LOGIC BLOOM · PHYSICS · CLASS 12

Wave Optics

Ray optics ends here · **NEET, JEE Main and JEE Advanced**

Ray optics treats light as a straight line and gets you a long way. Then light passes a narrow slit and bends, and two beams add up to darkness. Neither makes sense until you stop drawing rays and start drawing wavefronts. That switch is this whole chapter.

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Contents

0 How to Read This Set

Sections 1 to 7 are the full syllabus for **NEET and JEE Main**. Sections 8 and 9 are the **JEE Advanced** layer, where the pattern is shifted, immersed or lit with white light and you have to work out what happens.

THE WHOLE CHAPTER IN ONE LINE

Stop drawing rays. Draw wavefronts, and then compare path lengths.

Every result here comes from one question: by how much does one path exceed the other? Turn that into a phase difference and you have your answer.

THINK IT THROUGH

WHY RAY OPTICS HAD TO GIVE UP

- Ray optics assumes light travels in straight lines, which works whenever the obstacle is far larger than the wavelength.
- Visible light has a wavelength around **400 to 700 nm**, so a millimetre slit is already thousands of wavelengths wide and rays are fine.
- Shrink the slit towards the wavelength and the light spreads out. No arrangement of straight lines can explain that, so a new model is needed.

TRAP ALERT

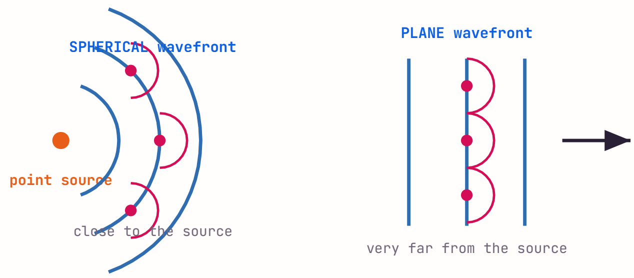
THE HABIT THAT FIXES THIS CHAPTER

- Never start from a formula. Start by asking which two paths you are comparing.
- Convert the path difference into a phase difference with $\phi = (2\pi/\lambda) \times \Delta x$.
- Then bright or dark follows immediately, and you will not confuse the interference condition with the diffraction one.

1 Huygens' Principle

A **wavefront** is a surface on which every point vibrates in the same phase. A ray is simply the normal to that surface, so rays are a shortcut, not the reality.

HUYGENS: EVERY POINT ON A WAVEFRONT IS ITSELF A NEW SOURCE



THE CONSTRUCTION

Every point on a wavefront sends out a secondary wavelet. The envelope of all **those wavelets is the NEXT wavefront.**

WHAT IT EXPLAINS

Reflection, refraction and the fact that light bends round an edge at all.

Each point becomes a fresh source. The envelope of the wavelets is the next wavefront.

WAVEFRONT	SHAPE	WHEN YOU SEE IT
Spherical	expanding sphere	near a point source
Cylindrical	expanding cylinder	from a line source, such as a slit
Plane	flat sheet	very far from any source, as with sunlight

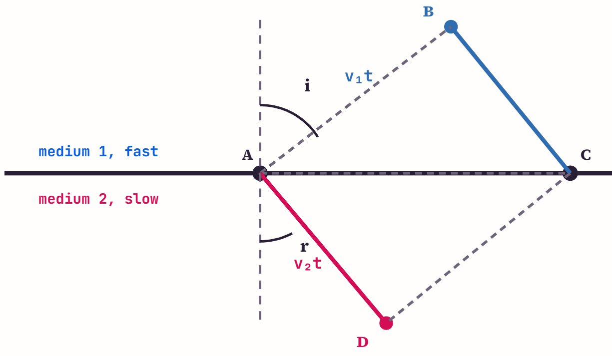
THINK IT THROUGH

WHAT HUYGENS EXPLAINS, AND WHAT HE COULD NOT

- It gives you the laws of **reflection and refraction** directly, by drawing the wavelets on the far side of a boundary.
- It predicts that light slows in a denser medium, **$v = c/\mu$**, which the particle model got exactly backwards.
- **It does not explain polarisation**, because Huygens assumed the waves were longitudinal. That correction came later.

