Edexcel International A Level (IAL) Physics

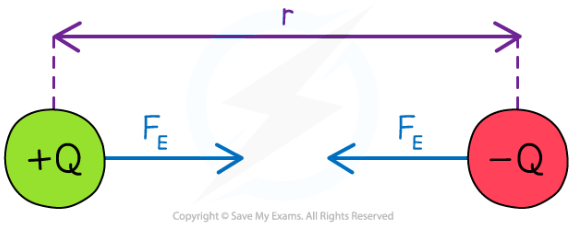
Your notes

Electric Fields

Contents

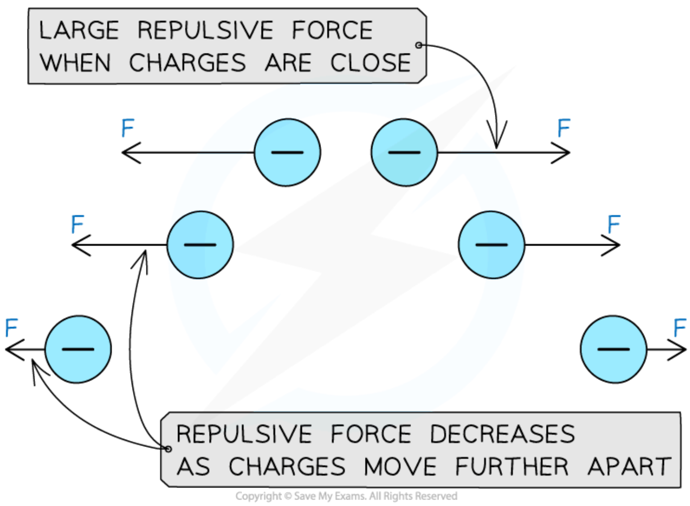
Defining an Electric Field

- An electric field is defined as a region of space in which a **charged** particle experiences a **force**
  - Hence, electric fields are a type of **force field**
- The charged particle could be stationary or moving, and will experience an electric force in that field
- All charged particles create their own electric fields
  - These fields exert an electrostatic force, F_E on other charged particles



The electrostatic force between two charges

- Like charges (positive and positive, or negative and negative) **repel** each other
  - This means the force on each charge are away from the other charge
- Opposite charged (positive and negative) **attract** each other
  - This means the force on each charge is towards the other charge
- The size of the force changes with distance



A repulsive force decreases with distance

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Examiner Tips and Tricks

Electric fields are slightly different in that a charged particle will experience a force in this field whether it's stationary or moving. Don't get this mixed up with a **magnetic** field, where a charged particle only experiences a force if it's **moving**.

Electric Field Strength

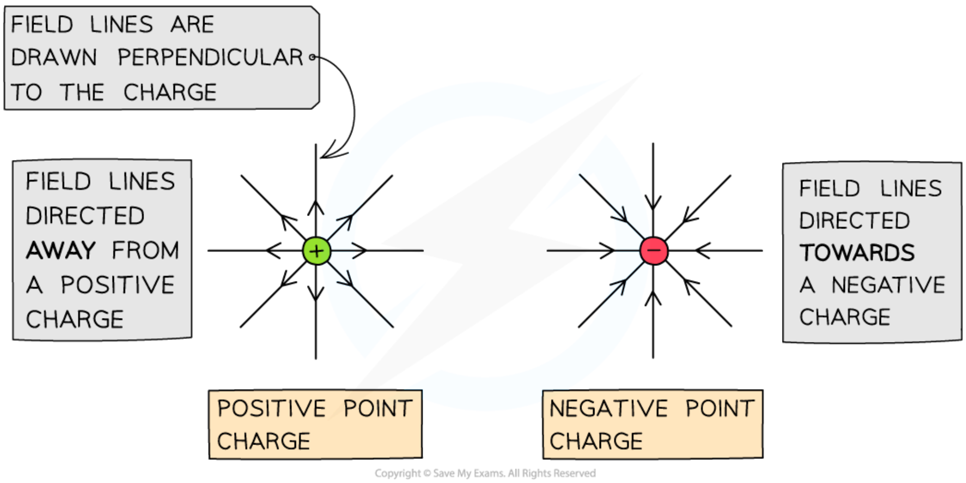
- The **electric field strength** at a point is defined as:

  The force per unit charge acting on a positive test 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
- Recall, the electric field strength is a **vector** quantity, it is always directed:
  - **Away** from a positive charge
  - **Towards** a negative charge
- This direction is also denoted by the direction of the electric field



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

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Worked Example

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

Calculate the charge of 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 values and calculate

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

Examiner Tips and Tricks

While the defining equation for electric field strength, $E = F / Q$ is defined for a positive test charge, it is still useable for negative charges in an electric field. You will find that, if you substitute a negative charge in for Q, the electric field strength E is also negative. This simply means that the vector representing the field points in the **opposite direction** than it would for a positive charge, as you should expect. Make sure you can interpret the direction of electric field lines for your exam!

Your notes

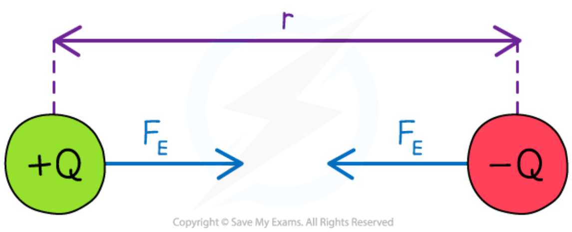
Electric Force between Two Charges

- All charged particles produce an electric field around them
  - 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 force F_E between two charges as expressed by Coulomb's Law is given by the equation:

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



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 to $(½)^2$ = ¼ of its original size
- ε_0 is a physical constant used to show the capability of a vacuum to permit electric fields
- If Q_1 and Q_2 are oppositely charged, then the electrostatic force F_E is negative

- This can be interpreted as an **attractive force** between Q_1 and Q_2

- If Q_1 and Q_2 are the same charge, then the electrostatic force F_E is positive
  - This can be interpreted as a **repulsive force** between Q_1 and Q_2

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Worked Example

An alpha particle is situated 2.0 mm away from a gold nucleus in a vacuum. Assuming they are point charges, calculate the magnitude of the 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

Answer:

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

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

Examiner Tips and Tricks

Remember to always **square** the distance, r between the charges!

