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Waves Class 11 Notes | CBSE Physics Chapter 14

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Waves Class 11 Notes | CBSE Physics Chapter 14

Waves is Chapter 14 of CBSE Class 11 Physics — the chapter that explains how sound reaches your ear, how a guitar string sings, and why an ambulance siren changes pitch as it speeds past you. A wave carries *energy* from one place to another without the medium itself travelling along, and once that single idea clicks, the whole chapter falls into place.

By the end of these notes you will be able to write the displacement equation of a progressive wave, calculate the speed of a wave on a string or of sound in air, set up standing waves in strings and pipes, find beat frequencies, and apply the Doppler effect. This is a steady-scoring chapter worth roughly 6–8 marks in boards, and a guaranteed question in NEET and JEE every single year.

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Key Concepts

1. What is a Wave?

A **wave** is a disturbance that travels through a medium, transporting energy and momentum from one point to another without any net transport of the medium itself. Drop a stone in a pond — the ripple spreads outward, but a floating leaf only bobs up and down; it does not move with the ripple.

Mechanical waves (water waves, sound, waves on a string) need a material medium to travel. Electromagnetic waves (light, radio) need no medium. This chapter deals mainly with mechanical waves.

2. Transverse and Longitudinal Waves

Waves are classified by the direction in which the particles of the medium vibrate relative to the direction the wave travels.

Transverse Wave	Longitudinal Wave
Particles vibrate perpendicular to the direction of wave propagation	Particles vibrate parallel to the direction of wave propagation
Made of crests and troughs	Made of compressions and rarefactions
Example: wave on a string, ripples on water, light	Example: sound waves in air, waves in a spring (pushed lengthwise)
Can travel only in solids and on liquid surfaces	Can travel in solids, liquids and gases

[DIAGRAM: A horizontal string showing crests and troughs (transverse) above a slinky showing alternating compressions and rarefactions (longitudinal), both with the wave-travel direction marked by an arrow.]

Key idea: Sound in air is always longitudinal because gases cannot sustain the shearing stress needed for a transverse wave.

3. Terms Used to Describe a Wave

- **Amplitude (A):** maximum displacement of a particle from its mean position.
- **Wavelength (λ):** distance between two consecutive points in the same phase (crest to crest, or compression to compression). SI unit: metre.
- **Time period (T):** time taken for one complete oscillation. Frequency $f = 1/T$, SI unit hertz (Hz).
- **Angular frequency:** $\omega = 2\pi f = 2\pi/T$. **Wave number:** $k = 2\pi/\lambda$.
- **Wave velocity (v):** the speed at which the disturbance travels: $v = f\lambda = \omega/k$.

4. Displacement Relation for a Progressive Wave

A **progressive (travelling) wave** moves continuously in one direction, carrying energy with it. For a sinusoidal wave travelling along the positive x-direction, the displacement y of a particle at position x and time t is:

$$y(x, t) = A \sin(kx - \omega t + \phi)$$

- **A** = amplitude, **k** = $2\pi/\lambda$ = angular wave number, **ω** = $2\pi f$ = angular frequency, **ϕ** = initial phase (phase constant).
- For a wave travelling in the **negative** x-direction: $y(x, t) = A \sin(kx + \omega t + \phi)$.
- The term **(kx - ω t)** is the **phase** of the wave.

Phase difference and path difference: a path difference of one wavelength λ corresponds to a phase difference of 2π . So **phase difference $\Delta\phi = (2\pi/\lambda) \times \text{path difference}$** .

5. Speed of a Travelling Wave

The speed of a wave is fixed by the properties of the medium, not by how the wave was produced. The general result is $v = f\lambda$.

Speed of a Transverse Wave on a String

For a stretched string, the wave speed depends on the tension and how heavy the string is:

$$v = \sqrt{T/\mu}$$

where T is the tension in the string and μ is the **linear mass density** (mass per unit length, kg/m). A tighter, lighter string carries waves faster — that is how a guitar is tuned.

Speed of a Longitudinal Wave

For a longitudinal wave in a medium of bulk modulus B and density ρ : $v = \sqrt{B/\rho}$. In a solid rod (Young's modulus Y): $v = \sqrt{Y/\rho}$.

