

Unit 14: Waves, Sound, and Physical Optics

This unit covers how waves behave, from sound traveling through air to light interfering through slits. It includes wave properties, sound and the Doppler effect, standing waves in strings and pipes, beats, and the interference and diffraction of light.

AP Physics 2

Waves, Sound, and Physical Optics

About 15 minutes to read

How to use this guide

Read it in order the first time because the ideas stack. Wave properties set up sound, sound sets up standing waves and beats, and the interference conditions for mechanical waves carry straight into double-slit and thin-film optics. The exam tests whether you can tell similar-looking situations apart, so after the first read, review with the trap boxes and the confusions table. Finish with the practice questions, then do the recall check on the last page out loud.

What this unit is worth. Waves, Sound, and Physical Optics is 12 to 15 percent of the AP Physics 2 exam. It also carries more look-alike equations than any other unit: double-slit bright fringes, single-slit minima, and standing-wave conditions all involve whole numbers of wavelengths, and the exam counts on you mixing them up.

14.1 Wave Properties

A **wave** carries energy through a medium or through space without carrying matter along with it. Each piece of the medium oscillates around its rest position while the disturbance moves on. **Frequency** f is the number of oscillations per second, **period** $T = 1/f$ is the time for one oscillation, and **wavelength** λ is the distance the disturbance travels in one period.

TYPE	MOTION	EXAMPLES
Transverse	The medium oscillates perpendicular to the direction the wave travels.	A wave on a string. All electromagnetic waves, including light.
Longitudinal	The medium oscillates parallel to the direction the wave travels.	Sound waves in air. A compressed slinky pushed along its length.

Wave speed, frequency, and wavelength are tied together by **$v = f\lambda$** . The frequency is set by the source, so when a wave crosses into a new medium the frequency stays the same while the speed and wavelength change to fit.

Worked example. A wave on a string has frequency 250 Hz and wavelength 0.80 m, so its speed is $v = f\lambda = 250 \times 0.80 = 200$ m/s. It then enters a thicker section of the string where the speed drops to 150 m/s. The frequency stays 250 Hz, and the new wavelength is $\lambda = v/f = 150/250 = 0.60$ m. Check: $250 \times 0.60 = 150$, which matches the new speed.

Trap. When a wave enters a new medium, the frequency does *not* change. The source sets the frequency, and the source did not change. It is the speed and wavelength that adjust. If a question gives a new speed and asks for the new wavelength, divide by the *original* frequency.

14.2 Sound

Sound is a longitudinal mechanical wave. Air molecules oscillate back and forth along the direction the wave travels, forming compressions (crowded regions) and rarefactions (spread-out regions). The **speed of sound in air** is about 343 m/s at 20°C, roughly a million times slower than light.

Intensity is power per unit area. The ear responds to an enormous range of intensities, so loudness is measured on the logarithmic **decibel scale**. Every increase of 10 dB means ten times the intensity. A whisper and a jet engine differ by a factor of about a trillion in intensity but only about 120 dB on the scale.

The **Doppler effect** shifts the observed frequency when source and observer move relative to each other. The AP equation sheet gives $f' = f_0(v + v_O)/(v - v_S)$. Take v_O as positive when the observer moves toward the source, and v_S as positive when the source moves toward the observer. Either approaching motion raises the observed frequency; moving away flips the sign and lowers it. The wave speed in the medium does not change.

Trap. Doppler questions punish sign errors. "Source approaches observer" makes the denominator $v - v_S$ smaller, so the frequency rises. And the speed of sound never changes in these problems. If an answer choice says the waves travel faster because the source is moving, it is wrong.

14.3 Standing Waves on Strings

When a wave reflects back on itself, the incident and reflected waves interfere to form a **standing wave**, a pattern that does not travel. A **node** is a point where the medium never moves. An **antinode** is a point where it oscillates with maximum amplitude.

A string fixed at both ends can only support standing waves with a node at each end, which forces the length to hold a whole number of half-wavelengths: $L = n\lambda/2$ for $n = 1, 2, 3, \dots$. The allowed frequencies are $f_n = nv/(2L)$. The $n = 1$ mode is the **fundamental**. The higher modes are **harmonics**, and each harmonic is a whole-number multiple of the fundamental. The first mode above the fundamental is called the first overtone, so on a string the second harmonic is the first overtone.

Worked example. A 0.65 m guitar string carries waves at 390 m/s. The fundamental is $f_1 = v/(2L) = 390/(2 \times 0.65) = 390/1.30 = 300$ Hz. The third harmonic is three times that, $f_3 = 3 \times 300 = 900$ Hz. As a check, the fundamental wavelength is $\lambda_1 = 2L = 1.30$ m, and $300 \times 1.30 = 390$ m/s, the given wave speed.

