HL IB Physics

Your notes

Electric & Magnetic Fields

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Your notes

Electric Charge

Electric Charge

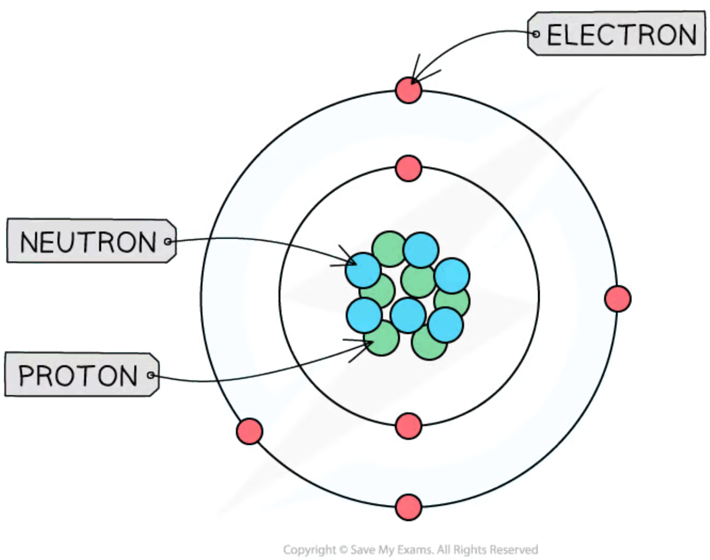
- Charge is the property of matter responsible for the electric force
- The unit of charge is the coulomb (C), where one coulomb is defined as:

The charge carried by an electric current of one ampere in one second

- Charge is a scalar quantity

Quantisation of Charge

- Matter is made up of atoms
  - **Electrons** have a **negative** charge
  - **Protons** have a **positive** charge
  - **Neutrons** are **neutral** (no charge)



The number of negative electrons in an atom balances the number of positive protons

- Most everyday objects are **neutral** (zero charge) because they contain atoms with **equal** numbers of protons and electrons
  - This is because protons and electrons both have a magnitude of charge equal to the elementary charge
- An object can become charged when it obtains an **excess** of protons or electrons
  - The quantity of charge will always equal a whole number of protons or electrons
  - Therefore, charge is quantised

Direction of Electric Forces

- When two charges are close together, they exert a **force** on each other, this could be:
  - **Attractive** (the objects get closer together)

- **Repulsive** (the objects move further apart)

Opposite charges attract, like charges repel

- Whether two objects attract or repel depends on their **charge**
  - If the charges are the **opposite**, they will **attract**
  - If the charges are the **same**, they will **repel**

Attraction or Repulsion Summary Table

Charge of Object 1	Charge of Object 2	Attract or repel?
Positive	Positive	Repel
Positive	Negative	Attract
Negative	Positive	Attract
Negative	Negative	Repel

Examiner Tip

Remember the saying: "**Opposites attract**".

Your notes

Conservation of Electric Charge

- In the same way that energy must be conserved, **charge** must also be conserved
- The law of conservation of charge states that

The total charge in an isolated system remains constant

- This means that charge:
  - **can** be transferred
  - **cannot** be created or destroyed
- In this context, an isolated system refers to the objects involved in the transfer of charge

Your notes

Your notes

Worked example

Four identical metal spheres have charges of q_A = −8.0 μC, q_B = −2.0 μC, q_C = +5.0 μC, and q_D = +12.0 μC.

(a) Two of the spheres are brought into contact briefly, and then they are separated. Which spheres are they if the final charge on each one is +5.0 μC?

(b) All four spheres are brought into contact briefly and then separated. What is the final charge on each sphere?

(c) How many electrons would have to be added to one of the spheres in (b) to make it electrically neutral?

Answer:

(a)

Step 1: Apply the principle of conservation of charge to the scenario

- When two charged spheres come into contact, the charges are shared between them until they are evenly distributed i.e. both spheres have the same charge
- The charge on each sphere is equal to the average of the two charges

$$Q_{final} = \frac{Q_1 + Q_2}{2}$$

Step 2: Determine the charge on each sphere

- For the average charge to be +5 μC, the sum of the two charges must be +10 μC
- This can only be achieved with charges $\mathbf{q_B}$ = −2.0 μC and $\mathbf{q_D}$ = +12.0 μC

$$Q_{final} = \frac{12.0 - 2.0}{2} = +5.0 \text{ μC}$$

(b)

Step 1: Apply the principle of conservation of charge to the scenario

- The charge on each sphere is equal to the average of the four charges (i.e. the total charge is equally distributed between all four spheres)

$$Q_{final} = \frac{Q_1 + Q_2 + Q_3 + Q_4}{4}$$

Step 2: Determine the charge on each sphere

- The average charge on each sphere is

$$Q_{final} = \frac{12.0 + 5.0 - 2.0 - 8.0}{4} = +1.75 \text{ μC}$$

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Note: you would also get the same result if you used $q_B = q_D = +5.0\ \mu C$

(c)

Step 1: Recall the charge of an electron and that charge is quantised

- Electrons have a charge of e = −1.60 × 10^{-19} C
- Therefore, the number of electrons required is

$$number\ of\ electrons = \frac{charge\ on\ sphere}{e}$$

Step 2: Determine the number of electrons required

$$number\ of\ electrons = \frac{1.75 \times 10^{-6}}{1.60 \times 10^{-19}} = 1.094 \times 10^{13}$$

- Therefore, 1.1 × 10^{13} electrons are required to neutralise one of the charges

Examiner Tip

The law of conservation of charge is also important when considering systems of particles and processes, such as nuclear decay

For example, in beta decay, when a neutron decays into a proton, an electron must also be produced to balance the charges

$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_e$$

charge on LHS = 0

charge on RHS = 1 + (−1) + 0 = 0

Millikan's Oil Drop Experiment

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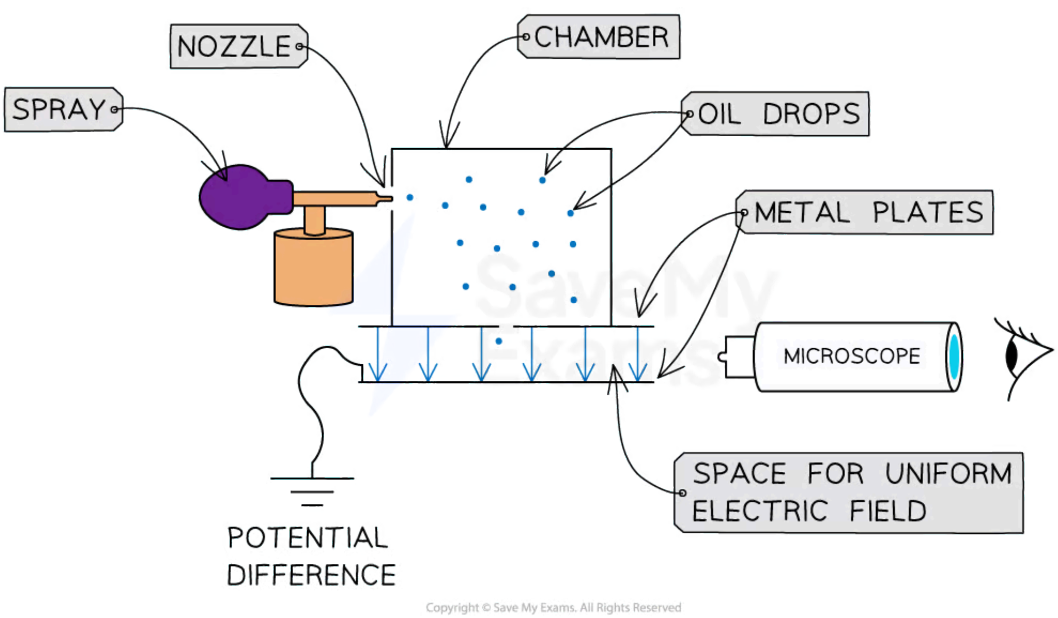
Millikan's Oil Drop Experiment

- This experiment was conducted by Millikan and Fletcher in 1909
- It determined the value of the fundamental elementary charge

Method for Millikan's Oil Drop Experiment

- A fine mist of **oil drops** is sprayed into a chamber
  - Oil is used instead of water because it does not evaporate quickly
  - This means the **mass** of the drops will remain **constant**
- As the drops pass out of the spray nozzle they are charged by friction (alternatively, they can also be ionised by X-rays)
  - Some drops **lose** electrons and become positively charged
  - Some drops **gain** electrons and become negatively charged
- The drops pass into a region between **two metal plates** and are viewed using a **microscope**

Equipment Set Up for Millikan's Oil Drop Experiment



In Millikan's Oil Drop Experiment oil is sprayed into a chamber before passing between metal plates where the electric and gravitational forces are compared

Electric vs Gravitational Force

No Electric Field

- The oil drops fall **under gravity** between the metal plates

- They reach a **terminal velocity** when the air resistance and gravitational force acting on the drop are **equal**

With Electric Field

- A **potential difference** is applied between the metal plates which creates an electric field
- The charged oil drops begin to **rise** when the electric field is strong enough
- This means the upward electrical force is greater than the gravitational force
- The equation for electric force is:

$$F = Eq$$

- Where:
  - E = electric field strength (N C^{-1})
  - F = electrostatic force on the charge (N)
  - q = charge (C)
- The distance the drops rise depends upon their **mass**
- With the correct potential difference applied, the electric and gravitational forces can become **equal** and **opposite**
- The equation for gravitational force, which comes from Newton's second law, is:

$$W = mg$$

- Where:
  - W = weight of drop (N)
  - m = mass of drop (kg)
  - g = gravitational field strength (N kg^{-1})
- By equating the electric and gravitational forces of the drops, the value of fundamental charge was determined to be 1.60×10^{-19} C
- The magnitude of the charge on any object is found to be a **multiple** of 1.60×10^{-19} C
- Therefore, Millikan's experiment provides evidence for the **quantisation of charge**

Your notes

Static Electricity

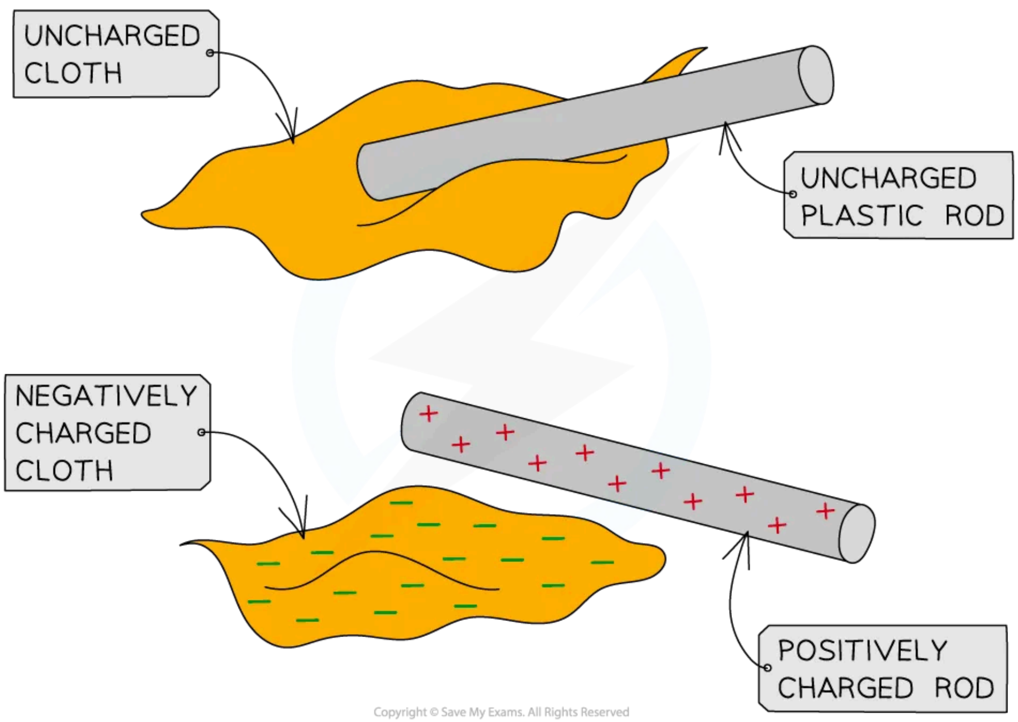
Your notes

Static Electricity

- There are several methods by which electric charge can be transferred, such as
  - charging by **friction**
  - charging by **electrostatic induction**
  - charging by **contact**

Charging by Friction

- When two insulators are rubbed together, electrons are transferred through **friction**
- Depending on the materials, one insulator will become **negatively** charged and the other **positively** charged
- For example, when a cloth and rod are rubbed together, electrons are transferred **from** the rod **to** the cloth
  - This occurs because negatively charged electrons are **transferred** from one material to the other
  - The material, in this case, the rod, **loses** electrons
  - Since electrons are negatively charged, the rod becomes **positively** charged
  - As a result, the cloth has **gained** electrons and therefore is left with an equal **negative** charge



Electrons are transferred onto the cloth by friction. The cloth becomes negatively charged and the rod becomes positively charged

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- Charging by friction is not limited to solid insulators, it can occur between any two substances e.g. liquid flowing in a pipe

Earthing

- To prevent a transfer of charge through contact, both bodies can be **grounded**
- This means they are connected electrically to the **earth**
- If a charged body is grounded (**earthed**), it will discharge until it has a potential of 0 V

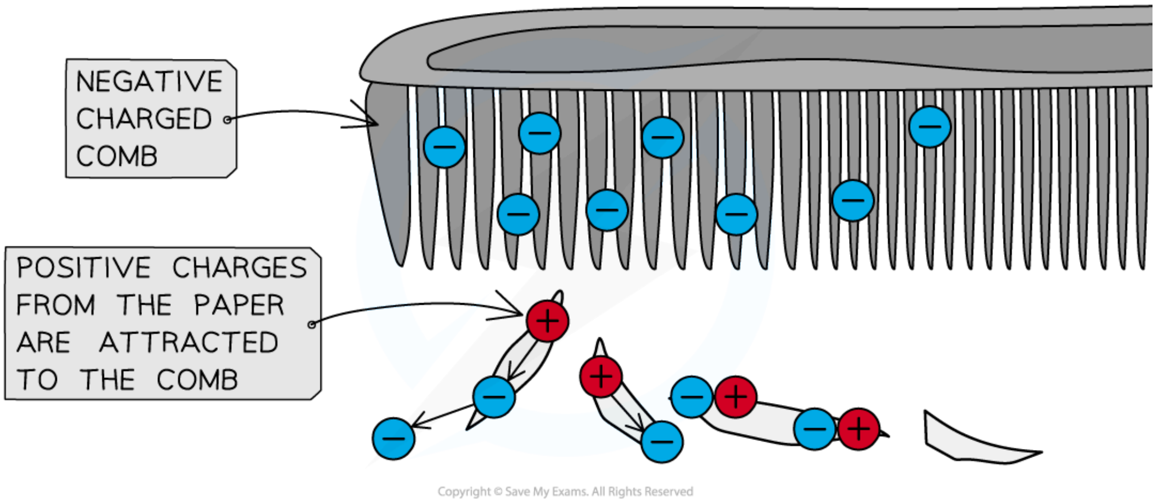
Earth Circuit Symbol

An Earth symbol in a circuit indicates a point that is kept at 0 V

- Electrical appliances are kept safely at 0 V by connection to an **earthed conductor**, usually a wire made from copper, that allows a current to flow to the Earth
  - This is because a current will always take the path of lower resistance
  - Since copper has a lower resistance than, for example, a person, any build-up of charge will flow to the Earth through the copper wire rather than the person

Charging by Electrostatic Induction

- Electrostatic induction is the separation of charge caused by a nearby charged object without any physical contact
  - **Note**: this is **not** the same as electromagnetic induction
- When a charged object is placed near a material, electrons in the material move towards or away from the surface
- This causes the charges within the material to be **redistributed**
- As a result, one side of the material gains an excess of either positive or negative charges

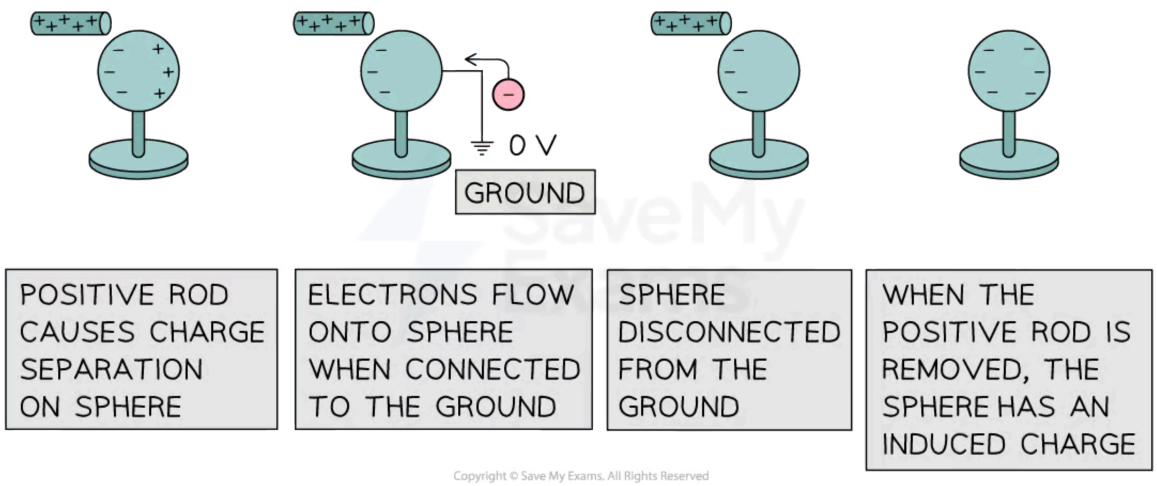


Electrostatic induction can be observed using a comb and small pieces of paper

- An everyday example of electrostatic induction is when a comb, previously charged by friction, is placed near small uncharged pieces of paper
  - The negative charge on the comb **repels** electrons away from the top of the paper, leaving the bottom negatively charged
  - The top of the paper is **attracted** towards the comb and the bottom of the paper is repelled
  - As the top of the paper is closer to the comb, the attractive force is larger than the repulsive force, so there is a **resultant upward force**

