

4 · Further Mechanics, Fields and Particles

Pearson Edexcel · International A-Level · Physics

From a collision to a particle accelerator

A car bumper and a particle detector seem very different. Both use momentum and forces. This unit follows those ideas into circular motion, electric fields, magnetic fields and particle interactions.

WPH14 assesses requirements 81–124 of the Issue 3 specification. It can also use knowledge from Units 1–2. Use the seven skill sheets in order. Check units, directions and the assumptions behind each equation. A familiar equation can give a wrong answer when its model does not fit.

Impulse and two-dimensional collisions

■ Force changes momentum

Momentum is the vector $\mathbf{p} = m\mathbf{v}$. Choose a positive direction before using signs. **Impulse** is the change in momentum. For constant force, or the average force over an interval:

$$F_{\text{average}}\Delta t = \Delta p = m(v - u)$$

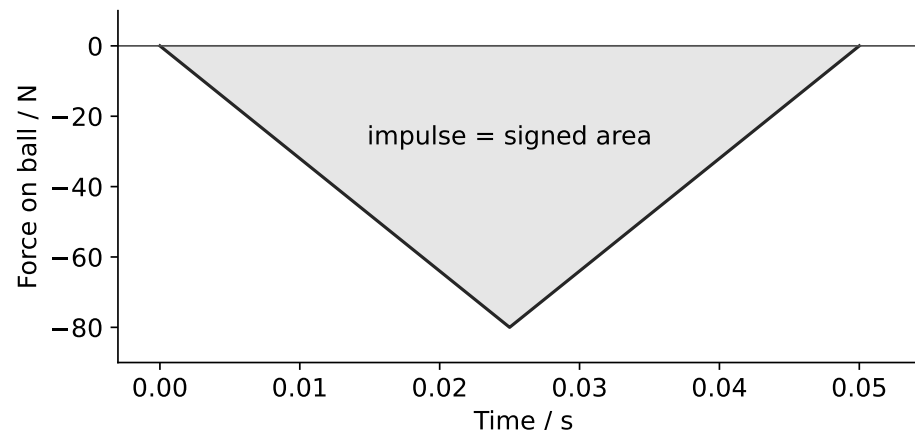
A changing force gives an impulse equal to the signed area under its force–time graph. A triangular pulse has area $\frac{1}{2} \times \text{base} \times \text{height}$. An area below the time axis is negative. The maximum force is not automatically the average force.

Worked example. A 0.20 kg ball approaches a wall at $+6.0 \text{ m s}^{-1}$. It rebounds at -4.0 m s^{-1} . Contact lasts 0.050 s. Find average force on the ball.

- Known: mass, signed initial/final velocities and contact time.
- Why: force impulse changes the ball's momentum; rebound reverses the sign.

$$\Delta p = m(v - u) = 0.20 \text{ kg} \times (-4.0 - 6.0) \text{ m s}^{-1} = -2.0 \text{ kg m s}^{-1}$$

$$F_{\text{average}} = \frac{\Delta p}{\Delta t} = \frac{-2.0 \text{ kg m s}^{-1}}{0.050 \text{ s}} = -40 \text{ N}$$



The force is opposite the chosen positive direction. The wall feels an opposite force. A deforming bumper or helmet increases stopping time. For the same momentum change, this reduces average force. It does not remove the momentum change.

■ Conserve each momentum component

An **isolated system** has no significant external impulse during the event. Its total momentum is conserved. Internal forces cancel in opposite pairs. Momentum conservation does not require kinetic energy conservation.

For a collision in a plane, resolve every momentum into two perpendicular axes:

$$\sum p_{x,\text{before}} = \sum p_{x,\text{after}} \quad \sum p_{y,\text{before}} = \sum p_{y,\text{after}}$$

Use the angle measured from the chosen axis. Include signs; a downward component is negative if upwards is positive. Do not add momentum magnitudes when directions differ.

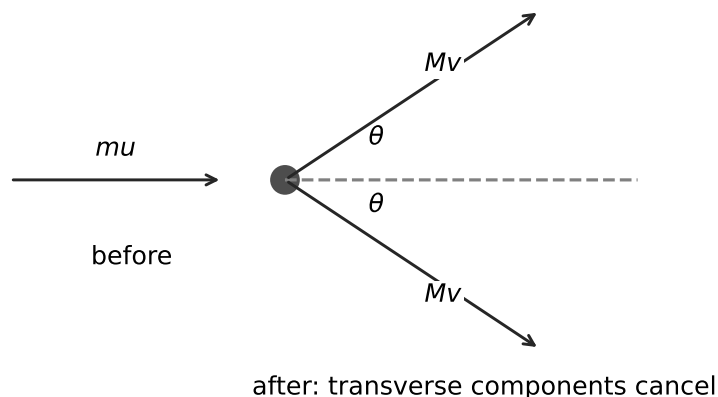
Worked example. A 0.10 kg sphere moving at 2.0 m s^{-1} strikes two stationary spheres, each 0.10 kg. It stops. The two others leave symmetrically at 1.2 m s^{-1} , at angles $+\theta$ and $-\theta$ to the original direction. Find their separation angle and classify the collision.

