

2 · Waves and Electricity

Pearson Edexcel · International A-Level · Physics

From a phone signal to its battery

Your phone receives waves and uses electrical energy. These seem different, but both depend on energy transfer. **Waves** carry energy without carrying matter along with them. A circuit transfers energy through moving charge.

This reference covers **WPH12 Waves and Electricity**, specification statements 33–80. The paper lasts 90 minutes and carries 80 marks. Use the formula list to support your reasoning. Explain why an equation fits the situation, show conversions, and finish comparisons with a conclusion.

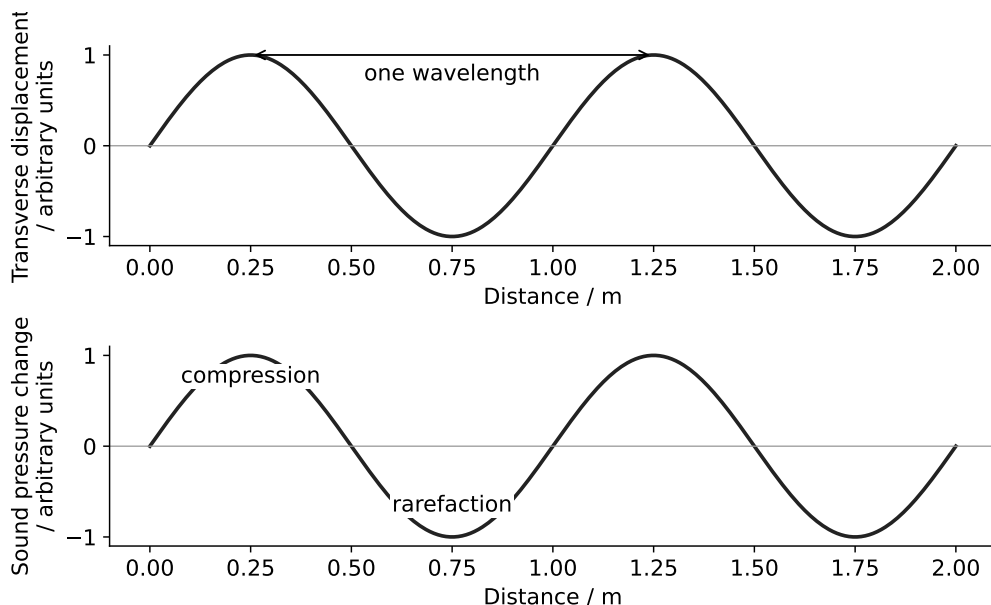
Wave quantities and graphs

A vibrating source repeats its motion. The **amplitude** is the greatest displacement from equilibrium. **Equilibrium** means the resting position. The **period** T is the time for one complete vibration. The **frequency** f is the number of complete vibrations each second; its unit is hertz, Hz.

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

The **wavelength** λ is the distance between nearest points vibrating in phase. The **wave speed** v is the speed at which a fixed phase, such as a crest, travels. It is not the speed of a vibrating particle.

- A **transverse wave** has vibrations perpendicular to its direction of travel. A rope moves up and down while its disturbance travels along the rope.
- A **longitudinal wave** has vibrations parallel to its direction of travel. Sound has **compressions**, where pressure and density are higher, and **rarefactions**, where they are lower.
- Air molecules move back and forth about their resting positions. They do not travel from the speaker to your ear with the sound.



Distance graphs show a whole wave at one instant.

■ Read the horizontal axis first

A displacement–distance graph is a snapshot. The separation of neighbouring crests gives λ . A displacement–time graph follows one particle. The separation of neighbouring peaks gives T . The same curve shape can represent either graph, but the quantities are different.

For a longitudinal wave, a pressure–distance graph shows compressions at pressure maxima. A molecular displacement–distance graph shows displacement along the direction of travel. Maximum compression occurs where displacement changes most rapidly towards the neighbouring molecules. Pressure maximum and displacement maximum are not at the same place; their patterns are one-quarter wavelength apart in a sinusoidal travelling sound wave.

Worked example. A microphone records 12 complete cycles in 0.030 s. Sound travels at 340 m s^{-1} . Find its frequency and wavelength.

- Known: cycle count, total time and speed. Frequency counts cycles per second; the wave equation then links speed to wavelength.

$$f = \frac{N}{t} = \frac{12}{0.030 \text{ s}} = 400 \text{ Hz}$$

$$v = f\lambda \quad \Rightarrow \quad \lambda = \frac{v}{f} = \frac{340 \text{ m s}^{-1}}{400 \text{ Hz}} = 0.85 \text{ m}$$

- Check: one cycle takes $T = 1/f = 0.0025 \text{ s}$. Twelve cycles take the stated 0.030 s.

Superposition and standing waves

A **wavefront** joins points at the same phase. **Phase** describes the stage of a vibration cycle. One complete cycle corresponds to 360° or 2π radians.

Superposition means adding the displacements of overlapping waves at each point. **Interference** is the resulting reinforcement or cancellation. **Coherent sources** have the same frequency and a constant phase difference. Their phase difference need not be zero.

