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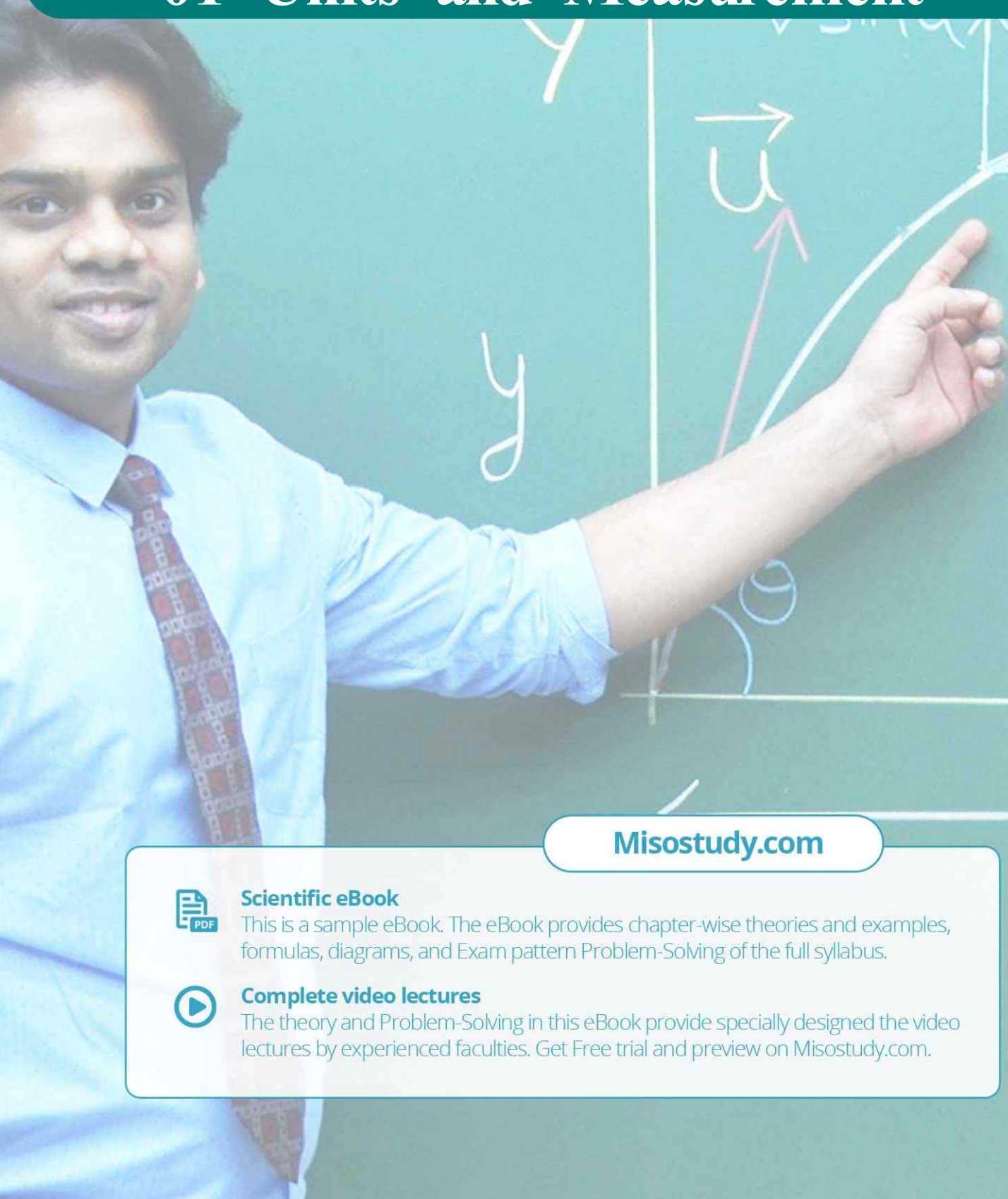
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Class 11 | Physics

01 Units and Measurement



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01. Physical Quantities

All the quantities which are used to describe the laws of physics are known as *physical quantities*.

Classification : Physical quantities can be classified on the following bases :

(A) Based on their directional properties

I. Scalars : The physical quantities which have only magnitude but no direction are called *scalar quantities*.

e.g. mass, density, volume, time, etc.

II. Vectors : The physical quantities which both magnitude and direction and obey laws of vector algebra are called *vector quantities*.

e.g. displacement, force, velocity, etc.

(B) Based on their dependency

I. Fundamental or base quantities : The quantities which do not depend upon other quantities for their complete definition are known as *fundamental or base quantities*.

e.g. length, mass, time, etc.

II. Derived quantities : The quantities which can be expressed in terms of the fundamental quantities are known as *derived quantities*.

e.g. Speed (=distance/time), volume, acceleration, force, pressure, etc.

Example

Classify the quantities displacement, mass, force, time, speed, velocity, acceleration, pressure and work under the following categories:

- base and scalar
- base and vector
- derived and scalar
- derived and vector

Solution

- mass, time
- displacement
- speed, pressure, work
- force, velocity, acceleration

02. Units of Physical Quantities

The chosen reference standard of measurement in multiples of which, a physical quantity is expressed is called the *unit* of that quantity.

System of Units

- FPS or British Engineering system** : In this system length, mass and time are taken as fundamental quantities and their base units are foot (ft), pound (lb) and second (s) respectively.
- CGS or Gaussian system** : In this system the fundamental quantities are length, mass and time and their respective units are centimeter (cm), gram (g) and second (s).
- MKS system** : In this system also the fundamental quantities are length, mass and time but their fundamental units are metre (m), kilogram (kg) and second (s) respectively.

- (iv) **International system (SI) of units** : This system is modification over the MKS system and so it is also known as *Rationalised MKS* system. Besides the three base units of MKS system four fundamental and two supplementary units are also included in this system.

SI BASE QUANTITIES AND THEIR UNITS			
S. No.	Physical quantity	Unit	Symbol
1	Length	metre	m
2	Mass	kilogram	kg
3	Time	second	s
4	Temperature	kelvin	K
5	Electric current	ampere	A
6	Luminous intensity	candela	cd
7	Amount of substance	mole	mol

03. Classification of Units

The units of physical quantities can be classified as follows :

(i) **Fundamental or base units**

The units of fundamental quantities are called *base units*. In SI there are seven base units.

(ii) **Derived units**

The units of derived quantities or the units that can be expressed in terms of the base units are called *derived units*.

$$\text{e.g. unit of speed} = \frac{\text{unit of distance}}{\text{unit of time}} = \frac{\text{metre}}{\text{second}} = \text{m/s}$$

Some derived units are named in honour of great scientists.

e.g. unit of force – newton (N), unit of frequency – hertz (Hz), etc.

(iii) **Supplementary units**

In International System (SI) of units two *supplementary units* are also defined viz. radian (rad) for plane angle and steradian (sr) for solid angle.

- **radian** : 1 radian is the angle subtended at the centre of a circle by an arc equal in length to the radius of the circle.
- **steradian** : 1 steradian is the solid angle subtended at the centre of a sphere, by the surface of the sphere which is equal in area to the square of the radius of the sphere.

(iv) **Practical units**

Due to the fixed sizes of SI units, some *practical units* are also defined for both fundamental and derived quantities. e.g. light year (ly) is a practical unit of distance (a fundamental quantity) and horse power (hp) is a practical unit of power (a derived quantity).

Practical units may or may not belong to a particular system of units but can be expressed in any system of units.

$$\text{e.g. } 1 \text{ mile} = 1.6 \text{ km} = 1.6 \times 10^3 \text{ m} = 1.6 \times 10^5 \text{ cm.}$$

01 Units and Measurement

Conversion factors

To convert a physical quantity from one set of units to the other, the required multiplication factor is called *conversion factor*.

Magnitude of a physical quantity = numeric value (n) × unit (u)

While conversion from one set of units to the other the magnitude of the quantity must remain same. Therefore

$$n_1 u_1 = n_2 u_2 \quad \text{or} \quad n u = \text{constant} \quad \text{or} \quad n \propto \frac{1}{u}$$

This is the numeric value of a physical quantity is inversely proportional to the base unit.

e.g. $1\text{m} = 100\text{cm} = 3.28\text{ft} = 39.4\text{inch}$
(SI) (CGS) (FPS)

Example The acceleration due to gravity is 9.8 m s^{-2} . Given its value in ft s^{-2}

Solution As $1\text{m} = 3.2\text{ft}$

$$\therefore 9.8\text{ m/s}^2 = 9.8 \times 3.28\text{ ft/s}^2 = 32.14\text{ ft/s}^2 \approx 32\text{ ft/s}^2$$

04. Dimensions

Dimensions of a physical quantity are the powers for exponents to which the base quantities are raised to represent that quantity.

Dimensional formula

The dimensional formula of any physical quantity is that expression which represents how and which of the base quantities are included in that quantity.

It is written by enclosing the symbols for base quantities with appropriate powers in square brackets i.e. []

e. g. Dimensional formula of mass in $[M^1 L^0 T^0]$ is the dimensional formula of the force and the dimensions of force are 1 in mass, 1 in length and -2 in time

05. Applications of Dimensional Analysis

(i) To convert a physical quantity from one system of units to the other :

This is based on a fact that magnitude of a physical quantity remains same whatever system is used for measurement i.e. magnitude = numeric value (n) × unit (u) = constant

$$\text{or } n_1 u_1 = n_2 u_2$$

So if a quantity is represented by $[M^a L^b T^c]$

$$\text{Then } n_2 = n_1 \left(\frac{u_1}{u_2} \right) = n_1 \left(\frac{M_1}{M_2} \right)^a \left(\frac{L_1}{L_2} \right)^b \left(\frac{T_1}{T_2} \right)^c$$

Here n_2 = numerical value in II system
 n_1 = numerical value in I system
 M_1 = unit of mass in I system
 M_2 = unit of mass in II system
 L_1 = unit of length in I system
 L_2 = unit of length in II system
 T_1 = unit of time in I system
 T_2 = unit of time in II system

Example

Convert 1 newton (SI unit of force) into dyne (CGS unit of force)

Solution

The dimensional equation of force is $[F] = [M^1 L^1 T^{-2}]$

Therefore if $n_1, u_1,$ and $n_2, u_2,$ corresponds to SI & CGS units respectively, then

$$n_2 = n_1 \left[\frac{M_1}{M_2} \right]^1 \left[\frac{L_1}{L_2} \right]^1 \left[\frac{T_1}{T_2} \right]^{-2} = 1 \left[\frac{\text{kg}}{\text{g}} \right] \left[\frac{\text{m}}{\text{cm}} \right] \left[\frac{\text{s}}{\text{s}} \right]^{-2} = 1 \times 1000 \times 100 \times 1 = 10^5 \therefore$$

1 newton = 10^5 dyne.