Trap. In a sound standing wave, a displacement node is a *pressure antinode*, and a displacement antinode is a *pressure node*. The air does not move at a displacement node, but the pressure swings the most there. If the question asks about pressure, flip every node and antinode label before answering.

14.4 Standing Waves in Pipes

Air columns in pipes resonate the same way strings do, but the boundary conditions depend on whether each end is open or closed. An **open end** is a displacement antinode, because the air there moves freely. A **closed end** is a displacement node, because the air cannot move against the wall.

PIPE	CONDITION	FREQUENCIES
Open at both ends	Antinode at each end. Length holds whole number of half-wavelengths.	$f_n = nv/(2L)$, $n = 1, 2, 3, \dots$ Every harmonic is present.
Closed at one end	Node at the closed end, antinode at the open end. Length holds odd number of quarter-wavelengths.	$f_n = nv/(4L)$, $n = 1, 3, 5, \dots$ Odd harmonics only.

Worked example. A pipe of length 0.60 m is closed at one end. With $v = 343$ m/s, the fundamental is $f_1 = v/(4L) = 343/(4 \times 0.60) = 343/2.40 \approx 143$ Hz. The next allowed mode is the third harmonic, which is the first overtone, $f_3 = 3 \times 143 \approx 429$ Hz. A closed pipe has no second harmonic, no fourth harmonic, and no other even multiples.

Trap. The first overtone of a closed pipe is the *third* harmonic, not the second. The overtone counts modes above the fundamental, while the harmonic counts multiples of the fundamental, and the closed pipe skips the even ones. Also check the pipe type before writing any equation: using $nv/(2L)$ on a closed pipe invents harmonics that cannot exist.

14.5 Beats

When two waves of slightly different frequency overlap, the interference alternates between constructive and destructive, and the listener hears the loudness swell and fade. The **beat frequency** is the difference, $f_{\text{beat}} = |f_1 - f_2|$. Two tuning forks at 440 Hz and 444 Hz produce 4 beats per second, heard as a slow pulsing on top of the tone.

14.6 Interference of Waves

When two waves meet, their displacements add point by point. **Constructive interference** happens when the waves arrive in step, crest on crest, and the amplitudes add. **Destructive interference** happens when they arrive exactly out of step, crest on trough, and the amplitudes cancel. In terms of **path difference**, the extra distance one wave travels:

INTERFERENCE	PATH DIFFERENCE CONDITION
Constructive (in step)	$\Delta L = m\lambda$, $m = 0, 1, 2, \dots$ A whole number of wavelengths.
Destructive (out of step)	$\Delta L = (m + 1/2)\lambda$. A whole number plus a half wavelength.

14.7 Double-Slit Interference

Light passing through two narrow slits spreads by diffraction, and the two waves interfere on a distant screen. **Bright fringes** appear where the path difference is a whole number of wavelengths: **$d \sin\theta = m\lambda$** , $m = 0, \pm 1, \pm 2, \dots$. Here d is the slit separation and θ is the angle from the central maximum. **Dark fringes** sit halfway between the bright ones, at $d \sin\theta = (m + 1/2)\lambda$.

Worked example. Slits 0.25 mm apart are lit by 600 nm light. For the second bright fringe ($m = 2$): $\sin\theta = m\lambda/d = 2 \times 6.0 \times 10^{-7} / (2.5 \times 10^{-4}) = 4.8 \times 10^{-3}$, so $\theta \approx 0.275^\circ$. On a screen 1.5 m away, the fringe sits $y = L \tan\theta \approx 1.5 \times 4.8 \times 10^{-3} = 7.2 \times 10^{-3}$ m, or 7.2 mm, from the center. (At these small angles $\tan\theta \approx \sin\theta$.)

Trap. The double-slit *bright* fringe condition, $d \sin\theta = m\lambda$, looks almost identical to the single-slit *minima* condition, $a \sin\theta = m\lambda$, and the exam mixes them on purpose. Bright double-slit fringes and dark single-slit fringes are different phenomena. Check whether the setup has two slits (bright) or one slit (dark) before writing the equation, and note the letter: d for slit *separation*, a for slit *width*.

14.8 Single-Slit Diffraction

A single slit still spreads the light, and different parts of the slit interfere with each other. The result is a broad bright **central maximum** flanked by dimmer fringes. The dark **minima** sit at **$a \sin\theta = m\lambda$** , $m = \pm 1, \pm 2, \dots$, where a is the slit width. The central maximum stretches from the $m = -1$ minimum to the $m = +1$ minimum, so narrowing the slit pushes the first minima outward and the central maximum gets wider.

