

Course Companion

International Baccalaureate · IB Diploma · Physics · SL

Every topic handout in one volume

exercises.lol

Contents

1. Kinematics	3
2. Forces and momentum	6
3. Work, energy and power	9
4. Thermal energy transfers	12
5. Greenhouse effect	15
6. Gas laws	18
7. Current and circuits	21
8. Simple harmonic motion	24
9. Wave model	27
10. C.3 Wave phenomena	30
11. C.4 Standing waves and resonance	34

12. Doppler effect.....	37
13. Gravitational fields.....	40
14. Electric and magnetic fields	43
15. Motion in electromagnetic fields	46
16. Structure of the atom.....	49
17. Radioactive decay	52
18. Fission.....	55
19. Fusion and stars	58
20. Experimental programme.....	61

Kinematics

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Scope and prerequisites

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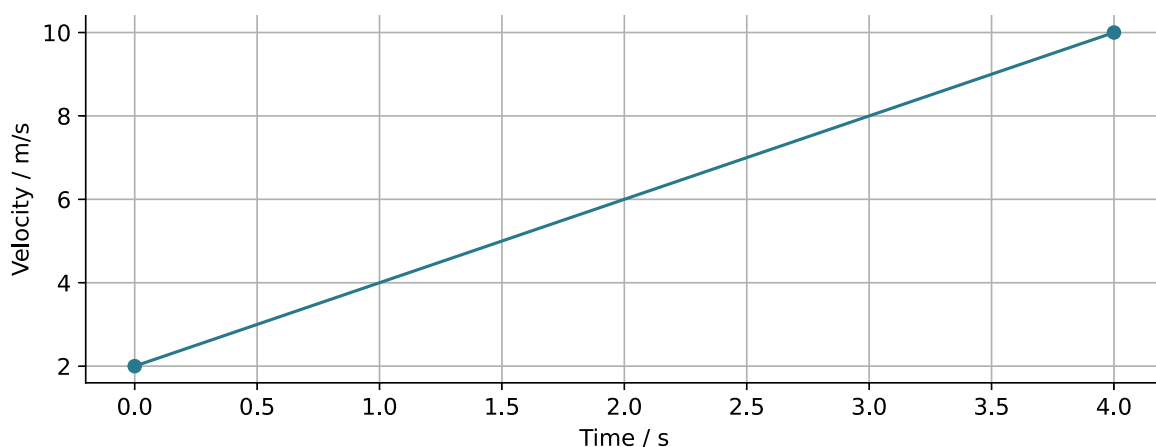
Motion graphs and acceleration

■ What would explain this observation?

- A speedometer gives a reading at one moment. A journey average can hide stops and rapid changes in speed.
-

■ Build the model

- Displacement includes direction; distance counts total path length.
- **Velocity** is change in displacement per time.
- **Acceleration** is change in velocity per time.
- velocity: Rate of change of displacement.
- acceleration: Rate of change of velocity.



A straight v - t line means constant acceleration: $a = (10 - 2) \div 4 = 2.0 \text{ m/s}^2$

■ Choose evidence that can test it

- The gradient of a displacement-time graph is velocity.
- The area under a velocity-time graph gives displacement.
- A constant-acceleration formula is valid only when its assumption is justified.

In the lab: Choose a positive direction and state it. Use a light gate or video with a known scale and frame interval for repeatable motion measurements. Avoid assuming hand timing is exact over very short intervals.

■ Work from known quantities

- Known: velocity rises uniformly from 2 to 10 metres per second in 4 s. $a = (v-u)/t$.
 $a = (10-2)/4 = 2$ metres per second squared.
- Displacement is trapezium area: $s = (u+v)t/2 = (2+10) \times 4/2 = 24$ m.

Your turn: Velocity changes from 3 to 15 metres per second in 6 s. Find acceleration.

■ Check the conclusion and its limits

- Negative velocity indicates direction under the chosen sign convention; it does not necessarily mean slowing down.

Not true: A negative velocity always means the object is slowing down. Negative velocity means motion opposite to the chosen positive direction. The object slows down only when the acceleration opposes the velocity; a negative velocity with negative acceleration is speeding up.

Key:

- Displacement includes direction; distance counts total path length.
- The gradient of a displacement-time graph is velocity.
- Watch for: negative velocity indicates direction under the chosen sign convention; it does not necessarily mean slowing down.

■ Write from an acceleration of 5 metres per second squared

- Velocity changes from 1 to 11 metres per second in 2 s.
- Find the acceleration and the displacement. A negative velocity is a direction.

■ Write from a gradient of minus 2

- A velocity-time line falls from 6 to 0 metres per second between $t = 0$ and $t = 3$ s.
- The gradient is $(0 - 6) \div 3 = -2$ metres per second squared – uniform deceleration, the sign only naming the chosen positive direction.

■ **Write from a displacement of 100 metres**

- An object moves at a steady 20 metres per second for 5 s.
- Displacement = $20 \times 5 = 100$ m, and its displacement-time graph is a straight line of gradient 20.

■ **Write from a negative final velocity**

- An object at $+8 \text{ m s}^{-1}$ decelerates at 2 m s^{-2} for 6 s.
- $v = 8 - 12 = -4 \text{ m s}^{-1}$: it stopped at $t = 4$ s and reversed – the formula tracks direction honestly.

Forces and momentum

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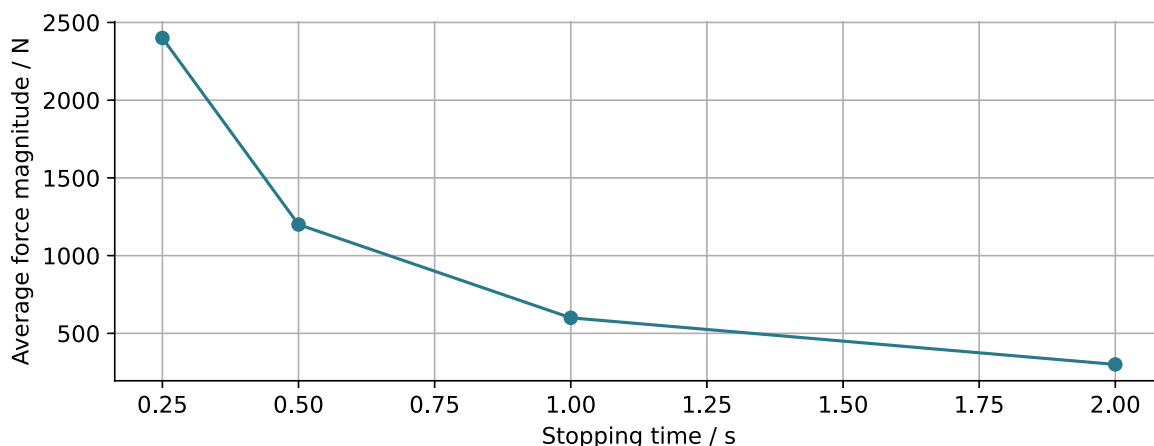
Forces, momentum and safe stopping

■ What would explain this observation?

- A passenger continues moving when a vehicle brakes. The seat belt provides the force needed to change the passenger **momentum**.

■ Build the model

- **Resultant force** causes acceleration, not motion itself.
- Momentum is mass multiplied by velocity.
- For an isolated system, total momentum is conserved even when kinetic energy is not.
- momentum: Mass multiplied by velocity.
- resultant force: The vector sum of forces on an object.



The same impulse, 600 N s, spread over a longer time needs a smaller force

■ Choose evidence that can test it

- Impulse equals momentum change.
- Increasing stopping time for the same momentum change reduces average force.
- Identify external forces before applying momentum conservation.

In the lab: Draw a free-body diagram containing only forces on the selected object. For spring measurements, add loads in steps within the elastic range and measure extension from the unloaded position.

■ Work from known quantities

- Known: a 60 kg passenger slows from 10 to 0 metres per second in 0.50 s. $\Delta p = m(v-u) = 60(0-10) = -600$ kg metres per second.
- Average $F = \Delta p / \Delta t = -600 / 0.50 = -1,200$ N.
- The sign shows the force opposes the initial motion.

Your turn: A 2 kg trolley travels at 3 metres per second. Find its momentum.

■ Check the conclusion and its limits

- Balanced forces do not require the object to be at rest.
- Mass and weight have different units and meanings.

Not true: An object moving at constant velocity must have a nonzero resultant force. By Newton's first law, constant velocity - including steady motion - means zero RESULTANT force. Forces can be present, but they balance; a nonzero resultant would change the velocity.

Key:

- Resultant force causes acceleration, not motion itself.
- Impulse equals momentum change.
- Watch for: balanced forces do not require the object to be at rest.

■ Write from a momentum of 21 kilogram metres per second

- A 3 kg trolley travels at 7 metres per second and stops in 0.30 s.
- Find the momentum and the average force. Constant velocity needs zero resultant force.

■ Write from a momentum change of 6 kilogram metres per second

- A 0.50 kg ball's velocity reverses from +6 to -6 metres per second in 0.25 s.
- The momentum change is $0.50 \times (-12) = -6$ kg m s⁻¹, so the average force is $-6 \div 0.25 = -24$ N - a REVERSAL changes momentum by twice the one-way value.

■ **Write from a stopping distance split of 36 metres**

- At 20 m s^{-1} a driver reacts for 0.60 s, then brakes for 24 m.
- Reaction distance $20 \times 0.60 = 12 \text{ m}$, total $12 + 24 = 36 \text{ m}$ – tiredness grows the first term, worn brakes the second.

■ **Write from a conserved total**

- A 2 kg trolley at 3 m s^{-1} couples with a stationary 1 kg trolley.
- Total momentum $6 \text{ kg m s}^{-1} = 3 \text{ kg} \times v$, so $v = 2 \text{ m s}^{-1}$ – the pair shares the momentum; the faster one does not keep it.

Work, energy and power

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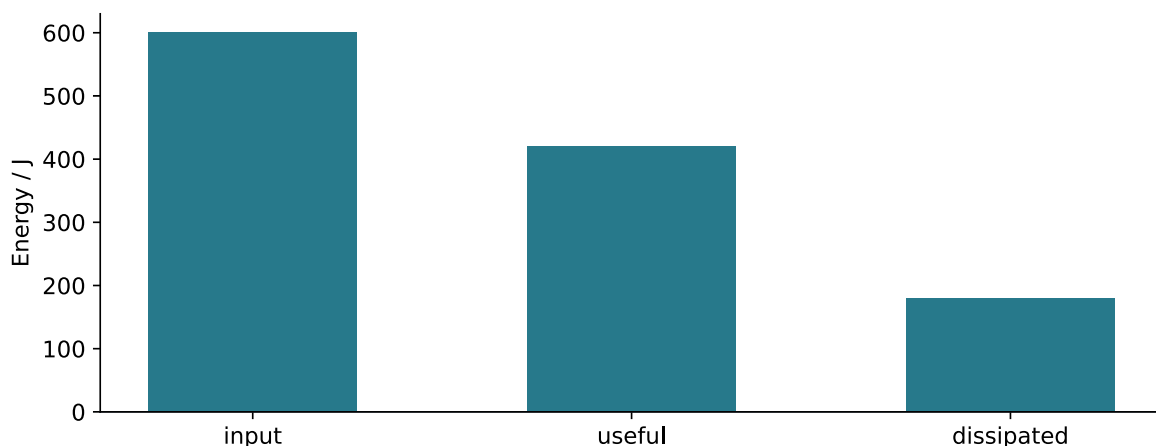
Energy stores, work and efficiency

■ What would explain this observation?

