

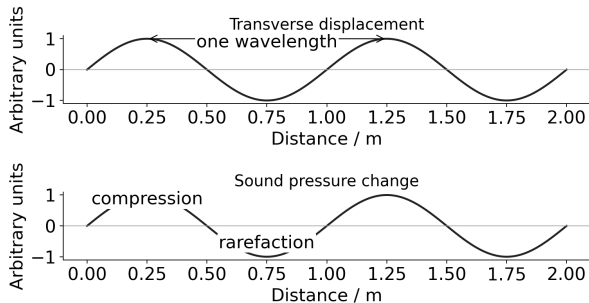
Unit 2: Waves and Electricity

WPH12 · Issue 3 · statements 33–80 · sheets 2.1–2.7

One unit, two forms of energy transfer

- Waves carry energy without transporting matter along the wave.
- Circuits transfer energy through charge flow.
- Use the reference, then skill sheets 2.1–2.7, then authentic sets.

Two graphs, two horizontal axes



- Read the horizontal axis before measuring a peak separation.
- A distance graph gives wavelength; a time graph gives period.

Sound moves energy, not air from source to listener

Sound: longitudinal

Each air molecule oscillates along the propagation direction, staying near its equilibrium position.

A compression moves onwards: pressure and density rise where neighbouring molecules crowd together.

Rope: transverse

A rope segment moves across the propagation direction while energy travels along the rope.

For sinusoidal travelling sound, pressure and molecular displacement maxima are a quarter wavelength apart.

Your turn: count cycles

- 12 cycles take 0.030 s; wave speed is 340 m/s.
- Find frequency, period and wavelength before advancing.

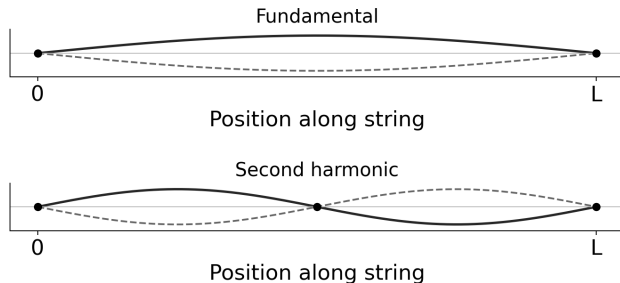
Cycle count to wavelength

- 1 **Known / model** 12 complete cycles in 0.030 s; $v = 340 \text{ m s}^{-1}$. Frequency counts cycles per second.
- 2 **Frequency** $f = N/t = 12/(0.030 \text{ s}) = 400 \text{ Hz}$.
- 3 **Period** $T = 1/f = 1/(400 \text{ Hz}) = 0.0025 \text{ s}$.
- 4 **Wavelength** $v = f\lambda \Rightarrow \lambda = v/f = (340 \text{ m s}^{-1})/(400 \text{ Hz}) = 0.85 \text{ m}$.
- 5 **Check** $12T = 12 \times 0.0025 \text{ s} = 0.030 \text{ s}$, the measured total time.

Phase is a stage in the cycle

- 1 Known / model** In-phase speakers: $\lambda = 0.80 \text{ m}$; path difference $\Delta x = 1.20 \text{ m}$.
Convert extra distance into cycles.
- 2 Phase** $\Delta\phi = (\Delta x/\lambda)360^\circ = (1.20/0.80)360^\circ = 540^\circ$.
- 3 Interpret** 540° differs from 180° by one complete cycle. Arriving vibrations are in opposite phase.
- 4 Conclusion** Destructive interference occurs. Complete silence additionally needs equal arriving amplitudes.

Standing waves: identify what stays still



- Locate end nodes and internal nodes.
- Compare two opposite snapshots without treating either as a travelling path.

The end conditions choose the wavelength

Fixed string: two fixed ends

Both ends are displacement nodes. The fundamental fits half a wavelength:

$$L = \lambda/2.$$

For $L = 0.60$ m, $\lambda = 2L = 1.20$ m.

Higher modes fit integer numbers of half-wavelengths.

Tube: one closed end

Closed end: displacement node and pressure antinode. Open end: approximately displacement antinode.

For $L_{\text{eff}} = 0.20$ m, $\lambda = 4L_{\text{eff}} = 0.80$ m.

At 425 Hz, $v = f\lambda = 340$ m s⁻¹.

Core practical 4: compare two signals

Connect generator reference to channel 1 and microphone to channel 2. Keep the microphone on the speaker axis.



Hold frequency fixed. Measure across several in-phase intervals; divide by the number of wavelengths.



