

PHYS11 CH:14 Invisible Vibrations

From Silence to Symphony

Mr. Gullo

December 2025

Outline

- 1 Introduction
- 2 Speed of Sound, Frequency, and Wavelength
- 3 Sound Intensity and Decibels
- 4 Doppler Effect and Sonic Booms
- 5 Sound Interference and Resonance
- 6 Summary

The Mystery

If a tree falls in the forest
and no one is there to hear it,
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The answer depends on how you define sound...

Physics says: yes, but no one perceives it.

Fallen Tree



Fallen Tree



The Mental Model

Tree hits ground → disturbs air particles → creates pressure waves → sound wave travels outward.

Learning Objectives

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- **14.1:** Describe speed of sound and how it changes in media
- **14.1:** Relate speed of sound to frequency and wavelength

14.1 Sound as a Mechanical Wave

Nature's Rule

Sound is a disturbance of matter transmitted from source outward as a longitudinal wave.

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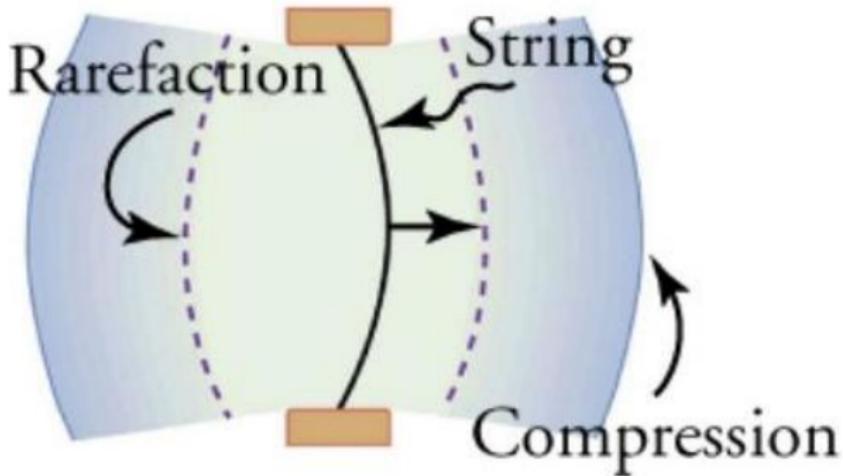
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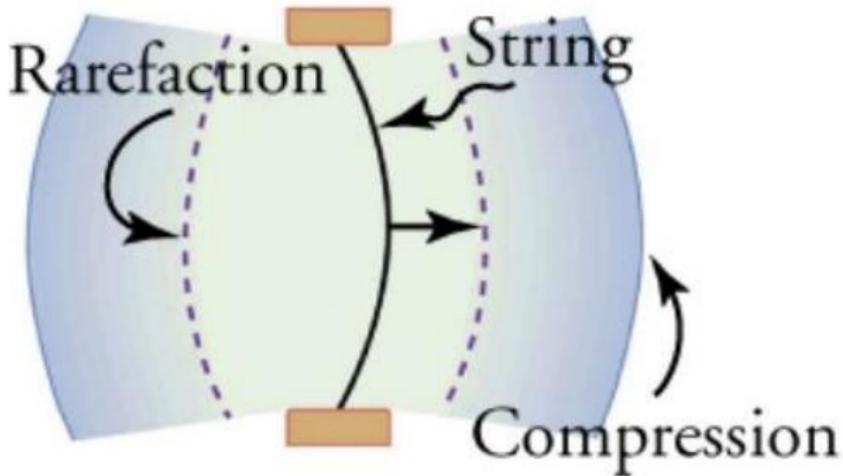
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- Matter must vibrate (compression and rarefaction)
- Energy transfers through medium
- **Requires matter** - no sound in vacuum

14.1 Vibrating String Creates Sound

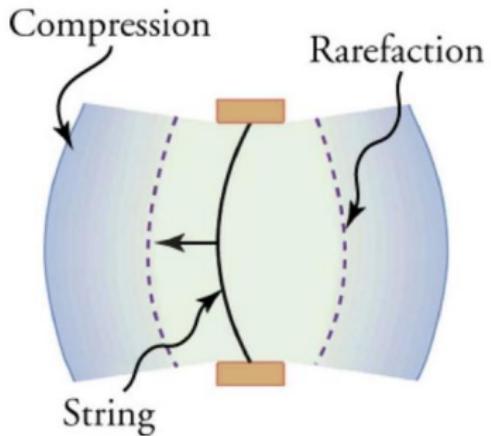


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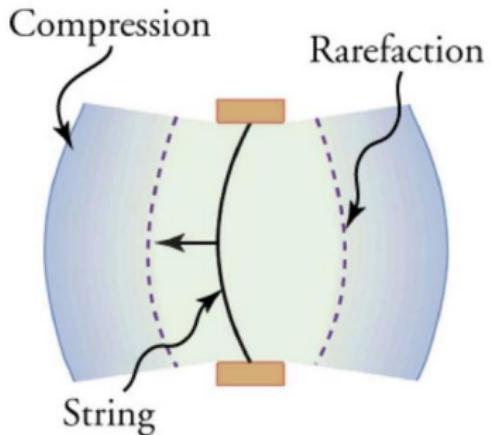


String oscillates → compresses air → creates pressure waves → longitudinal sound wave

