Module 6 Particles & Medical Physics

Module 6: Particles and medical physics

In this module, learners will learn about capacitors, electric field, electromagnetism, nuclear physics, particle physics and medical imaging.

Module 6 Particles & Medical Physics

Unit 2 Electric Fields

6.2 Electric fields

This section provides knowledge and understanding of Coulomb's law, uniform electric fields, electric potential and energy.

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics

5.2 Circular motion

5.3 Oscillations

5.4 Gravitational fields

5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors

You are here! → 6.2 Electric fields

6.3 Electromagnetism

6.4 Nuclear and particle physics

6.5 Medical imaging

6.2 Electric Fields

- 6.2.1 Point & Spherical Charges
- 6.2.2 Coulomb's Law
- 6.2.3 Uniform Electric Field
- 6.2.4 Electric Potential & Energy

6.2.1 Point & Spherical Charges

6.2.1 Point and spherical charges

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) electric fields are due to charges

(b) modelling a uniformly charged sphere as a point charge at its centre

(c) electric field lines to map electric fields

(d) electric field strength; $E = \dfrac{F}{Q}$.

<u>Fields.</u>

So not the things that cows live in, then?

Fields

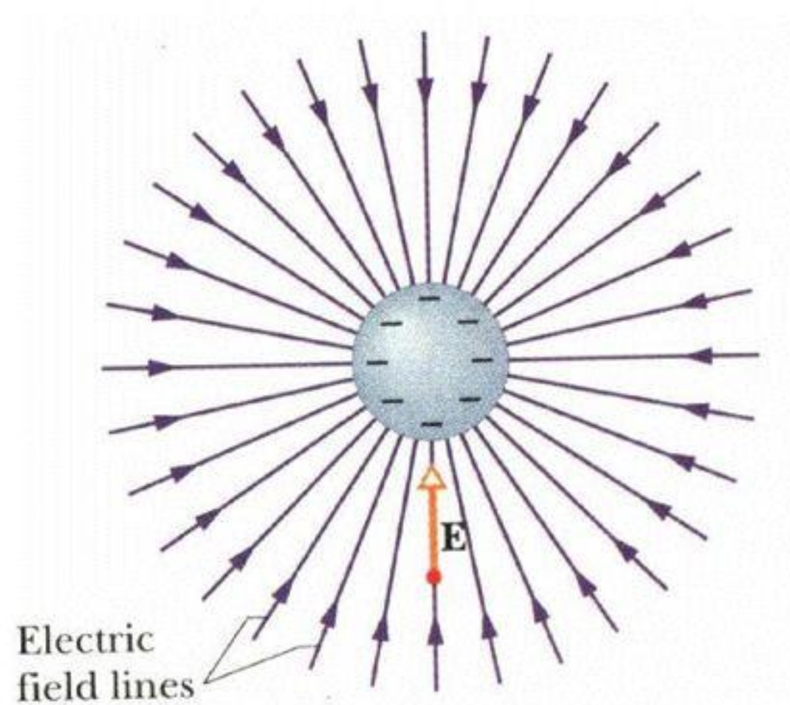
- A field is a region in which a certain type of object will experience a force at a distance.

- An electric (electrostatic) field is the region around a charged object. Other charged objects experience forces when placed into an electric field.

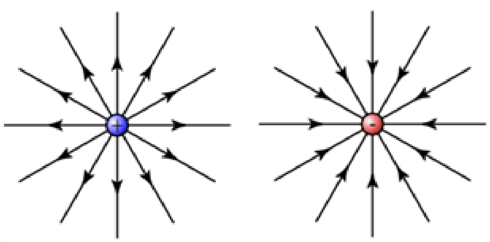
Electric Field Lines

- Field lines: useful way to visualize electric field E
- Field lines start at a positive charge, end at negative charge
- E at any point in space is tangential to field line
- Field lines are closer where E is stronger
- Field lines are always at right angles to a charged surface

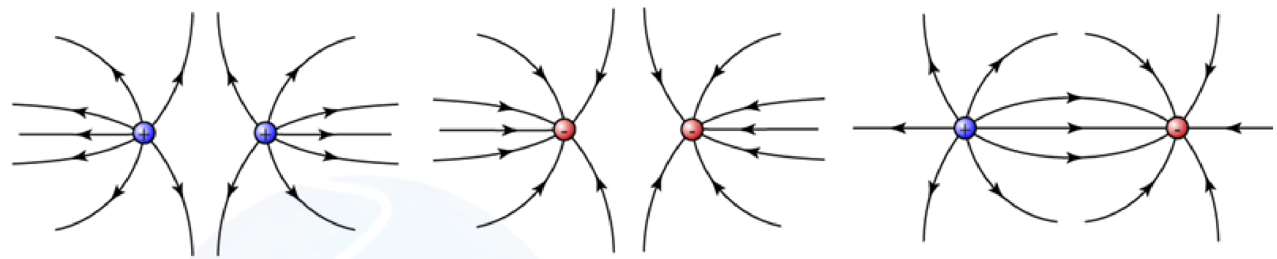
Example: a negative point charge — note spherical symmetry



