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Chapter 17

Electrostatics - Grade 11

17.1 Introduction

In Grade 10, you learnt about the force between charges. In this chapter you will learn exactly how to determine this force and about a basic law of electrostatics.

17.2 Forces between charges - Coulomb's Law

Like charges repel each other while opposite charges attract each other. If the charges are at rest then the force between them is known as the **electrostatic force**. The electrostatic force between charges increases when the magnitude of the charges increases or the distance between the charges decreases.
The electrostatic force was first studied in detail by Charles Coulomb around 1784. Through his observations he was able to show that the electrostatic force between two point-like charges is inversely proportional to the square of the distance between the objects. He also discovered that the force is proportional to the product of the charges on the two objects.

$$F \propto \frac{Q_1 Q_2}{r^2},$$

where Q_1 is the charge on the one point-like object, Q_2 is the charge on the second, and r is the distance between the two. The magnitude of the electrostatic force between two point-like charges is given by *Coulomb's Law*.

Definition: Coulomb's Law
Coulomb's Law states that the magnitude of the electrostatic force between two point charges is directly proportional to the magnitudes of each charge and inversely proportional to the square of the distance between the charges.

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

and the proportionality constant k is called the *electrostatic constant* and has the value:

$$k = 8{,}99 \times 10^9 \mathrm{N} \cdot \mathrm{m}^2 \cdot \mathrm{C}^{-2}.$$

Extension: Similarity of Coulomb's Law to the Newton's Universal Law of Gravitation.
Notice how similar Coulomb's Law is to the form of Newton's Universal Law of Gravitation between two point-like particles:

$$F_G = G\frac{m_1 m_2}{r^2},$$

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where m_1 and m_2 are the masses of the two particles, r is the distance between them, and G is the gravitational constant.

Both laws represent the force exerted by particles (masses or charges) on each other that interact by means of a field.

It is very interesting that Coulomb's Law has been shown to be correct no matter how small the distance, nor how large the charge. For example it still applies inside the atom (over distances smaller than 10^{-10}m).

Worked Example 110: Coulomb's Law I

Question: Two point-like charges carrying charges of $+3 \times 10^{-9}\text{C}$ and $-5 \times 10^{-9}\text{C}$ are $2\,\text{m}$ apart. Determine the magnitude of the force between them and state whether it is attractive or repulsive.

Answer

Step 1 : Determine what is required

We are required to find the force between two point charges given the charges and the distance between them.

Step 2 : Determine how to approach the problem

We can use Coulomb's Law to find the force.

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

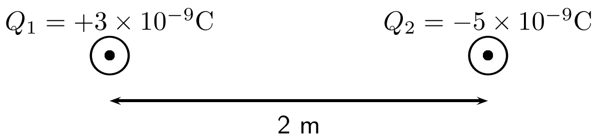
Step 3 : Determine what is given

We are given:

- $Q_1 = +3 \times 10^{-9}\text{C}$
- $Q_2 = -5 \times 10^{-9}\text{C}$
- $r = 2\,\text{m}$

We know that $k = 8{,}99 \times 10^{9}\text{N} \cdot \text{m}^2 \cdot \text{C}^{-2}$.

We can draw a diagram of the situation.



Step 4 : Check units

All quantities are in SI units.

Step 5 : Determine the magnitude of the force

Using Coulomb's Law we have

$$\begin{aligned} F &= k\frac{Q_1 Q_2}{r^2} \\ &= (8{,}99 \times 10^{9}\text{N} \cdot \text{m}^2/\text{C}^2)\frac{(3 \times 10^{-9}\text{C})(5 \times 10^{-9}\text{C})}{(2\text{m})^2} \\ &= 3{,}37 \times 10^{-8}\text{N} \end{aligned}$$

Thus the *magnitude* of the force is $3{,}37 \times 10^{-8}\text{N}$. However since both point charges have opposite signs, the force will be attractive.

Next is another example that demonstrates the difference in magnitude between the gravitational force and the electrostatic force.

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Worked Example 111: Coulomb's Law II

Question: Determine the electrostatic force and gravitational force between two electrons 10^{-10}m apart (i.e. the forces felt inside an atom)

Answer

Step 1 : Determine what is required

We are required to calculate the electrostatic and gravitational forces between two electrons, a given distance apart.

Step 2 : Determine how to approach the problem

We can use:

$$F_e = k\frac{Q_1 Q_2}{r^2}$$

to calculate the electrostatic force and

$$F_g = G\frac{m_1 m_2}{r^2}$$

to calculate the gravitational force.

Step 3 : Determine what is given

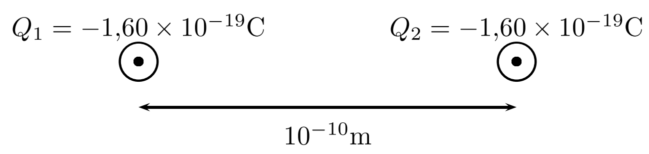
- $Q_1 = Q_2 = 1{,}6 \times 10^{-19}$ C(The charge on an electron)
- $m_1 = m_2 = 9{,}1 \times 10^{-31}$ kg(The mass of an electron)
- $r = 1 \times 10^{-10}$m

We know that:

- $k = 8{,}99 \times 10^{9}\ \mathrm{N \cdot m^2 \cdot C^{-2}}$
- $G = 6{,}67 \times 10^{-11}\ \mathrm{N \cdot m^2 \cdot kg^{-2}}$

All quantities are in SI units.

We can draw a diagram of the situation.



Step 4 : Calculate the electrostatic force

$$\begin{aligned} F_e &= k\frac{Q_1 Q_2}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(-1{,}60 \times 10^{-19})(-1{,}60 \times 10^{-19})}{(10^{-10})^2} \\ &= 2{,}30 \times 10^{-8}\ \mathrm{N} \end{aligned}$$

Hence the *magnitude* of the electrostatic force between the electrons is $2{,}30 \times 10^{-8}$N. Since electrons carry the same charge, the force is repulsive.

Step 5 : Calculate the gravitational force

$$\begin{aligned} F_g &= G\frac{m_1 m_2}{r^2} \\ &= (6{,}67 \times 10^{-11}\mathrm{N \cdot m^2/kg^2})\frac{(9.11 \times 10^{-31}\mathrm{C})(9.11 \times 10^{-31}\mathrm{kg})}{(10^{-10}\mathrm{m})^2} \\ &= 5{,}54 \times 10^{-51}\mathrm{N} \end{aligned}$$

The magnitude of the gravitational force between the electrons is $5{,}54 \times 10^{-51}$N. This is an attractive force.

Notice that the gravitational force between the electrons is much smaller than the electrostatic force. For this reason, the gravitational force is usually neglected when determining the force between two charged objects.

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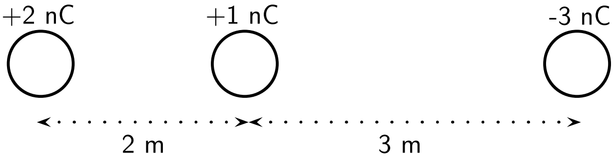
Important: We can apply Newton's Third Law to charges because, two charges exert forces of equal magnitude on one another in opposite directions.

Important: Coulomb's Law

When substituting into the Coulomb's Law equation, it is not necessary to include the signs of the charges. Instead, select a positive direction. Then forces that tend to move the charge in this direction are added, while forces that act in the opposite direction are subtracted.