14.1 Compressions and Rarefactions



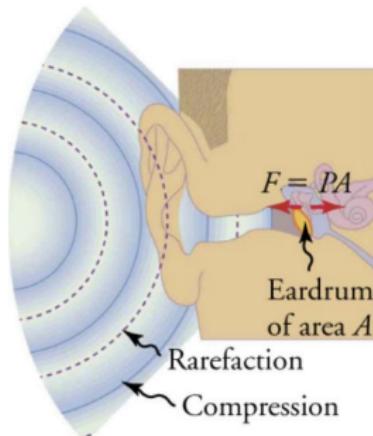
14.1 Compressions and Rarefactions



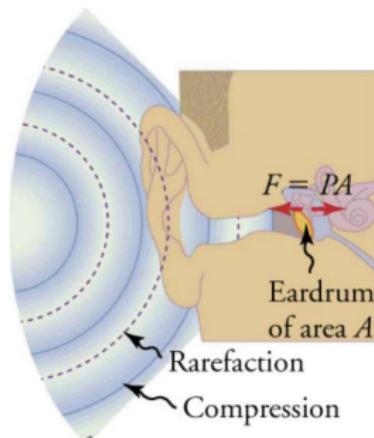
Analogy to Transverse Waves

- Compression = crest (high pressure)
- Rarefaction = trough (low pressure)
- Wavelength = distance between compressions

14.1 Sound Wave Enters Ear



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Compressions and rarefactions force eardrum to vibrate → converted to nerve impulses → brain interprets as sound

14.1 Speed of Sound

The Intuition Trap

Your brain expects: Denser material = slower sound

Reality: Speed depends on BOTH rigidity and density.

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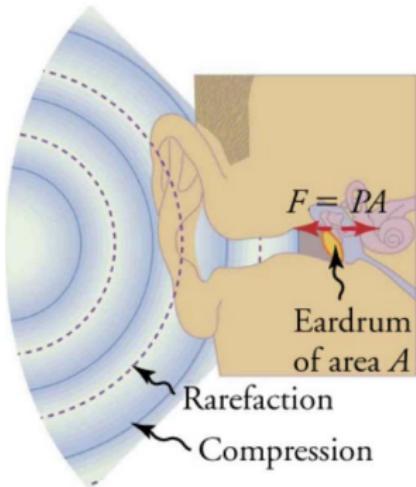
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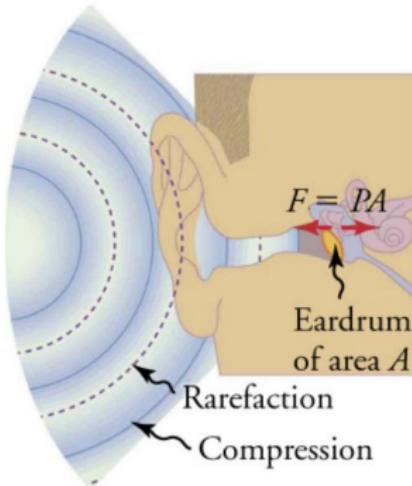
The rules:

- More rigid (less compressible) = faster sound
- Greater density = slower sound
- Solids: very rigid, so sound travels FAST despite density

14.1 Fireworks and Light vs Sound

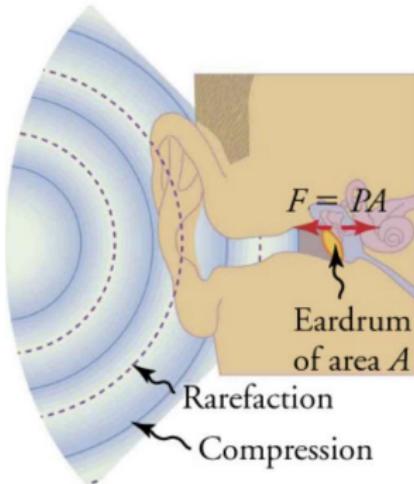


14.1 Fireworks and Light vs Sound



You see the flash BEFORE you hear the boom. Why?

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You see the flash BEFORE you hear the boom. Why?
Light: 3×10^8 m/s Sound: ~ 340 m/s in air

14.1 The Universal Wave Equation

The Law of All Waves

$$v = f\lambda$$

Speed equals frequency times wavelength.

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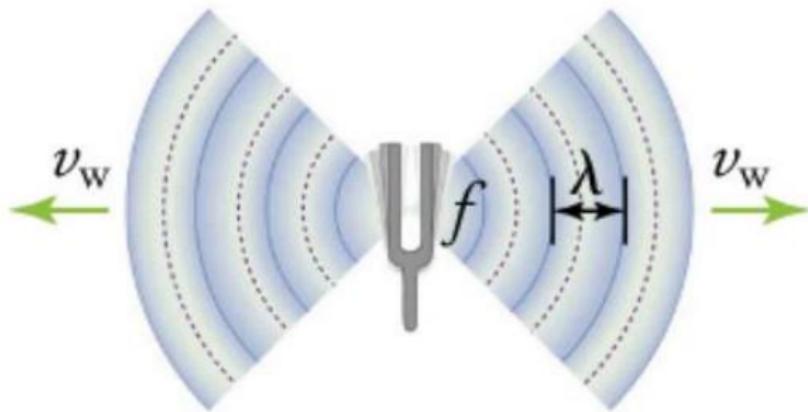
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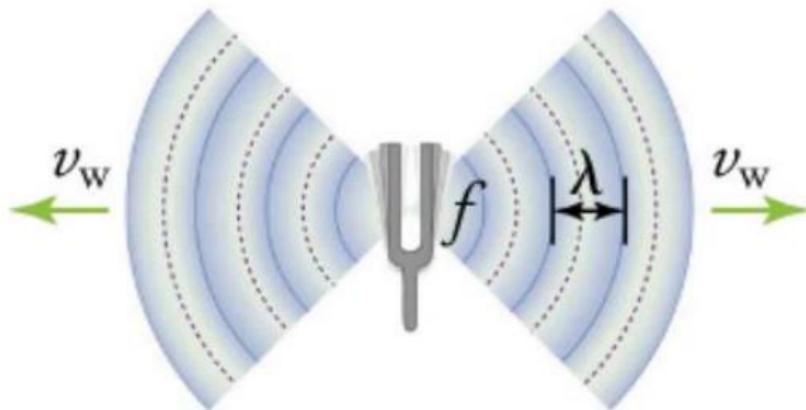
For sound:

