

Unit
13

ELECTROSTATICS

Why after running a plastic comb through our hair (on a dry day) attracts small pieces of paper?

After studying this chapter you should be able to

- ✓ describe simple experiments to show the production and detection of electric charge.
- ✓ describe experiments to show electrostatic charging by induction.
- ✓ state that there are positive and negative charges.
- ✓ describe the construction and working principle of electroscope.
- ✓ state and explain Coulomb's law.
- ✓ solve problems on electrostatic charges by using Coulomb's law.
- ✓ define electric field and electric field intensity.
- ✓ sketch the electric field lines for an isolated +ve and -ve point charges.
- ✓ describe the concept of electrostatic potential.
- ✓ define the unit "volt".
- ✓ describe potential difference as energy transfer per unit charge.
- ✓ describe one situation in which static electricity is dangerous and the precautions taken to ensure that static electricity is discharged safely.
- ✓ describe that the capacitor is charge storing device.
- ✓ define capacitance and its unit.
- ✓ derive the formula for the effective capacitance of a number of capacitors connected in series and in parallel.
- ✓ apply the formula for the effective capacitance of a number of capacitors connected in series and in parallel to solve related problems.

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- 13.1 Electric charge
 - 13.2 Electrostatic induction
 - 13.3 Electroscope
 - 13.4 Coulomb's law
 - 13.5 Electric field and its intensity
 - 13.6 Electrostatic potential
 - 13.7 Applications of electrostatics
 - 13.8 Dangers of Static charge
 - 13.9 Capacitors and capacitance
 - 13.10 Different types of capacitors
 - 13.11 Combination of capacitors
 - Key Points and Projects
 - Exercise

Electrostatics is the study of charges at rest. The electrostatic force just like force of gravity is an action at a distance force. In the opening picture of the chapter we see that a plastic comb that is run through hair and brought near tiny pieces of paper, attracts them.

A similar effect can be observed for plastic (or amber) rod rubbed with fur, as shown in figure 13.1. Similarly, balloon rubbed against hair also attracts a falling stream of water.

We sometime feel a shock when we

touch a metal doorknob after sliding across a car seat or walking across a synthetic carpet. In all these cases electrostatic force is in action.

But the electric force plays an even deeper role in our lives. According to atomic theory, electric forces between atoms and molecules hold them together to form liquids and solids, and electric forces are also involved in the metabolic processes that occur within our bodies.

13.1 ELECTRIC CHARGE

We have learnt already that an inherent property of an object is its mass. An object with smaller mass will have less inertia as compared to an object with larger mass. Along with mass, another inherent property of an object is its electrical charge.

FIGURE 13.1 - Charging

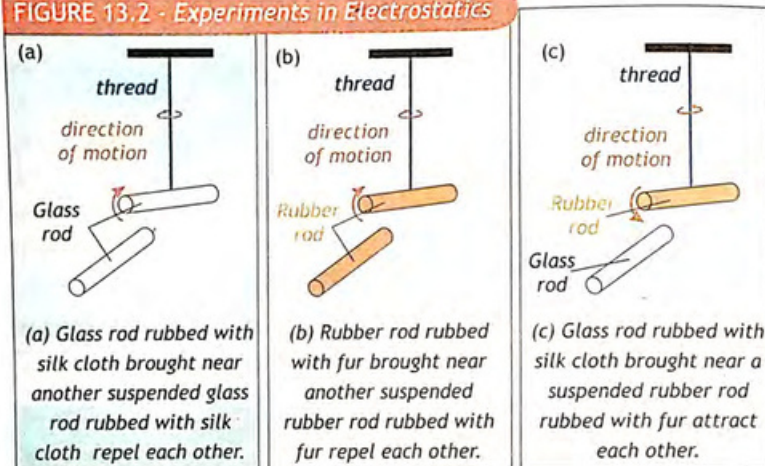


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Charge is measured in units of coulomb (C).

There are two kinds of charges: A simple experiment as shown in the figure 13.2 can be performed to show that there are two types of charges, one type is called positive and the other negative.

FIGURE 13.2 - Experiments in Electrostatics



From these observations we can conclude that

- ⊙ there are two types of charges and
- ⊙ similar charges repel and different charges attract.

Interestingly it is seen that after rubbing the silk cloth and animal fur also acquired the charge in opposite sense to glass rod and rubber rod respectively.

In grade 7, unit 6 'STRUCTURE OF ATOMS' we learnt that all matter is made up of atoms. Atoms have two kinds of charges: protons contained in the nucleus of atom have positive charge, whereas electrons clouding around the nucleus carry

FIGURE 13.3

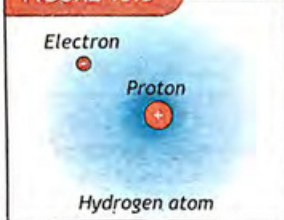


Table 13.1 BASIC CHARGES

Particle	Charge (C)	Mass (kg)
electron	-1.6×10^{-19}	9.109×10^{-31}
proton	$+1.6 \times 10^{-19}$	1.673×10^{-27}
neutron	0	1.675×10^{-27}

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negative charge, neutrons inside the nucleus have no charge, as shown in figure 13.3. The charge on an electron or proton (as shown in Table 13.1) is said to be an elementary or fundamental charge because all known charges are made up of electrons and protons and so all charges are integer multiples of the fundamental charge.

As all the matter is made of atoms, thus every material object has charges in it. We often do not notice the effects of electrical charges because most objects have the same number of electrons and protons in them (therefore, we have equal and opposite charges) and as a result the net effect is zero and so these objects are electrically neutral.

Electrification: Electric charge is not created in the process of charging objects, charges are only transferred between the objects. In electrification experiments in figure 3.2, it is seen that silk cloth/animal fur also attained charge. Thus, in those experiments, charge was not produced rather it was only transferred and we can say that objects can be charged by removal or addition of charges (specifically electrons) called electrification.

Since electrons can be transferred easily therefore if an object has a...

- Positive (+) charge - means it has less electrons than normal
- Negative (-) charge - means it has more electrons than normal

13.2 ELECTROSTATIC INDUCTION

A change in distribution of electrical charge in an object, caused by the influence of nearby charges is called **electrostatic induction**. This effect may be shown by bringing a negatively charged rubber strip near to an insulated metal sphere X which is touching a similar sphere Y (as shown in Figure 13.5 - a). Electrons in the spheres are repelled to the far side of Y.

If X and Y are separated, with the charged strip still in position, X is left with a positive charge (deficient of electrons) and Y with a negative charge (excess of electrons) as shown in Figure 13.5 - b. In this way electrostatic induction can be used to charge objects as in Figure 13.5 - c.

