Study Unit 1: Electrostatic force

Introduction

Matter consists of atoms. An atom consists of small, dense, positively charged nucleus with the negative electrons orbiting about the nucleus, in a manner similar to that of planets orbiting about the sun in the solar system. Any two bodies in the universe exerts a force on each other which is perpendicular to the product of their mases and inversely proportional to the square of the distance between them. the force between charged bodies is called electric force. this force is attractive if the bodies carry charges of opposite sign and repulsive if the charges are of the same sign. In this study unit the simple electrostatic phenomena and electric force is discussed in details.

Learning Outcomes of Study Unit 1

Upon completion of this study unit, you should be able to

1.1 Name the two types of charges and State its properties

1.2 Explain the use of electrostatics in detecting the charge

1.3 Describe the mechanism of charging by electrostatic induction

1.4 Describe the distribution of charge on a conductor

1.5 State coulomb's law of electrostatics

1.6 Compare the coulomb's and gravitational law of force

1.7 Calculate of the force between two-point charges

1.8 State superposition principle as applied to coulombs force

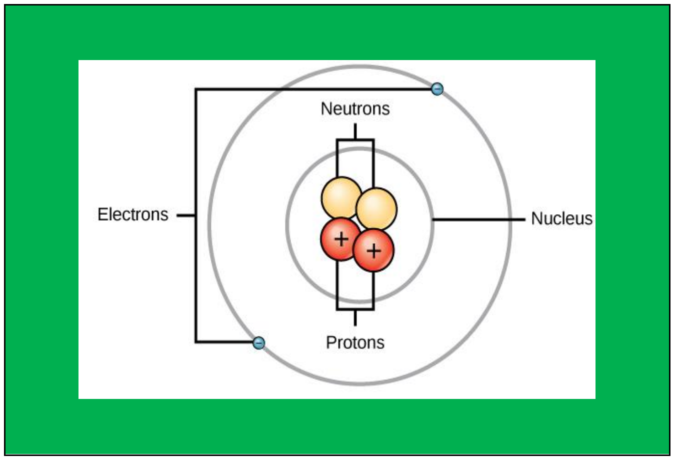
1.1 Electric charge and its properties

1.1.1 Electric charge is the physical property of matter that causes it to experience a force when placed in an electromagnetic field.

There are two types of electric charge: *positive* and *negative* (commonly carried by protons and electrons respectively). Like charges repel each other and unlike charges attract each other.

To understand the nature of charge, it is necessary to know the structure of an atom

1.1.2 structure of an atom



An atom consists of three basic particles: **Protons, electrons, and neutrons**. The nucleus (center) of the atom contains the protons (positively charged) and the neutrons (no charge). The outermost regions of the atom are called electron shells and contain the electrons (negatively charged). Atoms have different properties based on the arrangement and number of their basic particles. e.g. Hydrogen atom (H) contains only one proton, one electron, and no neutrons. This can be determined using the atomic number and the mass number of the element

Protons and neutrons have approximately the same mass, about 1.67×10^{-24} grams. Scientifically this amount of mass is defined as one atomic mass unit (amu) Electrons are much smaller in mass than protons, weighing only 9.11×10^{-28} grams or about 1/1800 of an atomic mass unit.

Electrons contribute greatly to the atom's charge, as each electron has a negative charge equal to the positive charge of a proton. Scientists define these charges as "+1" and "-1. " In an uncharged, neutral atom, the number of electrons orbiting the nucleus is equal to the number of protons inside the nucleus. In these atoms, the positive and negative charges cancel each other out, leading to an atom with no net charge

Particle	Charge	Mass(amu)	Location
Protons	+1	1	Nucleus
Electrons	-1	0	Orbitals
Neutrons	0	1	Nucleus

1.1.2 Separation of electric charges

Charge can be separated by various means. Here are some examples.