For waves of the same wavelength, the phase difference caused by a **path difference** Δx is:

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

For sources initially in phase, path differences $0, \lambda, 2\lambda, \dots$ give constructive interference. Half-integer wavelength differences give destructive interference. Complete cancellation also needs equal amplitudes. If sources start with a phase difference, include it too.

Worked example. Two in-phase speakers produce wavelength 0.80 m. Their paths to a microphone differ by 1.20 m.

- Known: path difference and wavelength. Convert path difference into cycles, then phase.

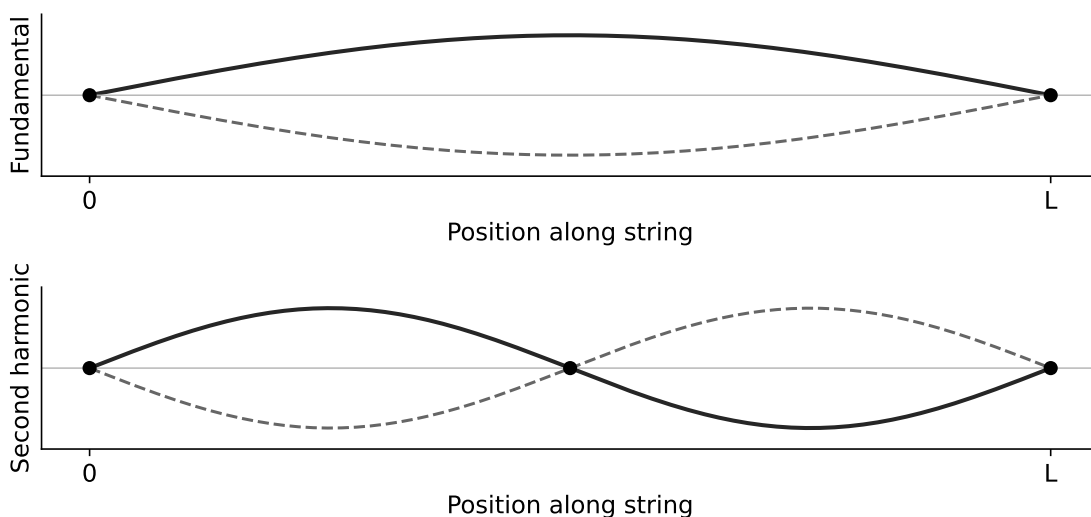
$$\Delta\phi = \frac{\Delta x}{\lambda} 360^\circ = \frac{1.20}{0.80} 360^\circ = 540^\circ$$

- 540° is equivalent to 180° . The waves arrive in opposite phase and interfere destructively. The sound need not become silent if the arriving amplitudes differ.

■ How a standing wave forms

A **standing wave** forms when two waves of the same frequency and similar amplitude travel in opposite directions and superpose. Reflection at a fixed string end supplies the returning wave.

- A **node** always has zero displacement. An **antinode** has the largest vibration amplitude.
- Adjacent nodes are $\lambda/2$ apart. A node and its nearest antinode are $\lambda/4$ apart.
- Points between the same pair of nodes vibrate in phase. Points in neighbouring sections vibrate in opposite phase.
- All points have the same frequency, except that a node does not vibrate. Amplitude depends on position.
- An ideal standing wave has no net energy transfer along it. A travelling wave carries energy along its direction of travel.



The end nodes remain still; the curve changes between the solid and dashed shapes.

For a string fixed at both ends, length L contains a whole number k of half-wavelengths:

$$L = \frac{k\lambda}{2} \quad v = \sqrt{\frac{T}{\mu}} \quad f = \frac{k}{2L} \sqrt{\frac{T}{\mu}}$$

Here T is **tension**, not period; μ is **mass per unit length** in kg m^{-1} . The fundamental has $k = 1$. At fixed mode, frequency increases with $\sqrt{T}$, decreases with L , and decreases with $\sqrt{\mu}$.

Worked example. A 0.60 m string has $\mu = 1.5 \times 10^{-3} \text{ kg m}^{-1}$ and tension 24 N. Find its fundamental frequency.

- Known: length, tension and linear density. The fundamental fits half a wavelength between the fixed ends.

$$v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{24}{1.5 \times 10^{-3}}} \text{ m s}^{-1} = 126 \text{ m s}^{-1}$$

$$f = \frac{v}{2L} = \frac{126 \text{ m s}^{-1}}{2 \times 0.60 \text{ m}} = 105 \text{ Hz}$$

- Doubling tension multiplies frequency by $\sqrt{2}$, rather than by two.

■ Standing sound in a closed tube

In the simplest standing sound wave in a tube closed at one end, the closed end is a molecular displacement node. The open end is approximately a displacement antinode. This fits one-quarter wavelength into the effective tube length, so $L_{\text{effective}} = \lambda/4$. The pressure pattern is reversed: the closed end is a pressure antinode. Do not call a pressure node a displacement node. Real tubes have a small open-end correction; use an effective length if the question supplies it.

Worked example. A closed tube has effective length 0.20 m and fundamental frequency 425 Hz. The end conditions give $\lambda = 4L = 0.80$ m; then $v = f\lambda = 425 \times 0.80 = 340$ m s⁻¹. A string fixed at both ends instead fits half a wavelength in its fundamental. Choose from the end conditions, not from the word “standing”.