ACTIVITY

Rub a balloon with your hairs for some time and attach it to the wall. It will cling to it. Why? Explain.

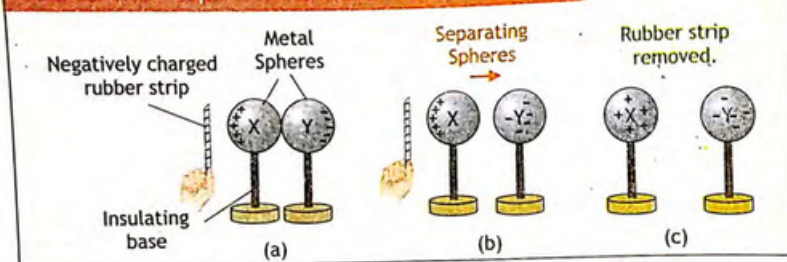


FIGURE 13.4 - Induction



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FIGURE 13.5 - Experiments in Electrostatic Induction



13.3 ELECTROSCOPE

Electroscope is a device used for detecting and testing the nature of charge on a body. It works on the principle that similar charges repel each other.

A simple form of electroscope consists of a metal bar which has a metallic sphere (ball) at its upper end. Thin flexible metal leaf (made of gold, silver, copper or any other metal) is attached to the lower end of metal bar. The lower part is enclosed in an insulated housing as shown in the figure 13.7.

FIGURE 13.7 - Electroscope

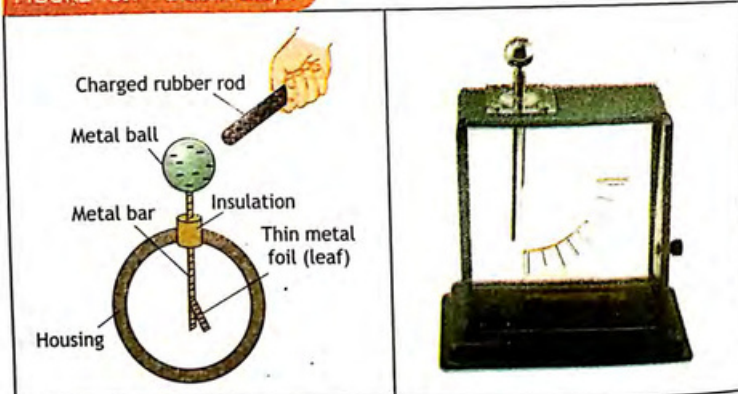


FIGURE 13.6



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Working: In order to detect charge on a body we touch the metal ball with it. For example, if we touch it with negatively charged rubber rod some of its excess electrons will be transferred to the ball and then they will spread throughout the metal rod and the metal foil. The flexible metal leaf will be repelled by the similar charge on the metal rod and will move away from the rod by rising higher. As more electrons are transferred to the electroscope, the metal leaf will rise higher. Alternatively if the rod is positively charged it will attract electrons from the electroscope, leaving a net positive charge on it. Once again the foil will rise.

However, to test the nature of charge on the body we charge the electroscope with some known charge first. Now if the same charge is added to the metal ball, it will increase divergence of flexible metal leaf and opposite charge will decrease the divergence allowing us to identify the unknown charge on the body.

ACTIVITY

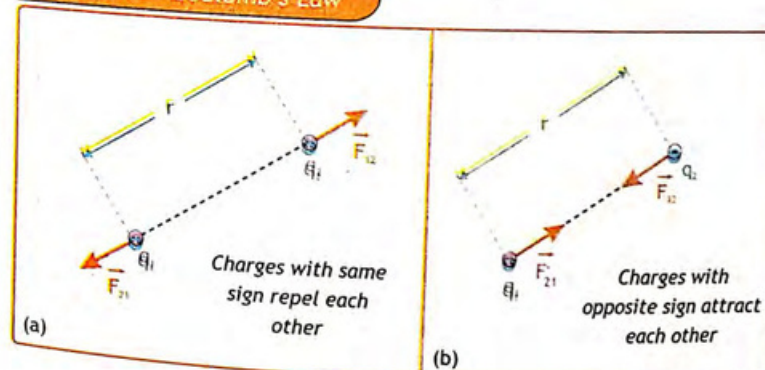
Rub a balloon with your hair for some time and turn on a water faucet just enough to have a very small but steady stream trickling out. Bring a balloon near the stream. What happens?

13.4 COULOMB'S LAW

Statement: The electric force between two stationary point charges is

- directly proportional to the product of the charges;
- inversely proportional to the square of the distance between them and
- is directed along the line joining these charges.

Figure 13.8 - Coulomb's Law



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Consider two point charges q_1 and q_2 separated by distance r as shown in figure 13.8. By definition of Coulomb's law

$$F_E \propto q_1 q_2 \quad \text{--- (1)}$$

$$\text{and } F_E \propto \frac{1}{r^2} \quad \text{--- (2)}$$

Combining equation 1 and equation 2, we get

$$F_E \propto \frac{q_1 q_2}{r^2}$$

Changing the sign of proportionality into equality

$$F_E = k \frac{q_1 q_2}{r^2} \quad \text{--- 13.1}$$

TIP: Point Charges

Coulomb's law can only be applied to **point charges** (charges of very small size). Practically the charged objects are considered point charges if the separation between the charges is made large as compared to the size of the charged objects.

Equation 13.1 gives coulomb force, where k is a constant of proportionality and is called the Coulomb constant. Here the charges ' q_1 ' and ' q_2 ' are considered as point charges as distance ' r ' is considered large as compared to their size.

COULOMB'S CONSTANT

The Coulomb constant k for vacuum in SI units has the value $9 \times 10^9 \text{ Nm}^2/\text{C}^2$, this constant is also written in the form

$$k = \frac{1}{4\pi\epsilon_0} \quad \text{--- (3)}$$

Where the constant ϵ_0 (lowercase Greek epsilon) is known as the permittivity of free space (vacuum) and has the value $8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$. Putting this value in above equation 3 we get the value of coulomb's constant $k = 8.998 \times 10^9 \text{ Nm}^2/\text{C}^2$.

The value of the Coulomb constant depends on the medium between the charges. If the space in between charges has matter in it, the value of the Coulomb's constant changes and as a result coulomb force changes. For any medium other than vacuum, the coulomb's constant has the form

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

The quantity ϵ is called permittivity of the material. A material medium with high permittivity is a medium which reduces the coulomb force between the charges to a greater degree as compared to the case where the charges are in vacuum. The permittivity for air (ϵ_{air}) is slightly greater than permittivity for vacuum the ϵ_0 , for most practical purposes they are taken as equal.

