

Electric fields

A-Level Physics

Electric fields



Lightning is a giant spark driven by a huge electric field.

An **electric field** 电场 is a region where a charge feels a **force** 力 from other charges. The **electric field strength** 电场强度 E at a point is the **force per unit positive charge** on a small positive **test charge** 检验电荷 placed there:

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

Unit: N C^{-1} (the same as V m^{-1} , as we will see). E is a **vector** 矢量, pointing the way the force acts on a **positive** charge. The force on a charge q is

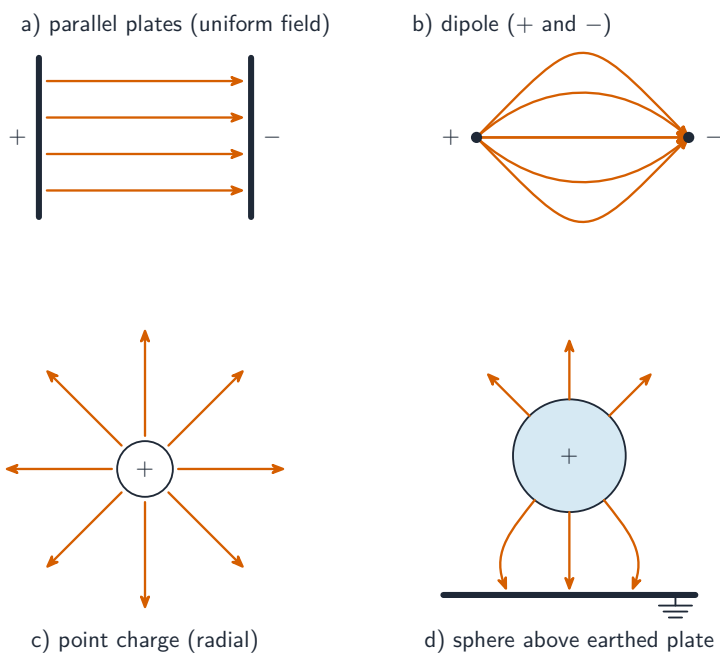
$$F = qE,$$

opposite to the field if q is negative.

Field lines

- **field lines** 场线 point the way the force acts on a positive test charge.
- lines start on **positive** charges and end on **negative** charges (or go to infinity).
- lines never cross; closer lines mean a stronger field.

Examples: a positive **point charge** 点电荷 has radial lines pointing out; a negative one has lines pointing in; two opposite charges (a **dipole** 偶极子) have lines curving from + to -; two parallel charged plates give a **uniform field** 匀强场 of equally spaced parallel lines.



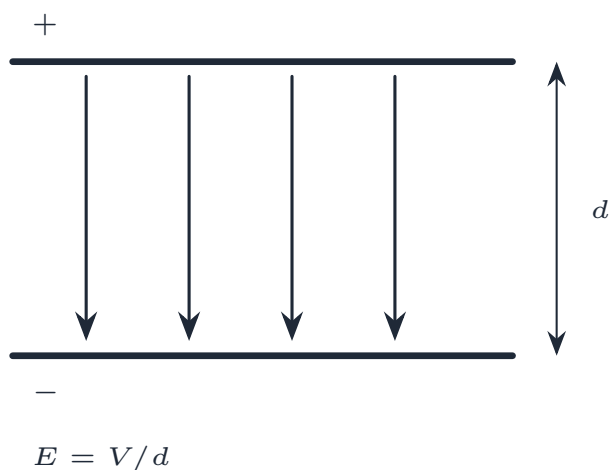
Field-line patterns for parallel plates, a dipole, a point charge, and a charged sphere above an earthed plate



A Van de Graaff generator stores a large static charge on its metal dome, making a strong electric field around it

Uniform electric fields

Between two parallel plates a distance d apart with **potential difference** 电势差 V between them, the field is uniform (apart from edge effects) with size



Between parallel plates the field is uniform, $E = V/d$

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

It points from the higher-potential plate to the lower one. The unit V m^{-1} comes straight from this and equals N C^{-1} .