- Why: transverse momenta cancel by symmetry; longitudinal momentum gives θ .

$$mu = 2Mv \cos \theta$$

$$\cos \theta = \frac{mu}{2Mv} = \frac{0.10 \text{ kg} \times 2.0 \text{ m s}^{-1}}{2 \times 0.10 \text{ kg} \times 1.2 \text{ m s}^{-1}} = 0.833$$

$$2\theta = 2 \cos^{-1} \left(\frac{mu}{2Mv} \right) = 2 \cos^{-1}(0.833) = 67.1^\circ$$



An **elastic collision** conserves total kinetic energy as well as momentum. An **inelastic collision** does not conserve kinetic energy; some becomes other forms of energy.

$$E_{k,\text{before}} = \frac{1}{2}mu^2 = \frac{1}{2} \times 0.10 \times 2.0^2 \text{ J} = 0.20 \text{ J}$$

$$E_{k,\text{after}} = 2 \times \frac{1}{2}Mv^2 = 2 \times \frac{1}{2} \times 0.10 \times 1.2^2 \text{ J} = 0.144 \text{ J}$$

This collision is inelastic. Total energy is still conserved. In an ordinary passive collision, kinetic energy cannot increase without an additional energy source.

For a **non-relativistic particle**, use $p = mv$ and $E_k = \frac{1}{2}mv^2$. Substituting $v = p/m$ gives:

$$E_k = \frac{1}{2}m \left(\frac{p}{m} \right)^2 = \frac{p^2}{2m}$$

At equal kinetic energy, $p = \sqrt{2mE_k}$: a larger mass has larger momentum. At equal momentum, a larger mass has smaller kinetic energy. These equations are not valid for a particle moving close to light speed.

■ Core practicals 9 and 10

For **core practical 9**, use a trolley, force sensor and data logger. Measure trolley mass and velocities just before/after contact using light gates or a motion sensor. Record the force–time pulse at a sampling rate fast enough to resolve it. Zero the force sensor; use consistent axes for force and velocity. Integrate the graph area and compare it with $m(v - u)$. Repeat for different contact forces or speeds. A graph of impulse against momentum change should have gradient close to one. Friction, sensor offsets and missed parts of the pulse can cause disagreement. Secure the track and catch the trolley safely.

For **core practical 10**, record small spheres colliding on a level surface using an overhead camera. Include a length scale in the collision plane and a known frame rate. Keep the camera perpendicular to reduce perspective error. Track centres over several frames before and after the short collision. Convert pixel displacements to metres and frame intervals to seconds. Determine both velocity components, then compare total momentum components and kinetic energies. Repeat with different approach directions. Include uncertainty from positions, timing and scale calibration. A small mismatch within uncertainty is not evidence that momentum fails. Keep spheres contained so they cannot fall or become a slipping hazard.

Circular motion

■ Angle, angular speed and tangential speed

An angle of one **radian** subtends an arc equal to the radius. Hence $\theta = s/r$, with angle in radians. One revolution is 2π radians or 360° .

$$\theta_{\text{rad}} = \theta_{\text{degrees}} \frac{2\pi}{360} \quad \omega = \frac{\Delta\theta}{\Delta t} = \frac{2\pi}{T} \quad v = \omega r$$

Angular velocity describes the rate of angular displacement. In the plane problems here, use its signed rotational rate or magnitude as appropriate. Points on one rigid turntable have the same angular speed. Points farther from its centre have larger **tangential speed**. Their velocity directions also vary around the circle.

Worked example. A wheel rotates at 120 revolutions per minute. Find angular speed and acceleration of a point 0.25 m from its centre.

$$f = \frac{N}{t} = \frac{120}{60 \text{ s}} = 2.0 \text{ Hz}$$

$$\omega = 2\pi f = 2\pi \times 2.0 \text{ s}^{-1} = 12.6 \text{ rad s}^{-1}$$

$$a = r\omega^2 = 0.25 \text{ m} \times (4\pi \text{ s}^{-1})^2 = 39.5 \text{ m s}^{-2}$$

Keep the unrounded angular speed during the calculation. Use radius, not diameter.

