

THEME C · WAVE BEHAVIOUR

SL & HL ≈ 40 min read

IB Physics C.3 Wave Phenomena — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). Everything up to and including Young's double-slit experiment is for SL and HL. Single-slit diffraction, the modulation of the double-slit pattern and multiple slits/diffraction gratings are **additional higher level** content and sit in the purple HL boxes.

 SL C.3 questions HL C.3 questions Flashcards Superposition simulation Double-slit simulation Diffraction grating simulation

What this page covers

- ✓ Describing waves in two and three dimensions with wavefronts and rays
- ✓ What happens to a wave at a boundary: reflection, refraction and transmission
- ✓ Diffraction of waves through a gap and around an object
- ✓ Drawing and reading wavefront-ray diagrams for refraction and diffraction
- ✓ Refractive index and Snell's law, $\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$; the critical angle and total internal reflection
- ✓ The principle of superposition for waves and pulses
- ✓ Why two-source interference needs coherent sources
- ✓ Path-difference conditions for constructive and destructive interference
- ✓ Young's double-slit experiment and the fringe separation $s = \frac{\lambda D}{d}$

- ✓ (HL) Single-slit diffraction, its intensity pattern and the first minimum at $\theta = \frac{\lambda}{b}$
- ✓ (HL) How diffraction at each slit controls the brightness of the double-slit fringes
- ✓ (HL) Interference from multiple slits and diffraction gratings, $n\lambda = d \sin \theta$, with monochromatic and white light

In one minute

- Wavefronts join points oscillating in phase; rays show the direction of energy transfer and are always perpendicular to the wavefronts.
- At a boundary a wave is partly reflected and partly transmitted. The **frequency never changes**; if the speed changes, the wavelength changes, and an oblique wave changes direction (refraction).
- Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$, angles measured from the **normal**. Going into a slower (higher- n) medium, the ray bends towards the normal.
- Total internal reflection needs two things: the wave travels towards a medium of *lower* refractive index, and the angle of incidence is *greater* than the critical angle, $\sin \theta_c = n_2/n_1$.
- Diffraction is the spreading of waves through gaps and around obstacles; it is significant when the gap is comparable to the wavelength.
- Coherent sources (constant phase difference) give a steady interference pattern: maxima where path difference = $n\lambda$, minima where it is $(n + \frac{1}{2})\lambda$. Double slit: $s = \lambda D/d$.
- **HL** Single slit: first minimum at $\theta = \lambda/b$. Gratings: sharp maxima at $n\lambda = d \sin \theta$; white light gives a spectrum in each order.

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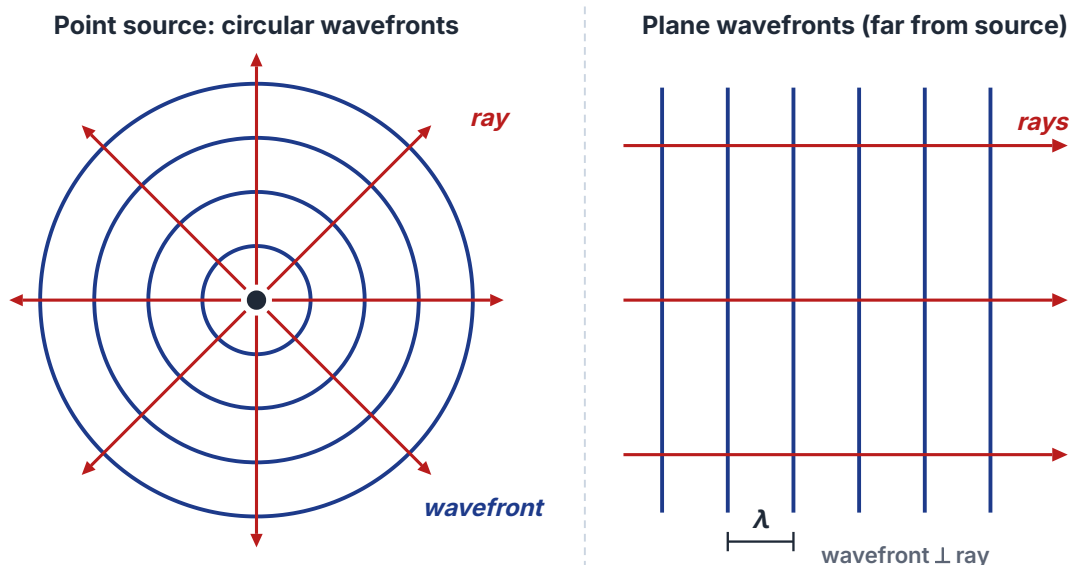
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How are waves in two and three dimensions described?

In C.2 a wave was a graph of displacement along a line. Water ripples spreading across a pond, sound leaving a loudspeaker and light from a lamp travel in two or three dimensions, so we need a way of showing *where* the wave is and *which way* it is going. IB uses two ideas: wavefronts and rays.

A wavefront is a line (in two dimensions) or surface (in three dimensions) joining neighbouring points that oscillate in phase, for example all the points on one crest. A ray is a line showing the direction in which the wave, and its energy, travels; rays are always perpendicular to the wavefronts.

- Wavefronts are usually drawn one per crest, so the distance between neighbouring wavefronts is one **wavelength** λ .
- A point source produces **circular** wavefronts on a surface (ripples) and **spherical** wavefronts in three dimensions; the rays spread out radially.
- Far from the source a small part of a large circle or sphere is almost flat: the wavefronts become **plane** (straight and parallel) and the rays are parallel. Light from the Sun or a laser beam is modelled this way.
- If the wave slows down, the wavefronts get closer together ($\lambda = v/f$ with f fixed).



Wavefronts (blue) are spaced one wavelength apart; rays (red) are perpendicular to them and show the direction of energy transfer.

What happens to a wave at a boundary between two media?

When a wave reaches a boundary between two media (for example air–glass, deep–shallow water, or air–concrete for sound), three things can happen to its energy, usually all at once:

- **Reflection** — part of the wave bounces back into the first medium.
- **Transmission** — part of the wave passes into the second medium. If it enters at an angle and its speed changes, it changes direction: this is **refraction**.
- Some energy may also be absorbed by the second medium (it is not transmitted further).

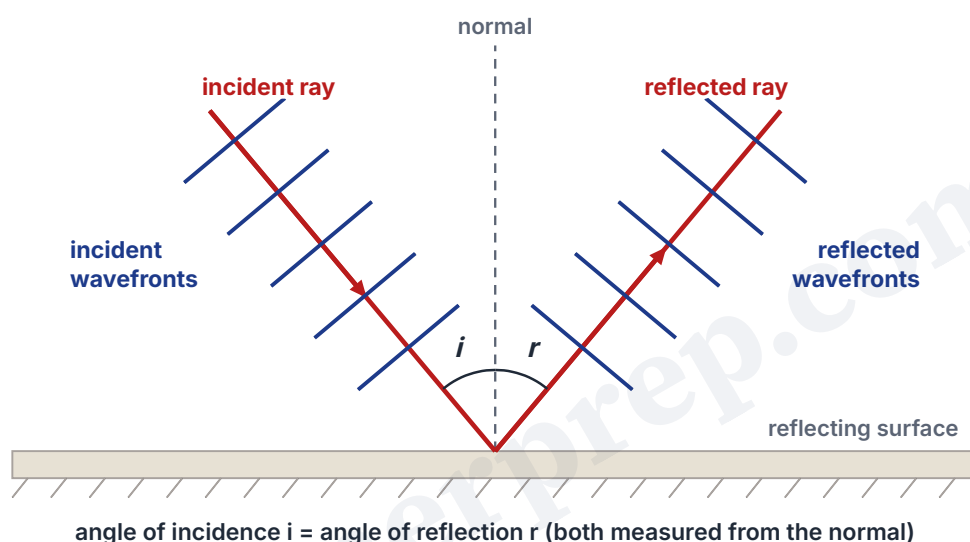
The frequency of a wave is set by its source and does not change at a boundary. If the speed changes on transmission, the wavelength changes in proportion: $\lambda = \frac{v}{f}$, so $\frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1}$.

Reflection

- **Law of reflection:** the angle of incidence equals the angle of reflection, $i = r$, both measured between the ray and the **normal** (the line at 90° to the surface)

at the point where the ray strikes it). The incident ray, reflected ray and normal lie in the same plane.

- The reflected wave travels in the same medium as the incident wave, so its speed, wavelength and frequency are unchanged. On a wavefront-ray diagram, the reflected wavefronts have the **same spacing** as the incident ones.



