General Physics

Contents

1. GENERAL PHYSICS (PHYSICS AND MEASUREMENT)

1.1 PHYSICS, TECHNOLOGY AND SOCIETY

1.1.1 What is physics?

Physics is the scientific study of matter and energy and how they interact with each other.
Physics covers a wide range of phenomena, from the smallest sub-atomic particles, to the largest galaxies. Included in this are the very most basic objects from which all other things are composed of, and therefore physics is sometimes said to be the "fundamental science".
Next very interesting question is how physics works?

As an *experimental* science, physics utilizes the scientific method to formulate and test hypotheses that are based on observation of the natural world. The goal of physics is to use the results of these experiments to formulate scientific laws, usually expressed in the language of mathematics, which can then be used to predict other phenomena.

In a broader sense, physics can be seen as the most fundamental of the natural sciences. Chemistry, for example, can be viewed as a complex application of physics, as it focuses on the interaction of energy and matter in chemical systems. We also know that biology is, at its heart, an application of chemical properties in living things, which means that it is also, ultimately, ruled by the physical laws.

Physics is the discipline devoted to understanding nature in a very general sense: the fundamental characteristic of physics is that it aims to gain knowledge, and hopefully understanding, of the general properties of world around us.

1.1.2 Physics, technology and society

There is a connection between physics, technology and society which can be seen in many examples:

The discipline of thermodynamics arose from the need to understand and improve the working of heat engines. The steam engine, as we know, is inseparable from the Industrial Revolution in England in the eighteenth century, which had great impact on the course of human civilization As late as 1933, the great physicist Ernest Rutherford had dismissed the possibility of tapping energy from atoms. But only a few years later, in 1938, Hahn and Meitner discovered the phenomenon of neutron-induced fission of uranium, which would serve as the basis of nuclear power reactors and nuclear weapons.

Yet another important example of physics giving rise to technology is the silicon 'chip' that triggered the computer revolution in the last three decades of the twentieth century.

1.1.3 Link between technology and physics

Technology	Scientific principle(s)
Steam engine	Laws of thermodynamics
Nuclear reactor	Controlled nuclear fission
Radio and Television	Generation, propagation and detection of electromagnetic waves
Computers	Digital logic
Lasers	Light amplification by stimulated emission of radiation
Production of ultra high magnetic fields	Superconductivity
Rocket propulsion	Newton's laws of motion
Electric generator	Faraday's laws of electromagnetic induction
Hydroelectric power	Conversion of gravitational potential energy into electrical energy
Aeroplane	Bernoulli's principle in fluid dynamics
Particle accelerators	Motion of charged particles in electromagnetic fields
Sonar	Reflection of ultrasonic waves
Optical fibres	Total internal reflection of light
Non-reflecting coatings	Thin film optical interference
Electron microscope	Wave nature of electrons
Photocell	Photoelectric effect
Fusion test reactor (Tokamak)	Magnetic confinement of plasma
Giant Metrewave Radio Telescope (GMRT)	Detection of cosmic radio waves
Bose-Einstein condensate	Trapping and cooling of atoms by laser beams and magnetic fields.

1.2 UNIT AND DIMENSIONS

1.2.1 Unit

Any standard of measurement used to measure the required physical quantity is called a unit of physical quantity.

Why do we need units?

We need units because we want to measure the Amount or quantity of some things. To make this measurement globally acceptable we need to put some unique measurement value. This value is called a UNIT.

The measurement of a physical quantity requires the following two steps.

1) To select a convenient unit (u) for measuring the required physical quantity.
2) To find the number of times that selected unit is contained in the physical quantity to be measured.

Then, Measurement of a physical quantity = nu

By international agreement a small number of physical quantities such as length, time etc. are chosen and assigned standards. These quantities are called '**base quantities**' and their units as '**base units**'. All other physical quantities are expressed in terms of these 'base quantities'. The units of these dependent quantities are called '**derived units**'.