■ Why acceleration points inward

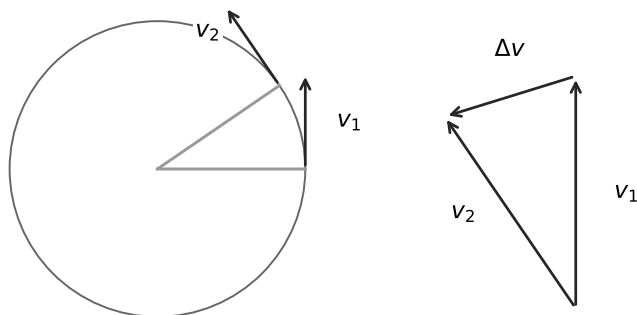
Uniform circular motion has constant speed but changing velocity. Draw the initial and final tangential velocity vectors. The change is $\Delta \mathbf{v} = \mathbf{v}_2 - \mathbf{v}_1$, not their sum. For a small angular change, the velocity triangle and radius triangle are similar:

$$\frac{\Delta v}{v} \approx \frac{\Delta s}{r} \quad \Delta s \approx v \Delta t$$

$$a = \lim_{\Delta t \rightarrow 0} \frac{\Delta v}{\Delta t} = \frac{v^2}{r} = r\omega^2$$

Tangential velocity vectors

$$\Delta \mathbf{v} = \mathbf{v}_2 - \mathbf{v}_1$$



The change in velocity points towards the centre in this limit. A resultant **centripetal force** is therefore needed:

$$\sum F_{\text{inward}} = ma = \frac{mv^2}{r} = mr\omega^2$$

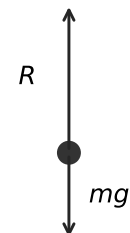
Centripetal force names the resultant of real forces. It is not an extra force to add to a force diagram. Friction can provide it on a turntable. Tension can provide it for a ball on a string.

■ Write the real-force equation

For clothing against the inside of a vertical drum, weight always points down. The drum's normal reaction points towards the centre. At constant speed:

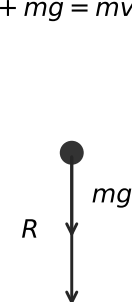
$$\text{bottom: } R - mg = \frac{mv^2}{r} \quad \text{top: } R + mg = \frac{mv^2}{r}$$

Bottom of drum



$$R - mg = mv^2/r$$

Top of drum



$$R + mg = mv^2/r$$

The required resultant has the same magnitude, but the reaction is larger at the bottom. If contact is lost, the surface cannot provide a pulling normal reaction. Check this before using a circular-path model.

For a horizontal turntable, the largest available friction must be at least $mr\omega^2$. If maximum friction is $mg/25$:

$$mr\omega^2 \leq \frac{mg}{25} \Rightarrow r \leq \frac{g}{25\omega^2}$$

Mass cancels because both required and available forces scale with mass. If the inward force disappears, motion initially follows the tangent. Gravity can then curve the later path; “tangent” describes the release direction.

Electric fields and potential

■ Force and potential describe different things

An **electric field** is a region where a charged particle experiences a force. **Electric field strength** is force per unit positive test charge:

$$\mathbf{E} = \frac{\mathbf{F}}{q} \quad \mathbf{F} = q\mathbf{E}$$

Its units are N C^{-1} or V m^{-1} . A positive charge feels force along the field; a negative charge feels force opposite it.

Electric potential is potential energy per unit charge relative to a chosen reference. For a charge q moved through a potential change:

$$\Delta U = q\Delta V \quad W_{\text{field}} = -q\Delta V$$

Potential is a scalar; field is a vector. A point with zero potential need not have zero field. Adding signed potentials is different from adding field vectors.

■ Radial and uniform fields

For point charges, or outside an isolated charged conducting sphere, with $k = 1/(4\pi\epsilon_0)$:

$$|F| = \frac{k|Q_1Q_2|}{r^2} \quad |E| = \frac{k|Q|}{r^2} \quad V = \frac{kQ}{r}$$

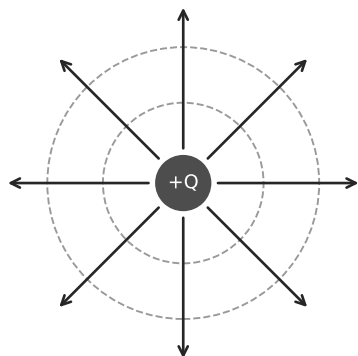
Here r is separation of charge centres; sphere distances are measured from its centre. Like charges repel, unlike charges attract. Potential takes the sign of Q when zero is at infinity.