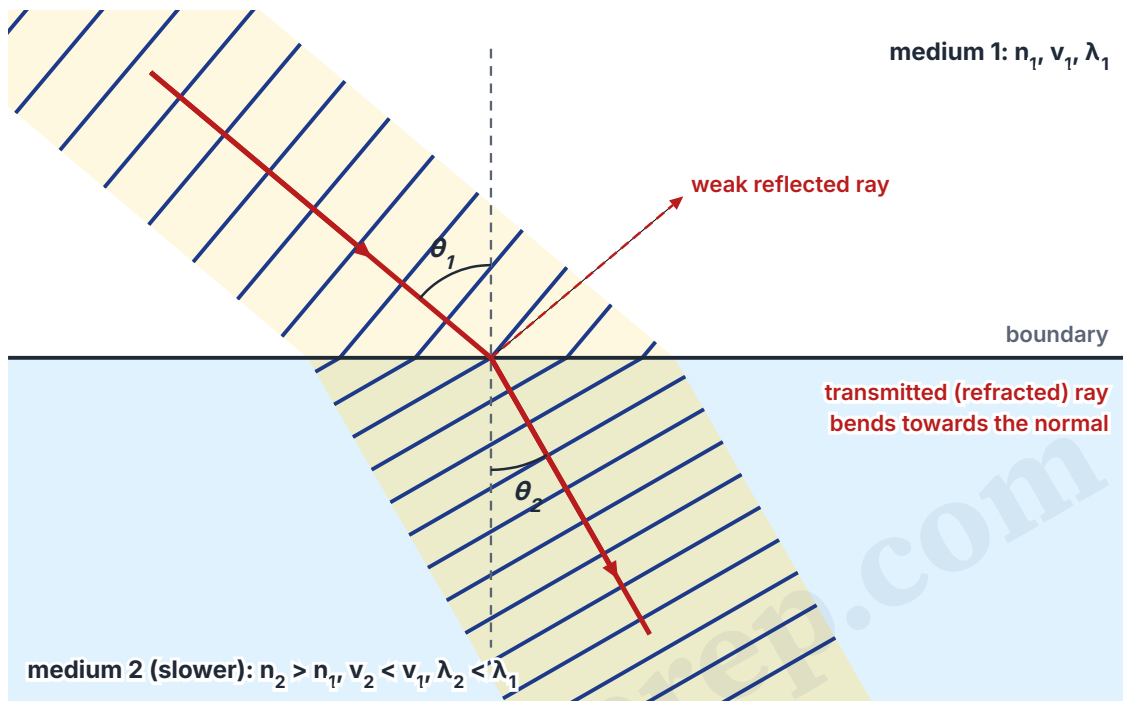
Reflection at a plane surface: the reflected wavefronts keep the same spacing (same λ), and each ray makes the same angle with the normal before and after reflection.

Refraction

Refraction is the change in direction of a wave when it crosses a boundary obliquely and its speed changes.

- When a wave slows down (e.g. light going from air into glass, or water waves moving into shallower water), the ray bends **towards** the normal. When it speeds up, it bends **away** from the normal.
- Why it bends: the part of a wavefront that reaches the boundary first slows down first, while the rest of the wavefront is still moving at the higher speed. The wavefront swings round, so the direction (perpendicular to it) changes.
- At **normal incidence** (along the normal) there is no change in direction, but the speed and wavelength still change.

- A partial reflection always accompanies refraction; it is weak for light at small angles of incidence.



Wavefront-ray diagram for a wave entering a medium where it travels at 0.65 times its original speed. $\theta_1 = 50^\circ$ and $\theta_2 = 30^\circ$ (29.9°). The wavefronts stay continuous across the boundary, but in medium 2 they are closer together ($\lambda_2 = 0.65 \lambda_1$) and the ray is closer to the normal.

EXAM TIP — DRAWING WAVEFRONT-RAY DIAGRAMS

Four things earn the marks: (1) transmitted wavefronts are **closer together** if the wave slows down (further apart if it speeds up); (2) each wavefront is **continuous** at the boundary — it meets the boundary at the same point from both sides; (3) rays are drawn **perpendicular** to the wavefronts; (4) reflected wavefronts keep the original spacing. Use a ruler and keep the wavelength constant within each medium.

How do Snell's law, the critical angle and total internal reflection work?

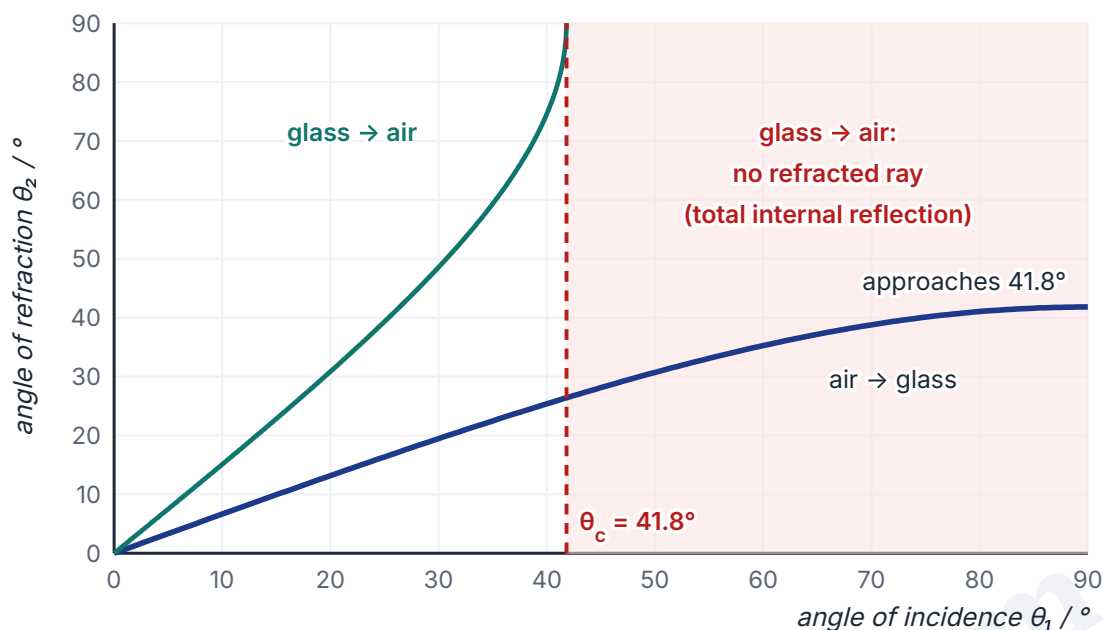
Refractive index and Snell's law

The (absolute) refractive index of a medium is the ratio of the speed of light in a vacuum to the speed of light in the medium, $n = \frac{c}{v}$. It has no unit, and $n \geq 1$.

Snell's law links the angles on either side of a boundary to the refractive indices and the wave speeds:

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1} \quad \Longleftrightarrow \quad n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- n_1, n_2 = refractive indices of the first and second media (no unit); θ_1 = angle of incidence, θ_2 = angle of refraction, both measured from the **normal**; v_1, v_2 = wave speeds in the two media (m s^{-1}).
- This equation is in the data booklet. $n = c/v$ is not printed separately: it follows from the equation if medium 1 is a vacuum ($n = 1, v = c$). Air has $n = 1.00$ to 3 s.f., so treat it like a vacuum.
- The v_2/v_1 part also applies to sound and water waves, where a "refractive index" is not normally used: $\frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$.
- Because the frequency is constant, $\frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1} = \frac{n_1}{n_2}$: light in glass of $n = 1.50$ has two-thirds of its wavelength in air.



Snell's law for air and glass ($n = 1.50$). From air into glass the angle of refraction can never exceed 41.8° . From glass into air the refracted ray reaches 90° when the angle of incidence is 41.8° — the critical angle; beyond it there is no refracted ray.

WORKED EXAMPLE 1 Easy · Calculate

Red laser light of wavelength 640 nm in air strikes the flat surface of a tank of water at an angle of incidence of 50° . The refractive index of water is 1.33.

Calculate (a) the angle of refraction, (b) the speed of the light in the water and (c) the wavelength of the light in the water.

$$\text{(a) } n_1 \sin \theta_1 = n_2 \sin \theta_2 \Rightarrow 1.00 \times \sin 50^\circ = 1.33 \sin \theta_2 \Rightarrow \sin \theta_2 = \frac{0.766}{1.33} = 0.576 \Rightarrow \theta_2 = \mathbf{35^\circ} \text{ (35.2^\circ)}$$

$$\text{(b) } v = \frac{c}{n} = \frac{3.00 \times 10^8}{1.33} = \mathbf{2.26 \times 10^8 \text{ m s}^{-1}}$$

$$\text{(c) The frequency is unchanged, so } \lambda_2 = \frac{\lambda_1}{n} = \frac{640}{1.33} = \mathbf{481 \text{ nm}}$$

Check: $f = \frac{c}{\lambda_1} = \frac{3.00 \times 10^8}{640 \times 10^{-9}} = 4.69 \times 10^{14} \text{ Hz}$ and $\frac{v}{f} = \frac{2.256 \times 10^8}{4.688 \times 10^{14}} = 4.81 \times 10^{-7} \text{ m}$. The light does not change colour in the water — colour is linked to frequency.

TRY IT YOURSELF

Refraction & Snell's law simulation: change the refractive indices and the angle of incidence, and find the angle at which the refracted ray disappears.