Snell's law falls straight out of it

SNELL'S LAW, DERIVED FROM WAVEFRONTS ALONE



THE WHOLE DERIVATION

$\sin i = v_1 t / AC \quad \sin r = v_2 t / AC$

divide: $\sin i / \sin r = v_1 / v_2 = \mu_2 / \mu_1$

WHAT IT SETTLED

Light must travel SLOWER in a denser medium, since $\mu = c/v$. Newton's particle model predicted the exact opposite.

Two media, one shared base AC, two different speeds. The ratio of the sines is forced.

THINK IT THROUGH

REFRACTION AT A RARER MEDIUM, AND TOTAL INTERNAL REFLECTION

- Going from dense to rare the wavefront speeds up, so the refracted ray bends **away** from the normal.
- At the **critical angle** the refracted wavefront runs flat along the surface, so r = 90°.
- Past it no wavefront can satisfy the geometry at all, so everything reflects. That is **total internal reflection**, with sin i(c) = 1/μ.

The Doppler effect for light

ONLY THE RADIAL SPEED COUNTS

For speeds far below c:

Δν/ν = – v(radial)/c and **Δλ/λ = + v(radial)/c** for a receding source

Motion across the line of sight gives no first-order shift at all.

TRAP ALERT

RED SHIFT AND BLUE SHIFT

- A source moving **away** stretches the wave, so λ increases. That is a **red shift**, and it is how we know distant galaxies are receding.
- A source moving **towards** you compresses it, giving a **blue shift**.
- Worked example: the hydrogen line at 6563 Å arrives 15 Å longer. Then $v = c\Delta\lambda/\lambda = 6.9 \times 10^5$ m/s, so the source is receding.
- Unlike sound, it makes no difference whether the source or the observer moves. Only their **relative** radial velocity enters.

2 Superposition and Coherence

When two waves meet, the displacements simply add. If they arrive in step the result is bigger, and if they arrive exactly out of step they cancel.

WHAT SUSTAINED INTERFERENCE REQUIRES

- The two sources must be **coherent**: a constant phase difference that does not drift.
- They must have the **same frequency**, and nearly the same amplitude for good contrast.
- They must be **narrow** and **close together**, or the fringes are too fine to see.
- The light should be **monochromatic**, otherwise each colour makes its own pattern.

TRAP ALERT

WHY TWO SEPARATE BULBS NEVER GIVE FRINGES

An ordinary source emits light in bursts lasting about **10^{-9} seconds**, each with a random phase. Two independent bulbs therefore change their phase relationship millions of times a second, so the pattern washes out long before your eye can register it. Young's answer was to split **one** wavefront into two, which is why a double slit works and two lamps do not.

Constructive against destructive

	CONSTRUCTIVE	DESTRUCTIVE
Phase difference φ	$0, 2\pi, 4\pi$ ... (even multiples of π)	$\pi, 3\pi, 5\pi$ ... (odd multiples)
Path difference Δx	$n\lambda$	$(2n-1)\lambda/2$
Amplitudes	add: $a_1 + a_2$	subtract: $a_1 - a_2$
Resulting intensity	$(\sqrt{I_1} + \sqrt{I_2})^2$	$(\sqrt{I_1} - \sqrt{I_2})^2$

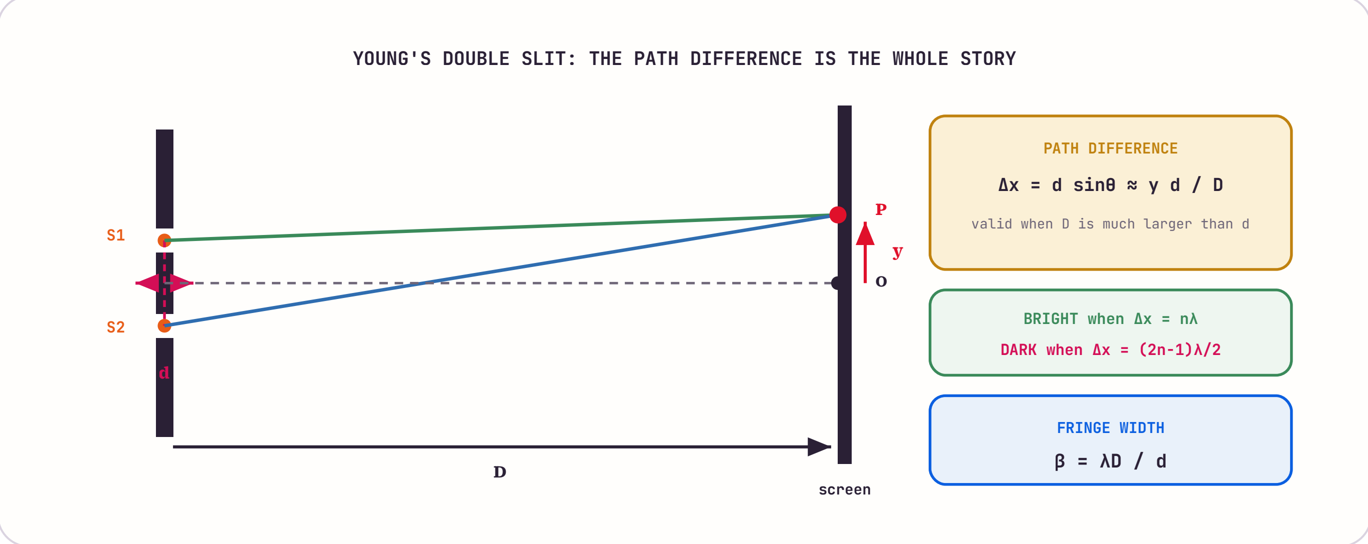
The link between the two rows at the top is worth writing on your hand: $\boldsymbol{\phi = (2\pi/\lambda) \times \Delta x}$. Convert once, and every condition in this chapter follows without being memorised separately.

