Collegedunia NCERT Notes

The Ultimate NCERT Revision Guide for Class 12 Physics

Chapter 10: Wave Optics

1 Introduction to Wave Optics

1.1 Wave Nature of Light

Light is a transverse electromagnetic wave. Understanding light purely through ray (geometric) optics — travelling in straight lines, obeying reflection and refraction — works well when objects and apertures are much larger than the wavelength of light. However, phenomena such as interference, diffraction, and polarisation cannot be explained by ray optics. **Wave optics** provides the framework to understand these phenomena based on the wave character of light.

The wavelength of visible light ranges from about 400 nm (violet) to 700 nm (red). Typical apertures in laboratory optics are of the order of millimetres to centimetres — far larger than the wavelength — which is why ray optics works so well in everyday situations.

Why We Need Wave Optics

Ray optics treats light as rays and cannot explain:

- **Interference** — bright and dark bands from two coherent sources
- **Diffraction** — bending of light around sharp edges or through small openings
- **Polarisation** — the transverse vector nature of light oscillations

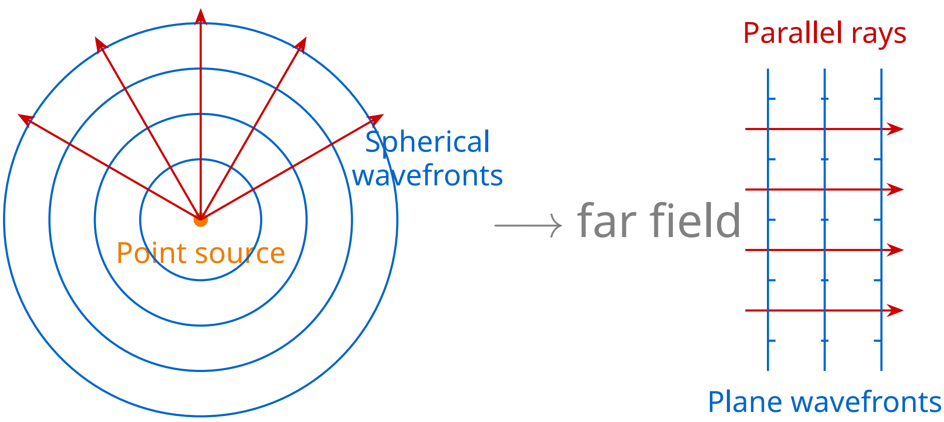
All three phenomena demand the full wave description.

1.2 Wavefronts

A **wavefront** is the locus of all points in the medium that oscillate in the same phase at a given instant. It is a surface of constant phase.

- **Spherical wavefront** — from a point source in a uniform medium; the wavefronts are concentric spheres expanding outward.

- **Cylindrical wavefront** — from a line source (e.g., a long, thin slit); wavefronts are coaxial cylinders.
- **Plane wavefront** — at very large distances from a point source, the curvature becomes negligible and the wavefront is approximately flat (planar).



Quick Tip

The direction of propagation of a wave (the ray direction) is always **perpendicular to the wavefront**. This is the geometric bridge between ray optics and wave optics.

2 Huygens' Principle

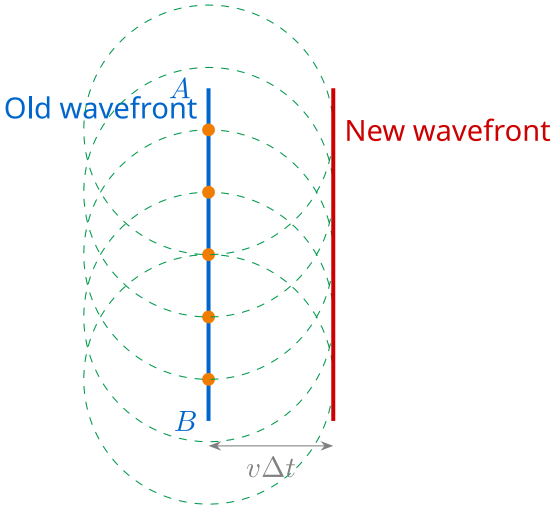
2.1 Statement of Huygens' Principle

Huygens' Principle provides a geometric method to find the new position of a wavefront at a later time, given its position at an earlier time.

