

# Wave Behaviour

IB SL Study Guide

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## How to Use This Guide

- **Wave Properties** — transverse vs longitudinal, amplitude, wavelength, frequency, wave speed, phase difference, intensity
- **Sound Waves** — longitudinal pressure waves, Doppler effect, decibel scale
- **Light and the EM Spectrum** — Snell's law, total internal reflection, refraction
- **Superposition and Interference** — constructive/destructive interference, double-slit, single-slit diffraction, gratings
- **Standing Waves** — nodes, antinodes, harmonics in strings and pipes

**A** *igned to IB Physics 2025 syllabus — Theme C: Wave Behaviour (first assessment 2025)*

**Jump to section:** Wave Properties · Sound Waves · Light and EM Spectrum · Superposition and Interference · Standing Waves · Practice Questions

**Videos on this page:** Watch: Doppler Effect

## Section 1: Wave Properties

### Transverse and Longitudinal Waves

A **wave** is a periodic disturbance that transfers energy through a medium (or, for electromagnetic waves, through a vacuum) without transferring matter.

#### MEMORISE THIS

Type	Direction of oscillation	Examples
<b>Transverse</b>	Perpendicular to the direction of wave travel	Light, all EM waves, waves on a string, seismic S-waves
<b>Longitudinal</b>	Parallel to the direction of wave travel	Sound, seismic P-waves, ultrasound

A longitudinal wave consists of alternating **compressions** (regions of higher pressure/density) and **rarefactions** (regions of lower pressure/density).

### Key Wave Quantities

#### MEMORISE THIS

Symbol	Quantity	Definition	SI Unit
$A$	amplitude	maximum displacement from equilibrium	m
$\lambda$	wavelength	distance between two successive points in phase (e.g., crest to crest)	m
$T$	period	time for one complete oscillation	s
$f$	frequency	number of complete oscillations per unit time	Hz ( $\text{s}^{-1}$ )
$v$	wave speed	speed at which the wave pattern moves	$\text{m s}^{-1}$

### Fundamental relationships:

$$f = \frac{1}{T} \quad v = f\lambda$$

### ⚠ EXAM ALERT

$v = f\lambda$  is in the data booklet but you must know when to use it. Wave speed  $v$  is determined by the medium (not by the source). When a wave passes from one medium to another, the **frequency stays constant** but the wavelength and speed both change. This is why light bends at an interface (refraction).

## Phase Difference

Two points on a wave are **in phase** if they have identical displacement and velocity at all times (separated by a whole number of wavelengths). **Anti-phase** (phase difference =  $180^\circ = \pi$  rad) means one is at a crest while the other is at a trough.

### 📖 MEMORISE THIS

$$\phi = \frac{\Delta x}{\lambda} \times 360^\circ \quad \text{or} \quad \phi = \frac{2\pi\Delta x}{\lambda} \text{ rad}$$

where  $\Delta x$  is the path difference or spatial separation.

- Path difference =  $n\lambda$  ( $n$  integer)  $\rightarrow$  in phase ( $\phi = 0^\circ, 360^\circ, \dots$ )
- Path difference =  $(n + \frac{1}{2})\lambda \rightarrow$  anti-phase ( $\phi = 180^\circ, 540^\circ, \dots$ )

## Intensity and the Inverse Square Law

**Intensity** is the power per unit area of wavefront:

### 📖 MEMORISE THIS

$$I = \frac{P}{A} \quad \text{unit: } \text{W m}^{-2}$$

For a **point source** radiating equally in all directions (spreading over the surface of a sphere of area  $4\pi r^2$ ):

$$I \propto \frac{1}{r^2}$$

**Intensity–amplitude relationship:**

$$I \propto A^2$$

Doubling the amplitude quadruples the intensity. Halving the distance from a source quadruples the intensity.