Worked Example 112: Coulomb's Law III

Question: Three point charges are in a straight line. Their charges are $Q_1 = +2 \times 10^{-9}\text{C}$, $Q_2 = +1 \times 10^{-9}\text{C}$ and $Q_3 = -3 \times 10^{-9}\text{C}$. The distance between Q_1 and Q_2 is $2 \times 10^{-2}\text{m}$ and the distance between Q_2 and Q_3 is $4 \times 10^{-2}\text{m}$. What is the net electrostatic force on Q_2 from the other two charges?



Answer

Step 1 : Determine what is required

We are needed to calculate the net force on Q_2. This force is the sum of the two electrostatic forces - the forces between Q_1 on Q_2 and Q_3 on Q_2.

Step 2 : Determine how to approach the problem

- We need to calculate the two electrostatic forces on Q_2, using Coulomb's Law equation.
- We then need to add up the two forces using our rules for adding vector quantities, because force is a vector quantity.

Step 3 : Determine what is given

We are given all the charges and all the distances.

Step 4 : Calculate the forces.

Force of Q_1 on Q_2:

$$\begin{aligned} F &= k\frac{Q_1Q_2}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(2 \times 10^{-9})(1 \times 10^{-9})}{(2 \times 10^{-9})} \\ &= 4{,}5 \times 10^{-5}\text{N} \end{aligned}$$

Force of Q_3 on Q_2:

$$\begin{aligned} F &= k\frac{Q_2Q_3}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(1 \times 10^{-9})(3 \times 10^{-9})}{(4 \times 10^{-9}} \\ &= 1{,}69 \times 10^{-5}\text{N} \end{aligned}$$

Both forces act in the same direction because the force between Q_1 and Q_2 is repulsive (like charges) and the force between Q_2 on Q_3 is attractive (unlike charges).

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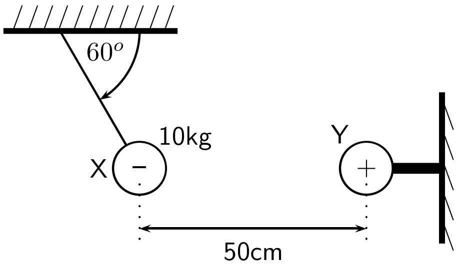
Therefore,

$$\begin{aligned} F_net &= 4{,}50 \times 10^{-5} + 4{,}50 \times 10^{-5} \\ &= 6{,}19 \times 10^{-5}\text{N} \end{aligned}$$

We mentioned in Chapter 9 that charge placed on a spherical conductor spreads evenly along the surface. As a result, if we are far enough from the charged sphere, electrostatically, it behaves as a point-like charge. Thus we can treat spherical conductors (e.g. metallic balls) as point-like charges, with all the charge acting at the centre.

Worked Example 113: Coulomb's Law: challenging question

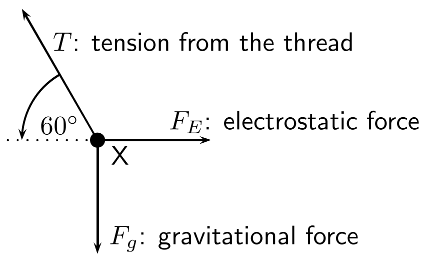
Question: In the picture below, X is a small negatively charged sphere with a mass of 10kg. It is suspended from the roof by an insulating rope which makes an angle of $60°$ with the roof. Y is a small positively charged sphere which has the same magnitude of charge as X. Y is fixed to the wall by means of an insulating bracket. Assuming the system is in equilibrium, what is the magnitude of the charge on X?



Answer
How are we going to determine the charge on X? Well, if we know the force between X and Y we can use Coulomb's Law to determine their charges as we know the distance between them. So, firstly, we need to determine the magnitude of the electrostatic force between X and Y.

Step 1 :
Is everything in S.I. units? The distance between X and Y is $50\text{cm} = 0{,}5\text{m}$, and the mass of X is 10kg.

Step 2 : Draw a force diagram
Draw the forces on X (with directions) and label.



Step 3 : Calculate the magnitude of the electrostatic force, F_E
Since nothing is moving (system is in equilibrium) the vertical and horizontal components of the forces must cancel. Thus

$$F_E = T\cos(60°); \qquad F_g = T\sin(60°).$$

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The only force we know is the gravitational force $F_g = mg$. Now we can calculate the magnitude of T from above:

$$T = \frac{F_g}{\sin(60°)} = \frac{(10)(10)}{\sin(60°)} = 115{,}5\text{N}.$$

Which means that F_E is:

$$F_E = T\cos(60°) = 115{,}5 \cdot \cos(60°) = 57{,}75\text{N}$$

Step 4 :
Now that we know the magnitude of the electrostatic force between X and Y, we can calculate their charges using Coulomb's Law. Don't forget that the magnitudes of the charges on X and Y are the same: $Q_\text{X} = Q_\text{Y}$. The magnitude of the electrostatic force is

$$\begin{aligned} F_E &= k\frac{Q_\text{X}Q_\text{Y}}{r^2} = k\frac{Q_\text{X}^2}{r^2} \\ Q_\text{X} &= \sqrt{\frac{F_E r^2}{k}} \\ &= \sqrt{\frac{(57.75)(0.5)^2}{8.99 \times 10^9}} \\ &= 5.66 \times 10^{-5}\text{C} \end{aligned}$$

Thus the charge on X is -5.66×10^{-5}C.

?

Exercise: Electrostatic forces

1. Calculate the electrostatic force between two charges of $+6\text{nC}$ and $+1\text{nC}$ if they are separated by a distance of 2mm.
2. Calculate the distance between two charges of $+4\text{nC}$ and -3nC if the electrostaticforce between them is $0{,}005\text{N}$.
3. Calculate the charge on two identical spheres that are similiarly charged if they are separated by 20cm and the electrostatic force between them is $0{,}06\text{N}$.

17.3 Electric field around charges

We have learnt that objects that carry charge feel forces from all other charged objects. It is useful to determine what the effect of a charge would be at every point surrounding it. To do this we need some sort of reference. We know that the force that one charge feels due to another depends on both charges (Q_1 and Q_2). How then can we talk about forces if we only have one charge? The solution to this dilemma is to introduce a *test charge*. We then determine the force that would be exerted on it if we placed it at a certain location. If we do this for every point surrounding a charge we know what would happen if we put a test charge at any location.
This map of what would happen at any point we call an electric field map. It is a map of the electric field *due to* a charge. It tells us how large the force on a test charge would be and in what direction the force would be. Our map consists of the lines that tell us how the test charge would move if it were placed there.

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Definition: Electric field
An electric field as a region of space in which an electric charge experiences a force. The direction of the electric field at a point is the direction that a positive test charge would move if placed at that point.

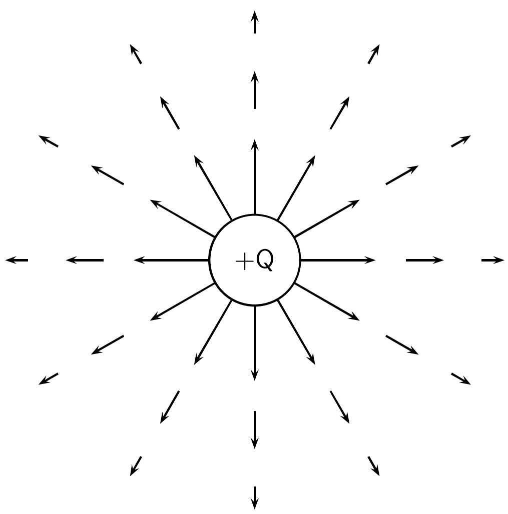
17.3.1 Electric field lines

The maps depend very much on the charge or charges that the map is being made for. We will start off with the simplest possible case. Take a single positive charge with no other charges around it. First, we will look at what effects it would have on a test charge at a number of points.
Electric field lines, like the magnetic field lines that were studied in Grade 10, are a way of representing the electric field at a point.