Charging a conducting sphere by induction

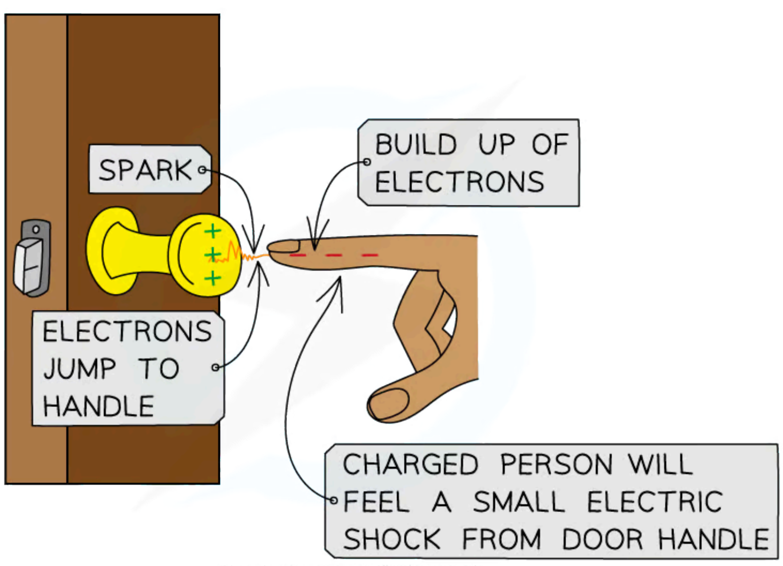
- An initially neutral conducting sphere can become charged by induction
  - A charged rod is brought near the sphere **without touching** it and causes the charges on it to separate
  - The sphere is **grounded** to allow electrons to move onto, or away from the sphere
  - When the charged rod and earth connection are removed, the **excess** charge remains



When a charged rod is brought near a conducting sphere without touching it, a charge can be induced when the sphere is connected and then disconnected to the Earth

Charging by Contact

- Charge can also be transferred when there is physical **contact** between two objects
- It often occurs between a **charged insulator** and an **earthed conductor**, when
  - There is a large potential difference between the two objects
  - The insulator prevents the charge from flowing out into a neighbouring object
- When the two objects touch, electrons **flow** from one to the other to **reduce** the potential difference between them
- An example of charge transfer via contact is a 'shock' felt when touching a doorknob

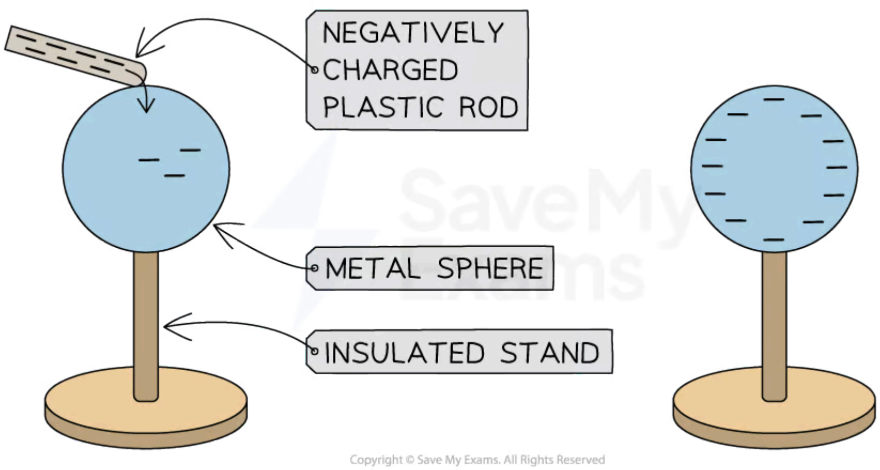


Charge transfer by contact can be felt as a 'shock' when a charge builds up on a person which is allowed to flow when they touch an earthed metallic object, such as a door handle

Your notes

Charging a conducting sphere by contact

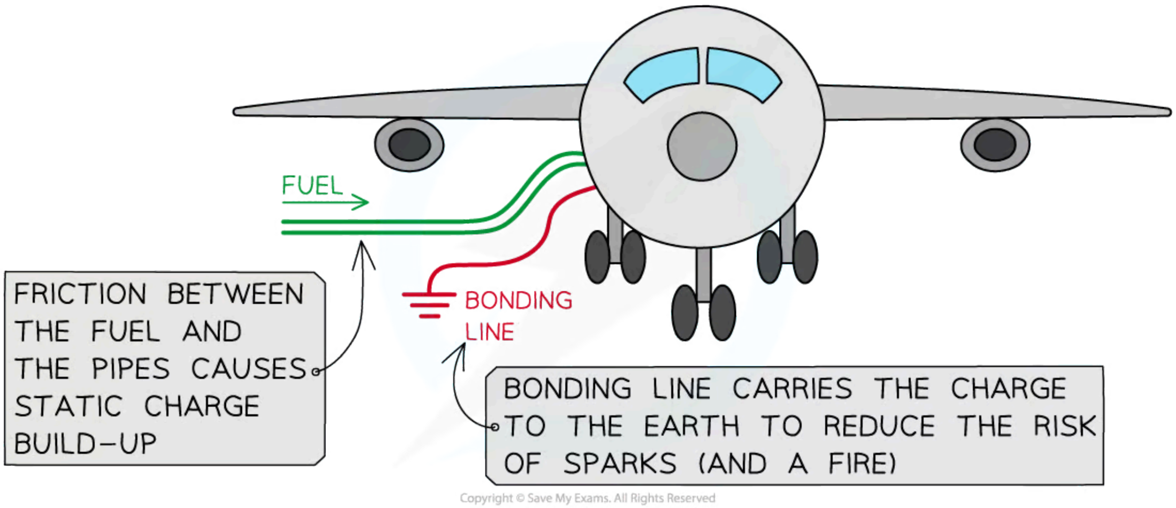
- An initially neutral conducting sphere can become charged by contact with a charged object
  - A charged rod is brought into **contact** with the sphere
  - Electrons are **transferred** from the rod onto the sphere
  - When the rod is removed, the **excess** charge remains



When a charged rod comes into contact with a conducting sphere, the charge flows between them

Dangers of Static Electricity

- When the **potential difference** between two objects becomes very large
  - the electric field between them becomes strong enough to cause the breakdown of air
  - a current can flow as an electrical discharge (spark) through the air
- This can be dangerous in certain situations, such as
  - **electrocution** e.g. by lightning
  - **ignition** of a fire or explosion by a spark
- A spark may ignite an explosion or fire when close to a flammable gas or liquid, for example, when refuelling aeroplanes
- The risk can be reduced by connecting the fuel tank to the Earth with a wire called the **bonding line**



The risks of sparks can be reduced when refuelling a plane by connecting a bonding line to the Earth to allow any excess build-up of charge to dissipate and travel to the ground

Examiner Tip

Materials only become positively charged because of the **loss** of electrons, rather than the 'gain' of any positive charge, which is a common misconception.

If asked to explain how things gain or lose charge, you must discuss **electrons** and explain whether something has gained or lost them. Remember when charging by friction, it is only the **electrons** that can move, not any 'positive' charge, therefore if an object gains a negative charge, something else must have gained a positive charge.

Your notes

Coulomb's Law

Coulomb's Law

- All charged particles generate an electric field
  - This field exerts a force on charged particles which are nearby
- The electric force between two charges is defined by Coulomb's law, which states that:

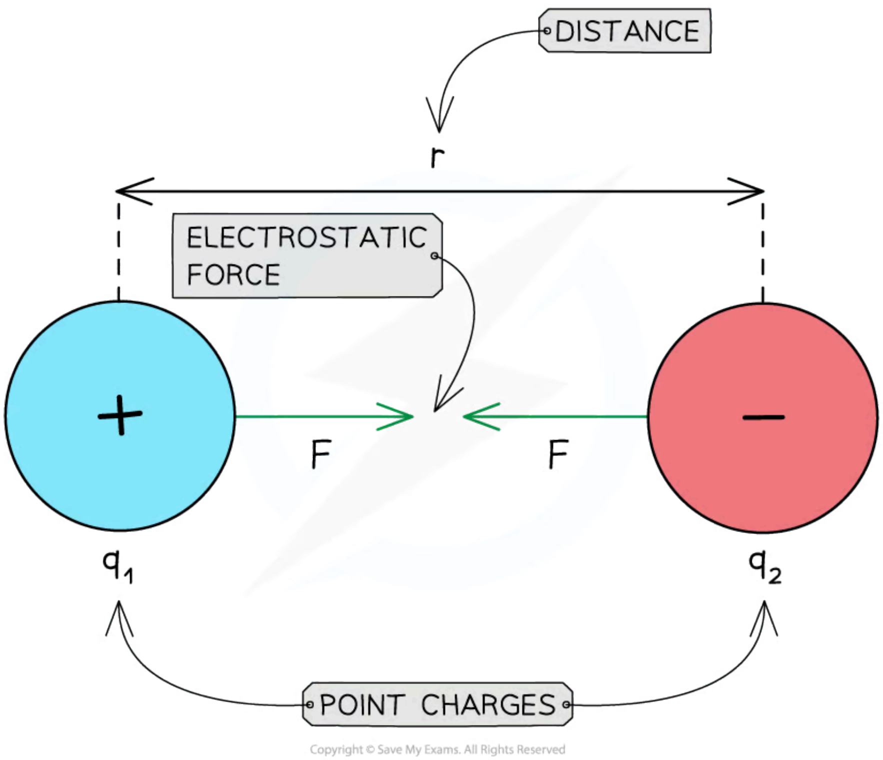
  The electric force between two point charges is directly proportional to the product of the charges and inversely proportional to the square of their separation

- This electric force can be calculated using the expression:

$$F = k\frac{q_1 q_2}{r^2}$$

- Where:
  - F = electric force (N)
  - q_1, q_2 = magnitudes of the charges (C)
  - r = distance between the centres of the two charges (m)
  - k = Coulomb constant (8.99×10^9 N m^2 C^{-2})
- Coulomb's law for two charges is analogous to Newton's law of gravitation for two masses
  - This means that electric and gravitational forces are very similar
  - For example, both forces follow an inverse square law with the separation between charge or mass

Electrostatic attraction between two charges



The attractive electric force F between two point charges +q_1 and −q_2 with a separation of r is defined by Coulomb's law

- Coulomb's constant is given by:

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

- Where ε_0 is the **permittivity of free space**
  - $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2} and refers to charges in a vacuum
  - The value of the permittivity of air is taken to be the same as ε_0
  - All other materials have a higher permittivity $\varepsilon > \varepsilon_0$
  - ε is a measure of the resistance offered by a material in creating an electric field within it
- The value of k depends on the material between the charges
  - In a **vacuum**, $k = 8.99 \times 10^9$ N m^2 C^{-2}

Repulsive & Attractive Forces

- Unlike the gravitational force between two masses which is only attractive, electric forces can be **attractive** or **repulsive**
- Between two charges of the **same type**:
  - The product q_1q_2 is positive, so the forces have positive signs
  - Positive forces mean the charges experience **repulsion**

- For two **opposite charges**:
  - The product q_1q_2 is negative, so the forces have negative signs
  - Negative forces mean the charges experience **attraction**

Your notes

Worked example

An alpha particle is placed 2.0 mm from a gold nucleus in a vacuum.

Taking them as point charges, calculate the magnitude of the electric force acting between the nuclei.

- Proton number of helium = 2
- Proton number of gold = 79

Answer:

Step 1: Write down the known quantities

- Separation between charges, r = 2.0 mm = 2.0×10^{-3} m
- Elementary charge, e = 1.60×10^{-19} C (from the data booklet)
- Coulomb constant, k = 8.99×10^{9} N m^2 C^{-2} (from the data booklet)

Step 2: Calculate the charges of the alpha particle and gold nucleus

- An alpha particle (helium nucleus) has 2 protons, hence it has a charge of:

$$q_1 = 2e = 2 \times (1.60 \times 10^{-19})$$

- A gold nucleus has 79 protons, hence it has a charge of:

$$q_2 = 79e = 79 \times (1.60 \times 10^{-19})$$

Step 3: Write down Coulomb's law

$$F = k\frac{q_1 q_2}{r^2}$$

Step 4: Substitute the values and calculate the magnitude of the electric force

$$F = (8.99 \times 10^{9}) \times \frac{2 \times 79 \times (1.60 \times 10^{-19})^2}{(2.0 \times 10^{-3})^2} = 9.1 \times 10^{-21} \text{ N (2 s.f.)}$$

Examiner Tip

You do not need to memorise the numerical value of the Coulomb's constant *k* or that of the permittivity of free space ε_0. They will both be given in the data booklet.

Unless specified in the question, you should assume that charges are located in a vacuum.

You should note that Coulomb's law can only be applied to charged spheres whose size is much smaller than their separation. Only in this case, the point charge approximation is valid. You must remember that the separation *r* must be taken from the centres of the spheres.

You cannot use Coulomb's law to calculate the electrostatic force between charges distributed on irregularly-shaped objects.

Your notes

Your notes

Different Values of Permittivity

- Permittivity is the measure of how easy it is to generate an electric field in a certain material
- The relativity permittivity ε_r is sometimes known as the **dielectric constant**
- For a given material, it is defined as:

The ratio of the permittivity of a material to the permittivity of free space

- Relativity permittivity can be expressed as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

- Where:
  - ε_r = relative permittivity
  - ε = permittivity of a material (F m^{-1})
  - ε_0 = permittivity of free space (F m^{-1})
- Relative permittivity has **no** units because it is a ratio of two values with the same unit
- When there is a material between two charges, the Coulomb constant becomes

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

- In air, the relative permittivity is 1, so $\varepsilon = \varepsilon_0$
- In other materials, the Coulomb constant **reduces** as $\varepsilon = \varepsilon_r\varepsilon_0$

Examples of Relative Permittivity

- Some values of relative permittivity for different insulators are shown in the table below:

Material	Relative Permittivity, ε_r
free space (vacuum)	1
air	1.00054
paper	4
polystyrene	3
ceramic	100 - 15 000
paraffin	2.3

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pure water	80

Worked example

Calculate the permittivity of a material that has a relative permittivity of 4.5 × 10^{11}. State an appropriate unit for your answer.

Answer:

Step 1: Write down the relative permittivity equation

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

Step 2: Rearrange for permittivity of the material ε

$$\varepsilon = \varepsilon_r \varepsilon_0$$

Step 3: Substitute the values and calculate

$$\varepsilon = (4.5 \times 10^{11}) \times (8.85 \times 10^{-12}) = 3.98 = 4.0 \text{ F m}^{-1} \text{ (2 s.f.)}$$

Your notes

Electric Field Strength

Electric Field Strength

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

The force per unit charge experienced by a small positive test charge placed 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 = electric force on the charge (N)
  - q = magnitude of the charge (C)
- Note that the definition specifies that a positive test charge is used
- This sets a clear convention for the **direction** of an electric field, for example, in a field of strength E:
  - A positive charge $+q$ experiences a force Eq in the direction of the field
  - A negative charge $-q$ experiences a force Eq in the **opposite** direction
- Hence, electric field strength is a **vector** quantity and is always directed:
  - **Away** from a positive charge
  - **Towards** a negative charge

Electric Field Strength due to a Point Charge

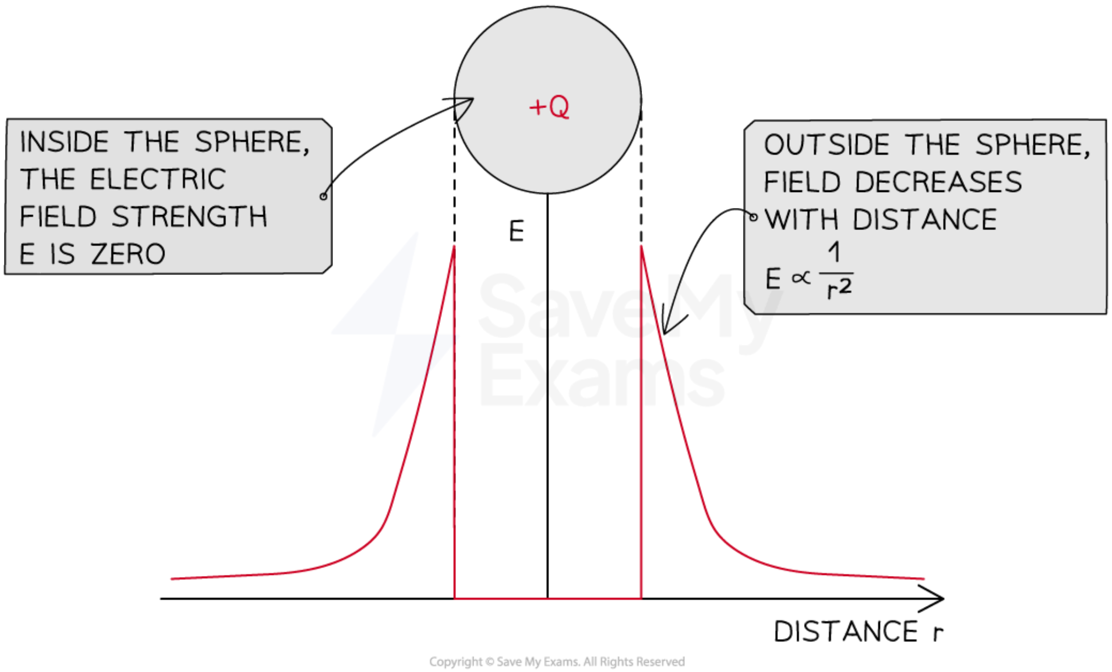
- The strength of an electric field due to a point charge decreases with the square of the distance
  - This is an inverse square law, similar to Coulomb's law
- Using Coulomb's law, this can be written as