Always look out for unit prefixes when substituting values into an equation. Check whether the charge has been converted into C instead of nC or μC, or the distance in mm to m to get a force *F* of newtons, N.

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Electric Field due to 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

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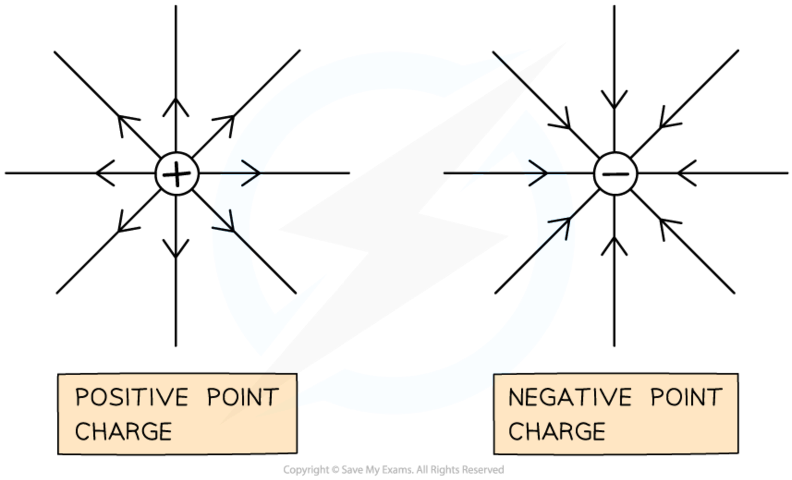
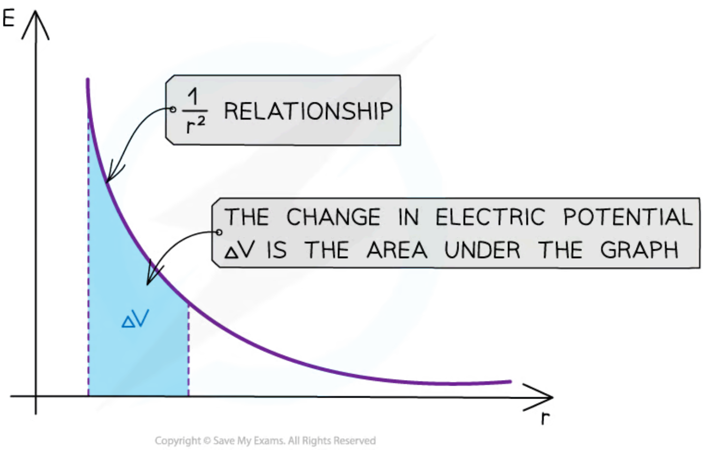


Positive and negative point charges and the direction of the electric field lines

- 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
  - The only difference is, gravitational field lines are always **towards** the mass, whilst electric field lines can be towards **or** away from the point charge
- The graph of *E* against *r* for a charge is:



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

- **The key features of this graph are**:

- The values for E are all positive
- 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 ΔV
- The graph has a steep decline as r increases

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Worked Example

Calculate the strength of the electric field at a distance of 2 m away from an electron, and state its direction.

Answer:

Step 1: Write out the equation for electric field strength

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

Step 2: Substitute quantities for charge, distance and permittivity of free space

- The charge on an electron $Q = -1.6 \times 10^{-19}$ C
- The distance $r = 2$ m
- Permittivity of free space $\varepsilon_0 = 8.85 \times 10^{-12}$
- Therefore:

$$E = \frac{-1.6 \times 10^{-19}}{4\pi \times (8.85 \times 10^{-12}) \times 2^2} = -3.6 \times 10^{-10} \text{ N C}^{-1}$$

Step 3: State the direction of the field

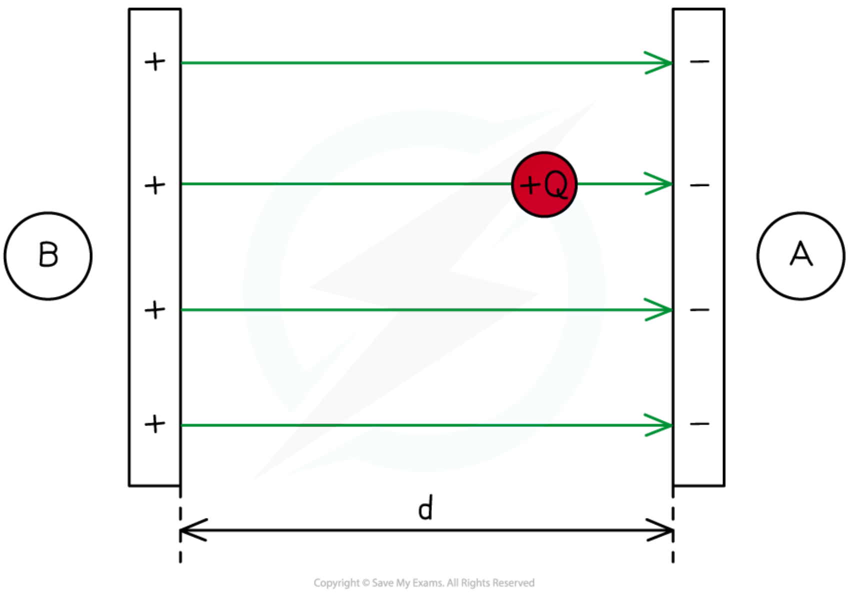
- The negative sign indicates the electric field is directed **towards the electron**

Examiner Tips and Tricks

Remember to **square** the distance in the electric field strength equation! Don't get this mixed up with the electric force between two charges equation, which has **two** charges (Q) in the equation, whilst the equation for E only has 1 Q, which is the one producing the electric field.

