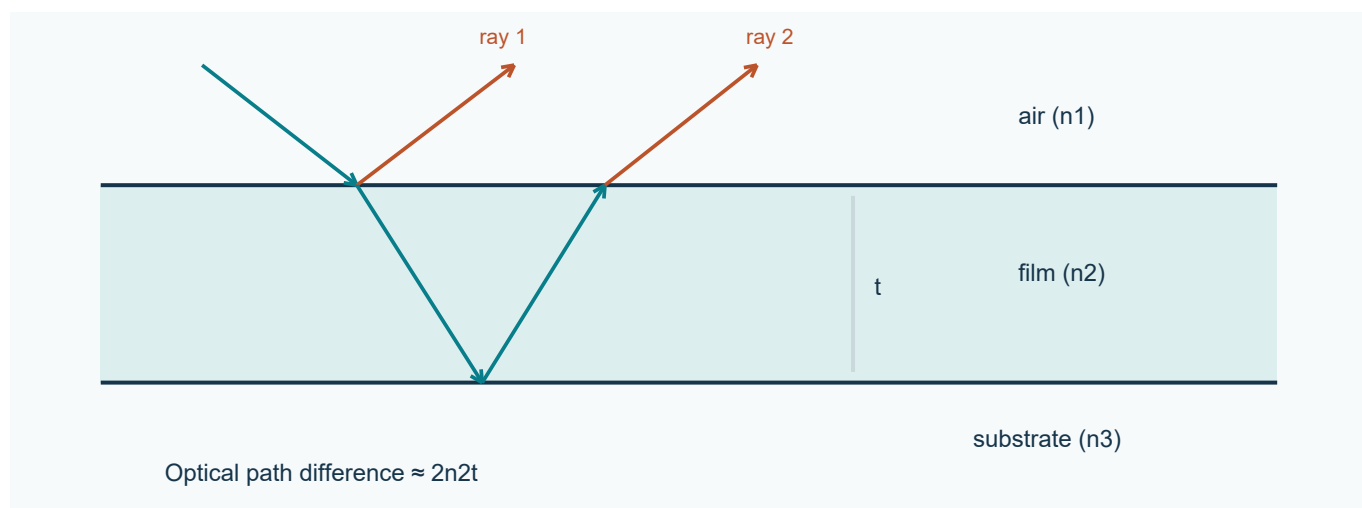
Use λ_0 , the wavelength in vacuum/approximately air.

Equivalently, extra geometric path $2t$ is compared with $\lambda_{\text{film}} = \lambda_0/n_f$.

Relative reflection phase	Constructive reflected light	Destructive reflected light
Exactly one phase reversal	$2n_f t = (m + \frac{1}{2})\lambda_0$	$2n_f t = m\lambda_0$
Zero or two reversals	$2n_f t = m\lambda_0$	$2n_f t = (m + \frac{1}{2})\lambda_0$

Here m is an integer selected for a physically allowed thickness. Extension beyond the normal-incidence assessment boundary: at non-normal incidence, the appropriate optical-path term becomes $2n_f t \cos \theta_{\text{film}}$; the normal-incidence version is the main model in the examples. Thin-film colors vary with thickness, wavelength and viewing angle.

Keep the original three thin-film cases together



Count the phase change of each reflected ray separately. A reflection from lower to higher index adds π in this ideal dielectric model. Rays are separated obliquely for visibility; the $2n_2t$ equations below use the normal-incidence limit.

Case at near-normal incidence	Reflection flips	Reflected-light condition
Air / oil 1.50 / water 1.33	One	Bright: $2nt = (m + \frac{1}{2})\lambda_0$
Air / low-index film 1.25 / water 1.33	Two	Bright: $2nt = m\lambda_0$
Air / coating 1.40 / glass 1.60	Two	Dark: $2nt = (m + \frac{1}{2})\lambda_0$

In the first case, the top reflection flips and the lower reflection does not. In the second and third, both flip: the relative reflection shift is zero. The film index in $2nt$ is always that of the middle layer. λ_0 is the vacuum wavelength.

CORRECTION TO A POSSIBLE LABEL AMBIGUITY

Use the stated numerical indices to count flips. A film of index 1.50 over water 1.33 has one flip, even if a handwritten label calls it “soap.” A film of index 1.25 over water 1.33 has two. The name of the liquid does not determine the answer.

Soap films and antireflection coatings

Example A: soap film in air

Take $n_{\text{film}} = 1.33$ between air on both sides. The top reflection reverses phase; the bottom does not. For strong reflected 600 nm light, the least positive constructive thickness satisfies $2nt = \lambda_0/2$, giving **$t = 113$ nm**. Very thin regions can look dark in reflection because the two reflected waves nearly cancel.

Example B: coating on glass

Air $\rightarrow$ coating $n = 1.38 \rightarrow$ glass $n = 1.52$ gives a phase reversal at both reflections. To reduce reflection of 550 nm light, use the smallest positive destructive thickness $t = \lambda_0/(4n) = \mathbf{99.6 \text{ nm}}$. The same quarter-wave thickness has a different role from the soap-film case because the reflection phase pattern differs.