Trap. The single-slit equation gives the *dark* fringes, not the bright ones. The one exception is the central maximum, which sits at $\theta = 0$ between the two first minima. If a question asks for the angle of a bright single-slit fringe (other than the center), the exam expects an approximation halfway between minima, not a $\sin\theta = m\lambda$.

14.9 Diffraction Gratings

A **diffraction grating** is thousands of evenly spaced slits. The principal maxima follow the same equation as the double slit, **$d \sin\theta = m\lambda$** , with d now the spacing between adjacent slits. With so many slits contributing, the maxima are much sharper, narrower, and brighter than a double slit's, with faint secondary maxima in between. That sharpness is why gratings are used to measure wavelengths precisely.

14.10 Thin-Film Interference

A thin film, like a soap bubble, reflects light from its front and back surfaces, and the two reflections interfere. Reflection from a **higher-index medium** flips the wave by half a cycle, a 180° **phase reversal**. Reflection from a **lower-index medium** causes no reversal. For a soap film in air, the front (air-to-film) reflection reverses while the back (film-to-air) reflection does not, so whether the interference is constructive or destructive depends on the film thickness compared with the wavelength. That is why the colors shift as the film thins.

Trap. Phase reversal depends on direction. Air to film reverses; film to air does not. Drawing both reflections with a reversal, or assigning the reversal to the wrong surface, flips every constructive and destructive conclusion that follows.

Confusions That Cost Points

PAIR	HOW TO KEEP THEM STRAIGHT
Double-slit bright vs single-slit minima	Two slits: bright fringes at $d \sin\theta = m\lambda$. One slit: dark minima at $a \sin\theta = m\lambda$. d is slit separation, a is slit width.
Open-open pipe vs closed pipe	Open-open: $f_n = nv/(2L)$ with every harmonic. Closed at one end: $f_n = nv/(4L)$ with odd harmonics only.
Harmonic vs overtone	The n th harmonic is n times the fundamental. The first overtone is the first mode above the fundamental. On a string the first overtone is the second harmonic; in a closed pipe it is the third.
Displacement node vs pressure node	In a sound standing wave, a displacement node is a pressure antinode. The air sits still where the pressure swings the most.
Frequency vs wavelength at a boundary	Frequency is set by the source and never changes at a boundary. Speed and wavelength adjust to fit the new medium.
Doppler approaching vs receding	Approaching motion raises the observed frequency; receding motion lowers it. The wave speed in the medium never changes.
Constructive vs destructive path difference	Constructive: $\Delta L = m\lambda$, a whole number of wavelengths. Destructive: $\Delta L = (m + 1/2)\lambda$, a whole number plus a half.

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next page, so complete the questions before checking them.

1. A wave of frequency 120 Hz travels on a string with wavelength 2.0 m. It crosses into a thicker section of the string where the wave speed drops to 180 m/s. What is the wavelength in the thicker section?

1. 0.67 m
2. 1.5 m
3. 2.0 m
4. 2.7 m

2. A string fixed at both ends vibrates at its third harmonic, 900 Hz. What is the fundamental frequency?

1. 300 Hz
2. 450 Hz
3. 1800 Hz
4. 600 Hz

3. A pipe of length 0.50 m is closed at one end. The speed of sound in air is 343 m/s. What is the frequency of the first overtone?

1. 172 Hz
2. 515 Hz
3. 343 Hz
4. 686 Hz

4. Monochromatic light passes through a double slit, and a pattern of bright and dark fringes appears on a distant screen. Which equation gives the angles of the bright fringes?

1. $d \sin\theta = (m + 1/2)\lambda$
2. $2d \sin\theta = m\lambda$
3. $d \sin\theta = m\lambda$
4. $a \sin\theta = m\lambda$

- 5.** An ambulance with its siren on drives toward a stationary observer. Compared with the frequency the siren emits, the frequency the observer hears is
1. lower
 2. the same
 3. higher, and the speed of sound is higher too
 4. higher
- 6.** Light strikes a thin soap film in air at near-normal incidence. Part of the light reflects from the front surface and part reflects from the back surface. Which reflection undergoes a 180° phase reversal?
1. Neither reflection
 2. The back-surface (film-to-air) reflection only
 3. The front-surface (air-to-film) reflection only
 4. Both reflections
- 7.** Two tuning forks sounding at 440 Hz and 444 Hz are struck at the same time. What beat frequency does a listener hear?
1. 442 Hz
 2. 2 Hz
 3. 884 Hz
 4. 4 Hz
- 8.** Light of fixed wavelength passes through a single slit, and the slit is then made narrower. What happens to the central maximum of the diffraction pattern?
1. It becomes wider
 2. It becomes narrower
 3. It stays the same width but gets dimmer
 4. It shifts to a larger angle

