JEE MAIN · PAPER 1 · PHYSICS

16 Optics

Formula & concept sheet

Light as rays and as waves: reflection and refraction, mirrors and lenses, prisms, the telescope and microscope, then interference, diffraction and polarisation. The sheet explains each idea first, with the sign conventions that decide most numericals, then gives the formulas, shortcuts and traps.

INSIDE THIS SHEET

1	Reflection and plane mirrors	2
2	Spherical mirrors	2
3	Refraction and total internal reflection	3
4	Thin lenses	4
5	Prism and dispersion	5
6	Optical instruments	6
7	Wave optics: Huygens' principle and interference	6
8	Diffraction and polarisation	8
9	Worked examples	8
10	Last-minute checklist	9

READ ALONGSIDE NCERT XII · Ray Optics and Optical Instruments; Wave Optics

HOW TO USE THIS SHEET

1. **Skim** — Read the Key ideas, then the formula cards.
2. **Memorise** — Learn the formulas and check every Trap box.
3. **Test** — Do the worked examples, then this chapter's PYQs.
4. **Revise** — Use the last-minute checklist before the exam.

Formula memorise · **Key idea** why it works · **Trap** marks lost here · **PYQ** how it is asked

Practise this chapter with real past-paper questions on Prep Vault. Written for revision, not as a first read.

CHAPTER 16

Optics

NCERT XII · Ray Optics and Optical Instruments; Wave Optics

Covers: reflection and plane mirrors · spherical mirrors · refraction, total internal reflection · lenses and lens maker's formula · prism and dispersion · microscope and telescope · Huygens' principle · Young's double slit · single-slit diffraction · polarisation.

1 Reflection and plane mirrors

LAWS OF REFLECTION The incident ray, the reflected ray and the normal lie in one plane, and the angle of incidence equals the angle of reflection, $i = r$ (both measured from the normal, not the surface).

PLANE MIRROR IMAGE

virtual, erect, same size

as far behind the mirror as the object is in front; left and right appear reversed

ROTATING THE MIRROR

turn by θ $\Rightarrow$ reflected ray turns 2θ

image of a fixed object moves through 2θ about the mirror's axis

FULL-LENGTH VIEW

mirror height $\geq \dfrac{h}{2}$

for a person of height h; independent of the distance

TWO INCLINED MIRRORS

$$N = \frac{360^\circ}{\theta} - 1$$

when $\dfrac{360^\circ}{\theta}$ is an even integer (any position), or an odd integer with the object on the bisector; parallel mirrors give endless images

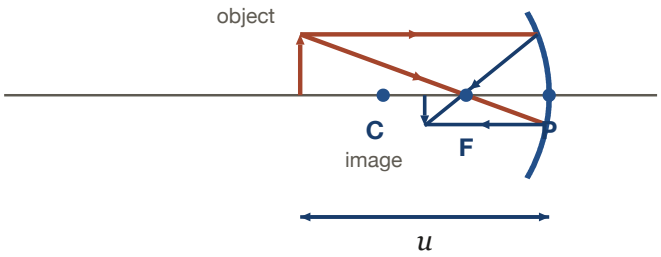
SPEED OF THE IMAGE

$v_{img} = -v_{obj}$ (normal component)

the image approaches a plane mirror as fast as the object does, so the two close at twice the object's speed

2 Spherical mirrors

SIGN CONVENTION (NEW CARTESIAN) Distances are measured from the **pole** of the mirror (or the optical centre of a lens), positive along the direction of the incident light. Heights are positive above the axis. So for a mirror with the object in front, $u < 0$; a **concave** mirror has $f < 0$ and $R < 0$, a **convex** mirror $f > 0$. Mirror formula: $\dfrac{1}{v} + \dfrac{1}{u} = \dfrac{1}{f}$ with $f = \dfrac{R}{2}$.



object beyond C: the image is real, inverted, smaller, between F and C (here $u = -90$, $f = -30$, $v = -45$, $m = -0.5$)

THREE RAYS LOCATE THE IMAGE

- A ray parallel to the axis reflects through the focus F.
- A ray through F reflects parallel to the axis.
- A ray through the centre of curvature C returns along itself.
- Where the reflected rays meet is a real image; where they appear to come from is a virtual one.