The standard for a unit should have the following characteristics.

(a) It should be well defined.
(b) It should be invariable (should not change with time)
(c) It should be convenient to use
(d) It should be easily accessible

The 14th general conference on weights and measures (in France) picked seven quantities as base quantities, thereby forming the **International System of Units** abbreviated as SI (System de International) system.

1.2.1.1 System of units

Commonly used systems of units are

(1) The fps system (foot, pound and seconds system)
(2) The mks system (metre, kilogram and second system)
(3) The cgs system (centimeter, gram and seconds system)
(4) The SI system (Systeme International)

The first three systems have just got the three mechanical quantities as the fundamental units (i.e. mass, length and time).

The fourth system, the SI system has seven fundamental units and two supplementary units (given in the table)

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

Apart from these seven base fundamental units, there are two supplementary units used

1. The plane angle measured in radian.
2. The solid angle measured in steradian.

1.2.1.2 Derived units

We can define all the derived units in terms of base units. For example, speed is defined to be the ratio of distance to time.

Unit of Speed = (unit of distance (length))/ (unit of time)

= m/s = ms^{-1} (Read as metre per sec.)

SOME DERIVED SI UNITS AND THEIR SYMBOLS

Quantity	Unit	Symbol	Express in base units
Force	newton	N	Kg-m/sec^2
Work	joules	J	Kg-m^2/sec^2
Power	watt	W	Kg-m^2/sec^3
Pressure	pascal	Pa	Kg m^{-1}/S^2

Important:

The following conventions are adopted while writing a unit.

(1) Even if a unit is named after a person the unit is not written in capital letters. i.e. we write joules not Joules.

(2) For a unit named after a person the symbol is a capital letter e.g. for joules we write 'J' and the rest of them are in lowercase letters e.g. seconds is written as 's'.

(3) The symbols of units do not have plural form i.e. 70 m not 70 ms or 10 N not 10Ns.

(4) Not more than one solid's is used i.e. all units of numerator written together before the '/' sign and all in the denominator written after that.
i.e. It is 1 ms^{-2} or 1 m/s^2 not 1m/s/s.

(5) Punctuation marks are not written after the unit
e.g. 1 litre = 1000 cc not 1000 c.c.

It has to be borne in mind that SI system of units is not the only system of units that is followed all over the world. There are some countries (though they are very few in number) which use different system of units. For example: the FPS (Foot Pound Second) system or the CGS (Centimeter Gram Second) system.

1.2.2 Dimensions

The unit of any derived quantity depends upon one or more fundamental units. This dependence can be expressed with the help of dimensions of that derived quantity. In other words, the dimensions of a physical quantity show how its unit is related to the fundamental units.

Dimension of a physical quantity are the powers to which the fundamental quantities must be raised to represent the given physical quantity.

The powers to which the fundamental quantities of mass (M), Length (L), time (T), temperature (K), current (A) are raised to get the required physical quantity.
Symbolically, dimensional formula for a physical quantity, say X is represented by putting it in the square bracket [X] (to be read as dimensional formula of X).
For example: energy has dimensional formula given by
$[Energy]=ML^2T^{-2}$
i.e. energy has dimensions, 1 in mass, 2 in length and –2 in time.

Dimension of a physical quantity are the powers to which the fundamental quantities must be raised to represent the given physical quantity.

Example: Density of a substance is defined to be the mass contained in unit volume of the substance.

Hence, [density] = ([mass])/ ([volume]) = $M/L^3 = ML^{-3}$

So, the dimensions of density are 1 in mass, -3 in length and 0 in time.

Hence the dimensional formula of density is written as $[\rho]= ML^{-3}T^0$

***Example*:** Identify the pair whose dimensions are equal.

a) Torque and work
b) Stress and energy
c) Force and stress
d) Force and work

Solution: Torque=Force × perpendicular distance
And Work= Force × distance
Therefore Torque and work are dimensionally equal

Example: Which of the following has the dimensions of pressure?

