WAVES – LIGHT AND SOUND

Chapter 1: Introduction to Waves

A wave is a repeating disturbance that transfers energy from one point to another without any net movement of matter.

Key Definition

- **Wave: A disturbance that travels through a medium (or space) carrying energy but not matter.**

Waves are everywhere — the sound you hear, the light you see, ripples on water, even earthquakes. All waves share common features such as wavelength, frequency, amplitude, and speed.

Classification of Waves

1. **Mechanical Waves: Require a medium (solid, liquid, or gas) to travel.**
   - **Examples: Sound waves in air, ripples on water, seismic waves in the Earth.**
2. **Electromagnetic Waves: Do not require a medium. They can travel through a vacuum.**
   - **Examples: Light, radio waves, microwaves.**

Waves are further divided based on the direction of particle motion:

- **Transverse Waves: Particles move perpendicular to the direction of wave propagation (e.g., light waves, water waves).**
- **Longitudinal Waves: Particles move parallel to the direction of propagation (e.g., sound waves in air).**

Chapter 2: Properties of Waves

Understanding wave properties is crucial for solving problems and applying them in technology.

Key Properties

1. **Wavelength (λ): The distance between two consecutive crests (for transverse waves) or compressions (for longitudinal waves).**
   - **Unit: meters (m)**
2. **Frequency (f): Number of waves passing a point in one second.**
   - **Unit: Hertz (Hz)**
   - **Formula:**

f=1Tf = \frac{1}{T}f=T1

where TTT = time period.

3. **Amplitude (A): The maximum displacement of particles from their equilibrium position. Higher amplitude means higher energy.**
4. **Wave Speed (v): The rate at which the wave travels through the medium.**
   - **Formula:**

v=fλv = f \lambdav=fλ

5. **Period (T): The time taken for one complete wave cycle.**

Worked Example

A wave on a string has a frequency of 50 Hz and a wavelength of 0.4 m. Find its speed.

Solution:

v=fλ=50×0.4=20 m/sv = f \lambda = 50 \times 0.4 = 20\ \text{m/s}v=fλ=50×0.4=20 m/s

Thus, the wave travels at 20 m/s.

Chapter 3: Wave Phenomena

Reflection

When a wave hits a surface, it bounces back.

- **Law of Reflection: Angle of incidence = Angle of reflection.**
- **Example: Echoes are caused by reflection of sound.**

Refraction

Bending of waves as they enter a different medium.

- **Formula (Snell's Law):**

n1sin⁡θ1=n2sin⁡θ2n_1 \sin \theta_1 = n_2 \sin \theta_2n1sinθ1=n2sinθ2

where nnn = refractive index, θ = angles with respect to normal.

Diffraction

Spreading of waves around edges or through openings.

- **Example: Hearing someone speaking around a corner.**

Interference

When two waves meet, they combine:

- **Constructive interference: Amplitudes add up (louder/brighter).**
- **Destructive interference: Amplitudes cancel out (silence/dark fringes).**

Chapter 4: Mechanical Waves

Mechanical waves are important in everyday life.

- **Transverse Example: Water waves — particles move up and down while the wave travels horizontally.**
- **Longitudinal Example: Sound waves — compressions and rarefactions travel along the direction of motion.**

Mechanical waves are disturbances that travel through a material medium (solid, liquid, or gas) due to the oscillation of particles. These waves cannot travel in a vacuum because they require matter to transfer energy.