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

- Where k = Coulomb constant (N m^2 C^{-2})
- A **charged sphere** acts the same as a point charge, with the same charge as the sphere, at the sphere's centre
  - Within the sphere, however, the electric field strength is zero
- This means that the **electric field** of a charged sphere, outside the sphere, is identical to that of a point charge

Graph of field strength against distance for a positive charge

Your notes

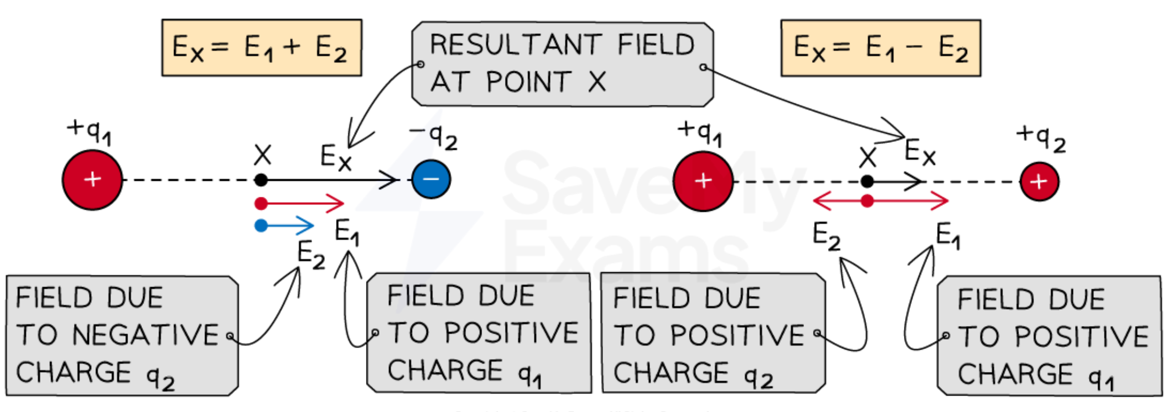


Electric field strength is zero inside a charged sphere and decreases with distance outside the sphere according to an inverse square law

Combining Electric Fields

- Both electric force and field strength are **vector** quantities
- Therefore, to find the electric force or field strength at a point due to multiple charges, each field can be combined by vector addition

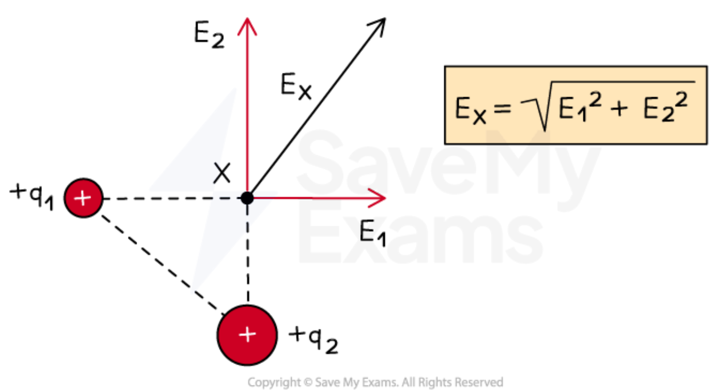
Vector addition of electric field along the same line



For charges along the same line, the resultant field is the vector addition of the field due to both charges at a particular point

- For a point on the same line as two charges q_1 and q_2, with field strengths E_1 and E_2 respectively, the **magnitude** of the resultant field will be:
  - The sum of the fields, $E_1 + E_2$, if they are both in the **same** direction
  - The difference between the fields, $E_1 - E_2$, if they are in **opposite** directions
- The **direction** of the resultant field depends on
  - the **types** of charge (positive or negative)
  - the **magnitude** of the charges
- For a point which makes a right-angled triangle with the charges, the resultant field can be determined using Pythagoras theorem

Vector addition of electric field components



For charges which make a right-angle triangle with point X, the resultant field is the vector addition of the field due to both charges using Pythagoras theorem

Worked example

A charged particle experiences a force of 0.3 N at a point where the magnitude of electric field strength is 3.5×10^4 N C^{-1}.

Calculate the magnitude of the charge on the particle.

Answer:

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 the values and calculate:

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

- The particle has a charge of 8.6×10^{-6} C or **8.6 μC**

Your notes

Your notes

Worked example

A metal sphere of diameter 15 cm is uniformly 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.

Answer:

Step 1: List the known quantities

- 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
- Coulomb constant, $k = 8.99 \times 10^9$ N m^2 C^{-2}

Step 2: Write down the equation for electric field strength

$$E = \frac{kq}{r^2}$$

- It is possible to treat the sphere as a point charge with the same total charge, as it is uniformly charged

Step 3: Rearrange for charge Q

$$q = \frac{Er^2}{k}$$

Step 4: Substitute in the values and calculate:

$$q = \frac{(1.5 \times 10^5) \times (7.5 \times 10^{-2})^2}{8.99 \times 10^9} = 9.38 \times 10^{-8} \text{ C}$$

- The sphere has a charge of 9.4×10^{-8} C or **94 nC**

Examiner Tip

When combining electric fields from multiple charges, remember that the point (e.g. point X in the examples above) represents a positive test charge, so the direction of the electric force or field will correspond to the signs of the charges; the direction of the force or field points **away** from a **positive** charge and **towards** a **negative** charge.

Your notes

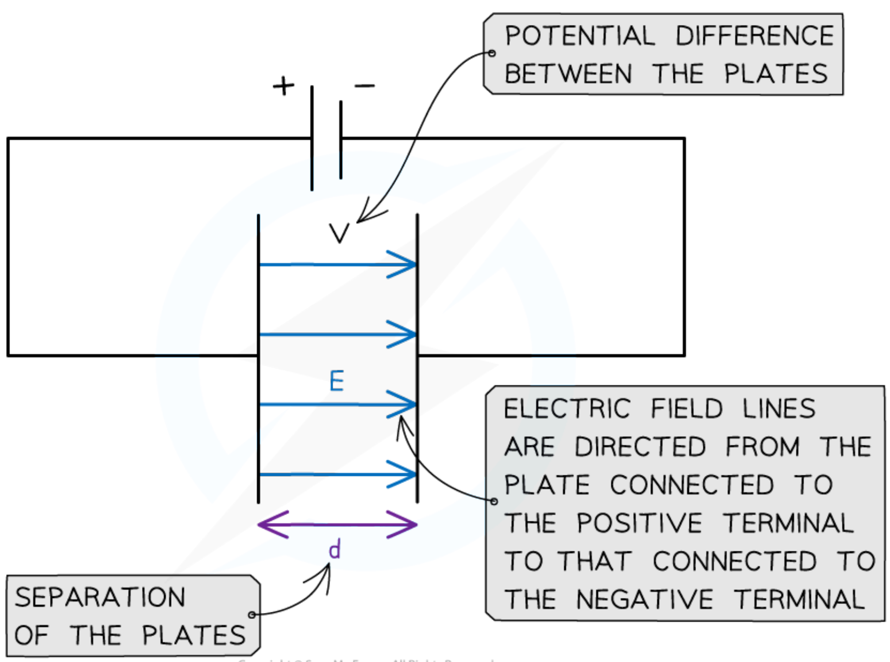
Electric Field Between Parallel Plates

- 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:** both units for electric field strength, V m^{-1} and N C^{-1}, are **equivalent**
- 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
- This equation cannot be used to find the electric field strength around a point charge
  - This is because the field around a point charge is radial
- The electric field between two plates is directed:
  - From the **positive plate** (i.e. the one connected to the positive terminal)
  - To the **negative plate** (i.e. the one connected to the negative terminal)

Uniform Electric Field Between two Parallel Plates



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

Your notes

Worked example

Two parallel metal plates separated by 3.5 cm have a potential difference of 7.9 kV between them.

Calculate the electric force acting on a point charge of 2.6×10^{-15} C when placed between the plates.

Answer:

Step 1: List the known quantities

- Potential difference between plates, V = 7.9 kV = 7900 V
- Distance between plates, d = 3.5 cm = 0.035 m
- Charge, $q = 2.6 \times 10^{-15}$ C

Step 2: Equate the equations for electric field strength

E field between parallel plates: $E = \frac{V}{d}$

E field on a point charge: $E = \frac{F}{q}$

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

Step 3: Rearrange the expression for electric force F

$$F = \frac{qV}{d}$$

Step 4: Substitute values to calculate the force on the point charge

$$F = \frac{(2.6 \times 10^{-15}) \times 7900}{0.035} = 5.9 \times 10^{-10} \text{ N (2 s.f.)}$$

Examiner Tip

Remember the equation for electric field strength with *V* and *d* is only valid for **parallel plates**, and **not** for point charges

However, when a point charge moves between two parallel plates, the two equations for electric field strength can be equated:

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

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

Your notes

Your notes

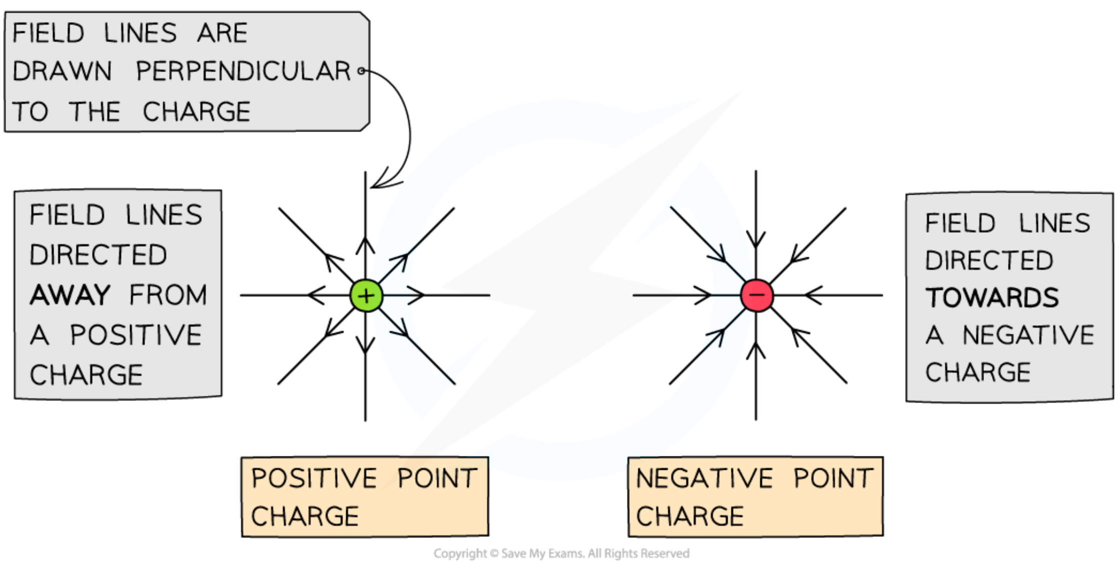
Electric Field Lines

Representing Electric Fields

- Field lines are used to represent the **direction** and **magnitude** of an electric field
- In an electric field, field lines are always directed from the positive charge to the negative charge
- In a **uniform** electric field, the field lines are **equally spaced** at **all** points, this means that
  - The electric field strength is **constant** at all points in the field
  - The force on a test charge has the **same** magnitude and direction at all points in the field
- In a **radial** electric field, the field lines spread out with distance, this means that
  - The field lines are **equally spaced** as they exit the surface of the charge
  - However, the radial separation between the field lines **increases** with distance
  - Therefore, the magnitude of electric field strength and the force on a test charge **decreases** with distance

Electric Field around a Point Charge

- 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 around a point charge are directed away from a positive charge and towards a negative charge

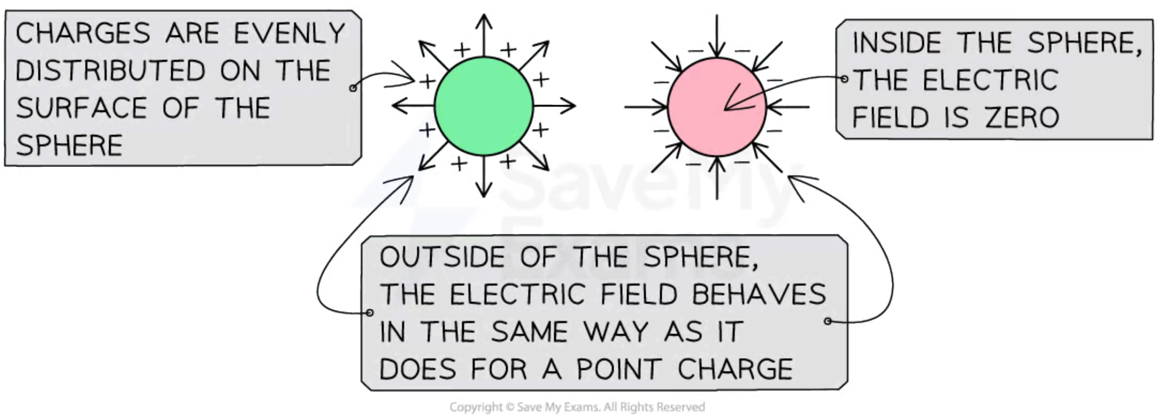
- A radial field spreads uniformly to or from the charge in all directions, but the strength of the field **decreases** with distance
  - The electric field is **stronger** where the lines are **closer** together
  - The electric field is **weaker** where the lines are **further** apart
- This shares many similarities to radial gravitational field lines around a point mass

Your notes

- 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

Electric Field around a Conducting Sphere

- When a conducting sphere (whether solid or hollow) becomes charged:
  - Repulsive forces between isolated point charges cause them to become **evenly distributed** across the surface of the sphere
  - The isolated point charges will either be an excess of negative charges (electrons) or positive charges (protons)
- The resulting electric field around the sphere is the same as it would be if all the charges were placed at the centre
  - This means that a charged conducting sphere can be treated in the same way as a **point charge** in calculations

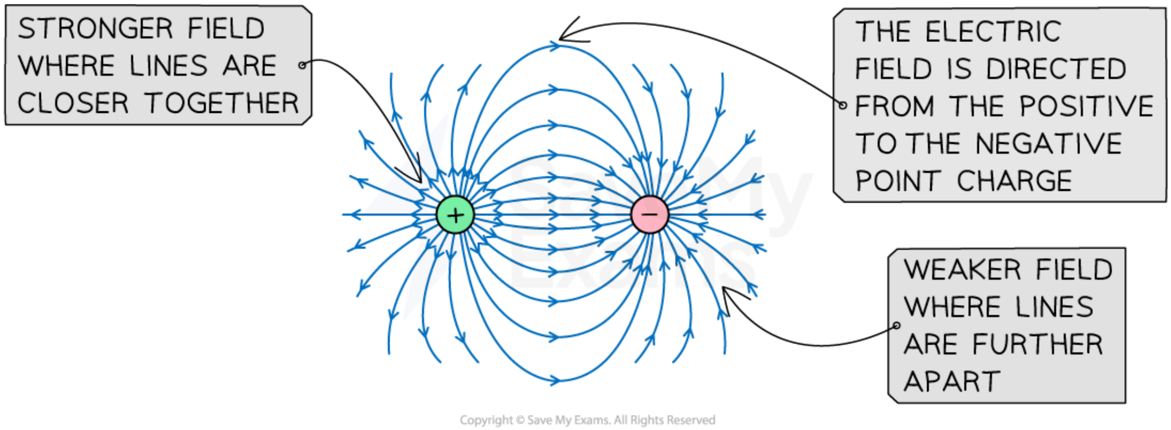


Electric field lines around a charged conducting sphere are similar to the field lines around a point charge

- Field lines are **always perpendicular** to the surface of a conducting sphere
  - This is because the field lines show the **direction** of the **force** on a charge
  - If the lines were not perpendicular, that would mean there must be a parallel component of the electric force acting
  - This would cause charges on the surface of the conductor to move
  - If this happens, electric repulsion causes the charges to rearrange themselves until the parallel component of the force reduces to zero
- As a result of the perpendicular field lines, the electric field is **zero** at all points inside the sphere
  - This is because the forces on a test charge inside the sphere would **cancel** out

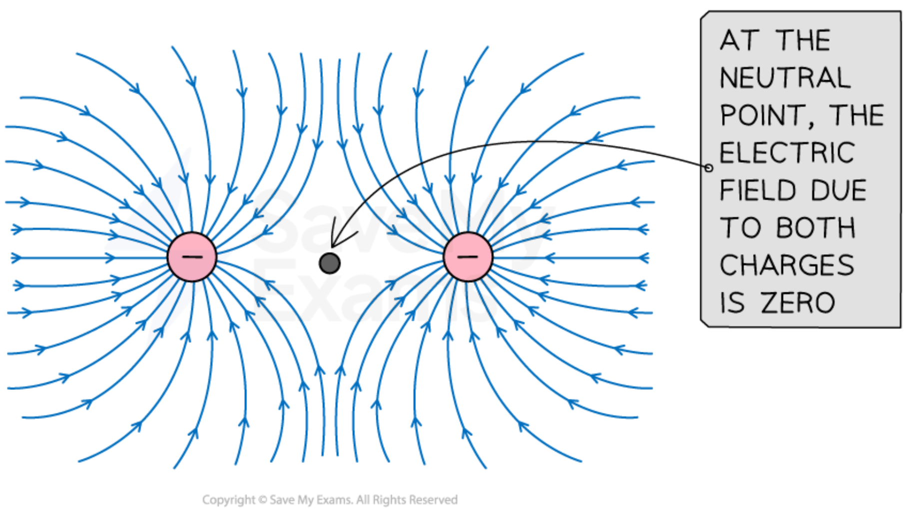
Electric Field between Two Point Charges