- A motor can transfer some input energy to lifting and the rest to heating. Useful output is part of the total energy transfer.

■ Build the model

- Work done by a constant force parallel to displacement is force multiplied by distance.
- Kinetic energy depends on speed squared.
- Energy is conserved when all transfers and stores are included.
- **power** : Energy transferred per unit time.
- **efficiency**: Useful output divided by total input.



Efficiency = useful $\div$ input = $420 \div 600 = 70\%$; the other 180 J is dissipated

■ Choose evidence that can test it

- Define the system and useful output before calculating efficiency.
- Doubling speed quadruples kinetic energy at constant mass.
- Power describes transfer per time, not total energy.

In the lab: Measure a lifting height and load, time the lift, and record electrical input with suitable instruments. Repeat trials and account for heating or friction as transfers, not missing energy.

■ Work from known quantities

- Known: a device receives 600 J and transfers 420 J usefully.
- Efficiency = useful output / total input.
- Efficiency = $420/600 = 0.70 = 70\%$.
- Over 3 s, useful power = useful energy/time = $420/3 = 140$ W.

Your turn: A device receives 250 J and gives 150 J useful output. Find efficiency as a percentage.

■ Check the conclusion and its limits

- Efficiency cannot exceed 100% for a properly defined energy balance.
- Energy dissipated by heating is still conserved.

Not true: Dissipated energy is destroyed. Energy is always conserved. “Dissipated” means spread into the surroundings as heating, where it becomes hard to use again - not destroyed.

Key:

- Work done by a constant force parallel to displacement is force multiplied by distance.
- Define the system and useful output before calculating efficiency.
- Watch for: efficiency cannot exceed 100% for a properly defined energy balance.

■ Write from an efficiency of 40 percent

- A device receives 300 J and gives 120 J of useful output.
- Find the efficiency. The other energy is dissipated, not destroyed.

■ Write from a useful output of 750 joules

- A machine takes in 1,200 J at an efficiency of 62.5 percent.
- Useful output = $0.625 \times 1,200 = 750$ J, dissipated 450 J – energy accounted, never destroyed.

■ **Write from an efficiency of 25 percent**

- A lift motor draws 4,000 J per floor and delivers 1,000 J of useful lifting.
- Efficiency = $1,000 \div 4,000 = 25$ percent, and the other 3,000 J is heated motor and cable – name where it goes.

■ **Write from a Sankey read**

- A diagram shows 100 J in: a 70 J useful arrow and a 30 J wasted arrow.
- Efficiency 70 percent – and the wasted arrow's WIDTH is the quantity: a Sankey diagram is an energy account drawn to scale.

Thermal energy transfers

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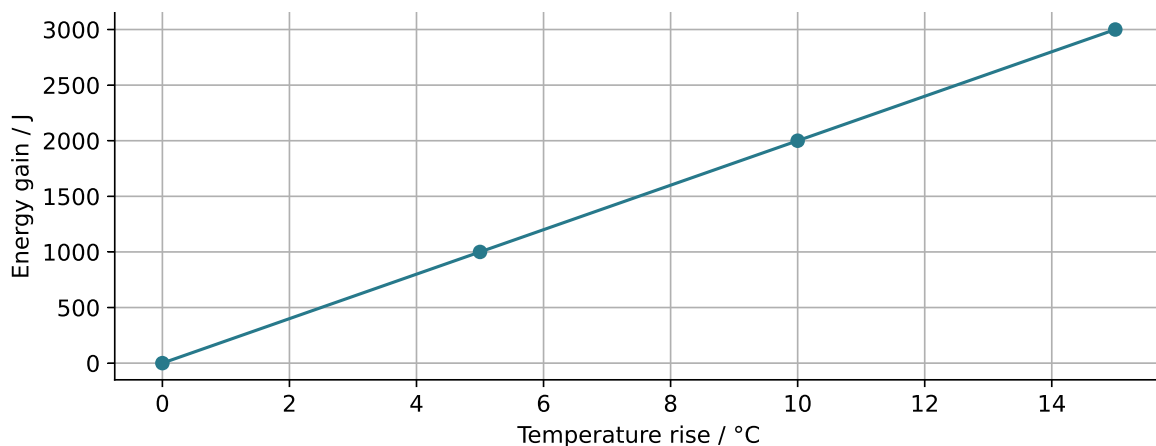
Thermal measurements and particle models

■ What would explain this observation?

- Two equal masses receive the same energy but show different temperature rises. Material properties determine how energy transfer changes temperature.

■ Build the model

- **Specific heat capacity** is energy needed to raise the temperature of unit mass by one degree.
- Specific **latent heat** relates energy to change of state without temperature change for the idealized process.
- specific heat capacity: Energy per mass per temperature rise.
- latent heat: Energy associated with a change of state.



$Q = mc\Delta T$: energy is proportional to temperature rise, here 200 J per °C

■ Choose evidence that can test it

- Temperature relates to particle motion in a model; internal energy includes kinetic and potential contributions.
- During a change of state, energy can change particle arrangements rather than temperature.

In the lab: Measure mass, electrical input and temperature change for an insulated block. Ensure the temperature sensor has good contact, allow time for equilibration, and consider energy transferred to the surroundings.

■ Work from known quantities

- Known: a 0.50 kg block gains 2,000 J and rises 10 °C.
- Use $E = mc\Delta T$.
- Rearranging gives $c = E/(m\Delta T)$. $c = 2,000/(0.50 \times 10) = 400$ J per kilogram per degree.
- Heat loss would make the value inferred from electrical input too large.

Your turn: A 2 kg sample with $c=500$ J per kilogram per degree warms by 3 °C. Find energy gain.

■ Check the conclusion and its limits

- A flat section of a heating curve can show a phase change, not absence of energy transfer.
- Do not substitute temperature for a temperature difference in $E = mc\Delta T$.

Not true: A temperature plateau always means zero energy transfer. A plateau on a heating curve marks a phase change, where energy goes into changing particle arrangement as latent heat. Energy transfer continues; only the temperature pauses.

Key:

- Specific heat capacity is energy needed to raise the temperature of unit mass by one degree.
- Temperature relates to particle motion in a model; internal energy includes kinetic and potential contributions.
- Watch for: A flat section of a heating curve can show a phase change, not absence of energy transfer.

■ Write from an energy gain of 4000 J

- A 0.40 kg sample with specific heat capacity 2000 J per kilogram per degree warms by 5 degrees.
- Find the energy gain. A temperature plateau can still transfer energy.

■ **Write from a final temperature of 30 degrees**

- A 2.0 kg block at 20 °C gains 8,000 J; its specific heat capacity is 400 J per kilogram per degree.
- The temperature rise is $8,000 \div (2.0 \times 400) = 10$ °C, so the final temperature is 30 °C.

■ **Write from a plateau read**

- A melting substance receives steady energy while its temperature holds constant.
- The energy is breaking bonds, not raising average particle kinetic energy – a plateau is energy stored, never energy wasted.

Greenhouse effect

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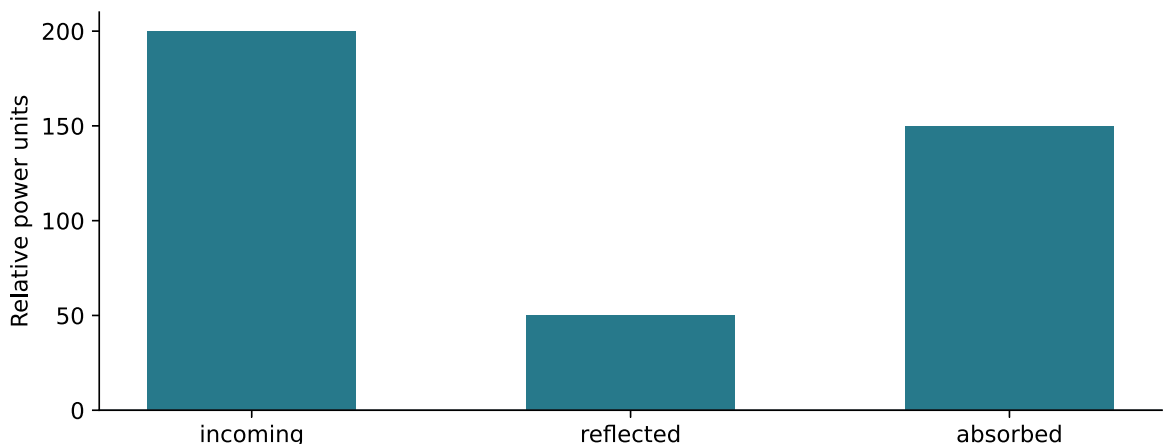
Climate evidence, energy budgets and policy

■ What would explain this observation?

- One cold day does not disprove a warming climate. Weather describes short-term conditions; climate describes distributions over longer times and regions.
-

■ Build the model

- The Earth energy balance includes incoming solar radiation, reflection, absorption and outgoing infrared radiation.
- Greenhouse gases absorb and emit infrared radiation.
- Feedback can alter the response to an initial forcing.
- **mitigation** : Actions addressing causes of environmental change.
- **adaptation** : Actions reducing harm from environmental impacts.



$$\text{Absorbed} = \text{incoming} - \text{reflected}: 200 - 50 = 150 \text{ units}$$

■ Choose evidence that can test it

- Distinguish mitigation, which addresses drivers, from adaptation, which reduces harm from impacts.
- A policy assessment needs evidence about effectiveness, cost, equity and uncertainty; one criterion is not the entire decision.

In the lab: Compare multi-year data using consistent baselines. State the region, timescale and uncertainty. At HL, connect a management decision to law, economics and ethics rather than treating these lenses as extra definitions only.

■ Work from known quantities

- Known: a surface receives 200 power units and reflects 50.
- Absorbed input = incoming-reflected = $200 - 50 = 150$.
- Reflected fraction = $50/200 = 0.25 = 25\%$.
- A change in reflectivity alters the absorbed budget under this model.

Your turn: Incoming energy is 240 units and reflected energy 72. Find reflected percentage.

■ Check the conclusion and its limits

- The greenhouse effect is not the same process as ozone depletion.
- A carbon footprint estimate depends on its system boundary.

Not true: One local weather observation establishes a global climate trend. Weather is a short-term local state; climate is the long-term statistical pattern. One cold day in one city cannot confirm or refute a global trend built from decades of worldwide records.

Key:

- The Earth energy balance includes incoming solar radiation, reflection, absorption and outgoing infrared radiation.
- Distinguish mitigation, which addresses drivers, from adaptation, which reduces harm from impacts.
- Watch for: the greenhouse effect is not the same process as ozone depletion.

■ Write from a reflected share of 16 percent

- Incoming energy is 250 units and reflected energy is 40 units.
- Find the reflected percentage. One local weather observation is not a climate trend.

■ **Write from an albedo of 0.60**

- A surface receives 500 units of incoming energy and reflects 300.
- $\text{Albedo} = 300 \div 500 = 0.60$ – the reflected fraction, leaving 200 units (0.40) absorbed.

