C.3 Wave phenomena

International Baccalaureate · IB Diploma · Physics · HL

Scope and prerequisites

Full guide C.3 scope (Wave phenomena) including the AHL block, first assessment 2025. Read directly from the acquired Physics guide, pages 47–48. Prerequisites: C.2 (v = fλ, transverse and longitudinal waves) and basic trigonometry.

These are original teaching examples, not actual measurements or completed assessed learner investigations.

Wavefronts, rays and behaviour at boundaries

In two and three dimensions a wave is drawn two ways: **wavefronts** – lines joining points in step (in phase), one wavelength apart – and **rays** – arrows perpendicular to the wavefronts showing the direction of travel. Sketches in this topic are limited to incident, reflected and transmitted waves.

At a **boundary** between media a wave does some or all of three things:

- **Reflection** – the wavefront returns from the boundary (angle of incidence = angle of reflection, both measured from the **normal**).
- **Transmission** – part of the wave passes into the second medium.
- **Refraction** – the transmitted wave changes direction because its speed changes: toward the normal entering a slower medium, away from it entering a faster one. Frequency is fixed by the source; wavelength changes with speed.

Snell's law, critical angle and total internal reflection

The refraction rule in ratio form:

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

where n is the **refractive index** of each medium and θ the angle between the ray and the normal. Equivalently $n_1 \sin\theta_1 = n_2 \sin\theta_2$; the larger refractive index means the slower speed in that medium.

Travelling from a slower to a faster medium (glass to air, $n_1 > n_2$), there is an angle beyond which no ray can escape: at the **critical angle** the refracted ray runs along the boundary,

$$\sin\theta_c = \frac{n_2}{n_1}$$

and beyond it all the light **reflects totally** back into the medium – **total internal**

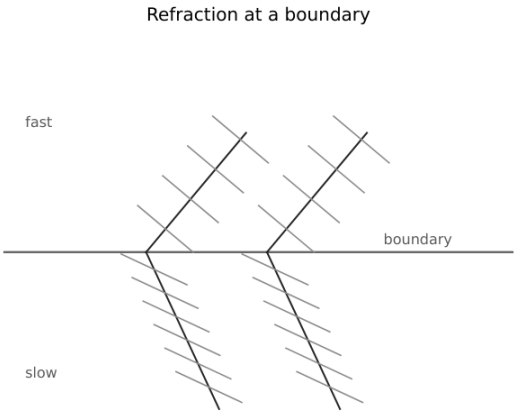
reflection (TIR), the principle of optical fibres.

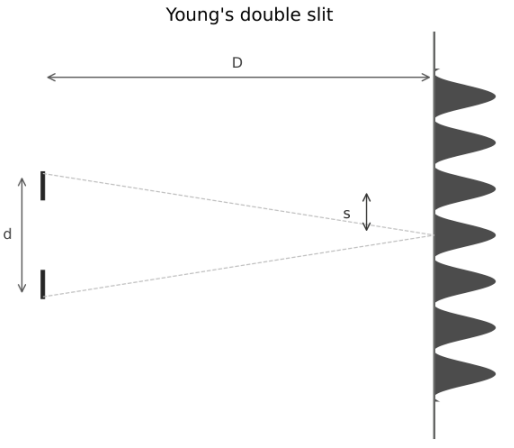
Worked check (refraction into glass). Air to glass, $n_{air} = 1.0$, $n_{glass} = 1.5$, incidence 40°: $\sin\theta_2 = (n_1/n_2)\sin\theta_1 = (1.0/1.5)(0.643) = 0.429$, so $\theta_2 = 25°$ – bent toward the normal, as expected entering a slower medium. The speeds follow the same ratio: $v_{glass} = c/1.5 = 2.0 \times 10^8$ m/s.

Worked check (critical angle). The same glass against air: $\sin\theta_c = 1.0/1.5 = 0.667$, so $\theta_c = 42°$. Any ray inside the glass hitting the wall at more than 42° to the normal is totally internally reflected.

Diffraction through an aperture

A wave meeting an obstacle or an opening does not travel in a perfectly straight line: it bends and spreads – **diffraction**. The spreading is strongest when the aperture is comparable to or smaller than the wavelength, which is why sound bends around doorways (metre wavelengths) while light (hundreds of nanometres) appears to travel straight. A wavefront-ray diagram shows plane wavefronts entering a slit and leaving as curved, spreading fronts.





Superposition and interference

When two waves **meet at a point**, displacements add – **superposition**. For a steady pattern the sources must be **coherent**: same frequency and a constant phase difference. Then the outcome depends on the **path difference** from the two sources:

$$\text{constructive: path difference} = n\lambda \qquad \text{destructive: path difference} = \left(n + \tfrac{1}{2}\right)\lambda$$

with n an integer. Constructive interference builds a maximum (two crests arrive together); destructive cancels to a minimum (a crest meets a trough).

