

MASTERING A-LEVEL PHYSICS PAPER 2

CHAPTER 4: ELECTROSTATICS

CONDUCTORS, INSULATORS AND SEMI-CONDUCTORS

- **Insulators** are substances which can be electrified by rubbing. They have electrons which are firmly bound to their atom and cannot move from one atom to another. Examples of insulators include paper, wood, rubber, glass, wool, fur, silk, e.t.c.
- **Conductors** are substances which cannot be electrified by rubbing. They have electrons which are weak bound to their atom and can freely move from one atom to another. Most metals like copper, aluminum, iron, gold, and silver are good conductors. The human body is also a conductor.
- **Semi-conductors** are substance whose conductive properties are between conductors and insulators. They have very few electrons and the number of electrons can be increased by heating the materials. Examples of semiconductors include Germanium, Silicon.

Differences between conductors and insulators in terms of static electricity

(1). Electron Flow:

- Conductors allow free flow of electrons from one atom to another. In conductors, electrons move freely through the material, creating an electric current.
- Insulators impede the flow of electrons. Electrons are tightly bound within atoms, restricting their movement.

(2). Electrical Energy Transfer:

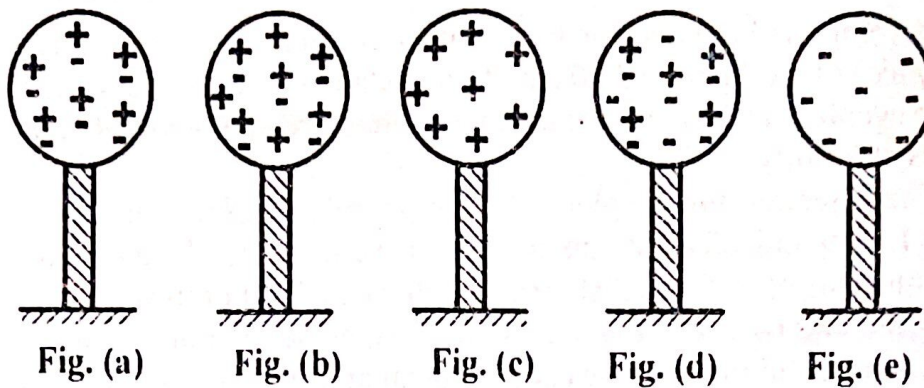
- **Conductors:** Permit electrical energy to pass through them. When an electrically charged electron enters a conductor, it displaces other free electrons, creating a chain reaction of charge flow.
- **Insulators:** Do not allow electrical energy to pass through. Their atomic structure prevents free electron movement, making them poor conductors of electricity.

(3). Safety Implications:

- Touching a conductor connected to a live circuit can result in electrocution due to the free flow of electrons.
- Insulators protect us from electric shock by resisting the flow of electrons.

Neutral, Positive and Negative conductors

A conductor can be either neutral, positively charged or negatively charged as shown below:



- **Neutral conductor:** A conductor is said to be neutral if it has an equal number of positive and negative charges. [See fig. (a) above].
- **Positively charged conductor:** A conductor is said to be positively charged if it loses some electrons, resulting in an excess of positive charge. [See fig. (b) above]. This net/excess positive charge remains balanced and distributed homogeneously on the conductor's surface. [See fig. (c) above].
- **Negatively charged conductor:** A conductor is said to be negatively charged if it gains some electrons, resulting in an excess of negative charge. [See fig. (d) above]. This net/excess negative charge remains balanced and distributed homogeneously on the conductor's surface. [See fig. (e) above].

ZERO POTENTIAL

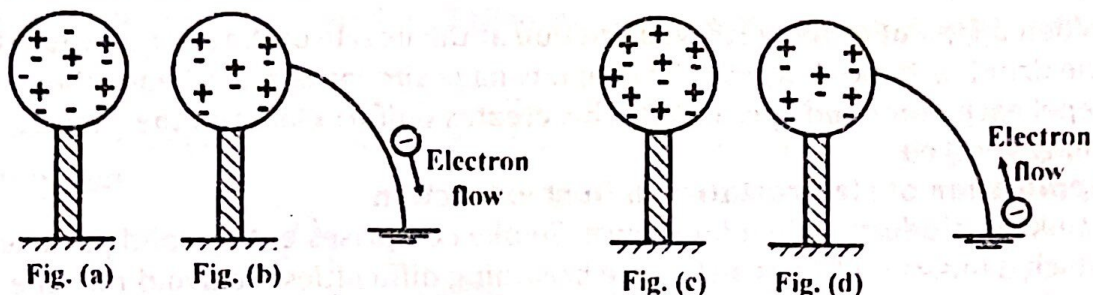
The earth is a good electric conductor such that if one point on it is at a higher positive potential than the other, electrons would flow through from the lower positive potential (negative potential) to a higher positive potential until the potentials are equal to zero. The potential of the earth will not be affected due to loss or gain of electrons because of its size. Hence the earth is called a practical zero potential.

EARTHING/GROUNDING A CONDUCTOR

Earthing is a process which neutralizes a charged conductor by providing a path for the excess electrons to flow away or for electrons to flow to the conductor.

The earth is a vast store of electrons and charged particles, so it can provide electrons to positively charged conductors, or take electrons from negatively charged conductors to make them neutral.

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When a negatively charged conductor shown in fig. (a) above is earthed, excess electrons will flow to earth and as a result, conductor becomes neutral as shown in fig. (b) above.

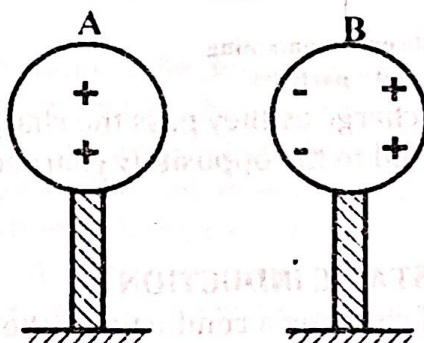
Also, when a positively charged conductor shown in fig. (c) above is earthed, electrons will flow from the earth so as to neutralize the conductor. Hence the conductor becomes neutral as shown in fig. (d) above.

THE LAW OF ELECTROSTATICS

It states that like charges repel each other while unlike charges attract each other.

Attraction of a charged body by an uncharged body

Consider a positively charged conductor, A, and an uncharged conductor, B, arranged as shown below.



When the two are brought close to each other, positive charges on an uncharged conductor will be repelled to the remote end of the conductor; leaving negative charges on the side close to the charged body.

Since unlike charges attract each other, the uncharged conductor will be attracted by the positively charged body.

Qn: Explain how a charged body attracts an uncharged conductor. [3]

Sol: A charged body (e.g negatively charged) is brought close to an uncharged conductor. The free electrons in the conductor are then repelled to the far side of the conductor; leaving the rear side positively charged. The attraction between the negative charge on the body and the induced positive charge is greater than the repulsion between the body and the more distant negative charge on the conductor. The resultant effect is the attraction of the conductor by the charged body.

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Qn: Explain briefly why a neutral metal body is attracted to a charged body when brought near it. [2]

Sol: When a neutral metal is brought near a charged material, opposite charge is induced on the near side of the metal; and charge similar to that of the charged body on the far side.

Since opposite charges are now closer to each other, the attraction force between the material is greater than the repulsion force. Hence the metal body is attracted.

CHARGING BY FRICTION/RUBBING

When two dissimilar insulators are rubbed together, heat is produced due to friction.

Soon, the heat becomes adequate for the insulators of low work function to release some of its electrons that are gained by the one of higher work function.

The insulator that lost electrons becomes positively charged while the one that gained electrons becomes negatively charged.

The number of electrons lost by one insulator is equal to the number of electrons gained by the other. Therefore, bodies have equal but opposite charges.

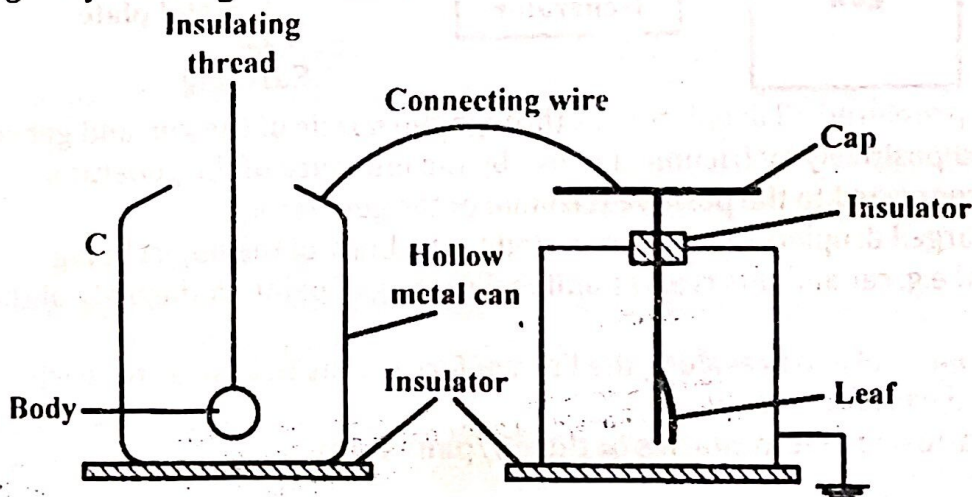
Qn: Explain why a pen rubbed in dry hair is able to attract small pieces of paper.

Sol: When a plastic pen is rubbed against dry hair, electrons are transferred from the hair to the pen. This process leaves the pen with a net charge.

The charged pen induces a dipole (a separation of positive and negative charges) in the small paper pieces nearby.

The side of the paper facing the pen becomes oppositely charged, leading to an attraction between the pen and the small pieces of paper.

An experiment to show that two bodies acquire equal but opposite charges by rubbing



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A hollow metal can, C , is connected to the cap of the electroscope using a connecting wire.

The two bodies are lowered one at a time into the can, C , and no leaf divergence is seen in both cases. This implies that the charges are initially uncharged.

The bodies are now rubbed vigorously and then lowered one at a time into the can, C , and the divergence observed. The leaf is seen to diverge in both cases.

One of the bodies is suspended/lowered into the can, C , and the leaf is seen to diverge.

The body is then removed and the electroscope is discharged.

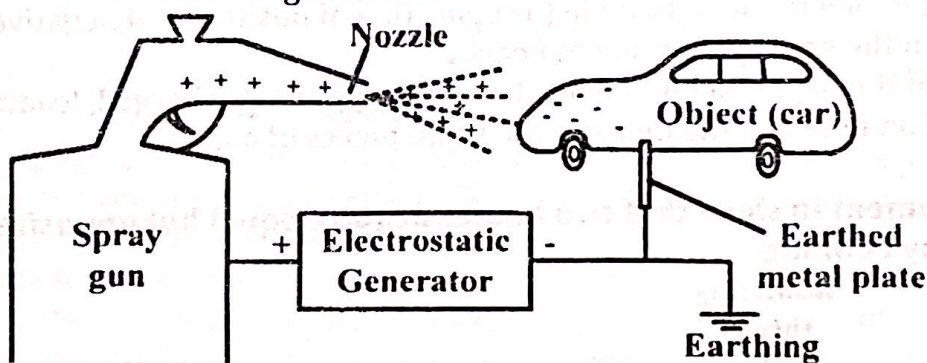
The other body is also suspended/lowered into the can, C , and the leaf is seen to diverge by the same extent as before. The body removed and the electroscope discharged.

Now the two bodies are both suspended into the can, C , and the leaf is seen not to diverge. This shows that the acquired charge on the two bodies neutralizes giving a net charged of zero.

Hence, when two objects are rubbed together, they acquire equal but opposite charges.

How the oil/paint spray works

The spray gun designed to produce tiny droplets of the oil paint has one of its terminals connected to the metal panel which is earthed and the other to the positive terminal of a generator.



Highly pressured oil droplets pass through the nozzle of the gun and get charged positively by friction and also by the influence of the generator when connected to the positive terminal of the generator.

The charged droplets then get attracted to the body of the object being sprayed e.g. car and this creates uniform coating of paint on the body of the object.

The droplets also travel along the lines of force of the field so as to reach hidden parts of the body.

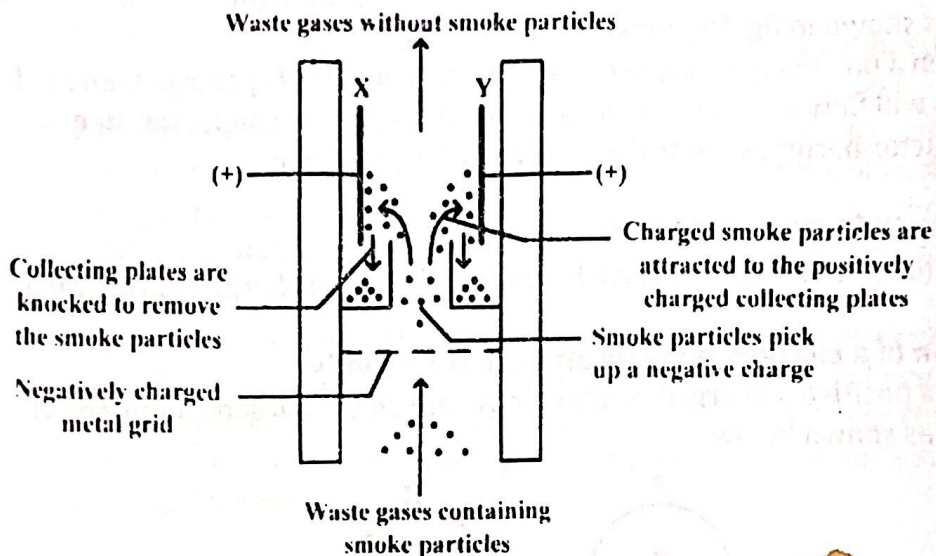
Application of electrostatics in the oil/pant spray

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When oil/paint is being sprayed, friction at the nozzle of the sprayer causes the droplets to be charged. The droplets have similar charges hence they repel each other and spread out. This creates uniform layer on the surface being sprayed.

Application of electrostatics in Dust extraction

Smoke is produced when fuels burn. Smoke comprises of tiny solid particles, which damage buildings and cause breathing difficulties. To avoid this, the smoke can be removed from waste gases before they pass out of the chimney. The electrostatic precipitator is a device used in chimneys for this job.

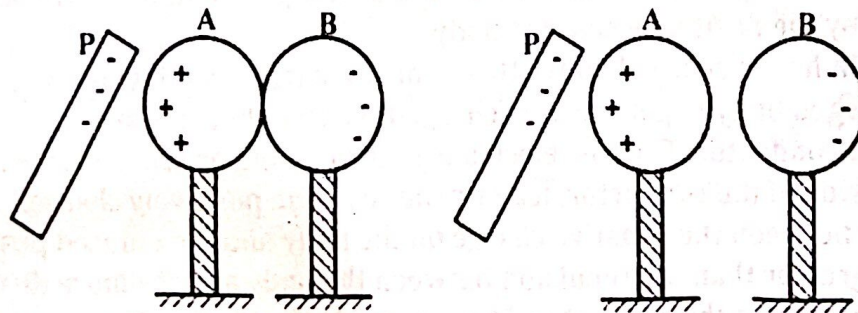


Smoke particles pick up a charge as they pass the charged metal grid. These smoke particles are attracted to the oppositely charged collecting plates up the chimney.

CHARGING BY ELECTROSTATIC INDUCTION

Induction is the process of charging a conductor without any contact with a charging body.

Consider two identical metal spheres A and B supported by insulating stands but in contact with each other. Suppose a negatively charged ebonite rod P is brought near A.

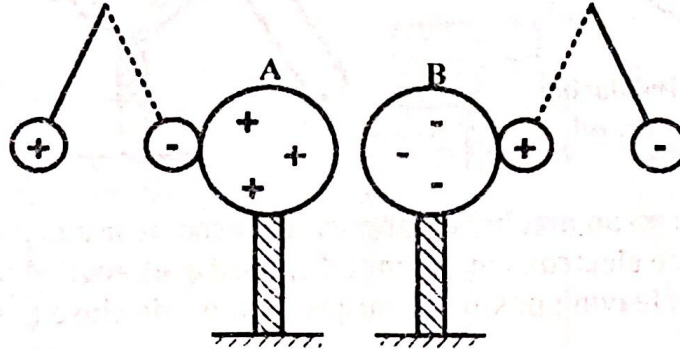


The positive charge is attracted towards end A and the negative charge is repelled towards the remote end of B.

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A and B are then separated while P is still in place. P is then removed and taken away.

Tests with a pitch ball show that A has a positive charge and B has a negative charge of the same amount. A and B are said to acquire charge by induction.



Qn: A negatively charged rod is brought up to an uncharged pitch ball suspended by a silk thread. The pitch ball first moves to the rod, touches it and then moves away. Explain these observations. [4]

Sol: The negatively charged rod induces a positive charge on the side of the ball nearer to it, and a negative charge on the far side of the ball. The attraction between the negative charge on the rod and the positive charge on the ball is greater than the repulsion between the negative charge on the rod and the negative charge on the far side of the ball. So the ball moves to the rod.

When the two come into contact, the positive charge on the ball is neutralized by some of the negative charge on the rod. Repulsion now results between the remaining negative charge on the rod and the negative charge remaining on the ball. The ball then moves away from the rod.

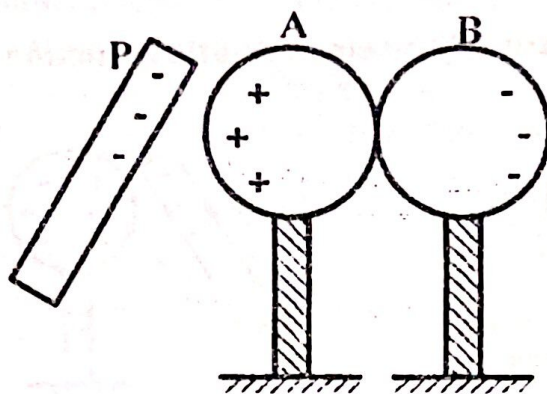
Alternatively: The negatively charged rod induces positive charge on the side of the ball nearest to it and negative charge to the far end of the ball. So the positive charge is attracted by the rod more than the negative charge is repelled in accordance with the inverse square law. Hence the net effect is an attraction of the ball.

When the ball touches the rod, all its positive charge is neutralized leaving it with excess negative charge. Since the rod has some residual negative charges, these do repel the now negatively charged ball. Consequently, the ball moves away.

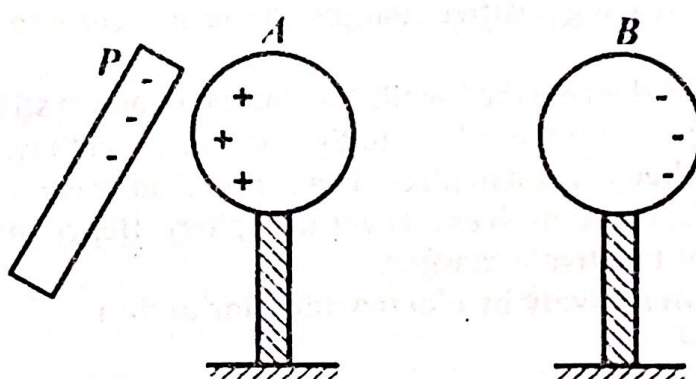
Qn: Two conducting spheres A and B supported on insulating stands are placed in contact. A negatively charged rod is then held near sphere A. After a short while, the spheres are separated after which the rod is also removed. With the aid of suitable diagrams, explain the processes which occur. [5]

Sol: When the spheres, A and B, are brought in contact and a negatively charged rod, P, brought near sphere, A, the negative charge on the rod, P, repels some free electrons to the extreme side of sphere, B. The near side of sphere, A, remains with excess positive charge as shown below.

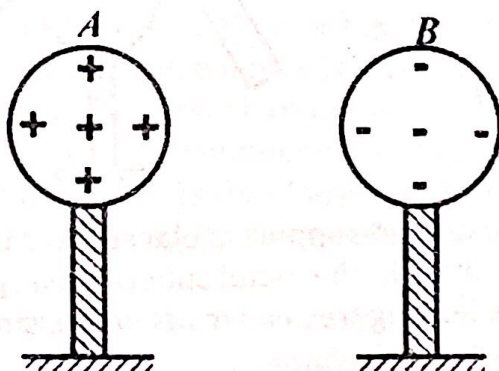
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When the spheres are separated with the rod still in place, sphere, *B*, moves away with excess negative charge while sphere, *A*, remains with excess positive charge as shown below.

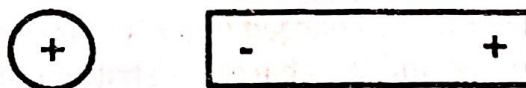


When the charged rod is now removed, the charge on each of the sphere distribute uniformly on the spheres as shown below.



Qn: Explain why a redistribution of charge occurs on uncharged metal rod when a positively charged metal sphere is brought near to one end. [3]

Sol:



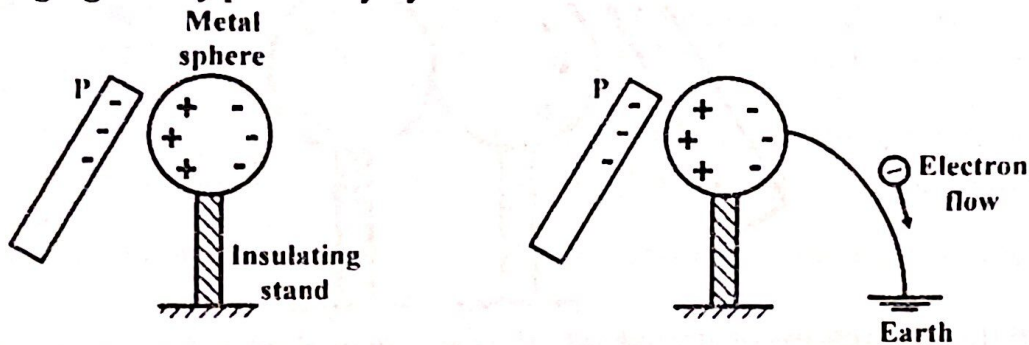
When the positively charged metal sphere is brought near the neutral metal rod, free negative charge gets attracted and moves towards the end of the rod near the sphere.

The opposite end is left with excess positive charge.

The rod thus becomes negatively charged on the near side to the sphere and positively charged on the far side.

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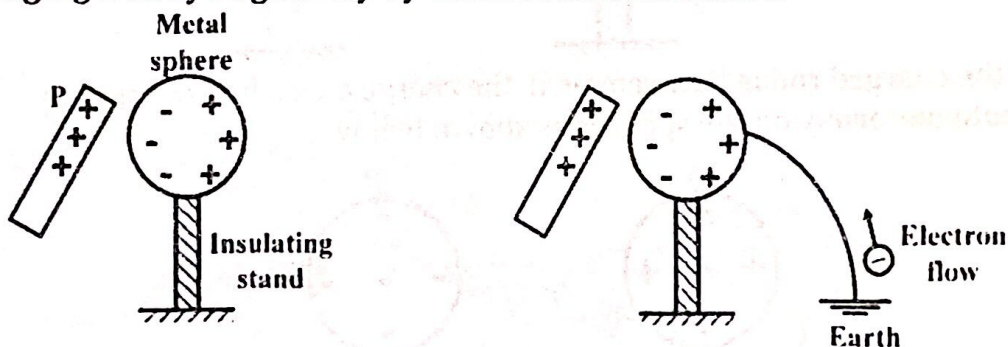
Charging a body positively by electrostatic induction



The metal sphere on an insulated support is placed near a negatively charged body. Free electrons in the metal sphere are repelled to the remote end of the sphere; leaving positive charges on the side close to the charged rod.

The metal sphere is then earthed while the charged body is still in place. Free electrons move from the sphere to the earth. The earth wire is broken while the charged body is still in place. The charged body is removed and the charges distribute themselves all over the sphere. Hence the metal sphere is said to be positively charged.

Charging a body negatively by electrostatic induction



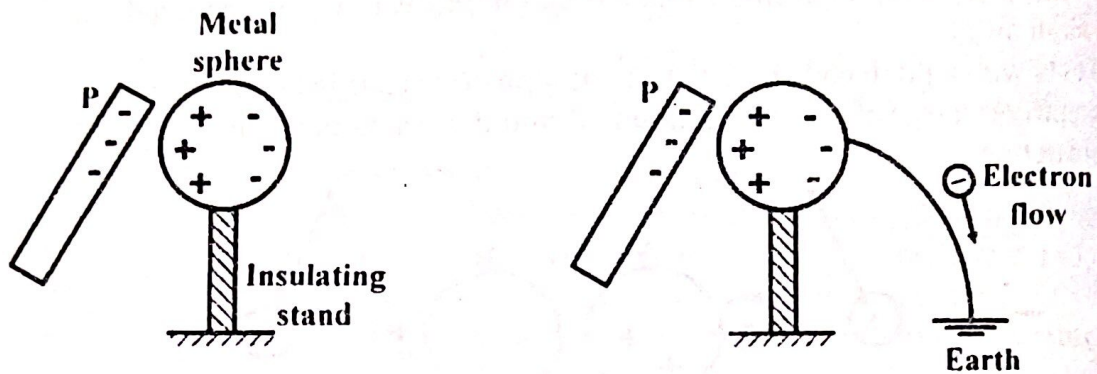
The metal sphere on an insulated support is placed near the positively charged body. Positive charges in the metal sphere are repelled to the remote end of the sphere; leaving free electrons on the side close to the charged body.