(ii) To check the dimensional correctness of a given physical relation

If in a given relation, the terms on both the sides have the same dimensions, then the relation is dimensionally correct. This is known as the principle of homogeneity of dimensions.

Example

Check the accuracy of the relation $T = 2\pi \sqrt{\frac{L}{g}}$ for a simple pendulum using

Solution

The dimensions of LHS = the dimension of $T = [M^0 L^0 T^1]$

The dimensions of RHS = $\left(\frac{\text{dimensions of length}}{\text{dimensions of acceleration}} \right)^{1/2}$ ($\because 2\pi$ is a dimensionless constant)

$$= \left[\frac{L}{LT^{-2}} \right]^{1/2} = [T^2]^{1/2} = [T] = [M^0 L^0 T^1]$$

Since the dimensions are same on both the sides, the relation is correct.

(iii) To derive relationship between different physical quantities

Using the same principle of homogeneity of dimensions new relations among physical quantities can be derived if the dependent quantities are known.

Example

It is known that the time of revolution T of a satellite around the earth depends on the universal gravitational constant G , the mass of the earth M , and the radius of the circular orbit R . Obtain an expression for T using dimensional analysis.

We have $[T] = [G]^a [M]^b [R]^c$

Solution

$$[M]^0 [L]^0 [T]^1 = [M]^{-a} [L]^{3a} [T]^{-2a} \times [M]^b \times [L]^c = [M]^{b-a} [L]^{c+3a} [T]^{-2a}$$

Comparing the exponents

$$\text{For } [T]: 1 = -2a \Rightarrow a = -\frac{1}{2} \quad \text{For } [M]: 0 = b - a \Rightarrow b = a = -\frac{1}{2}$$


$$\text{For } [L]: 0 = c + 3a \Rightarrow c = -3a = \frac{3}{2}$$

Putting the values we get $T \propto G^{-1/2} M^{-1/2} R^{3/2} \Rightarrow T \propto \sqrt{\frac{R^3}{GM}}$

The actual expression is $T = 2\pi \sqrt{\frac{R^3}{GM}}$

Dimensions of trigonometric, exponential, logarithmic function etc.

All trigonometric, exponential and logarithmic functions and their arguments are dimensionless.

NOTE  Trigonometric function $\sin\theta$ and its argument θ are dimensionless.

06. Limitations of this Method

- In Mechanics the formula for a physical quantity depending one more than three physical quantities cannot be derived. It can only be checked.
- This method can be used only if the dependency is of multiplication type. The formulae containing exponential, trigonometrical and logarithmic functions can't be derived using this method. Formulae containing more than one term which are added or subtracted like $s = ut + at^2/2$ also can't be derived.
- The relation derived from this method gives no information about the dimensionless constants.
- If dimensions are given, physical quantity may not be unique as many physical quantities have the same dimensions.
- It gives no information whether a physical quantity is a scalar or a vector.

07. Significant Figures or Digits

The significant figure (SF) in a measurement are the figure or digits that are known with certainty plus one that is uncertain.

Significant figures in a measured value of a physical quantity tell the number of digits in which we have confidence. Larger the number of significant figure obtained in a measurement, greater is its accuracy and vice versa.

Rules to find out the number of significant figures

- I Rule** : All the non-zero digits are significant e.g. 1984 has 4 SF.
- II Rule** : All the zeros between two non-zero digits are significant. e.g. 10806 has 5 SF
- III Rule** : All the zeros to the left of first non-zero digit are not significant. e.g. 00108 has 3 SF.
- IV Rule** : If the number is less than 1, zeros on the right of the decimal point but to the left of the first non-zero digit are not significant. e.g. 0.002308 has 4 SF.
- V Rule** : The trailing zeros (zeros to the right of the last non-zero digit) in a number with a decimal point are significant. e.g. 01.080 has 4 SF.

VI Rule : The trailing zeros in a number without a decimal point are not significant e.g. 010100 has 3 SF. But if the number comes from some actual measurement then the trailing zeros become significant. e.g. $m = 100$ kg has 3 SF.

VII Rule : When the number is expressed in exponential form, the exponential term does not affect the number of S.F. For example in $x = 12.3 = 1.23 \times 10^1 = 0.123 \times 10^2 = 0.0123 \times 10^3 = 123 \times 10^{-1}$ each term has 3 SF only.

Rules for arithmetical operations with significant figures

I Rule : In addition or subtraction the number of decimal places in the result should be equal to the number of decimal places of that term in the operation which contain lesser number of decimal places. e.g. $12.587 - 12.5 = 0.087 = 0.1$ (\because second term contain lesser i.e. one decimal place)

II Rule : In multiplication or division, the number of SF in the product or quotient is same as the smallest number of SF in any of the factors. e.g. $4.0 \times 0.12 = 0.484 = 0.48$

- To avoid the confusion regarding the trailing zeros of the numbers without the decimal point the best way is to report every measurement in scientific notation (in the power of 10). In this notation every number is expressed in the form $a \times 10^b$, where a is the base number between 1 and 10 and b is any positive or negative exponent of 10. The base number (a) is written in decimal form with the decimal after the first digit. While counting the number of SF only base number is considered (Rule VII).
- The change in the unit of measurement of a quantity does not effect the number of SF. For example in $2.308 \text{ cm} = 23.08 \text{ mm} = 0.02308 \text{ m} = 23080 \text{ }\mu\text{m}$ each term has 4 SF.

Example Write down the number of significant figures in the following.

- 165
- 2.05
- 34.000 m
- 0.005
- 0.02340 N m^{-1}
- 26900
- 26900 kg

Solution

- | | |
|--------------------------------|---------------------------------|
| (a) 165 | 3 SF (following rule I) |
| (b) 2.05 | 3 SF (following rule I & II) |
| (c) 34.000 m | 5 SF (following rule I & V) |
| (d) 0.005 | 1 SF (following rules I & IV) |
| (e) 0.02340 N m^{-1} | 4 SF (following rule I, IV & V) |
| (f) 26900 | 3 SF (see rule VI) |
| (g) 26900 kg | 5 SF (see rule VI) |

08. Rounding Off

To represent the result of any computation containing more than one uncertain digit, it is rounded off to appropriate number of significant figures.

Rules for rounding off the numbers :

- I Rule** : If the digit to be rounded off is more than 5, then the preceding digit is increased by one. e.g. $6.87 \approx 6.9$
- II Rule** : If the digit to be rounded off is less than 5, than the preceding digit is unaffected and is left unchanged. e.g. $3.94 \approx 3.9$
- III Rule** : If the digit to be rounded off is 5 than the preceding digit is increased by one if it odd and is left unchanged if it is even. e.g. $14.35 \approx 14.4$ and $14.45 \approx 14.4$

Example

The length, breadth and thickness of a metal sheet are 4.234 m, 1.005 m and 2.01 cm respectively. Give the area and volume of the sheet to correct number of significant figures.

Solution

length (l) = 4.234 m breadth (b) = 1.005 m

thickness (t) = 2.01 cm = 2.01×10^{-2} m

$$\begin{aligned} \text{Therefore area of the sheet} &= 2 (l \times b + b \times t + t \times l) \\ &= 2 (4.234 \times 1.005 + 1.005 \times 0.0201 + 0.0201 \times \\ &4.234) \text{ m}^2 \\ &= 2 (4.3604739) \text{ m}^2 = 8.720978 \text{ m}^2 \end{aligned}$$

Since area can contain a max^m of 3 SF (Rule II of article 4.2) therefore, rounding off, we get

$$\text{Area} = 8.72 \text{ m}^2$$

Like wise volume = $l \times b \times t = 4.234 \times 1.005 \times 0.0201 \text{ m}^3 = 0.0855289 \text{ m}^3$

Since volume can contain 3 SF, therefore, rounding off, we get

$$\text{Volume} = 0.0855 \text{ m}^3$$

09. Order of Magnitude

Order of magnitude of a quantity is the power of 10 required to represent that quantity. This power is determined after rounding off the value of the quantity properly. For rounding off, the last digit is simply ignored if it is less than 5 and, is increased by one if it is 5 or more than 5.

- When a number is divided by 10^x (where x is the order of the number) the result will always lie between 0.5 and 5 i.e. $0.5 \leq N/10^x < 5$

Example Order of magnitude of the following values can be determined as follows :

(a) $49 = 4.9 \times 10^1 \approx 10^1$

Solution \therefore Order of magnitude = 1

(b) $51 = 5.1 \times 10^1 \approx 10^2$

Solution \therefore Order of magnitude = 2

(c) $0.049 = 4.9 \times 10^{-2} \approx 10^{-2}$

Solution \therefore Order of magnitude = -2

(d) $0.050 = 5.0 \times 10^{-2} \approx 10^{-1}$

Solution \therefore Order of magnitude = -1

(e) $0.051 = 5.1 \times 10^{-2} \approx 10^{-1}$

Solution \therefore Order of magnitude = -1

• **Accuracy, Precision of Instruments and Errors in Measurement**

Accuracy and Precision

The result of every measurement by any measuring instrument contains some uncertainty. This uncertainty is called error. Every calculated quantity which is based on measured value, also has an error. Every measurement is limited by the reliability of the measuring instrument and skill of the person making the measurement. If we repeat a particular measurement, we usually do not get precisely the same result as each result is subjected to some experimental error. This imperfection in measurement can be described in terms of accuracy and precision. The accuracy of a measurement is a measure of how close the measured value is to the true value of the quantity. Precision tells us to what resolution or limit the quantity is measured, we can illustrate the difference between accuracy and precision with help of a example. Suppose the true value of a certain length is 1.234 cm. In one experiment, using a measuring instrument of resolution 0.1 cm, the measured value is found to be 1.1cm, while in another experiment using a measuring device of greater resolution of 0.01m, the length is determined to be 1.53cm. The first measurement has more accuracy (as it is closer to the true value) but less precision (as resolution is only 0.1 cm), while the second measurement is less accurate but more precise.