Electric Field & Potential

- A positive test charge has electric **potential energy** due to its position in an electric field
- The amount of electric potential energy depends on:
  - The magnitude of charge
  - The value of the **electric potential** in the field



Work is done on a positive test charge Q to move it from the negatively charged plate A to the positively charged plate B. This means its electric potential energy increases

- Electric potential is defined as the amount of work done per unit of charge at that point
- A stronger electric field means the electric potential changes **more rapidly** with distance as the test charge moves through it
- Hence, the relationship between the electric field strength and the electric potential is summarised as:

  The electric field strength is proportional to the gradient of the electric potential

- This means:
  - If the electric potential changes very rapidly with distance, the electric field strength is large
  - If the electric potential changes very gradually with distance, the electric field strength is small

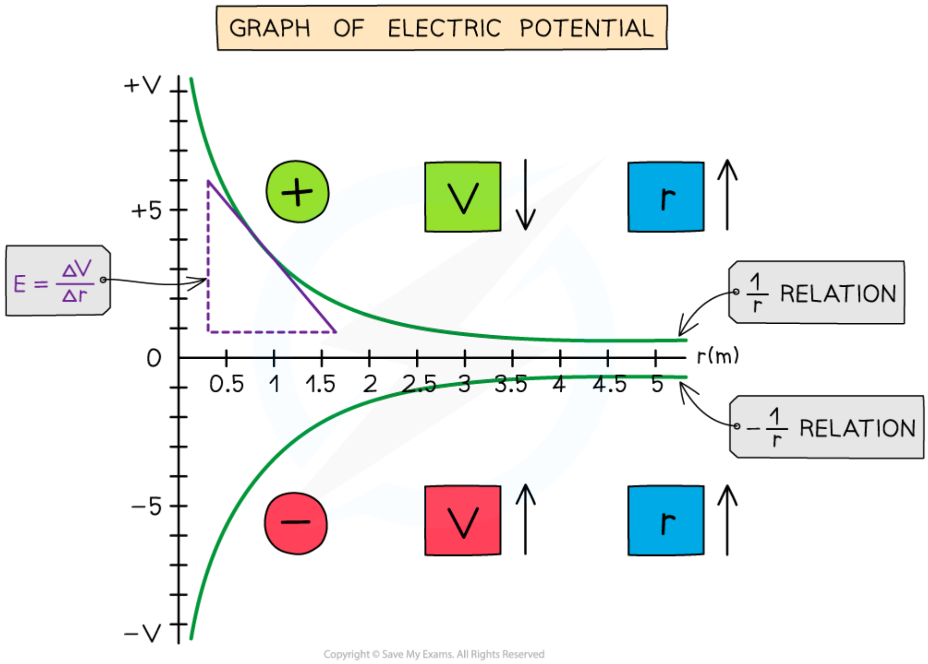
- An electric field can be defined in terms of the variation of **electric potential** at different points in the field**:**

  The electric field at a particular point is equal to the gradient of a potential-distance graph at that point

- The potential gradient in an electric field is defined as:

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

- The graph of potential *V* against distance *r* for a negative or positive charge is:



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:**
  - The values for *V* are all negative for a negative charge
  - The values for *V* are all positive for a positive charge
  - As *r* increases, *V* against *r* follows a 1/*r* relation for a positive charge and -1/*r* relation for a negative charge
  - The **gradient** of the graph at any particular point is the value of *E* at that point
  - The graph has a shallow increase (or decrease) as *r* increases
- The electric potential changes according to the charge creating the potential as the distance *r* increases from the centre:
  - If the charge is **positive**, the potential **decreases** with distance

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- If the charge is **negative**, the potential **increases** with distance

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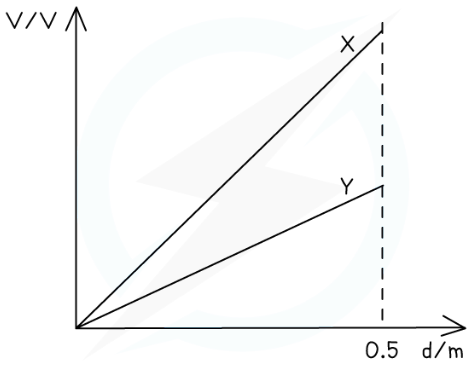
Worked Example

An electric field is set up between two pairs of oppositely charged plates, set X and set Y.

A graph showing how the electric potential *V* varies with distance *d* is shown for both set X and set Y.



State and explain which set creates the largest electric field strength.