The metal sphere is then earthed while the charged body is still in place. Free electrons move from the earth to the sphere and neutralize the positive charge on the sphere.

The earth wire is broken while the charged body is still in place. The charged body is also removed and the charges distribute themselves all over the sphere. Hence the metal sphere is said to be negatively charged.

Charging a body positively at zero potential (earth potential)

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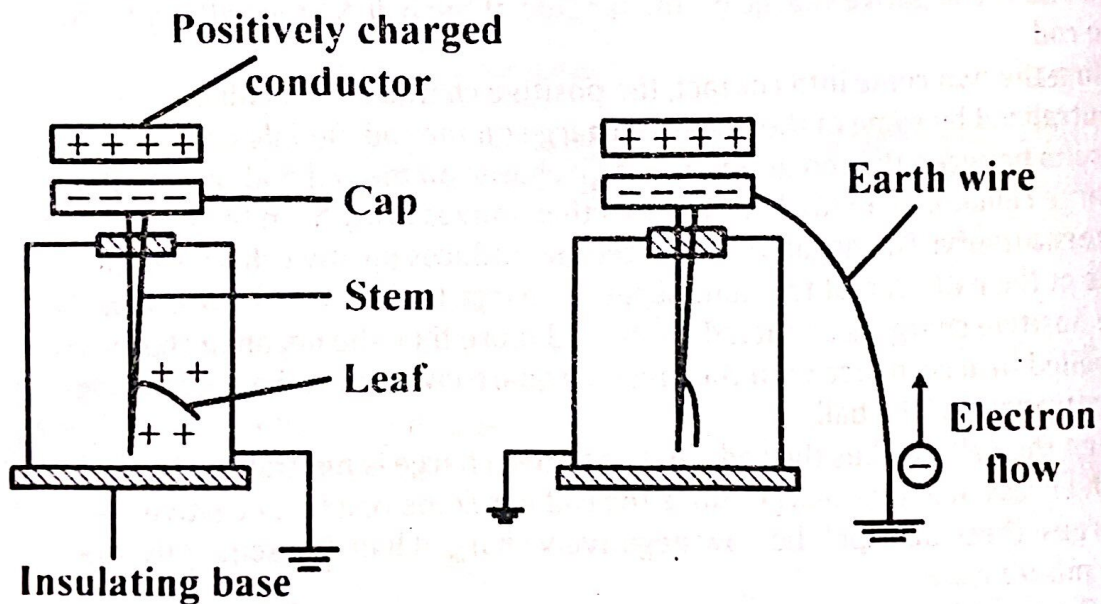


The metal sphere on an insulated support is placed near a negatively charged body. Free electrons in the metal sphere are repelled to the remote end of the sphere; leaving positive charges on the side close to the charged rod.

The metal sphere is then earthed while the charged body is still in place. Free electrons move from the sphere to the earth.

The charged body is gently taken away from the vicinity of the sphere. Electrons from the earth will flow back to the sphere and neutralize the positive charges on it. As long as the earth wire is not removed, the sphere will be at zero potential.

Charging a gold leaf electroscope negatively by induction



A positively charged rod is brought near the cap of the electroscope. Negative charges from the leaf are attracted to the cap leaving positive charges on the leaf hence the leaf diverges.

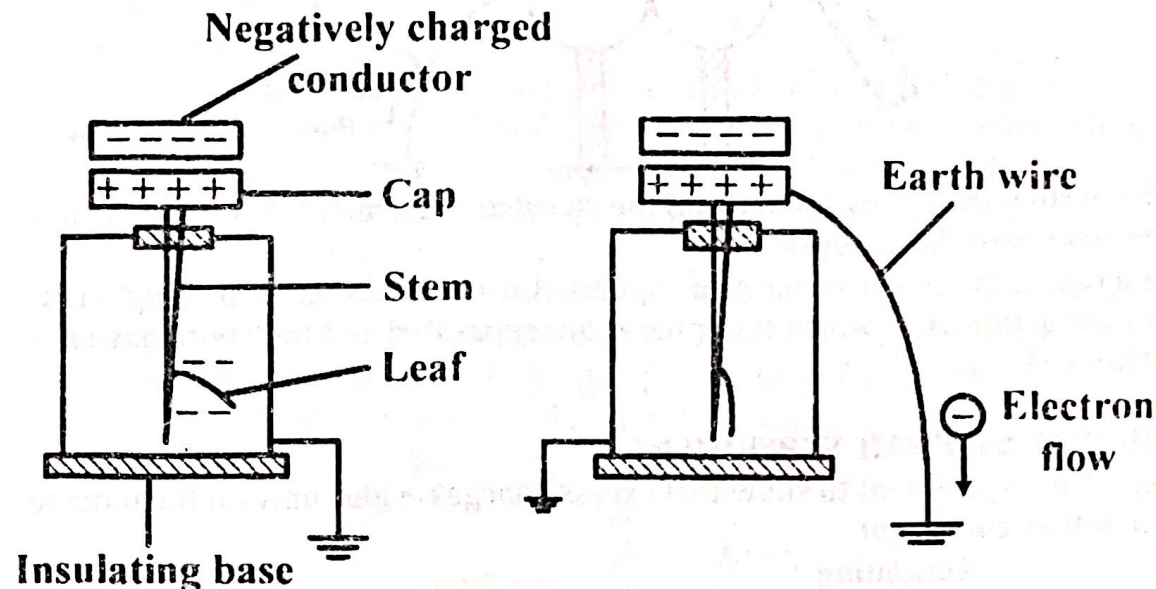
With the conductor still in position, the cap is earthed such that electrons from the earth neutralize the positive charges on the leaf and stem hence the leaf falls.

The earth wire is broken and the conductor is then removed and taken away. Negative charges will redistribute themselves in the leaf, stem, and

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cap; and the leaf will diverge again. The electroscope is therefore negatively charged.

Charging a gold leaf electroscope positively by induction



A negatively charged rod is brought near the cap of the electroscope.

Positive charges from the leaf are attracted to the cap leaving negative charges on the leaf hence the leaf diverges.

With the conductor still in position, the cap is earthed such that negative charges on the leaf and stem flow to earth hence the leaf falls.

The earth wire is broken and the conductor is then removed and taken away. Positive charges will redistribute themselves in the leaf, stem, and cap; and the leaf will diverge again. The electroscope is therefore positively charged.

Using a gold leaf electroscope to test for the sign of charge on a conductor

Consider a gold leaf electroscope charged positively by induction.

If a conductor of unknown charge is brought near the cap of the electroscope and the leaf diverges, then the conductor is positively charged.

If the leaf doesn't diverge, then the conductor is either negatively charged or neutral. The electroscope should therefore be discharged by touching its cap and the conductor is then brought near it.

if the leaf diverges, then the conductor is negatively charged but if it doesn't diverge, then the conductor is neutral.

Advantages of charging by induction

- An unlimited amount of electrons is obtained.
- It is not tedious to obtain the electrons.

Disadvantages of charging by induction

- It's tiresome when like charges are needed.

Uses of a gold leaf electroscope

- To detect the presence of charge on a body.

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- To test the quantity of charge on a charge body.
- To test for insulation properties of a material.
- To test the sign of charge on a charged body.

Qn: Describe how an electroscope can be used to distinguish a conductor from an insulator. [2]

Sol: An electroscope is given a charge and the leaf divergence noted. A material is then brought near the cap of the electroscope. If the leaf divergence reduces, then the material is a conductor. If there's no change in divergence, the material is an insulator.

CHARGING BY ELECTROSTATIC CONDUCTION

Charging by conduction is a process in electrostatics where a charged body directly interacts with a neutral conductor; resulting in the transfer of charge. The conductor acquires the same charge as the original body.

Here are the key points to understand:

- **Direct Contact:** Charging by conduction occurs when a charged body comes into contact with a neutral conductor (an object with no net charge).
- **Transfer of Electrons:** During conduction, electrons move from the charged body to the neutral conductor. If the charged body is negative, electrons flow from it to the neutral conductor, making the conductor negative as well. However, if the charged body is positive, electrons flow from the neutral conductor to the charged body, making the conductor positive as well.
- **Same Charge:** The neutral conductor takes on the same charge as the charged object. If the charged object is positively charged, the neutral conductor becomes positively charged too.
- **Reversibility:** Charging by conduction is reversible. The conductor can also be used to discharge the charged object if needed.

The different stages of charging by conduction

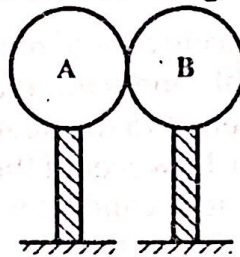
When a conductor is charged by conduction and then separated from the charging body, several important things occur:

- **Initial Charging:** Charging by conduction involves making physical contact between a charged object and a neutral conductor. During this contact, electrons move from the charged object to the neutral conductor, resulting in the conductor acquiring the same charge as the charged object.
- **Separation:** Once the charging process is complete, the charged conductor can be separated from the charging body. The charged conductor now carries an excess charge (either positive or negative) due to the transfer of electrons during conduction.

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- **Charge Distribution:** The excess charge on the conductor is evenly distributed over its surface. The conductor's potential (voltage) is now different from its initial state when it was neutral.
- **Neutralization:** When the conductor is separated from the charging body, it remains charged. However, if the conductor is brought into contact with another neutral conductor, it can transfer its charge to the second conductor. This process of transferring charge from one conductor to another is called neutralization.
- **Final State:** After separation, the charged conductor retains its charge until it interacts with other objects. The charging body (the original charged object) remains charged as well.
- **In summary,** when a conductor charged by conduction is separated from the charging body, it retains its charge until further interactions occur. The process of conduction allows for charge transfer, and the conductor's potential changes accordingly.

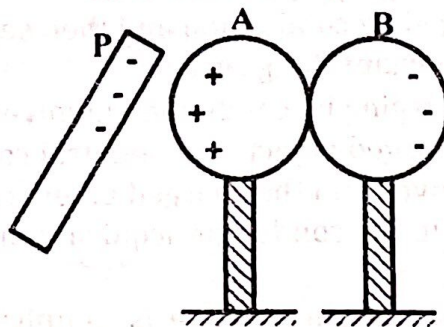
Qn: The figure below shows two conducting spheres *A* and *B* in contact with each other and each supported on insulating handle.



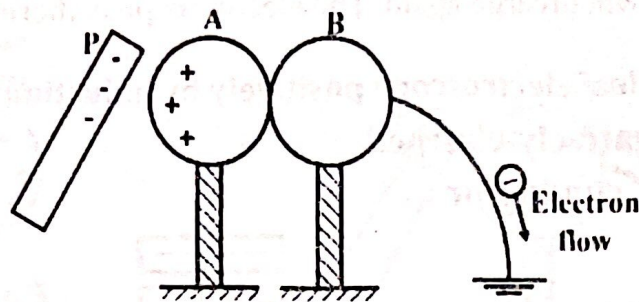
Explain how both can be charged with the same charge.

Sol:

With the conducting spheres, *A* and *B*, still in contact, a negatively charged rod, *P*, is brought near sphere, *A*. The negative charge on the rod, *P*, repels free electrons to the extreme side of sphere, *B* and attracts positive charge to the near side of sphere, *A*, as shown.



With the charged rod still in place, sphere, *B*, is earthed. Excess electrons on sphere *B* flow to earth leaving sphere *B* with no excess charge.

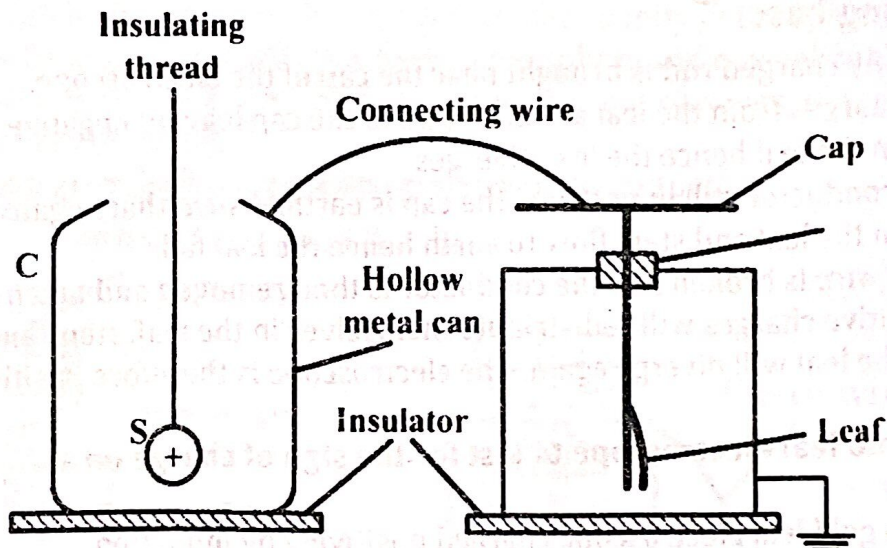


The earth wire is now broken and the charged rod gently taken away from the vicinity of the spheres.

As a result, the positive charge on sphere A is redistributed to both spheres by conduction after which the spheres are separated and they both have a positive charge.

FARADAY'S ICE PAIL EXPERIMENT

This is an experiment to show that excess charge resides only on the outside of a hollow conductor.



A positively charged metal sphere S is lowered into a metal can C using an insulating thread as shown above. The leaf of the electroscope is seen to diverge. When the sphere S is withdrawn from C, the leaf collapses.

The sphere S is again lowered and this time allowed to touch the inner surface of C. The leaf is seen to remain diverged at the same angle as before. When the S is withdrawn and tested for charge, it's found to have no charge. Hence there's no charge inside C but since the leaf is diverged, charge exists on the outside of C.

NOTE: From the above experiment, the following can be concluded:

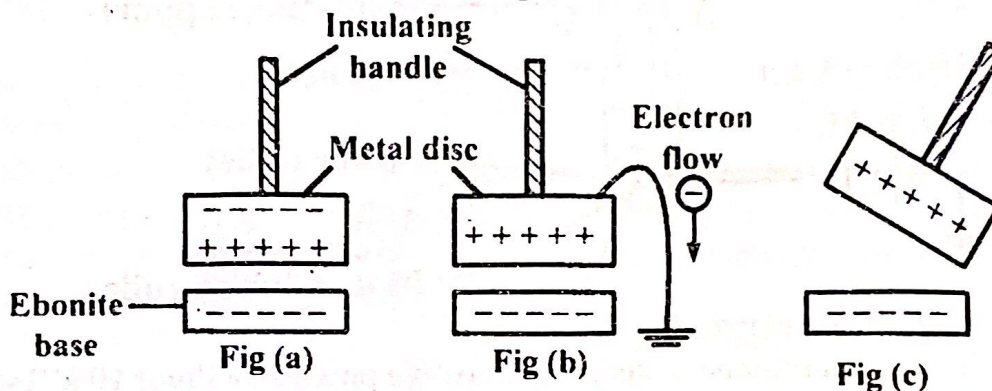
- When a charged body is enclosed in a hollow conductor, it induces a charge equal but opposite to its own on the inside of the conductor; and a charge similar to its own on the outside of the conductor.

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- The total charge inside a hollow conductor is zero. Either there are equal but opposite charges on the inside walls of a conductor or there's no charge at all.

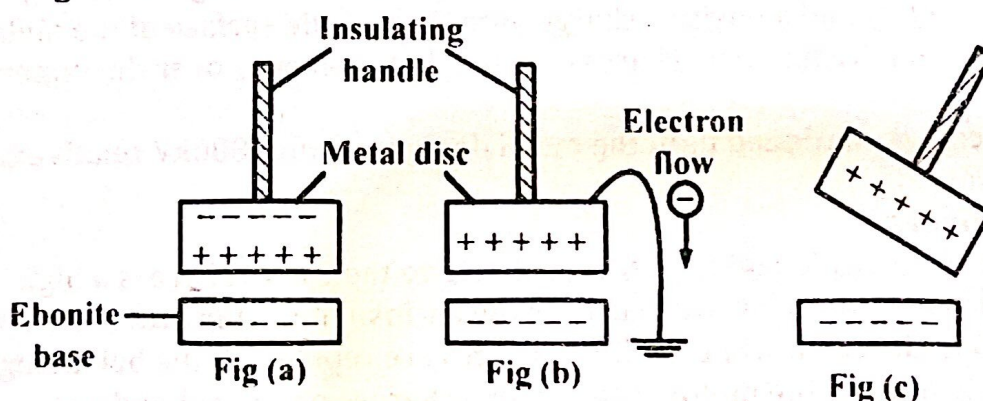
THE ELECTROPHORUS

It is an electrostatic device used to provide large amounts of charge. It consists of a Perspex base or ebonite base and a metal disc on an insulating handle. An ebonite base is charged negatively by rubbing it with fur. The metal disc is then laid upon it and acquires induced charges; positive underneath and negative charges on the top [as shown in fig (a)]. The metal disc is then earthed to allow flow of electrons to earth [as shown in fig (b)]. With the ebonite base still in place, the earth wire is broken, making the metal disc positively charged [as shown in fig (c)]. The electrophorus can now be used to charge other bodies.



Qn: Describe how an electrophorus is used for charging a Gold leaf electroscope connected to a hollow metal container positively to a high potential.

Sol: An electrophorus consists of an ebonite base and a metal disc on an insulating handle as shown below.



The ebonite base is charged negatively by rubbing it with fur.

The metal disc is then laid upon it and acquires induced charges; positive underneath and negative charges on the top.

The metal disc is then earthed to allow flow of electrons to earth.

With the ebonite base still in place, the earth wire is broken, making the metal disc positively charged.

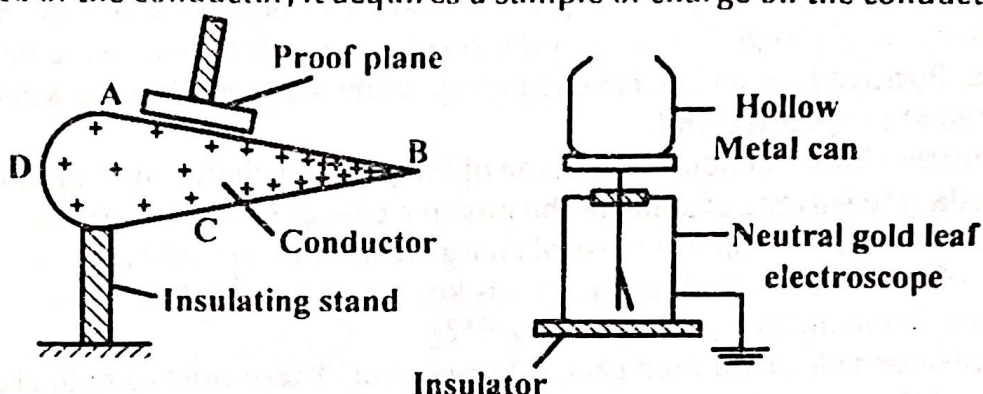
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The positive charge on the disc will be neutralized by the induced negative charge inside the hollow can leaving an induced positive charge on the outside surface of the hollow can and on the electroscope.

The metal disc is again charged as before and the procedure repeated until the electroscope is charged positively to a high potential.

DISTRIBUTION OF CHARGE ON A POINTED CONDUCTOR

Consider a positively charged conductor pointed at one end and placed on an insulating stand as shown below. When a proof plane is placed at the surface of the conductor, it acquires a sample of charge on the conductor.



To investigate the distribution of charge, the proof plane is placed on the surface of the conductor at A and then transferred into the can without touching it. The divergence, θ , of the leaf is noted. The proof plane is removed and discharged.

The procedures above are repeated for different points say B, C, D on the surface of the conductor.

It's found that the divergence is greatest when the proof plane is at B, the sharpest end of the conductor.

Therefore, surface charge density increases with increase in curvature and is greatest when the curvature is greatest.

Alternatively: A proof plane is placed on the surface of the conductor and then transferred to a hollow metal can placed on the cap of the electroscope without touching the can. The deflection, θ , of the electroscope is noted. The proof plane and the electroscope are then discharged.

Samples of charge are picked from different parts of the conductor and the procedure repeated to obtain the corresponding deflection of the electroscope.

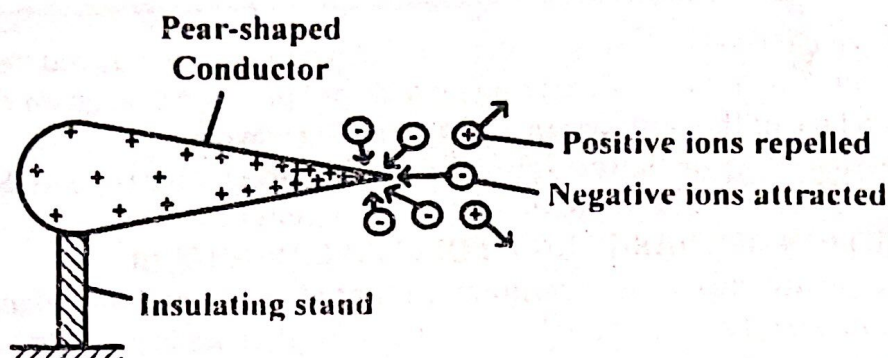
It's observed that the greatest deflection is obtained when the samples of charge are picked from the sharpest end of the conductor.

Therefore, surface charge density increases with increase in curvature and is greatest when the curvature is greatest.

CORONA DISCHARGE (ACTION AT POINTS)

Consider a positively charged pointed conductor placed on an insulating stand in air as shown below.

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Because of the high charge density at the sharply pointed end, the electric field there is very high. This causes the surrounding air molecules to be ionized. Positive ions will be repelled away while negative charges will be attracted at the pointed end.

The negative ions will neutralize some of the positive charge at the pointed end leading to leakage of some of the positive charge on the conductor.

The net result is the apparent loss of charge from the pointed end of a conductor to the surrounding air. This is known as corona discharge.

Qn: What is meant by corona discharge?[2]

Sol: Consider a sharp pointed charged conductor. There exists a high charge density at the pointed end. Ionization of air takes place around the sharp end. Charges similar to those on the conductor are repelled while charges opposite to those on the conductor are attracted and hence discharge the conductor. This is known as corona discharge.

Qn: Explain why a charged spherical conductor loses charge faster when a pin is attached to it. [3]

Sol: The point of the pin is highly curved (sharp) and hence has a great charge density. Thus an intense electric field intensity arises near the sharp point of the pin. Background ionizing radiation always produces electrons in air. These are then accelerated by the intense electric field intensity causing ionization of air by collision.

The ions with charge like the one at the pin are strongly repelled away from it. The ions with charge opposite to the one on the pin occurs and the conductor discharges rapidly.

Qn: Some Vehicles carrying Petroleum, have a metallic chain dangling at the rear end of the vehicle. Explain the role of this chain. [3]

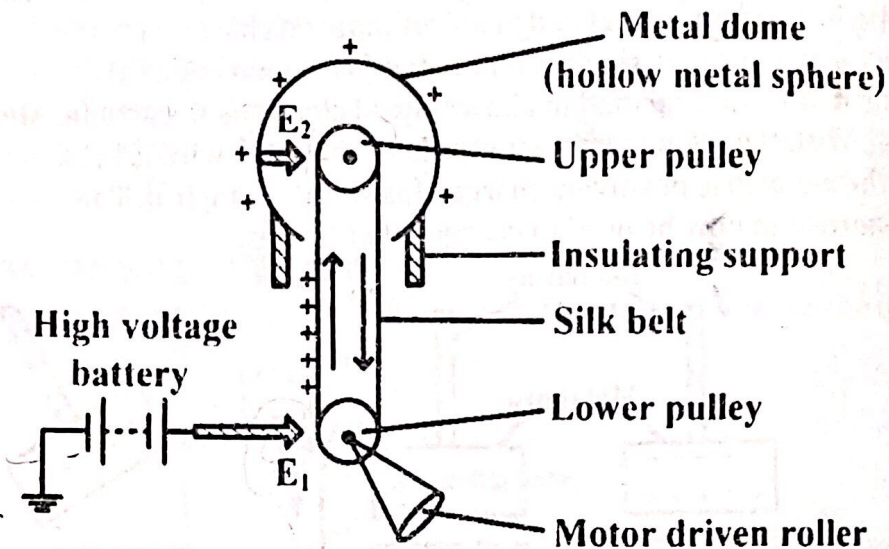
Sol: The motion of vehicles causes ionization of air molecules and a vehicle in turn gets charged. The charge is drawn down to the lowest point on the chain since it's a sharp point on the vehicle. When the vehicle passes over say a hump or a pothole, the chain makes contact with the earth and discharges the whole vehicle rendering it safe again.

Applications of corona discharge

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- **Van de Graaff generator:** This used for producing very high voltages. Large machine of this type are used with high voltage x-ray tube sand in atom splitting experiments.
- **Lightning conductor:** This is a sharp spiked or a sharp pointed conductor which is connected to a copper strip attached to the building and connected to the earth.

Action of a Van de Graaff generator



E_1 and E_2 are metal electrodes.

Electrode E_1 is maintained at very high positive potential (about 10 kV) with respect to earth by a high voltage battery so there's a high electric field intensity around the spikes which ionize the air around E_1 .

Negative ions are attracted to E_1 and neutralized, while positively ions are repelled to the silk belt which carries them up into the metal dome.

On reaching E_2 , the positive charge on the belt induces a negative charge on the spikes of E_2 and a positive charge onto the outside surface of the metal dome. Corona discharge discharges the belt before it goes over the upper pulley.

