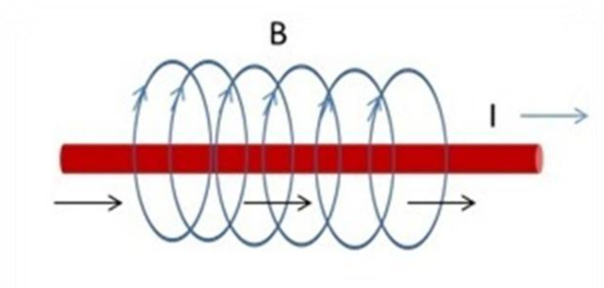
Class 12 Physics Electric Charges Fields Notes

<u>Electric Charge</u>

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

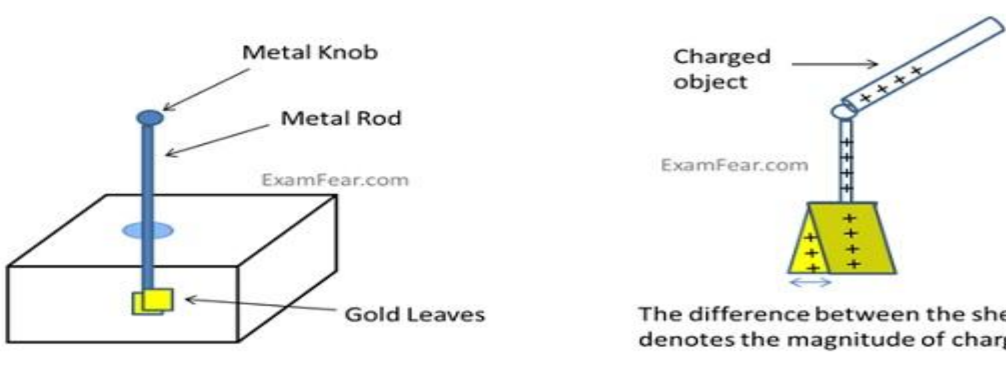


Current flowing through a conductor creates a magnetic field around it.

- **Electromagnetism is the phenomenon of the interaction of electric currents or fields and magnetic fields.**
- **When insulating surfaces are rubbed against each other, a static charge is developed which gets discharged after getting in contact with a conductor.**
- **Only one of the two charges(or polarity) gets developed on rubbing – either positive or negative. An object becomes positively charged when it loses the loosely bound electrons to another object while rubbing. The other object gains electrons and becomes negatively charged.**
- **When like charges are brought near, they repel each other. Unlike charges attract each other.**
- **The charges get neutralized when the two bodies are brought in contact.**
- **An example of electric charge generation through rubbing of glass rod with silk and plastic rod with silk is mentioned below:**

Two glass rods rubbed with silk get electrified with charges of same polarity. They repel as they have like charges.

One glass rod and one plastic rod rubbed with silk get electrified with different polarity. Hence they attract.



The difference between the sheets denotes the magnitude of charge

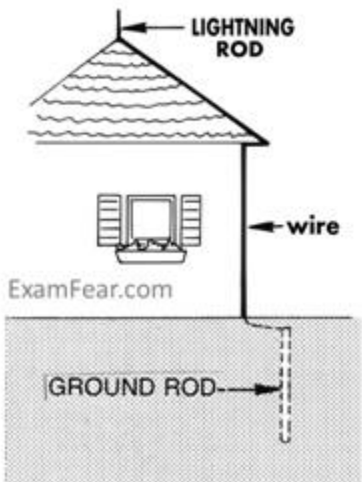
Gold-Leaf Electrscope – when charged object touch the metal rod, the connected gold leaves get separated (repulsion).

<u>Conductors and Insulators</u>

Criteria	**Conductors**	**Insulators**
Definition	**Substances which**	**Substances which**

	allow electricity to pass through them are called conductors.	do not allow electricity to pass through them are called insulators.
Electron Movement	Free movement	None or very low
Charge transfer	Charge gets distributed over whole body once it is transferred to a conductor.	Charge stays at one place when transferred to an insulator.
Examples	Human body, Metals, water	Plastic, wood, glass

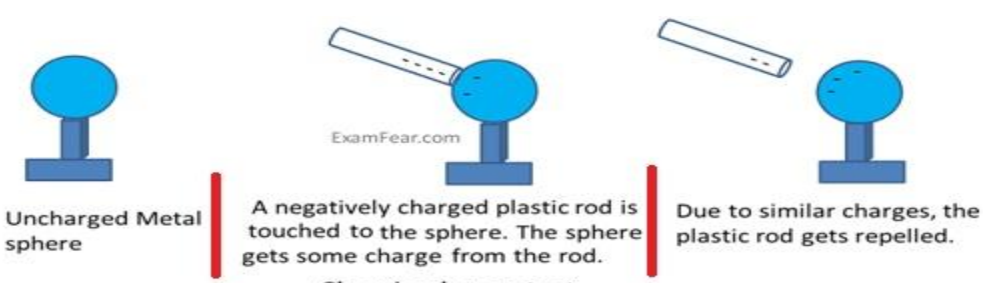
- **Semiconductors offer resistance to movement of charges which is between conductors and non-conductors.**
- **The process where excess charge from a body or object goes to ground, by touching the charge carrying conducting body to earth is called earthing or grounding.**



Application of grounding. A protective lightning rod placed over the house attracts and directs the lighting to the ground.