10. Errors

The difference between the true value and the measured value of a quantity is known as the error of measurement.

Errors may arise from different sources and are usually classified as follows

Systematic or Controllable Errors

Systematic errors are the errors whose causes are known. They can be either positive or negative. Due to the known causes these errors can be minimised. Systematic errors can further be classified into three categories

- (i) **Instrumental errors** :- These errors are due to imperfect design or erroneous manufacture or misuse of the measuring instrument. These can be reduced by using more accurate instruments.
- (ii) **Environmental errors** :- These are due to the changes in external environmental conditions such as temperature, pressure, humidity, dust vibrations or magnetic and electrostatic fields.

(iii) **Observational errors** :- These errors arise due to improper setting of the apparatus or carelessness in taking observations.

Random Errors

These errors are due to unknown causes. Therefore they occur irregularly and are variable in magnitude and sign. Since the causes of these errors are not known precisely they can not be eliminated completely. For example, when the same person repeats the same observation in the same conditions, he may get different readings different times.

Random errors can be reduced by repeating the observation a large number of times and taking the arithmetic mean of all the observations. This mean value would be very close to the most accurate reading.

NOTE

If the number of observations is made n times then the random error reduces to $\left(\frac{1}{n}\right)$ times.

Gross Errors : Gross errors arise due to human carelessness and mistakes in reading the instruments or calculating and recording the measurement results.

For example :-

- (i) Reading instrument without proper initial settings.
- (ii) Taking the observations wrongly without taking necessary precautions.
- (iii) Exhibiting mistakes in recording the observations.
- (iv) Putting improper values of the observations in calculations.

These errors can be minimised by increasing the sincerity and alertness of the observer.

11. Representation of Errors

Errors can be expressed in the following ways

Absolute Error (Δa) : The difference between the true value and the individual measured value of the quantity is called the absolute error of the measurement.

Suppose a physical quantity is measured n times and the measured values are $a_1, a_2, a_3, \dots, a_n$. The arithmetic mean (a_m) of these values is

$$a_m = \frac{a_1 + a_2 + a_3 + \dots + a_n}{n} = \frac{1}{n} \sum_{i=1}^n a_i \quad \dots(i)$$

If the true value of the quantity is not given then mean value (a_m) can be taken as the true value. Then the absolute errors in the individual measured values are

$$\Delta a_1 = a_m - a_1$$

$$\Delta a_2 = a_m - a_2$$

.....

.....

$$\Delta a_n = a_m - a_n$$

The arithmetic mean of all the absolute errors is defined as the final or mean absolute error $(\Delta a)_m$ or Δa of the value of the physical quantity a

$$(\Delta a)_m = \frac{|\Delta a_1| + |\Delta a_2| + \dots + |\Delta a_n|}{n} = \frac{1}{n} \sum_{i=1}^n |\Delta a_i| \quad \dots(ii)$$

So if the measured value of a quantity be 'a' and the error in measurement be Δa , then the true value (a_t) can be written as

$$a_t = a \pm \Delta a \quad \dots(\text{iii})$$

Relative or Fractional Error : It is defined as the ratio of the mean absolute error $((\Delta a)_m$ or $\overline{\Delta a}$) to the true value or the mean value (a_m or \bar{a}) of the quantity measured.

$$\text{Relative or fractional error} = \frac{\text{Mean absolute error}}{\text{Mean value}} = \frac{(\Delta a)_m}{a_m} \text{ or } \frac{\overline{\Delta a}}{\bar{a}} \quad \dots(\text{iv})$$

When the relative error is expressed in percentage, it is known as percentage error, percentage error = relative error $\times 100$

$$\text{or percentage error} = \frac{\text{mean absolute error}}{\text{true value}} \times 100\% = \frac{\overline{\Delta a}}{a} \times 100\% \quad \dots(\text{v})$$

12. Propagation of Errors in Mathematical Operations

Rule I : The maximum absolute error in the sum or difference of the two quantities is equal to the sum of the absolute errors in the individual quantities.

If $X = A + B$ or $X = A - B$ and if $\pm \Delta A$ and $\pm \Delta B$ represent the absolute errors in A and B respectively, then the maximum absolute error in $X = \Delta X = \Delta A + \Delta B$ and

$$\text{Maximum percentage error} = \frac{\Delta X}{X} \times 100 \quad \dots(\text{i})$$

The result will be written as $X \pm \Delta X$ (in terms of absolute error)

$$\text{or } X \pm \frac{\Delta X}{X} \times 100\% \text{ (in terms of percentage error)}$$

Rule II : The maximum fractional or relative error in the product or division of quantities is equal to the sum of the fractional or relative errors in the individual quantities.

$$\text{If } X = A \times B \quad \text{or} \quad X = A/B$$

$$\text{then } \frac{\Delta X}{X} = \pm \left(\frac{\Delta A}{A} + \frac{\Delta B}{B} \right) \quad \dots(\text{ii})$$

Rule III : The maximum fractional error in a quantity raised to a power (n) is n times the fractional error in the quantity itself, i.e.

$$\text{If } X = A^n \quad \text{then} \quad \frac{\Delta X}{X} = n \left(\frac{\Delta A}{A} \right) \quad \dots(\text{viii})$$

$$\text{If } X = A^p B^q C^r \quad \text{then} \quad \frac{\Delta X}{X} = \left[p \left(\frac{\Delta A}{A} \right) + q \left(\frac{\Delta B}{B} \right) + r \left(\frac{\Delta C}{C} \right) \right]$$

$$\text{If } X = \frac{A^p B^q}{C^r} \quad \text{then} \quad \frac{\Delta X}{X} = \left[p \left(\frac{\Delta A}{A} \right) + q \left(\frac{\Delta B}{B} \right) + r \left(\frac{\Delta C}{C} \right) \right]$$

IMPORTANT POINTS

- Systematic errors are repeated consistently with the repetition of the experiment and are produced due to improper conditions or procedures that are consistent in action whereas random errors are accidental and their magnitude and sign cannot be predicated from the knowledge of the measuring system and conditions of measurement. Systematic errors can therefore be minimised by improving experimental techniques, selecting better instruments and improving personal skills whereas random errors can be minimised by repeating the observation several times.
- Mean absolute error has the units and dimensions of the quantity itself whereas fractional or relative error is unitless and dimensionless.
- Absolute errors may be positive in certain cases and negative in other cases.

Example The initial and final temperatures of water as recorded by an observer are $(40.6 \pm 0.2)^\circ\text{C}$ and $(78.3 \pm 0.3)^\circ\text{C}$. Calculate the rise in temperature with proper error limits.

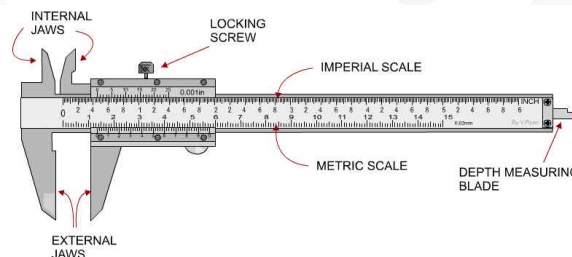
Solution Given $\theta_1 = (40.6 \pm 0.2)^\circ\text{C}$ and $\theta_2 = (78.3 \pm 0.3)^\circ\text{C}$
 Rise in temp. $\theta = \theta_2 - \theta_1 = 78.3 - 40.6 = 37.7^\circ\text{C}$.
 $\Delta\theta = \pm(\Delta\theta_1 + \Delta\theta_2) = \pm(0.2 + 0.3) = \pm 0.5^\circ\text{C}$ \therefore rise in temperature = $(37.7 \pm 0.5)^\circ\text{C}$

13. Least Count

The smallest value of a physical quantity which can be measured accurately with an instrument is called the least count (L. C.) of the measuring instrument.

Least Count of Vernier Callipers

Suppose the size of one main scale division (M.S.D.) is M units and that of one vernier scale division (V. S. D.) is V units. Also let the length of 'a' main scale divisions is equal to the length of 'b' vernier scale divisions.



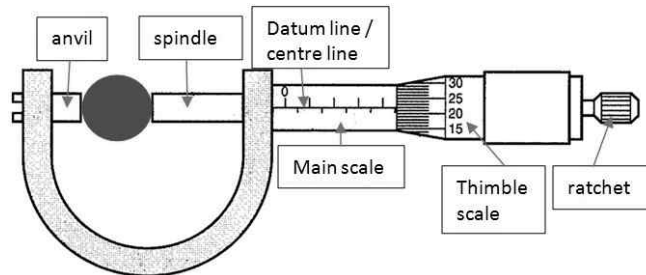
$$aM = bV \Rightarrow V = \frac{a}{b}M$$

$$\therefore M - V = M - \frac{a}{b}M \text{ or } M - V = \left(\frac{b-a}{b}\right)M$$

The quantity $(M - V)$ is called vernier constant (V. C.) or least count (L. C.) of the vernier callipers.

$$\text{L.C.} = M - V = \left(\frac{b-a}{b}\right)M$$

Least Count of screw gauge or spherometer



$$\text{Least Count} = \frac{\text{Pitch}}{\text{Total number of divisions on the circular scale}}$$

where pitch is defined as the distance moved by the screw head when the circular scale is given one complete rotation. i.e.

$$\text{Pitch} = \frac{\text{Distance moved by the screw on the linear scale}}{\text{No. of full rotations given}}$$

NOTE With the decrease in the least count of the measuring instrument, the accuracy of the measurement increases and the error in the measurement decreases.

Example One cm on the main scale of vernier callipers is divided into ten equal parts. If 20 divisions of vernier scale coincide with 8 small divisions of the main scale. What will be the least count of callipers ?

Solution 20 div. of vernier scale = 8 div. of main scale $\Rightarrow 1 \text{ V.S.D.} = \left(\frac{8}{20}\right) \text{ M.S.D.} = \left(\frac{2}{5}\right) \text{ M.S.D.}$

$$\begin{aligned} \text{Least count} &= 1 \text{ M.S.D.} - 1 \text{ V.S.D.} = 1 \text{ M.S.D.} - \left(\frac{2}{5}\right) \text{ M.S.D.} = \\ &= \left(1 - \frac{2}{5}\right) \text{ M.S.D.} \end{aligned}$$

$$= \frac{3}{5} \text{ M.S.D.} = \frac{3}{5} \times 0.1 \text{ cm} = 0.06 \text{ cm}$$

$$(\because 1 \text{ M.S.D.} = \frac{1}{10} \text{ cm} = 0.1 \text{ cm})$$

NOTE The final absolute error in this type of questions is taken to be equal to the least count of the measuring instrument.