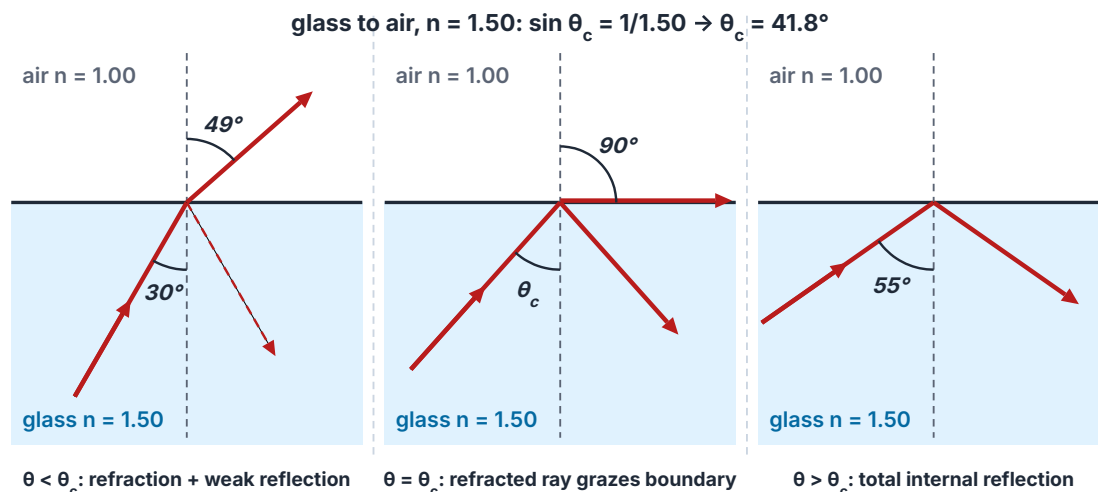
Critical angle and total internal reflection

When light travels from a medium of higher refractive index into one of lower refractive index (glass $\rightarrow$ air, water $\rightarrow$ air), it speeds up and bends away from the normal, so $\theta_2 > \theta_1$. As θ_1 increases, θ_2 reaches 90° first.

The critical angle θ_c is the angle of incidence, in the medium of higher refractive index, for which the angle of refraction is 90° . For any angle of incidence greater than θ_c , all the light is reflected back into the first medium: total internal reflection.

$$n_1 \sin \theta_c = n_2 \sin 90^\circ \quad \Rightarrow \quad \sin \theta_c = \frac{n_2}{n_1} \quad \left(\sin \theta_c = \frac{1}{n} \text{ into air} \right)$$

- n_1 = refractive index of the medium the light is **in** (the larger one), n_2 = refractive index of the medium on the other side. Not in the data booklet as written — derive it from Snell's law with $\theta_2 = 90^\circ$.
- **Two conditions** for total internal reflection: the light travels towards a medium of lower refractive index, *and* the angle of incidence exceeds the critical angle. It can never happen when light goes from air into glass.
- At exactly θ_c the refracted ray grazes along the boundary. Below θ_c , there is refraction plus a weak partial reflection; above it, the reflected ray carries (almost) all the energy.
- Uses: optical fibres (light zig-zags along the core by repeated total internal reflection), reflecting prisms in binoculars and periscopes, the sparkle of cut diamonds ($n = 2.42$, small critical angle).



Light in glass ($n = 1.50$) meeting the glass–air boundary at 30° , at the critical angle 41.8° , and at 55° . Only in the third case is all the light reflected; the reflected ray obeys $i = r$ in every case.

WORKED EXAMPLE 2 Medium · Determine / Explain

A straight perspex rod (refractive index 1.49) is used as a light guide in an aquarium, so it is surrounded by water of refractive index 1.33.

(a) Determine the critical angle at the perspex–water boundary. (b) Light inside the rod strikes its side at an angle of incidence of 70° . Deduce whether any light leaves the rod at that point. (c) Another ray strikes the side at 58° . Calculate the angle at which it enters the water. (d) The same rod in air traps every ray that strikes the side at more than 42° . Explain why it leaks more light in water.

$$\text{(a)} \quad \sin \theta_c = \frac{n_2}{n_1} = \frac{1.33}{1.49} = 0.893 \Rightarrow \theta_c = \mathbf{63^\circ} \text{ (63.2^\circ)}$$

(b) $70^\circ > 63.2^\circ$, and the light is travelling towards a lower refractive index, so it is **totally internally reflected — no light leaves**. (Check: Snell's law would need $\sin \theta_2 = \frac{1.49 \sin 70^\circ}{1.33} = 1.05$, which is impossible.)

(c) $\sin \theta_2 = \frac{1.49 \sin 58^\circ}{1.33} = 0.950 \Rightarrow \theta_2 = \mathbf{72^\circ} \text{ (71.8^\circ)}$ to the normal, bent away from the normal.

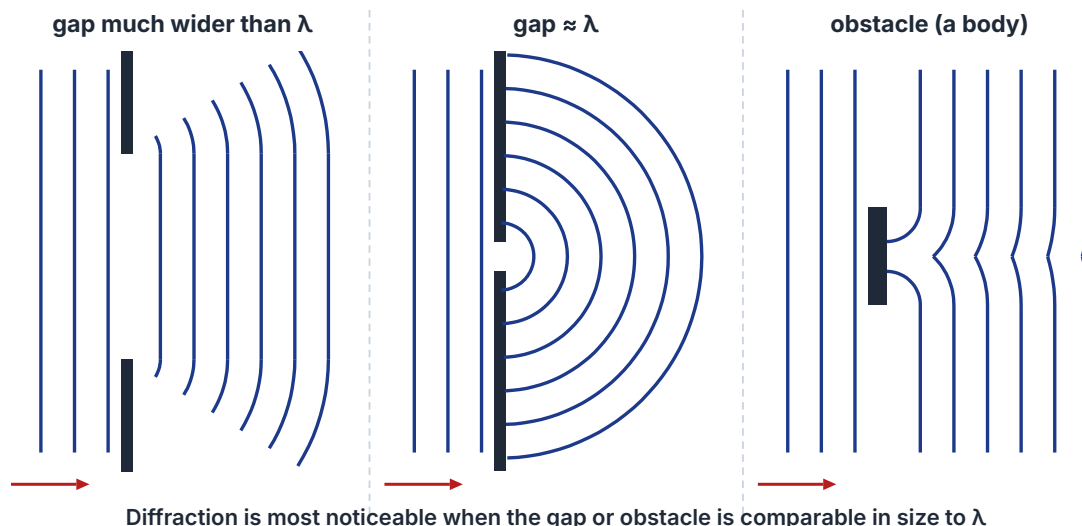
(d) In air $\sin \theta_c = \frac{1}{1.49}$, giving $\theta_c = 42.2^\circ$. Water has a refractive index closer to that of perspex, so the critical angle is larger (63.2°). Rays striking

the side at angles between 42.2° and 63.2° are trapped when the rod is in air but escape into the water.

What is diffraction?

Diffraction is the spreading of a wave as it passes through an aperture (gap) or around the edge of an obstacle.

- Diffraction is **significant when the aperture or obstacle is comparable in size to the wavelength** (or smaller). A gap much wider than λ lets the wave through almost unchanged, with slight curving only at the edges.
- The wavelength, frequency and speed are **unchanged** by diffraction (the wave stays in the same medium) — only the shape of the wavefronts and the direction of travel change.
- A gap of about one wavelength turns plane wavefronts into almost circular ones: the gap behaves like a new point source.
- Waves also bend around a body into the region behind it. With a body much larger than λ , a sharp shadow forms; with a small body, the waves close in behind it.
- *Everyday contrast:* sound of frequency 340 Hz (speed 340 m s^{-1}) has $\lambda = \frac{340}{340} = 1.0 \text{ m}$, similar to a doorway, so you hear someone around a corner. Visible light ($\lambda \approx 5 \times 10^{-7} \text{ m}$) is about two million times smaller than the doorway, so you cannot see them.
- Long-wavelength radio waves diffract around hills and buildings; short-wavelength (higher-frequency) signals need a clear line of sight.



Wavefront diagrams for diffraction. The spacing of the wavefronts (λ) is the same before and after the barrier. Through a gap similar to λ the emerging wavefronts are nearly semicircular; behind an obstacle the wavefronts curve into the shadow region.

EXAM TIP — KEEP λ CONSTANT

On diffraction diagrams the commonest error is drawing the wavefronts closer together (or further apart) after the gap. Diffraction does not change the medium, so it does not change v , f or λ . If you are asked to sketch the wavefronts beyond a narrow gap, draw arcs centred on the gap with the same spacing as the incident wavefronts.