### WORKED EXAMPLE

#### Worked Example C1 — Inverse square law:

A point source of sound has intensity  $I_1 = 4.0 \text{ W m}^{-2}$  at a distance  $r_1 = 2.0 \text{ m}$ . Find the intensity at  $r_2 = 6.0 \text{ m}$ .

$$\frac{I_2}{I_1} = \frac{r_1^2}{r_2^2} = \frac{4.0}{36} = \frac{1}{9}$$

$$I_2 = \frac{4.0}{9} \approx 0.44 \text{ W m}^{-2}$$

## Section 2: Sound Waves

### Properties of Sound

Sound is a **longitudinal** mechanical wave — it requires a medium and cannot travel through a vacuum.

#### MEMORISE THIS

- Speed of sound in air: approximately  $340 \text{ m s}^{-1}$  at room temperature (increases with temperature)
- Speed of sound in solids > liquids > gases (denser, stiffer media transmit sound faster)
- Sound consists of alternating compressions and rarefactions in the medium
- Frequency range for human hearing: approximately 20 Hz to 20,000 Hz

### Decibel Scale

The **decibel (dB)** scale is a logarithmic scale for sound intensity level. You need a qualitative understanding: the scale compresses a very wide range of intensities ( $10^{12}$ :1) into a manageable scale (0–120 dB). Every increase of 10 dB corresponds to a tenfold increase in intensity. The IB SL exam only tests qualitative knowledge here.

### The Doppler Effect

The **Doppler effect** is the change in observed frequency of a wave when the source and observer are in relative motion.

#### MEMORISE THIS

**Doppler formula (given in data booklet):**

$$f' = f_s \frac{v \pm v_o}{v \mp v_s}$$

### Symbol Meaning

$f'$	observed frequency
$f_s$	source frequency
$v$	wave speed in the medium
$v_o$	speed of observer
$v_s$	speed of source

### Sign rule:

- Top sign (+ for observer, – for source): source/observer **approaching** (observed frequency increases)
- Bottom sign (– for observer, + for source): source/observer **receding** (observed frequency decreases)

**Memory trick:** “Observer on top, source on bottom. Moving toward = frequency increases (use signs that increase the fraction).”

### WORKED EXAMPLE

#### Worked Example C2 – Ambulance Doppler shift:

An ambulance siren emits sound at  $f_s = 800$  Hz. The ambulance moves toward a stationary observer at  $v_s = 30$  m s<sup>-1</sup>. Speed of sound  $v = 340$  m s<sup>-1</sup>.

(a) Frequency heard as ambulance approaches:

$$f' = 800 \times \frac{340+0}{340-30} = 800 \times \frac{340}{310} = 800 \times 1.097 \approx 878 \text{ Hz}$$

(b) Frequency heard as ambulance recedes:

$$f' = 800 \times \frac{340}{340+30} = 800 \times \frac{340}{370} = 800 \times 0.919 \approx 735 \text{ Hz}$$

The observer hears the frequency drop from 878 Hz to 735 Hz as the ambulance passes.

**HL** The full derivation of the Doppler formula from first principles — considering wavefront compression and expansion geometrically — is an HL topic. At SL, you are expected to apply the formula and explain the effect qualitatively.

### EXAM ALERT

**Doppler direction errors are very common.** Source approaching observer: use  $v - v_s$  in the denominator (smaller denominator = larger fraction = higher frequency). Getting the signs backward is the most frequent error. Write out the full formula and substitute carefully rather than trying to memorise direction shortcuts.

▶ Watch: Doppler Effect — Khan Academy

VIDEO

## Section 3: Light and the Electromagnetic Spectrum

### The EM Spectrum

All electromagnetic waves travel at  $c = 3.00 \times 10^8 \text{ m s}^{-1}$  in a vacuum. They differ only in frequency (and therefore wavelength).

#### MEMORISE THIS

**EM spectrum order (increasing frequency / decreasing wavelength):**

Radio → Microwave → Infrared → Visible → UV → X-ray → Gamma

Mnemonic: **R**ather **M**ighty **I**gnorant **V**igilantes **U**se **X**-ray **G**uns

Visible light occupies approximately 400 nm (violet) to 700 nm (red). For visible: ROYGBIV from longest to shortest wavelength (red to violet).

