Physics (0625)

IGCSE • Extended • CAIE

Comprehensive Cheat Sheet

The Practice Book
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1 Electricity and magnetism

KEY FORMULAS

Electric current

$$I = \frac{Q}{t}$$

Current is the rate of flow of charge, in amperes (1 A = 1 C/s). Use to link a current I flowing for a time t to the charge Q that passes, rearranging to $Q = It$.

Electrical power

$$P = IV$$

Power is the energy transferred per second, in watts (W). Use for the power dissipated by a component carrying current I across a potential difference V.

Potential difference and e.m.f.

$$V = \frac{E}{Q}$$

Voltage is the energy transferred per unit charge, in volts (1 V = 1 J/C). Use to find the energy E given to or delivered by a charge Q moving through a voltage V.

Resistance and Ohm's law

$$V = IR$$

Defines resistance $R = V/I$, in ohms (Ω). Use to find any one of voltage, current or resistance for a component when the other two are known.

Resistors in parallel

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$

The combined resistance of resistors in parallel is found by adding the reciprocals. The result is always *smaller* than the smallest branch. Use when components are on separate branches sharing the same voltage.

Resistors in series

$$R = R_1 + R_2 + \dots$$

The combined resistance of resistors in series is the sum of the separate resistances. Use when components share a single loop, so the same current flows through each.

Transformer turns ratio

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

For a transformer the ratio of primary to secondary voltage equals the ratio of the numbers of turns on the two coils. Use to find an unknown voltage or number of turns; more turns means a higher voltage on that side.

Potential divider output

$$V_{out} = V \times \frac{R_2}{R_1 + R_2}$$

Two resistors in series split the supply voltage in proportion to their resistances. Use to find the voltage across R_2, the larger resistor taking the larger share. The ratio form $\frac{V_1}{V_2} = \frac{R_1}{R_2}$ gives the same result.

Power in terms of resistance

$$P = I^2 R = \frac{V^2}{R}$$

Combine $P = IV$ with $V = IR$ to get two further forms. Use $P = I^2 R$ when the current and resistance are known (for example heat lost in a cable) and $P = V^2/R$ when the voltage and resistance are known.

Resistance of a wire

$$R = \frac{\rho L}{A}$$

The resistance of a wire is proportional to its length L and inversely proportional to its cross-sectional area A; ρ is the resistivity of the material. Use to compare wires: a longer or thinner wire has a higher resistance.

KEY CONCEPTS

- **Connecting an ammeter and a voltmeter**: An *ammeter* measures current and is connected in *series*, in the same loop as the component, so the same current passes through both. A *voltmeter* measures potential difference and is connected in *parallel*, across the component. An ideal ammeter has zero resistance and an ideal voltmeter has infinite resistance.
- **Electric charge and charging by friction**: There are two kinds of charge, positive and negative; like charges repel and unlike charges attract. Charging an insulator by friction transfers *electrons*: the object that gains electrons becomes negative and the one that loses them becomes positive. Protons never move, so charging is always about where the electrons go.
- **Inducing an e.m.f.**: Moving a magnet near a coil, or moving a wire so that it cuts magnetic field lines, *induces* an e.m.f. across the conductor; if the circuit is complete a current flows. The induced e.m.f. is larger when the motion is faster, the magnet is stronger, or the coil has more turns.
- **Live, neutral and earth wires**: A mains plug carries three wires: the *live* (brown) carries the alternating supply, the *neutral* (blue) completes the circuit, and the *earth* (green and yellow) is a safety path to ground. A *fuse* and a switch are always placed in the live wire so the appliance is isolated from the supply when they break the circuit.
- **Magnetic field and field lines**: A magnetic field is the region where a magnet exerts a force on another magnet or on a magnetic material. It is drawn with *field lines* that run from the *north* pole to the *south* pole outside the magnet. Where the lines are close together the field is strong; where they are spread apart it is weak. Like poles repel and unlike poles attract.
- **Magnetic field of a current**: An electric current produces a magnetic field around itself. Around a straight wire the field is a set of concentric circles whose direction is given by the *right-hand grip rule* (thumb along the conventional current, fingers curl the field). Winding the wire into a *solenoid* gives a field like a bar magnet's, strong and uniform inside.
- **The a.c. generator**: Rotating a coil in a magnetic field makes the field through the coil change continuously, inducing an *alternating* e.m.f. The coil connects to the external circuit through *slip rings* and brushes. The output is a sine curve, with one complete cycle per revolution of the coil.
- **The d.c. motor**: In a d.c. motor a current-carrying coil in a magnetic field feels opposite forces on its two sides, one pushed up and one pushed down, which turn the coil. A *split-ring commutator* reverses the current in the coil every half turn, so the forces always drive the rotation the same way and the coil spins continuously.