- Contact of dissimilar materials is followed by physical separation (combing hair).
- The belt of a Van de Graaff generator carries charge. Here also dissimilar materials (the belt and the pulley) are contacted, and separated. Charge is drawn off the belt, and stored on the dome.
- In a battery charge is separated by chemical means.
- Diffusion of charge occurs in living cells. Ions of one sign of charge can move more readily through the permeable wall of a cell, than those of the other sign.
- Charge is separated by convection in thunderclouds. All charge separation involves the expenditure of energy. The energy is released, for example in a spark, when the charged particles recombine.

1.1.3 Properties of electric charges

- **Charge is quantized.** This means that electric charge comes in discrete amounts, and there is a smallest possible amount of charge that an object can have. In the SI system, this smallest amount is $e = 1.602 \times 10^{-19} C$. No free particle can have less charge than this, and, therefore, the charge on any object, the charge on all objects must be an integer multiple of this amount. All macroscopic, charged objects have charge because electrons have either been added or taken away from them, resulting in a net charge.
- **The magnitude of the charge is independent of the type.** Phrased another way, the smallest possible positive charge (to four significant figures) is $+1.602 \times 10^{-19} C$, and the smallest possible negative charge is $-1.602 \times 10^{-19} C$; these values are exactly equal.
- **Charge is conserved.** Charge can neither be created nor destroyed; it can only be transferred from place to place, from one object to another. Frequently, we speak of two charges "canceling"; this is verbal shorthand. It means that if two objects that have equal

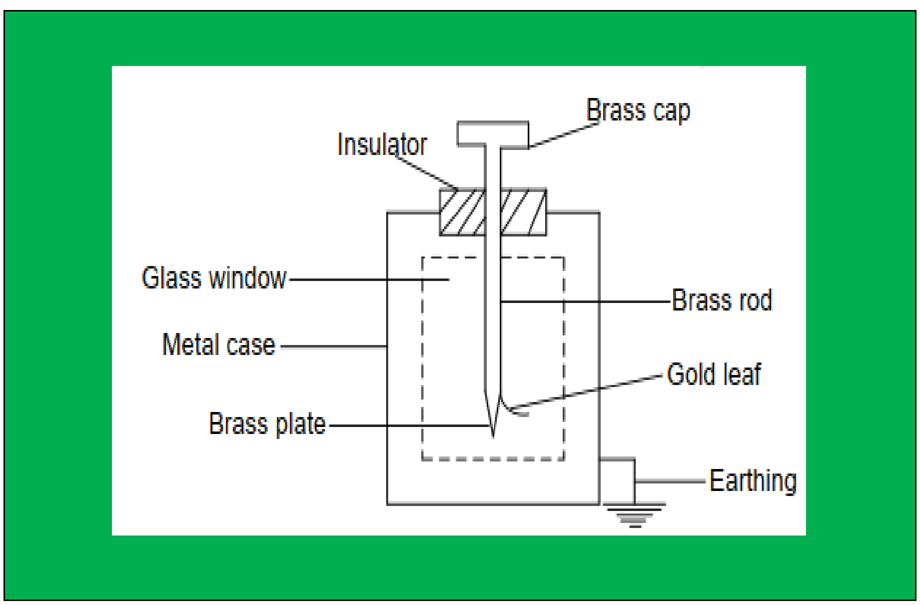
and opposite charges are physically close to each other, then the (oppositely directed) forces they apply on some other charged object cancel, for a net force of zero. It is important that you understand that the charges on the objects by no means disappear, however. The net charge of the universe is constant.

- **Charge is conserved in closed systems.** In principle, if a negative charge disappeared from your lab bench and reappeared on the Moon, conservation of charge would still hold. However, this never happens. If the total charge you have in your local system on your lab bench is changing, there will be a measurable flow of charge into or out of the system. Again, charges can and do move around, and their effects can and do cancel, but the net charge in your local environment (if closed) is conserved. The last two items are both referred to as the **law of conservation of charge**.

1.2 Detection of electric charge

This done with help of gold leaf electroscope. the gold leaf electroscope consists of

- a brass cap and brass rod connected by a brass rod.
- A gold leaf is fixed together with a brass rod.
- The brass rod, gold leaf and part of brass rod are put inside a metallic box which is enclosed with glass windows.