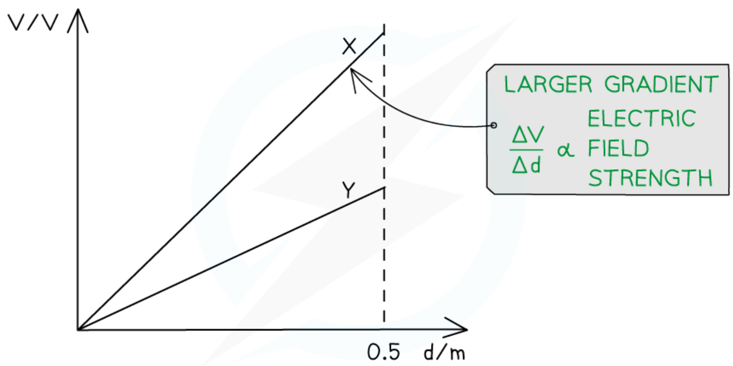
Answer:

Step 1: Recall the relationship between electric field strength and electric potential

- The electric field strength is proportional to the **gradient** of the electric potential

Step 2: Interpret the gradient of the potential-distance graph

- Set X has a larger gradient than set Y



Step 3: State and explain the conclusion

- Set X creates a larger electric field strength

- This is because the **gradient** of the potential between the plates is larger than it is for set Y

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Examiner Tips and Tricks

Remember that whether the electric potential increases or decreases depends on the charge that is producing the potential!

Electric Field between Parallel Plates

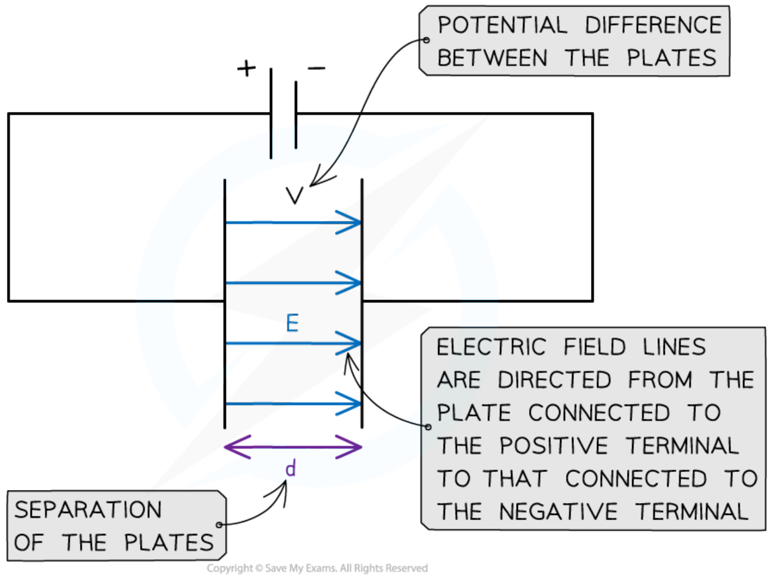
- The magnitude of the electric field strength in a **uniform** field between two charged parallel plates is defined as:

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

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

- The electric field strength is now defined by the units **V m^{-1}**
  - Therefore, the units V m^{-1} are equivalent to the units **N C^{-1}**
- The equation shows:
  - The greater the **voltage** (potential difference) 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.

Answer:

Step 1: Write down the known values

- Potential difference, $V = 7.9$ kV $= 7.9 \times 10^3$ V
- Distance between plates, $d = 3.5$ 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

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

Examiner Tips and Tricks

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 $E = F/Q$)

Your notes

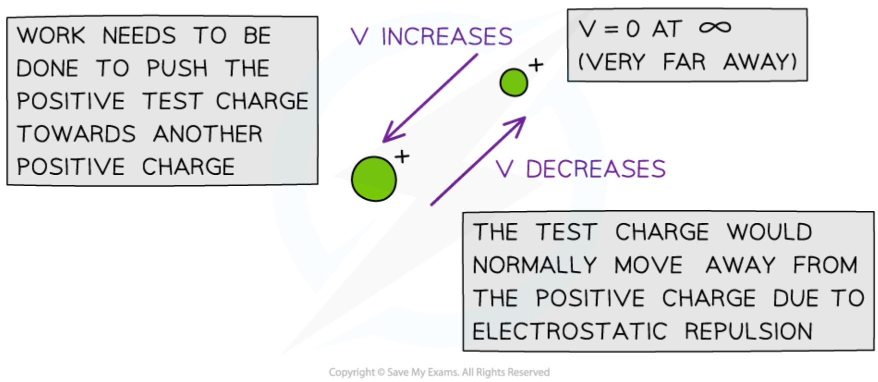
Electric Potential for a Radial Field

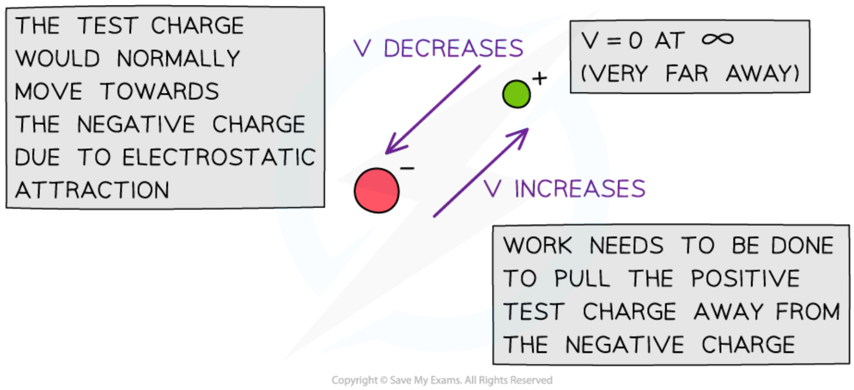
Electric Potential Energy

- In order to move a positive charge closer to another positive charge, work must be done to overcome the force of repulsion between them
  - Similarly, to move a positive charge away from a negative charge, work must be done to overcome the force of attraction between them
- Energy is therefore transferred to the charge that is being pushed upon
  - This means its **potential energy** increases
- If the positive charge is free to move, it will start to move away from the repelling charge
  - As a result, its potential energy decreases back to 0
- This is analogous to the gravitational potential energy of a mass increasing as it is being lifted upwards and decreasing as it falls
- The electric potential at a point is defined as:

  The work done per unit charge in bringing a positive test charge from infinity to that point

- Electric potential is a **scalar** quantity
  - This means it doesn't have a direction
- However, you will still see the electric potential with a positive or negative sign. This is because the electric potential is:
  - **Positive** around an isolated positive charge
  - **Negative** around an isolated negative charge
  - **Zero** at infinity
- Positive work is done to move a positive test charge from infinity to a point around a positive charge and negative work is done to move it to a point around a negative charge. This means:
  - When a positive **test charge** moves closer to a **negative** charge, its electric potential **decreases**
  - When a positive test charge moves closer to a **positive** charge, its electric potential **increases**





The electric potential V decreases in the direction the test charge would naturally move in due to repulsion or attraction

Electric Potential due to a Point Charge

- The **electric potential** in the radial field due to a **point charge** is defined as:

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

- Where:
  - V = the electric potential (V)
  - Q = the point charge producing the potential (C)
  - ε_0 = permittivity of free space (F m^{-1})
  - r = distance from the centre of the point charge (m)
- This equation shows that for a positive test charge:
  - As the distance r from the charge Q **decreases**, the potential V **increases** (becomes more positive)

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- This is because more work has to be done on the positive test charge to overcome the repulsive force of Q
- For a negative test charge:
  - As the distance from the charge *r* **decreases**, the potential *V* **decreases** (becomes more negative)
  - This is because less work has to be done on the negative test charge since the attractive force becomes stronger the nearer it gets to Q

- Unlike the **gravitational potential** equation, the electric potential can be positive or negative, because Q can be positive or negative
- The electric **potential** varies according to 1 / r
  - Note, this is different to electric **field strength**, which varies according to 1 / r^2

Worked Example

The electric potential at a distance *r* from a proton is *V*.

What is the value of the electric potential at a distance three-times farther?

Answer:

Step 1: Write the equation for electric potential

- The electric potential is given by the equation:

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

Step 2: Write the transformed equation for a distance three times as large

- The charge Q remains constant (due to the proton)
- The potential *V* becomes *V'*
- The distance *r* becomes 3*r*
- Hence the transformed equation becomes:

$$V' = \frac{Q}{4\pi\varepsilon_0 (3r)} = \frac{1}{3}\frac{Q}{4\pi\varepsilon_0 r} = \frac{1}{3}V$$

Step 3: Write a conclusion

- Therefore, when the distance from a charge Q gets three times larger, the value of the electric potential decreases by a factor 1/3, because the potential is inversely proportional to distance *r*

Your notes

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Examiner Tips and Tricks

- Electric **potential** *V* is inversely proportional to radial distance, $V \propto \frac{1}{r}$
- Electric **field strength** *E* is inversely proportional to radial distance squared, $E \propto \frac{1}{r^2}$
- Make sure you remember these variations and that you can describe them in words!

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.

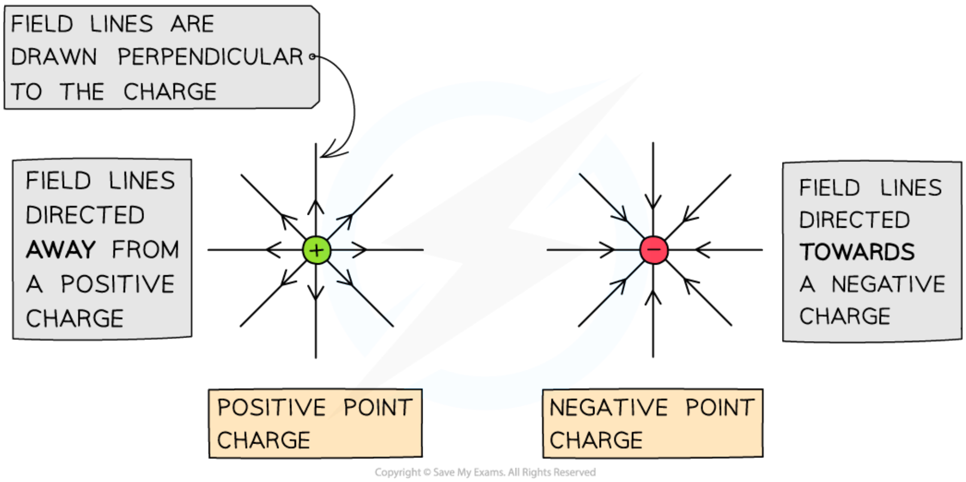
Using Field Lines & Equipotential Diagrams

Electric field lines

- 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
  - electric field strength is **constant** at all points in the field
  - the force acting on a test charge has the **same** magnitude and direction at all points in the field
- In a **radial** electric field:
  - the field lines are equally spaced as they exit the surface of the charge but the distance between them **increases** with distance
  - the electric field strength **decreases** with distance from the charge producing the field
  - the magnitude of the force acting on a test charge **decreases** with distance

Electric field around a point charge

- Around a point charge, the electric field is **radial** and the 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**