### Refraction and Snell's Law

**Refraction** is the change in direction of a wave as it passes from one medium to another, caused by the change in wave speed.

#### MEMORISE THIS

**Snell's Law:**

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

**Refractive index:**

$$n = \frac{c}{v_{\text{medium}}} = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

- Angles are measured from the **normal** (perpendicular to the interface), not from the surface.
- Light bends toward the normal when entering a denser medium (higher  $n$ ), and away from the normal when entering a less dense medium.
- For vacuum (or approximately for air):  $n = 1.00$ .

### WORKED EXAMPLE

#### Worked Example C3 — Snell's Law:

A ray of light in air ( $n_1 = 1.00$ ) strikes a glass surface ( $n_2 = 1.50$ ) at an angle of incidence  $\theta_1 = 40^\circ$ .

(a) Find the angle of refraction  $\theta_2$ .

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \implies \sin \theta_2 = \frac{1.00 \times \sin 40^\circ}{1.50} = \frac{0.643}{1.50} = 0.429$$

$$\theta_2 = \arcsin(0.429) \approx 25.4^\circ$$

The ray bends toward the normal on entering the denser glass — confirmed by  $\theta_2 < \theta_1$ .

(b) Calculate the critical angle for this glass–air interface.

At the critical angle,  $\theta_2 = 90^\circ$ , so  $\sin \theta_c = n_2/n_1 = 1/n$  (for glass to air):

$$\sin \theta_c = \frac{n_{\text{air}}}{n_{\text{glass}}} = \frac{1.00}{1.50} = 0.667 \implies \theta_c \approx 41.8^\circ$$

## Total Internal Reflection

### MEMORISE THIS

#### Conditions for TIR:

1. Light is in the **denser** medium (higher  $n$ ) and trying to enter the less dense medium.
2. The angle of incidence **exceeds** the critical angle:  $\theta > \theta_c$ .

$$\sin \theta_c = \frac{n_2}{n_1} \quad (n_1 > n_2)$$

**Applications:** optical fibres (telecommunications, endoscopes), diamond brilliance (high  $n \rightarrow$  small  $\theta_c \rightarrow$  most light totally internally reflected), periscope prisms.

### IB TIP

**Optical fibres work via TIR.** A glass core ( $n \approx 1.5$ ) surrounded by cladding ( $n$  slightly lower) ensures that light entering at an angle greater than  $\theta_c$  is totally internally reflected along the fibre. Signal loss occurs from absorption and scattering, not from TIR itself. This is a common short-answer topic in IB exams.

## Section 4: Superposition and Interference

### Principle of Superposition

When two or more waves meet at a point, the resultant displacement is the **vector sum** of the individual displacements at that instant.

#### MEMORISE THIS

**Constructive interference:** waves arrive in phase (path difference =  $n\lambda$ ,  $n = 0, 1, 2, \dots$ )

Resultant amplitude =  $A_1 + A_2$  (maximum)

**Destructive interference:** waves arrive anti-phase (path difference =  $(n + \frac{1}{2})\lambda$ )

Resultant amplitude =  $|A_1 - A_2|$  (minimum; zero if  $A_1 = A_2$ )

For a stable (coherent) interference pattern, the sources must have the **same frequency** and a **constant phase relationship** (coherent sources).

### Young's Double-Slit Experiment

Two coherent slits separated by distance  $d$  produce alternating bright and dark fringes on a screen at distance  $D$ .

#### MEMORISE THIS

**Fringe spacing (distance between adjacent bright fringes):**

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

Symbol	Meaning	Relationship
$s$	fringe spacing	increases with $\lambda$ and $D$ ; decreases with $d$
$\lambda$	wavelength of light	
$D$	slit-to-screen distance	
$d$	slit separation	

The formula is in the **data booklet**.

