Cambridge AS & A Level · Physics 9702 · Notes

Electric fields A2

Read online at **pastopic.com/cambridge/physics-9702/notes/electric-fields**

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Read first: **Electricity**, **Kinematics**

What you need to know

By the end of this topic you should be able to:

1. **Understand that an electric field is a field of force**, and **define electric field** (field strength E) as the force per unit positive charge on a charge placed at that point.
2. **Recall and use** $F = qE$ for the force on a charge q in a field of strength E.
3. **Draw an electric field with field lines.**
4. **Recall and use** $E = \dfrac{\Delta V}{\Delta d}$ for the uniform field between two charged parallel plates.
5. **Describe what a uniform field does to a moving charged particle**: a constant force, so a constant acceleration along the field lines.
6. **Treat a charged conducting sphere as a point charge at its centre** for any point outside it.
7. **Recall and use Coulomb's law**, $F = \dfrac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$, for the force between two point charges in free space.
8. **Recall and use** $E = \dfrac{Q}{4\pi\varepsilon_0 r^2}$ for the field strength of a point charge.
9. **Define electric potential** at a point as the work done per unit positive charge in bringing a small test charge from infinity to that point.
10. **Use the fact that field strength is minus the potential gradient**, $E = -\dfrac{dV}{dx}$.
11. **Use** $V = \dfrac{Q}{4\pi\varepsilon_0 r}$ for the potential of a point charge.
12. **Use** $E_P = \dfrac{Qq}{4\pi\varepsilon_0 r}$ for the electric potential energy of two point charges, and see how it comes from the idea of potential.

Charge, current and potential difference come from Electricity; the equations of uniformly accelerated motion come from Kinematics.

Understand it

A field of force

Charges push and pull on each other: like charges repel, unlike charges attract. We say a charge sets up an **electric field** around itself, a region where another charge feels a force. Put a small **positive** test charge q at a point, measure the force F on it, and divide:

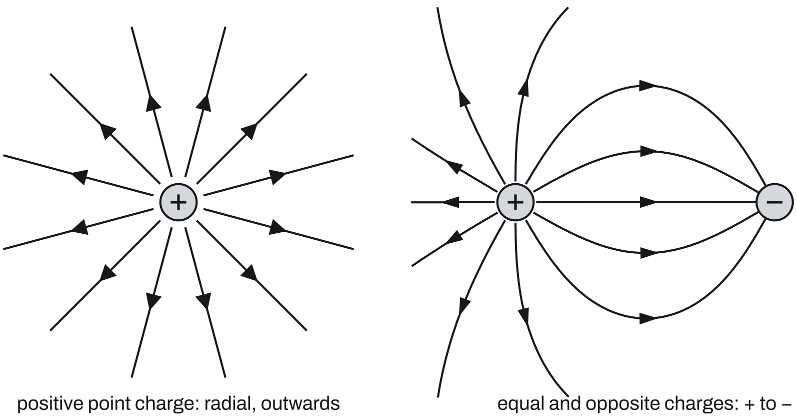
$$E = \frac{F}{q}$$

This is the **electric field strength**, in N C^{-1} (the same as V m^{-1}). It is a vector, and its direction is the direction of the force on a **positive** charge. A negative charge in the same field feels a force the **opposite** way. Turned round, the force on any charge is $F = qE$: a 4.0 nC charge in a field of 3.0×10^4 N C^{-1} feels 1.2×10^{-4} N.

Electric and gravitational fields are both fields of force, but gravity only attracts and acts on mass, while the electric force can attract or repel and acts on charge. For an electron or proton the electric force is usually so much bigger than its weight that the weight can be ignored; for an oil drop or a dust grain the weight matters.

Field lines

A **field line** shows the direction of the force on a small **positive** charge placed on it. Lines start on positive charges and end on negative charges, they never cross, and the closer together they are, the stronger the field.



positive point charge: radial, outwards   equal and opposite charges: + to −

- **Point charge or charged sphere**: straight **radial** lines, meeting the surface at right angles. Arrows point **away** from a positive charge and **towards** a negative one. They spread out, showing the field getting weaker.
- **Two opposite charges**: curved lines from $+$ to $-$. **Two like charges**: the lines push apart, and there is a point between them where the field is zero.
- **Between two parallel plates**: straight, parallel, **equally spaced** lines from the positive (higher potential) plate to the negative (lower potential) plate, meeting each plate at right angles. Equal spacing means the field is **uniform**: the same strength and direction everywhere between the plates (except near the edges).

Uniform field between parallel plates

Connect two parallel plates a distance d apart to a potential difference V. The field between them is uniform, with strength

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

Plates 0.050 m apart with 600 V across them give $E = 1.2 \times 10^4$ V m^{-1}. Only the p.d. and the separation matter: not the plates' area, not where between the plates the charge is, and not any resistor in series with the supply (once the plates are charged, no current flows, so there is no p.d. across it). Double the p.d. and E doubles; double the gap and E halves.

A potential is only ever relative, so a pair of plates at $+300$ V and $+500$ V has the same field as a pair at 0 V and $+200$ V: it is the **difference** that counts. The field points from the higher-potential plate to the lower one.

