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7.4 Electric Fields

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

7.4 Electric Fields

CONTENTS

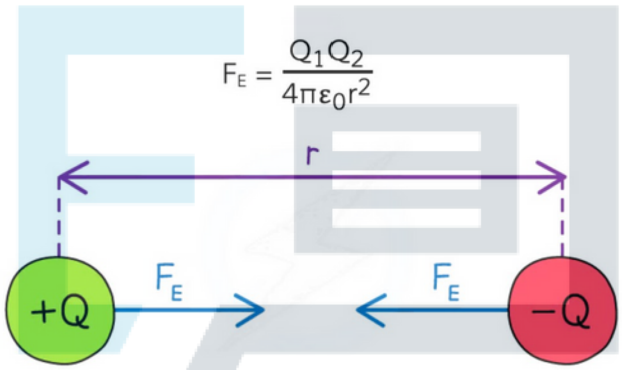
7.4.1 Coulomb's Law

Coulomb's Law

- All charged particles produce an electric field around it
  - This field exerts a force on any other charged particle within range
- The electrostatic force between two charges is defined by **Coulomb's Law**
  - Recall that the charge of a uniform spherical conductor can be considered as a point charge at its centre
- Coulomb's Law states that:

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

- The Coulomb equation is defined as:



The electrostatic force between two charges is defined by Coulomb's Law

- Where:
  - F_E = electrostatic force between two charges (N)
  - Q_1 and Q_2 = two point charges (C)
  - ε_0 = permittivity of free space
  - r = distance between the centre of the charges (m)

- The $1/r^2$ relation is called the inverse square law
  - This means that when the separation of two charges doubles, the electrostatic force between them reduces by $(½)^2 = ¼$
- ε_0 is a physical constant used to show the capability of a vacuum to permit electric fields

- If there is a positive and negative charge, then the electrostatic force is negative
  - This can be interpreted as an **attractive force**
- If the charges are the same, the electrostatic force is positive
  - This can be interpreted as a **repulsive force**

- Since uniformly charged spheres can be considered as point charges, Coulomb's law can be applied to find the electrostatic force between them as long as the separation is taken from the **centre** of both spheres

Worked Example

An alpha particle is situated 2.0 mm away from a gold nucleus in a vacuum. Assuming them to be point charges, calculate the magnitude of the electrostatic force acting on each of the charges.

Atomic number of helium = 2

Atomic number of gold = 79

Charge of an electron = 1.60×10^{-19} C

Step 1: Write down the known quantities

- Distance, r = 2.0 mm = 2.0×10^{-3} m

  The charge of one proton = $+1.60 \times 10^{-19}$ C

  An alpha particle (helium nucleus) has 2 protons

- Charge of alpha particle, $Q_1 = 2 \times 1.60 \times 10^{-19} = +3.2 \times 10^{-19}$ C

  The gold nucleus has 79 protons

- Charge of gold nucleus, $Q_2 = 79 \times 1.60 \times 10^{-19} = +1.264 \times 10^{-17}$ C

Step 2: The electrostatic force between two point charges is given by Coulomb's Law

