PHYS11 CH:14 Invisible Vibrations

From Silence to Symphony

Mr. Gullo

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Outline

The Mystery

If a tree falls in the forest
and no one is there to hear it,
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Physics says: yes, but no one perceives it.

Fallen Tree

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The Mental Model

Tree hits ground $\rightarrow$ disturbs air particles $\rightarrow$ creates pressure waves $\rightarrow$ 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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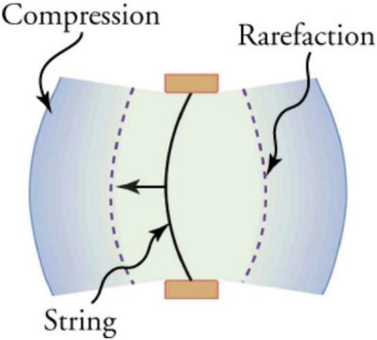
What makes it sound:

- 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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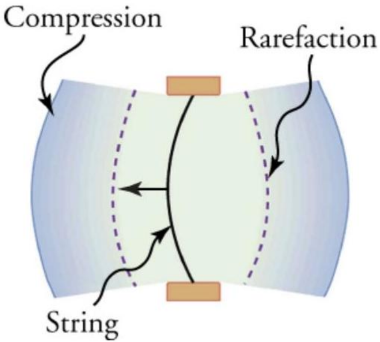
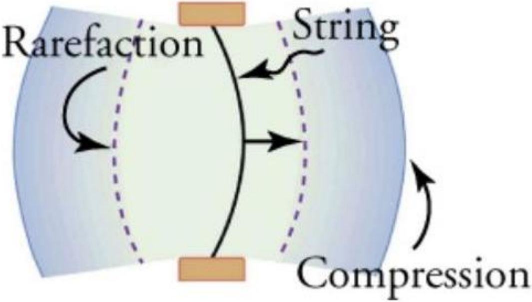


String oscillates $\rightarrow$ compresses air $\rightarrow$ creates pressure waves $\rightarrow$ longitudinal sound wave

14.1 Compressions and Rarefactions



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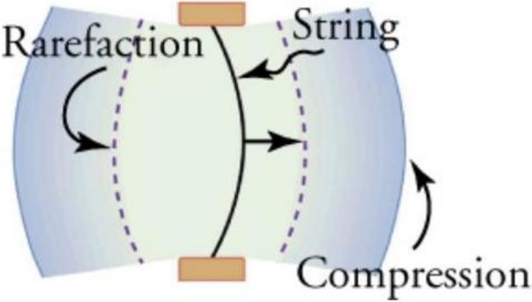
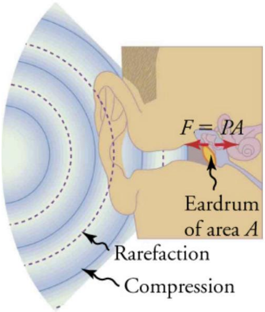


Analogy to Transverse Waves

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

14.1 Sound Wave Enters Ear



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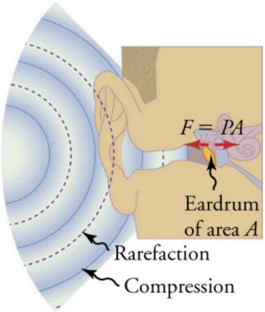

Compressions and rarefactions force eardrum to vibrate $\rightarrow$ converted to nerve impulses $\rightarrow$ brain interprets as sound

The Intuition Trap

Your brain expects: Denser material = slower sound
Reality: Speed depends on BOTH rigidity and density.

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- 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

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

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

Speed equals frequency times wavelength.

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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

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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:

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

Find: λ_{max} and λ_{min}

Can you decode the range? Work silently.

Compare: Wavelength Calculation

Turn and talk (2 min):

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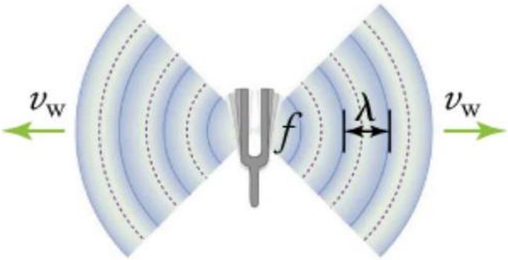
- **14.2:** Describe the decibel scale for measuring intensity
- **14.2:** Solve problems involving sound intensity
- **14.2:** Describe how humans produce and hear sounds

14.2 Loudness and Amplitude



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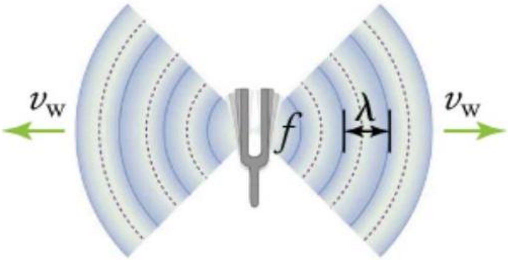