JEE Main Pattern Exercise (1)

1. Match Column I with Column II and select the correct answer using the codes given below the lists.

Column I	Column II
(a) Boltzmann's constant	(p) $[ML^2T^{-1}]$
(b) Coefficient of viscosity	(q) $[ML^{-1}T^{-1}]$
(c) Planck's constant	(r) $[MLT^{-3}K^{-1}]$
(d) Thermal conductivity	(s) $[ML^2T^{-2}K^{-1}]$

2. In the equation $\int \frac{dt}{\sqrt{2at-t^2}} = a^x \sin^{-1} \left[\frac{t}{a} - 1 \right]$. The value of x is

- (a) 1 (c) 0
(b) -1 (d) 2

3. Let $[\epsilon_0]$ denote the dimensional formula of the permittivity of vacuum. If $M =$ mass, $L =$ length, $T =$ Time and $A =$ electric current, then

- (a) $[\epsilon_0] = [M^{-1} L^{-3} T^2 A]$
(b) $[\epsilon_0] = [M^{-1} L^{-3} T^4 A^2]$
(c) $[\epsilon_0] = [M^{-2} L^2 T^{-1} A^{-2}]$
(d) $[\epsilon_0] = [M^{-1} L^2 T^{-1} A^2]$

4. The equation of state of a gas is given by $\left(P + \frac{a}{V^3}\right)(V - b^2) = cT$, where P , V , T are pressure, volume and temperature respectively, and a , b , c , are constants. The dimensions of a and b are respectively.

- (a) ML^8T^{-2} and $L^{3/2}$
(b) ML^5T^{-2} and L^3
(c) ML^5T^{-2} and L^6
(d) ML^6T^{-2} and $L^{3/2}$

5. Which one of the following is NOT correct?

- (a) Dimensional formula of thermal conductivity (K) is $M^1L^1T^{-3}K^{-1}$
(b) Dimensional formula of potential (V) is $M^1L^2T^3A^{-1}$
(c) Dimensional formula of permeability of free space (μ_0) is $M^1L^1T^{-2}A^{-2}$
(d) Dimensional formula of RC is $M^0L^0T^{-1}$.

01 Units and Measurement

6. A cube has side of length 1.2×10^{-2} m. Calculate its volume.
 (a) $1.7 \times 10^{-6} \text{ m}^3$
 (b) $1.73 \times 10^{-6} \text{ m}^3$
 (c) $1.70 \times 10^{-6} \text{ m}^3$
 (d) $1.732 \times 10^{-6} \text{ m}^3$
7. The density of a solid ball is to be determined in an experiment. The diameter of the ball is measured with a screw gauge, whose pitch is 0.5 mm and there are 50 divisions on the circular scale. The reading on the main scale is 2.5 mm and that on the circular scale is 20 divisions. If the measured mass of the ball has a relative error of 2%, the relative percentage error in the density is
 (a) 0.9%
 (b) 2.4%
 (c) 3.1%
 (d) 4.2%
8. **Column I** gives three physical quantities. Select the appropriate units for the choices given in **Column II**. Some of the physical quantities may have more than one choice.

Column I	Column II
Capacitance	ohm-second
Inductance	Coulomb ² -joule ⁻¹
Magnetic induction	Coulomb (volt) ⁻¹ , Newton (ampere metre) ⁻¹ , volt-second (ampere) ⁻¹

9. In the determination of Young's modulus $\left(Y = \frac{4MLg}{\pi ld^2} \right)$ by using Searle's method, a wire of length $L = 2\text{m}$ and diameter $d = 0.5 \text{ mm}$ is used. For a load $M = 2.5 \text{ kg}$, an extension $l = 0.25 \text{ mm}$ in the length of the wire is observed. Quantities d and l are measured using a screw gauge and a micrometer, respectively. They have the same pitch of 0.5 mm. The number of divisions on their circular scale is 100. The contributions to the maximum probable error of the Y measurement is
 (a) due to the errors in the measurements of d and l are the same
 (b) due to the error in the measurement of d is twice that due the error in the measurement of l
 (c) due to the error in the measurement of l is twice that due to the error in the measurement of d
 (d) due to the error in the measurement of d is four times that due to the error in the measurement of l

10. Match the physical quantities given in **Column I** with dimensions expressed in terms of mass (M), length (L), time (T), and charge (Q) given in **Column II** and write the correct answer against the matched quantity in a tabular form in your answer book.

Column I	Column II
Angular momentum	$[ML^2T^{-2}]$
Latent heat	$[ML^2Q^{-2}]$
Torque	$[ML^2T^{-1}]$
Capacitance	$[ML^3T^{-1}Q^{-2}]$
Inductance	$[M^{-1}L^{-2}T^2Q^2]$
Resistivity	$[L^2T^{-2}]$



JEE Advanced Pattern Exercise (1)

(Only One Correct Option)

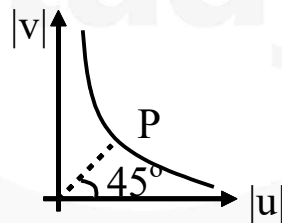
1. A person measures the depth of a well by measuring the time interval between dropping a stone and receiving the sound of impact with the bottom of the well. The error in his measurement of time is $\delta T = 0.01$ s and he measures the depth of the well to be $L = 20$ m. Take the acceleration due to gravity $g = 10 \text{ ms}^{-2}$ and the velocity of sound is 300 ms^{-1} . Then the fractional error in the measurement, $\frac{\delta L}{L}$, is closest to.

- (a) 1% (c) 3%
(b) 5% (d) 0.2%

2. If $\vec{A} \times \vec{B} = \vec{C} + \vec{D}$, then select the correct alternative.

- (a) \vec{B} is parallel to $\vec{C} + \vec{D}$
(b) \vec{A} is perpendicular to \vec{C}
(c) Component of \vec{C} along $\vec{A} =$ component of \vec{D} along \vec{A}
(d) Component of \vec{C} along $\vec{A} = -$ component of \vec{D} along \vec{A}

3. The $|\mu|, |v|$ graph for a concave mirror is as shown in figure. Here $|\mu| > |f|$. A line passing through origin of slope 1 cuts the graph at point P . Then co-ordinates of point P are



- (a) $(2f, 2f)$ (c) $(f, 2f)$
(b) $(2f, f)$ (d) (f, f)

4. The x - y plane is the boundary between two transparent media. Medium-1 with $z \geq 0$ has a refractive index $\sqrt{2}$ and medium-2 with $z \leq 0$ has a refractive index $\sqrt{3}$. A ray of light in medium-1 given by vector $\vec{A} = \sqrt{3}\hat{i} - \hat{k}$ is incident on the plane of separation. The unit vector in the direction of the refracted ray in medium-2 is

- (a) $\frac{1}{\sqrt{2}}(\hat{k} - \hat{i})$ (c) $\frac{1}{\sqrt{2}}(\hat{i} - \hat{k})$
(b) $\frac{1}{\sqrt{2}}(\hat{i} + \hat{j})$ (d) $\frac{1}{\sqrt{2}}(\hat{i} + \hat{k})$



01 Units and Measurement

(One or More Correct Option)

5. A length-scale (l) depends on the permittivity (ϵ) of a dielectric material, Boltzmann's constant (k_B), the absolute temperature (T) the number per unit volume (n) of certain charged particles, and the charge (q) carried by each of the particles. Which of the following expression (s) for l is (are) dimensionally correct?

(a) $l = \sqrt{\left(\frac{nq^2}{\epsilon k_B T}\right)}$

(c) $l = \sqrt{\left(\frac{q^2}{\epsilon n^{2/3} k_B T}\right)}$

(b) $l = \sqrt{\left(\frac{\epsilon k_B T}{nq^2}\right)}$

(d) $l = \sqrt{\left(\frac{q^2}{\epsilon n^{1/3} k_B T}\right)}$

6. Planck's constant h , speed of light c and gravitational constant G are used to form a unit of length L and a unit of mass M . Then, the correct options is/are

(a) $M \propto \sqrt{c}$

(c) $L \propto \sqrt{h}$

(b) $M \propto \sqrt{G}$

(d) $L \propto \sqrt{G}$

7. In terms of potential difference V , electric current I , permittivity ϵ_0 , permeability μ_0 and speed of light c , the dimensionally correct equations is/are

(a) $\mu_0 I^2 = \epsilon_0 V^2$

(c) $I = \epsilon_0 c V$

(b) $\epsilon_0 I = \mu_0 V$

(d) $\mu_0 c I = \epsilon_0 V$

(Integer Type Questions)

8. To find the distance d over which a signal can be seen clearly in foggy conditions, a railway engineer uses dimensional analysis and assumes that the distance depends on the mass density ρ of the fog, intensity (power/area) S of the light from the signal and its frequency f . The engineer finds that d is proportional to $S^{1/n}$. The value of n is
9. The energy of a system as a function of time t is given as $E(t) = A^2 \exp(-at)$, where $a = 0.2\text{s}^{-1}$. The measurement of A has an error of 1.25%. If the error in the measurement of time is 1.50%, the percentage error in the value of $E(t)$ at $t = 5$ s is

(Passage Based Questions)

10. A dense collection of equal number of electrons and positive ions is called neutral plasma. Certain solids containing fixed positive ions surrounded by free electrons can be treated as neutral plasma. Let N be the number density of free electrons, each of mass m . When the electron are subjected to an electric field, they are displaced relatively away form the heavy positive ions. If the electric field becomes zero, the electrons begin to oscillate about the positive ions with a natural angular frequency ω_p , which is called the plasma frequency. To sustain the oscillations, a time varying electric field needs to be applied that has an angular frequency ω , where a part of the energy is absorbed and a part of it is reflected. As ω approaches ω_p , all the free electrons are set to resonance together and all the energy is reflected. This is the explanation of high reflectivity of metals.

- (i) Taking the electronic charge as e and the permittivity as ϵ_0 , use dimensional analysis to determine the correct expression for ω_p .