6. Speed of Sound — Newton's Formula and Laplace's Correction

Sound is a longitudinal wave, so its speed in a gas is $v = \sqrt{B/\rho}$. The question is which bulk modulus B to use.

Newton's Formula

Newton assumed that sound travels through air under **isothermal** conditions (constant temperature). Then B equals the pressure P , giving:

$$v = \sqrt{P/\rho}$$

For air at STP this gives about **280 m/s** — but the measured value is about 332 m/s. Newton's formula is roughly 15% too low.

Laplace's Correction

Laplace pointed out that compressions and rarefactions happen so fast that there is no time for heat to flow — the process is **adiabatic**, not isothermal. The relevant bulk modulus is then γP , where $\gamma = C_p/C_v$ is the ratio of specific heats ($\gamma = 1.4$ for air).

$$v = \sqrt{\gamma P/\rho}$$

This gives about **332 m/s**, matching experiment. **Factors affecting speed of sound:** it increases with temperature ($v \propto \sqrt{T}$ in kelvin), increases with humidity, but is independent of pressure (at constant temperature) and of frequency.

7. Principle of Superposition of Waves

When two or more waves travel through the same medium at the same time, the resultant displacement at any point is the **vector sum** of the displacements due to each individual wave.

$$y = y_1 + y_2 + y_3 + \dots$$

This single principle explains interference, standing waves, and beats. After they cross, each wave continues as if the other was never there.

8. Reflection of Waves

When a wave hits a boundary, part of it is reflected. What happens to the phase depends on the boundary.

- **Reflection from a rigid (fixed) boundary:** the wave is reflected with a **phase change of π** (180°). A crest returns as a trough. (Example: string fixed to a wall.)
 - **Reflection from a free (open) boundary:** the wave is reflected with **no phase change**. A crest returns as a crest. (Example: open end of an organ pipe.)
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9. Standing (Stationary) Waves

When two identical waves of the same frequency and amplitude travel in **opposite directions** and superpose, they form a **standing wave** — a pattern that appears to stand still instead of travelling.

The resultant of $y_1 = A \sin(kx - \omega t)$ and $y_2 = A \sin(kx + \omega t)$ is:

$$y = 2A \sin(kx) \cos(\omega t)$$

- **Nodes:** points of permanently zero displacement, where $2A \sin(kx) = 0$. They occur at $x = 0, \lambda/2, \lambda, \dots$ (spacing $\lambda/2$).
- **Antinodes:** points of maximum displacement (amplitude $2A$). They occur halfway between nodes (spacing $\lambda/2$).
- Distance between a node and the nearest antinode is $\lambda/4$.
- A standing wave does **not** transport energy along the medium — energy stays trapped between the boundaries.

[DIAGRAM: A standing wave on a string showing fixed nodes (N) at the ends and along the string, with antinodes (A) bulging between them; node-to-node spacing labelled $\lambda/2$.]

10. Normal Modes of a Stretched String

A string fixed at both ends can vibrate only at certain frequencies, called its **normal modes** or harmonics, because both ends must be nodes.

For a string of length L , the allowed wavelengths are $\lambda = 2L/n$ ($n = 1, 2, 3, \dots$), so the frequencies are:

$$f_n = n \cdot v / 2L = (n/2L) \sqrt{T/\mu}, \text{ where } n = 1, 2, 3, \dots$$

- **n = 1:** fundamental frequency (first harmonic), $f_1 = v/2L$.
- **n = 2:** second harmonic (first overtone), $f_2 = 2f_1$.
- A string produces **all harmonics** — both even and odd — so its overtones are $2f_1, 3f_1, 4f_1, \dots$

11. Normal Modes in Air Columns (Organ Pipes)

Sound waves form standing waves inside pipes. An **open end is an antinode** (free to vibrate) and a **closed end is a node** (cannot vibrate).

Open Pipe (open at both ends)

Both ends are antinodes. The allowed frequencies are:

$$f_n = n \cdot v / 2L \quad (n = 1, 2, 3, \dots)$$

An open pipe gives **all harmonics** ($1f, 2f, 3f, \dots$), which is why it sounds richer.