MIRROR MAGNIFICATION

$$m = \frac{h_i}{h_o} = -\frac{v}{u} = \frac{f}{f-u}$$

$m < 0$ inverted (real image), $m > 0$ erect (virtual); $|m| > 1$ enlarged

LIMITING CHECK

object at infinity: $v = f$

a convex mirror always gives a virtual, erect, diminished image between P and F

CONCAVE MIRROR: IMAGE AGAINST OBJECT POSITION

OBJECT	IMAGE	NATURE AND SIZE
at infinity	at F	real, inverted, a point
beyond C	between F and C	real, inverted, smaller
at C	at C	real, inverted, same size
between F and C	beyond C	real, inverted, enlarged
at F	at infinity	real, inverted, enlarged
between F and P	behind the mirror	virtual, erect, enlarged

TRAP

The mirror formula has a **plus** ($\frac{1}{v} + \frac{1}{u}$), the lens formula a **minus**. Insert the signs with every number, and a focal length in a liquid does not change for a mirror, only for a lens.

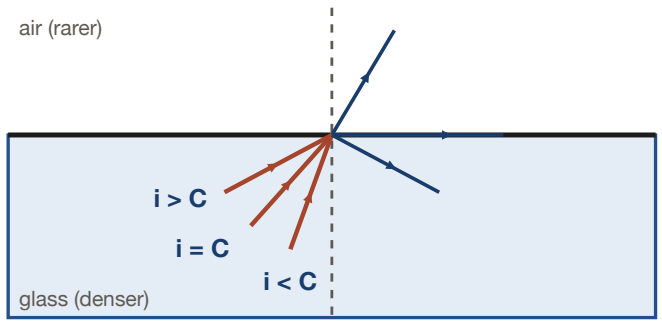
QUICK CHECK

A concave mirror has $f = -15$ cm and the object is 10 cm in front. Where is the image and what is m?

Answer: $1/v = 1/f - 1/u = -1/15 + 1/10 = 1/30$, so $v = +30$ cm (behind the mirror, virtual) and $m = -v/u = +3$.

3 Refraction and total internal reflection

SNELL'S LAW Light bends at an interface because its speed changes, $n = c/v$. Passing from medium 1 to 2: $n_1 \sin i = n_2 \sin r$. Entering a denser medium the ray bends **towards** the normal. The frequency stays the same; the speed and wavelength fall by n.



below C the ray escapes, bending away from the normal; at C it grazes the surface ($r = 90°$); beyond C it is totally reflected

TOTAL INTERNAL REFLECTION

- Only when light goes from a **denser to a rarer** medium and only if $i > C$, the critical angle, $\sin C = \frac{n_2}{n_1}$ ($= \frac{1}{n}$ for glass to air).
- Uses: optical fibres, prism binoculars and periscopes, the sparkle of a diamond (small C), the mirage.

APPARENT DEPTH

$$d_{app} = \frac{d}{n}$$

object in a denser medium seen from above, near-normal viewing

SHIFT THROUGH A SLAB

$$t\left(1 - \frac{1}{n}\right)$$

apparent shift of an object seen through a slab of thickness t and index n

SINGLE SPHERICAL SURFACE

$$\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$$

$R > 0$ when the centre of curvature is on the side the light goes to

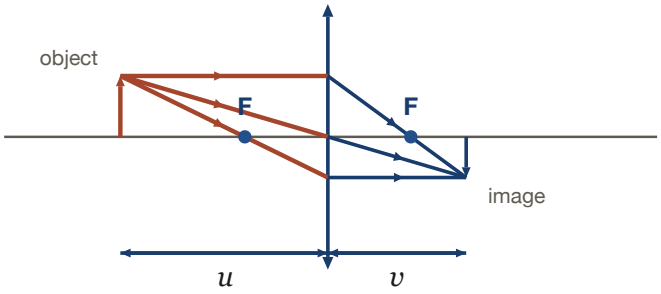
KEY IDEA

Critical angles to remember: water to air $\approx 48.6^\circ$ ($\sin C = \frac{3}{4}$), glass $\approx 41.8^\circ$, diamond $\approx 24.4^\circ$. A ray at 45° inside glass is totally reflected, one at 30° is not.

