

THEME C · WAVE BEHAVIOUR

SL & HL ≈ 25 min read

IB Physics C.4 Standing Waves and Resonance — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). C.4 is identical for SL and HL — there is no additional HL content in this sub-topic.



SL C.4 questions



HL C.4 questions



Flashcards



Standing waves simulation



Resonance simulation

What this page covers

- ✓ How a standing wave is formed when two identical waves travelling in opposite directions superpose
- ✓ Nodes and antinodes, and how the amplitude and the phase change from point to point along a standing wave
- ✓ Standing wave patterns on strings with fixed and free ends
- ✓ Standing wave patterns for air in open and closed pipes, described with displacement nodes and antinodes
- ✓ Finding the wavelength and frequency of the n th harmonic from the length and the wave speed
- ✓ Natural frequency, driving frequency and resonance, and how the amplitude depends on the driving frequency
- ✓ How damping lowers the maximum amplitude and shifts the resonant frequency
- ✓ Light, critical and heavy damping, and the useful and destructive effects of resonance

In one minute

- A **standing wave** forms when two identical waves travelling in opposite directions superpose — usually a wave and its reflection.
- **Nodes** never move; **antinodes** have the largest amplitude. Adjacent nodes are $\lambda/2$ apart; a node and the next antinode are $\lambda/4$ apart.
- All points between two adjacent nodes move **in phase**; points on opposite sides of a node are in **antiphase** (π rad).
- Fixed ends of strings and closed ends of pipes are nodes; free ends and open ends are antinodes. Same-type ends give all harmonics $f_n = nv/(2L)$; mixed ends give only odd harmonics $f_n = nv/(4L)$.
- **Resonance**: the amplitude of a driven system is greatest when the driving frequency is equal (or very close) to its natural frequency.
- More **damping** → lower, broader resonance peak at a slightly lower frequency. Critical damping returns a system to equilibrium in the shortest time without oscillating.

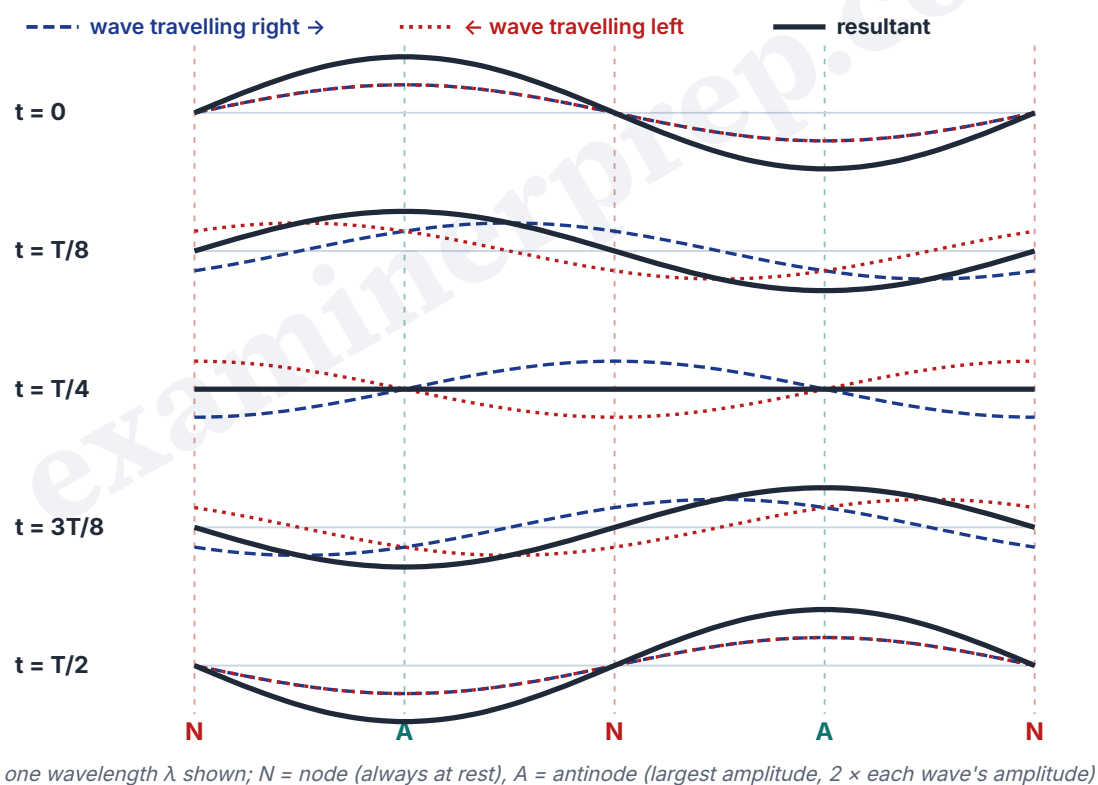
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How does a standing wave form?

A standing (stationary) wave is formed by the superposition of two waves of the same frequency, wavelength, amplitude and speed travelling in opposite directions.

- In practice the second wave is almost always a **reflection** of the first — from the clamped end of a string or the end of a pipe.
- At every point the displacement is the sum of the two travelling waves' displacements (the principle of superposition, C.3).
- At some points the two waves *always* cancel: these are **nodes**. Midway between them the waves alternately reinforce in both directions: these are **antinodes**, with amplitude twice that of each travelling wave.
- The pattern does not move along the medium — hence “standing”. Each point simply oscillates up and down (or back and forth) with its own fixed amplitude.
- You only need two waves: you are not asked about standing waves made from more than two waves.



The two travelling waves move one-eighth of a wavelength in opposite directions between rows. Their sum (black) never moves at the nodes N; at $t = T/4$ the waves cancel everywhere and the string is momentarily straight.

