

THEME D · FIELDS

SL & HL

≈ 40 min read

IB Physics D.2 Electric and Magnetic Fields — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). Sections 1–8 are for SL and HL: electric charge, charging, Coulomb's law, electric field strength, field lines, the uniform field between plates, Millikan's experiment and magnetic field patterns. The additional HL content — electric potential energy, electric potential, potential gradient and equipotential surfaces — is in the two purple **HL** sections that follow.



SL D.2 questions



HL D.2 questions



Flashcards



Electric field simulation

What this page covers

- ✓ The two kinds of electric charge and the direction of the forces between them
- ✓ Coulomb's law, $F = k \frac{q_1 q_2}{r^2}$ with $k = \frac{1}{4\pi\epsilon_0}$, for charged bodies treated as point charges, including the effect of the permittivity of the medium
- ✓ Conservation of electric charge
- ✓ Millikan's oil-drop experiment as evidence that electric charge is quantised
- ✓ Transferring charge by friction, by contact and by electrostatic induction, and the role of earthing (grounding)
- ✓ Electric field strength as force per unit charge, $E = \frac{F}{q}$
- ✓ Sketching and interpreting electric field lines, and how the density of lines shows the field strength

- ✓ The uniform field between oppositely charged parallel plates, $E = \frac{V}{d}$, and its edge effects
- ✓ Magnetic field lines for a bar magnet, a straight wire, a flat circular coil and an air-core solenoid; finding the field direction from the current
- ✓ Electric potential energy as the work done to assemble a system from infinite separation, $E_p = k \frac{q_1 q_2}{r}$ (HL)
- ✓ Electric potential as a scalar, zero at infinity, $V_e = \frac{kQ}{r}$, and the work done $W = q\Delta V_e$ in joules and electronvolts (HL)
- ✓ Field strength as potential gradient, $E = -\frac{\Delta V_e}{\Delta r}$; equipotential surfaces and how they relate to field lines (HL)

In one minute

- There are two kinds of charge: like charges repel, unlike charges attract. Charge is **conserved** and **quantised** in units of $e = 1.60 \times 10^{-19}$ C (Millikan).
- Bodies are charged by moving **electrons**: by friction, by contact, or by induction with an earth connection.
- Coulomb's law: $F = k \frac{q_1 q_2}{r^2}$ — an inverse-square law, like gravity, but it can attract or repel, and it is weaker in a medium of larger permittivity.
- Electric field strength is force per unit positive charge, $E = \frac{F}{q}$ ($\text{N C}^{-1} = \text{V m}^{-1}$). Field lines show the direction of the force on a positive charge; closer lines mean a stronger field. Between parallel plates $E = \frac{V}{d}$, uniform except at the edges.
- Magnetic field lines run from N to S outside a magnet and form closed loops; a straight current is circled by its field (right-hand grip rule); a solenoid's field is uniform inside and like a bar magnet's outside.
- HL: $E_p = k \frac{q_1 q_2}{r}$, $V_e = \frac{kQ}{r}$ (scalar, zero at infinity, sign of Q), $E = -\frac{\Delta V_e}{\Delta r}$, $W = q\Delta V_e$. Equipotentials are perpendicular to field lines, and

no work is done moving a charge along one.

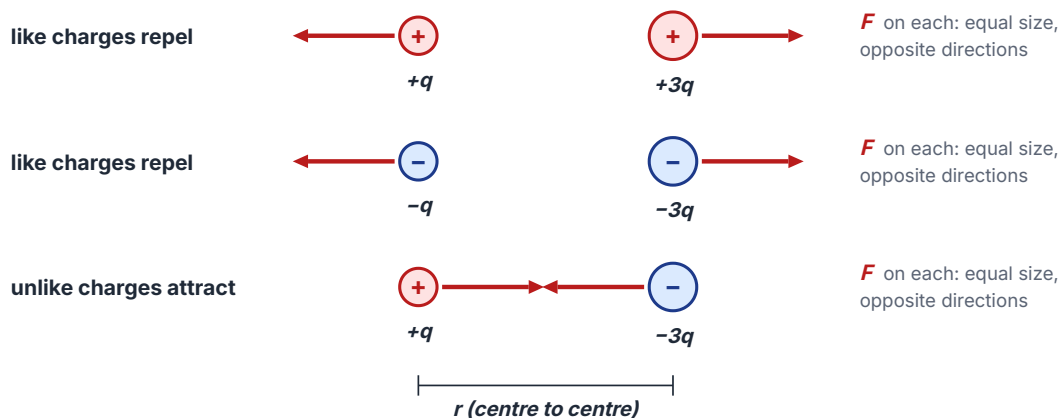
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What are the two types of electric charge, and how do they interact?

Electric charge is a property of matter, like mass. Unlike mass, it comes in two types, called **positive** and **negative**. In ordinary matter the positive charge is carried by protons in the nucleus and the negative charge by electrons; a neutral atom has equal numbers of each.

Like charges repel and unlike charges attract; the forces on the two charges are equal in magnitude, opposite in direction and act along the line joining them.



Forces form a Newton's third law pair even when the charges are unequal.

Forces between point charges. Whatever the sizes of the two charges, the force on each has the same magnitude: the forces are a Newton's third law pair. Only the type of charge decides whether they attract or repel.

- Charge is measured in **coulombs** (C). It is a scalar with a sign.
- **Conservation of charge:** the total charge of an isolated system never changes. Charge can be moved from one body to another, but it is never created or destroyed on its own: when a rod becomes negative, something else becomes equally positive.
- **Quantisation:** every charge found on an isolated body is a whole-number multiple of the elementary charge, $q = ne$, with $e = 1.60 \times 10^{-19}$ C (data booklet). The electron carries $-e$ and the proton $+e$.
- **Conductors** (metals) contain free electrons that move easily through them, so charge spreads over a conductor. In **insulators** (plastics, glass, dry air) the electrons are bound to their atoms, so charge stays where it was placed.

How can charge be transferred by friction, contact and induction?

In every method below only **electrons** move; the positive nuclei stay fixed in the material. A body becomes negative by gaining electrons and positive by losing them.

Friction

- Rubbing two different insulators together transfers electrons from one surface to the other. Rubbing polythene with a wool cloth, for example, moves electrons from the cloth to the polythene.
- The two bodies end with **equal and opposite** charges, as conservation of charge requires.

Contact

- When a charged conductor touches a neutral (or differently charged) conductor, electrons flow between them until the charge is shared out. If they are **identical spheres**, each ends with half the total charge.
- The total charge is unchanged: a sphere with -6 units touched against a neutral sphere gives -3 units on each.

Charging by friction

before: both neutral



after rubbing: 2 electrons moved cloth $\rightarrow$ rod



Charge is transferred, not created:
total charge = 0 before and after.
Only electrons move.

Charging by contact (identical metal spheres)

before



touch, then separate: electrons flow A $\rightarrow$ B



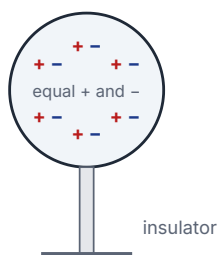
identical spheres share the total charge equally

Left: rubbing moves electrons from the cloth to the polythene rod, leaving the rod negative and the cloth equally positive. Right: touching identical metal spheres shares the charge equally. In both cases the total charge is conserved.

Electrostatic induction and earthing

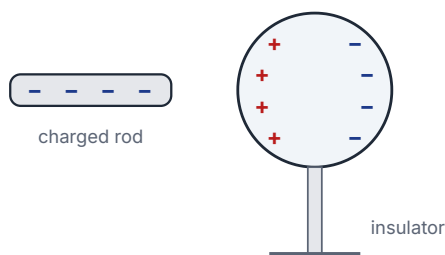
A charged body can charge a conductor *without touching it*. Bringing a charged rod near a conductor makes its free electrons move, separating the charge within the conductor; this is **electrostatic induction**. An **earth** (ground) connection then lets electrons flow between the conductor and the Earth, which is so large that it can supply or absorb any number of electrons without its own charge changing noticeably.

1 Neutral sphere on an insulating stand



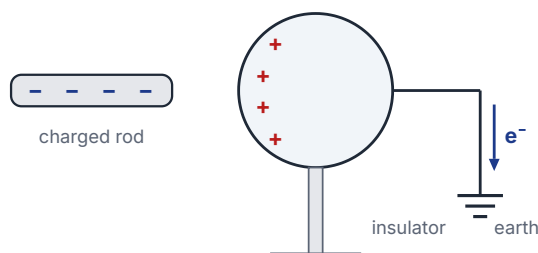
2 Negative rod brought near

free electrons repelled to the far side
(sphere still neutral overall)



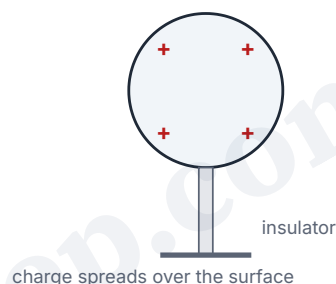
3 Sphere earthed, rod still near

electrons flow from sphere to earth



4 Earth removed, then rod removed

sphere left positively charged



Charging a metal sphere by induction. (2) The negative rod repels free electrons to the far side. (3) While the rod is still near, earthing lets those electrons escape to earth. (4) The earth connection is removed first, then the rod: the sphere keeps a positive charge, opposite to the rod's.