Between large parallel plates, away from edges, the field is approximately uniform:

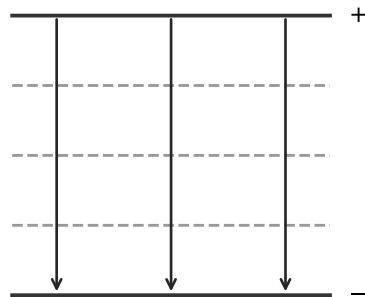
$$|E| = \frac{|\Delta V|}{d}$$

The field points from higher to lower potential. Plate separation d is perpendicular to the plates. An **equipotential** has the same potential everywhere. Field lines cross equipotentials at right angles. Moving along one involves no change in electric potential energy.

Radial field and equipotentials



Uniform field between plates



The radial field is the negative potential gradient: $E_r = -dV/dr$. For a positive source, the signed area under its E - r curve from r to infinity equals $V(r)$. The area from zero to r is not that potential. In a uniform field, closer equally spaced potential levels mean stronger field.

Worked example. A sphere of radius 0.20 m has potential 9.0 kV. Find charge and field at 0.30 m from its centre. Use $k = 8.99 \times 10^9 \text{ N m}^2\text{C}^{-2}$.

$$Q = \frac{Vr}{k} = \frac{9.0 \times 10^3 \text{ V} \times 0.20 \text{ m}}{8.99 \times 10^9 \text{ N m}^2\text{C}^{-2}} = 2.00 \times 10^{-7} \text{ C}$$

$$E = \frac{kQ}{r^2} = \frac{8.99 \times 10^9 \times 2.00 \times 10^{-7}}{0.30^2} \text{ N C}^{-1} = 2.00 \times 10^4 \text{ N C}^{-1}$$

Use the surface radius to find charge, then the new centre-distance to find field. Do not reuse the surface distance for the second step.

■ Compare electrical and gravitational forces

A stationary charged oil drop can satisfy $|q|E = mg$. Use $m = \rho V$ if density and volume are given. Divide the charge magnitude by $e = 1.60 \times 10^{-19} \text{ C}$ to test whether it is close to an integer multiple. Charge sign follows the direction of force required, not its magnitude alone.

To lift a spherical grain, compare qE with $\rho(4\pi r^3/3)g$. Radius is half the listed diameter. A calculated maximum diameter is a threshold: choose the largest listed diameter below it. On an inclined panel, the normal component of weight is $mg \cos \theta$. The electric force perpendicular to the panel need overcome that component to detach a grain; gravity also has a downslope component.

Capacitors and RC circuits

■ Charge storage and energy

A **capacitor** stores separated charge on two conductors. They carry equal and opposite charges in the ideal two-plate model. The quoted charge Q is the magnitude on either plate, not the sum of both magnitudes. **Capacitance** is charge stored per unit p.d.:

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

One farad is one coulomb per volt. For constant capacitance, a V - Q graph is straight through the origin with gradient $1/C$. Its area gives the work needed to transfer charge onto the capacitor:

$$W = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{Q^2}{2C}$$

The factor one half appears because p.d. rises from zero while charge is transferred. It is not QV at the final voltage throughout charging. For discharge between non-zero voltages, subtract the two stored energies:

$$\Delta W = \frac{1}{2}C(V_{\text{initial}}^2 - V_{\text{final}}^2)$$

This is different from $\frac{1}{2}C(V_{\text{initial}} - V_{\text{final}})^2$.

■ Charging and discharging

In an ideal series resistor–capacitor charging circuit, initially uncharged, the capacitor p.d. is zero. The resistor initially has the full supply p.d., so current is maximum. As charge builds, capacitor p.d. rises. Resistor p.d. and current fall. At full charge, current is zero and capacitor p.d. equals supply p.d.

For discharge through a fixed resistance, use signed current consistently or work with its magnitude:

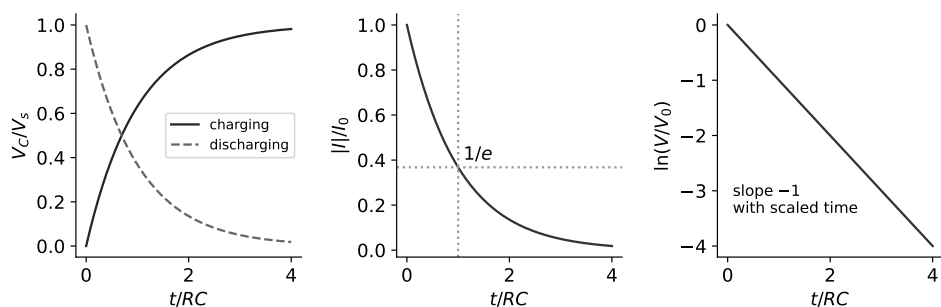
$$Q = Q_0 e^{-t/RC} \quad V = V_0 e^{-t/RC} \quad |I| = I_0 e^{-t/RC}$$

