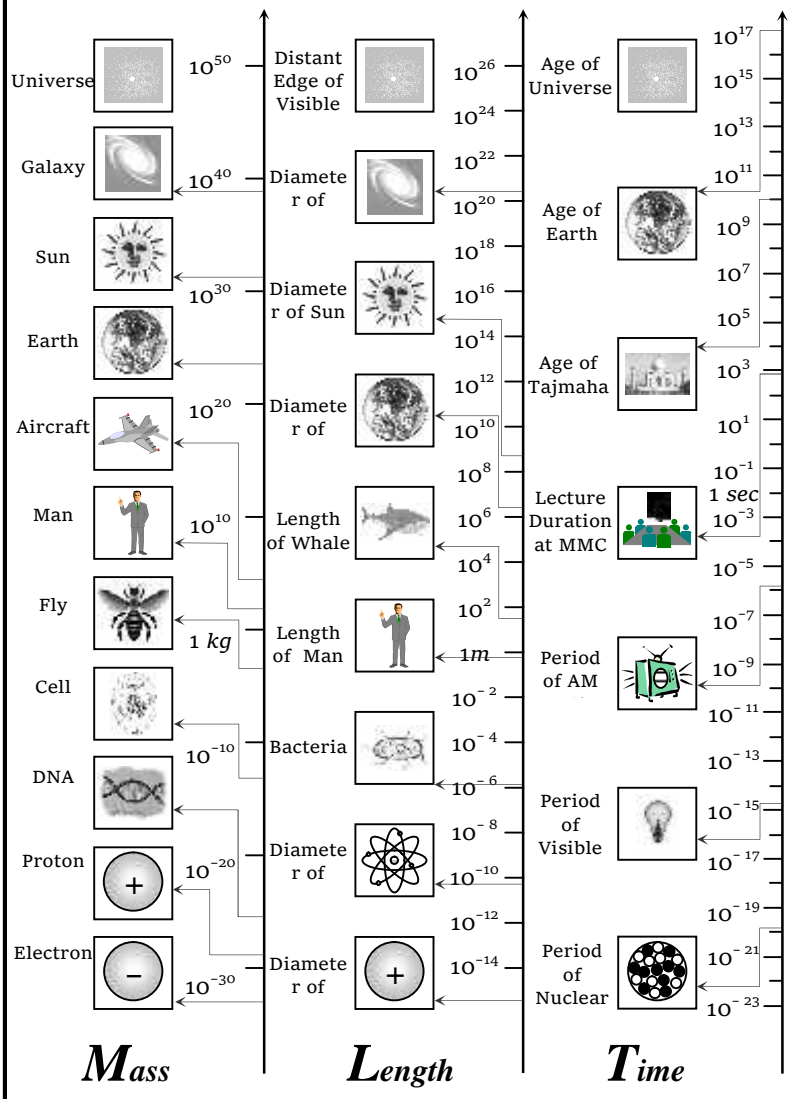




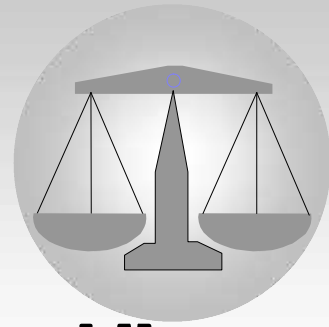
Chapter
1

Units, Dimensions and Measurement

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An indication of range over which measurements are made. Measurements of Time and Length extend over a range of 10^{40} and measurement of Mass extend over a range 10^{80} .



Units, Dimensions and Measurement

1.1 Physical Quantity

A quantity which can be measured and by which various physical happenings can be explained and expressed in form of laws is called a physical quantity. For example length, mass, time, force *etc.*

On the other hand various happenings in life *e.g.*, happiness, sorrow *etc.* are not physical quantities because these can not be measured.

Measurement is necessary to determine magnitude of a physical quantity, to compare two similar physical quantities and to prove physical laws or equations.

A physical quantity is represented completely by its magnitude and unit. For example, 10 *metre* means a length which is ten times the unit of length 1 *kg*. Here 10 represents the numerical value of the given quantity and *metre* represents the unit of quantity under consideration. Thus in expressing a physical quantity we choose a unit and then find that how many times that unit is contained in the given physical quantity, *i.e.*

$$\text{Physical quantity } (Q) = \text{Magnitude} \times \text{Unit} = n \times u$$

Where, n represents the numerical value and u represents the unit. Thus while expressing definite amount of physical quantity, it is clear that as the unit(u) changes, the magnitude(n) will also change but product ' nu ' will remain same.

$$\text{i.e.} \quad n u = \text{constant}, \quad \text{or} \quad n_1 u_1 = n_2 u_2 = \text{constant}; \quad \therefore n \propto \frac{1}{u}$$

i.e. magnitude of a physical quantity and units are inversely proportional to each other. Larger the unit, smaller will be the magnitude.

1.2 Types of Physical Quantity

(1) **Ratio (numerical value only)** : When a physical quantity is a ratio of two similar quantities, it has no unit.

e.g. Relative density = Density of object/Density of water at 4°C

Refractive index = Velocity of light in air/Velocity of light in medium

Strain = Change in dimension/Original dimension

Note : Angle is exceptional physical quantity, which though is a ratio of two similar physical quantities (angle = arc / radius) but still requires a unit (degrees or radians) to specify it along with its numerical value.

(2) **Scalar (Magnitude only)** : These quantities do not have any direction *e.g.* Length, time, work, energy *etc.*

Magnitude of a physical quantity can be negative. In that case negative sign indicates that the numerical value of the quantity under consideration is negative. It does not specify the direction.

Scalar quantities can be added or subtracted with the help of following ordinary laws of addition or subtraction.

(3) **Vector (magnitude and direction)** : *e.g.* displacement, velocity, acceleration, force *etc.*

Vector physical quantities can be added or subtracted according to vector laws of addition. These laws are different from laws of ordinary addition.

Note : □ There are certain physical quantities which behave neither as scalar nor as vector. For example, moment of inertia is not a vector as by changing the sense of rotation its value is not changed. It is also not a scalar as it has different values in different directions (*i.e.* about different axes). Such physical quantities are called Tensors.

1.3 Fundamental and Derived Quantities

(1) **Fundamental quantities** : Out of large number of physical quantities which exist in nature, there are only few quantities which are independent of all other quantities and do not require the help of any other physical quantity for their definition, therefore these are called absolute quantities. These quantities are also called fundamental or base quantities, as all other quantities are based upon and can be expressed in terms of these quantities.

(2) **Derived quantities**: All other physical quantities can be derived by suitable multiplication or division of different powers of fundamental quantities. These are therefore called derived quantities.

If length is defined as a fundamental quantity then area and volume are derived from length and are expressed in term of length with power 2 and 3 over the term of length.

Note : □ In mechanics Length, Mass and time are arbitrarily chosen as fundamental quantities. However this set of fundamental quantities is not a unique choice. In fact any three quantities in mechanics can be termed as fundamental as all other quantities in mechanics can be expressed in terms of these. *e.g.* if speed and time are taken as fundamental quantities, length will become a derived quantity because then length will be expressed as $\text{Speed} \times \text{Time}$. and if force and acceleration are taken as fundamental quantities, then mass will be defined as $\text{Force} / \text{acceleration}$ and will be termed as a derived quantity.

1.4 Fundamental and Derived Units

Normally each physical quantity requires a unit or standard for its specification so it appears that there must be as many units as there are physical quantities. However, it is not so. It has been found that if in *mechanics* we choose arbitrarily units of any *three* physical quantities we can express the units of all other physical quantities in mechanics in terms of these. Arbitrarily the physical quantities *mass*, *length* and *time* are chosen for this purpose. *So any unit of mass, length and time in mechanics is called a fundamental, absolute or base unit. Other units which can be expressed in terms of fundamental units, are called derived units.* For example light year or *km* is a fundamental units as it is a unit of length while s^{-1} , m^2 or kg/m are derived units as these are derived from units of time, mass and length respectively.

System of units : A complete set of units, both fundamental and derived for all kinds of physical quantities is called system of units. The common systems are given below –

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(1) **CGS system** : The system is also called Gaussian system of units. In it length, mass and time have been chosen as the fundamental quantities and corresponding fundamental units are centimetre (*cm*), gram (*g*) and second (*s*) respectively.

(2) **MKS system** : The system is also called Giorgi system. In this system also length, mass and time have been taken as fundamental quantities, and the corresponding fundamental units are *metre*, kilogram and second.

(3) **FPS system** : In this system foot, pound and second are used respectively for measurements of length, mass and time. In this system force is a derived quantity with unit poundal.

(4) **S. I. system** : It is known as International system of units, and is infact extended system of units applied to whole physics. There are seven fundamental quantities in this system. These quantities and their units are given in the following table

Quantity	Name of Unit	Symbol
Length	metre	<i>m</i>
Mass	kilogram	<i>kg</i>
Time	second	<i>s</i>
Electric Current	ampere	<i>A</i>
Temperature	Kelvin	<i>K</i>
Amount of Substance	mole	<i>mol</i>
Luminous Intensity	candela	<i>cd</i>

Besides the above seven fundamental units two supplementary units are also defined – Radian (*rad*) for plane angle and Steradian (*sr*) for solid angle.

Note : Apart from fundamental and derived units we also use very frequently practical units. These may be fundamental or derived units

e.g., light year is a practical unit (fundamental) of distance while horse power is a practical unit (derived) of power.

Practical units may or may not belong to a system but can be expressed in any system of units
e.g., 1 mile = 1.6 km = 1.6×10^3 m.

1.5 S.I. Prefixes

In physics we have to deal from very small (*micro*) to very large (*macro*) magnitudes as one side we talk about the atom while on the other side of universe, *e.g.*, the mass of an electron is 9.1×10^{-31} kg while that of the sun is 2×10^{30} kg. To express such large or small magnitudes simultaneously we use the following prefixes :

Power of 10	Prefix	Symbol
10^{18}	exa	<i>E</i>

10^{15}	peta	<i>P</i>
10^{12}	tera	<i>T</i>
10^9	giga	<i>G</i>
10^6	mega	<i>M</i>
10^3	kilo	<i>k</i>
10^2	hecto	<i>h</i>
10^1	deca	<i>da</i>
10^{-1}	deci	<i>d</i>
10^{-1}	centi	<i>c</i>
10^{-3}	milli	<i>m</i>
10^{-6}	micro	\sim
10^{-9}	nano	<i>n</i>
10^{-12}	pico	<i>p</i>
10^{-15}	femto	<i>f</i>
10^{-18}	atto	<i>a</i>

1.6 Standards of Length, Mass and Time

(1) **Length** : Standard metre is defined in terms of wavelength of light and is called atomic standard of length.

The metre is the distance containing 1650763.73 wavelength in vacuum of the radiation corresponding to orange red light emitted by an atom of krypton-86.

Now a days metre is defined as length of the path travelled by light in vacuum in $1/299,7792,458$ part of a second.

(2) **Mass** : The mass of a cylinder made of platinum-iridium alloy kept at International Bureau of Weights and Measures is defined as 1 *kg*.

On atomic scale, 1 *kilogram* is equivalent to the mass of 5.0188×10^{25} atoms of ${}^6\text{C}^{12}$ (an isotope of carbon).

(3) **Time** : 1 *second* is defined as the time interval of 9192631770 vibrations of radiation in Cs-133 atom. This radiation corresponds to the transition between two hyperfine level of the ground state of Cs-133.

1.7 Practical Units

(1) **Length** :

(i) 1 fermi = 1 *fm* = 10^{-15} *m*

(ii) 1 X-ray unit = 1*XU* = 10^{-13} *m*

(iii) 1 angstrom = 1 \AA = 10^{-10} *m* = 10^{-8} *cm* = 10^{-7} *mm* = 0.1 \sim *mm*

(iv) 1 micron = \sim *m* = 10^{-6} *m*

(v) 1 astronomical unit = 1 *A.U.* = 1.49×10^{11} *m* \approx 1.5×10^{11} *m* \approx 10^8 *km*

(vi) 1 Light year = 1 *ly* = 9.46×10^{15} *m*

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(vii) 1 Parsec = 1pc = 3.26 light year

(2) **Mass :**

(i) Chandra Shekhar unit : 1 CSU = 1.4 times the mass of sun = 2.8×10^{30} kg

(ii) Metric tonne : 1 Metric tonne = 1000 kg

(iii) Quintal : 1 Quintal = 100 kg

(iv) Atomic mass unit (amu) : amu = 1.67×10^{-27} kg mass of proton or neutron is of the order of 1 amu

(3) **Time :**

(i) Year : It is the time taken by earth to complete 1 revolution around the sun in its orbit.