Key Concepts & Definitions

- **Medium: The substance (air, water, rope, metal, etc.) through which a wave travels.**
- **Particle Vibration: In mechanical waves, particles vibrate around a fixed position but do not travel with the wave — only energy moves forward.**
- **Restoring Force: A mechanical wave exists only if there is a restoring force (elasticity, tension, pressure) that tries to return particles to equilibrium.**

Types of Mechanical Waves

Mechanical waves are classified based on the direction of particle vibration relative to wave propagation:

1. **Transverse Waves**
   - **Definition: Particles vibrate perpendicular to the direction of wave travel.**
   - **Examples: Waves on a rope, light waves (though light is electromagnetic), water surface ripples.**
   - **Key Feature: Have crests (high points) and troughs (low points).**
   - **Diagram: (Imagine a sine wave with peaks and valleys along a rope)**
2. **Longitudinal Waves**
   - **Definition: Particles vibrate parallel to the direction of wave travel.**
   - **Examples: Sound waves, seismic P-waves.**
   - **Key Feature: Consist of compressions (high-pressure regions) and rarefactions (low-pressure regions).**

  - **Diagram: (Imagine alternating compressed and stretched regions along a slinky)**

3. **Surface Waves**
   - **Definition: Particles move in a circular motion, combining longitudinal and transverse motion.**
   - **Example: Water waves at the ocean surface.**

Key Properties of Mechanical Waves

- **Amplitude (A): Maximum displacement of particles from their rest position. Represents energy of the wave.**
- **Wavelength (λ): Distance between two successive crests, troughs, or compressions.**
- **Frequency (f): Number of oscillations per second (unit: Hertz, Hz).**
- **Period (T): Time taken for one complete oscillation (T = 1/f).**
- **Wave Speed (v): Distance traveled by the wave per second.**

Formulas for Mechanical Waves

1. **Wave Speed Formula**

v=fλv = f \lambdav=fλ

Where vvv = speed, fff = frequency, λλλ = wavelength.

2. **Hooke's Law (for stretched mediums like strings):**

F=−kxF = -kxF=−kx

(Restoring force is proportional to displacement)

3. **Speed of Wave on a String:**

v=Tμv = \sqrt{\frac{T}{\mu}}v=μT

Where TTT = tension in the string, μμμ = mass per unit length.

4. **Speed of Sound in Air:**

v=γRTMv = \sqrt{\frac{\gamma RT}{M}}v=MγRT

Where γγγ = adiabatic index, RRR = gas constant, TTT = temperature, MMM = molar mass.

Energy Transmission

The energy of a mechanical wave is proportional to the square of its amplitude:

E∝A2E \propto A^2E∝A2

This means doubling the amplitude quadruples the energy carried by the wave.

Examples for Better Understanding

- **Sound Waves: Your voice creates longitudinal waves in air. The compressions and rarefactions travel to your friend's ear — they hear the sound, but the air itself does not travel with it.**
- **Guitar String: When plucked, the string vibrates transversely, sending mechanical waves that make the air vibrate — this produces sound.**
- **Earthquakes: Seismic waves travel through Earth’s crust. P-waves are longitudinal, S-waves are transverse. This is how scientists locate epicenters.**

Key Points to Remember

- **Mechanical waves cannot travel in space (no medium = no wave).**
- **The medium moves but does not transport matter forward.**
- **Energy transfer is what makes mechanical waves useful — from sound to seismic detection**

Chapter 5: Sound Waves

Sound is a mechanical longitudinal wave. It needs a medium and cannot travel in vacuum.

- **Speed of Sound: Depends on medium and temperature.**
  - **~343 m/s in air at 20°C**
  - **Faster in liquids, fastest in solids.**

Pitch, Loudness, and Quality

- **Pitch: Depends on frequency (high pitch = high frequency).**
- **Loudness: Depends on amplitude/intensity. Measured in decibels (dB).**
- **Quality (Timbre): Allows you to distinguish between different instruments playing the same note.**

Worked Example

If the speed of sound is 340 m/s and the frequency is 170 Hz, find the wavelength.

λ=vf=340170=2 m\lambda = \frac{v}{f} = \frac{340}{170} = 2\ \text{m}λ=fv =170340=2 m

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Chapter 6: Applications of Sound

- **SONAR: Ships and submarines use sound waves to measure depth.**
- **Medical Imaging: Ultrasound used to see unborn babies.**
- **Echolocation: Bats and dolphins locate objects by listening to echoes.**
- **Doppler Effect: Change in pitch when source is moving (e.g., ambulance siren).**

Chapter 7: Music, Noise, and Resonance

- **Noise:** Random, unpleasant vibrations.
- **Music:** Regular, periodic vibrations.
- **Resonance:** Large amplitude vibration at natural frequency.
    - Example: Swinging pushes in sync make swing go higher.
- **Standing Waves:** Produced when incident and reflected waves overlap, creating nodes (no motion) and antinodes (maximum motion).