Huygens' Principle

1. Every point on a given wavefront acts as a **secondary source** that emits secondary (or Huygens') wavelets in all forward directions, with the same speed as the original wave.
2. The new wavefront at a later time is the **forward-going envelope (tangent surface)** of all these secondary wavelets.

The secondary wavelets travel only in the forward direction — the backward envelope is not taken because it would imply a backward wave, which is not observed. This is a physical assumption built into the principle.



Quick Tip

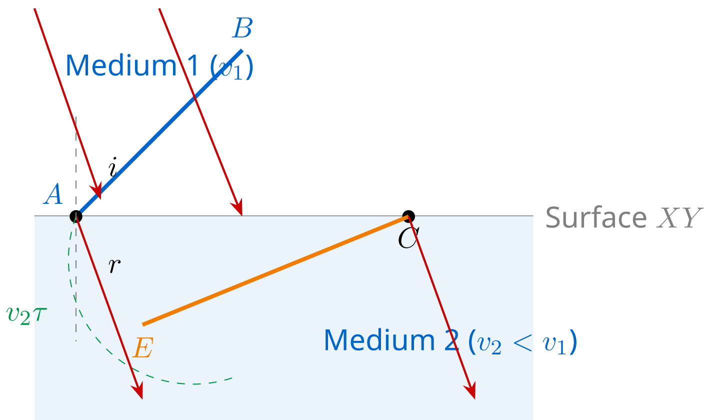
Huygens' Principle applies to all waves: sound, water, light. For light, we deal with electromagnetic waves travelling at $c = 3 \times 10^8$ m/s in vacuum.

2.2 Refraction of a Plane Wave at a Plane Surface (Huygens' Construction)

Consider a plane wavefront AB incident at a refracting surface XY separating medium 1 (speed v_1) from medium 2 (speed $v_2 < v_1$, i.e., denser medium).

Let the time for the wavefront to go from B to C (along the surface) be τ. Then $BC = v_1\tau$. In the same time τ, the secondary wavelet from A travels a distance $v_2\tau$ into medium 2, reaching point E.

The refracted wavefront EC is tangent to the sphere of radius $v_2\tau$ centred at A.



Snell's Law from Huygens' Principle

From the geometry of the Huygens' construction:

$$\frac{\sin i}{\sin r} = \frac{BC}{AE} = \frac{v_1 \tau}{v_2 \tau} = \frac{v_1}{v_2}$$

Since refractive index $n = c/v$, we get $n_1 v_1 = n_2 v_2$ (constant), and:

$$\boxed{n_1 \sin i = n_2 \sin r}$$

This is Snell's Law, derived from Huygens' Principle.

- When light travels from rarer to denser medium: $v_2 < v_1$, so $\lambda_2 < \lambda_1$ but the frequency ν is unchanged.
- The wavelength in medium of refractive index n is $\lambda' = \lambda_0 / n$, where λ_0 is the vacuum wavelength.

Common Mistake

The **frequency** of light does not change when it passes from one medium to another. Only the wavelength and speed change. So $\lambda' = \lambda/n$, not $\lambda \cdot n$.

2.3 Reflection of a Plane Wave (Huygens' Construction)

Using a similar Huygens' construction for a plane wave incident on a plane mirror, one can show that the angle of incidence equals the angle of reflection:

$$\angle i = \angle r$$

This is the Law of Reflection derived rigorously from wave theory.

Laws from Huygens' Principle

Both the law of reflection ($\angle i = \angle r$) and Snell's law of refraction ($n_1 \sin i = n_2 \sin r$) follow directly from Huygens' Principle and the geometry of the wavefront construction. This confirms that wave optics contains ray optics as a special case.

3 Interference of Light

3.1 Principle of Superposition

When two or more waves overlap in space, the resultant displacement at any point is the **algebraic sum** of the displacements due to each individual wave.