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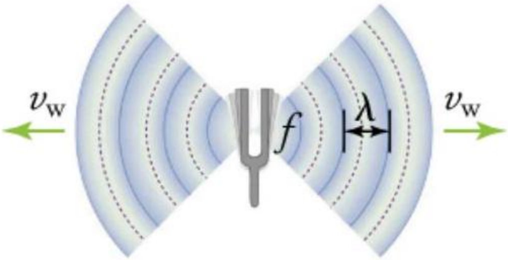

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The Connection

Louder sound = greater amplitude = more energy transferred

14.2 Sound Intensity

Universal Law: Intensity

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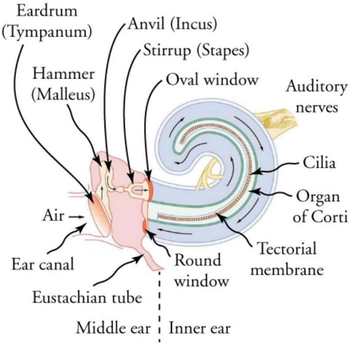
Key insight: $I \propto (\Delta p)^2$ where Δp is pressure amplitude.
Intensity is proportional to amplitude squared!

14.2 Pressure Amplitude Graphs



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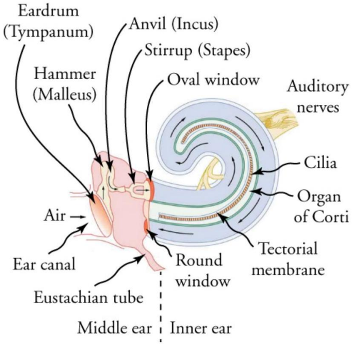

More intense sound has larger pressure maxima and minima, greater forces on objects.

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/m^2 (threshold of human hearing)

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- Doubling intensity adds about 3 dB
- 0 dB = threshold of hearing (10^{-12} W/m^2)

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:

- $\Delta p = 0.656$ Pa
- $v = 331$ m/s (air at 0°C)
- $\rho = 1.29$ kg/m^3 (air density)
- $I_0 = 10^{-12}$ 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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$$\boxed{\beta = 87.0 \text{ dB}}$$

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

14.2 How We Hear

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Sound waves $\rightarrow$ eardrum vibrates $\rightarrow$ bones amplify $\rightarrow$ cochlea converts to electrical signals $\rightarrow$ brain interprets

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

Why Ambulances Lie to You

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Your ears are being fooled.

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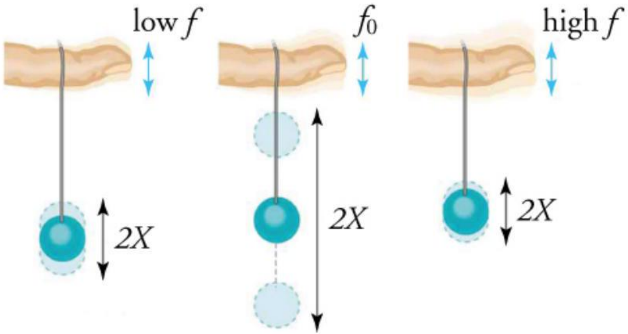
The Illusion

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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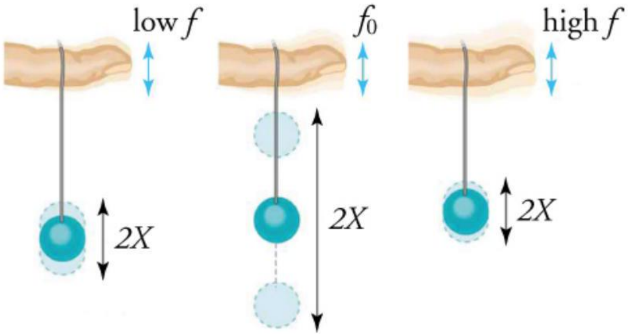

When source and observers are stationary, wavelength and frequency are same in all directions.

14.3 Moving Source

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

Intuition check:

- Source approaching: denominator smaller $\rightarrow$ frequency higher
- Source receding: denominator larger $\rightarrow$ frequency lower

14.3 Sonic Booms

What happens when source speed approaches sound speed?

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Sonic Boom

Constructive interference of sound created by object moving faster than sound.
All waves superimpose at same instant $\to$ huge amplitude $\to$ 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:

- $f_s = 150$ Hz
- $v_s = 35$ m/s
- $v_w = 340$ 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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Name wheel: One pair share your sign logic.