■ **Write from an enhanced greenhouse chain**

- Carbon dioxide concentration rises; say what happens next, link by link.
- More CO₂ re-absorbs more outgoing infrared, the surface warms until outgoing energy balances again – name the mechanism; “traps heat” names nothing.

■ **Write from a budget balance test**

- A planet absorbs 240 power units and emits 240.
- The budget balances – for now: any persistent gap between absorbed and emitted FORCES temperature change until balance returns. An imbalance is the signature of change.

Gas laws

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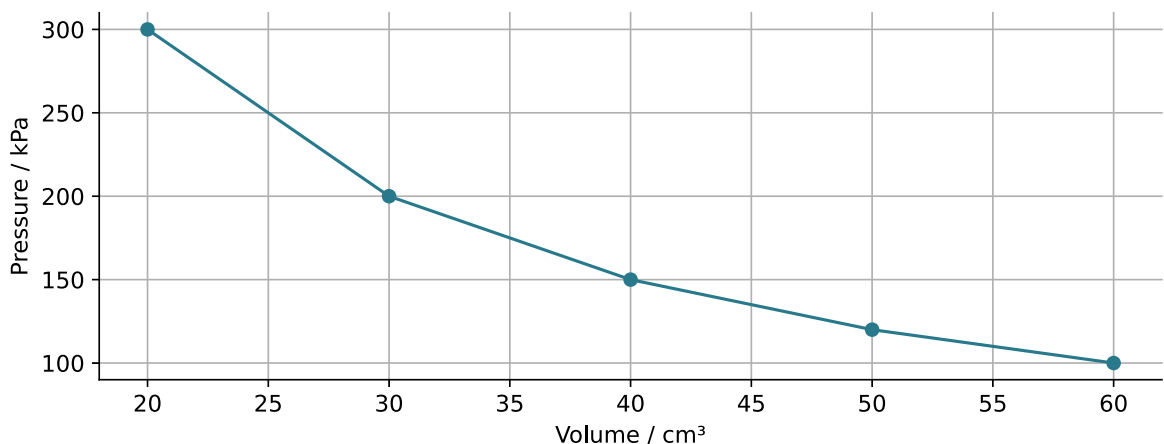
Gas models and absolute temperature

■ What would explain this observation?

- A sealed gas container changes pressure when heated. Celsius ratios cannot predict the pressure change because the gas model uses **absolute temperature**.
-

■ Build the model

- In a gas model, particles move randomly and pressure results from momentum transfer at walls.
- The **ideal gas** equation connects pressure, volume, amount and absolute temperature.
- absolute temperature: Temperature on the kelvin scale.
- ideal gas: A gas model with specified simplifying assumptions.



At constant temperature pV stays constant: $300 \times 20 = 100 \times 60 = 6,000$

■ Choose evidence that can test it

- At fixed amount and volume, pressure is proportional to kelvin temperature.
- At fixed temperature and amount, pressure is inversely proportional to volume.
- State which quantities are fixed before choosing a relationship.

In the lab: Use approved apparatus with a temperature range and pressure limit set by the teacher. Allow thermal equilibrium and record pressure against kelvin temperature. Never heat an improvised sealed vessel.

■ Work from known quantities

- Known: pressure is 100 kPa at 300 K, with fixed volume and amount.
- At 330 K, $p_2/p_1 = T_2/T_1$. $p_2 = p_1 T_2/T_1 = 100 \times 330/300 = 110$ kPa.
- A 30 °C rise is a 30 K change, but the temperature ratio must use kelvin.

Your turn: At fixed volume, pressure is 120 kPa at 300 K. Find pressure at 350 K.

■ Check the conclusion and its limits

- An ideal gas is a model with conditions of validity.
- Celsius zero is not zero molecular motion, and internal energy is not determined by pressure alone.

Not true: A gas pressure ratio can always use Celsius temperatures. Ratios of temperatures are meaningful only from absolute zero. 300 K to 350 K is a ratio of 350/300; the same temperatures in Celsius, 27 and 77, give 77/27 - a different, wrong answer.

Key:

- In a gas model, particles move randomly and pressure results from momentum transfer at walls.
- At fixed amount and volume, pressure is proportional to kelvin temperature.
- Watch for: an ideal gas is a model with conditions of validity.

■ Write from a pressure of 96 kPa

- At fixed volume, the pressure is 80 kPa at 250 K.
- Find the pressure at 300 K. The ratio must use kelvin.

■ Write from a celsius trap

- A gas at 27 °C is warmed to 127 °C at fixed volume.
- Kelvin runs 300 K to 400 K, so pressure rises by $400 \div 300 \approx 1.33$ – treating 27 → 127 as the ratio is the classic error.

■ **Write from a halved volume**

- A gas's volume is halved at fixed temperature.
- Molecules meet the walls twice as often, so pressure doubles – Boyle's law as collision counting, pV constant.

■ **Write from an absolute zero read**

- A constant-volume gas's pressure line is extrapolated downward.
- It reaches zero pressure at $-273\text{ }^{\circ}\text{C} = 0\text{ K}$ – the kelvin scale is DEFINED by that intercept, not found by a thermometer.

■ **Write from a doubled kelvin temperature**

- A fixed-volume gas at 150 K is warmed to 300 K.
- The pressure doubles – P over T is constant, and kelvin doubling IS pressure doubling at fixed volume.

Current and circuits

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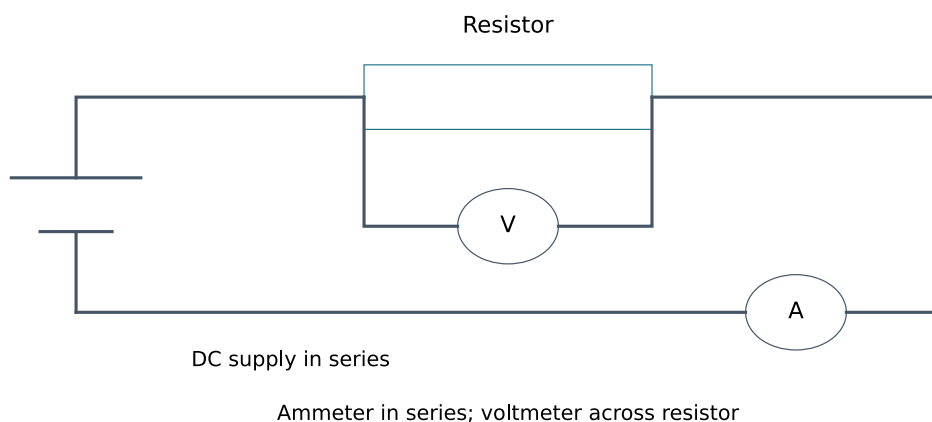
Current, potential difference and resistance

■ What would explain this observation?

- A lamp becomes dimmer when another is added in series. **Current** and energy transfer depend on the whole circuit, not only one lamp.
-

■ Build the model

- Current is charge passing per time.
- **Potential difference** is energy transferred per charge.
- Resistance is potential difference divided by current for a stated operating point.
- current: Rate of flow of charge.
- potential difference: Energy transferred per unit charge.



An ammeter goes in series to measure current; a voltmeter goes in parallel across the component

■ Choose evidence that can test it

- Current is the same through components in series.
- Potential differences add around the series path.
- In parallel, branches share the same potential difference, while branch currents sum at a junction.

In the lab: Place an ammeter in series and a voltmeter in parallel. For an I-V investigation, change voltage in steps, reverse polarity when appropriate and limit current to reduce heating.

■ Work from known quantities

- Known: a resistor has 6.0 V across it and carries 0.30 A.
- Use $R = V/I$.
- $R = 6.0/0.30 = 20$ ohms.
- Power = VI .
- Power = $6.0 \times 0.30 = 1.8$ W.
- These quantities describe the same operating point.

Your turn: A component has 12 V across it and carries 0.40 A. Find resistance.

■ Check the conclusion and its limits

- Current is not used up by a lamp.
- A filament heats up, so its resistance need not remain constant as voltage changes.

Not true: A lamp uses up electric current as charge passes through it. Current is a flow of charge, and charge is conserved: the same current enters and leaves a lamp. The lamp transfers energy from the charges to heat and light; it does not consume the charges.

Key:

- Current is charge passing per time.
- Current is the same through components in series.
- Watch for: current is not used up by a lamp.

■ Write from a resistance of 24 ohms

- A component has 12 V across it and carries 0.50 A.
- Find the resistance and the power. A lamp does not use up current.

■ **Write from a power of 6.0 watts**

- A component has 12 V across it and carries 0.50 A.
- $P = VI = 6.0 \text{ W}$, checked by $P = I^2 R = 0.25 \times 24 = 6.0 \text{ W}$ – two routes, one answer.

■ **Write from a series total of 15 ohms**

- A 6-ohm and a 9-ohm resistor connect in series, then in parallel.
- Series: 15 ohm (one current); parallel: $54 \div 15 = 3.6 \text{ ohm}$ – series adds resistances, parallel adds conductances.

Simple harmonic motion

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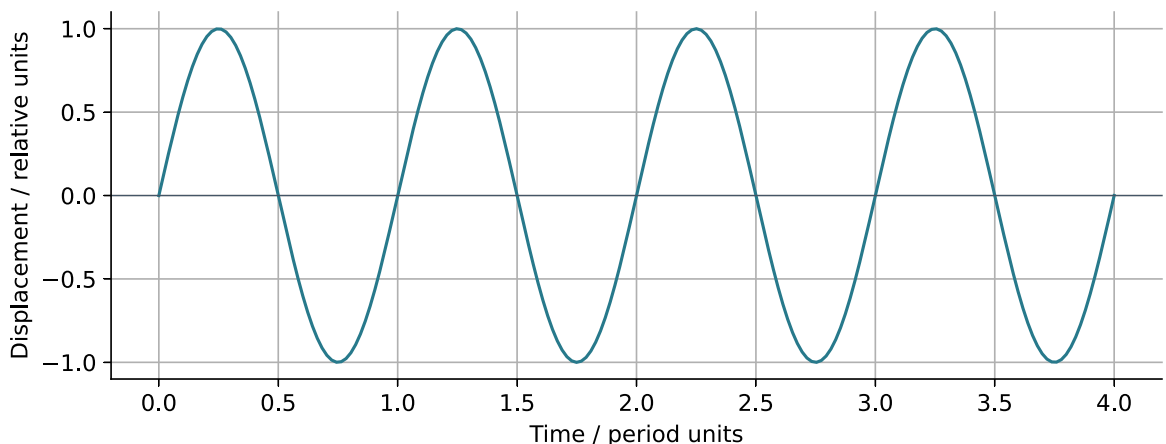
Oscillation, resonance and phase

■ What would explain this observation?

- A swing gains a large amplitude when pushes arrive with the right timing. The forcing frequency and **damping** help determine the response.
-

■ Build the model

- Simple harmonic motion has acceleration proportional to displacement and directed toward equilibrium.
- Period is time per cycle; frequency is its reciprocal.
- Damping transfers energy away from the oscillating system.
- **resonance**: A large response to periodic forcing near a natural frequency.
- **damping**: Energy transfer out of an oscillating system.