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

Solution: Pressure=Force/Area

$=MLT^{-2}/L^{2}$
$=ML^{-1}T^{-2}$

1.2.2.1 Dimensional equation

Whenever the dimension of a physical quantity is equated with its dimensional formula, we get a dimensional equation.

1.2.2.2 Principal of homogeneity

According to this principle, we can add and multiply physical quantities with same or different dimensional formulae at our convenience, however no such rule applies to addition and subtraction, where only like physical quantities (scalars, and vectors with vectors) can only be added or subtracted.

The dimensions of the physical quantities on the left hand side of an equation must be the same as that on the right hand side.

1.2.2.3 Uses of dimensional analysis:

The method of dimensional analysis is useful in the following cases:

(i) To find the unit of a given physical quantity in a given system of units:

By expressing a physical quantity in terms of basic quantity we find its dimensions. In the dimensional formula replacing M, L, T by the fundamental units of the required system, we get the unit of physical quantity. However, sometimes we assign a specific name to this unit.

Example: Force is numerically equal to the product of mass and acceleration
i.e. Force = mass x acceleration

or [F] = mass x velocity/time
= mass x displacement/ $(time)^2$
= mass x length/ $(time)^2$

$= [M] \times [LT^{-2}] = [MLT^{-2}]$

Its unit in SI system will be $Kgms^{-2}$ which is given a specific name "newton (N)".
Similarly, its unit in CGS system will be $gmcms^{-2}$ which is called "dyne".

(ii) To find dimensions of physical constants or coefficients:

The dimension of a physical quantity is unique because it is the nature of the physical quantity and the nature does not change. If we write any formula or equation incorporating the given physical constant, we can find the dimensions of the required constant or co-efficient.

Example: In Vander Wall's equation

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT,$$

What are the dimensions of a and b? Here, P is pressure, V is volume, T is temperature and R is gas constant.

Solution: The given equation is

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT,$$

As pressure can be added only to pressure therefore, a / V^2 represents pressure P

i.e. $\frac{a}{V^2} = P$ or $a = PV^2$

$= (ML^{-1}T^{-2})(L^3)^2 = [M^1L^5T^{-2}]$

Again, from volume V, we can subtract only the volume. Therefore, b must be representing volume only i.e.

$b = V = [L^3] = [M^0L^3T^0]$

(iii) To convert a physical quantity from one system of units to another:

This is based on the fact that for a given physical quantity,

Magnitude x unit = constant

So, when unit changes, magnitude will also change.

Example: Convert one Newton into dyne

Solution: Dimensional formula for Newton = $[MLT^{-2}]$

Or 1 N = 1 Kg m/s^2; But 1 kg = 10^3 g and 1 m = 10^2 cm

Therefore 1 N = ((10^3 g) (10^2 cm))/s^2 = 10^5 g cm/s^2 = 10^5 dyne

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

This is based on the principle that the dimensions of the terms on both sides on an equation must be same. This is known as the **'principle of homogeneity'**. If the dimensions of the terms on both sides are same, the equation is dimensionally correct, otherwise not.

Caution: It is not necessary that a dimensionally correct equation is also physically correct but a physically correct equation has to be dimensionally correct.

Example: Check the accuracy of the relation $v = \frac{1}{2l}\sqrt{\frac{T}{m}}$, where v is the frequency, l is length, T is tension and m is mass of unit length of the string.

Solution: The given relations is

$$v = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

Writing the dimensions on either side, we get

L.H.S. $= v = [T^{-1}]$

$= [M^0L^0T^{-1}]$

R.H.S. $= \frac{1}{2l}\sqrt{\frac{T}{m}}$

As ½ has no dimensions, tension is force and m = mass/length.