The voltage relation follows from $Q = CV$ with constant C . Current magnitude follows from $|I| = V/R$ with constant R . The **time constant** is $\tau = RC$. After one time constant, Q , V and current magnitude are $e^{-1} \approx 0.368$ of their initial values. After three time constants they are about 5%, not zero. Stored energy falls faster because it depends on V^2 .

For charging from an ideal constant supply V_s :

$$V_C = V_s(1 - e^{-t/RC}) \quad V_R = V_s e^{-t/RC} \quad I = \frac{V_s}{R} e^{-t/RC}$$

A charging capacitor voltage rises towards V_s ; charging current falls towards zero. Do not sketch the same curve for both quantities. Equal V_C and V_R means each is $V_s/2$, reached at $t = RC \ln 2$.



Taking natural logs of the discharge equation gives:

$$\ln V = \ln V_0 - \frac{t}{RC}$$

Thus a graph of $\ln V$ against t has gradient $-1/(RC)$ and intercept $\ln V_0$. The same forms hold for Q and current magnitude. Use consistent measurement units inside the logged numerical values.

Worked example. A $100 \mu\text{F}$ capacitor discharges from 12.0 V through $20.0 \text{ k}\Omega$. Find p.d. after 3.0 s and energy lost.

$$\tau = RC = 20.0 \times 10^3 \Omega \times 100 \times 10^{-6} \text{ F} = 2.00 \text{ s}$$

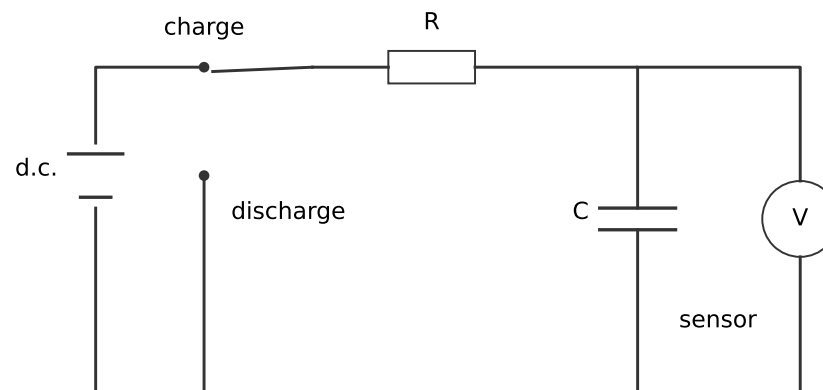
$$V = V_0 e^{-t/RC} = 12.0 \text{ V} \times e^{-3.0/2.00} = 2.68 \text{ V}$$

$$\Delta W = \frac{1}{2}C(V_0^2 - V^2) = \frac{1}{2} \times 100 \times 10^{-6} \text{ F} \times (12.0^2 - 2.68^2) \text{ V}^2 = 6.84 \times 10^{-3} \text{ J}$$

The lost stored energy becomes mainly heat in the discharge resistance. Use unrounded voltage in the final calculation.

■ Core practical 11 and useful extensions

Use a low-voltage d.c. supply, resistor, capacitor and switch. Charge through the resistor, then disconnect the supply and discharge through the known resistance. Connect a voltage sensor, data logger or oscilloscope across the capacitor. Record time and p.d.; choose a sampling interval short compared with RC . Use an instrument input resistance large compared with the discharge resistance, otherwise it changes the discharge path.



Keep R and C fixed, repeat after restoring the same initial charge, and compare measured curves with exponential predictions. Determine RC from the $1/e$ level or a log-fit gradient. Avoid taking logs of readings near zero where relative uncertainty is large. For a resistance-tolerance test, calculate $R = -\Delta t/[C \ln(V_2/V_1)]$ during one uninterrupted discharge and compare with both limits of the permitted interval.

Use correct polarity for an electrolytic capacitor and remain below its voltage rating. Discharge it safely through a resistor before altering connections; do not short a charged capacitor. Leakage, sensor loading and resistor heating can change the measured curve.