<u>Charging by Contact</u>

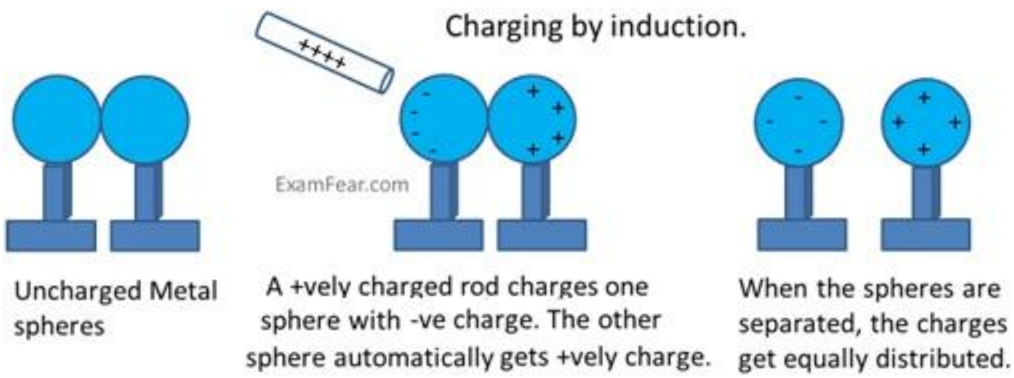
When a charged object is touched to another object, the other object also gets charged with same polarity due to charge transfer. This is called charge by contact.



Charging by contact

Charging by Induction

When a charged object is brought closer to another object (not touched), the original object doesn't lose any charge and the other object gets charged as well with opposite polarity. The other extreme end of the newly charged object develops polarity same as that of the charged object. This type of charging is called charge by induction.



Properties of electric charge

Electric charge for a body is considered as Point charges if their size is very small in comparison to the distance between them. So the charge is considered to be concentrated at one point. Following are the properties of electric charge in terms of point charges:

1. **Additivity of charges:**
   - **Point charges are scalars and can be added algebraically. If q_1, q_2, q_3, … q_n, are point charges, the total charge q_{tot}=q_1+ q_2 + q_3+ q_n**
   - **Charges have no direction but can be positive or negative.**
2. **Conservation of charges:**
   - **Total charge in an isolated system is always conserved. When there are many bodies in an isolated system, the charges get transferred from one body to another but the net charge of the system remains same.**
   - **During rubbing or natural forces, no new charge is created. The charges are either redistributed or a neutron breaks up into proton and electron of equal and opposite charge.**
3. **Quantization of charges:**
   - **The charge is always represented in the form of, q = ne. Here n is an integer and e is the charge (- for electron and + for proton). Magnitude of e = 1.602192 X 10^{-19} This is called quantization of charge.**
   - **SI unit of charge is Coulomb (C).**
   - **Quantization is usually ignored at macroscopic levels (µC) because at that point, charges are taken to be continuous.**

Example ExamFear.com

When a polythene piece is rubbed with wool, a negative charge is developed in polythene. Hence, polythene becomes negatively charged and wool becomes positively charged. If after rubbing the charge found on wool is 3 x 10^{-7}C,

1. The **number of electrons transferred** can be calculated using q = ne
   n = q/e = -3 x 10^{-7}/-1.6 x 10^{-19} = **1.87 x 10^{12}**
2. There will also be transfer of mass as the electrons transferred have some mass.
   1 electron has mass = 9.1 x 10^{-3} kg.
   Total mass transferred = 9.1 x 10^{-3} x 1.87 x 10^{12} = **1.706 x 10^{-18} kg**

Coulomb's Law

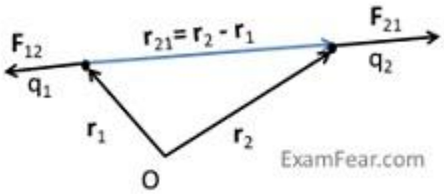
Coulomb's law states that Force exerted between two point charges:

- **Is inversely proportional to square of the distance between these charges and**
- **Is directly proportional to product of magnitude of the two charges**
- **Acts along the line joining the two point charges.**

$$F = k\frac{|q_1 q_2|}{r^2} \text{ where } k = \frac{1}{4\pi\varepsilon_0}$$

$$\text{So, } F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$$

Here $\varepsilon_0 = 8.854 \times 10^{-12}\ C^2\ N^{-1}\ m^{-2}$ is called permittivityof free space.



As per coulombs law,

$$\mathbf{F}_{21} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{21}^2}\hat{\mathbf{r}}_{21}$$

- This is valid for any sign of charges q_1 and q_2
- $\mathbf{F}_{12} = -\mathbf{F}_{21}$
- These forces are considered in vacuum.