Chapter 8: Light Waves and the Electromagnetic Spectrum

Light is an electromagnetic wave — it does not need a medium.

- **Electromagnetic Spectrum:** Radio waves → Microwaves → Infrared → Visible → UV → X-rays → Gamma rays.
- **Visible Light:** Red (longest λ) to violet (shortest λ).

Chapter 9: Ray Optics

Ray optics treats light as straight-line rays.

- **Reflection:** Image formation in mirrors.
- **Refraction:** Explained by Snell's Law.
- **Critical Angle & Total Internal Reflection:** Used in optical fibers.

Example Problem

A ray travels from air (n=1) to water (n=1.33) at an angle of 30°. Find angle of refraction.

$$\sin \theta_2 = \frac{n_1}{n_2} \sin \theta_1 = \frac{1}{1.33} \sin 30° = 0.3759$$

$\theta_2=\arcsin(0.3759)\approx 22.1^\circ$**$\theta_2 = \arcsin(0.3759) \approx 22.1^\circ$ $\theta_2=\arcsin(0.3759)\approx 22.1^\circ$**

Chapter 10: Wave Optics

When light behaves like a wave:

- **Interference: Young's double-slit experiment proves light is a wave.**
- **Diffraction: Light bends around edges.**
- **Polarization: Blocks certain vibrations, used in sunglasses.**

Wave optics (or physical optics) is the branch of physics that studies light as a wave rather than as rays (geometric optics). It explains phenomena like interference, diffraction, and polarization — effects that cannot be explained if we treat light only as straight-line rays.

Key Idea: Light as a Wave

Light is an electromagnetic wave — it consists of oscillating electric and magnetic fields that are perpendicular to each other and to the direction of propagation. Its wave nature becomes evident when we observe effects that depend on phase differences between two or more light waves.

Core Principles of Wave Optics

1. Huygens' Principle

- **Every point on a wavefront can be considered as a source of secondary spherical wavelets.**
- **The new wavefront is the tangent surface to all these secondary wavelets.**
- **This principle helps explain reflection, refraction, and diffraction of light.**

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2. Interference of Light

Interference is the superposition of two or more coherent light waves, resulting in regions of constructive and destructive interference.

- Constructive Interference: Waves meet in phase → Bright fringes.
- Destructive Interference: Waves meet out of phase → Dark fringes.

Young’s Double-Slit Experiment (YDSE):

- Two narrow slits act as coherent sources.
- The interference pattern on a screen consists of alternating bright and dark fringes.

Formula for Fringe Width:

Δy=λDd\Delta y = \frac{\lambda D}{d}Δy=dλD

Where:

- λ\lambdaλ = wavelength of light
- DDD = distance between slits and screen
- ddd = separation between slits

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3. Diffraction of Light

Diffraction is the bending of light waves around edges and obstacles. It proves that light spreads into regions where geometric optics predicts shadow.

- Single-Slit Diffraction: Central maximum is widest; intensity decreases for higher-order fringes.

Formula for First Minima:

asinθ=nλ(n=1,2,3,…)a \sin \theta = n \lambda \quad (n = 1, 2, 3, …)asinθ=nλ(n=1,2,3,…)

Where aaa = slit width, θθθ = diffraction angle, nnn = order of minimum.

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4. Polarization

Polarization is the phenomenon where the vibrations of the electric field vector are restricted to one plane.

- **Unpolarized light: Vibrations occur in many planes.**
- **Polarized light: Vibrations occur in a single plane.**

Malus' Law:

I=I0cos2θI = I_0 \cos^2 \thetaI=I0cos2θ

Where I0I_0I0 is initial intensity, θθθ is angle between transmission axis of polarizer and analyzer.