- Arrows on the field lines indicate the direction of the field, i.e. the direction a positive test charge would move.
- Electric field lines therefore point away from positive charges and towards negative charges.
- Field lines are drawn closer together where the field is stronger.

17.3.2 Positive charge acting on a test charge

At each point we calculate the force on a test charge, q, and represent this force by a vector.



We can see that at every point the positive test charge, q, would experience a force pushing it away from the charge, Q. This is because both charges are positive and so they repel. Also notice that at points further away the vectors are shorter. That is because the force is smaller if you are further away.

Negative charge acting on a test charge

If the charge were negative we would have the following result.

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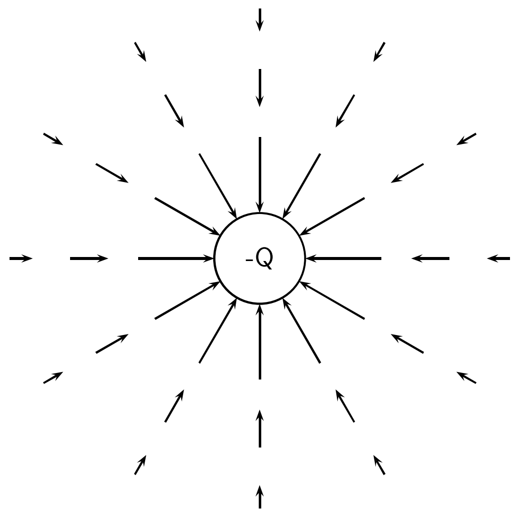
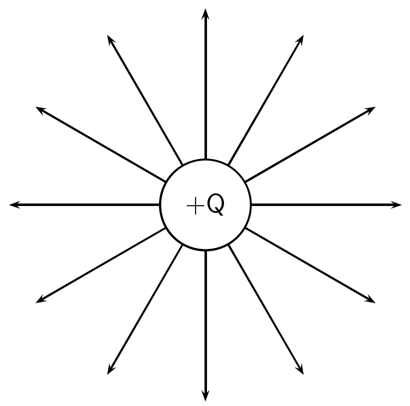


Notice that it is **almost** identical to the positive charge case. This is important – the arrows are the same length because the magnitude of the charge is the same and so is the magnitude of the test charge. Thus the **magnitude** (size) of the force is the same. The arrows point in the opposite direction because the charges now have opposite sign and so the test charge is **attracted** to the charge. Now, to make things simpler, we draw continuous lines showing the path that the test charge would travel. This means we don't have to work out the magnitude of the force at many different points.

Electric field map due to a positive charge



Some important points to remember about electric fields:

- There is an electric field at **every point** in space surrounding a charge.
- Field lines are merely a **representation** – they are not real. When we draw them, we just pick convenient places to indicate the field in space.
- Field lines always start at a **right-angle** (90^o) to the charged object causing the field.
- Field lines **never** cross.

17.3.3 Combined charge distributions

We will now look at the field of a positive charge and a negative charge placed next to each other. The net resulting field would be the addition of the fields from each of the charges. To start off with let us sketch the field maps for each of the charges separately.

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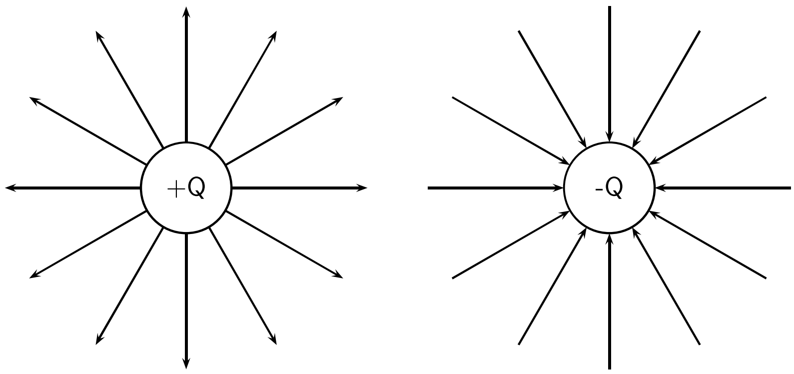
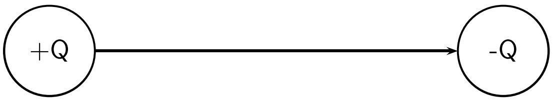
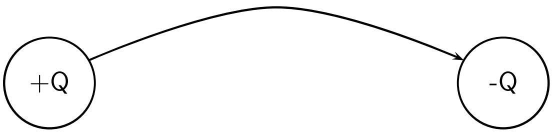
Electric field of a negative and a positive charge in isolation



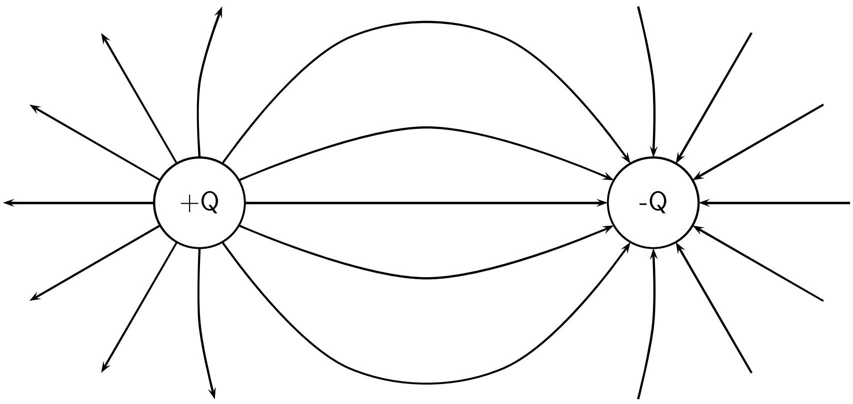
Notice that a test charge starting off directly between the two would be pushed away from the positive charge and pulled towards the negative charge in a straight line. The path it would follow would be a straight line between the charges.



Now let's consider a test charge starting off a bit higher than directly between the charges. If it starts closer to the positive charge the force it feels from the positive charge is greater, but the negative charge also attracts it, so it would move away from the positive charge with a tiny force attracting it towards the negative charge. As it gets further from the positive charge the force from the negative and positive charges change and they are equal in magnitude at equal distances from the charges. After that point the negative charge starts to exert a stronger force on the test charge. This means that the test charge moves towards the negative charge with only a small force away from the positive charge.