TRAP

TIR needs $n_1 > n_2$. Going from rarer to denser the ray always refracts. Water seems shallower from above because $d_{app} = d/n$, not nd.

4 Thin lenses



object beyond $2F$: the image is real, inverted, smaller, between F and $2F$ (here $u = -75$, $f = 30$, $v = 50$, $m = -\frac{2}{3}$)

THIN LENS A lens that bends rays at two curved surfaces. Lens formula (New Cartesian): $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$; convex $f > 0$, concave $f < 0$. Magnification $m = \frac{v}{u}$ ($m < 0$ real and inverted).

RAYS

- Parallel to the axis: through F on the far side.
- Through the optical centre: undeviated.
- Through F on the near side: emerges parallel.

LENS MAKER'S FORMULA

$$\frac{1}{f} = \left(\frac{n_{lens}}{n_{medium}} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$R_1 > 0$ for a surface whose centre is on the outgoing side; biconvex: $R_1 > 0$, $R_2 < 0$

LENS IN A LIQUID

$$\frac{f_{liq}}{f_{air}} = \frac{n-1}{\frac{n}{n_{liq}} - 1}$$

a convex lens in a liquid denser than the glass becomes diverging

POWER

$P = \frac{1}{f}$ (f in m)

dioptre; negative for a diverging lens; lenses in contact: $P = P_1 + P_2$

LENSES SEPARATED BY d

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

in contact $d = 0$: $\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2}$

MAGNIFICATION-DRIVEN

$u = f\left(\frac{1}{m} - 1\right)$

from $m = \frac{f}{f+u}$; skips solving for v

DISPLACEMENT METHOD

$f = \frac{D^2 - x^2}{4D}$

object-screen distance D, lens positions x apart; smallest D is $4f$

CONVEX LENS: IMAGE AGAINST OBJECT POSITION

OBJECT	IMAGE	NATURE AND SIZE
beyond $2F$	between F and $2F$	real, inverted, smaller
at $2F$	at $2F$	real, inverted, same size
between F and $2F$	beyond $2F$	real, inverted, enlarged
at F	at infinity	real, inverted, enlarged
between F and the lens	same side as the object	virtual, erect, enlarged

A concave lens always gives a virtual, erect, diminished image.

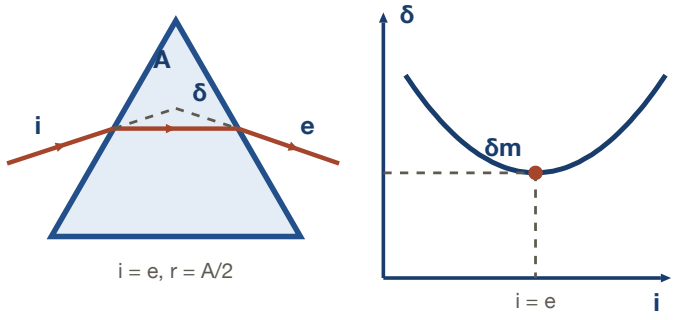
KEY IDEA

Biconvex lens, $n = 1.5$, equal radii R: $f = R$. Plano-convex: $f = 2R$. The same $|m| = 2$ occurs twice for a convex lens: $m = -2$ (real) at $u = -1.5f$ and $m = +2$ (virtual) at $u = -0.5f$, ratio 3.

TRAP

Use f in **metres** in $P = 1/f$. A lens's focal length changes in a liquid; a mirror's does not. Include the minus sign of a diverging lens when adding powers.

5 Prism and dispersion



$\delta = i + e - A$; it is least when the ray crosses symmetrically ($i = e$, $r_1 = r_2 = A/2$), here $A = 60°$, $n = 1.5$, $\delta_m = 37°$

PRISM

- $r_1 + r_2 = A$ and the deviation is $\delta = i + e - A$.
- δ is least (δ_m) when the ray crosses symmetrically: $i = e$, $r_1 = r_2 = A/2$. For a thin prism $\delta = (n - 1)A$.
- n is larger for blue than red, so blue bends more: white light **disperses** into a spectrum.