- **The motor effect and Fleming's left-hand rule**: A current-carrying conductor placed in a magnetic field experiences a force, the *motor effect*, because the two fields interact. *Fleming's left-hand rule* gives the direction: the thumb is the force (motion), the first finger is the field (north to south), and the second finger is the current. The force reverses if either the current or the field is reversed.
- **Conventional current and electron flow**: Two direction conventions must both be known. *Conventional current* is defined as flowing from the positive terminal to the negative terminal around the external circuit. The actual charge carriers in a metal are *free electrons*, which drift the opposite way, from negative to positive. Direct current (d.c.) flows one way; alternating current (a.c.) repeatedly reverses.
- **Current versus voltage graphs**: The *I-V characteristic* shows how a component behaves. A metallic resistor at constant temperature is *ohmic*: the graph is a straight line through the origin, so resistance is constant. A *filament lamp* heats up as the current rises, its resistance increases, and the graph curves over. A *diode* conducts only one way, so its graph is flat in reverse and rises steeply once forward.
- **E.m.f. versus potential difference**: *E.m.f.* (electromotive force) is the energy a source such as a cell gives to each coulomb of charge it pushes round the circuit. *Potential difference* (p.d.) is the energy each coulomb delivers to a component. Both are measured in volts with a voltmeter in parallel; the distinction is energy *supplied* by the source versus energy *transferred* in a component.
- **Electric field patterns**: An *electric field* is a region where a charge feels a force, drawn with lines pointing from positive to negative. Learn the two standard shapes: *radial* lines spreading out around a point charge or charged sphere, and a *uniform* field of parallel, evenly spaced lines between two oppositely charged parallel plates.
- **Lenz's law and the direction of the induced current**: *Lenz's law* states that an induced current always flows in the direction that *opposes the change* producing it, because energy must be conserved. Pushing a north pole into a coil makes the coil's near face become a north pole that repels the magnet, so work has to be done against this repulsion, and that work becomes the electrical energy generated.
- **Series and parallel rules**: In *series* the current is the same at every point, the resistances add, and the potential differences across the components add up to the supply voltage. In *parallel* each branch has the full supply voltage across it, the branch currents add up to the total current drawn from the supply, and the combined resistance is less than the smallest branch.
- **Increasing the turning effect**: The turning effect of a d.c. motor is increased by raising the current, adding more turns to the coil, using a stronger magnet, or using a coil of larger area. These all increase the force on the coil sides or the leverage of that force, giving a greater torque and a faster spin.
- **Sensor potential dividers**: Replacing one resistor in a potential divider with a *thermistor* or a *light-dependent resistor* (LDR) makes the output voltage respond to the surroundings. A thermistor's resistance falls as it gets hotter and an LDR's resistance falls as it gets brighter, so the divider output changes with temperature or light and can switch a circuit on or off.

EXAM TIPS

TIP A *fuse* is a thin wire in the live line that melts and breaks the circuit if the current grows too large; it must be rated *just above* the appliance's normal operating current. Together with the *earth* wire it protects a metal-cased appliance: a fault sends a large current to earth, which blows the fuse before the case can become live and give a shock.

TIP When comparing two field patterns, the stronger field is the one whose lines are packed *closer together*, especially near the poles. A *plotting compass* placed in the field lines up along a line and points the way the field acts, so it can be used to map the field shape. Only iron, steel, cobalt and nickel are magnetic materials.

TIP The magnetic field of a solenoid is made stronger by *increasing the current*, *adding more turns* to the coil, or inserting a *soft-iron core*. Soft iron is used because it magnetises strongly when the current is on but loses almost all its magnetism when the current is switched off, which is what an electromagnet needs.

TIP A *diode* allows current to flow in one direction only; it conducts when *forward biased* (positive supply to the triangle, or anode) and blocks current when reverse biased. A *light-emitting diode*

(LED) is a diode that emits light when it conducts, so it too must be connected the right way round or no current flows and it stays dark.

TIP The induced e.m.f. is *greatest* when the coil is horizontal, because it is then cutting field lines at the fastest rate, and *zero* when the coil is vertical, because it is moving along the lines and cutting none. Spinning the coil faster makes the output both larger in peak value and higher in frequency.