Superposition Principle

$$y = y_1 + y_2$$

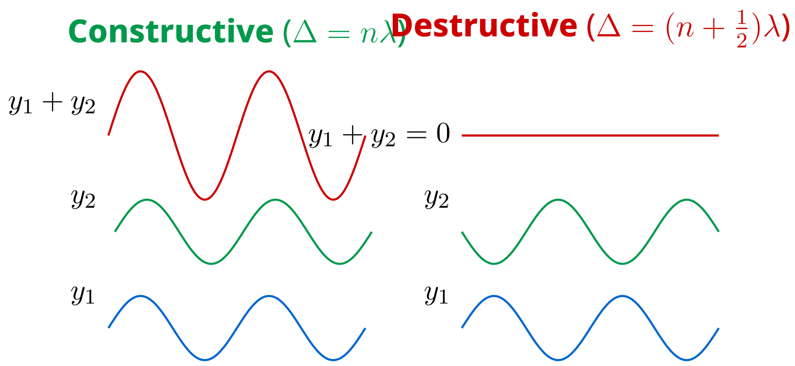
For two harmonic waves of the same frequency:

$$y_1 = a_1 \cos(\omega t), \quad y_2 = a_2 \cos(\omega t + \phi)$$

Resultant amplitude: $A^2 = a_1^2 + a_2^2 + 2a_1 a_2 \cos\phi$
Resultant intensity: $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$

Constructive interference (bright fringe): $\phi = 0, 2\pi, 4\pi, \ldots$ i.e., path difference $\Delta = 0, \lambda, 2\lambda, \ldots$

Destructive interference (dark fringe): $\phi = \pi, 3\pi, \ldots$ i.e., path difference $\Delta = \lambda/2, 3\lambda/2, \ldots$



3.2 Coherent Sources

Two sources are **coherent** if they maintain a constant phase difference over time. Ordinary light sources (bulbs, flames) are incoherent because the phase difference fluctuates randomly, resulting in no sustained interference pattern.

Conditions for Sustained Interference

1. Sources must be **coherent** — same frequency and a constant (not necessarily zero) phase difference.
2. Sources should be **monochromatic** (single wavelength) for sharp fringes.
3. The amplitudes should be comparable for high fringe contrast (visibility).
4. The sources must be **narrow** (point-like or line-like) so wavefronts overlap properly.

Laser Coherence

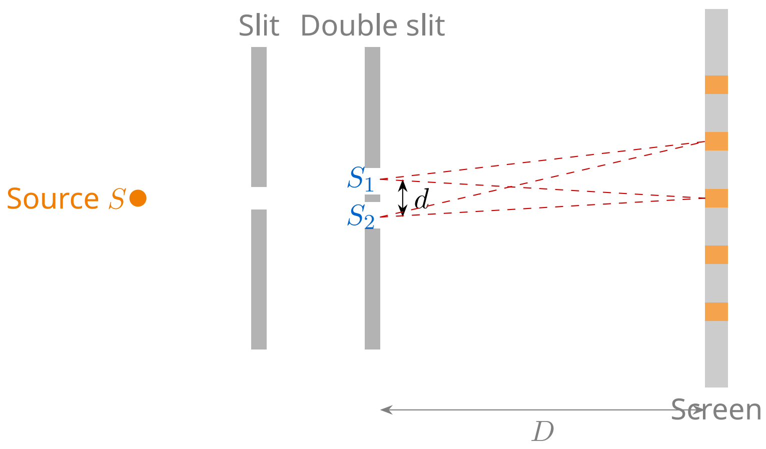
Lasers are highly coherent sources because they emit light via stimulated emission, keeping all photons in phase. This is why lasers are used in holog-

> raphy, interferometry, and fibre-optic communications where sustained interference is essential.

3.3 Young's Double Slit Experiment (YDSE)

Thomas Young (1801) demonstrated interference of light using two closely-spaced slits, proving the wave nature of light. This was a landmark experiment in the history of physics.