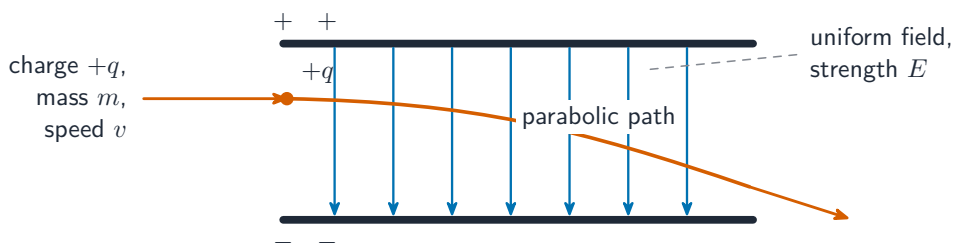
Worked example. Two parallel plates 5.0 mm apart have a p.d. of 200 V between them. Find the field strength, and the force on an electron in the gap. ($e = 1.6 \times 10^{-19} \text{ C}$.)

$$E = \frac{V}{d} = \frac{200}{5.0 \times 10^{-3}} = 4.0 \times 10^4 \text{ V m}^{-1}, \quad F = qE = (1.6 \times 10^{-19})(4.0 \times 10^4) = 6.4 \times 10^{-15} \text{ N}.$$

A charged particle in a uniform field

A charge q in a uniform field feels a **constant force** $F = qE$, so a **constant acceleration** $a = qE/m$ — just like a mass in a uniform gravitational field.

- released **at rest**, it speeds up along the field (positive charge) or against it (negative charge), gaining **kinetic energy** 动能.
- entering **at right angles** to the field, it follows a **parabolic** 抛物线 path — like a **projectile** 抛体 in gravity. This is how a **cathode-ray tube** 阴极射线管 used to steer its beam.



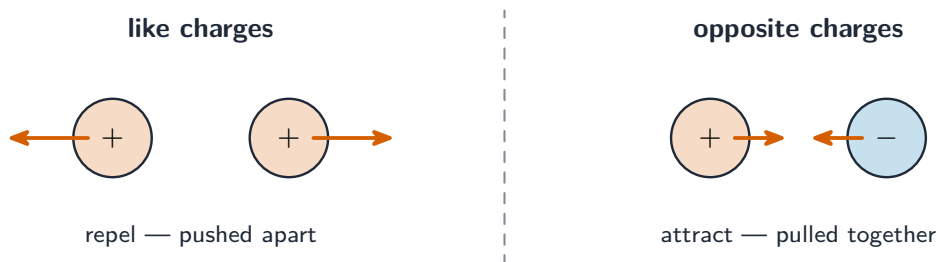
A charge entering a uniform field at right angles follows a parabolic path, like a projectile

Coulomb's law

For two point charges Q_1 and Q_2 a distance r apart in free space, each feels a force of size

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}.$$

This is **Coulomb's law** 库仑定律. Here $\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$ is the **permittivity of free space** 真空电容率, and $1/(4\pi\epsilon_0) \approx 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$. The force is along the line joining the charges: **repulsive** for like charges, **attractive** for opposite charges.



Like charges repel; opposite charges attract — the force is along the line joining them

Worked example. Find the electrostatic force between point charges of $+2.0 \text{ nC}$ and $+3.0 \text{ nC}$ placed 4.0 cm apart. ($1/(4\pi\epsilon_0) = 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$.)

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} = \frac{(9.0 \times 10^9)(2.0 \times 10^{-9})(3.0 \times 10^{-9})}{(0.040)^2} \approx 3.4 \times 10^{-5} \text{ N (repulsive)}.$$

Spheres treated as point charges

A spherical **conductor** 导体 with total charge Q gives, at any point **outside**, the same field as a point charge Q at its centre (measure r from the centre). **Inside** a hollow charged conductor the field is zero, so the conductor is an **equipotential** 等势面.

Electric field due to a point charge

Coulomb's law gives the force between **two** charges. Divide it by the test charge ($E = F/q$) and you are left with the field of the source charge Q **alone**. The field at distance r from a point charge Q is

$$E = \frac{Q}{4\pi\epsilon_0 r^2}.$$

It points out from a positive Q , in towards a negative Q , and falls as $1/r^2$ — just like **gravitational field** 重力场 strength, except gravity is always attractive. For several charges, add the fields as a **vector sum** 矢量和.

Electric potential

Electric potential 电势 V at a point is the **work done per unit positive charge** in bringing a small positive test charge from **infinity** 无穷远 to that point:

$$V = \frac{W}{q}.$$

Unit: V. The potential is **zero at infinity**. For a positive source charge $V > 0$ everywhere outside; for a negative source charge $V < 0$.