Read several complete cycles using the time base; divide to obtain T . Use $f = 1/T$ and $v = f\lambda$.



Repeat and reduce wall reflections. Measuring longer distance/time spans reduces percentage uncertainty.

Core practical 5: vary one cause

Change / keep fixed	Measurement and test
Tension; same L , μ , mode	Vary hanging mass, $T \approx mg$. Plot f^2 against T ; expect a straight line.
Length; same T , μ , mode	Measure between end nodes. Plot f against $1/L$.
Linear density; same T , L , mode	Measure $\mu = m/l$ for each string. Plot f^2 against $1/\mu$.

Use the evidence

Find resonance from both directions and repeat. Secure the stand; keep clear of falling masses.

Your turn: is the cell sufficient?

Your turn

A solar cell has area 25 cm^2 , incident intensity 800 W m^{-2} and efficiency 20%. Can it supply 0.50 W ?

Attempt the complete task before advancing. Show the method and interpret the result.

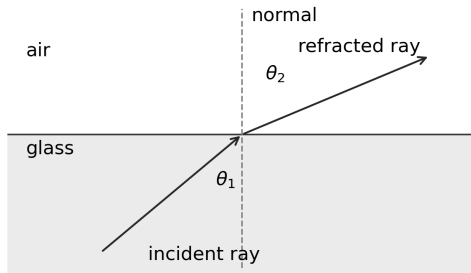
Intensity needs an area conversion

- 1 **Known / reason** $I = 800 \text{ W m}^{-2}$, area 25 cm^2 , efficiency 20%. Compare useful output with 0.50 W.
- 2 **Area** $A = 25 \times 10^{-4} \text{ m}^2 = 0.0025 \text{ m}^2$.
- 3 **Incident power** $P_{\text{in}} = IA = 800 \text{ W m}^{-2} \times 0.0025 \text{ m}^2 = 2.0 \text{ W}$.
- 4 **Useful power** $P_{\text{out}} = \eta P_{\text{in}} = 0.20 \times 2.0 \text{ W} = 0.40 \text{ W}$.
- 5 **Decision** $0.40 \text{ W} < 0.50 \text{ W}$: it cannot supply the required useful power.

Decision

A 0.50 W device cannot run from this useful output.

Refraction: measure from the normal



- Frequency stays constant at the boundary.
- Higher refractive index means lower speed and shorter wavelength.

Total internal reflection needs both conditions

- 1 **Known / reason** Glass $n_1 = 1.50$ to air $n_2 = 1.00$; incidence 45° . First check direction, then the boundary angle.
- 2 **Direction** The ray travels from higher to lower refractive index: total internal reflection is possible.
- 3 **Critical angle** $C = \sin^{-1}(n_2/n_1) = \sin^{-1}(1.00/1.50) = 41.8^\circ$.
- 4 **Comparison** $45^\circ > 41.8^\circ$: both conditions hold, so total internal reflection occurs.

Decision

At exactly the critical angle the refracted ray runs along the boundary.

Measure index; test polarisation

Measure refractive index

Trace the block; mark two points on each external ray. Reconstruct the internal ray and draw the normal.

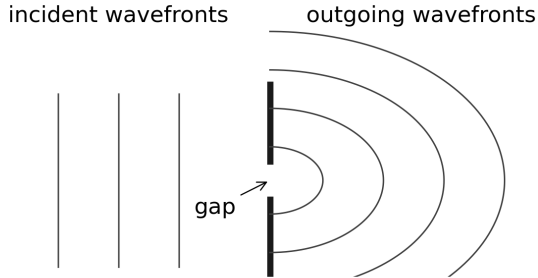
Repeat incidence angles. Plot $\sin i$ vertically against $\sin r$; air-to-block gradient gives relative index. Use a narrow beam and widely spaced marks.

Test plane polarisation

Rotate a second polariser: parallel transmission directions give maximum brightness; perpendicular directions ideally give darkness.

The forward propagation direction remains the same. Selecting one transverse vibration direction shows that light is transverse.

Huygens: build the next wavefront



- Points at the opening supply secondary wavelets.
- Their forward envelope gives the next wavefront.
- A gap comparable to wavelength produces strong spreading.