Answer Key

- 1. B.** The frequency is set by the source and stays 120 Hz in the new medium, so $\lambda = v/f = 180/120 = 1.5$ m. C keeps the old wavelength, treating λ as the fixed quantity when it is f that is fixed. D computes $(240/180) \times 2.0 = 2.7$ m, inverting the ratio. A computes $f/v = 0.67$, the reciprocal of the wavelength.
- 2. A.** For a string fixed at both ends, $f_n = nf_1$, so $f_1 = 900/3 = 300$ Hz. B halves the frequency, as if the third harmonic were twice the fundamental. C doubles instead of dividing by 3, which no harmonic series supports. D uses the ratio $2/3$ instead of $1/3$.
- 3. B.** The fundamental is $f_1 = v/(4L) = 343/(4 \times 0.50) = 343/2.0 = 171.5$ Hz. A closed pipe supports only odd harmonics, so the first overtone is the third harmonic: $f_3 = 3 \times 171.5 = 514.5 \approx 515$ Hz. A answers the fundamental instead of the overtone. C computes 2×171.5 , applying the open-pipe series with its even harmonics to a closed pipe. D computes 4×171.5 , using $n = 4$ as if every harmonic existed.
- 4. C.** Bright fringes from two slits sit where the path difference is a whole number of wavelengths: $d \sin\theta = m\lambda$. D is the single-slit *minima* condition, a different setup giving dark fringes. A gives the dark fringes of the double slit. B adds a factor of 2 that appears in no interference condition.
- 5. D.** In $f' = f_0(v + v_O)/(v - v_S)$, a source moving toward the observer makes the denominator smaller than v , so the observed frequency is higher than the emitted one. A makes the sign error, treating approach like recession. B confuses wave speed, which is unchanged, with frequency. C gets the frequency right but wrongly claims the speed of sound changes too.
- 6. C.** The front reflection goes from air (lower n) to film (higher n), so it undergoes the 180° reversal. The back reflection goes from film to air, higher to lower n , so it does not. D ignores the direction rule entirely. A denies any reversal. B assigns the reversal to the wrong surface.
- 7. D.** The beat frequency is the difference: $|440 - 444| = 4$ Hz, heard as four loudness pulses per second. A gives 442 Hz, the average, which is the perceived pitch of the combined tone, not the beat. B halves the difference for no reason the beat formula supports. C adds the frequencies.
- 8. A.** The first minima sit at $\sin\theta = \pm\lambda/a$, so a smaller slit width a pushes the minima to larger angles and the central maximum between them gets wider. B inverts the relationship. C confuses width with brightness: the pattern does dim, but the width changes too. D misplaces the central maximum, which stays centered at $\theta = 0$.

When you check your answers, note which distinction each miss came from. Make a flashcard for that distinction and drill it spaced out over the next few days instead of rereading the whole section. If you missed one of these questions, the same distinction is worth practicing again in Rycal, where the Waves, Sound, and Physical Optics deck has flashcards for it and more practice questions use the same kinds of traps.

One-Page Recall Check

Say each answer out loud before you look back, and mark the ones you cannot finish. Anything you cannot say out loud yet belongs in your flashcard deck. In Rycal, add those items to the Waves, Sound, and Physical Optics deck and let spaced review bring them back over the next few days.

- State $v = f\lambda$ and explain which of the three quantities is fixed by the source.
- Distinguish a transverse wave from a longitudinal wave and give an example of each.
- Give the speed of sound in air at 20°C.
- Explain what the decibel scale measures and what an increase of 10 dB means for intensity.
- Write the Doppler expression from the equation sheet and state the sign rule for approaching versus receding motion.
- Define node and antinode in a standing wave.
- Give the allowed frequencies for a string fixed at both ends.
- Give the harmonic series for an open-open pipe and for a pipe closed at one end.
- Explain how displacement nodes and pressure nodes relate in a sound standing wave.
- State the beat frequency rule and use it on 440 Hz and 444 Hz.
- State the path-difference conditions for constructive and destructive interference.
- Write the double-slit bright-fringe condition and the single-slit minima condition, and say which is which.
- Explain how a diffraction grating pattern differs from a double-slit pattern with the same slit spacing.
- Explain phase reversal in thin-film interference, including which surface of a soap film in air reverses.

Where to go next. Turn every missed item above into flashcards and drill them spaced out over several days rather than in one sitting. In Rycal, open the Waves, Sound, and Physical Optics deck under AP Physics 2. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Wave, Frequency, Period, Wavelength, Transverse wave, Longitudinal wave, Sound, Intensity, Decibel, Doppler effect, Standing wave, Node, Antinode, Fundamental, Harmonic, Overtone, Beat frequency, Constructive interference, Destructive interference, Path difference, Double-slit interference, Single-slit diffraction, Diffraction grating, Thin-film interference, Phase reversal.

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