Now we can fill in the other lines quite easily using the same ideas. The resulting field map is:



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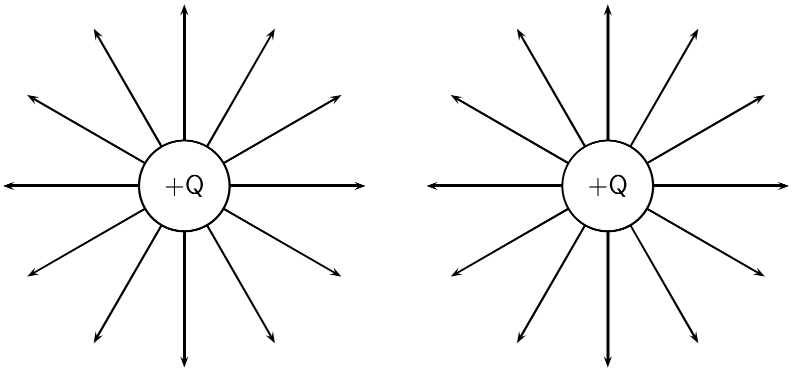
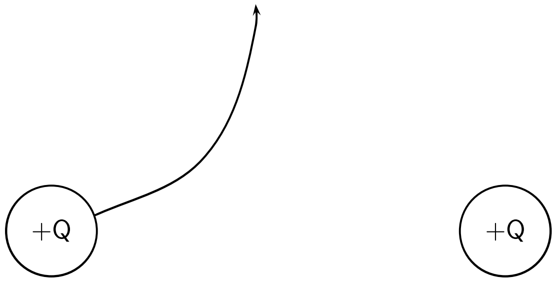
Two like charges : both positive

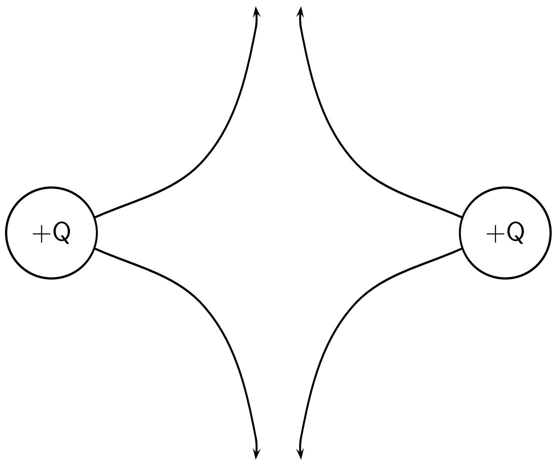
For the case of two positive charges things look a little different. We can't just turn the arrows around the way we did before. In this case the test charge is repelled by both charges. This tells us that a test charge will never cross half way because the force of repulsion from both charges will be equal in magnitude.



The field directly between the charges cancels out in the middle. The force has equal magnitude and opposite direction. Interesting things happen when we look at test charges that are not on a line directly between the two.



We know that a charge the same distance below the middle will experience a force along a reflected line, because the problem is symmetric (i.e. if we flipped vertically it would look the same). This is also true in the horizontal direction. So we use this fact to easily draw in the next four lines.



Working through a number of possible starting points for the test charge we can show the electric field map to be:

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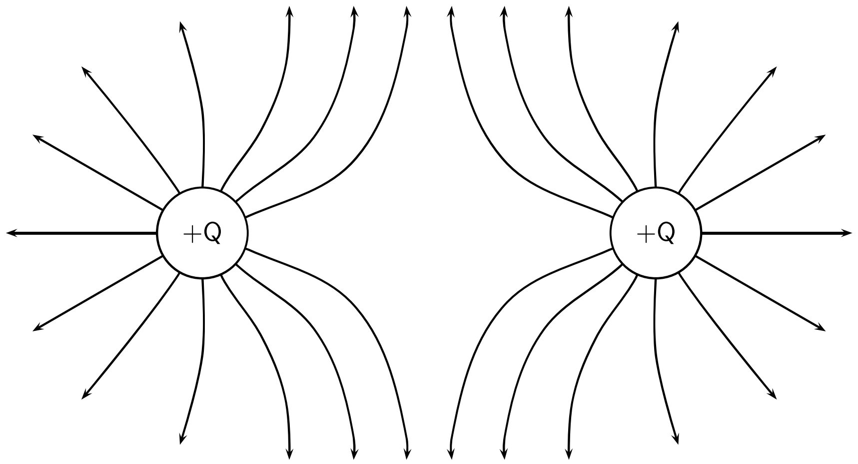
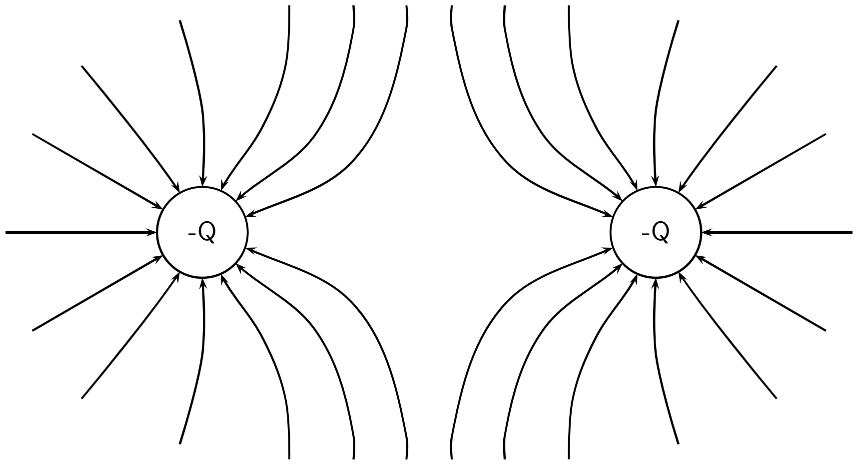


Two like charges : both negative

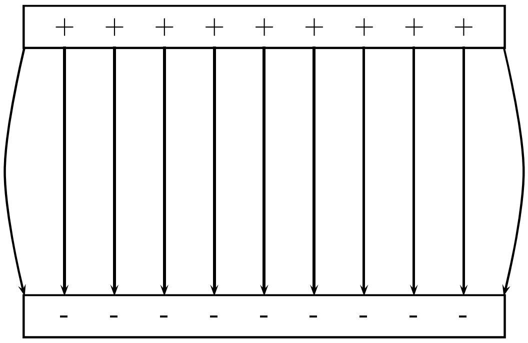
We can use the fact that the direction of the force is reversed for a test charge if you change the sign of the charge that is influencing it. If we change to the case where both charges are negative we get the following result:



17.3.4 Parallel plates

One very important example of electric fields which is used extensively is the electric field between two charged parallel plates. In this situation the electric field is constant. This is used for many practical purposes and later we will explain how Millikan used it to measure the charge on the electron.

Field map for oppositely charged parallel plates



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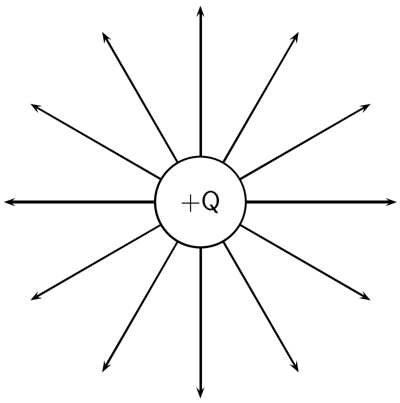
This means that the force that a test charge would feel at any point between the plates would be identical in magnitude and direction. The fields on the edges exhibit fringe effects, *i.e. they bulge outwards*. This is because a test charge placed here would feel the effects of charges only on one side (either left or right depending on which side it is placed). Test charges placed in the middle experience the effects of charges on both sides so they balance the components in the horizontal direction. This is clearly not the case on the edges.

Strength of an electric field

When we started making field maps we drew arrows to indicate the strength of the field and the direction. When we moved to lines you might have asked "Did we forget about the field strength?". We did not. Consider the case for a single positive charge again:



Notice that as you move further away from the charge the field lines become more spread out. In field map diagrams the closer field lines are together the stronger the field. Therefore, the electric field is stronger closer to the charge (the electric field lines are closer together) and weaker further from the charge (the electric field lines are further apart).
The magnitude of the electric field at a point as the force per unit charge. Therefore,

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

E and F are vectors. From this we see that the force on a charge q is simply:

$$F = E \cdot q$$

The force between two electric charges is given by:

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

(if we make the one charge Q and the other q.) Therefore, the electric field can be written as:

$$E = k\frac{Q}{r^2}$$

The electric field is the force per unit of charge and hence has units of newtons per coulomb.