Grating method: spacing before angle

- 1 **Known / reason** 600 lines per mm; first order at 18.0° . Normal incidence permits $k\lambda = d \sin \theta$.
- 2 **Convert / spacing** $N = 600 \times 10^3 \text{ m}^{-1}$; $d = 1/N = 1.67 \times 10^{-6} \text{ m}$.
- 3 **Rearrange** $\lambda = d \sin \theta / k$.
- 4 **Substitute** $\lambda = (1.67 \times 10^{-6} \text{ m}) \sin 18.0^\circ / 1 = 5.15 \times 10^{-7} \text{ m} = 515 \text{ nm}$.
- 5 **Measurement** On a screen use $\theta = \tan^{-1}(x/D)$; average corresponding left and right spots. Keep laser beams below eye level.

Electrons: evidence and calculation are different

- 1 Evidence** A crystal produces an electron diffraction pattern. Regular atom spacing supplies the diffracting structure.
- 2 Known / model** $p = 2.0 \times 10^{-24} \text{ kg m s}^{-1}$; $h = 6.63 \times 10^{-34} \text{ J s}$. Use the de Broglie relation.
- 3 Calculate** $\lambda = h/p = (6.63 \times 10^{-34})/(2.0 \times 10^{-24}) \text{ m} = 3.3 \times 10^{-10} \text{ m}$.
- 4 Interpret** Increasing momentum reduces wavelength. Use $p = mv$ only when the non-relativistic model is valid.

Echoes: separate distance and resolution

- 1 Known / reason** Metal sound speed 5900 m s^{-1} ; delay $12 \mu\text{s}$. Delay includes outward and return travel.
- 2 Equation** $2s = vt \Rightarrow s = vt/2$.
- 3 Substitute** $s = (5900 \text{ m s}^{-1})(12 \times 10^{-6} \text{ s})/2 = 0.0354 \text{ m}$.
- 4 Interpret** The boundary is about 35 mm away. Omitting the return journey doubles the answer.
- 5 Resolution** Shorter pulses separate closer arrival times; shorter wavelengths help distinguish smaller features. These are different limits.

Why light needs two descriptions

Wave evidence

Interference requires superposition; diffraction describes spreading at edges and gaps.

Polarisation selects a transverse vibration direction. A photon model must retain these successful wave predictions.

Discrete transfer

The photoelectric effect and atomic spectra require discrete energy transfer:
 $E = hf = hc/\lambda$.

Use the description suited to the measurement. Diffraction does not mean electrons become sound waves.

Photoelectric effect: follow one photon

One surface electron absorbs one photon with energy hf . The work function ϕ is the minimum escape energy.



If $hf < \phi$, there is no ordinary single-photon emission, even when intensity is increased. The threshold is $f_0 = \phi/h$.



Above threshold, energy conservation gives $hf = \phi + E_{k,\max}$.
The fastest electrons have $E_{k,\max} = hf - \phi$.



Other emitted electrons can lose more energy inside the material. Maximum energy is not the energy of every emitted electron.

Frequency and intensity change different things

Controlled comparison	Predicted observation / reason
Higher intensity, fixed $f > f_0$	More photons arrive each second: photoelectron emission rate rises. Maximum kinetic energy is unchanged.
Higher f , still above threshold	Each photon carries more energy. $E_{k,\max} = hf - \phi$ rises.
Higher f , fixed intensity	Same power but larger hf : fewer photons per second. Do not assume the emission rate rises.
Higher intensity, $f < f_0$	No ordinary single-photon emission: each photon still lacks the escape energy.

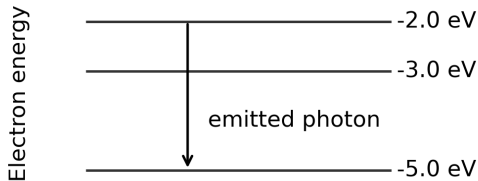
Your turn: convert before subtracting

- $f = 8.0 \times 10^{14}$ Hz; $\phi = 2.0$ eV.
- Use $h = 6.63 \times 10^{-34}$ J s and $e = 1.60 \times 10^{-19}$ C.
- Find maximum kinetic energy and stopping potential.

Photoelectron energy to stopping potential

- 1 **Known / reason** $f = 8.0 \times 10^{14}$ Hz; $\phi = 2.0$ eV. Use energy conservation with matching units.
- 2 **Photon energy** $E = hf = (6.63 \times 10^{-34} \text{ J s})(8.0 \times 10^{14} \text{ Hz}) = 5.304 \times 10^{-19} \text{ J}$.
- 3 **Work function** $\phi = (2.0 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) = 3.20 \times 10^{-19} \text{ J}$.
- 4 **Maximum energy** $E_{k,\text{max}} = hf - \phi = (5.304 - 3.20) \times 10^{-19} \text{ J} = 2.1 \times 10^{-19} \text{ J}$.
- 5 **Stopping potential**
 $V_s = E_{k,\text{max}}/e = (2.104 \times 10^{-19} \text{ J})/(1.60 \times 10^{-19} \text{ C}) = 1.3 \text{ V}$ (guard digits retained).