- v = speed of sound (m/s) - depends on medium
- f = frequency (Hz) - set by source
- λ = wavelength (m) - adjusts automatically

14.1 Sound Wave Anatomy

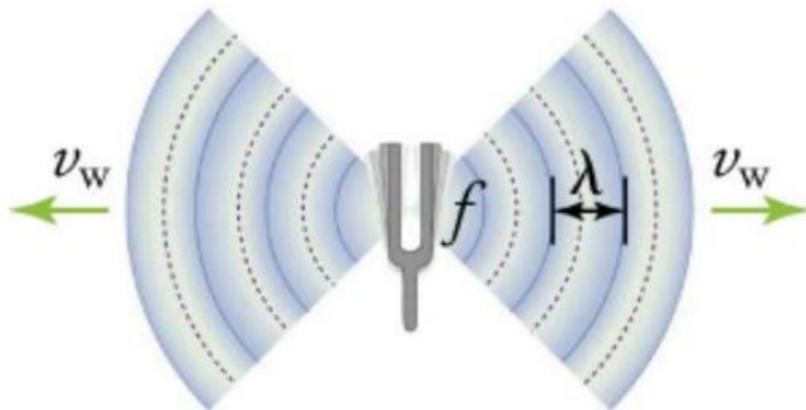


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Source vibrates at frequency $f \rightarrow$ propagates at $v \rightarrow$ wavelength λ

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Distance between adjacent compressions = one wavelength

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But all instruments arrive in sync, regardless of distance.

The Consequence

Since $v = f\lambda$ and v is constant, higher frequency means shorter wavelength.

Attempt: Decoding Audible Sound

The Challenge (3 min, silent)

Calculate the wavelengths of sounds at the extremes of human hearing, 20 Hz and 20,000 Hz, when sound travels at 348.7 m/s.

Given:

- $v = 348.7 \text{ m/s}$
- $f_{\min} = 20 \text{ Hz}, f_{\max} = 20,000 \text{ Hz}$

Find: λ_{\max} and λ_{\min}

Can you decode the range? Work silently.

Compare: Wavelength Calculation

Turn and talk (2 min):

- ① What equation connects speed, frequency, and wavelength?
- ② How did you solve for wavelength?
- ③ Which frequency gives the LONGEST wavelength? Why?

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Reveal: The Range of Human Hearing

Self-correct in a different color:

Equation: $v = f\lambda \rightarrow \lambda = \frac{v}{f}$

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Check: Deep bass (20 Hz) has wavelength of a bus. High treble (20 kHz) is the size of your thumb.

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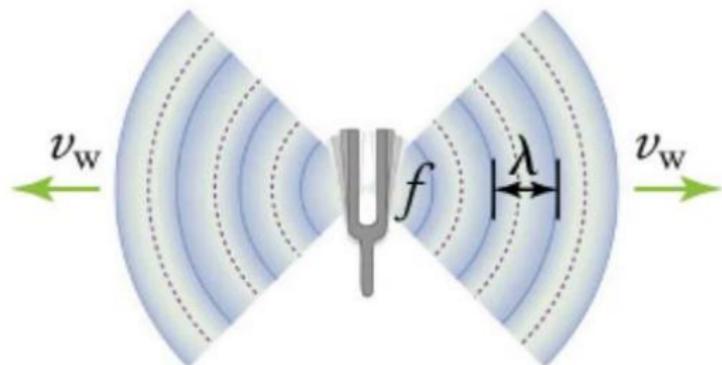
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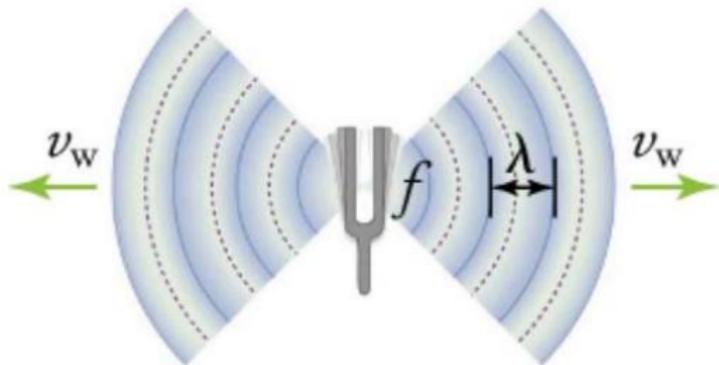
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- **14.2:** Relate amplitude to loudness and energy
 - **14.2:** Describe the decibel scale for measuring intensity
 - **14.2:** Solve problems involving sound intensity
 - **14.2:** Describe how humans produce and hear sounds