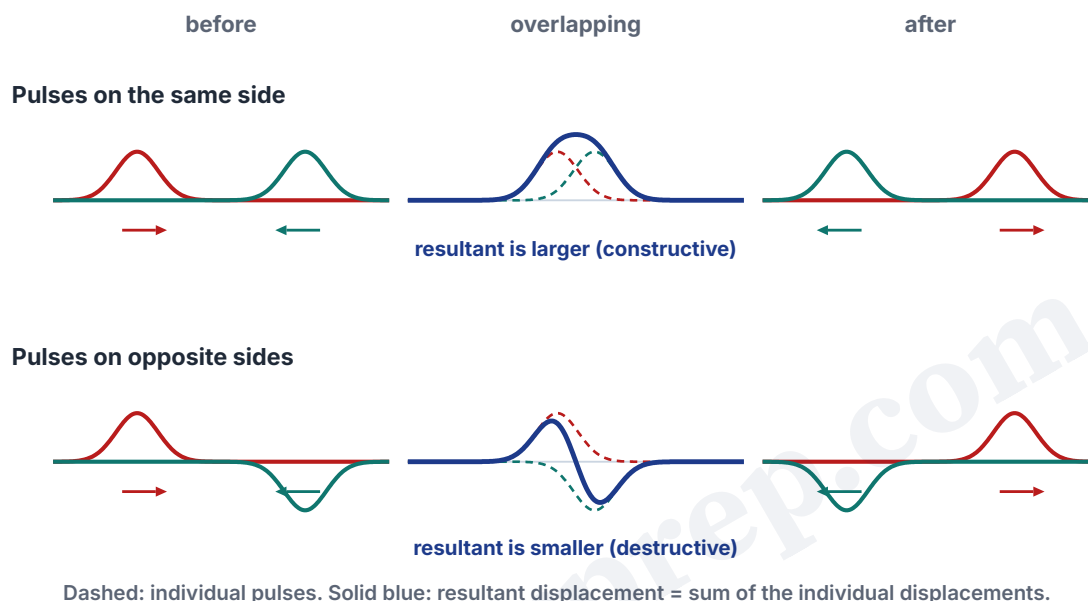
What happens when two waves meet?

Principle of superposition: when two or more waves (or pulses) meet at a point, the resultant displacement at that point is the sum of the displacements that each wave would produce on its own.

- Displacements have signs (up positive, down negative, say), so they can add or partly cancel.
- Pulses or waves **pass through each other**: once they separate, each continues exactly as before, with its original shape, speed and direction.
- Two waves of the same frequency, with amplitudes A_1 and A_2 , meeting **in phase** give a resultant amplitude $A_1 + A_2$ (constructive interference). Meeting

in **antiphase** (phase difference π rad), they give $|A_1 - A_2|$ (destructive interference) — zero if the amplitudes are equal.

- Destructive interference does not destroy energy: it is redistributed to the places where the interference is constructive.



Two pulses on a string, before, while and after they overlap. While they overlap the string's displacement (blue) is the sum of the two individual displacements (dashed). Afterwards, both pulses continue unchanged.

TRY IT YOURSELF

C.3 Wave Superposition simulation: send pulses and waves towards each other and watch the resultant displacement build up point by point.

What conditions produce interference from two sources?

When waves from two sources overlap in a region, superposition gives places of permanently large amplitude (maxima) and permanently small amplitude (minima): an **interference pattern**. For the pattern to stay in one place long enough to be observed, the sources must be coherent.

Two sources are coherent if they have a constant phase difference. (This requires them to have the same frequency.)

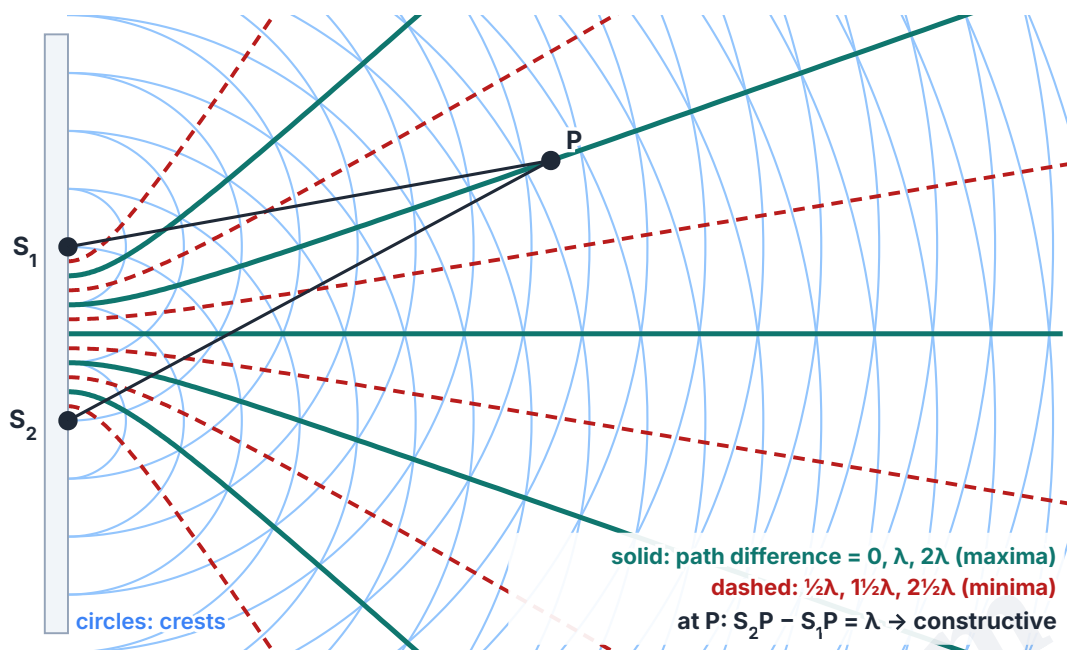
- Coherent sources do not need to be *in phase* — only the phase difference must not change with time.
- Two separate lamps are not coherent: each emits light in short random bursts, so the phase difference changes millions of times a second and any pattern averages out to uniform illumination.
- Practical coherent sources come from **one** original source: two loudspeakers driven by the same signal generator, two dippers on one vibrating bar in a ripple tank, or two slits illuminated by the same laser.

Path difference

For two sources that oscillate **in phase**, the phase difference at a point P depends only on the extra distance travelled by one wave, the path difference $S_2P - S_1P$:

constructive: path difference = $n\lambda$ destructive: path difference =

- $n = 0, 1, 2, \dots$ (an integer); λ = wavelength (m). Both conditions are in the data booklet.
- A path difference of a whole number of wavelengths means the waves arrive in phase (crest meets crest); an odd number of half-wavelengths means they arrive in antiphase (crest meets trough).
- The line of points equidistant from the sources (path difference 0) is always a maximum for in-phase sources.
- If the sources were in antiphase, the two conditions would swap. Questions will normally tell you the sources are in phase.



Crests (circles) from two coherent sources S_1 and S_2 , 3λ apart. Along the solid lines the path difference is a whole number of wavelengths and crests always meet crests (maxima); along the dashed lines it is an odd number of half-wavelengths (minima). P lies on the $n = 1$ maximum line.

WORKED EXAMPLE 3 Medium · Calculate / Explain

Two loudspeakers are connected to the same signal generator and emit sound in phase at 680 Hz. The speed of sound is 340 m s^{-1} . A microphone M is 4.20 m from one loudspeaker and 5.45 m from the other.

- (a) Determine whether M is at a point of maximum or minimum loudness. (b) Determine the lowest frequency at which M would detect a maximum. (c) The sound at M is quiet but not silent. Suggest one reason.

(a) $\lambda = \frac{v}{f} = \frac{340}{680} = 0.500 \text{ m}$. Path difference = $5.45 - 4.20 = 1.25 \text{ m}$,
and $\frac{1.25}{0.500} = 2.5$, so the path difference is $(2 + \frac{1}{2})\lambda$: **destructive interference — a minimum.**

(b) A maximum needs path difference = $n\lambda$. The lowest frequency means the longest wavelength, $n = 1$: $\lambda = 1.25 \text{ m}$, so $f = \frac{340}{1.25} = \mathbf{272 \text{ Hz}}$

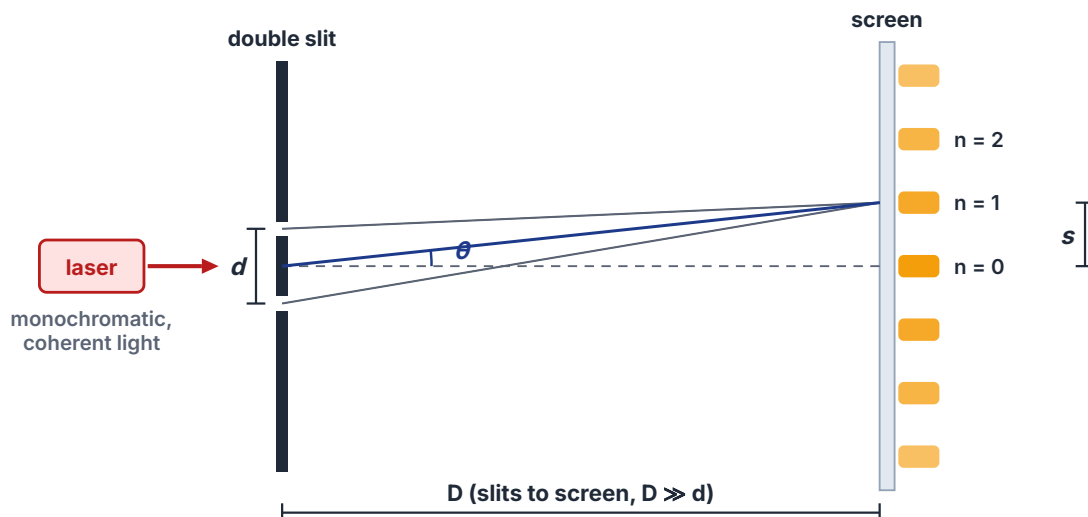
(c) The waves from the two loudspeakers do not have equal amplitudes at M, because M is further from one loudspeaker than the other, so they cannot cancel completely. (Sound reflected from the walls also reaches M.)

