IB Physics SL Wave Behaviour Guide 2026 — Complete

IB SL Study Guide

Contents

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
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Aligned to IB Physics 2025 syllabus — Theme C: Wave Behaviour (first assessment 2025)

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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
Transverse	Perpendicular to the direction of wave travel	Light, all EM waves, waves on a string, seismic S-waves
Longitudinal	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
λ	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 (s^{-1})
v	wave speed	speed at which the wave pattern moves	m s^{-1}

Fundamental relationships:

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

⚠ 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

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

where Δx is the path difference or spatial separation.

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

Intensity and the Inverse Square Law

Intensity is the power per unit area of wavefront:

MEMORISE THIS

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

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 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 $v_s = 30 \text{ m s}^{-1}$. Speed of sound $v = 340 \text{ m s}^{-1}$.

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

MEMORISE THIS

EM spectrum order (increasing frequency / decreasing wavelength):

$\text{Radio} \to \text{Microwave} \to \text{Infrared} \to \text{Visible} \to \text{UV} \to \text{X-ray} \to \text{Gamma}$

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 θ_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 → small θ_c → 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 θ_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 $= n\lambda, n = 0, 1, 2, \ldots$)

$$\text{Resultant amplitude} = A_1 + A_2 \quad \text{(maximum)}$$

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

$$\text{Resultant amplitude} = |A_1 - A_2| \quad \text{(minimum; zero if } A_1 = A_2\text{)}$$

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 λ and D; decreases with d
λ	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 $\lambda = 600$ nm passes through two slits separated by $d = 0.30$ mm. The screen is $D = 2.0$ 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:

$\sin\theta = \frac{m\lambda}{b} \quad m = \pm1, \pm2, \pm3, \ldots$

- 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, $1, 2, \ldots$).

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

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):

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

- $n = 1$: 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:

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

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

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^{-1}.

(a) Find the fundamental frequency.

$f_1 = \frac{v}{2L} = \frac{256}{2\times0.64} = \frac{256}{1.28} = 200$ Hz

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

$\lambda_3 = \frac{2L}{3} = \frac{2\times0.64}{3} = \frac{1.28}{3} \approx 0.43$ 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 λ 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 $f_s = 1200\ \mathrm{Hz}$. The speed of sound in air is $v = 340\ \mathrm{m\ s^{-1}}$.

(a) The source moves toward a stationary observer at $v_s = 25\ \mathrm{m\ s^{-1}}$. 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.

November 2026 Exam Predictions

Based on past IB Physics paper patterns, Theme C questions in November 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.