■ Core practical 4: speed of sound

Use a signal generator, speaker, movable microphone and **two-beam oscilloscope**. Connect one oscilloscope channel to the generator reference signal and the other to the microphone output. Both traces have the same frequency.

1. Keep frequency constant. Move the microphone along a measured line away from the speaker. Find a position where the traces are in phase.
2. Move to another in-phase position. Consecutive in-phase positions are one wavelength apart. Measure across several wavelengths and divide by their number.
3. Read the period from the time-base scale: count horizontal divisions across several cycles, then divide. Find $f = 1/T$ and use $v = f\lambda$.
4. Repeat positions and frequencies. Keep the microphone on the speaker axis. Reduce reflected sound by working away from walls. Measure position from a fixed microphone reference point.

Measuring several wavelengths reduces the percentage uncertainty in the distance. Measuring several periods does the same for time. A resonance-tube experiment can also measure sound speed, but it does not replace this specified practical.

■ Core practical 5: vibrating string

Use a vibration generator driven by a signal generator. Run the string over a pulley to a hanging mass. The tension is about mg when pulley friction is small. Increase frequency until a clear standing-wave pattern forms.

- Investigate tension: keep L , μ and mode fixed. Vary hanging mass. Plot f^2 against T ; the gradient for the fundamental is $1/(4L^2\mu)$.
- Investigate length: keep tension, string type and mode fixed. Plot f against $1/L$.
- Investigate linear density: measure string mass and length, $\mu = m/l$. Use different strings with fixed tension, vibrating length and mode. Plot f^2 against $1/\mu$.
- Measure length between the end nodes. Find the resonance from both higher and lower frequencies and repeat. Secure the stand and keep clear of falling masses.

Intensity, refraction and polarisation

Intensity is power per unit area perpendicular to the energy flow:

$$I = \frac{P}{A}$$

Its unit is W m^{-2} . For a receiver, incident power is $P = IA$. Useful output is smaller if efficiency is below 100%. Convert area carefully: $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$.

Worked example. Radiation intensity is 800 W m^{-2} over a 25 cm^2 solar cell. Efficiency is 20%. Can it supply 0.50 W?

- Known: intensity, area, efficiency. First find incident power, then useful power.

$$P_{\text{in}} = IA = 800 \text{ W m}^{-2} \times 25 \times 10^{-4} \text{ m}^2 = 2.0 \text{ W}$$

$$P_{\text{out}} = \eta P_{\text{in}} = 0.20 \times 2.0 \text{ W} = 0.40 \text{ W}$$

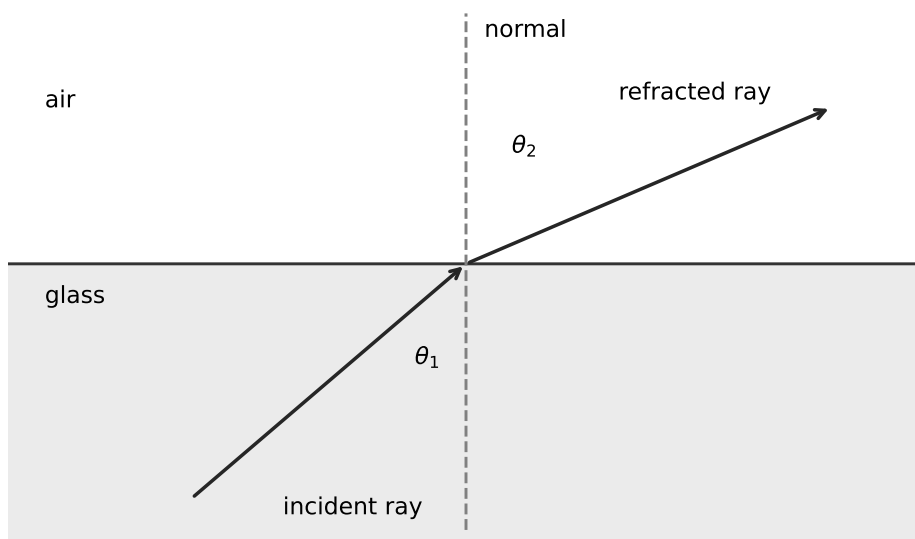
- $0.40 \text{ W} < 0.50 \text{ W}$, so it cannot supply the required useful power.

■ Refraction and total internal reflection

Refraction is a change in wave direction when speed changes at an interface. A ray entering along the normal changes speed without changing direction. The **normal** is perpendicular to the boundary. Measure all ray angles from it.

$$n = \frac{c}{v} \quad n_1 \sin \theta_1 = n_2 \sin \theta_2$$

The **refractive index** n compares vacuum light speed c with speed in the material. Frequency stays constant across the boundary, so wavelength changes with speed. Entering higher n bends the ray towards the normal; entering lower n bends it away.



The ray bends away from the normal when it enters the lower-index medium.

Total internal reflection requires travel from higher to lower refractive index and incidence greater than the **critical angle** C .

$$\sin C = \frac{n_2}{n_1} \quad \text{for material to air: } \sin C = \frac{1}{n}$$

At C the refracted angle is 90° ; call incidence greater than C total internal reflection. Below C , some energy is normally reflected and some transmitted. An optical fibre uses a higher-index core and lower-index cladding. Raising the cladding index raises the critical angle and can stop a previously reflected ray being trapped.