- The induced charge is always **opposite** to the charge on the rod, and the rod itself loses no charge.
- The order matters: if the rod is removed before the earth connection is broken, electrons flow back from earth and the sphere ends neutral.
- Induction also explains why a charged rod attracts small **neutral** objects (scraps of paper, a stream of water): the near side becomes oppositely charged and the far side like-charged (in an insulator no electrons flow; the charges within each molecule shift slightly, which has the same effect). The near charge is closer, so the attraction is stronger than the repulsion.
- Touching a charged conductor to earth **discharges** it completely. Earthing is used for safety, for example at fuel pumps, to stop charge building up.

What does Coulomb's law state?

The electric force between two point charges is directly proportional to the product of the charges and inversely proportional to the square of their separation.

$$F = k \frac{q_1 q_2}{r^2} \quad k = \frac{1}{4\pi\epsilon_0}$$

- F = electric force on each charge (N); q_1, q_2 = the charges (C); r = separation of the charges, centre to centre (m); k = Coulomb constant, $8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$; ϵ_0 = permittivity of free space, $8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$. Both equations and both constants are in the data booklet.
- Substituting signed charges: a **positive** F means repulsion (like charges) and a **negative** F means attraction. In most answers it is clearer to use magnitudes and state the direction in words.
- It is an inverse-square law, exactly like Newton's law of gravitation (D.1): double r and the force falls to $\frac{1}{4}$.
- **Point charges:** the law applies to point charges, to **uniformly charged spheres** (measure r between centres) and to any charged bodies whose separation is much larger than their size.

The effect of the medium: permittivity

The constant ϵ_0 is for a vacuum. When the charges are in another insulating medium, replace ϵ_0 by the **permittivity** ϵ of that medium: $F = \frac{q_1 q_2}{4\pi\epsilon r^2}$. Every material has ϵ larger than ϵ_0 , so the force between the same charges is **smaller** in a material than in a vacuum.

Medium	Permittivity $\epsilon / \text{C}^2 \text{N}^{-1} \text{m}^{-2}$	Force compared with vacuum
vacuum	8.85×10^{-12}	1
air	$\approx 8.85 \times 10^{-12}$	≈ 1 (air is treated as a vacuum)
polythene	$\approx 2.0 \times 10^{-11}$	≈ 0.44
glass	$\approx 4.4 \times 10^{-11}$ (varies with type)	≈ 0.2
water	$\approx 7.1 \times 10^{-10}$	≈ 0.012

Values are typical, for comparing orders of magnitude; an exam question always gives the permittivity it wants you to use. The large permittivity of water is why ionic solids such as salt dissolve: the attraction between the ions is about 80 times weaker in water.

WORKED EXAMPLE 1 Easy · Calculate / State

Two small identical metal spheres carry charges of $+3.0 \text{ nC}$ and -5.0 nC . Their centres are 4.0 cm apart in air.

(a) Calculate the electric force between them and state whether it is attractive or repulsive. (b) The spheres are touched together and then returned to 4.0 cm apart. Calculate the new force. (c) The original charges are instead placed 4.0 cm apart in an oil of permittivity $1.9 \times 10^{-11} \text{ C}^2 \text{N}^{-1} \text{m}^{-2}$. Calculate the force.

$$\text{(a)} \quad F = k \frac{q_1 q_2}{r^2} = \frac{8.99 \times 10^9 \times 3.0 \times 10^{-9} \times 5.0 \times 10^{-9}}{(0.040)^2} = \mathbf{8.4 \times 10^{-5} \text{ N}},$$

attractive ($8.43 \times 10^{-5} \text{ N}$; unlike charges)

(b) Total charge = $+3.0 - 5.0 = -2.0 \text{ nC}$ (conserved), shared equally: -1.0 nC each.

$$F = \frac{8.99 \times 10^9 \times (1.0 \times 10^{-9})^2}{(0.040)^2} = \mathbf{5.6 \times 10^{-6} \text{ N, repulsive}} \quad (5.62 \times 10^{-6} \text{ N})$$

$$\text{(c)} \quad F = \frac{q_1 q_2}{4\pi\epsilon r^2} = \frac{3.0 \times 10^{-9} \times 5.0 \times 10^{-9}}{4\pi \times 1.9 \times 10^{-11} \times (0.040)^2} = \mathbf{3.9 \times 10^{-5} \text{ N}} \quad (3.93 \times 10^{-5} \text{ N}), \text{ smaller by the factor } \epsilon/\epsilon_0 = 2.15.$$

What is electric field strength?

A charged body creates an **electric field** in the space around it: a region in which any other charge experiences a force.

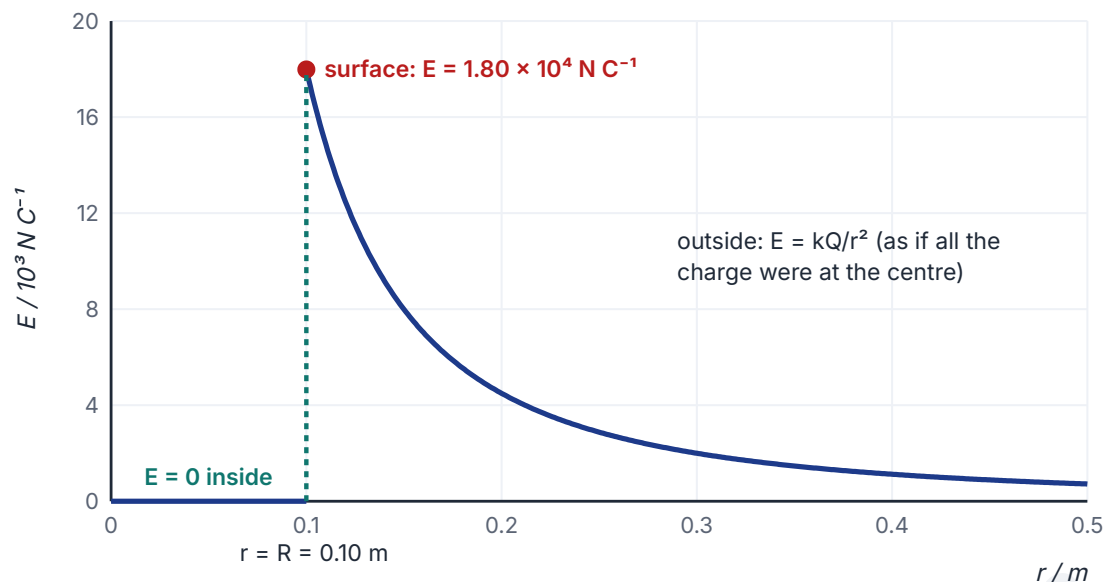
The electric field strength at a point is the electric force per unit charge experienced by a small positive test charge placed at that point.

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

- E = electric field strength (N C^{-1} , equivalent to V m^{-1}); F = force on the test charge (N); q = test charge (C). In the data booklet.
- E is a **vector**. Its direction is the direction of the force on a **positive** charge. A negative charge (an electron) feels a force **opposite** to E .
- The test charge must be small, so that it does not disturb the charges that create the field.
- **Point charge** Q : putting $q_1 = Q$, $q_2 = q$ in Coulomb's law and dividing by q gives $E = \frac{kQ}{r^2}$. This form is **not** printed in the data booklet; combine the two equations above to obtain it.
- **Several charges**: add the field strengths as **vectors**. On the line joining two charges this means adding or subtracting magnitudes, with directions taken into account.

Inside and outside a charged conducting sphere

- The charge on a conductor sits on its outer **surface**; the free electrons move until there is no force on them inside the metal. So $E = 0$ everywhere inside a charged conductor, solid or hollow.
- Outside, the sphere behaves as if all its charge were at its centre: $E = \frac{kQ}{r^2}$, with r measured from the centre. The field is strongest just outside the surface.



Electric field strength against distance r from the centre of a charged conducting sphere of radius 0.10 m (used in worked example 3). E is zero inside, jumps to its maximum at the surface and then falls as $1/r^2$: at $r = 0.20 \text{ m}$ (twice the radius) it is a quarter of the surface value.

WORKED EXAMPLE 2 Medium · Determine / State

A point charge of $+4.0 \mu\text{C}$ is fixed at A and a point charge of $+1.0 \mu\text{C}$ is fixed at B, 0.30 m from A.

- (a) Determine the electric field strength at the midpoint of AB and state its direction. (b) Determine the distance from A of the point on AB where the electric field strength is zero. (c) Calculate the force on an electron placed at the midpoint and state its direction.