MINIMUM DEVIATION

$$n = \frac{\sin\frac{A + \delta_m}{2}}{\sin\frac{A}{2}}$$

$n = \cot\frac{A}{2} \Rightarrow \delta_m = \pi - 2A$

ANGULAR DISPERSION

$$\delta_v - \delta_r = (n_v - n_r)A$$

thin prism

DISPERSIVE POWER

$$\omega = \frac{n_v - n_r}{n_y - 1}$$

n_y for yellow (mean) light; depends only on the material

MINIMUM DEVIATION FORMULA

$i = e$ and $r_1 = r_2 = r$	the symmetric crossing, where δ is least
$r_1 + r_2 = A \Rightarrow r = \frac{A}{2}$	geometry of the prism
$\delta_m = 2i - A \Rightarrow i = \frac{A + \delta_m}{2}$	from $\delta = i + e - A$
$n = \frac{\sin i}{\sin r} = \frac{\sin\frac{A+\delta_m}{2}}{\sin\frac{A}{2}}$	Snell's law at the first face

DEVIATION WITHOUT DISPERSION

$$(n_v - n_r)A = (n'_v - n'_r)A'$$

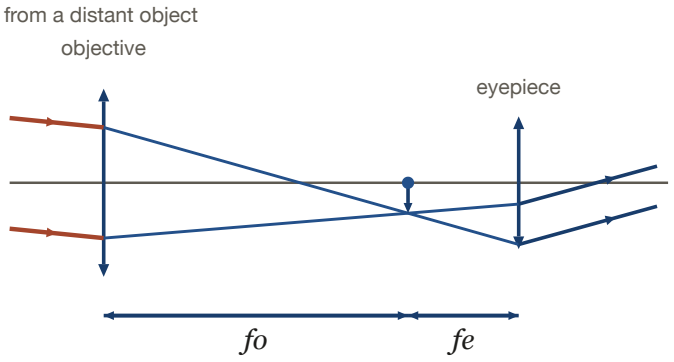
two prisms of different glass placed opposite: the colours recombine, the beam is still bent

DISPERSION WITHOUT DEVIATION

$$(n - 1)A = (n' - 1)A'$$

opposed prisms whose deviations cancel; the colours still spread

6 Optical instruments



normal adjustment: the intermediate image sits at the common focus, the tube length is $f_o + f_e$ and $M = \frac{f_o}{f_e}$

TELESCOPE AND MICROSCOPE

- Least distance of distinct vision $D = 25$ cm. Magnifying power depends on where the final image is: at D (strained eye) or at infinity (relaxed eye, normal adjustment).
- **Astronomical telescope**: a long-focus objective makes a real image of a distant object, the eyepiece magnifies it. A reflecting telescope uses a mirror as objective: no chromatic aberration and a larger aperture.
- **Compound microscope**: a short-focus objective makes a magnified real image, the eyepiece magnifies that.

SIMPLE MICROSCOPE

$M = 1 + \frac{D}{f}$ (image at D)

$M = \frac{D}{f}$ (image at ∞)

a convex lens used as a magnifier

COMPOUND MICROSCOPE

$M = m_o m_e \approx \frac{L}{f_o} \cdot \frac{D}{f_e}$

image at infinity; L = tube length. Image at D: $M = m_o \left(1 + \frac{D}{f_e}\right)$

TELESCOPE

$M = \frac{f_o}{f_e}, \quad L = f_o + f_e$

normal adjustment; image at D: $M = \frac{f_o}{f_e}\left(1 + \frac{f_e}{D}\right)$

TELESCOPE RESOLUTION

$\Delta\theta = \frac{1.22\lambda}{D_{ap}}$

smallest resolvable angle (radians); D_{ap} = aperture **diameter**

TRAP

Check where the final image is before choosing a magnification formula. A larger objective aperture gives better resolution and brighter images; a longer f_o gives larger magnification.

7 Wave optics: Huygens' principle and interference

HUYGENS' PRINCIPLE Every point on a wavefront is a source of secondary wavelets; the new wavefront is the envelope of the wavelets a moment later. It gives the laws of reflection and refraction, and shows that in a medium the wave speed is c/n while the frequency is unchanged. A point source gives spherical wavefronts, a distant source plane ones.