Potential due to a point charge

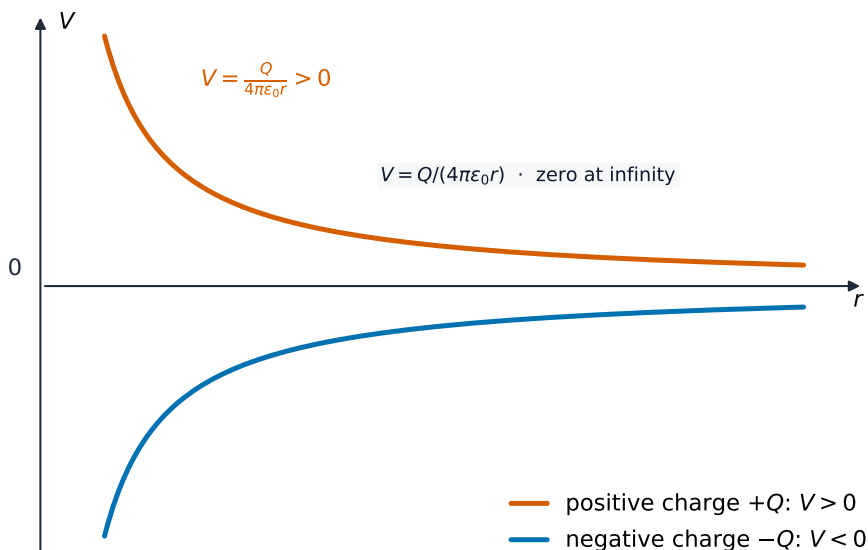
$$V = \frac{Q}{4\pi\epsilon_0 r}.$$

Note the $1/r$ here (compared with $1/r^2$ for the field). V is a **scalar** 标量; for several charges, add the potentials (with sign).

Worked example. Find the electric potential 4.0 cm from a point charge of +3.0 nC. ($1/(4\pi\epsilon_0) = 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$.)

$$V = \frac{Q}{4\pi\epsilon_0 r} = \frac{(9.0 \times 10^9)(3.0 \times 10^{-9})}{0.040} \approx 6.8 \times 10^2 \text{ V}.$$

Because potential is a scalar, the potential from several charges is simply their sum (each with its own sign) — no directions to resolve.



The potential near a point charge varies as $1/r$ — positive for a positive charge, negative for a negative one

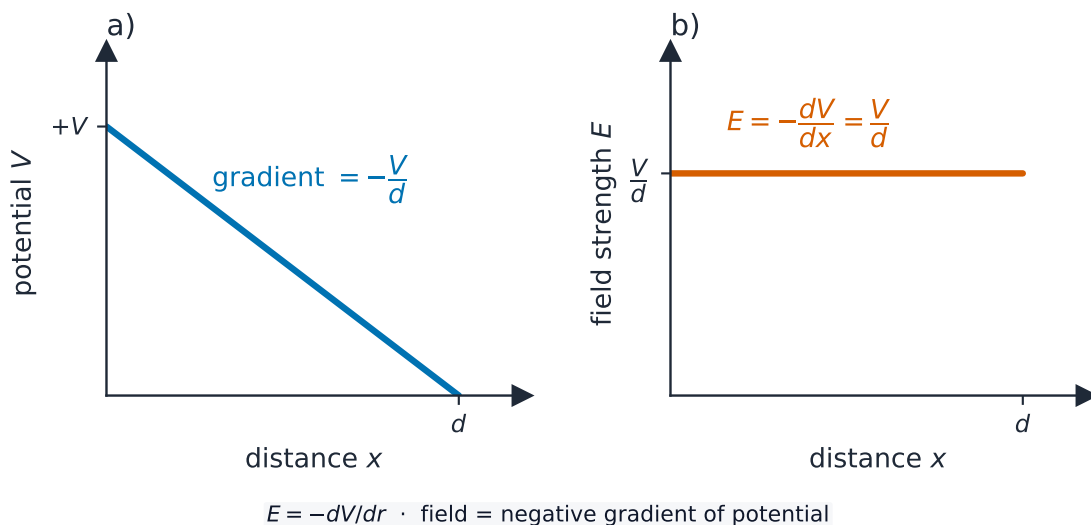
Link between field and potential

The field equals the **negative potential gradient** 电势梯度:

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

Between parallel plates V changes evenly with position, giving $E = V/d$ as before. The minus sign means the field points towards **lower** potential. For a point charge,

$$-\frac{dV}{dr} = \frac{Q}{4\pi\epsilon_0 r^2} = E.$$



In a uniform field the potential falls steadily with distance, so the field strength V/d is constant

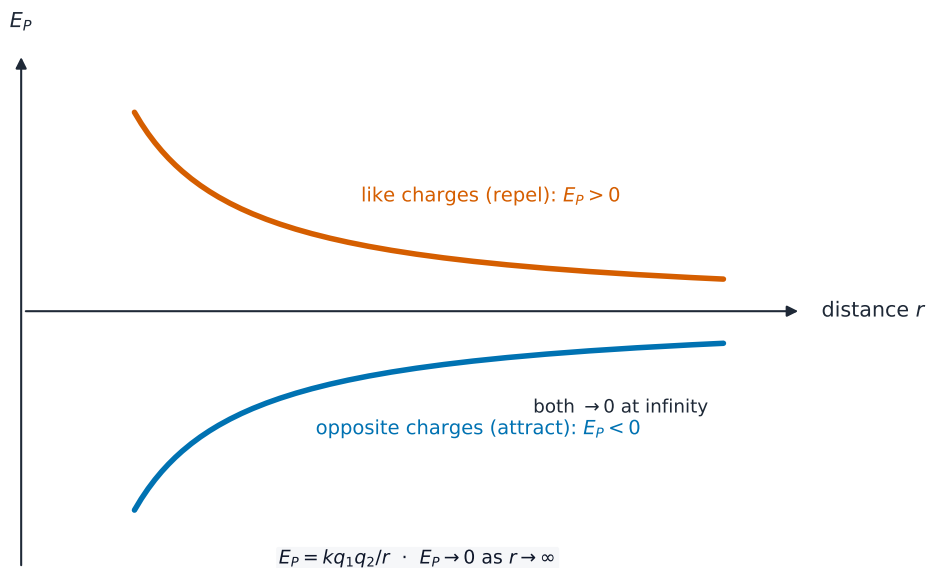
Electric potential energy

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

$$E_P = \frac{Qq}{4\pi\epsilon_0 r}.$$

- **like** charges: $E_P > 0$ — stored energy that would be released if they flew apart.
- **opposite** charges: $E_P < 0$ — a **bound** 束缚 system; energy must be supplied to separate them.

In both cases $E_P \rightarrow 0$ as $r \rightarrow \infty$.



Electric PE of two charges: positive for like charges, a negative well for opposite charges

Worked-example pattern

An **electron** 电子 orbits a **nucleus** 原子核 of charge $+Ze$ at distance r . The Coulomb attraction provides the **centripetal force** 向心力:

$$\frac{Ze^2}{4\pi\epsilon_0 r^2} = \frac{m_e v^2}{r}, \quad v = \sqrt{\frac{Ze^2}{4\pi\epsilon_0 m_e r}}.$$

The total energy is kinetic plus potential:

$$E_{\text{total}} = \frac{1}{2}m_e v^2 - \frac{Ze^2}{4\pi\epsilon_0 r} = -\frac{Ze^2}{8\pi\epsilon_0 r},$$

which is negative (a bound state).

Gravitational versus electric

The two field theories look alike:

Quantity	Gravitational	Electric
Source	mass M (always positive)	charge Q (can be $\pm$)
Field strength	$g = GM/r^2$	$E = Q/(4\pi\epsilon_0 r^2)$
Force on test object	$F = mg$	$F = qE$
Potential	$\phi = -GM/r$	$V = Q/(4\pi\epsilon_0 r)$
PE of two	$-GMm/r$	$Qq/(4\pi\epsilon_0 r)$
Nature	always attractive	attractive or repulsive

The minus sign in the **gravitational potential** 引力势 reflects that gravity is always attractive; the electric potential takes the sign of the source charge.

Exam tips

- **Coulomb's law** $F = Q_1 Q_2 / 4\pi\epsilon_0 r^2$ (inverse-square, but can attract or repel).
- Distinguish a **uniform field** ($E = V/d$, between plates) from a **radial field** ($E = Q/4\pi\epsilon_0 r^2$).
- Electric potential $V = Q/4\pi\epsilon_0 r$ (sign follows the charge); the field points from high to low potential.