Standing waves compared with travelling waves

Property	Travelling (progressive) wave	Standing wave
Energy	transferred in the direction of travel	no net transfer of energy; energy is stored in the region between the boundaries
Amplitude	the same for every point (no energy loss)	varies with position: zero at nodes, maximum at antinodes
Phase	changes continuously along one wavelength (2π rad per λ)	same for all points between adjacent nodes; changes by π rad across a node
Wavelength	distance between adjacent points in phase	twice the distance between adjacent nodes
Frequency	all points oscillate at the wave frequency	all points (except nodes) oscillate at the same frequency
Waveform	moves along at the wave speed	does not move along the medium

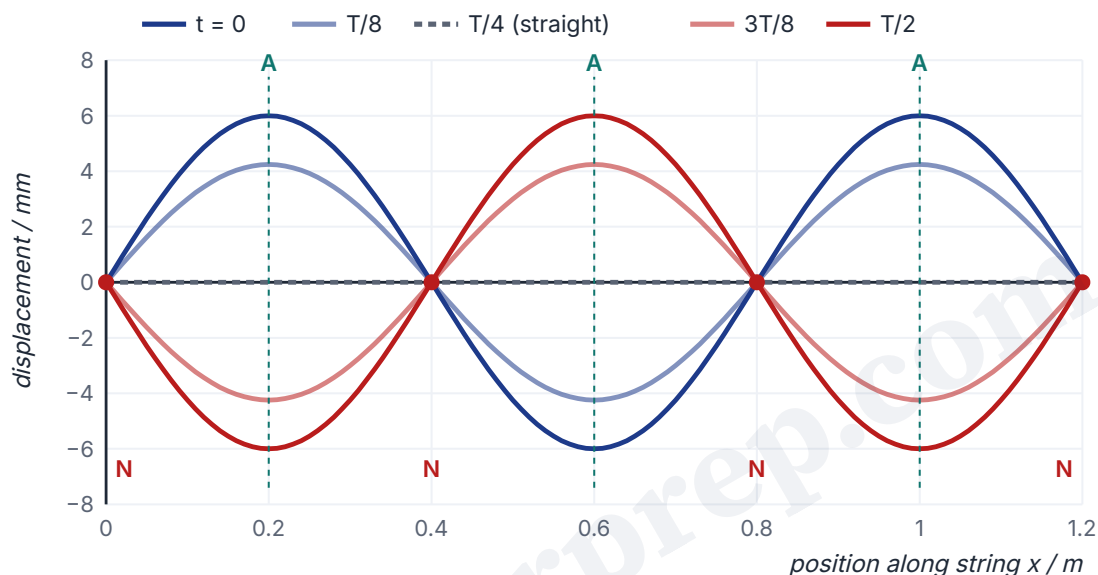
What are nodes and antinodes, and how do amplitude and phase vary?

A node is a point on a standing wave where the displacement is always zero. An antinode is a point where the amplitude of oscillation is a maximum.

- Distance between **adjacent nodes** (or adjacent antinodes) = $\frac{\lambda}{2}$. Distance from a node to the **next antinode** = $\frac{\lambda}{4}$.
- Relative amplitude:** the amplitude rises smoothly from zero at a node to its maximum at the antinode, then falls back to zero at the next node. Two points the same distance either side of an antinode have equal amplitudes.
- Phase:** every point in one "loop" (between adjacent nodes) moves in step — they all reach maximum displacement together and pass through zero together. Phase difference = 0.
- Points in **neighbouring loops** (one node between them) move in opposite directions: phase difference = π rad. Points two loops apart are back in

phase.

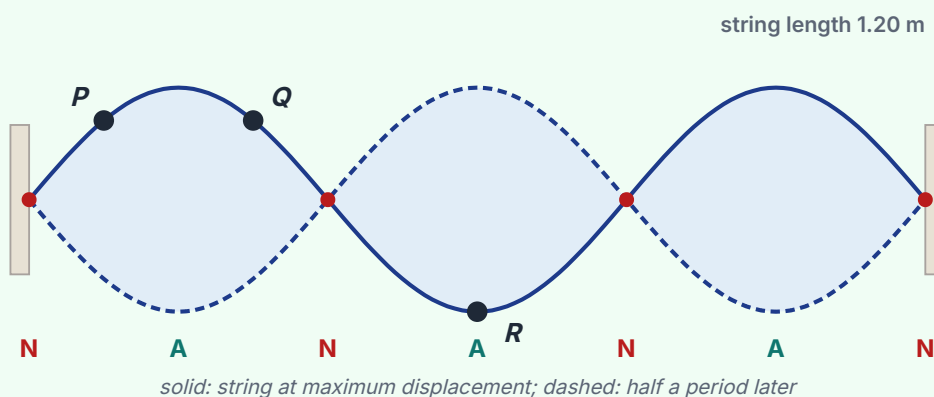
- **Energy within the wave:** when the string is at maximum displacement every point is momentarily at rest (energy stored as elastic potential energy); when the string is straight every point (except the nodes) moves at its maximum speed (energy is kinetic).



Snapshots of a third-harmonic standing wave on a 1.20 m string during half a period (pale curves at $T/8$ and $3T/8$). The shape scales up and down but never moves sideways: the nodes N stay at the same positions.

WORKED EXAMPLE 1 Easy · Determine / State

A string of length 1.20 m is fixed at both ends and vibrates in its third harmonic. The amplitude at each antinode is 6.0 mm. Points P, Q and R on the string are 0.10 m, 0.30 m and 0.60 m from the left-hand end.



The string at two instants half a period apart. Red dots mark the nodes.

(a) Determine the wavelength. (b) State the phase difference between P and Q, and between P and R. (c) State the amplitude of R and compare the amplitudes of P and Q. (d) State the number of nodes on the string, including the ends.

(a) There are three loops, each $\lambda/2$ long: $\frac{\lambda}{2} = \frac{1.20}{3} = 0.40 \text{ m}$, so $\lambda = \mathbf{0.80 \text{ m}}$

(b) P and Q both lie in the first loop (0 to 0.40 m): phase difference **0**. R lies in the second loop (0.40 m to 0.80 m), across one node from P: phase difference **$\pi \text{ rad}$** (antiphase).

(c) R is at 0.60 m, the middle of the second loop, so it is an antinode: amplitude **6.0 mm**. P and Q are each 0.10 m from the antinode at 0.20 m, symmetrically placed, so **their amplitudes are equal** (and smaller than 6.0 mm).