PHASE AND PATH

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

path difference $\lambda \leftrightarrow 2\pi$

TWO-SOURCE INTENSITY

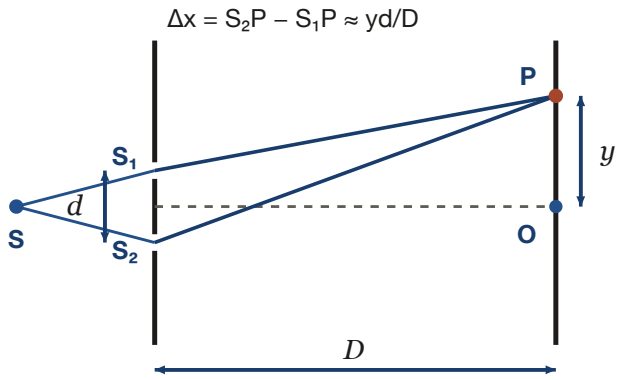
$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$

equal sources: $I = 4I_0\cos^2\frac{\phi}{2}$; sources must be **coherent** (constant phase difference)

MAX TO MIN RATIO

$\frac{I_{max}}{I_{min}} = \left(\frac{\sqrt{I_1} + \sqrt{I_2}}{\sqrt{I_1} - \sqrt{I_2}}\right)^2$

$I \propto$ slit width; widths $4:1$ give amplitudes $2:1$ and a ratio of 9



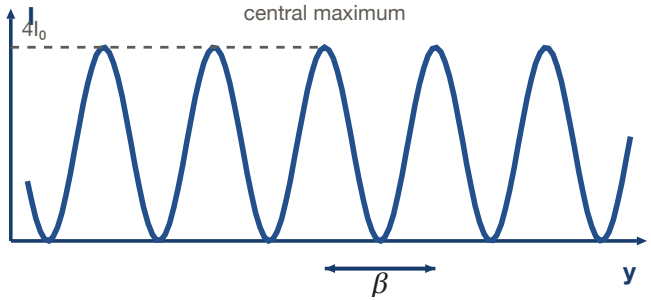
path difference $\Delta x \approx \frac{yd}{D}$ (for $D \gg d$): bright where $\Delta x = n\lambda$, dark where $\Delta x = (n + \frac{1}{2})\lambda$

YOUNG'S DOUBLE SLIT (YDSE)

- Two coherent slits d apart, a screen D away. The path difference at height y is $\Delta x \approx \frac{yd}{D}$.
- Bright fringes at $\Delta x = n\lambda$, dark at $(n + \frac{1}{2})\lambda$; all fringes have equal width $\beta = \frac{\lambda D}{d}$, independent of the order.
- White light: the central fringe is white, coloured fringes on either side.

FRINGE POSITIONS IN YDSE

$S_2P - S_1P \approx d\sin\theta \approx \frac{yd}{D}$	small angles, $D \gg d$
bright: $\frac{yd}{D} = n\lambda \Rightarrow y_n = \frac{n\lambda D}{d}$	waves arrive in phase
$\beta = y_{n+1} - y_n = \frac{\lambda D}{d}$	the same for every order



equal slits: $I = 4I_0\cos^2\frac{\phi}{2}$, maxima $4I_0$ and minima 0, all fringes of the same width $\beta = \frac{\lambda D}{d}$

FRINGE WIDTH

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

angular width $\frac{\lambda}{d}$; in a medium $\beta' = \frac{\beta}{\mu}$; doubling d halves β

THIN FILM ON ONE SLIT

shift $= \frac{(\mu - 1)tD}{d}$

toward the covered slit; the pattern moves by $\frac{(\mu - 1)t}{\lambda}$ fringes

FRINGES COINCIDE

$n\lambda_1 = m\lambda_2$

take the smallest integers: 480 nm and 600 nm first coincide at order 5 of the 480 nm pattern

TRAP

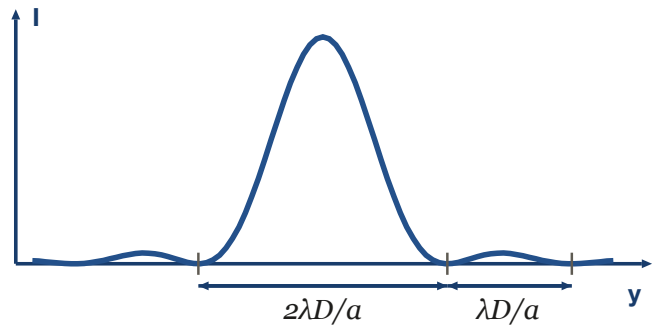
Intensity goes as slit **width**, amplitude as its square root. In YDSE $n\lambda$ gives **maxima**; in a single slit $a\sin\theta = n\lambda$ gives **minima**.