Worked check. Two coherent sources in phase, wavelength 0.50 m. A point 3.00 m from one source and 3.75 m from the other has path difference 0.75 m $= 1.5\lambda = (1+\frac{1}{2})\lambda$ – destructive: a minimum. Moving the point until the path difference is 1.00 m $= 2\lambda$ restores a maximum.

Young's double-slit experiment

Light through one narrow slit then two narrow slits (coherent by construction) produces bright and dark **fringes** on a screen – interference, the evidence that light is a wave. The fringe separation is

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

where d is the slit separation and D the slit-to-screen distance.

Worked check (measuring a wavelength). Slits 0.20 mm apart, screen 2.4 m away, and 12 bright fringes counted across 55 mm (11 gaps, so $s = 55/11 = 5.0$ mm): $\lambda = sd/D = (5.0 \times 10^{-3})(0.20 \times 10^{-3})/2.4 = 4.2 \times 10^{-7}$ m – violet-blue light.

Single-slit diffraction, modulation and gratings (guide C.3, AHL)

Single-slit diffraction: light of wavelength λ through one rectangular slit of width b (monochromatic, normal incidence) spreads into a broad central maximum with weaker side fringes. The first minimum sits at

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

so a narrower slit spreads the light wider – diffraction grows as the aperture shrinks toward the wavelength. The effect of slit width on the intensity is qualitative: the central peak dominates, and its width is what the equation tracks.

A real double-slit is two single slits, so the fine double-slit fringes ride under the broader single-slit pattern: **the single-slit pattern modulates the double-slit interference pattern** – fringe heights follow the envelope of one slit's diffraction.

Many parallel slits – a **diffraction grating** of spacing d – sharpen each maximum into a bright narrow line at

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

with $n = 0, 1, 2, \ldots$ the order. Because each wavelength has its own angle, white light through a grating splits into a spectrum per order (violet nearest the straight-through direction), and the number of visible orders is capped by $\sin\theta \leq 1$.

Worked check (single slit). $b = 0.10$ mm, $\lambda = 500$ nm: $\sin\theta = 5.0 \times 10^{-7}/1.0 \times 10^{-4} = 5.0 \times 10^{-3}$, so $\theta = 0.29°$. Widening the slit to 0.40 mm divides the angle by four: $\theta = 0.072°$ – the pattern contracts as the aperture grows.

Worked check (grating orders). A grating with 600 lines per millimetre: $d = 1.0 \times 10^{-3}/600 = 1.7 \times 10^{-6}$ m. With $\lambda = 600$ nm: order 1 at $\sin\theta = 0.36$ ($\theta = 21°$), order 2 at $\sin\theta = 0.72$ ($\theta = 46°$), and order 3 would need $\sin\theta = 1.08$ – impossible, so only two orders appear. At 400 nm (violet) order 1 sits at $\sin\theta = 0.24$ (14°): one grating, one flash of white light, and the first-order spectrum spreads from 14° to 21°.

Check yourself

1. State what is meant by a wavefront and how a ray is related to it.
2. A ray crosses from air into water ($n = 1.3$) at 50° to the normal. Calculate the refraction angle.
3. State the condition for total internal reflection, and why a fish tank can mirror-image objects at glancing angles.
4. Compare the diffraction of sound and of light through a doorway, with a reason.
5. Two coherent sources 0.040 m apart emit 0.060 m waves in phase. A point lies 0.30 m from one source along a line perpendicular to the source line; state its path difference class (constructive or destructive) if it is 0.33 m from the other source.
6. In a double-slit set-up the slit separation is halved and the screen moved twice as far away. What happens to the fringe separation?
7. A double-slit experiment with green light gives fringes 4.0 mm apart. Estimate the new separation if blue light of half the wavelength is used with the same geometry.

Answers: 1 a line of points in phase, one wavelength apart; the ray is everywhere perpendicular to the wavefronts and shows travel direction; 2 $\sin\theta_2 = (1.0/1.3)\sin 50° = 0.588$, $\theta_2 = 36°$; 3 travel from a slower (higher-n) medium toward a faster one at more than the critical angle – then no transmission exists; beyond the critical angle the inside of the glass surface acts as a mirror; 4 sound (wavelengths of metres, comparable with the doorway) diffracts strongly around the opening, light (wavelengths hundreds of nanometres, far smaller) spreads negligibly and appears to travel straight; 5 path difference 0.03 m $= \frac{1}{2}(0.060$ m) – destructive; 6 $s = \lambda D/d$ doubles from D and doubles again from d – four times wider; 7 $s \propto \lambda$, so 2.0 mm.