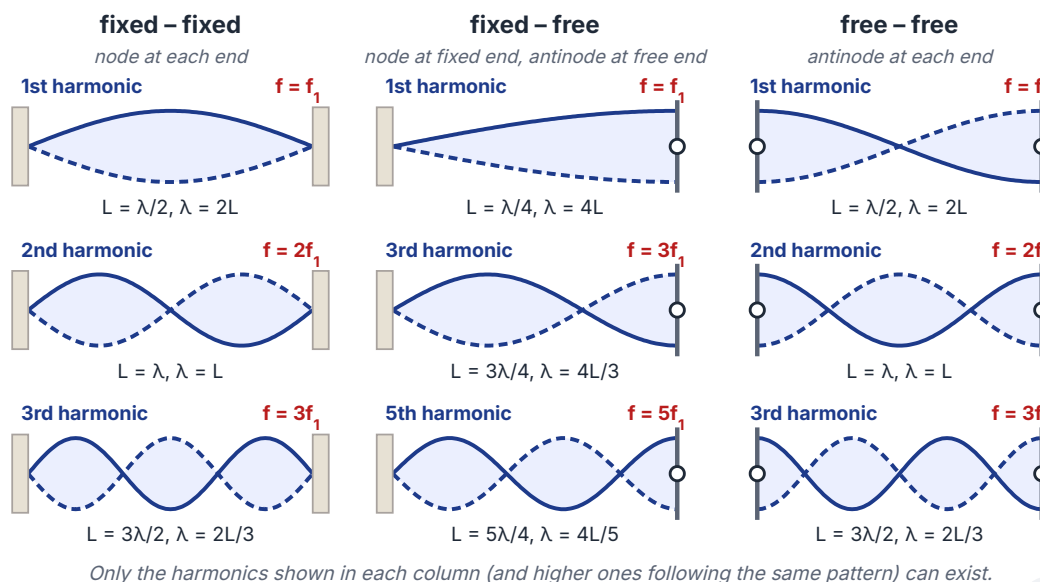
(d) Nodes at 0, 0.40, 0.80 and 1.20 m: **4 nodes**

Which standing waves can form on a string?

A standing wave can only exist if it “fits” the boundary conditions at both ends. This allows only certain wavelengths — and therefore only certain frequencies — called **harmonics**.

A fixed end of a string is always a node. A free end (for example a light ring that can slide on a frictionless rod) is always an antinode.

- The lowest-frequency mode is the **first harmonic**, f_1 . The harmonic number is f_n/f_1 , so the n th harmonic has frequency nf_1 .
- The wave speed v on a given string is set by the string (its tension and mass per unit length), not by the harmonic — so every harmonic has the same v , and $f = v/\lambda$ (data booklet $v = f\lambda$).



Displacement envelopes (solid and dashed: half a period apart) for the first three possible modes with each pair of boundary conditions. Count quarter-wavelengths: from a node to an antinode is $\lambda/4$.

Both ends the same (fixed–fixed or free–free)

The length must hold a whole number of half-wavelengths:

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

One end fixed, one end free

The length must hold an odd number of quarter-wavelengths, so only **odd harmonics** exist:

$$L = \frac{n\lambda_n}{4} \Rightarrow \lambda_n = \frac{4L}{n}, \quad f_n = \frac{nv}{4L}, \quad n = 1, 3, 5, \dots$$

where

- L = length of the string (or pipe) / m
- λ_n = wavelength of the n th harmonic / m
- f_n = frequency of the n th harmonic / Hz
- v = speed of the travelling waves that make up the standing wave / m s^{-1}
- n = harmonic number (no unit)

None of these harmonic equations is in the data booklet. Do not memorise them blindly — sketch the pattern, count the half- or quarter-wavelengths in L , then use $v = f\lambda$.

WORKED EXAMPLE 2 Medium · Calculate / Explain

A guitar string has a vibrating length of 0.640 m between its two fixed ends. Its first harmonic frequency is 196 Hz.

(a) Calculate the speed of the waves on the string. (b) Calculate the frequency and wavelength of the third harmonic. (c) The guitarist touches the string lightly at its midpoint, which forces a node there. Determine the lowest frequency the string can now produce, and explain your answer.

(a) First harmonic: $L = \lambda_1/2$, so $\lambda_1 = 2(0.640) = 1.28$ m.

$$v = f_1 \lambda_1 = 196 \times 1.28 = 250.9 \rightarrow \mathbf{251 \text{ m s}^{-1}}$$

$$\mathbf{(b) } f_3 = 3f_1 = 3 \times 196 = \mathbf{588 \text{ Hz}}; \lambda_3 = \frac{2L}{3} = \frac{2(0.640)}{3} = \mathbf{0.427 \text{ m}}$$

Check: $588 \times 0.4267 = 251 \text{ m s}^{-1}$ — the same wave speed, as it must be.

(c) Only modes with a node at the midpoint can now exist. The first harmonic has an antinode there, so it is suppressed; the even harmonics (2nd, 4th, ...) all have a node at the midpoint. The lowest is the second harmonic: $f_2 = 2 \times 196 = \mathbf{392 \text{ Hz}}$ (with $\lambda_2 = L = 0.640$ m).

TRY IT YOURSELF

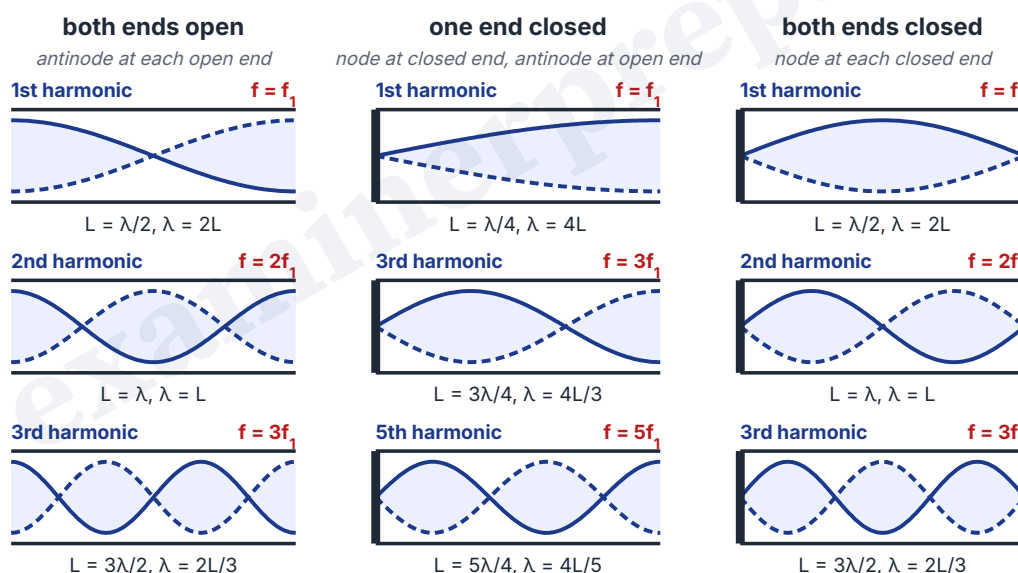
C.4 Standing Waves simulation: change the length, wave speed and boundary conditions and watch which harmonics can form — and where the nodes and antinodes sit.