The process is continued until the metal dome is about 1000kV relative to the earth.

Alternatively:

Electrode E_1 is made highly positive relative to the earth. There is a high charge density around it which breaks the air insulation. Electrons are attracted to the earth while positive charges are repelled to the belt being driven upwards by the motor. The positive charges on the belt induces negative charges on E_2 and positive charges on the sphere. The high charge density at E_2 breaks the air insulation and E_2 repels negative charges onto the belt which is then discharged before it goes over the pulley. The process continues until the sphere builds up to a high voltage.

LIGHTNING

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Various processes including friction between air molecules and nuclear radiations from the earth's core lead to electric charging of particles in the atmosphere. In the clouds, these charges separate such that positive ions occupy the top while negative charges settle at the base. This is partly because the earth has a high affinity for negative charges.

Quite often, neutralization of these charges occurs between two different clouds, two parts of the same cloud or even between a cloud and the surrounding air. Most discharges, however, occur between the charged clouds and the earth. In this process, the negative charges on the cloud induce positive charges at points on the earth's surface including trees, buildings and the soil. Due to electrostatic attraction, the negative charges flow to the earth while positive ions move upwards. This flow constitutes electric current and occurs along the paths of least resistance. Electric power lines, being good conductors, are examples of preferred paths for this flow.

But the high voltage due to these charges can cause serious damage especially to the transformer. Earthing lines are therefore usually provided to conduct the charges immediately and safely to the earth. Also, an automatic circuit breaker disconnects the transformer and power line to protect them in case of an intense discharge. This explains the occasional power black-out during thunderstorms.

As charges force their way through the poorly conducting air, electrical energy is converted into light and heat. Sometimes the heat causes a sudden expansion of the air and this leads to the accompanying thunder. Whereas lightning may be visible to a distance of more than 150 km any accompanying thunder can be heard within a radius of only about 15 km. Sometimes the heat produced is so much that it causes explosive expansion of water in the trees or moisture in the buildings as the discharge occurs through them. This is a form of lightning that leads to the splitting and shattering of such structures.

Charges can also be brought down from the clouds by rainwater. So, as it rains the clouds lose their charge gradually. Therefore, serious lightning strikes usually occur just before it starts raining or during the early stage of the downpour

LIGHTNING TARGETS

(a). Tall objects:

Tall objects such as trees act as sharp points on the earth's surface and also raise the induced positive charges closer to the clouds. Trees also produce a trail of water vapour that provides a conducive path for electric discharge. Accordingly, they attract the charges on the clouds more strongly than do the other objects nearby. If there are many trees, the discharge current is shared among them so that each of them conducts a small and safe value hence harmless discharge occurs. In contrast, a tall isolated object tends to

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pull all the charge to itself. Thus, it draws a large current and is at a high risk of a lightning strike.

(b). Sooty objects:

An object that is covered with soot is a likely target for a lightning strike and more so if it is tall. Violent discharges have been observed to occur on unprotected sooty chimneys.

(c). Red soil:

Red soil is rich in iron compounds, especially iron (III) oxide. These are easily magnetized and charged by induction thereby becoming attracting sites for the negative charges on the moving clouds. Objects standing on these sites are therefore at risk. However, such areas may still be safe, depending on the vegetation and type of cloud among others.

PROTECTION AGAINST LIGHTNING

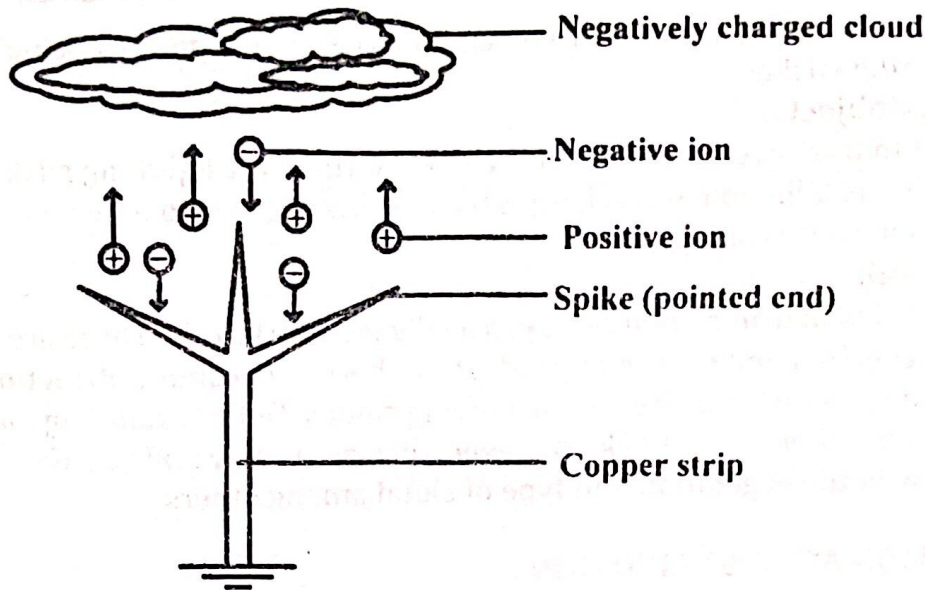
- Many tall trees should be grown in the home as these help in safe discharge.
- Avoid walking in the open fields when it is raining as you would be the tallest isolated object. What is more, the human body is a good conductor and more so when it is wet.
- Taking shelter on a verandah, under a tree and, worse still, an isolated tree should be avoided. This is because the shelter will already have charges induced on it to attract those on the cloud. These charges would then flow through the human body as it is a better conductor. In addition, avoid contact with metallic poles.
- It is unsafe to gather in groups in the open when the rains are approaching. A group of conducting objects draw more charge towards themselves. Although the current will be shared it may nevertheless be too high for the human body which can safely conduct a current of only 0.1 A.
- Install a lightning arrestor (conductor). The type of soil should be considered to determine the right metal for this purpose. Some metal-soil combinations would even increase the risk of a lightning strike.

LIGHTNING ARRESTORS

This consists of a thick copper strip fixed to the outside wall and projecting above the highest point of a building. The top of this strip is spike-shaped while its foot is attached to a copper plate buried in the earth to help in fast dissipation of charges.

Action of a lightning conductor

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When negatively charged clouds pass over the spikes (pointed ends) of a lightning conductor, positive charges will be induced at the spikes while negative charges will flow to earth through the conductor. Due to the high charge density at the spikes, the electric field intensity there is very high and thus, corona discharge occurs. Positive ions are repelled to the clouds while negative ions are conducted to the ground.

The positive ions which are attracted to the clouds neutralize some of the negative charge on the clouds.

This reduces the possibility of lightning occurring. However, if the discharge occurs, current flows through the lightning conductor safely to earth. Either way, the building is protected from lightning.

NOTE: Lightning is a rapid high current discharge between the clouds or between the clouds and the ground. When lightning takes place, the large current produced passes through the building and can cause buildings to burn down.

Qn: (i). Explain how lightning can cause damage to buildings. [3]

(ii). Explain the action of a lightning conductor. [2]

Sol: (i). As clouds drift in air, they gradually become negatively charged by friction. The increasing electric field eventually breaks the air insulation and a large current begins to flow. This current consists of electrons which collide with air molecules, causing heating and emission of light which destroys buildings.

ALT:

Clouds in relative motion get charged when they rub against each other. The resulting charge leads to a high potential difference between the earth and the charged clouds and thus the charge is forced to flow towards the earth. When this charge passes through the building, it makes it to burn.

(ii). Clouds become negatively charged by friction as they move through air.

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The negatively charged clouds induce positive charge at the spikes of the conductor. There is high charge density around the spikes, which causes ionization of air around it. Negative charges are attracted by the conductor and safely conducted to earth. The positive charges are repelled upwards which then discharges the clouds thus preventing the likelihood of lightning.

Alternatively:

When a negatively charged cloud passes over a building, it induces positive charges on the spikes of the conductor and repels electrons to the copper plate where they are dissipated to earth.

High concentration of positive charge at the spikes builds up high electric field intensity around the spikes that ionizes air molecules around the spikes.

Electrons are attracted to the spikes and neutralized while positive ions are repelled towards the cloud that neutralizes the effect hence the house is protected from lightning.

Likely Qn: Explain how lightning can cause severe damage to buildings.

Name one device that can be used to prevent such damage and explain how it works. [5]

OTHER APPLICATIONS OF ELECTROSTATICS

(a) Finger printing

On touching an article, the projections (ridges) on the finger leave on the surface a pattern of the finger marks which in many cases are invisible. By charging the article to a high voltage in the presence of a fine powder, the particles are attracted to and align themselves along the marks. This reveals the finger print. The print may be fed into a computer which will quickly select from its "memory" the matching print and hence the name and details of the person, if registered in the country.

(b). Photocopying

In photocopying, the original print is illuminated with a strong beam of light. This casts a shadow of the print onto a charged metal plate. The dark regions of the plate acquire a high charge and attract a fine photocopying powder (toner) of a desired colour. By contact, this is transferred onto a paper and fixed to produce a photostat copy.

(c). Dust precipitator

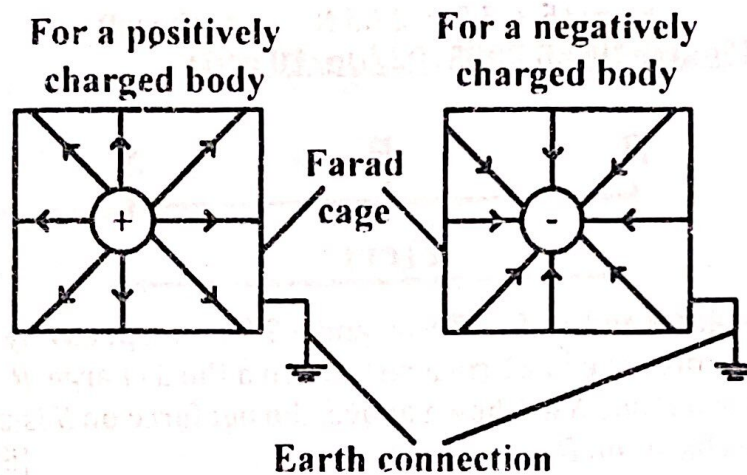
Gaseous wastes from factories need to be free from solid pollutants such as metal dust; and so are the gases intended for chemical synthesis. Removal of dust particles is achieved by passing the gases between charged plates. These attract and precipitate the dust.

ELECTROSTATIC SHIELDING

Electrostatic shielding is the creation of an electrically neutral space in the neighborhood of an electric field however strong it is.

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The fact that there's no charge inside a closed conductor when it contains no charged bodies can be used to protect any person or instrument from intense electric fields by enclosing them in the hollow conductor. Therefore, a charged body can be screened against external electric fields by electrostatic shielding. This is done by surrounding the charged body with an enclosed conductor (farad cage) which is connected to earth as shown below.

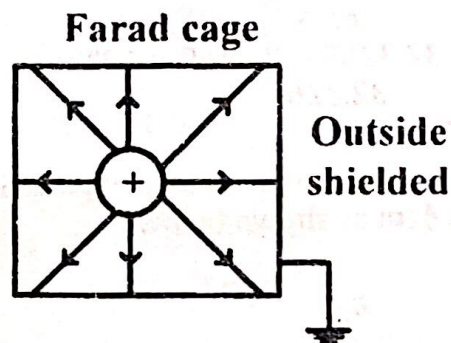


The charge induced by the charged body on the outside of the farad cage and that due to external electric fields will then flow to earth. In this way the charged body has been screened against external electric fields.

NOTE: The field due to the charged body is confined only inside the farad cage since the charge induced on the outside of the cage flows to earth. Therefore, a person or any instrument can be protected from intense electric fields of any charged body by enclosing it in a farad cage.

Qn: Explain with the aid of a diagram the term **electrostatic shielding**. [3]

Sol: Consider a positively charged body surrounded with an earthed enclosed conductor known as a farad cage.



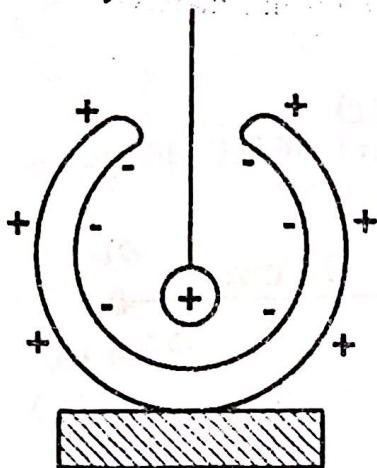
The positively charged body induces an equal but negative charge on the inside of the container and an equal magnitude of positive charge on the outside.

Since the outer surface is earthed, the charge there will flow to earth (be neutralized) and as a result, the field due to the charged body will be confined only inside the farad cage.

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In this way, the charged body has been screened against external electric fields and also; the outside surface of the cage is shielded from the influence of the charged body, a process known as electrostatic shielding.

Alternatively:



The test material is suspended in an almost enclosed conducting can. It induces an equal and opposite charge inside the can and a similar charge on its outer walls, such that the net charge inside the can is zero. Any external field only affects charge distribution on the outer surface of the can. Hence the material is shielded from the external field.

COULOMB'S LAW

Coulomb's law states that the force between two point charges Q_1 and Q_2 is directly proportional to the product of the magnitude of the charges and inversely proportional to the square of their distance of separation r . That is,

$$F \propto \frac{Q_1 Q_2}{r^2}, \quad \Rightarrow F = k \left(\frac{Q_1 Q_2}{r^2} \right)$$

where k is the constant of proportionality and is given by

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

Where ϵ is permittivity of the medium in which the two charges are located. Therefore,

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

In free space, $F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}$

Where ϵ_0 is the permittivity of free space and is $= 8.85 \times 10^{-12} \text{ F m}^{-1}$. The constant,

$$k = \left[\frac{1}{4\pi \times 8.85 \times 10^{-12}} \right] = 9 \times 10^9 \text{ m F}^{-1}$$

Therefore, in free space, the electrostatic force

$$F = \frac{k Q_1 Q_2}{r^2}, \quad \text{where,} \quad k = 9 \times 10^9 \text{ m F}^{-1}$$

RELATIVE PERMITTIVITY (DIELECTRIC CONSTANT)

Relative permittivity is the ratio of the permittivity of a material/medium to the permittivity of free space. That is,

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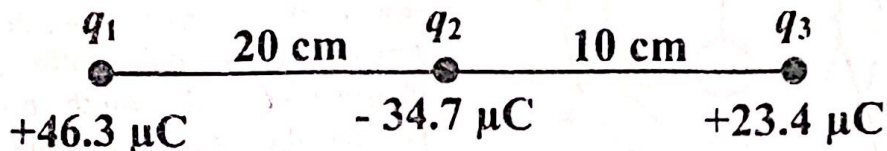
$$\text{Relative permittivity} = \frac{\text{permittivity of a material}}{\text{permittivity of free space}}$$

$$\epsilon_r = \frac{\epsilon_m}{\epsilon_0}, \quad \Rightarrow \epsilon_m = \epsilon_r \epsilon_0$$

WORKED EXAMPLES

Question 1: (Source UNEB 2012/P2/Qn. 9 c)

The figure below shows charges q_1 , q_2 and q_3 of $+46.3\mu\text{C}$, $-34.7\mu\text{C}$ and $+23.4\mu\text{C}$ respectively, placed in a straight line in air.



Find the force on q_3 .

[6]

Sol:

$$F = \frac{kQ_1Q_2}{r^2}$$

Force on q_3 due to charge q_1 ,

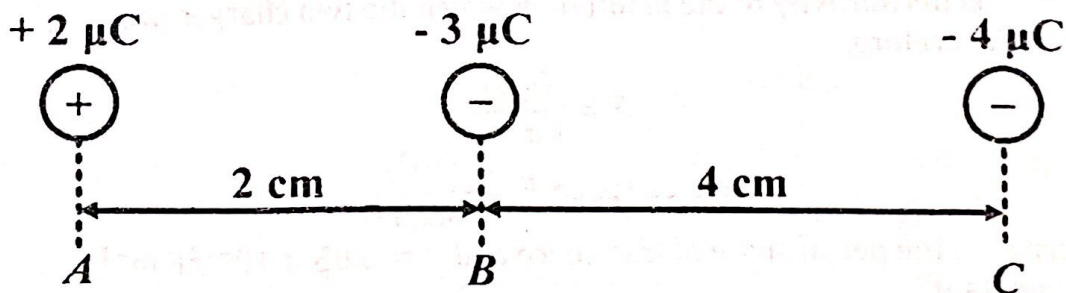
$$F_{q_3,1} = \frac{9 \times 10^9 \times 23.4 \times 10^{-6} \times 46.3 \times 10^{-6}}{0.3^2} = 108.342 \text{ N, to the right}$$

Force on q_3 due to charge q_2 ,

$$F_{q_3,2} = \frac{9 \times 10^9 \times 23.4 \times 10^{-6} \times 34.7 \times 10^{-6}}{0.1^2} = 730.782 \text{ N, to the left}$$

$$\text{Net force on } q_3 = 730.782 - 108.342 = 622.44 \text{ N, to the left}$$

Qn 2: Charges of $+2 \mu\text{C}$, $-3 \mu\text{C}$ and $-4 \mu\text{C}$ are placed in liquid of relative permittivity 9.0 when they are separated as shown below.



Find the resultant force on the charge at B.

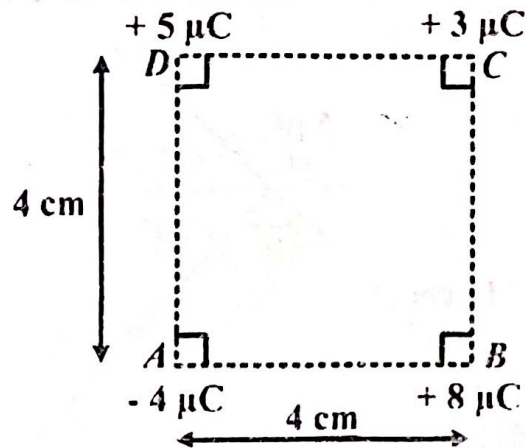
Sol:

$$\text{Permittivity of liquid, } k_l = \frac{k}{\epsilon_r} = \frac{9 \times 10^9}{9} = 1 \times 10^9 \text{ m F}^{-1}$$

$$F = \frac{k_l Q_1 Q_2}{r^2}$$

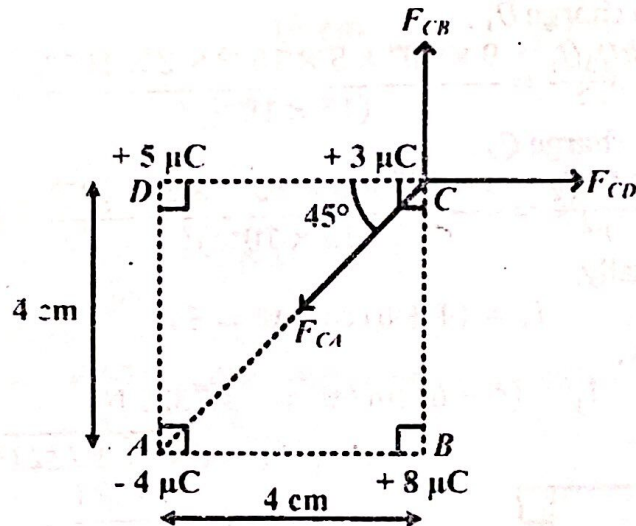
Force at B due to charge at A,

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Find the resultant force on the charge at C.

Sol:



$$CA = \sqrt{4^2 + 4^2} = 5.6569 \text{ cm}$$

$$F = \frac{kQ_1Q_2}{r^2}$$

Force at C due to charge at A,

$$F_{CA} = \frac{9 \times 10^9 \times 4 \times 10^{-6} \times 3 \times 10^{-6}}{(5.6569 \times 10^{-2})^2} = 33.7495 \text{ N}$$

Force at C due to charge at B,

$$F_{BC} = \frac{9 \times 10^9 \times 8 \times 10^{-6} \times 3 \times 10^{-6}}{(4 \times 10^{-2})^2} = 135 \text{ N}$$

Force at C due to charge at D,

$$F_{DC} = \frac{9 \times 10^9 \times 5 \times 10^{-6} \times 3 \times 10^{-6}}{(4 \times 10^{-2})^2} = 84.375 \text{ N}$$

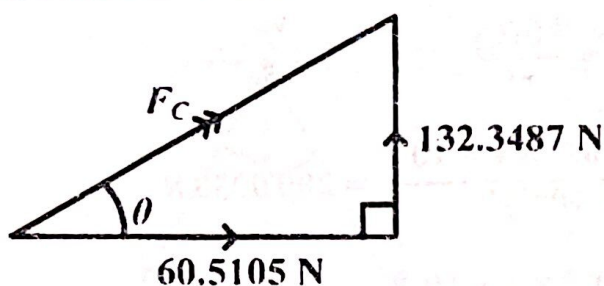
Resolving horizontally,

$$F_x = 84.375 - 33.7495 \cos 45^\circ = 60.5105 \text{ N}$$

Resolving vertically,

$$F_y = 135 - 33.7495 \sin 45^\circ = 132.3487 \text{ N}$$

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$$F_c = \sqrt{60.5105^2 + 132.3487^2}$$

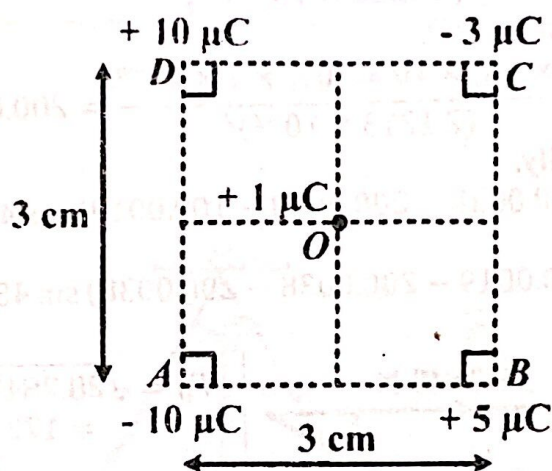
$$= 145.5256 \text{ N}$$

$$\tan \theta = \frac{132.3487}{60.5105}$$

$$\theta = 65.43^\circ$$

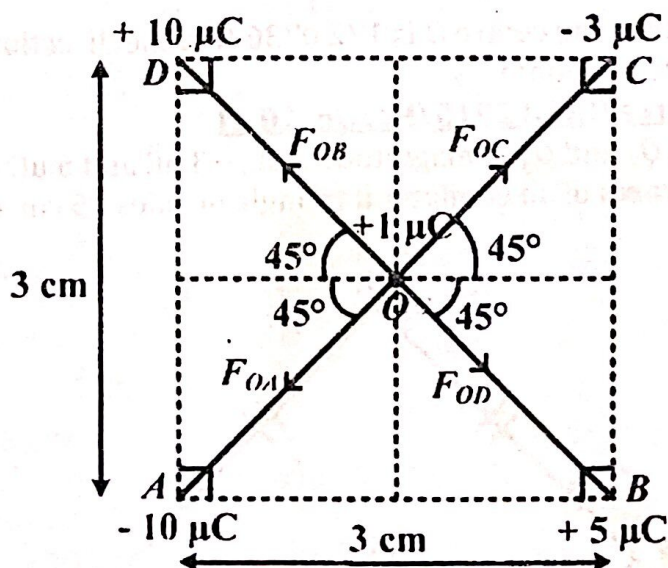
The resultant force is 145.5256 N in the direction 65.43° above the positive horizontal.

Qn 5: Charges $-10 \mu\text{C}$, $+5 \mu\text{C}$, $-3 \mu\text{C}$ and $+10 \mu\text{C}$ are placed at the edges A, B, C, and D of a square of sides 3 cm as shown below.



Find the resultant force on the charge of $+1 \mu\text{C}$ placed at the centre of the square, O as shown above.