How does Young's double-slit experiment work?

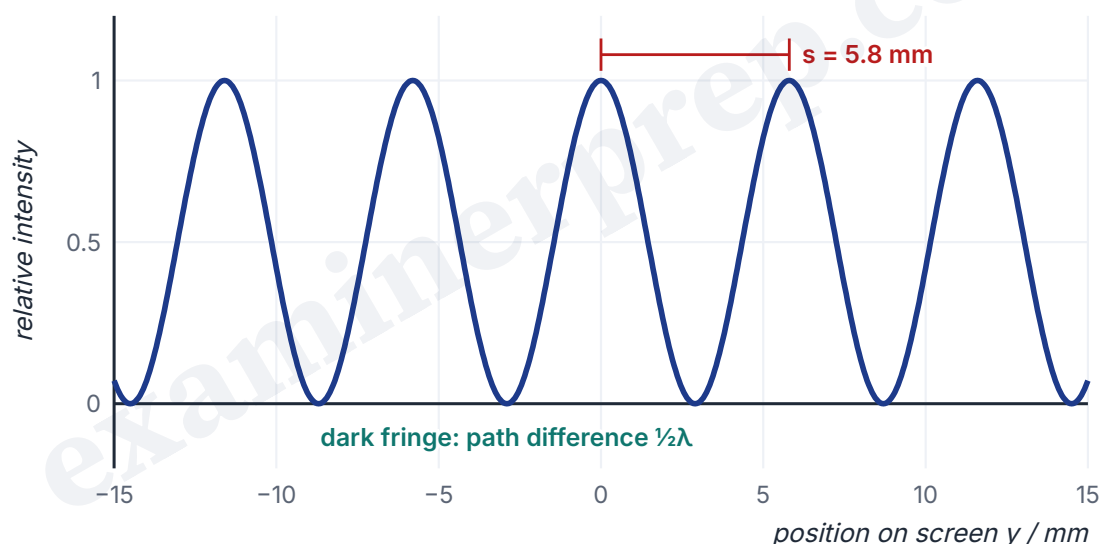
Monochromatic, coherent light (usually a laser) falls on two narrow parallel slits a distance d apart. Light diffracts through each slit, so the two beams overlap and interfere. On a screen a distance D away, a pattern of equally spaced bright and dark **fringes** appears.

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

- s = fringe separation: the distance between the centres of neighbouring bright (or dark) fringes (m); λ = wavelength (m); D = distance from the slits to the screen (m); d = separation of the slits, centre to centre (m). In the data booklet.
- The equation assumes $D \gg d$, so the angles are small. In practice d is a fraction of a millimetre and D is a metre or more.
- **Where it comes from:** the path difference from the slits to a point at angle θ is $d \sin \theta \approx d\theta$. A bright fringe needs $d\theta = n\lambda$, and its distance from the centre is $y = D\theta = \frac{n\lambda D}{d}$. Neighbouring fringes differ by one in n , so $s = \frac{\lambda D}{d}$.
- The fringes get further apart if λ or D increases, and closer together if the slits are moved further apart.
- **White light:** each wavelength makes its own fringes. The central fringe is white (zero path difference for every colour); the other fringes are coloured, with blue nearer the centre than red because $s \propto \lambda$. Only a few fringes are visible before the colours overlap.
- Measure s by measuring across many fringes and dividing — this reduces the percentage uncertainty.



Young's double-slit arrangement (not to scale: in a real experiment D is several thousand times d).
The $n = 1$ bright fringe is where the path difference from the two slits is one wavelength.



Idealised double-slit pattern for very narrow slits, using the data in worked example 4 ($s = 5.8$ mm).
The bright fringes are equally spaced and, at SL, treated as equally bright. HL students see below why real fringes fade away from the centre.

WORKED EXAMPLE 4 Medium · Show that / Determine

A student shines a laser on a double slit of separation 0.25 mm. On a screen 2.40 m from the slits the distance across 10 fringe spacings (from the centre of one bright fringe to the centre of the eleventh) is 58 mm.

- Show that the wavelength of the laser light is about 600 nm.
- The screen is moved to 1.60 m from the slits. Determine the new fringe separation.
- Explain why the student measured across 10 fringe spacings.
- One slit is covered. Describe what happens to the pattern.

$$(a) s = \frac{58}{10} = 5.8 \text{ mm. } \lambda = \frac{sd}{D} = \frac{5.8 \times 10^{-3} \times 0.25 \times 10^{-3}}{2.40} = 6.04 \times 10^{-7} \text{ m} = \mathbf{604 \text{ nm} \approx 600 \text{ nm}}$$

$$(b) s = \frac{\lambda D}{d} = \frac{6.04 \times 10^{-7} \times 1.60}{0.25 \times 10^{-3}} = \mathbf{3.9 \text{ mm} (3.87 \text{ mm})}. \text{ Equivalently, } s \propto D: 5.8 \times \frac{1.60}{2.40} = 3.87 \text{ mm}.$$

(c) A single fringe spacing is only a few millimetres, so the absolute uncertainty of the ruler (about 1 mm) would be a large fraction of it. Measuring across 10 spacings gives a reading with the same absolute uncertainty; dividing by 10 to find s divides that uncertainty by 10 as well, so the percentage uncertainty in s is ten times smaller.

(d) With only one slit there is no second coherent source, so the interference fringes disappear. A broad patch of light remains on the screen, produced by diffraction at the single uncovered slit (and it is less bright).

TRY IT YOURSELF

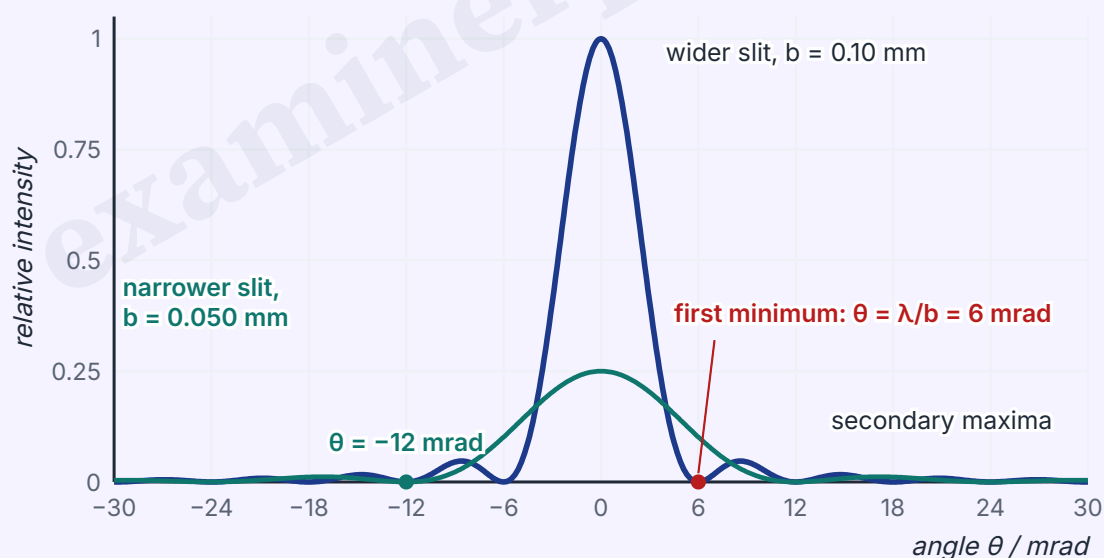
C.3 Double-Slit Interference simulation: change λ , d and D and check that the fringe separation follows $s = \lambda D/d$.

HL What does a single-slit diffraction pattern look like?

When monochromatic light passes through one narrow rectangular slit of width b , the screen shows a **bright, wide central maximum** with much fainter, narrower maxima on either side, separated by dark minima. The pattern arises because waves from different parts of the same slit interfere with each other.

$$\theta = \frac{\lambda}{b}$$

- θ = angle (in **radians**) between the centre of the pattern and the **first minimum**; λ = wavelength (m); b = slit width (m). In the data booklet (HL). It is a small-angle result.
- **Why there is a minimum there:** divide the slit into a top half and a bottom half. At the angle where $b \sin \theta = \lambda$, each point in the top half has a partner a distance $b/2$ below it whose wave travels $\lambda/2$ further. Every pair arrives in antiphase and cancels, so the screen is dark.
- The central maximum spans $-\lambda/b$ to $+\lambda/b$: its angular width is $\frac{2\lambda}{b}$, and its width on a screen at distance D is about $\frac{2\lambda D}{b}$.
- The secondary maxima are about **half as wide** as the central maximum and much less intense (the first is under 5 % of the central intensity).
- **Narrower slit** (smaller b): the pattern spreads out (wider central maximum) and becomes **less intense**, because less light passes through.
Longer wavelength: the pattern also spreads out.