Which standing waves can form in a pipe?

Sound in a pipe is a **longitudinal** wave: the air molecules oscillate along the axis of the pipe. Reflection at the ends sets up a standing wave in the air column. In IB Physics the pattern is always described with **displacement** nodes and antinodes.

At a closed end the air cannot move, so there is a displacement node. At an open end the air moves freely, so there is a displacement antinode.

Pipe	Ends	First harmonic	Harmonics present	f_n
Open at both ends	antinode – antinode	$L = \lambda/2$	all: $f_1, 2f_1, 3f_1, \dots$	$\frac{nv}{2L}$
Closed at one end	node – antinode	$L = \lambda/4$	odd only: $f_1, 3f_1, 5f_1, \dots$	$\frac{nv}{4L}, n$ odd
Closed at both ends	node – node	$L = \lambda/2$	all: $f_1, 2f_1, 3f_1, \dots$	$\frac{nv}{2L}$



Envelopes show the amplitude of the longitudinal displacement of the air, drawn sideways for clarity.

Displacement envelopes for the first three possible harmonics in each type of pipe. A pipe closed at one end has the lowest first harmonic for a given length ($\lambda = 4L$) and has no even harmonics.

- The envelopes are drawn sideways, but the air actually moves **along** the pipe. Make this clear in words if you are asked to describe the motion of the air.
- For a given length, closing one end of an open pipe **halves** the first harmonic frequency (λ doubles from $2L$ to $4L$).
- Phase works exactly as on a string: air molecules in the same loop move in phase, those across a displacement node move in antiphase. In the first

harmonic of a pipe closed at one end there is only one node (at the closed end), so **all** the air in the pipe moves in phase.

WORKED EXAMPLE 3 Medium · Show that / Explain

A pipe of length 0.32 m is closed at one end and open at the other. The speed of sound in the air is 340 m s^{-1} .

(a) Show that the frequency of the first harmonic is about 270 Hz. (b) Calculate the frequency of the next harmonic that the pipe can produce. (c) A student suggests the pipe can also resonate at 531 Hz. Explain why this is not possible. (d) The closed end is removed so that the pipe is open at both ends. Calculate the new first harmonic frequency.

(a) Node at the closed end, antinode at the open end: $L = \frac{\lambda_1}{4}$, so $\lambda_1 = 4(0.32) = 1.28 \text{ m}$.
 $f_1 = \frac{v}{\lambda_1} = \frac{340}{1.28} = \mathbf{266 \text{ Hz} \approx 270 \text{ Hz}}$

(b) Only odd harmonics exist, so the next is the third: $f_3 = 3 \times 265.6 = \mathbf{797 \text{ Hz}}$

(c) $531 \text{ Hz} = 2f_1$, the second harmonic, with $\lambda = 340/531 = 0.640 \text{ m} = 2L$. That pattern needs the *same* type of point at both ends ($L = \lambda/2$). This pipe must have a node at the closed end and an antinode at the open end, so L must be an odd number of quarter-wavelengths: **even harmonics cannot form**.

(d) Antinodes at both ends: $L = \lambda/2$, $\lambda = 0.64 \text{ m}$; $f_1 = \frac{340}{0.64} = \mathbf{531 \text{ Hz}}$ — double the closed-pipe value.

WORKED EXAMPLE 4 Hard · Explain / Determine

A tuning fork of frequency 512 Hz vibrates above the open top of a vertical tube. The bottom of the tube dips into water, and the water level is lowered slowly. A loud sound is first heard when the air column is 0.168 m long, and next when it is 0.502 m long.

(a) Explain why a loud sound is heard only at certain lengths of air column. (b) Determine the wavelength of the sound and the speed of sound. (c) State which harmonic is formed when the air column is 0.502 m long, and determine the distance below the top of the tube of the displacement node that is not at the water surface. (d) Predict the length of the air column at the next loud sound.

(a) The air column (closed by the water, open at the top) has natural frequencies that depend on its length. When one of them equals 512 Hz, the fork drives the air at its natural frequency: **resonance** occurs and a large-amplitude standing wave forms, with a displacement node at the water surface and an antinode at the open top.

(b) Successive resonances differ by half a wavelength ($\lambda/4$ to $3\lambda/4$):

$$\frac{\lambda}{2} = 0.502 - 0.168 = 0.334 \text{ m} \rightarrow \lambda = \mathbf{0.668 \text{ m}}$$

$$v = f\lambda = 512 \times 0.668 = \mathbf{342 \text{ m s}^{-1}}$$

(c) $0.502 \text{ m} = 3\lambda/4$: the **third harmonic**. From the top: antinode, node at $\lambda/4$, antinode at $\lambda/2$, node at the water. The upper node is $\frac{0.668}{4} = \mathbf{0.167 \text{ m}}$ below the top.

(d) Add another half-wavelength: $0.502 + 0.334 = 0.836 \text{ m} \rightarrow \mathbf{0.836 \text{ m}}$ ($5\lambda/4$, the fifth harmonic).

What is resonance?