2 Motion, forces and energy

KEY FORMULAS

Acceleration

$$a = \frac{\Delta v}{\Delta t}$$

Acceleration is the change in velocity per unit time. Use for uniformly changing motion; on a speed-time graph it equals the gradient of the line.

Density

$$\rho = \frac{m}{V}$$

Mass per unit volume of a substance. Use to decide floating (an object floats on a fluid of greater density) and to identify materials; water has a density of 1000 kg/m³.

Kinetic energy

$$E_k = \frac{1}{2}mv^2$$

The energy a body has because of its motion. Use whenever a mass changes speed; it depends on the *square* of the speed, so doubling the speed quadruples the kinetic energy.

Moment of a force

$$M = Fd$$

The turning effect of a force about a pivot, where d is the perpendicular distance from the pivot to the line of action of the force. Measured in newton metres (N·m).

Momentum

$$p = mv$$

Momentum is mass times velocity, a vector measured in kg·m/s. Use it in collision and explosion problems, where the total momentum of a system is conserved.

Newton's second law

$$F = ma$$

The resultant force on a body equals its mass times its acceleration. Always find the *resultant* force first, then divide by the mass to get the acceleration.

Power

$$P = \frac{E}{t}$$

Power is the rate of transferring energy or doing work, measured in watts (1 W = 1 J/s). Equivalently $P = W/t$ for work W done in time t.

Pressure

$$p = \frac{F}{A}$$

Pressure is the force acting normally per unit area, measured in pascals (1 Pa = 1 N/m²). The same force on a smaller area gives a greater pressure.

Resultant of two perpendicular forces

$$R = \sqrt{F_1^2 + F_2^2}$$

Combines two forces acting at right angles into a single resultant. Use when two perpendicular forces (or any perpendicular vectors) act at a point; for other angles use a scale drawing.

Weight

$$W = mg$$

The gravitational force on a mass m in a field of strength g. Use to convert between mass in kilograms and weight in newtons; on Earth $g \approx 9.8$ N/kg.

Work done

$$W = Fd$$

Work is the energy transferred when a force moves its point of application a distance d in the direction of the force. Measured in joules; no movement means no work is done.

Change in gravitational potential energy

$$\Delta E_p = mg\Delta h$$

The energy transferred when a mass m is raised or lowered through a height Δh. For a falling object with no air resistance, the gravitational potential energy lost equals the kinetic energy gained.

Efficiency

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

The fraction of the input energy that is transferred to a useful form. Use it for any device or process; no real machine reaches 100% because some energy is always wasted, usually as heat.

Hooke's Law

$$F = kx$$

The force on a spring is proportional to its extension x, where k is the spring constant, up to the *limit of proportionality*. Beyond that limit the spring stretches more for each added newton.

Impulse

$$Ft = \Delta(mv)$$

The impulse of a force equals the change in momentum it produces. Use it to show that lengthening the contact time of a collision reduces the force, which is how crumple zones and airbags protect passengers.

Pressure in a liquid

$$\Delta p = \rho g \Delta h$$

The increase in pressure with depth Δh in a fluid of density ρ. Use it for dams, divers and manometers; pressure rises the deeper you go and acts equally in all directions at a given depth.