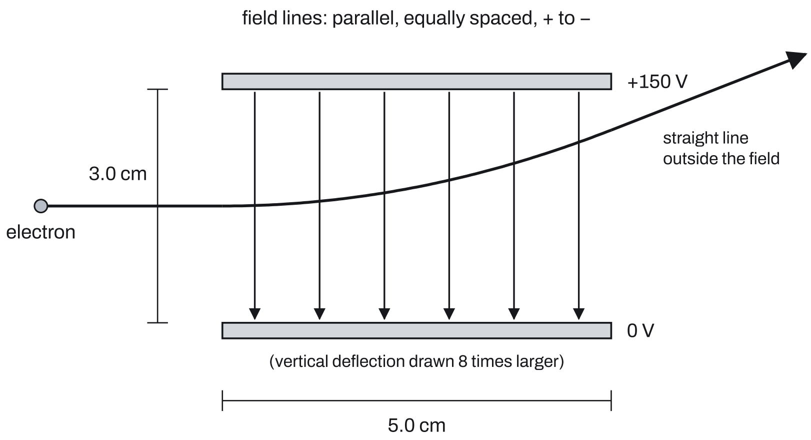
A charge moving in a uniform field

In a uniform field the force qE is the same everywhere, so the particle has a **constant acceleration**

$$a = \frac{qE}{m}$$

along the field lines (positive charges with the field, negative charges against it). All the constant-acceleration equations from Kinematics apply.

- **Moving along the field lines**: it speeds up or slows down in a straight line. The acceleration does **not** change as it moves.
- **Entering at right angles to the field**: like a ball thrown sideways under gravity. The velocity **across** the field stays constant; the velocity **along** the field grows steadily. The path between the plates is a **parabola**, bending towards the plate of opposite charge. Outside the plates there is no force, so the path is a **straight line**.
- **Comparing particles**: the force depends only on the charge ($F = qE$); the acceleration depends on $\frac{q}{m}$. A proton and an electron feel forces of the same size in opposite directions, but the electron's acceleration is about 1830 times bigger.
- **Energy**: a charge q moving through a potential difference V gains kinetic energy qV. An electron accelerated through 200 V gains $1.60 \times 10^{-19} \times 200 = 3.2 \times 10^{-17}$ J.



A charge can be held **stationary** between horizontal plates if the electric force balances its weight: $qE = mg$. The electric force must point up, so for a charge held still the field must point down if the charge is positive, and up if it is negative.

A charged sphere acts as a point charge

On a conducting sphere the charge spreads evenly over the **surface**. For any point **outside** the sphere, it acts exactly as if all the charge were a point charge at the centre. So every distance r in the point-charge formulas is measured **from the centre**.

Inside a hollow or solid conducting sphere the field is **zero**: the charge sits all round the surface, and if there were a field inside, the free charges would move until it disappeared.

Coulomb's law

The force between two point charges is proportional to the **product of the charges** and inversely proportional to the **square of their separation**:

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

$\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1} is the **permittivity of free space**, and $\dfrac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9$ m F^{-1} (both on the data sheet). A positive answer means repulsion (like charges), a negative one attraction. The two charges feel forces of the same size in opposite directions.

Field strength of a point charge

Put a small test charge q at distance r from a point charge Q. Coulomb's law gives the force, and dividing by q gives the field:

$$E = \frac{F}{q} = \frac{Q}{4\pi\varepsilon_0 r^2}$$

- $E \propto \dfrac{1}{r^2}$: a $+1.0$ nC charge gives 99.9 N C^{-1} at 0.30 m and a quarter of that, 25.0 N C^{-1}, at 0.60 m.

- The field points **away** from a positive charge and **towards** a negative one. On opposite sides of the charge the fields point in opposite directions, so on a graph with one direction chosen as positive, E changes sign as you pass through the charge.
- **Two or more charges**: field strength is a vector, so add the fields **with their directions**. Between two **opposite** charges both fields point the same way (from the $+$ towards the $-$), so their sizes add. Between two **like** charges they point opposite ways, so there is a point where they cancel.

Electric potential

The **electric potential** V at a point is the **work done per unit positive charge** in bringing a small test charge **from infinity** to that point. It is measured in volts (J C^{-1}), and it is zero at infinity. For a point charge:

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

- **Near a positive charge V is positive**: a positive test charge is repelled, so work must be done **on** it to push it in from infinity. **Near a negative charge V is negative**: the test charge is attracted, and the field does the work instead.
- $V \propto \dfrac{1}{r}$, not $\dfrac{1}{r^2}$: the $+1.0$ nC charge gives 30.0 V at 0.30 m and 15.0 V at 0.60 m (halved, not quartered).
- Potential is a **scalar**. With two or more charges, **add** the potentials, each with its own sign. Between a positive and a negative charge there is a point where they cancel and $V = 0$.