$\therefore$ R.H.S. $= \frac{1}{L}\sqrt{\frac{MLT^{-2}}{ML^{-1}}}$

$= \frac{1}{L}\sqrt{L^2T^{-2}}$

$= \frac{1}{L}(LT^{-1})$

$= T^{-1} = [M^0L^0T^{-1}]$

As L.H.S. = R.H.S., dimensionally

$\therefore$ Formula is correct.

(v) As a research tool to derive new relations:

The theory of dimensions (in the light of principal of homogeneity) provides us with a powerful tool of research in the preliminary stages of investigation [It must be again emphasized that mere dimensional correctness of an equation does not ensure its physical correctness]

Example: The frequency of vibration (v) of a string may depend upon length (l) of the string, tension (T) in the string and mass per unit length (m) of the string. Using the method of dimensions, derive the formula for$v$.

Solution: Let $v = Kl^aT^bm^c$ ...(i)

Where K is dimensionless constant of proportionality and $a,\ b,\ c$ are the powers of $l,\ T$ and m respectively to represent$v$.

The tension T stands for force whose dimensions are $[M^1L^1T^{-2}]$ and

$m = \frac{\text{mass}}{\text{length}} = \frac{M}{L} = [M^1L^{-1}]$

Writing the dimensions in (i), we get

$[M^0L^0T^{-1}] = L^a(M^1L^1T^{-2})^b(ML^{-1})^c$

$=L^aM^bL^bT^{-2b}M^cL^{-c}$

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

Applying the principle of homogeneity of dimensions, we get

$b + c = 0$ ...(ii)

$a+b-c=0$ ...(iii)

$-2b = -1$ or $b = 1/2$

from (ii), $c = -b = -\frac{1}{2}$

from (iii),

$a + \frac{1}{2} + \frac{1}{2} = 0$ or $a = -1$

Putting these values in (i), we get

$v = Kl^{-1}T^{1/2}m^{-1/2}$

or $v = \frac{K}{l}\sqrt{\frac{T}{m}}$

This is the required formula.

1.2.2.4 Limitations of the theory of dimensions

The limitations are as follows:

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

(ii) Numerical constants, having no dimensions, cannot be deduced by using the concepts of dimensions.

(iii) The method of dimensions cannot be used to derive relations other than product of power functions. Again, expressions containing trigonometric or logarithmic functions also cannot be derived using dimensional analysis, e.g.

$$s = ut + (½)at^2 \quad \text{or} \quad y = a \sin\omega t$$

cannot be derived. However, their dimensional correctness can be verified.

(iv) If a physical quantity depends on more than three physical quantities, method of dimensions cannot be used to derive its formula. For such equations, only the dimensional correctness can be checked. For example, the time period of a physical pendulum, moment of inertia I, mass m and length l is given by the following equation.

$$T = 2\Pi\sqrt{(I/mgl)}$$

(I is known as the moment of Inertia with dimensions of $[ML^2]$ through dimensional analysis), though we can still check the dimensional correctness of the equation.

(v) Even if a physical quantity depends on three Physical quantities, out of which two have the same dimensions, the formula cannot be derived by theory of dimensions, and only its correctness can be checked.

1.3 SIGNIFICANT FIGURES AND ERROR ANALYSIS

1.3.1 Significant figures

The number of figures required to specify a given measurement are called significant figures. Though the last digit of the measurement is always doubtful, yet it is included in the number of significant figures. As an example if we measure the length of an object as 5.46 cm, then it has 3 significant figures.

1.3.1.1 Rules for calculating significant figures

(1) All non-zero digits are significant.

(2) The significant digits in a number are equal to the number of digits counted from the first non-zero digit on the left to the last digit on the right.

(3) All zeros occurring in between non-zero digits are significant e.g. 12.0032 have six significant figures.

(4) For numbers having absolute value less than 1, all zeros lying in between a decimal point and the first non-zero digit on the right side of it are non-significant. The number 0.00235 has only three significant figures.