As with Coulomb's law calculations, do not substitute the sign of the charge into the equation for electric field. Instead, choose a positive direction, and then either add or subtract the contribution to the electric field due to each charge depending upon whether it points in the positive or negative direction, respectively.

Worked Example 114: Electric field 1

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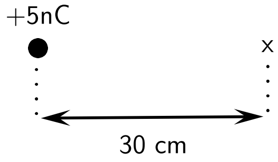
Question: Calculate the electric field strength $30/rmcm$ from a $5/rmnC$ charge.



Answer

Step 1 : Determine what is required

We need to calculate the electric field a distance from a given charge.

Step 2 : Determine what is given

We are given the magnitude of the charge and the distance from the charge.

Step 3 : Determine how to approach the problem

We will use the equation:

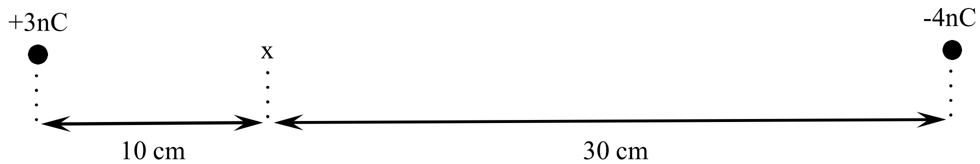
$$E = k\frac{Q}{r^2}.$$

Step 4 : Solve the problem

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(5 \times 10^{-9})}{(0{,}3)^2} \\ &= 4{,}99 \times 102\text{N.C}^{-1} \end{aligned}$$

Worked Example 115: Electric field 2

Question: Two charges of $Q_1 = +3/rmnC$ and $Q_2 = -4/rmnC$ are separated by a distance of $50/rmcm$. What is the electric field strength at a point that is $20/rmcm$ from Q_1 and $50/rmcm$ from Q_2? The point lies beween Q_1 and Q_2.



Answer

Step 1 : Determine what is required

We need to calculate the electric field a distance from two given charges.

Step 2 : Determine what is given

We are given the magnitude of the charges and the distances from the charges.

Step 3 : Determine how to approach the problem

We will use the equation:

$$E = k\frac{Q}{r^2}.$$

We need to work out the electric field for each charge separately and then add them to get the resultant field.

Step 4 : Solve the problem

We first solve for Q_1:

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(3 \times 10^{-9})}{(0{,}2)^2} \\ &= 6{,}74 \times 102\text{N.C}^{-1} \end{aligned}$$

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Then for Q_2:

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(4 \times 10^{-9})}{(0{,}3)^2} \\ &= 2{,}70 \times 102\mathrm{N.C}^{-1} \end{aligned}$$

We need to add the two electric field beacuse both are in the same direction. The field is away from Q_1 and towards Q_2. Therefore,
$E_total = 6{,}74 \times 102 + 2{,}70 \times 102 = 9{,}44 \times 102\mathrm{N.C}^{-1}$

17.4 Electrical potential energy and potential

The *electrical potential energy* of a charge is the energy it has because of its position relative to other charges that it interacts with. The potential energy of a charge Q_1 relative to a charge Q_2 a distance r away is calculated by:

$$U = \frac{kQ_1Q_2}{r}$$

Worked Example 116: Electrical potential energy 1

Question: What is the electric potential energy of a $7\mathrm{nC}$ charge that is 2 cm from a $20\mathrm{nC}$?
Answer
Step 1 : Determine what is required
We need to calculate the electric potential energy (U).
Step 2 : Determine what is given
We are given both charges and the distance between them.
Step 3 : Determine how to approach the problem
We will use the equation:

$$U = \frac{kQ_1Q_2}{r}$$

Step 4 : Solve the problem

$$\begin{aligned} U &= \frac{kQ_1Q_2}{r} \\ &= \frac{(8.99 \times 10^9)(7 \times 10^{-9})(20 \times 10^{-9})}{(0{,}02)} \\ &= 6{,}29 \times 10{-}5\mathrm{J} \end{aligned}$$

17.4.1 Electrical potential

The electric potential at a point is the electrical potential energy per unit charge, i.e. the potential energy a positive test charge would have if it were placed at that point.
Consider a positive test charge $+Q$ placed at A in the electric field of another positive point charge.

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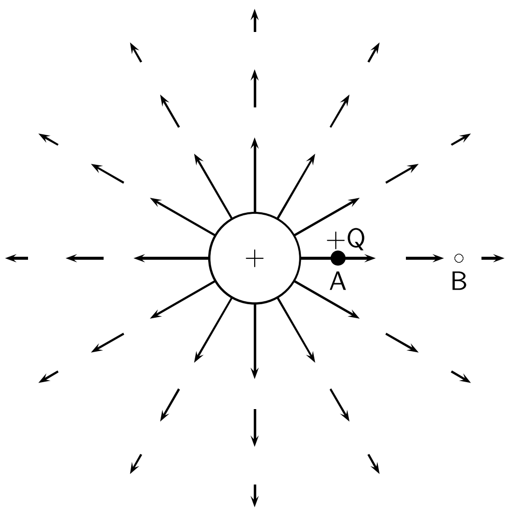

The test charge moves towards B under the influence of the electric field of the other charge. In the process the test charge loses electrical potential energy and gains kinetic energy. Thus, at A, the test charge has more potential energy than at B – **A is said to have a higher electrical potential than B**.

The potential energy of a charge at a point in a field is defined as the work required to move that charge from infinity to that point.

Definition: Potential difference

The **potential difference between two points** in an electric field is defined as the **work required to move a unit positive test charge from the point of lower potential to that of higher potential**.

If an amount of work W is required to move a charge Q from one point to another, then the potential difference between the two points is given by,

$$V = \frac{W}{Q} \qquad \text{unit : J.C}^{-1} \text{ or V (the volt)}$$

From this equation we can define the volt.

Definition: The Volt

One volt is the potential difference between two points in an electric field if one joule of work is done in moving one coulomb of charge from the one point to the other.

Worked Example 117: Potential difference

Question: What is the potential difference between two point in an electric field if it takes 600J of energy to move a charge of 2C between these two points.

Answer

Step 5 : Determine what is required

We need to calculate the potential difference (V) between two points in an electric field.

Step 6 : Determine what is given

We are given both the charges and the energy or work done to move the charge between the two points.

Step 7 : Determine how to approach the problem

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We will use the equation:

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

Step 8 : Solve the problem

$$\begin{aligned} V &= \frac{W}{Q} \\ &= \frac{600}{2} \\ &= 300\text{V} \end{aligned}$$

17.4.2 Real-world application: lightning

Lightning is an atmospheric discharge of electricity, usually, but not always, during a rain storm. An understanding of lightning is important for power transmission lines as engineers who need to know about lightning in order to adequately protect lines and equipment.