(a) $\sqrt{\frac{Ne}{m\epsilon_0}}$

(b) $\sqrt{\frac{m\epsilon_0}{Ne}}$

(c) $\sqrt{\frac{Ne^2}{m\epsilon_0}}$

(d) $\sqrt{\frac{m\epsilon_0}{Ne^2}}$

- (ii) Estimate the wavelength at which plasma reflection will occur for a metal having the density of electrons $N = 4 \times 10^{27} \text{ m}^{-3}$. Take $\epsilon_0 \approx 10^{-30}$, and $m \approx 10^{-30}$, where these quantities are in proper SI units.

(a) 800 nm

(b) 600 nm

(c) 300 nm

(d) 200 nm

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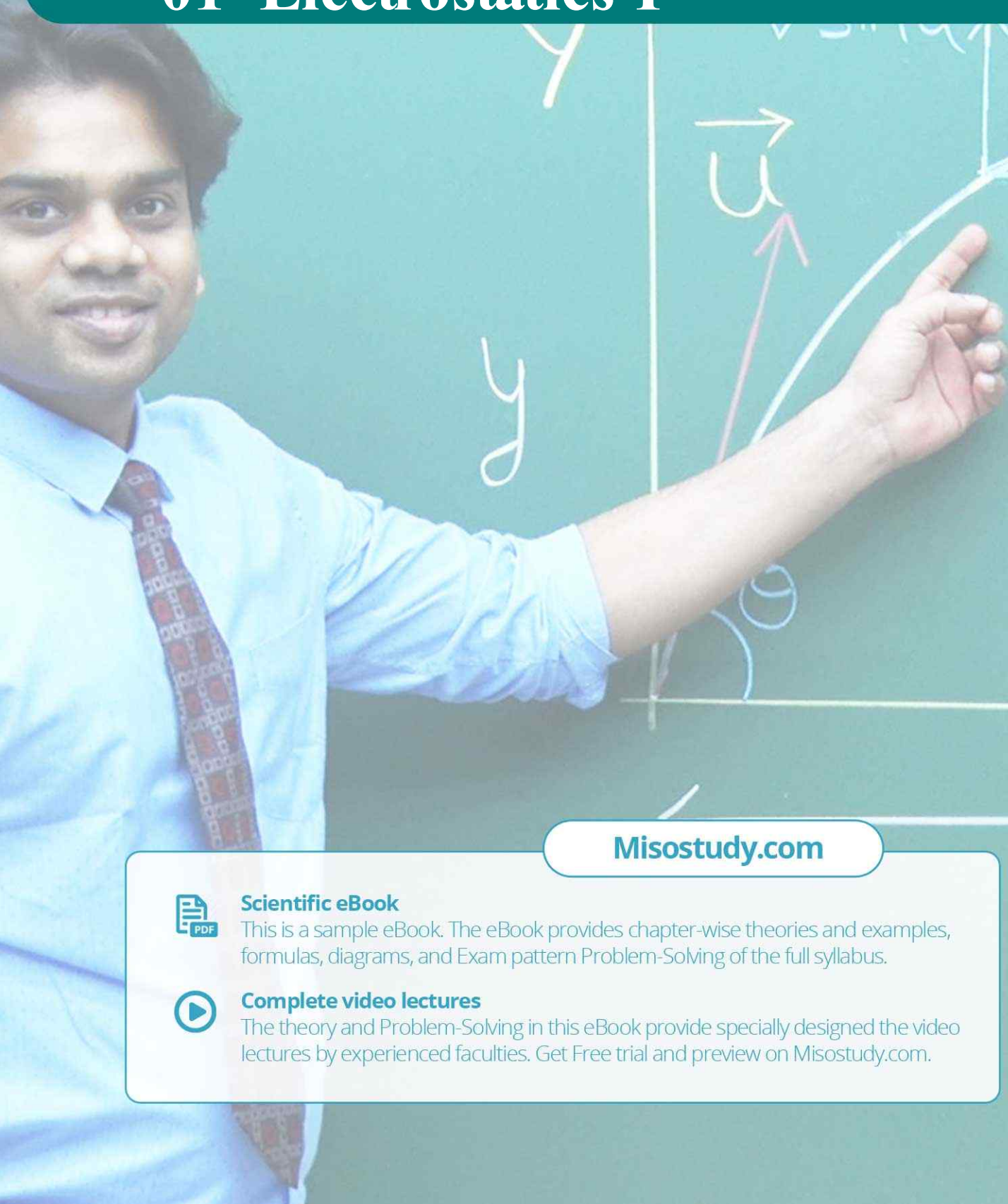
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01 Electrostatics-I



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01 Electrostatics-I

01. Introduction

Electrostatics, deals with the study of charges in rest. These stationary charges occurs due to friction of two insulating bodies, therefore it is often called frictional electricity.

Important points

- (i) Gravitational force is the weakest while nuclear force is the strongest force of the nature
- (ii) Nuclear force does not depend upon charge, it acts equally between proton-proton, proton neutron and neutron-neutron.
- (iii) There are weak forces acting in β -degradation in radio-activity.
- (iv) A stationary charge produces electric field while a moving charge produce electric as well as magnetic field.
- (v) Moving charge produce electric field as well as magnetic field but does not radiate energy while uniform acceleration.
- (vi) Accelerated charge produce electric field as well as magnetic field and radiate energy.

02. Charge

Property of a substance by virtue of which it can repel or attract another charged substance.

Charges are of two types

- (a) **Positive charge** : Lesser number of electrons than number of protons.
- (b) **Negative charge** : More number of electrons than number of protons

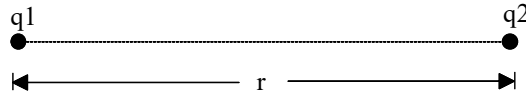
Important Points : Only, electron is responsible for a substance to be charged and not the proton.

Properties of Charge

- (i) Like charges repel while unlike charges attract each other.
- (ii) Charge is quantized in nature i.e. The magnitude of charge possessed by different objects is always and integral multiple of charge of electron (or proton) i.e. $q = \pm ne$ where $n = 1, 2, 3, \dots$
- (iii) The minimum possible charge that can exist in nature is the charge of electron which has a magnitude of $e = 1.60207 \times 10^{-19}$ coulomb. This is also known as quantum of charge or fundamental charge.
- (iv) In an isolated system the algebraic sum of total charge remains constant. This is the law of 'Conservation of charge'.

03. Coulomb's Law

The force of attraction or repulsion between two stationary point charges is directly proportional to the product of charges and inversely proportional to the square of distance between them. This force acts along the line joining the two. If q_1 & q_2 are charges in consideration r , the distance between them and F , the force acting between them



Then, $F \propto q_1 q_2$

$$F \propto 1/r^2$$

$$\therefore F \propto \frac{q_1 q_2}{r^2}$$

$$\Rightarrow F = K \frac{q_1 q_2}{r^2}, \text{ where } k = \text{constant.}$$

$$K = \frac{1}{4\pi\epsilon_0\epsilon_r} = \frac{9 \times 10^9}{\epsilon_r} \text{ Nm}^2\text{C}^{-2}$$

where,


ϵ_0 = Electric permittivity of vacuum or air

$$= 8.85 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2} \text{ and}$$

K or ϵ_r = Relative permittivity or Dielectric constant or Specific inductive capacity

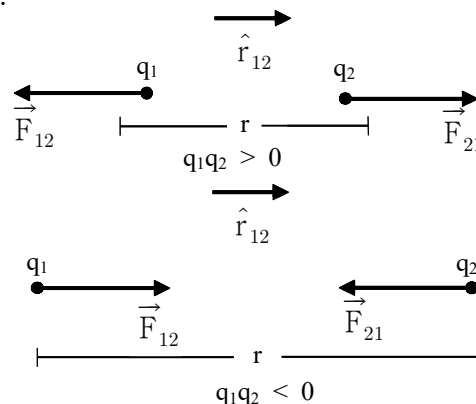
$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \Rightarrow \epsilon = \epsilon_0 \epsilon_r$$

[Newton's law for particles is analogous to coulomb's law for rest charge. The difference is that Newton's law gives attraction force while coulomb's law gives attraction as well as repulsion force]

- NOTE**  (i) Coulomb's law is applicable to point charges only. But it can be applied for distributed charges also
- (ii) This law is valid only for stationary charges and cannot be applied for moving charges.
- (iii) This law is valid only if the distance between two charges is not less than 10^{-15} m

Direction

Direction of the force acting between two charges depends upon their nature and it is along the line joining two charges.



\vec{F}_{21} = force on q_2 due to q_1

$$\vec{F}_{21} = \frac{q_1 q_2}{4\pi\epsilon_0\epsilon_r r_{12}^2} \hat{r}_{12} \quad \dots\dots(A)$$

(where \hat{r}_{12} is a unit vector pointing from q_1 to q_2)

\vec{F}_{12} = Force on q_1 due to q_2

$$\vec{F}_{12} = \frac{q_1 q_2}{4\pi\epsilon_0\epsilon_r r_{12}^2} \hat{r}_{21} \quad \dots\dots(B)$$

(where \hat{r}_{21} is a unit vector pointing from q_2 to q_1)

⇒ Electric force between two charges not depends on neighbouring charges.

⇒ If a dielectric slab (ϵ_r) of thickness 't' is placed between two charges (distance d), force decreases.

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} \quad \text{where } r = d - t + t\sqrt{\epsilon_r}$$

04. Electric Field

A charge produces something called an electric field in the space around it and this electric field exerts a force on any charge placed in it.

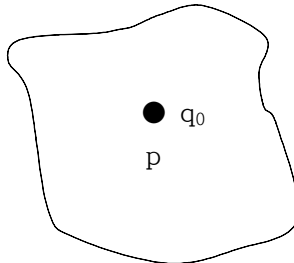
NOTE The electric field does not exert force on source charge.

Electric field Intensity

Force experienced by a unit positive charge placed in an electric field at a point is called electric field intensity at that point. It is also known as electric field simply. Let q_0 be the positive test charge placed in an electric field. If \vec{F} is the force experienced by this charge, then

$$\vec{E} = \lim_{q_0 \rightarrow 0} \frac{\vec{F}}{q_0}$$

- (i) Unit : N/C or volt/metre
- (ii) This is a vector quantity and its direction is the same as force on the positive test charge.