Some electric field patterns



Field pattern of
a pointed electrode



Field pattern of
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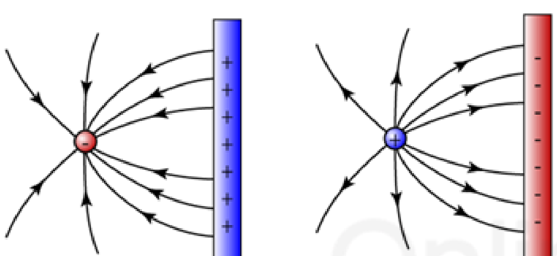
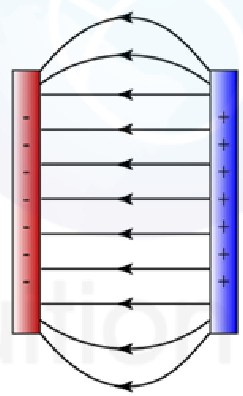
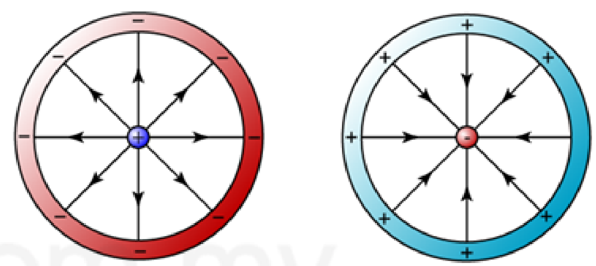


Field pattern of
a pointed electrode
and a plane electrode



Field pattern of
two plane electrodes



Field pattern of
a pointed electrode
and a ring electrode

Electric Field Strength

- Electric Field Strength, E, is the force experienced per unit positive charge at a point in space.

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

Units of E are: Newtons per Coulomb, NC^{-1}

- E is a vector quantity.
  - The direction of the field is the direction a positive charge would move if placed at that point in the field.
  - Electric fields point towards negative charges and away from positive charges.

6.2.1 Point & Spherical Charges (review)

6.2.1 Point and spherical charges

Learning outcomes

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(a) electric fields are due to charges

(b) modelling a uniformly charged sphere as a point charge at its centre

(c) electric field lines to map electric fields

(d) electric field strength; $E = \dfrac{F}{Q}$.

What is Coulomb’s Law

6.2.2 Coulomb's Law

6.2.2 Coulomb's law

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Coulomb's law; $F = \frac{Qq}{4\pi\varepsilon_0 r^2}$ for the force between two point charges

(b) electric field strength $E = \frac{Q}{4\pi\varepsilon_0 r^2}$ for a point charge

(c) similarities and differences between the gravitational field of a point mass and the electric field of a point charge

(d) the concept of electric fields as being one of a number of forms of field giving rise to a force.

Coulomb's Law

Any two point charges exert an electrostatic force on each other which is directly proportional to the product of both charges and inversely proportional to the square of the distance between them.

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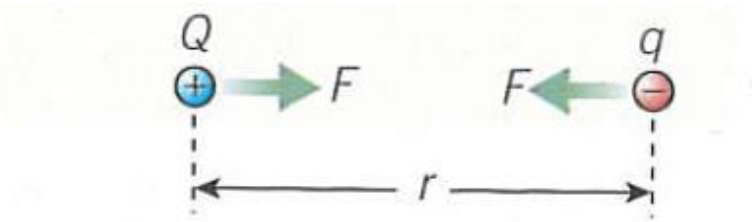
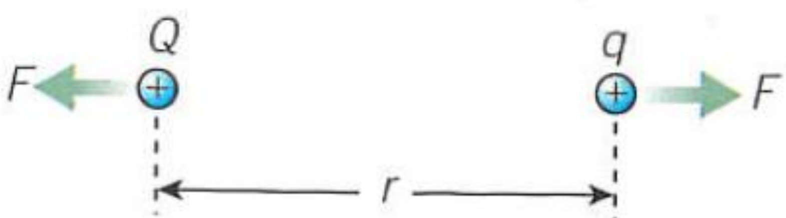


a *unlike charges attract*

$$F \propto Qq \qquad F \propto \frac{1}{r^2}$$



b *like charges repel*

$$F = k\frac{Qq}{r^2}$$

So what is k?

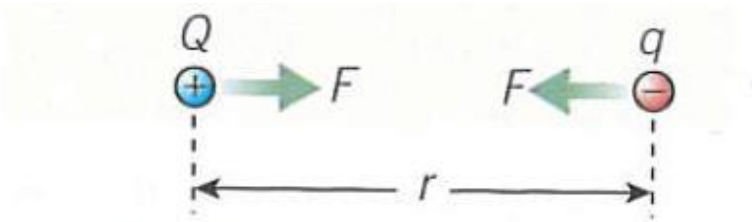
$$k = \frac{1}{4\pi\varepsilon_0}$$

- Where, ε_0 is the permittivity of free space.