#### WORKED EXAMPLE

##### Worked Example C4 — Double-slit fringe spacing:

Light of wavelength  $\lambda = 600 \text{ nm}$  passes through two slits separated by  $d = 0.30 \text{ mm}$ . The screen is  $D = 2.0 \text{ m}$  away.

$$s = \frac{\lambda D}{d} = \frac{600 \times 10^{-9} \times 2.0}{0.30 \times 10^{-3}} = \frac{1.2 \times 10^{-6}}{3.0 \times 10^{-4}} = 4.0 \times 10^{-3} \text{ m} = 4.0 \text{ mm}$$

## Single-Slit Diffraction

A single slit of width  $b$  produces a central bright maximum flanked by dark fringes.

### MEMORISE THIS

**Position of dark fringes in single-slit diffraction:**

$$\sin \theta = \frac{m\lambda}{b} \quad m = \pm 1, \pm 2, \pm 3, \dots$$

- The **central maximum** is the widest and brightest.
- The first dark fringe occurs at  $\sin \theta_1 = \lambda/b$ .
- Narrower slit ( $b$  smaller)  $\rightarrow$  wider diffraction pattern (more spreading).

## Diffraction Gratings

A diffraction grating has many parallel slits, producing sharper, brighter maxima than a double-slit.

### MEMORISE THIS

**Grating equation (principal maxima):**

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

where  $d$  is the slit spacing ( $d = 1/\text{number of lines per metre}$ ) and  $n$  is the order (0, 1, 2, ...).

The maximum order is limited by  $\sin \theta \leq 1$ , so  $n_{\max} = d/\lambda$ .

### EXAM ALERT

**$n$  in the grating equation is the order number, NOT the number of moles or refractive index.** In IB papers all three appear — make sure you know from context which  $n$  is which. In the grating equation specifically,  $n$  is always the order of the maximum (0 = central, 1 = first order, etc.).

### IB TIP

**Exam command term “outline”:** For interference experiments, a full “outline” answer earns marks for: (1) naming the setup (double-slit, grating), (2) stating the condition for constructive or destructive interference, (3) giving the relevant formula. Always write the formula.

## Section 5: Standing Waves

### Formation of Standing Waves

A **standing (stationary) wave** forms when two identical waves travelling in opposite directions superpose. Unlike a travelling wave, a standing wave does not transfer energy along the medium.

#### MEMORISE THIS

- **Nodes:** points of zero displacement (permanent destructive interference)
- **Antinodes:** points of maximum displacement (permanent constructive interference)
- Adjacent nodes are separated by  $\lambda/2$
- The amplitude varies from zero (at nodes) to maximum (at antinodes)
- All points between two adjacent nodes oscillate **in phase** but with different amplitudes

### Harmonics in Strings and Pipes

A string fixed at both ends, or an open pipe, forms standing waves with **nodes at the fixed ends** (or antinodes at both open ends for an open pipe).

#### MEMORISE THIS

**Stretched string (or open pipe) — both ends are nodes (or both antinodes for open pipe):**

$$L = \frac{n\lambda_n}{2} \quad n = 1, 2, 3, \dots \quad f_n = \frac{nv}{2L}$$

- $n = 1$ : fundamental (1st harmonic),  $f_1 = v/(2L)$
- $n = 2$ : 2nd harmonic,  $f_2 = 2f_1$
- $n = 3$ : 3rd harmonic,  $f_3 = 3f_1$

**Closed pipe (one open end, one closed end) — node at closed end, antinode at open end:**

$$L = \frac{(2n-1)\lambda_n}{4} \quad n = 1, 2, 3, \dots \quad f_n = \frac{(2n-1)v}{4L}$$

Only **odd harmonics** are present:  $f_1, f_3, f_5, \dots$

### WORKED EXAMPLE

#### Worked Example C5 — Harmonics in a string:

A guitar string of length  $L = 0.64$  m has a wave speed  $v = 256$  m s<sup>-1</sup>.

(a) Find the fundamental frequency.

$$f_1 = \frac{v}{2L} = \frac{256}{2 \times 0.64} = \frac{256}{1.28} = 200 \text{ Hz}$$

(b) What is the wavelength of the 3rd harmonic?

$$\lambda_3 = \frac{2L}{3} = \frac{2 \times 0.64}{3} = \frac{1.28}{3} \approx 0.43 \text{ m}$$

(c) Find  $f_3$ :  $f_3 = 3f_1 = 3 \times 200 = 600$  Hz, or  $f_3 = v/\lambda_3 = 256/0.427 \approx 600$  Hz.