QUICK CHECK

Equal sources of intensity I_0 with a path difference $\lambda/3$. Resultant intensity?

Answer: $\phi = \frac{2\pi}{3}$, $I = 4I_0\cos^2\frac{\pi}{3} = I_0$.

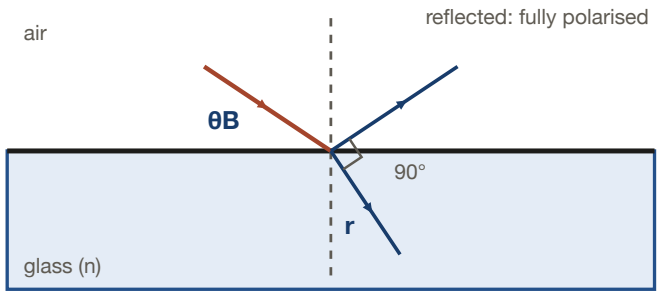
8 Diffraction and polarisation



minima at $a \sin\theta = n\lambda$; the central maximum is $\frac{2\lambda D}{a}$ wide, every secondary maximum $\frac{\lambda D}{a}$, and far weaker

SINGLE-SLIT DIFFRACTION

- A slit of width a spreads light into a pattern: a wide bright central maximum with weaker, narrower maxima on both sides.
- Minima at $a \sin\theta = n\lambda$ ($n = \pm1, \pm2, \ldots$); the central maximum is bounded by $n = \pm1$.
- Linear width of the central maximum $\frac{2\lambda D}{a}$, twice that of each secondary maximum, $\frac{\lambda D}{a}$. Distance between the mth and nth minima: $|n - m|\frac{\lambda D}{a}$.



at the polarising angle $\tan\theta_B = n$ the reflected and refracted rays are at 90°, so $\theta_B + r = 90^\circ$ (here $n = 1.5$, $\theta_B = 56.3^\circ$)

POLARISATION In unpolarised light the electric vector points in all directions across the beam; a Polaroid passes only one direction, so the light is **plane polarised** and, from unpolarised light, its intensity falls to half. This shows light is a transverse wave.

BREWSTER'S LAW

$$\tan\theta_B = n$$

reflected light fully polarised, reflected $\perp$ refracted; $\theta_B + r = 90^\circ$

MALUS'S LAW

$$I = I_0 \cos^2\theta$$

polarised light of intensity I_0 through a Polaroid at angle θ to its direction

UNPOLARISED LIGHT

$$I = \frac{I_0}{2}$$

after the first Polaroid; then apply $\cos^2\theta$ for each later one

THIRD POLAROID BETWEEN CROSSED ONES

$$I = \frac{I_0}{8}\sin^2 2\theta$$

unpolarised I_0; maximum $\frac{I_0}{8}$ at $\theta = 45^\circ$

TRAP

A Polaroid does not halve light that is already polarised: use $\cos^2\theta$. Halve only for **unpolarised** input.

SANITY CHECK

Crossed Polaroids (90°) give zero; parallel ones (0°) give the full intensity. Check any chain against these two limits.

9 Worked examples

CONVEX LENS

$f = 20$ cm, object 30 cm from the lens. Image position and magnification?

$\frac{1}{v} = \frac{1}{f} + \frac{1}{u} = \frac{1}{20} - \frac{1}{30} = \frac{1}{60}$: $v = 60$ cm (real); $m = v/u = -2$

SAME MAGNIFICATION TWICE

A convex lens $f = 20$ cm gives magnification 2 at two object distances. Ratio of the distances?

$u = f(1/m - 1)$: $m = -2 \Rightarrow 30$ cm, $m = +2 \Rightarrow 10$ cm; ratio 3

LENS IN A LIQUID

A biconvex lens ($n = 1.5$, $f = 20$ cm in air) is put in a liquid of index 1.6. New focal length?