Vector representation of the Coulombs law

Example ExamFear.com

When the electrostatic force on a sphere having charge 0.4 µC by another sphere of charge -0.8 µC is 0.2N, the distance between the two spheres can be calculated using the Coulomb's law:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$$

$F = 9 \times 10^9 \times 0.4 \times 10^{-6} \times 0.8 \times 10^{-6} / r^2$

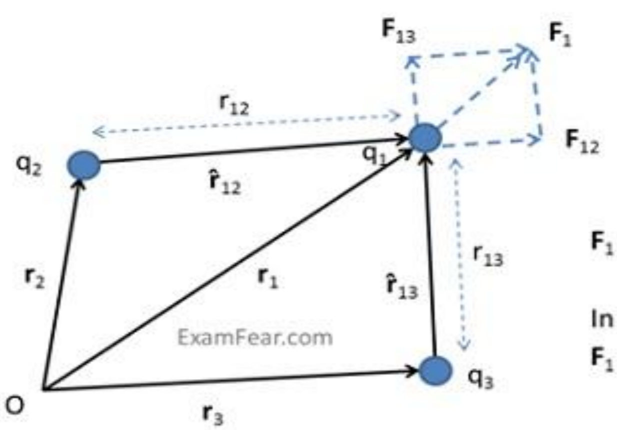
$r^2 = 144 \times 10^{-4}$

r = 0.12 m

Also, since $F_{12} = -F_{21}$, both spheres will attract each other with same force in opposite directions.

<u>Forces between multiple charges –Superposition principle</u>

As per the principle of superposition, the force on any charge due to a number of other charges is the vector sum of all the forces on that charge due to other charges, taken one at a time.



$$\mathbf{F}_{12} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}^2}\hat{\mathbf{r}}_{12}$$

$$\mathbf{F}_{13} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_3}{r_{13}^2}\hat{\mathbf{r}}_{13}$$

$$\mathbf{F}_1 = \mathbf{F}_{12} + \mathbf{F}_{13} = \frac{1}{4\pi\varepsilon_0}\left[\frac{q_1 q_2}{r_{12}^2}\hat{\mathbf{r}}_{12} + \frac{q_1 q_3}{r_{13}^2}\hat{\mathbf{r}}_{13}\right]$$

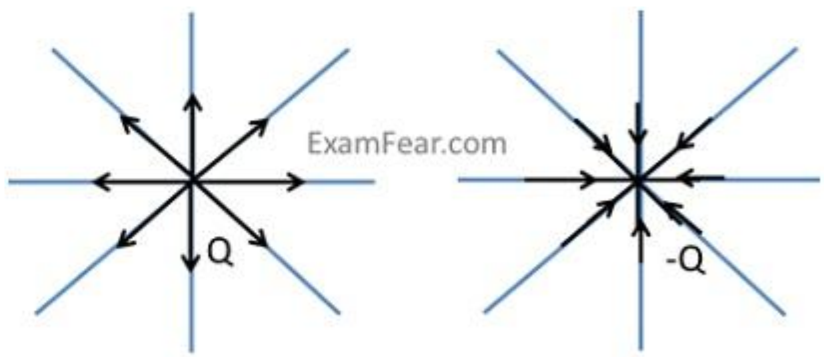
In case of n charges,

$$\mathbf{F}_1 = \mathbf{F}_{12} + \mathbf{F}_{13} + \dots + \mathbf{F}_{1n} = \frac{q_1}{4\pi\varepsilon_0}\sum_{i=2}^{n}\frac{q_i}{r_{1i}^2}\hat{\mathbf{r}}_{1i}$$

System of 3 charges. The equations of forces is calculated for n charges also.

Electric Field

Electric field is a force produced by a charge near its surroundings. This force is exerted on other charges when brought in the vicinity of this field.



$$E(r) = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}\hat{r}$$

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}\hat{r}$$

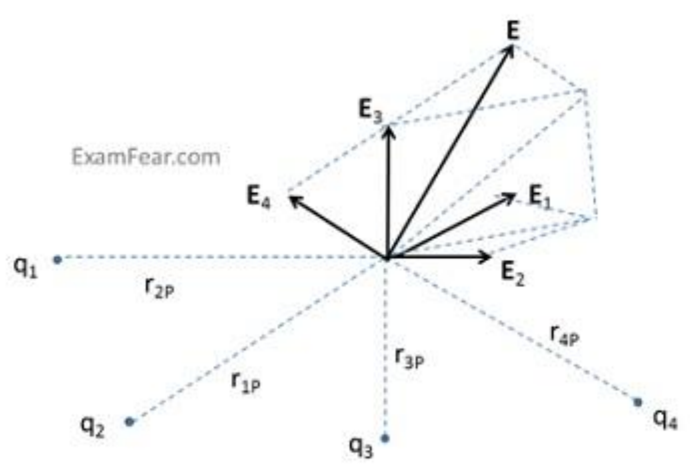
$$F(r) = q\,E(r)$$

Electric field due to charge Q and -Q

- **SI unit of electric field is N/C (Force/Charge).**
- **Electric field due to a charge at a point is the force that a unit positive charge would experience if placed at that point.**
- **The charge generating electric field is called source charge and the charge which experiences this field is called test charge. Practically, to keep source charge undisturbed due to the electric field of test charge, the test charge is kept infinitely small.**
- **Since F(Force) is proportional to q (Charge), the electric field is independent of q but depends on r (space coordinates).**
- **The electric field is symmetric in spherical coordinates.**
- **The concept of Electric field is used to account for the time delay for a charged body to experience force from the field of a source charge.**