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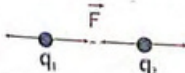
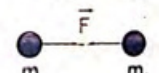
The attraction of an uncharged object by a charged object near it is due to electrostatic induction. For example, it is the reason for the opening question 'Why after running a plastic comb through our hair on a dry day does the comb attract small pieces of paper?'. The influence of the charge on the comb redistributes the charges in the paper due to electrostatic induction.



Charges in the pieces of paper with the same sign (polarity) are pushed away while charges with opposite sign are pulled closer. This change in distance means the attractive force due to the closer opposite sign charges is greater than the repulsion due to the same sign charges which have been pushed further away. As coulomb forces decrease as distance between similar charge is increased, on the other hand it increases for dissimilar charges, as a result it overcomes inertia and lifts small pieces of paper. This creates a net attractive force which pulls the paper towards the comb.

We have noticed that Coulomb's law is similar to Newton's law of universal gravitation. Table 13.2 gives a comparison between these two laws.

TABLE 13.2 COMPARISON OF COULOMB'S LAW AND NEWTON'S LAW OF UNIVERSAL GRAVITATION

Electric Force	Comparison	Gravitational Force
Force is between charge as key quantity 	Coulomb Force is both attractive or repulsive, while the gravitational force is only attractive	Force is between mass as a key quantity 
$\vec{F}_E \propto q_1 q_2$	Force varies directly with product of key quantity (charge/mass)	$\vec{F}_G \propto m_1 m_2$
$\vec{F}_E \propto \frac{1}{r^2}$	Force varies with square of distance between the key quantities (charge/mass)	$\vec{F}_G \propto \frac{1}{r^2}$
$\vec{F}_E = k \frac{q_1 q_2}{r^2}$	Equations are similar with appropriate constant applied	$\vec{F}_G = G \frac{m_1 m_2}{r^2}$

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TipBits

How adhesive tape work? Since the electrostatic force depends on the inverse square of the distance between the charges, it becomes larger for smaller distances, such as those involved when a strip of adhesive tape is stuck to a smooth surface. Electrons shift over the small distances between the tape and the surface. As a result, the materials become oppositely charged. Since the distance between the charges is relatively small, the electrostatic force of attraction is large enough to contribute to the adhesive bond.



EXAMPLE 13.1: FORCE BETWEEN PROTONS

The two protons and two neutrons in the nucleus of the helium atom are held together by the strong force, which is required to overcome the electrostatic repulsion between the protons. The charge of each proton is $q_p = +1.6 \times 10^{-19} \text{ C}$. A distance of approximately $r = 2 \times 10^{-15} \text{ m}$ separates the two protons. Calculate the magnitude of the electrostatic force between the protons.

GIVEN

Charge on proton ' q_p ' = $+1.6 \times 10^{-19} \text{ C}$.

Distance ' r ' = $2 \times 10^{-15} \text{ m}$

Coulomb Constant ' k ' = $9 \times 10^9 \text{ Nm}^2/\text{C}^2$

REQUIRED

Force ' F_e ' = ?

SOLUTION: Using Coulomb's Law, we can find the force

$$F_e = k \frac{q_p \times q_p}{r^2}$$

Putting values $F_e = 9 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2} \frac{(1.6 \times 10^{-19} \text{ C}) \times (1.6 \times 10^{-19} \text{ C})}{(2 \times 10^{-15} \text{ m})^2}$

Hence $F_e = 57.6 \text{ N} = 58 \text{ N}$ — **Answer**

Therefore, the two protons in the atomic nucleus of a helium atom push each other with a force of 58 N.

EXTENSION EXERCISE 13.1

Considering the small size of nuclear particles, 58 N is a very large force. How are the protons kept together in the nucleus?

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ASSIGNMENT 13.1: FORCE BETWEEN CHARGED METAL SPHERES

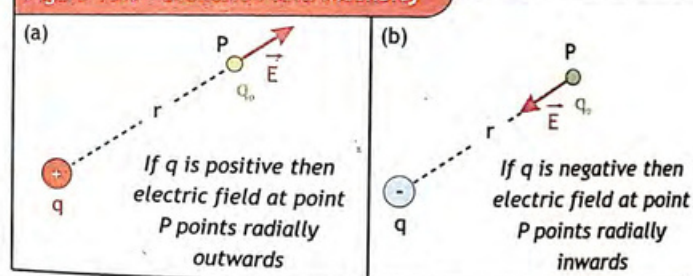
A small metal sphere with a charge of $-2.10 \times 10^{-6} \text{ C}$ is brought near an identical sphere with a positive charge of $1.50 \times 10^{-6} \text{ C}$ so that the distance between the centres of the two spheres is 3.30 cm. Calculate the magnitude of the force that each charge exerts on the other.

13.5 ELECTRIC FIELD AND ITS INTENSITY

The region around a charge in which an electric test charge would experience an electric force is called **electric field**, and the strength of the field (equal to the force experienced by a $(+1 \text{ C})$ test charge) at any point is called **electric field intensity**.

An electric field exists in the region of space around a charged object in three dimensions. When another charged object enters this electric field, an electric force acts on it even without any physical contact between the charges.

Figure 13.9 - Electric Field Intensity



Consider a small positive test charge q_0 near the greater magnitude charge q as shown in figure 13.9. Now the electric field E at any point in space is defined as the force F_e acting on unit positive charge q_0 , divided by the magnitude of test charge q_0 , mathematically

$$\vec{E} = \frac{\vec{F}_e}{q_0}$$

13.2

TIP: Test Charges

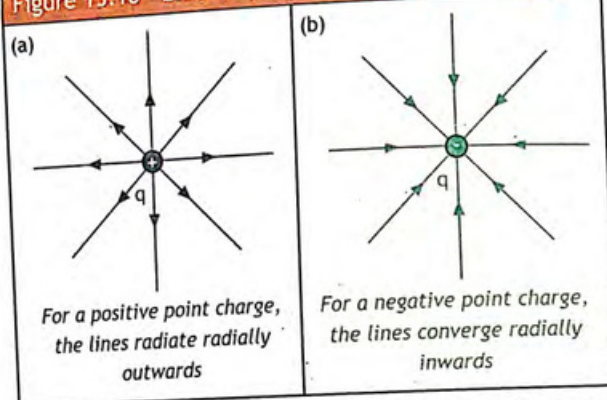
By convention, test charge is always taken as positive. The size of test charge is kept small, such that it does not effect charge distribution on object and distort the field created by source (original) charge.

Equation 13.2 gives the mathematical form of electric field intensity. The SI unit of electric field intensity is newton per coulomb (NC^{-1}). It is a vector quantity having direction in which a positive test charge would move under the influence of force.