Extension: Formation of lightning

1. **Charge separation**
   The first process in the generation of lightning is charge separation. The mechanism by which charge separation happens is still the subject of research. One theory is that opposite charges are driven apart and energy is stored in the electric field between them. Cloud electrification appears to require strong updrafts which carry water droplets upward, supercooling them to -10 to -20 ^{o}C. These collide with ice crystals to form a soft ice-water mixture called graupel. The collisions result in a slight positive charge being transferred to ice crystals, and a slight negative charge to the graupel. Updrafts drive lighter ice crystals upwards, causing the cloud top to accumulate increasing positive charge. The heavier negatively charged graupel falls towards the middle and lower portions of the cloud, building up an increasing negative charge. Charge separation and accumulation continue until the electrical potential becomes sufficient to initiate lightning discharges, which occurs when the gathering of positive and negative charges forms a sufficiently strong electric field.
2. **Leader formation**
   As a thundercloud moves over the Earth's surface, an equal but opposite charge is induced in the Earth below, and the induced ground charge follows the movement of the cloud. An initial bipolar discharge, or path of ionized air, starts from a negatively charged mixed water and ice region in the thundercloud. The discharge ionized channels are called leaders. The negative charged leaders, called a "stepped leader", proceed generally downward in a number of quick jumps, each up to 50 metres long. Along the way, the stepped leader may branch into a number of paths as it continues to descend. The progression of stepped leaders takes a comparatively long time (hundreds of milliseconds) to approach the ground. This initial phase involves a relatively small electric current (tens or hundreds of amperes), and the leader is almost invisible compared to the subsequent lightning channel. When a step leader approaches the ground, the presence of opposite charges on the ground enhances the electric field. The electric field is highest on trees and tall buildings. If the electric field is strong enough, a conductive discharge (called a positive streamer) can develop from these points. As the field increases, the positive streamer may evolve into a hotter, higher current leader which eventually connects to the descending stepped leader from the cloud. It is also possible for many streamers to develop from many different

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objects simultaneously, with only one connecting with the leader and forming the main discharge path. Photographs have been taken on which non-connected streamers are clearly visible. When the two leaders meet, the electric current greatly increases. The region of high current propagates back up the positive stepped leader into the cloud with a "return stroke" that is the most luminous part of the lightning discharge.

3. **Discharge** When the electric field becomes strong enough, an electrical discharge (the bolt of lightning) occurs within clouds or between clouds and the ground. During the strike, successive portions of air become a conductive discharge channel as the electrons and positive ions of air molecules are pulled away from each other and forced to flow in opposite directions. The electrical discharge rapidly superheats the discharge channel, causing the air to expand rapidly and produce a shock wave heard as thunder. The rolling and gradually dissipating rumble of thunder is caused by the time delay of sound coming from different portions of a long stroke.

Important: Estimating distance of a lightning strike

The flash of a lightning strike and resulting thunder occur at roughly the same time. But light travels at 300 000 kilometres in a second, almost a million times the speed of sound. Sound travels at the slower speed of 330 m/s in the same time, so the flash of lightning is seen before thunder is heard. By counting the seconds between the flash and the thunder and dividing by 3, you can estimate your distance from the strike and initially the actual storm cell (in kilometres).

17.5 Capacitance and the parallel plate capacitor

17.5.1 Capacitors and capacitance

A parallel plate capacitor is a device that consists of two oppositely charged conducting plates separated by a small distance, which stores charge. When voltage is applied to the capacitor, electric charge of equal magnitude, but opposite polarity, build up on each plate.

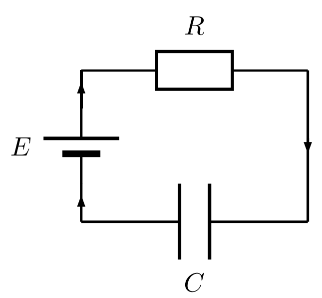

Figure 17.1: A capacitor (C) connected in series with a resistor (R) and an energy source (E).

Definition: Capacitance
Capacitance is the charge stored per volt and is measured in farad (F)

Mathematically, capacitance is the ratio of the charge on a single plate to the voltage across the plates of the capacitor:

$$C = \frac{Q}{V}.$$

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Capacitance is measured in farads (F). Since capacitance is defined as $C = \frac{Q}{V}$, the units are in terms of charge over potential difference. The unit of charge is the coulomb and the unit of the potential difference is the volt. One farad is therefore the capacitance if one coulomb of charge was stored on a capacitor for every volt applied.
1 C of charge is a very large amount of charge. So, for a small amount of voltage applied, a 1 F capacitor can store a enormous amount of charge. Therefore, capacitors are often denoted in terms of microfarads (1×10^{-6}), nanofarads (1×10^{-9}), or picofarads (1×10^{-12}).

Important: Q is the magnitude of the charge stored on either plate, not on both plates added together. Since one plate stores positive charge and the other stores negative charge, the total charge on the two plates is zero.

Worked Example 118: Capacitance

Question: Suppose that a 5 V battery is connected in a circuit to a 5 pF capacitor. After the battery has been connected for a long time, what is the charge stored on each of the plates?
Answer
To begin remember that after a voltage has been applied for a long time the capacitor is fully charged. The relation between voltage and the maximum charge of a capacitor is found in equation ??.

$$CV = Q$$

Inserting the given values of $C = 5\text{F}$ and $V = 5\text{V}$, we find that:

$$\begin{aligned} Q &= CV \\ &= (5 \times 10^{-12} F)(5V) \\ &= 2{,}5 \times 10^{-11} C \end{aligned}$$

17.5.2 Dielectrics

The electric field between the plates of a capacitor is affected by the substance between them. The substance between the plates is called a dielectric. Common substances used as dielectrics are mica, perspex, air, paper and glass.
When a dielectric is inserted between the plates of a parallel plate capacitor the dielectric becomes polarised so an electric field is induced in the dielectric that opposes the field between the plates. When the two electric fields are superposed, the new field between the plates becomes smaller. Thus the voltage between the plates decreases so the capacitance increases.
In every capacitor, the dielectric keeps the charge on one plate from travelling to the other plate. However, each capacitor is different in how much charge it allows to build up on the electrodes per voltage applied. When scientists started studying capacitors they discovered the property that the voltage applied to the capacitor was proportional to the maximum charge that would accumulate on the electrodes. The constant that made this relation into an equation was called the capacitance, C. The capacitance was different for different capacitors. But, it stayed constant no matter how much voltage was applied. So, it predicts how much charge will be stored on a capacitor when different voltages are applied.

17.5.3 Physical properties of the capacitor and capacitance

The capacitance of a capacitor is proportional to the surface area of the conducting plate and inversely proportional to the distance between the plates. It is also proportional to the

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permittivity of the *dielectric*. The dielectric is the non-conducting substance that separates the plates. As mentioned before, dielectrics can be air, paper, mica, perspex or glass.
The capacitance of a parallel-plate capacitor is given by:

$$C = \epsilon_0 \frac{A}{d}$$

where ϵ_0 is the permittivity of air, A is the area of the plates and d is the distance between the plates.

Worked Example 119: Capacitance

Question: What is the capacitance of a capacitor in which the dielectric is air, the area of the plates is $0{,}001\text{m}^2$ and the distance between the plates is $0{,}02\text{m}$?

Answer

Step 1 : Determine what is required

We need to determine the capacitance of the capacitor.

Step 2 : Determine how to approach the problem

We can use the formula:

$$C = \epsilon_0 \frac{A}{d}$$

Step 3 : Determine what is given.

We are given the area of the plates, the distance between the plates and that the dielectric is air.

Step 4 : Determine the capacitance

$$\begin{aligned} C &= \epsilon_0 \frac{A}{d} && (17.1)\\ &= \frac{(8{,}9 \times 10-12)(0{,}001)}{0{,}02} && (17.2)\\ &= 4{,}45 \times 10-13\text{F} && (17.3) \end{aligned}$$

17.5.4 Electric field in a capacitor

The electric field strength between the plates of a capacitor can be calculated using the formula:
$E = \frac{V}{d}$ where E is the electric field in J.C^{-1}, V is the potential difference in V and d is the distance between the plates in m.