(ii) Lunar month : It is the time taken by moon to complete 1 revolution around the earth in its orbit.

$$1 L.M. = 27.3 \text{ days}$$

(iii) Solar day : It is the time taken by earth to complete one rotation about its axis with respect to sun. Since this time varies from day to day, average solar day is calculated by taking average of the duration of all the days in a year and this is called Average Solar day.

$$1 \text{ Solar year} = 365.25 \text{ average solar day}$$

or average solar day = $\frac{1}{365.25}$ the part of solar year

(iv) Sedrial day : It is the time taken by earth to complete one rotation about its axis with respect to a distant star.

$$1 \text{ Solar year} = 366.25 \text{ Sedrial day} = 365.25 \text{ average solar day}$$

Thus 1 Sedrial day is less than 1 solar day.

(v) Shake : It is an obsolete and practical unit of time.

$$1 \text{ Shake} = 10^{-8} \text{ sec}$$

1.8 Dimensions of a Physical Quantity

When a derived quantity is expressed in terms of fundamental quantities, it is written as a product of different powers of the fundamental quantities. The powers to which fundamental quantities must be raised in order to express the given physical quantity are called its dimensions.

To make it more clear, consider the physical quantity force

$$\text{Force} = \text{mass} \times \text{acceleration} = \frac{\text{mass} \times \text{velocity}}{\text{time}} = \frac{\text{mass} \times \text{length/time}}{\text{time}} = \text{mass} \times \text{length} \times (\text{time})^{-2} \dots (i)$$

Thus, the dimensions of force are 1 in mass, 1 in length and -2 in time.

Here the physical quantity that is expressed in terms of the base quantities is enclosed in square brackets to indicate that the equation is among the dimensions and not among the magnitudes.

Thus equation (i) can be written as [force] = $[MLT^{-2}]$.

Such an expression for a physical quantity in terms of the fundamental quantities is called the dimensional equation. If we consider only the R.H.S. of the equation, the expression is termed as dimensional formula.

Thus, dimensional formula for force is, $[MLT^{-2}]$.

1.9 Important Dimensions of Complete Physics

Mechanics

S. N.	Quantity	Unit	Dimension
(1)	Velocity or speed (v)	m/s	$[M^0L^1T^{-1}]$
(2)	Acceleration (a)	m/s^2	$[M^0LT^{-2}]$
(3)	Momentum (P)	$kg\cdot m/s$	$[M^1L^1T^{-1}]$
(4)	Impulse (I)	<i>Newton-sec</i> or $kg\cdot m/s$	$[M^1L^1T^{-1}]$
(5)	Force (F)	<i>Newton</i>	$[M^1L^1T^{-2}]$
(6)	Pressure (P)	<i>Pascal</i>	$[M^1L^{-1}T^{-2}]$
(7)	Kinetic energy (E_K)	<i>Joule</i>	$[M^1L^2T^{-2}]$
(8)	Power (P)	<i>Watt</i> or <i>Joule/s</i>	$[M^1L^2T^{-3}]$
(9)	Density (d)	kg/m^3	$[M^1L^{-3}T^0]$
(10)	Angular displacement (θ)	<i>Radian (rad.)</i>	$[M^0L^0T^0]$
(11)	Angular velocity ($\dot{\theta}$)	<i>Radian/sec</i>	$[M^0L^0T^{-1}]$
(12)	Angular acceleration ($\ddot{\theta}$)	<i>Radian/sec²</i>	$[M^0L^0T^{-2}]$
(13)	Moment of inertia (I)	$kg\cdot m^2$	$[M^1L^2T^0]$
(14)	Torque (τ)	<i>Newton-meter</i>	$[M^1L^2T^{-2}]$
(15)	Angular momentum (L)	<i>Joule-sec</i>	$[M^1L^2T^{-1}]$
(16)	Force constant or spring constant (k)	<i>Newton/m</i>	$[M^1L^0T^{-2}]$
(17)	Gravitational constant (G)	$N\cdot m^2/kg^2$	$[M^{-1}L^3T^{-2}]$
(18)	Intensity of gravitational field (E_g)	N/kg	$[M^0L^1T^{-2}]$
(19)	Gravitational potential (V_g)	<i>Joule/kg</i>	$[M^0L^2T^{-2}]$
(20)	Surface tension (T)	N/m or <i>Joule/m²</i>	$[M^1L^0T^{-2}]$
(21)	Velocity gradient (V_g)	$Second^{-1}$	$[M^0L^0T^{-1}]$
(22)	Coefficient of viscosity (η)	$kg/m\cdot s$	$[M^1L^{-1}T^{-1}]$
(23)	Stress	N/m^2	$[M^1L^{-1}T^{-2}]$
(24)	Strain	No unit	$[M^0L^0T^0]$
(25)	Modulus of elasticity (E)	N/m^2	$[M^1L^{-1}T^{-2}]$
(26)	Poisson Ratio (ν)	No unit	$[M^0L^0T^0]$
(27)	Time period (T)	<i>Second</i>	$[M^0L^0T^1]$
(28)	Frequency (n)	<i>Hz</i>	$[M^0L^0T^{-1}]$

Heat

S. N.	Quantity	Unit	Dimension
(1)	Temperature (T)	<i>Kelvin</i>	$[M^0L^0T^0, ^\circ]$
(2)	Heat (Q)	<i>Joule</i>	$[ML^2T^{-2}]$

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S. N.	Quantity	Unit	Dimension
(3)	Specific Heat (c)	<i>Joule/kg-K</i>	$[M^0L^2T^{-2}K^{-1}]$
(4)	Thermal capacity	<i>Joule/K</i>	$[M^1L^2T^{-2}K^{-1}]$
(5)	Latent heat (L)	<i>Joule/kg</i>	$[M^0L^2T^{-2}]$
(6)	Gas constant (R)	<i>Joule/mol-K</i>	$[M^1L^2T^{-2}K^{-1}]$
(7)	Boltzmann constant (k)	<i>Joule/K</i>	$[M^1L^2T^{-2}K^{-1}]$
(8)	Coefficient of thermal conductivity (K)	<i>Joule/m-s-K</i>	$[M^1L^1T^{-3}K^{-1}]$
(9)	Stefan's constant (\dagger)	<i>Watt/m²-K⁴</i>	$[M^1L^0T^{-3}K^{-4}]$
(10)	Wien's constant (b)	<i>Meter-K</i>	$[M^0L^1T^0K^{-1}]$
(11)	Planck's constant (h)	<i>Joule-s</i>	$[M^1L^2T^{-1}]$
(12)	Coefficient of Linear Expansion (α)	<i>Kelvin⁻¹</i>	$[M^0L^0T^0K^{-1}]$
(13)	Mechanical eq. of Heat (J)	<i>Joule/Calorie</i>	$[M^0L^0T^0]$
(14)	Vander wall's constant (a)	<i>Newton-m⁴</i>	$[ML^5T^{-2}]$
(15)	Vander wall's constant (b)	<i>m³</i>	$[M^0L^3T^0]$

Electricity

S. N.	Quantity	Unit	Dimension
(1)	Electric charge (q)	<i>Coulomb</i>	$[M^0L^0TA^1]$
(2)	Electric current (I)	<i>Ampere</i>	$[M^0L^0TA^{-1}]$
(3)	Capacitance (C)	<i>Coulomb/volt or Farad</i>	$[M^{-1}L^{-2}T^4A^2]$
(4)	Electric potential (V)	<i>Joule/coulomb</i>	$M^1L^2T^{-3}A^{-1}$
(5)	Permittivity of free space (ϵ_0)	$\frac{\text{Coulomb}^2}{\text{Newton} \cdot \text{meter}^2}$	$[M^{-1}L^{-3}T^4A^2]$
(6)	Dielectric constant (K)	Unitless	$[M^0L^0T^0]$
(7)	Resistance (R)	<i>Volt/Ampere or ohm</i>	$[M^1L^2T^{-3}A^{-2}]$
(8)	Resistivity or Specific resistance (...)	<i>Ohm-meter</i>	$[M^1L^3T^{-3}A^{-2}]$
(9)	Coefficient of Self-induction (L)	$\frac{\text{volt} \cdot \text{second}}{\text{ampere}}$ or <i>henery or ohm-second</i>	$[M^1L^2T^{-2}A^{-2}]$
(10)	Magnetic flux (ω)	<i>Volt-second or weber</i>	$[M^1L^2T^{-2}A^{-1}]$
(11)	Magnetic induction (B)	$\frac{\text{newton}}{\text{ampere} \cdot \text{meter}} \frac{\text{Joule}}{\text{ampere} \cdot \text{meter}^2}$ $\frac{\text{volt} \cdot \text{second}}{\text{meter}^2}$ or <i>Tesla</i>	$[M^1L^0T^{-2}A^{-1}]$
(12)	Magnetic Intensity (H)	<i>Ampere/meter</i>	$[M^0L^{-1}T^0A^1]$
(13)	Magnetic Dipole Moment (M)	<i>Ampere-meter²</i>	$[M^0L^2T^0A^1]$
(14)	Permeability of Free Space (μ_0)	$\frac{\text{Newton}}{\text{ampere}^2}$ or $\frac{\text{Joule}}{\text{ampere}^2 \cdot \text{meter}}$ or $\frac{\text{Volt} \cdot \text{second}}{\text{ampere} \cdot \text{meter}}$ or $\frac{\text{Ohm} \cdot \text{second}}{\text{meter}}$ or $\frac{\text{henery}}{\text{meter}}$	$[M^1L^1T^{-2}A^{-2}]$

S. N.	Quantity	Unit	Dimension
(15)	Surface charge density (\dagger)	Coulomb metre ⁻²	$[M^0L^{-2}T^1A^1]$
(16)	Electric dipole moment (p)	Coulomb – meter	$[M^0L^1T^1A^1]$
(17)	Conductance (G) ($1/R$)	ohm ⁻¹	$[M^{-1}L^{-2}T^3A^2]$
(18)	Conductivity (\dagger) ($1/\dots$)	ohm ⁻¹ meter ⁻¹	$[M^{-1}L^{-3}T^3A^2]$
(19)	Current density (J)	Ampere/m ²	$M^0L^{-2}T^0A^1$
(20)	Intensity of electric field (E)	Volt/meter, Newton/coulomb	$M^1L^1T^{-3}A^{-1}$
(21)	Rydberg constant (R)	m ⁻¹	$M^0L^{-1}T^0$

1.10 Quantities Having Same Dimensions

S. N.	Dimension	Quantity
(1)	$[M^0L^0T^{-1}]$	Frequency, angular frequency, angular velocity, velocity gradient and decay constant
(2)	$[M^1L^2T^{-2}]$	Work, internal energy, potential energy, kinetic energy, torque, moment of force
(3)	$[M^1L^{-1}T^{-2}]$	Pressure, stress, Young's modulus, bulk modulus, modulus of rigidity, energy density
(4)	$[M^1L^1T^{-1}]$	Momentum, impulse
(5)	$[M^0L^1T^{-2}]$	Acceleration due to gravity, gravitational field intensity
(6)	$[M^1L^1T^{-2}]$	Thrust, force, weight, energy gradient
(7)	$[M^1L^2T^{-1}]$	Angular momentum and Planck's constant
(8)	$[M^1L^0T^{-2}]$	Surface tension, Surface energy (energy per unit area)
(9)	$[M^0L^0T^0]$	Strain, refractive index, relative density, angle, solid angle, distance gradient, relative permittivity (dielectric constant), relative permeability etc.
(10)	$[M^0L^2T^{-2}]$	Latent heat and gravitational potential
(11)	$[M^0L^2T^{-2} \text{ } ^{-1}]$	Thermal capacity, gas constant, Boltzmann constant and entropy
(12)	$[M^0L^0T^1]$	$\sqrt{l/g}, \sqrt{m/k}, \sqrt{R/g}$, where l = length g = acceleration due to gravity, m = mass, k = spring constant
(13)	$[M^0L^0T^1]$	$L/R, \sqrt{LC}, RC$ where L = inductance, R = resistance, C = capacitance
(14)	$[ML^2T^{-2}]$	$I^2Rt, \frac{V^2}{R}t, VIt, qV, LI^2, \frac{q^2}{C}, CV^2$ where I = current, t = time, q = charge, L = inductance, C = capacitance, R = resistance

1.11 Application of Dimensional Analysis

(1) **To find the unit of a physical quantity in a given system of units** : Writing the definition or formula for the physical quantity we find its dimensions. Now in the dimensional formula replacing M , L and T by the fundamental units of the required system we get the unit of physical quantity. However, sometimes to this unit we further assign a specific name, e.g., Work = Force \times Displacement

$$\text{So } [W] = [MLT^{-2}] \times [L] = [ML^2T^{-2}]$$

So its units in C.G.S. system will be $g \text{ cm}^2/\text{s}^2$ which is called *erg* while in M.K.S. system will be $kg \text{ m}^2/\text{s}^2$ which is called *joule*.