The electroscope is charged negatively by touching the brass cap with a negatively charged amber rod

The leaf of the electroscope diverging owing to the repulsion between negatively charged gold leaf. The amount of divergence is a measure of amount of charge on the leaf.

A body carrying charge of unknown sign is then brought near the cap of negatively charged electroscope. An increase in the divergence of the leaf is a proof that the body is negatively charged. If the divergence of the leaf decreases, the body either carries positive charge or neutral. The electroscope is discharged by touching it with finger. It then given a positive charge by touching the metal cap with a glass rod rubbed with silk cloth. The body of unknown charge is brought near the metal cap of electroscope. If the leaf of the electroscope diverge further, then the body carries positive charge. If the divergence of the leaves decreases, the body is neutral.

1.2.1 charging by friction

When two dissimilar bodies are rubbed together, heat is generated due to friction

- The heat is sufficient to make the material of lower work function to release some electron, which are taken up by other material.
- The one which lost electrons become positively charged while the one which gained electrons becomes negatively charged
- The number of electrons lost is equal to the number of electrons acquire therefore two insulating bodies rubbed together acquire equal and opposite charges.

Examples of charging by friction

- When a polythene rod (ebonite rod) is rubbed with fur (woolen duster), the ebonite rod becomes negatively charged while the duster becomes positively charged.
- If a glass rod (cellulose acetate) is rubbed with silk, a glass rod becomes positively charged while the silk becomes negatively charged.

1.2.2 Conductors and insulators

Conductors

Electrical conductors are materials in which some of the electrons are free electrons. examples of good conductors include.

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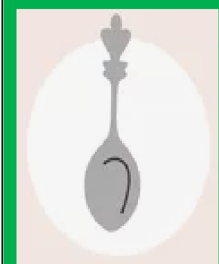
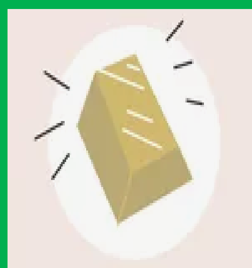
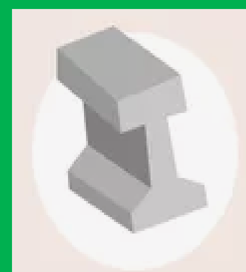
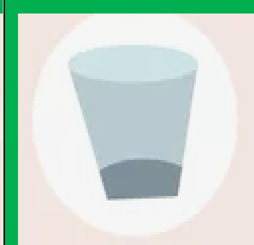
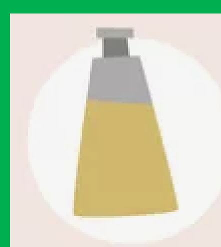
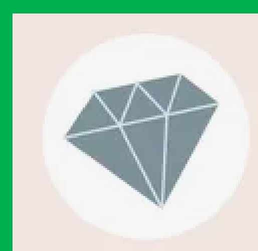
				

Insulators. Materials such as rubber, Nylon and glass, that don't allow the free movement of charges

Rubber	Glass	Oil	Diamond	Dry wood
				

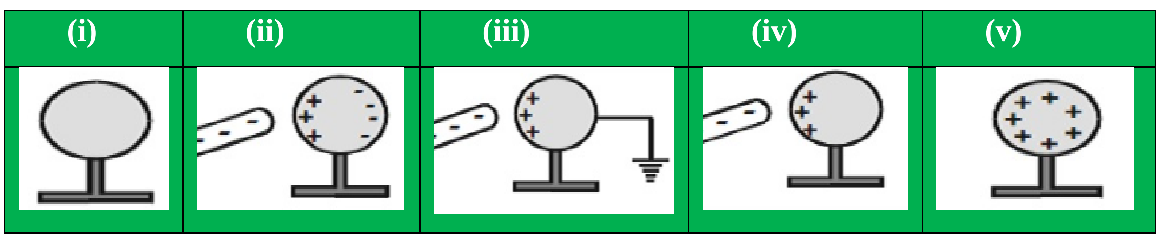
In terms of electronic structure, conductors are materials whose atoms have one or two outer electrons each loosely bound to parent nucleus. These electrons are called valence or conduction electrons . they wander through the lattice of material under the influence of thermal agitation. When an electric potential difference is applied a cross the conductor theses are nearly free electrons come under the directive influence of p.d and drift through the material thus constituting an electric current in the conductor.