One complete oscillation takes one period T ; $f = 1/T$

■ Choose evidence that can test it

- Velocity is greatest near equilibrium for ideal SHM, while acceleration magnitude is greatest at extreme displacement.
- Resonance can occur near the natural frequency under periodic driving, with amplitude limited by damping.

In the lab: Measure time for several complete oscillations and divide. Define a cycle consistently and use a small displacement when the model requires it. Keep pendulum paths clear and record damping effects rather than assuming perfect motion.

■ Work from known quantities

- Known: 20 cycles take 32 s.
- $T = \text{total time} / \text{cycles} = 32 / 20 = 1.6 \text{ s}$.
- Frequency $= 1/T = 1/1.6 = 0.625 \text{ Hz}$.
- A shorter total timing interval would make reaction-time error a larger fraction of the measurement.

Your turn: 30 cycles take 45 s. Find period.

■ Check the conclusion and its limits

- Not every repeated motion is SHM.
- A force proportional to displacement but directed away from equilibrium does not produce SHM.

Not true: Every periodic motion satisfies the condition for simple harmonic motion. SHM needs a restoring force proportional to displacement and directed TOWARD equilibrium. Motion that merely repeats - a bouncing ball, a circular orbit - is periodic without satisfying that condition.

Key:

- Simple harmonic motion has acceleration proportional to displacement and directed toward equilibrium.
- Velocity is greatest near equilibrium for ideal SHM, while acceleration magnitude is greatest at extreme displacement.
- Watch for: not every repeated motion is SHM.

■ Write from a period of 2.5 s

- 20 cycles take 50 s.
- Find the period and the frequency. Not every periodic motion is simple harmonic.

■ **Write from a frequency of 2.5 hertz**

- A pendulum completes 10 cycles in 4.0 s.
- Period = 0.40 s, frequency = $1 \div 0.40 = 2.5 \text{ Hz}$ – count cycles, divide time, invert.

■ **Write from a defining SHM check**

- A small-angle pendulum and a bouncing ball are both periodic.
- Only the pendulum is SHM: restoring force proportional to displacement, directed toward equilibrium – periodicity alone is not the criterion.

■ **Write from a frequency doubled**

- A simple pendulum's length is quartered.
- $T \propto \sqrt{L}$, so T halves and frequency doubles – the square root is the whole trick.

Wave model

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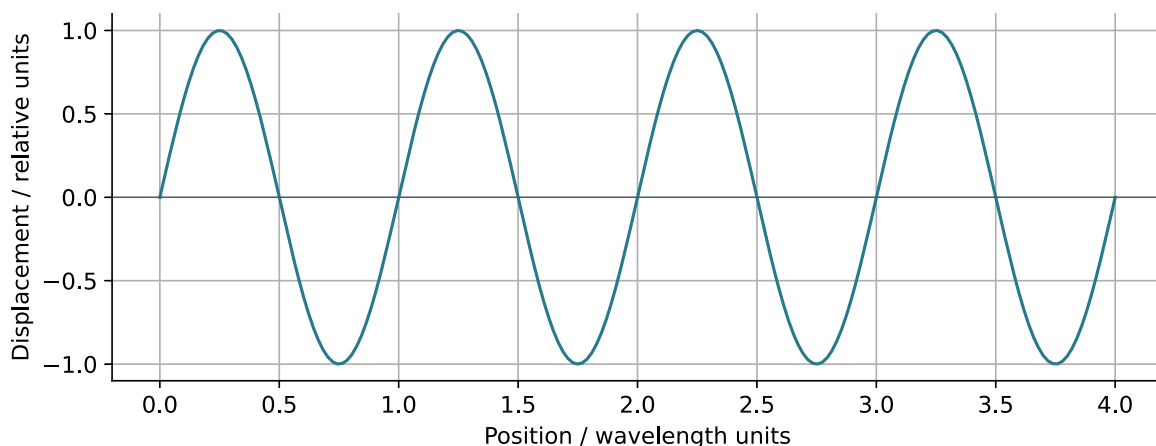
Waves, measurement and refraction

■ What would explain this observation?

- A wave can carry energy across water while a floating marker mainly oscillates. Energy transfer and bulk transfer of matter are different.
-

■ Build the model

- **Frequency** is oscillations per time; **wavelength** is distance between successive points in phase.
- Wave speed equals frequency multiplied by wavelength.
- Transverse oscillations are perpendicular to propagation.
- wavelength: Distance between successive points in phase.
- frequency: Number of oscillations per unit time.



One wavelength is the length of one complete cycle; $v = f\lambda$

■ Choose evidence that can test it

- At a boundary, frequency stays fixed by the source.
- A change of speed changes wavelength.
- Refraction follows from speed differences; angles are measured from the normal.

In the lab: Measure several wavelengths and divide to reduce fractional reading uncertainty. Use a ray box with a normal drawn at the boundary. Keep the beam away from eyes and record incident and refracted angles clearly.

■ Work from known quantities

- Known: frequency 5 Hz and wavelength 0.40 m.
- Use $v = f\lambda$. $v = 5 \times 0.40 = 2.0$ metres per second.
- If speed falls to 1.5 metres per second at the same frequency, wavelength = $v/f = 1.5/5 = 0.30$ m.

Your turn: Frequency is 8 Hz and wavelength is 0.25 m. Find wave speed.

■ Check the conclusion and its limits

- The wave frequency does not change simply because the medium changes.
- A longitudinal wave has oscillations parallel to propagation.

Not true: Wave frequency always changes when a wave enters a new medium. Frequency is fixed by the source, so it stays the same across a boundary. What changes is speed, and therefore wavelength through $v = f \times \text{wavelength}$.

Key:

- Frequency is oscillations per time; wavelength is distance between successive points in phase.
- At a boundary, frequency stays fixed by the source.
- Watch for: the wave frequency does not change simply because the medium changes.

■ Write from a wave speed of 4.8 metres per second

- Frequency is 12 Hz and wavelength is 0.40 m.
- Find the wave speed. If the speed becomes 3.6 metres per second at a boundary, find the new wavelength. Frequency stays the same.

■ **Write from a time delay of 1.5 seconds**

- Lightning is seen; thunder arrives 1.5 s later (sound at 340 m s^{-1}).
- Distance = $340 \times 1.5 = 510 \text{ m}$ – light’s travel time is negligible at this scale, so the delay IS the sound’s travel time.

■ **Write from a boundary sentence**

- A wave passes into a slower medium.
- One sentence, four facts: frequency unchanged (set by the source), speed falls, wavelength shortens, the ray bends toward the normal.

C.3 Wave phenomena

International Baccalaureate · IB Diploma · Physics · SL

Scope and prerequisites

Full guide C.3 scope (Wave phenomena), first assessment 2025. Read directly from the Physics guide, pages 47–48. Prerequisites: C.2 ($v = f\lambda$, 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**

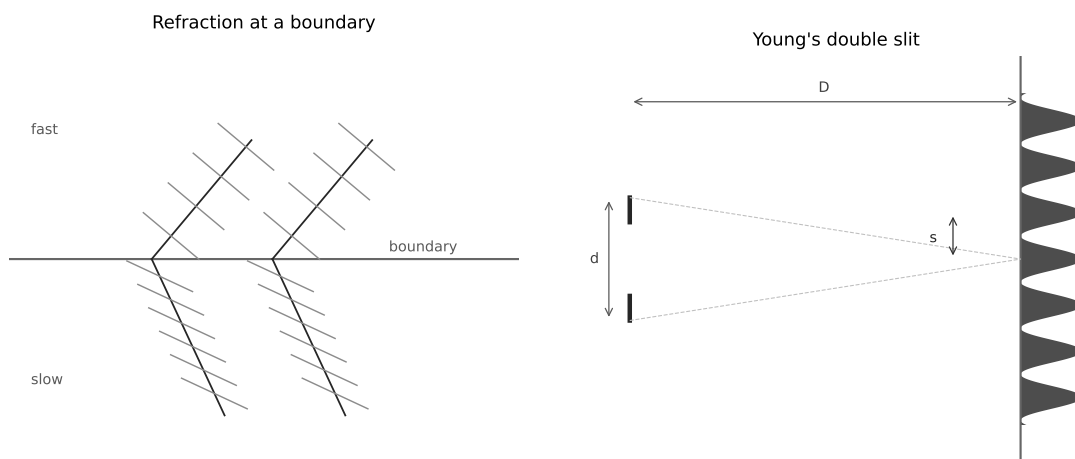
reflection (TIR), the principle of optical fibres.

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 $\theta_2 = 25^\circ$ – 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 $\theta_c = 42^\circ$. 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.



Wavefronts refracting at a boundary (left) and the geometry of Young's double-slit fringes (right).

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:

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

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 = 2λ 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.

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 with green light gives fringes 4.0 mm apart. Estimate the new separation with blue light of half the wavelength.

Answers: 1 a line of points in phase, one wavelength apart; the ray is everywhere perpendicular to the wavefronts and shows travel direction; 2 $\sin \theta_2 = (1.0/1.3) \sin 50^\circ = 0.588$, $\theta_2 = 36^\circ$; 3 travel from a slower (higher- n) medium toward a faster one at more than the critical angle; beyond it the surface mirrors totally; 4 sound (metre wavelengths, comparable with the doorway) diffracts strongly around the opening; light (hundreds of nanometres) spreads negligibly; 5 path difference 0.03 m = $\frac{1}{2}(0.060$ m)

– destructive; 6 $s \propto D/d$: four times wider; 7 $s \propto \lambda$, so 2.0 mm.

■ **Write from a critical angle**

- Light travels from glass ($n = 1.5$) toward air.
- The critical angle satisfies $\sin \theta_c = 1 \div 1.5 = 0.667$, so $\theta_c \approx 41.8^\circ$ – beyond it, every ray reflects totally back: the fibre-optic condition.

■ **Write from a boundary sentence**

- A wave passes into a slower medium.
- One sentence, four facts: frequency unchanged (set by the source), speed falls, wavelength shortens, the ray bends toward the normal.

C.4 Standing waves and resonance

International Baccalaureate · IB Diploma · Physics · SL

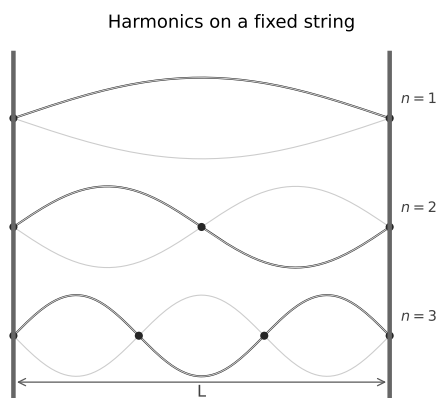
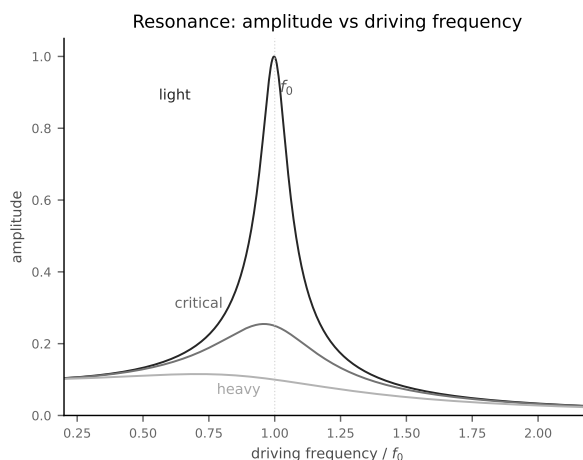
Scope and prerequisites

Full guide C.4 scope (Standing waves and resonance), first assessment 2025. Read directly from the Physics guide, pages 48–49. Prerequisites: C.1 (oscillation vocabulary) and C.3 (superposition).