Sol:



$$\overline{AC} = \sqrt{3^2 + 3^2} = 4.2426 \text{ cm}, \quad r = \frac{1}{2} \times \overline{AC} = \frac{1}{2} \times 4.2426 = 2.1213 \text{ cm}$$

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$$F = \frac{kQ_1Q_2}{r^2}$$

Force at O due to charge at A,

$$F_{OA} = \frac{9 \times 10^9 \times 10 \times 10^{-6} \times 1 \times 10^{-6}}{(2.1213 \times 10^{-2})^2} = 200.0038 \text{ N}$$

Force at O due to charge at B,

$$F_{OB} = \frac{9 \times 10^9 \times 5 \times 10^{-6} \times 1 \times 10^{-6}}{(2.1213 \times 10^{-2})^2} = 100.0019 \text{ N}$$

Force at O due to charge at C,

$$F_{OC} = \frac{9 \times 10^9 \times 3 \times 10^{-6} \times 1 \times 10^{-6}}{(2.1213 \times 10^{-2})^2} = 60.0012 \text{ N}$$

Force at O due to charge at D,

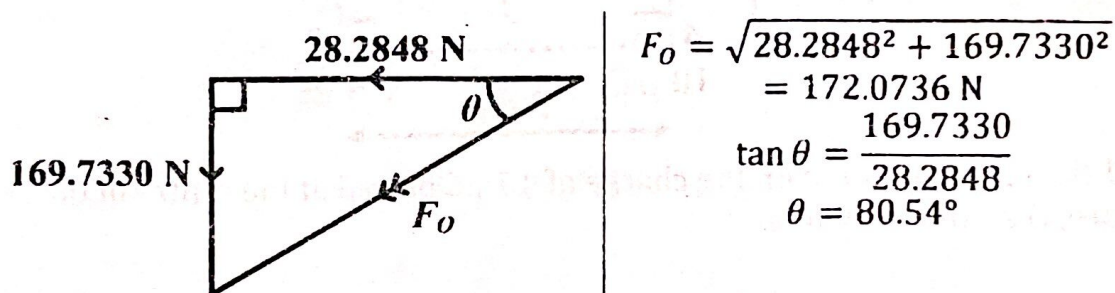
$$F_{OD} = \frac{9 \times 10^9 \times 10 \times 10^{-6} \times 1 \times 10^{-6}}{(2.1213 \times 10^{-2})^2} = 200.0038 \text{ N}$$

Resolving horizontally,

$$F_x = (60.0012 + 200.0038 - 200.0038 - 100.0019) \cos 45^\circ = -28.2848 \text{ N}$$

Resolving vertically,

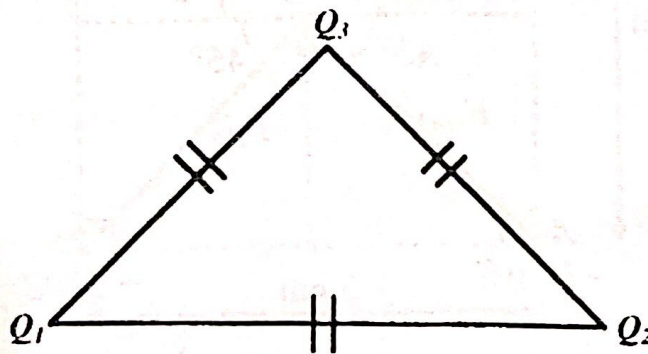
$$F_y = (60.0012 + 100.0019 - 200.0038 - 200.0038) \sin 45^\circ = -169.7330 \text{ N}$$



The resultant force at the centre O is 172.0736 N in the direction 80.54° below the negative horizontal.

Question 6: (Source UNEB 2015/P2/Qn. 10 d)

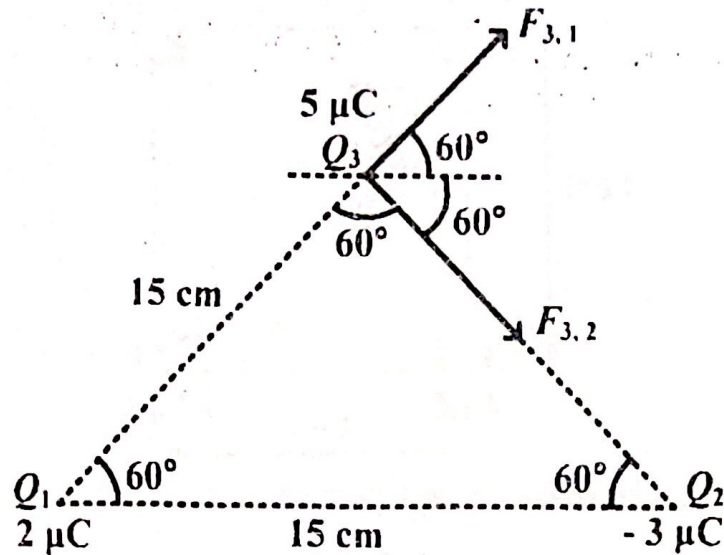
Three charges Q_1 , Q_2 and Q_3 of magnitude $2 \mu\text{C}$, $-3 \mu\text{C}$ and $5 \mu\text{C}$ respectively are situated at corners of an equilateral triangle of sides 15 cm as shown in figure below.



Calculate the net force on Q_3 .

Sol:

[5]



Force on Q_3 due to charge Q_1 ,

$$F_{3,1} = \frac{kQ_3Q_1}{r^2} = \frac{9 \times 10^9 \times 5 \times 10^{-6} \times 2 \times 10^{-6}}{(15 \times 10^{-2})^2} = 4 \text{ N}$$

Force on Q_3 due to charge Q_2 ,

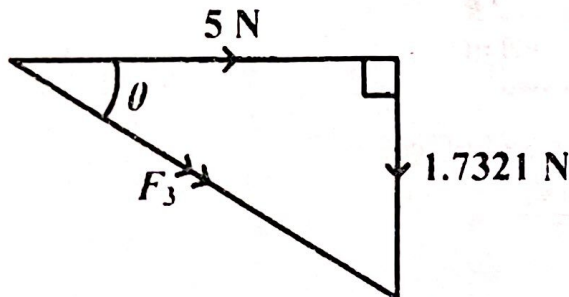
$$F_{3,2} = \frac{kQ_3Q_2}{r^2} = \frac{9 \times 10^9 \times 5 \times 10^{-6} \times 3 \times 10^{-6}}{(15 \times 10^{-2})^2} = 6 \text{ N}$$

Resolving horizontally,

$$F_x = (4 + 6) \cos 60^\circ = 5 \text{ N}$$

Resolving vertically,

$$F_y = (4 - 6) \sin 60^\circ = -1.7321 \text{ N}$$

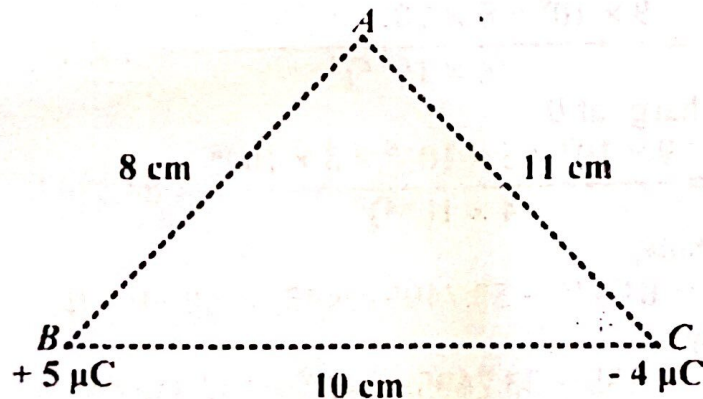


$$F_3 = \sqrt{5^2 + 1.7321^2} = 5.2915 \text{ N}$$

$$\tan \theta = \frac{1.7321}{5}, \quad \theta = 19.11^\circ$$

The resultant force on Q_3 is 5.2915 N in the direction 19.11° below the positive horizontal.

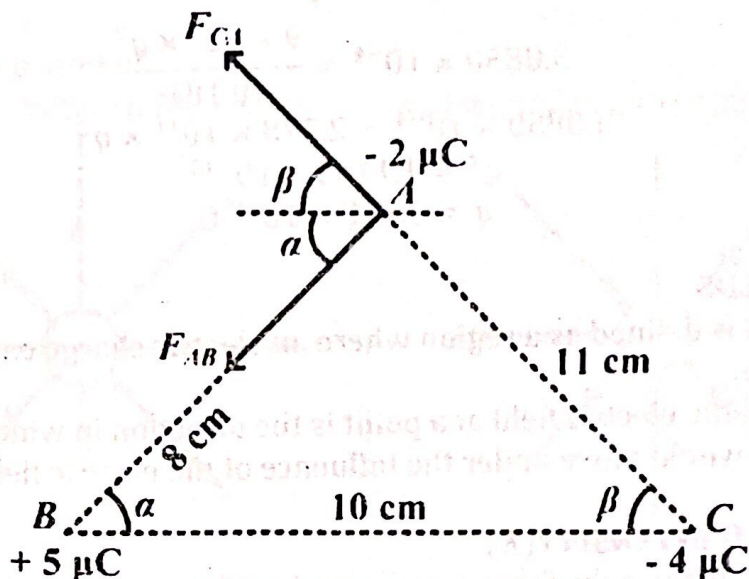
Qn 7: The figure below shows charges of $+5\mu\text{C}$ and $-4\mu\text{C}$ placed at the corners B and C respectively of a triangle ABC of sides 8 cm, 10 cm and 11 cm.



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Find the electric force exerted on a charge of $-2\mu\text{C}$ when placed at A.

Sol:



$$F = \frac{kQ_1Q_2}{r^2}$$

$$F_{AB} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 5 \times 10^{-6}}{0.08^2} = 14.0625 \text{ N}$$

$$F_{CA} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 4 \times 10^{-6}}{0.11^2} = 5.9504 \text{ N}$$

Using cosine rule,

$$11^2 = 8^2 + 10^2 - 2 \times 8 \times 10 \cos \alpha$$

$$121 = 164 - 160 \cos \alpha$$

$$160 \cos \alpha = 43$$

$$\cos \alpha = \frac{43}{160}$$

$$\alpha = 74.41^\circ$$

Using sine rule,

$$\frac{\sin \beta}{8} = \frac{\sin 74.41^\circ}{11}$$

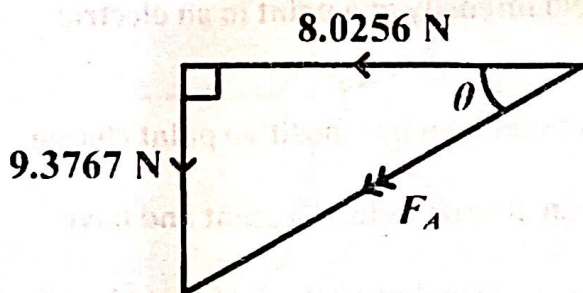
$$\beta = 44.47^\circ$$

Resolving horizontally,

$$F_x = -14.0625 \cos 74.41^\circ - 5.9504 \cos 44.47^\circ = -8.0256 \text{ N}$$

Resolving vertically,

$$F_y = 5.9504 \sin 44.47^\circ - 14.0625 \sin 74.41^\circ = -9.3767 \text{ N}$$



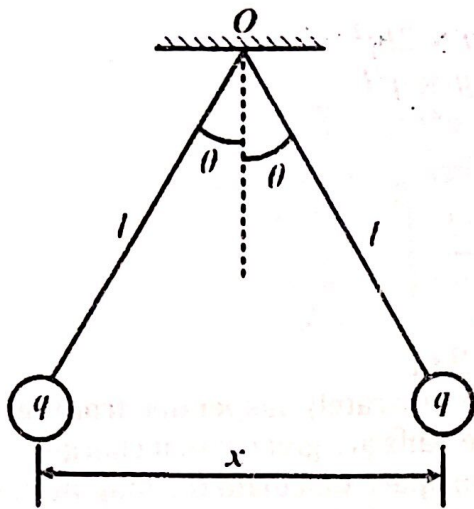
$$F_A = \sqrt{8.0256^2 + 9.3767^2} = 12.3423 \text{ N}$$

$$\tan \theta = \frac{9.3767}{8.0256}, \theta = 49.44^\circ$$

The resultant force at A is 12.3423 N in the direction 49.44° below the negative horizontal.

Question 8: (Source UNEB 2001/P2/Qn. 9 b(ii))

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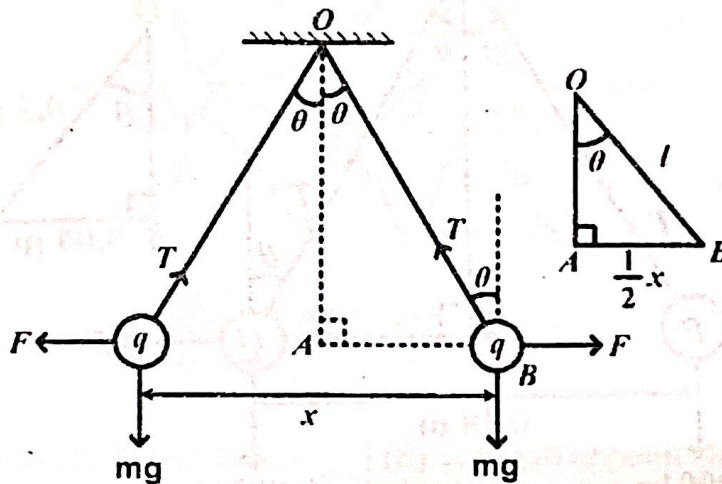
Two identical conducting balls of mass, m are each suspended in air from a silk thread of length, l . When the two balls are each given identical charge, q , they move apart as shown.

If at equilibrium each thread makes a small angle θ , with the vertical, show that the separation x is given by

$$x = \left[\frac{q^2 l}{2\pi\epsilon m g} \right]^{1/3}$$

Where ϵ is permittivity of air. [6]

Sol:



For $\triangle OAQ$,
From, $\triangle OAB$

$$\sin \theta = \frac{0.5x}{l} = \frac{x}{2l}$$

For small angles,

$$\sin \theta \approx \theta, \quad \Rightarrow \theta = \frac{x}{2l}$$

Resolving vertically,

$$T \cos \theta = mg \quad \rightarrow (1)$$

Resolving horizontally,

$$T \sin \theta = F$$

$$\text{but, } F = \frac{q^2}{4\pi\epsilon x^2}$$

$$T \sin \theta = \frac{q^2}{4\pi\epsilon x^2} \quad \rightarrow (2)$$

Equation (2) \div (1) gives:

$$\frac{T \sin \theta}{T \cos \theta} = \frac{q^2}{4\pi\epsilon x^2 mg}$$

$$\tan \theta = \frac{q^2}{4\pi\epsilon x^2 mg}$$

For small angles,

$$\tan \theta \approx \theta$$

$$\Rightarrow \tan \theta \approx \frac{x}{2l}$$

$$\frac{x}{2l} = \frac{q^2}{4\pi\epsilon x^2 mg}$$

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$$4\pi\epsilon x^3 mg = 2lq^2$$

$$2\pi\epsilon x^3 mg = q^2 l$$

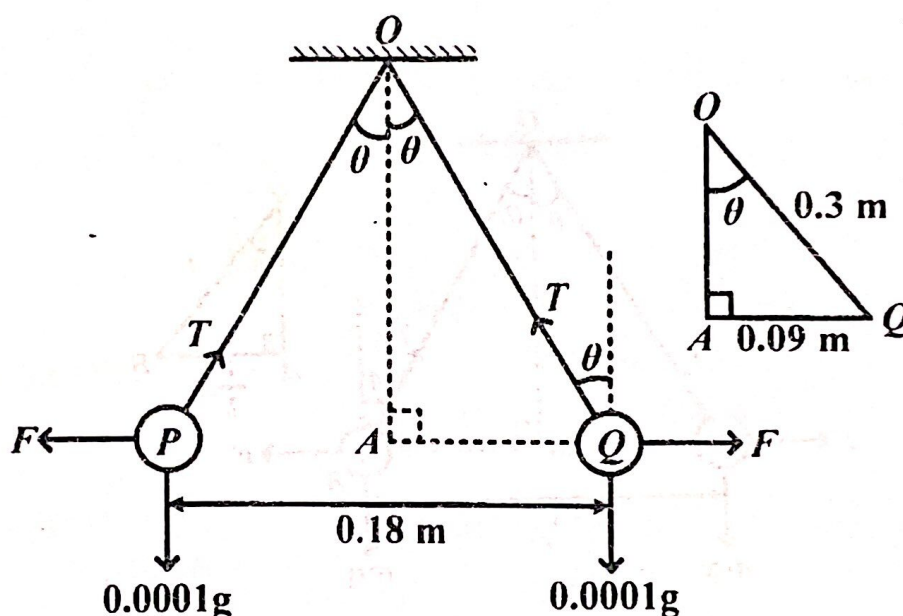
$$x^3 = \frac{q^2 l}{2\pi\epsilon mg}$$

$$x = \left[\frac{q^2 l}{2\pi\epsilon mg} \right]^{1/3}$$

Question 9: (Source UNEB 2011/P2/Qn. 9 c)

Two pith ball P and Q each of mass 0.1 g are separately suspended from the same point by threads 30cm long. When the balls are given equal charges, they repel each other and come to rest 18cm apart. Calculate the magnitude of charge on each ball. [6]

Sol:



For $\triangle OAQ$,

$$\sin \theta = \frac{0.09}{0.3}, \quad \Rightarrow \theta = 17.458^\circ$$

Resolving vertically,

$$\begin{aligned} T \cos 17.458^\circ &= 0.0001g \\ T \cos 17.458^\circ &= 0.0001 \times 9.81 \\ T &= 1.0284 \times 10^{-3} \text{ N} \end{aligned}$$

Resolving horizontally,

$$\begin{aligned} T \sin 17.458^\circ &= F \\ F &= 1.0283 \times 10^{-3} \times \sin 17.458^\circ \\ F &= 3.0850 \times 10^{-4} \text{ N} \end{aligned}$$

Let q be the magnitude of charge on each ball.

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$$F = \frac{kq^2}{r^2}$$
$$3.0850 \times 10^{-4} = \frac{9 \times 10^9 \times q^2}{(0.18)^2}$$
$$3.0850 \times 10^{-4} = 2.778 \times 10^{11} \times q^2$$
$$q^2 = 1.1105 \times 10^{-15}$$
$$q = 3.332 \times 10^{-8} \text{ C}$$

ELECTRIC FIELDS

An electric field is defined as a region where an electric charge experiences an electric force.

The direction of the electric field at a point is the direction in which a small positive charge would move under the influence of the electric field if placed at that point.

ELECTRIC FIELD INTENSITY (E)

Electric field intensity is the force experienced by (or acting on) a positive charge of 1 C placed at a point in the electric field.

It's a vector quantity and it's measured in Newtons per coulomb (N C^{-1})

From the definition of electric field intensity,

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

Where E is the electric field intensity, F is the electrostatic force, and Q is the charge placed in the field.

Expression for electric field intensity at a point

Electric field intensity at a point is defined as the force acting on a positive charge of 1C placed at a point in the electric field.

Consider a point charge Q placed in a medium of permittivity ϵ . Let the test charge Q_0 be at a distance r from Q .

By coulomb's law

$$F = \frac{QQ_0}{4\pi\epsilon r^2}, \quad \Rightarrow E = \frac{F}{Q_0} = \frac{\left(\frac{QQ_0}{4\pi\epsilon r^2}\right)}{Q_0} = \frac{Q}{4\pi\epsilon r^2}$$

This is the expression of the electric field intensity at a point in an electric field.

Electric field lines

An electric field line is the path or direction taken by a positive point charge of 1 C placed in an electric field.

Electric field lines give the direction of an electric field at a point and have the following properties:

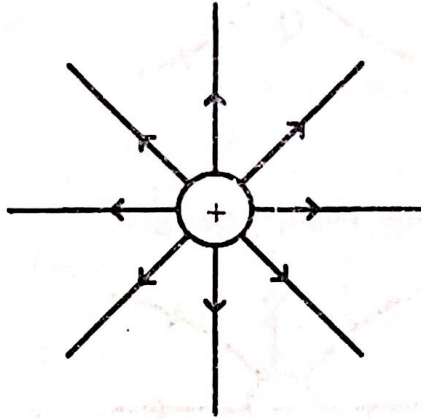
- They originate from the positive charge and go to the negative charge.
- They are symmetrical.
- No two of the electric field lines will ever cross each other.

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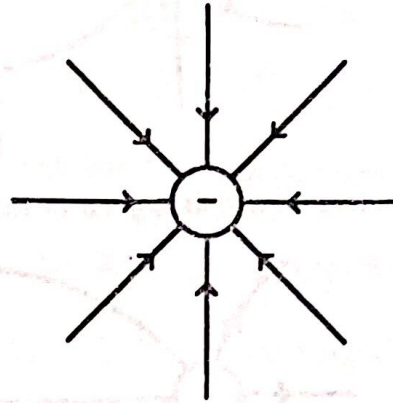
- The number of electric field lines leaving a positive charge or entering a negative charge is proportional to the charge (electric field intensity).

Electric field patterns

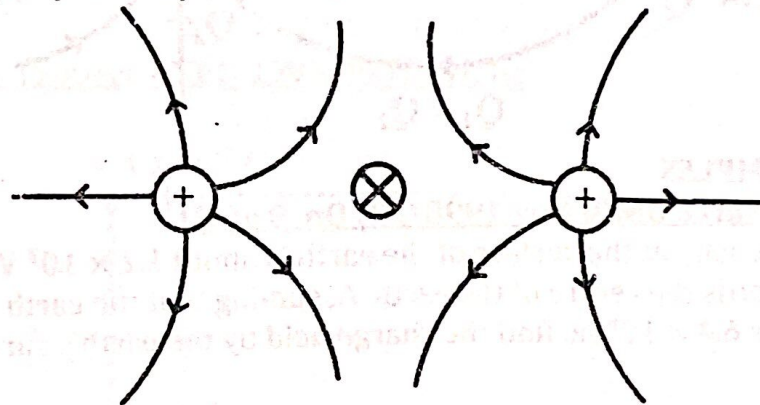
(1). Isolated positive point charge



(2). Isolated negative point charge

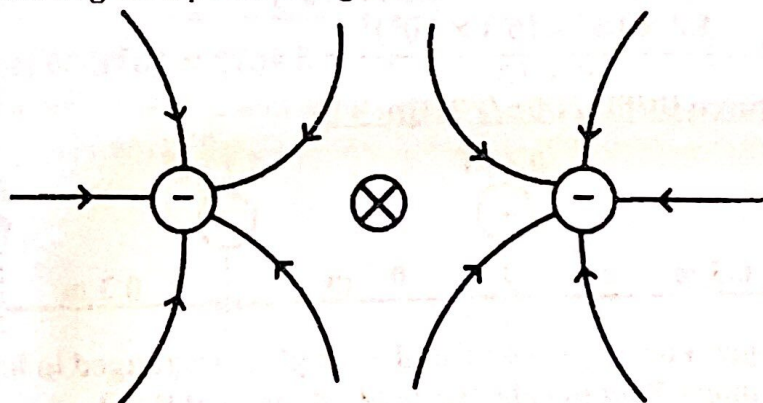


(3). Two equal positive point charges



⊗ Is the neutral point

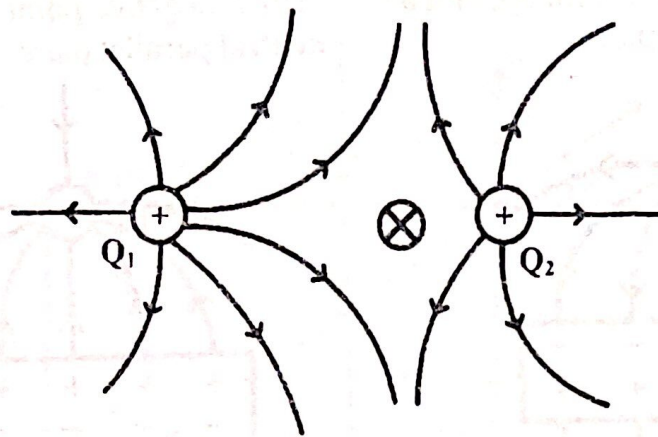
(4). Two equal negative point charges



⊗ Is the neutral point

(5). Two unequal positive point charges

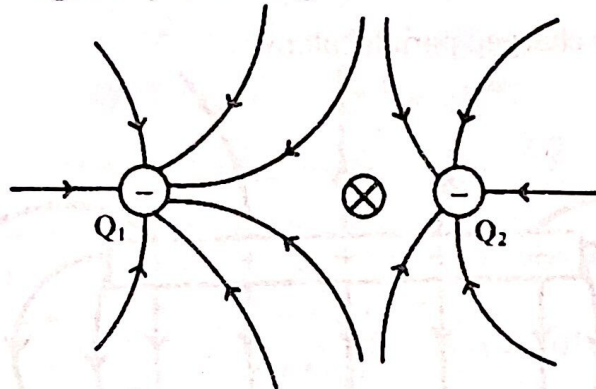
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⊗ Is the neutral point

$$Q_1 > Q_2$$

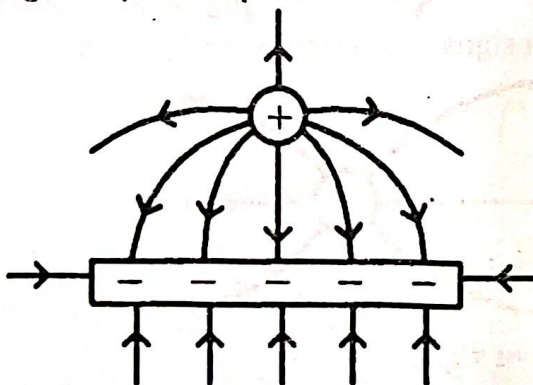
(6). Two unequal negative point charges



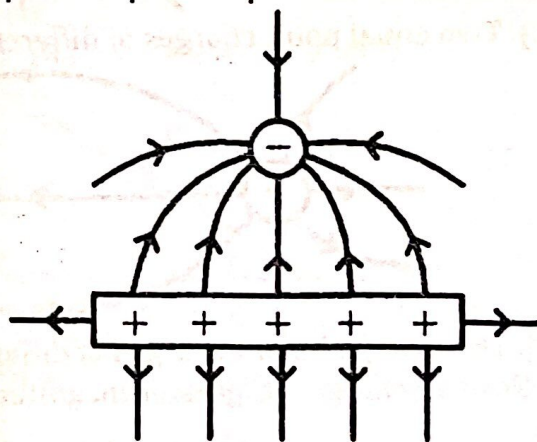
⊗ Is the neutral point

$$Q_1 > Q_2$$

(7). A positive point charge and a negative parallel plate

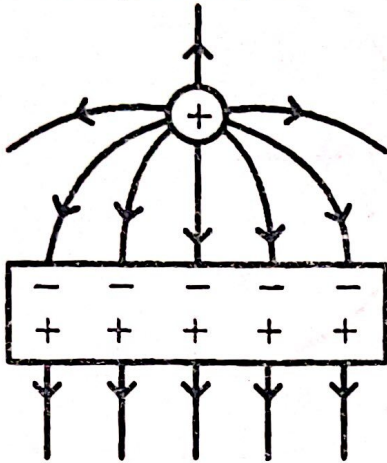


(8). A negative point charge and a positive parallel plate

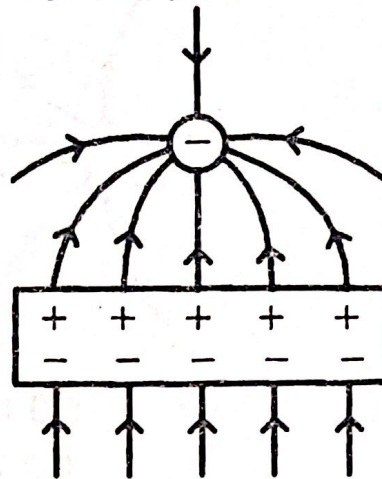


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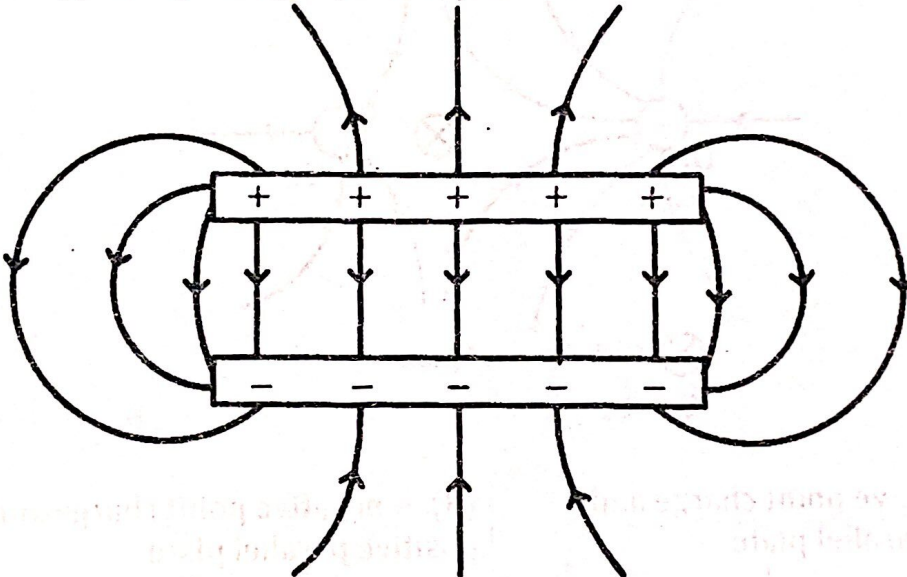
(9). A positive point charge and a neutral parallel plate