Single-slit patterns for light of wavelength 600 nm, drawn with the same incident light. Halving the slit width from 0.10 mm to 0.050 mm doubles the angle of the first minimum (6 mrad $\rightarrow$ 12 mrad) and greatly reduces the intensity of the central maximum.

HL How does the single-slit pattern modulate the double-slit pattern?

Real slits are not infinitely narrow. Each slit of a double slit produces its own single-slit diffraction pattern, and the light from the two slits then interferes. The result is the double-slit fringe pattern “inside” the single-slit envelope.

- The **positions** of the bright fringes are set by the slit **separation** d ($d \sin \theta = n\lambda$, spacing $s = \lambda D/d$).
- The **intensities** of the fringes are set by the slit **width** b : they follow the single-slit pattern, so fringes fade away from the centre and almost vanish near $\theta = \lambda/b$.
- If an interference maximum falls exactly on a diffraction minimum, that fringe is **missing**. This happens for order $n = d/b$ when d/b is a whole number.
- The number of bright fringes inside the central diffraction maximum depends on d/b : if $d/b = 3$, the orders 0, ± 1 and ± 2 lie inside and ± 3 is missing — five fringes.
- Making the slits **wider** (same d) does not move the fringes, but the envelope narrows, so fewer fringes appear in the central maximum, and those fringes are brighter because more light gets through.

WORKED EXAMPLE 5 Hard · Determine / Predict

Light of wavelength 550 nm falls normally on two slits, each of width 0.050 mm, whose centres are 0.20 mm apart. The pattern is observed on a screen 1.50 m away.

(a) Calculate the angle between the centre of the pattern and the first minimum of the single-slit envelope. (b) Determine the width of the central diffraction maximum on the screen. (c) Calculate the separation of the interference fringes. (d) Determine the number of bright fringes inside the central diffraction maximum. (e) The slit width is doubled to 0.10 mm, with the same slit separation. Predict how the pattern changes.

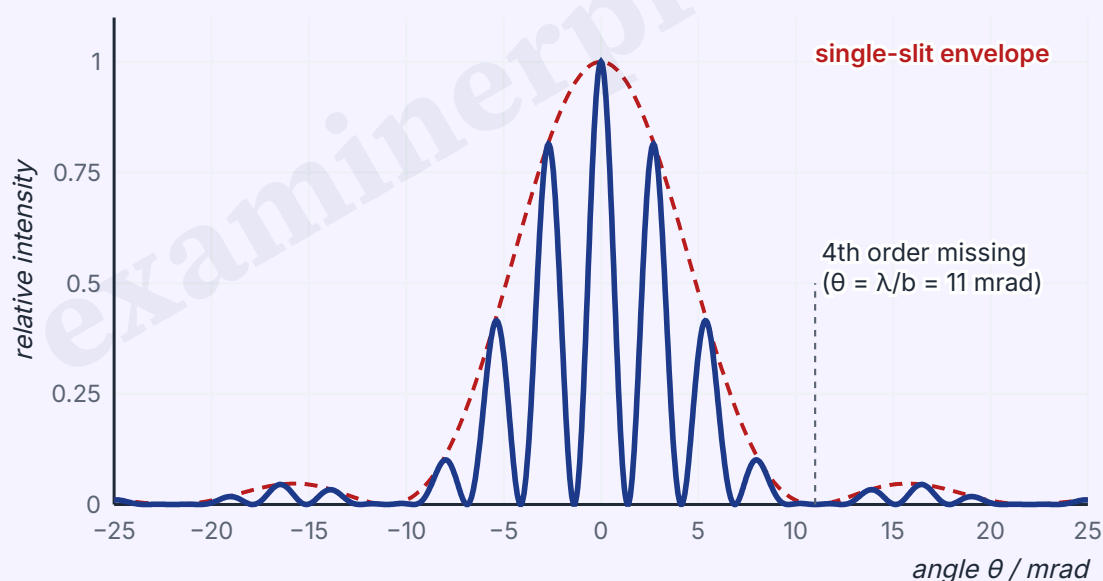
$$\text{(a)} \quad \theta = \frac{\lambda}{b} = \frac{550 \times 10^{-9}}{0.050 \times 10^{-3}} = \mathbf{0.011 \text{ rad}} \text{ (11 mrad)}$$

$$\text{(b)} \quad \text{Width} \approx 2\theta D = 2 \times 0.011 \times 1.50 = \mathbf{0.033 \text{ m} = 33 \text{ mm}}$$

$$(c) s = \frac{\lambda D}{d} = \frac{550 \times 10^{-9} \times 1.50}{0.20 \times 10^{-3}} = \mathbf{4.1 \text{ mm}} \text{ (4.125 mm)}$$

(d) The n th-order fringe is at $\theta = \frac{n\lambda}{d} = n \times 2.75 \text{ mrad}$. The 4th order is at 11 mrad, exactly on the diffraction minimum, so it is missing. Inside the central maximum: $n = 0, \pm 1, \pm 2, \pm 3 \rightarrow \mathbf{7 \text{ bright fringes}}$. (Check: $33 \text{ mm} \div 4.125 \text{ mm} = 8$ spacings, with the fringes at each edge missing.)

(e) The fringe separation is unchanged (4.1 mm), because it depends on d , not b . The first diffraction minimum moves in to $\frac{550 \times 10^{-9}}{0.10 \times 10^{-3}} = 5.5 \text{ mrad}$, which now coincides with the 2nd-order fringe. Only $\mathbf{3 \text{ bright fringes}}$ ($0, \pm 1$) lie inside the narrower central maximum, and they are brighter because more light passes through the wider slits.



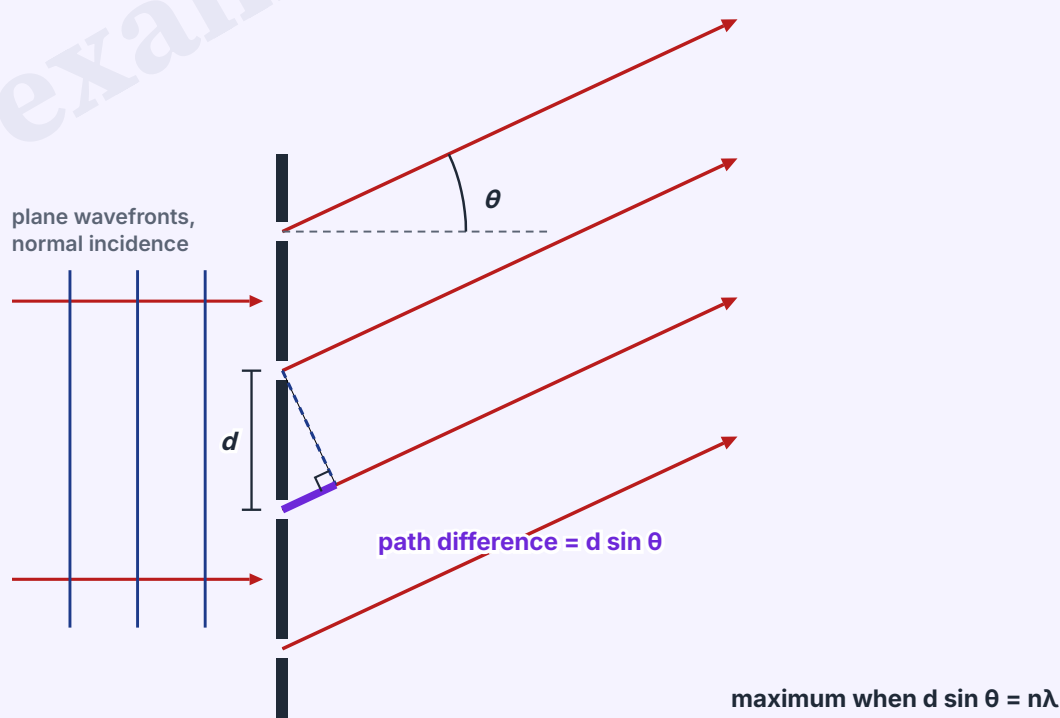
Double-slit pattern for $\lambda = 550 \text{ nm}$, $d = 0.20 \text{ mm}$ and $b = 0.050 \text{ mm}$ (worked example 5). The dashed curve is the single-slit envelope. Because $d = 4b$, the 4th-order fringe coincides with the first diffraction minimum at 11 mrad and is missing.

HL What patterns do multiple slits and diffraction gratings produce?