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

Standing waves: superposition of opposites

Two **identical waves travelling in opposite directions** – usually a wave and its reflection – superpose into a **standing wave** : the pattern stays put while the medium oscillates inside it. Where the two always cancel there is a **node** (zero displacement); where they always reinforce there is an **antinode** (maximum amplitude). Two points between neighbouring nodes oscillate **in phase** ; points on opposite sides of a node are in **antiphase** – unlike a travelling wave, the phase does not march along.



First three harmonics on a string fixed at both ends, and the resonance curves of a driven oscillator under light, critical and heavy damping.

Boundary conditions: strings and pipes

The ends decide which wavelengths fit. A fixed string end (or the closed end of a pipe) must be a displacement **node**; a free string end (or the open end of a pipe) must be an **antinode**. Pipes are described in displacement terms only (pressure nodes are not required, and no end corrections).

Boundaries	Allowed wavelengths	Harmonic frequencies
Fixed–fixed string; closed–closed pipe (node–node)	$\lambda_n = 2L/n$	$f_n = nv/2L$
Fixed–free string; closed–open pipe (node–antinode)	$\lambda_n = 4L/(2n - 1)$	$f_n = (2n - 1)v/4L$ – odd harmonics only
Free–free string; open–open pipe (antinode–antinode)	$\lambda_n = 2L/n$	$f_n = nv/2L$

The lowest-frequency mode is the **first harmonic** (the terms "fundamental" and "overtone" are not used in this course). Determining the wavelength and frequency of the n th harmonic from the length and wave speed is a required skill.

Worked check (string). A string of length 0.60 m carries waves at 240 m/s. First harmonic: $\lambda_1 = 2L = 1.2$ m, $f_1 = v/2L = 240/1.2 = 200$ Hz; the second harmonic doubles to 400 Hz, the third to 600 Hz.

Worked check (closed–open pipe). A pipe closed at one end, open at the other, length 0.40 m, air at 340 m/s: $f_1 = v/4L = 340/1.6 = 213$ Hz; the next harmonic is the third, $f_3 = 3f_1 = 638$ Hz – even harmonics cannot form.

Worked check (open–open pipe). The same pipe opened at both ends: $f_1 = v/2L = 340/0.80 = 425$ Hz, an octave above the closed–open first harmonic, and every harmonic is allowed.

Resonance and damping

Every elastic system has a **natural frequency** – the rate at which it oscillates when left alone. Drive it with a periodic force and the response depends on the **driving frequency** : when the driving frequency approaches the natural frequency the amplitude grows sharply – **resonance** . Energy arrives at exactly the rate the system can absorb it, so the amplitude at resonance is limited only by how fast energy dissipates.

Damping – the removal of oscillation energy – reshapes the response: it lowers the maximum amplitude, shifts the resonant peak slightly below the natural frequency, and broadens it.

- **Light damping** – a tall, sharp peak; large resonant amplitude (a swing pushed gently at its natural frequency).
- **Critical damping** – the oscillation dies away in the shortest time without passing the equilibrium point; the resonance peak has effectively vanished (car suspension).

- **Heavy damping** – slow, sluggish return; the system barely responds at any driving frequency (a heavy door closer).

Resonance is wanted and engineered (musical instruments, radio tuning, MRI) and unwanted or destructive (the Tacoma Narrows bridge, machinery shaking itself apart, soldiers breaking step on a bridge) – the guide asks for both sides.

Check yourself

1. State how a standing wave forms, and why nodes stay fixed while the medium between them moves.
2. Two points on a standing wave lie either side of a node, each 0.15 m from it. State their phase difference.
3. A string fixed at both ends is 0.75 m long and carries waves at 150 m/s. Calculate the first and second harmonic frequencies.
4. Explain why a closed–open pipe produces only odd harmonics.
5. A pipe of length 0.50 m is open at both ends; the air speed is 340 m/s. Calculate the first harmonic frequency and the wavelength of the second harmonic.
6. Sketch or describe how the resonance curve of a lightly damped system changes as damping increases.
7. Give one useful and one destructive effect of resonance, with the physical reason each happens.

Answers: 1 two identical waves travelling in opposite directions superpose; at a node their displacements always cancel, so it never moves, while between nodes the superposition oscillates; 2 antiphase – 180° (π rad) apart; 3 $f_1 = v/2L = 150/1.5 = 100$ Hz, $f_2 = 200$ Hz; 4 the closed end must be a node and the open end an antinode, so only an odd number of quarter-wavelengths fits – even harmonics cannot meet both conditions; 5 $f_1 = v/2L = 340/1.0 = 340$ Hz; $\lambda_2 = L = 0.50$ m; 6 the peak falls, broadens, and shifts slightly below the natural frequency; 7 useful – a radio circuit tuned to resonance picks one station out of many because it responds only near its natural frequency; destructive – driving at the natural frequency feeds energy in faster than it dissipates, so the amplitude grows until the structure fails.

Doppler effect

International Baccalaureate · IB Diploma · Physics · SL

Scope and prerequisites

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Prerequisites: read the stated quantities and units, and use arithmetic and the model conditions below.

The examples are original and fictional: they are not real measurements or real student investigations.

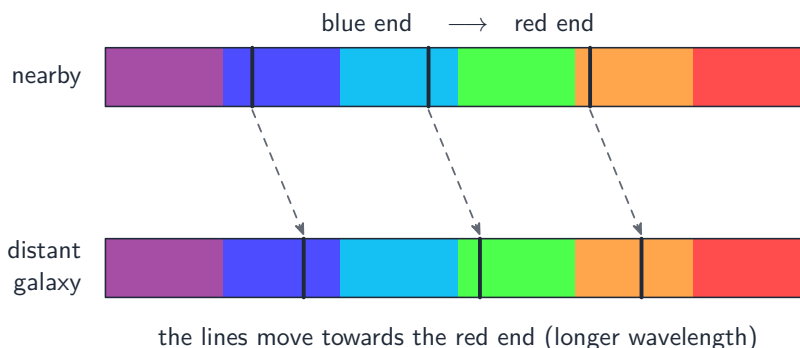
Spectral shifts: a low-speed astronomical estimate

■ What would explain this observation?

- A recognizable spectral line appears at a longer wavelength in a distant source. Its shift can provide evidence of recession along the line of sight.

■ Build the model

- Relative source-observer motion changes observed frequency or wavelength.
- For light at a relative speed much smaller than c , the magnitude of the fractional wavelength shift is approximately v/c .
- Recession corresponds to longer wavelength, and approach to shorter wavelength.
- **redshift** : Shift of an identified line toward longer wavelength.
- **rest wavelength** : Wavelength of the line measured with no relative source motion.



Every line shifts towards longer wavelength: $z = \Delta\lambda/\lambda$, and $v \approx cz$ at low speed

■ Choose evidence that can test it

- Compare a identified line with its laboratory rest wavelength.
- Use $z = (\text{observed} - \text{rest})/\text{rest}$, then v approximately cz in the stated low-speed model.
- Do not apply this approximation without checking the regime or treating a cosmological redshift as a simple exact velocity.

In the lab: Use attributed spectra with calibration and line identification. Compare several lines for a consistent shift. State uncertainty and distinguish relative line-of-sight motion from an unmeasured transverse component.

■ Work from known quantities

- Known: a 500 nm rest line is observed at 501 nm. $z = (501 - 500)/500 = 0.002$.
- With $c = 3.0 \times 10^8$ m/s, v approximately 6.0×10^5 m/s away.
- The sound-source denominator formula is not the required SL light approximation.

Your turn: A 600 nm rest line is observed at 601.2 nm. Find $z = (\text{observed} - \text{rest})/\text{rest}$.

■ Check the conclusion and its limits

- The approximate shift relation does not show that light travels faster from an approaching source.
- A single unidentified line cannot safely establish a redshift.

Not true: An observed redshift means light speed increased. Light speed in vacuum is the same for all observers. Redshift is a change in observed wavelength from relative motion (or expanding space), not light travelling faster or slower.

Key:

- Relative source-observer motion changes observed frequency or wavelength.
- Compare a identified line with its laboratory rest wavelength.
- Watch for: the approximate shift relation does not show that light travels faster from an approaching source.

■ Write from a redshift of 0.005

- A 500 nm rest line is observed at 502.5 nm.
- Find z . Redshift does not mean the speed of light increased.

■ **Write from a blue shift of 0.001**

- A 600 nm rest line is observed at 599.4 nm.
- $z = (599.4 - 600) \div 600 = -0.001$, so $v \approx 0.001c = 3.0 \times 10^5 \text{ m s}^{-1}$ TOWARD the observer – the sign carries the direction.

■ **Write from a unit check on z**

- A worksheet quotes $z = 0.002$ “nanometres”.
- $z = \Delta\lambda \div \lambda$ is a ratio with NO units: quote v as a fraction of c first ($0.002c$), converting to metres per second only at the end.

Gravitational fields

International Baccalaureate · IB Diploma · Physics · SL

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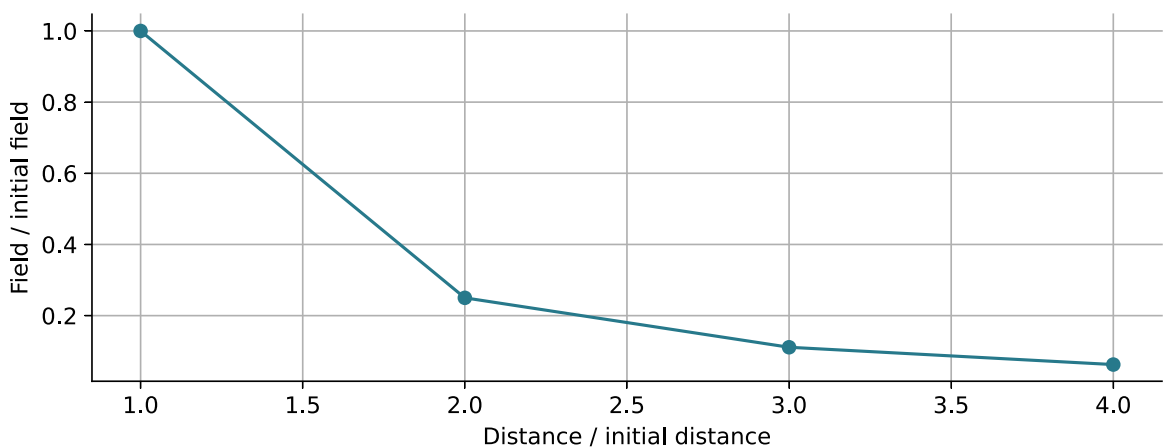
Gravitational fields and orbital motion

■ What would explain this observation?

- An orbiting satellite is continuously falling while moving sideways. Being in orbit does not require gravity to vanish.