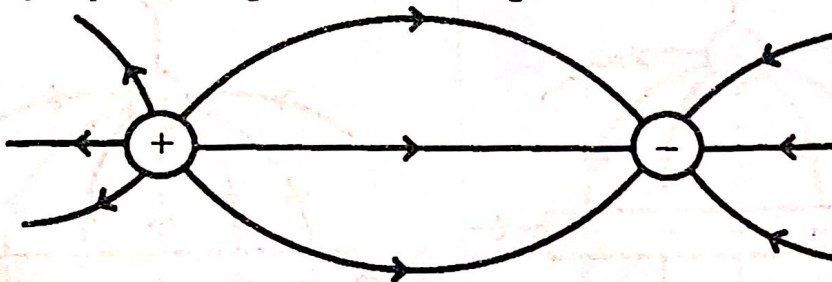
(10). A negative point charge and a neutral parallel plate



(11). Two oppositely charged parallel plates



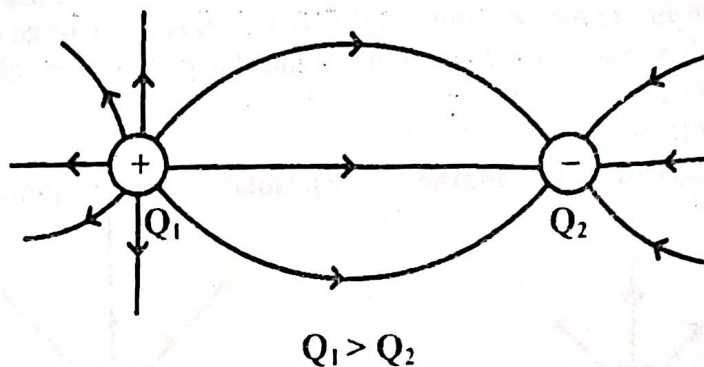
(12). Two equal point charges of different signs



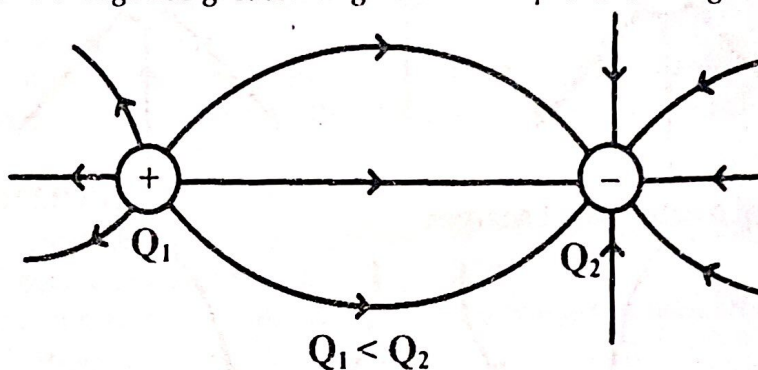
(13). Two unequal point charges of different signs

(a). Positive charge has greater magnitude than negative charge

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(b). Negative charge has greater magnitude than positive charge



WORKED EXAMPLES

Question 1: (Source UNEB Nov 1998/P2/Qn. 9 a(ii))

The electric intensity at the surface of the earth is about $1.2 \times 10^2 \text{ V m}^{-1}$ and points towards the centre of the earth. Assuming that the earth is a sphere of radius $6.4 \times 10^6 \text{ m}$, find the charge held by the earth's surface. [3]

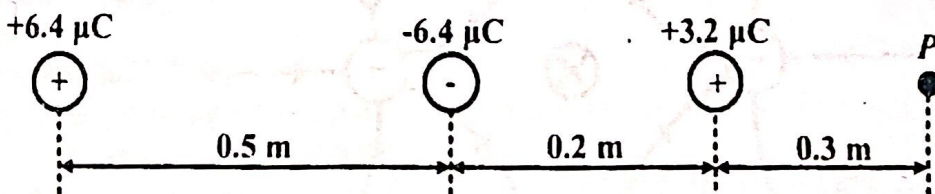
Sol:

$$\text{Electric field intensity, } E = \frac{kQ}{r^2}$$

$$1.2 \times 10^2 = \frac{9 \times 10^9 \times Q}{(6.4 \times 10^6)^2}$$

$$Q = \frac{1.2 \times 10^2 \times (6.4 \times 10^6)^2}{9 \times 10^9} = 5.4613 \times 10^5 \text{ C}$$

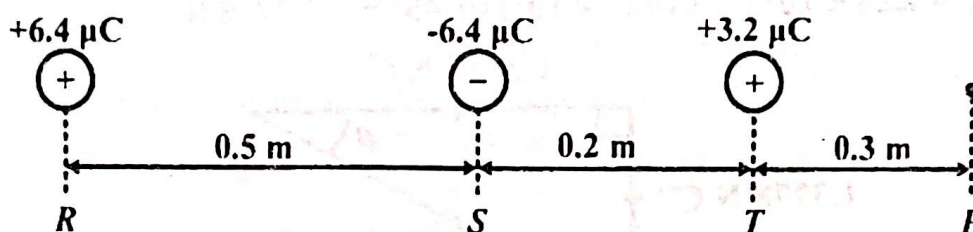
Question 2: (Source UNEB 2006/P2/Qn. 9 b)



Three point charges $+6.4 \mu\text{C}$, $-6.4 \mu\text{C}$ and $+3.2 \mu\text{C}$ are arranged in line as shown in figure above. Find the electric field intensity at P. [6]

Sol:

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Electric field intensity, $E = \frac{kQ}{r^2}$

$$E_{PR} = \frac{9 \times 10^9 \times 6.4 \times 10^{-6}}{(0.5 + 0.2 + 0.3)^2} = 5.76 \times 10^4 \text{ N C}^{-1}, \quad \text{to the right}$$

$$E_{PS} = \frac{9 \times 10^9 \times 6.4 \times 10^{-6}}{(0.2 + 0.3)^2} = 2.304 \times 10^5 \text{ N C}^{-1}, \quad \text{to the left}$$

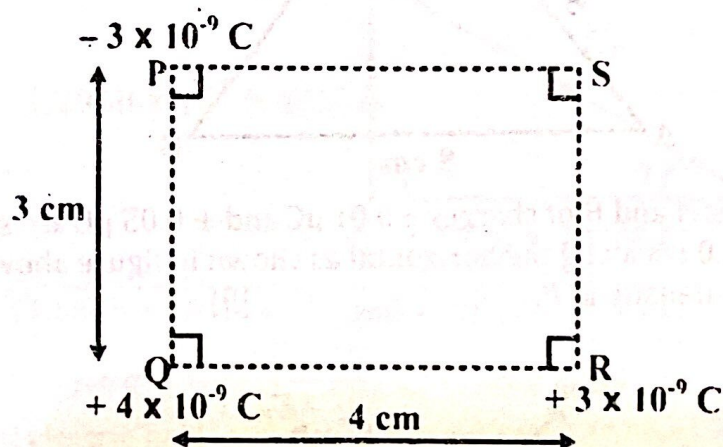
$$E_{PT} = \frac{9 \times 10^9 \times 3.2 \times 10^{-6}}{(0.3)^2} = 3.2 \times 10^5 \text{ N C}^{-1}, \quad \text{to the right}$$

Resultant electric field intensity at P,

$$E_P = E_{PR} - E_{PS} + E_{PT} = 5.76 \times 10^4 - 2.304 \times 10^5 + 3.2 \times 10^5$$

$$= 1.472 \times 10^5 \text{ N C}^{-1}, \quad \text{to the right}$$

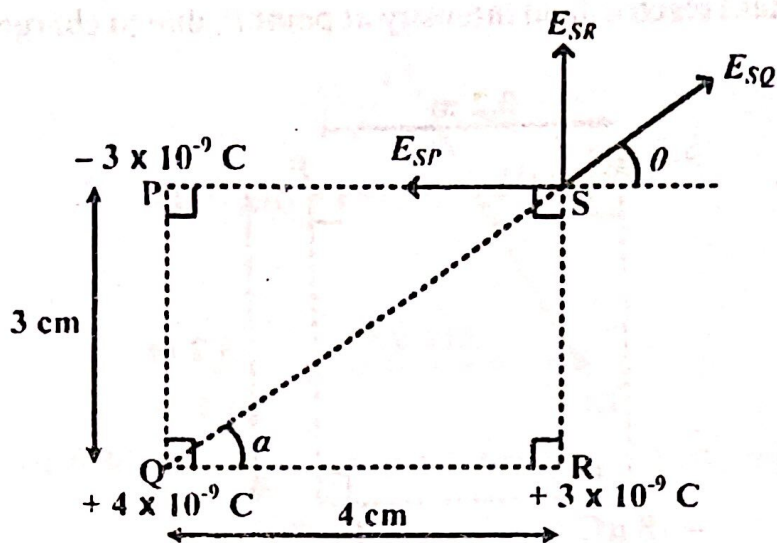
Question 3: (Source UNEB 1995/P2/Qn. 8 b)



Three charges of $-3 \times 10^{-9} \text{ C}$, $+4 \times 10^{-9} \text{ C}$ and $+3 \times 10^{-9} \text{ C}$ are placed in a vacuum at the vertices P, Q and R respectively of a rectangle PQRS of sides 3 cm \times 4 cm as shown in figure above. Calculate the resultant electric field intensity at S. [7]

Sol:

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For ΔSQR ,

$$\overline{QS} = \sqrt{3^2 + 4^2} = 5 \text{ cm}$$

$$\tan \theta = \frac{3}{4}, \quad \Rightarrow \theta = 36.87^\circ$$

Electric field intensity, $E = \frac{kQ}{r^2}$

$$E_{SP} = \frac{kQ_P}{r_{SP}^2} = \frac{9 \times 10^9 \times 3 \times 10^{-9}}{(4 \times 10^{-2})^2} = 1.6875 \times 10^4 \text{ N C}^{-1}$$

$$E_{SR} = \frac{kQ_R}{r_{SR}^2} = \frac{9 \times 10^9 \times 3 \times 10^{-9}}{(3 \times 10^{-2})^2} = 3 \times 10^4 \text{ N C}^{-1}$$

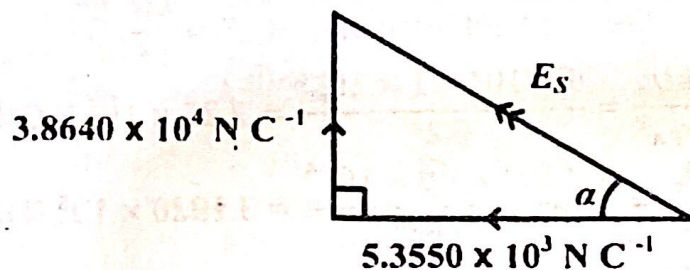
$$E_{SQ} = \frac{kQ_Q}{r_{SQ}^2} = \frac{9 \times 10^9 \times 4 \times 10^{-9}}{(5 \times 10^{-2})^2} = 1.44 \times 10^4 \text{ N C}^{-1}$$

Resolving horizontally,

$$E_x = (1.44 \times 10^4) \cos 36.87^\circ - 1.6875 \times 10^4 \\ = -5.3550 \times 10^3 \text{ N C}^{-1}$$

Resolving vertically,

$$E_y = (1.44 \times 10^4) \sin 36.87^\circ + 3 \times 10^4 = 3.8640 \times 10^4 \text{ N C}^{-1}$$



$$E_S = \sqrt{(5.3550 \times 10^3)^2 + (3.8640 \times 10^4)^2} = 3.9009 \times 10^4 \text{ N C}^{-1}$$

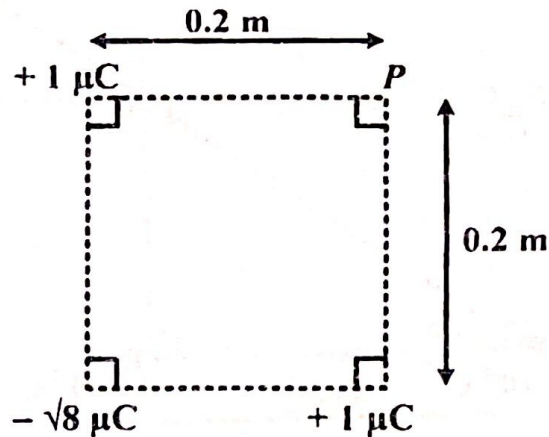
$$\tan \alpha = \frac{3.8640 \times 10^4}{5.3550 \times 10^3}, \quad \Rightarrow \alpha = 82.11^\circ$$

The resultant electric field intensity at S is $3.9009 \times 10^4 \text{ N C}^{-1}$ in the direction 82.11° above the negative horizontal.

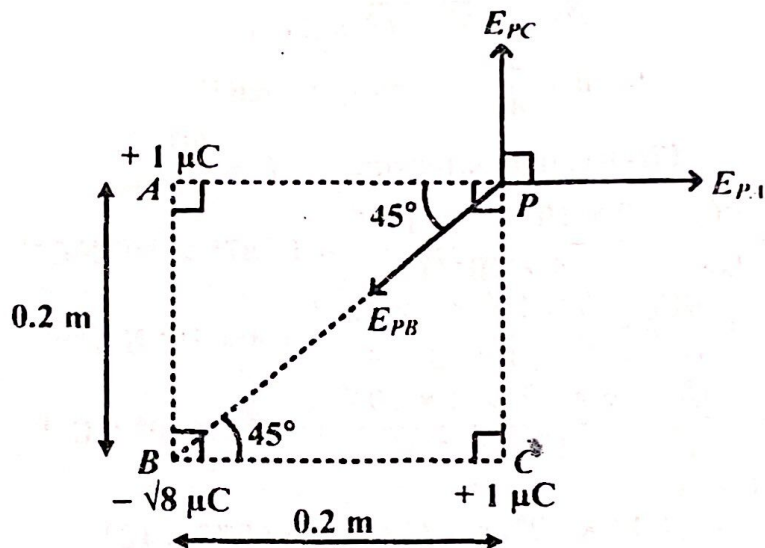
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Question 4: (Source UNEB 1994/P2/Qn. 10 d)

Find the resultant electric field intensity at point P , due to charges shown in figure below. [6]



Sol:



For $\triangle BCP$,

$$\overline{PB} = \sqrt{0.2^2 + 0.2^2} = \sqrt{0.08} \text{ m}$$

Electric field intensity, $E = \frac{kQ}{r^2}$

$$E_{PA} = \frac{kQ_A}{r_{PA}^2} = \frac{9 \times 10^9 \times 1 \times 10^{-6}}{0.2^2} = 2.25 \times 10^5 \text{ N C}^{-1}$$

$$E_{PB} = \frac{kQ_B}{r_{PB}^2} = \frac{9 \times 10^9 \times \sqrt{8} \times 10^{-6}}{(\sqrt{0.08})^2} = 3.1820 \times 10^5 \text{ N C}^{-1}$$

$$E_{PC} = \frac{kQ_C}{r_{PC}^2} = \frac{9 \times 10^9 \times 1 \times 10^{-6}}{0.2^2} = 2.25 \times 10^5 \text{ N C}^{-1}$$

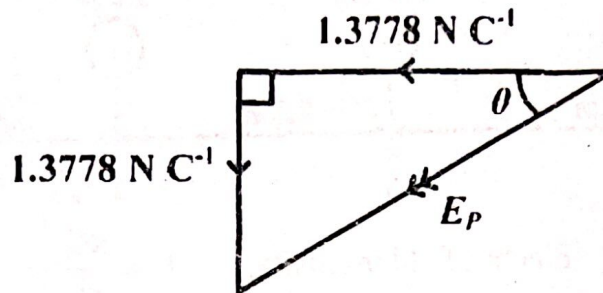
Resolving horizontally,

$$E_x = 2.25 \times 10^5 - (3.1820 \times 10^5) \cos 45^\circ = -1.3778 \text{ N C}^{-1}$$

Resolving vertically,

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$$E_y = 2.25 \times 10^5 - (3.1820 \times 10^5) \sin 45^\circ = -1.3778 \text{ N C}^{-1}$$

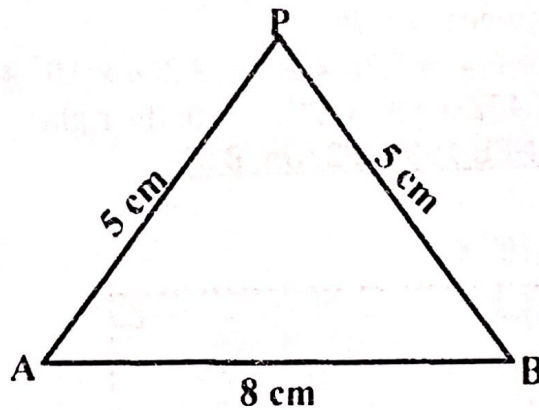


$$E_P = \sqrt{1.3778^2 + 1.3778^2} = 1.9485 \text{ N C}^{-1}$$

$$\tan \theta = \frac{1.3778}{1.3778}, \quad \Rightarrow \theta = 45^\circ$$

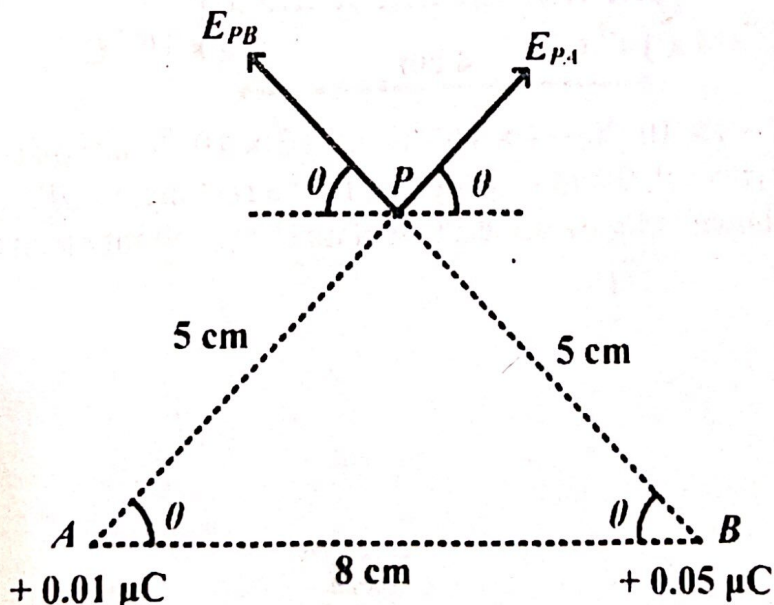
The resultant electric field intensity at P is 1.9485 N C^{-1} in the direction 45° below the negative horizontal.

Question 5: (Source UNEB 2002/P2/Qn. 9 c)



Two point charges A and B of charges $+0.01 \mu\text{C}$ and $+0.05 \mu\text{C}$ are separated by a distance of 8.0 cm along the horizontal as shown in figure above. Find the electric field intensity at P . [9]

Sol:



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Electric field intensity, $E = \frac{kQ}{r^2}$

Electric field intensity at P due to charge at A ,

$$E_{PA} = \frac{9 \times 10^9 \times 0.01 \times 10^{-6}}{(5 \times 10^{-2})^2} = 3.6 \times 10^4 \text{ N C}^{-1}$$

Electric field intensity at P due to charge at B ,

$$E_{PB} = \frac{9 \times 10^9 \times 0.05 \times 10^{-5}}{(5 \times 10^{-2})^2} = 1.8 \times 10^5 \text{ N C}^{-1}$$

Using cosine rule

$$5^2 = 5^2 + 8^2 - 2 \times 5 \times 8 \cos \theta$$

$$25 = 89 - 80 \cos \theta$$

$$80 \cos \theta = 64$$

$$\cos \theta = 0.8$$

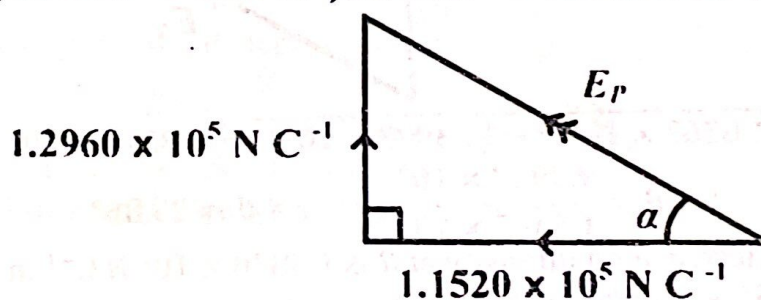
$$\theta = 36.87^\circ$$

Resolving horizontally,

$$E_x = (3.6 \times 10^4 - 1.8 \times 10^5) \cos 36.87^\circ = -1.1520 \times 10^5 \text{ N C}^{-1}$$

Resolving vertically,

$$E_y = (3.6 \times 10^4 + 1.8 \times 10^5) \sin 36.87^\circ = 1.2960 \times 10^5 \text{ N C}^{-1}$$



$$E_P = \sqrt{(1.1520 \times 10^5)^2 + (1.2960 \times 10^5)^2} = 1.7340 \times 10^5 \text{ N C}^{-1}$$

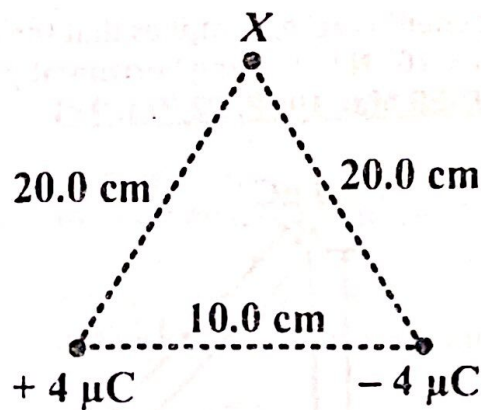
$$\tan \alpha = \frac{1.2960 \times 10^5}{1.1520 \times 10^5}, \quad \Rightarrow \alpha = 48.37^\circ$$

The resultant electric field intensity at P is $1.7340 \times 10^5 \text{ N C}^{-1}$ in the direction 48.37° above the negative horizontal.

Question 6: (Source UNEB Nov 1998/P2/Qn. 9 b)

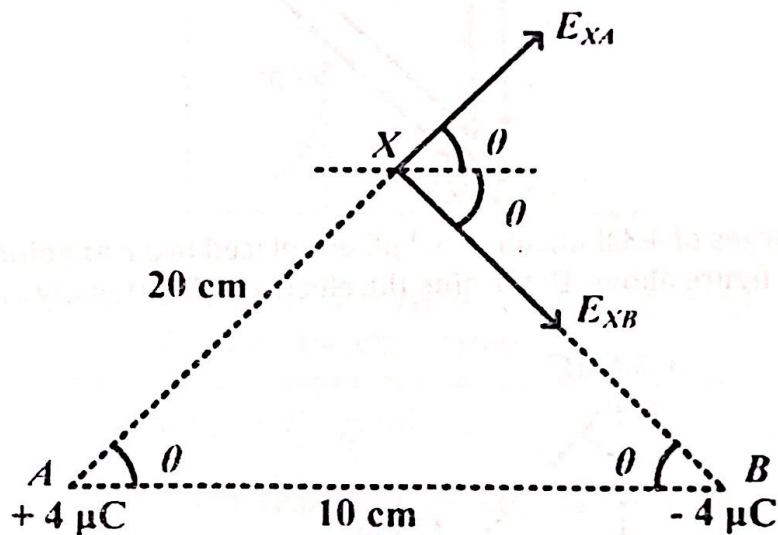
Two point charges $+4.0 \mu\text{C}$ and $-4.0 \mu\text{C}$ are separated by 10.0 cm in air as shown in figure below.