KEY CONCEPTS

- **Centre of gravity and stability**: The *centre of gravity* is the single point at which the whole weight of an object appears to act. An object is more stable when its centre of gravity is low and its base is wide, and it topples only when the line of action of its weight falls outside the base.
- **Renewable and non-renewable resources**: A *renewable* resource is replaced as fast as it is used (solar, wind, hydroelectric, geothermal, tidal and biomass). A *non-renewable* resource is used far faster than it forms (coal, oil, gas and nuclear fuel). Comparisons weigh reliability, cost and pollution against each other.
- **Conservation of momentum**: When no external force acts, the total momentum of a system before an event equals the total momentum after it. This holds for collisions, where objects may stick together or bounce apart, and for explosions, where the momenta produced are equal and opposite.
- **Most resources trace back to the Sun**: Fossil fuels are ancient stored sunlight, and wind, waves and hydroelectric power are all driven by solar heating of the atmosphere and oceans. The exceptions are nuclear (from uranium), geothermal (the Earth's hot interior) and tidal (mainly the Moon's gravity). The Sun's own energy comes from the nuclear fusion of hydrogen into helium.
- **Principle of moments**: For a body in equilibrium, the total clockwise moment about any pivot equals the total anticlockwise moment about that pivot. Full equilibrium also requires no resultant force, so the body neither accelerates nor turns.
- **Reading a speed-time graph**: On a speed-time graph the *gradient* of the line gives the acceleration and the *area* under the line gives the distance travelled. A horizontal line means constant speed, an upward slope means acceleration and a downward slope means deceleration.
- **Scalars and vectors**: A *scalar* quantity has size only (mass, time, distance, speed, energy). A *vector* quantity has both size and direction (force, velocity, acceleration, momentum). Vectors along the same line add or subtract directly, while perpendicular vectors combine using Pythagoras.
- **Floating and measuring volume**: An object floats on a fluid when its average density is less than the fluid's, which is why a steel ship floats: its hollow shape lowers its average density. The volume of an irregular solid is found from the rise in the water level when the solid is fully submerged in a measuring cylinder.
- **Terminal velocity**: A falling object accelerates at first, but as its speed rises the air resistance on it grows until it balances the weight. The resultant force is then zero, so the object stops accelerating and falls at a steady *terminal velocity*. A larger surface area gives a lower terminal velocity.

EXAM TIPS

TIP Before applying $F = ma$, combine all the forces on the body into a single resultant, subtracting any friction or drag that opposes the motion. Dividing the resultant force by the mass then gives the acceleration.

TIP Mass (in kilograms) measures the quantity of matter and is the same everywhere. Weight (in newtons) is the gravitational force mg and changes with the field strength g, so the same object weighs less on the Moon than on Earth. Mass also measures *inertia*, the resistance to any change in motion.

TIP Hang an irregular flat sheet freely from a pin so it can swing, then hang a plumb line from the same pin and mark the vertical line on the sheet. Repeat from a second point; the centre of gravity lies where the two marked lines cross, because a suspended object settles with its centre of gravity directly below the pivot.

TIP Work is done only when the point of application of a force moves in the direction of the force. Holding a heavy bag still, or pushing on a wall that does not move, transfers no mechanical work however much effort it feels like, because the distance moved is zero.

TIP In a crash the passenger's momentum must fall to zero. A crumple zone, airbag or seatbelt makes this change happen over a longer time. Since the impulse Ft is fixed by the momentum change, a longer time t means a smaller force F on the passenger.

3 Nuclear physics

KEY FORMULAS

Alpha decay equation

$$^{A}_{Z}X \rightarrow \; ^{A-4}_{Z-2}Y + \; ^{4}_{2}\mathrm{He}$$

Use for alpha decay. The nucleus loses an alpha particle, so the nucleon number A falls by 4 and the proton number Z falls by 2. Balance the top row and the bottom row separately.

Beta-minus decay equation

$$^{A}_{Z}X \rightarrow \; ^{A}_{Z+1}Y + \; ^{0}_{-1}\mathrm{e}$$

Use for beta-minus decay. A neutron becomes a proton and emits a fast electron, so Z rises by 1 while A stays the same.

Corrected count rate

$$\text{corrected count rate} = \text{measured count rate} - \text{background count rate}$$

Use whenever a source's count rate is measured. Background radiation is always present, so subtract the background rate (measured with no source) before quoting the activity of a source.

Fraction remaining after n half-lives

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n, \qquad n = \frac{t}{T_{1/2}}$$

Use to find how much of a sample is left. n is the number of half-lives in the time elapsed t. The same factor applies to the number of nuclei, the mass, the activity or the corrected count rate.

Neutron number from nuclide notation

$$^{A}_{Z}X, \qquad \text{neutrons} = A - Z$$

Use to read a nuclide. Z is the proton number (which fixes the element) and A is the nucleon number (protons plus neutrons), so the neutron count is $A - Z$.