All electrons in the atoms of an insulator are strongly bound to their nuclei. Except when extremely large p.ds are applied, these electrons can not be made to drift in these materials

1.3 Charging by electrostatic induction

Is charging without contact between changing body and the body being charged

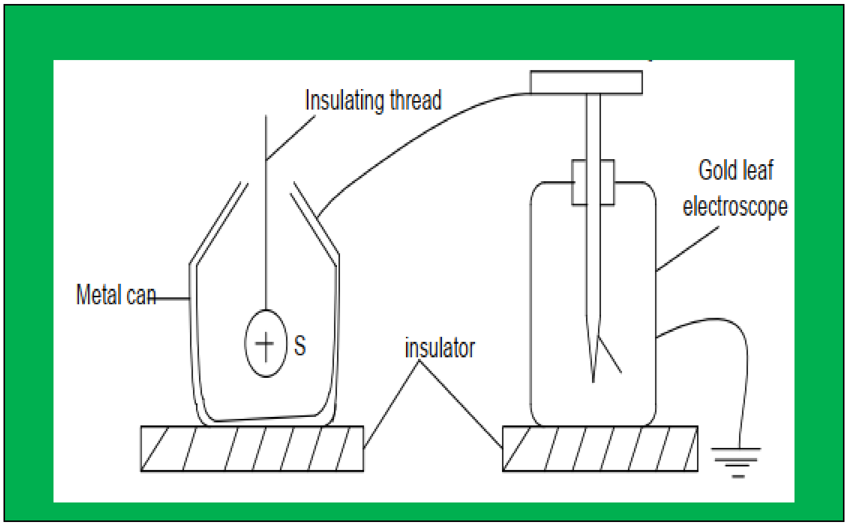
- Metal sphere on an insulating stand is placed near the negatively charged body. Free electrons in the metal sphere are repelled to the far end of the sphere as shown in fig (ii) below.
- The sphere is earthed while the charged body is still in position as shown in (iii). Free electrons move from the sphere to the earth.
- The earthing wire is removed while the charged rod is still in position as shown in (iv)
- The charged body is removed and charges distributes themselves all over the sphere. Hence the metal sphere is now positively charged.



1.3.1 Faradays ice - pail experiment

- A positively charged metal sphere, S is lowered into a metal can (without touching it) connected to a gold leaf electroscope. The leaf of the electroscope diverges
- S is withdrawn, the leaf of the electroscope collapses
- S is again lowered inside the metal (without touching it), the leaf of the electroscope diverges to the same extent as before.
- S is then allowed to touch the can. The divergence of the leaf remains unchanged
- S is withdrawn and on testing, it is found to have no charge

- There must have been charge inside the can equal and opposite to the charge on S. since the leaf remains diverged, the charge on the can must be residing on the outside of it. This charge is equal to that which was originally on S

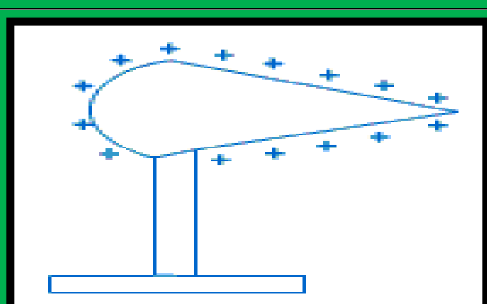
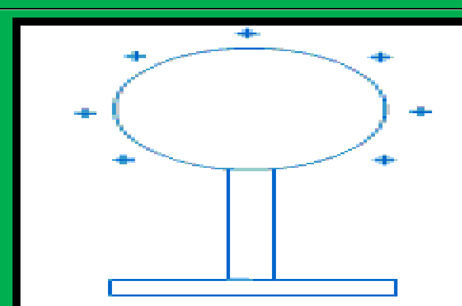


1.4 Distribution of charge on a conductor.

Surface density is the quantity of charge per unit area of the surface of a conductor.