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Find the electric field intensity at point X a distance of 20.0 cm from each charge. [8]

Sol:



Electric field intensity, $E = \frac{kQ}{r^2}$

$$E_{XA} = \frac{kQ_A}{r_{XA}^2} = \frac{9 \times 10^9 \times 4 \times 10^{-6}}{(20 \times 10^{-2})^2} = 9 \times 10^5 \text{ N C}^{-1}$$

$$E_{XB} = \frac{kQ_B}{r_{XB}^2} = \frac{9 \times 10^9 \times 4 \times 10^{-6}}{(20 \times 10^{-2})^2} = 9 \times 10^5 \text{ N C}^{-1}$$

Using cosine rule

$$\begin{aligned}
 20^2 &= 20^2 + 10^2 - 2 \times 20 \times 10 \cos \theta \\
 400 &= 500 - 400 \cos \theta \\
 400 \cos \theta &= 100 \\
 \cos \theta &= 0.25 \\
 \theta &= 75.52^\circ
 \end{aligned}$$

Resolving horizontally,

$$\begin{aligned}
 E_x &= (9 \times 10^5 + 9 \times 10^5) \cos 75.52^\circ \\
 &= 4.5008 \times 10^5 \text{ N C}^{-1}
 \end{aligned}$$

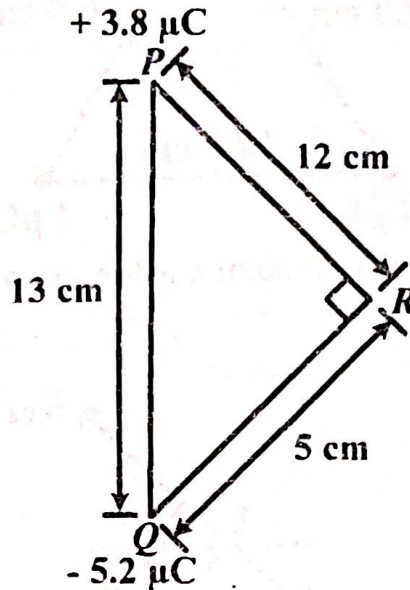
Resolving vertically,

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$$E_y = (9 \times 10^5 - 9 \times 10^5) \cos 75.52^\circ = 0 \text{ N C}^{-1}$$

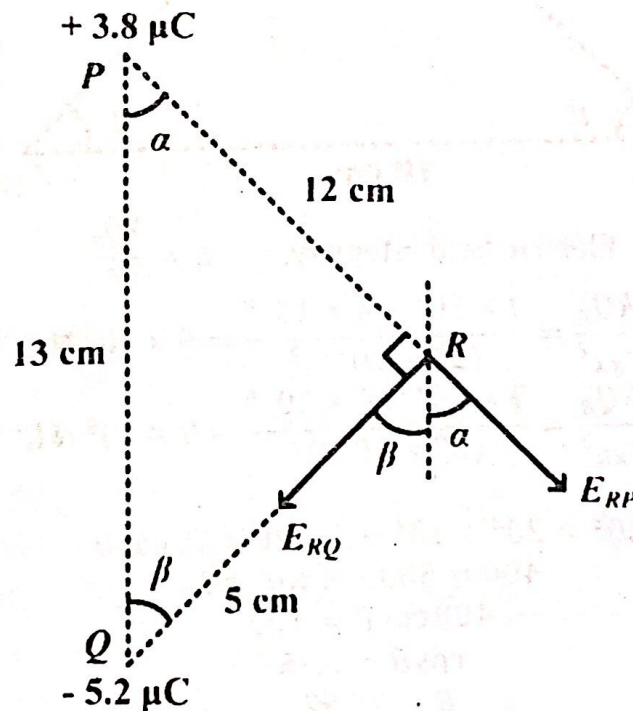
Since the vertical component is zero, it implies that the electric field intensity at X is $4.5008 \times 10^5 \text{ N C}^{-1}$ acting horizontally to the right.

Question 7: (Source UNEB Mar 1998/P2/Qn. 9 c)



Two point charges of $+3.8 \mu\text{C}$ and $-5.2 \mu\text{C}$ are placed in air at points P and Q as shown in figure above. Determine the electric field intensity at R . [7]

Sol:



Electric field intensity, $E = \frac{kQ}{r^2}$

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$$E_{RP} = \frac{kQ_1}{r_2^2} = \frac{9 \times 10^9 \times 3.8 \times 10^{-6}}{(12 \times 10^{-2})^2} = 2.3750 \times 10^6 \text{ N C}^{-1}$$

$$E_{RQ} = \frac{kQ_2}{r_2^2} = \frac{9 \times 10^9 \times 5.2 \times 10^{-6}}{(5 \times 10^{-2})^2} = 1.8720 \times 10^7 \text{ N C}^{-1}$$

but, $\sin \alpha = \frac{5}{13} \Rightarrow \alpha = 22.62^\circ$

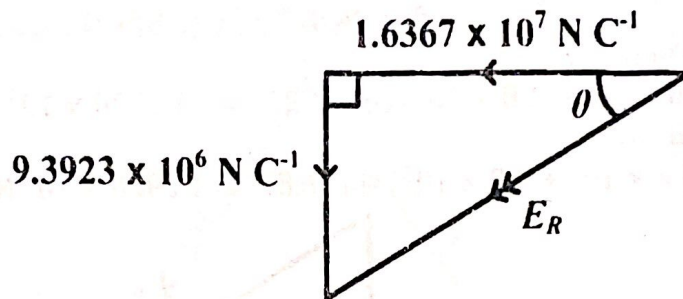
Also, $\beta = 90 - \alpha = 90 - 22.62 = 67.38^\circ$

Resolving horizontally,

$$E_x = (2.3750 \times 10^6) \sin 22.62^\circ - (1.8720 \times 10^7) \sin 67.38^\circ = -1.6367 \times 10^7 \text{ N C}^{-1}$$

Resolving vertically,

$$E_y = -(2.3750 \times 10^6) \cos 22.62^\circ - (1.8720 \times 10^7) \cos 67.38^\circ = -9.3923 \times 10^6 \text{ N C}^{-1}$$



$$E_R = \sqrt{(1.6367 \times 10^7)^2 + (9.3923 \times 10^6)^2} = 1.8870 \times 10^7 \text{ N C}^{-1}$$

$$\tan \theta = \frac{9.3923 \times 10^6}{1.6367 \times 10^7} \Rightarrow \theta = 29.85^\circ$$

The resultant electric field intensity at R is $1.8870 \times 10^7 \text{ N C}^{-1}$ in the direction 29.85° below the negative horizontal.

ELECTRIC FLUX (Φ)

Electric flux is defined as the product of electric field intensity and the area of the surface perpendicular to the electric field.

Expression for electric flux through a spherical surface enclosing a point charge Q in vacuum

Consider a sphere of radius r drawn in space and concentric with a point charge $+Q$ as shown below.

Electric field intensity of the sphere

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

Surface area of the sphere perpendicular to the electric field, $A = 4\pi r^2$.

Therefore, electric flux

$$\phi = EA = \left[\left(\frac{Q}{4\pi\epsilon_0 r^2} \right) (4\pi r^2) \right] = \frac{Q}{\epsilon_0}$$

(total flux through a spherical surface in a given medium) = $\left[\frac{\text{charge inside the sphere}}{\text{permittivity of the medium}} \right]$

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This is the expression which shows that the total flux through a spherical surface enclosing a point charge is constant.

Electric flux can also be defined as the ratio of the total charge enclosed in a medium to the permittivity of the medium.

NOTE: It can now be seen that the total flux crossing any sphere drawn outside and concentrically around a point charge is a constant. It doesn't depend on its distance from the charged sphere. This is known as Gauss's theorem.

GAUSS'S THEOREM

It states that the total flux passing through any closed sphere, whatever its shape, is always equal to (Q/ϵ_0) where Q is the total charge enclosed by the sphere.

Or: It states that the total flux crossing any sphere drawn outside and concentric round a point charge is constant.

SURFACE CHARGE DENSITY (σ)

Surface charge density is defined as the charge per unit area of a region of the body. That is,

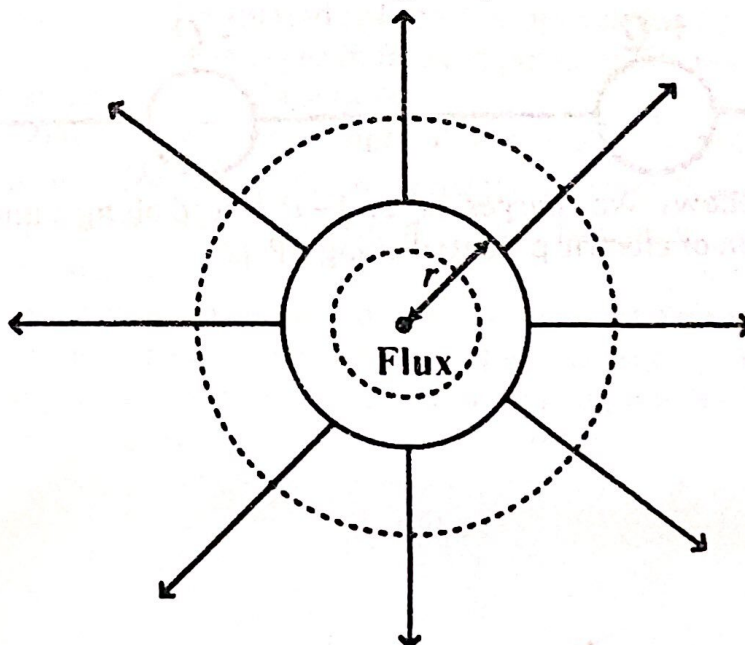
$$\sigma = \frac{Q}{A} = \frac{Q}{4\pi r^2}$$

Also from the expression of electric field intensity

$$E = \frac{Q}{4\pi\epsilon_0 r^2} = \left(\frac{Q}{4\pi r^2}\right)\left(\frac{1}{\epsilon_0}\right) = \frac{\sigma}{\epsilon_0}$$

Thus, surface charge density, $\sigma = \epsilon_0 E$

Electric field intensity outside a charged sphere



The flux through a spherical surface of radius r , concentric with a small sphere carrying a charge Q is given by

$$\phi = EA, \quad \text{also, } \phi = \frac{Q}{\epsilon_0}$$

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Equating the two equations gives

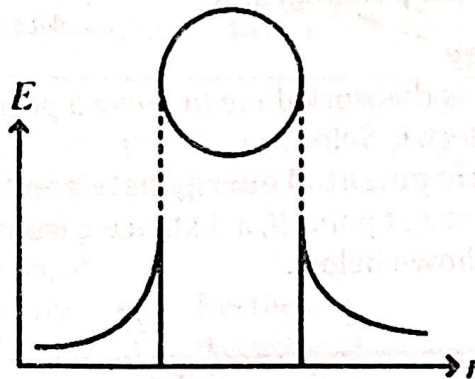
$$EA = \frac{Q}{\epsilon_0} \Rightarrow E = \frac{Q}{A\epsilon_0} = \frac{Q}{(4\pi r^2)\epsilon_0} \Rightarrow E \propto \frac{1}{r^2}$$

Thus outside a charged sphere, field behaves as if all the charge on the sphere were concentrated at its centre.

Electric field intensity inside a charged sphere

Inside a charged sphere, there are no charges and therefore, electric field intensity must be zero everywhere inside a charged sphere.

A graph showing the variations of electric field intensity inside and outside a sphere



ELECTRIC POTENTIAL

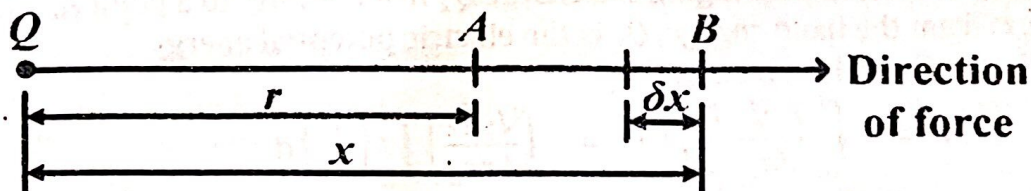
Electric potential is the work done to move/transfer a positive charge of 1 C from infinity to a point against the electrostatic field.

Or: Electric potential, V , at a point is the work done to move a positive charge of 1 C from infinity to that point against electrostatic repulsion.

It's a scalar quantity and therefore the potential due to a number of charges is added algebraically.

Expression of the electric potential due to a point charge

Consider a positive charge of 1 C, placed at point B, a distance x from charge, Q , situated in a vacuum as shown below.



The electric force F experienced by the positive charge of 1 C due to charge, Q , is given by:

$$F = \frac{Q \times 1}{4\pi\epsilon_0 x^2} = \frac{Q}{4\pi\epsilon_0 x^2}$$

Assuming that the force on the 1 C charge remains constant over a small distance, δx , in the direction against electrostatic repulsion, the work done is given by:

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$$\delta W = F \times (-\delta x) = -\left(\frac{Q}{4\pi\epsilon_0 x^2}\right) \delta x$$

The total work done in bringing the positive charge of 1 C from infinity to a point A, a distance, r , from the fixed charge, Q , is the electric potential at A and is given by:

$$W = -\int_{\infty}^r \left(\frac{Q}{4\pi\epsilon_0 x^2}\right) dx = -\left(\frac{Q}{4\pi\epsilon_0}\right) \int_{\infty}^r \left(\frac{1}{x^2}\right) dx$$

$$W = -\left(\frac{Q}{4\pi\epsilon_0}\right) \left[\frac{-1}{x}\right]_{\infty}^r = -\left(\frac{Q}{4\pi\epsilon_0}\right) \left(\frac{-1}{r} - \frac{-1}{\infty}\right) = \frac{Q}{4\pi\epsilon_0 r}$$

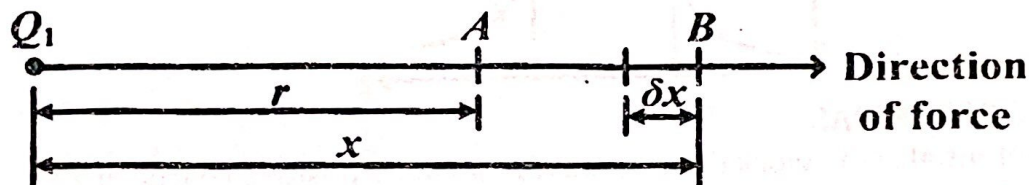
\therefore Electric potential at A, $V = \frac{Q}{4\pi\epsilon_0 r}$

Electric potential energy

Electric potential energy is the work done to move a positive charge from infinity to a point in an electric field.

Expression of the electric potential energy between two point charges

Consider a charge, Q_2 , placed at point B, a distance x from the charge, Q_1 , situated in a vacuum as shown below.



The electric force F experienced by the charge, Q_2 , due to charge, Q_1 , is given by:

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

Assuming that the force on Q_2 remains constant over a small distance, δx , in the direction against electrostatic repulsion, the work done is given by:

$$\delta W = F \times (-\delta x) = -\left(\frac{Q_1 Q_2}{4\pi\epsilon_0 x^2}\right) \delta x$$

The total work done, W , in bringing the charge Q_2 from infinity to a point A, a distance, r , from the fixed charge, Q_1 is the electric potential energy between Q_1 and Q_2 and is given by:

$$W = -\int_{\infty}^r \left(\frac{Q_1 Q_2}{4\pi\epsilon_0 x^2}\right) dx = -\left(\frac{Q_1 Q_2}{4\pi\epsilon_0}\right) \int_{\infty}^r \left(\frac{1}{x^2}\right) dx$$

$$W = -\left(\frac{Q_1 Q_2}{4\pi\epsilon_0}\right) \left[\frac{-1}{x}\right]_{\infty}^r = -\left(\frac{Q_1 Q_2}{4\pi\epsilon_0}\right) \left(\frac{-1}{r} - \frac{-1}{\infty}\right) = \frac{Q_1 Q_2}{4\pi\epsilon_0 r}$$

\therefore Electric potential energy = $\frac{Q_1 Q_2}{4\pi\epsilon_0 r}$

Qn: Explain briefly what happens to potential energy as two point charges of the same sign are brought closer. [2]

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Sol: Since like charges repel, work has to be done against the repulsive forces between them to bring them closer.

This work is stored as electric potential energy of the system.

Therefore, potential energy of two like charges increases when the charges are brought closer together.

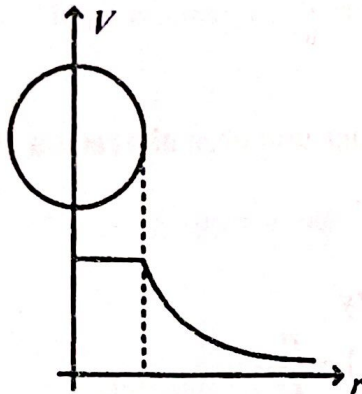
Electric potential due to a conducting sphere

The potential V at a point on the sphere is given by

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

Where r is the radius of the sphere.

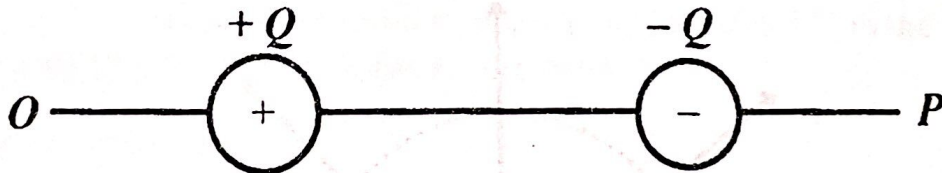
Electric potential inside and outside a sphere



Within the sphere (at all points inside the sphere), the electric potential is constant and is equal to that at its surface. There is no net charge inside.

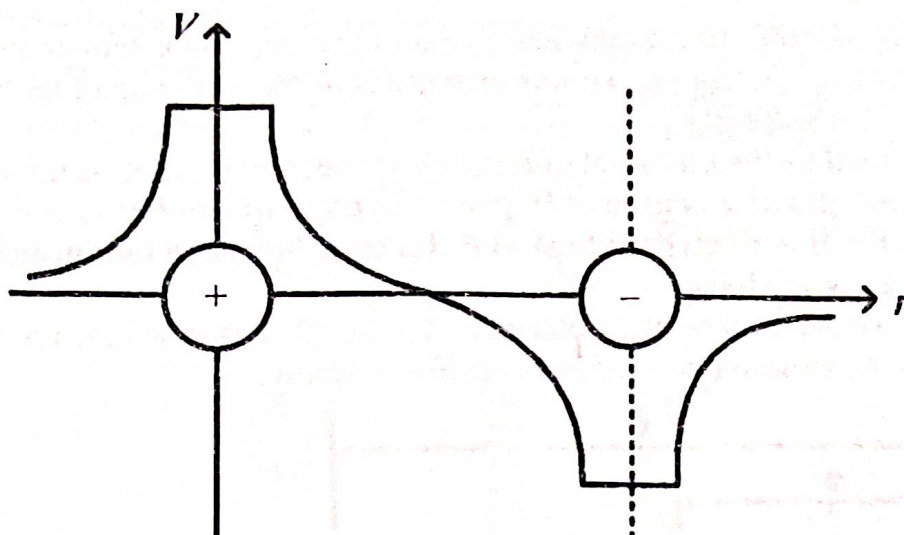
Outside the sphere the potential is inversely proportional to the distance r from the centre of the sphere. i.e. $V \propto \frac{1}{r}$.

Qn:

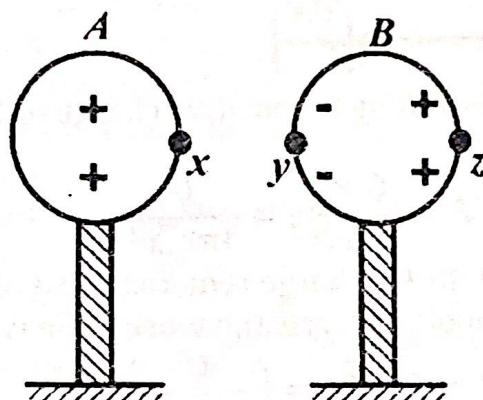


The figure above shows two charges $+Q$ and $-Q$ placed along a line OP . sketch the variation of electric potential along OP . [2]

Sol:



Effect of a neutral conductor on the potential of a charged conducting sphere

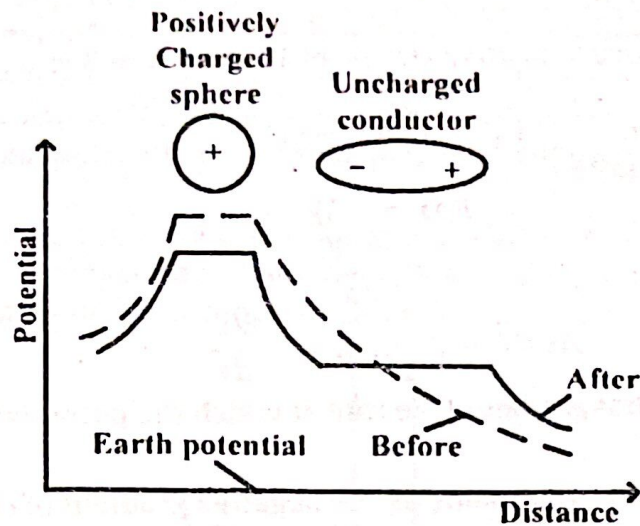


When a positively charged insulated sphere A is placed close to a neutral insulated sphere B, positive charges in B are repelled while negative charges are attracted to a side close to A.

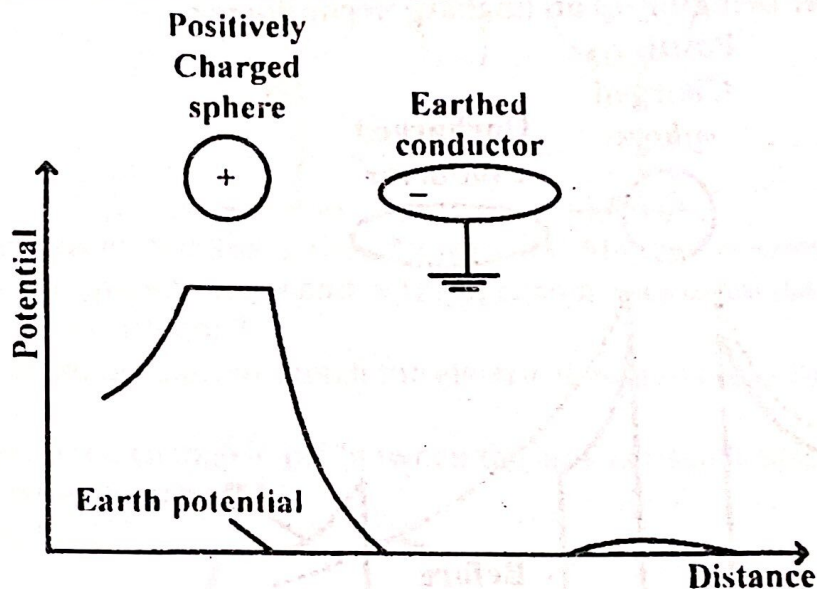
The resultant potential at x on the sphere, $V = V_y + V_z + V_x$; the potentials due to charges at y, z, and the sphere A respectively. Since V_y and V_z have opposite signs and z is farther away, the negative charges at y effectively reduce the potential at A.

Likely Qn: Explain how the presence of a neutral conductor near a charged conducting sphere may reduce the potential of the sphere. [3]

A graph showing the potential distribution near a positive charge before and after bringing up an uncharged conductor

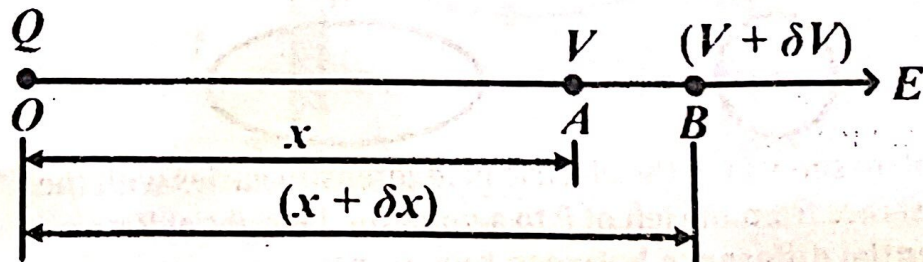


A graph showing the potential distribution near a positive charge in the presence of an earthed conductor



The relationship between the electric field intensity E and electric potential V

Consider two neighboring points A and B in the field of a point charge, Q , so close together that the electric field intensity between them is constant and is equal to E as shown below.