■ Build the model

- **Gravitational field** strength is force per unit mass.
- A gravitational force can provide the **centripetal force** for a circular orbit.
- Field and potential describe different quantities.
- gravitational field: A description of gravitational force per unit mass.
- centripetal force: Net force toward the centre of a curved path.



Inverse square: double the distance and the field falls to a quarter

■ Choose evidence that can test it

- For a point mass or outside a spherical mass, field strength follows an inverse-square distance dependence.
- Use distance from the centre, not height above the surface alone.

In the lab: State the circular-orbit approximation and ignore atmospheric drag only when justified. Draw the force toward the central body and velocity tangential to the orbit. Do not add an outward force merely because the path is circular.

■ Work from known quantities

- Known: field strength is 8 units at distance r from a spherical source.
- At $2r$, $g_2/g_1 = (r/2r)^2 = 1/4$. $g_2 = 8/4 = 2$ units.
- The gravitational force on a fixed test mass decreases in the same ratio.

Your turn: Field strength is 18 units at r . Find it at $3r$ for an inverse-square field.

■ Check the conclusion and its limits

- Weightlessness in an orbiting spacecraft means apparent weight is small in free fall, not that there is no gravitational field.

Not true: Gravity is zero everywhere a spacecraft experiences apparent weightlessness. An orbiting spacecraft is in free fall: gravity is nearly as strong there as on the ground and supplies the centripetal force. Crew and craft fall together, so nothing presses them down - that is apparent weightlessness, not zero gravity.

Key:

- Gravitational field strength is force per unit mass.
- For a point mass or outside a spherical mass, field strength follows an inverse-square distance dependence.
- Watch for: weightlessness in an orbiting spacecraft means apparent weight is small in free fall, not that there is no gravitational field.

■ Write from a field strength of 4 units

- An inverse-square field has strength 36 units at distance r .
- Find the strength at $3r$. Apparent weightlessness in orbit is not zero gravity.

■ Write from a tripling

- The field strength is 12 units at distance r from a spherical source.
- At $3r$: $g = 12 \div 9 \approx 1.3$ units – inverse-SQUARE, so a tripled distance divides by nine, not three.

■ **Write from a faster inner orbit**

- Two circular orbits, one at half the radius of the other.
- $v^2 = GM/r$, so the inner satellite moves FASTER – gravity must supply more centripetal force closer in.

■ **Write from a weight on Mars**

- Surface gravity on Mars is about 3.7 N kg^{-1} ; an astronaut has mass 60 kg.
- Weight there = $60 \times 3.7 = 222 \text{ N}$, against $60 \times 9.8 \approx 588 \text{ N}$ on Earth – MASS is constant, weight is local.

Electric and magnetic fields

International Baccalaureate · IB Diploma · Physics · SL

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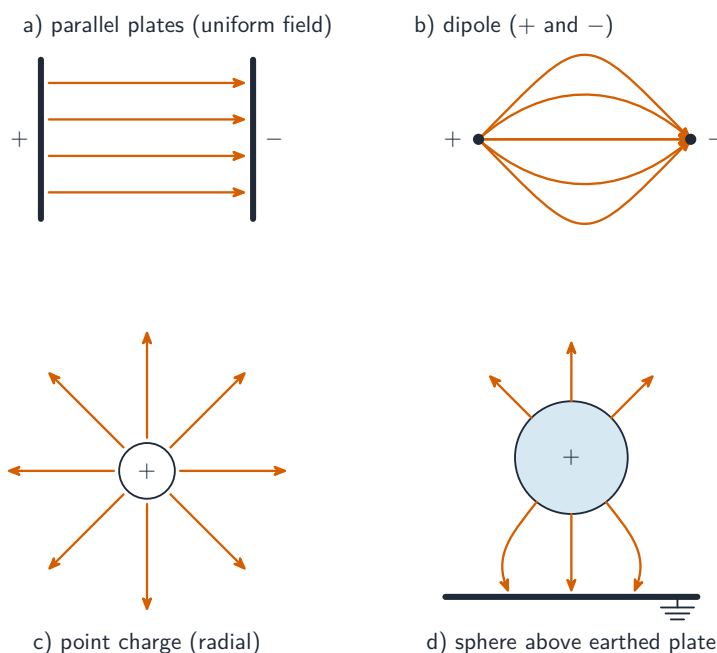
Electric fields: force and a positive test charge

■ What would explain this observation?

- A negatively charged particle experiences an electric force opposite to the field direction. Field direction is defined using a positive **test charge**.
-

■ Build the model

- **Electric field strength** is force per unit positive test charge.
- Like charges repel and unlike charges attract.
- Field lines point away from positive charges and toward negative charges.
- Closely spaced lines represent a stronger field within a consistently drawn diagram.
- electric field strength: Electric force per unit positive test charge.
- test charge: A small charge used to probe an electric field.



Field lines run from positive to negative; between parallel plates they are evenly spaced, so the field is uniform

■ Choose evidence that can test it

- In a uniform field between ideal parallel plates, $E = V/d$ away from edge effects.
- The force is $F = qE$, so its direction reverses for a negative charge.
- Coulomb force between ideal point charges decreases with separation squared.

In the lab: Sketch labelled plate polarities, field arrows and the charge before calculating. Convert separation to metres. In school, use simulations or approved low-voltage electrostatic models rather than exposed high-voltage equipment.

■ Work from known quantities

- Known: plate potential difference is 120 V and separation is 0.020 m.
- $E = V/d = 6,000 \text{ V/m}$.
- A +2.0 microcoulomb charge experiences $F = qE = 0.012 \text{ N}$ along the field; a -2.0 microcoulomb charge experiences the same magnitude opposite to it.

Your turn: Use $E = V/d$. Find E for 100 V across 0.025 m.

■ Check the conclusion and its limits

- Field strength is a vector.
- Potential difference is energy per charge and is not the same quantity.
- A field-line drawing is a model, not a set of physical threads.

Not true: Every charged particle experiences a force along the electric field direction. Field direction is defined by the force on a POSITIVE charge. A negative particle feels a force opposite to the field, so the field direction is not every particle's force direction.

Key:

- Electric field strength is force per unit positive test charge.
- In a uniform field between ideal parallel plates, $E = V/d$ away from edge effects.
- Watch for: field strength is a vector.

■ Write from a field of 3000 volts per metre

- A potential difference of 60 V is across a gap of 0.020 m.
- Find the electric field strength. A negative charge feels the opposite force.

■ Write from an energy gain of 3.2 times ten to the minus 17 joules

- A proton (charge 1.6×10^{-19} C) accelerates through 200 V.
- Energy = $qV = 3.2 \times 10^{-17}$ J = 200 eV – the volt is energy per unit charge, so a 200 V gap gives a proton exactly 200 eV.

■ Write from a zero-work path

- A charge moves along an equipotential surface.
- $\Delta V = 0$, so the energy change $q\Delta V = 0$ – the field does no work; motion perpendicular to field lines changes nothing.

■ Write from a force pair in one field

- Between plates with $E = 6,000$ V per metre, charges of +2.0 and –2.0 micro-coulombs sit in turn.
- Each feels a 0.012 N force – SAME size, opposite directions: the field acts on the charge, never for it.

■ Write from a field between plates

- Parallel plates 0.040 m apart carry a potential difference of 160 V.
- $E = V \div d = 4,000$ V per metre, uniform between the plates – the field a charge feels everywhere in the gap.

Motion in electromagnetic fields

International Baccalaureate · IB Diploma · Physics · SL

Scope and prerequisites

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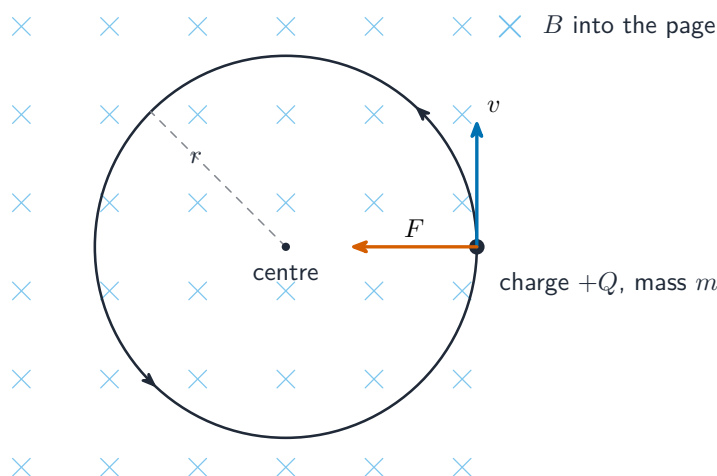
Magnetic forces: turn velocity without increasing speed

■ What would explain this observation?

- A charged particle curves in a uniform magnetic field. Its direction changes although the **magnetic force** alone does not increase its kinetic energy.
-

■ Build the model

- The magnetic force magnitude is $F = |q|vB \sin\theta$.
- It is perpendicular to velocity and magnetic field, with direction determined by charge sign.
- For perpendicular entry into a uniform field, it can provide the centripetal force for circular motion.
- **magnetic force**: Force due to a magnetic field on a moving charge or current.
- **momentum** : Mass multiplied by velocity in the classical model.



$$BQv = \frac{mv^2}{r} \Rightarrow r = \frac{mv}{BQ}$$

The magnetic force is always perpendicular to v , so it bends the path into a circle: $r = mv/(qB)$

■ Choose evidence that can test it

- Equate magnetic force with mv^2/r to obtain $r = mv/(|q|B)$ for perpendicular motion.
- A stronger field makes a smaller radius at fixed momentum.
- Parallel entry gives zero magnetic force in this model.

In the lab: Draw velocity, field and force as separate arrows using stated into/out-of-page conventions. Use supplied beam data or a simulation. Do not treat a current-carrying wire direction as identical to electron-motion direction.

■ Work from known quantities

- Known: a particle has $m = 2.0 \times 10^{-27}$ kg, $v = 3.0 \times 10^6$ m/s, $|q| = 1.0 \times 10^{-19}$ C and $B = 0.20$ T. $r = mv/(|q|B) = 0.30$ m.
- The calculation assumes non-relativistic motion and perpendicular entry.

Your turn: Use $r = mv/(|q|B)$. For $m = 2 \times 10^{-27}$ kg, $v = 2 \times 10^6$ m/s, $|q| = 1 \times 10^{-19}$ C and $B = 0.20$ T, find r .

■ Check the conclusion and its limits

- A magnetic force can change momentum direction without doing work.
- Adding an electric field can change the energy, so conclusions about a magnetic field alone do not cover every combined-field apparatus.

Not true: A magnetic force alone continuously increases the kinetic energy of a charged particle. A force perpendicular to the velocity does no work (work = force $\times$ distance ALONG the force), so a magnetic field alone cannot change a particle's kinetic energy - only its direction. Speeding up needs a field component along the motion, which only an electric field provides.

Key:

- The magnetic force magnitude is $F = |q|vB \sin\theta$.
- Equate magnetic force with mv^2/r to obtain $r = mv/(|q|B)$ for perpendicular motion.
- Watch for: A magnetic force can change momentum direction without doing work.

■ Write from an orbital radius of 0.50 m

- Use $r = mv$ divided by the product of charge magnitude and magnetic field.
- Take $m = 2$ times 10 to the minus 27 kg, $v = 2$ times 10 to the 6 metres per second, charge magnitude 1 times 10 to the minus 19 coulomb and $B = 0.08$ T. A magnetic force perpendicular to the velocity does no work.