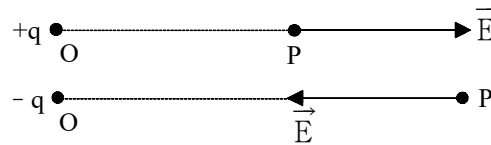


- (iii) Since \vec{E} is the force on unit charge, force on charge q is. $\vec{F} = q\vec{E}$.

- (iv) Dimension is $[M^1L^1T^{-3}A^{-1}]$
 (v) Electric field due to a point charge is

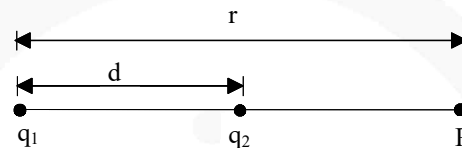
$$\vec{E} = \frac{kq}{r^2} \cdot \hat{r}$$

- (vi) Direction of electric field due to positive charge is away from charge while direction of electric field due to negative charge is towards the charge.



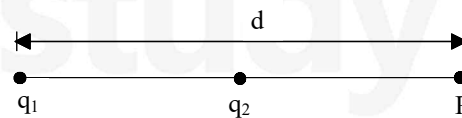
Special point

- (a) If q_1 and q_2 are at a distance r and both have the same type of charge, then the distance 'd' of the point from q_1 where electric field is zero is given by $d = \frac{\sqrt{q_1} r}{(\sqrt{q_1} + \sqrt{q_2})}$. This point will lie between line joining q_1 & q_2 .



- (b) If q_1 and q_2 have opposite charges then distance 'd' of the point 'p' from q_1 where electric field is zero is given by

$$d = \frac{\sqrt{q_1} r}{\sqrt{q_1} - \sqrt{q_2}}, \quad [|q_1| > |q_2|]$$



- (c) There charges $+Q_1$, $+Q_2$ and q are placed on a straight line. If this system of charges is in equilibrium, charge q should be a given

$$q = \frac{Q_1 Q_2}{(\sqrt{Q_1} + \sqrt{Q_2})^2}$$

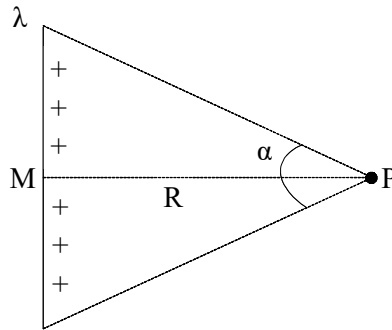
⇒ For measuring \vec{E} practically a test charge (+ve) of magnitude much less than the source charge should be used.

⇒ Electric force on a charge in uniform E is constant and hence acceleration is constant, so equations of motion can be used

$$\text{(acceleration } a = \frac{qE}{m})$$

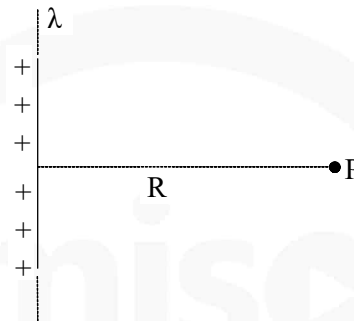
⇒ Electric field due to linear charge distribution (a) Finite wire

(d) Finite wire



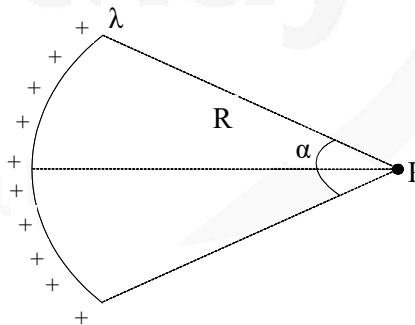
$$E_p = \frac{2k\lambda}{R} \sin \frac{\alpha}{2}$$

(e) Infinite wire ($\alpha = 180^\circ$)



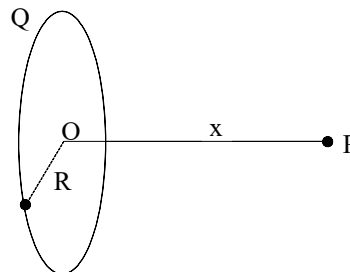
$$E_p = \frac{2k\lambda}{R}$$

(f) Charged arc



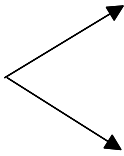
$$E_p = \frac{2k\lambda}{R} \sin \left(\frac{\alpha}{2} \right)$$

(g) Charged ring of radius R



at and axial point $E_p = \frac{kQx}{(R^2+x^2)^{3/2}}$;

$$x \gg R \Rightarrow E_p = \frac{kQ}{x^2}$$

If 

$$x \ll R \Rightarrow E_p = \frac{kqx}{R^2}$$

As x is increases: \vec{E} due to ring first \uparrow then \downarrow and at $X = \frac{R}{\sqrt{2}}$ it is maximum.

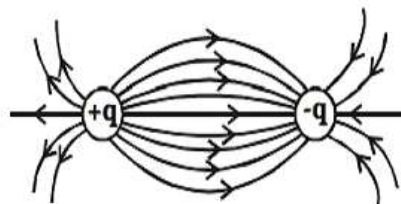
Electric lines of forces : (ELF)

The electric field in a region can be represented by drawing certain curves known as electric lines of force.

An electric line of force is that imaginary smooth curve drawn in an electric field along which a free isolated unit positive charge moves.

Properties

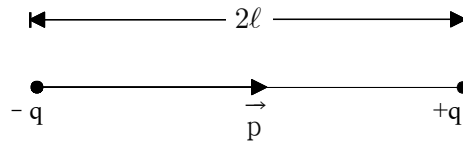
- (i) Imaginary
- (ii) Can never cross each other
- (iii) Can never be closed loops
- (iv) The number of lines originating or terminating on a charge is proportional to the magnitude of charge. In rationalised MKS $\left(\frac{1}{\epsilon_0}\right)$ system electric lines are associated with unit charge, so if a body encloses q , total lines of force associated with it (called flux) will be q/ϵ_0 .
- (v) Total lines of force may be fractional as lines of force are imaginary.



- (vi) Lines of force ends or starts normally at the surface of a conductor.
- (vii) If there is no electric field there will be no lines of force.
- (viii) Lines of force per unit area normal to the area at a point represents magnitude of intensity, crowded lines represent strong field while distant weak field.
- (ix) Tangent to the line of force at a point in an electric field gives the direction of intensity. So a positive charge free to move follow the line of force.

05. Electric Dipole

- (i) An system consisting of two equal and opposite charges separated by a small distance is termed and electric dipole.



Example : Na^+Cl^- , H^+Cl^- etc.

- (ii) An isolated atom is not a dipole because centre of positive charge coincides with centre of negative centres. But if atom is placed in an electric field, then the positive and negative centres are displaced relative to each other and atom become a dipole.
- (iii) **DIPOLE MOMENT:** The product of the magnitude of charges and distance between them is called the dipole moment.

It is denoted by \vec{p} and $|\vec{p}| = q \times 2l$

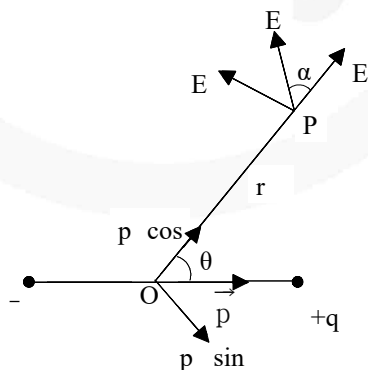
- (a) This is a vector quantity which is directed from negative to positive charge.
 (b) Unit : C-m
 (c) Dimension : $[M^0L^1T^1A^1]$

Electric field due to a dipole

- (i) There are two components of electric field at any point
- (a) $E_r \rightarrow$ in the direction of \vec{r}
 (b) $E_\theta \rightarrow$ in the direction perpendicular to \vec{r}

$$E_r = \frac{1}{4\pi\epsilon_0} \cdot \frac{2p \cos \theta}{r^3}$$

$$E_\theta = \frac{1}{4\pi\epsilon_0} \cdot \left(\frac{p \sin \theta}{r^3} \right)$$



- (i) Resultant

$$E = \sqrt{E_r^2 + E_\theta^2} = \frac{p}{4\pi\epsilon_0 r^3} \sqrt{1 + 3\cos^2 \theta}$$

- (ii) Angle between the resultant \vec{E} and \vec{r} , α given

$$\text{by } \alpha = \tan^{-1} \left(\frac{E_\theta}{E_r} \right) = \tan^{-1} \left(\frac{1}{2} \tan \theta \right)$$

(iii) If $\theta = 0$, i.e. point is on the axis -

$$E_{\text{axis}} = \frac{2kp}{r^3} \quad (r \gg \ell)$$

(iv) If $\theta = 90^\circ$, i.e. point is on the line bisecting the dipole perpendicularly

$$E_{\text{equatorial}} = \frac{kp}{r^3} \quad (r \gg \ell)$$

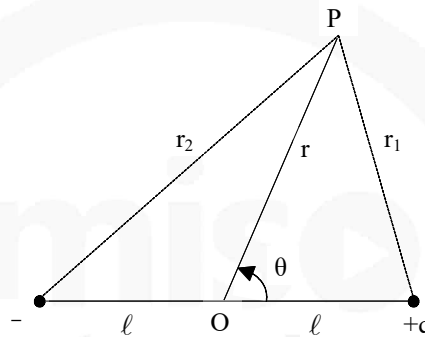
(v) So, $E_{\text{axis}} = 2E_{\text{equatorial}}$ (for same r)

$$(vi) \quad E_{\text{axis}} = \frac{1}{4\pi\epsilon_0} \cdot \frac{2pr}{(r^2 - \ell^2)^2}$$

$$E_{\text{equatorial}} = \frac{1}{4\pi\epsilon_0} \cdot \frac{p}{(r^2 + \ell^2)^{3/2}}$$

where $p = q \cdot (2\ell)$

(vii)



potential at a general point.

$$V = \frac{1}{4\pi\epsilon_0} \frac{p \cos \theta}{r^2}$$

(viii) If $\theta = 0^\circ$, $V_{\text{axis}} = \frac{kp}{r^2}$

(ix) If $\theta = 90^\circ$, $V_{\text{equator}} = 0$

(x) Here we see that $V = 0$ but $E \neq 0$ for points at equatorial position.