If the potential at A is V and that at B is $(V + \delta V)$, the potential difference between two points A and B will be given by:

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$$V_{AB} = V_A - V_B = V - (V + \delta V) = -\delta V \rightarrow (1)$$

The work done to move a positive charge of 1C from A to B is also equal to p.d and is given by:

$$V_{AB} = E\delta x \rightarrow (2)$$

Equating (1) and (2) gives:

$$E\delta x = -\delta V$$

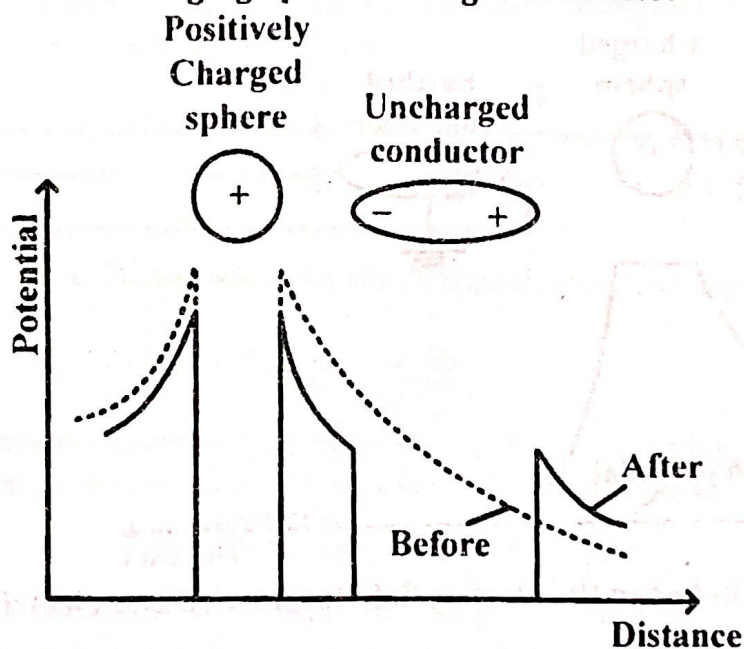
$$E = \frac{-\delta V}{\delta x}$$

$$\text{As } \delta x \rightarrow 0, \quad E = -\frac{dV}{dx}$$

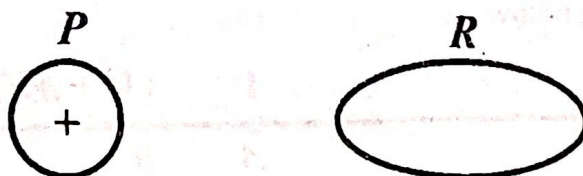
Where $\frac{dV}{dx}$ is the potential gradient (the rate at which the potential rises with distance).

i.e. electric field intensity is the same as the negative gradient of electric potential.

A graph showing the electric field intensity near a positive charge before and after bringing up an uncharged conductor



Likely Qn: A positively charged metal sphere P is placed adjacent to a neutral conductor R as shown in figure below.



Sketch a graph to show how the electric field intensity varies with the horizontal distance from the left of P to a point on the right of R.

Electric potential difference between two points

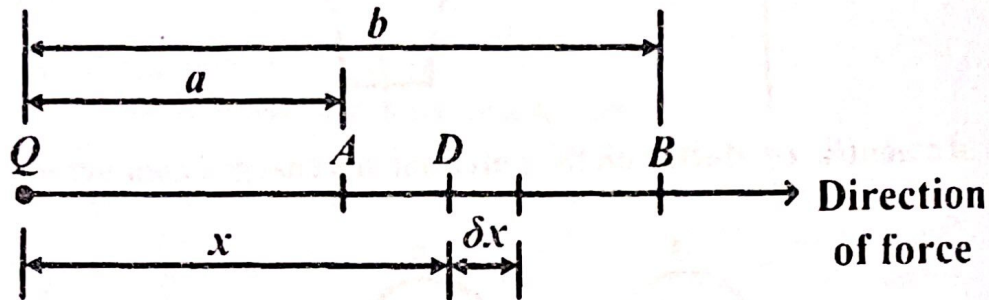
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Electric potential difference between two points is the work done to move a positive charge of 1C from one point to another in the direction of force. It's measured in volts (V).

A volt is defined as the potential difference between two points if the work done to move a positive charge of 1C from one point to another is one joule.

Expression for the electric potential difference between two points in the field of a point charge

Consider a positive charge of 1 C placed at a point, D, distance, x , from a fixed point charge, Q , situated in a vacuum as shown below.



The electric force F experienced by the positive charge of 1 C due to charge, Q , is given by:

$$F = \frac{Q \times 1}{4\pi\epsilon_0 x^2} = \frac{Q}{4\pi\epsilon_0 x^2}$$

Assuming that the force on the 1 C charge remains constant over a small distance, δx , in the direction of the force, the work done is given by:

$$\delta W = F \times \delta x = \left(\frac{Q}{4\pi\epsilon_0 x^2} \right) \delta x$$

The total work done in bringing the positive charge of 1 C from point A to point B is the potential difference, V_{AB} , between points A and B and is given by:

$$W = \int_a^b \left(\frac{Q}{4\pi\epsilon_0 x^2} \right) dx = \left(\frac{Q}{4\pi\epsilon_0} \right) \int_a^b \left(\frac{1}{x^2} \right) dx$$

$$W = \left(\frac{Q}{4\pi\epsilon_0} \right) \left[\frac{-1}{x} \right]_a^b = \left(\frac{Q}{4\pi\epsilon_0} \right) \left(\frac{-1}{b} - \frac{-1}{a} \right)$$

$$W = \left(\frac{Q}{4\pi\epsilon_0} \right) \left(\frac{1}{a} - \frac{1}{b} \right)$$

$$\therefore V_{AB} = \left(\frac{Q}{4\pi\epsilon_0} \right) \left(\frac{1}{a} - \frac{1}{b} \right)$$

Note:

$$V_A = \frac{Q}{4\pi\epsilon_0 a}, \quad V_B = \frac{Q}{4\pi\epsilon_0 b}$$

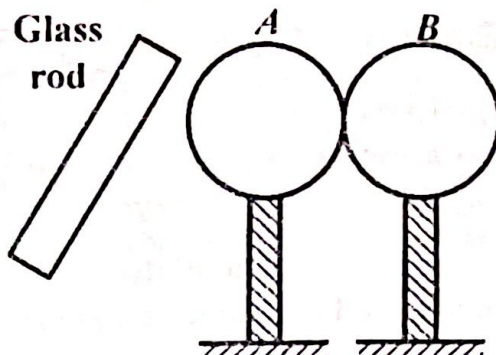
$$\therefore V_{AB} = \frac{Q}{4\pi\epsilon_0 a} - \frac{Q}{4\pi\epsilon_0 b} = V_A - V_B$$

If the positive charge of 1 C is replaced by a positive charge, Q_1 , it implies that the total work done in moving a charge Q_1 from A to B is given by:

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$$W_{:B} = Q_1 V_{AH}, \quad \text{where } V_{AB} = (V_A - V_B)$$

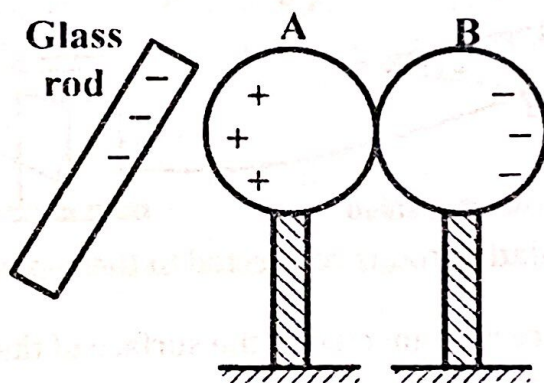
Qn: Two metal spheres A and B are supported on insulating stands and placed in contact as shown in figure below.



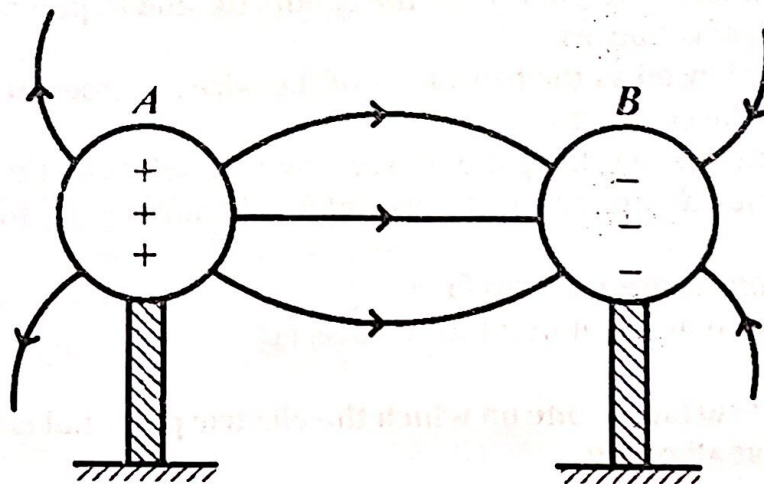
A glass rod, charged positively, is held close to sphere A. The spheres are then separated while the glass rod is in place.

- (i). State the charge acquired by each of the spheres. [1]
- (ii). Sketch the electric field pattern between the spheres. [2]
- (iii). Explain how the p.d between the spheres changes as the spheres are moved further apart. [2]

Sol: (i). Sphere A acquires a negative charge while sphere B acquires a positive charge.



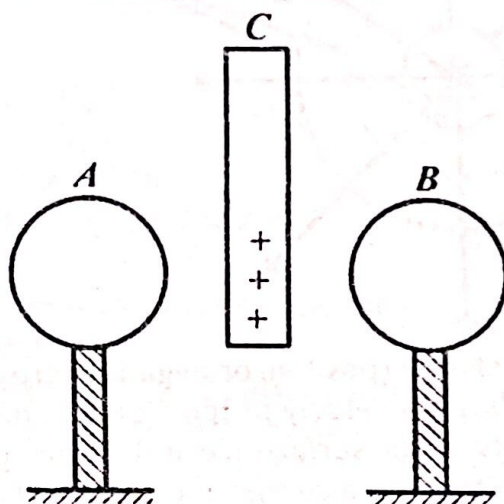
(ii).



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(iii). When two oppositely charged spheres are in the neighborhood of each other, the potential difference between them is lowered. But when the spheres are moved further apart, the potential difference between them increases.

Qn: The diagram shows two metallic spheres A and B placed apart and each supported on an insulating stand. A positively charged plate C is placed mid-way between them but without touching them.



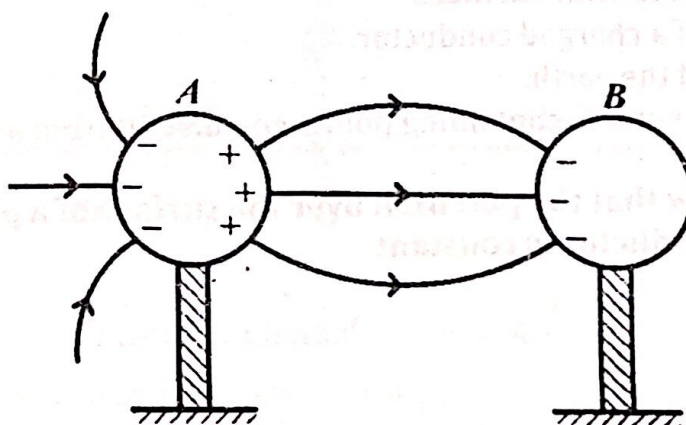
B is momentarily earthed in the presence of C. Finally C is withdrawn.

(i). Draw the spheres at the end of the operation and show the charge distribution over them. [2]

(ii). On the same diagram sketch the electric field pattern in the region of the spheres. [2]

(iii). Explain the change in p.d between the spheres as the spheres are moved further apart. [2]

Sol: (i) and (ii).



(iii). As the spheres are moved apart, potential difference (p.d) rises.

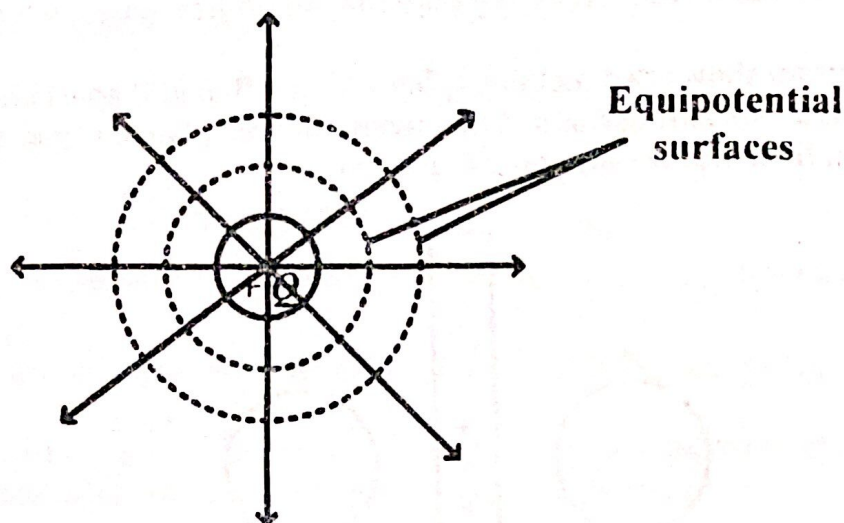
This is because the neutralizing effect of the opposite charges on the spheres becomes smaller at a greater separation so that the magnitude of the electric potential of each sphere rises. Hence increased p.d.

EQUIPOTENTIAL SURFACES

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An equipotential surface is a surface on which the electric potential is constant at all points.

OR: This is a surface drawn through all points at the same potential in an electric field.



All spheres centred on a charge (positive or negative) are equipotential surfaces whose potentials are inversely proportional to their radii. This implies that all points on the surface are at the same potential. Therefore, the work done to move a charge along the surface is zero.

Characteristics of equipotential surfaces

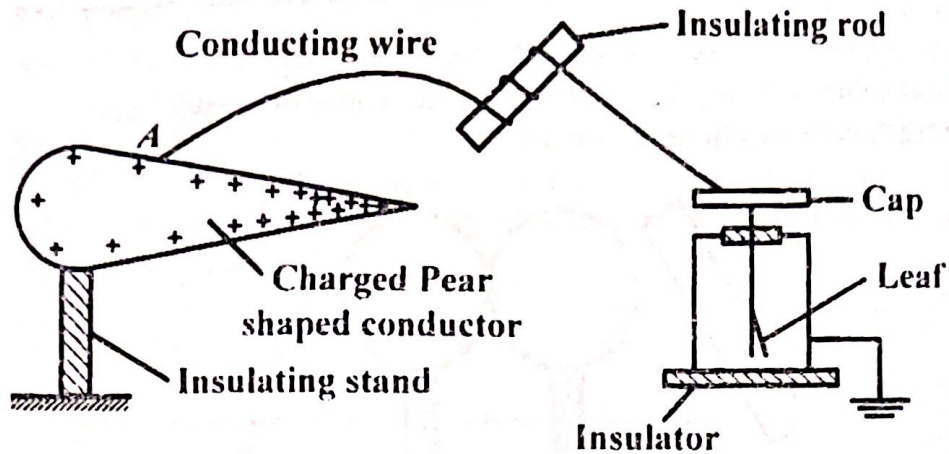
- All points on the surface are at the same potential.
- The work done to move a charge from one point on the surface to another is zero.
- The electric field lines are mutually perpendicular to the equipotential surface. (Equipotential surfaces are always at right angles to the lines of force).

Examples of equipotential surfaces

- The surface of a charged conductor.
- The surface of the earth.
- An imaginary surface containing points equidistant from a point of charge.

Experiment to show that the potential over the surface of a pear-shaped charged conductor is constant

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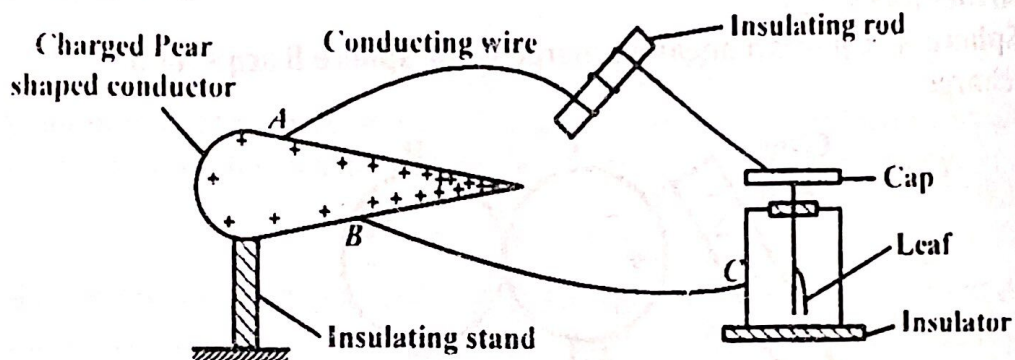
A wire wound on an insulating rod is connected to the cap of a neutral gold leaf electroscope.

The free end, A, of the wire is moved over the surface of the conductor.

The divergence of the leaf remains the same as the wire is moved from one point to another on the surface of the conductor.

The potential is thus constant over the pear-shaped charged conductor.

Alternatively:



A wire wound on an insulating rod is connected to the cap of a neutral gold leaf electroscope.

The free end, A, of the wire is connected to the surface of the charged conductor.

Another wire is connected to point B on the conductor and to point C on the electroscope. The leaf collapses.

The leaf remains collapsed as the free end A of the wire is tapped at different points on the conductor.

This implies that the p.d between any two points on the conductor is zero thus the potential is constant at all points on its surfaces.

Qn: (i). Explain an **equipotential surface**. [4]

(ii). Give an example of an equipotential surface. [1]

Sol:

(i). An equipotential surface is one on which the electric potential is the same (or constant) at all points.

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The work done to move a charge from one point to another along the surface is zero.

This implies that the electric field is perpendicular to the surface.

(ii). The surface of a charged conductor.

Qn: Explain why the electric field intensity close to the surface of a charged conductor is always at right angles to the surface of the conductor. [3]

Sol: The surface of a charged body is an equipotential surface. So when a charge moves on the surface of the conductor, no energy change occurs and no work is done. This means that the component of the force due to the electric field along the surface of the conductor is zero. Hence the electric field lines are perpendicular to the surface of the conductor.

Alternatively: Every conductor is considered as an equi-potential surface. Electric field lines connect points of different potentials, thus if the field lines were at other angles to the surface other than 90° they would cancel out each other, since electric force on any charge acts along the direction of the field.

Electric field lines do not cross each other, so this can only be achieved if they are normal to the surface of the conductor.

Qn: Explain why the electric field intensity along the surface of a charged sphere is zero.

Sol: the surface of a charge sphere is an equi-potential surface. The potential, V , along its surface is therefore constant implying that the change in potential is zero. i.e. $dV = 0$. Since electric field intensity is equal to negative potential gradient, $\frac{dV}{dx}$, then,

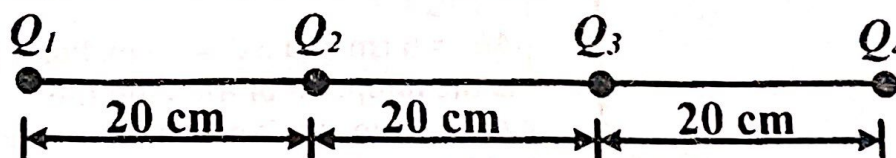
$$E = -\frac{dV}{dx} = \frac{0}{dx} = 0$$

Note: The only component of electric field is that which is normal to the surface.

WORKED EXAMPLES

Question 1: (Source UNEB 1997/P2/Qn. 9 b)

The figure below shows charges Q_1 , Q_2 , Q_3 and Q_4 of -1 C, $+2$ C, -3 C and $+4$ C arranged in a straight line in a vacuum.



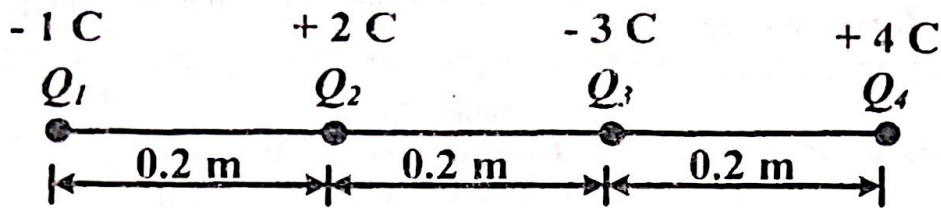
- (i). Calculate the potential energy of Q_2 . [5]
(ii). What is the significance of the sign of the potential energy in (i) above?

[1]

Sol:

(i).

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Electric potential, $V = k \frac{Q}{r}$

Electric potential at Q_2 ,

$$V_{Q_2} = k \left(\frac{Q_1}{r_1} + \frac{Q_3}{r_3} + \frac{Q_4}{r_4} \right) = 9 \times 10^9 \times \left[\frac{-1}{0.2} + \frac{-3}{0.2} + \frac{4}{(0.2 + 0.2)} \right]$$

$$= -9 \times 10^{10} \text{ V}$$

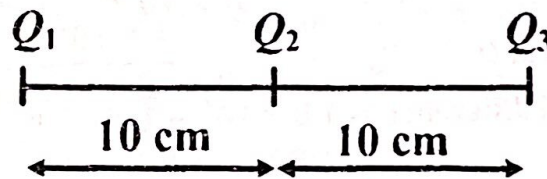
Potential energy at $Q_2 = Q_2 \cdot V_{Q_2} = 2 \times (-9 \times 10^{10}) = -1.8 \times 10^{11} \text{ J}$

(ii).

The negative sign means that work is done by the electric field to bring the charge from infinity to that point.

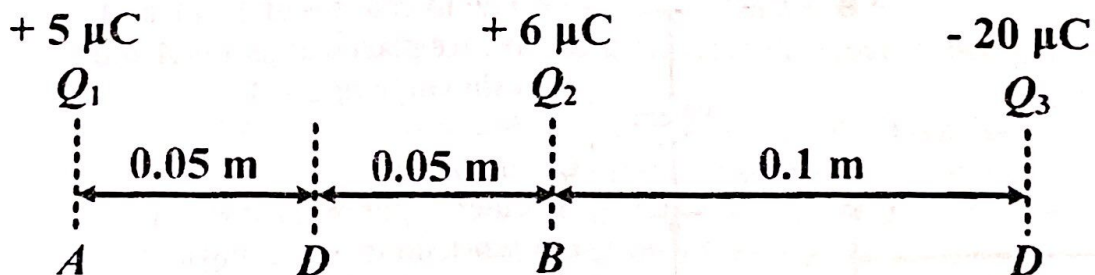
Question 2: (Source UNEB 2003/P2/Qn. 10 c(ii))

Three point charges Q_1 , Q_2 and Q_3 of magnitude $+5 \mu\text{C}$, $+6 \mu\text{C}$ and $-20 \mu\text{C}$ respectively are situated along a straight line as shown in figure below.



Calculate the electric potential mid-way between Q_1 and Q_2 . [3]

Sol:



Electric potential, $V = k \frac{Q}{r}$

Electric potential mid-way between Q_1 and Q_2 ,

$$V_D = k \left(\frac{Q_1}{r_{DA}} + \frac{Q_2}{r_{DB}} + \frac{Q_3}{r_{DC}} \right)$$

$$= 9 \times 10^9 \times \left[\frac{5 \times 10^{-6}}{0.05} + \frac{6 \times 10^{-6}}{0.05} + \frac{-20 \times 10^{-6}}{(0.05 + 0.1)} \right] = 7.8 \times 10^5 \text{ V}$$

Question 3: (Source UNEB 2019/P2/Qn. 8 c)

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In figure 3, points P and Q are at distances 30.0 cm and 20.0 cm from a point charge of $4.0 \mu\text{C}$, respectively.

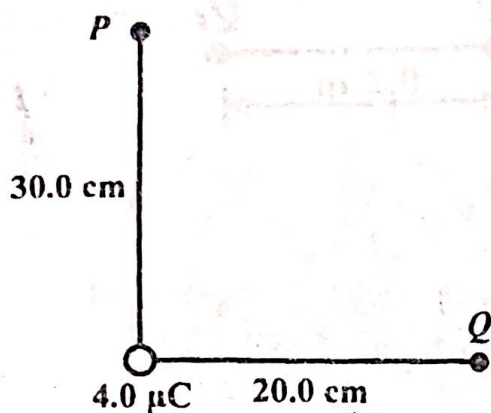


Fig. 3

Calculate the:

- (i). electric potential difference between P and Q . [5]
- (ii). energy required to bring a charge of $+1.0 \mu\text{C}$ from infinity to point Q . [3]

Sol:

(i).

Electric potential, $V = \frac{kQ}{r}$

Electric potential at P , $V_P = \frac{9 \times 10^9 \times 4 \times 10^{-6}}{30 \times 10^{-2}} = 1.2 \times 10^5 \text{ V}$

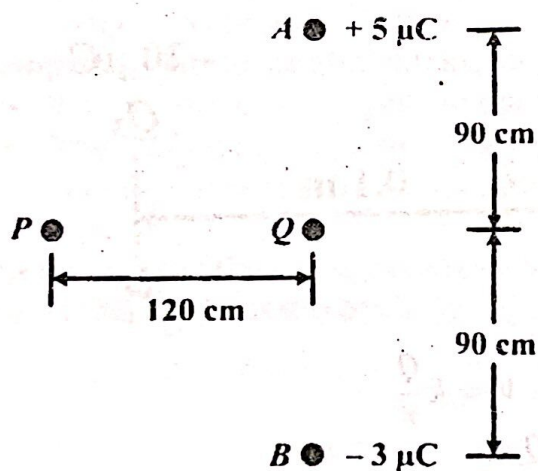
Electric potential at Q , $V_Q = \frac{9 \times 10^9 \times 4 \times 10^{-6}}{20 \times 10^{-2}} = 1.8 \times 10^5 \text{ V}$

Electric potential difference = $1.8 \times 10^5 - 1.2 \times 10^5 = 6 \times 10^4 \text{ V}$

(ii).