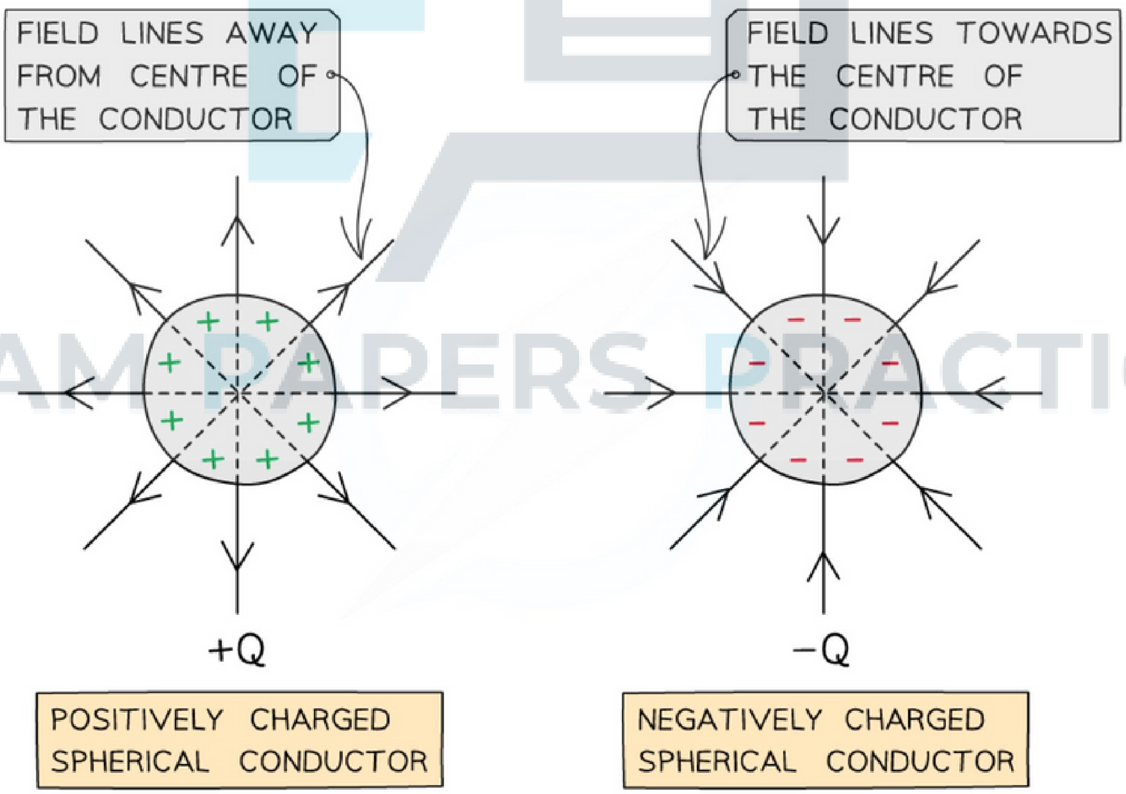
$$F_E = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

Step 3: Substitute values into Coulomb's Law

$$F_E = \frac{(3.2 \times 10^{-19}) \times (1.264 \times 10^{-17})}{(4\pi \times 8.85 \times 10^{-12}) \times (2.0 \times 10^{-3})^2} = 9.092.. \times 10^{-21} = \mathbf{9.1 \times 10^{-21}\ N}\ (2\ \text{s.f.})$$

Approximations of Coulomb's Law

- When calculating the force between two charges, air is treated as a **vacuum**
  - This is why ε_0, the permittivity of **free** space is used
- For a point outside a spherical conductor, the charge of the sphere may be considered to be a **point charge** at its centre
  - A **uniform** spherical conductor is one where its charge is **distributed evenly**
- The electric field lines around a spherical conductor are therefore **identical to those around a point charge**
  - An example of a spherical conductor is a **charged sphere**
- The field lines are **radial** and their direction depends on the charge of the sphere
  - If the spherical conductor is **positively** charged, the field lines are directed **away** from the centre of the sphere
  - If the spherical conductor is **negatively** charged, the field lines are directed **towards** the centre of the sphere



Electric field lines around a uniform spherical conductor are identical to those on a point charge

Exam Tip

You may have noticed that the electric fields share many similarities to the gravitational fields. The main difference being the gravitational force is always attractive, whilst electrostatic forces can be attractive **or** repulsive. You should make a list of all the similarities and differences you can find, as this could come up in an exam question.