Sample problems based on unit finding

Problem 1. The equation $\left(P + \frac{a}{V^2}\right)(V - b) = \text{constant}$. The units of a is

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- (a) Dyne \times cm⁵ (b) Dyne \times cm⁴ (c) Dyne / cm³ (d) Dyne / cm²

Solution : (b) According to the principle of dimensional homogeneity $[P] = \left[\frac{a}{V^2} \right]$

$$\Rightarrow [a] = [P] [V^2] = [ML^{-1}T^{-2}][L^6] = [ML^5T^{-2}]$$

or unit of $a = gm \times cm^5 \times sec^{-2} = \text{Dyne} \times cm^4$

Problem 2. If $x = at + bt^2$, where x is the distance travelled by the body in kilometre while t the time in seconds, then the units of b are

- (a) km/s (b) km-s (c) km/s² (d) km-s²

Solution : (c) From the principle of dimensional homogeneity $[x] = [bt^2] \Rightarrow [b] = \left[\frac{x}{t^2} \right] \therefore \text{Unit of } b = km/s^2.$

Problem 3. The unit of absolute permittivity is

- (a) Farad - meter (b) Farad / meter (c) Farad/meter² (d) Farad

Solution : (b) From the formula $C = 4\pi\epsilon_0 R \therefore \epsilon_0 = \frac{C}{4\pi R}$

By substituting the unit of capacitance and radius : unit of $\epsilon_0 = \text{Farad/ meter}.$

Problem 4. Unit of Stefan's constant is

- (a) Js⁻¹ (b) Jm⁻²s⁻¹K⁻⁴ (c) Jm⁻² (d) Js

Solution : (b) Stefan's formula $\frac{Q}{At} = \dagger T^4 \therefore \dagger = \frac{Q}{AtT^4} \therefore \text{Unit of } \dagger = \frac{\text{Joule}}{m^2 \times \text{sec} \times K^4} = Jm^{-2}s^{-1}K^{-4}$

Problem 5. The unit of surface tension in SI system is

- (a) Dyne / cm² (b) Newton/m (c) Dyne/cm (d) Newton/m²

Solution : (b) From the formula of surface tension $T = \frac{F}{l}$

By substituting the S.I. units of force and length, we will get the unit of surface tension = Newton/m

Problem 6. A suitable unit for gravitational constant is

- (a) kg metre sec⁻¹ (b) Newton metre⁻¹ sec (c) Newton metre²kg⁻² (d) kg metre sec⁻¹

Solution : (c) As $F = \frac{Gm_1m_2}{r^2} \therefore G = \frac{Fr^2}{m_1m_2}$

Substituting the unit of above quantities unit of $G = \text{Newton metre}^2\text{kg}^{-2}.$

Problem 7. The SI unit of universal gas constant (R) is

- (a) Watt K⁻¹mol⁻¹ (b) Newton K⁻¹mol⁻¹ (c) Joule K⁻¹mol⁻¹ (d) Erg K⁻¹mol⁻¹

Solution : (c) Ideal gas equation $PV = nRT \therefore [R] = \frac{[P][V]}{[nT]} = \frac{[ML^{-1}T^{-2}][L^3]}{[mole][K]} = \frac{[ML^2T^{-2}]}{[mole][K]}$

So the unit will be Joule K⁻¹mol⁻¹.

(2) **To find dimensions of physical constant or coefficients** : As dimensions of a physical quantity are unique, we write any formula or equation incorporating the given constant and then by substituting the dimensional formulae of all other quantities, we can find the dimensions of the required constant or coefficient.

(i) Gravitational constant : According to Newton's law of gravitation $F = G \frac{m_1 m_2}{r^2}$ or $G = \frac{Fr^2}{m_1 m_2}$

Substituting the dimensions of all physical quantities $[G] = \frac{[MLT^{-2}][L^2]}{[M][M]} = [M^{-1}L^3T^{-2}]$

(ii) Planck constant : According to Planck $E = h\epsilon$ or $h = \frac{E}{\epsilon}$

Substituting the dimensions of all physical quantities $[h] = \frac{[ML^2T^{-2}]}{[T^{-1}]} = [ML^2T^{-1}]$

(iii) Coefficient of viscosity : According to Poiseuille's formula $\frac{dV}{dt} = \frac{fpr^4}{8\eta l}$ or $\eta = \frac{fpr^4}{8l(dV/dt)}$

Substituting the dimensions of all physical quantities $[\eta] = \frac{[ML^{-1}T^{-2}][L^4]}{[L][L^3/T]} = [ML^{-1}T^{-1}]$

Sample problems based on dimension finding

Problem 8. $X = 3YZ^2$ find dimension of Y in (MKSA) system, if X and Z are the dimension of capacity and magnetic field respectively

- (a) $M^{-3}L^{-2}T^{-4}A^{-1}$ (b) ML^{-2} (c) $M^{-3}L^{-2}T^4A^4$ (d) $M^{-3}L^{-2}T^8A^4$

Solution : (d) $X = 3YZ^2 \therefore [Y] = \frac{[X]}{[Z^2]} = \frac{[M^{-1}L^{-2}T^4A^2]}{[MT^{-2}A^{-1}]^2} = [M^{-3}L^{-2}T^8A^4].$

Problem 9. Dimensions of $\frac{1}{\sqrt{\mu_0 \epsilon_0}}$, where symbols have their usual meaning, are

- (a) $[LT^{-1}]$ (b) $[L^{-1}T]$ (c) $[L^{-2}T^2]$ (d) $[L^2T^{-2}]$

Solution : (d) We know that velocity of light $C = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \therefore \frac{1}{\sqrt{\mu_0 \epsilon_0}} = C$

\therefore So $\left[\frac{1}{\sqrt{\mu_0 \epsilon_0}} \right] = [LT^{-1}]^2 = [L^2T^{-2}].$

Problem 10. If L , C and R denote the inductance, capacitance and resistance respectively, the dimensional formula for C^2LR is

- (a) $[ML^{-2}T^{-1}I^0]$ (b) $[M^0L^0T^3I^0]$ (c) $[M^{-1}L^{-2}T^6I^2]$ (d) $[M^0L^0T^2I^0]$

Solution : (b) $[C^2LR] = \left[C^2L^2 \frac{R}{L} \right] = \left[(LC)^2 \left(\frac{R}{L} \right) \right]$

and we know that frequency of LC circuits is given by $f = \frac{1}{2f} \frac{1}{\sqrt{LC}}$ i.e., the dimension of LC is equal to $[T^2]$ and $\left[\frac{L}{R}\right]$ gives the time constant of $L-R$ circuit so the dimension of $\frac{L}{R}$ is equal to $[T]$.

By substituting the above dimensions in the given formula $\left[(LC)^2\left(\frac{R}{L}\right)\right] = [T^2]^2 [T^{-1}] = [T^3]$.

Problem 11. A force F is given by $F = at + bt^2$, where t is time. What are the dimensions of a and b

- (a) MLT^{-3} and ML^2T^{-4} (b) MLT^{-3} and MLT^{-4} (c) MLT^{-1} and MLT^0 (d) MLT^{-4} and MLT^1

Solution : (b) From the principle of dimensional homogeneity $[F] = [at]$ $\therefore [a] = \left[\frac{F}{t}\right] = \left[\frac{MLT^{-2}}{T}\right] = [MLT^{-3}]$

Similarly $[F] = [bt^2]$ $\therefore [b] = \left[\frac{F}{t^2}\right] = \left[\frac{MLT^{-2}}{T^2}\right] = [MLT^{-4}]$.

Problem 12. The position of a particle at time t is given by the relation $x(t) = \left(\frac{v_0}{r}\right)(1 - e^{-rt})$, where v_0 is a constant and $r > 0$. The dimensions of v_0 and r are respectively

- (a) $M^0L^1T^{-1}$ and T^{-1} (b) $M^0L^1T^0$ and T^{-1} (c) $M^0L^1T^{-1}$ and LT^{-2} (d) $M^0L^1T^{-1}$ and T

Solution : (a) From the principle of dimensional homogeneity $[r t] = \text{dimensionless}$ $\therefore [r] = \left[\frac{1}{t}\right] = [T^{-1}]$

Similarly $[x] = \frac{[v_0]}{[r]}$ $\therefore [v_0] = [x][r] = [L][T^{-1}] = [LT^{-1}]$.

Problem 13. The dimensions of physical quantity X in the equation $\text{Force} = \frac{X}{\text{Density}}$ is given by

- (a) $M^1L^4T^{-2}$ (b) $M^2L^{-2}T^{-1}$ (c) $M^2L^{-2}T^{-2}$ (d) $M^1L^{-2}T^{-1}$

Solution : (c) $[X] = [\text{Force}] \times [\text{Density}] = [MLT^{-2}] \times [ML^{-3}] = [M^2L^{-2}T^{-2}]$.

Problem 14. Number of particles is given by $n = -D \frac{n_2 - n_1}{x_2 - x_1}$ crossing a unit area perpendicular to X - axis in unit time, where n_1 and n_2 are number of particles per unit volume for the value of x meant to x_2 and x_1 . Find dimensions of D called as diffusion constant

- (a) M^0LT^2 (b) $M^0L^2T^{-4}$ (c) M^0LT^{-3} (d) $M^0L^2T^{-1}$

Solution : (d) $(n) = \text{Number of particle passing from unit area in unit time} = \frac{\text{No. of particle}}{A \times t} = \frac{[M^0L^0T^0]}{[L^2][T]} = [L^{-2}T^{-1}]$

$[n_1] = [n_2] = \text{No. of particle in unit volume} = [L^{-3}]$

Now from the given formula $[D] = \frac{[n][x_2 - x_1]}{[n_2 - n_1]} = \frac{[L^{-2}T^{-1}][L]}{[L^{-3}]} = [L^2T^{-1}]$.

Problem 15. E , m , l and G denote energy, mass, angular momentum and gravitational constant respectively, then the dimension of $\frac{El^2}{m^5 G^2}$ are

- (a) Angle (b) Length (c) Mass (d) Time

Solution : (a) $[E] = \text{energy} = [ML^2T^{-2}]$, $[m] = \text{mass} = [M]$, $[l] = \text{Angular momentum} = [ML^2T^{-1}]$
 $[G] = \text{Gravitational constant} = [M^{-1}L^3T^{-2}]$

Now substituting dimensions of above quantities in $\frac{El^2}{m^5 G^2} = \frac{[ML^2T^{-2}] \times [ML^2T^{-1}]^2}{[M^5] \times [M^{-1}L^3T^{-2}]^2} = [M^0L^0T^0]$

i.e., the quantity should be angle.

Problem 16. The equation of a wave is given by $Y = A \sin \left(\frac{x}{v} - k \right)$ where S is the angular velocity and v is the linear velocity. The dimension of k is

- (a) LT (b) T (c) T^{-1} (d) T^2

Solution : (b) According to principle of dimensional homogeneity $[k] = \left[\frac{x}{v} \right] = \left[\frac{L}{LT^{-1}} \right] = [T]$.

Problem 17. The potential energy of a particle varies with distance x from a fixed origin as $U = \frac{A\sqrt{x}}{x^2 + B}$, where A and B are dimensional constants then dimensional formula for AB is

- (a) $ML^{7/2}T^{-2}$ (b) $ML^{11/2}T^{-2}$ (c) $M^2L^{9/2}T^{-2}$ (d) $ML^{13/2}T^{-3}$

Solution : (b) From the dimensional homogeneity $[x^2] = [B] \therefore [B] = [L^2]$

As well as $[U] = \frac{[A][x^{1/2}]}{[x^2] + [B]} \Rightarrow [ML^2T^{-2}] = \frac{[A][L^{1/2}]}{[L^2]} \therefore [A] = [ML^{7/2}T^{-2}]$

Now $[AB] = [ML^{7/2}T^{-2}] \times [L^2] = [ML^{11/2}T^{-2}]$

Problem 18. The dimensions of $\frac{1}{2} \epsilon_0 E^2$ ($\epsilon_0 = \text{permittivity of free space ; } E = \text{electric field}$) is

- (a) MLT^{-1} (b) ML^2T^{-2} (c) $ML^{-1}T^{-2}$ (d) ML^2T^{-1}

Solution : (c) Energy density = $\frac{1}{2} \epsilon_0 E^2 = \frac{\text{Energy}}{\text{Volume}} = \left[\frac{ML^2T^{-2}}{L^3} \right] = [ML^{-1}T^{-2}]$

Problem 19. You may not know integration. But using dimensional analysis you can check on some results. In the integral $\int \frac{dx}{(2ax - x^2)^{1/2}} = a^n \sin^{-1} \left(\frac{x}{a} - 1 \right)$ the value of n is

- (a) 1 (b) -1 (c) 0 (d) $\frac{1}{2}$

Solution : (c) Let $x = \text{length} \therefore [X] = [L]$ and $[dx] = [L]$

By principle of dimensional homogeneity $\left[\frac{x}{a} \right] = \text{dimensionless} \therefore [a] = [x] = [L]$

By substituting dimension of each quantity in both sides: $\frac{[L]}{[L^2 - L^2]^{1/2}} = [L^n] \therefore n = 0$

Problem 20. A physical quantity $P = \frac{B^2 l^2}{m}$ where B = magnetic induction, l = length and m = mass. The dimension of P is

- (a) MLT^{-3} (b) $ML^2T^{-4}I^{-2}$ (c) $M^2L^2T^{-4}I$ (d) $MLT^{-2}I^{-2}$

Solution : (b) $F = BIL \therefore$ Dimension of $[B] = \frac{[F]}{[I][L]} = \frac{[MLT^{-2}]}{[I][L]} = [MT^{-2}I^{-1}]$

Now dimension of $[P] = \frac{B^2 l^2}{m} = \frac{[MT^{-2}I^{-1}]^2 \times [L^2]}{[M]} = [ML^2T^{-4}I^{-2}]$

Problem 21. The equation of the stationary wave is $y = 2a \sin\left(\frac{2fct}{\}$ $\right) \cos\left(\frac{2fx}{\}$ $\right)$, which of the following statements is wrong

- (a) The unit of ct is same as that of $\}$ (b) The unit of x is same as that of $\}$
 (c) The unit of $2fc/\}$ is same as that of $2fx/\}$ t (d) The unit of $c/\}$ is same as that of $x/\}$

Solution : (d) Here, $\frac{2fct}{\}$ as well as $\frac{2fx}{\}$ are dimensionless (angle) i.e. $\left[\frac{2fct}{\}\right] = \left[\frac{2fx}{\}\right] = M^0 L^0 T^0$

So (i) unit of $c t$ is same as that of $\}$ (ii) unit of x is same as that of $\}$ (iii) $\left[\frac{2fc}{\}\right] = \left[\frac{2fx}{\} t}\right]$

and (iv) $\frac{x}{\}$ is unit less. It is not the case with $\frac{c}{\}$.