- Permittivity is the ability of a substance to store electrical charge.
  - Units are Fm^{-1}
  - Permittivity of free space (vacuum) is $8.85 \times 10^{-12} Fm^{-1}$

Coulomb's Law

Any two point charges exert an electrostatic force on each other which is directly proportional to the product of both charges and inversely proportional to the square of the distance between them.



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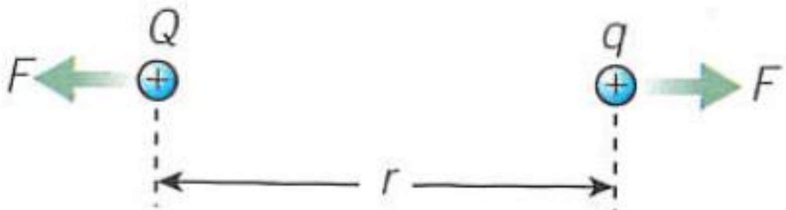


b *like charges repel*

$$F \propto Qq \qquad F \propto \frac{1}{r^2}$$

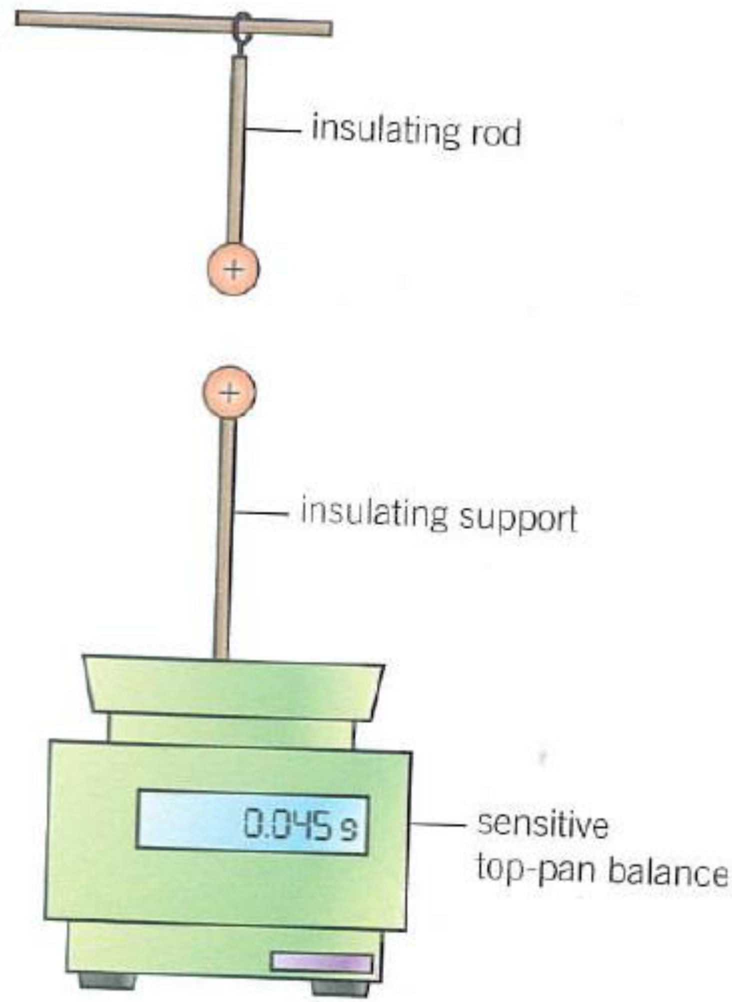
$$F = k\frac{Qq}{r^2}$$

$$F = \frac{Qq}{4\pi\varepsilon_0\, r^2}$$

How could we investigate Coulomb's Law?

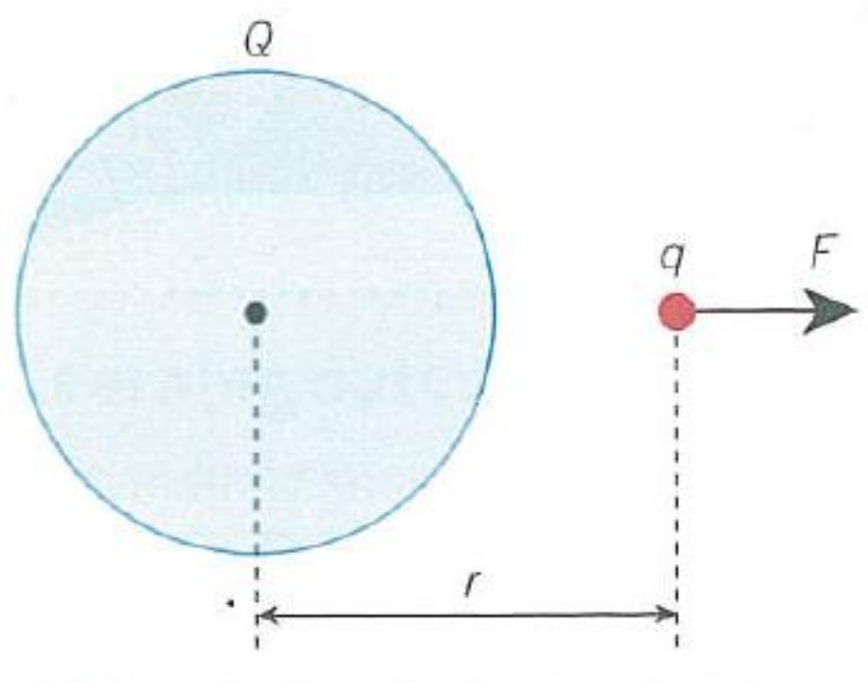
- Coulomb's Law can apply to large uniformly charged objects as though they are point charges.
  - Note: the separation, r, must be taken from the centres of the charged spheres.