(xi) Again, if $r \gg d$ is not true and $d = 2\ell$,

$$V_{\text{axis}} = \frac{1}{4\pi\epsilon_0} \cdot \frac{p}{(r^2 - \ell^2)}$$

$$V_{\text{equator}} = 0$$

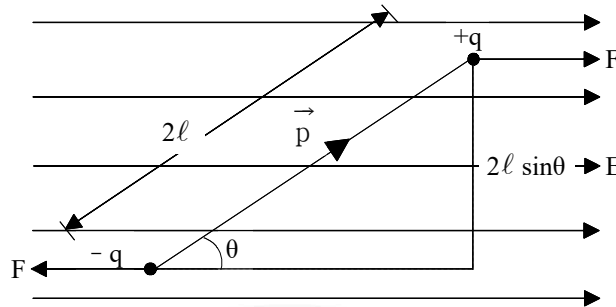
- NOTE** ↗
- (i) This is not essential that at a point, where $E = 0$, V will also be zero there eg. inside a uniformly charged sphere, $E = 0$ but $V \neq 0$
 - (ii) Also if $V = 0$, it is not essential for E to be zero eg. in equatorial position of dipole $V = 0$, but $E \neq 0$

Electric Dipole In an Electric Field – Uniform Electric Field

(i) When an electric dipole is placed in a uniform electric field, A torque acts on it which subjects the dipole to rotatory motion. This τ is given by $\tau = pE \sin\theta$ or $\vec{\tau} = \vec{p} \times \vec{E}$

(ii) Potential energy of the dipole

$$U = -pE \cos\theta = -\vec{p} \cdot \vec{E}$$



Cases

- If $\theta = 0^\circ$, i.e. $\vec{p} \parallel \vec{E}$, $\tau = 0$ and $U = -pE$, dipole is in the minimum potential energy state and no torque acting on it and hence it is in the stable equilibrium state.
- For $\theta = 180^\circ$, i.e. \vec{p} and \vec{E} are in opposite direction, then $\tau = 0$ but $U = pE$ which is maximum potential energy state. Although it is in equilibrium but it is not a stable state and a slight perturbation can disturb it.
- $\theta = 90^\circ$, i.e. $\vec{p} \perp \vec{E}$, then $\tau = pE$ (maximum) and $U = 0$

Work done in rotating an electric dipole in and electric field

- To rotate the dipole by an angle θ from the state of stable equilibrium $W = pE(1 - \cos\theta)$.
- Work done in rotating the dipole from θ_1 to θ_2 in an uniform electric field $W = pE(\cos\theta_1 - \cos\theta_2)$
- Work done in rotating the dipole through 180° from stable equilibrium state $W = 2pE = 2$ (potential energy)

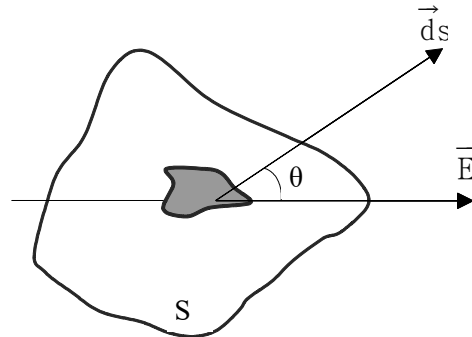
06. Electric Flux

- It is denoted by ' ϕ '.
- It is a scalar quantity.
- It is defined as the total number of lines of force passing normally through a curved surface placed in the field.
- It is given by the dot product of \vec{E} and normal infinitesimal \vec{ds} area integrated over a closed surface.

$$d\phi = \vec{E} \cdot \vec{ds}$$

$$\phi = \oint \vec{E} \cdot \vec{ds} = \oint E ds \cos\theta$$

where θ = angle between electric field and normal to the area



- (v) Unit : (a) $\text{N}\cdot\text{m}^2/\text{C}$ (b) volt – meter
- (vi) Dimension : $[\text{ML}^3\text{T}^{-3}\text{A}^{-1}]$
- (vii) Flux due to a positive charge goes out of the surface while that due to negative charge comes into the surface.
- (viii) Value of electric flux is independent of shape and size of the surface.
- (ix) If only a dipole is present in the surface then net flux is zero.
- (x) Net flux from a surface is zero does not imply that intensity of electric field is also zero.

07. Gauss's Law

This law states that electric flux ϕ_E through any closed surface is equal to $1/\epsilon_0$ times the net charge 'q' enclosed by the surface i.e

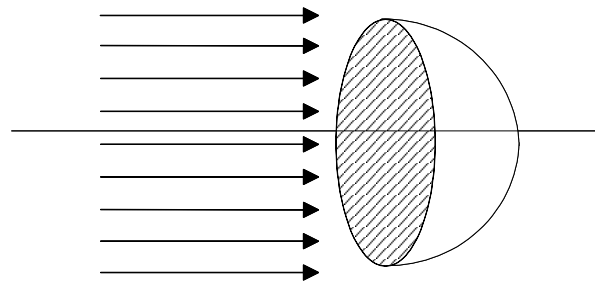
$$\phi_E = \oint \vec{E} \cdot \vec{ds} = \frac{q}{\epsilon_0}$$

Important point about flux

- Independent of distances between charges inside the surface and their distribution.
- Independent of shape, size and nature of surface.
- Net flux due to a charge outside the surface will be zero.
- Gauss law is valid only for the vector fields which obey inverse square law

Example

A hemispherical surface of radius R is kept in a uniform electric field E such that E is parallel to the axis of hemi-sphere, Net flux from the surface will be

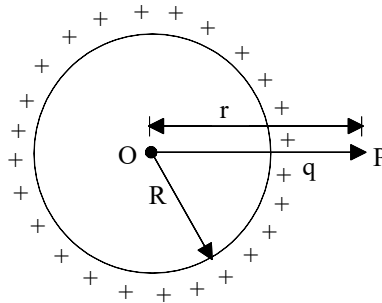


Solution

$$\begin{aligned} \phi &= \oint \vec{E} \cdot \vec{ds} = E \cdot \pi R^2 \\ &= (E) (\text{Area of surface perpendicular to } E) \\ &= E \cdot \pi R^2. \end{aligned}$$

08. Application of Gauss's Law

Electric field due to a solid conducting sphere/Hollow conducting sphere.



(i) **Case: 1** $r > R$ $\vec{E} = \frac{kq}{r^2} \hat{r} = \frac{1}{\epsilon_0} \frac{\sigma R^2}{r^2} \hat{r}$

Case: 2 $r = R$ $\vec{E} = \frac{\sigma}{\epsilon_0} \hat{r}$

Case: 3 $r < R$ $\vec{E} = 0$

i.e. At point interior to a conducting or a hollow sphere, electric field intensity is zero.

- (ii) For points outside the sphere, it behaves like all the charge is present at the centre.
 (iii) Intensity of electric field is maximum at the surface

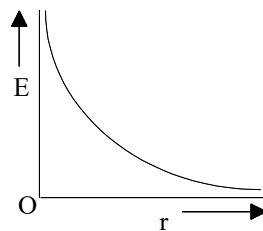
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- (iv) Electric field at the surface is always perpendicular to the surface.
 (v) For points, near the surface of the conductor, $E = \frac{\sigma}{\epsilon_0}$ perpendicular to the surface

Electric field due to infinitely long charge

- (i) A long wire is given a line charge density λ . If wire is positively charged, direction of \vec{E} will be away from the wire (outward \perp) while for a negatively charged wire, direction of \vec{E} will be (inward \perp) towards the wire.
 (ii) E at point p

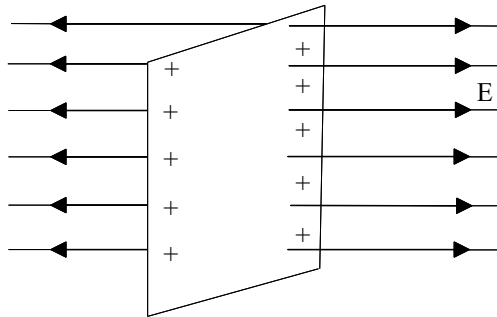
$$\vec{E} = \frac{\lambda}{2\pi\epsilon_0 r} \hat{r} \quad \text{or} \quad E = \frac{\lambda}{2\pi\epsilon_0 r}$$



- (iii) Potential difference between points A (r_1) & B(r_2) = $V_2 - V_B = \frac{\lambda}{2\pi\epsilon_0} \ln \left(\frac{r_2}{r_1} \right)$
 (iv) Potential difference between points A (r_1) & B(r_2) = $V_2 - V_B = \frac{\lambda}{2\pi\epsilon_0} \ln \left(\frac{r_2}{r_1} \right)$

Electric field at a point due to an infinite sheet of charge

- (i) If σ = surface charge density. Intensity at points near to the sheet $\vec{E} = \frac{\sigma}{2\epsilon_0} \hat{r}$



- (ii) Direction of electric field is perpendicular to the sheet of charge.
 (iii) Intensity of electric field does not depend upon the distance of points from the sheet for the points in front of sheet i.e. There is an equipotential region near the charged sheet.
 (iv) Potential difference between two points A & B at distances r_1 & r_2 respectively is

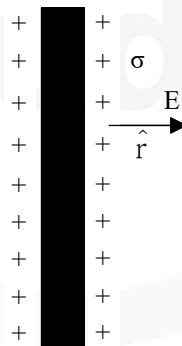
$$V_A - V_B = \frac{\sigma}{2\epsilon_0} (r_2 - r_1)$$

Electric field due to infinite charged metal plate

- (i) Intensity at points near the plate $\vec{E} = \frac{\sigma}{\epsilon_0} \hat{r}$

where σ = surface charge density

- (ii) \vec{E} is independent of distance of the point from the plate and also of the area of sheet i.e. There is an equipotential region near the plate.