A quarter-wave thickness is not a universal “constructive” or “destructive” rule. Always draw the layers, label their indices and count the relative phase changes. The wavelength in the quarter-wave formula is the wavelength inside the coating when written as $t = \lambda_{\text{coating}}/4$.

Depth of explanation

Destructive phase alignment minimizes reflection, but exact cancellation also requires matching the amplitudes of the reflected waves. For an ideal single coating at normal incidence, the amplitude-matching condition is $n_{\text{coating}} = \sqrt{(n_{\text{air}} n_{\text{substrate}})}$. This is an extension; it explains why not every quarter-wave coating gives zero reflected intensity.

For transparent lossless layers, reduced reflection generally corresponds to increased transmission, not destroyed energy. Real coatings can absorb light and are designed for particular wavelength/angle ranges. A single layer cannot perfectly remove reflections over every color and angle.

The original two-speaker problem and slit experiment

Two in-phase speakers are 0.75 m apart. A measurement line is 5.0 m away and parallel to the speaker separation. With $f = 2500$ Hz and sound speed 343 m/s, $\lambda = 0.1372$ m. Near the center, use the same path-difference geometry as two slits.

RELATIONSHIP AND CONDITIONS

First quiet point: $d \sin \theta = \lambda/2$

$\sin \theta = 0.1372/(2 \times 0.75) = 0.09147$

$y = L \tan \theta \approx 0.459$ m

The corresponding minimum exists on the opposite side of center. Lowering f increases λ , so the minima move farther from center. Real unequal amplitudes or room reflections prevent a perfectly silent minimum.

Measure a slit separation using a known laser wavelength

Measure a long distance L , then measure across several bright-fringe spacings and divide by their number. Plot fringe position y against signed order m . With small angles, slope $s = \lambda L/d$, so $d = \lambda L/s$. Repeat measurements and use a best-fit line.

RETAIN THE GRAPH AND ERROR REASONING

Measure from the central maximum, not a screen edge. Using several fringes reduces the relative uncertainty from locating one bright center. If angles are appreciable, calculate θ from $\tan \theta = y/L$ and fit $\sin \theta$ against order instead.

Wave experiments and evidence

A | Determine a laser wavelength

Use a double slit of known separation d and a screen at measured distance L . Mark the central fringe and several maxima on both sides. Measure the span from order $-m$ to $+m$ to reduce fractional position error; divide by $2m$ to get Δy . Repeat for several L values. Plot Δy against L ; the slope is λ/d . Use $y = L \tan \theta$ and $d \sin \theta = m\lambda$ if the small-angle assumption fails.

Keep slit orientation fixed, measure L perpendicular to the screen and avoid saturating the bright-fringe position by judging a broad glare spot. An uncertain slit separation directly affects inferred wavelength. Do not confuse half a bright-to-bright spacing with one full spacing.

B | Determine sound speed with a resonance tube

For a tube closed at one end and driven at known frequency f , find successive resonant lengths L_1 and L_2 . Their difference is approximately $\lambda/2$, so $v = 2f(L_2 - L_1)$. Taking the difference can largely cancel an approximately constant end correction. Repeat with several frequencies and record room temperature.

Example data

At $f = 500$ Hz, successive resonances occur at 0.170 m and 0.510 m. The difference is 0.340 m, so $v = 2(500)(0.340) = \mathbf{340 \text{ m/s}}$. Using $v = 4fL_1$ gives the same ideal value, but is more sensitive to an end correction.

For polarization demonstrations, rotate an analyzer while keeping source intensity and detector position fixed. Repeat with a third polarizer between crossed filters. The sequence of transmission directions explains the change in intensity without needing a different propagation speed.

Student practice

1. A string has $\mu = 0.0050 \text{ kg/m}$ and tension 20 N. Find wave speed.
2. A wave has period 0.010 s and wavelength 0.30 m. Find f and v .
3. A wave enters a medium where speed halves. What happens to f and λ ?
4. Two forks at 440 Hz and 444 Hz sound together. Find the beat frequency.
5. A fixed-fixed string 0.60 m long has speed 120 m/s. Find its first three harmonic frequencies.
6. A 0.50 m closed-open pipe has sound speed 340 m/s. Find its first three allowed frequencies.

Review: diffraction, films and polarization

7. A single slit 0.20 mm wide receives 500 nm light. The screen is 2.0 m away. Find central-maximum width.
8. A double slit of separation 0.50 mm receives 600 nm light, with $L = 1.5$ m. Find fringe spacing and the first dark-fringe position.
9. A 600 lines/mm grating receives 500 nm light. Find the first-order angle.
10. A soap film of index 1.25 in air strongly reflects 500 nm light at normal incidence. Find the least positive thickness.
11. Extension: unpolarized intensity 100 W/m^2 passes through two ideal polarizers at 45° to one another. Find transmitted intensity.
12. A source approaches an observer. What happens to observed pitch? Does this require a change in the source's own oscillation frequency?