How will the balance reading change as the two balls get closer together?



Electric Field Strength

- If: $$F = \frac{Qq}{4\pi\varepsilon_0\ r^2}$$
- And: $$E = \frac{F}{q}$$
- Then: $$E = \frac{Q}{4\pi\varepsilon_0\ r^2}$$



- So: The electric field strength, E, is directly proportional to the charge, Q, and follows the inverse square law with distance, r. Where have we heard that before?

Be careful!!

	Gravitational field	Electric field
property that creates the field	mass	charge
type of field produced	always attractive (direction of field always towards object)	positive point charges produce a repulsive field (direction of field away from object, repels a positive charge) negative point charges produce an attractive field (direction of field towards object, attracts a positive charge)
field strength	gravitational field strength is the force per unit mass $g = \frac{F}{m}$	electric field strength is the force per unit positive charge $E = \frac{F}{Q}$
force between particles	force $\propto$ product of masses force $\propto \frac{1}{\text{separation}^2}$	force $\propto$ product of charges force $\propto \frac{1}{\text{separation}^2}$
force and field strength equations	$F = -\frac{GMm}{r^2}$ $g = -\frac{GM}{r^2}$	$F = \frac{Qq}{4\pi\varepsilon_0 r^2}$ $E = \frac{Q}{4\pi\varepsilon_0 r^2}$
type of field	point masses produce a radial field	point charges produce a radial field

6.2.2 Coulomb's Law (review)

6.2.2 Coulomb's law

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Coulomb's law; $F = \dfrac{Qq}{4\pi\varepsilon_0 r^2}$ for the force between two point charges

(b) electric field strength $E = \dfrac{Q}{4\pi\varepsilon_0 r^2}$ for a point charge

(c) similarities and differences between the gravitational field of a point mass and the electric field of a point charge

(d) the concept of electric fields as being one of a number of forms of field giving rise to a force.

6.2.3 Uniform electric Field

6.2.3 Uniform electric field

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) uniform electric field strength; $E = \frac{V}{d}$

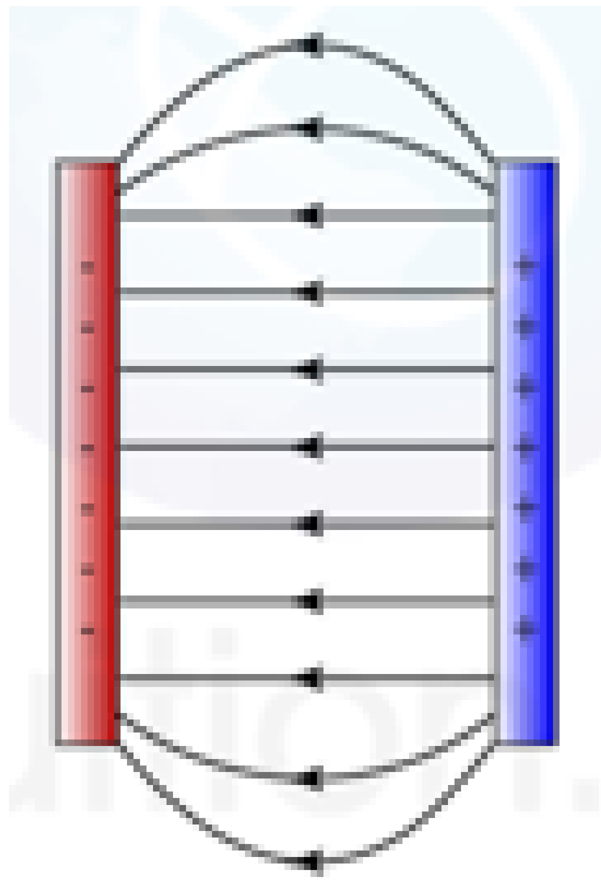
(b) parallel plate capacitor; permittivity;
$C = \frac{\varepsilon_0 A}{d}$; $C = \frac{\varepsilon A}{d}$; $\varepsilon = \varepsilon_r \varepsilon_0$

(c) motion of charged particles in a uniform electric field.

Can we calculate the Electric Field Strength of a uniform field?