- For two **opposite** charges:
  - The field lines are directed from the positive charge to the negative charge
  - The **closer** the charges are brought together, the stronger the **attractive** electric force between them becomes



The electric field lines between two opposite charges are directed from the positive to the negative charge. The field lines connect the surfaces of the charges to represent attraction

- For two charges of the **same** type:
  - The field lines are directed **away** from two positive charges or **towards** two negative charges
  - The **closer** the charges are brought together, the stronger the **repulsive** electric force between them becomes
  - There is a **neutral point** at the midpoint between the charges where the resultant electric force is zero

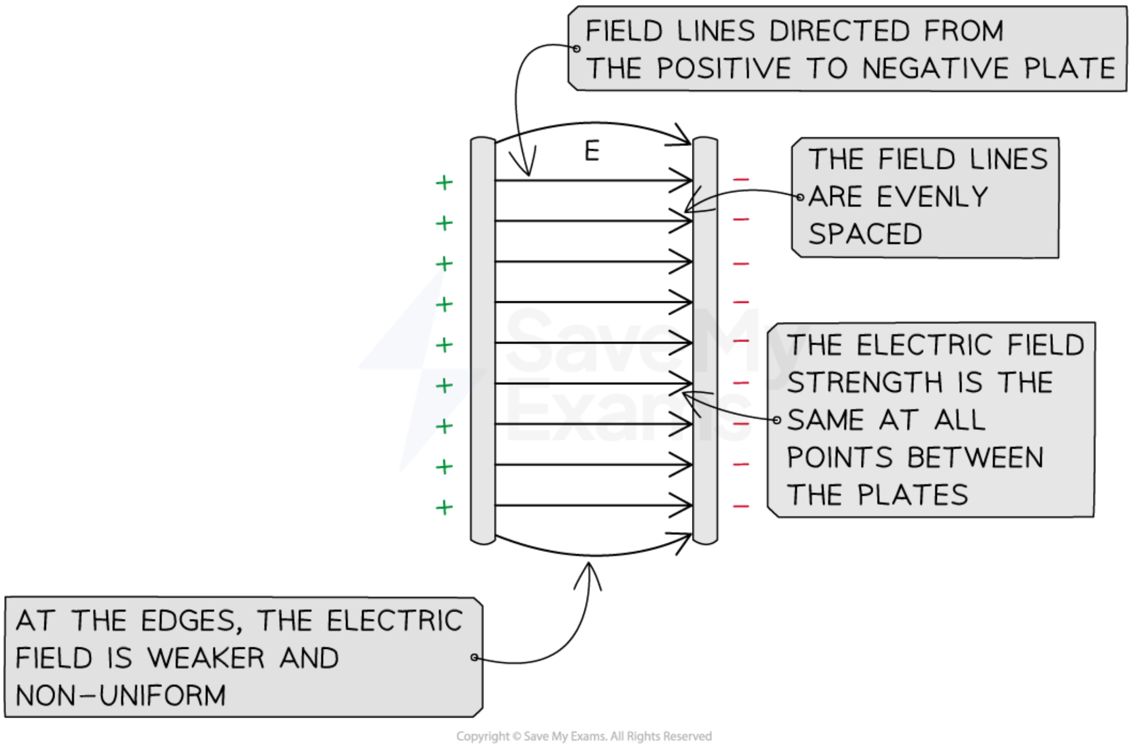


The electric field lines between two like charges are directed away from positive charges or towards negative charges. The field lines do not connect the surfaces of the charges to represent repulsion

Electric Field between Two Parallel Plates

- When a potential difference is applied between two parallel plates, they become charged
  - The electric field between the plates is **uniform**

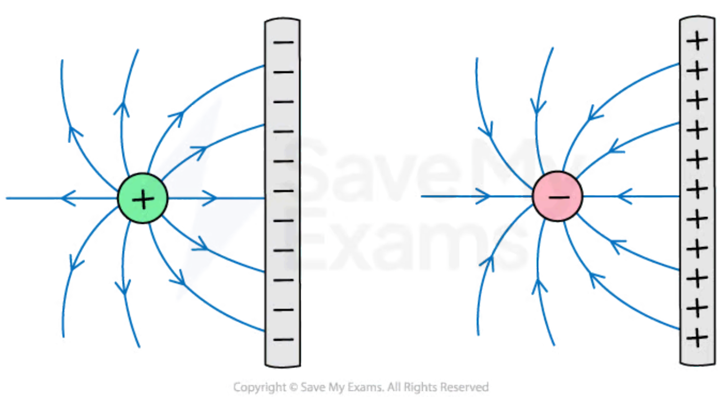
- The electric field beyond the edges of the plates is **non-uniform**



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

Electric Field between a Point Charge and Parallel Plate

- The field around a point charge travelling between two parallel plates combines
  - The field around a point charge
  - The field between two parallel plates



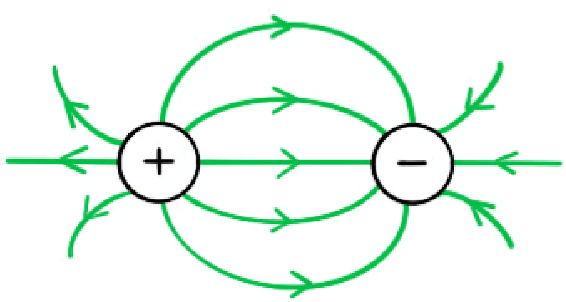
The electric field lines between a point charge and a parallel plate are similar to the field between two opposite charges. The field lines become parallel when they touch the plate

Worked example

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

Answer:

- Electric field lines around point charges have arrows which point radially outwards for positive charges and radially inwards for negative charges
- Arrows (representing force on a positive test charge) point **from the positive charge to the negative charge**



Examiner Tip

Always label the arrows on the field lines! The lines must also touch the surface of the source charge or plates and they must **never** cross.

Your notes

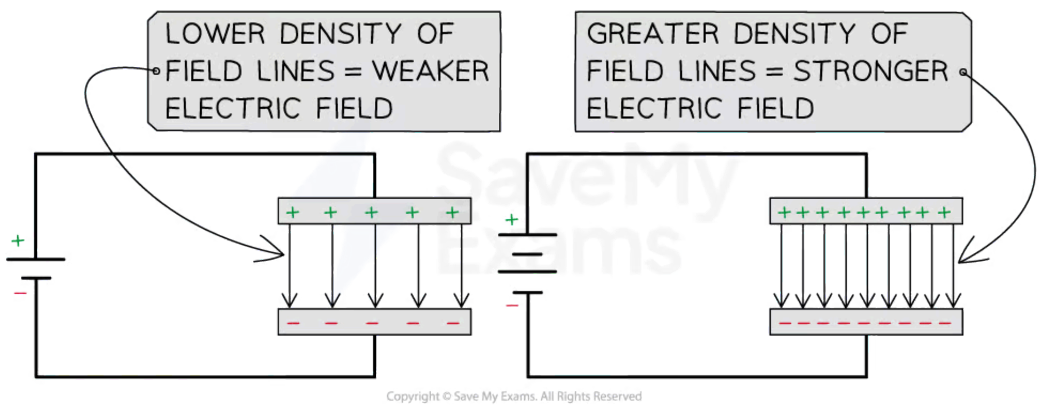
Your notes

Electric Field Strength & Line Density

- The spacing, or **density**, of field lines, represents the **strength** of an electric field
  - A **stronger** field is represented by the field lines which are **closer** together
  - A **weaker** field is represented by the field lines which are **further** apart

Strength of a Uniform Field

- The **strength** of a uniform electric field, such as between two parallel plates, depends on the size of the potential difference between them
- When a **higher** potential difference is applied across the plates:
  - The density of the field lines is **higher**
  - The electric field is **stronger**
  - The force that acts on a test charge in the field is **greater**
- When a **lower** potential difference is applied across the plates:
  - The density of the field lines is **lower**
  - The electric field is **weaker**
  - The force that acts on a test charge in the field is **lower**

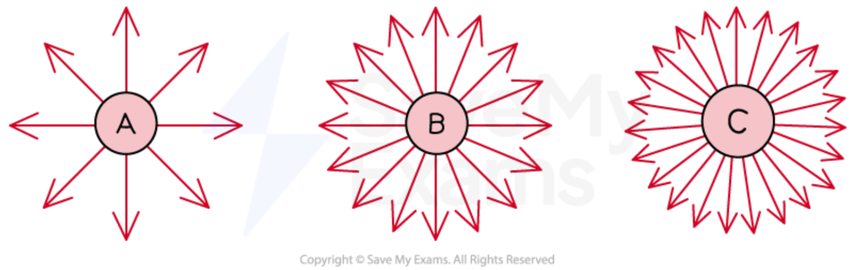


The greater the potential difference, the stronger the electric field and the greater the density of the field lines between the plates

- In a uniform field, the field lines will **always** be equally spaced, but the spacing will increase or decrease depending on the field strength

Strength of a Radial Field

- Since electric field strength decreases with distance from a point charge, radial fields are considered to be **non-uniform**
- The **strength** of a radial electric field depends on
  - The magnitude of the charge
  - The distance between the charge and a point



The greater the magnitude of a point charge, the stronger its electric field and the greater the density of the field lines around it

- Sphere A (from the diagram) has the **lowest density** of field lines, which means it has
  - The **weakest** electric field
  - The **smallest** magnitude of **charge** at its surface
- Sphere C (from the diagram) has the **highest density** of field lines, which means it has
  - The **strongest** electric field
  - The **greatest** magnitude of **charge** at its surface
- The shape of a radial field occurs because field lines must be **perpendicular** to any conducting surface
  - Therefore, electric field lines are equally spaced at the surface of a point charge

Electric Potential (HL)

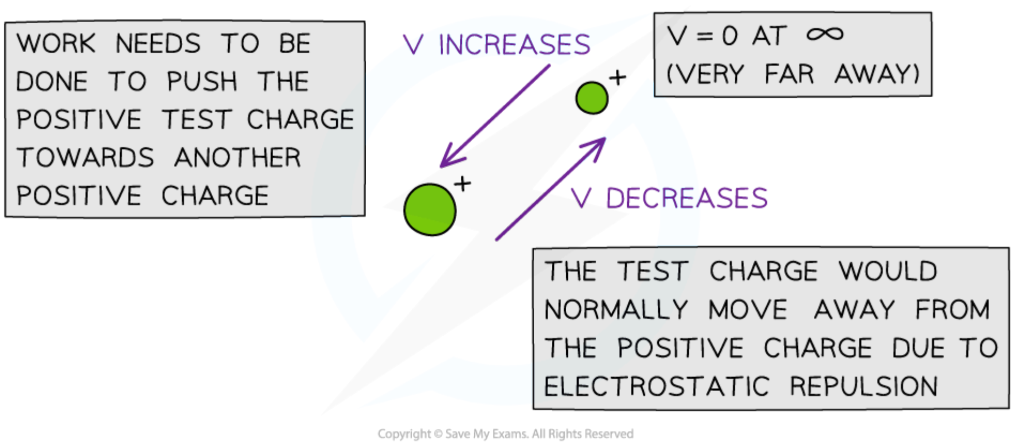
Your notes

Electric Potential

- The electric potential at a point is defined as:
  The work done per unit charge in taking a small positive test charge from infinity to a defined point
- Electric potential is measured in J C^{-1} or V
- It is a **scalar** quantity but has a positive or negative sign to indicate the sign of the charge
  - In a similar way to gravitational potential, electric potential also has a value of **zero** at **infinity**
- The electric potential at a point depends on:
  - The magnitude of the point **charge**
  - The **distance** between the charge and the point

Electric potential for a positive charge

- Around an isolated **positive** charge, electric potential:
  - has a **positive** value
  - **increases** when a test charge moves closer
  - **decreases** when a test charge moves away

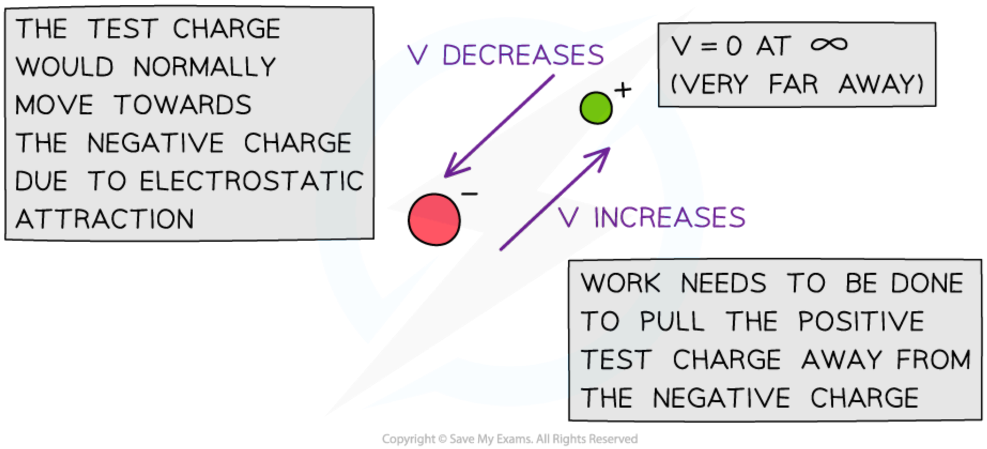


For a positive charge, the electric potential decreases in the direction a positive test charge would move in due to the electrostatic repulsion

Electric potential for a negative charge

- Around an isolated **negative** charge, electric potential:
  - has a **negative** value
  - **decreases** when a test charge moves closer
  - **increases** when a test charge moves away

Your notes



For a negative charge, the electric potential decreases in the direction a positive test charge would move in due to the electrostatic attraction

Examiner Tip

One way to remember whether the electric potential increases or decreases with respect to the distance from the charge is by the direction of the electric field lines. The potential always **decreases** in the **same** direction as the field lines and vice versa.

Calculating Electric Potential

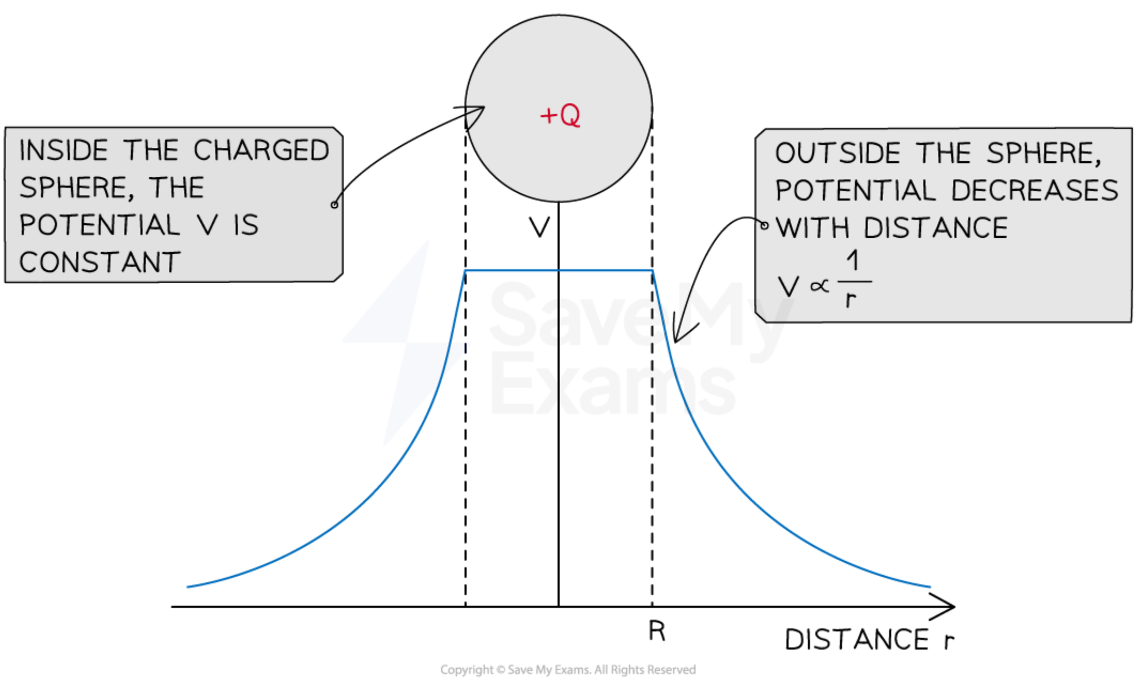
Your notes

- The electric potential around a point charge can be calculated using:

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

- Where:
  - V_e = electric potential (V)
  - Q = magnitude of the charge producing the potential (C)
  - k = Coulomb constant (N m^2 C^{-2})
  - r = distance from the centre of the point charge (m)
- For a positive (+) charge:
  - potential V_e **increases** as the separation r **decreases**
  - energy must be supplied to a positive test charge to overcome the repulsive force
- For a negative (–) charge:
  - potential V_e **decreases** as the separation r **increases**
  - energy is released as a positive test charge moves in the direction of the attraction force
- The electric potential has an inversely proportional relationship with distance
- Unlike gravitational potential which is always negative, the sign of the charge corresponds to the sign of the electric potential
- **Note:** this equation also applies to a conducting sphere. The charge on the sphere is treated as if it is concentrated at the centre of the sphere, i.e. like a point charge

Graph of potential against distance for a positive charge



Electric potential is constant inside a charged sphere and decreases with distance outside the sphere

Your notes

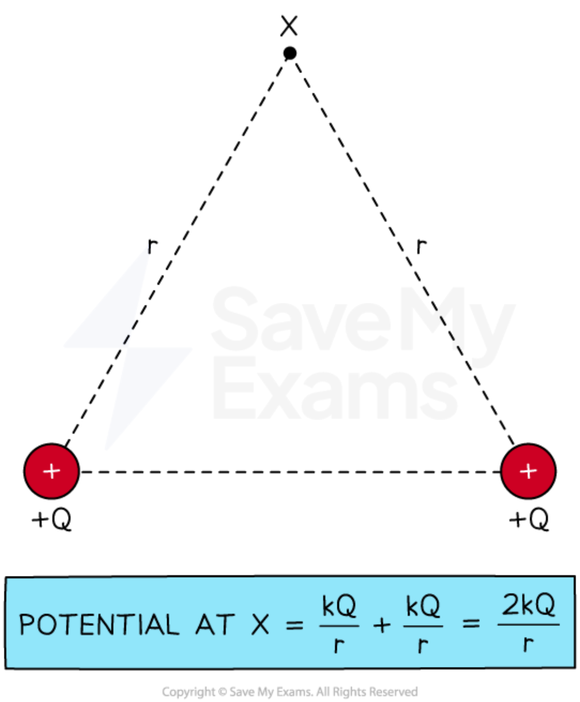
Combining Electric Potentials

- To find the potential at a point caused by multiple charges, each potential can be combined by addition
- For example, the combined potential of two point charges at a point is:

$$V = \frac{kQ_1}{r_1} + \frac{kQ_2}{r_2}$$

- Where:
  - Q_1, Q_2 = magnitude of the charges (C)
  - r_1, r_2 = distance between each charge and the point (m)

How to determine resultant electric potential



Point X makes an equilateral triangle of length r with two equal positive charges Q. The combined potential of both charges at X is double the potential due to one of the charges

Your notes

Worked example

A Van de Graaff generator has a spherical dome of radius 15 cm. It is charged up to a potential of 240 kV.