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An easy way to visualize an electric field is to draw lines that follow the same direction as the electric field intensity vector E at any point. These lines are called electric field lines.

Figure 13.10 - Electric field lines for point charges



Electric field intensity vectors help to visualize the electric field. Electric field lines are a kind of "map" that gives the direction and strength of the field at various places. The direction of the lines is radially outward for a positive charge and radially inward for a negative charge as shown in figure 13.10.

EXAMPLE 13.2: ELECTRIC FIELD INTENSITY

A positive test charge of $30 \mu\text{C}$ is placed in an electric field. Force on it is 0.600 N . What is the magnitude of electric field at the location of test charge?

GIVEN

Test Charge $q_0 = 30 \mu\text{C} = 30 \times 10^{-6} \text{ C}$.

Force ' F_e ' = 0.600 N

REQUIRED

Electric field intensity ' E ' = ?

SOLUTION: By definition of electric field intensity

$$\vec{E} = \frac{\vec{F}_e}{q_0}$$

Putting values $\vec{E} = \frac{0.600 \text{ N}}{30 \times 10^{-6} \text{ C}}$

Hence $\vec{E} = 2.00 \times 10^4 \text{ NC}^{-1}$ — **Answer**

Therefore, the magnitude of electric field is $2 \times 10^4 \text{ N/C}$.

NOT FOR SALE**ASSIGNMENT 13.2: FORCE IN AN ELECTRIC FIELD**

If a charge of $4 \mu\text{C}$ is placed in a uniform field of strength 2 NC^{-1} , what force will it experience?

13.6 ELECTRIC POTENTIAL

The electric potential energy ' U ' per unit charge ' q ' in an electric field is called electric potential V .

$$V = \frac{U}{q} = \frac{W}{q} \quad \text{13.3}$$

The electric potential units of joules per coulomb (J C^{-1}), or volt (V) in honor of Italian scientist Alessandro Volta. The potential at a point is one volt, when it requires one joule of work to move a positive charge of one coulomb from a point of ZERO potential to that point.

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

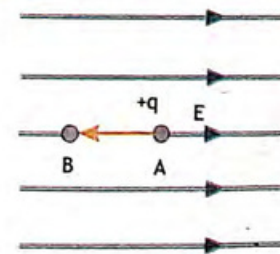
The concept of electric potential is closely related to electric field. Electric field is the force per unit charge, whereas the electric potential is the energy per unit charge. However electric potential is a scalar quantity. Since, it is easier to solve problems with scalars, therefore, it is simpler to solve problems with electric potential rather than electric field.

Let us consider a positive charge $+q$ is placed in an electric field at point B as shown in the figure 13.11. If the charge is allowed to move freely, it will acquire kinetic energy and will move from B to A. Conversely, we can say that an external force is required to keep the charge at rest or to move with uniform velocity from A to B. Thus

$$V_B - V_A = \frac{W_{AB}}{q} \quad \text{13.4}$$

Often point A is taken to be at infinity, meaning a large distance from the charges that produce the electric field, and the electric potential at A is taken to be zero. Note that the choice of zero potential at infinity is taken arbitrarily and for

Figure 13.11 - Electric Potential

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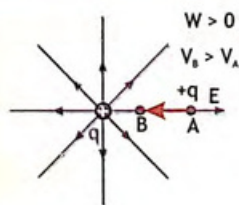
simplicity, such that

$$V = \frac{W}{q} \quad \text{13.5}$$

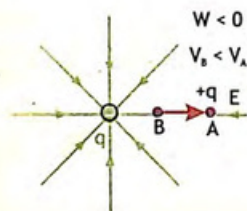
In equation 13.5, V (by definition) the Work that must be done against the Electric Field to bring a test charge q from infinity to a specific location.

POSITIVE AND NEGATIVE WORK DONE

The work done W_{AB} in moving charge $+q$ from point A to point B can be positive negative or zero, thus the potential at point B can be higher, lower or equal to potential at point A.



For example, in order for a positive test charge to be brought closer to an isolated positive charge $+Q$, the work must be done by an external agent, the work done in this case is positive. In this case, the electric potential at point B is higher than electric potential at point A. Alternately, we can observe that $V_B > V_A$ by noting that the electric field would push a positive charge from B to A, which is always from high potential to low potential.



On the other hand, if the isolated charge is negative ($-Q$), the positive test charge must be restrained from moving from point A to point B and the work done must be negative. In this case, the electric potential at point B is lower than electric potential at point A. Alternately, we can observe that $V_B < V_A$ by noting that the electric field would pull a positive charge from A to B, which is always from high potential (A) to low potential (B).

EXAMPLE 13.3: WORK DONE

How much work must be done to increase the potential of a charge $2.5 \times 10^{-7} \text{ C}$ by 100 V?

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GIVEN

Charge ' q ' = $2.5 \times 10^{-7} \text{ C}$

Change in potential ' ΔV ' = 100 V

REQUIRED

Work Done ' W ' = ?

SOLUTION: By definition of electric potential

$$V = \frac{W}{q} \quad \text{or} \quad W = qV$$

Putting values $W = 2.5 \times 10^{-7} \text{ C} \times 100 \text{ V}$

Hence $W = 2.5 \times 10^{-5} \text{ J}$ — Answer

EXTENSION EXERCISE 13.2

How the units coulomb (C) multiplied by volt (V) gives joule (J)?

ASSIGNMENT 13.3: WORK DONE IN AN ELECTRIC FIELD

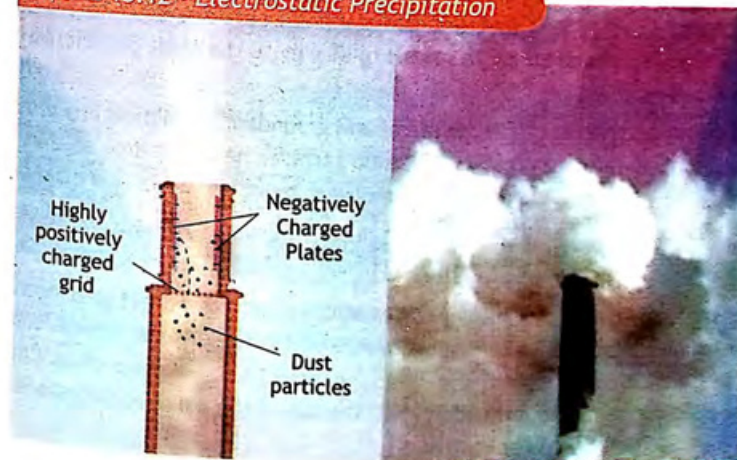
How much work is done in moving a charge of 3 C from a point at 118 V to a point at 138 V in an electric field?