14.2 Loudness and Amplitude

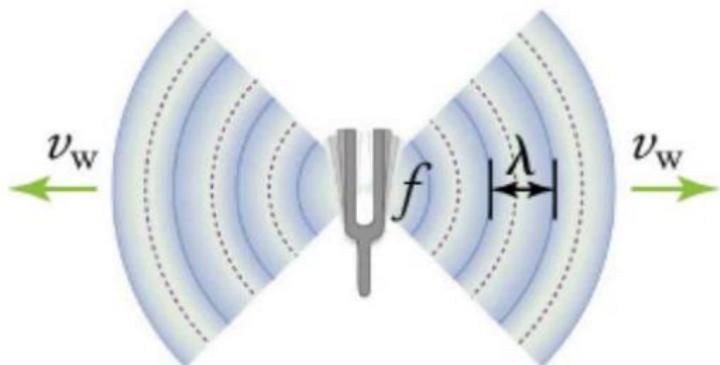


14.2 Loudness and Amplitude



Loudness relates to how energetically the source vibrates.

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The Connection

Louder sound = greater amplitude = more energy transferred

14.2 Sound Intensity

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 - A = area (m^2) - surface through which wave passes

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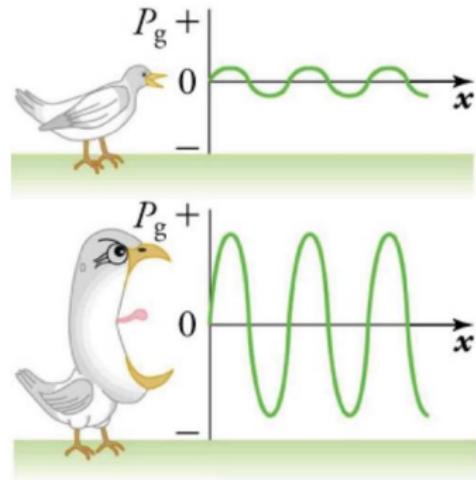
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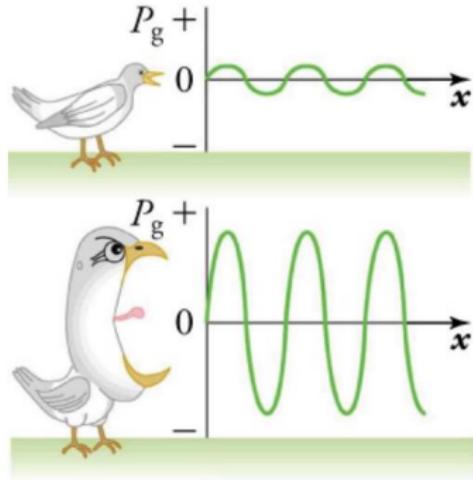
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Key insight: $I \propto (\Delta p)^2$ where Δp is pressure amplitude.
Intensity is proportional to amplitude squared!

14.2 Pressure Amplitude Graphs



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More intense sound has larger pressure maxima and minima, greater forces on objects.

14.2 Why Decibels?

Civilian View vs. Reality

Civilian: "Intensity in W/m^2 makes sense."

Physicist: "Human ears perceive logarithmically, not linearly."

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The Decibel Scale

$$\beta \text{ (dB)} = 10 \log_{10} \left(\frac{I}{I_0} \right)$$

where $I_0 = 10^{-12}$ W/m² (threshold of human hearing)

14.2 Understanding the Decibel Scale

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- Each factor of 10 in intensity = 10 dB

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- 0 dB = threshold of hearing (10^{-12} W/m²)

Examples

- Whisper: 20 dB
- Conversation: 60 dB
- Rock concert: 120 dB (pain threshold)

Attempt: Calculating Decibels

The Challenge (3 min, silent)

A sound wave in air at 0°C has pressure amplitude 0.656 Pa. Calculate the sound intensity level in decibels.

Given:

- $\Delta p = 0.656 \text{ Pa}$
- $v = 331 \text{ m/s}$ (air at 0°C)
- $\rho = 1.29 \text{ kg/m}^3$ (air density)
- $I_0 = 10^{-12} \text{ W/m}^2$

Find: β in dB

Two steps: find intensity, then decibels. Work silently.

Compare: Decibel Calculation

Turn and talk (2 min):

- ① What formula did you use to find intensity from pressure?
- ② What values did you substitute?
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Reveal: From Pressure to Decibels

Self-correct in a different color:

Step 1 - Find intensity: $I = \frac{(\Delta p)^2}{2\rho v}$

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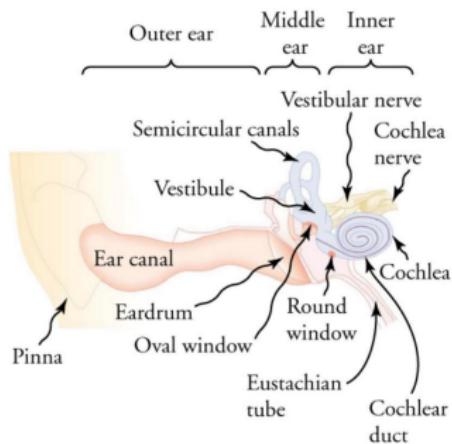
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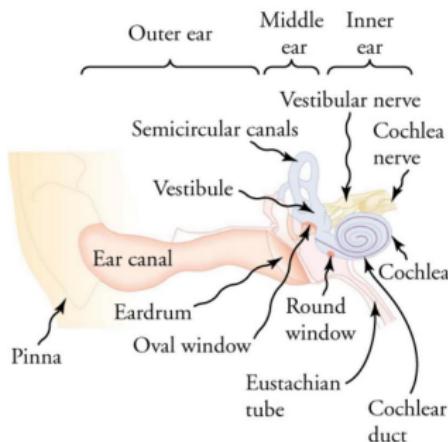
$$\boxed{\beta = 87.0 \text{ dB}}$$

Check: 87 dB is about as loud as heavy traffic - reasonable.

14.2 How We Hear



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Sound waves → eardrum vibrates → bones amplify → cochlea converts to electrical signals → brain interprets

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- **14.3:** Calculate frequency shift using Doppler formula

Why Ambulances Lie to You

The siren isn't changing pitch.
Your ears are being fooled.

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The Illusion

Ambulance plays one constant note. You hear two different pitches approaching vs. receding.

What's happening?

14.3 Stationary Source and Observers

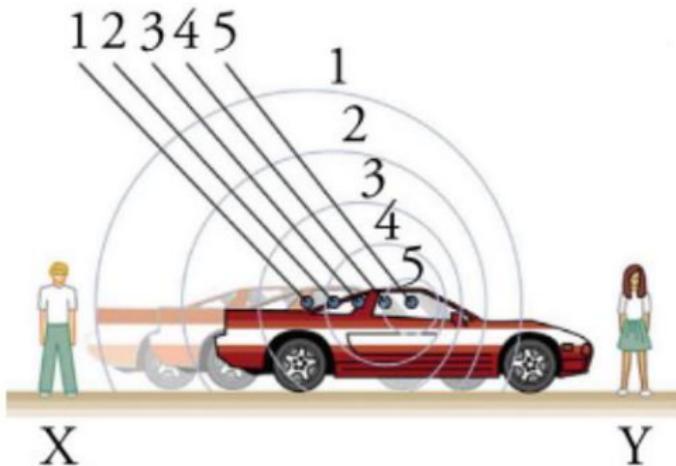


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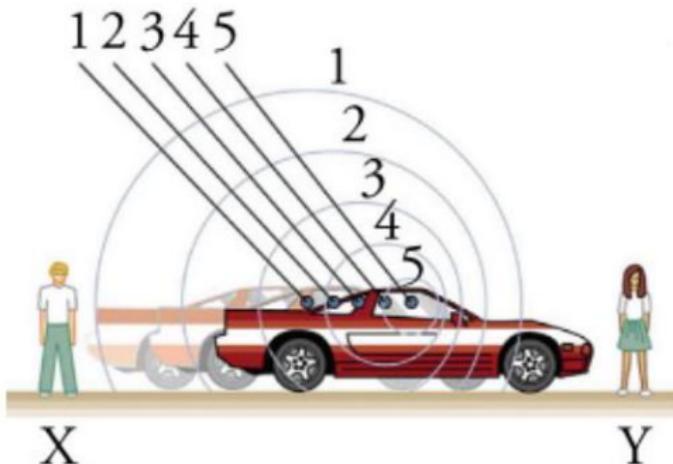


When source and observers are stationary, wavelength and frequency are same in all directions.

14.3 Moving Source

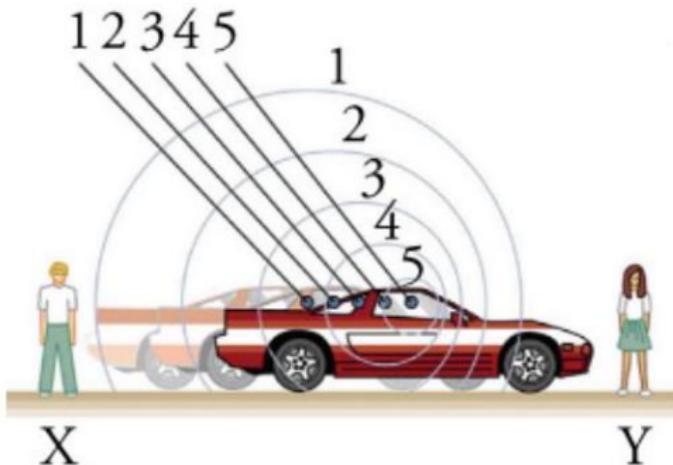


14.3 Moving Source



Source moving right → waves bunch up ahead, spread out behind

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Source moving right \rightarrow waves bunch up ahead, spread out behind
Observer on right: shorter λ , higher f
Observer on left: longer λ , lower f

14.3 The Doppler Effect Formula

For Moving Source, Stationary Observer

$$f_{\text{obs}} = f_s \left(\frac{v_w}{v_w \pm v_s} \right)$$

Use minus for motion toward observer, plus for motion away.

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For Moving Source, Stationary Observer

$$f_{\text{obs}} = f_s \left(\frac{v_w}{v_w \pm v_s} \right)$$

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Intuition check:

- Source approaching: denominator smaller → frequency higher
- Source receding: denominator larger → frequency lower

14.3 Sonic Booms

What happens when source speed approaches sound speed?