■ Write from a doubled radius

- The same particle enters the same field at half the strength.
- $r = mv \div (qB)$, so halving B DOUBLES the radius – the spiral loosens as the field weakens.

■ Write from a speed-independent period

- A fast and a slow particle of equal mass orbit in the same field.
- $T = 2\pi m \div (qB)$ contains no v : the faster one travels a larger circle in the SAME time.

Structure of the atom

International Baccalaureate · IB Diploma · Physics · SL

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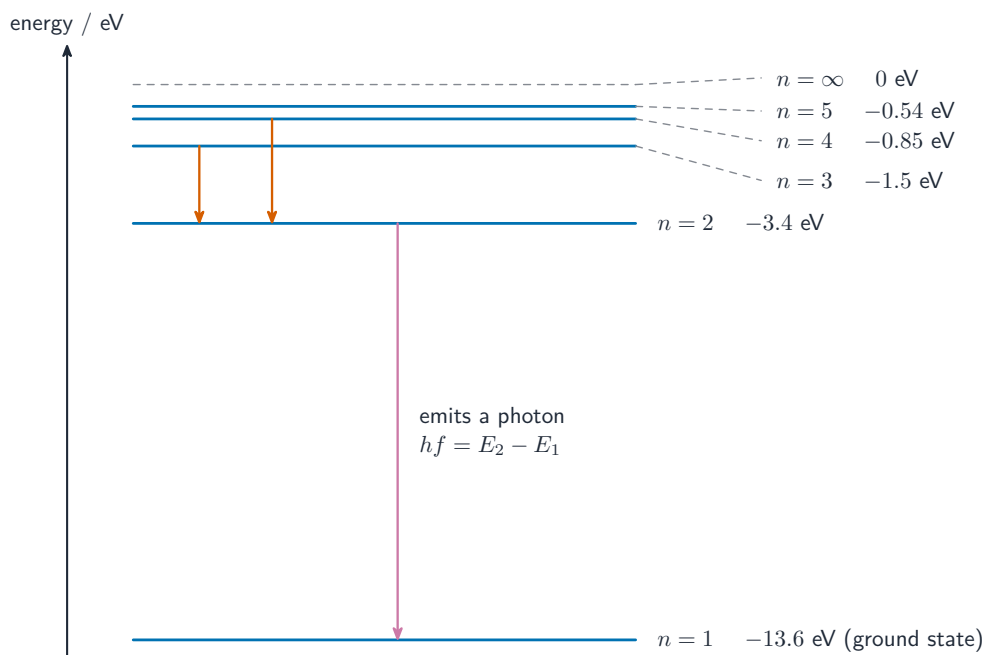
Atomic models and line spectra

■ What would explain this observation?

- An excited gas produces separate coloured lines rather than every wavelength. The pattern is evidence for discrete atomic energy differences.

■ Build the model

- Atoms have a small positive nucleus and electrons.
- Emission and absorption spectra arise from transitions between discrete **energy levels**.
- A photon energy equals the level difference and obeys $E = hf$.
- **emission spectrum** : Wavelength pattern of radiation emitted by a source.
- **energy level** : An allowed energy state in a model.



A downward transition emits one photon whose energy equals the level difference: $hf = E_2 - E_1$

■ Choose evidence that can test it

- An emitted photon corresponds to a transition to a lower energy level.
- Absorption requires a compatible energy difference.
- Rutherford scattering supported a small dense nucleus, but that experiment alone did not establish the complete quantum model.

In the lab: Read a labelled energy-level diagram before calculating. Keep joules and electronvolts distinct and use the given constants. Compare attributed spectra at a common wavelength scale and avoid looking at unsafe light sources.

■ Work from known quantities

- Known: energy levels are -6.0 and -2.0 eV.
- A downward transition releases $4.0 \text{ eV} = 6.4 \times 10^{-19} \text{ J}$ using $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.
- With $h = 6.4 \times 10^{-34} \text{ J s}$ for this rounded exercise, frequency is $1.0 \times 10^{15} \text{ Hz}$.

Your turn: Levels are -7.0 and -2.0 eV. Find the energy emitted in the downward transition.

■ Check the conclusion and its limits

- Negative bound-state energies are relative to a chosen zero; they do not mean a negative photon energy is emitted.
- A larger downward energy difference gives higher frequency.

Not true: A negative bound-state energy means an emitted photon has negative energy. Level energies are measured relative to a chosen zero (a free electron at rest), so bound states are negative. The photon energy is the positive DIFFERENCE between levels - differences of negative numbers are positive.

Key:

- Atoms have a small positive nucleus and electrons.
- An emitted photon corresponds to a transition to a lower energy level.
- Watch for: negative bound-state energies are relative to a chosen zero; they do not mean a negative photon energy is emitted.

■ Write from a photon energy of 6 electronvolts

- Levels are minus 9.0 and minus 3.0 electronvolts.
- Find the photon energy of the downward transition. A negative level does not make the photon energy negative.

■ Write from an ionisation energy read

- An energy level sits at -5.0 eV .
- Ionisation needs $+5.0 \text{ eV} = 8.0 \times 10^{-19} \text{ J}$ – the ground-state binding energy read backwards.

■ Write from a three-level count

- Levels at -5 , -3 and -1 eV .
- Transitions of 2, 4 and 2 eV – three transitions but only TWO distinct photon energies: count transitions, then count distinct lines.

Radioactive decay

International Baccalaureate · IB Diploma · Physics · SL

Scope and prerequisites

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Prerequisites: read the stated quantities and units, and use arithmetic and the model conditions below.

The examples are original and fictional: they are not real measurements or real student investigations.

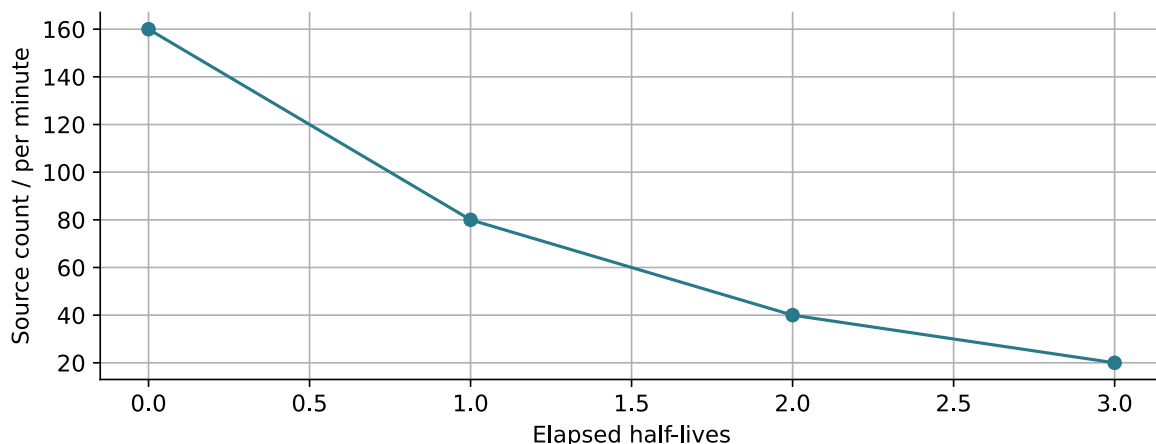
Nuclear changes and radiation evidence

■ What would explain this observation?

- A detector records counts even when the classroom source is removed. Background must be considered before attributing every count to the source.

■ Build the model

- Radioactive decay is spontaneous and random for an individual nucleus.
- **Half-life** describes the time for half the undecayed nuclei in a large population to decay, or for background-corrected activity to halve.
- half-life: Time for activity or undecayed population to halve.
- **background radiation** : Radiation measured apart from the investigated source.



Each half-life halves the count rate: $160 \rightarrow 80 \rightarrow 40 \rightarrow 20$

■ Choose evidence that can test it

- Subtract background counts measured over the same time interval.
- Distinguish irradiation from contamination.
- Shielding, distance and reduced exposure time can reduce risk under a school-controlled procedure.

In the lab: Use teacher-managed sources and the school radiation rules. Record count duration and repeat background measurements. Do not extrapolate a half-life from one nucleus or from uncorrected readings.

■ Work from known quantities

- Known: measured count rate falls from 100 to 55 counts per minute; background is 10.
- Source rates are 90 and 45, so one half-life has elapsed.
- Without subtraction, 55/100 would obscure the exact half in this example.

Your turn: An initial source count is 160 per minute. Find it after three half-lives.

■ Check the conclusion and its limits

- An irradiated object is not automatically radioactive.
- A half-life does not predict the exact decay time of one nucleus.

Not true: Half-life predicts the exact decay time of an individual nucleus. Radioactive decay is random at the level of single nuclei. Half-life is a statistical quantity: it predicts the fraction of a LARGE number of nuclei decaying in a given time, never the moment one nucleus will decay.

Key:

- Radioactive decay is spontaneous and random for an individual nucleus.
- Subtract background counts measured over the same time interval.
- Watch for: an irradiated object is not automatically radioactive.

■ Write from 50 counts per minute

- An initial source count is 200 per minute.
- Find the count after two half-lives. Half-life does not time one nucleus.

■ Write from two half-lives

- A source reads 160 counts per minute above background.
- After two half-lives: $160 \rightarrow 80 \rightarrow 40$ – each halving is independent of the last.

■ **Write from a background-subtracted table**

- Raw readings are 110 then 60, with background 10.
- Corrected: 100 then 50 – exactly one half-life; the raw ratio $60 \div 110 \approx 0.55$ would misjudge the decay.

■ **Write from a decay-curve read**

- A corrected count rate is 400 per minute and halves every 8 minutes.
- At 24 minutes: $400 \rightarrow 200 \rightarrow 100 \rightarrow 50$ – three half-lives, three halvings, and the curve never reaches zero.

Fission

International Baccalaureate · IB Diploma · Physics · SL

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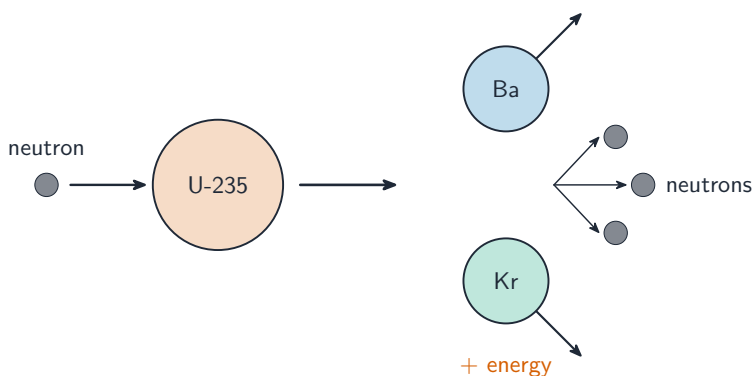
Fission : conserve charge and nucleons, account for energy

■ What would explain this observation?

- A neutron can trigger a heavy nucleus to split, releasing energy and further neutrons. Whether the process becomes a **chain reaction** depends on what happens to those neutrons.