Atomic transitions produce particular frequencies



- Photon energy equals the level difference.
- Largest downward gap gives shortest wavelength.
- Absorption and re-emission need not eject a surface electron.

Define current, voltage and resistance separately

- 1 Definitions** $I = \Delta Q / \Delta t$ measures charge flow; $V = W / Q$ measures energy transferred per coulomb.
- 2 Known / charge** $I = 0.40 \text{ A}$ for $t = 30 \text{ s}$. $Q = It = 0.40 \text{ A} \times 30 \text{ s} = 12 \text{ C}$.
- 3 Electron count** $N = Q / e = (12 \text{ C}) / (1.60 \times 10^{-19} \text{ C}) = 7.5 \times 10^{19}$ electrons.
- 4 Resistance** $R = V / I$ defines operating-point resistance. Ohm's law additionally requires $I \propto V$ at constant physical conditions.

Conservation builds the circuit rules

Series: one charge path

Charge conservation gives the same steady current through each resistor.

Energy per coulomb adds: $V = V_1 + V_2$.

$V = IR_1 + IR_2 = I(R_1 + R_2)$, so
 $R_s = R_1 + R_2$.

Parallel: shared terminals

Each branch spans the same p.d. Charge conservation gives $I = I_1 + I_2$.

$I = V/R_1 + V/R_2$, so

$1/R_p = 1/R_1 + 1/R_2$. The combination is smaller than either branch.

Your turn: reconstruct the branches

Your turn

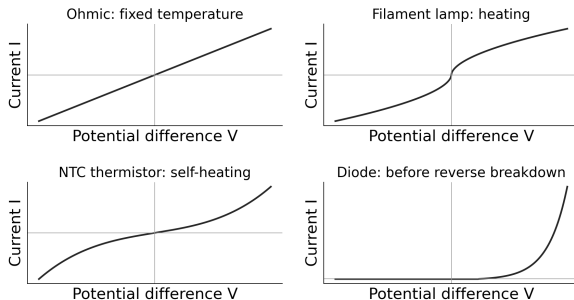
A $6\ \Omega$ resistor is parallel to $3\ \Omega$, then in series with $4\ \Omega$ across $12\ \text{V}$. Find total current and both branch currents.

Attempt the complete task before advancing. Show the method and interpret the result.

Reduce the circuit; then restore each branch

- 1 Known / model** $6\ \Omega$ and $3\ \Omega$ are parallel, then $4\ \Omega$ in series across $12\ \text{V}$. Reduce the parallel section first.
- 2 Equivalent resistance** $R_p = (1/6 + 1/3)^{-1}\ \Omega = 2\ \Omega$; $R_{\text{total}} = R_p + R_s = 6\ \Omega$.
- 3 Total current** $I = V/R_{\text{total}} = (12\ \text{V})/(6\ \Omega) = 2\ \text{A}$.
- 4 Branch voltage** $V_p = IR_p = 2\ \text{A} \times 2\ \Omega = 4\ \text{V}$.
- 5 Restore branches** $I_6 = V_p/R_6 = (4\ \text{V})/(6\ \Omega) = 0.67\ \text{A}$;
 $I_3 = V_p/R_3 = (4\ \text{V})/(3\ \Omega) = 1.33\ \text{A}$. Sum: $2.0\ \text{A}$.

Component curves: state the temperature condition



- Read current vertically and voltage horizontally.
- For a curved graph, V/I uses the origin-to-point line.

Core practical 7: measure material resistivity

- 1 **Measurement** Use a micrometer at several positions/orientations; check zero. Find $R = V/I$ for several contact separations l .
- 2 **Area** $A = \pi d^2/4 = \pi(0.40 \times 10^{-3} \text{ m})^2/4 = 1.26 \times 10^{-7} \text{ m}^2$.
- 3 **Graph model** $R = \rho l/A$, so an R - l best-fit gradient is ρ/A . Given gradient: $3.5 \text{ } \Omega \text{ m}^{-1}$.
- 4 **Resistivity** $\rho = A \times \text{gradient} = (1.26 \times 10^{-7} \text{ m}^2)(3.5 \text{ } \Omega \text{ m}^{-1}) = 4.4 \times 10^{-7} \text{ } \Omega \text{ m}$.
- 5 **Control / limitation** Use low current and switch off between readings to limit heating. Repetition reduces scatter, not micrometer zero error.