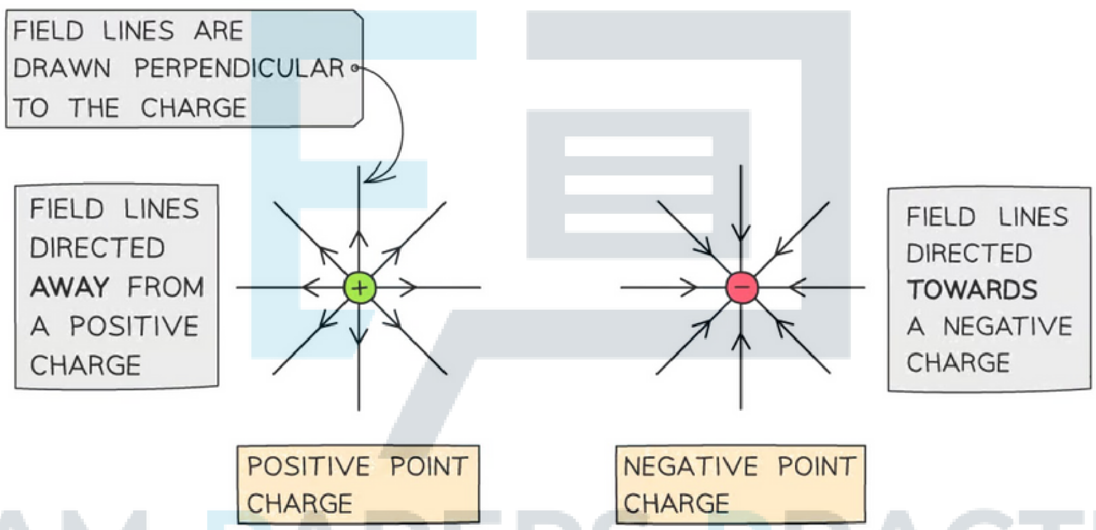
7.4.2 Electric Field Lines

Representing Electric Fields

- The direction of electric fields is represented by electric field lines
- Electric field lines are directed from positive to negative
  - Therefore, the field lines must be pointed **away** from the **positive** charge and **towards** the **negative** charge

- A radial field spreads uniformly to or from the charge in all directions
  - e.g. the field around a point charge or sphere

- Around a **point charge**, the electric field lines are directly radially inwards or outwards:
  - If the charge is **positive** (+), the field lines are radially **outwards**
  - If the charge is **negative** (-), the field lines are radially **inwards**



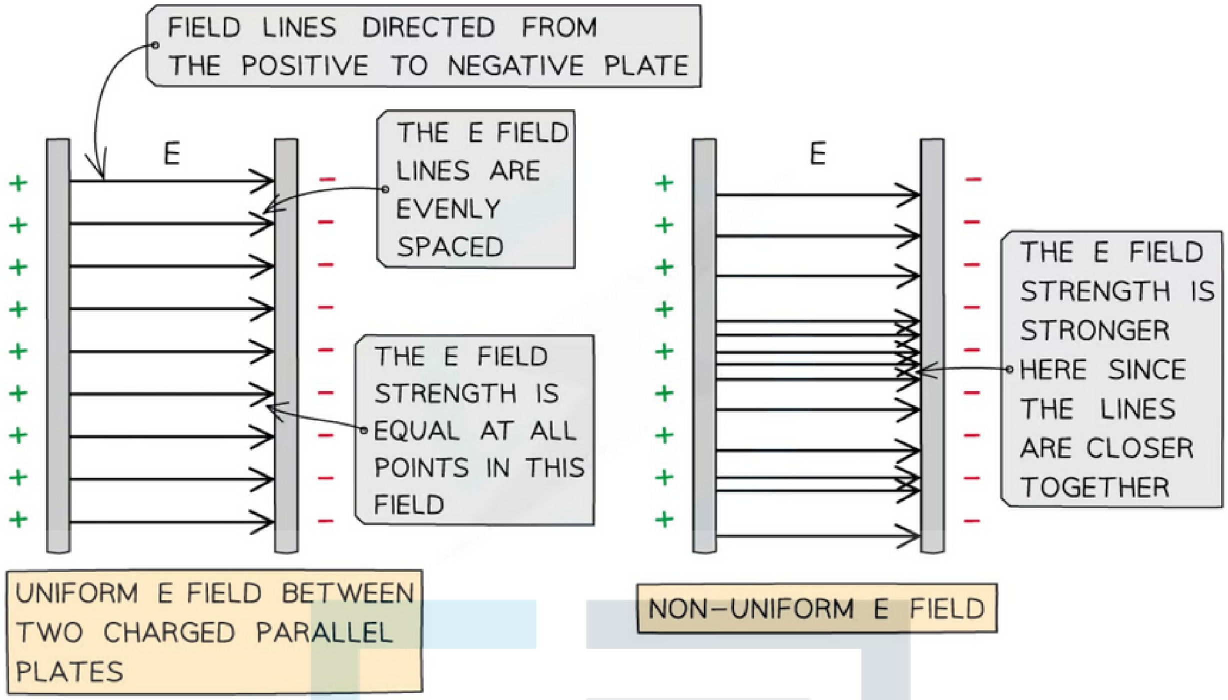
Electric field lines point away from a positive charge and point towards a negative charge

- This shares many similarities to radial gravitational field lines around a point mass
- Since gravity is only an attractive force, the field lines will look similar to the negative point charge, whilst electric field lines can be in either direction

- A uniform electric field has the same electric field strength throughout the field
  - For example, the field between oppositely charged parallel plates

- This is represented by **equally spaced** field lines
  - This shares many similarities to uniform gravitational field lines on the surface of a planet