Electric field due to system of charges

According to the superposition principle, the total electric field at a point in space is equal to the vector sum of individual fields present.



$$E_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r_{1P}{}^2}\hat{r}_{1P}$$

$$E_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{r_{2P}{}^2}\hat{r}_{2P}$$

Since $E(r) = E_1 + E_2 + E_3 + \ldots + E_n$

$$E(r) = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{q_i}{r_{iP}{}^2}\hat{r}_{iP}$$

Total field is vector sum of individual charges

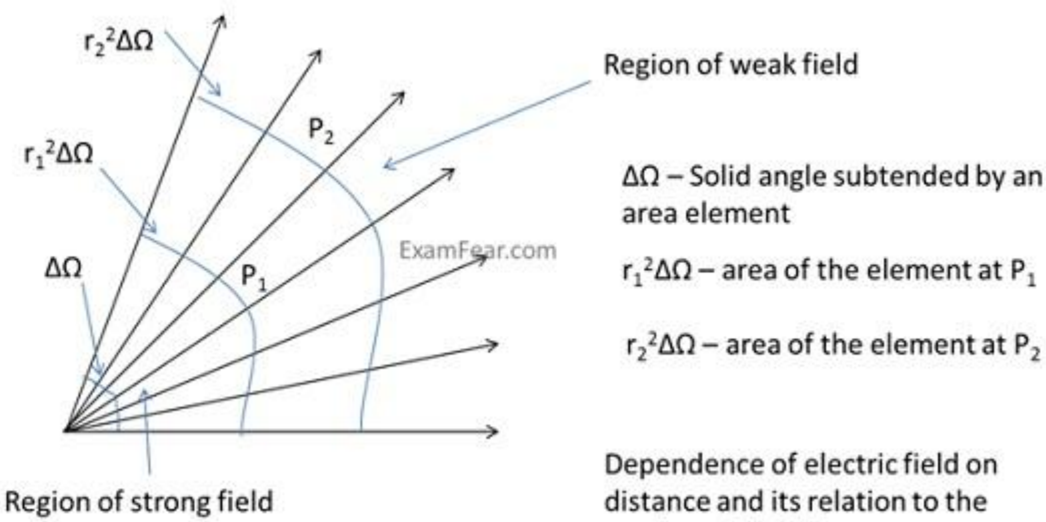
Electric field at a point due to system of charges

Electric Field Lines

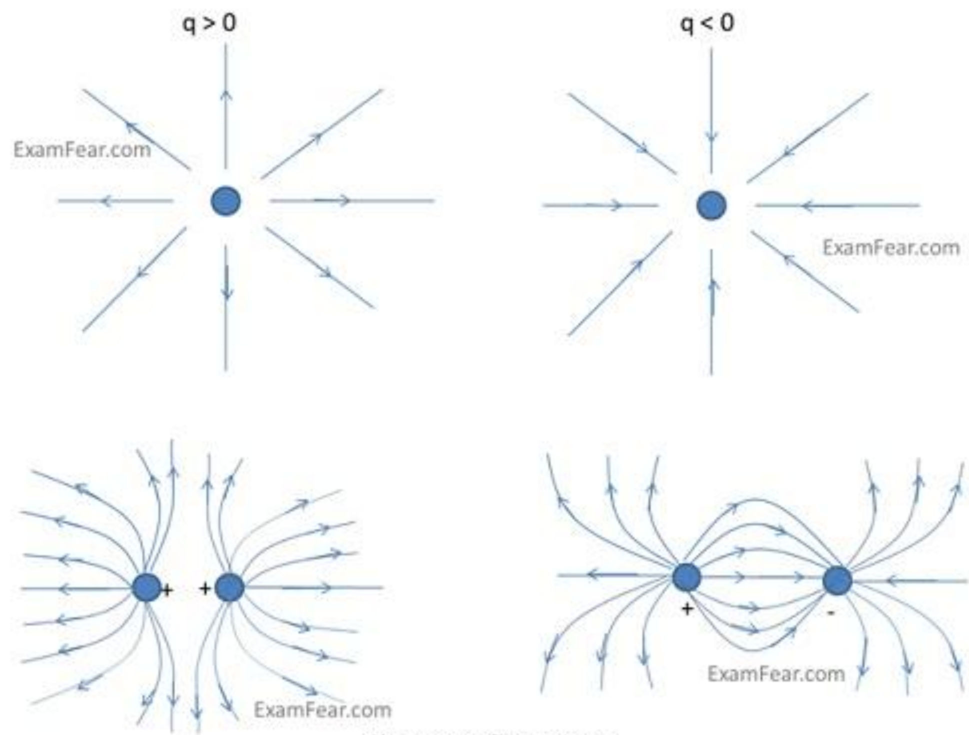
Electric field lines are a pictorial way of representing electric field around a configuration of charges.