Calculate

(a) the charge stored on the dome
(b) the potential at a distance of 30 cm from the dome

Answer:

Part (a)

Step 1: List down the known quantities

- Radius of the dome, r = 15 cm = 15×10^{-2} m
- Potential difference, V = 240 kV = 240×10^{3} V
- Coulomb constant, $k = 8.99 \times 10^{9}$ N m^{2} C^{-2}

Step 2: Write down the equation for the electric potential due to a point charge

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

Step 3: Rearrange for charge Q

$$Q = \frac{rV}{k}$$

Step 4: Substitute in values

$$Q = \frac{0.15 \times (240 \times 10^{3})}{8.99 \times 10^{9}} = 4.0 \times 10^{-6} = 4.0\ \mu\text{C}$$

Part (b)

Step 1: Write down the known quantities

- Charge stored in the dome, Q = 4.0×10^{-6} C
- Distance, r = radius of the dome + distance from the dome = 15 + 30 = 45 cm = 0.45 m
  - **Note**: we are treating the Van de Graaff as a point charge, so we take the distance from the centre of the dome

Step 2: Write down the equation for electric potential due to a point charge

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

Your notes

Step 3: Substitute in values

$$V = \frac{(8.99 \times 10^9) \times (4.0 \times 10^{-6})}{0.45} = 79.9 \times 10^3 = 80 \text{ kV (2 s.f.)}$$

Electric Potential Energy (HL)

Your notes

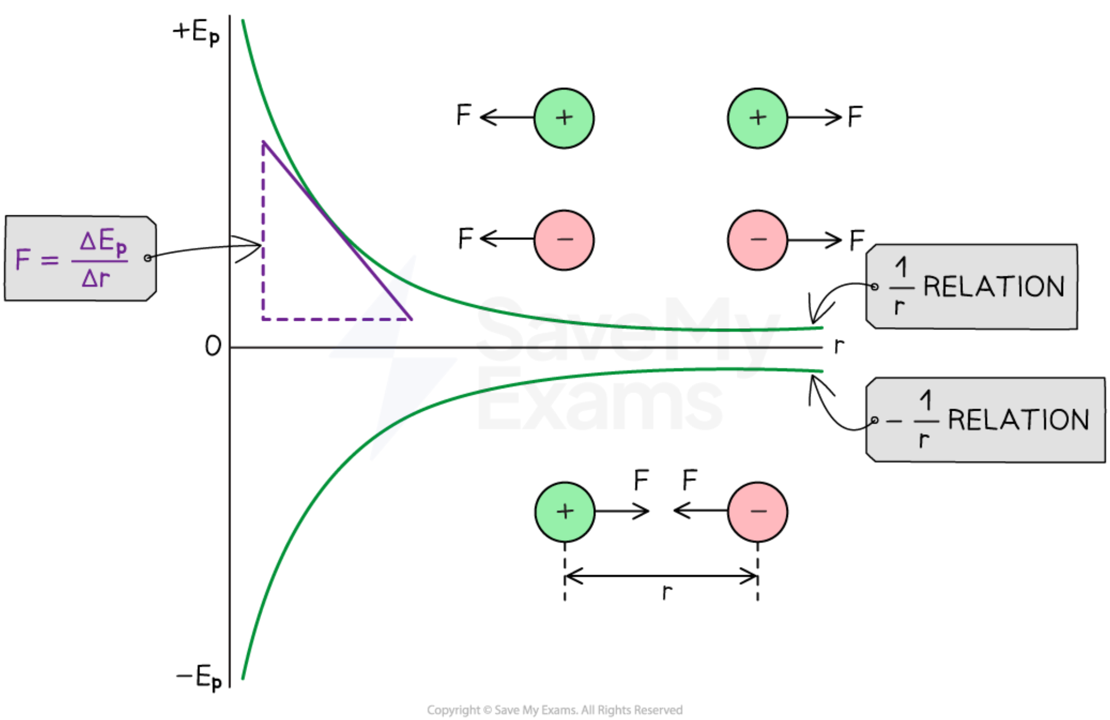
Electric Potential Energy

- In a system of two or more charges, **electric potential energy** is stored due to the electric forces between them
- The electric potential energy of a system is defined as

The work done in bringing all the charges in a system to their positions from infinity

- Electric potential energy can be positive or negative depending on the charges involved
  - This is different to gravitational potential energy which **always** has a negative value
- Electric potential energy has a **positive** value when:
  - the electric force is **repulsive** i.e. between two **similar** charges
  - energy is **released** as charges become separated
- Electric potential energy has a **negative** value when:
  - the electric force is **attractive** i.e. between two **opposite** charges
  - energy must be **supplied** to separate the charges
- A graph of potential energy E_p against distance *r* can be drawn for two like charges and two opposite charges
- The **gradient** of the graph at any particular point is the value of electric force *F* at that point

Graph of electric potential energy against distance



The electric potential energy of two similar charges decreases with distance and increases for two opposite charges

Your notes

Your notes

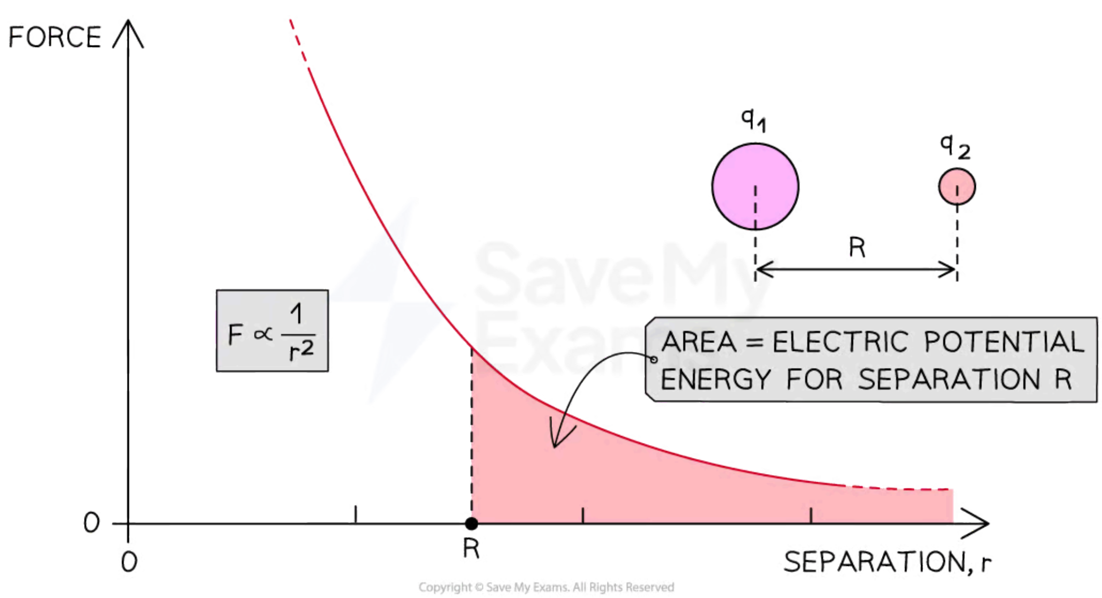
Electric Potential Energy Equation

- The electric potential energy of two point charges is given by:

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

- Where:
  - E_p = electric potential energy (J)
  - q_1, q_2 = magnitudes of the charges (C)
  - r = distance between the centres of the two charges (m)
  - k = Coulomb constant (N m^2 C^{-2})
- Similar to electric potential, values of electric potential energy depend on the signs of q1 and q2
  - By definition, potential V = 0 at infinity, therefore E_p = 0 at infinity
- The electric potential energy of two charges separated by a distance R can also be determined from the **area under a force-distance graph**
  - However, determining this area for distances between R and infinity is difficult, so it is much simpler to use the equation above

Determining area under an electric force-distance graph



The area under the force-distance graph represents the electric potential energy of two similar point charges separated by R

Change in Electric Potential Energy

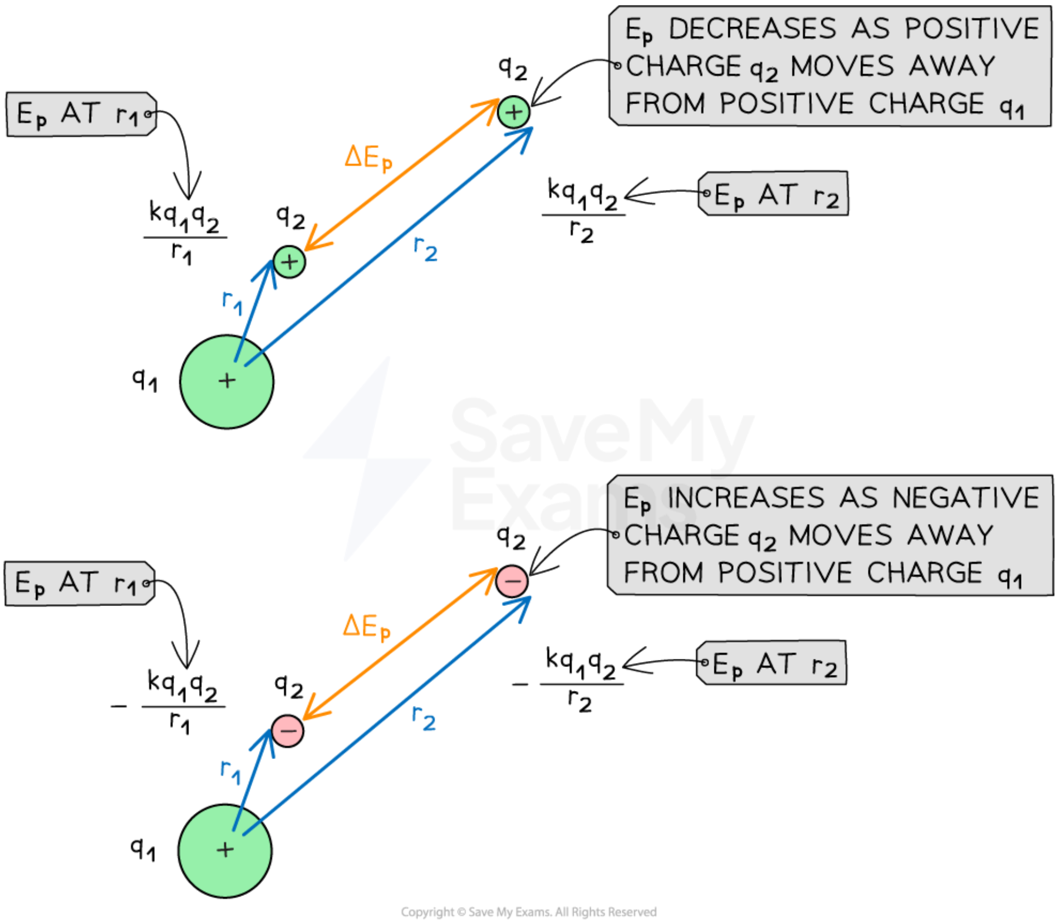
- There is a **change in electric potential energy** when one charge moves away from another
  - This is because work must be done **on** the field to bring similar charges together, or to separate opposite charges

Your notes

- Conversely, work is done **by** the field to separate similar charges, or to bring opposite charges together
- When a charge q_2 moves away from a charge q_1, the change in electric potential energy is equal to:

$$\Delta E_p = kq_1q_2\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

- Where:
  - r_1 = initial separation between charges (m)
  - r_2 = final separation between charges (m)

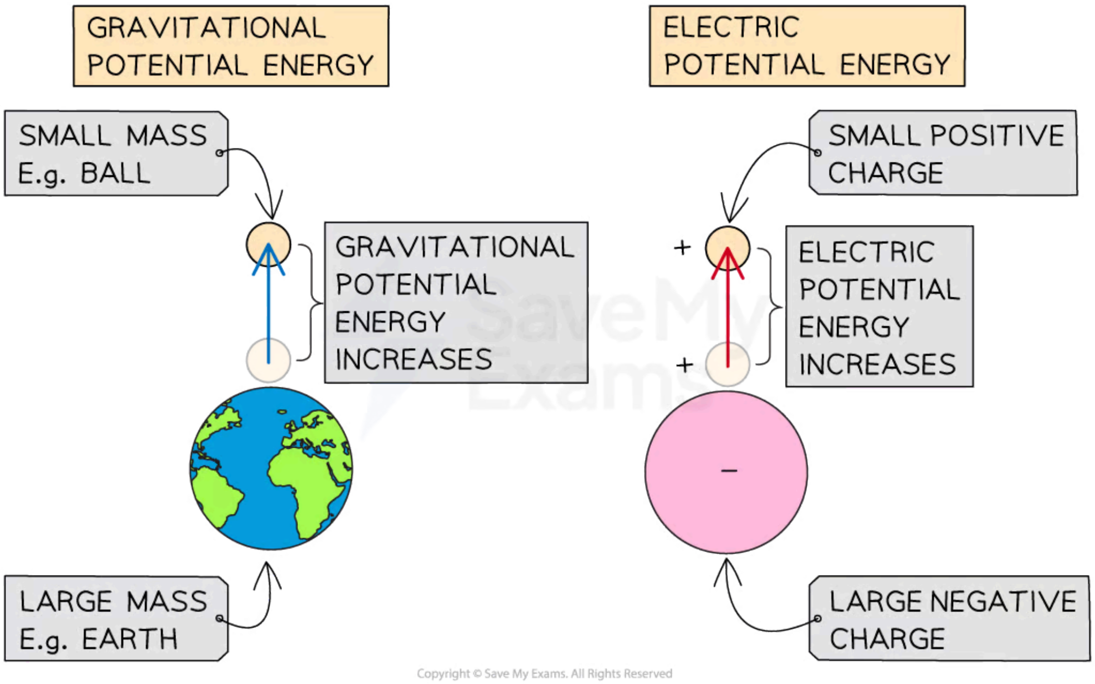


There is a change in electric potential energy when a point charge moves away from another charge

- The change in electric potential energy between two charges is analogous to the **change in gravitational potential energy** between two masses

Comparing gravitational and electric potential energy

Your notes

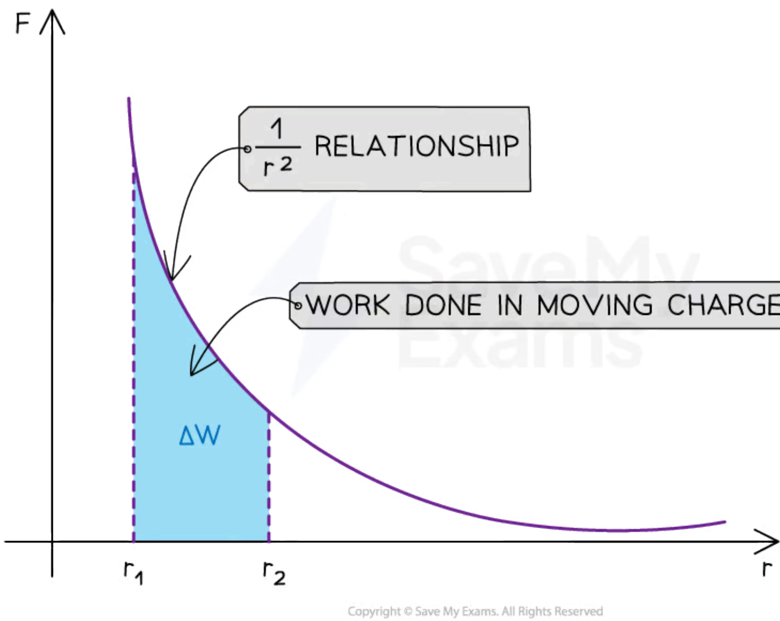


When a small mass is lifted on Earth, there is an increase in gravitational potential energy. This is similar to the increase in electric potential energy when a negative charge moves away from a positive charge

Determining work done from a force-distance graph

- The work done in moving a charge can also be determined from the area under a force-distance graph
- This is equivalent to the change in electric potential energy of a moving charge

Your notes



The area under a force-distance graph represents the change in electric potential energy, or the work done in moving the charge

Your notes

Worked example

An α-particle $^{4}_{2}\text{He}$ is moving directly towards a stationary gold nucleus $^{197}_{79}\text{Au}$.