(3) To convert a physical quantity from one system to the other : The measure of a physical quantity is $nu = \text{constant}$

If a physical quantity X has dimensional formula $[M^a L^b T^c]$ and if (derived) units of that physical quantity in two systems are $[M_1^a L_1^b T_1^c]$ and $[M_2^a L_2^b T_2^c]$ respectively and n_1 and n_2 be the numerical values in the two systems respectively, then $n_1[u_1] = n_2[u_2]$

$$\Rightarrow n_1 [M_1^a L_1^b T_1^c] = n_2 [M_2^a L_2^b T_2^c]$$

$$\Rightarrow n_2 = n_1 \left[\frac{M_1}{M_2} \right]^a \left[\frac{L_1}{L_2} \right]^b \left[\frac{T_1}{T_2} \right]^c$$

where M_1, L_1 and T_1 are fundamental units of mass, length and time in the first (known) system and M_2, L_2 and T_2 are fundamental units of mass, length and time in the second (unknown) system. Thus knowing the values of fundamental units in two systems and numerical value in one system, the numerical value in other system may be evaluated.

Example : (1) conversion of *Newton* into *Dyne*.

The Newton is the S.I. unit of force and has dimensional formula $[MLT^{-2}]$.

So $1 N = 1 kg \cdot m / sec^2$

$$\text{By using } n_2 = n_1 \left[\frac{M_1}{M_2} \right]^a \left[\frac{L_1}{L_2} \right]^b \left[\frac{T_1}{T_2} \right]^c = 1 \left[\frac{kg}{gm} \right]^1 \left[\frac{m}{cm} \right]^1 \left[\frac{sec}{sec} \right]^{-2} = 1 \left[\frac{10^3 gm}{gm} \right]^1 \left[\frac{10^2 cm}{cm} \right]^1 \left[\frac{sec}{sec} \right]^{-2} = 10^5$$

$$\therefore 1 N = 10^5 \text{ Dyne}$$

(2) Conversion of gravitational constant (G) from C.G.S. to M.K.S. system

The value of G in C.G.S. system is 6.67×10^{-8} C.G.S. units while its dimensional formula is $[M^{-1}L^3T^{-2}]$

So $G = 6.67 \times 10^{-8} \text{ cm}^3/\text{g s}^2$

$$\begin{aligned} \text{By using } n_2 &= n_1 \left[\frac{M_1}{M_2} \right]^a \left[\frac{L_1}{L_2} \right]^b \left[\frac{T_1}{T_2} \right]^c = 6.67 \times 10^{-8} \left[\frac{\text{gm}}{\text{kg}} \right]^{-1} \left[\frac{\text{cm}}{\text{m}} \right]^3 \left[\frac{\text{sec}}{\text{sec}} \right]^{-2} \\ &= 6.67 \times 10^{-8} \left[\frac{\text{gm}}{10^3 \text{ gm}} \right]^{-1} \left[\frac{\text{cm}}{10^2 \text{ cm}} \right]^3 \left[\frac{\text{sec}}{\text{sec}} \right]^{-2} = 6.67 \times 10^{-11} \end{aligned}$$

$$\therefore G = 6.67 \times 10^{-11} \text{ M.K.S. units}$$

Sample problems based on conversion

Problem 22. A physical quantity is measured and its value is found to be nu where n = numerical value and u = unit. Then which of the following relations is true

- (a) $n \propto u^2$ (b) $n \propto u$ (c) $n \propto \sqrt{u}$ (d) $n \propto \frac{1}{u}$

Solution : (d) We know $P = nu = \text{constant} \therefore n_1 u_1 = n_2 u_2$ or $n \propto \frac{1}{u}$.

Problem 23. In C.G.S. system the magnitude of the force is 100 dynes. In another system where the fundamental physical quantities are kilogram, metre and minute, the magnitude of the force is

- (a) 0.036 (b) 0.36 (c) 3.6 (d) 36

Solution : (c) $n_1 = 100$, $M_1 = \text{g}$, $L_1 = \text{cm}$, $T_1 = \text{sec}$ and $M_2 = \text{kg}$, $L_2 = \text{meter}$, $T_2 = \text{minute}$, $x = 1$, $y = 1$, $z = -2$

By substituting these values in the following conversion formula $n_2 = n_1 \left[\frac{M_1}{M_2} \right]^x \left[\frac{L_1}{L_2} \right]^y \left[\frac{T_1}{T_2} \right]^z$

$$n_2 = 100 \left[\frac{\text{gm}}{\text{kg}} \right]^1 \left[\frac{\text{cm}}{\text{meter}} \right]^1 \left[\frac{\text{sec}}{\text{minute}} \right]^{-2}$$

$$n_2 = 100 \left[\frac{\text{gm}}{10^3 \text{ gm}} \right]^1 \left[\frac{\text{cm}}{10^2 \text{ cm}} \right]^1 \left[\frac{\text{sec}}{60 \text{ sec}} \right]^{-2} = 3.6$$

Problem 24. The temperature of a body on Kelvin scale is found to be X K. When it is measured by a Fahrenheit thermometer, it is found to be X F. Then X is

- (a) 301.25 (b) 574.25 (c) 313 (d) 40

Solution : (c) Relation between centigrade and Fahrenheit $\frac{K - 273}{5} = \frac{F - 32}{9}$

According to problem $\frac{X - 273}{5} = \frac{X - 32}{9} \therefore X = 313$.

Problem 25. Which relation is wrong

- (a) 1 Calorie = 4.18 Joules (b) $1 \text{ \AA} = 10^{-10} \text{ m}$
 (c) $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ Joules}$ (d) $1 \text{ Newton} = 10^{-5} \text{ Dynes}$

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Solution : (d) Because 1 *Newton* = 10^5 *Dyne*.

Problem 26. To determine the Young's modulus of a wire, the formula is $Y = \frac{F}{A} \cdot \frac{L}{\Delta L}$; where L = length, A = area of cross-section of the wire, ΔL = Change in length of the wire when stretched with a force F . The conversion factor to change it from CGS to MKS system is

- (a) 1 (b) 10 (c) 0.1 (d) 0.01

Solution : (c) We know that the dimension of young's modulus is $[ML^{-1}T^{-2}]$

C.G.S. unit : $gm \text{ cm}^{-1} \text{ sec}^{-2}$ and M.K.S. unit : $kg. m^{-1} \text{ sec}^{-2}$.

By using the conversion formula: $n_2 = n_1 \left[\frac{M_1}{M_2} \right]^1 \left[\frac{L_1}{L_2} \right]^{-1} \left[\frac{T_1}{T_2} \right]^{-2} = \left[\frac{gm}{kg} \right]^1 \left[\frac{cm}{meter} \right]^{-1} \left[\frac{sec}{sec} \right]^{-2}$

\therefore Conversion factor $\frac{n_2}{n_1} = \left[\frac{gm}{10^3 gm} \right]^1 \left[\frac{cm}{10^2 cm} \right]^{-1} \left[\frac{sec}{sec} \right]^{-2} = \frac{1}{10} = 0.1$

Problem 27. Conversion of 1 MW power on a new system having basic units of mass, length and time as 10kg, 1dm and 1 minute respectively is

- (a) 2.16×10^{12} unit (b) 1.26×10^{12} unit (c) 2.16×10^{10} unit (d) 2×10^{14} unit

Solution : (a) $[P] = [ML^2T^{-3}]$

Using the relation $n_2 = n_1 \left[\frac{M_1}{M_2} \right]^x \left[\frac{L_1}{L_2} \right]^y \left[\frac{T_1}{T_2} \right]^z = 1 \times 10^6 \left[\frac{1kg}{10kg} \right]^1 \left[\frac{1m}{1dm} \right]^2 \left[\frac{1s}{1min} \right]^{-3}$ [As $1MW = 10^6 W$]

$$= 10^6 \left[\frac{1kg}{10kg} \right] \left[\frac{10dm}{1dm} \right]^2 \left[\frac{1sec}{60sec} \right]^{-3} = 2.16 \times 10^{12} \text{ unit}$$

Problem 28. In two systems of relations among velocity, acceleration and force are respectively $v_2 = \frac{r}{s} v_1$, $a_2 = r s a_1$ and $F_2 = \frac{F_1}{rs}$. If r and s are constants then relations among mass, length and time in two systems are

- (a) $M_2 = \frac{r}{s} M_1, L_2 = \frac{r^2}{s^2} L_1, T_2 = \frac{r^3 T_1}{s}$ (b) $M_2 = \frac{1}{r^2 s^2} M_1, L_2 = \frac{r^3}{s^3} L_1, T_2 = T_1 \frac{r}{s^2}$
- (c) $M_2 = \frac{r^3}{s^3} M_1, L_2 = \frac{r^2}{s^2} L_1, T_2 = \frac{r}{s} T_1$ (d) $M_2 = \frac{r^2}{s^2} M_1, L_2 = \frac{r}{s^2} L_1, T_2 = \frac{r^3}{s^3} T_1$

Solution : (b) $v_2 = v_1 \frac{r}{s} \Rightarrow [L_2 T_2^{-1}] = [L_1 T_1^{-1}] \frac{r}{s}$ (i)

$a_2 = a_1 r s \Rightarrow [L_2 T_2^{-2}] = [L_1 T_1^{-2}] r s$ (ii)

and $F_2 = \frac{F_1}{rs} \Rightarrow [M_2 L_2 T_2^{-2}] = [M_1 L_1 T_1^{-2}] \times \frac{1}{rs}$ (iii)

Dividing equation (iii) by equation (ii) we get $M_2 = \frac{M_1}{(rs)rs} = \frac{M_1}{r^2 s^2}$

Squaring equation (i) and dividing by equation (ii) we get $L_2 = L_1 \frac{r^3}{S^3}$

Dividing equation (i) by equation (ii) we get $T_2 = T_1 \frac{r}{S^2}$

Problem 29. If the present units of length, time and mass (m, s, kg) are changed to $100m, 100s$, and $\frac{1}{10} kg$ then

- (a) The new unit of velocity is increased 10 times (b) The new unit of force is decreased $\frac{1}{1000}$ times
 (c) The new unit of energy is increased 10 times (d) The new unit of pressure is increased 1000 times

Solution : (b) Unit of velocity = m/sec ; in new system = $\frac{100m}{100sec} = \frac{m}{sec}$ (same)

Unit of force = $\frac{kg \times m}{sec^2}$; in new system = $\frac{1}{10} kg \times \frac{100m}{100sec \times 100sec} = \frac{1}{1000} \frac{kg \times m}{sec^2}$

Unit of energy = $\frac{kg \times m^2}{sec^2}$; in new system = $\frac{1}{10} kg \times \frac{100m \times 100m}{100sec \times 100sec} = \frac{1}{10} \frac{kg \times m^2}{sec^2}$

Unit of pressure = $\frac{kg}{m \times sec^2}$; in new system = $\frac{1}{10} kg \times \frac{1}{100} m \times \frac{1}{100sec \times 100sec} = 10^{-7} \frac{kg}{m \times sec^2}$

Problem 30. Suppose we employ a system in which the unit of mass equals $100 kg$, the unit of length equals $1 km$ and the unit of time $100 s$ and call the unit of energy *eluoj* (joule written in reverse order), then

- (a) $1 \text{ eluoj} = 10^4 \text{ joule}$ (b) $1 \text{ eluoj} = 10^{-3} \text{ joule}$ (c) $1 \text{ eluoj} = 10^{-4} \text{ joule}$ (d) $1 \text{ joule} = 10^3 \text{ eluoj}$

Solution : (a) $[E] = [ML^2T^{-2}]$

$1 \text{ eluoj} = [100 kg] \times [1km]^2 \times [100 sec]^{-2} = 100 kg \times 10^6 m^2 \times 10^{-4} sec^{-2} = 10^4 kg m^2 \times sec^{-2} = 10^4 \text{ Joule}$

Problem 31. If $1gm \text{ cms}^{-1} = x \text{ Ns}$, then number x is equivalent to

- (a) 1×10^{-1} (b) 3×10^{-2} (c) 6×10^{-4} (d) 1×10^{-5}

Solution : (d) $gm - cm s^{-1} = 10^{-3} kg \times 10^{-2} m \times s^{-1} = 10^{-5} kg \times m \times s^{-1} = 10^{-5} \text{ Ns}$

(4) To check the dimensional correctness of a given physical relation : This is based on the 'principle of homogeneity'. According to this principle the dimensions of each term on both sides of an equation must be the same.