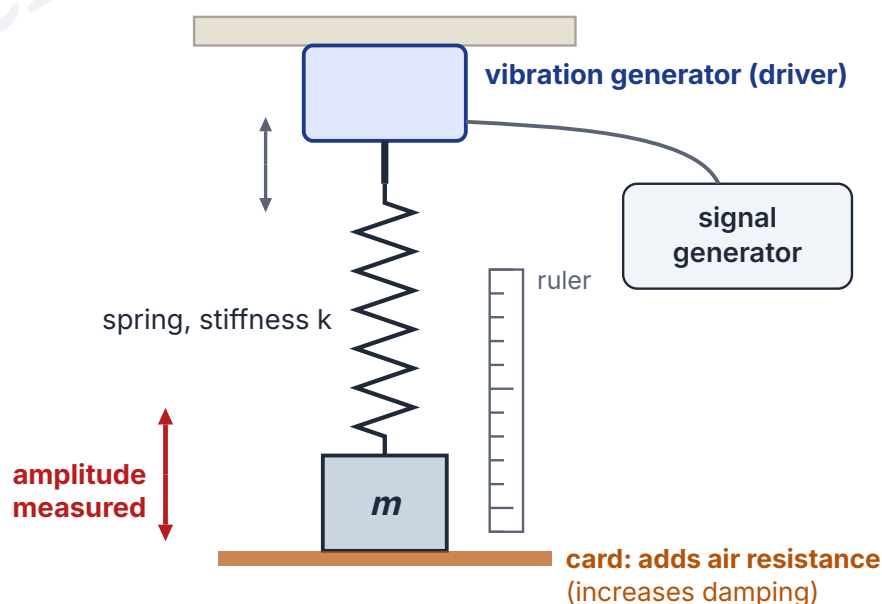
The natural frequency of a system is the frequency at which it oscillates when it is displaced and then left to oscillate freely, with no driving force.

- A mass on a spring and a simple pendulum each have one natural frequency, given by the C.1 equations $T = 2\pi\sqrt{m/k}$ and $T = 2\pi\sqrt{l/g}$ (both in the data booklet), with $f = 1/T$.
- A string or an air column has **many** natural frequencies: its harmonics.

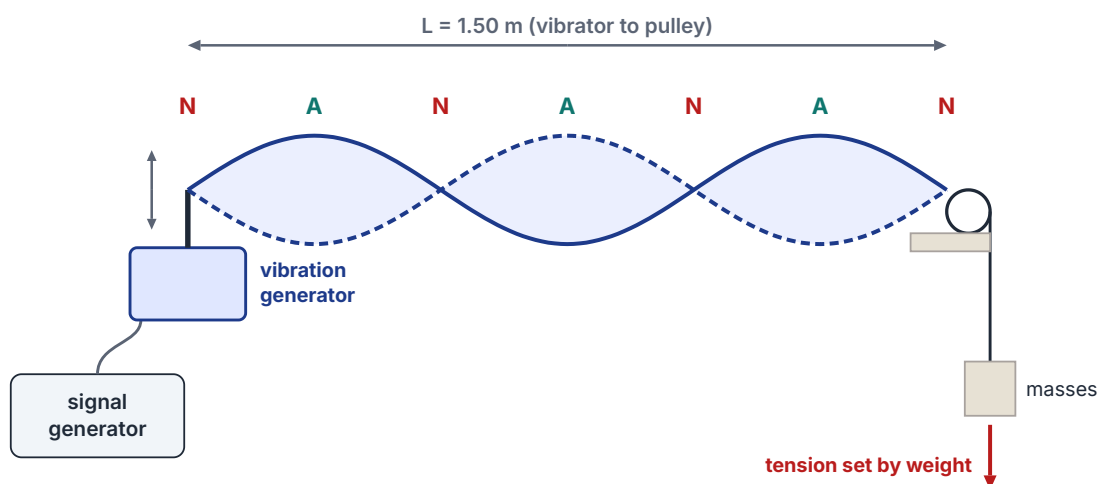
- When a periodic **driving force** acts, the system is forced to oscillate. Once any start-up motion has died away, it oscillates at the **driving frequency**, not at its natural frequency.

Resonance is the large increase in the amplitude of a driven system that occurs when the driving frequency is equal (or very close) to a natural frequency of the system.

- Why (energy):** at resonance the driving force is in step with the velocity of the system, so the driver does positive work throughout every cycle. The energy transferred per cycle is a maximum.
- The amplitude grows until the energy **dissipated** per cycle (by friction, air resistance and so on) equals the energy **supplied** per cycle by the driver. Then the amplitude stays constant.
- Driven well below the natural frequency, the system just follows the driver with a small amplitude; driven well above it, the system cannot keep up and the amplitude falls towards zero.
- Standing waves on strings and in pipes are resonances: the vibration generator, bow or lips drive the medium, and a large-amplitude standing wave forms only at a harmonic frequency.



A driven oscillator. The signal generator sets the driving frequency; the amplitude of the mass is measured with the ruler. Adding the card increases air resistance and therefore the damping.



Resonance on a string. The vibrator end moves only slightly, so it is very nearly a node. A clear, large-amplitude pattern appears only when the driving frequency matches a harmonic of the string.

WORKED EXAMPLE 5 Hard · Determine / Deduce

In the apparatus above, the vibrator runs at a fixed frequency of 50 Hz. The string between the vibrator and the pulley is 1.50 m long, and a standing wave with three loops forms. Both ends may be treated as nodes.

(a) Determine the speed of the waves on the string. (b) The hanging mass is increased so that the wave speed becomes 75 m s^{-1} . Deduce the number of loops now seen. (c) The mass is then adjusted so the wave speed is 60 m s^{-1} . Deduce whether a large-amplitude standing wave forms. (d) With the original wave speed, determine the lowest vibrator frequency that would produce a standing wave.