THINK IT THROUGH

TWO SOURCES THAT ARE COHERENT

- **Young's double slit:** one wavefront is divided by two slits, so the two halves keep step forever. This is division of **wavefront**.
- **Thin films, such as a soap bubble or oil on water:** one beam is partly reflected and partly transmitted, so the two parts come from the same original wave. This is division of **amplitude**, and it is why a soap film shows colours.
- **A laser:** coherent by construction, which is exactly why laser light gives such sharp fringes with no need for a narrow source slit.

3 Young's Double Slit



One wavefront, split in two. Everything follows from how much further one path runs.

THE FOUR RESULTS YOU NEED

Path difference $\Delta x = d \sin\theta \approx yd/D$

Bright fringe $\Delta x = n\lambda$, so $y = n\lambda D/d$

Dark fringe $\Delta x = (2n-1)\lambda/2$

Fringe width $\beta = \lambda D/d$, the same for every fringe

A worked example

Take $\lambda = 600$ nm, $d = 1$ mm and $D = 1$ m. Then $\beta = (600 \times 10^{-9} \times 1) / 10^{-3} =$ **0.6 mm**. The fifth bright fringe sits 3.0 mm from the centre, and the angular fringe width is $\lambda/d = 6 \times 10^{-4}$ radian.

THINK IT THROUGH

WHAT CHANGES THE FRINGE WIDTH, AND WHAT DOES NOT

- **Wider spacing**: increase λ or D, or decrease d.
- Red fringes are wider than blue, since red has the longer wavelength.
- **Changing the slit WIDTH does not change β**. It only changes the brightness and the contrast. Only the slit **separation** d matters.
- The central fringe is always bright, because there the two paths are exactly equal.

▶ PLAY

FRINGES NOT MAKING SENSE?

Move the screen and watch the spacing change.

Drag D and d and see the fringe width respond live, then switch the colour and watch red spread wider than blue. **logicbloom.co.in/download** · Free to start.

SCAN

4 Intensity in Interference

INTENSITY, AND WHERE THE ENERGY GOES

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

For equal sources: $\mathbf{I = 4I_0\cos^2(\phi/2)}$

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

IF THE SLIT WIDTHS ARE	AMPLITUDES ARE	$I_{MAX} : I_{MIN}$
equal	equal	maximum contrast, dark fringes fully black
4 : 1	2 : 1	9 : 1
9 : 1	3 : 1	4 : 1
16 : 1	4 : 1	2 : 1