- A **non-uniform** electric field has varying electric field strength throughout
- The strength of an electric field is determined by the spacing of the field lines:
  - A **stronger** field is represented by the field lines **closer** together
  - A **weaker** field is represented by the field lines **further** apart



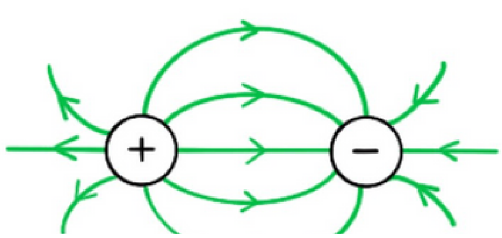
The electric field between two parallel plates is directed from the positive to the negative plate. A uniform E field has equally spaced field lines

- The electric field lines are directed from the **positive** to the **negative** plate
- A radial field is considered a **non-uniform** field
  - So, the electric field strength *E* is different depending on how far you are from a charged particle

Worked Example

Sketch the electric field lines between the two point charges in the diagram below.

- Electric field lines around point charges are radially outwards for positive charges and radially inwards for negative charges
- The field lines must be drawn with arrows **from the positive charge to the negative charge**



Exam Tip

Always label the arrows on the field lines! The lines must also touch the surface of the source charge or plates.

7.4.3 Electric Field Strength

Electric Field Strength Definition

- An electric field is a region of space in which an electric charge "feels" a force
- The **electric field strength** at a point is defined as:

The electrostatic force per unit positive charge acting on the charge at that point

- The electric field strength can be calculated using the equation:

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

- Where:
  - E = electric field strength ($N\ C^{-1}$)
  - F = electrostatic force on the charge (N)
  - Q = charge (C)

- It is important to use a positive test charge in this definition, as this determines the direction of the electric field
- The electric field strength is a **vector** quantity, it is always directed:
  - **Away** from a positive charge
  - **Towards** a negative charge
- Recall that **opposite charges** (positive and negative) charges **attract** each other
- Conversely, **like charges** (positive and positive or negative and negative) **repel** each other

Worked Example

A charged particle is in an electric field with electric field strength $3.5 \times 10^4\ N\ C^{-1}$ where it experiences a force of 0.3 N.

Calculate the charge of the particle.

Step 1: Write down the equation for electric field strength

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

Step 2: Rearrange for charge Q

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

Step 3: Substitute in values and calculate

$$Q = \frac{0.3}{3.5 \times 10^4} = 8.571 \times 10^{-6} = \mathbf{8.6 \times 10^{-6}\ C\ (2\ s.f)}$$

7.4.4 Uniform Electric Field

Uniform Electric Field Strength

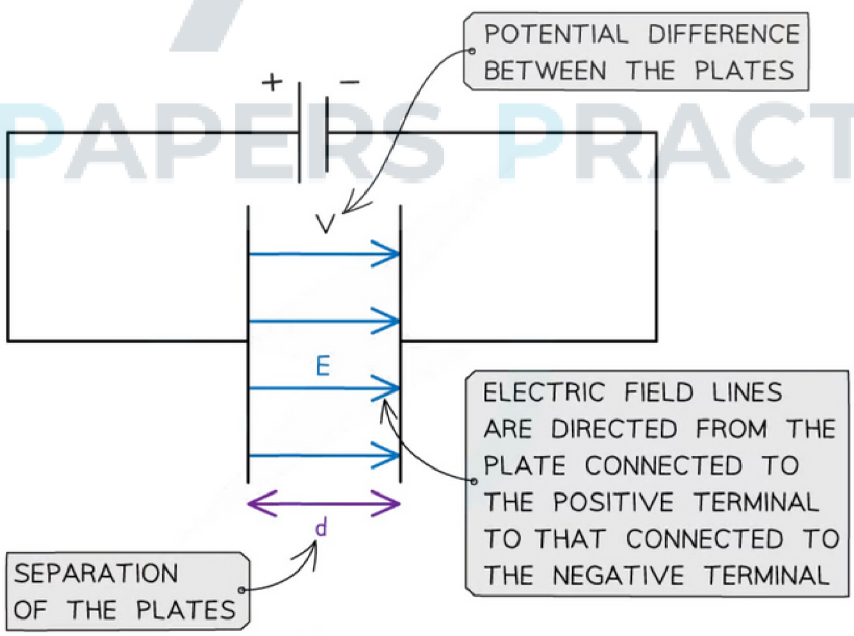
- The magnitude of the electric field strength in a **uniform** field between two charged parallel plates is defined as:

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

- Where:
  - E = electric field strength ($V\ m^{-1}$)
  - V = potential difference between the plates (V)
  - d = separation between the plates (m)

- **Note:** the electric field strength is now also defined by the units **$V\ m^{-1}$**
- The equation shows:
  - The greater the **voltage** between the plates, the **stronger** the field
  - The greater the **separation** between the plates, the **weaker** the field

- Remember this equation cannot be used to find the electric field strength around a point charge (since this would be a radial field)
- The direction of the electric field is from the plate connected to the **positive** terminal of the cell to the plate connected to the **negative** terminal



The E field strength between two charged parallel plates is the ratio of the potential difference and separation of the plates

- **Note**: if one of the parallel plates is **earthed**, it has a voltage of 0 V

Worked Example

Two parallel metal plates are separated by 3.5 cm and have a potential difference of 7.9 kV. Calculate the electric force acting on a stationary charged particle between the plates that has a charge of 2.6×10^{-15} C.

Step 1: Write down the known values

- Potential difference, $V = 7.9\text{ kV} = 7.9 \times 10^3$ V
- Distance between plates, $d = 3.5\text{ cm} = 3.5 \times 10^{-2}$ m
- Charge, $Q = 2.6 \times 10^{-15}$ C

Step 2: Calculate the electric field strength between the parallel plates

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

$$E = \frac{7.9 \times 10^3}{3.5 \times 10^{-2}} = 2.257 \times 10^5 \text{ V m}^{-1}$$

Step 3: Write out the equation for electric force on a charged particle

$$F = QE$$

Step 4: Substitute electric field strength and charge into electric force equation

$$F = QE = (2.6 \times 10^{-15}) \times (2.257 \times 10^5) = 5.87 \times 10^{-10}\text{ N} = 5.9 \times 10^{-10}\text{ N (2 s.f.)}$$

Exam Tip

Remember the equation for electric field strength with V and d is only used for **parallel plates**, and not for point charges (where you would use $E = F/Q$)

Derivation of Electric Field Strength Between Plates

- When two points in an electric field have a different potential, there is a **potential difference** between them
  - To move a charge across that potential difference, **work** needs to be done
  - Two parallel plates with a potential difference ΔV across them create a uniform electric field
- The electric field strength between the plates is given by the equations:

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

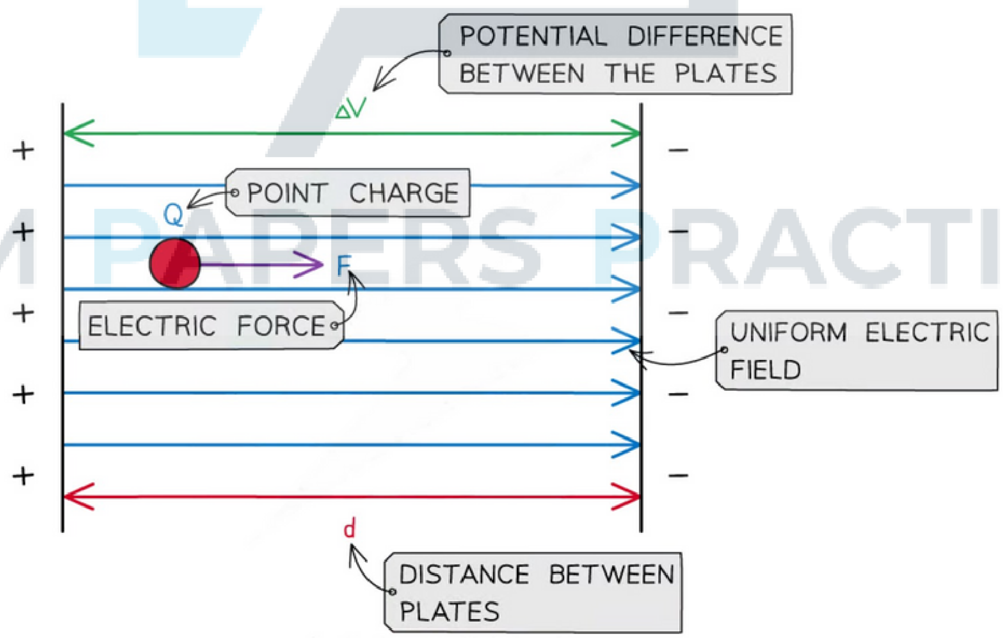
- Rearranging the fractions by multiplying by Q and *d* on both sides, gives:

$$Fd = \Delta VQ$$

- When a charge Q moves from one plate to the other, its work done is

$$W = Fd$$

- Where:
  - W = work done (J)
  - F = force (N)
  - d = distance (m)