Setup: A monochromatic light source illuminates a single slit S, which then acts as a coherent source for two slits S_1 and S_2 separated by distance d. A screen is placed at distance D from the slits ($D \gg d$).



YDSE — Key Expressions (Board 2025-26)

Position of n-th bright fringe (from centre):

$$y_n = \frac{n\lambda D}{d}, \quad n = 0, \pm 1, \pm 2, \dots$$

Position of n-th dark fringe:

$$y_n = \frac{(2n-1)\lambda D}{2d}, \quad n = \pm 1, \pm 2, \dots$$

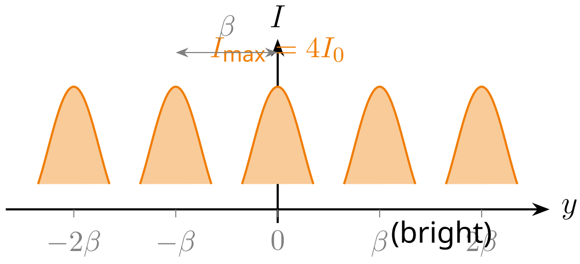
Fringe width (spacing between consecutive bright or dark fringes):

$$\beta = \frac{\lambda D}{d}$$

Angular fringe width: $\theta = \lambda / d$

- λ = wavelength of light, D = slit-to-screen distance, d = slit separation
- Fringe width $\beta \propto \lambda$; using white light gives coloured fringes since different wavelengths produce different fringe widths.
- The central fringe ($n = 0$) is always bright and located at the centre.

- Fringe width is **the same** for both bright and dark fringes.



YDSE Quick Check

If d is halved, fringe width β doubles. If D is doubled, β also doubles. If λ is halved (e.g., blue light instead of red), fringes become narrower. Memorise $\beta = \lambda D/d$.

Common Mistake

Students confuse path difference and phase difference. They are related by:

$$\phi = \frac{2\pi}{\lambda}\Delta$$

A path difference of λ corresponds to a phase difference of 2π (one full cycle), not π.

3.4 Intensity Distribution in YDSE

If both slits have equal width and produce waves of amplitude a and equal intensity I_0:

Intensity in YDSE

$$I = 4I_0 \cos^2\left(\frac{\phi}{2}\right)$$

where $\phi = \frac{2\pi d \sin\theta}{\lambda} \approx \frac{2\pi dy}{\lambda D}$ for small angles.

- $I_{\text{max}} = 4I_0$ (at bright fringes, $\phi = 2n\pi$)
- $I_{\text{min}} = 0$ (at dark fringes, $\phi = (2n+1)\pi$)

Energy is conserved — the total energy is the same; it is just redistributed (bright fringes get more, dark fringes get less).

3.5 YDSE with White Light and with a Medium

- **White light**: the central fringe remains white, but higher-order fringes become coloured (violet closest to centre, red outermost) because $\beta \propto \lambda$.

- **Immersed in medium of refractive index** n: wavelength reduces to λ/n, so $\beta' = \lambda D/(nd) = \beta/n$.
- **Glass slab of thickness** t **over one slit**: introduces an extra optical path $(\mu - 1)t$, shifting the central bright fringe by $\Delta y = (\mu - 1)t\, D/d$.

Shift Due to Glass Slab in YDSE

Extra optical path introduced by slab of thickness t and refractive index μ:

$$\Delta = (\mu - 1)t$$

Lateral shift of central fringe:

$$\Delta y = \frac{(\mu - 1)t\, D}{d}$$

The shift is towards the slab side.

Quick Tip

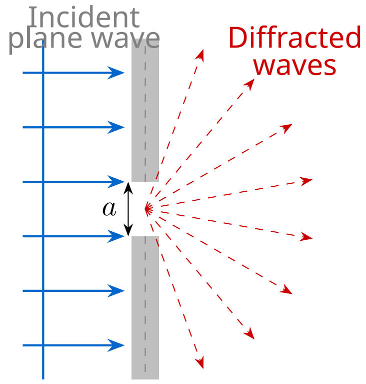
In YDSE, if a glass slab is placed over S_1, the pattern shifts toward S_1. The bright/dark fringe order does not change; only the entire pattern moves.

