Electric and magnetic fields

D.2 · SL and AHL

Why does a car door give you a shock?

> Charges exert forces on each other through the fields they create.

- Sliding off the seat rubs electrons from one surface to the other.
- The charge jumps to the metal as a tiny spark.
- This unit: charge $\rightarrow$ Coulomb $\rightarrow$ fields $\rightarrow$ magnetism $\rightarrow$ potential.

Two types of charge

Negative

Electrons added.

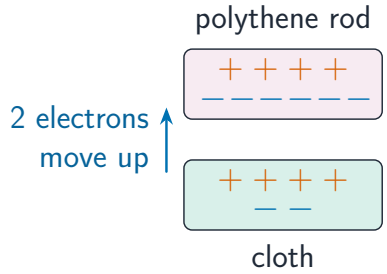
Each electron carries $-e$.

Positive

Electrons removed.

$e = 1.60 \times 10^{-19}$ C.

Charging by friction moves electrons



rod: 6 $-$, 4 $+$ $\Rightarrow$ net $-2e$

total stays zero; protons stay put

cloth: 2 $-$, 4 $+$ $\Rightarrow$ net $+2e$

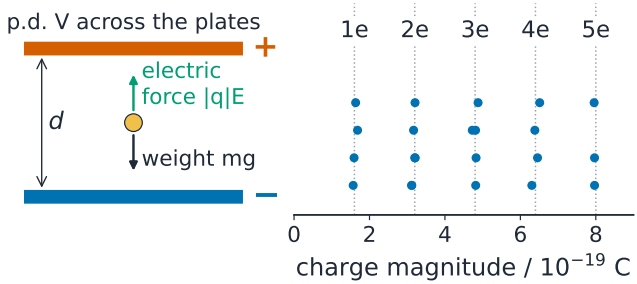
Protons stay put; the total charge stays zero

Charging by induction



- Friction and contact move charge directly.
- Remove the earth before the rod, or the charge flows back.

Millikan's oil drops



- In the no-buoyancy suspension model, $|q|E = mg$, so $|q| = mgd/V$.
- With the upper plate positive, a suspended drop needs negative charge; invented magnitudes cluster near multiples of e.

Coulomb's law

- $+3.0$ and -2.0 μC 0.20 m apart attract with 1.35 N.
- In water ($\varepsilon_r = 80$) the force is 80 times smaller.

$$F = \frac{k|q_1 q_2|}{r^2} \qquad k = \frac{1}{4\pi\varepsilon_0}$$

Force magnitude here; direction follows charge signs. A uniform linear dielectric is a model, not a full theory of salt solubility.

Like charges repel, unlike attract

like charges



repel — pushed apart

opposite charges



attract — pulled together

$F = kq_1q_2/r^2$, along the line joining them

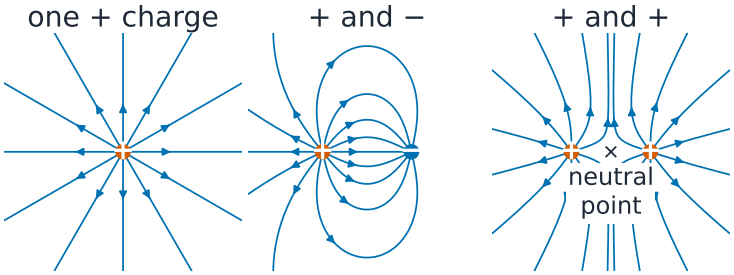
Electric field strength

- Force per unit charge on a small positive test charge.
- 0.10 m from $+2.0$ nC, $E = 1.8 \times 10^3$ N C^{-1}.

$$E = \frac{F}{q} \qquad E = \frac{kQ}{r^2}$$

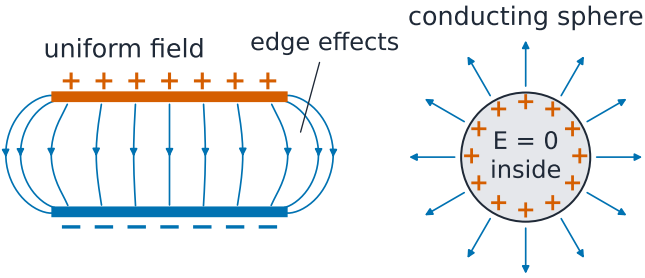
A negative charge is pushed against the field.

Electric field lines



- Away from positive and towards negative charges; lines can extend to infinity.
- Closer lines mean a stronger field.

Plates and conductors



- Uniform between plates, with edge effects at the ends.
- Zero field in conducting material at electrostatic equilibrium; a cavity must be empty for zero cavity field.

The uniform field

- 2.0 kV across 4.0 cm gives 5.0×10^{4} V m^{-1}.
- An electron feels 8.0×10^{-15} N anywhere between the plates.

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

Sketch polarities, field and charge; convert the gap to metres. Use a simulation or approved low-voltage model in school, never exposed high voltage.

Check: a stronger field

Your turn

For ideal broad plates, the gap is halved and voltage magnitude doubled. By what factor does electric-force magnitude on the same electron change?