At a distance of 4.7×10^{-15} m the α-particle momentarily comes to rest.

Calculate the electric potential energy of the particles at this instant.

Answer:

Step 1: Write down the known quantities

- Distance, $r = 4.7 \times 10^{-15}$ m
- Elementary charge, e = 1.60×10^{-19} C
- Coulomb constant, $k = 8.99 \times 10^{9}$ N m^{2} C^{-2}

Step 2: Determine the magnitudes of the charges

- An alpha particle (helium nucleus) contains 2 protons
  - Charge of alpha particle, q_1 = 2e
- The gold nucleus contains 79 protons
  - So, charge of gold nucleus, q_2 = 79e

Step 3: Write down the equation for electric potential energy

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

Step 4: Substitute values into the equation

$$E_p = (8.99 \times 10^{9}) \times \frac{2 \times 79 \times (1.60 \times 10^{-19})^2}{(4.7 \times 10^{-15})} = 7.7 \times 10^{-12} \text{ J (2 s.f.)}$$

Examiner Tip

When calculating electric potential energy, make sure you **do not** square the distance!

Your notes

Electric Potential Gradient (HL)

Work Done on a Charge

- When a charge moves through an electric field, work is done
- The work done in moving a charge q is given by:

$$W = q\Delta V$$

- Where:
  - W = work done on or by the field (J)
  - q = magnitude of charge moving in the field (C)
  - ΔV = potential difference between two points (J C^{-1})

Electrical Potential Difference

- Two points at different distances from a charge will have different electric potentials
  - This is because the electric potential increases with distance from a negative charge and decreases with distance from a positive charge
- Therefore, there will be an **electric potential difference** between the two points equal to:

$$\Delta V = V_f - V_i$$

- Where:
  - V_f = final electric potential (J C^{-1})
  - V_i = initial electric potential (J C^{-1})
- The potential difference due to a point charge can be written:

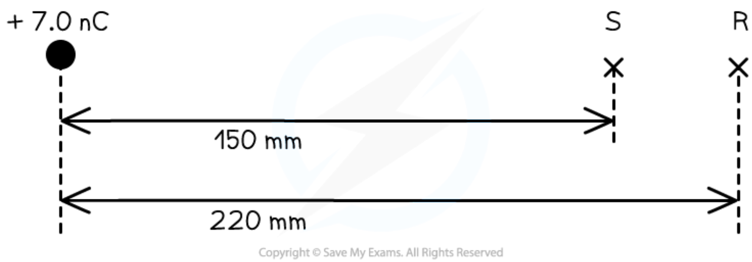
$$\Delta V = kQ\left(\frac{1}{r_f} - \frac{1}{r_i}\right)$$

- Where
  - Q = magnitude of point charge producing the potential
  - k = Coulomb constant (N m^2 C^{-2})
  - r_f = final distance from charge Q (m)
  - r_i = initial distance from charge Q (m)

Your notes

Worked example

A point charge of +7.0 nC is located 150 mm and 220 mm from points S and R respectively.



Calculate the work done when a +3.0 nC charge moves from R to S.

Answer:

Step 1: Write down the known quantities

- Final distance from charge, r_S = 150 mm = 0.15 m
- Initial distance from charge, r_R = 220 mm = 0.22 m
- Magnitude of charge producing the potential, Q = +7.0 nC = +7.0 × 10^{-9} C
- Magnitude of charge moving in the potential, q = +3.0 nC = +3.0 × 10^{-9} C
- Coulomb constant, k = 8.99 × 10^9 N m^2 C^{-2}

Step 2: Calculate the electric potential difference between R and S

$$\Delta V = kQ\left(\frac{1}{r_S} - \frac{1}{r_R}\right)$$

$$\Delta V = (8.99 \times 10^9)(7.0 \times 10^{-9})\left(\frac{1}{0.15} - \frac{1}{0.22}\right) = 133.5 \text{ V}$$

Step 3: Calculate the work done by the moving charge

$$W = q\Delta V$$

$$W = (3.0 \times 10^{-9}) \times 133.5 = 4.0 \times 10^{-7} \text{ J}$$

Your notes

Examiner Tip

Remember that q in the work done equation is the charge that is being moved, whilst Q is the charge which is producing the potential.

Make sure not to get these two mixed up, as both could be given in the question (like the worked example) and you will be expected to choose the correct one.

Electric Potential Gradient

- An electric field can be described in terms of the variation of electric potential at different points in the field
  - This is known as the **potential gradient**
- The potential gradient of an electric field is defined as:

  The rate of change of electric potential with respect to displacement in the direction of the field

- A graph of potential *V* against distance *r* can be drawn for a positive or negative charge *Q*
- This is a graphical representation of the equation:

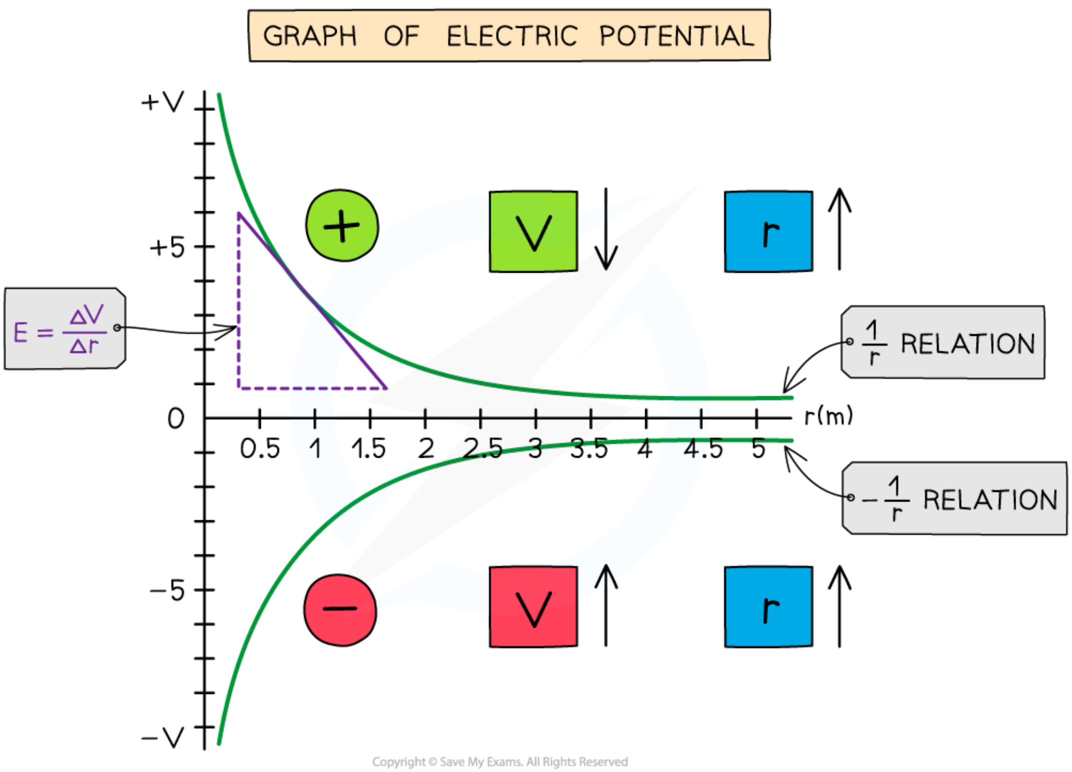
$$V = \frac{kQ}{r}$$

- The **gradient** of the *V*-*r* graph at any particular point is equal to the electric field strength *E* at that point
- This can be written mathematically as:

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

- Where:
  - *E* = electric field strength ($V\ m^{-1}$)
  - ΔV = potential difference between two points (V)
  - Δr = displacement in the direction of the field (m)
- The negative sign is included to indicate that the direction of the field strength *E* opposes the direction of increasing potential

Graph of electric potential against distance



The electric potential around a positive charge decreases with distance and increases with distance around a negative charge

- **The key features of this graph are:**
  - All values of potential are negative for a negative charge
  - All values of potential are positive for a positive charge
  - As r increases, V against r follows a $1/r$ relation for a positive charge and a $-1/r$ relation for a negative charge
  - The **gradient** of the graph at any particular point is equal to the field strength E at that point
  - The curve is shallower than the corresponding E-r graph

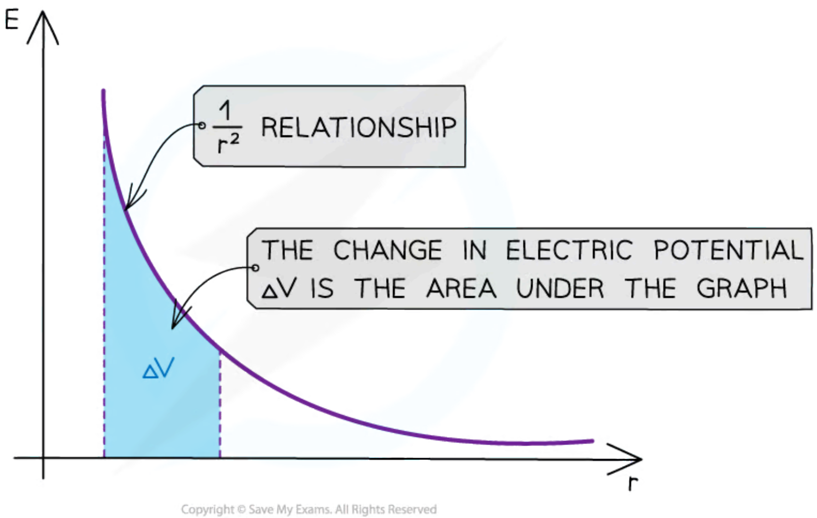
Determining potential from a field-distance graph

- The potential difference due to a charge can also be determined from the area under a field-distance graph
- A graph of field strength E against distance r can be drawn for a positive or negative charge Q
- This is a graphical representation of the equation:

$$E = \frac{kQ}{r^2}$$

- The **area** under the E-r graph between two points is equal to the potential difference ΔV between those points

Your notes

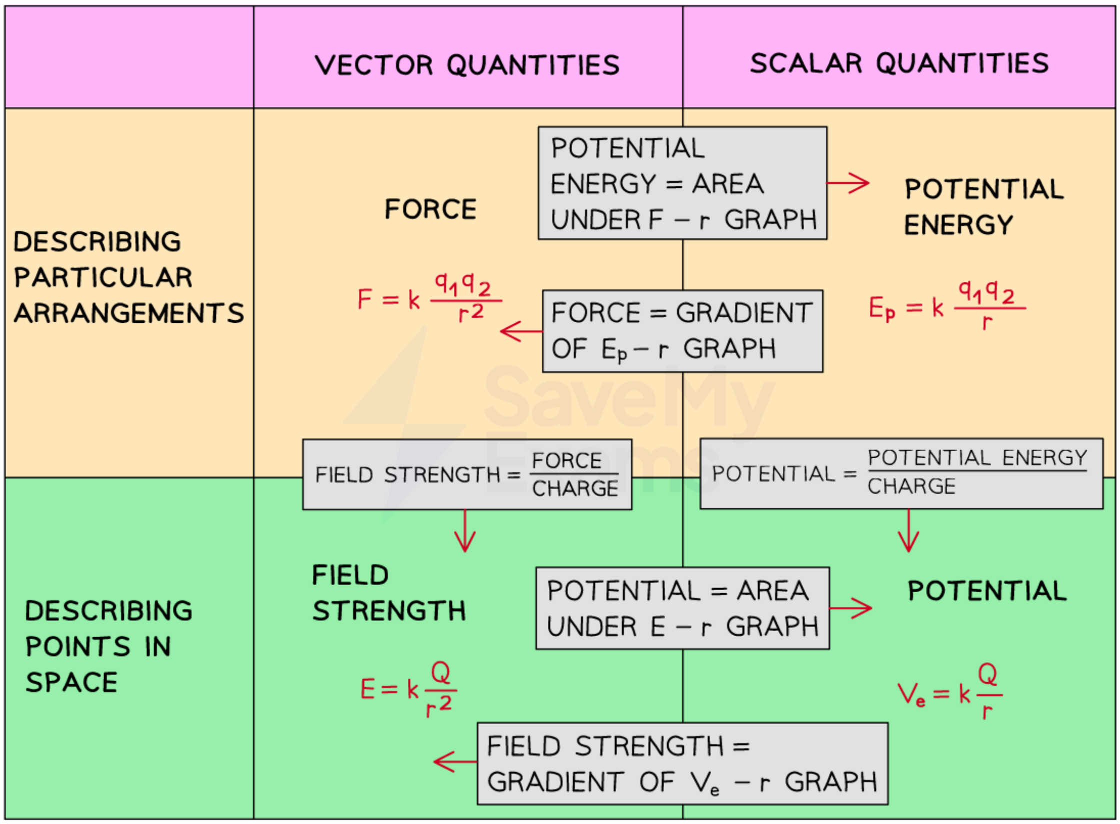


The electric field strength E has a 1/r^2 relationship

- **The key features of this graph are**:
  - All values of field strength are negative for a negative charge
  - All values of field strength are positive for a positive charge
  - As *r* increases, *E* against *r* follows a 1/r^2 relation (inverse square law)
  - The **area** under this graph is the change in electric potential Δ*V*
  - The curve is steeper than the corresponding *V*-*r* graph

Examiner Tip

There are many equations and graphs to learn in this topic. A good way to revise these is to find a way of organising the knowledge in a way that resonates with you, here is an example of one possible way to do this:



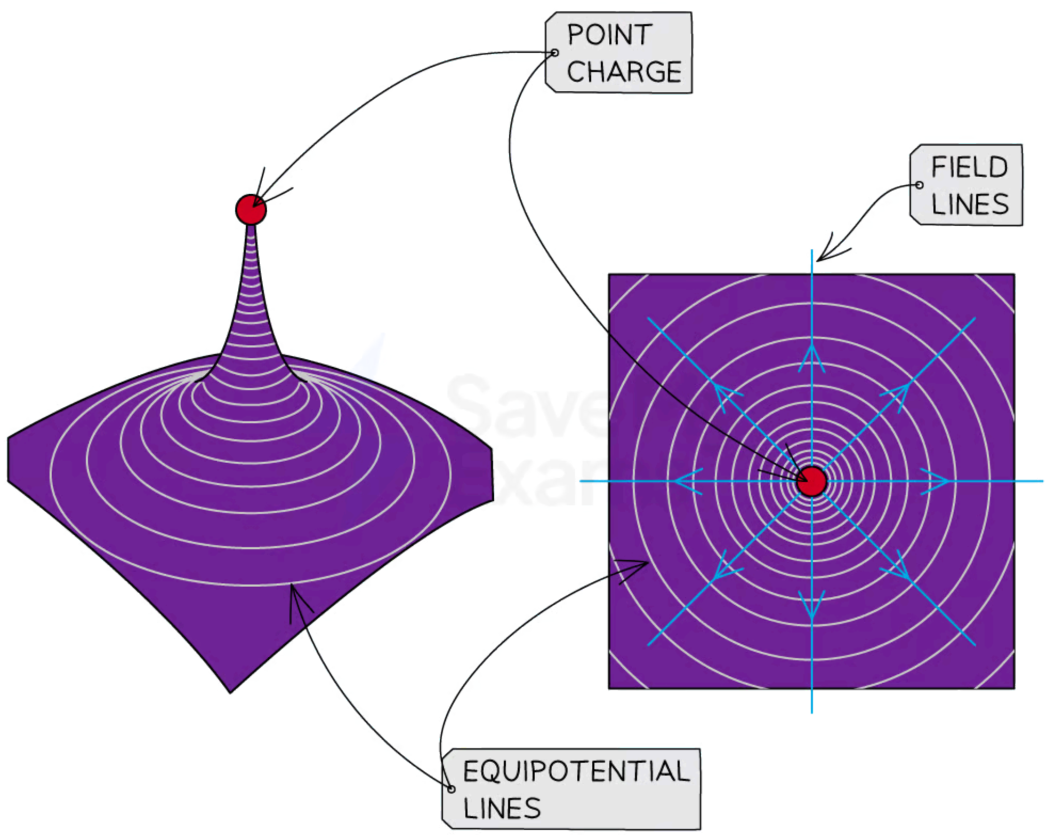
Your notes

Your notes

Electric Equipotential Surfaces (HL)

Electric Equipotential Surfaces

- Equipotential surfaces are lines of **equal electric potential**
  - They are always **perpendicular** to the electric field lines
  - In a radial field, the equipotential lines are represented by concentric circles around the charge
  - The equipotential lines become farther away from each other with increasing radius
  - In a uniform electric field, the equipotential lines are equally spaced
- If a charge moves along an equipotential surface (or line), **no work is done**
  - This means the potential energy of the charge does not change
- Equipotential lines are used to represent **potential gradient**
- For example, for a positive point charge:
  - The lines become **closer** together nearer the charge, this represents the potential gradient becoming steeper
  - If a positive test charge is pushed towards the charge, more work must be done to move it gradually closer



The left side image shows the equipotential lines for a point charge acting like contours on a map. They are perpendicular to the field lines, as shown on the right side image