(a) At 0.15 m from each: $E_A = \frac{8.99 \times 10^9 \times 4.0 \times 10^{-6}}{0.15^2} = 1.60 \times 10^6 \text{ N C}^{-1}$ (pointing away from A, towards B); $E_B = \frac{8.99 \times 10^9 \times 1.0 \times 10^{-6}}{0.15^2} = 4.00 \times 10^5 \text{ N C}^{-1}$ (pointing away from B, towards A).

Resultant $= 1.60 \times 10^6 - 4.00 \times 10^5 = 1.2 \times 10^6 \text{ N C}^{-1}$ towards B

(b) At distance x from A: $\frac{k(4.0 \mu\text{C})}{x^2} = \frac{k(1.0 \mu\text{C})}{(0.30 - x)^2} \Rightarrow \frac{x}{0.30 - x} = \sqrt{4} = 2 \Rightarrow x = 0.20 \text{ m}$ from A (closer to the smaller charge).

(c) $F = qE = 1.60 \times 10^{-19} \times 1.20 \times 10^6 = 1.9 \times 10^{-13} \text{ N towards A}$ ($1.92 \times 10^{-13} \text{ N}$) — opposite to E , because the electron is negative.

WORKED EXAMPLE 3 Medium · Determine (graph) / Explain

The graph above shows how the electric field strength varies with distance r from the centre of a charged metal sphere of radius 0.10 m.

(a) Use the graph to determine the charge on the sphere. (b) Calculate the field strength at $r = 0.25 \text{ m}$. (c) Explain why the field strength is zero for $r < 0.10 \text{ m}$.

(a) At the surface, $r = 0.10 \text{ m}$ and $E = 1.8 \times 10^4 \text{ N C}^{-1}$. Outside, $E = \frac{kQ}{r^2}$, so $Q = \frac{Er^2}{k} = \frac{1.8 \times 10^4 \times 0.10^2}{8.99 \times 10^9} = 2.0 \times 10^{-8} \text{ C}$ (+20 nC)

(b) $E = \frac{8.99 \times 10^9 \times 2.0 \times 10^{-8}}{0.25^2} = 2.9 \times 10^3 \text{ N C}^{-1}$ ($2.88 \times 10^3 \text{ N C}^{-1}$) — or by ratio, $1.8 \times 10^4 \times (0.10/0.25)^2$.

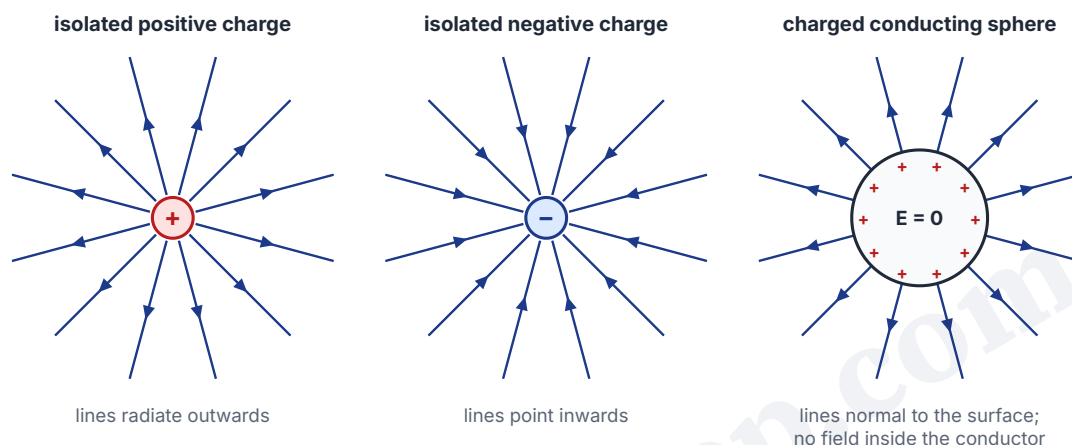
(c) The sphere is a conductor, so the charge resides on its outer surface. If there were a field inside the metal, free electrons would move until it was cancelled; in equilibrium there is no force on the free charges, so $E = 0$ everywhere inside.

How are electric field lines drawn and interpreted?

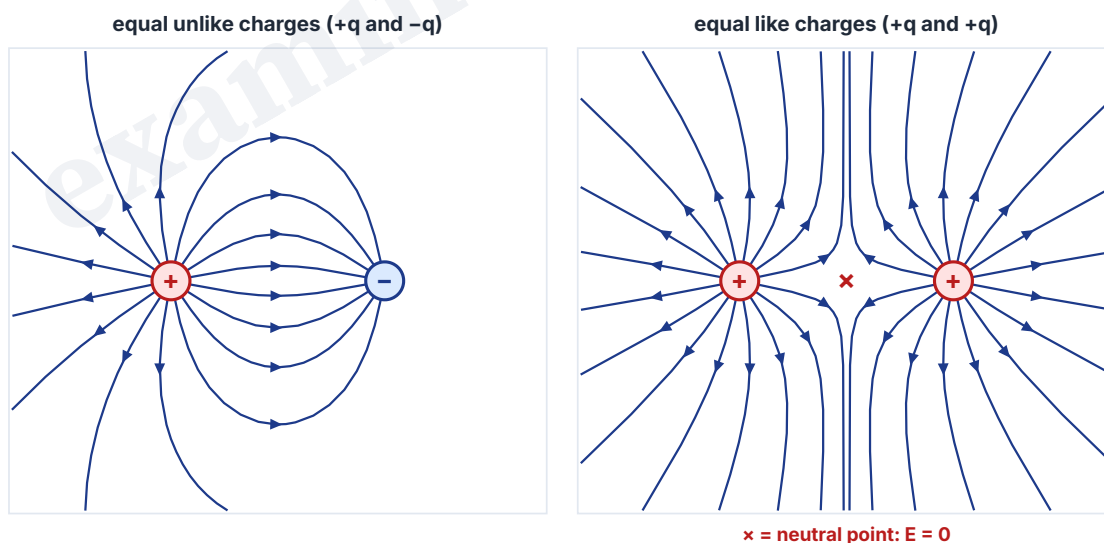
An electric field line shows the direction of the force on a small positive test charge; the closer together the field lines, the stronger the field.

- Lines start on **positive** charges and end on **negative** charges (or continue to infinity). The arrows point away from + and towards –.
- Lines **never cross**: the field has only one direction at each point.
- Lines meet the surface of a conductor at **right angles**, and there are no lines inside a conductor.

- **Field line density and field strength:** the number of lines per unit area crossing a surface at right angles to them is proportional to E . Spreading lines show a weakening field; parallel, equally spaced lines show a **uniform** field.
- The number of lines drawn from a charge should be proportional to its size: a charge $2q$ gets twice as many lines as q .



Radial fields. Around an isolated point charge the lines are radial — outwards for a positive charge, inwards for a negative one — and spread out, so E weakens with distance. A charged conducting sphere has the same pattern outside, with lines normal to its surface, and no field inside.



Field lines for two equal point charges, traced numerically from Coulomb's law. Left: unlike charges — lines run from $+$ to $-$, densest between the charges. Right: like charges — the lines repel each other, and at the midpoint ($\times$) the fields cancel to give a neutral point.

TRY IT YOURSELF

D.2 Electric field simulation: place positive and negative charges, watch the field lines form, and move a test charge to see how the size and direction of

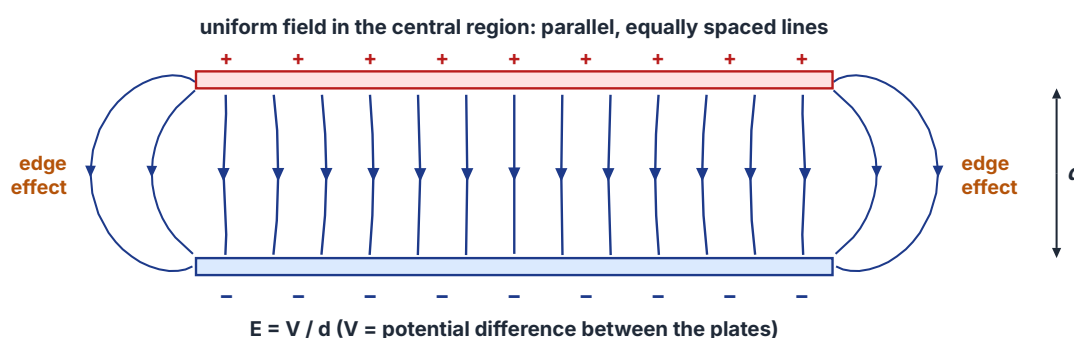
the force change from point to point.

What is the electric field between two parallel plates?

Two parallel metal plates connected to a power supply carry equal and opposite charges. Between them, away from the edges, the field is **uniform**: the same size and direction everywhere.