If $X = A \pm (BC)^2 \pm \sqrt{DEF}$,

then according to principle of homogeneity $[X] = [A] = [(BC)^2] = [\sqrt{DEF}]$

If the dimensions of each term on both sides are same, the equation is dimensionally correct, otherwise not. A dimensionally correct equation may or may not be physically correct.

Example : (1) $F = mv^2 / r^2$

By substituting dimension of the physical quantities in the above relation –

$$[MLT^{-2}] = [M][LT^{-1}]^2 / [L]^2$$

i.e. $[MLT^{-2}] = [MT^{-2}]$

As in the above equation dimensions of both sides are not same; this formula is not correct dimensionally, so can never be physically.

$$(2) s = ut - (1/2)at^2$$

By substituting dimension of the physical quantities in the above relation –

$$[L] = [LT^{-1}][T] - [LT^{-2}][T^2]$$

$$\text{i.e. } [L] = [L] - [L]$$

As in the above equation dimensions of each term on both sides are same, so this equation is dimensionally correct. However, from equations of motion we know that $s = ut + (1/2)at^2$

Sample problems based on formulae checking

Problem 32. From the dimensional consideration, which of the following equation is correct

$$(a) T = 2f \sqrt{\frac{R^3}{GM}} \quad (b) T = 2f \sqrt{\frac{GM}{R^3}} \quad (c) T = 2f \sqrt{\frac{GM}{R^2}} \quad (d) T = 2f \sqrt{\frac{R^2}{GM}}$$

$$\text{Solution : (a) } T = 2f \sqrt{\frac{R^3}{GM}} = 2f \sqrt{\frac{R^3}{gR^2}} = 2f \sqrt{\frac{R}{g}} \quad [\text{As } GM = gR^2]$$

Now by substituting the dimension of each quantity in both sides.

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

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

Problem 33. A highly rigid cubical block A of small mass M and side L is fixed rigidly onto another cubical block B of the same dimensions and of low modulus of rigidity y such that the lower face of A completely covers the upper face of B. The lower face of B is rigidly held on a horizontal surface. A small force F is applied perpendicular to one of the side faces of A. After the force is withdrawn block A executes small oscillations. The time period of which is given by

$$(a) 2f \sqrt{\frac{My}{L}} \quad (b) 2f \sqrt{\frac{L}{My}} \quad (c) 2f \sqrt{\frac{ML}{y}} \quad (d) 2f \sqrt{\frac{M}{yL}}$$

$$\text{Solution : (d) } \text{Given } m = \text{mass} = [M], y = \text{coefficient of rigidity} = [ML^{-1}T^{-2}], L = \text{length} = [L]$$

By substituting the dimension of these quantity we can check the accuracy of the given formulae

$$[T] = 2f \left(\frac{[M]}{[Y][L]} \right)^{1/2} = \left[\frac{M}{ML^{-1}T^{-2}L} \right]^{1/2} = [T].$$

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

Problem 34. A small steel ball of radius r is allowed to fall under gravity through a column of a viscous liquid of coefficient of viscosity. After some time the velocity of the ball attains a constant value known as terminal velocity v_T . The terminal velocity depends on (i) the mass of the ball. (ii) y (iii) r and (iv) acceleration due to gravity g . which of the following relations is dimensionally correct

$$(a) v_T \propto \frac{mg}{yr} \quad (b) v_T \propto \frac{yr}{mg} \quad (c) v_T \propto yrmg \quad (d) v_T \propto \frac{mgr}{y}$$

$$\text{Solution : (a) } \text{Given } v_T = \text{terminal velocity} = [LT^{-1}], m = \text{Mass} = [M], g = \text{Acceleration due to gravity} = [LT^{-2}]$$

r = Radius = $[L]$, y = Coefficient of viscosity = $[y]$

By substituting the dimension of each quantity we can check the accuracy of given formula $v_T \propto \frac{mg}{yr}$

$$\therefore [LT^{-1}] = \frac{[M][LT^{-2}]}{[ML^{-1}T^{-1}][L]} = [LT^{-1}]$$

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

Problem 35. A dimensionally consistent relation for the volume V of a liquid of coefficient of viscosity y flowing per second through a tube of radius r and length l and having a pressure difference p across its end, is

$$(a) V = \frac{fpr^4}{8yl} \quad (b) V = \frac{fyl}{8pr^4} \quad (c) V = \frac{8pyl}{fr^4} \quad (d) V = \frac{fpy}{8lr^4}$$

Solution : (a) Given V = Rate of flow = $\frac{\text{Volume}}{\text{sec}} = [L^3 T^{-1}]$, P = Pressure = $[ML^{-1}T^{-2}]$, r = Radius = $[L]$

y = Coefficient of viscosity = $[ML^{-1}T^{-1}]$, l = Length = $[L]$

By substituting the dimension of each quantity we can check the accuracy of the formula $V = \frac{fPr^4}{8yl}$

$$\therefore [L^3 T^{-1}] = \frac{[ML^{-1}T^{-2}][L^4]}{[ML^{-1}T^{-1}][L]} = [L^3 T^{-1}]$$

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

Problem 36. With the usual notations, the following equation $S_t = u + \frac{1}{2}a(2t - 1)$ is

- (a) Only numerically correct (b) Only dimensionally correct
 (c) Both numerically and dimensionally correct (d) Neither numerically nor dimensionally correct

Solution : (c) Given S_t = distance travelled by the body in t^{th} sec. = $[LT^{-1}]$, a = Acceleration = $[LT^{-2}]$,

v = velocity = $[LT^{-1}]$, t = time = $[T]$

By substituting the dimension of each quantity we can check the accuracy of the formula

$$S_t = u + \frac{1}{2}a(2t - 1)$$

$$\therefore [LT^{-1}] = [LT^{-1}] + [LT^{-2}][T] \Rightarrow [LT^{-1}] = [LT^{-1}] + [LT^{-1}]$$

Since the dimension of each terms are equal therefore this equation is dimensionally correct. And after deriving this equation from Kinematics we can also proof that this equation is correct numerically also.

Problem 37. If velocity v , acceleration A and force F are chosen as fundamental quantities, then the dimensional formula of angular momentum in terms of v , A and F would be

- (a) $FA^{-1}v$ (b) $Fv^3 A^{-2}$ (c) $Fv^2 A^{-1}$ (d) $F^2 v^2 A^{-1}$

Solution : (b) Given, v = velocity = $[LT^{-1}]$, A = Acceleration = $[LT^{-2}]$, F = force = $[MLT^{-2}]$

By substituting, the dimension of each quantity we can check the accuracy of the formula

[Angular momentum] = $Fv^3 A^{-2}$

$$[ML^2 T^{-1}] = [MLT^{-2}][LT^{-1}]^3 [LT^{-2}]^{-2}$$

$$= [ML^2T^{-1}]$$

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

Problem 38. The largest mass (m) that can be moved by a flowing river depends on velocity (v), density (\dots) of river water and acceleration due to gravity (g). The correct relation is

(a) $m \propto \frac{v^4}{g^2}$ (b) $m \propto \frac{v^6}{g^2}$ (c) $m \propto \frac{v^4}{g^3}$ (d) $m \propto \frac{v^6}{g^3}$

Solution : (d) Given, $m = \text{mass} = [M]$, $v = \text{velocity} = [LT^{-1}]$, $\dots = \text{density} = [ML^{-3}]$, $g = \text{acceleration due to gravity} = [LT^{-2}]$

By substituting, the dimension of each quantity we can check the accuracy of the formula

$$m = K \frac{v^6}{g^3}$$

$$\Rightarrow [M] = \frac{[ML^{-3}][LT^{-1}]^6}{[LT^{-2}]^3}$$

$$= [M]$$

L.H.S. = R.H.S. *i.e.*, the above formula is Correct.

(5) As a research tool to derive new relations : If one knows the dependency of a physical quantity on other quantities and if the dependency is of the product type, then using the method of dimensional analysis, relation between the quantities can be derived.

Example : (i) Time period of a simple pendulum.

Let time period of a simple pendulum is a function of mass of the bob (m), effective length (l), acceleration due to gravity (g) then assuming the function to be product of power function of m , l and g

i.e., $T = Km^x l^y g^z$; where $K = \text{dimensionless constant}$

If the above relation is dimensionally correct then by substituting the dimensions of quantities –

$$[T] = [M]^x [L]^y [LT^{-2}]^z$$

or $[M^0L^0T^1] = [M^xL^{y+z}T^{-2z}]$

Equating the exponents of similar quantities $x = 0$, $y = 1/2$ and $z = -1/2$

So the required physical relation becomes $T = K\sqrt{\frac{l}{g}}$

The value of dimensionless constant is found ($2f$) through experiments so $T = 2f\sqrt{\frac{l}{g}}$

(ii) Stoke's law : When a small sphere moves at low speed through a fluid, the viscous force F , opposing the motion, is found experimentally to depend on the radius r , the velocity of the sphere v and the viscosity y of the fluid.

So $F = f(y, r, v)$

If the function is product of power functions of y , r and v , $F = Ky^x r^y v^z$; where K is dimensionless constant.

If the above relation is dimensionally correct $[MLT^{-2}] = [ML^{-1}T^{-1}]^x [L]^y [LT^{-1}]^z$

or $[MLT^{-2}] = [M^x L^{-x+y+z} T^{-x-z}]$

Equating the exponents of similar quantities $x = 1$; $-x + y + z = 1$ and $-x - z = -2$

Solving these for x , y and z , we get $x = y = z = 1$

So eqⁿ (i) becomes $F = Kyrv$

On experimental grounds, $K = 6f$; so $F = 6fyrv$

This is the famous Stoke's law.

Sample problem based on formulae derivation

Problem 39. If the velocity of light (c), gravitational constant (G) and Planck's constant (h) are chosen as fundamental units, then the dimensions of mass in new system is

- (a) $c^{1/2}G^{1/2}h^{1/2}$ (b) $c^{1/2}G^{1/2}h^{-1/2}$ (c) $c^{1/2}G^{-1/2}h^{1/2}$ (d) $c^{-1/2}G^{1/2}h^{1/2}$

Solution : (c) Let $m \propto c^x G^y h^z$ or $m = K c^x G^y h^z$

By substituting the dimension of each quantity in both sides

$$[M^1 L^0 T^0] = K [LT^{-1}]^x [M^{-1} L^3 T^{-2}]^y [ML^2 T^{-1}]^z = [M^{-y+z} L^{x+3y+2z} T^{-x-2y-z}]$$

By equating the power of M , L and T in both sides: $-y + z = 1$, $x + 3y + 2z = 0$, $-x - 2y - z = 0$

By solving above three equations $x = 1/2$, $y = -1/2$ and $z = 1/2$.

$$\therefore m \propto c^{1/2} G^{-1/2} h^{1/2}$$

Problem 40. If the time period (T) of vibration of a liquid drop depends on surface tension (S), radius (r) of the drop and density (ρ) of the liquid, then the expression of T is

- (a) $T = K\sqrt{\rho r^3 / S}$ (b) $T = K\sqrt{\rho^{1/2} r^3 / S}$ (c) $T = K\sqrt{\rho r^3 / S^{1/2}}$ (d) None of these

Solution : (a) Let $T \propto S^x r^y \rho^z$ or $T = K S^x r^y \rho^z$

By substituting the dimension of each quantity in both sides

$$[M^0 L^0 T^1] = K [MT^{-2}]^x [L]^y [ML^{-3}]^z = [M^{x+z} L^{y-3z} T^{-2x}]$$

By equating the power of M , L and T in both sides $x + z = 0$, $y - 3z = 0$, $-2x = 1$

By solving above three equations $\therefore x = -1/2$, $y = 3/2$, $z = 1/2$

$$\text{So the time period can be given as, } T = K S^{-1/2} \rho^{3/2} \dots^{1/2} = K \sqrt{\frac{\rho r^3}{S}}$$

Problem 41. If P represents radiation pressure, C represents speed of light and Q represents radiation energy striking a unit area per second, then non-zero integers x , y and z such that $P^x Q^y C^z$ is dimensionless, are

- (a) $x = 1, y = 1, z = -1$ (b) $x = 1, y = -1, z = 1$ (c) $x = -1, y = 1, z = 1$ (d) $x = 1, y = 1, z = 1$

Solution : (b) $[P^x Q^y C^z] = M^0 L^0 T^0$

By substituting the dimension of each quantity in the given expression

$$[ML^{-1} T^{-2}]^x [MT^{-3}]^y [LT^{-1}]^z = [M^{x+y} L^{-x+z} T^{-2x-3y-z}] = M^0 L^0 T^0$$

by equating the power of M , L and T in both sides: $x + y = 0$, $-x + z = 0$ and $-2x - 3y - z = 0$

by solving we get $x = 1, y = -1, z = 1$.