Experiments on distribution of charge on conductors have shown that

- There is no charge on the inside of a hollow conductor, but resides on the outer surface
- Charges are equally distributed on spherical conductors
- Charges are highly concentrated on sharp or curved surfaces in irregularly shaped conductors

Irregularly shaped conductors: Charges are highly concentrated on sharp or curved surfaces	**Spherical conductors:** Charges are equally distributed
	

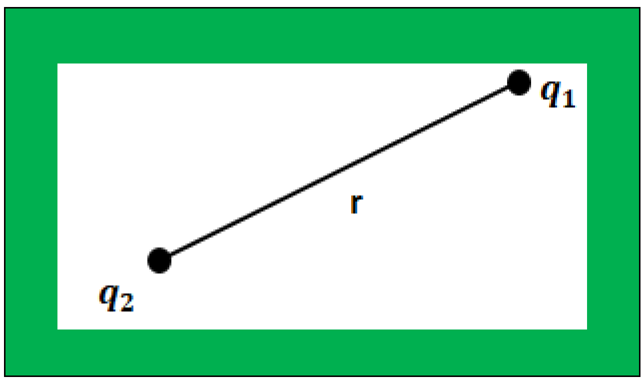
1.5 Coulomb's force

Charles Coulomb (**1736 – 1806** French physicist) measured the magnitudes of electric forces between two small charged spheres.

The force is inversely proportional to the square of the separation r between the charges and directed along the line joining them

The force is proportional to the product of the charges, q_1 and q_2 , on the two particles.

The electrical force between two stationary point charges is given by Coulomb's Law. Mathematically,



$$\boldsymbol{F_e = \frac{k|q_1||q_2|}{r^2}}$$

Where k is the constant

The force between two-point charges of the same sign is repulsive; while that between unlike charges is attractive. The value of k depends on the medium in which the charges are placed. In a vacuum (or free space, $k = \frac{1}{4\pi\varepsilon_0} 9.00x10^9 Nm^2c^{-2}$) where e($\varepsilon_0 = 8.85x10^{-12} Fm^{-1}$) is the permittivity of free space

1.6 Comparison of coulombs force and gravitational force

Let’s consider the electron and proton of a hydrogen atom are separated (on the average) by a distance of approximately 5.3 $x10^{-11}m$. Find the magnitudes of the electric force and the gravitational force between the two particles.

Solution

The magnitude of electric force

$$F_e = \frac{k|e||e|}{r^2} = \frac{(9.0x10^9)x(1.6x10^{-19})^2}{(5.3x10^{-11})^2} = 8.23x10^{-8}N$$

Now consider for the case gravitational force

$$F_G = \frac{G\left|M_p M_e\right||e|}{{r_o}^2} = \frac{6.67x10^{-11}x9.11x10^{-31}x1.67x10^{-27}}{(5.29x10^{-11})^2} = 3.63x10^{-47}N$$

Thus, the gravitational force between charged atomic particles is negligible when compared with the electric force.

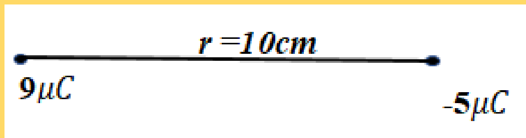
1.5.1 Differences between Coulomb’s force and Gravitational force

Coulomb’s force	Gravitational force
It May be attractive or repulsive	It is always attractive
It depends upon the medium between the charges	It is independent of the medium between the masses
It is much stronger	Is much weaker than coulombs force
It is given by $\boldsymbol{F_e} = \frac{\boldsymbol{k|e||e|}}{\boldsymbol{r^2}}$	It is given by $\boldsymbol{F_G} = \frac{\boldsymbol{G\left|M_p M_e\right||e|}}{\boldsymbol{{r_o}^2}}$