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

- E = field strength between the plates (V m^{-1}); V = potential difference between the plates (V); d = separation of the plates (m). In the data booklet.
- The field lines are parallel, equally spaced and run from the positive plate to the negative plate, perpendicular to both.
- **Edge effects:** near the edges of the plates the lines bulge outwards and spread apart, so the field there is weaker and no longer uniform. $E = V/d$ applies only in the central region.
- Because E is uniform, a charge between the plates feels the **same force**, $F = qE$, wherever it is — the electrical counterpart of the uniform gravitational field near the Earth's surface.
- E depends only on V and d : halving the separation at fixed V doubles the field.

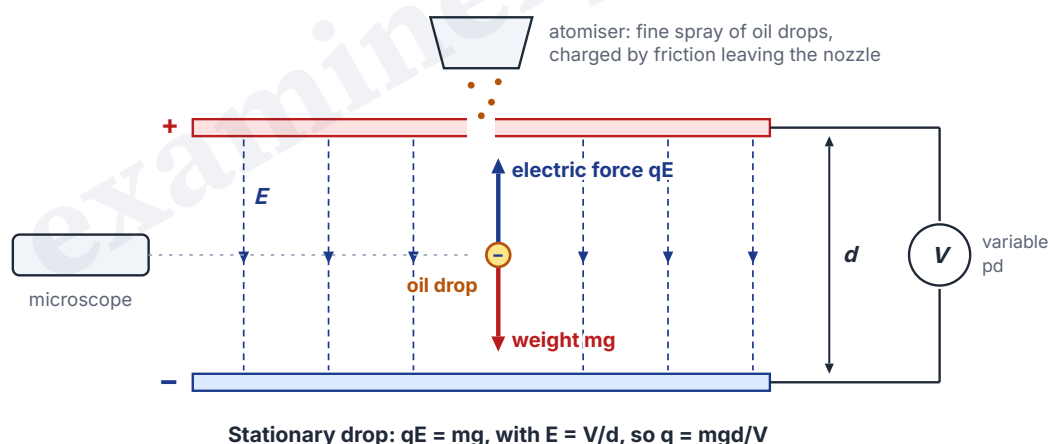


Field lines between oppositely charged parallel plates, traced numerically from the charge on the plates. In the central region the lines are straight, parallel and equally spaced (uniform field); at the ends they curve outwards — the edge effect.

Example. Plates 4.0 cm apart have a potential difference of 2000 V. The field is $E = \frac{2000}{0.040} = 5.0 \times 10^4 \text{ V m}^{-1}$. An electron between them feels a force $F = eE = 1.60 \times 10^{-19} \times 5.0 \times 10^4 = 8.0 \times 10^{-15} \text{ N}$, towards the positive plate. Crossing the whole gap, the field does work $Fd = 8.0 \times 10^{-15} \times 0.040 = 3.2 \times 10^{-16} \text{ J}$ on it. In electronvolts this is simply 2000 eV, since an electron moving through a potential difference of 1 V gains $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.

How did Millikan's experiment show that charge is quantised?

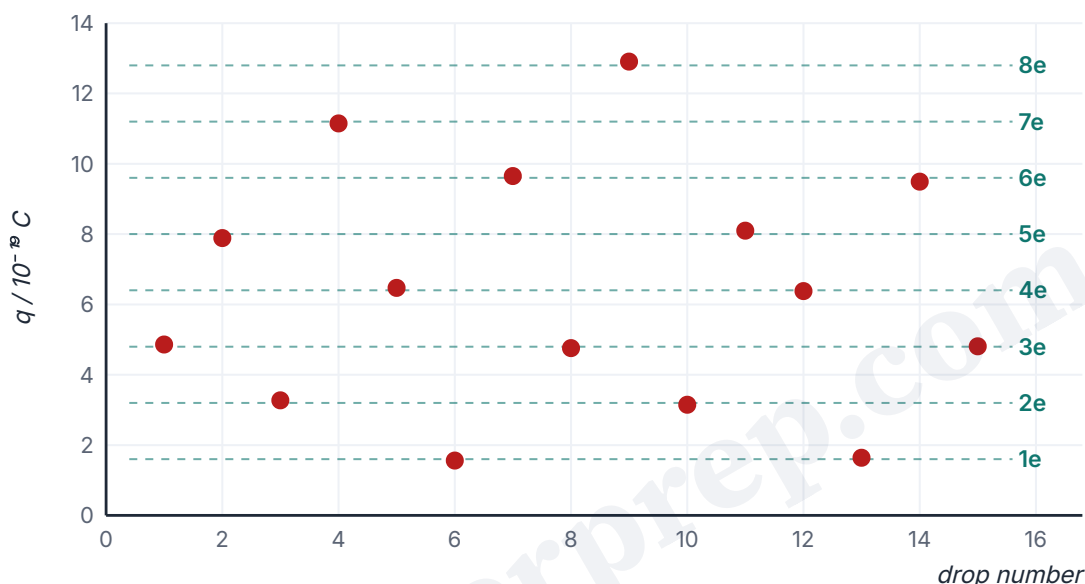
Millikan sprayed tiny oil drops between two horizontal metal plates. Friction in the spray nozzle gave the drops small charges. Adjusting the potential difference between the plates, he could hold a single drop stationary, viewed through a microscope.



The principle of Millikan's experiment. A negatively charged drop is held stationary when the upward electric force qE balances its weight mg . The field is uniform between the plates and points from the positive to the negative plate.

- For a **stationary** drop: $qE = mg$. With $E = \frac{V}{d}$ (previous section): $q = \frac{mgd}{V}$.
- The mass m comes from the drop's radius and the density of the oil: $m = \frac{4}{3}\pi r^3 \rho$. (Millikan found the radius from the drop's terminal speed when the field was switched off; you are not expected to reproduce this.)

- The forces are only this simple because the drop is at rest: the buoyancy of the air is negligible and there is no drag.
- Result:** every measured charge was a whole-number multiple of 1.60×10^{-19} C. No drop ever carried, say, $2.5e$. This is the evidence that charge is **quantised**, with e as the smallest free unit of charge.



Charges measured on fifteen oil drops (illustrative data, scatter about $\pm 2\%$). The values fall on or close to the lines $q = e, 2e, 3e \dots$ and never between them. Dividing the total charge (96.1×10^{-19} C) by the total number of elementary charges (60) gives $e = 1.60 \times 10^{-19}$ C.

WORKED EXAMPLE 4 Medium · Show that / Deduce

In a Millikan-type experiment the plates are 8.0 mm apart. An oil drop of radius $1.10 \mu\text{m}$ and density 880 kg m^{-3} is held stationary when the potential difference is 800 V.

- (a) Show that the charge on the drop is about 4.8×10^{-19} C. (b) Deduce the number of excess electrons on the drop. (c) The drop later picks up one more electron. Calculate the potential difference now needed to hold it stationary.

(a) $m = \frac{4}{3}\pi r^3 \rho = \frac{4}{3}\pi (1.10 \times 10^{-6})^3 \times 880 = 4.91 \times 10^{-15} \text{ kg}$; weight $mg = 4.91 \times 10^{-15} \times 9.8 = 4.81 \times 10^{-14} \text{ N}$.

$$E = \frac{V}{d} = \frac{800}{8.0 \times 10^{-3}} = 1.0 \times 10^5 \text{ V m}^{-1}, \text{ so } q = \frac{mg}{E} = \frac{4.81 \times 10^{-14}}{1.0 \times 10^5} = \mathbf{4.81 \times 10^{-19} \text{ C}} \approx 4.8 \times 10^{-19} \text{ C}$$

(b) $n = \frac{q}{e} = \frac{4.81 \times 10^{-19}}{1.60 \times 10^{-19}} = 3.01$, so **3 electrons** (n must be a whole number).