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

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

14.4 Resonance

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- Child on swing pushed at swing's natural frequency

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Examples:

- Piano strings vibrate when you sing at their frequency
- Child on swing pushed at swing's natural frequency
- Tuning fork and air column resonate at matching frequency

14.4 Resonance

Universal Law: Resonance

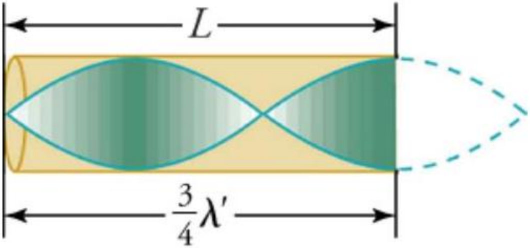
Systems oscillate best at their natural frequency. Driving a system at its natural frequency produces resonance.

Examples:

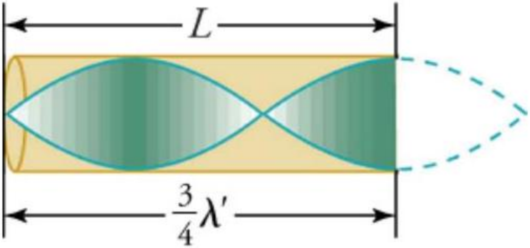
- Piano strings vibrate when you sing at their frequency
- Child on swing pushed at swing's natural frequency
- Tuning fork and air column resonate at matching frequency

The Mental Model

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

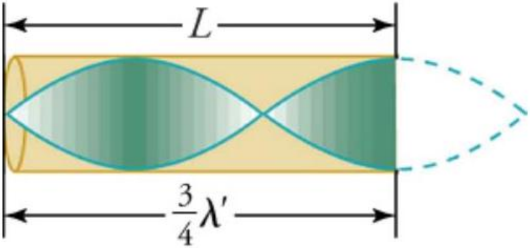

L
$\frac{3}{4}\lambda'$

14.4 Paddle Ball Resonance



Move finger at ball's natural frequency $\rightarrow$ amplitude grows dramatically

14.4 Paddle Ball Resonance



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

14.4 Beat Frequency

Beats from Superposition

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

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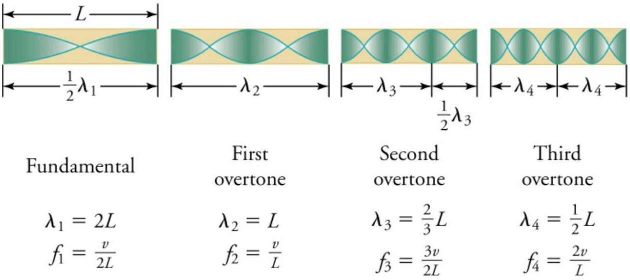
Beats from Superposition

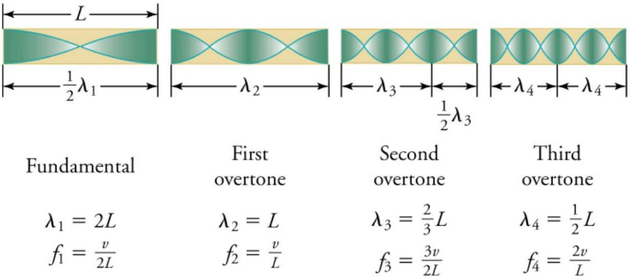
Two waves with slightly different frequencies superimpose → alternating constructive and destructive interference → amplitude varies in time.

$$f_B = |f_1 - f_2|$$

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

14.4 Beat Pattern





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

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Closed end: node (no displacement)
Open end: antinode (maximum displacement)

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Open end: antinode (maximum displacement)
Fundamental: $\lambda = 4L$ so $f_1 = \frac{v}{4L}$

14.4 Harmonics in Closed Pipe

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Closed-pipe resonator: $f_n = n\frac{v}{4L}$ where $n = 1, 3, 5, \ldots$

Only odd harmonics!

14.4 Open-Pipe Resonator

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Both ends: antinodes (maximum displacement)

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

- $f_1 = 128$ Hz (fundamental)
- $v = 344$ 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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$$L = \frac{344 \text{ m/s}}{4(128 \text{ Hz})} = \frac{344}{512} = \boxed{0.672 \text{ m} = 67.2 \text{ cm}}$$

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

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The Revelations

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4. Doppler effect: motion changes observed frequency
5. Resonance: driving at natural frequency maximizes energy
6. Harmonics: geometry restricts allowed frequencies

Key Equations

$$v = f\lambda \tag{1}$$

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

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

$$f_{\text{obs}} = f_s\left(\frac{v_w}{v_w \pm v_s}\right) \tag{4}$$

$$f_B = |f_1 - f_2| \tag{5}$$

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

$$f_n = n\frac{v}{2L} \text{ (open)}, \quad n = 1, 2, 3, \ldots \tag{7}$$

Homework

Complete the assigned problems

posted on the LMS