1.7 Calculation of the force between two-point charges

Example 1.7.1

Consider two-point charges +$\boldsymbol{9\mu C}$ and -5μC placed 10cm apart in free space as show below



Solution

The charges exert forces $\vec{F}_1$ and $\vec{F}_2$ on each other. The forces are attractive. $\vec{F}_1 = -\vec{F}_2$

But $\vec{F}_1 = \frac{|q_1||q_2|}{4\pi\varepsilon_0 r^2}\hat{\imath}$ where $\hat{\imath}$ is the unit vector pointing in the positive x-direction

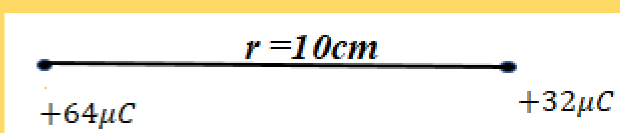
$$\vec{F}_1 = \frac{|q_1||q_2|}{4\pi\varepsilon_0 r^2}$$

$$\vec{F}_1 = \frac{(9.0x10^9)x9.0x10^{-6}(5.0x10^{-6})}{(10.0x10^{-2})^2}\hat{\imath}$$

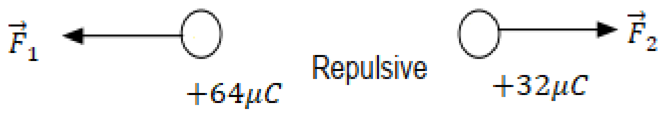
$$\vec{F}_1 = 40.5\hat{\imath}N(\text{attractive})$$

Examples 1.7.2

Let now consider two-point charges of $+64\mu C$ and $+32\mu C$ separated by a distance of 10.0cm



Solution



The charges exert forces $\vec{F}_1$ and $\vec{F}_2$ on each other. The forces are repulsive.

$$\vec{F}_1 = -\vec{F}_2 \quad \text{But} \quad \vec{F}_1 = \frac{|q_1||q_2|}{4\pi\varepsilon_0 r^2}\hat{\imath}$$

$$\vec{F}_1 = \frac{(9.0x10^9)x64x10^{-6}x32x10^{-6}}{(10.0x10^{-2})^2}\hat{\imath}$$

$$\vec{F}_1 = 1.84x10^3\hat{\imath}N(\text{attractive})$$

1.8 Superposition principle

If more than two charged particles exist in a system, then the Coulomb force exerted on one particle is the summation of all of the Coulomb forces between that particle and the rest of the particles in the ensemble:

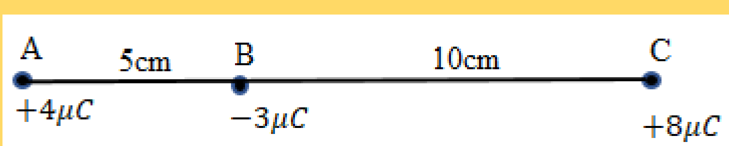
$$\vec{F}_e = \sum_i^N F_i\hat{x} + \sum_j^N F_j\hat{y} + \sum_k^N F_k\hat{z}$$

where F_i is the component Coulomb forces of all N particles in the $\boldsymbol{x}$ direction, F_j is the component forces in the $\boldsymbol{y}$ direction, and F_z is the component forces in the z direction Equation above is known as the **principle of superposition**

1.7.1 Applications of superposition principle in electric force

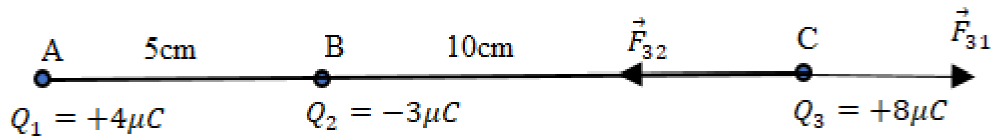
Example 1

Three-point charges are placed at point A, B and C as shown below. Calculate the resultant force on the charge at C