Worked Example 120: Electric field in a capacitor

Question: What is the strength of the electric field in a capacitor which has a potential difference of 300V between its parallel plates that are $0{,}02\text{m}$ apart?

Answer

Step 1 : Determine what is required

We need to determine the electric field between the plates of the capacitor.

Step 2 : Determine how to approach the problem

We can use the formula:
$E = \frac{V}{d}$

Step 3 : Determine what is given.

We are given the potential difference and the distance between the plates.

Step 4 : Determine the electric field

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$$E = \frac{V}{d} \quad (17.4)$$
$$= \frac{300}{0{,}02} \quad (17.5)$$
$$= 1{,}50 \times 104\mathrm{J.C}^{-1} \quad (17.6)$$
$$(17.7)$$

?

Exercise: Capacitance and the parallel plate capacitor

1. Determine the capacitance of a capacitor which stores $9 \times 10^{-9}\mathrm{C}$ when a potential difference of 12 V is applied to it.
2. What charge will be stored on a $5\mu\mathrm{F}$ capacitor if a potential difference of $6\mathrm{V}$ is maintained between its plates?
3. What is the capacitance of a capacitor that uses air as its dielectric if it has an area of $0{,}004\mathrm{m}^2$ and a distance of $0{,}03\mathrm{m}$ between its plates?
4. What is the strength of the electric field between the plates of a charged capacitor if the plates are $2\mathrm{mm}$ apart and have a potential difference of $200\mathrm{V}$ across them?

17.6 Capacitor as a circuit device

17.6.1 A capacitor in a circuit

When a capacitor is connected in a DC circuit, current will flow until the capacitor is fully charged. After that, no further current will flow. If the charged capacitor is connected to another circuit with no source of emf in it, the capacitor will discharge through the circuit, creating a potential difference for a short time. This is useful, for example, in a camera flash. Initially, the electrodes have no net charge. A voltage source is applied to charge a capacitor. The voltage source creates an electric field, causing the electrons to move. The charges move around the circuit stopping at the left electrode. Here they are unable to travel across the dielectric, since electrons cannot travel through an insulator. The charge begins to accumulate, and an electric field forms pointing from the left electrode to the right electrode. This is the opposite direction of the electric field created by the voltage source. When this electric field is equal to the electric field created by the voltage source, the electrons stop moving. The capacitor is then fully charged, with a positive charge on the left electrode and a negative charge on the right electrode.
If the voltage is removed, the capacitor will discharge. The electrons begin to move because in the absence of the voltage source, there is now a net electric field. This field is due to the imbalance of charge on the electrodes–the field across the dielectric. Just as the electrons flowed to the positive electrode when the capacitor was being charged, during discharge, the electrons flow to negative electrode. The charges cancel, and there is no longer an electric field across the dielectric.

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17.6.2 Real-world applications: capacitors

Capacitors are used in many different types of circuitry. In car speakers, capacitors are often used to aid the power supply when the speaker require more power than the car battery can provide. Capacitors are also used to in processing electronic signals in circuits, such as smoothing voltage spikes due to inconsistent voltage sources. This is important for protecting sensitive electronic compoments in a circuit.

17.7 Summary

1. Objects can be **positively**, **negatively** charged or **neutral**.
2. Charged objects feel a force with a magnitude:

$$F = k\frac{Q_1Q_2}{r^2}$$

3. The force is attractive for unlike charges and repulsive for like charges.
4. A test charge is $+1\text{C}$
5. Electric fields start on positive charges and end on negative charges
6. The electric field is constant between equally charged parallel plates
7. A charge in an electric field, just like a mass under gravity, has potential energy which is related to the work to move it.
8. A capacitor is a device that stores charge in a circuit.

17.8 Exercises - Electrostatics

1. Two charges of $+3\text{nC}$ and -5nC are separated by a distance of 40cm. What is the electrostatic force between the two charges?
2. Two insulated metal spheres carrying charges of $+6\text{nC}$ and -10nC are separated by a distance of 20 mm.

   A What is the electrostatic force between the spheres?

   B The two spheres are touched and then separated by a distance of 60mm. What are the new charges on the spheres?

   C What is new electrostatic force between the spheres at this distance?
3. The electrostatic force between two charged spheres of $+3\text{nC}$ and $+4\text{nC}$ respectively is $0{,}04\text{N}$. What is the distance between the spheres?
4. Calculate the potential difference between two parallel plates if it takes 5000J of energy to move 25C of charge between the plates?
5. Draw the electric field pattern lines between:

   A two equal positive point charges.

   B two equal negative point charges.
6. Calculate the electric field between the plates of a capacitor if the plates are 20mm apart and the potential difference between the plates is 300V.
7. Calculate the electrical potential energy of a 6nC charge that is 20cm from a 10nC charge.
8. What is the capacitance of a capacitor if it has a charge of $0{,}02\text{C}$ on each of its plates when the potential difference between the plates is 12V?

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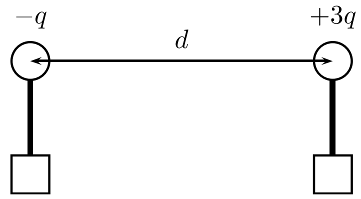
9. [SC 2003/11] Two small identical metal spheres, on insulated stands, carry charges -q and $+3q$ respectively. When the centres of the spheres are separated by a distance d the one exerts an electrostatic force of magnitude F on the other.



The spheres are now made to touch each other and are then brought back to the same distance d apart. What will be the magnitude of the electrostatic force which one sphere now exerts on the other?

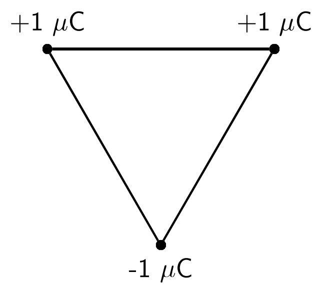
A $\frac{1}{4}F$

B $\frac{1}{3}F$

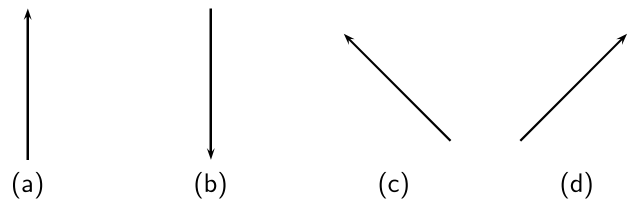
C $\frac{1}{2}F$

D $3F$

10. [SC 2003/11] Three point charges of magnitude +1 μC, +1 μC and -1 μC respectively are placed on the three corners of an equilateral triangle as shown.



Which vector best represents the direction of the resultant force acting on the -1 μC charge as a result of the forces exerted by the other two charges?



11. [IEB 2003/11 HG1 - Force Fields] **Electric Fields**

A Write a statement of Coulomb's law.

B Calculate the magnitude of the force exerted by a point charge of +2 nC on another point charge of -3 nC separated by a distance of 60 mm.

C Sketch the electric field between two point charges of +2 nC and -3 nC, respectively, placed 60 mm apart from each other.

12. [IEB 2003/11 HG1 - Electrostatic Ping-Pong]

Two charged parallel metal plates, X and Y, separated by a distance of 60 mm, are connected to a d.c. supply of emf 2 000 V in series with a microammeter. An initially uncharged conducting sphere (a graphite-coated ping pong ball) is suspended from an insulating thread between the metal plates as shown in the diagram.

