Topic C.4

STANDING WAVES & RESONANCE

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered	Exam Relevance
Formation & node/antinode spacing	P1 & P2 (SL + HL)
Phase rules	N–N = λ/2
String & pipe harmonics	$f_n = nv/2L$
Resonance	Resonance curves
Types of damping	Critical vs heavy damping

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The Big Picture — How C.4 Fits Together

STANDING WAVES & RESONANCE
two opposite travelling waves
make a stationary pattern

- **Formation**: 2 opposite waves, no energy transfer
- **Nodes & Antinodes**: N: zero; A: $2A$; $\lambda/2$ apart
- **Strings & Pipes**: fixed/closed→N, free/open→A
- **Resonance**: $f_{\text{drive}}=f_0$, max amplitude
- **Damping**: lowers & broadens the peak

§1 — Formation of Standing Waves

Topic C.4

Standing Wave Formation

A standing wave = superposition of two **identical** waves travelling in **opposite directions**.

$$y = 2A\sin(kx)\cos(\omega t)$$

Amplitude at position x: $|2A\sin(kx)|$ — varies with position, fixed in space.

TRICK Both waves must have the same f, λ, and A. If A differs, nodes are not zero-amplitude — but IB assumes perfect reflection unless stated.

TRICK **Standing vs travelling:** standing = stationary pattern, *no* energy transfer, amplitude varies (0 at N, $2A$ at A); travelling = moves, transfers energy, uniform amplitude.

TRAP Standing waves do **not** transfer energy along the medium. Marks are lost if you say "energy travels from N to A".

NOTE Node separation = $\lambda/2$. Antinode separation = $\lambda/2$. Node-to-antinode = $\lambda/4$.

§2 — Nodes, Antinodes & Phase

Topic C.4

Phase Rules

- Points in the **same segment** (between 2 nodes): **in phase** ($\Delta\phi = 0$)
- Points in **adjacent segments** (across 1 node): **in antiphase** ($\Delta\phi = \pi$)
- Crossing n nodes: $\Delta\phi = n\pi$ rad
- Adjacent antinodes: $\Delta\phi = \pi$ (they are in **adjacent** segments)

TRAP Adjacent antinodes have $\Delta\phi = \pi$, NOT zero! They oscillate in antiphase.

TRICK Count the nodes between two points. Each node adds π to the phase difference.

§3 — Standing Waves in Strings

Topic C.4

Boundary	Harmonics	Formula
Both fixed (N–N)	All: $1, 2, 3, \ldots$	$f_n = \frac{nv}{2L}$
Fixed + Free (N–A)	Odd only: $1, 3, 5, \ldots$	$f_n = \frac{(2n-1)v}{4L}$
Both free (A–A)	All: $1, 2, 3, \ldots$	$f_n = \frac{nv}{2L}$

TRICK For N–A or A–N: only **odd** harmonics. Ratio of frequencies = 1:3:5:7...

TRAP The lowest frequency is the **first harmonic** — never say “fundamental” or “overtone” in IB exams.

NOTE Number of nodes = harmonic number + 1 (for fixed-fixed). Number of antinodes = harmonic number.

FROM THE PHOTON QUESTION BANK

Given a stated harmonic (e.g. “third harmonic $= 180\,$Hz”), find f_1 first, then scale. Only **even** harmonics of a fixed–fixed string have a node at the midpoint.

§4 — Standing Waves in Pipes

Topic C.4

Boundary	Harmonics	Formula
Both open (A–A)	All: $1, 2, 3, \ldots$	$f_n = \frac{nv}{2L}$
Closed + Open (N–A)	Odd only: $1, 3, 5, \ldots$	$f_n = \frac{(2n-1)v}{4L}$
Both closed (N–N)	All: $1, 2, 3, \ldots$	$f_n = \frac{nv}{2L}$

TRAP Closed end = displacement **node**. Open end = displacement **antinode**. This is for the **displacement** of air molecules — do not confuse with pressure.

TRICK Open-open and closed-open of the same length: $f_{1,\text{open-open}} = 2 \times f_{1,\text{closed-open}}$. The closed-open pipe has half the first-harmonic frequency.

NOTE No end corrections are needed in IB Physics Topic C.4. Use L directly. (The open-end antinode really sits slightly *beyond* the pipe — the “end correction” — but ignore it unless given.)

Resonance Tube — Speed of Sound

Tuning fork over an air column closed at the water surface (N) and open at top (A). Loud resonances at $L = \frac{\lambda}{4}, \frac{3\lambda}{4}, \ldots$; successive lengths differ by

$$\Delta L = \frac{\lambda}{2} \quad \Rightarrow \quad v = f\lambda = 2f\,\Delta L$$

Differencing lengths cancels the end correction.

FROM THE PHOTON QUESTION BANK

Closed pipe: fundamental $\lambda = 4L$, odd harmonics only $(f, 3f, 5f)$. For resonance-tube data, use $\Delta L = \lambda/2$ so $v = 2f\,\Delta L$ (kills the end correction).

§5 — Resonance

Topic C.4

Resonance Condition

Resonance occurs when $f_{\text{drive}} \approx f_0$ (natural frequency).
At resonance: amplitude is **maximum**, energy transfer is **most efficient**.

Effect of Damping on Resonance Curve

Damping	Peak amplitude	Peak width
Increases	Decreases	Increases (broader)
Increases	Resonant f slightly $\downarrow$	(below f_0)

TRICK Sketch: light damping = tall, narrow peak; heavy damping = short, broad peak. Both curves cross the frequency axis at the same point (f_0 approximately).

TRICK **Two frequencies:** natural f_0 (how the system wants to vibrate) vs driving f_{drive} (external push). Resonance $=$ they match $\Rightarrow$ max amplitude.

TRAP Resonant frequency (peak of curve) $\neq f_0$ for heavily damped systems. For lightly damped, they are approximately equal.

§6 — Types of Damping

Topic C.4

Type	Motion	Example
Light damping	Oscillatory, amplitude $\downarrow$ exponentially	Pendulum in air
Critical damping	Fastest return, no oscillation	Car shock absorbers
Heavy damping	Slow return, no oscillation	Hydraulic door closer

NOTE Critical damping = the **minimum** damping needed to prevent oscillation and return to equilibrium as fast as possible.

TRAP Heavy damping is NOT faster than critical — it is **slower**. Critical is the fastest non-oscillatory return.

§7 — Forced Oscillations, Phase & Examples

Topic C.4

Steady State & Phase Lag

After the **transient** dies out, the driven system oscillates at the **driving** frequency with constant amplitude (energy in per cycle = energy lost to damping).

Phase lag of oscillation behind driver: $f \ll f_0$: $\varphi \approx 0$ (in phase) $f = f_0$: $\varphi = \frac{\pi}{2}$ $f \gg f_0$: $\varphi = \pi$ (antiphase).

NOTE **Examples of resonance.** Useful: musical instruments, quartz clock crystals, microwave ovens (water molecules), radio/TV tuning circuits. Harmful: bridges/buildings in wind or earthquakes, a glass shattering at its natural frequency.

TRAP In the steady state the system oscillates at the **driving** frequency, not its own natural frequency.