- **An electric field line is a curve drawn in such a way that the tangent to it at each point is in direction of the net field at that point.**

- **Electric field is inversely proportional to the square of the distance; hence electric field near the charge is high and keeps on decreasing as we go farther from the charge. The electric field lines, however, remain constant but are very far apart (at higher distances) as compared to lesser distance.**



Dependence of electric field on distance and its relation to the number of field lines



Charge configurations

Electric Flux

Electric flux is the measure of flow of the electric field through a given area. Electric flux is proportional to the number of electric field lines going through a normally perpendicular surface.

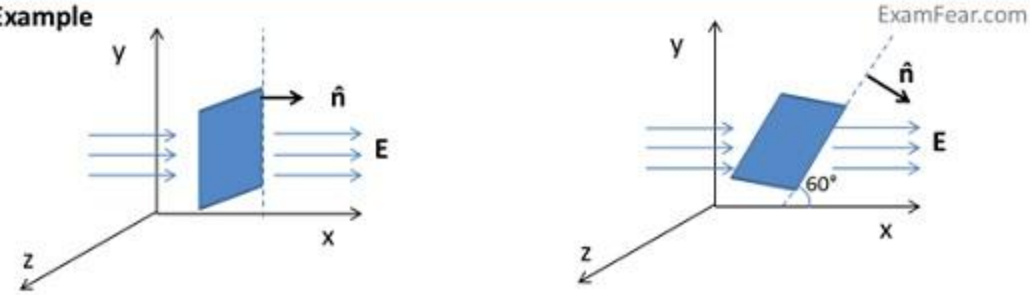
Number of field lines crossing area element when the area element is kept perpendicular will be E ΔS.

Number of field lines crossing area element when the area element is kept at an angle θ will be E ΔS cos θ.

Electric Flux

- The orientation of area element decides the amount of electric flux. Thus, the area element is a vector.
- The vector associated with every area element of a closed surface is taken to be in the direction of the outward normal.
- **Area element vector ΔS = ΔSn̂, ΔS is magnitude of area element and n̂ is unit vectorin the direction of outward normal.**
- **Electric flux, Δϕ = EΔS = E ΔScosθ, θ is angle between E and ΔS.**
- **Unit of electric flux is $NC^{-1}m^2$.**
- **Total flux through a surface, ϕ ≈ Σ EΔS**

Example



For a uniform electric field **E** = 3 x 10^3 î N/C, the flux through a square sheet of 10 cm side parallel to y-z plane will be:

ϕ = |**E**|A cosθ

ϕ = 3 x 10^3 x (10^{-1}x10^{-1}) x cos 0

ϕ = 30 Nm^2/C

When the plane makes an angle of 60° with x-axis, the flux will be:

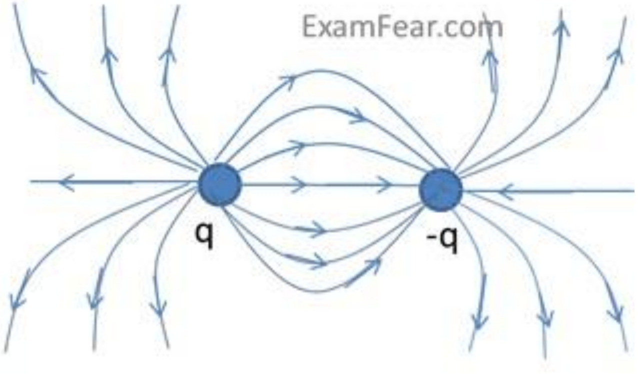
ϕ = 3 x 10^3 x (10^{-1}x10^{-1}) x cos 60

ϕ = 15 Nm^2/C

Electric Dipole

An electric dipole is a pair of equal and opposite point charges q and –q, separated by a distance of 2a.

- **Direction from –q to q is the direction of the dipole.**
- **The mid-point of locations of –q and q is called the center of the dipole.**
- **Total charge of an electric dipole is zero but since the charges are separated by some distance the electric field do not cancel out.**
- **Dipole moment is the mathematical product of the separation of the ends of a dipole and the magnitude of the charges (2a x q).**
- **Some molecules like H_2O, have permanent dipole moment as their charges do not coincide. These molecules are called polar molecules.**
- **Permanent dipoles have a dipole moment irrespective of any external Electric field.**

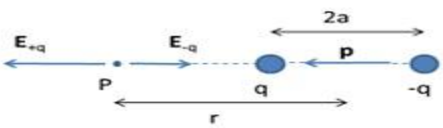


An electric Dipole

Electric field of an electric dipole

Electric field of an electric dipole at a point in space depends upon the position of the point.