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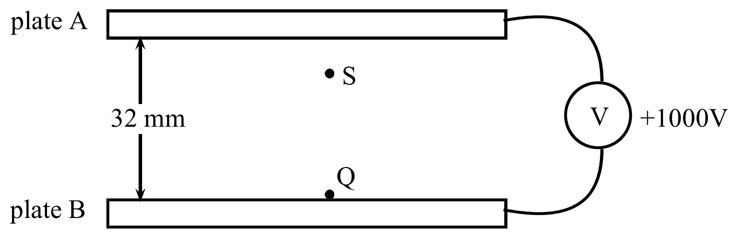


When the ping pong ball is moved to the right to touch the positive plate, it acquires a charge of +9 nC. It is then released. The ball swings to and fro between the two plates, touching each plate in turn.

A How many electrons are removed from the ball when it acquires a charge of +9 nC?

B Explain why a current is established in the circuit.

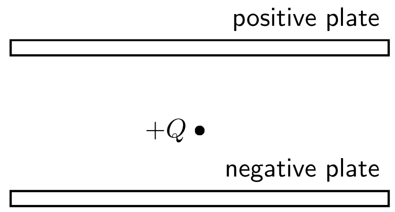
C Determine the current if the ball takes 0,25 s to swing from Y to X.

D Using the same graphite-coated ping pong ball, and the same two metal plates, give TWO ways in which this current could be increased.

E Sketch the electric field between the plates X and Y.

F How does the electric force exerted on the ball change as it moves from Y to X?

13. [IEB 2005/11 HG] A positive charge Q is released from rest at the centre of a uniform electric field.



How does Q move immediately after it is released?

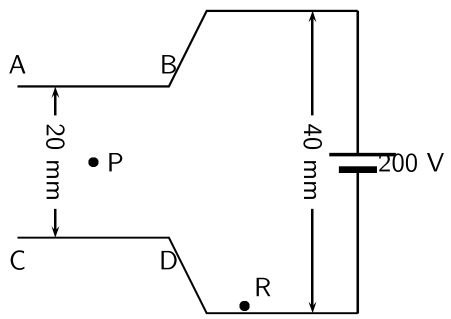
A It accelerates uniformly.

B It moves with an increasing acceleration.

C It moves with constant speed.

D It remains at rest in its initial position.

14. [SC 2002/03 HG1] The sketch below shows two sets of parallel plates which are connected together. A potential difference of 200 V is applied across both sets of plates. The distances between the two sets of plates are 20 mm and 40 mm respectively.



When a charged particle Q is placed at point R, it experiences a force of magnitude F. Q is now moved to point P, halfway between plates AB and CD. Q now experiences a force of magnitude ...

A $\frac{1}{2}F$

B F

C $2F$

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D $4F$

15. [SC 2002/03 HG1] The electric field strength at a distance x from a point charge is E. What is the magnitude of the electric field strength at a distance $2x$ away from the point charge?

    A $\frac{1}{4}E$

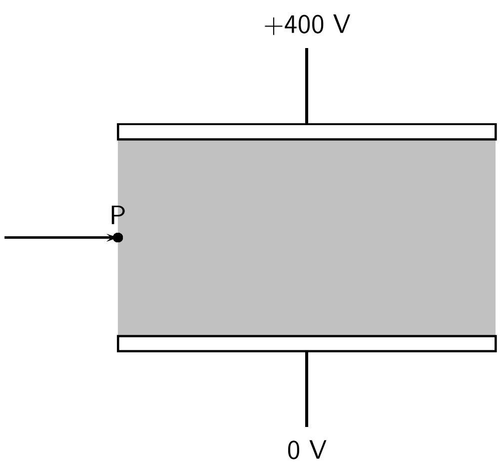
    B $\frac{1}{2}E$

    C $2E$

    D $4E$

16. [IEB 2005/11 HG1]

    An electron (mass 9,11 $\times$ 10^{-31} kg) travels horizontally in a vacuum. It enters the shaded regions between two horizontal metal plates as shown in the diagram below.



A potential difference of 400 V is applied across the places which are separated by 8,00 mm.
The electric field intensity in the shaded region between the metal plates is uniform. Outside this region, it is zero.

A Explain what is meant by the phrase **"the electric field intensity is uniform"**.

B Copy the diagram and draw the following:

i. The electric field between the metal plates.

ii. An arrow showing the direction of the electrostatic force on the electron when it is at **P**.

C Determine the magnitude of the electric field intensity between the metal plates.

D Calculate the magnitude of the electrical force on the electron during its passage through the electric field between the plates.

E Calculate the magnitude of the acceleration of the electron (due to the electrical force on it) during its passage through the electric field between the plates.

F After the electron has passed through the electric field between these plates, it collides with phosphorescent paint on a TV screen and this causes the paint to glow. What energy transfer takes place during this collision?

17. [IEB 2004/11 HG1] A positively-charged particle is placed in a uniform electric field. Which of the following pairs of statements correctly describes the potential energy of the charge, and the force which the charge experiences in this field?

    Potential energy — Force

    A Greatest near the negative plate — Same everywhere in the field

    B Greatest near the negative plate — Greatest near the positive and negative plates

    C Greatest near the positive plate — Greatest near the positive and negative plates

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D Greatest near the positive plate — Same everywhere in the field

18. [IEB 2004/11 HG1 - TV Tube]

    A speck of dust is attracted to a TV screen. The screen is negatively charged, because this is where the electron beam strikes it. The speck of dust is neutral.

    A What is the name of the electrostatic process which causes dust to be attracted to a TV screen?

    B Explain why a neutral speck of dust is attracted to the negatively-charged TV screen?

    C Inside the TV tube, electrons are accelerated through a uniform electric field. Determine the magnitude of the electric force exerted on an electron when it accelerates through a potential difference of 2 000 V over a distance of 50 mm.

    D How much kinetic energy (in J) does one electron gain while it accelerates over this distance?

    E The TV tube has a power rating of 300 W. Estimate the maximum number of electrons striking the screen per second.

19. [IEB 2003/11 HG1] A point charge is held stationary between two charged parallel plates that are separated by a distance d. The point charge experiences an electrical force F due to the electric field E between the parallel plates.
    What is the electrical force on the point charge when the plate separation is increased to 2d?

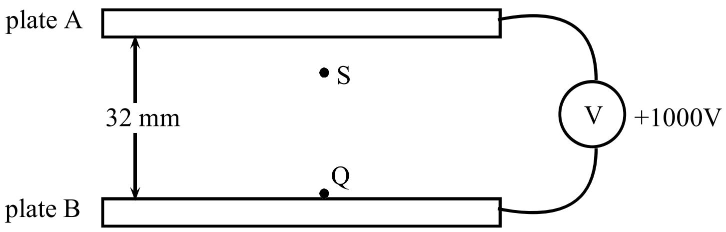
    A $\frac{1}{4}$ F

    B $\frac{1}{2}$ F

    C 2 F

    D 4 F

20. [IEB 2001/11 HG1] - **Parallel Plates**
    A distance of 32 mm separates the horizontal parallel plates A and B.
    B is at a potential of +1 000 V.



    A Draw a sketch to show the electric field lines between the plates A and B.

    B Calculate the magnitude of the electric field intensity (strength) between the plates.
    A tiny charged particle is stationary at S, 8 mm below plate A that is at zero electrical potential. It has a charge of 3,2 $\times$ 10^{-12} C.

    C State whether the charge on this particle is positive or negative.

    D Calculate the force due to the electric field on the charge.

    E Determine the mass of the charged particle.
    The charge is now moved from S to Q.

    F What is the magnitude of the force exerted by the electric field on the charge at Q?

    G Calculate the work done when the particle is moved from S to Q.

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