13.7 PRACTICAL APPLICATIONS OF ELECTROSTATICS

Electrostatic phenomena has wide applications in daily life.

A. **Electrostatic precipitator and dust extraction:** Electrostatic phenomena can be used to separate dust from smoke particles. To reduce air pollution, modern day coal burning power stations extract dust from the smoke in chimneys before releasing it to the environment by a process called electrostatic precipitation.

FIGURE 13.12 - Electrostatic Precipitation



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For this purpose chimneys have a highly positively charged grid (usually a wire gauze) and negatively charged plates as shown in the figure 13.12. When smoke rising from chimney containing smoke and dust particles pass through the positively charged grid they acquire a positive charge. These charged particles are attracted by the negatively charged plate and are deposited on them. Thus, the smoke coming out of chimney is free from dust and other particles.

B. Electro painting: Electrostatic spray painting is a method in which electrostatically charged paint is applied as shown in figure 13.13. This method reduce the paint usage and uneven coating that result from using a regular spray painter, both for powder and liquid paint.

FIGURE 13.13 - Electro painting



One type of system applies a negative electric charge to the paint while it is in the container. Other systems apply the charge in the barrel of the spray painter gun. The paint is then pushed through the gun, rubbing against the side, and gaining a static electric charge as it moves. Since the paint particles all have the same charge, they repel each other. This helps to distribute the paint particles evenly and get uniform coverage.

Usually the object being painted is metal and grounded, but almost any product can be finished electrostatically. The paint particles have a charge so they are attracted to the opposite charge of the object being painted. This makes the particles less likely to stay in the air.

13.8 DANGERS OF STATIC CHARGE

Apart from useful applications of electrostatics - it can sometimes be dangerous. For example, lightning is the result of large scale charge separation occurring within a thundercloud. Lightning involves the dielectric breakdown of air. Charge separation occurs within a thundercloud; the top of the cloud becomes positive and the lower part becomes negative.

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The negative charge at the bottom of the thundercloud induces positive charge on the Earth just underneath the cloud as shown in figure 13.14. When the electric field between the cloud and the earth becomes large enough, the air undergoes dielectric breakdown, meaning it momentarily becomes a good conductor of electricity allowing the negative charge to jump from the cloud to the earth. A lightning channel is completed and electrons rush to the ground making the channel glow in the process. A total of about 20 C to 25 C of electronic charge is transferred from the thundercloud to the surface.

FIGURE 13.14 - Lightning

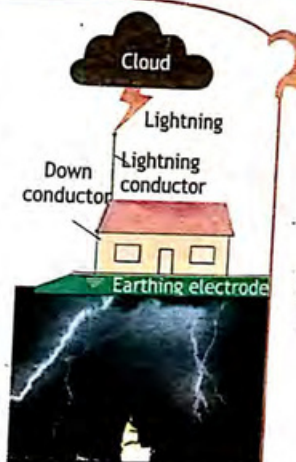


Tip Bits

Lightning conductors/rods: The purpose of Lightning conductors is to protect structures against direct lightning strikes. By catching the lightning and running the discharge current to earth, they avoid damage connected with the lightning strike itself and circulation of the associated current.

How can we protect our self during a thunderstorm? We should stay indoors or in an automobile if possible. When caught in the open, we should keep low, stay away from any tall tree; if lightning strikes the tree, charge traveling down the tree and then along the surface will put us in danger.

If trapped in such situation we should try to go in a nearby ditch or low spot keeping our head low and feet as close together as possible.



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13.9 CAPACITOR

Capacitor is a device used for storing charge, it consists of two conductors separated from (without touching) each other, carrying charges of equal magnitude but opposite sign.

Figure 13.15 shows the basic elements of any capacitor — two isolated conductors (having charge $+Q$ and $-Q$) of any shape. No matter what their geometry, flat or not, we call these conductors plates. Each capacitor plate carries a charge of the same magnitude, one positive and the other negative. Due to the charges, the electric potential of the positive plate exceeds that of the negative plate by an amount V .

The insulating medium that separates the plates of capacitor (air or some other insulating material) is referred to as dielectric.

Capacitance of capacitor: The capacitance C of a capacitor, is the ratio of the magnitude of the charge on either conductor to the magnitude of the potential difference between them.

When charge Q is increased on the plates of the capacitor the potential difference V also increases and vice versa as shown in figure 13.16, thus we can write

$$Q \propto V \quad \text{or} \quad Q = CV$$

Where C is the constant of proportionality and is called the capacitance of a capacitor.

therefore $C = \frac{Q}{V}$ — 13.6

The capacitance of a capacitor is the amount of charge the capacitor can store per unit of potential difference. The capacitance of a capacitor depends upon the size and shape of the plates. It also depends upon the separation and the nature of insulating material in-between the plates.

Units of Capacitance: The SI unit of capacitance is coulombs per volt or the farad (F), named in honor of Michael Faraday, such that

$$1 \text{ F} = 1 \text{ C/V}$$

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FIGURE 13.15

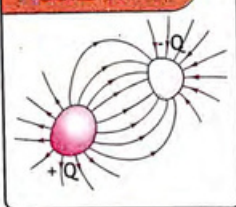
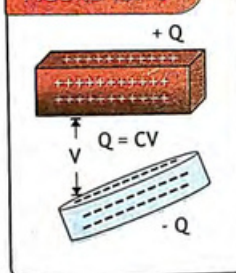


FIGURE 13.16



The farad is a very large unit of capacitance. In practice, typical devices have capacitances ranging from microfarads (10^{-6} F) to picofarads (10^{-12} F). For practical purposes, capacitors often are labeled " μF " for microfarads and " pF " for picofarads.

Capacitors can be charged by applying a potential difference across its plates by using a battery. A charging of parallel plate capacitor by using a battery, as shown in Fig. 13.17.

Note that if we double the voltage, we would not do anything to the capacitance. Instead, we would double the charge stored on the capacitor. However, if we try to overfill the capacitor by placing too much voltage across it, the electric field between the plates will become so strong that dielectric breakdown will occur causing current to spark between the plates, destroying the capacitor. Thus capacitors have a maximum voltage!