A smoothing capacitor charges near supply peaks and discharges into the load between them. A smaller load resistance gives a smaller time constant, faster discharge and less smoothing. For two identical series capacitors, the same magnitude of charge appears on each. Their equal p.d.s share the supply, so each stores half the charge of one identical capacitor connected alone. This sharing is a useful bridge to the selected paper; it does not replace the main capacitance model.

Magnetic forces and induction

■ Directions, flux and force

Magnetic flux density B describes the field's force effect. For a straight wire of length l in a uniform field:

$$F = BIl \sin \theta$$

Here θ is between conventional current and field. Only the length inside the field counts. For one charged particle:

$$F = |q|vB \sin \theta$$

Use **Fleming's left-hand rule**: first finger along field, second along conventional current, thumb gives force. A positive charge moves with conventional current. Reverse the result for an electron's motion. Dot symbols mean out of the page; crosses mean into it.

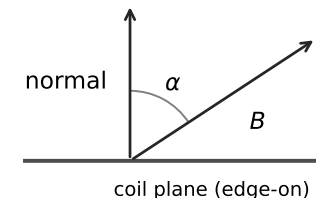
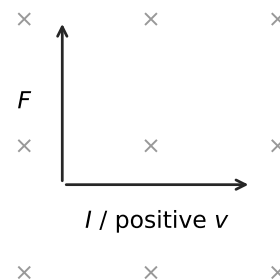
Magnetic force is perpendicular to velocity, so it changes direction without doing work. It cannot, alone, increase the particle's kinetic energy. If $\mathbf{v}$ is parallel to $\mathbf{B}$, magnetic force is zero.

Magnetic flux through a flat area in a uniform field is:

$$\phi = BA \cos \alpha$$

Here α is between field and the area's normal, not the plane itself. The unit is the weber. **Flux linkage** is $N\phi$ when the same flux links each of N turns.

Field into page; force upwards Flux uses angle to area normal



$$\phi = BA \cos \alpha$$

Worked example. A coil has 40 turns and radius 0.015 m. A uniform 0.020 T field is perpendicular to its plane. Find flux linkage.

$$A = \pi r^2 = \pi(0.015 \text{ m})^2 = 7.07 \times 10^{-4} \text{ m}^2$$

$$N\phi = NBA = 40 \times 0.020 \text{ T} \times 7.07 \times 10^{-4} \text{ m}^2 = 5.65 \times 10^{-4} \text{ Wb}$$

Use radius, not diameter, and multiply by turns only when finding linkage. A balance under magnets measures the opposite reaction to a force on a separately supported wire. Convert a balance reading change Δm to force Δmg , not Δm itself.

■ A changing linkage induces an e.m.f.

Electromagnetic induction occurs when flux linkage changes. Relative movement of a coil and magnet can cause it. Rotating the coil or changing current in another linked coil can also cause it. A stationary coil in a constant field has no induced e.m.f. merely because flux is present.

Faraday's law relates e.m.f. magnitude to rate of flux-linkage change. **Lenz's law** gives the opposing direction:

$$\mathcal{E} = -\frac{d(N\phi)}{dt} \quad |\mathcal{E}_{\text{average}}| = \frac{|\Delta(N\phi)|}{\Delta t}$$

Induced current, if the circuit is closed, produces a magnetic effect opposing the change that caused it. It does not always oppose the existing field: when that field decreases, the induced effect helps maintain it. This opposition is consistent with energy conservation.

Worked example. Flux through each of 50 turns decreases from 6.0×10^{-5} to 2.0×10^{-5} Wb in 0.020 s. Find average induced e.m.f. magnitude.

$$|\mathcal{E}| = \frac{N|\phi_2 - \phi_1|}{\Delta t} = \frac{50 \times |2.0 - 6.0| \times 10^{-5} \text{ Wb}}{0.020 \text{ s}} = 0.10 \text{ V}$$

Faster movement, stronger field, more turns or larger linked area can increase the rate. Explain which quantity actually changes. In a magnetic-strip reader, reversing pole orientation reverses signal direction. For a straight boundary swept across an area of width L at speed v , $\Delta A/\Delta t = Lv$, giving $|\mathcal{E}| = NBLv$ under that uniform-field model. Wireless charging uses alternating current in one coil, producing changing magnetic field and changing linkage in the phone coil. That induces an e.m.f. The receiving circuit can then charge the battery. Equal turn counts do not ensure equal voltages: some flux may fail to link the other coil, especially with separation or without an iron core.

Nuclear structure, accelerators and tracks

■ The nucleus and scattering evidence

In ${}_Z^AX$, **proton number** Z counts protons and **nucleon number** A counts protons plus neutrons. The neutron count is $A - Z$. A neutral atom has Z electrons; an ion need not.