Closed Pipe (closed at one end)

The closed end is a node and the open end an antinode. The allowed frequencies are:

$$f_n = n \cdot v / 4L \quad (n = 1, 3, 5, \dots \text{ only odd})$$

A closed pipe gives **only odd harmonics** ($1f, 3f, 5f, \dots$). Its fundamental $v/4L$ is half that of an open pipe of the same length.

Pipe	Fundamental	Harmonics present
Open pipe	$v/2L$	All (1, 2, 3, 4...)
Closed pipe	$v/4L$	Only odd (1, 3, 5...)

12. Beats

When two sound waves of **slightly different frequencies** superpose, the loudness rises and falls periodically. These periodic variations in intensity are called **beats**.

The number of beats heard per second equals the difference of the two frequencies:

$$\text{Beat frequency} = |f_1 - f_2|$$

- Beats are audible only if $|f_1 - f_2|$ is less than about 10 Hz (the ear cannot resolve faster fluctuations).
- Used to **tune musical instruments** — when the beats vanish, the two notes are identical.

13. The Doppler Effect

The **Doppler effect** is the apparent change in the frequency (pitch) of a sound when the source, the observer, or both are moving relative to each other. An approaching ambulance sounds higher-pitched; as it moves away the pitch drops.

The general formula for the observed frequency f' is:

$$f' = f \cdot (v \pm v_o) / (v \mp v_s)$$

where v is the speed of sound, v_o the observer's speed and v_s the source's speed.

Sign Convention

- Take all velocities positive along the direction **from source to observer**.
- Use the **top sign** when source and observer move **towards** each other (frequency increases).
- Use the **bottom sign** when they move **away** from each other (frequency decreases).

Note: for light the Doppler shift gives the "red shift" of receding stars, but the sound formula above is not symmetric in v_o and v_s — moving the source is not the same as moving the observer.

Weightage in Board & Entrance Exams

Exam	Typical Weightage	Most-Tested Areas
CBSE Board (Class 11)	6–8 marks	Progressive wave equation, organ pipes, beats, Doppler effect
JEE Main / Advanced	1–2 questions	Standing waves, string & pipe harmonics, Doppler numericals
NEET	1–2 questions	Speed of sound, beats, Doppler effect, wave equation

[TABLE: Question-type split — VSA (1 mark): wave types, definitions, beat frequency; SA (2–3 marks): wave equation, Newton-Laplace, pipe harmonics; LA (5 marks): standing-wave derivation, Doppler-effect derivation.]

Important Definitions

Term	Definition
Wave	A disturbance that transfers energy through a medium without net transfer of matter
Transverse wave	Particles vibrate perpendicular to the direction of propagation (crests and troughs)
Longitudinal wave	Particles vibrate parallel to propagation (compressions and rarefactions)
Wavelength (λ)	Distance between two consecutive points in the same phase
Wave velocity	Speed at which the disturbance travels: $v = f\lambda$
Progressive wave	A wave that travels continuously transporting energy: $y = A \sin(kx - \omega t)$
Laplace's correction	Sound propagates adiabatically, so $v = \sqrt{\gamma P/\rho}$
Standing wave	Pattern formed by two opposite waves: $y = 2A \sin(kx) \cos(\omega t)$; no energy transport
Node / Antinode	Point of zero displacement / maximum displacement in a standing wave
Beats	Periodic rise and fall of loudness when two close frequencies superpose; rate = $ f_1 - f_2 $
Doppler effect	Apparent change in frequency due to relative motion of source and observer

Solved Examples

Example 1

A wave has frequency 500 Hz and wavelength 0.66 m. Find its speed.

Answer: $v = f\lambda = 500 \times 0.66 = \mathbf{330 \text{ m/s}}$.

Example 2

A string of linear mass density 2 g/m is stretched with a tension of 80 N. Find the speed of a transverse wave on it.

Answer: $\mu = 2 \text{ g/m} = 0.002 \text{ kg/m}$. $v = \sqrt{T/\mu} = \sqrt{80/0.002} = \sqrt{40000} = \mathbf{200 \text{ m/s}}$.