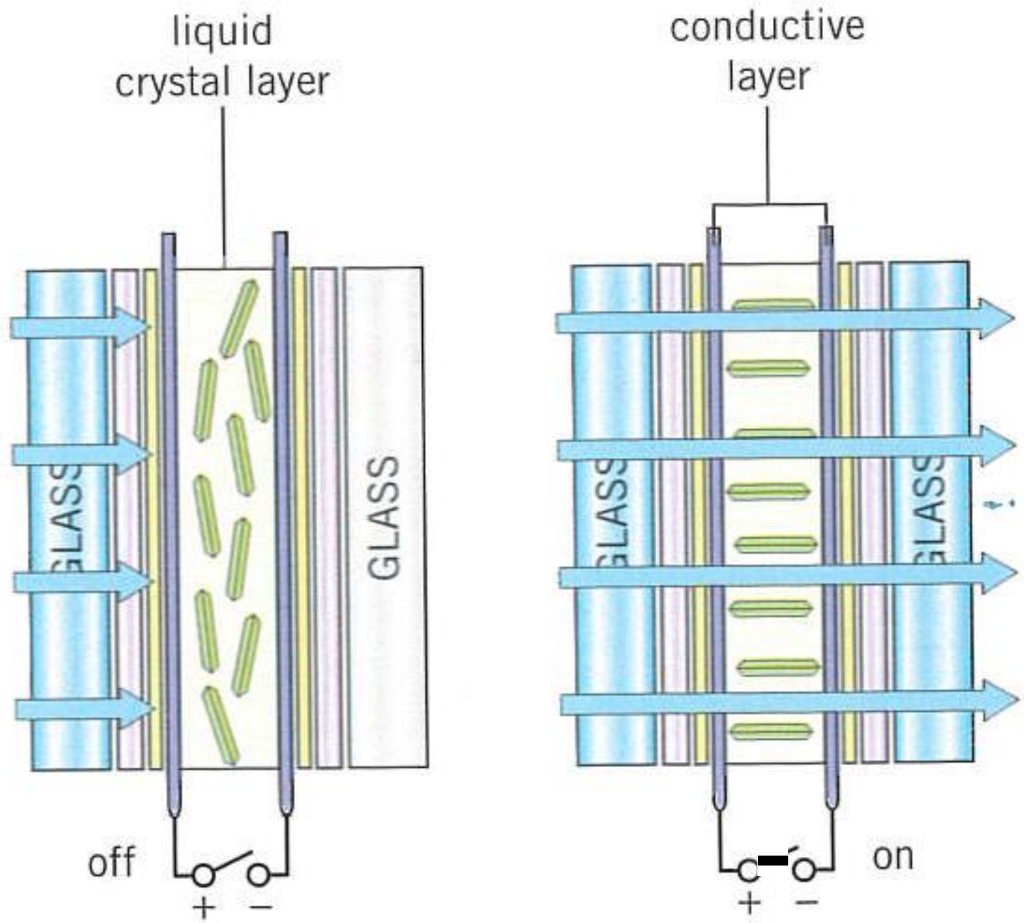
Remember the uniform electric field shape between two plates?

- Draw it.

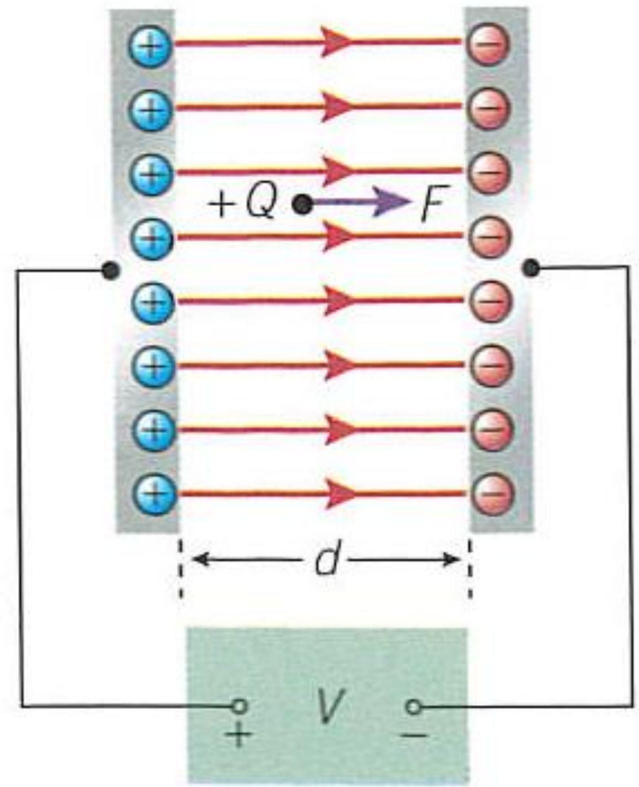


Liquid Crystal Displays use Uniform Fields across two plates

- When the electric field is applied, crystals align allowing light to pass through.
- With the field removed, crystals are randomised and light cannot pass.



Electric Field Strength, E



- A charge, Q, experiences a force, F, between the plates with potential difference, V, and separation, d.