The older distributed-positive-charge model could explain small deflections but not the observed rare large-angle alpha scattering. Most alpha particles pass nearly straight through thin foil, showing that most of the atom is empty space. A small fraction experience very large deflections. Positive alpha particles feel strong electrostatic repulsion near a small, dense, positive nucleus containing most atomic mass. Few large-angle events show that the nucleus occupies a small fraction of the atom's volume. Keep each observation linked to the particular conclusion it supports.

■ Make, accelerate and steer a beam

Thermionic emission releases electrons from a heated metal. Heating supplies energy so some electrons can leave the surface. A positive accelerating electrode attracts them through a vacuum. A potential difference changes kinetic energy by the electric work:

$$\Delta E_k = q(V_{\text{initial}} - V_{\text{final}})$$

For speed calculations use the positive energy gain $|q||\Delta V|$ only when the particle is accelerated through the field in the appropriate direction. Starting from rest, well below light speed:

$$\frac{1}{2}mv^2 = |q||\Delta V|$$

A **linear accelerator** uses alternating p.d. across gaps between drift tubes. Particles accelerate in gaps and are shielded inside the conducting tubes. The polarity reverses

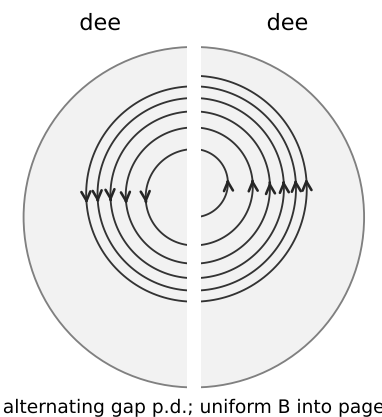
while particles are inside, so the next gap accelerates them again. At constant alternating frequency, increasing speed requires longer tubes to maintain the time between successive gaps. Across n equal accelerating gaps, total kinetic-energy gain is $n|q|V_{\text{gap}}$. A **cyclotron** uses a magnetic field perpendicular to two hollow dees. Electric field accelerates particles across the gap. Inside a dee, magnetic force curves the path without increasing speed. Polarity reverses during each half-turn, allowing another energy gain at the next crossing. With perpendicular entry:

$$|q|vB = \frac{mv^2}{r} \Rightarrow r = \frac{mv}{B|q|} = \frac{p}{B|q|}$$

$$T = \frac{2\pi r}{v} = \frac{2\pi m}{B|q|} \quad f = \frac{B|q|}{2\pi m}$$

In the non-relativistic model, the period is independent of speed. Increasing speed increases radius. Time in one dee is $T/2$, not T . The formula assumes constant field and fixed mass in this model; synchronisation fails as relativistic effects become important.

Cyclotron: radius grows after each gap



Worked example. A proton moves perpendicular to $B = 0.40 \text{ T}$ with momentum $2.0 \times 10^{-20} \text{ kg m s}^{-1}$. Use proton mass $1.67 \times 10^{-27} \text{ kg}$.

$$r = \frac{p}{B|q|} = \frac{2.0 \times 10^{-20}}{0.40 \times 1.60 \times 10^{-19}} \text{ m} = 0.313 \text{ m}$$

$$t_{\text{dee}} = \frac{T}{2} = \frac{\pi m}{B|q|} = \frac{\pi \times 1.67 \times 10^{-27}}{0.40 \times 1.60 \times 10^{-19}} \text{ s} = 8.20 \times 10^{-8} \text{ s}$$

When starting instead from a de Broglie wavelength, use $p = h/\lambda$, then $E_k = p^2/(2m)$ and $V = E_k/|q|$. Check that the non-relativistic assumption remains suitable.

■ **Read detector evidence carefully**

Charged particles ionise matter along their paths, leaving detectable tracks. A neutral particle does not make a direct ionisation track in this model. Its presence can be inferred from missing momentum or from charged products it later produces.

In a known perpendicular magnetic field, curvature direction together with travel direction can identify charge sign. Without field direction, curvature alone cannot give sign. Radius gives momentum through $p = B|q|r$; comparing radii requires knowledge of charge magnitude. A tightening track often shows momentum being lost. Do not infer travel direction from a constant-radius arc alone.

Conserve charge, total energy and vector momentum at an interaction. If visible outgoing momenta do not add to the incoming momentum, a neutral product may carry the missing component. Draw a vector balance rather than guessing from the number of tracks.

High energies probe nucleon structure in two ways. Large momentum gives a short de Broglie wavelength, allowing small structure to be resolved. High collision energy also allows new massive particles to be created. Quarks are not observed as isolated free particles; do not describe a high-energy collision simply as removing a free quark.