If the number of equally spaced slits is increased from two to many, the principal maxima stay in the **same places** but become much **sharper** and **brighter**. A diffraction grating takes this to the extreme: hundreds of slits per millimetre.

$$n\lambda = d \sin \theta$$

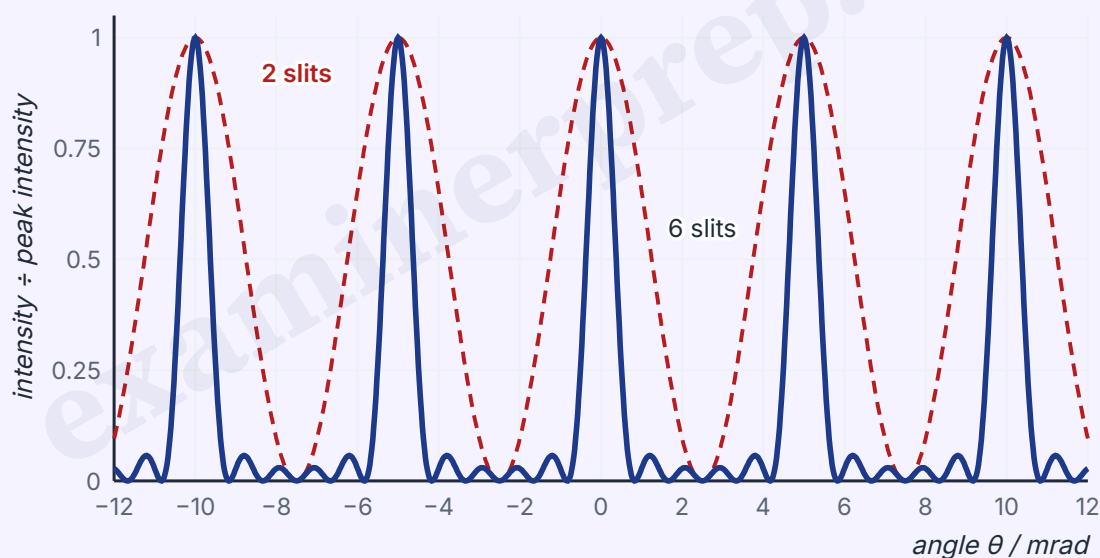
- n = order of the maximum (0, 1, 2, ...); λ = wavelength (m); d = separation of adjacent slits (m); θ = angle of the n th-order maximum from the straight-through direction. In the data booklet (HL).
- $d \sin \theta$ is the path difference between rays from **adjacent** slits. When it equals $n\lambda$, the waves from *all* the slits arrive in phase.
- A grating with N lines per millimetre has $d = \frac{1}{N}$ mm. For example, 600 lines mm^{-1} gives $d = 1.67 \times 10^{-6}$ m.
- The angles are large, so do **not** use the small-angle approximation or $s = \lambda D/d$ for a grating.
- **Highest order:** since $\sin \theta \leq 1$, $n \leq \frac{d}{\lambda}$. Round *down* to a whole number.



Light leaving neighbouring slits of a grating at angle θ . The dashed line is perpendicular to the rays, so the extra distance travelled from the lower slit is $d \sin \theta$. A maximum occurs when this path difference is a whole number of wavelengths.

Why more slits give sharper maxima

- With two slits, moving slightly away from a maximum only makes the two waves slightly out of phase, so the intensity falls off gradually: broad fringes.
- With many slits, a small move away from the maximum gives a small phase difference between neighbouring slits but a large one across the whole grating. Waves from slits far apart cancel, so the intensity drops to zero very close to the principal maximum.
- Between principal maxima there are weak secondary maxima ($N - 2$ of them for N slits); for a grating they are negligible, giving dark gaps between very sharp, bright lines. This is why gratings are used to measure wavelengths precisely.



Intensity patterns for 2 slits and 6 slits with the same separation (0.12 mm, $\lambda = 600$ nm), each scaled to its own peak. The principal maxima are at the same angles, but with 6 slits they are much narrower, with four weak secondary maxima between them. (The 6-slit peaks are also much brighter in reality.)

White light and several wavelengths

- The zero-order maximum ($\theta = 0$) has zero path difference for every wavelength, so with white light it is **white**.
- In every other order the colours separate into a **spectrum**, because $\sin \theta = n\lambda/d$: violet (shortest λ) is nearest the centre and red furthest out.

- Higher orders are spread over larger angles, and the second and third orders **overlap** for typical gratings. Some orders may be incomplete if red would need $\sin \theta > 1$.
- A light source that emits a few separate wavelengths (e.g. a gas-discharge lamp) gives a set of sharp coloured lines in each order instead of a continuous spectrum. Two close wavelengths are more widely separated in higher orders.

WORKED EXAMPLE 6 Hard · Show that / Determine

White light containing all wavelengths from 400 nm to 700 nm is incident normally on a diffraction grating with 600 lines per millimetre.

(a) Calculate the slit separation d . (b) Determine the angular width of the first-order spectrum. (c) Show that the second- and third-order spectra overlap. (d) Determine the highest order in which the complete visible spectrum is seen. (e) Calculate the wavelength in the third order that is seen at the same angle as 700 nm in the second order.

$$\text{(a) } d = \frac{1}{600} \text{ mm} = \frac{1 \times 10^{-3}}{600} = \mathbf{1.67 \times 10^{-6} \text{ m}}$$

$$\text{(b) } n = 1: \sin \theta = \frac{400 \times 10^{-9}}{1.667 \times 10^{-6}} = 0.240 \Rightarrow \theta = 13.9^\circ; \sin \theta = \frac{700 \times 10^{-9}}{1.667 \times 10^{-6}} = 0.420 \Rightarrow \theta = 24.8^\circ.$$

$$\text{Angular width} = 24.8^\circ - 13.9^\circ = \mathbf{10.9^\circ}$$

$$\text{(c) Red end of 2nd order: } \sin \theta = \frac{2 \times 700 \times 10^{-9}}{1.667 \times 10^{-6}} = 0.840 \Rightarrow \theta = 57.1^\circ.$$

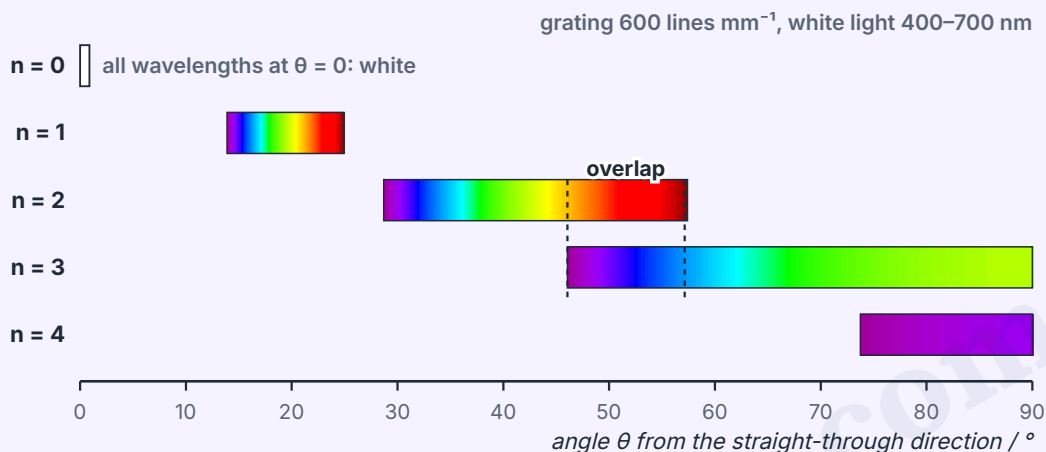
$$\text{Violet end of 3rd order: } \sin \theta = \frac{3 \times 400 \times 10^{-9}}{1.667 \times 10^{-6}} = 0.720 \Rightarrow \theta = 46.1^\circ.$$

The third order starts (46.1°) before the second order ends (57.1°), so **they overlap**.

$$\text{(d) For 700 nm, } n \leq \frac{d}{\lambda} = \frac{1.667 \times 10^{-6}}{700 \times 10^{-9}} = 2.38, \text{ so red light appears only up to the 2nd order. The highest complete spectrum is the } \mathbf{2nd}$$

order. (In the 3rd order $\sin \theta = 1.26$ for 700 nm, which is impossible.)

(e) Same angle means the same $d \sin \theta$, so $3\lambda = 2 \times 700 \text{ nm} \Rightarrow \lambda = 467 \text{ nm}$ (blue).



Angular positions of the spectra for white light (400–700 nm) on a grating with 600 lines mm^{-1} (worked example 6), computed from $n\lambda = d \sin \theta$. The second and third orders overlap; the third order only reaches about 556 nm and the fourth about 417 nm before θ would exceed 90° .

TRY IT YOURSELF

C.3 Diffraction Grating simulation: change the number of lines per millimetre and the wavelength, and watch the orders move and sharpen.

Exam tips for C.3

EXAM TIP 1 — “STATE AND EXPLAIN” THE WAVELENGTH CHANGE

When light enters a slower medium, a complete answer has two parts: the wavelength **decreases**, *because* the frequency stays the same while the speed decreases ($\lambda = v/f$). Saying only that “the wave slows down” or that “the frequency changes” loses marks — the frequency is fixed by the source.

EXAM TIP 2 — ANGLES FROM THE NORMAL

Every angle in Snell's law and in the critical-angle condition is measured from the **normal**, not from the surface. Many diagrams in questions give the angle between the ray and the surface; subtract it from 90° first. In geometric problems (rectangular blocks, prisms) find the angle of incidence at the second surface from the geometry before testing for total internal reflection.