(c) Now $q = 4e = 6.4 \times 10^{-19} \text{ C}$. $V = \frac{mgd}{q} = \frac{4.81 \times 10^{-14} \times 8.0 \times 10^{-3}}{6.4 \times 10^{-19}} = \mathbf{601 \text{ V}}$ (about 600 V)

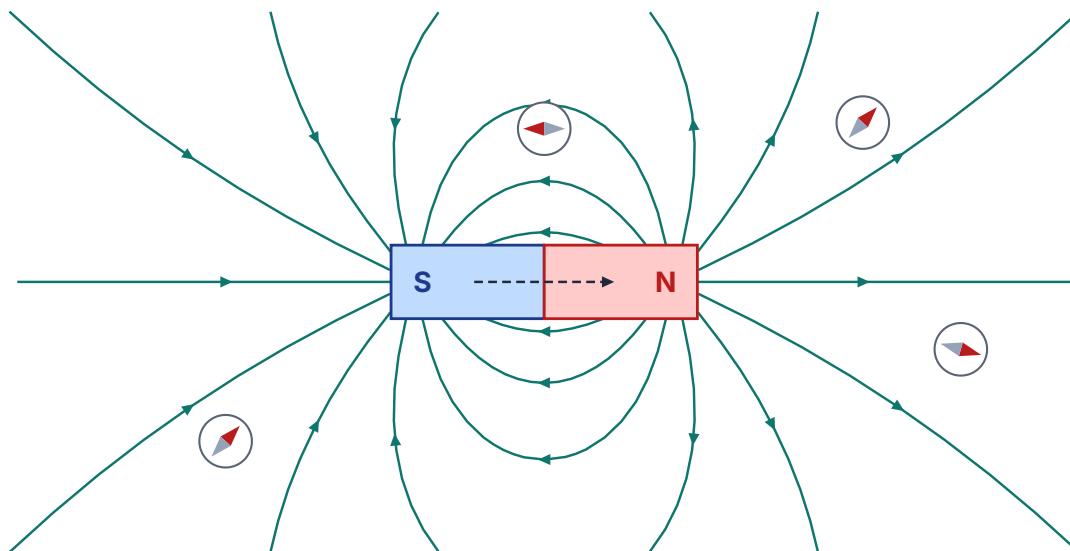
Check: $V \propto 1/q$, so going from 3e to 4e scales 800 V by $\frac{3}{4}$: 600 V.

What do magnetic field lines show?

Magnets and electric currents create **magnetic fields**. A magnetic field is shown with field lines, using the same rules as for electric fields.

A magnetic field line shows the direction in which the north pole of a small compass needle points at each place in the field; the closer together the lines, the stronger the field.

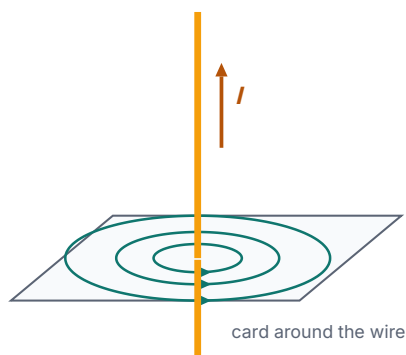
- Outside a magnet, lines run from the **north** pole to the **south** pole. Inside the magnet they continue from S to N, so magnetic field lines are always **closed loops** — there are no isolated magnetic poles.
- Lines never cross, and they are closest together near the poles, where the field is strongest.
- The patterns can be plotted with a small compass moved step by step, or shown with iron filings (which show the shape but not the direction).



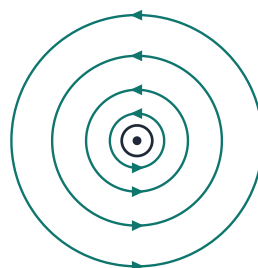
The magnetic field of a bar magnet, traced numerically by modelling the poles as point sources. Outside the magnet the lines go from N to S; the dashed arrow shows them continuing from S to N inside. Each compass needle's north end (red) points along the local field line.

Straight current-carrying wire

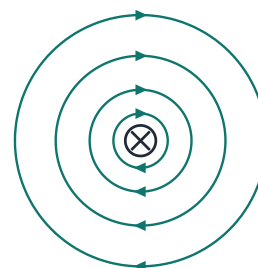
- The lines are **concentric circles** centred on the wire, in planes perpendicular to it. They get further apart with distance: the field weakens.
- **Right-hand grip rule:** grip the wire with the right hand, thumb pointing along the conventional current; the fingers curl in the direction of the field lines.
- On diagrams, $\odot$ means current **out of** the page (field anticlockwise) and $\otimes$ means current **into** the page (field clockwise).
- Reversing the current reverses the direction of the field but not its shape.



Right-hand grip rule: thumb along the current, fingers curl in the direction of B .
Seen from above: anticlockwise.



current out of the page
field anticlockwise



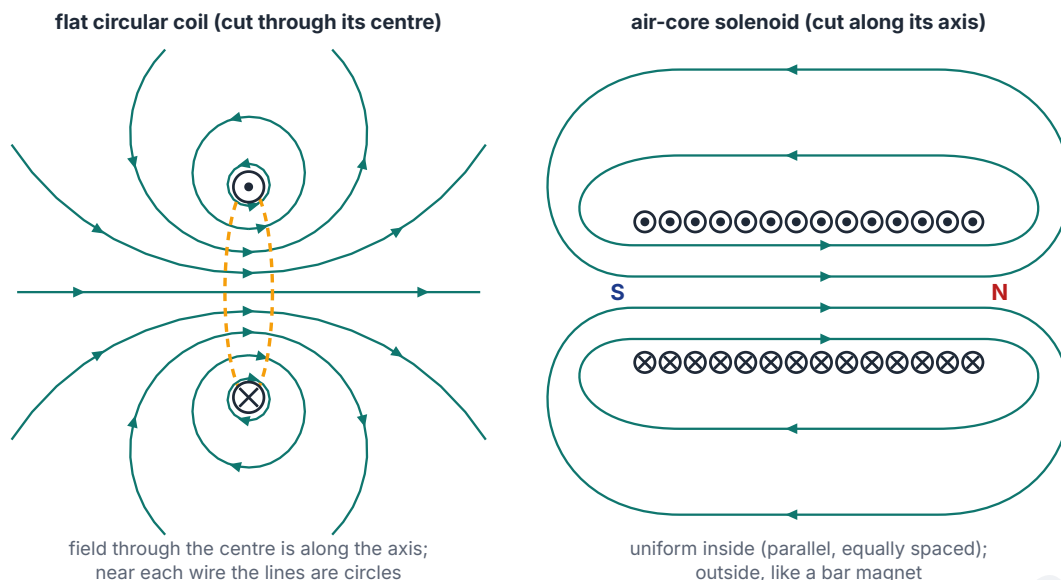
current into the page
field clockwise

Spacing grows with distance: the field weakens.

The field of a long straight wire. Left: a current upwards through a horizontal card gives circular field lines that run anticlockwise seen from above. Right: the same field seen end-on, for current out of and into the page. The spacing of the circles increases with distance because the field weakens.

Flat circular coil and air-core solenoid

- **Flat coil:** close to each side of the wire the lines are nearly circles (as for a straight wire). At the centre the contributions from all parts of the loop add, giving a strong field along the axis of the coil.
- **Solenoid** (a long coil of many turns): **inside**, the lines are parallel, equally spaced and along the axis — the field is **uniform** (apart from near the ends). **Outside**, the field is weak and has the same shape as that of a bar magnet.
- **Which end is N?** Curl the fingers of the right hand in the direction of the current in the turns; the thumb points along the field inside, towards the north-pole end. Equivalently, looking at an end, current flowing *anticlockwise* makes that end a **north** pole.



Magnetic fields of a flat circular coil and an air-core solenoid, both drawn as cross-sections through the axis ($\odot$ current out of the page, $\otimes$ into the page). The coil's lines are traced numerically from the field of its current; the solenoid is drawn schematically. Inside the solenoid the field is uniform; outside it has the same shape as a bar magnet's, with N at the end the field lines leave.

In D.2 you only need these four field *patterns* and how to find the field direction. The force on a current or a moving charge in a magnetic field is in D.3; equations for the strength of the field of a wire or a solenoid are not required.

HL: What are electric potential energy and electric potential?

HL Electric potential energy of a system

The electric potential energy of a system of charges is the work done to assemble the system from infinite separation of its charges.

$$E_p = k \frac{q_1 q_2}{r}$$

- E_p = electric potential energy of the two-charge system (J); q_1, q_2 = the charges, **with their signs** (C); r = their separation (m). In the data booklet.
- **Like charges:** work must be done to push them together, so E_p is **positive** and increases as r decreases.

- **Unlike charges:** the attraction does the work as they come together, so E_p is **negative**, like the gravitational case in D.1.
- $E_p = 0$ at infinite separation. It is a scalar and belongs to the **system**, not to either charge alone.
- **More than two charges:** add $k \frac{q_i q_j}{r_{ij}}$ for every pair. Three charges of +2.0 nC at the corners of an equilateral triangle of side 5.0 cm have $E_p = 3 \times \frac{8.99 \times 10^9 \times (2.0 \times 10^{-9})^2}{0.050} = 2.16 \times 10^{-6} \text{ J}$.