4 Diffraction

4.1 What is Diffraction?

Diffraction is the bending and spreading of waves when they encounter an obstacle or pass through a narrow aperture. It is a consequence of Huygens' Principle — every point on a wavefront inside the aperture acts as a new source of secondary wavelets, and these spread out beyond the geometric shadow.

Diffraction is significant when the aperture/obstacle size a is comparable to the wavelength λ. When $a \gg \lambda$, diffraction effects are negligible and ray optics holds. When $a \sim \lambda$, diffraction is prominent.



4.2 Single Slit Diffraction

When a plane wave of wavelength λ falls normally on a slit of width a, the transmitted light produces a diffraction pattern on a distant screen. The pattern consists of a **bright central maximum** flanked by alternating dark minima and weaker secondary maxima.

Condition for dark minima (minima of intensity): The slit is divided into $2N$ equal halves; secondary wavelets from corresponding pairs cancel:

$$a \sin\theta = m\lambda \quad (m = \pm1, \pm2, \pm3, \ldots)$$

Width of central maximum: The first minima are at $\sin\theta \approx \pm\lambda/a$. For small angles, the angular half-width of the central maximum is $\theta \approx \lambda/a$, so the full angular width is $2\lambda/a$.

Single Slit Diffraction

Minima (dark fringes):

$$a \sin\theta = m\lambda, \quad m = \pm1, \pm2, \ldots$$

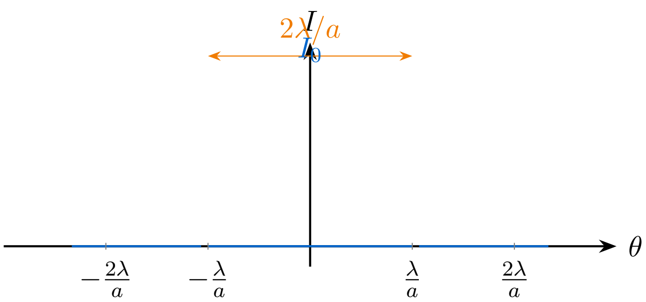
Width of central maximum on screen at distance D:

$$w = \frac{2\lambda D}{a}$$

Half-angular width of central maximum:

$$\theta_0 = \frac{\lambda}{a}$$

Secondary maxima occur approximately at $a \sin\theta = (m + \frac{1}{2})\lambda$.



Key Features of Single Slit Pattern

- The central maximum is **twice as wide** as each secondary maximum.
- The intensity of the first secondary maximum is about **4.5%** of the central maximum.
- Narrower slit ($a \downarrow$) $\Rightarrow$ wider central maximum (more spreading): $w =$

$2\lambda D/a$.

- If $a \ll \lambda$, the diffracted light spreads in almost all directions.

Board Exam Favourite

"If the slit width is doubled" — the central maximum becomes **narrower** (width halved) and **brighter** (intensity increases as more light enters). State both effects.

4.3 Diffraction vs Interference — Key Differences

Both produce bright and dark bands, but they arise from different physics.

Interference	Diffraction
Two (or more) coherent sources	Single slit (continuous aperture)
All bright fringes have equal intensity	Central maximum is much brighter; side maxima fade rapidly
Dark fringes are perfectly dark (equal amplitudes)	Dark minima are perfectly dark; secondary maxima have lower intensity
Fringe width is uniform	Central fringe is twice as wide as secondary maxima
Governed by $y_n = n\lambda D/d$	Governed by $a \sin\theta = m\lambda$

"Two vs One"

Interference = **inter**action of two slits (two, external). **Diffr**action = bending at **one** slit (single). When you see a question mention "single slit," think diffraction.

4.4 Poisson's Bright Spot

When a circular opaque obstacle is placed in the path of a light beam, a bright spot appears at the exact centre of its geometric shadow. This seems paradoxical but follows directly from Huygens' Principle: the secondary wavelets from the rim of the obstacle are all equidistant from the central point and arrive in phase, constructively interfering to form a bright spot. This phenomenon was predicted theoretically and confirmed experimentally, providing strong evidence for the wave nature of light.