Worked example. Light travels from glass of index 1.50 into air. Does an incidence angle of 45° produce total internal reflection?

- Known: the two indices and incidence angle. Find the boundary angle before comparing.

$$C = \sin^{-1} \left(\frac{n_2}{n_1} \right) = \sin^{-1} \left(\frac{1.00}{1.50} \right) = 41.8^\circ$$

- The light travels towards lower index and $45^\circ > 41.8^\circ$. Both conditions hold, so total internal reflection occurs.

■ Measuring refractive index

Place a rectangular transparent block on paper and trace its outline. Use a narrow ray-box beam. Mark two points on the incident ray and two on the emerging ray. Remove the block and join the boundary points to reconstruct the ray inside. Draw the normal at entry and measure incidence i and refraction r with a protractor.

Repeat for several incidence angles, keeping the same material and light colour. Plot $\sin i$ vertically against $\sin r$ horizontally. For air into the block, the gradient is the block's refractive index relative to air. Use a large triangle on a best-fit line. Narrow beams and widely separated ray marks reduce direction uncertainty. Very small angles give large percentage angle uncertainties.

■ Plane polarisation

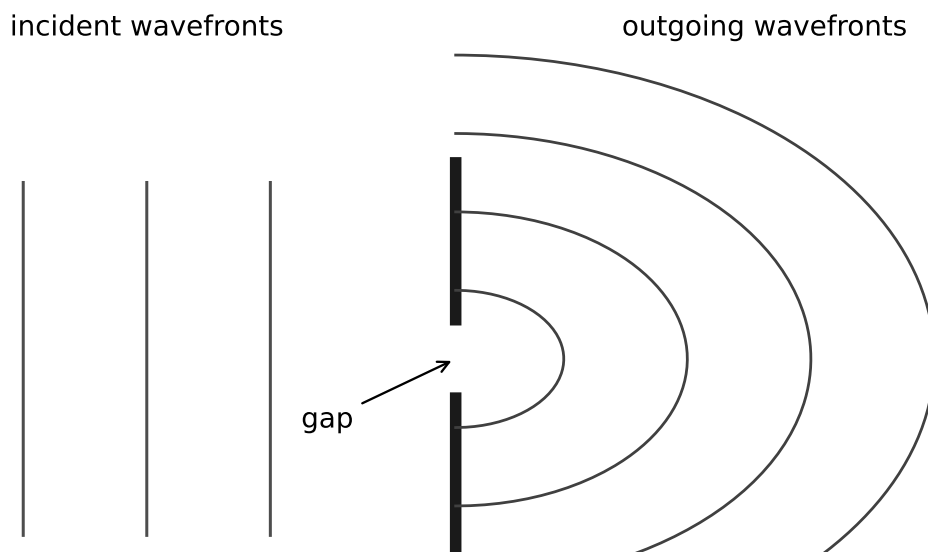
Plane polarisation restricts transverse vibrations to one plane containing the propagation direction. Unpolarised light has vibrations in many planes. A polariser transmits one vibration direction. Rotate a second polariser: parallel transmission directions give maximum brightness; perpendicular directions ideally give darkness. The ray still travels forward; its vibration direction changes selection.

Longitudinal waves cannot be plane polarised because their vibration is already along propagation. Polarisation is therefore evidence that light is transverse.

Diffraction and pulse-echo

Diffraction is the spreading of waves at a gap or edge. Spreading is greater when the gap width is comparable to the wavelength. A wide gap still diffracts at its edges, but the central wave spreads less.

In **Huygens' construction**, each point on a wavefront acts as a source of secondary wavelets. Draw wavelets of equal radius after the same time. Their forward common tangent gives the new wavefront. At a narrow gap only a small part of the original front supplies wavelets, so the emerging fronts spread widely. This explains spreading without inventing a change of frequency at the slit.



The gap limits which points supply the outgoing wavelets.

■ Gratings and core practical 6

A **diffraction grating** contains many equally spaced slits. Bright maxima occur when contributions from neighbouring slits arrive in phase:

$$k\lambda = d \sin \theta$$

Here k is the integer **order**, d is slit spacing, and θ is measured from the straight-through direction. The equation assumes normal incidence. If the grating has N lines per metre, $d = 1/N$. Do not confuse grating order with refractive index; printed papers may use n for either.

Worked example. A grating has 600 lines per millimetre. First-order light appears at 18.0° . Find its wavelength.

- Known: line density and first-order angle. Convert line density before taking its reciprocal.

$$d = \frac{1}{N} = \frac{1}{600 \times 10^3 \text{ m}^{-1}} = 1.67 \times 10^{-6} \text{ m}$$
$$\lambda = \frac{d \sin \theta}{k} = \frac{1.67 \times 10^{-6} \text{ m} \times \sin 18.0^\circ}{1} = 5.15 \times 10^{-7} \text{ m}$$

- This is 515 nm. Check each proposed higher order using $k\lambda/d \leq 1$.