Electric potential

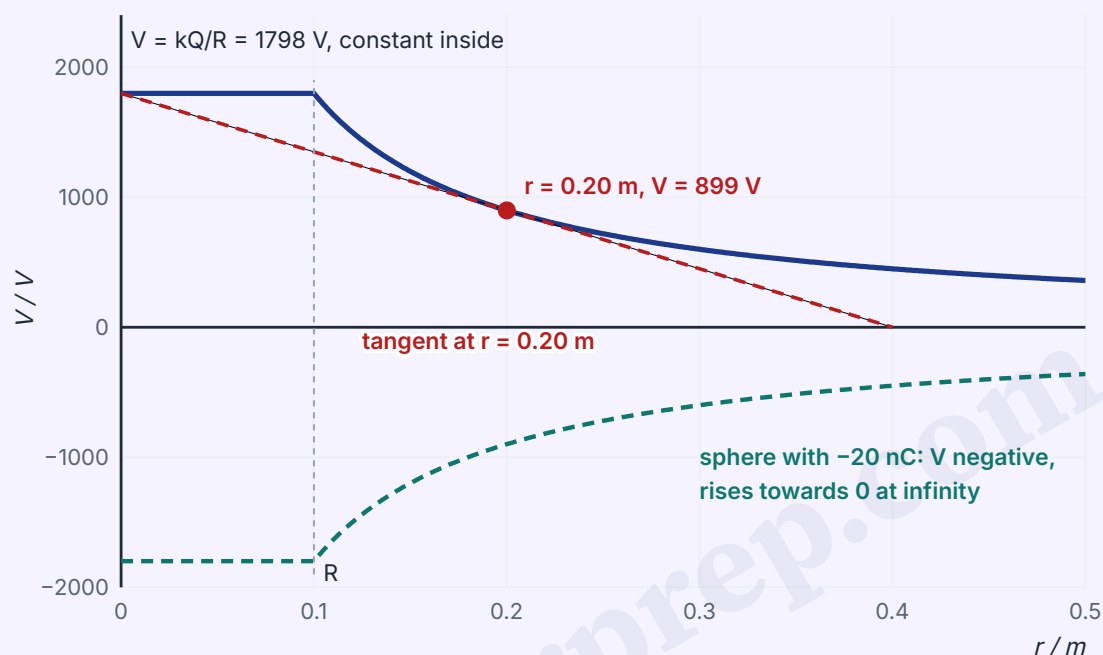
The electric potential at a point is the work done per unit charge in bringing a small positive test charge from infinity to that point.

$$V_e = \frac{kQ}{r} \qquad W = q \Delta V_e$$

- V_e = electric potential (V, equivalent to J C^{-1}); Q = charge creating the field, with its sign (C); r = distance from it (m); W = work done in moving charge q between two points (J); ΔV_e = potential difference between them (V). Both are in the data booklet.
- Potential is a **scalar** with **zero defined at infinity**. It is positive near a positive charge and negative near a negative charge.
- For several charges, **add the potentials algebraically** — no vector components needed. At the centre of a 0.20 m square with +2.0 nC at each corner (distance 0.141 m from each), $V_e = 4 \times \frac{8.99 \times 10^9 \times 2.0 \times 10^{-9}}{0.141} = 509 \text{ V}$, even though $E = 0$ there by symmetry. The work to bring a +1.0 nC charge from infinity to that point is $W = q \Delta V_e = 1.0 \times 10^{-9} \times 509 = 5.1 \times 10^{-7} \text{ J}$.
- A charge q at a point of potential V_e has potential energy $E_p = qV_e$. A positive charge released from rest moves to **lower** potential; a negative charge (an electron) moves to **higher** potential. Either way, its potential energy decreases and its kinetic energy increases.
- **Joules and electronvolts:** $W = q \Delta V_e$ gives joules when q is in coulombs. For a particle of charge $\pm e$, the work in electronvolts is

numerically equal to the potential difference in volts: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.

- W depends only on the start and end points, not on the path taken.



Electric potential against distance from the centre of the conducting sphere of worked example 3 ($R = 0.10 \text{ m}$, $Q = +20 \text{ nC}$; solid line) and of the same sphere carrying -20 nC (dashed). Inside, V is constant at its surface value kQ/R because $E = 0$ there. Outside, $V = kQ/r$. The red tangent at $r = 0.20 \text{ m}$ is used in worked example 6.

WORKED EXAMPLE 5 HL · Medium · Determine / Calculate

A point charge of $+6.0 \text{ nC}$ is fixed at A and a point charge of -2.0 nC is fixed at B, 0.40 m from A. P is the midpoint of AB. Point Q lies on the line AB, beyond B, 0.20 m from B.

- (a) Calculate the electric potential at P and at Q. (b) Determine the work done by the electric field on a proton that moves from P to Q (by any path), in eV and in J. (c) Calculate the electric potential energy of the system of the two fixed charges. (d) Comment on the electric field strength at Q.

$$\begin{aligned} \text{(a) } V_P &= \frac{8.99 \times 10^9 \times 6.0 \times 10^{-9}}{0.20} + \\ &\frac{8.99 \times 10^9 \times (-2.0 \times 10^{-9})}{0.20} = 269.7 - 89.9 = \mathbf{180 \text{ V}} \end{aligned}$$

Q is 0.60 m from A and 0.20 m from B: $V_Q = \frac{8.99 \times 10^9 \times 6.0 \times 10^{-9}}{0.60} + \frac{8.99 \times 10^9 \times (-2.0 \times 10^{-9})}{0.20} = 89.9 - 89.9 = 0 \text{ V}$

(b) The proton moves from 180 V to 0 V, to lower potential, so the field does positive work: $W = e(V_P - V_Q) = e \times 180 \text{ V} = 180 \text{ eV} = 2.9 \times 10^{-17} \text{ J}$ ($2.88 \times 10^{-17} \text{ J}$). (The work done *by an external agent*, $q\Delta V_e$, is -180 eV .)

(c) $E_p = k \frac{q_1 q_2}{r} = \frac{8.99 \times 10^9 \times 6.0 \times 10^{-9} \times (-2.0 \times 10^{-9})}{0.40} = -2.7 \times 10^{-7} \text{ J}$ — negative because the charges attract.

(d) $E_A = \frac{k(6.0 \text{ nC})}{0.60^2} = 150 \text{ N C}^{-1}$ away from A; $E_B = \frac{k(2.0 \text{ nC})}{0.20^2} = 450 \text{ N C}^{-1}$ towards B. Resultant: **300 N C⁻¹ towards B**.
So at Q the potential is zero but the field strength is not: E depends on how fast V changes, not on the value of V .

HL: How are field strength, potential gradient and equipotentials related?

HL Field strength as potential gradient

$$E = -\frac{\Delta V_e}{\Delta r}$$

- The electric field strength is the negative of the **potential gradient**. In the data booklet. This is why V m^{-1} is a unit of field strength.
- On a V_e - r graph, the magnitude of E at a point is the magnitude of the **gradient of the tangent** at that point.
- The minus sign means that the field points in the direction of **decreasing** potential.

- Between parallel plates the potential falls **linearly** from one plate to the other, so the gradient is constant: $E = V/d$ is the special case of a uniform field.
- Inside a charged conductor $E = 0$, so the potential gradient is zero: V_e is the same everywhere inside as on the surface.

WORKED EXAMPLE 6 HL · Hard · Determine (graph) / Calculate

The solid line in the graph above shows the potential around the conducting sphere of radius 0.10 m carrying +20 nC.

(a) Use the tangent drawn at $r = 0.20$ m to determine the electric field strength there, and check your answer using Coulomb's law. (b) An electron is released from rest at $r = 0.30$ m. Determine its kinetic energy, in eV and in J, when it reaches the surface of the sphere. (c) Calculate its speed at the surface, and comment on whether a non-relativistic calculation is justified.

(a) The tangent passes through (0, 1798 V) and (0.40 m, 0).

Gradient = $-\frac{1798}{0.40} = -4.5 \times 10^3 \text{ V m}^{-1}$, so $E = -\frac{\Delta V_e}{\Delta r} = 4.5 \times 10^3 \text{ V m}^{-1}$, directed away from the sphere. (Accept $4.3\text{--}4.7 \times 10^3 \text{ V m}^{-1}$ from a hand-drawn tangent.)

Check: $E = \frac{kQ}{r^2} = \frac{8.99 \times 10^9 \times 20 \times 10^{-9}}{0.20^2} = 4.50 \times 10^3 \text{ N C}^{-1} \checkmark$

(b) $V_e(0.30) = \frac{8.99 \times 10^9 \times 20 \times 10^{-9}}{0.30} = 599 \text{ V}$; at the surface

$V_e = 1798 \text{ V}$. The electron moves to higher potential, gaining kinetic energy $e\Delta V_e$ with $\Delta V_e = 1798 - 599 = 1199 \text{ V}$:

$E_k = 1.2 \times 10^3 \text{ eV} = 1.9 \times 10^{-16} \text{ J}$ (1199 eV; $1.92 \times 10^{-16} \text{ J}$)

(c) $v = \sqrt{\frac{2E_k}{m_e}} = \sqrt{\frac{2 \times 1.92 \times 10^{-16}}{9.110 \times 10^{-31}}} = 2.1 \times 10^7 \text{ m s}^{-1}$ ($2.05 \times 10^7 \text{ m s}^{-1}$). This is about 7 % of the speed of light, small enough for $E_k = \frac{1}{2}mv^2$ to be a good approximation.