Field is minus the potential gradient

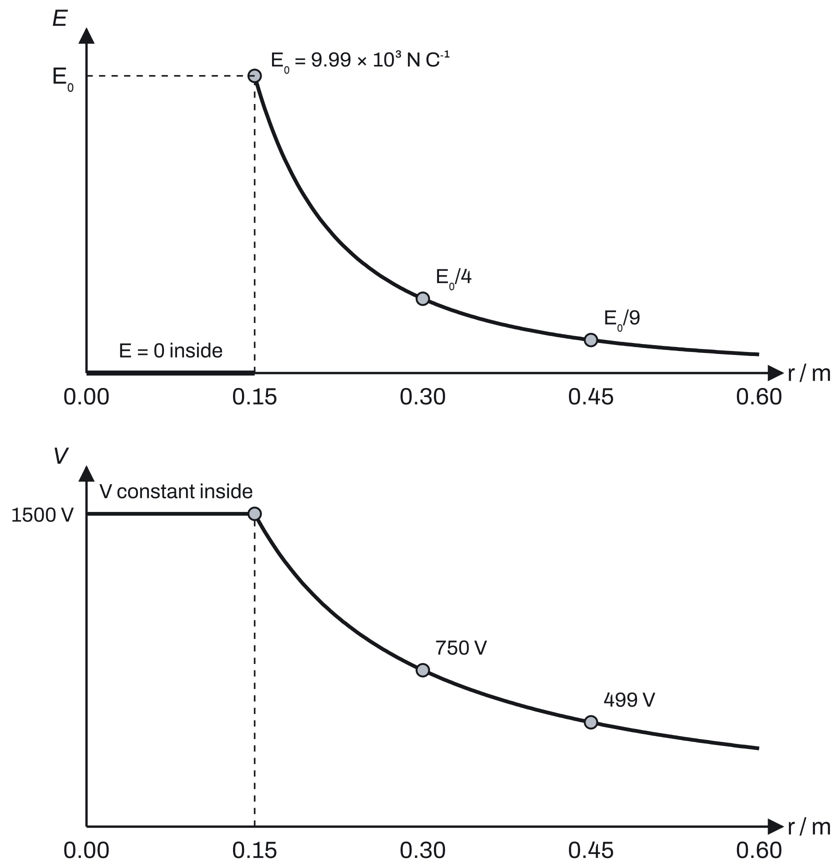
Field strength and potential are linked:

$$E = -\frac{dV}{dx}$$

The field strength equals the **potential gradient**, and the minus sign says the field points the way the potential **falls**. The steeper the V graph, the stronger the field; where the V graph is flat (a maximum or minimum), $E = 0$. For example, if the potential falls from 300 V to 120 V over 0.060 m along a field line, the field is 3000 V m^{-1} in that direction. Between parallel plates V falls steadily from one plate to the other, which is the same as $E = \frac{V}{d}$.

For a point charge, the gradient of $V = \dfrac{Q}{4\pi\varepsilon_0 r}$ has size $\dfrac{Q}{4\pi\varepsilon_0 r^2}$, which is E. So at the surface of a sphere of radius r, $E = \dfrac{V}{r}$: you can get one from the other without finding Q.

Because field is a gradient and potential is a sum of signed numbers, V and E can **never both be zero** at a point between two charges. For $V = 0$ the charges must have **opposite** signs; but then their fields between them point the **same** way and add, so $E \neq 0$. For $E = 0$ the charges must have the **same** sign, and then their potentials add and cannot cancel.



Inside the conducting sphere, $E = 0$, so the potential does not change: it stays at the surface value all the way to the centre.

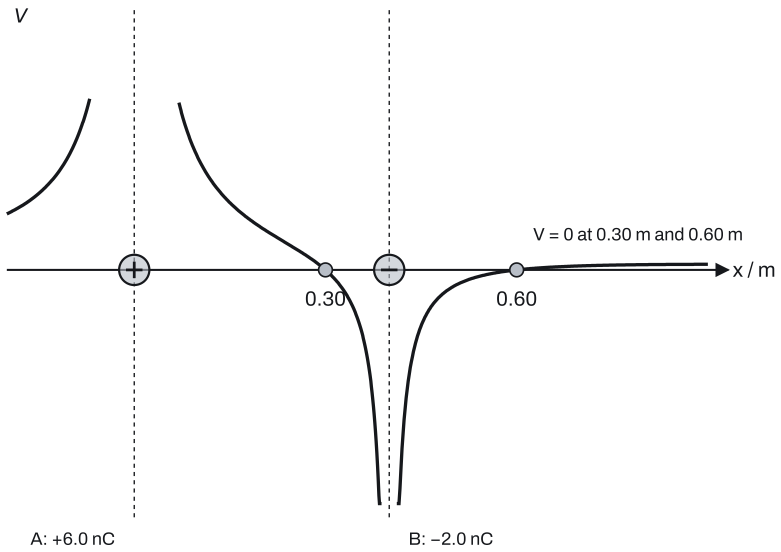
Electric potential energy

A charge q at a point where the potential is V has **electric potential energy** $E_P = qV$. For two point charges Q and q a distance r apart:

$$E_P = qV = \frac{Qq}{4\pi\varepsilon_0 r}$$

It is the energy stored **between the pair**, zero when they are infinitely far apart.

- **Like charges** (both positive or both negative): E_P is **positive**. Work was done to push them together, and if released they fly apart, turning E_P into kinetic energy.
- **Unlike charges**: E_P is **negative**, like gravity. Work must be done to pull them apart.
- A charge released in a field moves the way that **lowers** its potential energy: a positive charge towards lower potential, a negative charge towards higher potential. If the potential graph is at a minimum (or maximum) where the charge sits, the resultant force on it is zero.



Key facts and formulas

"Given" means it is on the data sheet printed in the paper (V and E_P for point charges are on the Paper 4 sheet). "Learn it" means you must remember it.