$\frac{f_l}{f_a} = \frac{0.5}{1.5/1.6 - 1} = -8$, so $f_l = -160$ cm (diverging)

MINIMUM DEVIATION

A prism with $A = 60^\circ$ and $n = \sqrt{2}$. Minimum deviation?

$\sin\frac{60^\circ + \delta_m}{2} = \sqrt{2}\sin 30^\circ = \frac{1}{\sqrt{2}}$, so $\frac{60^\circ + \delta_m}{2} = 45^\circ$, $\delta_m = 30^\circ$

TELESCOPE AND MICROSCOPE

Telescope $f_o = 100$ cm, $f_e = 5$ cm (normal adjustment); microscope $f_o = 1$ cm, $f_e = 5$ cm, tube 20 cm, image at infinity.

telescope: $M = 20$, tube 105 cm; microscope: $M = \frac{L}{f_o}\frac{D}{f_e} = 20 \times 5 = 100$

YDSE AND A FILM

$\lambda = 600$ nm, $D = 1$ m, $d = 1$ mm. Fringe width in air and in water ($\mu = 4/3$); shift when a 10 μm film of $\mu = 1.5$ covers one slit?

$\beta = 0.6$ mm; in water 0.45 mm; shift $\frac{(\mu - 1)tD}{d} = 5$ mm (≈ 8.3 fringes) toward the covered slit

SINGLE SLIT

$\lambda = 500$ nm, $a = 0.2$ mm, screen 1 m away. Width of the central maximum?

$\frac{2\lambda D}{a} = \frac{2 \times 500 \times 10^{-9} \times 1}{0.2 \times 10^{-3}} = 5$ mm

POLAROIDS

Unpolarised light I_0 passes two Polaroids at 30°. Transmitted intensity?

$\frac{I_0}{2}\cos^2 30^\circ = \frac{3I_0}{8}$

APPARENT DEPTH AND TIR

A coin lies 12 cm under water ($n = 4/3$). Apparent depth? And does a ray meeting a glass-air surface at 45° escape ($n = 1.5$)?

$d_{app} = 12/(4/3) = 9$ cm; $\sin C = 1/1.5 \Rightarrow C = 41.8^\circ < 45^\circ$: totally reflected

LENSES IN CONTACT

A convex lens $f = 20$ cm touches a concave one $f = -10$ cm. Equivalent focal length?

$P = 5 - 10 = -5$ D, so $F = -20$ cm (diverging)

10 Last-minute checklist

BEFORE YOU ANSWER

Signs first (New Cartesian: distances from the pole, positive along the incident light). Is it a mirror (plus) or a lens (minus)? Is the object in air or a liquid? In wave optics: maxima or minima, width or intensity?

- Mirror $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$, $f = R/2$, $m = -v/u$; lens $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$, $m = v/u$; $P = 1/f$ with f in metres.
- Snell $n_1 \sin i = n_2 \sin r$; $\sin C = n_2/n_1$; $d_{app} = d/n$; lens maker $\frac{1}{f} = (n_{rel} - 1)(\frac{1}{R_1} - \frac{1}{R_2})$.
- Prism $\delta = i + e - A$, $n = \frac{\sin\frac{A+\delta_m}{2}}{\sin\frac{A}{2}}$, thin $(n-1)A$; $\omega = \frac{n_v - n_r}{n_y - 1}$.
- Telescope $M = f_o/f_e$, $L = f_o + f_e$; microscope $M \approx \frac{L}{f_o}\frac{D}{f_e}$; $\Delta\theta = 1.22\lambda/D_{ap}$.
- YDSE $\beta = \lambda D/d$ (divide by μ in a medium); film shift $(\mu - 1)tD/d$; $I = 4I_0\cos^2(\phi/2)$; widths $4:1$ give $I_{max}/I_{min} = 9$.
- Single slit minima $a\sin\theta = n\lambda$, central width $2\lambda D/a$; Malus $I_0\cos^2\theta$; Brewster $\tan\theta_B = n$.

Now test it. Practise this chapter with past-paper and bank questions on Prep Vault. **Practice this chapter →**