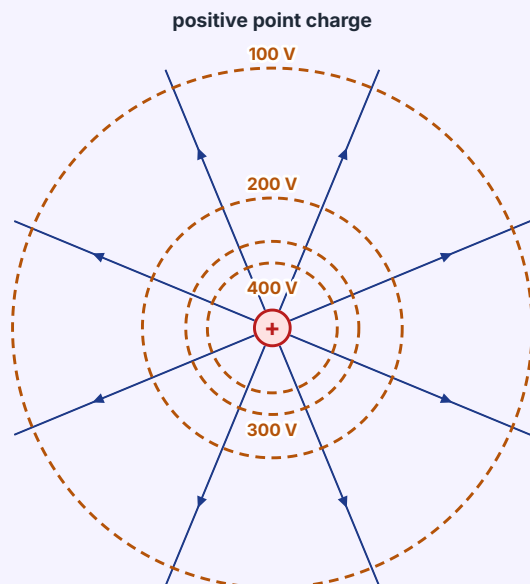
Using the field strength instead would need integration, because E changes along the path; the potential gives the energy change in one subtraction. That is the main

Equipotential surfaces

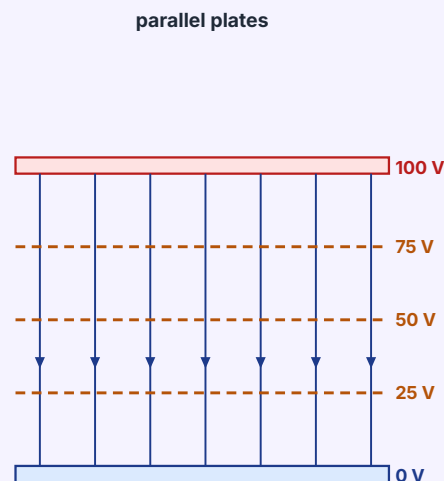
An equipotential surface joins points at the same electric potential. No work is done in moving a charge along an equipotential surface.

- **Equipotentials are always perpendicular to field lines.** If the field had a component along an equipotential, moving a charge along it would involve work, contradicting $W = q\Delta V_e = 0$.
- Drawn for **equal steps** in potential, equipotentials are **closest together where the field is strongest**, since $|E| = \Delta V_e / \Delta r$.
- Given equipotentials, sketch field lines crossing each at right angles, pointing from higher to lower potential. Given field lines, equipotentials cross them at right angles.

Situation	Shape of the equipotentials
point charge	concentric spheres; for equal steps in V_e they get further apart with distance ($r \propto 1/V_e$)
oppositely charged parallel plates	flat planes parallel to the plates, equally spaced for equal steps (uniform field); they curve near the edges
solid or hollow charged conducting sphere	outside: concentric spheres, as for a point charge at the centre; the whole conductor, including the hollow inside, is one equipotential at kQ/R
up to four point charges	add the potentials of each charge at every point; near each charge the surfaces are almost spheres; for two equal unlike charges the plane midway between them is at $V_e = 0$



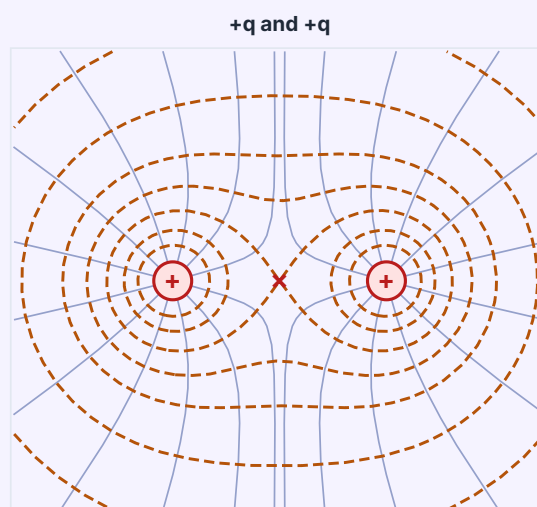
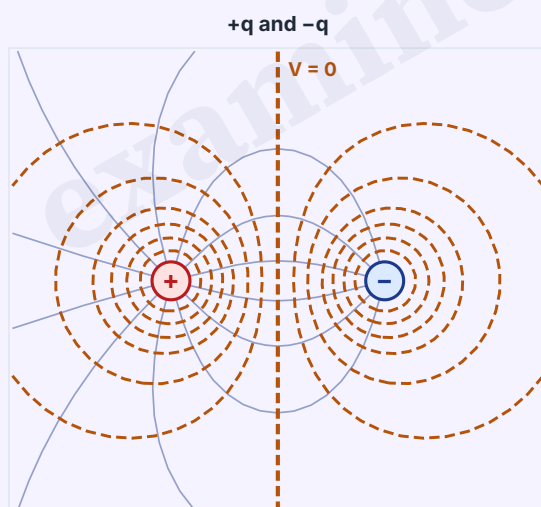
equal steps in V : the surfaces get further apart as the field weakens ($r \propto 1/V$)



equal 25 V steps, equally spaced:
the field is uniform

field lines (solid) $\perp$ equipotentials (dashed)

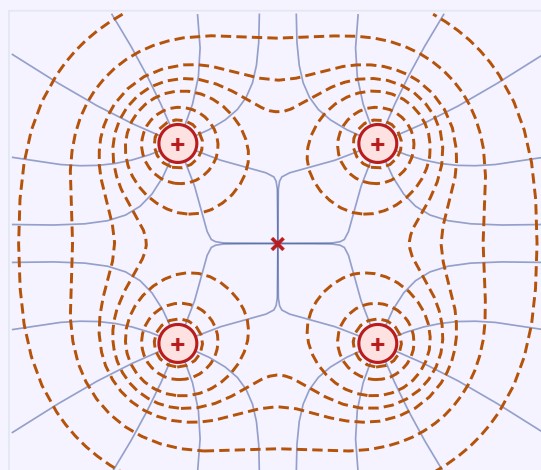
Equipotentials (dashed) and field lines (solid). Left: a positive point charge, with equipotentials at 100 V, 200 V, 300 V and 400 V (equal steps) — their radii are in the ratio $1 : 1/2 : 1/3 : 1/4$, so they crowd together near the charge, where the field is strongest. Right: parallel plates with a 100 V potential difference, where equal steps of 25 V are equally spaced.



x : $E = 0$ but $V \neq 0$

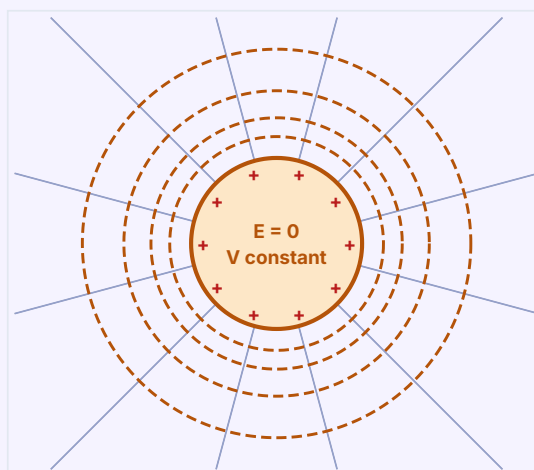
Equipotentials (dashed, computed by adding the potentials of the two charges) with the field lines shown faintly. Left: equal unlike charges — the perpendicular bisector is the $V = 0$ equipotential. Right: equal like charges — at the neutral point the field is zero, but the potential is not.

four equal positive charges



× : $E = 0$ at the centre, but $V = 4kq/r \neq 0$

charged conducting sphere



same pattern for a solid or a hollow sphere

Left: four equal positive charges at the corners of a square — close to each charge the equipotentials are circles; further out they merge into single closed surfaces around the whole group. At the centre $E = 0$ but $V = 4kq/r$. Right: a charged conducting sphere — outside, concentric equipotentials (equal steps) as for a point charge; the conductor itself, solid or hollow, is a single equipotential.

Exam tips for D.2

EXAM TIP 1 — FIELD LINES ARE MARKED ON THE DETAILS

When sketching field lines, the marks depend on: arrows on every line (away from +, towards -); lines that touch conductors at right angles; no crossing lines; symmetry; and, for parallel plates, equally spaced straight lines in the middle with curved lines at the edges. A neat pattern without arrows usually scores nothing.

EXAM TIP 2 — SAY HOW THE ELECTRONS MOVE

In "explain how the sphere becomes charged" questions, describe the movement of **electrons** and only electrons: "electrons are repelled to the far side", "electrons flow from the sphere to earth". Answers that describe positive charge flowing, or charge being "created", lose the mark. For induction, state the order: earth connection removed *before* the rod.

EXAM TIP 3 — COMPARE THE ELECTRIC FORCE WITH THE WEIGHT

When asked whether gravity can be ignored for an electron or ion in a field, calculate **both** forces (or both accelerations) and compare them numerically. For an electron in a field of a few thousand V m^{-1} , eE is around 10^{14} times $m_e g$. "The electron is very light" on its own is not enough. For a Millikan drop the opposite is true: the weight matters and is balanced by qE .