(a) Three loops: $3 \times \frac{\lambda}{2} = 1.50 \text{ m} \rightarrow \lambda = 1.00 \text{ m}$. $v = f\lambda = 50 \times 1.00 = 50 \text{ m s}^{-1}$

(b) $\lambda = \frac{v}{f} = \frac{75}{50} = 1.50 \text{ m}$. Number of loops $= \frac{L}{\lambda/2} = \frac{1.50}{0.75} = 2 \text{ loops}$

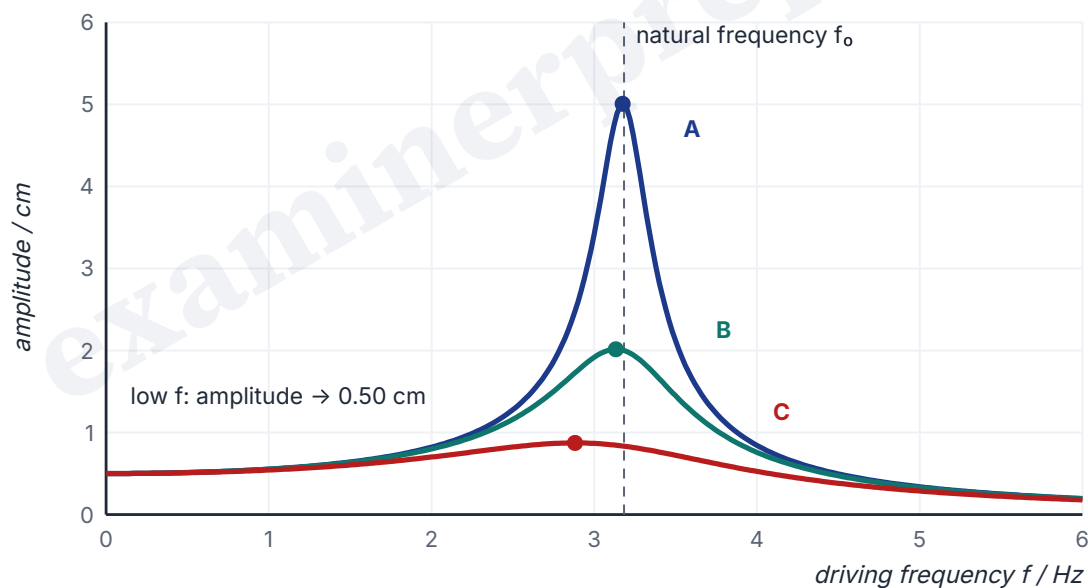
(c) $\lambda = \frac{60}{50} = 1.20 \text{ m}$; $\frac{L}{\lambda/2} = \frac{1.50}{0.60} = 2.5$. This is not a whole number, so 50 Hz is not a natural frequency of the string: **no resonance — the string vibrates at 50 Hz with only a small amplitude.**

(d) First harmonic (one loop, $\lambda = 2L = 3.00$ m): $f_1 = \frac{v}{2L} = \frac{50}{3.00} = 16.7$
→ 17 Hz

How does damping affect resonance?

Damping is the dissipation of the energy of an oscillating system by resistive forces, such as friction or fluid resistance, which reduces the amplitude of the oscillation.

Plotting the steady amplitude against the driving frequency gives a **resonance curve** (the frequency response of the oscillator). Only a qualitative understanding is required.



Computed resonance curves for a mass of 0.50 kg on a spring of stiffness 200 N m^{-1} , driven by a force of amplitude 1.0 N with three different degrees of damping. Dots mark the peaks.

As damping **increases**:

- the **maximum amplitude decreases** — more energy is dissipated per cycle, so the energy balance is reached at a smaller amplitude;
- the **resonant frequency** (where the peak occurs) **decreases slightly**, moving further below the natural frequency f_0 ;

- the peak becomes **broader (flatter)** — the system responds over a wider range of driving frequencies.

With light damping the peak is tall, sharp and at almost exactly f_0 . Far from resonance, damping has little effect: all the curves come together at low frequency, and a more heavily damped curve lies below a more lightly damped one at every frequency.

WORKED EXAMPLE 6 Hard · Calculate / Identify / Explain

The resonance curves above are for the driven mass–spring system shown earlier, with $m = 0.50 \text{ kg}$ and $k = 200 \text{ N m}^{-1}$.

(a) Calculate the natural frequency of the system. (b) Identify the curve with the greatest damping, giving two pieces of evidence from the graph. (c) For curve A at the peak, the driver keeps transferring energy to the system, yet the amplitude stays at 5.0 cm. Explain why.

$$\text{(a)} \quad T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{0.50}{200}} = 0.314 \text{ s}; \quad f_0 = \frac{1}{T} = \mathbf{3.18 \text{ Hz}}$$

(b) Curve C. Its maximum amplitude is the smallest (about 0.9 cm, against 5.0 cm for A), and its peak is at a noticeably lower frequency (about 2.9 Hz) than the natural frequency of 3.18 Hz. Its peak is also the broadest.

(c) At a steady amplitude the energy supplied by the driver in each cycle is **equal to the energy dissipated** by the resistive forces in each cycle, so the total energy of the oscillator — and hence its amplitude — no longer increases.

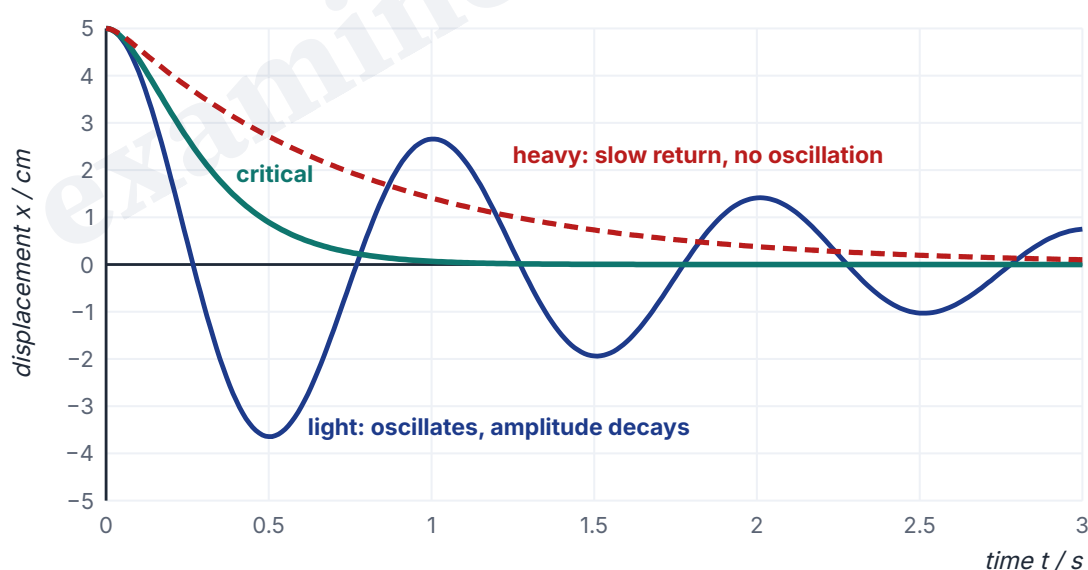
TRY IT YOURSELF

C.4 Resonance simulation: sweep the driving frequency through the natural frequency, then increase the damping and watch the peak fall, broaden and shift.