Applications: Sunglasses (reduce glare), LCD screens, stress analysis in materials.

Key Formulas in Wave Optics

Phenomenon	Key Formula
Path difference for constructive interference	Δx=nλ\Delta x = n \lambdaΔx=nλ
Path difference for destructive interference	Δx=(n+12)λ\Delta x = (n + \frac{1}{2}) \lambdaΔx=(n+21)λ
Fringe width (YDSE)	Δy=λDd\Delta y = \frac{\lambda D}{d}Δy=dλD
Condition for nth diffraction minimum (single slit)	asinθ=nλa \sin \theta = n \lambdaasinθ=nλ
Condition for nth diffraction maximum (grating)	dsinθ=nλd \sin \theta = n \lambdadsinθ=nλ
Malus' Law (polarization)	I=I0cos2θI = I_0 \cos^2 \thetaI=I0cos2θ

Applications of Wave Optics

- **Interference:** Used in anti-reflection coatings, soap bubbles' colors, Newton's rings (lens testing).
- **Diffraction:** Explains resolution limits of optical instruments (microscopes, telescopes).
- **Polarization:** Used in sunglasses, 3D movies, and stress analysis in materials.

Examples

Interference Example:
Two slits separated by 0.2 mm0.2 \text{ mm}0.2 mm, screen distance 1.0 m1.0 \text{ m}1.0 m, light of wavelength 600 nm600 \text{ nm}600 nm.

Δy=λDd=600×10−9×1.00.2×10−3=3×10−3 m=3 mm\Delta y = \frac{\lambda D}{d} = \frac{600 \times 10^{-9} \times 1.0}{0.2 \times 10^{-3}} = 3 \times 10^{-3} \, m = 3 \, mmΔy=dλD=0.2×10−3600×10−9×1.0=3×10−3m=3mm

Thus, fringe width is 3 mm.

2. **Diffraction Example:**
   Light of 500 nm500 \text{ nm}500 nm passes through a 0.1 mm0.1 \text{ mm}0.1 mm slit. Find angle of first minimum:

asinθ=λ⇒sinθ=λa=5×10−71×10−4=5×10−3a \sin \theta = \lambda \quad \Rightarrow \quad \sin \theta = \frac{\lambda}{a} = \frac{5 \times 10^{-7}}{1 \times 10^{-4}} = 5 \times 10^{-3}asinθ=λ⇒sinθ=aλ=1×10−45×10−7=5×10−3
θ=sin−1(0.005)≈0.286°.\theta = \sin^{-1}(0.005) \approx 0.286°.θ=sin−1(0.005)≈0.286°.

Summary Table – Wave Optics vs. Ray Optics

Aspect	Wave Optics	Ray Optics
Nature of Light	Considers light as a wave	Considers light as straight rays
Explains	Interference, diffraction, polarization	Reflection, refraction, image formation
Accuracy	More accurate for small-scale effects	Approximation (fails for very small apertures)

Chapter 11: Speed of Light and Relativity

- **Speed of Light: c=3×108 m/sc = 3 \times 10^8\ \text{m/s}c=3×108 m/s**
- **Einstein showed this is the fastest anything can travel.**
- **Leads to time dilation and other relativity effects.**

Chapter 12: Applications of Light

- **Fiber Optics: Internet data transmission.**
- **Lasers: Used in surgery, barcode scanners, communication.**
- **Microscopes & Telescopes: Extend human vision.**

Chapter 13: Comparing Sound and Light

Aspect	Sound	Light
Medium Required	Yes	No
Speed in Air	343 m/s	3×1083 × 10^83×108 m/s
Wave Type	Longitudinal	Transverse
Example Uses	SONAR, music	Vision, communication

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COMPLETE FORMULA SHEET FOR WAVES

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1. General Wave Formulas

1. **Wave Speed:**

v=fλv = f \lambdav=fλ

where:

- vvv = wave speed (m/s)
- fff = frequency (Hz)
- λ\lambdaλ = wavelength (m)

2. **Frequency – Period Relation:**

f=1T,T=1ff = \frac{1}{T}, \quad T = \frac{1}{f}f=T1,T=f1

3. **Wave Equation (Simple Harmonic Motion):**

y(x,t)=Asin(kx−ωt)y(x, t) = A \sin (kx - \omega t)y(x,t)=Asin(kx−ωt)

where:

- AAA = amplitude
- k=2πλk = \frac{2\pi}{\lambda}k=λ2π (wave number)
- ω=2πf\omega = 2\pi fω=2πf (angular frequency)

4. **Wave Number:**

k=2πλk = \frac{2 \pi}{\lambda}k=λ2π

5. **Angular Frequency:**

ω=2πf\omega = 2 \pi fω=2πf

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2. Sound Wave Formulas

1. **Speed of Sound in Medium:**

v=Bρv = \sqrt{\frac{B}{\rho}}v=ρB

where:

- BBB = bulk modulus of medium
- ρ\rhoρ = density of medium

2. **Sound Intensity:**

I=PAI = \frac{P}{A}I=AP

where:

- PPP = power of sound source
- AAA = area through which sound passes

3. **Sound Level (Decibels):**

L=10log10(II0)L = 10 \log_{10}\left(\frac{I}{I_0}\right)L=10log10(I0I)

where:

- I0=10−12 W/m^{2}I_0 = 10^{-12}\ \text{W/m^2}I0=10−12 W/m^2 (threshold of hearing)

4. **Doppler Effect:**

When **observer moves towards source** (or vice versa):

f′=fv±vov∓vsf' = f \frac{v \pm v_o}{v \mp v_s}f′=fv∓vsv±vo

where:

- f′f'f′ = apparent frequency
- fff = actual frequency
- vvv = speed of sound
- vov_ovo = velocity of observer
- vsv_svs = velocity of source
(Signs depend on direction — towards means add in numerator, subtract in denominator)

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3. Standing Wave Formulas

1. **String Fixed at Both Ends:**

λn=2Ln,fn=nv2L\lambda_n = \frac{2L}{n}, \quad f_n = \frac{nv}{2L}λn=n2L,fn=2Lnv

where n=1,2,3,…n = 1, 2, 3, \dotsn=1,2,3,…

2. **Open Pipe (Both Ends Open):**

fn=nv2Lf_n = \frac{nv}{2L}fn=2Lnv

3. **Closed Pipe (One End Closed):**

fn=nv4L,n=1,3,5,…f_n = \frac{nv}{4L}, \quad n = 1, 3, 5, \dotsfn=4Lnv,n=1,3,5,…

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4. Energy in Waves

1. **Energy in Simple Harmonic Motion:**

E=12kA2E = \frac{1}{2} k A^2E=21kA2

where kkk = spring constant, AAA = amplitude

2. **Power Transmitted by Wave:**

P=12μω2A2vP = \frac{1}{2} \mu \omega^2 A^2 vP=21μω2A2v

where:

- μ\muμ = mass per unit length of string

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5. Reflection and Refraction