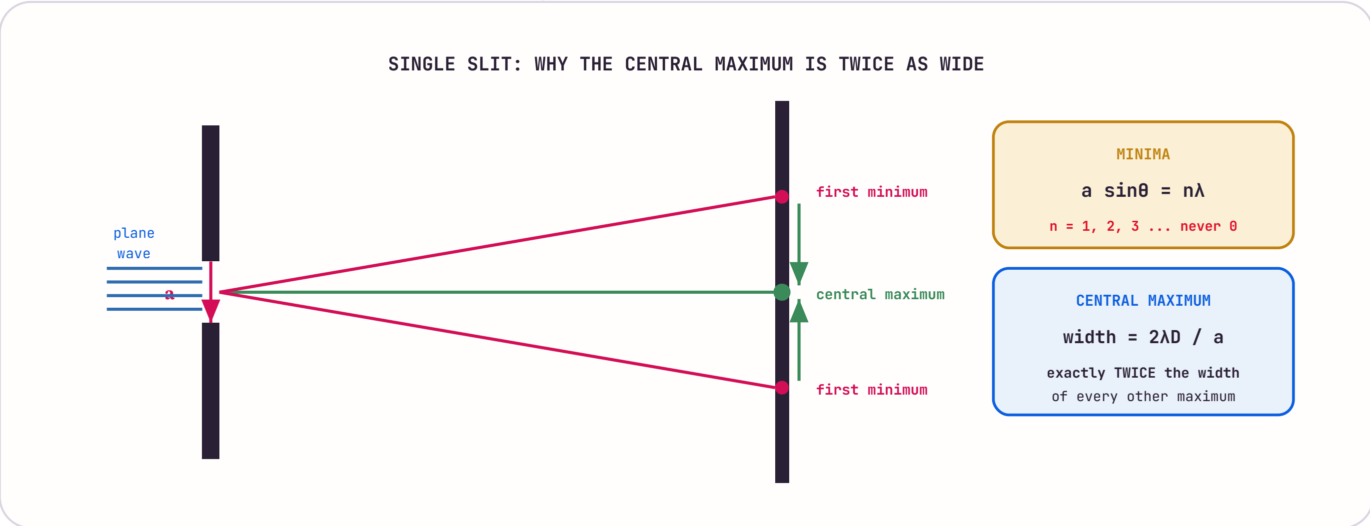
THINK IT THROUGH

INTERFERENCE DOES NOT DESTROY ENERGY

- At a bright fringe the intensity is $\mathbf{4I_0}$, not $2I_0$, because amplitudes add and intensity goes as amplitude squared.
- At a dark fringe it is zero. The energy missing there is exactly the extra energy appearing at the bright fringes.
- Averaged across the screen the intensity is $\mathbf{2I_0}$, precisely what you would get with no interference at all. Energy is redistributed, never lost.

5 Diffraction at a Single Slit

Now there is only one slit. Light from the top of the slit interferes with light from the bottom, so the wavefront interferes with itself.



Divide the slit into pairs of strips. Each pair cancels when the extra path is half a wavelength.

SINGLE SLIT RESULTS

Minima $a \sin\theta = n\lambda$, with $n = 1, 2, 3$ ... *never $n = 0$*

Secondary maxima $a \sin\theta = (2n+1)\lambda/2$

Half angular width of the central maximum $\theta = \lambda/a$

Linear width of the central maximum $2\lambda D/a$

With $\lambda = 500$ nm, $a = 0.1$ mm and $D = 1$ m, the central maximum is $2(500 \times 10^{-9})(1)/10^{-4}$ = **10 mm** wide, and every other maximum is half that.

TRAP ALERT

TWO SIGN TRAPS IN ONE FORMULA

- **$n = 0$ is not a minimum**. Putting $n = 0$ into $a \sin\theta = n\lambda$ gives the centre of the pattern, which is the brightest point of all.
- The condition for a **minimum** in diffraction looks exactly like the condition for a **maximum** in interference. They are opposite. Check which experiment you are in before writing anything.
- Narrower slit means **wider** pattern. The spreading goes as $1/a$, which feels backwards until you accept that light is a wave.

How bright are the secondary maxima?

INTENSITY ACROSS THE PATTERN

$\mathbf{I = I_0 (\sin \beta / \beta)^2}$, with $\beta = \pi a \sin\theta / \lambda$

The first secondary maximum is only about **4.7 percent** of the central one, and the second about 1.7 percent. That is why the pattern fades so fast.