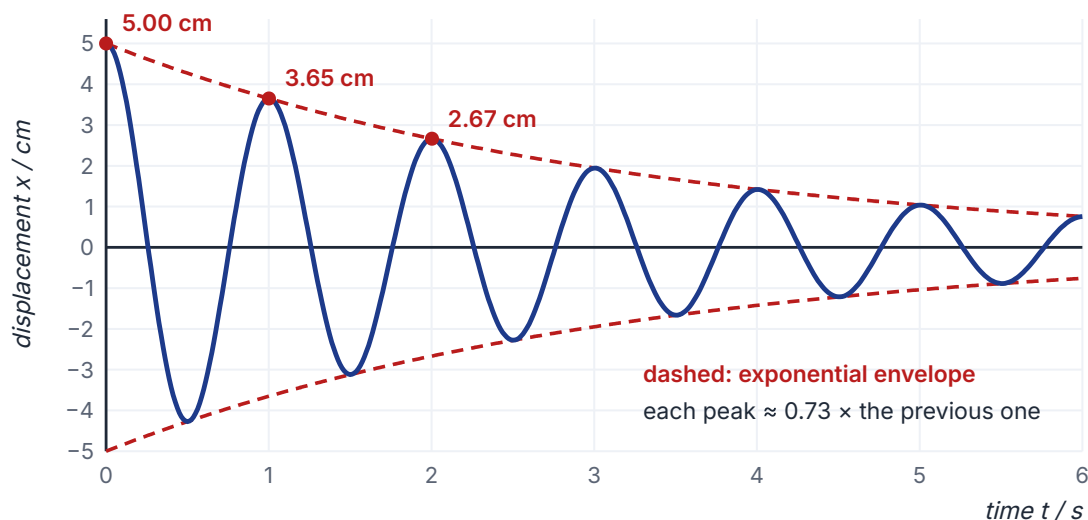
What are light, critical and heavy damping?

When a damped system is displaced and released with no driving force, the degree of damping decides how it returns to equilibrium.

Type	Behaviour after release	Examples
Light (under-damping)	Oscillates about equilibrium; the amplitude decreases gradually (exponentially — by the same fraction each cycle). The period is almost unchanged.	pendulum swinging in air, plucked guitar string, tuning fork
Critical	Returns to equilibrium in the shortest possible time without oscillating (no overshoot).	car suspension (close to critical), needles of analogue meters
Heavy (over-damping)	Does not oscillate; returns to equilibrium more slowly than with critical damping.	slow, controlled door-closing mechanisms; a pendulum in thick oil



Computed displacement–time graphs for the same oscillator (natural period 1.0 s) released from rest at 5 cm with light, critical and heavy damping. Critical damping is effectively back at equilibrium after about 1 s.



Light damping in detail. The amplitude follows an exponential envelope: each peak is about 0.73 times the previous one (5.00 → 3.65 → 2.67 cm), while the period stays at about 1.0 s.

- **HL LINK** The total energy of an oscillator is $E_T = \frac{1}{2}m\omega^2x_0^2$ (C.1, HL), so it is proportional to the amplitude squared: keeping 73 % of the amplitude each cycle means keeping only about 53 % of the energy.
- Critical damping is chosen when a system must settle quickly — a car should not bounce after a bump, and a meter needle should reach its reading without swinging past it.

When is resonance useful and when is it destructive?

Useful resonance	Destructive (unwanted) resonance
Musical instruments: strings and air columns resonate at their harmonics; the body of a guitar or violin resonates to make the sound louder.	Bridges and footbridges driven by wind or by footsteps. A London footbridge swayed sideways on its opening day in 2000 when walkers' steps fell into step with its motion; dampers were fitted to cure it.
Tuning a radio: an electrical circuit is adjusted so that its natural frequency matches one station, which is then picked out strongly.	Buildings during earthquakes, when the ground shakes at a frequency close to a natural frequency of the building.
Quartz clocks and watches: a quartz crystal is kept oscillating at its natural frequency, which provides a very stable time base.	Machines and vehicles: parts rattle or vibrate violently at particular engine speeds, causing noise and fatigue damage.
Magnetic resonance imaging (MRI): nuclei absorb energy from radio waves at their natural frequency.	A wine glass shattered by a sound at its natural frequency.

Unwanted resonance is reduced by **adding damping** (shock absorbers, rubber mounts, the large tuned mass dampers in tall buildings) or by changing the mass or stiffness of a structure so that its natural frequencies are far from any likely driving frequency.

Exam tips for C.4

EXAM TIP 1 — PHASE ON A STANDING WAVE IS NOT PHASE ON A TRAVELLING WAVE

On a travelling wave, phase difference = $2\pi \times \frac{\text{distance}}{\lambda}$. On a standing wave that rule does **not** apply: any two points between the same pair of adjacent nodes have phase difference 0, and points in neighbouring loops have π rad. Before calculating anything, count the nodes between the two points.

EXAM TIP 2 — SAY “FIRST HARMONIC”, AND COUNT HARMONICS PROPERLY

The lowest mode is the **first harmonic**; the IB does not use the older words for it. For a pipe closed at one end the next mode after the first harmonic is the **third** harmonic ($3f_1$), not the second. The harmonic number is always f_n/f_1 .

EXAM TIP 3 — DRAW THE ENVELOPE, START WITH THE ENDS

When sketching a standing wave, decide the end conditions first (fixed/closed = node, free/open = antinode), then draw both the solid and dashed curves meeting at every node. For pipes, label them as **displacement** nodes and antinodes. A curve that does not close at a closed end, or that is pinched at an open end, loses the mark.