Example 3

For a progressive wave $y = 0.05 \sin(20x - 600t)$ (SI units), find the amplitude, wave number, angular frequency, wavelength and speed.

Answer: $A = 0.05 \text{ m}$; $k = 20 \text{ rad/m}$; $\omega = 600 \text{ rad/s}$. $\lambda = 2\pi/k = 2\pi/20 = \mathbf{0.314 \text{ m}}$. $v = \omega/k = 600/20 = \mathbf{30 \text{ m/s}}$.

Example 4

A pipe closed at one end has length 0.5 m. Taking the speed of sound as 340 m/s, find its fundamental frequency.

Answer: Closed pipe fundamental $f = v/4L = 340/(4 \times 0.5) = 340/2 = \mathbf{170 \text{ Hz}}$.

Example 5

Two tuning forks of frequencies 256 Hz and 260 Hz are sounded together. Find the beat frequency.

Answer: Beat frequency $= |f_1 - f_2| = |256 - 260| = \mathbf{4 \text{ Hz}}$ (4 beats per second).

Example 6

A source emitting sound of frequency 500 Hz moves towards a stationary observer at 30 m/s. Taking $v = 330 \text{ m/s}$, find the apparent frequency.

Answer: Source approaching: $f' = f \cdot v/(v - v_s) = 500 \times 330/(330 - 30) = 500 \times 330/300 = \mathbf{550 \text{ Hz}}$.

Important Questions for Board Exams

1-Mark Questions (VSA)

1. Why can transverse waves not travel through gases?
2. What is the phase difference corresponding to a path difference of one wavelength?
3. State the relation between wave velocity, frequency and wavelength.
4. Why does a closed organ pipe produce only odd harmonics?
5. Two sound waves of frequencies 400 Hz and 404 Hz are sounded together. How many beats are heard per second?

2–3-Mark Questions (SA)

1. State Newton's formula for the speed of sound in air and explain Laplace's correction.
2. Distinguish between transverse and longitudinal waves with one example each.
3. Derive the expression for the frequency of the n th harmonic of a string fixed at both ends.
4. What are beats? Write the expression for beat frequency and state one use of beats.

5-Mark Questions (LA)

1. Using the principle of superposition, derive the equation of a standing wave and obtain the positions of nodes and antinodes.
2. Derive an expression for the apparent frequency heard by a stationary observer when the source of sound moves towards and then away from the observer (Doppler effect).

3. Compare the modes of vibration of an open organ pipe and a closed organ pipe, deriving the frequencies of their harmonics.
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Quick Revision Points

- Wave transfers energy, not matter; $v = f\lambda = \omega/k$
 - Transverse: $\perp$ vibration, crests/troughs; Longitudinal: $\parallel$ vibration, compressions/rarefactions
 - Progressive wave: $y = A \sin(kx - \omega t)$; $k = 2\pi/\lambda$, $\omega = 2\pi f$
 - Phase difference $\Delta\phi = (2\pi/\lambda) \times \text{path difference}$
 - Wave on string: $v = \sqrt{T/\mu}$; longitudinal: $v = \sqrt{B/\rho}$
 - Speed of sound — Newton: $v = \sqrt{P/\rho}$; Laplace (adiabatic): $v = \sqrt{\gamma P/\rho}$; $v \propto \sqrt{T}$
 - Superposition: resultant displacement = sum of individual displacements
 - Rigid boundary $\rightarrow$ phase change π ; free boundary $\rightarrow$ no phase change
 - Standing wave: $y = 2A \sin(kx) \cos(\omega t)$; node–node = $\lambda/2$, node–antinode = $\lambda/4$; no energy transport
 - String (both ends fixed): $f_n = (n/2L)\sqrt{T/\mu}$, all harmonics
 - Open pipe: $f_n = nv/2L$ (all harmonics); Closed pipe: $f_n = nv/4L$ (odd harmonics only)
 - Beats: beat frequency = $|f_1 - f_2|$, audible if $< \sim 10$ Hz
 - Doppler: $f' = f(v \pm v_o)/(v \mp v_s)$; towards $\rightarrow$ higher pitch
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Next Chapter: Class 12 Physics — Electric Charges and Fields



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