Where ray optics finally breaks

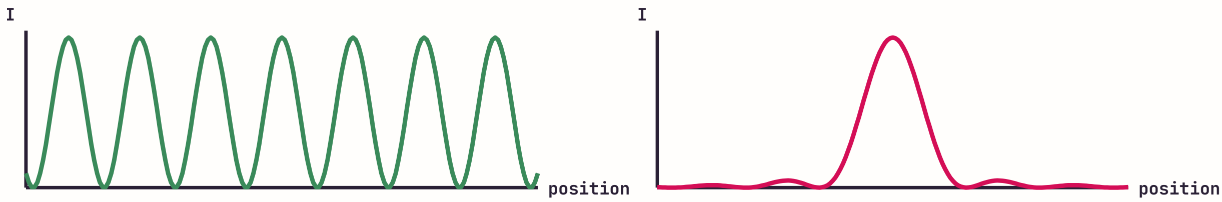
THINK IT THROUGH

FRESNEL DISTANCE

- A beam through an aperture a spreads by about λ/a, so after a distance z it has widened by roughly zλ/a.
- Set that equal to a itself and you get the **Fresnel distance, Z(F) = a^2/λ**.
- Closer than Z(F) the spreading is negligible and ray optics is safe. Beyond it, diffraction dominates and rays stop meaning anything.
- For a 1 mm aperture at 500 nm, Z(F) is about **2 metres**, which is why a laser pointer looks like a straight line across a room but not across a field.

6 Interference against Diffraction

THE TWO PATTERNS LOOK ALIKE UNTIL YOU MEASURE THEM



INTERFERENCE, two slits

all maxima the SAME brightness
and equally spaced

DIFFRACTION, one slit

central maximum is WIDE and bright,
the rest fade away fast

Interference comes from TWO separate wavefronts. Diffraction comes from different parts of the SAME wavefront. That single difference explains every other difference below.

Same experiment room, two very different graphs.

THE COMPARISON THAT ANSWERS MOST ONE-MARK QUESTIONS

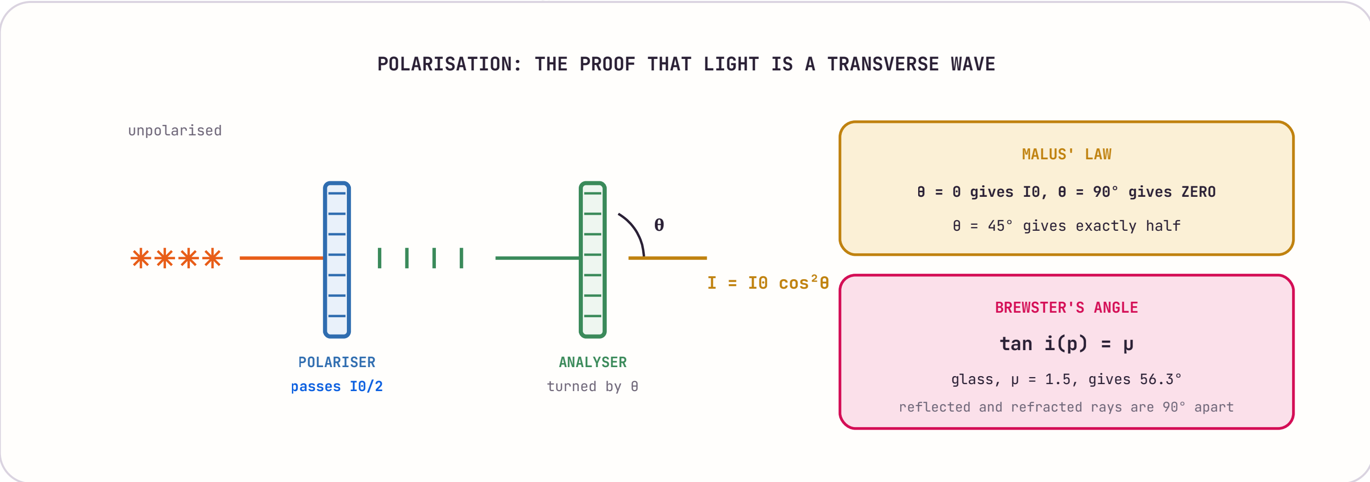
	INTERFERENCE	DIFFRACTION
Comes from	two separate wavefronts	different parts of the SAME wavefront
Fringe width	all fringes equally wide	central max is twice the rest
Intensity of maxima	all maxima equally bright	falls off rapidly away from centre
Minima	perfectly dark	not perfectly dark
Condition for maxima	$\Delta x = n\lambda$	$a \sin\theta = (2n+1)\lambda/2$
Condition for minima	$\Delta x = (2n-1)\lambda/2$	$a \sin\theta = n\lambda$

Note the conditions are SWAPPED between the two columns. That is the trap.

Learn this table as a table. Questions are often lifted straight from a single row.

7 Polarisation

Interference and diffraction prove light is a **wave**. Only polarisation proves it is a **transverse** wave, because a longitudinal wave such as sound cannot be polarised at all.