Your notes

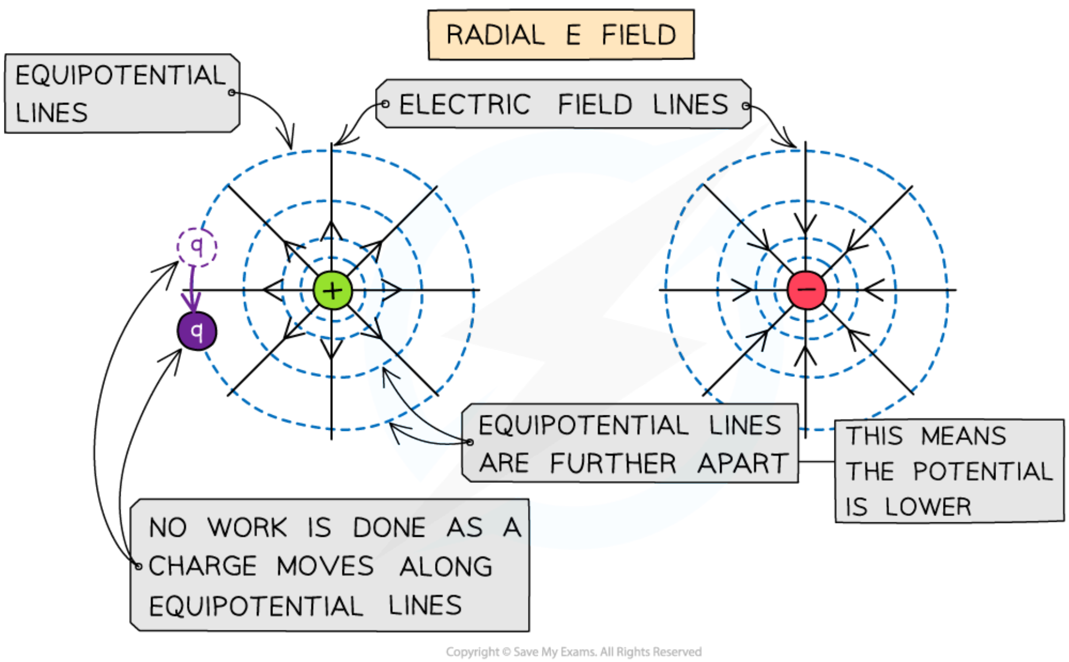
Your notes

Equipotential Surfaces & Electric Field Lines

- Equipotential surfaces can be drawn to represent the electric potential for a number of scenarios, such as
  - for a point charge
  - for multiple charges (up to four point charges)
  - inside and outside solid and hollow charged conducting spheres
  - between two oppositely charged parallel plates

Equipotential surface for a point charge

- In a **radial** field, such as around a point charge, the equipotential lines:
  - are concentric circles around the charge
  - become progressively further apart with distance



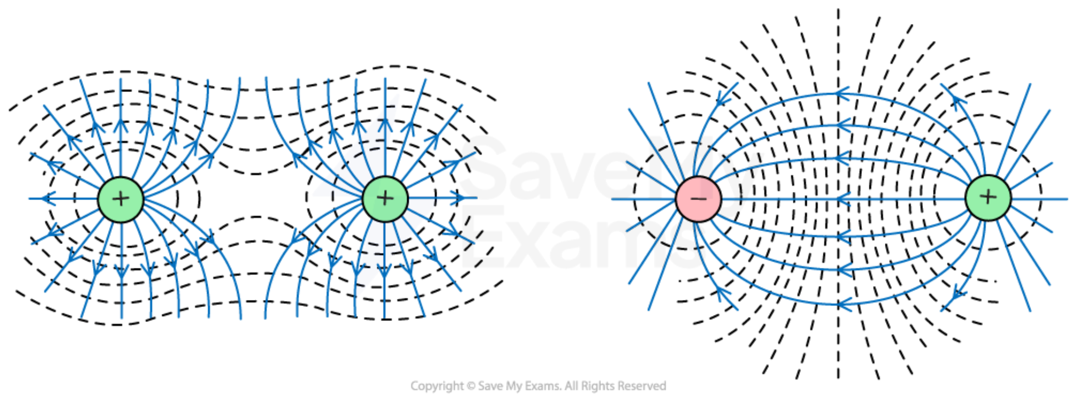
Equipotential lines for a radial electric field are concentric circles which increase in radius and are perpendicular to the field lines

- If a charged conducting sphere replaced a point charge, the equipotential surface would be the **same**

Equipotential surface for multiple charges

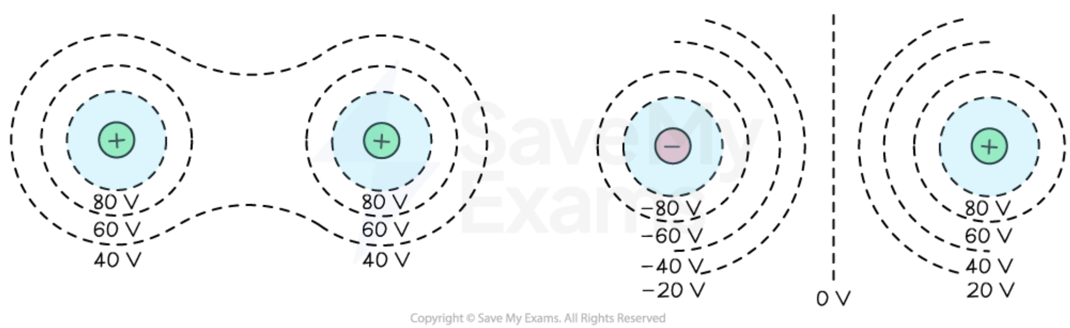
- The equipotential surfaces for a **dipole** (two opposite charges) and for two like charges are shown below:

Your notes



The equipotential surface for multiple charges can be obtained by drawing curves which are perpendicular to the field lines

- An equipotential surface between two **opposite** charges can be identified by a central line at a potential of 0 V
  - This is the point where the opposing potentials cancel
- An equipotential surface between two **like** charges can be identified by a region of empty space between them
  - This is the point where the resultant field is zero

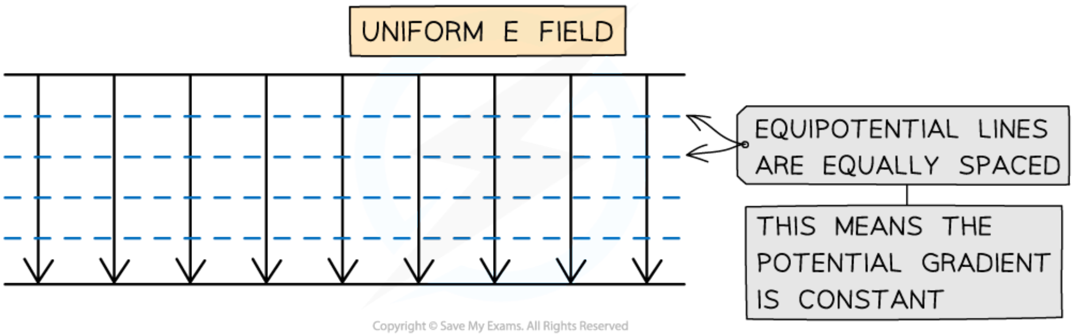


Equipotential lines show that the potential has the greatest value near the charge and decreases with distance

Equipotential surface between parallel plates

- In a **uniform** field, such as between two parallel plates, the equipotential lines are:
  - horizontal straight lines
  - parallel
  - equally spaced

Your notes

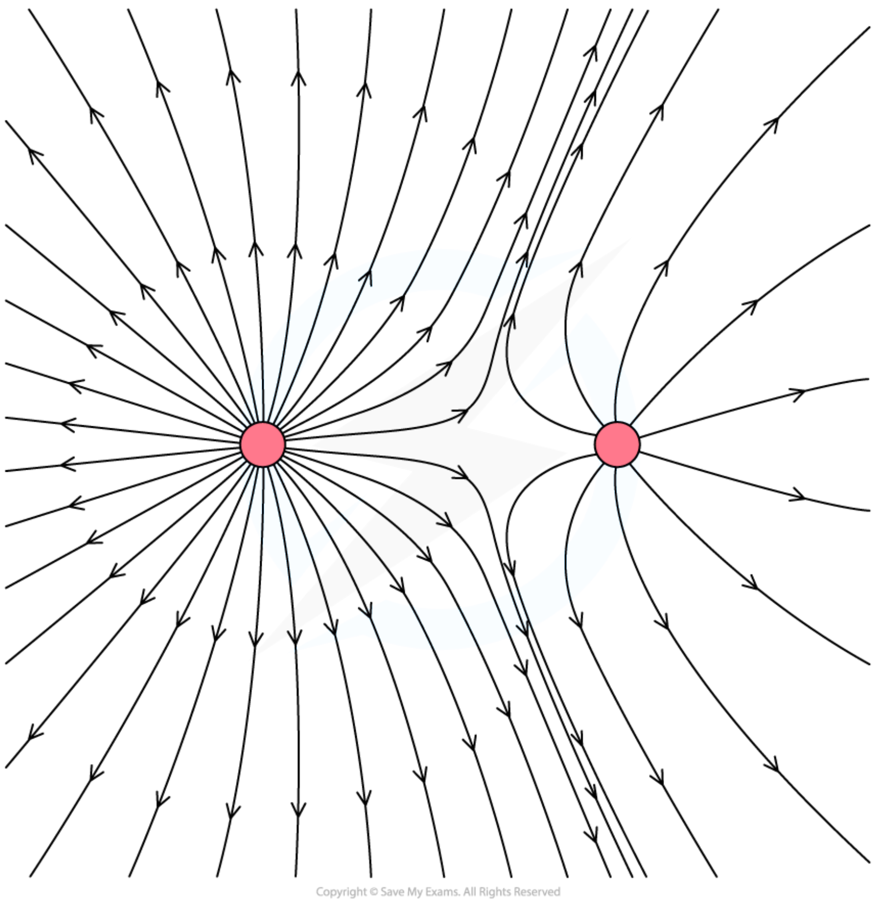


The equipotential lines for a uniform field are evenly spaced parallel lines which are perpendicular to the field lines

Your notes

Worked example

In the following diagram, two electric charges are shown which include the electric field lines



(a) Draw the lines of equipotential including at least four lines and at least one that encircles both charges

(b) By considering the field lines and equipotentials from part (a), state what can be assumed about the two charges

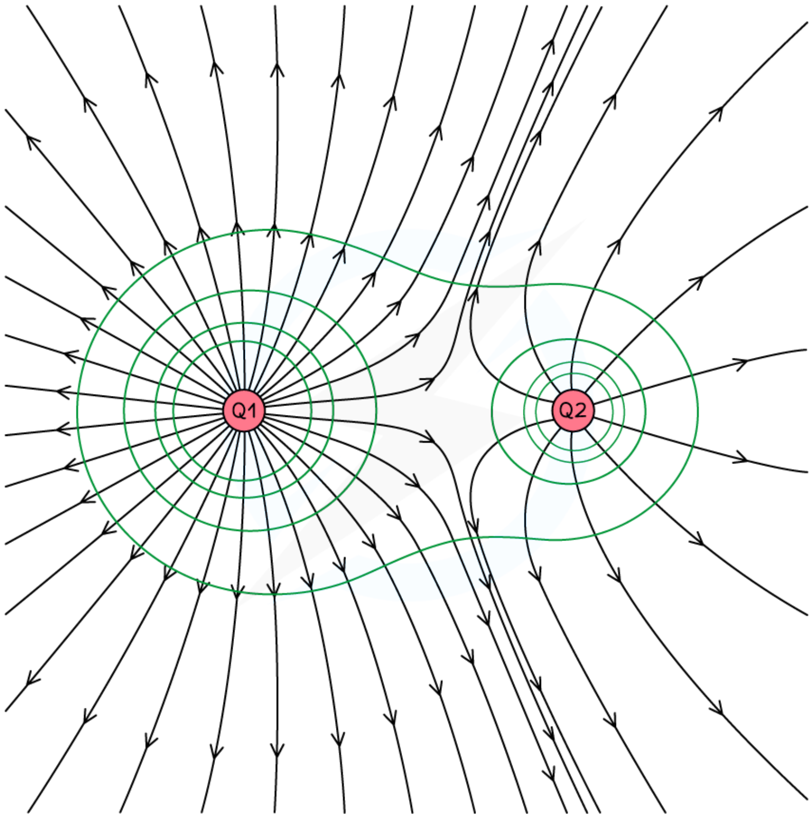
Answer:

Part (a)

- The lines of equipotential need to be perpendicular to the field lines at all times
- These lines are almost circular when they are near the charges
- And when moving out further the lines of equipotential cover both charges.

Your notes

- The lines of equipotential can be seen below



Part (b)

- It can be assumed that both charges are positive since the field lines point outwards.
- It can also be assumed that the charge on the left has a larger charge than the charge on the right since:
  - It has a greater density of field lines
  - It has a larger sphere of influence shown by the lines of equipotential
  - The point of zero electric field strength between the two charges is closer to the right charge

Examiner Tip

The distinction between radial and uniform fields is an important one, remember:

- a **radial** field is made up of lines which follow the **radius** of a circle
- a **uniform** field is made up of lines which are a **uniform** distance apart

When drawing equipotential lines, remember that they do **not** have arrows since they have no particular direction and are not vectors.

Your notes

Magnetic Fields

Representing Magnetic Fields

- A magnetic field is a **region of space** in which a **magnetic pole** will **experience a force**
- A magnetic field is created either by:
  - **Moving** electric charge
  - **Permanent** magnets
- Permanent magnets are materials that produce a magnetic field
- A stationary charge will **not** produce a magnetic field
- A magnetic field is sometimes referred to as a **B-field**
- A magnetic field is created around a **current-carrying wire** due to the movement of electrons
- Although magnetic fields are invisible, they can be observed by the force that pulls on magnetic materials, such as iron or the movement of a needle in a plotting compass

Magnetic Flux Density

- The strength of a magnetic field can be described by the density of its field lines
- The **magnetic flux density** *B* of a field is defined as

The number of magnetic field lines passing through a region of space per unit area

- Magnetic flux density is measured in **teslas** (T)
- One tesla, 1 T, is defined as

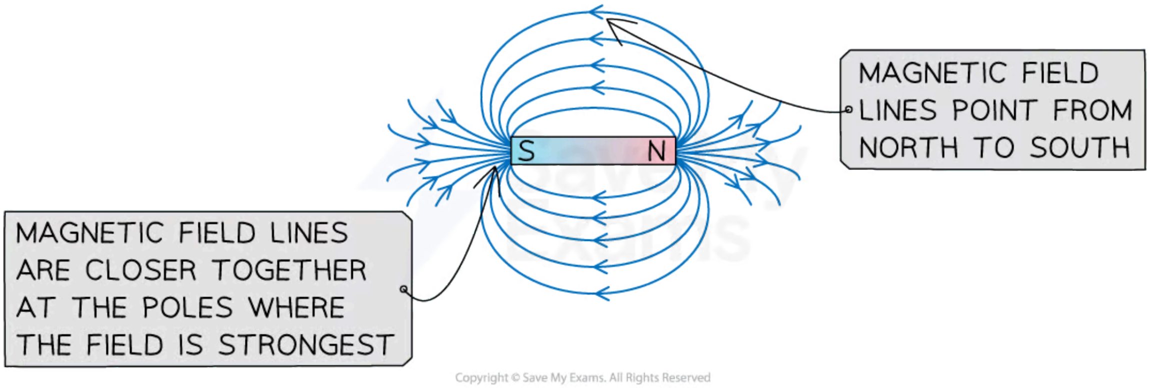
The flux density that causes a force of 1 N on a 1 m wire carrying a current of 1 A at right angles to the field

- The higher the flux density, the **stronger** the magnetic field i.e. regions where field lines are **closer** together
- The lower the flux density, the **weaker** the magnetic field i.e. regions where field lines are **further** apart

Representing Magnetic Fields

- Like with electric fields, field lines are used to represent the **direction** and **magnitude** of a magnetic field
- In a magnetic field, field lines are always directed from the **north** pole to the **south** pole

Your notes



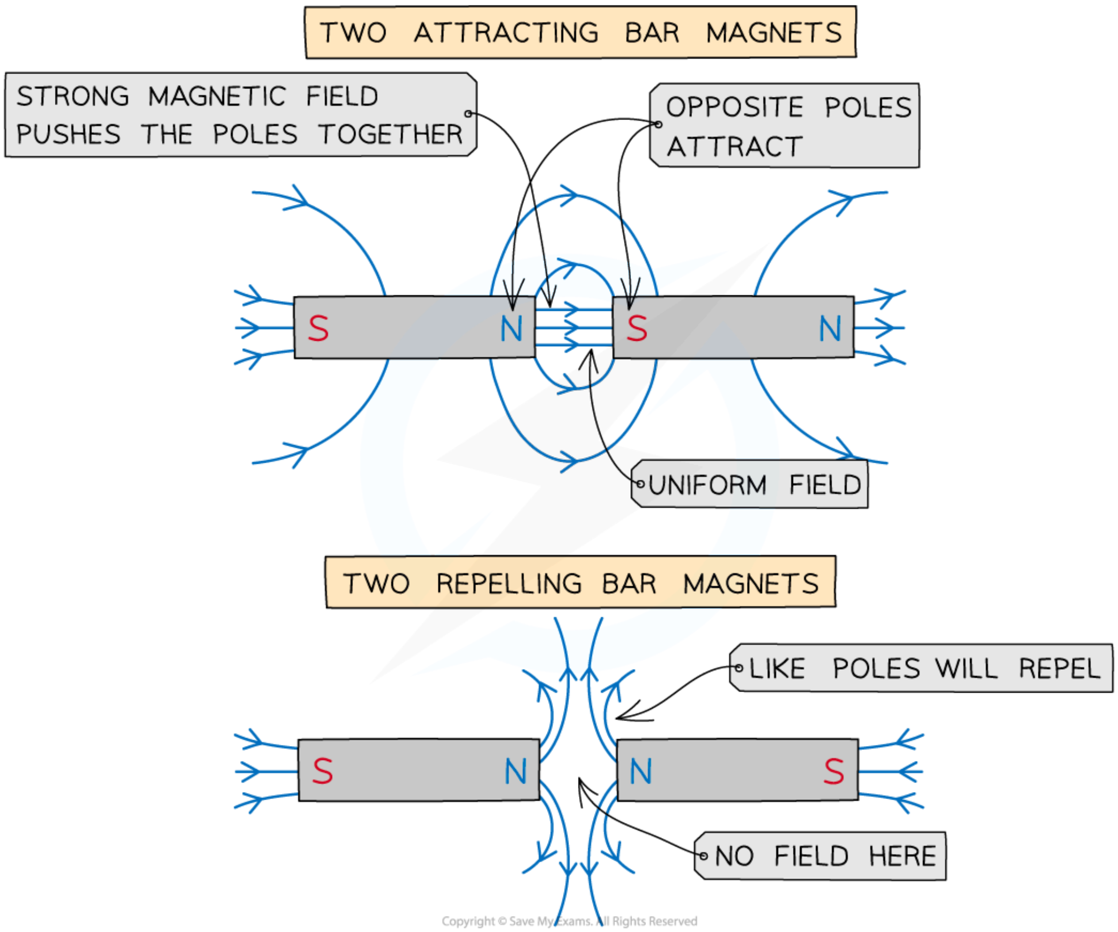
The magnetic field lines around a bar magnet show the field is strongest at the two poles