The work done on the charge depends on the electric force and the distance between the plates

- Therefore, the work done in moving a charge Q through a potential difference ΔV between parallel plates is also given by:

$$W = \Delta VQ$$

Worked Example

Calculate the force needed to move an electron between two parallel plates 2 m apart with a potential difference of 400 V between them

Step 1: Rearrange the equations for E for the force F

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

$$F = \frac{\Delta VQ}{d}$$

Step 2: Substitute in the values

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

$\Delta V = 400$ V

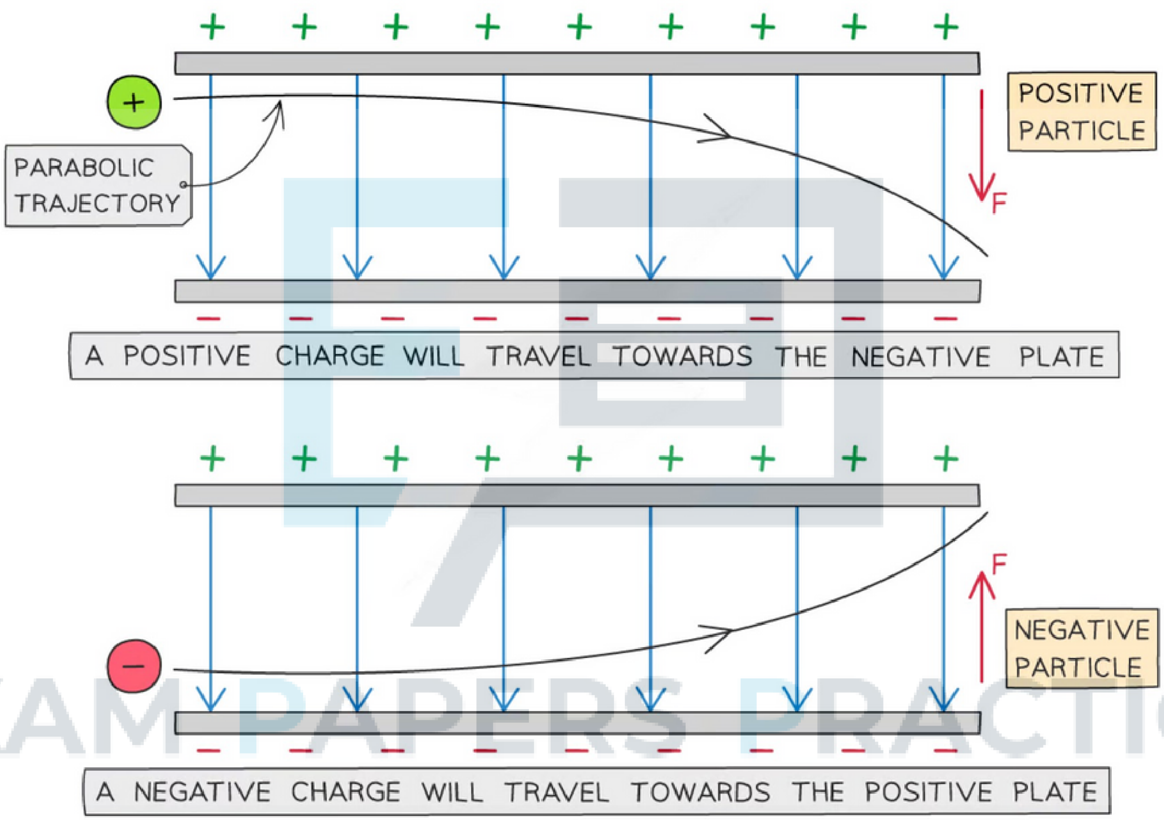
$d = 2$ m

$$F = \frac{400 \times (-1.60 \times 10^{-19})}{2} = -3.2 \times 10^{-17} \text{ N}$$