Drift speed is a small directed average

Count carriers crossing an area

In time Δt , carriers drift distance $v\Delta t$.
The swept volume is $Av\Delta t$.

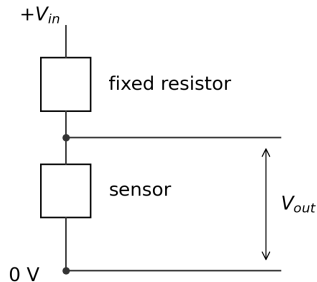
Number crossing: $nAv\Delta t$. Charge crossing: $\Delta Q = nqAv\Delta t$, hence $I = nqvA$.

Apply to series wires

The same current passes through both wires, but drift speeds need not match.
 $v = I/(nqA)$.

With equal carrier density, halving area doubles drift speed. Random thermal motion is not this small directed average.

Uniform wire to potential divider



- Uniform current-carrying wire: voltage drop is proportional to distance.
- An unloaded divider shares voltage in proportion to resistance.
- A significant load changes the output branch resistance.

Calculate the named divider output

- 1 Known / reason** $V_{\text{in}} = 6.0 \text{ V}$; upper resistor $2.0 \text{ k}\Omega$. Output is across the lower LDR; assume negligible load current.
- 2 Model** $V_{\text{out}} = V_{\text{in}} R_{\text{LDR}} / (R_f + R_{\text{LDR}})$.
- 3 Dark:** $4.0 \text{ k}\Omega$ $V_{\text{dark}} = 6.0 \text{ V} \times 4.0 / (2.0 + 4.0) = 4.0 \text{ V}$.
- 4 Bright:** $1.0 \text{ k}\Omega$ $V_{\text{bright}} = 6.0 \text{ V} \times 1.0 / (2.0 + 1.0) = 2.0 \text{ V}$.
- 5 Interpret** More illumination lowers the lower-arm resistance and its voltage share. Output across the fixed upper resistor rises instead.

A sensor explanation must reach the named output

Environmental change	Carrier mechanism → named output
Metal gets hotter	Lattice vibrations and scattering increase. Resistance rises; carrier number stays roughly unchanged.
Lower-arm NTC gets hotter	Mobile carrier density rises; resistance falls. Output across the NTC falls.
Lower-arm LDR gets brighter	Carrier density rises; resistance falls. Its supply-voltage share and output fall.

Use the evidence

An upper-arm sensor reverses the output trend. Identify the terminals first.

E.m.f. supplies energy; internal resistance uses some

Energy per coulomb

E.m.f. $\mathcal{E}$ is energy supplied per coulomb.
Terminal p.d. V is energy per coulomb available externally.

Internal heating takes Ir per coulomb:
 $\mathcal{E} = V + Ir$. With load R , $I = \mathcal{E}/(R + r)$.

Power balance

Multiply by current: $\mathcal{E}I = VI + I^2r$.
Source power equals external power plus internal heating.

At negligible current, Ir approaches zero and terminal p.d. approaches e.m.f.
Never short-circuit a cell.

Your turn: interpret the cell graph

Your turn

The terminal-voltage line passes through $(0.20 \text{ A}, 1.40 \text{ V})$ and $(0.60 \text{ A}, 1.20 \text{ V})$. Find internal resistance and e.m.f.

Attempt the complete task before advancing. Show the method and interpret the result.

Core practical 8: intercept and negative gradient

- 1 **Known / graph** A V - I best-fit line passes through (0.20 A, 1.40 V) and (0.60 A, 1.20 V).
- 2 **Model** $V = \mathcal{E} - Ir$, vertical intercept is $\mathcal{E}$ and gradient is $-r$.
- 3 **Internal resistance**
$$r = -\Delta V / \Delta I = -(1.20 - 1.40) \text{ V} / [(0.60 - 0.20) \text{ A}] = 0.50 \text{ } \Omega.$$
- 4 **E.m.f.** $\mathcal{E} = V + Ir = 1.40 \text{ V} + 0.20 \text{ A} \times 0.50 \text{ } \Omega = 1.50 \text{ V}.$
- 5 **Check / control** The second point also gives 1.50 V. Repeat load settings; open the switch between readings to limit heating and discharge.

Check yourself

- Explain why a standing-wave node stays still.
- Distinguish increasing photon frequency from increasing intensity.
- Explain why a loaded divider needs a parallel combination.