KEY CONCEPTS

- **Isotopes**: Isotopes are atoms of the same element (same proton number Z) with different numbers of neutrons (different nucleon number A). They have identical chemical behaviour because they have the same electron arrangement, but they differ in nuclear mass and stability.
- **Nature of alpha, beta and gamma radiation**: Alpha (α) is a helium nucleus $^{4}_{2}\mathrm{He}$: most ionising, stopped by paper. Beta-minus (β^-) is a fast electron $^{0}_{-1}\mathrm{e}$: medium ionising, stopped by a few mm of aluminium. Gamma (γ) is a high-energy electromagnetic wave: least ionising, only reduced by thick lead or concrete.
- **Nuclear model of the atom**: An atom is a tiny, dense, positively charged *nucleus* of protons and neutrons surrounded by *electrons* in mostly empty space. The nucleus holds almost all the mass. A neutral atom has equal protons and electrons; losing an electron makes a positive *ion* and gaining one makes a negative ion.
- **Reducing radiation dose (time, distance, shielding)**: Ionising radiation damages living cells, so handlers reduce their *dose* with three levers: less *time* near the source, more *distance* from it

(intensity falls steeply with distance), and *shielding* such as lead or concrete between source and body. Sources are stored in lead-lined boxes and handled with tongs.

- **Alpha-scattering evidence**: In the alpha-scattering experiment most alpha particles passed straight through thin gold foil (the atom is mostly empty space), a few were deflected through large angles (the positive charge is concentrated), and a very few bounced almost straight back (the nucleus is tiny, dense and holds nearly all the mass). This established the nuclear model.
- **Background radiation**: Background radiation is the low level of ionising radiation always present, even with no source nearby. Its main sources are radon gas from rocks and soil (usually the largest), rocks and building materials, cosmic rays, food and drink, and medical procedures. Most background is natural; only a small part is artificial.
- **Dangers of ionising radiation**: Ionising radiation can break chemical bonds inside living cells, including in DNA. A large dose kills cells outright (radiation burns or sickness); a smaller dose can damage DNA so a cell survives but multiplies abnormally, which may cause cancer or, in reproductive cells, heritable mutations. The risk rises with the dose received.
- **Definition of half-life**: The half-life $T_{1/2}$ of an isotope is the time taken for half the undecayed nuclei in a sample to decay, equivalently the time for the activity (or corrected count rate) to fall to half its value. It is constant for a given isotope: the same time passes for each successive halving, whatever the starting amount.
- **Penetrating power and absorbers**: The more ionising a radiation, the less penetrating it is, because it spends its energy ionising atoms near where it starts. Alpha is stopped by paper or a few cm of air, beta by a few mm of aluminium, and gamma is only reduced (never fully stopped) by thick lead or concrete.
- **Spontaneous and random decay**: Radioactive decay is *spontaneous* (nothing external, such as heating, pressure or chemical change, alters the rate) and *random* (you cannot predict which nucleus decays next or when). Over the huge numbers of nuclei in a real sample this randomness averages into a smooth, predictable decay curve.
- **Hazard inside versus outside the body**: Which radiation is most dangerous depends on where the source is. *Outside* the body, gamma (and to a lesser extent beta) is the greater hazard because alpha cannot penetrate the skin. *Inside* the body (a swallowed or inhaled source) the ranking reverses: alpha is the most dangerous because it is intensely ionising and deposits all its energy in a small volume of tissue, while gamma largely passes straight out.

EXAM TIPS

TIP Because alpha and beta are charged, they deflect in electric and magnetic fields in *opposite* directions, while uncharged gamma passes straight through. Beta deflects much more than alpha for the same field because it is far lighter, even though alpha carries more charge.

TIP Match isotopes by the *bottom* number Z, not the top number A. Two nuclei are isotopes only if they share the same Z. Nuclei with the same A but different Z (for example ${}^{40}_{19}\mathrm{K}$ and ${}^{40}_{18}\mathrm{Ar}$) are different elements, not isotopes.

4 Space physics

KEY FORMULAS

Hubble's law

$$v = H_0 d$$

Recession speed of a galaxy equals the Hubble constant H_0 times its distance d. Use to find how fast a distant galaxy is moving away, or, rearranged, to find its distance. With d in metres and H_0 in s^{-1} the speed is in m/s.

Orbital speed

$$v = \frac{2\pi r}{T}$$

Speed of any body in a circular orbit: one lap covers the circumference $2\pi r$ in the orbital period T. Use for the Moon, a planet or a satellite. Keep r in metres and T in seconds for a speed in m/s.

Age of the Universe

$$\text{age} \approx \frac{1}{H_0}$$

Running the expansion backwards estimates the age of the Universe as one divided by the Hubble constant. With H_0 in s^{-1} the age comes out in seconds; divide by 3.15×10^7 to convert to years (about 14 billion years).

Orbital period and frequency

$$T = \frac{1}{f}$$

The orbital period T (time for one lap) and the orbital frequency f (laps per second) are reciprocals. Use to convert a frequency into a period before substituting into $v = 2\pi r/T$.