Diffraction Limits Optical Instruments

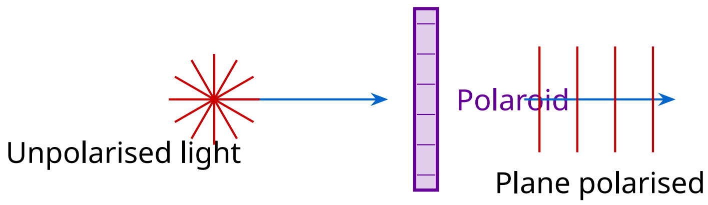
The ability of a telescope or microscope to resolve two closely-spaced objects (resolving power) is ultimately limited by diffraction at the aperture. A wider aperture diffracts less, giving a sharper (smaller) Airy disc, and thus better resolution. This is why large telescopes have better resolving power.

5 Polarisation

5.1 Transverse Nature of Light and Polarisation

Light is a **transverse electromagnetic wave** — the electric and magnetic field vectors oscillate perpendicular to the direction of propagation. In ordinary (unpolarised) light, the electric field oscillates in all directions perpendicular to the propagation direction, with random orientation changing rapidly.

Plane polarised (linearly polarised) light has the electric field oscillating in only one specific plane. The plane containing the direction of propagation and the electric field vector is the **plane of polarisation** (or plane of vibration).



5.2 Methods of Polarisation

1. **Polaroid sheets** — selectively absorb one component of the electric field (dichroism). They transmit only the component parallel to the transmission axis.
2. **Reflection (Brewster's Law)** — at the Brewster angle, the reflected beam is completely plane polarised.
3. **Double refraction (birefringence)** — crystals like calcite and quartz split a ray into ordinary and extraordinary rays, both polarised at right angles.
4. **Scattering** — light scattered by small particles (e.g., sky) is partially or fully polarised perpendicular to the plane of scattering.

5.3 Malus' Law

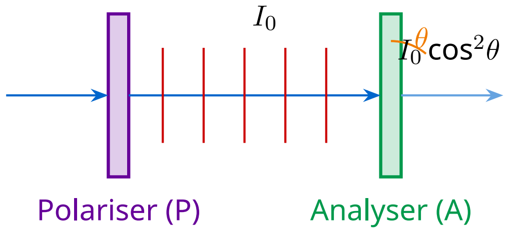
When plane polarised light of intensity I_0 passes through a second polaroid (analyser) with its transmission axis making an angle θ with the polarisation direction of the incident light:

Malus' Law

$$\boxed{I = I_0 \cos^2\theta}$$

- $\theta = 0°$: $I = I_0$ (maximum transmission — axes parallel)
- $\theta = 90°$: $I = 0$ (complete extinction — axes perpendicular/crossed)

- $\theta = 45°$: $I = I_0/2$



Malus' Law Memory

"Malus — Maximum at zero, minimum at 90." The cosine-squared factor means intensity is maximum when analyser aligns with polariser ($\cos 0° = 1$) and zero when crossed ($\cos 90° = 0$).

5.4 Brewster's Law

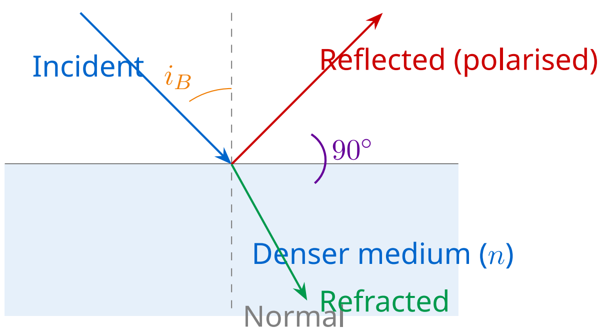
When unpolarised light is reflected from a dielectric surface, the reflected light is **completely plane polarised** when the angle of incidence equals the **Brewster angle** i_B (also called polarising angle).