One polariser halves the intensity. The second one then follows Malus' law.

THE TWO LAWS

Malus' law $I = I_0 \cos^2\theta$

Brewster's law $\tan i_p = \mu$, and at that angle the reflected and refracted rays are exactly 90° apart

SITUATION	TRANSMITTED INTENSITY
unpolarised light through one polariser	always exactly $I_0/2$
then through an analyser at θ	$(I_0/2)\cos^2\theta$
analyser at 0°	full intensity
analyser at 45°	half
analyser at 90° (crossed)	zero, complete extinction

THINK IT THROUGH

BREWSTER'S ANGLE, WITH A NUMBER

For glass with $\mu = 1.5$, $i_p = \tan^{-1}(1.5) =$ **56.3°**. For water at $\mu = 1.33$ it is 53.1°. At that angle the **reflected** light is completely plane polarised, which is exactly how polarising sunglasses cut glare from a wet road or a water surface.

Polarisation by scattering, and why the sky is blue

THINK IT THROUGH

TWO FACTS INSIDE ONE PHENOMENON

- Sunlight sets air molecules vibrating, and they re-radiate. But a vibrating charge radiates **nothing along its own line of vibration**, so light scattered at 90° to the sun comes out plane polarised.
- Scattered intensity goes as **$1/\lambda^4$**, which is Rayleigh scattering. Blue at 450 nm scatters about **6 times** more than red at 700 nm, so the sky looks blue.
- At sunset the light crosses far more atmosphere, so most of the blue has already been scattered sideways and what reaches you is red.
- Check it yourself: view blue sky 90° from the sun through a polaroid and rotate it. The brightness visibly changes.

TIER 2

The JEE Advanced layer

Everything so far is complete for NEET and JEE Main. Advanced moves the apparatus: it immerses the whole thing in water, slips a sheet of glass over one slit, or swaps in white light.

8 Shifting and Changing the Pattern

CHANGE MADE	WHAT HAPPENS TO β	WHY
whole set-up put in water	β becomes β/μ	the wavelength inside is λ/μ
D doubled	β doubles	β is proportional to D
d doubled	β halves	β is inversely proportional to d
slit width increased	no change to β	only brightness and contrast change
one slit covered	fringes vanish	a single slit diffraction pattern is left
white light used	white centre, coloured edges	each colour has its own β

A TRANSPARENT SHEET OVER ONE SLIT

A sheet of thickness t and index μ adds an extra path of $(\mu - 1)t$.

The whole pattern shifts by $\Delta y = (\mu - 1)t\, D / d = (\mu - 1)t\, \beta / \lambda$

It shifts **towards** the covered slit, and the fringe width β does not change.


TRAP ALERT

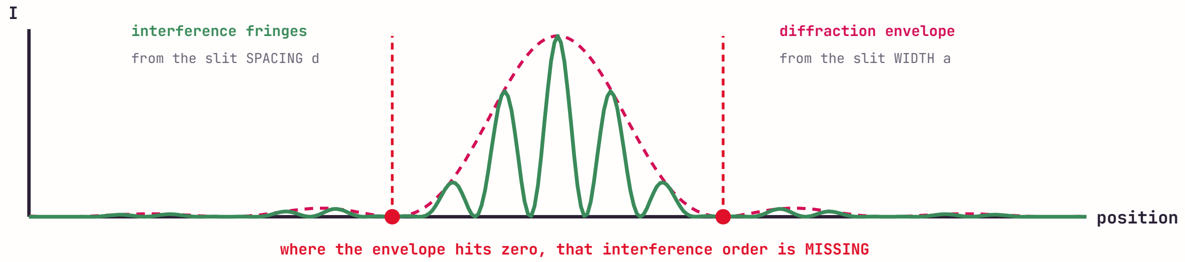
THREE ADVANCED RESULTS WORTH CARRYING

- **The shift is towards the slit you covered**, not away from it, because that path now takes longer and the equal-path point moves across to compensate.
- In **white light** the centre is white, since every colour has zero path difference there. The first fringe on each side is violet nearest the centre and red furthest, because violet has the shortest wavelength.
- Immersing the apparatus shrinks β by a factor μ, and does **not** change the number of fringes on the screen in the same way you might guess, so compute rather than assume.

Missing orders in a real double slit

A real double slit has slits of finite width, so you never see pure interference. The fringes sit **inside** a diffraction envelope set by the slit width.