■ Build the model

- In nuclear **fission** a heavy nucleus splits into lighter nuclei.
- Proton number and nucleon number balance in a nuclear equation.
- The total rest mass can decrease; the difference corresponds to released energy through $E = \Delta mc^2$.
- fission: Splitting of a heavy nucleus into lighter nuclei.
- chain reaction: A sequence in which products initiate further events.



Neutron in, two fragments and two or three neutrons out, with energy released

■ Choose evidence that can test it

- Separate conservation of nucleon number from conservation of total energy.
- Released neutrons may initiate further fissions, escape or be absorbed.
- A controlled reactor and an uncontrolled chain reaction have different neutron-management conditions.

In the lab: Balance a supplied nuclear equation, use the specified mass data and identify the system. Analyse models or published reactor data; this is not a school attempt to produce fission or handle reactor materials.

■ Work from known quantities

- Known: U-235 absorbs one neutron, forming Ba-141, Kr-92 and three neutrons.
- Nucleon balance: $235+1 = 141+92+3 = 236$.
- Proton balance: $92 = 56+36$.
- A mass decrease of 2.0×10^{-28} kg corresponds to 1.8×10^{-11} J using $c=3.0 \times 10^8$ m/s.

Your turn: A U-235 nucleus plus one neutron produces fragments with mass numbers 141 and 92. How many neutrons balance the equation?

■ Check the conclusion and its limits

- Mass number is not a precise mass in kilograms.
- Balanced integer labels alone do not calculate the released energy.
- Radioactive decay and neutron-induced fission are not interchangeable descriptions.

Not true: A balanced nucleon-number equation alone gives the energy release in joules. Integer mass and charge labels only check conservation; they say nothing about energy. The released energy comes from the small decrease in actual MASS via $E = mc^2$, which needs measured masses, not mass numbers.

Key:

- In nuclear fission a heavy nucleus splits into lighter nuclei.
- Separate conservation of nucleon number from conservation of total energy.
- Watch for: mass number is not a precise mass in kilograms.

■ Write from 2 balancing neutrons

- A U-235 nucleus plus one neutron produces fragments with mass numbers 140 and 94.
- Find how many neutrons balance the nucleon number. That count is not the energy release in joules.

■ **Write from a conserved check**

- U-235 absorbs a neutron: Xe-140 + Sr-94 + two neutrons.
- Nucleons: $236 = 140 + 94 + 2$. Protons: $92 = 54 + 38$. BOTH balances must hold – if either fails, the equation is wrong.

■ **Write from a mass-defect direction**

- Fission products are weighed against the reactants.
- The products weigh LESS: the missing mass appears as energy through $E = \Delta mc^2$, because binding energy per nucleon rises toward iron.

Fusion and stars

International Baccalaureate · IB Diploma · Physics · SL

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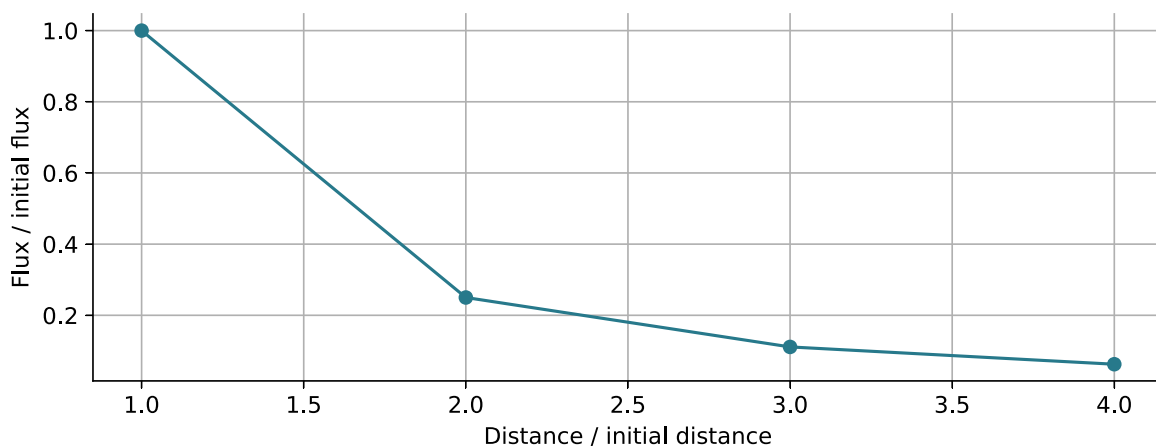
Stars, radiation and scale

■ What would explain this observation?

- Two stars can have the same apparent brightness while having different luminosities. Distance changes the **flux** reaching an observer.
-

■ Build the model

- **Luminosity** is total power emitted; flux is power received per area.
- A stellar spectrum carries information about surface temperature and composition.
- Fusion transfers energy as light nuclei combine.
- luminosity: Total emitted power.
- flux: Power received per unit area.



Inverse square: the same power spread over $4\pi d^2$, so twice as far gives a quarter of the flux

■ Choose evidence that can test it

- For isotropic emission without absorption, flux follows an inverse-square relationship with distance.
- Observed brightness alone therefore cannot establish luminosity.

In the lab: Keep distance units consistent, identify which quantities are intrinsic to the star, and distinguish observational evidence from a model of stellar evolution. Do not confuse a red giant stage with every possible final remnant.

■ Work from known quantities

- Known: distance doubles while luminosity remains fixed.
- Use F proportional to $1/d^2$.
- Flux ratio = $1/2^2 = 1/4$.
- A flux of 12 units becomes 3 units.
- This assumes no change in absorption or source output.

Your turn: A source gives flux 18 units. Find flux at three times the distance.

■ Check the conclusion and its limits

- The Sun is not expected to become a supernova.
- Redshift can support cosmological expansion; it does not mean every nearby object must move away from every observer.

Not true: Apparent brightness alone always determines a star luminosity. Apparent brightness depends on distance as well as luminosity ($F = L/4\pi d^2$). A dim-looking star may be very luminous but far away, so brightness alone cannot fix luminosity without a distance.

Key:

- Luminosity is total power emitted; flux is power received per area.
- For isotropic emission without absorption, flux follows an inverse-square relationship with distance.
- Watch for: the Sun is not expected to become a supernova.

■ Write from a flux of 8 units

- A source gives flux 32 units.
- Find the flux at twice the distance. Apparent brightness alone does not give luminosity.

■ **Write from a distance tripled**

- A source gives flux 45 units at distance d .
- At $3d$: $45 \div 9 = 5$ units – the inverse-square law, one more time.

■ **Write from an apparent-brightness trap**

- Sirius outshines Betelgeuse in our sky, yet Betelgeuse emits far more light.
- Apparent brightness folds in distance ($F = L \div 4\pi d^2$) – “brightest in the sky” is a claim about d as much as L .

■ **Write from a luminosity comparison**

- Star A delivers twice the Sun’s power at twice the Sun’s distance.
- Its flux here $= 2 \div 2^2 =$ half the Sun’s – luminosity is emission; flux is what ARRIVES, divided by $4\pi d^2$.

Experimental programme

International Baccalaureate · IB Diploma · Physics · SL

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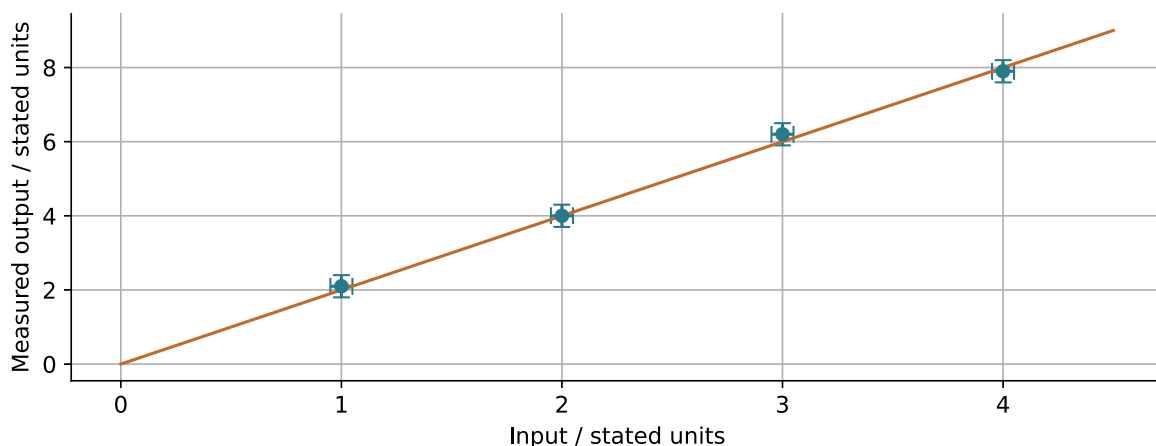
Uncertainty, gradients and model testing

■ What would explain this observation?

- A line passing near every data point is useful, but its gradient can still be uncertain. A graph is evidence for a model within the measurement range.
-

■ Build the model

- Random variation makes repeated readings differ.
- **Systematic error** shifts results consistently.
- Absolute **uncertainty** has the measured unit; relative or percentage uncertainty compares uncertainty with the measured value.
- uncertainty: A quantified limitation on a measured result.
- systematic error: A consistent measurement bias.



Every point lies within its uncertainty of the line of best fit

■ Choose evidence that can test it

- For a product or quotient, adding fractional uncertainties is a common maximum-uncertainty approximation.
- For a difference, add absolute uncertainties.
- A nonzero intercept can reveal an offset or an incomplete model.

In the lab: Show units on axes and choose a sensible scale. Plot uncertainty bars where justified, draw a best-fit line rather than joining every point, and estimate steepest and shallowest plausible gradients when the course method calls for them.

■ Work from known quantities

- Known: length = 50.0 mm with uncertainty 1.0 mm.
- Percentage uncertainty = absolute uncertainty/value $\times 100 = 1.0/50.0 \times 100 = 2.0\%$.
- For a quotient of two independently measured quantities with maximum percentage uncertainties 2% and 3%, the summed maximum estimate is 5%.

Your turn: A 40 cm reading has an absolute uncertainty of 1 cm. Find percentage uncertainty.

■ Check the conclusion and its limits

- Repeating readings reduces random uncertainty in a mean but does not automatically remove a zero error.
- Do not quote more decimal places than your measurement can support.

Not true: Repeating a measurement always removes a calibration offset. Repeating and averaging reduces RANDOM scatter in the mean. A calibration offset shifts every reading identically, so repeats land on the same wrong value; only recalibration removes it.

Key:

- Random variation makes repeated readings differ.
- For a product or quotient, adding fractional uncertainties is a common maximum-uncertainty approximation.
- Watch for: repeating readings reduces random uncertainty in a mean but does not automatically remove a zero error.

■ Write from a percentage uncertainty of 4 percent

- A 50 cm reading has an absolute uncertainty of 2 cm.
- Find the percentage uncertainty. Repeating the reading does not remove a calibration offset.

■ **Write from a product uncertainty**

- Two measured factors carry 3% and 4% maximum uncertainties.
- The product carries $3 + 4 = 7\%$ – percentage uncertainties ADD for products and quotients.

■ **Write from a repetition gain**

- A measurement is repeated four times and averaged.
- The mean's random uncertainty falls to about half a single reading's – but repetition never touches a SYSTEMATIC error: a zero error repeats too.