Let $\vec{F}_{31}$ be the force exerted on Q_3 by Q_1 while $\vec{F}_{32}$ is the force exerted on Q_3 by Q_2 the force $\vec{F}_{31}$

Is the repulsive while $\vec{F}_{32}$ is the attractive



$$\vec{F}_{31} = \frac{|Q_3||Q_1|}{4\pi\varepsilon_0 {r_{31}}^2}\hat{\imath}$$

$$\vec{F}_{31} = \frac{(9.0x10^9)x4x10^{-6}x8x10^{-6}}{(15.0x10^{-2})^2}\hat{\imath}$$

$$\vec{F}_{31} = 12.8\hat{\imath}N(Repulsive)$$

$$\vec{F}_{32} = \frac{|Q_3||Q_2|}{4\pi\varepsilon_0 {r_{32}}^2}\hat{\imath}$$

$$\vec{F}_{32} = \frac{(9.0x10^9)x3x10^{-6}x8x10^{-6}}{(10.0x10^{-2})^2}\hat{\imath}$$

$$\vec{F}_{32} = 21.6\hat{\imath}N(attractive)$$

By super position principle the force on Q_3due to Q_2 and Q_1together is

$$\vec{\boldsymbol{F}} = \vec{F}_{31} - \vec{F}_{32}$$

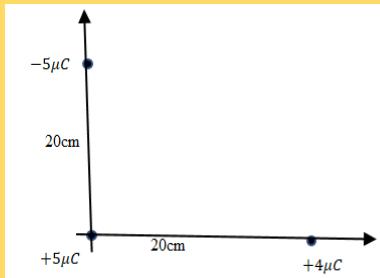
$$\vec{F} = (12.8 - 21.6)\hat{\imath}N$$

$$\vec{F} = -8.8\hat{\imath}N$$

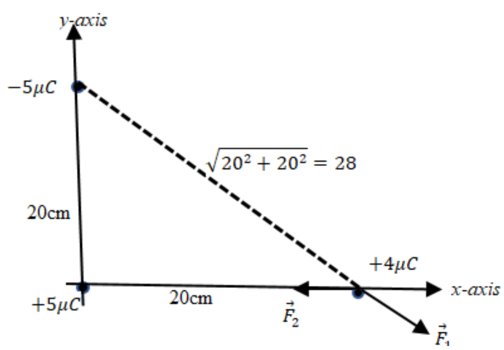
The resultant force has the magnitude of $8.8\hat{\imath}N$ and points in the negative x direction

Example 2

Three charged objects are placed as shown below. Find the net force on the object with the charge of -4μC.



solution



$$\vec{F}_{31} = \frac{|Q_3||Q_2|}{4\pi\varepsilon_0 r^2}\hat{\imath}$$

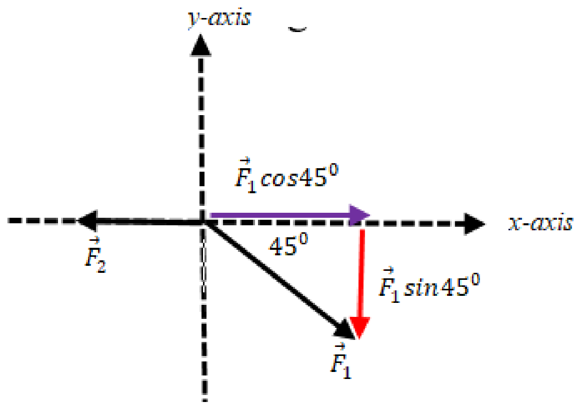
$$\vec{F}_1 = \frac{(9.0x10^9)x4x10^{-6}x5x10^{-6}}{(28.0x10^{-2})^2}$$