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As $v_s \rightarrow v_w$, denominator in $f_{\text{obs}} = f_s \left(\frac{v_w}{v_w - v_s} \right)$ approaches zero...

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Observed frequency approaches infinity!

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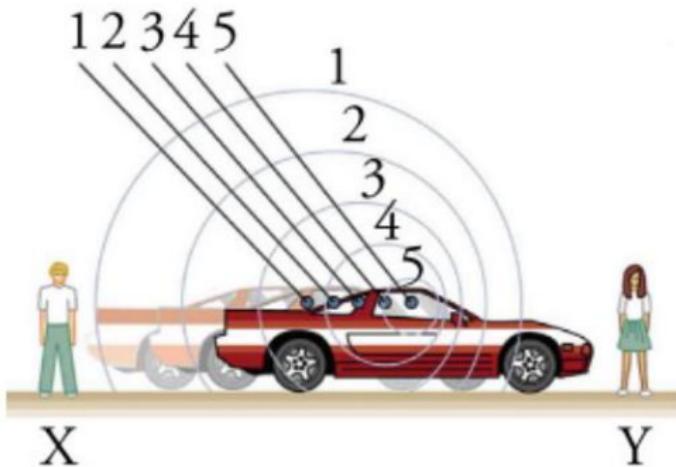
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Sonic Boom

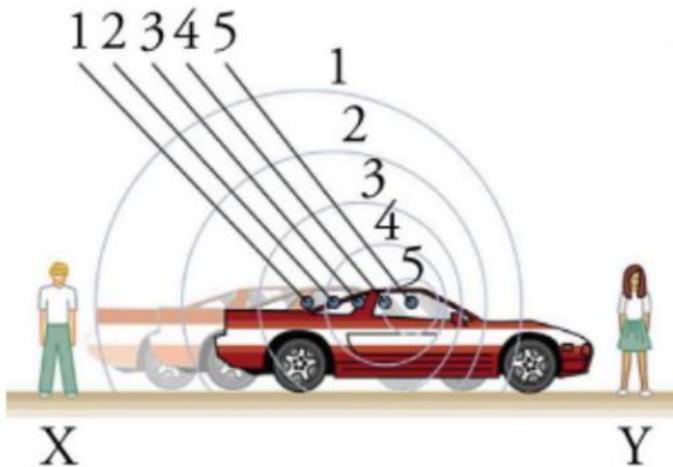
Constructive interference of sound created by object moving faster than sound.

All waves superimpose at same instant → huge amplitude → BOOM!

14.3 Sonic Boom Geometry



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Two booms: one from nose, one from tail. Time separation equals time for aircraft to pass by a point.

Attempt: Doppler Shift Calculation

The Challenge (3 min, silent)

A train has 150 Hz horn and moves at 35 m/s. Speed of sound is 340 m/s. What frequencies are observed by stationary person as train approaches and recedes?

Given:

- $f_s = 150 \text{ Hz}$
- $v_s = 35 \text{ m/s}$
- $v_w = 340 \text{ m/s}$

Find: $f_{\text{obs, approaching}}$ and $f_{\text{obs, receding}}$

Which sign for approaching? Receding? Work silently.

Compare: Doppler Strategy

Turn and talk (2 min):

- ① Which formula did you use?
- ② Approaching: plus or minus sign? Why?
- ③ Receding: plus or minus sign? Why?
- ④ How did you check if answer was reasonable?

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Receding (use plus): $f_{\text{obs}} = f_s \left(\frac{v_w}{v_w + v_s} \right)$

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Approaching (use minus): $f_{\text{obs}} = f_s \left(\frac{v_w}{v_w - v_s} \right)$

$$f_{\text{obs}} = 150 \left(\frac{340}{340 - 35} \right) = 150 \left(\frac{340}{305} \right) = 167 \text{ Hz} \approx 170 \text{ Hz}$$

Receding (use plus): $f_{\text{obs}} = f_s \left(\frac{v_w}{v_w + v_s} \right)$

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Check: Shift up by 20 Hz, down by 10 Hz. Asymmetric - correct!

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

- **14.4:** Describe resonance and beats

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- **14.4:** Contrast open-pipe and closed-pipe resonators
- **14.4:** Solve problems involving harmonics and beat frequency

14.4 Resonance

Universal Law: Resonance

Systems oscillate best at their natural frequency. Driving a system at its natural frequency produces resonance.

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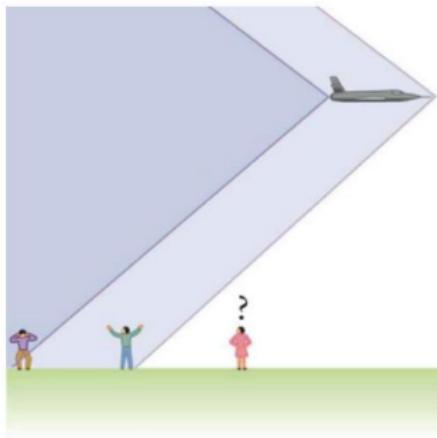
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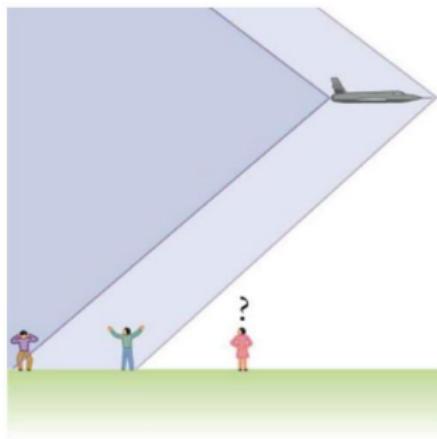
The Mental Model

Resonance is when driving frequency matches natural frequency, creating maximum energy transfer.