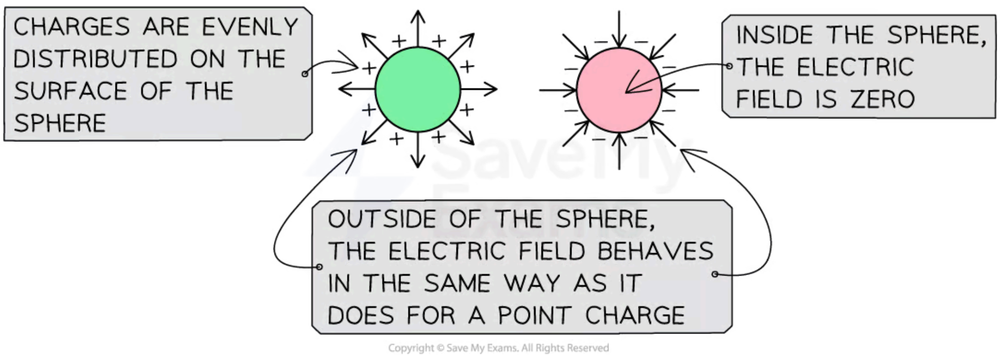


Electric field lines around a point charge are directed away from a positive charge and towards a negative charge

- A radial field spreads uniformly to (or from) the charge in all directions, and the strength of the field is indicated by the spacing of the field lines
  - 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
  - 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 becomes charged, the electric field around it is the **same** as it would be if all the charge was concentrated at the **centre**
  - This means that a charged sphere can be treated in the same way as a **point charge** in calculations

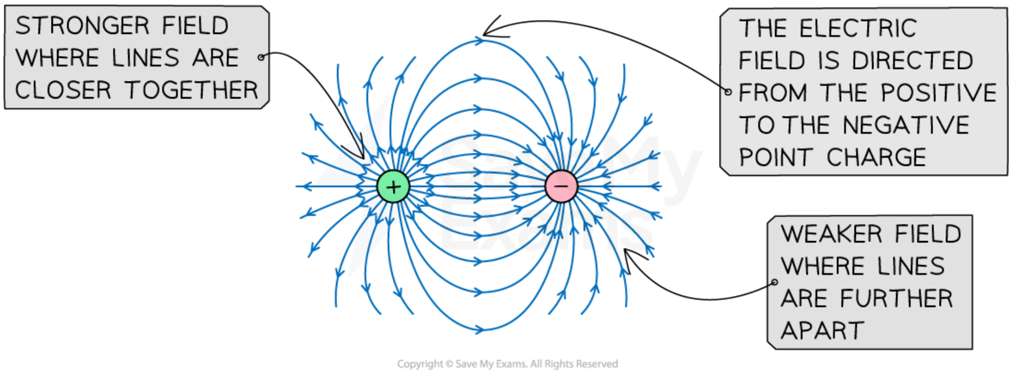


Electric field lines around a charged conducting sphere are similar to the field lines around a point charge

- **Note:** field lines are **always perpendicular** to the surface of a conducting sphere

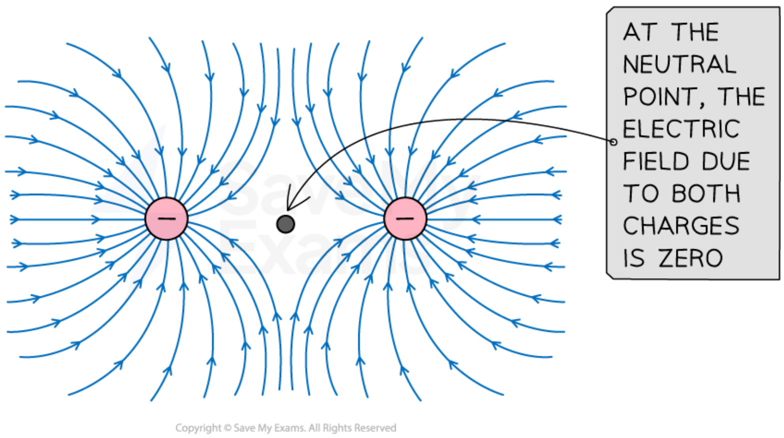
Electric field between two point charges

- 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



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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

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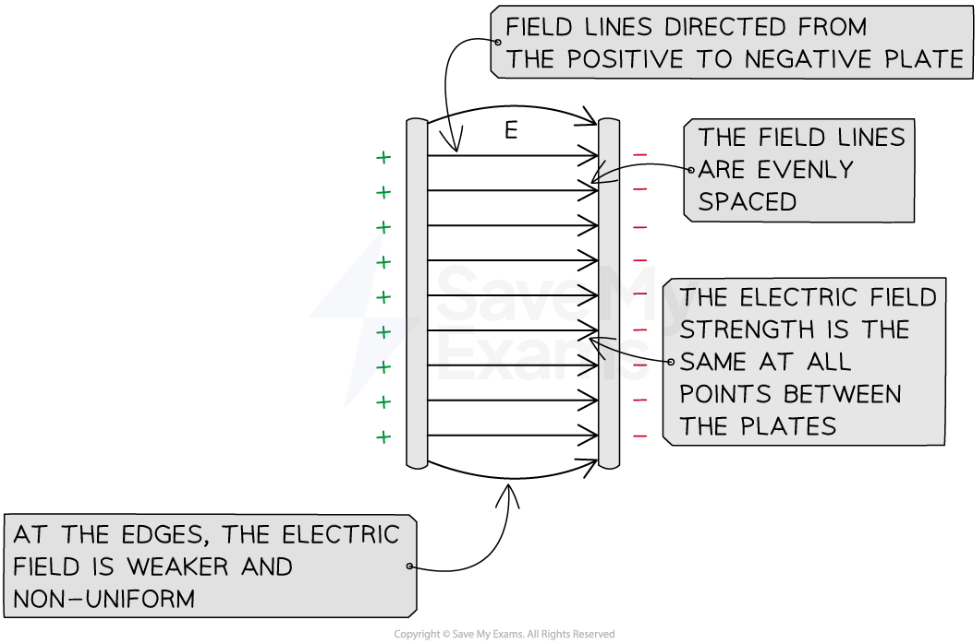
Electric field between two parallel plates