EXAM TIP 3 — PROVE TOTAL INTERNAL REFLECTION, DON'T JUST CLAIM IT

To decide whether light emerges, either compare the angle of incidence with a calculated critical angle, or show that Snell's law would require $\sin \theta_2 > 1$. Then state the conclusion. Both routes earn full credit; an unsupported "it is totally internally reflected" does not.

EXAM TIP 4 — DEFINE COHERENCE PRECISELY

Coherent means a **constant phase difference**. "Same frequency" alone, "same amplitude" or "in phase" are not accepted as definitions. When asked why two separate lamps cannot produce visible fringes, say the phase difference between them changes randomly and rapidly, so the pattern is not stable.

EXAM TIP 5 (HL) — SEPARATION SETS POSITIONS, WIDTH SETS INTENSITIES

For multiple-choice questions about changing a double slit: changing the slit **separation** moves the fringes ($s \propto 1/d$); changing the slit **width** leaves the fringe positions alone but changes the envelope — wider slits give a narrower envelope and a brighter central maximum. For a grating, always round d/λ *down* to get the highest order, and work in radians for $\theta = \lambda/b$.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Light changes frequency (colour) when it enters glass.	The frequency is set by the source; the boundary cannot change how many waves arrive per second.	Speed and wavelength change; frequency stays the same.
Rays always bend towards the normal at a boundary.	The direction of bending depends on whether the wave speeds up or slows down.	Slower medium (larger n): towards the normal. Faster medium: away from it.
Total internal reflection can happen when light goes from air into glass.	Going into glass, $\theta_2 < \theta_1$, so θ_2 can never reach 90° .	TIR needs travel towards a lower refractive index and $\theta > \theta_c$.
Diffraction changes the wavelength.	The wave stays in the same medium, so its speed and frequency are unchanged.	Only the wavefront shape and direction change; λ is constant.
At a point of destructive interference, energy is destroyed.	Energy is conserved in superposition.	Energy is redistributed from the minima to the maxima.
(HL) A narrower single slit gives a narrower central maximum.	$\theta = \lambda/b$: smaller b means a larger angle.	Narrower slit $\rightarrow$ wider, dimmer central maximum.

How this topic connects

Young's fringes and the case for light as a wave

Interference fringes can only be explained by superposing two waves whose phase difference depends on path difference: where light from both slits arrives, the screen can be *darker* than with one slit alone. A stream of particles from two slits would simply add, never cancel. Young's result (around 1801) was therefore strong evidence for the wave model of light, against Newton's particle ("corpuscular") model, and it allowed the first measurement of the wavelength of

light (around 10^{-7} m) from $\lambda = sd/D$. (HL students meet the twist in E.2: the photoelectric effect shows that light also behaves as particles, photons, so light shows wave–particle duality.)

Electron diffraction: experimental evidence that matter has a wavelength

Diffraction and interference are signatures of waves. When a beam of electrons is fired through a thin layer of crystalline material (such as graphite), the electrons produce a diffraction pattern of rings on a screen — they behave as waves with a wavelength comparable to the spacing of the atoms. Changing the electrons' speed changes the ring sizes, showing that their wavelength depends on their momentum. This is developed quantitatively at HL in E.2 (de Broglie wavelength). It is a NOS example of a model (wave behaviour) being extended to objects for which it was not originally intended, because of new experimental evidence.

Superposition in action: interference patterns and standing waves

This question from C.2 is answered by the principle of superposition: displacements add at every point. Travelling waves from coherent sources produce a steady interference pattern of maxima and minima (this page). Two identical waves travelling in opposite directions along the same line superpose to form a **standing wave**, with fixed nodes and antinodes — the subject of C.4. Noise-cancelling headphones use destructive interference deliberately by generating sound in antiphase with the unwanted noise.

Tools & inquiry — measuring refraction and wavelength (NOS: evidence for models)

- **Refractive index of a block:** trace rays through a glass or perspex block (ray box or pins) for several angles of incidence. Plot $\sin \theta_1$ (air) against $\sin \theta_2$ (block): a straight line through the origin with gradient n . A graph uses all the data and reveals anomalous points, which a single pair of angles cannot. Angles measured with a protractor carry an uncertainty of about $\pm 1^\circ$.

- **Wavelength from a double slit:** measure across many fringes, repeat for several values of D and plot s against D ; the gradient is λ/d . Measure d with a travelling microscope or use the manufacturer's value.
- **(HL) Wavelength from a grating:** measure the angle to the first and second orders on both sides of the centre and halve the angle between them — this removes the need to locate the straight-through position exactly and greatly reduces the error from the grating not being exactly perpendicular to the beam.
- **Safety:** never look along a laser beam; keep it below eye level and use a low-power class 2 laser.

Key equations

Equation	Use	In data booklet?
$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$	Snell's law, refraction	yes
$n = \frac{c}{v}$	absolute refractive index	no — Snell's law with medium 1 a vacuum
$\sin \theta_c = \frac{n_2}{n_1}$	critical angle ($n_1 > n_2$)	no — set $\theta_2 = 90^\circ$ in Snell's law
$v = f\lambda$	wavelength change on refraction (f constant)	yes (C.2)
path difference = $n\lambda$	constructive interference (in-phase sources)	yes
path difference = $(n + \frac{1}{2})\lambda$	destructive interference (in-phase sources)	yes
$s = \frac{\lambda D}{d}$	double-slit fringe separation ($D \gg d$)	yes
$\theta = \frac{\lambda}{b}$ HL	angle to first minimum of single-slit diffraction (rad)	yes (HL)
$n\lambda = d \sin \theta$ HL	maxima for multiple slits and gratings	yes (HL)
$d = \frac{1}{N}$ HL	slit separation from lines per unit length	no

Check your understanding

1. Water waves of wavelength 1.5 cm travel at 0.30 m s^{-1} in deep water. They cross into shallow water, where their speed is 0.20 m s^{-1} , with an angle of incidence of 40° . Determine the frequency, the wavelength in the shallow water and the angle of refraction.

$f = \frac{v}{\lambda} = \frac{0.30}{0.015} = 20 \text{ Hz}$, unchanged in the shallow water. $\lambda_2 = \frac{0.20}{20} = 0.010 \text{ m} = 1.0 \text{ cm}$. $\sin \theta_2 = \frac{v_2}{v_1} \sin \theta_1 = \frac{0.20}{0.30} \sin 40^\circ = 0.429 \Rightarrow \theta_2 = 25^\circ$ (25.4°), bent towards the normal.

2. Diamond has a refractive index of 2.42. Calculate the critical angle for a diamond–air boundary and explain why cut diamonds sparkle.

$\sin \theta_c = \frac{1}{2.42} \Rightarrow \theta_c = 24^\circ$ (24.4°). The critical angle is small, so most light inside the stone meets a surface at more than 24° and is totally internally reflected several times before leaving through the top faces, making the stone bright.

3. A double slit illuminated with red light of wavelength 640 nm gives fringes 4.0 mm apart. The light is changed to blue light of wavelength 480 nm and the slit separation is halved. Determine the new fringe separation.

$s = \frac{\lambda D}{d}$, so $s \propto \frac{\lambda}{d}$. New $s = 4.0 \times \frac{480}{640} \times 2 = 6.0 \text{ mm}$.

4. (HL) Laser light of wavelength 633 nm passes through a single slit of width 0.10 mm. Calculate the width of the central maximum on a screen 2.0 m away.

$\theta = \frac{\lambda}{b} = \frac{633 \times 10^{-9}}{0.10 \times 10^{-3}} = 6.3 \times 10^{-3} \text{ rad}$. Width $\approx 2\theta D = 2 \times 6.33 \times 10^{-3} \times 2.0 = 0.025 \text{ m} = 25 \text{ mm}$.

5. (HL) Yellow light of wavelength 589 nm is incident normally on a grating with 300 lines per millimetre. Determine the angle of the second-order maximum and the highest order that can be observed.

$d = \frac{1 \times 10^{-3}}{300} = 3.33 \times 10^{-6} \text{ m}$. $\sin \theta = \frac{2 \times 589 \times 10^{-9}}{3.333 \times 10^{-6}} = 0.353 \Rightarrow \theta = 20.7^\circ$. Highest order: $\frac{d}{\lambda} = \frac{3.333 \times 10^{-6}}{589 \times 10^{-9}} = 5.66$, so $n = 5$.

Practise C.3 with exam-style questions

Original Paper 1A, 1B and 2 questions on refraction, total internal reflection, diffraction, interference and (HL) gratings, with full mark schemes. Tick the questions you want and print them as your own test.

SL C.3 questions

HL C.3 questions

Revise and explore

- [Flashcards](#) — choose IB Physics and filter to C.3 Wave phenomena. Free, no sign-up.
- [C.3 Wave Superposition simulation](#)
- [C.3 Double-Slit Interference simulation](#)
- [C.3 Diffraction Grating simulation \(HL\)](#)
- [Refraction & Snell's law simulation](#)
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← Previous: C.2 Wave model · Next: C.4 Standing waves and resonance →

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