14.4 Paddle Ball Resonance

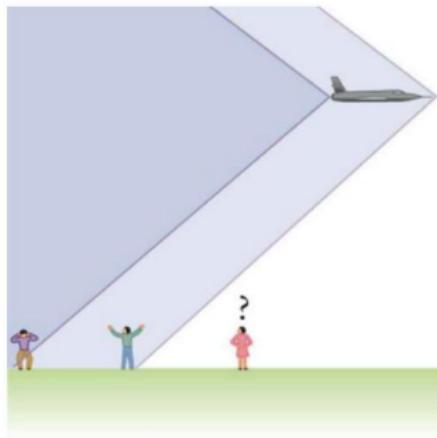


14.4 Paddle Ball Resonance



Move finger at ball's natural frequency → amplitude grows dramatically

14.4 Paddle Ball Resonance



Move finger at ball's natural frequency → amplitude grows dramatically
Move too slow or too fast → amplitude stays small

14.4 Beat Frequency

Beats from Superposition

Two waves with slightly different frequencies superimpose → alternating constructive and destructive interference → amplitude varies in time.

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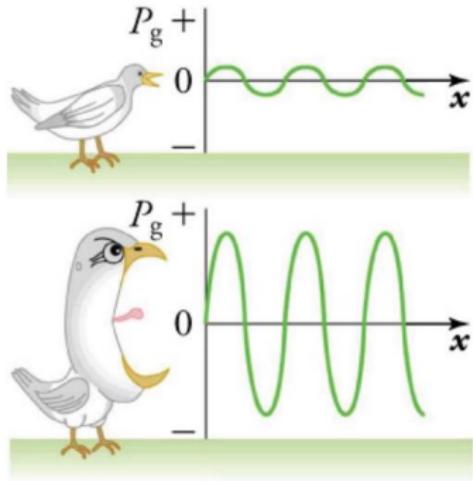
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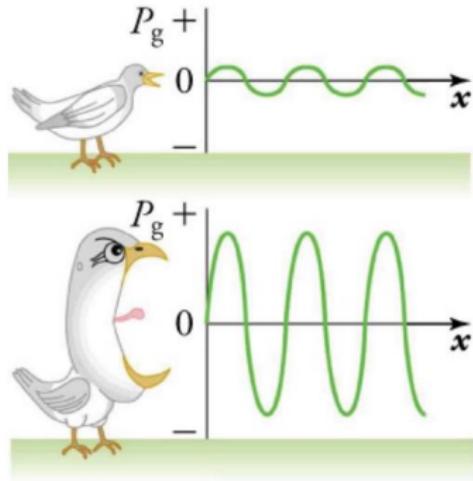
$$f_B = |f_1 - f_2|$$

You hear average frequency getting louder and softer at beat frequency.

14.4 Beat Pattern

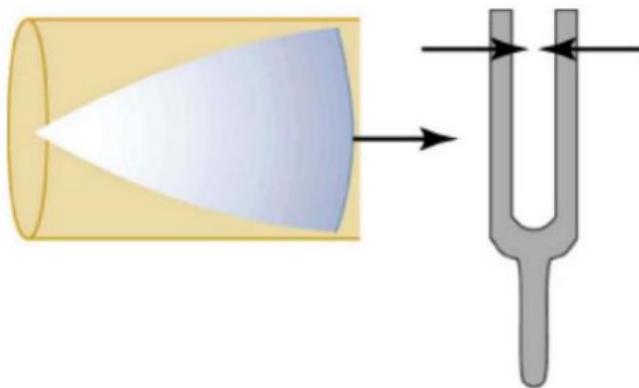


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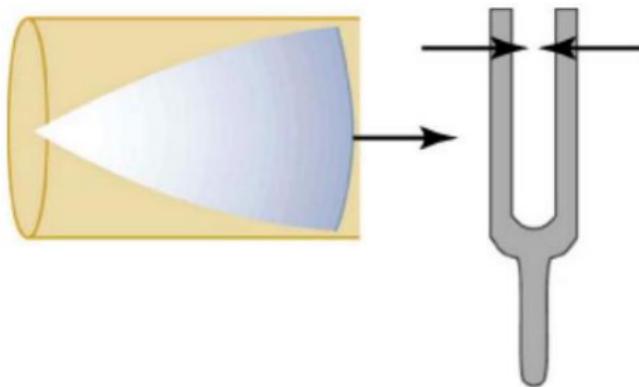


Amplitude oscillates at beat frequency while wave oscillates at average frequency.