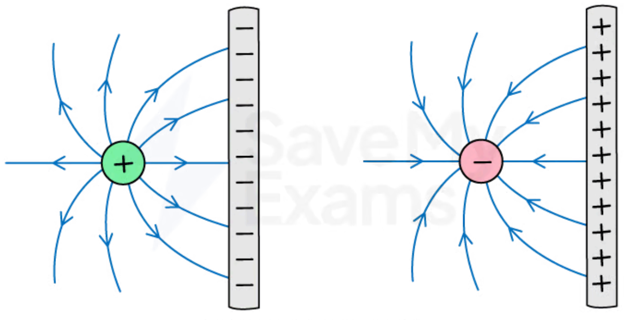
- When a potential difference is applied between two parallel plates, they become charged
  - The electric field between the plates is **uniform**
  - The electric field beyond the edges of the plates is **non-uniform**



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



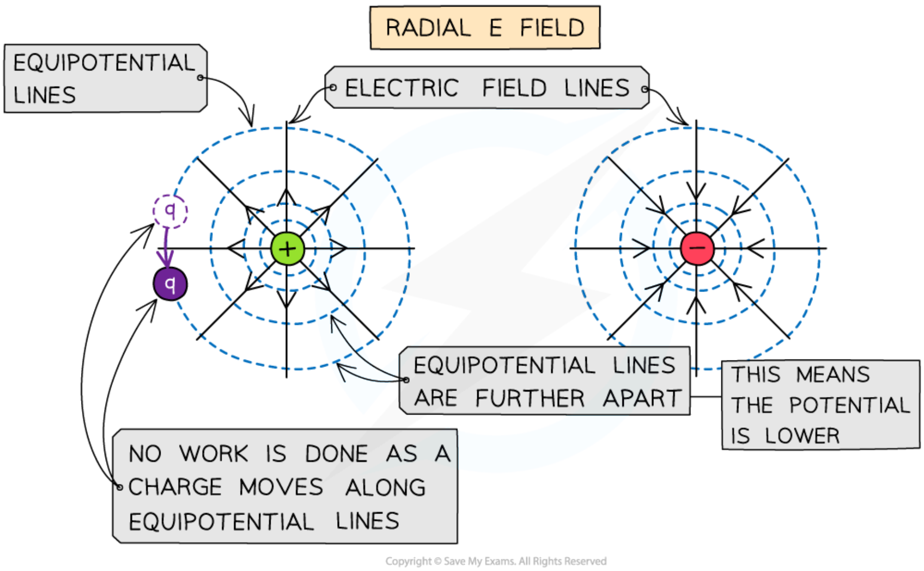
The electric field lines between a point charge and a parallel plate are similar to the field between two opposite charges. The field lines become parallel when they touch the plate

Equipotential diagrams

- Equipotential lines (2D) and surfaces (3D) join together points that have the **same electric potential**
- These are always:
  - **perpendicular** to the electric field lines in both radial and uniform fields
  - represented by **dotted** lines (unlike field lines, which are solid lines with arrows)
  - an **equal distance** from the source charge
- Equipotential surfaces can be drawn to represent a fixed electric potential for a number of scenarios, such as
  - for a point charge
  - for two or more charges
  - 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

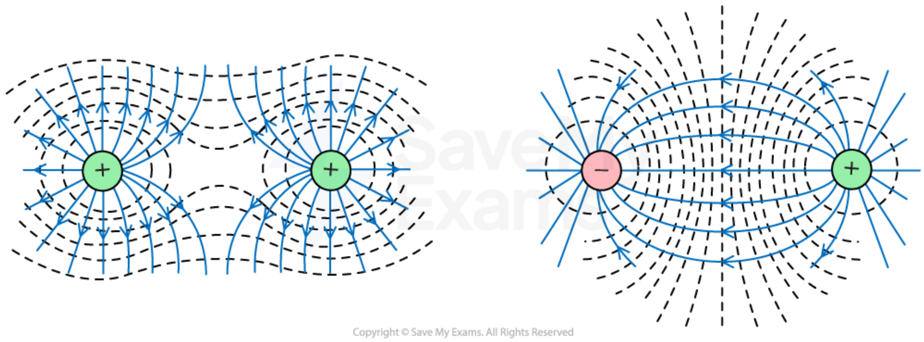


Equipotential lines for a radial electric field are concentric circles which increase in radius and are perpendicular to the field lines

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

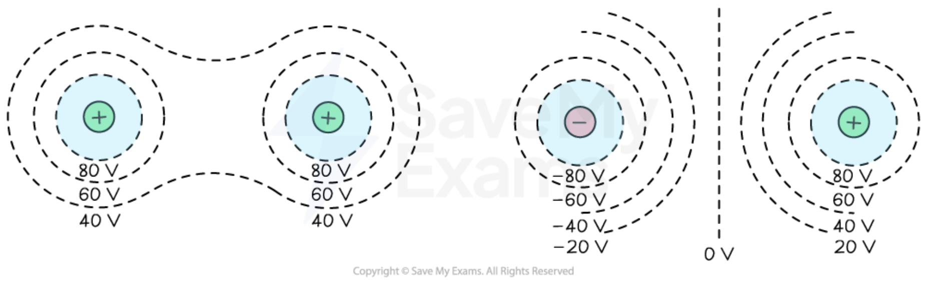
Equipotential surface for multiple charges