- The simplest representation of magnetic field lines can be seen around **bar magnets**
  - These can be mapped using iron filings or plotting compasses
- **The key aspects of drawing magnetic field lines are:**
  - Arrows point **out** of a north pole and **into** a south pole
  - The direction of the field line shows the direction of the force that a free magnetic north pole would experience at that point
  - The field lines are **stronger** the **closer** the lines are together
  - The field lines are **weaker** the **further apart** the lines are
  - Magnetic field lines **never** cross

Magnetic Field Between Two Bar Magnets

- When two bar magnets are pushed together, they either attract or repel each other:
  - Two **like** poles (north and north or south and south) **repel** each other
  - Two **opposite** poles (north and south) **attract** each other

Your notes



Two opposite poles attract each other and two like poles repel each other

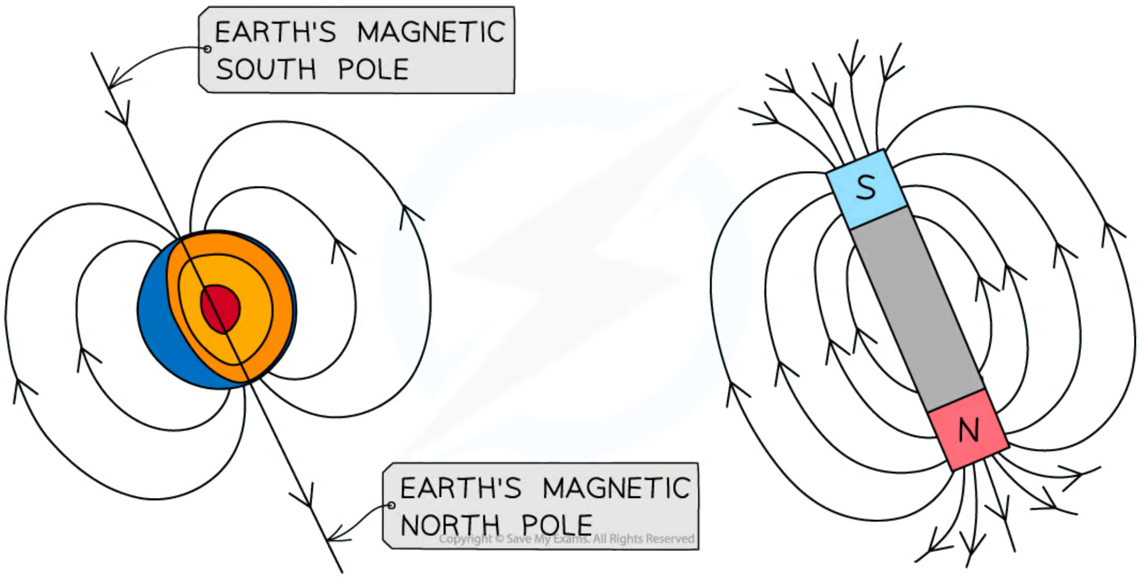
Uniform Magnetic Fields

- In a **uniform** magnetic field, the strength of the magnetic field is the same at all points
- This is represented by equally spaced parallel lines, just like electric fields

A uniform magnetic field has equally spaced field lines and is created when two opposite poles are held close together

The Earth's Magnetic Field

- On Earth, in the absence of any magnet or magnetic materials, a magnetic compass will always point north
- This is because the north pole of the compass is attracted to the Earth's magnetic south pole (which is the geographic north pole)



The Earth's magnetic field acts in a similar way to a bar magnet. A compass points to the Earth's magnetic south pole which is the geographic north pole

Your notes

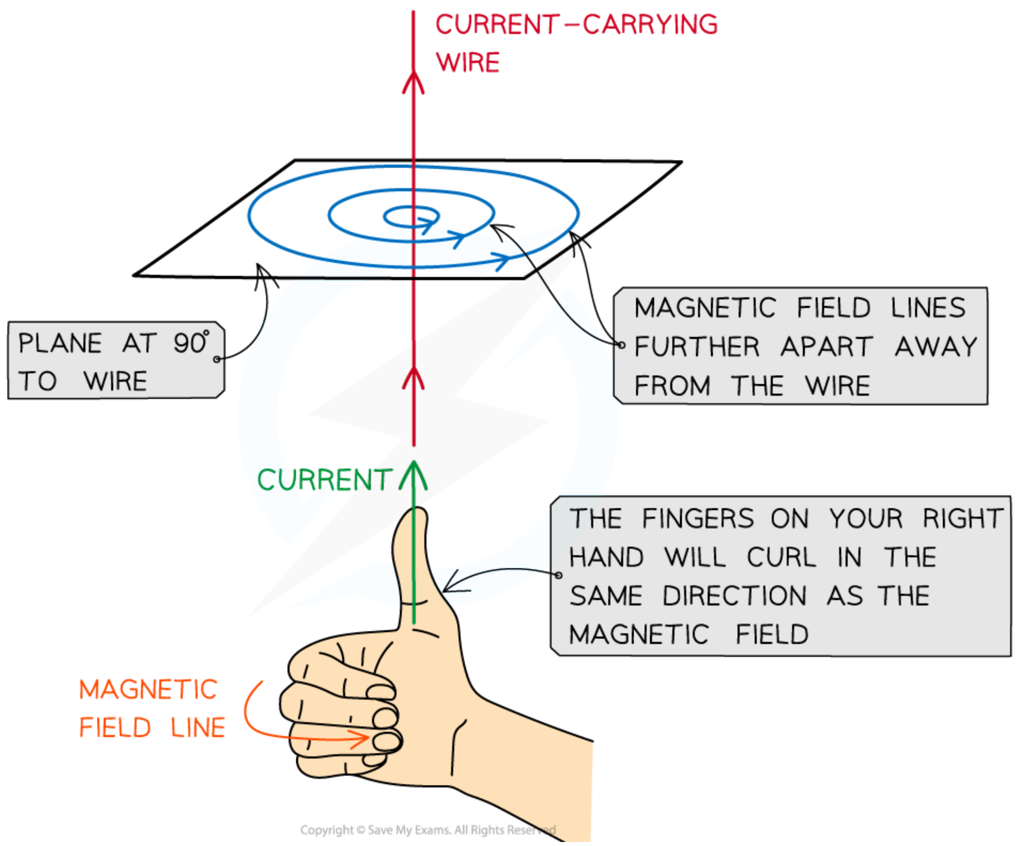
Your notes

Right Hand Grip Rule

- Magnetic fields are formed wherever a current flow, such as in:
  - long straight wires
  - long solenoids
  - flat circular coils

Magnetic Field around a Current-Carrying Wire

- Magnetic field lines in a current-carrying wire are circular rings, centred on the wire
- The field lines are closer together near the wire, where the field is strongest
- The field lines become further apart with distance from the wire as the field becomes weaker
- Reversing the current reverses the direction of the field



The direction of the field around a current-carrying wire can be determined using the right-hand grip rule

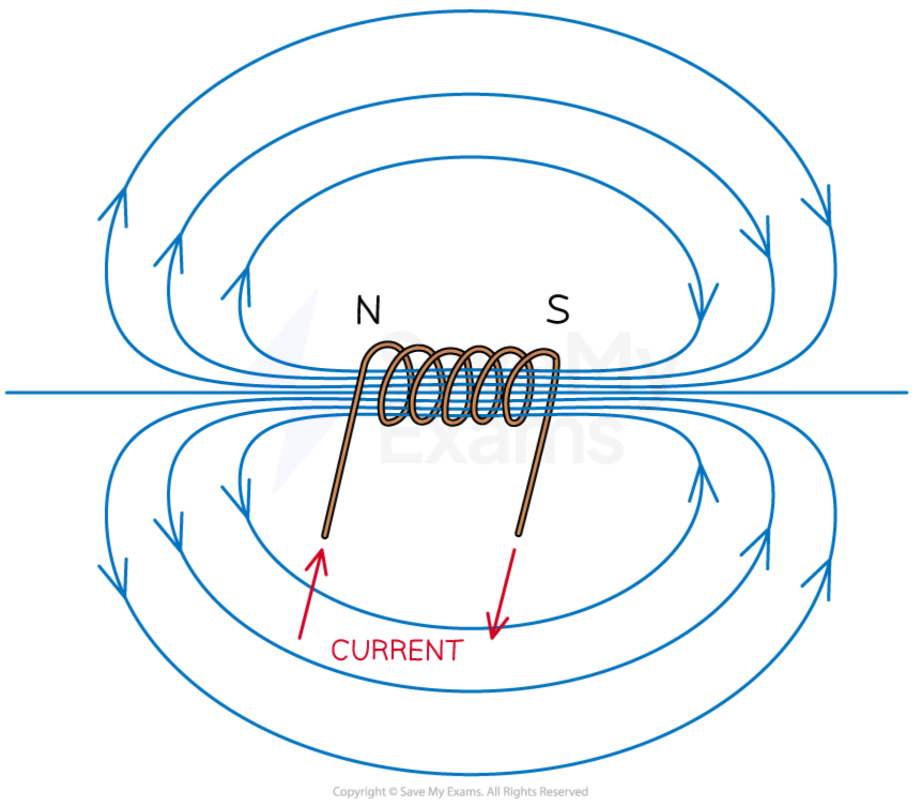
- The field lines are clockwise or anticlockwise around the wire, depending on the direction of the current
- The direction of the magnetic field can be determined using the **right-hand grip rule**
  - This is determined by pointing the **right-hand** thumb in the direction of the current in the wire and curling the fingers onto the palm

Your notes

- The direction of the curled fingers represents the direction of the magnetic field around the wire
- For example, if the current is travelling vertically upwards, the magnetic field lines will be directed anticlockwise, as seen from directly above the wire
- **Note:** the direction of the current is taken to be the conventional current i.e. from **positive** to **negative**, **not** the direction of electron flow

Magnetic Field around a Solenoid

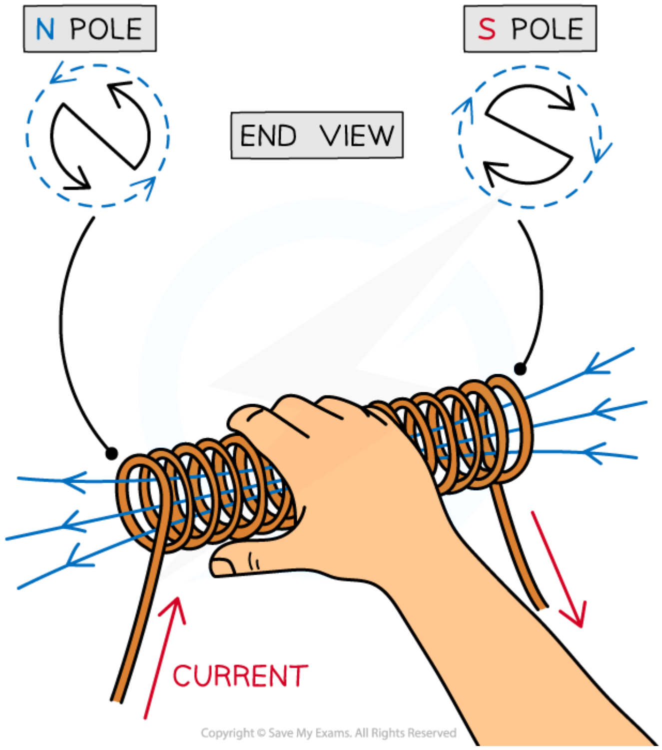
- As seen from a current-carrying wire, an electric current produces a magnetic field
- An electromagnet utilises this by using a coil of wire called a solenoid
    - This increases the magnetic flux density by adding more **turns** of wire into a smaller region of space
- One end of the solenoid becomes a north pole and the other becomes the south pole



The magnetic field lines around a solenoid are similar to a bar magnet

- As a result, the field lines around a solenoid are similar to a bar magnet
    - The field lines **emerge** from the **north** pole
    - The field lines **return** to the **south** pole
- The poles of the solenoid can be determined using the **right-hand grip rule**
    - The curled fingers represent the direction of the current flow around the coil
    - The thumb points in the direction of the field inside the coil, towards the **north pole**

Your notes

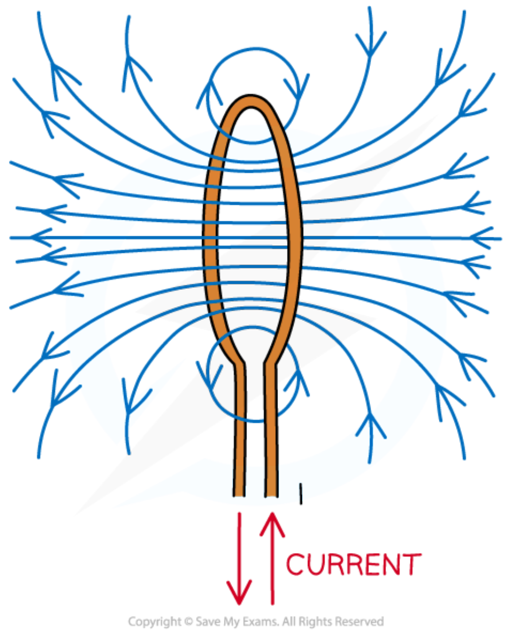


In a solenoid, the north pole forms at the end where the current flows anti-clockwise, and the south pole at the end where the current flows clockwise

Magnetic Field around a Flat Circular Coil

- A flat circular coil is equivalent to one of the coils of a solenoid
- The field lines emerge through one side of the circle (north pole) and enter through the other (south pole)
- As with a solenoid, the direction of the magnetic field depends on the direction of the current
  - This can be determined using the **right-hand grip rule**
  - It is easier to find the direction of the magnetic field on the straight part of the circular coil to determine which direction the field lines are passing through

Your notes

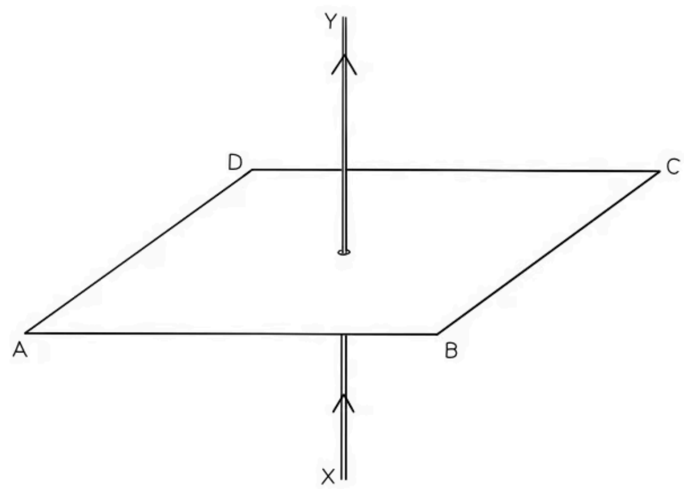


Magnetic field lines of many individual circular coils can be combined to make a solenoid

Your notes

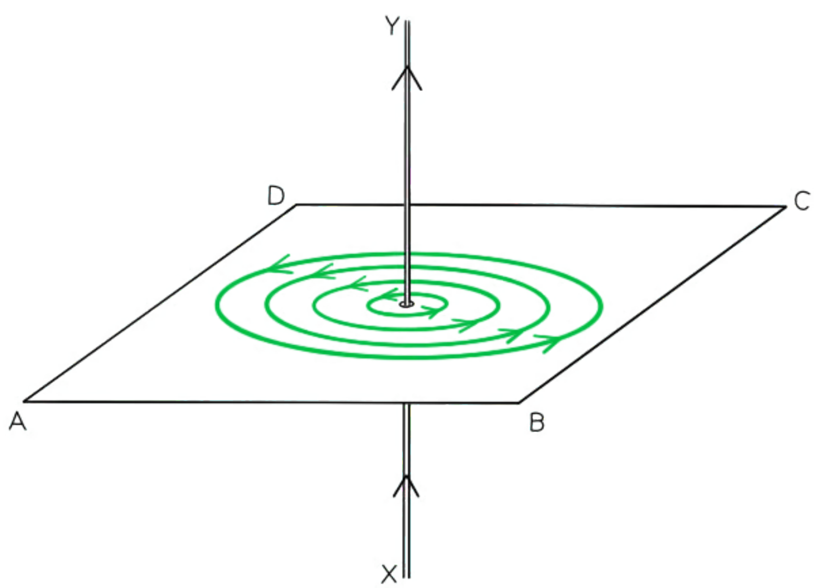
Worked example

The current in a long, straight vertical wire is in the direction XY, as shown in the diagram.



Sketch the pattern of the magnetic flux in the horizontal plane ABCD due to the current-carrying wire. Draw at least four flux lines.

Answer:



- Concentric circles

- Increasing separation between each circle
- Arrows drawn in an anticlockwise direction

Your notes

Examiner Tip

Remember to draw the arrows showing the direction of the field lines on every single field line you draw. Also, ensure that in a uniform magnetic field, the field lines are equally spaced.