- **The dipole field at a point is inversely proportional to the cube of distance from the center to the point.**
- **For a very small dipole, the 2a approaches zero. This is called point dipole.**

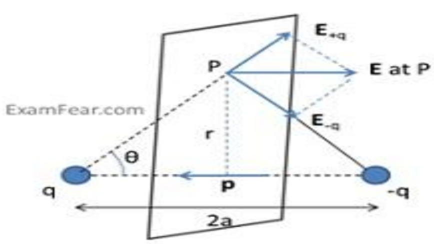


Electric field of a dipole at a point on the axis

$E_{-q} = -\frac{q}{4\pi\varepsilon_0(r+a)^2}\hat{\mathbf{p}}$ $\quad E_{+q} = \frac{q}{4\pi\varepsilon_0(r-a)^2}\hat{\mathbf{p}}$

Total field at P, $\mathbf{E} = \mathbf{E}_{+q} + \mathbf{E}_{-q} = \frac{q\,4ar}{4\pi\varepsilon_0(r^2-a^2)^2}\hat{\mathbf{p}}$

For r >> a, $\mathbf{E} = \frac{4qa}{4\pi\varepsilon_0(r^3)}\hat{\mathbf{p}} = \frac{2p}{4\pi\varepsilon_0(r^3)}$



Electric field of a dipole at a point on the equatorial plane of the dipole

$E_{-q} = E_{+q} = \frac{q}{4\pi\varepsilon_0(r^2+a^2)}$

Total field at P, $\mathbf{E} = -(\mathbf{E}_{+q} + \mathbf{E}_{-q})\cos\theta\,\hat{\mathbf{p}}$

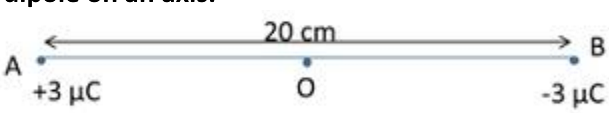
$\mathbf{E} = -\frac{2qa}{4\pi\varepsilon_0(r^2+a^2)^{3/2}}\hat{\mathbf{p}}$

For r >> a, $\mathbf{E} = -\frac{2qa}{4\pi\varepsilon_0(r^3)}\hat{\mathbf{p}} = -\frac{p}{4\pi\varepsilon_0(r^3)}$

p – dipole moment vector with magnitude q x 2a and directed from –q to q.

Example:

To calculate electric field at mid point of line joining two charges 3 & -3 μC, which are 20 cm apart, we can use the formla for electric field of a dipole on an axis.



$E_1 = \frac{q}{4\pi\varepsilon_0(r+a)^2}$ and $E_2 = -\frac{q}{4\pi\varepsilon_0(r-a)^2}$

$E = E_1 + E_2 = \frac{2q}{4\pi\varepsilon_0(a)^2}$, Since the magnitudes are equal and r = 0

$E = 2 \times 9 \times 10^9 \times 3 \times 10^{-6} / (10\times10^{-2})^2$

$E = 5.4 \times 10^6$ N/C

The direction will be along OB.

If a negative test charge of 1.5×10^{-9} C is placed at O, the force experienced by the charge will be, F = qE.

$F = 1.5 \times 10^{-9} \times 5.4 \times 10^6$

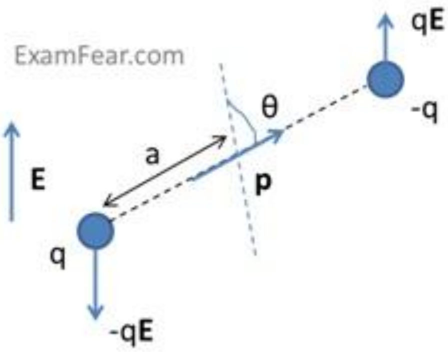
$F = 8.1 \times 10^{-3}$ N

The direction will be along OA because negative charge will be repelled by charge at point B but attracted by charge at point A.

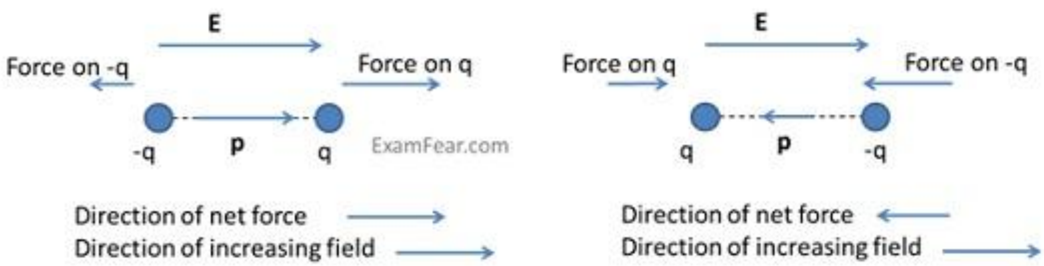
Dipole in a uniform electric field

When two charges in a dipole are separated by some distance, the forces acting at different points result in torque on the dipole.• The torque tries to align the dipole with electric field. Once aligned, the torque becomes 0.

- **Magnitude of torque = qE x 2a sinθ = 2qaE sinθ = pEsinθ.**
- **Direction of the torque= normal to the plane coming outwards.**



Permanent Dipole in a uniform electric field



Electric force on a dipole in parallel and antiparallel electric field.