$$\vec{F}_1 = 2.3N$$

$$\vec{F}_2 = \frac{(9.0x10^9)x4x10^{-6}x5x10^{-6}}{(20.0x10^{-2})^2}$$

$$\vec{F}_2 = 4.5N$$

F_1 and F_2 must be added together as vectors



Resolving horizontally

$$\vec{F}_x = -\vec{F}_2 - \vec{F}_1 cos45^0$$

$$\vec{F}_x = -4.5 + 2.3cos45^0$$

$$\vec{F}_x = -2.9\hat{\imath}N$$

Resolving vertically

$$\vec{F}_y = -\vec{F}_1 sin45^0$$

$$\vec{F}_y = -2.3sin45^0$$

$$\vec{F}_y = -1.6\hat{\jmath}N$$

The magnitude of the force

$$\vec{F} = \sqrt{\vec{F}_x^{\ 2} + \vec{F}_y^{\ 2}} = \sqrt{2.9^2 + 1.6^2} = 3.31N$$

The direction of $\vec{F}$ is

$$\theta = tan^{-1}\left(\frac{\vec{F}_y}{\vec{F}_x}\right) \theta = tan^{-1}\left(\frac{1.6}{2.9}\right)$$

$$\theta = 29^0$$

Self-Review Question (SRQs) for study unit 1

Now that you have completed this unit, you can measure how well you achieved its learning outcomes by answering the following questions. You can check your answers with the Notes on Self-Review Questions at the end of this study unit

1. Describe the structure of an atom
2. What is meant by conservation of charges?
3. Explain how electroscope can be used to test sign of charge on a given body
4. Explain four applications of electric charges
5. Explain the significance of faradays ice pail experiment
6. Explain how a metal spere can be charged negatively by induction
7. Distinguish conductors and insulators in terms of
   (i) Their electronic structure (ii) Flow of charge (iii) Their Examples
8. Define the following terms
   (i) Charging by friction (ii) Charging by electrostatic induction (iii) Surface density
9. Describe the structure of a gold leaf electroscope
10. Explain five applications of insulators and conductors.
11. State the coulombs law of electro statics, Compare it to Newton's Law of Gravity. What is the principle of superposition?
12. Two small identical conducting spheres are placed with their centers 0.30 m apart. One is given a charge of $\mathbf{12 \times 10^{-9} C}$, the other a charge of $\mathbf{-18 \times 10^{-9} C}$.

(i) Find the electrostatic force exerted on one sphere by the other.

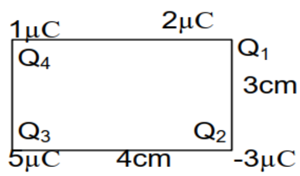
(ii) The spheres are connected by a conducting wire. Find the electrostatic force between the two after equilibrium is reached, where both spheres have the same charge.

13. Charge $q_1 = 6.00\ \mu C$ sits at 0.00 cm, charge $q_2 = 1.50\ \mu C$ sits at 3.00 cm, and charge $q_3 = -2.00\ \mu C$ sits at 5.00 cm.

   (i) Determine the electric field strength at a point 1.00 cm to the left of the middle charge.

   (ii) If charge q_3 is placed at this point, what are the magnitude and direction of the force on it?

14. Four-point charges $Q1$, $Q2$, $Q3$ and $Q4$are placed at different corners of rectangle Find the resultant force and its direction at Q_2



Summary

- There are only two types of electric charge and they are arbitrarily called positive and negative. Like charges repel and unlike charges attract each other. The unit of charge is the coulomb (C)
- Charge is always conserved. That is, the algebraic sum of the charges in a closed system does not change
- Electric charge is quantized, occurring only in discrete amounts
- The force between two charges is proportional to the product of their charges and inversely proportional to the square of the distance between them. The force acts along the line joining the two charges. $\boldsymbol{F_e} = \frac{\boldsymbol{k|q_1||q_2|}}{\boldsymbol{r^2}}$ The value of k depends on the medium in which the charges are placed. In a vacuum (or free space, $k = \frac{1}{4\pi\varepsilon_0} 9.00x10^9 Nm^2c^{-2}$) where e($\varepsilon_0 = 8.85x10^{-12} Fm^{-1}$) is the permittivity of free space

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