Formula	Status
Field strength $E = \dfrac{F}{q}$ (force per unit positive charge), so $F = qE$	Learn it
Uniform field between plates $E = \dfrac{\Delta V}{\Delta d} = \dfrac{V}{d}$	Learn it
Acceleration in a uniform field $a = \dfrac{qE}{m}$	Learn it
Coulomb's law $F = \dfrac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$	Learn it
Point charge $E = \dfrac{Q}{4\pi\varepsilon_0 r^2}$	Learn it
Potential of a point charge $V = \dfrac{Q}{4\pi\varepsilon_0 r}$	Given
Potential energy of two point charges $E_P = \dfrac{Qq}{4\pi\varepsilon_0 r}$	Given
$E_P = qV$; energy gained moving through a p.d. $= qV$	Learn it
$E = -\dfrac{dV}{dx}$ (field $=$ minus potential gradient); at a sphere's surface $E = \dfrac{V}{r}$	Learn it
$s = ut + \frac{1}{2}at^2$, $v^2 = u^2 + 2as$	Given

Formula	Status
$v = u + at$	Learn it
$e = 1.60 \times 10^{-19}$ C, $m_e = 9.11 \times 10^{-31}$ kg, $m_p = 1.67 \times 10^{-27}$ kg, $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}, $\dfrac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9$ m F^{-1}	Given

Units: N C^{-1} and V m^{-1} are the same unit for field strength. Potential is in V (J C^{-1}).

How to do it

In the Paper 1, 2 and 4 questions we have tagged for this topic (46 different questions, 2021–2025; 9 more appear on two papers), the types came up this often. 24 of the 46 questions mix two or more types, so the counts add up to more than 46.

Question type	Questions
Definitions, laws and explanations	20
Uniform fields: $E = \frac{V}{d}$ and $F = qE$	19
Charged particles moving in a uniform field	13
Point charges: Coulomb's law and field strength	11
Drawing and reading field lines	11
Potential and potential energy	10
Graphs of field strength and potential	9

1. Definitions, laws and explanations (20 questions)

Learn these, in meaning:

- **Electric field (strength)**: force per unit **positive** charge.
- **Electric potential** at a point: work done per unit positive charge in bringing a small test charge from infinity to the point. You need both "per unit charge" and "from infinity".
- **Coulomb's law**: the force between two point charges is proportional to the product of the charges and inversely proportional to the square of their separation.
- **A field line** shows the direction of the force on a positive charge at that point.
- **The link between field and potential**: the field strength equals minus the potential gradient, $E = -\frac{dV}{dx}$; mention the minus sign.

Variations you will meet:

- **Why is the potential near a positive charge positive?** Potential is zero at infinity; a positive test charge is repelled, so work has to be done **on** it to bring it closer.

- **Why is E_P of two like charges positive** (or of unlike charges negative)? Work is done on like charges to push them together; unlike charges attract, so work is done by the field as they come together.
- **Why can V and E not both be zero at one point** on the line between two charges? $V = 0$ needs opposite signs; $E = 0$ needs fields in opposite directions, so the same signs; both cannot be true at once. Make each step a separate point.
- **Why is E zero inside a charged conducting sphere?** The charge is all on the surface; if there were a field inside, charges in the conductor would move until it vanished.
- **Direction of the field, given the force** (or the other way round): the force on a positive charge is along the field, on a negative charge against it. A charge that moves in a straight horizontal line through a vertical field, with gravity acting, needs an upward electric force: a positive charge with the field up, or a negative charge with the field down.
- **Compare with gravity**: both fields are fields of force with radial lines round a point, both potentials are proportional to $\frac{1}{r}$ and zero at infinity. Gravity only attracts, so its potential is always negative; the electric potential can be either sign. Answer about the quantity asked (potential, not force).

2. Uniform fields: $E = \frac{V}{d}$ and $F = qE$ (19 questions)

1. **Field**: $E = \dfrac{V}{d}$ with d in metres. Unit V m^{-1} or N C^{-1}.
2. **Force**: $F = qE$ ($= \frac{qV}{d}$). Not $F = \frac{V}{d}$: that is the field.
3. **Direction**: the field points from the higher-potential plate to the lower one; the force on a negative charge points towards the higher-potential plate.

Variations you will meet:

- **A drop held still**: $qE = mg$, so $q = \dfrac{mgd}{V}$ or $m = \dfrac{qV}{gd}$. The electric force must be **up**: if the top plate is positive (field down), the drop's charge is negative.
- **Charge in electrons**: divide the charge by e; it must be a whole number.
- **The field is changed or reversed**: the drop is no longer balanced. Add the forces with their directions: if the electric force now points down, the resultant is $mg + qE$; if it is smaller but still up, the resultant is $mg - qE$. Then $a = \frac{F}{m}$.
- **Plates at two non-zero potentials**, or three plates: use the **difference** in potential across each gap, and that gap's width.
- **What changes E?** Only V and d. A wider gap weakens it; the plates' area and a series resistor make no difference.
- **Field lines compared** after a reversal: same spacing (same strength), opposite direction. "Compare" needs both the similarity and the difference.
- **Crossed electric and magnetic fields** (from Magnetic fields): the particle goes straight when the two forces are equal and opposite, $qE = Bqv$.