For CP6, aim a low-power laser normally at a grating and place a screen perpendicular to the central beam. Measure screen distance D and displacement x from the central spot to an order. Use $\tan \theta = x/D$, then the grating equation. Average corresponding left/right displacements, repeat distances, and use higher visible orders where measurement is clear. Measure from the grating to the screen, not from the laser casing. Do not substitute $\sin \theta = x/D$ unless a justified small-angle approximation is acceptable. Never look into the beam; keep it below eye level and stop stray beams.

■ Electrons also show wave behaviour

An electron beam passing through a thin crystal produces a diffraction pattern. Regular atom spacing provides the diffracting structure. Changing electron momentum changes the pattern spacing. This is evidence of wave behaviour; particles travelling along simple straight paths alone cannot explain the diffraction maxima.

The **de Broglie wavelength** is:

$$\lambda = \frac{h}{p}$$

For a non-relativistic electron, $p = mv$. If it gains kinetic energy by crossing a potential difference, $E_k = eV$ and $p = \sqrt{2mE_k}$. Use these links only when the question gives or requires that energy relation.

Worked example. An electron has momentum $2.0 \times 10^{-24} \text{ kg m s}^{-1}$. With $h = 6.63 \times 10^{-34} \text{ J s}$:

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{2.0 \times 10^{-24}} \text{ m} = 3.3 \times 10^{-10} \text{ m}$$

Increasing momentum reduces wavelength. Electrons have both particle and wave properties; diffraction does not mean that an electron becomes a sound wave.

■ Reflection, transmission and echoes

At an interface, part of a wave's energy may be **transmitted** and part reflected. A reflected pulse can locate a boundary. In **pulse-echo**, measured delay includes the outward and return journeys:

$$2s = vt \quad \Rightarrow \quad s = \frac{vt}{2}$$

Worked example. Ultrasound travels in metal at 5900 m s^{-1} . An echo returns after $12 \mu\text{s}$.

$$s = \frac{vt}{2} = \frac{5900 \text{ m s}^{-1} \times 12 \times 10^{-6} \text{ s}}{2} = 0.0354 \text{ m}$$

The boundary is 35 mm away, not 71 mm. A nearby echo may overlap the transmitted pulse. Shorter pulse duration reduces this blind region and separates close echoes. Shorter wavelength helps detect or distinguish smaller features. These are related limits, but pulse duration and wavelength are not the same quantity. Use the speed in the actual material, not automatically the speed in air.

Photons and the photoelectric effect

Wave ideas explain interference, diffraction and polarisation. They did not explain all observations of energy transfer. **Photons** describe discrete packets of electromagnetic energy:

$$E = hf = \frac{hc}{\lambda}$$

Historically, interference and diffraction supported wave models of light. Quantum ideas developed to explain observations including the photoelectric effect and atomic spectra. Modern physics uses both wave and photon descriptions according to the measurement. A successful new model must explain evidence that the older model explains too.

■ One photon and one electron

In the **photoelectric effect**, a surface electron absorbs a photon and may escape. The **work function** ϕ is the minimum energy needed to remove an electron from the surface. The **threshold frequency** is $f_0 = \phi/h$.

$$hf = \phi + E_{k,\max} = \phi + \frac{1}{2}mv_{\max}^2$$

- Below threshold, increasing intensity does not cause emission in the usual single-photon model.
- Above threshold, higher frequency raises maximum kinetic energy. A graph of $E_{k,\max}$ against f has gradient h , frequency intercept f_0 and extrapolated energy intercept $-\phi$.
- At fixed frequency above threshold, higher intensity supplies more photons per second. More electrons can be emitted per second, so the saturation photocurrent rises. Their maximum kinetic energy does not rise.
- Emission starts without the energy-building delay predicted by a simple continuous-wave energy model, even at low intensity above threshold.
- Electrons escape with a range of kinetic energies. Some lose more energy within the material. The equation describes the largest energy, not every electron's energy.

The **electronvolt** is an energy unit: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. It is not a unit of potential difference. A stopping potential V_s just prevents even the fastest photoelectrons reaching the collector, so $eV_s = E_{k,\max}$.

Worked example. Light of frequency $8.0 \times 10^{14} \text{ Hz}$ reaches a surface with work function 2.0 eV .

- Known: photon frequency and work function. Convert the work function into joules before subtracting.

$$\phi = 2.0 \times 1.60 \times 10^{-19} \text{ J} = 3.20 \times 10^{-19} \text{ J}$$

$$E_{k,\max} = hf - \phi = 6.63 \times 10^{-34} \text{ J s} \times 8.0 \times 10^{14} \text{ Hz} - 3.20 \times 10^{-19} \text{ J} = 2.10 \times 10^{-19} \text{ J}$$

$$V_s = \frac{E_{k,\max}}{e} = \frac{2.10 \times 10^{-19} \text{ J}}{1.60 \times 10^{-19} \text{ C}} = 1.3 \text{ V}$$

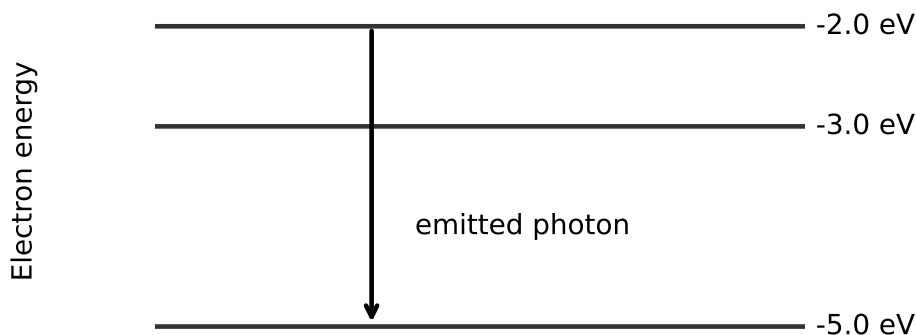
- The positive kinetic energy confirms that this frequency is above threshold. A negative subtraction would mean no emission, not negative kinetic energy.