A REAL DOUBLE SLIT: DIFFRACTION DECIDES WHICH FRINGES SURVIVE



Maxima need d sinθ = nλ. Envelope zeros need a sinθ = mλ. They coincide when n/m = d/a.
So if d/a = 3, orders 3, 6 and 9 never appear, however long you look for them.

The fine fringes come from the spacing d. The envelope over them comes from the width a.

TRAP ALERT

WHICH ORDERS VANISH

- Interference maxima need $d \sin\theta = n\lambda$. Envelope zeros need $a \sin\theta = m\lambda$.
- Where those coincide the fringe is **missing**, and that happens when **$n / m = d / a$**.
- So if $d = 3a$, the 3rd, 6th and 9th orders never appear. If $d = 2a$, every even order vanishes.
- The number of fringes inside the central envelope is therefore fixed by d/a alone, not by λ or D.

9 Resolving Power

Diffraction sets a hard limit on how close two objects can be and still be seen as two. No amount of magnification beats it, which is why bigger telescopes are built rather than stronger eyepieces.

THE TWO LIMITS

Telescope limit of resolution $\Delta\theta = 1.22\lambda/D$, so resolving power $= D/1.22\lambda$

Microscope limit $d_{min} = 1.22\lambda/(2\mu \sin\beta)$

THINK IT THROUGH

WHAT THE FORMULA TELLS YOU TO DO

- A **bigger aperture D** resolves better, which is the entire reason large telescopes exist.
- A **shorter wavelength** resolves better. That is why an electron microscope, using electron waves far shorter than light, sees what an optical one never can.
- For a 10 cm telescope at $\lambda = 550$ nm, the limit is about **6.7×10^{-6} radian**.
- **Rayleigh's criterion:** two points are just resolved when the central maximum of one falls on the first minimum of the other.

▶ PLAY

WANT TO SEE THE LIMIT FOR YOURSELF?

Shrink the aperture and watch two stars merge into one.

Slide the aperture down and see the Airy discs widen until they overlap. Rayleigh's criterion stops being a sentence. **logicbloom.co.in/download** · Free to start.

SCAN

★ Wave Optics · Fact Sheet

Every rule for revision day. Print this page alone.

WAVEFRONTS

Surface of constant phase

Ray is its normal
Spherical, cylindrical, plane.

HUYGENS

Every point is a new source

Envelope is the next wavefront
Explains reflection and refraction.

COHERENCE

Constant phase difference

Same frequency, narrow, close
Two bulbs can never do it.

YDSE

$\Delta x = d \sin\theta \approx yd/D$

Bright $n\lambda$, dark $(2n-1)\lambda/2$
$\beta = \lambda D/d$.

INTENSITY

$I = 4I_0\cos^2(\phi/2)$

Widths 4:1 gives Imax:Imin 9:1
Average stays $2I_0$.

SINGLE SLIT

Minima $a \sin\theta = n\lambda$, $n \neq 0$

Central width $2\lambda D/a$
TWICE every other maximum.

THE SWAP TRAP

$n\lambda$ is a MAXIMUM in interference

but a MINIMUM in diffraction.
Check which experiment.

POLARISATION

Proves light is TRANSVERSE

One polariser gives $I_0/2$
Malus: $I = I_0\cos^2\theta$.

BREWSTER

$\tan i(p) = \mu$

Glass 1.5 gives 56.3°
Reflected and refracted 90° apart.

IN WATER

λ becomes λ/μ

so β becomes β/μ
Fringes crowd together.

GLASS SHEET

Extra path $(\mu-1)t$

Shift = $(\mu-1)tD/d$
TOWARDS the covered slit.

RESOLVING POWER

Telescope $1.22\lambda/D$

Bigger D or smaller λ is better
Rayleigh: max on first min.

DOPPLER

$\Delta\lambda/\lambda = v(\text{radial})/c$

Receding gives RED shift
Only radial motion counts.

FRESNEL DISTANCE

$Z(F) = a^2/\lambda$

1 mm at 500 nm gives about 2 m
Beyond it, rays are meaningless.

MISSING ORDERS

Vanish when $n/m = d/a$

$d = 3a$ kills orders 3, 6, 9
Set by d/a alone.

BLUE SKY

Rayleigh scattering $\propto 1/\lambda^4$

Blue scatters about 6× red
90° scattered light is polarised.