7.4.5 Motion of Charged Particles

Motion of Charged Particles in an Electric Field

- A charged particle in an electric field will experience a force on it that will cause it to move
- If a charged particle remains still in a uniform electric field, it will move parallel to the electric field lines (along or against the field lines depending on its charge)
- If a charged particle in **motion** travels initially **perpendicular** through a uniform electric field (e.g. between two charged parallel plates), it will experience a constant electric force and travel in a **parabolic trajectory**



The parabolic path of charged particles in a uniform electric field

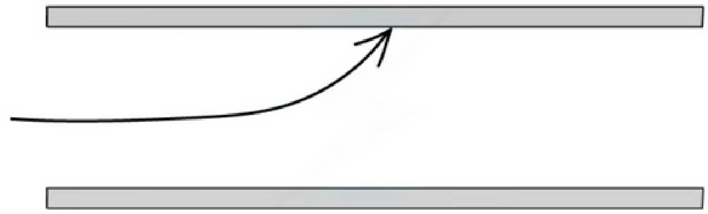
- The direction of the parabola will depend on the charge of the particle
  - A **positive** charge will be deflected towards the **negative** plate
  - A **negative** charge will be deflected towards the **positive** plate
- The force on the particle is the same at all points and is always in the same direction
- **Note:** an uncharged particle, such as a neutron experiences no force in an electric field and will therefore travel straight through the plates undeflected

- The amount of deflection depends on the following properties of the particles:
  - **Mass** – the greater the mass, the smaller the deflection and vice versa

- **Charge** – the greater the magnitude of the charge of the particle, the greater the deflection and vice versa
- **Speed** – the greater the speed of the particle, the smaller the deflection and vice versa

Worked Example

A single proton travelling with a constant horizontal velocity enters a uniform electric field between two parallel charged plates.The diagram shows the path taken by the proton.



Draw the path taken by a boron nucleus that enters the electric field at the same point and with the same velocity as the proton.Atomic number of boron = 5

Mass number of boron = 11

Step 1: Compare the charge of the boron nucleus to the proton

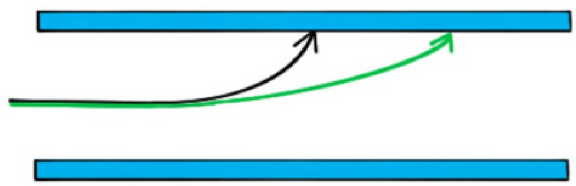
- Boron has 5 protons, meaning it has a charge 5 × greater than the proton
- The force on boron will therefore be 5 × greater than on the proton

Step 2: Compare the mass of the boron nucleus to the proton

- The boron nucleus has a mass of 11 nucleons meaning its mass is 11 × greater than the proton
- The boron nucleus will therefore be less deflected than the proton

Step 3: Draw the trajectory of the boron nucleus

- Since the mass comparison is much greater than the charge comparison, the boron nucleus will be **much less deflected** than the proton
- The nucleus is positively charged since the neutrons in the nucleus have no charge
  - Therefore, the shape of the path will be the same as the proton



7.4.6 Radial Electric Field

Electric Field of a Point Charge

- The electric field strength describes how strong or weak an electric field is at that point
- A point charge produces a **radial** field
    - A charge sphere also acts like a point charge
- The electric field strength *E* at a distance *r* due to a point charge Q in free space is defined by:

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

- Where:
    - Q = the point charge producing the radial electric field (C)
    - *r* = distance from the centre of the charge (m)
    - ε_0 = permittivity of free space (F m^{-1})
- This equation shows:
    - Electric field strength in a radial field is **not constant**
    - As the distance from the charge *r* increases, *E* decreases by a factor of $1/r^2$
- This is an inverse square law relationship with distance
    - This means the field strength *E* decreases by a factor of **four** when the distance *r* is **doubled**
- **Note:** this equation is only for the field strength around a **point charge** since it produces a radial field

- The electric field strength is a **vector** Its direction is the same as the electric field lines
    - If the charge is negative, the E field strength is negative and points **towards** the centre of the charge
    - If the charge is positive, the E field strength is positive and points **away** from the centre of the charge
- This equation is analogous to the gravitational field strength around a point mass

> **Worked Example**
>
> A metal sphere of diameter 15 cm is negatively charged. The electric field strength at the surface of the sphere is 1.5×10^5 V m^{-1}. Determine the total surface charge of the sphere.