■ Atomic line spectra

Atoms have **discrete energy levels**. An electron moving down between two allowed levels emits a photon. Moving up requires absorption of the matching energy:

$$|\Delta E| = hf = \frac{hc}{\lambda}$$

A line spectrum has particular frequencies because only certain level differences are allowed. The largest downward energy difference gives the highest frequency and shortest wavelength. Count possible transitions by checking level pairs and which upper levels are populated; do not automatically count the number of levels as the number of lines.



The photon energy equals the difference between the two levels.

Worked example. An electron drops from -2.0 eV to -5.0 eV.

$$E_{\gamma} = E_{\text{upper}} - E_{\text{lower}} = [-2.0 - (-5.0)] \text{ eV} = 3.0 \text{ eV}$$

$$f = \frac{E_{\gamma}}{h} = \frac{3.0 \times 1.60 \times 10^{-19} \text{ J}}{6.63 \times 10^{-34} \text{ J s}} = 7.2 \times 10^{14} \text{ Hz}$$

Photon absorption in a material does not always eject an electron from its surface. Excitation followed by emission, for example in a light-activated material, is not automatically the photoelectric effect.

Current, resistance and circuits

Current is the rate of charge flow. Conventional current follows the direction positive charges would move. In a metal, electrons drift in the opposite direction.

$$I = \frac{\Delta Q}{\Delta t} \quad V = \frac{W}{Q} \quad R = \frac{V}{I}$$

One ampere is one coulomb per second. **Potential difference** V is energy transferred per unit charge between two points. Resistance R is defined by the ratio V/I at an

operating point. **Ohm's law** is the extra condition $I \propto V$ when temperature and other physical conditions stay constant. Not every resistor or component obeys it.

Worked example. A current of 0.40 A flows for 30 s. Find the number of electrons passing a point.

$$Q = It = 0.40 \text{ A} \times 30 \text{ s} = 12 \text{ C}$$

$$N = \frac{Q}{e} = \frac{12 \text{ C}}{1.60 \times 10^{-19} \text{ C}} = 7.5 \times 10^{19}$$

■ Conservation gives the circuit rules

Charge conservation means charge does not build up at a steady-current junction. Total current entering equals total current leaving. Current is not used up by a resistor.

Energy conservation means the total energy supplied per coulomb around a complete loop equals the energy transferred per coulomb. The sum of voltage rises equals the sum of voltage drops.

For series resistors, the same current passes through each and their potential differences add:

$$V = V_1 + V_2 = IR_1 + IR_2 \Rightarrow R_{\text{series}} = R_1 + R_2$$

For parallel resistors, each has the same p.d. and the branch currents add:

$$I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2} \Rightarrow \frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

A parallel combination has smaller resistance than its smallest branch resistance. A voltmeter connects in parallel across a component; an ideal voltmeter has infinite resistance. An ammeter connects in series; an ideal ammeter has zero resistance.

Worked example. A 6.0Ω resistor is parallel to 3.0Ω . The combination is in series with 4.0Ω across 12 V.

- Known: circuit arrangement. Reduce the parallel section first, then apply the series rule.

$$R_p = \left(\frac{1}{6.0} + \frac{1}{3.0} \right)^{-1} \Omega = 2.0 \Omega$$

$$I = \frac{V}{R_p + R_s} = \frac{12 \text{ V}}{(2.0 + 4.0) \Omega} = 2.0 \text{ A}$$

$$V_p = IR_p = 2.0 \text{ A} \times 2.0 \Omega = 4.0 \text{ V}$$

$$I_6 = \frac{V_p}{6.0 \Omega} = 0.67 \text{ A} \quad I_3 = \frac{V_p}{3.0 \Omega} = 1.33 \text{ A}$$