3. Charged particles moving in a uniform field (13 questions)

1. Find $E = \dfrac{V}{d}$, then $F = qE$ and $a = \dfrac{qE}{m}$. The acceleration is **constant**, parallel to the field lines.
2. **Along the field**: use the constant-acceleration equations, for example $v^2 = u^2 + 2as$ to find a stopping distance.
3. **Across the field**: split the motion. Across: constant speed, $t = \dfrac{L}{v}$ for plates of length L. Along the field: $u = 0$, so $y = \frac{1}{2}at^2$ and $v_y = at$.
4. **Path**: a smooth curve (parabola) between the plates, bending towards the plate of opposite sign, starting where the field starts, then a **straight line** after the plates.

Variations you will meet:

- **Ratios for different particles**: force $\propto q$, acceleration $\propto \dfrac{q}{m}$. An ion of charge $+2e$ and mass 7 u has twice the proton's force but only $\frac{2}{7}$ of its acceleration; an electron is pushed the opposite way with about 1830 times the proton's acceleration. Two isotopes have the same charge, so the **same force**, but the heavier one has the smaller acceleration.
- **Final speed after crossing a field sideways**: the speed across the field is unchanged; the extra velocity along the field depends on $\frac{q}{m}$. A particle with a smaller $\frac{q}{m}$ leaves with a smaller speed and a smaller deflection.
- **Graphs against time**: in a uniform field, acceleration–time is a horizontal line; velocity (or momentum) along the field changes linearly (a straight line; its gradient is the acceleration, or the force for momentum). Distance from rest grows as t^2 (a curve).
- **Why the path is not a circle**: the force always points the same way (along the field lines), so it is not always at right angles to the velocity.
- **Energy route**: the kinetic energy gained crossing a p.d. V is qV.

4. Point charges: Coulomb's law and field strength (11 questions)

1. **Force**: $F = \dfrac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ with r the **centre-to-centre** distance, **squared**.
2. **Field**: $E = \dfrac{Q}{4\pi\varepsilon_0 r^2}$. Direction: away from $+$, towards $-$.
3. Use $\frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9$ as a **multiplier**, or $\varepsilon_0 = 8.85 \times 10^{-12}$ inside $4\pi\varepsilon_0$; don't put 8.99×10^9 in place of $4\pi\varepsilon_0$.

Variations you will meet:

- **Two charges, resultant field at a point**: work out each field, decide each direction, then add (same direction) or subtract (opposite directions). In symbols, charges Q and $3Q$ of opposite sign at distances x and $3x$: $E = \dfrac{Q}{4\pi\varepsilon_0 x^2} + \dfrac{3Q}{4\pi\varepsilon_0 (3x)^2} = \dfrac{4Q}{12\pi\varepsilon_0 x^2} = \dfrac{Q}{3\pi\varepsilon_0 x^2}$ if the fields point the same way.
- **Where the field is zero** (two like charges): set the sizes equal and take square roots: charges $+9$ nC and $+1$ nC, 0.40 m apart: $\dfrac{x}{0.40 - x} = \sqrt{9} = 3$, so $x = 0.30$ m from the 9 nC charge.

- **Field at the surface from a value elsewhere**: $E \propto \frac{1}{r^2}$, so at a third of the distance it is nine times as strong.
- **Resultant force direction** on a charge between or beside two others: draw each force (attraction towards an unlike charge, repulsion from a like one) and add them as vectors; the bigger charge or the nearer one wins.
- **A charged ball hanging on a thread** next to another charge: three forces (tension along the thread, weight down, electric force horizontal). Resolve: $\tan\theta = \dfrac{F_E}{mg}$.
- **An electron orbiting a nucleus**: the Coulomb force provides the centripetal force, $\dfrac{Qe}{4\pi\varepsilon_0 r^2} = \dfrac{mv^2}{r}$ (see Motion in a circle).
- **Combining with gravity**: at the surface of a sphere, $\dfrac{g}{E} = \dfrac{GM}{Q/(4\pi\varepsilon_0)} = 4\pi\varepsilon_0 G\dfrac{M}{Q}$, because the r^2 cancels.

5. Drawing and reading field lines (11 questions)

- **Charged sphere or point charge**: at least four straight radial lines, evenly spaced, meeting the surface at right angles; arrows **away** from a positive charge. Start the lines at the surface, not inside. Don't draw circles (those are equipotentials).
- **Parallel plates**: at least four straight lines at right angles to the plates, **equally spaced**, going all the way from one plate to the other, arrows from $+$ (higher potential) to $-$.
- **Two opposite point charges**: curved lines from $+$ to $-$, the straight one along the line joining them; they never cross.
- **Direction at a point near a sphere**: along the radius through that point, away from the centre for a positive sphere.
- **Reading a diagram**: equally spaced parallel lines mean a uniform field, so the force on a charge is the same wherever it moves inside it.

6. Potential and potential energy (10 questions)

1. **Potential**: $V = \dfrac{Q}{4\pi\varepsilon_0 r}$, keeping the **sign** of Q. Unit V.
2. **Two or more charges**: $V = \dfrac{1}{4\pi\varepsilon_0}\left(\dfrac{Q_1}{r_1} + \dfrac{Q_2}{r_2}\right)$, adding signed values.
3. **Potential energy of a pair**: $E_P = \dfrac{Qq}{4\pi\varepsilon_0 r}$ with **both** charges and the **separation** (not squared). Keep the sign: positive for like charges, negative for unlike.