Redshift and recession speed

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

For speeds well below the speed of light, the fractional increase in wavelength equals the recession speed as a fraction of the speed of light. Use to find a galaxy's speed v from its measured redshift, where $\Delta\lambda$ is the wavelength increase, λ the original wavelength and $c = 3.0 \times 10^8$ m/s.

KEY CONCEPTS

- **Elliptical orbits and changing speed**: Orbits are *ellipses* (slightly squashed circles), not perfect circles, with the Sun at one focus. Because the distance to the Sun changes around the orbit, the speed changes too: a body moves *fastest at its closest point* to the Sun and slowest at its farthest. A comet on a long stretched orbit shows this most dramatically.
- **Redshift and the expanding Universe**: Light from distant galaxies is shifted to longer (redder) wavelengths: *redshift*. The further away a galaxy is, the greater its redshift, so the faster it is receding. This is evidence that the whole Universe is *expanding* from an initial hot, dense state, the Big Bang.
- **Spin versus orbit**: The Earth *spins* on its axis once every 24 hours, which gives day and night. Separately it *orbits* the Sun once a year, and because its axis is tilted this gives the seasons. The Moon orbits the Earth about once a month, and the changing fraction of its sunlit half that faces us gives the *phases*.

- **Structure of the Solar System**: The Solar System is one star, the Sun, plus eight planets with their moons, together with dwarf planets, asteroids and comets, all held in orbit by the Sun's gravity. The four inner planets are small and rocky; the four outer planets are large gas and ice giants.
- **The Sun and nuclear fusion**: The Sun is an average star powered by *nuclear fusion* of hydrogen into helium in its core, releasing the energy that lights and warms the Solar System. Stars are gathered by gravity into *galaxies*; our galaxy is the Milky Way.
- **Evidence for the Big Bang**: Two independent observations support the Big Bang: the *redshift* of distant galaxies, which shows everything is flying apart, and the *cosmic microwave background radiation* (CMBR), a faint microwave glow coming from every direction that is the cooled-down remnant of the hot early Universe.
- **Galaxies and light-years**: A *galaxy* is a vast group of many billions of stars held together by gravity. Distances between stars and galaxies are measured in *light-years*: one light-year is the distance light travels in one year (about 9.5×10^{15} m). A light-year is a unit of distance, not time.
- **Life cycle of a star**: Every star begins as a *nebula* (a cloud of gas and dust) that gravity pulls into a *protostar* and then a stable *main-sequence star*. Its fate depends on its *mass*: a star like the Sun swells to a red giant then shrinks to a white dwarf; a much heavier star becomes a red supergiant, explodes as a supernova, and leaves a neutron star or a black hole.

EXAM TIPS

TIP For a "which planet orbits faster" question with no numbers, the answer is set by distance: the planet *closer to the Sun* moves faster, because the Sun's gravitational pull on it is stronger. The same rule explains why a comet is fastest near the Sun and slowest far out.

TIP Orbital periods are usually quoted in days or hours, so convert to seconds before using $v = 2\pi r/T$. For example 27.3 days is $27.3 \times 24 \times 3600 = 2.36 \times 10^{6}$ s. Forgetting this conversion is the most common way to lose the marks.

TIP The single word that selects a star's death path is *mass*. A star about the size of the Sun ends as a red giant then a white dwarf; a star much more massive ends as a red supergiant, then a supernova, then a neutron star or black hole. Read the question for the star's mass before committing to an ending.

5 Thermal physics

KEY FORMULAS

Boyle's Law (pressure and volume)

$$p_1 V_1 = p_2 V_2$$

For a fixed mass of gas at constant temperature, pressure is inversely proportional to volume. Use when a gas is compressed or expanded without any change in temperature.

Kelvin temperature conversion

$$T_K = \theta_C + 273$$

Converts a Celsius temperature θ_C to the absolute (Kelvin) scale. Always convert to kelvin before substituting a temperature into a gas-law ratio.

Specific heat capacity equation

$$\Delta E = mc\Delta\theta$$

Energy to change the temperature of mass m by $\Delta\theta$ with no change of state. Here c is the specific heat capacity in J/(kg·°C).

Specific latent heat equation

$$E = mL$$

Energy to change the state of mass m at constant temperature. L is the specific latent heat (of fusion for melting and freezing, of vaporisation for boiling and condensing).