Fast muons can reach the ground because their average lifetime measured in the Earth’s frame is increased at speeds close to c . This does not mean they exceed light speed. Unit 4 requires the significance of this lifetime increase, not use of relativistic equations.

Particles, antiparticles and conservation

■ **Families and antiparticles**

In the **quark–lepton model** –, baryons and mesons contain quarks. Leptons are fundamental particles in the model.

- A **baryon** contains three quarks, for example a proton uud or neutron udd . An antibaryon contains three antiquarks.
- A **meson** contains one quark and one antiquark, for example a pion.
- A **lepton** is fundamental, for example an electron or neutrino. A positron is an antilepton, not a meson.
- A photon is the quantum of electromagnetic radiation; it is neither a baryon nor a lepton.

Up-type quarks have charge $+2e/3$ and down-type quarks $-e/3$. Antiquarks have opposite charges. For example, uud sums to $+e$ and udd to zero. The symmetry of the quark families predicted a top quark before it was observed. Classification models make testable predictions, not just lists of known particles.

An **antiparticle** has the same rest mass as its particle and opposite electric charge

when charged. Other relevant additive quantum numbers also reverse. An electron has lepton number $+1$; its positron has -1 . Both have baryon number zero. A neutral antiparticle can differ in quantum numbers despite having no electric charge.

■ **Check conserved totals**

Assign baryon number $+1$ to a baryon, -1 to an antibaryon, and zero to mesons/leptons/photons. Quarks carry $+1/3$ and antiquarks $-1/3$. Assign lepton number $+1$ to a lepton and -1 to an antilepton. Compare total charge, baryon number and lepton number on both sides of a proposed reaction. Also check energy and momentum. Passing the listed conservation checks alone does not prove that an interaction will occur; it establishes that those laws do not forbid it.

Worked example. Test $n \rightarrow p + e^- + \bar{\nu}_e$.

Quantity	Before	After
Charge / e	0	$+1 - 1 + 0 = 0$
Baryon number	1	$1 + 0 + 0 = 1$
Lepton number	0	$0 + 1 - 1 = 0$

The antineutrino balances the electron’s lepton number. Changing it to a neutrino would make the final total $+2$, so that proposed equation would fail this check. Preserve bars and charge signs when interpreting supplied particle symbols.

■ **Rest energy, creation and annihilation**

Mass–energy equivalence relates a rest-mass change to energy:

$$\Delta E = c^2 \Delta m$$

In **pair production** , energy creates a particle–antiparticle pair. The energy must at least supply both rest masses; extra energy can become kinetic energy or recoil. Momentum must also be conserved, so the surrounding interaction matters. In **annihilation** , particle and antiparticle can turn into photons. A pair initially at rest producing two photons gives equal photon energies and opposite momenta. Each photon carries one particle’s rest energy for an equal-mass pair; the total is twice that value.

One electronvolt is e joules: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. MeV means 10^6 eV and GeV means 10^9 eV . A quoted mass in MeV/c^2 is a mass unit, not an energy unit. Multiply by c^2 to get its corresponding rest energy.

Worked example. Convert a mass of $140 \text{ MeV}/c^2$ to kilograms.

$$mc^2 = 140 \times 10^6 \times 1.60 \times 10^{-19} \text{ J} = 2.24 \times 10^{-11} \text{ J}$$

$$m = \frac{E}{c^2} = \frac{2.24 \times 10^{-11} \text{ J}}{(3.00 \times 10^8 \text{ m s}^{-1})^2} = 2.49 \times 10^{-28} \text{ kg}$$

Use the same units before comparing masses. Percentage difference from an accepted value is $100 \times |m_{\text{predicted}} - m_{\text{accepted}}|/m_{\text{accepted}}$. State the reference value. In threshold questions, distinguish rest-energy supply from kinetic energy; do not use $p = mv$ for a photon or a particle close to c .

Check yourself

- Can you use signed impulse and two momentum components, then test kinetic energy separately?
- Can you derive centripetal acceleration and draw only actual forces?
- Can you distinguish field vectors, signed potential and energy changes?
- Can you choose the correct capacitor curve and use log slope or tolerance evidence?
- Can you explain induction as a change in linkage, including the opposing direction?
- Can you separate electric acceleration from magnetic steering and halve a cyclotron period correctly?
- Can you preserve particle symbols, conservation totals and energy/mass units?

The skill sheets develop these methods before authentic past-paper tasks. Original practice also covers requirements not sampled in the two recent papers. A short sample of authentic questions does not define the whole syllabus.