**Resonance** occurs when a system is driven at a frequency that matches a natural frequency (harmonic). At resonance, the amplitude of oscillation is maximum and energy transfer from the driving source is most efficient.

### EXAM ALERT

**Pipes often catch students out.** For a closed pipe, the closed end is always a **node** and the open end is always an **antinode** — only odd harmonics can form. If an exam question mentions “a pipe closed at one end” and asks for the next resonant frequency above the fundamental, the answer is  $3f_1$  (not  $2f_1$ ). Forgetting this costs marks frequently.

## Exam-Style Practice Questions

### Paper 1 Style (MCQ)

**Q1.** Light of wavelength  $\lambda$  passes through a double slit of separation  $d$ . The interference pattern is observed on a screen at distance  $D$ . The slit separation is then doubled. What happens to the fringe spacing?

- A. It doubles.
- B. It is halved.
- C. It is unchanged.
- D. It increases by a factor of 4.

► Answer

**Q2.** Which of the following correctly identifies the conditions needed for total internal reflection?

- A. Light travelling from a less dense to a more dense medium at any angle.

B. Light travelling from a more dense to a less dense medium at an angle less than the critical angle.

C. Light travelling from a more dense to a less dense medium at an angle greater than the critical angle.

D. Light travelling along the normal at any interface.

► Answer

### Paper 2 Style (Structured Response)

**Q3.** A source emits sound at frequency  $f_s = 1200$  Hz. The speed of sound in air is  $v = 340$  m s<sup>-1</sup>.

(a) The source moves toward a stationary observer at  $v_s = 25$  m s<sup>-1</sup>. Calculate the frequency heard by the observer. [2]

(b) Calculate the frequency heard when the source moves away from the observer at the same speed. [1]

(c) State and explain why the observed frequency drops as the source passes the observer. [2]

► Mark-scheme answers

#### EXAM ALERT

##### Common Theme C errors that cost marks:

1. Measuring angles from the surface rather than from the normal in Snell's Law — always use the angle with the normal (perpendicular to the interface).
2. Getting Doppler sign conventions wrong — write out the full formula and substitute; do not guess.
3. Confusing single-slit ( $\sin \theta = m\lambda/b$ ) with grating ( $n\lambda = d \sin \theta$ ) — both look similar but the physics is different.
4. Forgetting that only odd harmonics exist in a pipe closed at one end.
5. Stating that total internal reflection occurs when going from low- $n$  to high- $n$  medium — it only occurs going from high to low.
6. Using the grating formula for a double-slit fringe spacing question — use  $s = \lambda D/d$  for fringe spacing; grating formula gives angle of maxima.

## May 2026 Exam Predictions

Based on past IB Physics paper patterns, Theme C questions in May 2026 are likely to include:

- **Paper 1 MCQ:** Snell's Law / critical angle calculation (frequently tested), or a standing wave harmonics question (identify the correct harmonic diagram).

- **Paper 2 Short Answer:** A double-slit or diffraction grating calculation with follow-up “explain the effect of” question (e.g., “explain the effect on the fringe pattern of using light with a longer wavelength”).
- **Doppler effect:** Numerical calculation plus qualitative explanation — both parts appear regularly.
- **Standing waves in pipes/strings:** Sketch the standing wave pattern and calculate frequency or wavelength. Closed-pipe odd-harmonics restriction is a reliable examiner favourite.

 **IB TIP**

**Drawing standing wave diagrams:** IB examiners award a mark for each node and antinode correctly placed. When sketching, always: (1) mark all nodes with an N and antinodes with an A, (2) ensure nodes are at fixed ends (strings, closed pipe ends), antinodes at free/open ends, (3) draw the envelope of motion (not a snapshot of a single moment). Label the wavelength and length of the medium.