W=Fd

$$F = EQ$$

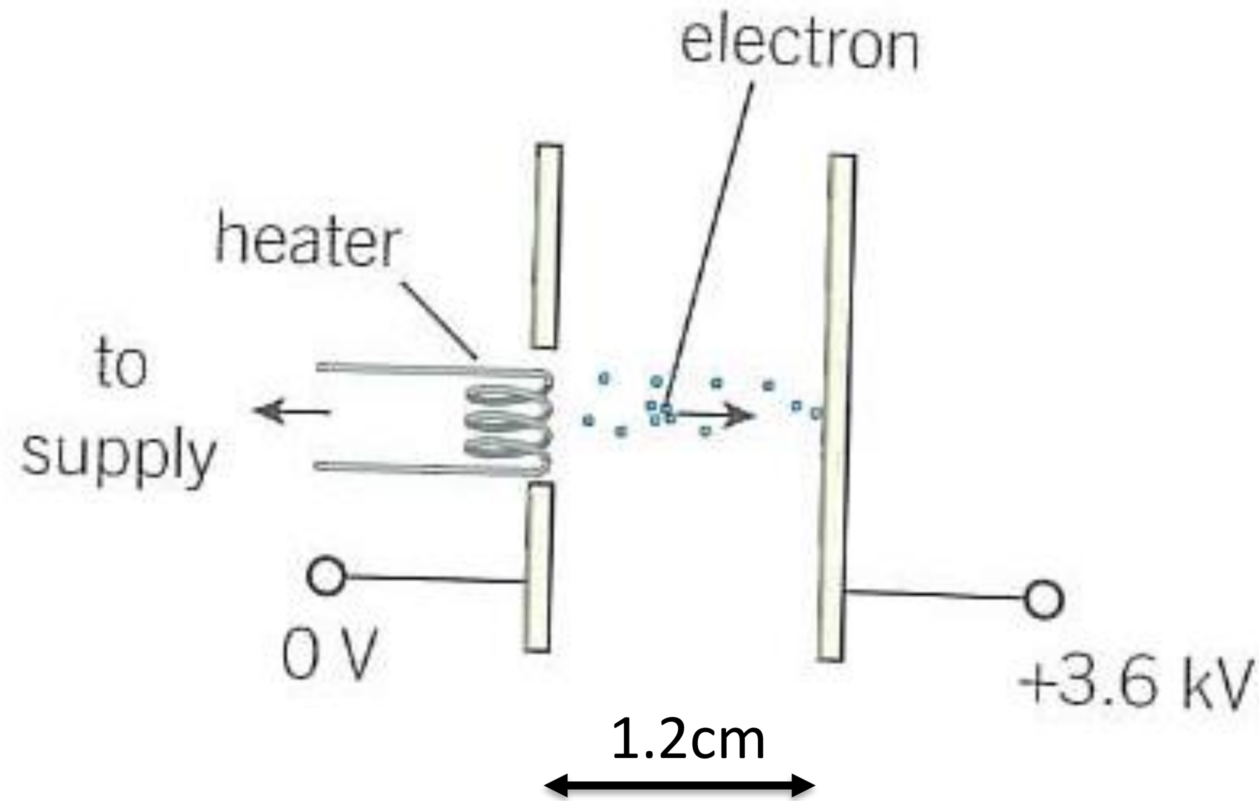
VQ=EQd

V=Ed

$$V = \frac{W}{Q} \Rightarrow W = VQ$$

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

What is the acceleration of the electron?

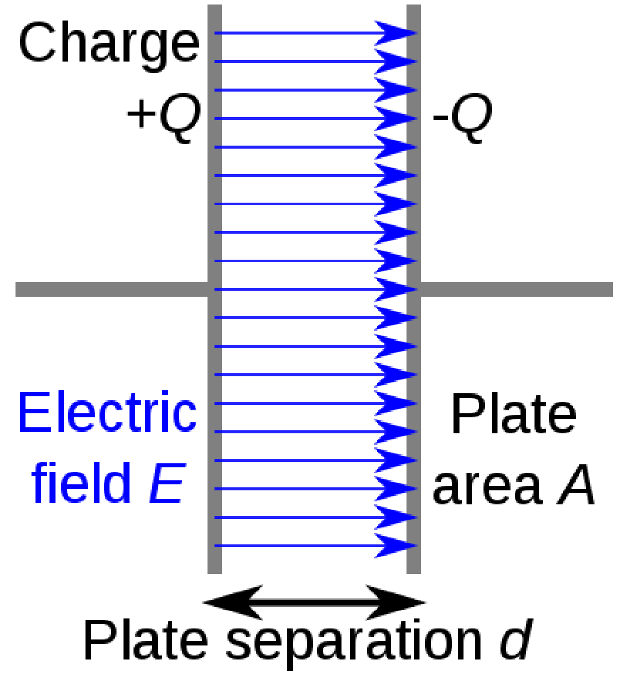


Uniform Fields & Capacitance

- The capacitance depends on the Separation, Area of overlap & the insulating properties of the dielectric between the plates.

$$C \propto \frac{A}{d}$$

For an air gap (or vacuum) the constant is the permittivity of free space



$$C = \frac{\varepsilon_0 A}{d}$$

Permitivity = the ability of a substance to store electrical charge

- Sometimes the insulator is something other than air.