EXAM TIP 4 — VECTORS FOR E, SCALARS FOR V (HL)

Field strengths from several charges must be added as **vectors**, with a direction stated in the answer. Potentials are added as **signed scalars** — include the minus sign for a negative charge and never take components. A common error is to add potentials as magnitudes, or to give a field strength with no direction.

EXAM TIP 5 — SKETCHING V AGAINST R (HL)

For a positive point charge the sketch must be **positive everywhere**, **decreasing** and approaching zero **asymptotically** — never touching or crossing the r-axis. For a negative charge it is the mirror image below the axis. Be ready to say what the gradient represents: it is the negative of the electric field strength.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Rubbing a rod creates charge on it.	The cloth always ends with an equal and opposite charge.	Friction transfers electrons; total charge is conserved.
A positively charged body has gained protons.	Protons are bound in nuclei and do not move between bodies in charging.	A positive body has lost electrons .
The larger charge exerts the larger force.	The forces on the two charges are a Newton's third law pair.	The forces are equal in magnitude and opposite in direction.
Field lines show the path a charge will follow.	A line shows the direction of the force, i.e. of the acceleration, not of the velocity.	A charge moves along a field line only if it starts from rest in a straight-line field (such as between plates).
There is a field inside a charged metal sphere, strongest at the centre.	Free electrons move until there is no force on them inside the conductor.	$E = 0$ inside a conductor; the charge is on the surface.
(HL) Where the potential is zero, the field strength is zero too.	E is set by the potential <i>gradient</i> , not the potential itself.	Between two unlike charges $V_e = 0$ on the bisector, yet E is large there; between two like charges $E = 0$ at the midpoint, yet $V_e \neq 0$.

How this topic connects

Electric, magnetic and gravitational fields: a shared toolkit

Electric and gravitational fields are described with the same tools. Both forces follow an **inverse-square law** between point sources ($F = Gm_1m_2/r^2$ and $F = kq_1q_2/r^2$); both fields are defined as force per unit "test" quantity ($g = F/m$, $E = F/q$); and at HL both have a scalar potential that is zero at infinity,

with field strength equal to minus the potential gradient and equipotentials perpendicular to field lines. The differences: gravity only attracts, while electric forces attract or repel, so gravitational potential is always negative but electric potential can have either sign; electric forces depend on the medium (permittivity) while gravity does not; and electric forces are vastly stronger — between two protons the electric repulsion is 1.2×10^{36} times the gravitational attraction. Magnetic fields are shown with the same field-line rules, but their lines form **closed loops**, because there are no isolated magnetic poles to start or end on.

Curved tracks in magnetic fields: identifying particles and probing matter

A charged particle moving across a magnetic field feels a force perpendicular to its velocity (D.3), so it follows a curved path whose radius depends on its mass, charge and speed. Measuring the curvature of particle tracks in a known field therefore reveals the sign of the charge and the charge-to-mass ratio of the particle. Combined with Millikan's value of e , such measurements gave the mass of the electron, and the same principle is still used to identify charged particles in detectors. The field patterns of this page — especially the uniform field inside a solenoid — are how such known fields are produced.

Discrete amounts in nature: charge and other quantised quantities

Millikan's experiment is a classic example of evidence driving a model: the measured charges clustered at whole multiples of e , and no fractional values appeared among free charges. Other quantities that come in discrete amounts include the **energy of electrons in atoms**, which can take only certain values and so gives line spectra (E.1); the **energy of light**, delivered in photons of energy hf (E.1; the photoelectric effect in E.2 at HL); and **matter** itself, made of a whole number of atoms or particles. Quantities such as mass, distance and time are, as far as we can measure, continuous. Recognising quantisation requires precise data and careful treatment of uncertainty: Millikan's grouping of charges only works because the uncertainty in each measurement is much smaller than e .

Tools & inquiry — analysing charge data and mapping fields (NOS: evidence and models)

- **Finding a quantum from data:** with a set of measured charges, look for the largest value that divides them all into near-whole numbers. Assign a whole number n to each, then estimate e as $\sum q / \sum n$, or as the gradient of a graph of q against n .
- **Uncertainties:** in $q = \frac{4\pi r^3 \rho g d}{3V}$ the radius is cubed, so its percentage uncertainty counts three times — the radius measurement limits the precision of the whole experiment.
- **Mapping magnetic fields:** plot field lines by moving a small plotting compass and marking where its needle points, step by step; a magnetic field sensor can measure how the strength changes with distance.
- **Mapping equipotentials (HL):** on conducting paper with a potential difference across two electrodes, a voltmeter probe finds points at the same potential; joining them gives equipotential lines, and the field lines can be drawn perpendicular to them.
- **NOS — fields as models:** field lines are a visual model, not physical objects. The same field can be described algebraically ($E = kQ/r^2$, $V_e = kQ/r$) or visually (field lines, equipotentials), and each description answers different questions more easily.

Key equations

Equation	Use	Level	In data booklet?
$F = k \frac{q_1 q_2}{r^2},$ $k = \frac{1}{4\pi\epsilon_0}$	force between two point charges (replace ϵ_0 by ϵ in a medium)	SL & HL	yes
$E = \frac{F}{q}$	electric field strength	SL & HL	yes
$E = \frac{kQ}{r^2}$	field of a point charge or outside a charged sphere	SL & HL	no — combine $F = kq_1q_2/r^2$ and $E = F/q$
$E = \frac{V}{d}$	uniform field between parallel plates	SL & HL	yes
$q = ne, q = \frac{mgd}{V}$	quantised charge; stationary drop in Millikan's experiment	SL & HL	no — from $qE = mg$ and $E = V/d$
$E_p = k \frac{q_1 q_2}{r}$	electric potential energy of two charges	HL	yes
$V_e = \frac{kQ}{r}$	electric potential of a point charge	HL	yes
$E = -\frac{\Delta V_e}{\Delta r}$	field strength as potential gradient	HL	yes
$W = q\Delta V_e$	work done moving a charge between two points (J or eV)	HL	yes

Check your understanding

1. A polythene rod has a charge of -4.8 nC after being rubbed with a cloth. Calculate the number of electrons transferred, and state the charge on the cloth.

$$n = \frac{4.8 \times 10^{-9}}{1.60 \times 10^{-19}} = 3.0 \times 10^{10} \text{ electrons, transferred from the cloth to the rod. By conservation of charge the cloth has a charge of } \mathbf{+4.8 \text{ nC}}.$$

2. One of two point charges is doubled and their separation is halved. State the factor by which the force between them changes.

$F \propto \frac{q_1 q_2}{r^2}$, so the factor is $\frac{2}{(1/2)^2} = 8$. The force becomes eight times larger.

3. Two parallel plates 2.5 cm apart have a potential difference of 150 V. Calculate the force on an electron between the plates and compare it with the electron's weight.

$E = \frac{150}{0.025} = 6.0 \times 10^3 \text{ V m}^{-1}$; $F = eE = 1.60 \times 10^{-19} \times 6.0 \times 10^3 = 9.6 \times 10^{-16} \text{ N}$, towards the positive plate. Weight = $m_e g = 9.110 \times 10^{-31} \times 9.8 = 8.9 \times 10^{-30} \text{ N}$. The electric force is about 1×10^{14} times larger, so gravity is negligible.

4. Three oil drops in a Millikan experiment have charges of $3.2 \times 10^{-19} \text{ C}$, $8.0 \times 10^{-19} \text{ C}$ and $11.2 \times 10^{-19} \text{ C}$. Show that these support the idea that charge is quantised.

Dividing by $1.6 \times 10^{-19} \text{ C}$ gives 2.0, 5.0 and 7.0 — all whole numbers. Each charge is an integer multiple of the same elementary charge, $e = 1.6 \times 10^{-19} \text{ C}$; no larger common unit (such as $3.2 \times 10^{-19} \text{ C}$) divides all three.

5. (HL) The electric potential 0.50 m from the centre of a small charged sphere is 360 V. Determine the charge on the sphere, the potential 1.0 m from its centre and the field strength 0.50 m from its centre.

$Q = \frac{V_e r}{k} = \frac{360 \times 0.50}{8.99 \times 10^9} = 2.0 \times 10^{-8} \text{ C}$. $V_e \propto 1/r$, so at 1.0 m $V_e = 180 \text{ V}$.
 $E = \frac{kQ}{r^2} = \frac{V_e}{r} = \frac{360}{0.50} = 720 \text{ V m}^{-1}$, directed away from the sphere.

Practise D.2 with exam-style questions

Original Paper 1A, 1B and 2 questions on electric and magnetic fields, with full mark schemes. Tick the questions you want and print them as your own test.

SL D.2 questions

HL D.2 questions

Revise and explore

- [Flashcards](#) — choose IB Physics and filter to D.2 Electric and magnetic fields. Free, no sign-up.
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