Problem 42. The volume V of water passing through a point of a uniform tube during t seconds is related to the cross-sectional area A of the tube and velocity u of water by the relation $V \propto A^r u^s t^x$, which one of the following will be true

- (a) $r = s = x$ (b) $r \neq s = x$ (c) $r = s \neq x$ (d) $r \neq s \neq x$

Solution : (b) Writing dimensions of both sides $[L^3] = [L^2]^r [LT^{-1}]^s [T]^x \Rightarrow [L^3 T^0] = [L^{2r+s} T^{x-s}]$

By comparing powers of both sides $2r + s = 3$ and $x - s = 0$

Which give $s = x$ and $r = \frac{1}{2}(3 - s)$ i.e. $r \neq s = x$.

Problem 43. If velocity (V), force (F) and energy (E) are taken as fundamental units, then dimensional formula for mass will be

- (a) $V^{-2}F^0E$ (b) V^0FE^2 (c) $VF^{-2}E^0$ (d) $V^{-2}F^0E$

Solution : (d) Let $M = V^a F^b E^c$

Putting dimensions of each quantities in both side $[M] = [LT^{-1}]^a [MLT^{-2}]^b [ML^2T^{-2}]^c$

Equating powers of dimensions. We have $b + c = 1$, $a + b + 2c = 0$ and $-a - 2b - 2c = 0$

Solving these equations, $a = -2$, $b = 0$ and $c = 1$

So $M = [V^{-2}F^0E]$

Problem 44. Given that the amplitude A of scattered light is :

- (i) Directly proportional to the amplitude (A_0) of incident light.
- (ii) Directly proportional to the volume (V) of the scattering particle
- (iii) Inversely proportional to the distance (r) from the scattered particle
- (iv) Depend upon the wavelength (λ) of the scattered light. then:

- (a) $A \propto \frac{1}{\lambda}$ (b) $A \propto \frac{1}{\lambda^2}$ (c) $A \propto \frac{1}{\lambda^3}$ (d) $A \propto \frac{1}{\lambda^4}$

Solution : (b) Let $A = \frac{KA_0 V \lambda^x}{r}$

By substituting the dimension of each quantity in both sides

$$\Rightarrow [L] = \frac{[L] \cdot [L^3] [L^x]}{[L]}$$

$$\therefore [L] = [L^{3+x}]; \Rightarrow 3 + x = 1 \text{ or } x = -2$$

$$\therefore A \propto \lambda^{-2}$$

1.12 Limitations of Dimensional Analysis

Although dimensional analysis is very useful it cannot lead us too far as,

(1) If dimensions are given, physical quantity may not be unique as many physical quantities have same dimensions. For example if the dimensional formula of a physical quantity is $[ML^2T^{-2}]$ it may be work or energy or torque.

(2) Numerical constant having no dimensions $[K]$ such as $(1/2)$, 1 or $2f$ etc. cannot be deduced by the methods of dimensions.

(3) The method of dimensions can not be used to derive relations other than product of power functions. For example,

$$s = ut + (1/2)at^2 \quad \text{or} \quad y = a \sin \omega t$$

cannot be derived by using this theory (try if you can). However, the dimensional correctness of these can be checked.

(4) The method of dimensions cannot be applied to derive formula if in mechanics a physical quantity depends on more than 3 physical quantities as then there will be less number (= 3) of equations than the unknowns (>3). However still we can check correctness of the given equation dimensionally. For example $T = 2\pi \sqrt{1/mgl}$ can not be derived by theory of dimensions but its dimensional correctness can be checked.

(5) Even if a physical quantity depends on 3 physical quantities, out of which two have same dimensions, the formula cannot be derived by theory of dimensions, e.g., formula for the frequency of a tuning fork $f = (d/L^2)v$ cannot be derived by theory of dimensions but can be checked.

1.13 Significant Figures

Significant figures in the measured value of a physical quantity tell the number of digits in which we have confidence. Larger the number of significant figures obtained in a measurement, greater is the accuracy of the measurement. The reverse is also true.

The following rules are observed in counting the number of significant figures in a given measured quantity.

(1) All non-zero digits are significant.

Example: 42.3 has three significant figures.
243.4 has four significant figures.
24.123 has five significant figures.

(2) A zero becomes significant figure if it appears between to non-zero digits.

Example : 5.03 has three significant figures.
5.604 has four significant figures.
4.004 has four significant figures.

(3) Leading zeros or the zeros placed to the left of the number are never significant.

Example : 0.543 has three significant figures.
0.045 has two significant figures.
0.006 has one significant figures.

(4) Trailing zeros or the zeros placed to the right of the number are significant.

Example : 4.330 has four significant figures.
433.00 has five significant figures.
343.000 has six significant figures.

(5) In exponential notation, the numerical portion gives the number of significant figures.

Example : 1.32×10^{-2} has three significant figures.

1.32×10^4 has three significant figures.

1.14 Rounding Off

While rounding off measurements, we use the following rules by convention:

(1) If the digit to be dropped is less than 5, then the preceding digit is left unchanged.

Example : $x = 7.82$ is rounded off to 7.8, again $x = 3.94$ is rounded off to 3.9.

(2) If the digit to be dropped is more than 5, then the preceding digit is raised by one.

Example : $x = 6.87$ is rounded off to 6.9, again $x = 12.78$ is rounded off to 12.8.

(3) If the digit to be dropped is 5 followed by digits other than zero, then the preceding digit is raised by one.

Example : $x = 16.351$ is rounded off to 16.4, again $x = 6.758$ is rounded off to 6.8.

(4) If digit to be dropped is 5 or 5 followed by zeros, then preceding digit is left unchanged, if it is even.

Example : $x = 3.250$ becomes 3.2 on rounding off, again $x = 12.650$ becomes 12.6 on rounding off.

(5) If digit to be dropped is 5 or 5 followed by zeros, then the preceding digit is raised by one, if it is odd.

Example : $x = 3.750$ is rounded off to 3.8, again $x = 16.150$ is rounded off to 16.2.

1.15 Significant Figures in Calculation

In most of the experiments, the observations of various measurements are to be combined mathematically, *i.e.*, added, subtracted, multiplied or divided as to achieve the final result. Since, all the observations in measurements do not have the same precision, it is natural that the final result cannot be more precise than the least precise measurement. The following two rules should be followed to obtain the proper number of significant figures in any calculation.

(1) The result of an addition or subtraction in the number having different precisions should be reported to the same number of decimal places as are present in the number having the least number of decimal places. The rule is illustrated by the following examples :

(i)	$\begin{array}{r} 33.3 \\ 3.11 \\ + 0.313 \\ \hline 36.723 \end{array}$	← (has only one decimal place) ← (answer should be reported to one decimal place)
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Answer = 36.7

(ii)	$\begin{array}{r} 3.1421 \\ 0.241 \\ + 0.09 \\ \hline 3.4731 \end{array}$	← (has 2 decimal places) ← (answer should be reported to 2 decimal places)
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Answer = 3.47

(iii)	$\begin{array}{r} 62.831 \\ - 24.5492 \\ \hline 38.2818 \end{array}$	← (has 3 decimal places) ← (answer should be reported to 3 decimal places after rounding off)
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Answer = 38.282

(2) The answer to a multiplication or division is rounded off to the same number of significant figures as is possessed by the least precise term used in the calculation. The rule is illustrated by the following examples :

$$\begin{array}{r} \text{(i)} \quad 142.06 \\ \times 0.23 \\ \hline 32.6738 \end{array} \quad \begin{array}{l} \leftarrow \text{(two significant figures)} \\ \leftarrow \text{(answer should have two significant figures)} \end{array}$$

Answer = 33

$$\begin{array}{r} \text{(ii)} \quad 51.028 \\ \times 1.31 \\ \hline 66.84668 \end{array} \quad \leftarrow \text{(three significant figures)}$$

Answer = 66.8

$$\text{(iii)} \quad \frac{0.90}{4.26} = 0.2112676$$

Answer = 0.21

1.16 Order of Magnitude

In scientific notation the numbers are expressed as, Number = $M \times 10^x$. Where M is a number lies between 1 and 10 and x is integer. Order of magnitude of quantity is the power of 10 required to represent the quantity. For determining this power, the value of the quantity has to be rounded off. While rounding off, we ignore the last digit which is less than 5. If the last digit is 5 or more than five, the preceding digit is increased by one. For example,

(1) Speed of light in vacuum = $3 \times 10^8 \text{ ms}^{-1} \approx 10^8 \text{ m/s}$ (ignoring $3 < 5$)

(2) Mass of electron = $9.1 \times 10^{-31} \text{ kg} \approx 10^{-30} \text{ kg}$ (as $9.1 > 5$).

Sample problems based on significant figures

Problem 45. Each side a cube is measured to be 7.203 m. The volume of the cube up to appropriate significant figures is

- (a) 373.714 (b) 373.71 (c) 373.7 (d) 373

Solution : (c) Volume = $a^3 = (7.023)^3 = 373.715 \text{ m}^3$

In significant figures volume of cube will be 373.7 m^3 because its side has four significant figures.

Problem 46. The number of significant figures in 0.007 m^2 is

- (a) 1 (b) 2 (c) 3 (d) 4

Solution : (a)

Problem 47. The length, breadth and thickness of a block are measured as 125.5 cm, 5.0 cm and 0.32 cm respectively. Which one of the following measurements is most accurate

- (a) Length (b) Breadth (c) Thickness (d) Height

Solution : (a) Relative error in measurement of length is minimum, so this measurement is most accurate.

Problem 48. The mass of a box is 2.3 kg. Two marbles of masses 2.15 g and 12.39 g are added to it. The total mass of the box to the correct number of significant figures is

- (a) 2.340 kg (b) 2.3145 kg. (c) 2.3 kg (d) 2.31 kg

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Solution : (c) Total mass = $2.3 + 0.00215 + 0.01239 = 2.31 \text{ kg}$

Total mass in appropriate significant figures be 2.3 kg .

Problem 49. The length of a rectangular sheet is 1.5 cm and breadth is 1.203 cm . The area of the face of rectangular sheet to the correct no. of significant figures is :

- (a) 1.8045 cm^2 (b) 1.804 cm^2 (c) 1.805 cm^2 (d) 1.8 cm^2

Solution : (d) Area = $1.5 \times 1.203 = 1.8045 \text{ cm}^2 = 1.8 \text{ cm}^2$ (Upto correct number of significant figure).

Problem 50. Each side of a cube is measured to be 5.402 cm . The total surface area and the volume of the cube in appropriate significant figures are :

- (a) $175.1 \text{ cm}^2, 157 \text{ cm}^3$ (b) $175.1 \text{ cm}^2, 157.6 \text{ cm}^3$
(c) $175 \text{ cm}^2, 157 \text{ cm}^3$ (d) $175.08 \text{ cm}^2, 157.639 \text{ cm}^3$

Solution : (b) Total surface area = $6 \times (5.402)^2 = 175.09 \text{ cm}^2 = 175.1 \text{ cm}^2$ (Upto correct number of significant figure)

Total volume = $(5.402)^3 = 175.64 \text{ cm}^3 = 175.6 \text{ cm}^3$ (Upto correct number of significant figure).

Problem 51. Taking into account the significant figures, what is the value of $9.99 \text{ m} + 0.0099 \text{ m}$

- (a) 10.00 m (b) 10 m (c) 9.9999 m (d) 10.0 m

Solution : (a) $9.99 \text{ m} + 0.0099 \text{ m} = 9.999 \text{ m} = 10.00 \text{ m}$ (In proper significant figures).