- In these cases we multiply the permittivity of free space by the relative permittivity of the insulator to give us the overall permittivity of the insulating substance:

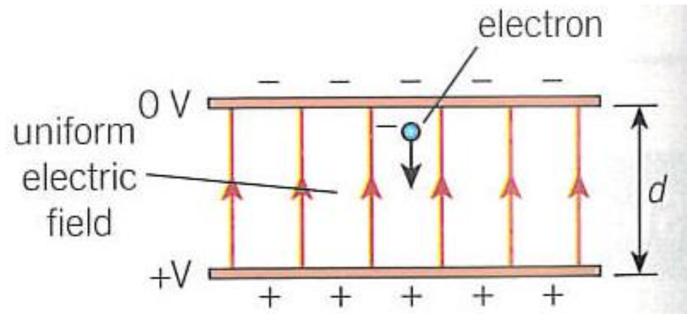
$$\varepsilon = \varepsilon_r \varepsilon_0$$

$$C = \frac{\varepsilon A}{d}$$

Material	ε_r
vacuum	1 (by definition)
air	1.0006
perspex	3.3
paper	4.0
mica	7.0
barium titanate	1200

How do charged particles behave in a uniform electric field?

Calculate the acceleration of the electron



▲ **Figure 2** *The electron is accelerated by the electric field as it travels towards the positive plate*

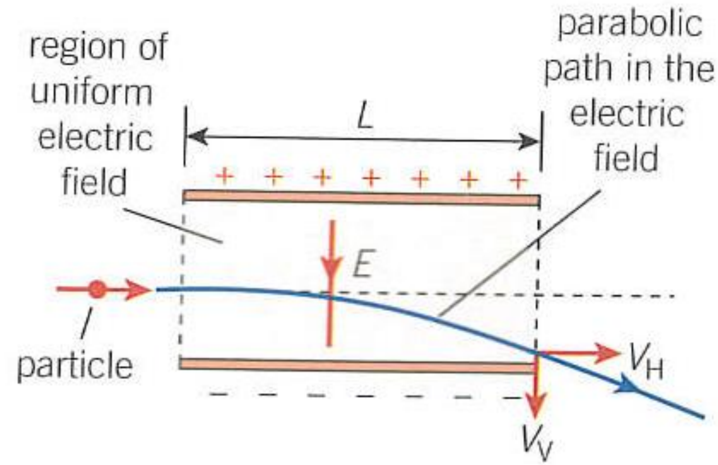
- The force on the electron is constant in a uniform electric field.
- So acceleration will be constant.
  - You could use SUVAT
- Remember these equations:

$$W = VQ$$

$$F = EQ$$

$$F = ma \qquad E = \frac{V}{d}$$

Charged particles moving at right angles to the uniform field



▲ **Figure 4** *A charged particle is deflected by an electric field*

- Vertical motion & horizontal motion can be described separately.
- With this example:
  - Horizontally:
    - No acceleration.
    - So v_h remains constant.
    - And time, $t = L/v_h$
  - Vertically:
    - Acceleration, a = F/m
    - Initial velocity, u = 0
    - Final velocity, v = u + at

$$a = \frac{F}{m} = \frac{EQ}{m}$$

$$v_v = 0 + \frac{EQ}{m} \times \frac{L}{v_h} = \frac{EQL}{mv_h}$$

6.2.3 Uniform Electric Field (review)

6.2.3 Uniform electric field

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) uniform electric field strength; $E = \dfrac{V}{d}$

(b) parallel plate capacitor; permittivity;
$C = \dfrac{\varepsilon_0 A}{d}$; $C = \dfrac{\varepsilon A}{d}$; $\varepsilon = \varepsilon_r \varepsilon_0$

(c) motion of charged particles in a uniform electric field.

6.2.4 Electric Potential & Energy

6.2.4 Electric potential and energy

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) electric potential at a point as the work done in bringing unit charge from infinity to the point; electric potential is zero at infinity

(b) electric potential $V = \dfrac{Q}{4\pi\varepsilon_0 r}$ at a distance r from a point charge; changes in electric potential

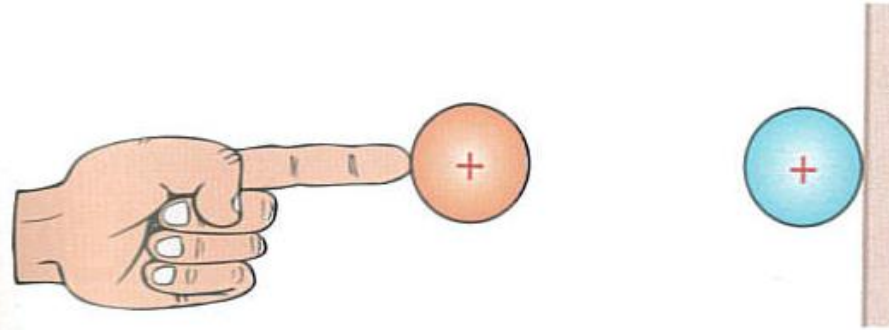
(c) capacitance $C = 4\pi\varepsilon_0 R$ for an isolated sphere

(d) force–distance graph for a point or spherical charge; work done is area under graph

(e) electric potential energy $E = Vq = \dfrac{Qq}{4\pi\varepsilon_0 r}$ at a distance r from a point charge Q.