Energy required = $Q \cdot V_Q = 1 \times 10^{-6} \times 1.8 \times 10^5 = 1.8 \times 10^{-1} \text{ J}$

Question 4: (Source UNEB 2018/P2/Qn. 9 c)



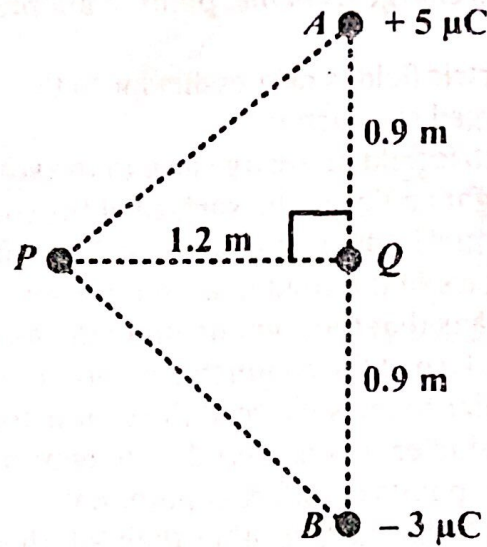
Two point charges of $+5 \mu\text{C}$ and $-3 \mu\text{C}$ are placed at points A and B as shown in figure 4.

Calculate the:

- (i). electric potential at P . [3]
- (ii). work done in moving a charge of $-3 \mu\text{C}$ from P to Q . [4]

Sol:

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(i).

$$\overline{AP} = \overline{PB} = \sqrt{1.2^2 + 0.9^2} = \sqrt{0.63} = 1.5 \text{ m}$$

Electric potential, $V = k \frac{Q}{r}$

Electric potential at P,

$$V_P = k \left(\frac{Q_A}{r_{PA}} + \frac{Q_B}{r_{PB}} \right) = 9 \times 10^9 \times \left(\frac{5 \times 10^{-6}}{1.5} + \frac{-3 \times 10^{-6}}{1.5} \right) = 1.2 \times 10^4 \text{ V}$$

(ii).

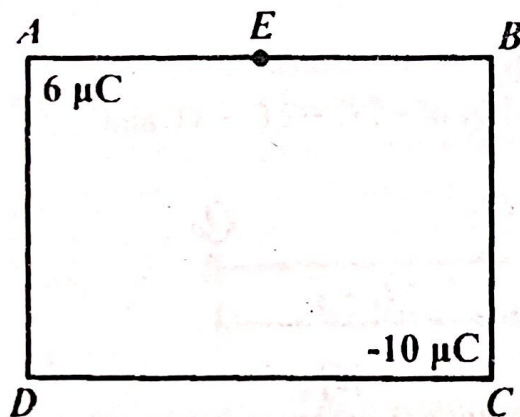
Electric potential at Q,

$$V_Q = k \left(\frac{Q_A}{r_{QA}} + \frac{Q_B}{r_{QB}} \right) = 9 \times 10^9 \times \left(\frac{5 \times 10^{-6}}{0.9} + \frac{-3 \times 10^{-6}}{0.9} \right) = 2 \times 10^4 \text{ V}$$

$$\text{Work done from } P \text{ to } Q = Q_1(V_Q - V_P)$$

$$= -3 \times 10^{-6} \times (2 \times 10^4 - 1.2 \times 10^4) = -2.4 \times 10^{-2} \text{ J}$$

Question 5: (Source UNEB 2010/P2/Qn. 9 b)

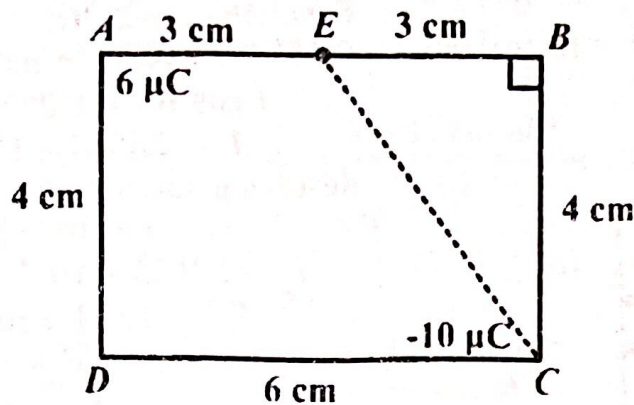


Two charges of magnitude $6 \mu\text{C}$ and $-10 \mu\text{C}$ are placed at the corners of a rectangle ABCD as shown in figure below.

$AB = 6 \text{ cm}$ and $BC = 4 \text{ cm}$. Point E is the midpoint of AB. Find the work done in taking a point charge of $1.6 \times 10^{-10} \text{ C}$ from D to E. [5]

Sol:

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$$\overline{CE} = \sqrt{3^2 + 4^2} = 5 \text{ cm}$$

Electric potential, $V = k \frac{Q}{r}$

Electric potential at D,

$$V_D = k \left(\frac{Q_A}{r_{DA}} + \frac{Q_C}{r_{DC}} \right) = 9 \times 10^9 \times \left(\frac{6 \times 10^{-6}}{4 \times 10^{-2}} + \frac{-10 \times 10^{-6}}{6 \times 10^{-2}} \right) = -1.5 \times 10^5 \text{ V}$$

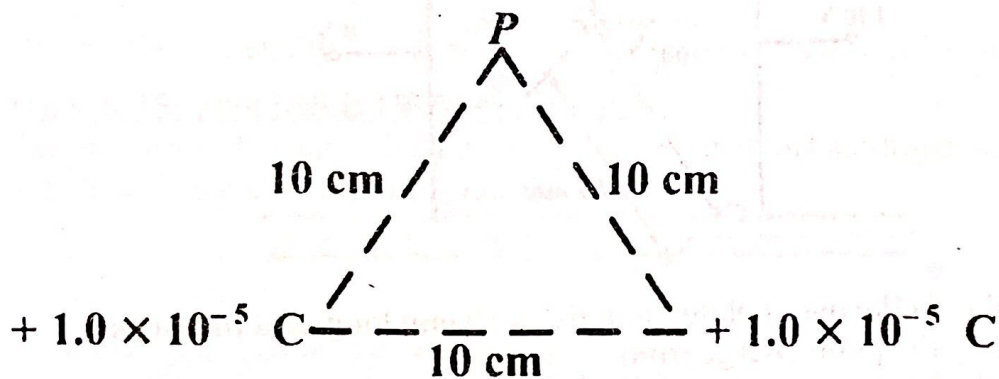
Electric potential at E,

$$V_E = k \left(\frac{Q_A}{r_{EA}} + \frac{Q_C}{r_{EC}} \right) = 9 \times 10^9 \times \left(\frac{6 \times 10^{-6}}{3 \times 10^{-2}} + \frac{-10 \times 10^{-6}}{5 \times 10^{-2}} \right) = 0 \text{ V}$$

$$\begin{aligned} \text{Work done from D to E} &= Q \times (V_E - V_D) = 1.6 \times 10^{-10} \times (0 + 1.5 \times 10^5) \\ &= 2.4 \times 10^{-5} \text{ J} \end{aligned}$$

Question 6: (Source UNEB 2013/P2/Qn. 10 c(ii))

Two point charges of $1.0 \times 10^{-5} \text{ C}$ are placed 10 cm apart as shown in figure below.



Calculate the electric potential at P.

[3]

Sol:

Electric potential, $V = k \frac{Q}{r}$

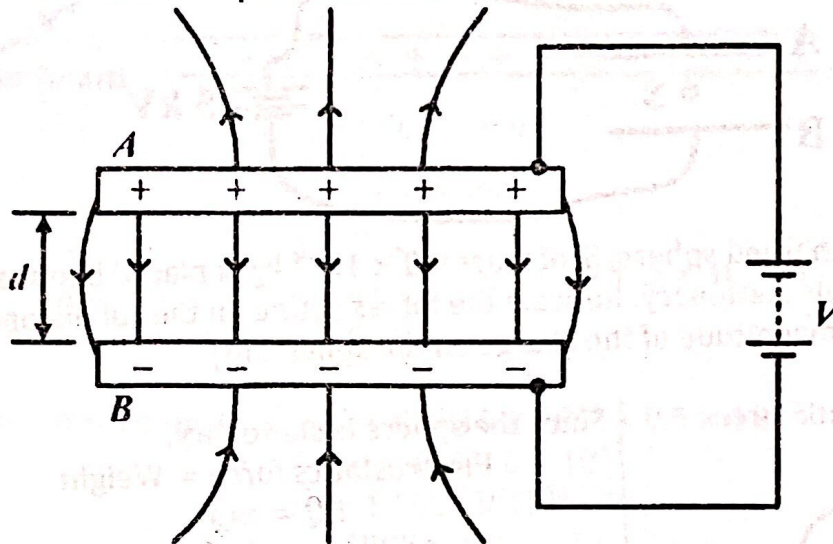
Electric potential at P, $V_P = k \left(\frac{Q_A}{r_{PA}} + \frac{Q_B}{r_{PB}} \right)$

$$= 9 \times 10^9 \times \left(\frac{1 \times 10^{-5}}{10 \times 10^{-2}} + \frac{1 \times 10^{-5}}{10 \times 10^{-2}} \right) = 1.8 \times 10^6 \text{ V}$$

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ELECTRIC FIELD INTENSITY BETWEEN TWO PARALLEL CONDUCTING PLATE

Consider two parallel conducting plates A and B , a distance, d , apart; and between which there is a potential difference, V , as shown:



It should be noted that the field between the plates is uniform apart from the edges.

From $E = -\frac{dV}{dx}$, it implies that the potential gradients at all the points between A and B , away from the edges, are equal.

Thus, for a uniform field,

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

The S.I unit for electric field intensity using the formula above is: volt per metre (V m^{-1}).

Case 1: If a charged particle is placed inside an electric field, it will be attracted towards a plate having a charge opposite to that of the particle.

The electrostatic force of attraction, acting on the particle, is thus given by:

$$F = EQ, \quad \text{where } Q \text{ is the magnitude of charge on the particle}$$

Case 2: If a charged particle is placed inside the field shown in the diagram above and it remains stationary, it implies that the weight of the particle is equal to the electrostatic force acting on the particle. i.e.

$$F = mg, \quad \text{where } m \text{ is the mass of the particle}$$

Case 3: If a charged particle is moving inside the field and in a direction perpendicular to the field, the electrostatic force acting on the particle is also given by:

$$F = ma, \quad \text{where } m \text{ is the mass and } a \text{ is the acceleration}$$

Note: The equations of motion can also be used to obtain the velocity of the moving charged particle.

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WORKED EXAMPLES

Question 1: (Source UNEB 2016/P2/Qn. 9 b(iii))

Two metal plates A and B, 30 cm apart are connected to a 5 kV d.c supply as shown in figure below.



When a small charged sphere, S, of mass 9.0×10^{-3} kg is placed between the plates, it remains stationary. Indicate the forces acting on the sphere and determine the magnitude of the charge on the sphere. [4]

Sol:

Electrostatic force



Since the sphere is stationary,

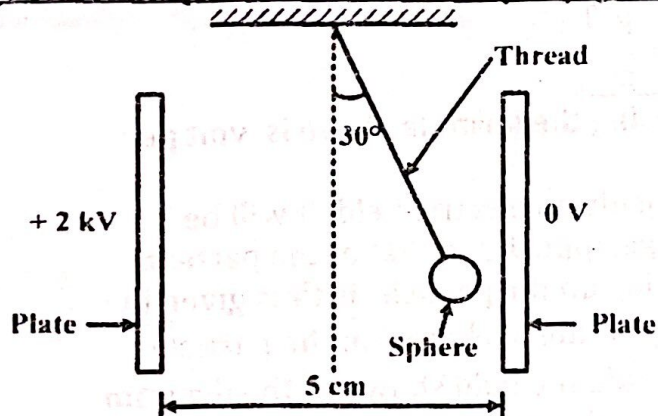
Electrostatics force = Weight

$$EQ = mg$$

$$\frac{V}{d} \times Q = mg$$

$$Q = \frac{mgd}{V} = \frac{9.0 \times 10^{-3} \times 9.81 \times 30 \times 10^{-2}}{5 \times 10^3} = 5.2974 \times 10^{-6} \text{ C}$$

Question 2: (Source UNEB 2014/P2/Qn. 8 d)



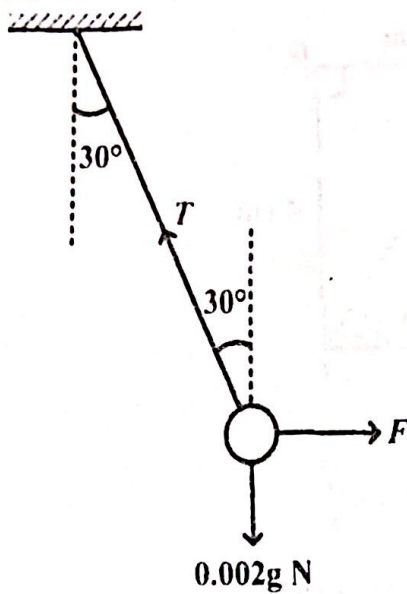
A charged polystyrene sphere of mass 2 g is suspended by a fine nylon thread between two plates 5 cm apart as shown below.

When a p.d of 2 kV is applied across the plates, the thread attached to the sphere deflects through an angle of 30° . Calculate the charge on the sphere. [6]

Sol:

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Apply as



on the
id

Resolving vertically,

$$T \cos 30^\circ = 0.002g$$

$$T \cos 30^\circ = 0.002 \times 9.81$$

$$T = 2.2655 \times 10^{-2} \text{ N}$$

Resolving horizontally,

$$T \sin 30^\circ = F$$

$$F = 2.2655 \times 10^{-2} \times \sin 30^\circ$$

$$F = 1.1328 \times 10^{-2} \text{ N}$$

But, $F = EQ$

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

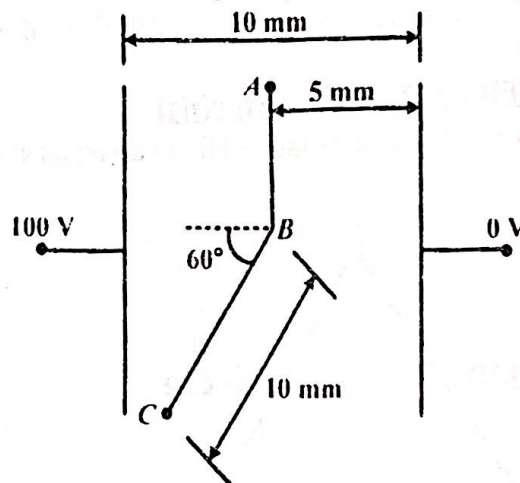
$$Q = \frac{Fd}{V}$$

$$= \frac{1.1328 \times 10^{-2} \times 5 \times 10^{-2}}{2 \times 10^3}$$

$$= 2.8320 \times 10^{-7} \text{ C}$$

Question 3: (Source UNEB 2020/P2/Qn. 9 d)

Figure 4 shows two parallel metal plates placed 10 mm apart in a vacuum with a potential difference of 100 V between them. A point charge of $+2 \mu\text{C}$ is transferred from A to C following the path shown.



If AB is parallel to the metal plates, and BC is 10 mm long, find the work done in moving the point charge from:

(i). A to B and explain your answer. [2]

(ii). B to C. [4]

Sol:

(i).

Electric potential at A, $V_A = \frac{5}{10} \times 100 = 50 \text{ V}$

Electric potential at B, $V_B = \frac{5}{10} \times 100 = 50 \text{ V}$

Work done in moving the charge from A to B,

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$$W_{AB} = Q \times (V_B - V_A) = 2 \times 10^{-6} \times (50 - 50) = 0 \text{ J}$$

Reason: There is no change in electric potential from A to B.

(ii).

$$\text{Electric potential at C, } V_C = \frac{5 + 10 \cos 60^\circ}{10} \times 100 = 100 \text{ V}$$

Work done in moving the charge from B to C,

$$W_{BC} = Q \times (V_C - V_B) = 2 \times 10^{-6} \times (100 - 50) = 1 \times 10^{-4} \text{ J}$$

Question 4: (Source UNEB 1994/P2/Qn. 8 e)

A particle of charge $+4 \times 10^{-9} \text{ C}$ is situated between two parallel plates across which a d.c potential difference is applied. When the particle is moved 6.0 cm against the electric field, $8 \times 10^{-5} \text{ J}$ of energy is used and the kinetic energy of the particle changes by $6.5 \times 10^{-5} \text{ J}$. Calculate:

(i). the work done by the electric field. [2]

(ii). the magnitude of the electric field. [3]

Sol:

(i).

$$\text{Change in K.E} = \left(\begin{array}{c} \text{Work done by} \\ \text{moving the charge} \end{array} \right) - \left(\begin{array}{c} \text{Work done by} \\ \text{electric field} \end{array} \right)$$

$$6.5 \times 10^{-5} = 8 \times 10^{-5} - W_{\text{field}}$$

$$W_{\text{field}} = 8 \times 10^{-5} - 6.5 \times 10^{-5} = 1.5 \times 10^{-5} \text{ J}$$

(ii).

$$W_{\text{field}} = QV$$

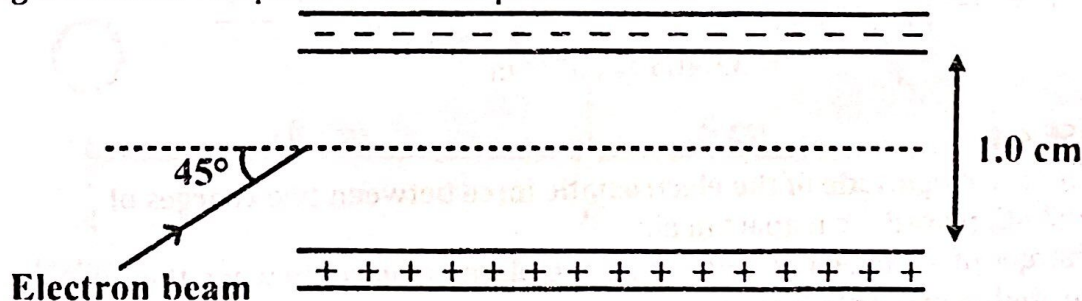
$$1.5 \times 10^{-5} = 4 \times 10^{-9} \times V$$

$$V = \frac{1.5 \times 10^{-5}}{4 \times 10^{-9}} = 3.750 \times 10^3 \text{ V}$$

$$\text{Electric field intensity, } E = \frac{V}{d} = \frac{3.750 \times 10^3}{6 \times 10^{-2}} = 6.25 \times 10^4 \text{ V m}^{-1}$$

Question 5: (Source UNEB 1999/P2/Qn. 10 c)

Two large oppositely charged plates are fixed 1.0 cm apart as shown in the figure below. The p.d between the plates is 50 V.

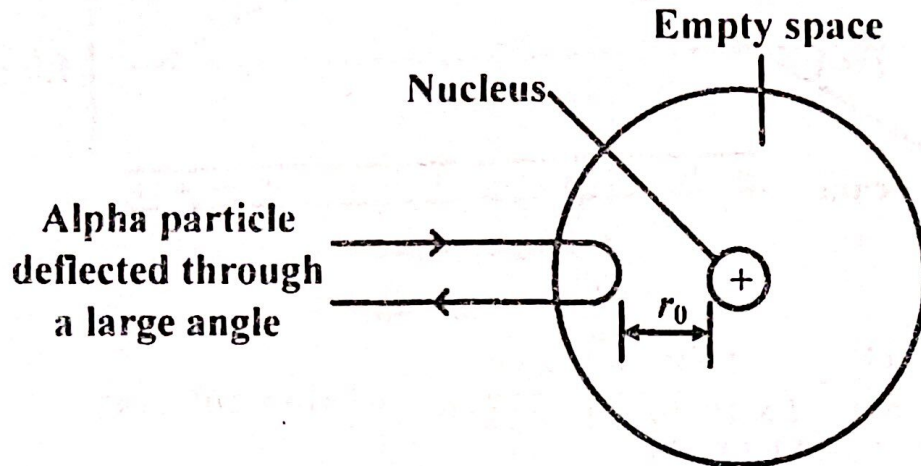


An electron enters the region between the plates at an angle of 45° as shown. Find the maximum speed the electrons must have in order for them not to strike the upper plate. (Mass of an electron $9.11 \times 10^{-31} \text{ kg}$) [8]

Sol:

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Suppose an alpha particle of mass, m , moving with initial velocity, v , collides head on with an atom of atomic number, Z . The particle is deflected as shown below.



The particle will be slowed down until it comes to rest at a distance, r_0 , from the nucleus and then repelled back. r_0 is the closest distance of approach. At r_0 , the kinetic energy of the alpha particle is converted to potential energy of the nucleus-alpha particle system. If e is the magnitude of electronic charge, then,

Charge of alpha particle, $Q_1 = 2e$,

Charge of nucleus, $Q_2 = Ze$

$$\left(\begin{array}{l} \text{initial kinetic energy of} \\ \text{the alpha particle in joules} \end{array} \right) = \left(\begin{array}{l} \text{potential energy of the} \\ \text{nucleus - alpha particle system} \\ \text{at distance of closest approach} \end{array} \right)$$

$$\boxed{\frac{1}{2}mv^2 = \frac{Q_1Q_2}{4\pi\epsilon_0r_0}}$$

WORKED EXAMPLES

Question 1: (Source UNEB 2020/P2/Qn. 9 e)

An alpha particle of charge $+3.2 \times 10^{-19}$ C and mass 6.8×10^{-27} kg travels with a velocity V directly towards a nitrogen nucleus which has a charge of $+11.2 \times 10^{-19}$ C. The alpha particle reverses direction at a distance of 9.4×10^{-15} m from the nitrogen nucleus.

(i). Explain why the alpha particle reverses direction. [2]

(ii). Find the initial velocity V of the alpha particle. [4]

Sol: (i). The alpha particle loses kinetic energy as it approaches the nitrogen nucleons and this is transferred to electrostatic potential energy in the field. At some point, all the kinetic energy of the alpha particle is lost and it is repelled back by nitrogen nucleons.

Alternatively:

The repulsion between the charges retards the motion of the alpha particle. At some point, the velocity of the particle is below zero.

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Thus the repulsion causes the particle to reverse its direction.

(ii). On closest approach, all the kinetic energy of the alpha particle is converted into electrostatic energy of the alpha particle/nitrogen nucleus system.

$$\begin{aligned} \left(\begin{array}{l} \text{initial kinetic energy of} \\ \text{the alpha particle in joules} \end{array} \right) &= \left(\begin{array}{l} \text{potential energy of the} \\ \text{nucleus - alpha particle system} \\ \text{at distance of closest approach} \end{array} \right) \\ \frac{1}{2} m V^2 &= \frac{k Q_a Q_n}{r} \\ \frac{1}{2} \times 6.8 \times 10^{-27} \times V^2 &= \frac{9 \times 10^9 \times 3.2 \times 10^{-19} \times 11.2 \times 10^{-19}}{9.4 \times 10^{-15}} \\ V &= \sqrt{\frac{2 \times 9 \times 10^9 \times 3.2 \times 10^{-19} \times 11.2 \times 10^{-19}}{9.4 \times 10^{-15} \times 6.8 \times 10^{-27}}} = 1.0046 \times 10^7 \text{ m s}^{-1} \end{aligned}$$

Question 2: (Source UNEB 1999/P2/Qn. 9 c)

Alpha particles (charge = $+2e$), each having kinetic energy $1.0 \times 10^{-12} \text{ J}$ are incident head-on, on gold nuclei (charge = $+79e$) in a gold foil. Calculate the distance of closest approach of an α -particle to a gold nucleus. ($e = 1.6 \times 10^{-19} \text{ C}$). [4]

Sol:

On closest approach, all the kinetic energy of the alpha particle is converted into electrostatic energy of the alpha particle/gold nucleus system.

$$\begin{aligned} \left(\begin{array}{l} \text{initial kinetic energy of} \\ \text{the alpha particle in joules} \end{array} \right) &= \left(\begin{array}{l} \text{potential energy of the} \\ \text{nucleus - alpha particle system} \\ \text{at distance of closest approach} \end{array} \right) \\ 1.0 \times 10^{-12} &= \frac{k Q_a Q_g}{r} \\ 1.0 \times 10^{-12} &= \frac{k \times 2e \times 79e}{r} \\ r &= \frac{9 \times 10^9 \times 158 \times e^2}{1.0 \times 10^{-12}} = \frac{9 \times 10^9 \times 158 \times (1.6 \times 10^{-19})^2}{1.0 \times 10^{-12}} \\ &= 3.6403 \times 10^{-14} \text{ m} \end{aligned}$$

EXERCISE 4.1

Qn 1: Find the magnitude of the electrostatic force between two charges of $1 \mu\text{C}$ and $2 \mu\text{C}$; placed 3 cm apart in air.

Qn 2: Charges of $-3 \mu\text{C}$, $+4 \mu\text{C}$ and $-7 \mu\text{C}$ are placed in vacuum when they are separated as shown below.