Variations you will meet:

- **Where** $V = 0$ between a positive and a negative charge: set $\dfrac{Q_1}{r_1} = \dfrac{|Q_2|}{r_2}$. For $+3$ nC and -1 nC, 0.20 m apart: $\dfrac{3}{x} = \dfrac{1}{0.20 - x}$ gives $x = 0.15$ m from the $+3$ nC charge. There is a second point beyond the smaller charge: $\dfrac{3}{x} = \dfrac{1}{x - 0.20}$ gives $x = 0.30$ m. For equal and opposite charges the only such point (other than infinity) is the **midpoint**.

- **In symbols**: charges Q and $-nQ$ give $V = 0$ where $\frac{r_2}{r_1} = n$.
- **Charge or radius of a sphere**: from V at the surface, $Q = 4\pi\varepsilon_0 rV$; with both V and E at the surface, $r = \frac{V}{E}$. A sphere with $V = 2000$ V at $r = 0.10$ m holds $Q = 4\pi \times 8.85 \times 10^{-12} \times 0.10 \times 2000 = 2.22 \times 10^{-8}$ C, and $E = \frac{2000}{0.10} = 2.00 \times 10^4$ V m-1 at its surface.
- **Capacitance of a sphere**: $C = \frac{Q}{V} = 4\pi\varepsilon_0 r$ (see Capacitance). Two spheres joined share charge until they have the **same potential**.
- **Released charges**: two like charges fly apart; E_P turns into kinetic energy, the force and acceleration **decrease** as they separate, and if the masses are equal the speeds stay equal and opposite (momentum is conserved).
- **Energy of a charge crossing a p.d.**: $\Delta E_P = q\Delta V$, which becomes kinetic energy.

7. Graphs of field strength and potential (9 questions)

Sketching (outside a sphere of radius R, or a point charge):

- E **against** r: zero inside a conducting sphere; E_0 at the surface; then falling as $\frac{1}{r^2}$: $\frac{E_0}{4}$ at $2R$, $\frac{E_0}{9}$ at $3R$. Getting less steep, never reaching zero.
- V **against** r: constant inside the sphere at the surface value V_0; then falling as $\frac{1}{r}$: $\frac{V_0}{2}$ at $2R$, $\frac{V_0}{3}$ at $3R$. A negative sphere gives the same shape below the axis.
- **Signed** E **on both sides of a sphere** (one direction positive): for a positive sphere E is positive to the right ($+E_0$ at $x = R$, $+\frac{E_0}{4}$ at $2R$) and **negative** to the left ($-E_0$ at $x = -R$, $-\frac{E_0}{4}$ at $-2R$). Each branch gets smaller in size moving away, so the left branch gets **steeper** as it approaches $-R$ and the right branch gets **less steep** moving away from R.
- V **between two equal and opposite charges**: large positive near the $+$, large negative near the $-$, zero at the **midpoint**. The curve is symmetric about the midpoint (turned upside down), steepest near each charge and least steep in the middle.
- **Potential along a line between two parallel plates**: a straight line from one plate's potential to the other's (the field is uniform).

Reading a V–x graph between two spheres:

- **Radius** of each sphere: where the curve goes flat (the potential is constant inside the conductor).
- **Sign** of each charge: V positive near it means positive; a curve rising to a peak at each sphere means both positive; one side positive and one negative means opposite charges.
- **Relative size** of the charges: $Q = 4\pi\varepsilon_0 rV$, so compare rV at each surface; for a single sphere use any point (x, V) on the curve outside it.
- **Field** at a point: the gradient; where V has a minimum (or maximum) between the spheres, $E = 0$ there.
- **A charge released on the line**: a positive charge moves towards lower potential, and speeds up as long as the potential keeps falling. At the minimum of the V curve a positive charge stays at rest: the forces from the two spheres are equal and opposite.

Reading an E–x graph: the radius is where E is largest (the surface), and $Q = 4\pi\varepsilon_0 r^2 E$ from any point outside, with r in metres.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

Two horizontal metal plates in a vacuum are 3.5 cm apart. The top plate is at a potential of $+2800$ V and the bottom plate is earthed. A small charged drop of mass 6.5×10^{-15} kg is held at rest between the plates.

(a) Calculate the electric field strength between the plates. **[2]**

(b) Determine the magnitude and the sign of the charge on the drop, and the number of elementary charges it carries. **[4]**

(c) The p.d. is suddenly halved. Determine the acceleration of the drop. **[2]**

Solution

(a) $E = \dfrac{V}{d} = \dfrac{2800}{0.035}$ **C1** $= 8.0 \times 10^4$ V m-1. **A1**

(b) The electric force balances the weight: $qE = mg$. **C1** $q = \dfrac{6.5 \times 10^{-15} \times 9.81}{8.0 \times 10^4} = 8.0 \times 10^{-19}$ C. **A1** $\dfrac{8.0 \times 10^{-19}}{1.60 \times 10^{-19}} = 5$ elementary charges. **B1** The top plate is positive, so the field points down; the force on the drop points up, against the field, so the charge is **negative**. **B1**

(c) The field and the electric force halve, so the upward force is now $\frac{1}{2}mg$. Resultant $= mg - \frac{1}{2}mg = \frac{1}{2}mg$, downwards. **C1** $a = \dfrac{g}{2} = 4.9$ m s-2 downwards. **A1**

Example 2

An electron moving horizontally at 3.0×10^7 m s-1 enters the region between two horizontal plates, midway between them. The plates are 5.0 cm long and 3.0 cm apart. The top plate is at $+150$ V and the bottom plate at 0 V. The field is uniform between the plates and zero outside.