Practice solutions

1. $v = \sqrt{(20/0.0050)} = \mathbf{63.2\ m/s}$.

2. $f = 1/T = \mathbf{100\ Hz}$; $v = f\lambda = \mathbf{30\ m/s}$.

3. Frequency stays fixed at the stationary interface; wavelength **halves**.

4. $|444 - 440| = \mathbf{4\ Hz}$.

5. $f_1 = v/(2L) = 100\ \text{Hz}$. Harmonics: **100, 200, 300 Hz**.

6. $f_1 = v/(4L) = 170\ \text{Hz}$. Odd harmonics: **170, 510, 850 Hz**.

Answers: diffraction, films and polarization

7. Width = $2\lambda L/a = 0.010 \text{ m} = 1.0 \text{ cm}$.

8. $\Delta y = \lambda L/d = 1.8 \text{ mm}$. First dark fringe is **0.90 mm** from center on either side.

9. $d = 1/(600 \times 10^3) \text{ m}$. $\sin \theta = \lambda/d = 0.300$, so **$\theta = 17.5^\circ$** .

10. One reflection phase reversal, so $t = \lambda_0/(4n) = 100 \text{ nm}$.

11. $I = (100/2)\cos^2 45^\circ = 25 \text{ W/m}^2$.

12. The observed frequency/pitch **increases**; the source frequency can remain unchanged.

Original notes and syllabus map

The source sequence determines the teaching order. Repeated examples are consolidated while distinct reasoning, diagrams and comparisons are retained.

Original source	Content retained
N15, pp.1-4,7 Waves 14.1-14.4 + Optics 13.1-13.3.pdf	Wave types, EM spectrum, wavefronts and reflection
N16, pp.2-11 Waves 14.1-14.6 + Optics 13.3.pdf	Graph pairs, boundaries, polarization, Doppler, pulse sums and beats
N17, pp.1-10 Waves 14.6-14.8 - Standing Waves and Diffraction.pdf	Fixed/free standing waves, pipes, doorway diffraction and path differences
N18, pp.1-14 Waves 14.7-14.8.pdf	Double slit → grating → single slit → envelope sequence
N19, pp.1-9 Waves 14.7-14.9.pdf	Interference review and three thin-film cases
N20, pp.1-5 Waves 14.8-14.9 + Optics 13.4.pdf	Film comparison and overlap questions
N22, pp.1-11 Waves 14.6-14.8 - Interference Review.pdf	Formula comparison, speaker example and experimental design

Curriculum: supplied *AP Physics 2 Course and Exam Description*, 2026, Unit 14. Topic labels on each content page show where the syllabus connects to the original lesson. Extensions remain labeled.

Clarifications and independent references

Point checked	Treatment in this chapter
Boundary phase	Use displacement and the specified string model; frequency stays fixed.
Doppler	Moving source changes front spacing; moving observer changes encounter rate.
Single versus double slit	Integer order is dark for a single slit and bright for two in-phase narrow slits.
Thin films	Count relative reflection phase and use the numerical indices.
Scope	Malus's law and numerical sound Doppler formulas are extensions; qualitative ideas remain core.

Independent checks

[OpenStax: thin-film interference](#)

[OpenStax: single-slit diffraction](#)

Constants and calculations use the values stated in each example. Historical practice provides context and reasoning patterns. New worked questions and corrected explanations are distinguished from an official answer key.

Master summary: wave patterns side by side

System	Geometrical condition	Frequency / position	Main distinction
Traveling wave	One wavelength per period	$v = f\lambda$; $f = 1/T$	x graph gives λ ; t graph gives T
Fixed-fixed / open-open	$L = n\lambda/2$	$f_n = nv/(2L)$, $n = 1, 2, 3, \dots$	Same-type ends; all harmonics
Fixed-free / closed-open	$L = n\lambda/4$	$f_n = nv/(4L)$, $n = 1, 3, 5, \dots$	Mixed ends; odd harmonics
Two coherent narrow slits	Bright: $d \sin \theta = m\lambda$	$\Delta y \approx \lambda L/d$	Dark: half-integer path difference
Grating	Principal bright: $d \sin \theta = m\lambda$	$d = \text{reciprocal line density}$	Keep $\sin \theta$; count allowed orders
One slit	Dark: $a \sin \theta = m\lambda$; $m \neq 0$	Central width $\approx 2\lambda L/a$	a is width; broad central maximum
Reflected thin film: one flip	Bright: $2nt = (m + \frac{1}{2})\lambda_0$	Dark: $2nt = m\lambda_0$	Near-normal incidence
Reflected thin film: zero/two flips	Bright: $2nt = m\lambda_0$	Dark: $2nt = (m + \frac{1}{2})\lambda_0$	Relative phase flips cancel

Also remember: $I = P/A$; intensity scales with amplitude squared under the stated fixed-medium conditions. Beats occur at $|f_1 - f_2|$. An open pipe end is a displacement antinode but a pressure node.