EXAM TIP 4 — NAME BOTH FREQUENCIES WHEN YOU DEFINE RESONANCE

“Resonance is when the amplitude is a maximum” is incomplete. Write that the **driving frequency equals the natural frequency** of the system, giving the maximum amplitude. If asked to explain, add the energy idea: the energy transferred per cycle from the driver is greatest.

EXAM TIP 5 — SKETCHING A MORE DAMPED RESONANCE CURVE

Three features earn the marks: a **lower** peak, the peak **shifted slightly to a lower frequency**, and a **broad**er curve. The new curve should lie below the original everywhere and approach the same amplitude at low frequency. Do not move the peak to a higher frequency.

Common misconceptions

Misconception	Why it is wrong	Correct idea
The wavelength of a standing wave is the distance between adjacent nodes.	Each loop is only half a wavelength.	Node to node = $\lambda/2$; node to antinode = $\lambda/4$.
A standing wave carries energy along the string.	Two equal waves carry equal energy in opposite directions.	No net energy transfer; energy is stored and swaps between kinetic and potential.
Points closer to each other have a smaller phase difference.	That is true for travelling waves only.	Same loop: in phase. Neighbouring loops: π rad.
A pipe closed at one end produces every harmonic.	A closed end must be a node and an open end an antinode.	Only odd harmonics: $f_1, 3f_1, 5f_1, \dots$
A driven system oscillates at its own natural frequency.	In the steady state the driver sets the frequency.	It oscillates at the driving frequency; amplitude is largest when that equals the natural frequency.
Critical damping stops the motion instantly.	The system still takes time to return.	Critical damping returns the system to equilibrium in the shortest time <i>without oscillating</i> .

How this topic connects

Damping and peak amplitude: the energy balance of a driven oscillator

The amplitude grows until the energy dissipated per cycle equals the energy supplied per cycle by the driver. The more energy the system dissipates at a given amplitude (the heavier the damping), the sooner this balance is reached, so the maximum amplitude is lower (worked example 6). A system with very little dissipation can build up a dangerously large amplitude — the reason dampers are

added to bridges and tall buildings (see the table of useful and destructive resonance).

Natural frequency and SHM: where resonance gets its frequency

The natural frequency of a lightly damped system is the frequency of its free simple harmonic motion: $f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$ for a mass–spring system or $\frac{1}{2\pi} \sqrt{\frac{g}{l}}$ for a pendulum (from the C.1 period equations). Resonance happens when a driver matches this frequency. In a standing wave, every point (other than a node) performs simple harmonic motion at the same frequency, with an amplitude that depends on its position.

Vibrating molecules and infrared absorption: a resonance model of the greenhouse effect

Model the bonds in a molecule such as CO₂ or H₂O as springs between masses. The molecule then has natural frequencies of vibration, some of them in the infrared. Infrared radiation emitted by the Earth's surface at those frequencies drives the molecules into resonance, so it is strongly absorbed and then re-emitted in all directions — partly back towards the surface (B.2). This is a model: real molecules obey quantum rules, but the simple resonance picture explains why each greenhouse gas absorbs strongly only in particular infrared bands. (Why N₂ and O₂ hardly absorb infrared at all needs more than this model: their vibrations do not change the distribution of charge in the molecule.)

Tools & inquiry — measuring with standing waves

- **Speed of sound with a resonance tube** (worked example 4): use the difference between successive resonance lengths, $\Delta L = \lambda/2$, and repeat while raising and lowering the water to bracket the loudest point.
- **Linearising:** for a tube closed at one end in its first harmonic, $L = \frac{v}{4} \times \frac{1}{f}$. Plot L against $1/f$ for a set of tuning forks; the gradient is $v/4$. A non-zero intercept reveals a systematic error.

- **Strings** (Melde-type apparatus): measure across several loops and divide, rather than measuring one loop, to reduce the percentage uncertainty in λ . Nodes are sharper than antinodes, so measure between nodes.
- Stroboscopes or a phone's slow-motion video make the in-phase / antiphase motion of neighbouring loops visible.

Key equations

Equation	Use	In data booklet?
$v = f\lambda$	links frequency and wavelength of every harmonic	yes (C.2)
node to node = $\frac{\lambda}{2}$; node to antinode = $\frac{\lambda}{4}$	reading wavelengths from a pattern	no — learn them
$\lambda_n = \frac{2L}{n}, f_n = \frac{nv}{2L}, n = 1, 2, 3, \dots$	string fixed-fixed or free-free; pipe open-open or closed-closed	no — derive from a sketch
$\lambda_n = \frac{4L}{n}, f_n = \frac{nv}{4L}, n = 1, 3, 5, \dots$	string fixed-free; pipe closed at one end	no — derive from a sketch
$T = 2\pi\sqrt{\frac{m}{k}}, T = 2\pi\sqrt{\frac{l}{g}}, f = \frac{1}{T}$	natural frequency of a mass-spring system or pendulum	yes (C.1)

Check your understanding

1. Adjacent nodes on a standing wave are 12 cm apart and the frequency is 250 Hz. Calculate the speed of the travelling waves.

$$\lambda = 2 \times 0.12 = 0.24 \text{ m}; v = f\lambda = 250 \times 0.24 = 60 \text{ m s}^{-1}.$$

2. A pipe open at both ends is 0.85 m long. The speed of sound is 340 m s^{-1} . Calculate the frequencies of the first three harmonics.

$$f_1 = \frac{v}{2L} = \frac{340}{1.70} = 200 \text{ Hz}; \text{ all harmonics exist, so } 200 \text{ Hz, } 400 \text{ Hz and } 600 \text{ Hz}.$$

3. A pipe closed at one end has a first harmonic of 150 Hz. Which of 300 Hz, 450 Hz and 600 Hz can it also produce?

Only 450 Hz (the third harmonic). Even multiples of 150 Hz are not possible for a pipe closed at one end.

4. Two points on a standing wave are separated by exactly one node. State their phase difference and compare their directions of motion.

π rad (antiphase): whenever one moves up, the other moves down.

5. Explain why a car's suspension is designed to be close to critically damped.

After a bump the car returns to its equilibrium position in the shortest time without oscillating. Light damping would make it bounce repeatedly; heavy damping would make it slow to recover, so it could not respond to the next bump.

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