(a) Calculate the acceleration of the electron between the plates, and state its direction. **[3]**

(b) Calculate the vertical distance the electron has moved when it leaves the plates. **[3]**

(c) A proton enters in the same way at the same speed. State two ways its path differs from the electron's, with a reason. **[2]**

Solution

(a) $E = \dfrac{150}{0.030} = 5000$ V m^{-1}. **C1** $a = \dfrac{eE}{m_e} = \dfrac{1.60 \times 10^{-19} \times 5000}{9.11 \times 10^{-31}}$ **C1** $= 8.78 \times 10^{14}$ m s^{-2}, upwards (towards the positive plate). **A1**

(b) The horizontal speed is constant, so the time between the plates is $t = \dfrac{0.050}{3.0 \times 10^{7}} = 1.67 \times 10^{-9}$ s. **C1** Vertically, starting from zero: $y = \frac{1}{2}at^2 = \frac{1}{2} \times 8.78 \times 10^{14} \times (1.67 \times 10^{-9})^2$ **C1** $= 1.22 \times 10^{-3}$ m. **A1**

(c) The proton is deflected **downwards** (towards the negative plate), because its charge is positive. **B1** Its deflection is much smaller: the force is the same size but its mass is about 1830 times larger, so its acceleration is about 1830 times smaller (the deflection is 6.65×10^{-7} m). **B1**

The second diagram in "Understand it" shows this electron's path.

Example 3

Point charge A of $+6.0$ nC and point charge B of -2.0 nC are fixed 0.40 m apart in a vacuum.

(a) On the line through A and B, find the two points, other than at infinity, where the electric potential is zero. Give their distances from A. **[3]**

(b) Calculate the electric field strength at the point between the charges found in (a), and state its direction. **[3]**

(c) Calculate the electric potential energy of the two charges. **[2]**

Solution

(a) $V = 0$ where $\dfrac{6.0}{x} = \dfrac{2.0}{r_B}$, with r_B the distance from B. **C1** Between the charges, $r_B = 0.40 - x$: $6.0(0.40 - x) = 2.0x$, so $x = 0.30$ m. **A1** Beyond B, $r_B = x - 0.40$: $6.0(x - 0.40) = 2.0x$, so $x = 0.60$ m. **A1**

(b) At 0.30 m from A the point is 0.10 m from B. Both fields point from A towards B (away from $+$, towards $-$), so they add. **C1** $E = 8.99 \times 10^{9} \left(\dfrac{6.0 \times 10^{-9}}{0.30^2} + \dfrac{2.0 \times 10^{-9}}{0.10^2} \right)$ **C1** $= 2.40 \times 10^{3}$ N C^{-1}, towards B. **A1**

(c) $E_P = \dfrac{Qq}{4\pi\varepsilon_0 r} = \dfrac{8.99 \times 10^{9} \times 6.0 \times 10^{-9} \times (-2.0 \times 10^{-9})}{0.40}$ **C1** $= -2.70 \times 10^{-7}$ J. **A1** (Negative: the charges attract.)

The fourth diagram in "Understand it" shows V along this line.

Example 4

An isolated conducting sphere of radius 0.15 m in a vacuum carries a charge of $+25$ nC.

(a) Calculate the potential at the surface of the sphere. **[2]**

(b) Show that the field strength at the surface is about 1.0×10^4 N C^{-1}. **[2]**

(c) State the potential and the field strength at a point 0.45 m from the centre. **[2]**

(d) A proton is released from rest at the surface. Calculate its speed when it is very far from the sphere. **[3]**

Solution

(a) $V = \dfrac{Q}{4\pi\varepsilon_0 r} = \dfrac{8.99 \times 10^9 \times 25 \times 10^{-9}}{0.15}$ **C1** $= 1.50 \times 10^3$ V. **A1**

(b) $E = \dfrac{Q}{4\pi\varepsilon_0 r^2} = \dfrac{8.99 \times 10^9 \times 25 \times 10^{-9}}{0.15^2}$ **M1** $= 9.99 \times 10^3$ N C^{-1} $\approx 1.0 \times 10^4$ N C^{-1}. **A1** (Or $E = \frac{V}{r} = \frac{1498}{0.15}$.)

(c) 0.45 m is three times the radius: $V = \dfrac{1498}{3} = 499$ V **B1** and $E = \dfrac{9.99 \times 10^3}{9} = 1.11 \times 10^3$ N C^{-1}. **B1**

(d) At infinity $V = 0$, so the proton loses potential energy $eV = 1.60 \times 10^{-19} \times 1498 = 2.40 \times 10^{-16}$ J, which becomes kinetic energy. **C1** $\frac{1}{2} m_p v^2 = 2.40 \times 10^{-16}$ **C1**, so $v = \sqrt{\dfrac{2 \times 2.40 \times 10^{-16}}{1.67 \times 10^{-27}}} = 5.36 \times 10^5$ m s^{-1}. **A1**

The third diagram in "Understand it" shows E and V for this sphere.