Example ExamFear.com

If an electric dipole with dipole moment 4×10^{-19} Cm is aligned at 30° with the direction of uniform electric field of magnitude 5×10^{4} N C^{-1}, the torque acting on the dipole can be calculated using:

$$\tau = \rho E \sin\theta$$

$\tau = 4 \times 10^{-9} \times 5 \times 10^{4} \times \sin 30$
$\tau = 20 \times 10^{-5} \times 1/2$
$\tau = 10^{-5}$ Nm

Continuous Charge Distribution

Type of charge distribution	Denoted by	Value	Unit
Line Charge	λ (Line charge density)	ΔQ/Δl, Δl is small line element of wire that contains microscopic charged constituents and ΔQ is charge contained in the	C/m

		line element.	
Surface Charge	σ (surface charge density)	ΔQ/ΔS, ΔSis an area element on the surface of a conductor and ΔQ is charge on that element.	C/m^2
Volume Charge	ρ (volume charge density)	ΔQ/ΔV, ΔV is a volume element which includes a large number of microscopically charged constituents and ΔQ is charge on that element.	C/m^3

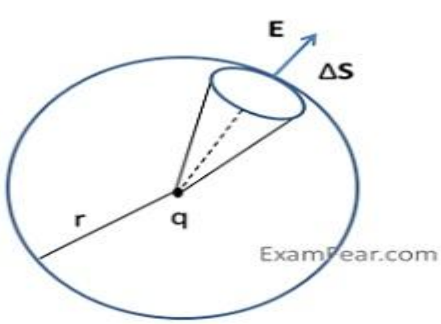
Electric field due to above volume charge distribution (for 1 and n volume elements) will be:

$$\Delta \mathbf{E} = \frac{1}{4\pi\varepsilon_0} \frac{\rho \Delta V}{r^2} \hat{\mathbf{r}}' \qquad \mathbf{E} \approx \frac{1}{4\pi\varepsilon_0} \Sigma \frac{\rho \Delta V}{r^2} \hat{\mathbf{r}}'$$

<u>Gauss's Law</u>

According to Gauss's law, the total of the electric flux out of a closed surface is equal to the charge enclosed divided by the permittivity. The total electric flux through a closed surface is zero if no charge is enclosed by the surface.

- **Gauss's law is true for any closed surface, no matter what its shape or size.**
- **The term q on the right side of Gauss's lawincludes the sum of all charges enclosed by the surface. The charges may be located anywhere inside the surface.**
- **In the situation when the surface is so chosen that there are some charges inside and some outside, the electric field [whose flux appears on the left side of Eq. (1.31)] is due to all the charges, both inside and outside S. The term q on the right side of Gauss's law, however, represents only the total charge inside S.**
- **The surface that we choose for the application of Gauss's law is called the Gaussian surface. The Gaussian surface can pass through a continuous charge distribution.**
- **Gauss's law is useful for the calculation of the electrostatic field for a symmetric system.**
- **Gauss's law is based on the inverse square dependence on distance contained in the Coulomb's law. Any violation of Gauss's law will indicate departure from the inverse square law.**



Flux through a sphere of radius r, with charge q at its center.

Flux through area element ΔS is,

$\Delta\phi = \mathbf{E} \cdot \Delta\mathbf{S} = \frac{q}{4\pi\varepsilon_0 r^2} \hat{\mathbf{r}} \cdot \Delta\mathbf{S}$

Since $\hat{\mathbf{r}}$ and $\Delta\mathbf{S}$ have same direction,

$\Delta\phi = \frac{q}{4\pi\varepsilon_0 r^2} \Delta S$

For all area elements, the flux will be,

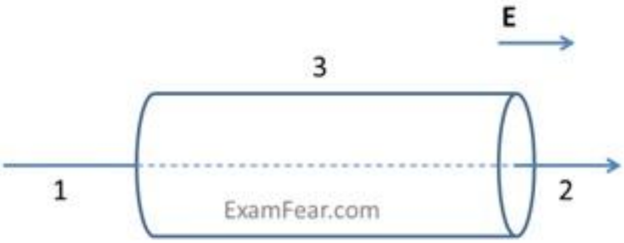
$\phi = \Sigma_{all\,\Delta S} \frac{q}{4\pi\varepsilon_0 r^2} \Delta S$

For same r of each area element,

$\phi = \frac{q}{4\pi\varepsilon_0 r^2} \Sigma_{all\,\Delta S} \Delta S = \frac{q}{4\pi\varepsilon_0 r^2} S$

Area of sphere = $4\pi r^2$,

$\phi = \frac{q}{\varepsilon_0}$



Flux through a cylinder

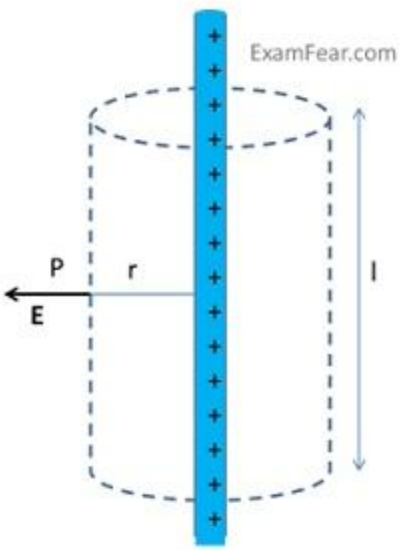
$\phi_1 = -ES_1$, outward normal opposite to E