FIGURE 13.17



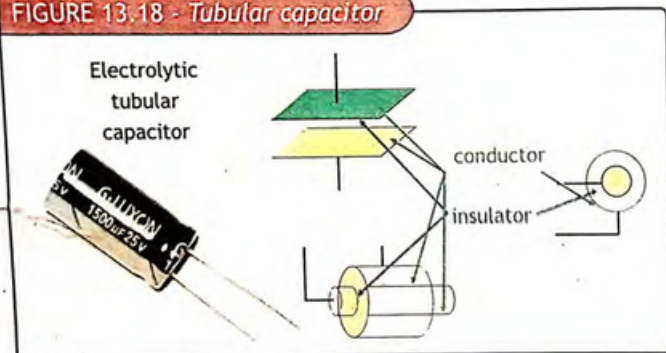
13.10 TYPES OF CAPACITORS

There are different types of capacitors. These capacitors are of various sizes and shapes, depending upon their construction and dielectric used between them; each one has its own set of characteristics and applications. These capacitors may have fixed or variable capacitance values.

Electrolytic tubular capacitor is the most popular for values greater than about 1 microfarad, having one of the highest levels of capacitance for a given volume. This type of capacitor is constructed by using two thin foils of aluminum, with leads for proper polarity connection. An electrolyte-soaked paper sheet is placed between them and the two plates are wound around on one another and placed in a can with emerging leads ready to use as shown in figure 13.18.

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FIGURE 13.18 - Tubular capacitor



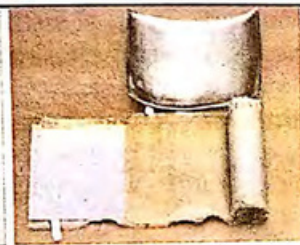
ACTIVITY

INSIDE A CAPACITOR

Tubular capacitors that are not in use can be torn apart to look how it is made from inside. They are metals foils wrapped in a tubular shaped cylinder separated by paper acting as insulating material between the conductors as dielectric.



A disassembled capacitor, showing the foil conducting plates and the thin sheet of insulating material.



The metal foil and Mylar sandwich shown can be rolled up with an insulating layer to produce a capacitor with a compact geometry.

EXAMPLE 13.4: CAPACITOR OF MP3 PLAYER

A typical capacitor in an MP3 player has $C = 0.10 \mu\text{F}$. If a charge $5.0 \mu\text{C}$ is placed on the plates, what is the voltage across the capacitor?

GIVEN

Charge $q = 5 \mu\text{C} = 5 \times 10^{-6} \text{C}$.

Capacitance ' C ' = $0.10 \mu\text{F} = 0.10 \times 10^{-6} \text{F}$

REQUIRED

Voltage ' V ' = ?

SOLUTION: The capacitance of capacitor is

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

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or $V = \frac{Q}{C}$ Putting values $V = \frac{5 \times 10^{-6} \text{C}}{0.10 \times 10^{-6} \text{F}}$

or $V = \frac{5 \times 10^{-6} \cancel{\text{C}}}{0.10 \times 10^{-6} \cancel{\text{C/V}}}$ Hence $V = 50 \text{ V}$ — **Answer**

Therefore, the voltage across the capacitor in Mp3 player is 50 V.

ASSIGNMENT 13.4: CAPACITANCE

The potential difference across the plates of the capacitor is 500 V. The charge on each plate is 0.02 C. What is the capacitance of the capacitor?

HEART DEFIBRILLATOR



During a heart attack, the heart produces a rapid, unregulated pattern of beats, a condition known as cardiac fibrillation. Cardiac fibrillation can often be stopped by sending a very fast discharge of electrical energy through the heart. For this purpose, emergency medical personnel use defibrillators, such as the one being used in Figure. A paddle is connected to each plate of a large capacitor, and the paddles are placed on the chest near the heart. The capacitor is charged to a potential difference of about a thousand volts. The capacitor is then discharged in a few thousandths of a second; the discharge current passes through a paddle, the heart, and the other paddle. Within a few seconds, the heart often returns to its normal beating pattern.

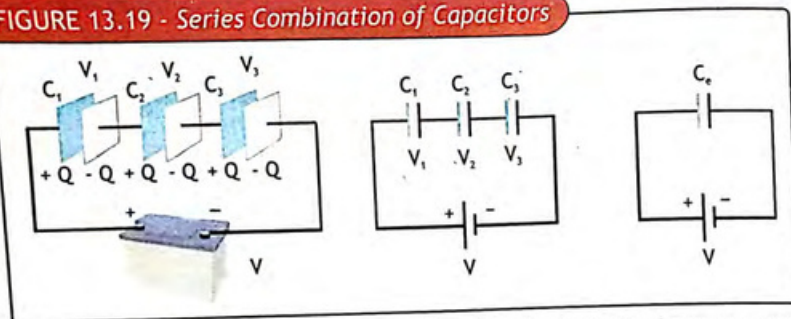
13.11 COMBINATION OF CAPACITORS

In practice, two or more capacitors are sometimes joined together. In studying electric circuits, we use a simplified pictorial representation called a circuit diagram. Such a diagram uses circuit symbols to represent various circuit elements. The circuit symbols are connected by straight lines that represent the wires between the circuit elements. The circuit symbol for capacitor is ' $||$ '.

A. Series Combination of Capacitors: When the capacitors are connected plate to plate then they are said to be connected in series, three capacitors having capacitance C_1 , C_2 and C_3 are shown in the figure 13.19 as series combination.

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FIGURE 13.19 - Series Combination of Capacitors



When battery is connected to a series combination of capacitors, the same current flows through each capacitor which means charge of $+Q$ is placed on the left plate of each capacitor and an equal charge of $-Q$ on the right plate of each capacitor. As a result each capacitor gets an equal amount of charge Q on each of its plates.

$$Q_1 = Q_2 = Q_3 = Q \quad \text{--- (1)}$$

When the three capacitors in the circuit are charged, the sum of the potential drops across all three must equal the potential difference supplied by the battery.

$$V = V_1 + V_2 + V_3 \quad \text{--- (2)}$$

Since the capacitance of capacitor is $C = \frac{Q}{V}$ or $V = \frac{Q}{C}$

Therefore, each voltage can be written as

$$V_1 = \frac{Q_1}{C_1} \quad \text{and} \quad V_2 = \frac{Q_2}{C_2} \quad \text{and} \quad V_3 = \frac{Q_3}{C_3} \quad \text{and} \quad V = \frac{Q}{C_e}$$

Where C_e is the equivalent capacitance of a single capacitor that has the same effect on the circuit as the series combination when it is connected to the battery. Hence equation 2 can be written as

$$\frac{Q}{C_e} = \frac{Q_1}{C_1} + \frac{Q_2}{C_2} + \frac{Q_3}{C_3} \quad \text{--- (3)}$$

From equation 1 in equation 3 can be written as $\frac{Q}{C_e} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$

$$\text{or} \quad \frac{Q}{C_e} = Q \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right)$$

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Hence $\frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad \text{--- 13.7}$

Generally for 'n' number of capacitors connected in series

$$\frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots + \frac{1}{C_n} \quad \text{--- 13.8}$$

From equation 13.7 and equation 13.8 it is clear that in series combination, the equivalent capacitance is always smaller than any individual capacitance in combination.