- (iii) Direction of electric field is perpendicular to the plate.
 (iv) Potential difference between two point A (r_1) and B (r_2) ($r_1 < r_2$) near the plate is

$$\Delta V = V_A - V_B = \frac{\sigma}{\epsilon_0} (r_2 - r_1)$$

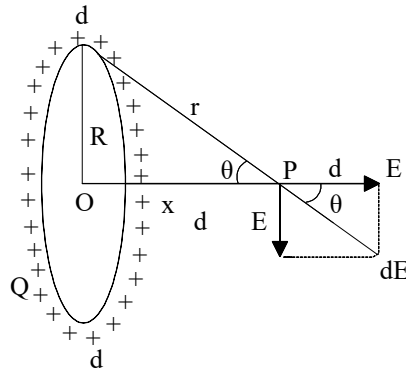
Electric field due to charged ring : Q charge is distributed over a ring of radius R.

- (i) Intensity of electric field at a distance x from the centre of ring along it's axis-

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q \cos\theta}{r^2} = \frac{Qx}{4\pi\epsilon_0 r^3} \quad (\because \cos\theta = x/r)$$

$$= \frac{1}{4\pi\epsilon_0} \frac{Qx}{(R^2 + x^2)^{3/2}} \quad [\because r = \sqrt{R^2 + x^2}]$$

and it's direction will be along the axis of the ring.



- (ii) Intensity will be zero at the centre of the ring.
 (iii) Intensity will be maximum at a distance $R/\sqrt{2}$ from the centre and

$$E_{\max} = \frac{2}{3\sqrt{3}} \cdot \frac{1}{4\pi\epsilon_0} \cdot \frac{Q}{R^2}$$

- (iv) Electric potential at a distance x from centre,

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{\sqrt{(x^2 + R^2)}}$$

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JEE Main Pattern Exercise (1)

1. A particle of charges Q and mass m travels through a potential difference V from rest. The final momentum of the particle is

- (a) $\frac{mv}{Q}$ (c) $\sqrt{2mQV}$
 (b) $2Q\sqrt{mV}$ (d) $\sqrt{\frac{2QV}{m}}$

2. Three concentric conducting spherical shells carry charges as follows $+4Q$ on the inner shell, $-2Q$ on the middle shell and $-5Q$ on the outer shell. The charge on the inner surface of the outer shell is

- (a) 0 (c) $-Q$
 (b) $4Q$ (d) $-2Q$

3. The work done against electric forces in increasing the potential difference of a condenser from 20V to 40V is W . The work done in increasing its potential difference from 40V to 50 V will be

- (a) $4W$ (c) $2W$
 (b) $\frac{3W}{4}$ (d) $\frac{W}{2}$

4. The plate separation in a parallel plate condenser is d and plate area is A . If it is charged to V volt and battery is disconnected then the work done in increasing the plate separation to $2d$ will be

- (a) $\frac{3}{2} \frac{\epsilon_0 A V^2}{d}$ (c) $\frac{2\epsilon_0 A V^2}{d}$
 (b) $\frac{\epsilon_0 A V^2}{d}$ (d) $\frac{\epsilon_0 A V^2}{2d}$

5. A parallel plate condenser is connected to a battery of e.m.f. 4 volt. If a plate of dielectric constant 8 is inserted into it, then the potential difference on the condenser will be

- (a) 0.5V (c) 4V
 (b) 2V (d) 32V

01 Electrostatics-I

6. A solid sphere of radius R is charged uniformly. At what distance from its surface is the electrostatic potential half of the potential at the centre?
- (a) R (c) $R/3$
(b) $R/2$ (d) $2R$
7. A particle of charge $1 \mu\text{C}$ and mass 1 gm moving with a velocity of 4 m/s is subjected to a uniform electric field of magnitude 300 V/m for 10s . Its final speed cannot be
- (a) 0.5 m/s (c) 3 m/s
(b) 4 m/s (d) 6 m/s
8. Electric field on the axis of a small electric dipole at a distance r is \vec{E}_1 and \vec{E}_2 at a distance of $2r$ on a line of perpendicular bisector. Then
- (a) $\vec{E}_2 = -\vec{E}_{1/8}$ (c) $\vec{E}_2 = -\vec{E}_{1/4}$
(b) $\vec{E}_2 = -\vec{E}_{1/16}$ (d) $\vec{E}_2 = \vec{E}_{1/8}$
9. An electric field is given by $\vec{E} = (y\hat{i} + x\hat{j})\text{N/C}$. The work done in moving a 1C charge from $\vec{r}_A = (2\hat{i} + 2\hat{j})\text{m}$ to $\vec{r}_B = (4\hat{i} + \hat{j})\text{m}$ is
- (a) $+ 4 \text{ J}$ (c) $+ 8 \text{ J}$
(b) $- 4 \text{ J}$ (d) zero
10. A hollow metal sphere of radius 5 cm is charged such that the potential on its surface is 10 V . The potential at the centre of the sphere is
- (a) zero
(b) 10 V
(c) same as at a point 5 cm away from the surface
(d) same as at a point 25 cm away from the surface

JEE Advanced Pattern Exercise (1)

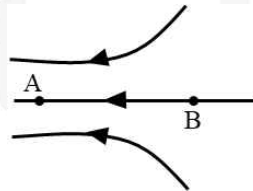
(Q1 & 2) Only One Correct Option

- The potential field of an electric field $\vec{E} = (y\hat{i} + x\hat{j})$ is
 - $V = -xy + \text{constant}$
 - $V = -(x + y) + \text{constant}$
 - $V = -(x^2 + y^2) + \text{constant}$
 - $V = \text{constant}$
- Capacity of an isolated sphere is increased n times when it is enclosed by an earthed concentric sphere. The ratio of their radii is

<ol style="list-style-type: none"> $\frac{n^2}{n-1}$ $\frac{n}{n-1}$ 	<ol style="list-style-type: none"> $\frac{2n}{n+1}$ $\frac{2n+1}{n+1}$
--	--

(Q3) More than One Correct Option

- Figure shows some of the electric field lines corresponding to an electric field. The figure suggests that ($E =$ electric field, $V =$ potential)



- | | |
|--|--|
| <ol style="list-style-type: none"> $E_A > E_B$ $E_A < E_B$ | <ol style="list-style-type: none"> $V_A > V_B$ $V_A < V_B$ |
|--|--|

(Q4 to 5) Comprehension Type

Passage

A charge $q = (-2 \times 10^{-9})$ C is placed at $(1\text{m}, 2\text{m}, 3\text{m})$. There is a point $P = (2\text{m}, -3\text{m}, 4\text{m})$

- A unit vector in the direction of electric field at P due to charge q will be

- | | |
|---|---|
| <ol style="list-style-type: none"> $\frac{1}{3\sqrt{3}}(\hat{i} - 5\hat{j} + \hat{k})$ $\frac{1}{3\sqrt{3}}(-\hat{i} + 5\hat{j} - \hat{k})$ | <ol style="list-style-type: none"> $\frac{1}{5\sqrt{2}}(3\hat{i} + 4\hat{j} - 5\hat{k})$ $\frac{1}{5\sqrt{2}}(-3\hat{i} + 4\hat{j} - 5\hat{k})$ |
|---|---|

5. Component of electric field along x -axis at point P would be

- (a) $\frac{1}{5\sqrt{3}}$ N/C (c) $\frac{2}{9\sqrt{3}}$ N/C
 (b) $\frac{9}{5\sqrt{3}}$ N/C (d) $8\sqrt{3}$ N/C

(Q6 & 7) Only One Correct Option

6. A spherical charged conductor has surface charge density σ . The electric field on its surface is E and electric potential of conductor is V . Now the radius of the sphere is halved keeping the charge to be constant. The new values of electric field and potential would be

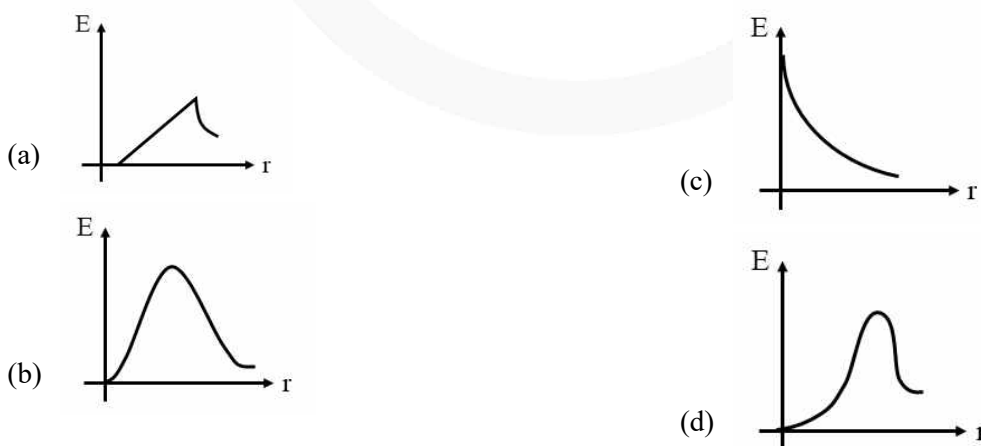
- (a) $2E, 2V$ (c) $4E, 4V$
 (b) $4E, 2V$ (d) $2E, 4V$

7. Two concentric spherical conducting shells of radii R and $2R$ carry charges Q and $2Q$ respectively. Change in electric potential on the outer shell when both are connected by a conducting wire is $\left(k = \frac{1}{4\pi\epsilon_0}\right)$

- (a) zero (c) $\frac{kQ}{R}$
 (b) $\frac{3kQ}{2R}$ (d) $\frac{2kQ}{R}$

(Q8) More than One Correct Option

8. A circular ring carries a uniformly distributed positive charge. The electric field (E) and potential (V) varies with distance (r) from the centre of the ring along its axis as



(Q9) Matrix Match Type

9. In the figure shown, P is a point on the surface of an imaginary sphere. Match the following.

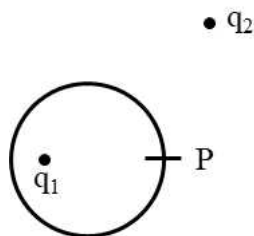


Table-1	Table-2
(a) Electric field at point P	(p) due to q_1 only
(b) Electric flux through a small area at P	(q) due to q_2 only
(c) Net electric flux through whole sphere	(r) due to both q_1 and q_2

(Q10) Integer Type

10. The centers of two identical small conducting spheres are 1 m apart. They carry charges of opposite kind and attract each other with a force F . When they are connected by conducting thin wire they repel each other with a force $F/3$. The ratio of magnitude of charges carried by the spheres initially is $n : 1$. Find value of n .