Brewster's Law

$$\tan i_B = n = \frac{n_2}{n_1}$$

where n is the refractive index of the denser medium with respect to the rarer one.
At the Brewster angle, the reflected and refracted rays are **perpendicular** to each other:

$$i_B + r = 90°$$



Brewster Angle Calculation

For glass ($n = 1.5$), $i_B = \arctan(1.5) \approx 56.3°$. For water ($n = 1.33$), $i_B \approx 53.1°$. Always check: $i_B + r = 90°$ to verify.

5.5 Polarisation of Unpolarised Light through a Single Polaroid

When ordinary (unpolarised) light passes through a single polaroid:

$$I_{\text{transmitted}} = \frac{I_0}{2}$$

Half the intensity is absorbed, as the polaroid transmits only one of the two perpendicular components.

Uses of Polaroids

- **Polaroid sunglasses**: reduce glare from reflected horizontal light (roads, water surfaces) by blocking horizontal polarisation.
- **LCD screens**: liquid crystals rotate polarisation of backlight, controlled by electric fields to produce images.
- **3D cinema**: two projectors emit oppositely polarised light; special glasses allow each eye to see only one image.
- **Photography**: polaroid filters reduce reflections and increase colour saturation.

Polarisation in Nature

Bees and certain other insects can detect the polarisation of skylight and use it for navigation, even when the sun is not directly visible. The sky is partially polarised due to scattering of sunlight by air molecules (Rayleigh scattering).

6 Quick Reference Summary

Complete Formula List

Huygens' Principle and Refraction

- Snell's Law: $n_1 \sin i = n_2 \sin r$
- Wavelength in medium: $\lambda' = \lambda_0/n$
- Speed in medium: $v = c/n$
- Frequency unchanged on refraction: $\nu' = \nu$

Interference (YDSE)

- Fringe width: $\beta = \frac{\lambda D}{d}$
- n-th bright fringe: $y_n = n\beta = \frac{n\lambda D}{d}$
- n-th dark fringe: $y_n = \left(n - \frac{1}{2}\right)\beta$

- Intensity: $I = 4I_0 \cos^2(\phi/2)$, $I_{\text{max}} = 4I_0$, $I_{\text{min}} = 0$
- Phase–path relation: $\phi = \frac{2\pi}{\lambda}\Delta$
- Slab shift: $\Delta y = \frac{(\mu - 1)tD}{d}$, extra path $= (\mu - 1)t$
- In medium: $\beta' = \frac{\beta}{n}$

Diffraction (Single Slit)

- Dark minima: $a \sin\theta = m\lambda$, $m = \pm 1, \pm 2, \ldots$
- Width of central maximum: $w = \frac{2\lambda D}{a}$
- Half angular width: $\theta_0 = \lambda/a$
- Secondary maxima (approx.): $a \sin\theta = (m + \frac{1}{2})\lambda$

Polarisation

- Malus' Law: $I = I_0 \cos^2\theta$
- Brewster's Law: $\tan i_B = n$
- Brewster condition: $i_B + r = 90°$
- Through single polaroid: $I = I_0/2$

Important Conceptual Points for Board/JEE

- Huygens' principle does not predict a backward-travelling wavefront (this is a physical assumption).
- Young's experiment was the first demonstration of the wave nature of light (1801).
- Coherent sources are essential for interference; incoherent sources give only uniform illumination.
- The central maximum in single-slit diffraction is twice as wide as the secondary maxima.
- Polarisation proves light is *transverse*; longitudinal waves (like sound) cannot be polarised.
- At Brewster angle, reflected beam is fully polarised; transmitted beam is partially polarised.
- Malus' law: intensity goes to zero for crossed polaroids ($\theta = 90°$).
- Interference preserves energy — it is redistributed, not created or destroyed.

Board Exam Strategy

Wave Optics typically carries 5–8 marks in the CBSE board exam. Expect: one derivation (laws of refraction via Huygens OR Brewster angle explanation), one YDSE numerical (fringe width/position), one single-slit qualitative/width question, and one Malus' Law numerical. Practice all four types.