Problem 52. The value of the multiplication 3.124×4.576 correct to three significant figures is

- (a) 14.295 (b) 14.3 (c) 14.295424 (d) 14.305

Solution : (b) $3.124 \times 4.576 = 14.295 = 14.3$ (Correct to three significant figures).

Problem 53. The number of the significant figures in $11.118 \times 10^{-6} \text{ V}$ is

- (a) 3 (b) 4 (c) 5 (d) 6

Solution : (c) The number of significant figure is 5 as 10^{-6} does not affect this number.

Problem 54. If the value of resistance is 10.845 ohms and the value of current is 3.23 amperes , the potential difference is 35.02935 volts . Its value in significant number would be

- (a) 35 V (b) 35.0 V (c) 35.03 V (d) 35.025 V

Solution : (b) Value of current (3.23 A) has minimum significant figure (3) so the value of potential difference $V (= IR)$ have only 3 significant figure. Hence its value be 35.0 V .

1.17 Errors of Measurement

The measuring process is essentially a process of comparison. Inspite of our best efforts, the measured value of a quantity is always somewhat different from its actual value, or true value. This difference in the true value of a quantity is called error of measurement.

(1) **Absolute error :** Absolute error in the measurement of a physical quantity is the magnitude of the difference between the true value and the measured value of the quantity.

Let a physical quantity be measured n times. Let the measured value be $a_1, a_2, a_3, \dots, a_n$. The arithmetic mean of these value is $a_m = \frac{a_1 + a_2 + \dots + a_n}{n}$

Usually, a_m is taken as the true value of the quantity, if the same is unknown otherwise.

By definition, absolute errors in the measured values of the quantity are

$$\Delta a_1 = a_m - a_1$$

$$\Delta a_2 = a_m - a_2$$

.....

$$\Delta a_n = a_m - a_n$$

The absolute errors may be positive in certain cases and negative in certain other cases.

(2) **Mean absolute error** : It is the arithmetic mean of the magnitudes of absolute errors in all the measurements of the quantity. It is represented by $\overline{\Delta a}$. Thus

$$\overline{\Delta a} = \frac{|\Delta a_1| + |\Delta a_2| + \dots + |\Delta a_n|}{n}$$

Hence the final result of measurement may be written as $a = a_m \pm \overline{\Delta a}$

This implies that any measurement of the quantity is likely to lie between $(a_m + \overline{\Delta a})$ and $(a_m - \overline{\Delta a})$.

(3) **Relative error or Fractional error** : The relative error or fractional error of measurement is defined as the ratio of mean absolute error to the mean value of the quantity measured. Thus

$$\text{Relative error or Fractional error} = \frac{\text{mean absolute error}}{\text{mean value}} = \frac{\overline{\Delta a}}{a_m}$$

(4) **Percentage error** : When the relative/fractional error is expressed in percentage, we call it percentage error. Thus

$$\text{Percentage error} = \frac{\overline{\Delta a}}{a_m} \times 100\%$$

1.18 Propagation of Errors

(1) **Error in sum of the quantities** : Suppose $x = a + b$

Let Δa = absolute error in measurement of a

Δb = absolute error in measurement of b

Δx = absolute error in calculation of x i.e. sum of a and b .

The maximum absolute error in x is $\Delta x = \pm(\Delta a + \Delta b)$

Percentage error in the value of $x = \frac{(\Delta a + \Delta b)}{a + b} \times 100\%$

(2) **Error in difference of the quantities** : Suppose $x = a - b$

Let Δa = absolute error in measurement of a ,

Δb = absolute error in measurement of b

Δx = absolute error in calculation of x i.e. difference of a and b .

The maximum absolute error in x is $\Delta x = \pm(\Delta a + \Delta b)$

Percentage error in the value of $x = \frac{(\Delta a + \Delta b)}{a - b} \times 100\%$

(3) **Error in product of quantities** : Suppose $x = a \times b$

Let Δa = absolute error in measurement of a ,

Δb = absolute error in measurement of b

Δx = absolute error in calculation of x i.e. product of a and b .

The maximum fractional error in x is $\frac{\Delta x}{x} = \pm \left(\frac{\Delta a}{a} + \frac{\Delta b}{b} \right)$

Percentage error in the value of x = (Percentage error in value of a) + (Percentage error in value of b)

(4) **Error in division of quantities** : Suppose $x = \frac{a}{b}$

Let Δa = absolute error in measurement of a ,

Δb = absolute error in measurement of b

Δx = absolute error in calculation of x i.e. division of a and b .

The maximum fractional error in x is $\frac{\Delta x}{x} = \pm \left(\frac{\Delta a}{a} + \frac{\Delta b}{b} \right)$

Percentage error in the value of x = (Percentage error in value of a) + (Percentage error in value of b)

(5) **Error in quantity raised to some power** : Suppose $x = \frac{a^n}{b^m}$

Let Δa = absolute error in measurement of a ,

Δb = absolute error in measurement of b

Δx = absolute error in calculation of x

The maximum fractional error in x is $\frac{\Delta x}{x} = \pm \left(n \frac{\Delta a}{a} + m \frac{\Delta b}{b} \right)$

Percentage error in the value of x = n (Percentage error in value of a) + m (Percentage error in value of b)

Note : □ The quantity which have maximum power must be measured carefully because it's contribution to error is maximum.

Sample problems based on errors of measurement

Problem 55. A physical parameter a can be determined by measuring the parameters b , c , d and e using the relation $a = b^r c^s / d^x e^u$. If the maximum errors in the measurement of b , c , d and e are $b_1\%$, $c_1\%$, $d_1\%$ and $e_1\%$, then the maximum error in the value of a determined by the experiment is

(a) $(b_1 + c_1 + d_1 + e_1)\%$

(b) $(b_1 + c_1 - d_1 - e_1)\%$

(c) $(rb_1 + sc_1 - xd_1 - ue_1)\%$

(d) $(rb_1 + sc_1 + xd_1 + ue_1)\%$

Solution : (d) $a = b^r c^s / d^x e^u$

So maximum error in a is given by

$$\begin{aligned} \left(\frac{\Delta a}{a} \times 100 \right)_{\max} &= r \cdot \frac{\Delta b}{b} \times 100 + s \cdot \frac{\Delta c}{c} \times 100 + x \cdot \frac{\Delta d}{d} \times 100 + u \cdot \frac{\Delta e}{e} \times 100 \\ &= (rb_1 + sc_1 + xd_1 + ue_1)\% \end{aligned}$$

Problem 56. The pressure on a square plate is measured by measuring the force on the plate and the length of the sides of the plate. If the maximum error in the measurement of force and length are respectively 4% and 2%, The maximum error in the measurement of pressure is

- (a) 1% (b) 2% (c) 6% (d) 8%

Solution : (d) $P = \frac{F}{A} = \frac{F}{l^2}$, so maximum error in pressure (P)

$$\left(\frac{\Delta P}{P} \times 100 \right)_{\max} = \frac{\Delta F}{F} \times 100 + 2 \frac{\Delta l}{l} \times 100 = 4\% + 2 \times 2\% = 8\%$$

Problem 57. The relative density of material of a body is found by weighing it first in air and then in water. If the weight in air is (5.00 ± 0.05) Newton and weight in water is (4.00 ± 0.05) Newton. Then the relative density along with the maximum permissible percentage error is

- (a) $5.0 \pm 11\%$ (b) $5.0 \pm 1\%$ (c) $5.0 \pm 6\%$ (d) $1.25 \pm 5\%$

Solution : (a) Weight in air = $(5.00 \pm 0.05) N$

Weight in water = $(4.00 \pm 0.05) N$

Loss of weight in water = $(1.00 \pm 0.1) N$

Now relative density = $\frac{\text{weight in air}}{\text{weight loss in water}}$ i.e. $R.D = \frac{5.00 \pm 0.05}{1.00 \pm 0.1}$

Now relative density with max permissible error = $\frac{5.00}{1.00} \pm \left(\frac{0.05}{5.00} + \frac{0.1}{1.00} \right) \times 100 = 5.0 \pm (1 + 10)\%$
 $= 5.0 \pm 11\%$

Problem 58. The resistance $R = \frac{V}{i}$ where $V = 100 \pm 5$ volts and $i = 10 \pm 0.2$ amperes. What is the total error in R

- (a) 5% (b) 7% (c) 5.2% (d) $\frac{5}{2}\%$

Solution : (b) $R = \frac{V}{I} \therefore \left(\frac{\Delta R}{R} \times 100 \right)_{\max} = \frac{\Delta V}{V} \times 100 + \frac{\Delta I}{I} \times 100 = \frac{5}{100} \times 100 + \frac{0.2}{10} \times 100 = (5 + 2)\% = 7\%$

Problem 59. The period of oscillation of a simple pendulum in the experiment is recorded as 2.63 s, 2.56 s, 2.42 s, 2.71 s and 2.80 s respectively. The average absolute error is

- (a) 0.1 s (b) 0.11 s (c) 0.01 s (d) 1.0 s

Solution : (b) Average value = $\frac{2.63 + 2.56 + 2.42 + 2.71 + 2.80}{5} = 2.62 \text{ sec}$

Now $|\Delta T_1| = 2.63 - 2.62 = 0.01$

$|\Delta T_2| = 2.62 - 2.56 = 0.06$

$|\Delta T_3| = 2.62 - 2.42 = 0.20$

$|\Delta T_4| = 2.71 - 2.62 = 0.09$

$|\Delta T_5| = 2.80 - 2.62 = 0.18$

Mean absolute error $\Delta T = \frac{|\Delta T_1| + |\Delta T_2| + |\Delta T_3| + |\Delta T_4| + |\Delta T_5|}{5} = \frac{0.54}{5} = 0.108 = 0.11 \text{ sec}$

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Problem 60. The length of a cylinder is measured with a meter rod having least count 0.1 cm. Its diameter is measured with vernier calipers having least count 0.01 cm. Given that length is 5.0 cm. and radius is 2.0 cm. The percentage error in the calculated value of the volume will be

- (a) 1% (b) 2% (c) 3% (d) 4%

Solution : (c) Volume of cylinder $V = \pi r^2 l$

$$\begin{aligned} \text{Percentage error in volume } \frac{\Delta V}{V} \times 100 &= \frac{2\Delta r}{r} \times 100 + \frac{\Delta l}{l} \times 100 \\ &= \left(2 \times \frac{0.01}{2.0} \times 100 + \frac{0.1}{5.0} \times 100 \right) = (1 + 2)\% = 3\% \end{aligned}$$

Problem 61. In an experiment, the following observation's were recorded : $L = 2.820 \text{ m}$, $M = 3.00 \text{ kg}$, $l = 0.087 \text{ cm}$, Diameter $D = 0.041 \text{ cm}$ Taking $g = 9.81 \text{ m/s}^2$ using the formula, $Y = \frac{4Mg}{fD^2l}$, the maximum permissible error in Y is

- (a) 7.96% (b) 4.56% (c) 6.50% (d) 8.42%

Solution : (c) $Y = \frac{4Mg}{fD^2l}$ so maximum permissible error in $Y = \frac{\Delta Y}{Y} \times 100 = \left(\frac{\Delta M}{M} + \frac{\Delta g}{g} + \frac{\Delta L}{L} + \frac{2\Delta D}{D} + \frac{\Delta l}{l} \right) \times 100$

$$= \left(\frac{1}{300} + \frac{1}{9.81} + \frac{1}{9820} + 2 \times \frac{1}{41} + \frac{1}{87} \right) \times 100 = 0.065 \times 100 = 6.5\%$$

Problem 62. According to Joule's law of heating, heat produced $H = I^2 R t$, where I is current, R is resistance and t is time. If the errors in the measurement of I , R and t are 3%, 4% and 6% respectively then error in the measurement of H is

- (a) $\pm 17\%$ (b) $\pm 16\%$ (c) $\pm 19\%$ (d) $\pm 25\%$

Solution : (b) $H = I^2 R t$

$$\therefore \frac{\Delta H}{H} \times 100 = \left(\frac{2\Delta I}{I} + \frac{\Delta R}{R} + \frac{\Delta t}{t} \right) \times 100 = (2 \times 3 + 4 + 6)\% = 16\%$$

Problem 63. If there is a positive error of 50% in the measurement of velocity of a body, then the error in the measurement of kinetic energy is

- (a) 25% (b) 50% (c) 100% (d) 125%

Solution : (c) Kinetic energy $E = \frac{1}{2} m v^2$

$$\therefore \frac{\Delta E}{E} \times 100 = \left(\frac{\Delta m}{m} + \frac{2\Delta v}{v} \right) \times 100$$

Here $\Delta m = 0$ and $\frac{\Delta v}{v} \times 100 = 50\%$

$$\therefore \frac{\Delta E}{E} \times 100 = 2 \times 50 = 100\%$$

Problem 64. A physical quantity P is given by $P = \frac{A^3 B^{\frac{1}{2}}}{C^{-4} D^{\frac{3}{2}}}$. The quantity which brings in the maximum percentage error

in P is

(a) A

(b) B

(c) C

(d) D

Solution : (c) Quantity C has maximum power. So it brings maximum error in P .