Common mistakes

- **Loose definitions.** Reports in 2021, 2022 and 2023 found potential defined as an energy ("the work done to bring a charge from infinity") with no **per unit charge**, and field strength given without **positive** charge. The June 2023 report said the syllabus wording, force per unit positive charge, is expected.
- **Saying what a field line does instead of what it shows.** "Lines go from positive to negative" is not what a field line indicates (November 2022): it shows the direction of the force on a positive charge.
- **Words missing from Coulomb's law.** Reports in March 2023 and June 2022 found the separation not squared, "indirectly" instead of "inversely", "distance" or "radius" instead of separation, and masses instead of charges.
- **Using the point-charge formula between plates.** Between plates the field is $\frac{V}{d}$ (November 2022); in June 2022 many used a point-charge formula for a field that was uniform. And $\frac{V}{d}$ is the field, not the force: multiply by q (March 2023).
- **Leaving out the weight.** For a drop or dust grain the weight matters: when the field changes, the resultant force is the weight and the electric force added with their directions (June 2021, November 2021).

- **Wrong idea of the acceleration.** In a uniform field the force, and so the acceleration, is constant; an acceleration–time graph is a horizontal line (June 2021). Isotopes feel the same force; the heavier one has the smaller acceleration (June 2021).
- **Deflection paths.** The curve should start where the field starts and become a straight line when the particle leaves the field (November 2022).
- **Field strength and potential mixed up.** $E \propto \frac{1}{r^2}$ but $V \propto \frac{1}{r}$ (June 2021). Inside a conducting sphere $E = 0$, not a rising line.
- $\frac{1}{4\pi\varepsilon_0}$ **used as** $4\pi\varepsilon_0$**.** 8.99×10^9 is the whole of $\frac{1}{4\pi\varepsilon_0}$ (November 2022).
- **Wrong numbers in** E_P**.** Use both charges (multiplied, not doubled) and the distance between their centres, not a radius and not squared. E_P for two like charges is positive (November 2022, March 2023).
- **Forces instead of fields.** When a question asks about field strength, talk about fields; when it asks about the force on a particle, give the force and its direction (November 2021).

How to get the marks

- **Definitions**: one mark per key phrase: "force per unit positive charge"; "work done per unit positive charge" + "(bringing a charge) from infinity"; "proportional to the product of the charges" + "inversely proportional to the square of the separation".
- **Calculations**: the mark scheme gives **C1** for the right equation with numbers in, then **A1** for the answer. Give 2 or 3 significant figures to match the data.
- **"Show that"**: write the formula, substitute every value (including constants and powers of ten), and give your answer to one more significant figure than the value printed.
- **"Give a unit"**: N C^{-1} or V m^{-1} for field strength, V for potential, J for potential energy.
- **Signs**: keep the sign of each charge in V and E_P. Say whether a charge is positive or negative when asked; a reason (the direction of the force compared with the field) often earns its own mark.
- **Field-line drawings**: straight lines, correct spacing (equal between plates, radial round a sphere), lines touching the surfaces at right angles, arrows in the right direction.
- **Sketches**: pass through the exact values (E_0 at R, $\frac{E_0}{4}$ at $2R$; V_0 at R, $\frac{V_0}{2}$ at $2R$), with the right curvature, and draw nothing where the question says to leave a region out.
- **"Describe and explain" the motion** of a released charge: say which way the resultant force points, what the particle does (accelerates towards...), and how the force or acceleration changes (for example, it decreases as the charges move apart).
- **"State three conclusions" from a graph**: give different kinds (radius, sign, relative size of charge), each backed by the graph.

Quick check

1. A charge of $+3.0$ μC is in a uniform field of strength 2.5×10^4 N C^{-1}. Calculate the force on it.
2. Two parallel plates 12 mm apart have a p.d. of 90 V between them. Calculate the field strength and the force on an electron between them.

3. Calculate the field strength and the potential at a distance of 0.25 m from a point charge of $+5.0$ nC.
4. The distance between two point charges is halved. By what factor does the force between them change? By what factor does their potential energy change?
5. Along a field line the potential falls from 400 V to 220 V over a distance of 4.0 cm. Calculate the average field strength and state its direction.

Answers

1. $F = qE = 3.0 \times 10^{-6} \times 2.5 \times 10^{4} = 0.075$ N, in the direction of the field.
2. $E = \dfrac{90}{0.012} = 7500$ V m^{-1}. $F = eE = 1.60 \times 10^{-19} \times 7500 = 1.2 \times 10^{-15}$ N, towards the positive plate.
3. $E = \dfrac{8.99 \times 10^{9} \times 5.0 \times 10^{-9}}{0.25^2} = 719$ N C^{-1}, away from the charge. $V = \dfrac{8.99 \times 10^{9} \times 5.0 \times 10^{-9}}{0.25} = 180$ V.
4. $F \propto \dfrac{1}{r^2}$, so the force becomes 4 times larger. $E_P \propto \dfrac{1}{r}$, so the potential energy doubles.
5. $E = \dfrac{400 - 220}{0.040} = 4500$ V m^{-1}, pointing the way the potential falls (from the 400 V end towards the 220 V end).

Past questions to try

- **9702/22/O/N/21 Q2**: a drop balanced between plates, then the field reversed, with its acceleration and motion.
- **9702/42/F/M/22 Q4**: the point where the potential of two charges is zero, and the field there.
- **9702/42/O/N/22 Q5**: the charge on a sphere from its potential graph, and the energy of two charged spheres.
- **9702/43/O/N/22 Q4**: field lines between plates and the path of a proton through them.