1. **Law of Reflection:**

θi=θr\theta_i = \theta_rθi=θr

2. **Snell's Law (Refraction):**

n1sinθ1=n2sinθ2n_1 \sin \theta_1 = n_2 \sin \theta_2n1sinθ1=n2sinθ2

3. **Refractive Index:**

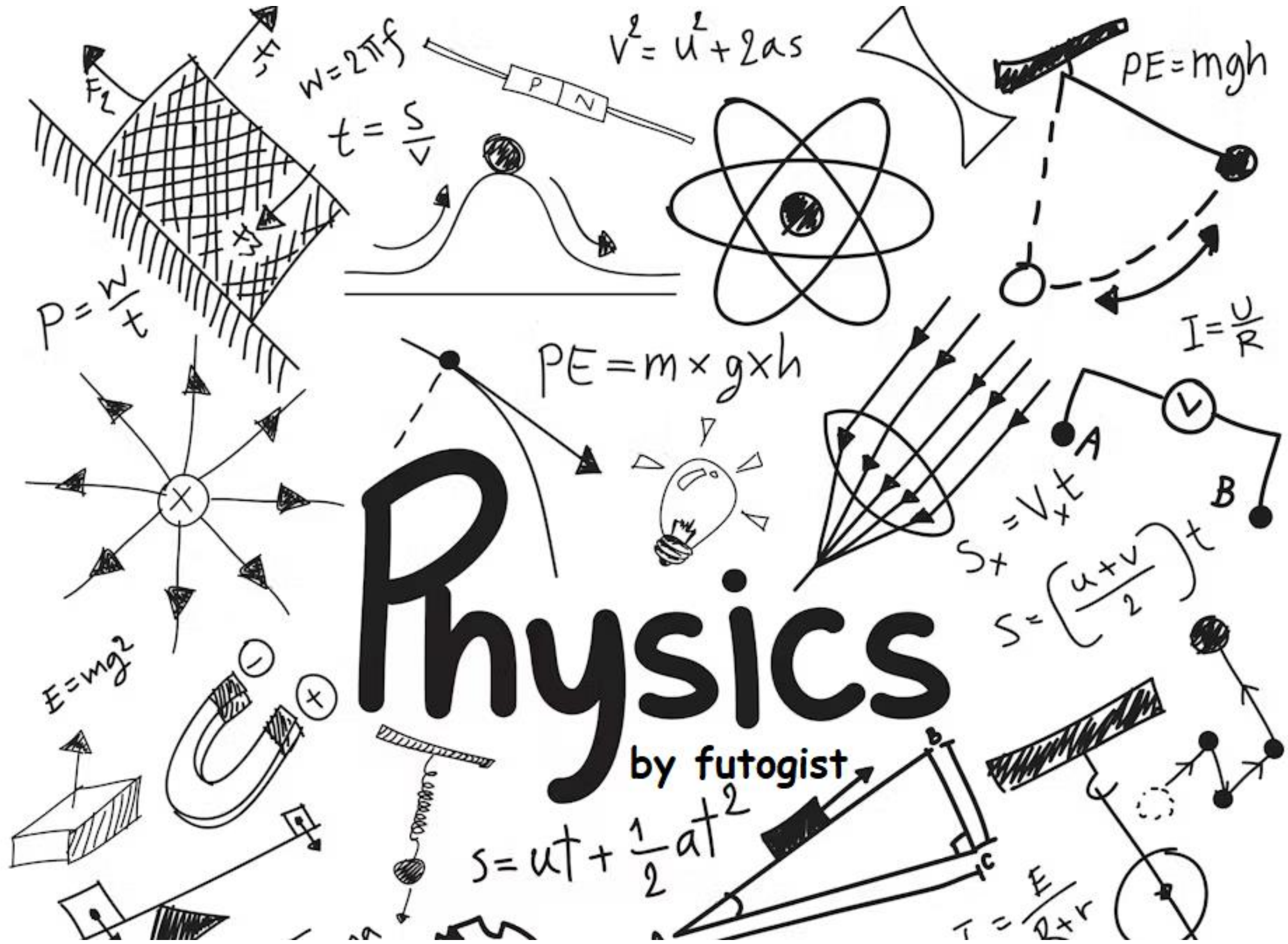
n=cvn = \frac{c}{v}n=vc

where:

- ccc = speed of light in vacuum
- vvv = speed of light in medium

4. **Critical Angle:**

sinθc=n2n1(n1>n2)\sin \theta_c = \frac{n_2}{n_1} \quad (n_1 > n_2)sinθc=n1n2(n1>n2)



Conclusion

Waves are not just a topic in physics they are the heartbeat of the universe. Every sound you hear, every color you see, every radio signal, and even the Wi-Fi you use every day are waves in action. By understanding how waves work, you gain the power to explain music, communication systems, medical imaging, and even the mysteries of space.

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