Practice Problems

Problems based on units and dimensions

- Number of base SI units is
(a) 4 (b) 7 (c) 3 (d) 5
- The unit of Planck's constant is
(a) *Joule* (b) *Joule/s* (c) *Joule/m* (d) *Joule- s*
- The unit of reactance is
(a) *Ohm* (b) *Volt* (c) *Mho* (d) *Newton*
- The dimension of $\frac{R}{L}$ are
(a) T^2 (b) T (c) T^{-1} (d) T^{-2}
- Dimensions of potential energy are
(a) MLT^{-1} (b) ML^2T^{-2} (c) $ML^{-1}T^{-2}$ (d) $ML^{-1}T^{-1}$
- The dimensions of electric potential are
(a) $[ML^2T^{-2}Q^{-1}]$ (b) $[MLT^{-2}Q^{-1}]$ (c) $ML^2T^{-1}Q$ (d) $ML^2T^{-2}Q$
- The physical quantities not having same dimensions are
(a) Speed and $(\sim_0V_0)^{-1/2}$ (b) Torque and work
(c) Momentum and Planck's constant (d) Stress and Young's modulus
- The dimensional formula for Boltzmann's constant is
(a) $[ML^2T^{-2}K^{-1}]$ (b) $[ML^2T^{-2}]$ (c) $[ML^0T^{-2}K^{-1}]$ (d) $[ML^{-2}T^{-1}K^{-1}]$
- Which of the following quantities is dimensionless
(a) Gravitational constant (b) Planck's constant (c) Power of a convex lens (d) None of these
- Which of the two have same dimensions
(a) Force and strain (b) Force and stress
(c) Angular velocity and frequency (d) Energy and strain
- The dimensions of pressure is equal to
(a) Force per unit volume (b) Energy per unit volume (c) Force (d) Energy
- Identify the pair whose dimensions are equal
(a) Torque and work (b) Stress and energy (c) Force and stress (d) Force and work
- A physical quantity x depends on quantities y and z as follows: $x = Ay + B \tan Cz$, where A, B and C are constants. Which of the following do not have the same dimensions
(a) x and B (b) C and z^{-1} (c) y and B/A (d) x and A
- $ML^3T^{-1}Q^{-2}$ is dimension of
(a) Resistivity (b) Conductivity (c) Resistance (d) None of these

15. Two quantities A and B have different dimensions. Which mathematical operation given below is physically meaningful
 (a) A/B (b) $A + B$ (c) $A - B$ (d) None of these
16. Let $[\epsilon_0]$ denotes the dimensional formula of the permittivity of the vacuum and $[\mu_0]$ that of the permeability of the vacuum. If $M =$ mass, $L =$ length, $T =$ time and $I =$ electric current, then
 (a) $[\epsilon_0] = M^{-1}L^{-3}T^2I$ (b) $[\epsilon_0] = M^{-1}L^{-3}T^4I^2$ (c) $[\mu_0] = MLT^{-2}I^{-2}$ (d) $[\mu_0] = ML^2T^{-1}I$
17. The dimension of quantity (L/RCV) is
 (a) $[A]$ (b) $[A]^2$ (c) $[A^{-1}]$ (d) None of these
18. The quantity $X = \frac{\epsilon_0 LV}{t}$; here ϵ_0 is the permittivity of free space, L is length, V is potential difference and t is time. The dimensions of X are same as that of
 (a) Resistance (b) Charge (c) Voltage (d) Current
19. The unit of permittivity of free space ϵ_0 is
 (a) *Coulomb/Newton-metre* (b) *Newton-metre²/Coulomb²*
 (c) *Coulomb²/(Newton-metre)²* (d) *Coulomb²/Newton-metre²*
20. Dimensional formula of capacitance is
 (a) $M^{-1}L^{-2}T^4A^2$ (b) $ML^2T^4A^{-2}$ (c) $MLT^{-4}A^2$ (d) $M^{-1}L^{-2}T^{-4}A^{-2}$
21. The dimensional formula for impulse is
 (a) MLT^{-2} (b) MLT^{-1} (c) ML^2T^{-1} (d) M^2LT^{-1}
22. The dimensions of universal gravitational constant are
 (a) $M^{-2}L^2T^{-2}$ (b) $M^{-1}L^3T^{-2}$ (c) $ML^{-1}T^{-2}$ (d) ML^2T^{-2}
23. How many wavelength of Kr^{86} are there in one metre
 (a) 1553164.13 (b) 1650763.73 (c) 652189.63 (d) 2348123.73
24. Light year is a unit of
 (a) Time (b) mass (c) Distance (d) Energy
25. L , C and R represent physical quantities inductance, capacitance and resistance respectively. The combination which has the dimensions of frequency is
 (a) $1/RC$ and R/L (b) $1/\sqrt{RC}$ and $\sqrt{R/L}$ (c) $1/\sqrt{LC}$ (d) C/L
26. In the relation $P = \frac{r}{S} e^{-\frac{rz}{k_s}}$, P is pressure, z is distance, k is Boltzmann constant and s is temperature. The dimensional formula of s will be
 (a) $[M^0L^2T^0]$ (b) $[M^1L^2T^1]$ (c) $[M^1L^0T^0]$ (d) $[M^0L^2T^1]$
27. If the acceleration due to gravity be taken as the unit of acceleration and the velocity generated in a falling body in one second as the unit of velocity then
 (a) The new unit of length is g metre (b) The new unit of length is 1 metre
 (c) The new unit of length is g^2 metre (d) The new unit of time is $\frac{1}{g}$ second
28. The famous Stefan's law of radiation states that the rate of emission of thermal radiation per unit by a black body is proportional to area and fourth power of its absolute temperature that is $Q = \dagger AT^4$ where $A =$ area, $T =$ temperature and \dagger is a universal constant. In the 'energy-length-time temperature' (E-L-T-K) system the dimension of \dagger is
 (a) $E^2T^2L^{-2}K^{-2}$ (b) $E^{-1}T^{-2}L^{-2}K^{-1}$ (c) $ET^{-1}L^{-3}K^{-4}$ (d) $ET^{-1}L^{-2}K^{-4}$

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29. The resistive force acting on a body moving with a velocity V through a fluid at rest is given by $F = C_D V^2 A$... where, C_D = coefficient of drag, A = area of cross-section perpendicular to the direction of motion. The dimensions of C_D are
(a) ML^3T^{-2} (b) $M^{-1}L^{-1}T^2$ (c) $M^{-1}L^{-1}T^{-2}$ (d) $M^0L^0T^0$
30. The dimensions of (angular momentum)/(magnetic moment) are :
(a) $[M^3LT^{-2}A^2]$ (b) $[MA^{-1}T^{-1}]$ (c) $[ML^2A^{-2}T]$ (d) $[M^2L^{-3}AT^2]$
31. The frequency n of vibrations of uniform string of length l and stretched with a force F is given by $n = \frac{p}{2l} \sqrt{\frac{F}{m}}$ where p is the number of segments of the vibrating string and m is a constant of the string. What are the dimensions of m
(a) $ML^{-1}T^{-1}$ (b) $ML^{-3}T^0$ (c) $ML^{-2}T^0$ (d) $ML^{-1}T^0$
32. Choose the wrong statement(s)
(a) A dimensionally correct equation may be correct (b) A dimensionally correct equation may be incorrect
(c) A dimensionally incorrect equation may be incorrect (d) A dimensionally incorrect equation may be incorrect
33. A certain body of mass M moves under the action of a conservative force with potential energy V given by $V = \frac{Kr}{x^2 + a^2}$ where x is the displacement and a is the amplitude. The units of K are
(a) *Watt* (b) *Joule* (c) *Joule-metre* (d) None of these.
34. The Richardson equation is given by $I = AT^2 e^{-B/kT}$. The dimensional formula for AB^2 is same as that for
(a) IT^2 (b) kT (c) IK^2 (d) IK^2/T
35. If the units of force, energy and velocity are 10 N , 100 J and 5 ms^{-1} , the units of length, mass and time will be
(a) $10\text{m}, 5\text{kg}, 1\text{s}$ (b) $10\text{m}, 4\text{kg}, 2\text{s}$ (c) $10\text{m}, 4\text{kg}, 0.5\text{s}$ (d) $20\text{m}, 5\text{kg}, 2\text{s}$.

Problems based on error of measurement

36. The period of oscillation of a simple pendulum is given by $T = 2\pi \sqrt{\frac{l}{g}}$ where l is about 100 cm and is known to 1mm accuracy. The period is about 2s . The time of 100 oscillations is measured by a stop watch of least count 0.1 s . The percentage error in g is
(a) 0.1% (b) 1% (c) 0.2% (d) 0.8%
37. The percentage errors in the measurement of mass and speed are 2% and 3% respectively. How much will be the maximum error in the estimation of the kinetic energy obtained by measuring mass and speed
(a) 11% (b) 8% (c) 5% (d) 1%
38. While measuring the acceleration due to gravity by a simple pendulum, a student makes a positive error of 1% in the length of the pendulum and a negative error of 3% in the value of time period. His percentage error in the measurement of g by the relation $g = 4\pi^2 \left(\frac{l}{T^2} \right)$ will be
(a) 2% (b) 4% (c) 7% (d) 10%
39. The random error in the arithmetic mean of 100 observations is x ; then random error in the arithmetic mean of 400 observations would be
(a) $4x$ (b) $\frac{1}{4}x$ (c) $2x$ (d) $\frac{1}{2}x$
40. What is the number of significant figures in 0.310×10^3
(a) 2 (b) 3 (c) 4 (d) 6
41. Error in the measurement of radius of a sphere is 1% . The error in the calculated value of its volume is
(a) 1% (b) 3% (c) 5% (d) 7%

42. The mean time period of second's pendulum is 2.00s and mean absolute error on the time period is 0.05s. To express maximum estimate of error, the time period should be written as
 (a) $(2.00 \pm 0.01) s$ (b) $(2.00 + 0.025) s$ (c) $(2.00 \pm 0.05) s$ (d) $(2.00 \pm 0.10) s$
43. A body travels uniformly a distance of $(13.8 \pm 0.2) m$ in a time $(4.0 \pm 0.3) s$. The velocity of the body within error limits is
 (a) $(3.45 \pm 0.2) ms^{-1}$ (b) $(3.45 \pm 0.3) ms^{-1}$ (c) $(3.45 \pm 0.4) ms^{-1}$ (d) $(3.45 \pm 0.5) ms^{-1}$
44. The percentage error in the above problem is
 (a) 7% (b) 5.95% (c) 8.95% (d) 9.85%
45. The unit of percentage error is
 (a) Same as that of physical quantity
 (b) Different from that of physical quantity
 (c) Percentage error is unit less
 (d) Errors have got their own units which are different from that of physical quantity measured
46. The decimal equivalent of $1/20$ upto three significant figures is
 (a) 0.0500 (b) 0.05000 (c) 0.0050 (d) 5.0×10^{-2}
47. If 97.52 is divided by 2.54, the correct result in terms of significant figures is
 (a) 38.4 (b) 38.3937 (c) 38.394 (d) 38.39
48. Accuracy of measurement is determined by
 (a) Absolute error (b) Percentage error (c) Both (d) None of these
49. The radius of a sphere is $(5.3 \pm 0.1) cm$. The percentage error in its volume is
 (a) $\frac{0.1}{5.3} \times 100$ (b) $3 \times \frac{0.1}{5.3} \times 100$ (c) $\frac{0.1 \times 100}{3.53}$ (d) $3 + \frac{0.1}{5.3} \times 100$
50. A thin copper wire of length l metre increases in length by 2% when heated through $10^\circ C$. What is the percentage increase in area when a square copper sheet of length l metre is heated through $10^\circ C$
 (a) 4% (b) 8% (c) 16% (d) None of the above.
51. In the context of accuracy of measurement and significant figures in expressing results of experiment, which of the following is/are correct
 (1) Out of the two measurements $50.14 cm$ and $0.00025 ampere$, the first one has greater accuracy
 (2) If one travels $478 km$ by rail and $397 m$. by road, the total distance travelled is $478 km$.
 (a) Only (1) is correct (b) Only (2) is correct (c) Both are correct (d) None of them is correct.



Answer Sheet (Practice problems)

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
b	d	a	c	b	a	c	a	d	c
11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
b	a	d	a	a	c	c	d	d	a
21.	22.	23.	24.	25.	26.	27.	28.	29.	30.
b	b	b	c	a	a	a	d	d	b
31.	32.	33.	34.	35.	36.	37.	38.	39.	40.
d	c	c	c	b	c	b	c	d	b
41.	42.	43.	44.	45.	46.	47.	48.	49.	50.
b	c	b	c	c	a	a	b	b	a
51.									
c									