$\phi_2 = +ES_2$, outward normal along E

$\phi_3 = 0$, outward normal perpendicular to E

$\phi = \phi_1 + \phi_2 + \phi_3$
$\phi = 0$ for $S_1 = S_2$

Applications of Gauss's Law
Field due to infinitely long straight uniformly charged wire



Flux through the two ends of Gaussian surface is 0, since the field is radial.
E is normal to the surface with constant magnitude.
Surface area of cylinder = $2\pi rl$

Flux through the Gaussian Surface,
= E x $2\pi rl$

Or, E x $2\pi rl = \lambda l/\varepsilon_0$

$E = \lambda/2\pi\varepsilon_0 r$
$\mathbf{E} = \lambda/2\pi\varepsilon_0 r\ \hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ is radial unit vector in the plane normal to the wire passing through the point. E is directed outwards if λ is positive and inwards if λ is negative.

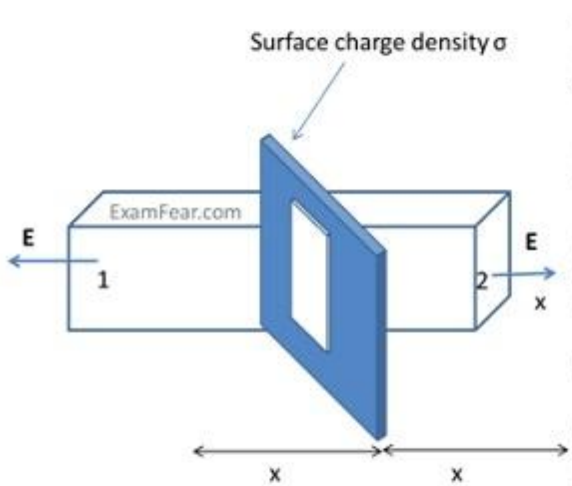
Example ExamFear.com

If an infinite line charge produces a field of 9×10^4 N/C at a distance of 2 cm, the linear charge density can be calculated as:

$$E = \lambda / 2\pi\varepsilon_0 d$$

$\lambda = 2\pi\varepsilon_0 d\ E$
$\lambda = 0.02 \times 9 \times 10^4 / (2 \times 9 \times 10^9)$
λ = 10 μC/m

Field due to auniformly charged infinitely plane sheet



The total flux will be combination of the faces 1 and 2 as other faces are parallel to electric field.

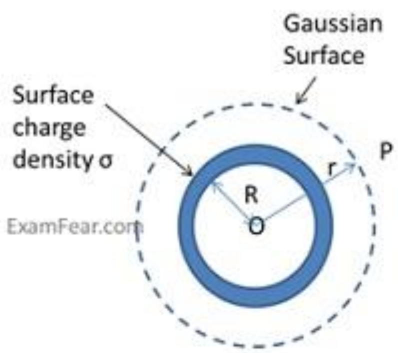
Net flux = 2EA
Charge enclosed by closed surface = σA

From Gauss's Law,
$2\,EA = \sigma A/\varepsilon_0$
Or, $E = \sigma/2\varepsilon_0$

$\mathbf{E} = \sigma/2\pi\varepsilon_0\,\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ is radial unit vector in the plane normal to the plane and going away from it. E is directed away from plane if σ is positive and towards if σ is negative.

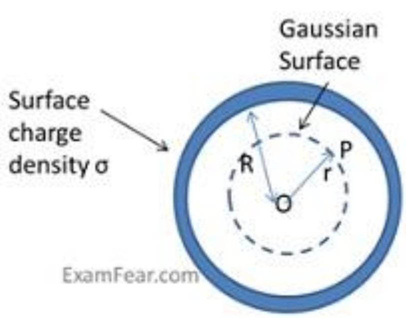
Field due to auniformly charged thin spherical shell



Field outside the shell:
Due to spherical symmetry, the electric field at each point of the gaussian surface has same magnitude. E and ΔS are parallel at every point.

Net flux = Charge enclosed
Or, $E \times 4\pi r^2 = \sigma/\varepsilon_0\, 4\pi R^2$
$E = q/4\pi\varepsilon_0 r^2$
$\mathbf{E} = q/4\pi\varepsilon_0 r^2\,\hat{\mathbf{r}}$

Electric field is directed outward if $q>0$ and inward if $q<0$.



Field inside the shell:
Due to spherical symmetry, the electric field at each point of the gaussian surface has same magnitude. E and ΔS are parallel at every point.

Net flux = Charge enclosed
Or, $E \times 4\pi r^2 = 0$ (since gaussian surface encloses no charge)
$E = 0$

Thus electric field due to uniformly charged thin shell is zero at all points.

Thank you.
Pdf notes (www.free-education.in)