EXAMPLE 13.5: SERIES COMBINATION OF CAPACITORS

Two capacitors of $5 \mu\text{F}$ and $10 \mu\text{F}$ are connected in series with the external source of voltage is 100 V . Calculate the total capacitance and the potential drop across each capacitor.

GIVEN:

Capacitor $C_1 = 5 \mu\text{F} = 5 \times 10^{-6} \text{ F}$

Capacitor $C_2 = 10 \mu\text{F} = 10 \times 10^{-6} \text{ F}$

Voltage $V = 100 \text{ V}$

WANTED:

Equivalent capacitance $C_{eq} = ?$

Potential drops V_1 and $V_2 = ?$

SOLUTION: For Series Combination the equivalent capacitance is

$$\frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{or} \quad \frac{1}{C_e} = \frac{C_2 + C_1}{C_1 C_2}$$

$$\text{or} \quad C_e = \frac{C_1 C_2}{C_2 + C_1} \quad \text{Putting values} \quad C_e = \frac{5 \times 10^{-6} \text{ F} \times 10 \times 10^{-6} \text{ F}}{5 \times 10^{-6} \text{ F} + 10 \times 10^{-6} \text{ F}}$$

$$\text{or} \quad C_e = \frac{50 \times 10^{-12} \text{ F}^2}{15 \times 10^{-6} \text{ F}}$$

$$C_e = 3.33 \times 10^{-6} \text{ F} = 3.33 \mu\text{F} \quad \text{--- Answer}$$

In series combination, the charge remains the same $q_1 = q_2 = Q$

The charge on each capacitor is $Q = C_e V$

$$\text{Putting values} \quad Q = 3.33 \times 10^{-6} \text{ F} \times 100 \text{ V}$$

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Hence $Q = 3.33 \times 10^{-4} \text{ C}$

Therefore $q_1 = q_2 = Q = 3.33 \times 10^{-4} \text{ C}$

However, series combination of circuit elements the voltage splits, the voltage across capacitor C_1 and capacitor C_2 as V_1 and V_2 , respectively

$$V_1 = \frac{Q}{C_1} \quad \text{Putting values} \quad V_1 = \frac{3.33 \times 10^{-4} \text{ C}}{5 \times 10^{-6} \text{ F}}$$

$$V_1 = 0.666 \times 10^2 \text{ V} = 66.6 \text{ V} \quad \text{Answer}$$

$$V_2 = \frac{Q}{C_2} \quad \text{Putting values} \quad V_2 = \frac{3.33 \times 10^{-4} \text{ C}}{10 \times 10^{-6} \text{ F}}$$

$$V_2 = 0.333 \times 10^2 \text{ V} = 33.3 \text{ V} \quad \text{Answer}$$

Note that $V_1 + V_2 = 66.6 + 33.3 = 100 = V$, that is the battery voltage is split between the two capacitors.

ASSIGNMENT 13.5: SERIES COMBINATION OF CAPACITORS

Two capacitors of capacitance $3 \mu\text{F}$ and $6 \mu\text{F}$ are connected in series to a 100 V battery. Calculate the equivalent capacitance and the voltage across each capacitor.

B. Parallel Combination of capacitors: When the capacitors are connected in different branches of the circuit, the capacitors are said to be connected in parallel. Three capacitors having capacitance C_1 , C_2 and C_3 are shown in the figure 13.20 as parallel combination.

In this configuration, the potential applied across each capacitor is same and is equal to the applied potential.

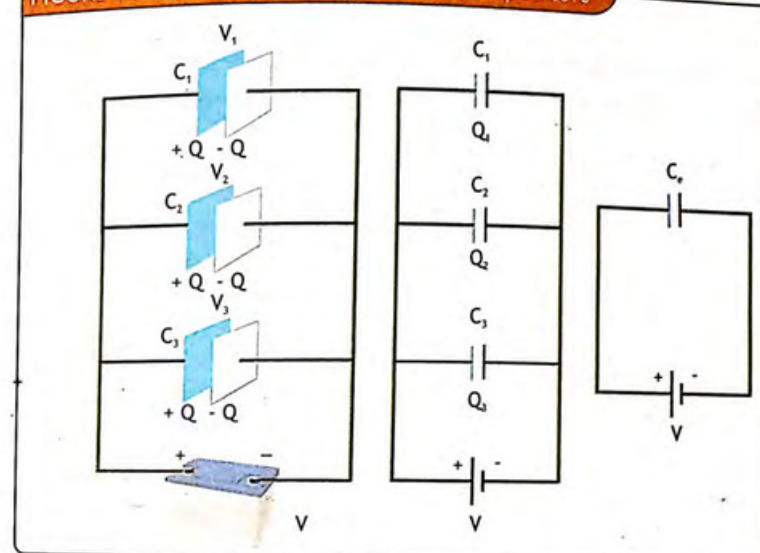
$$V_1 = V_2 = V_3 = V \quad \text{--- (1)}$$

Depending upon the capacitance, the capacitors acquire different amount of charges. Conservation of charge requires that the charge Q of the equivalent capacitor be equal to the sum of the charges on the individual capacitors. Such that the total charge is the sum of all the individual charges.

$$Q = Q_1 + Q_2 + Q_3 \quad \text{--- (2)}$$

NOT FOR SALE

FIGURE 13.20 - Parallel Combination of Capacitors



Since the capacitance of capacitor is

$$C = \frac{Q}{V} \quad \text{or} \quad Q = CV$$

Therefore, each charge can be written as

$$Q_1 = C_1 V_1 \quad \text{and} \quad Q_2 = C_2 V_2 \quad \text{and} \quad Q_3 = C_3 V_3 \quad \text{and} \quad Q = C_e V$$

Where C_e is the equivalent capacitance of a single capacitor that has the same effect on the circuit as the series combination when it is connected to the battery.

Hence equation 2 can be written as $C_e V = C_1 V_1 + C_2 V_2 + C_3 V_3 \quad \text{--- (3)}$

Putting equation 1 in equation 3 we get $C_e V = C_1 V + C_2 V + C_3 V$

$$\text{or} \quad C_e V = V(C_1 + C_2 + C_3)$$

Therefore $C_e = C_1 + C_2 + C_3 \quad \text{--- 13.9}$

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Generally for 'n' number of capacitors connected in parallel

$$C_e = C_1 + C_2 + C_3 + \dots + C_n$$

13.10

From equation 13.9 and equation 13.10 it is clear that in parallel combination the equivalent capacitance is always greater than any individual capacitance in combination.