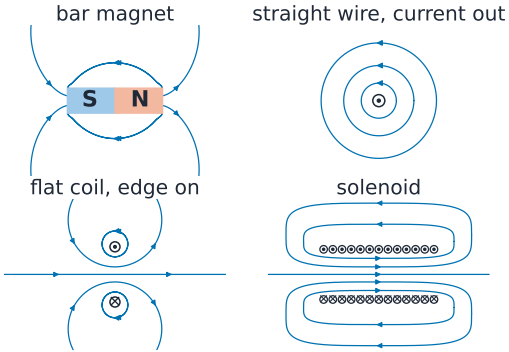
A. 1

B. 2

C. 4

D. 8

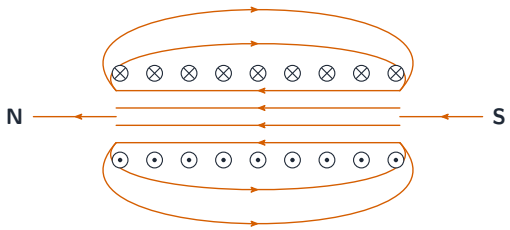
Magnetic field lines



- North to south outside a magnet; circles round a wire.
- **Right-hand grip rule**; ⊙ out of the page, ⊗ into it.

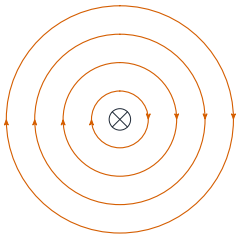
The field of a solenoid

field nearly uniform inside, spreads out like a bar magnet outside



Grip rule: fingers with the current, thumb points to N

The field around a straight wire



circular field lines (right-hand grip rule)

The field weakens with distance from the wire

Electric potential energy

- Like charges give positive E_p; unlike charges negative.
- $+3.0$ and -2.0 μC at 0.20 m have $E_p = -0.27$ J.

$$E_p = \frac{kq_1 q_2}{r}$$

Zero at infinite separation; include the signs.

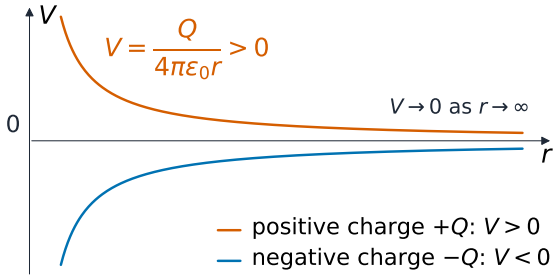
Electric potential

- A scalar, zero at infinity; add potentials with signs.
- Midway between $+4.0$ and -2.0 nC 0.20 m apart, $V = 180$ V.

$$V_e = \frac{kQ}{r}$$

Fields still add as vectors.

Potential around a point charge



$V = kQ/r$, zero at infinity

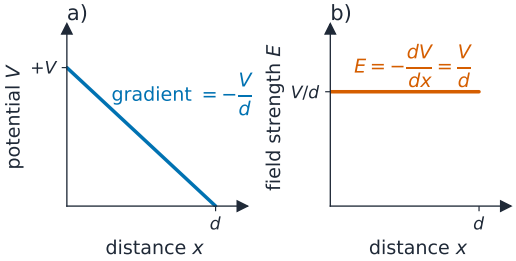
Potential gradient and work

- 1 eV $= 1.60 \times 10^{-19}$ J.
- From rest through a 2.0 kV rise, an electron reaches about 2.7×10^{7} m s^{-1}.

$$E_r = -\frac{dV_e}{dr} \qquad W_{\text{ext}} = q\Delta V_e$$

External work at unchanged kinetic energy; electric-field work has the opposite sign. A finite difference gives an average component.

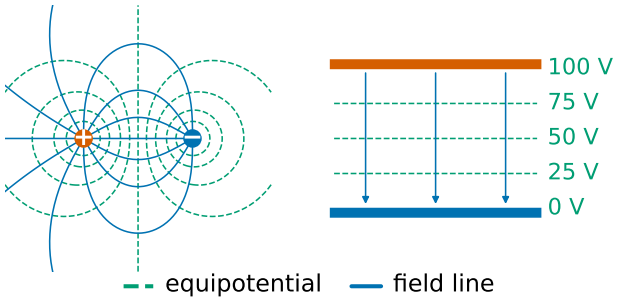
Field strength is the potential gradient



$E = -dV/dr$ · field = negative gradient of potential

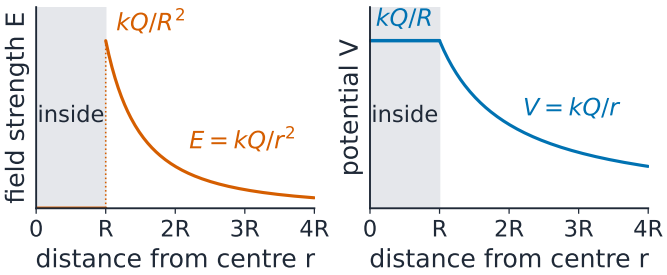
$$E = -\Delta V/\Delta x$$

Equipotential surfaces



- The **electric field** does zero work along an equipotential.
- Field lines cross equipotentials at right angles.

A charged conducting sphere



- Isolated sphere in equilibrium, with empty cavity if hollow: inside E = 0 and V = kQ/R.
- Outside, it behaves like a point charge at the centre.

Exam tips

> Field direction is the force on a positive test charge.

- The force on an electron is opposite to the field.
- Field lines never cross; zero field inside a conductor.
- Potentials add as scalars; fields add as vectors.

Check yourself

Try these

Use vacuum $k = 8.99 \times 10^9$ N m^2/C^2. Find force magnitude and direction between $+3.0$ µC and -2.0 µC, 0.20 m apart.

Describe how to charge a metal sphere positively by induction.

HL. Find the potential midway between $+4.0$ nC and -2.0 nC 0.20 m apart.