Pressure law (constant volume)

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

For a fixed mass of gas at constant *volume*, pressure is proportional to absolute temperature in kelvin. Use when a sealed rigid container of gas is heated or cooled.

Constant-pressure law (volume and temperature)

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

For a fixed mass of gas at constant *pressure*, volume is proportional to absolute temperature in kelvin. Use when a gas is free to expand as it is heated, for example a gas trapped by a movable piston.

KEY CONCEPTS

- **Conduction**: Conduction is the transfer of thermal energy through a material without the material itself moving. Particles at the hot end vibrate more and pass energy to their neighbours through collisions. Metals also conduct through a sea of *free electrons*, which makes them the best conductors.
- **Convection**: Convection is the transfer of thermal energy through a *fluid* (a liquid or a gas) by the bulk movement of the fluid. Warmer fluid expands, becomes less dense and rises, while cooler, denser fluid sinks to replace it. Convection cannot occur in a solid or a vacuum.

- **Particle model of matter**: All matter is made of particles in constant motion. In a *solid* the particles vibrate about fixed positions in a regular lattice; in a *liquid* they are still close together but free to move past one another; in a *gas* they are far apart and move rapidly in all directions, filling the container.
- **Thermal radiation**: Thermal radiation is the transfer of thermal energy as *infrared* electromagnetic waves. It needs no medium, so it can travel through a vacuum, which is how energy from the Sun reaches the Earth. Every object above absolute zero emits thermal radiation.
- **Convection currents**: A convection current is a continuous circulation in a fluid: warm fluid rises, cools and sinks further away, then flows back toward the heat source. This is why a heater placed low warms a whole room and why the hot water in a tank collects at the top.
- **Evaporation versus boiling**: *Boiling* happens throughout a liquid at one fixed temperature, its boiling point. *Evaporation* happens only at the surface and at any temperature below boiling. During evaporation the fastest molecules escape first, lowering the average kinetic energy of those left behind, so the liquid cools.
- **Reducing unwanted heat transfer**: Unwanted heat transfer is reduced by tackling each mechanism. Trapped air or a vacuum cuts conduction and convection because there are few particles to carry energy, while shiny or light surfaces cut radiation. This is the basis of loft insulation, double glazing and survival blankets.
- **Temperature and kinetic energy**: The Kelvin temperature of a substance is a measure of the *average kinetic energy* of its particles. Raising the temperature makes the particles move faster, so they collide more often and more forcefully. At *absolute zero* (0 K) particle motion is at a minimum.
- **Thermal expansion of solids, liquids and gases**: When a substance is heated its particles move more and take up more room, so the substance expands. For the same temperature rise the expansion is greatest for *gases*, smaller for *liquids* and least for *solids*, because weaker bonds let particles move apart more easily.
- **Thermal expansion in engineering**: Because solids expand when heated, structures must allow for the movement. Bridges sit on rollers or include *expansion joints*, overhead cables and railway rails are laid with small gaps, and a *bimetallic strip* (two metals that expand by different amounts) bends when heated and is used to switch thermostats.
- **Why metals are the best conductors**: In a metal the outer electrons are free to move through the lattice. When one end is heated these *free electrons* gain kinetic energy and carry it quickly to the cooler end, on top of the slower neighbour-to-neighbour vibration found in every solid. Non-metals have no free electrons, so they conduct far more slowly.

EXAM TIPS

TIP A *matt black* surface is both the best absorber and the best emitter of infrared radiation. A *shiny, light-coloured* surface is the poorest absorber and poorest emitter, so it is the best reflector. A good absorber is always a good emitter.

TIP In $\Delta E = mc\Delta\theta$ always use the temperature *change* $\Delta\theta$, never the starting or final temperature. Keep the mass in kilograms. A degree Celsius and a kelvin are the same size, so a temperature change is numerically identical in either unit.

TIP Gases conduct poorly because their particles are far apart. Materials that trap small pockets of still air, such as wool, foam and fibreglass, are good insulators, provided the air cannot circulate and remove heat by convection.

6 Waves

KEY FORMULAS

Critical angle

$$\sin c = \frac{1}{n}$$

Gives the critical angle c for a ray inside a medium of refractive index n. At an angle of incidence greater than c the ray is totally internally reflected.

Refractive index

$$n = \frac{\sin i}{\sin r}$$

Refractive index of a medium from the angle of incidence i in air and the angle of refraction r in the medium. A larger n means light slows more and bends more.