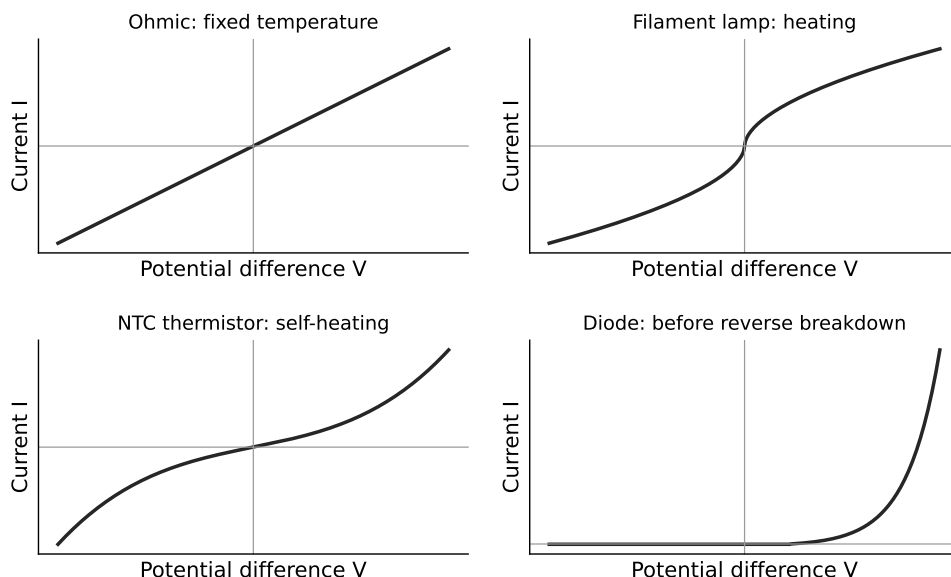
- Check: branch currents add to 2.0 A. The remaining series resistor has an 8.0 V drop.

■ Power and component graphs

Electrical power is energy transferred each second. Substituting $V = IR$ into $P = VI$ gives the other forms:

$$P = VI = I^2R = \frac{V^2}{R} \quad W = Pt = VIt$$

Use voltage across, and current through, the same component. The resistance forms apply to its operating-point resistance; do not assume a heating lamp has constant resistance.



Axes and temperature conditions matter when interpreting these schematic curves.

- Ohmic conductor at constant temperature: straight line through the origin. On an I -vertical, V -horizontal graph its gradient is $1/R$.
- Filament lamp: as voltage magnitude rises, heating increases resistance. The I - V curve becomes less steep.
- NTC thermistor: heating lowers resistance. If current heats it sufficiently, the curve becomes steeper. At a controlled fixed temperature its behaviour over a suitable range can be approximately ohmic. Do not claim every thermistor curve must bend under every measurement condition.
- Diode: very small reverse current before breakdown; forward current rises rapidly after a characteristic knee. It conducts mainly in one direction. A real diode does not have one constant resistance.

For a curved graph, $R = V/I$ uses a line from the origin to the operating point. The tangent gradient is not generally $1/R$.

■ Resistivity and core practical 7

Resistivity ρ is a material property at a stated temperature:

$$R = \frac{\rho l}{A} \quad A = \frac{\pi d^2}{4}$$

Lengthening a uniform wire increases resistance. Increasing cross-sectional area decreases it. Doubling diameter gives four times the area and one-quarter the resistance, if material, length and temperature stay unchanged.

For CP7, connect a uniform wire, ammeter, power supply, switch and current-limiting resistor in series. Connect a voltmeter across the measured wire length. Measure several lengths and find $R = V/I$ for each. Plot R against l : gradient = ρ/A , so $\rho = A \times \text{gradient}$.

Measure diameter with a micrometer at several positions and orientations; check its zero. Measure length between the actual electrical contacts. Use a small current and switch off between readings to limit heating. Keep contacts secure. A non-zero intercept may indicate contact or lead resistance. Repeating readings reduces scatter but does not remove a diameter zero error. Because area depends on d^2 , a small percentage diameter uncertainty contributes about twice that percentage to area uncertainty.

Worked example. A wire diameter is 0.40 mm. An R - l graph has gradient $3.5 \, \Omega \text{ m}^{-1}$.

$$A = \frac{\pi d^2}{4} = \frac{\pi(0.40 \times 10^{-3} \text{ m})^2}{4} = 1.26 \times 10^{-7} \text{ m}^2$$

$$\rho = A \times \text{gradient} = 1.26 \times 10^{-7} \text{ m}^2 \times 3.5 \, \Omega \text{ m}^{-1} = 4.4 \times 10^{-7} \, \Omega \text{ m}$$

■ The charge-carrier model

The **drift velocity** v is the small mean directed velocity of charge carriers, not their random thermal speed:

$$I = nqvA$$

Here n is the number of mobile carriers per unit volume, q is charge magnitude per carrier, and A is cross-sectional area. A larger carrier density allows the same current with a smaller drift speed. In series wires the current is the same; changing n or A changes v .

Materials have different resistivities because their carrier densities and the ease of carrier motion differ. More scattering reduces drift speed for the same applied potential gradient. Carrier density alone does not explain every difference between materials.

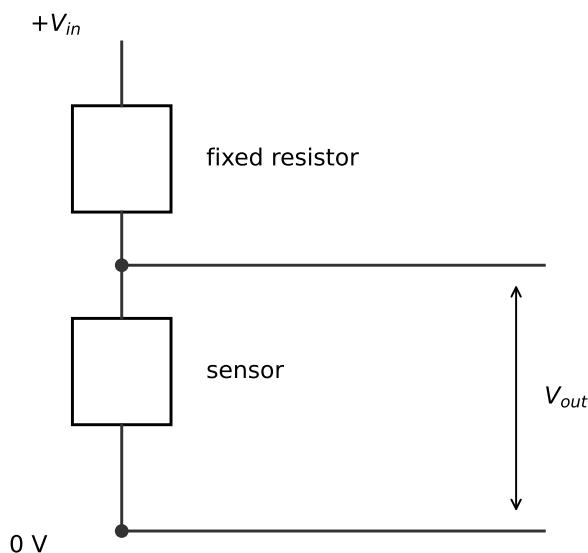
Potential dividers, sensors and cells

Along a uniform wire carrying steady current at constant temperature, resistance grows in proportion to distance. The potential drop therefore grows in proportion to distance too. A potential–distance graph is straight. This assumes uniform material and area; a tapered or unevenly heated wire need not give a straight line.