Just like elastic & gravitational, is there an electric potential energy?

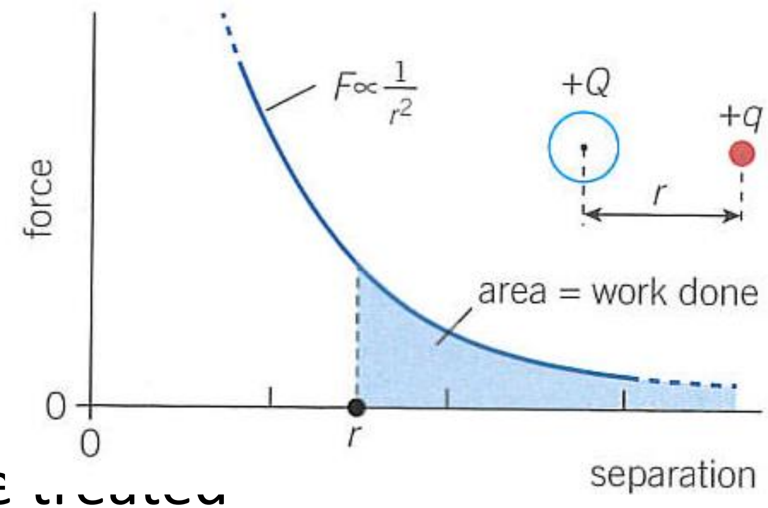
Elastic Potential Energy



▲ Figure 1 *Work must be done to bring these positive charges close together*

- Charged particles can store energy.
- Here the two charges repel so work must be done to bring them together.
  - You have to push harder the closer they get.
  - To release the stored electrical potential energy, just let go.

Force-Distance graphs for $+^{ve}$ charged particles



- Charged spheres & points can be treated equally.
- We have already seen how the force varies with separation in Coulombs' Law:

$$F = \frac{Qq}{4\pi\varepsilon_0\, r^2}$$

- Work done (or energy) = Fd
  - Where d = r, so:

$$E = \frac{Qq}{4\pi\varepsilon_0\, r}$$

- The work done to bring the particles from a separation of infinity to r is the shown by the shaded region under the graph.

Swapping the Charge

- If one of the particles is negative:
  - Force between them will be attractive rather than repulsive.
  - F will be negative
  - The value for E will be negative

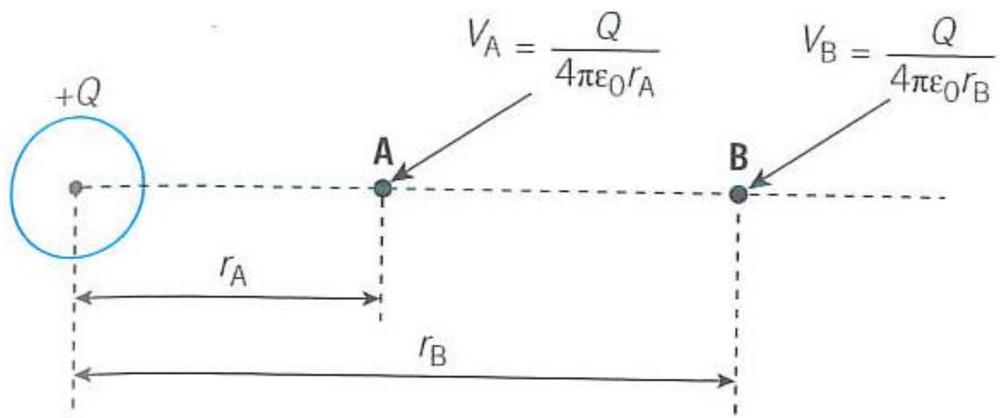
  - E will now represent the energy required to separate the two particles from where they are to infinity.

Electrical Potential, V

- Definition:
  - The work done per unit charge in bringing a positive charge from infinity to that point.

$$V = \frac{E}{q} = \frac{Qq}{4\pi\varepsilon_0 rq} = \frac{Q}{4\pi\varepsilon_0 r}$$

  - The unit for electrical potential is the volt (JC^{-1})
  - Potential Difference is the difference in electrical potential between two points around the particle of charge, Q.



Capacitance of a Sphere

- A capacitor stores charge across its plates remember.
- What if one of the "plates" were a sphere of radius, R?
  - It could still store charge.
- Therefore:

$$C = \frac{Q}{V} = \frac{4\pi\varepsilon_0 RV}{V} = 4\pi\varepsilon_0 R$$

6.2.4 Electric Potential & Energy (review)

6.2.4 Electric potential and energy

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6.1 Capacitors

Complete! → 6.2 Electric fields

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