Wave equation

$$v = f\lambda$$

Wave speed equals frequency times wavelength. Use for any wave to find one quantity from the other two; v in m/s, f in Hz, λ in m.

Refractive index as a speed ratio

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the medium}}$$

Refractive index is also the ratio of the wave speeds. Light slows on entering a denser medium, which is why it bends toward the normal.

Speed of sound from an echo

$$v = \frac{2d}{t}$$

An echo travels to a reflecting surface a distance d away and back, a total path of $2d$, in time t. Use it to find the speed of sound, or rearrange to find the distance to the surface.

KEY CONCEPTS

- **Converging and diverging lenses**: A *converging* (convex) lens bends parallel rays inward to meet at the *principal focus*, a distance equal to the focal length f from the lens. A *diverging* (concave) lens spreads parallel rays apart so they appear to come from a focus on the same side.
- **Law of reflection and the plane-mirror image**: The angle of incidence equals the angle of reflection, both measured from the *normal*. The image in a plane mirror is the same size as the object, as far behind the mirror as the object is in front, upright, laterally inverted and *virtual*.
- **Order of the electromagnetic spectrum**: In order of increasing frequency and decreasing wavelength the regions are radio, microwave, infrared, visible, ultraviolet, X-rays and gamma. All electromagnetic waves are transverse and travel through a vacuum at the same speed, 3.0×10^8 m/s.
- **Sound as a longitudinal wave**: Sound is a *longitudinal* wave of compressions and rarefactions produced by a vibrating source. It needs a medium, so it cannot travel through a vacuum, and it

travels fastest in solids, slower in liquids and slowest in gases.

- **Transverse and longitudinal waves**: A wave transfers *energy* from place to place without transferring matter. In a *transverse* wave the vibration is at right angles to the direction of travel, as in light and water ripples; in a *longitudinal* wave the vibration is along the direction of travel, as in sound.
- **Dispersion of white light by a prism**: White light is a mixture of colours. A prism refracts each colour by a slightly different amount, because the glass has a slightly higher refractive index for shorter wavelengths, so the light fans out into the spectrum red, orange, yellow, green, blue, indigo, violet. Violet bends most and red least.
- **Real and virtual images**: A *real* image forms where refracted rays actually cross; it can be caught on a screen and is inverted. A *virtual* image forms where rays only appear to come from; it cannot be projected and is upright. A converging lens gives a real image when the object is beyond the focal length.
- **Total internal reflection and optical fibres**: When a ray travelling inside a denser medium meets the boundary at an angle greater than the critical angle, none of it escapes and it is all reflected back inside. This *total internal reflection* lets optical fibres carry light and data around bends without leaking.
- **Uses and dangers across the spectrum**: Each region has typical uses: radio for broadcasting, microwave for satellite and mobile links and for cooking, infrared for remote controls and heating, visible for sight, ultraviolet for sterilising and security marking, X-rays for medical imaging and gamma for sterilising and treating cancer. Higher-frequency waves carry more energy, so ultraviolet damages skin while X-rays and gamma can mutate cells.
- **Wave quantities and diffraction**: *Wavelength* λ is the length of one complete cycle, *amplitude* is the maximum displacement from the rest position, *frequency* f is the number of cycles per second in Hz, and the *period* is the time for one cycle. When a wave passes through a gap it spreads out, an effect called diffraction, which is greatest when the gap is about the same width as the wavelength.
- **Monochromatic light does not disperse**: *Monochromatic* light, such as a laser beam, is light of a single frequency. A prism still refracts it, bending its path, but it cannot be split into a spectrum because there is only one colour present to separate.
- **The magnifying glass**: When an object is placed *inside* the focal length of a converging lens, the refracted rays diverge and only appear to meet behind the lens. This produces a *virtual*, upright, enlarged image on the same side as the object, which is how a magnifying glass works.

EXAM TIPS

TIP The *normal* is the line drawn at 90° to the surface at the point where the ray strikes. Every angle in reflection and refraction is measured between the ray and the normal, never between the ray and the surface. Convert an angle given to the surface by subtracting it from 90° first.

TIP Total internal reflection occurs only when *both* conditions hold. The light must be travelling in the *denser* medium toward the less dense one, and the angle of incidence must be *greater than* the critical angle.

TIP In any echo or sonar problem the pulse travels to the surface *and back*, so the measured time covers a distance of $2d$. Always halve the round-trip distance to get the one-way distance to the reflector.

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