Step 1: Write down the known values

Electric field strength, $E = 1.5 \times 10^5$ V m^{-1}

Radius of sphere, $r = 15 / 2 = 7.5$ cm $= 7.5 \times 10^{-2}$ m

Step 2: Write out the equation for electric field strength

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

Step 3: Rearrange for charge Q

$$Q = 4\pi\varepsilon_0 E r^2$$

Step 4: Substitute in values

$$Q = (4\pi \times 8.85 \times 10^{-12}) \times (1.5 \times 10^5) \times (7.5 \times 10^{-2})^2 = 9.38 \times 10^{-8}\ \text{C} = 94\ \text{nC}\ (2\ \text{s.f})$$

Exam Tip

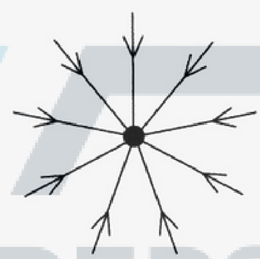
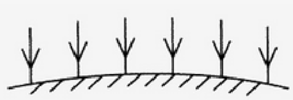
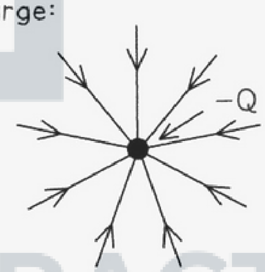
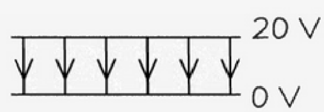
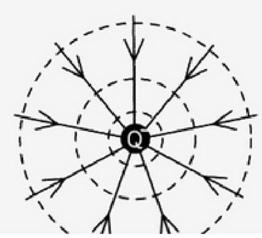
Remember to always **square** the distance in the electric field strength equation!

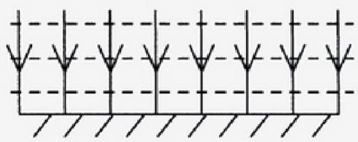
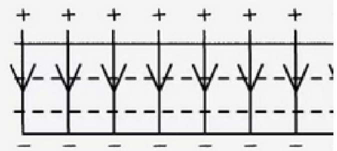
7.4.7 Comparing Gravitational & Electrostatic Forces

Gravitational v Electrostatic Forces

- The similarities and differences between gravitational and electrostatic forces are listed in the table below:

Table Comparing G and E Fields

	Gravitational Fields	Electric Fields
Origin of the force	Mass	Charge
Force between two point masses/ charges	$F_G = \frac{GM_1GM_2}{r^2}$	$F_E = \frac{Q_1Q_2}{4\pi\varepsilon_0 r^2}$
Type of Force	Attractive force	Attractive force (opposite charges) Repulsive force (like charges)
Field Strength	$g = \frac{F}{M}$	$E = \frac{F}{Q}$
Field strength due to a point mass/ charge	$g = \frac{GM}{r^2}$	$E = \frac{Q}{4\pi\varepsilon_0 r^2}$
Field Lines	Around a point mass:  In a uniform field (surface of a planet): 	Around a (negative) point charge:  In a uniform field (between charged) parallel plates: 
Potential	$V = -\frac{GM}{r}$	$V = \frac{Q}{4\pi\varepsilon_0 r}$
Equipotential Surfaces	Around a point mass: 	Around a point charge: 

	In a uniform field (surface of a planet): 	In a uniform field (betw charged) parallel plate 
Work Done on a Mass or Charge	$\Delta W = M\Delta V$	$\Delta W = Q\Delta V$

- The key similarities are:
  - The magnitude of the gravitational and electrostatic force between two point ma or charges are **inverse square law** relationships
  - The field lines around a **point mass** and **negative point charge** are identical
  - The field lines in a **uniform** gravitational and electric field are identical
  - The **gravitational field strength** and **electric field strength** both have a $1 / r^2$ relationship in a **radial field**
  - The **gravitational potential** and **electric potential** both have a $1 / r$ relationship
  - **Equipotential surfaces** for both gravitational and electric fields are **spherical** arc point mass or charge and **equally spaced** parallel lines in uniform fields
  - The work done in each field is either the product of the **mass** and change in poter or **charge** and change in potential

- The key differences are:
  - The gravitational force acts on particles with **mass** whilst the electrostatic force a on particles with **charge**
  - The gravitational force is **always** attractive whilst the electrostatic force can be attractive **or** repulsive
  - The gravitational potential is **always** negative whilst the electric potential can be negative **or** positive

Exam Tip

This topic could come up as long structured answer question, practice summing u this information as you would for a 6 mark question.