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



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

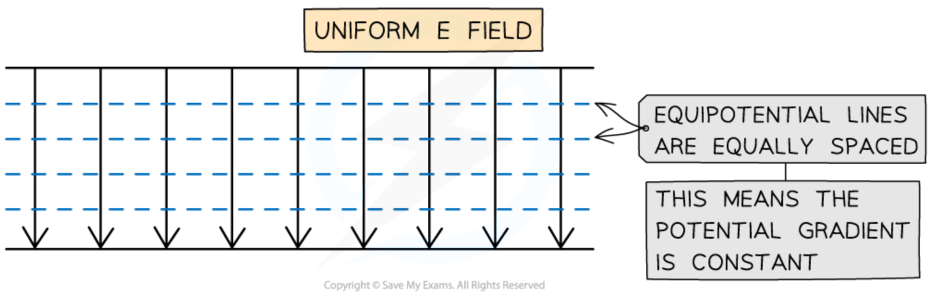
- An equipotential surface between two **opposite** charges can be identified by a central line at a potential of 0 V
  - This is the point where the opposing potentials cancel
- An equipotential surface between two **like** charges can be identified by a region of empty space between them
  - This is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



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

- The spacing between equipotential lines indicates the strength of the electric field
  - This is because they represent **potential gradient**
- Hence, equally spaced equipotential lines indicate a region of **constant** electric field strength

Worked Example

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

Your notes

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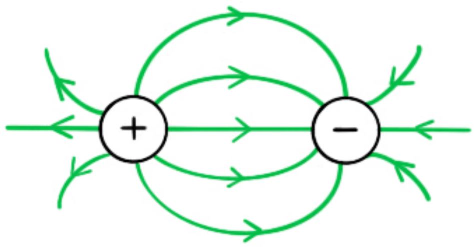
Answer:

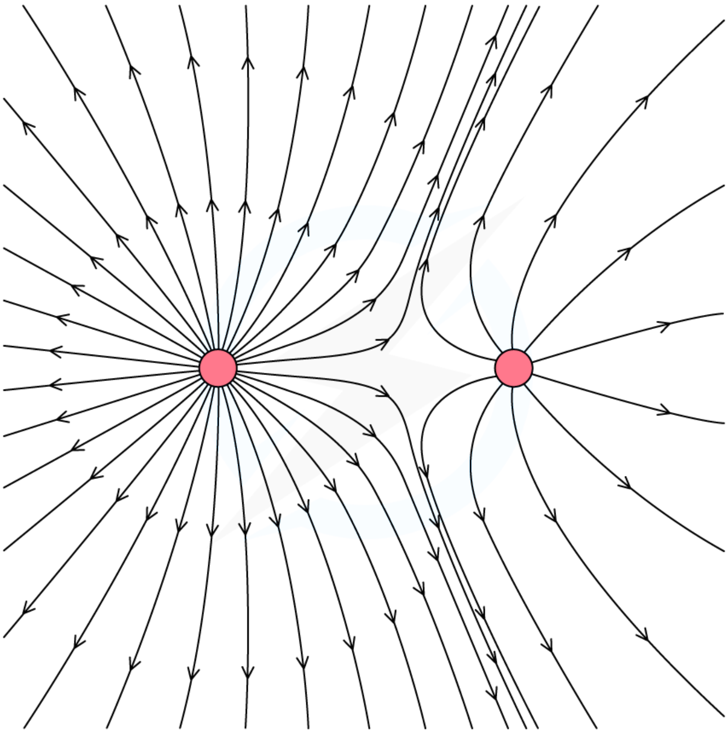
- Electric field lines around point charges have arrows which point radially outwards for positive charges and radially inwards for negative charges
- Arrows (representing force on a positive test charge) point **from the positive charge to the negative charge**



Worked Example

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

Your notes



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

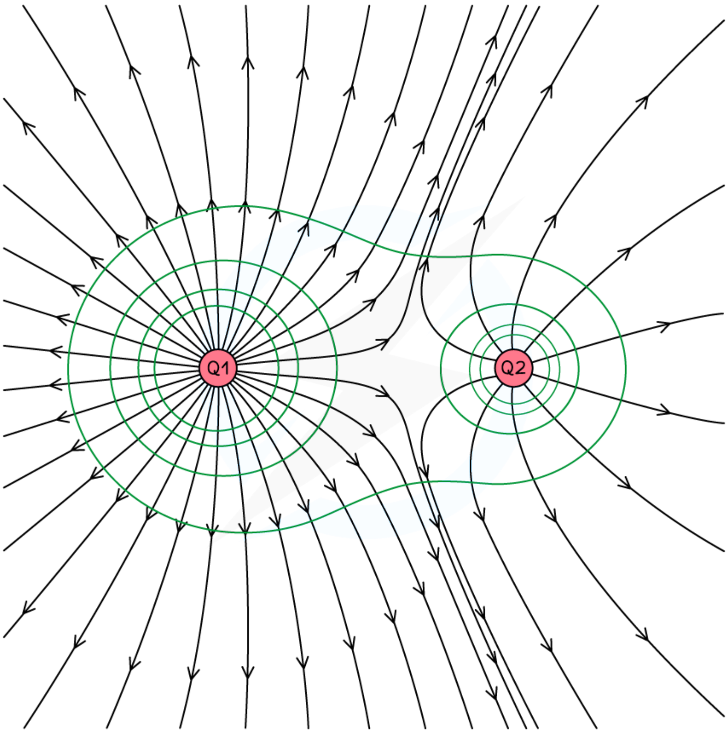
(b) By considering the field lines and equipotentials from part (a), state what can be assumed about the two charges

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.
- The lines of equipotential can be seen below

Your notes



Your notes

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 Tips and Tricks

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.

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.