EXAMPLE 13.6: PARALLEL COMBINATION OF CAPACITORS

Two capacitors of $4 \mu\text{F}$ and $8 \mu\text{F}$ are in parallel. In each case the external source of voltage is 100 V . Calculate the total capacitance and the charge on each capacitor.

GIVEN:

Capacitor $C_1 = 4 \mu\text{F} = 4 \times 10^{-6} \text{ F}$

Capacitor $C_2 = 8 \mu\text{F} = 8 \times 10^{-6} \text{ F}$

Voltage $V = 100 \text{ V}$

WANTED:

Equivalent capacitance $C_{eq} = ?$

Charge Q_1 and $Q_2 = ?$

SOLUTION: For Parallel Combination, the equivalent capacitance is

$$C_e = C_1 + C_2$$

Putting values $C_e = 4 \times 10^{-6} \text{ F} + 8 \times 10^{-6} \text{ F}$

Therefore $C_e = 12 \times 10^{-6} \text{ F} = 12 \mu\text{F}$

Answer

In parallel combination the voltage remains the same $V_1 = V_2 = V$

Since the applied voltage $V = 100 \text{ V}$, therefore $V_1 = V_2 = V = 100 \text{ V}$

In parallel combination the charge splits, the charge stored in first capacitor C_1 is

$q_1 = C_1 V$ Putting values $q_1 = 4 \times 10^{-6} \text{ C} \times 100 \text{ V}$

$q_1 = 400 \times 10^{-6} \text{ C} = 400 \mu\text{C}$

Answer

In parallel combination the charge splits, the charge stored in second capacitor C_2 is

$q_2 = C_2 V$ Putting values $q_2 = 8 \times 10^{-6} \text{ C} \times 100 \text{ V}$

$q_2 = 800 \times 10^{-6} \text{ C} = 800 \mu\text{C}$

Answer

NOT FOR SALE

ASSIGNMENT 13.6: PARALLEL COMBINATION OF CAPACITORS

Two capacitors of capacitance $3 \mu\text{F}$ and $6 \mu\text{F}$ are connected in parallel to a 800 V battery. Find the equivalent capacitance and charge on each capacitor.

Electrostatics: The study of charges at rest.

Electrostatic Induction: The process of charging without physical contact.

Electroscope: Instrument used for the detection and testing of electric charge.

Coulomb's Law: The electric force between two stationary point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

Electric field: The region around a charge where another charge will experience an electrostatic force.

Electric field intensity: The strength of the field at any point, given as the force per unit positive test charge.

Electric field lines: Representative lines for the electric field intensity.

Electric potential: The electric potential energy per unit charge in an electric field.

Capacitor: The device used for storing electrical energy.

Series combination of capacitors: The combination of capacitors connected plate to plate.

Parallel combination of capacitors: The combination of capacitors connected in different branches of circuit.

GROUP A 'AIRCRAFT ENGINEERING': Research why aircrafts are always positively charged when flying. This is seen when an aircraft lands during dry conditions, huge sparks are released to Earth as soon as the aircraft touches down. What problems are faced by air craft engineers and what remedial measurements are taken. Prepare a presentation to share your research with class fellows.

GROUP B 'PETROL STATION': Research why there are warning signs in petrol pumps such as 'turn off your vehicle' or 'do not use your cell phone'. What are the chances of petrol being ignited? Prepare a chart to display the hazards of static electricity at petrol station.

GROUP C 'UNIT NAME AFTER SCIENTISTS': Choose the name of an electric unit, such as coulomb, volt, or farad and research the life and work of the scientist after whom it was named.

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Write a brief essay for school magazine on this person and include a discussion of the work that justified the honor of having a unit named after him.

GROUP D 'REFUELING OIL TANKERS AND AIRCRAFTS': When refueling oil tankers or aircrafts the fuel rubbing along the pipe as it flows through it can cause an electrostatic charge, if this sparks. It could ignite the fuel causing a fire or explosion. What preventive measures can be taken to reduce the risks of fire explosion? Prepare a chart to display in the classroom.

GROUP E 'ELECTROSCOPE': Make your own electroscope of simple objects and donate it to the school laboratory.

EXERCISE

- MULTIPLE CHOICE QUESTIONS**
- When combing our hair, we shift electrons from our hair onto the comb. The charge on our hairs is
A. positive B. negative C. zero D. infinite
 - The unit of charge is
A. farad B. coulomb C. volt D. electron volt
 - Initially, sphere A has a charge of $-50e$ and sphere B has a charge of $+20e$. The spheres are made of conducting material and are identical in size. If the spheres then touch, what is the resulting charge on sphere A?
A. $+15e$ B. $-15e$ C. $+35e$ D. $-35e$
 - If the distance between two charged particles is halved, the Coulomb force between the two charged particles becomes
A. half B. one quarter C. double D. four times
 - The value of coulomb constant k , depends on
A. value of charges B. material medium
C. separation between charges D. all of these
 - An additional capacitor is added to a group of capacitors already connected in series, the equivalent capacitance
A. increase B. stay the same C. decrease D. goes to zero
 - The unit of electric potential is
A. farad B. coulomb C. volt D. NC^{-1}

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- Four identical $1\ \mu F$ capacitors are connected together electrically. What is the least possible capacitance of the combination?
A. $4\ \mu F$ B. $1\ \mu F$ C. $1/4\ \mu F$ D. $1/8\ \mu F$
- A capacitor C 'has a charge Q'. The actual charges on its plates are:
A. Q, Q B. Q, 0 C. Q, -Q D. $Q/2$, $-Q/2$

CONCEPTUAL QUESTIONS

Give a brief response to the following questions

- Normally, objects with large number of electrons are electrically neutral. Why?
- How does shuffling feet across a carpet cause hair to stand on our body?
- Why neutral objects are always attracted by charged object? Not repelled.
- Why the pieces of paper initially attracted by charged comb fly away when they touch it?
- Is it necessary for a charged body actually to touch the ball of the electroscope for the leaves to diverge? Defend your answer.
- How electrostatic painting is better than conventional spray painting?
- Why are lightning rods normally at a higher elevation than the buildings they protect?
- What would happen if two insulating plates were used instead of conducting plates to construct a capacitor?
- The sum of the charges on both plates of a capacitor is zero. What does a capacitor store?
- If you wish to store a large amount of energy in a capacitor bank, would you connect capacitors in series or parallel? Explain.

COMPREHENSIVE QUESTIONS

Give an extended response to the following questions

- What is electric charge? How objects can be electrified? Describe with the help of experiments.
- What is electrostatic induction? Explain.
- What is the function of electroscope? How can we use electroscope to find the presence and nature of charge on a body?

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