14.4 Standing Waves in Closed Pipe



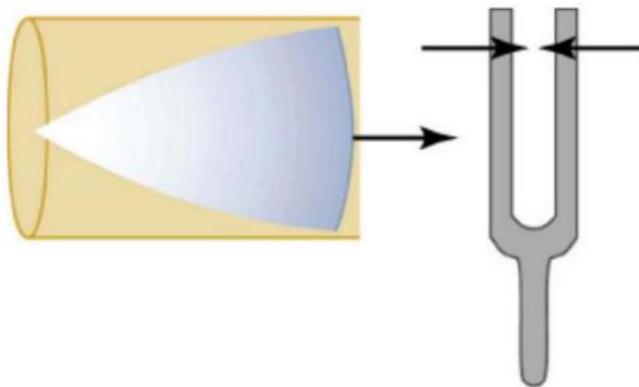
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Closed end: node (no displacement)

Open end: antinode (maximum displacement)

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Fundamental: $\lambda = 4L$ so $f_1 = \frac{v}{4L}$

14.4 Harmonics in Closed Pipe

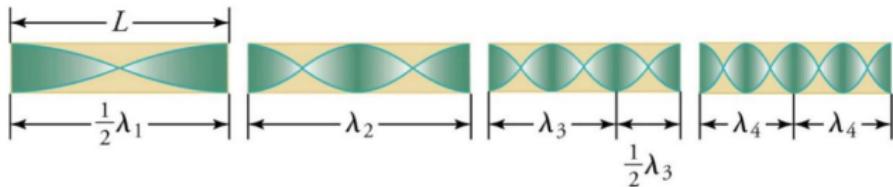


14.4 Harmonics in Closed Pipe



Closed-pipe resonator: $f_n = n \frac{v}{4L}$ where $n = 1, 3, 5, \dots$
Only odd harmonics!

14.4 Open-Pipe Resonator



Fundamental

$$\lambda_1 = 2L$$

$$f_1 = \frac{v}{2L}$$

First overtone

$$\lambda_2 = L$$

$$f_2 = \frac{v}{L}$$

Second overtone

$$\lambda_3 = \frac{2}{3}L$$

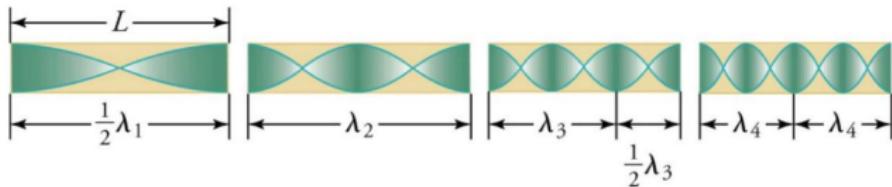
$$f_3 = \frac{3v}{2L}$$

Third overtone

$$\lambda_4 = \frac{1}{2}L$$

$$f_4 = \frac{2v}{L}$$

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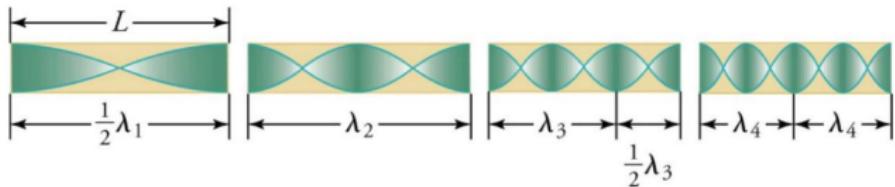
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$$f_4 = \frac{2v}{L}$$

Both ends: antinodes (maximum displacement)

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Both ends: antinodes (maximum displacement)

Open-pipe resonator: $f_n = n\frac{v}{2L}$ where $n = 1, 2, 3, \dots$

All harmonics!

Attempt: Closed-Pipe Length

The Challenge (3 min, silent)

Sound travels at 344 m/s. What length should a tube closed at one end have for fundamental frequency of 128 Hz?

Given:

- $f_1 = 128 \text{ Hz}$ (fundamental)
- $v = 344 \text{ m/s}$

Find: Length L

Which formula for closed pipe? Work silently.

Compare: Pipe Length Strategy

Turn and talk (2 min):

- ① Closed pipe or open pipe formula?
- ② What is n for the fundamental?
- ③ How did you solve for length L ?

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Name wheel: One pair share your approach.

Reveal: Tube Length for Resonance

Self-correct in a different color:

Closed-pipe formula: $f_n = n \frac{v}{4L}$ with $n = 1$ for fundamental

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Solve for L: $L = \frac{v}{4f_1}$

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$$L = \frac{344 \text{ m/s}}{4(128 \text{ Hz})} = \frac{344}{512} = \boxed{0.672 \text{ m} = 67.2 \text{ cm}}$$

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Check: About 2 feet - reasonable for a musical instrument.

What You Now Know

The Revelations

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- ⑤ Resonance: driving at natural frequency maximizes energy
- ⑥ Harmonics: geometry restricts allowed frequencies

Key Equations

$$v = f\lambda \quad (1)$$

$$I = \frac{P}{A} = \frac{(\Delta p)^2}{2\rho v} \quad (2)$$

$$\beta \text{ (dB)} = 10 \log_{10} \left(\frac{I}{I_0} \right) \quad (3)$$

$$f_{\text{obs}} = f_s \left(\frac{\nu_w}{\nu_w \pm \nu_s} \right) \quad (4)$$

$$f_B = |f_1 - f_2| \quad (5)$$

$$f_n = n \frac{\nu}{4L} \text{ (closed)}, \quad n = 1, 3, 5, \dots \quad (6)$$

$$f_n = n \frac{\nu}{2L} \text{ (open)}, \quad n = 1, 2, 3, \dots \quad (7)$$

Homework

Complete the assigned problems
posted on the LMS