A **potential divider** uses series resistances to share a supply voltage:

$$V_{\text{out}} = V_{\text{in}} \frac{R_{\text{across output}}}{R_1 + R_2}$$

The expression assumes the output is unloaded, or the attached load draws negligible current. If a load draws significant current, combine it in parallel with the output resistor first. Always identify which resistor the voltmeter spans.



Swapping the sensor and fixed resistor reverses the direction of the output change.

Worked example. A 6.0 V supply feeds a 2.0 k Ω fixed resistor above an LDR. Find the output across the LDR when its resistance changes from 4.0 to 1.0 k Ω .

$$V_{\text{dark}} = V_{\text{in}} \frac{R_{\text{LDR}}}{R_f + R_{\text{LDR}}} = 6.0 \text{ V} \times \frac{4.0}{2.0 + 4.0} = 4.0 \text{ V}$$

$$V_{\text{bright}} = V_{\text{in}} \frac{R_{\text{LDR}}}{R_f + R_{\text{LDR}}} = 6.0 \text{ V} \times \frac{1.0}{2.0 + 1.0} = 2.0 \text{ V}$$

The output across this LDR falls when illumination rises. The output across the fixed resistor rises. Explain the named output, not just “the voltage changes”.

■ Explain sensors using carriers

In a metal, heating increases lattice vibrations. Conduction electrons scatter more often. The mobile electron number stays approximately constant, but drift speed at a given potential gradient decreases, so resistance rises.

In a **negative-temperature-coefficient thermistor**, heating releases more mobile carriers. The carrier-density increase dominates, so resistance falls. Avoid saying heating reduces lattice vibrations.

In a **light-dependent resistor** (LDR), absorbed light releases additional mobile carriers. Increased illumination raises carrier density and lowers resistance. It does not need to work by electrons leaving its surface.

For linked explanations, give the full chain: environmental change $\rightarrow$ carrier/scattering change $\rightarrow$ resistance change $\rightarrow$ divider fraction change $\rightarrow$ named output change. Keep the circuit arrangement in view throughout.

■ E.m.f., internal resistance and core practical 8

Electromotive force $\mathcal{E}$ is energy supplied by the source per unit charge. It is measured in volts, despite its name. **Internal resistance** r causes energy transfer within the source when current flows. The terminal p.d. is the energy per coulomb available to the external circuit:

$$\mathcal{E} = V + Ir \quad V = \mathcal{E} - Ir \quad I = \frac{\mathcal{E}}{R + r}$$

The source supplies power $\mathcal{E}I$, the external circuit receives VI , and internal heating is I^2r . These add consistently. With negligible current, terminal p.d. approaches e.m.f. For CP8, connect a cell, ammeter, variable load and switch in series. Connect a high-resistance voltmeter across the cell terminals. Vary the external resistance and record pairs of V and I . Plot V vertically against I horizontally. The best-fit line has intercept $\mathcal{E}$ and gradient $-r$. Take the magnitude of the gradient for r .

Use several settings and repeat. Open the switch between readings, avoid very small load resistance, and keep the cell temperature and charge state as steady as possible. Never short-circuit the cell. A graph that curves may show changing internal resistance or e.m.f.; do not force one fixed r onto it without discussing the limitation.

Worked example. A cell graph passes through (0.20 A, 1.40 V) and (0.60 A, 1.20 V).

- Known: two points on the best-fit line. The gradient of $V = \mathcal{E} - Ir$ is $-r$.

$$r = -\frac{\Delta V}{\Delta I} = -\frac{1.20 - 1.40}{0.60 - 0.20} \Omega = 0.50 \Omega$$

$$\mathcal{E} = V + Ir = 1.40 \text{ V} + 0.20 \text{ A} \times 0.50 \Omega = 1.50 \text{ V}$$

- Check using the second point: $1.20 + 0.60 \times 0.50 = 1.50 \text{ V}$ too. The terminal p.d. falls as current rises.

Check yourself

Use the matching exercise sheet after each section: 2.1 wave graphs; 2.2 standing waves; 2.3 refraction; 2.4 diffraction; 2.5 photons; 2.6 circuits; 2.7 dividers and cells. Before using a past-paper set, check that you can:

- read an axis and identify whether it gives wavelength, period, pressure or displacement;
- explain a practical with apparatus, measurements, controlled variables, graph and precautions;
- distinguish phase from amplitude, and photon frequency from photon arrival rate;
- derive circuit combinations from charge and energy conservation;
- explain a sensor circuit as a connected causal chain;
- use an actual comparison to finish “deduce whether”, with units and a clear conclusion.

The reviewed January and June 2025 papers supply authentic examples, but do not test every requirement. Original practice fills the teaching gaps. Completing a sampled paper alone does not prove full syllabus coverage.