(5) All zeroes appearing after the last non-zero digit on right side of a decimal point are significant. The number 123.000 has six significant figures.

(6) Whenever there is no decimal, the concluding zeroes of the measurement are non-significant. e.g. 126000 have only 3 significant figures.

1.3.1.2 Significant figures in algebraic operations

During the algebraic operations of addition, subtraction, multiplication and division, the result contains the minimum number of significant figures in the component measurements.

NOTE	
1.	The powers of 10 and the zeroes on the left side of the measurement are not counted while counting the significant figures.
2.	Greater the number of significant figures in a measurement, smaller is the percentage error.
3.	For rounding off significant figures, if the succeeding figure is greater than 5 then the figure is increased by 1 else it is left unchanged. However, if the succeeding figure is 5 itself then the figure is raised by 1 if it is odd and left unchanged it is even.

Example: Add 17.35 g, 25.6 g; and 8.498 g and write the result with the correct number of significant figures.

Solutions: Out of the three given values of mass 25.6 g is least accurate, being correct only upto first place of decimal. The other two values of mass have to be rounded off to one place of decimal i.e.

$$17.35 \approx 17.4g \text{ and } 8.498 = 8.5\ g$$
$$\therefore\ 17.4 + 25.6 + 8.5 = 51.5\ g$$

1.3.2 Errors

The difference in the true value and the measured value of a quantity is called error of measurement. The errors in measurement can be broadly classified as systematic errors, random errors and gross errors.

1. The systematic errors are those errors that tend to be in one direction, either positive or negative. Infact, the causes of systematic errors are known. Therefore, such errors can be minimized.
2. The random errors are the errors which occur irregularly. The random errors may arise due to random and unpredictable variations in experimental conditions e.g. temperature, pressure, voltage supply, mechanical vibrations etc.
3. Gross errors arise on account of shear carelessness of the observer.

Consider a physical quantity measured by taking repeated number of observations say $x_1,\ x_2,\ x_3\ \ x_4 \dots\dots\dots\dots\dots\dots\dots\dots$. If $< x >\ or\ \bar{x}$ be the average value of the measurement, then error in the respective measurement is $x_1 - \bar{x},\ x_2 - \bar{x},\ x_3 - \bar{x},\ \dots$ and so on. This error which is the absolute difference between the true value and the observed value (or vice versa) is called absolute error (denoted by$\triangle x$). So,

$$\triangle x = |x\ \textit{experimental value} - x\ \textit{true value}|$$

We must keep in mind that absolute errors is always positive and never attains a negative value as it is protected by the modulus sign. So,
$\Delta x > 0$

Some of the sources of systematic errors are:

1. Instrumental errors which arise from the errors due to imperfect design or manufacture or calibration of the measuring instrument.
2. Imperfection in experimental technique or procedure.
3. Personal error arises due to inexperience of the observer.
4. Errors due to external causes such as temperature, pressure, humidity, wind velocity etc.
5. Least count error is the error associated with the resolution of the instrument

1.3.2.1 Percentage error

Percentage Error $= \frac{\Delta x}{x} \times 100\%$

1.3.2.2 Propagation of errors

1. **In case of addition and subtraction**

   If $x = A \pm B$
   Then $\Delta x = \Delta A \pm \Delta B$
   i.e. for both addition and subtraction the absolute errors are added up. The percentage of error in the value of x is
   Percentage error in value of $x = \left(\frac{\Delta A + \Delta B}{A \pm B}\right) \times 100\%$

2. In case of multiplication and division

If $y=AB$ or $y=\frac{A}{B}$

Then,

$$\frac{\Delta y}{y}=\frac{\Delta A}{A}+\frac{\Delta B}{B}$$

$$\Rightarrow \frac{\Delta y}{y}\times 100\% = \frac{\Delta A}{A}\times 100\% + \frac{\Delta B}{B}\times 100\%$$

$\Rightarrow$ Percentage error in value of $x=$ Percentage error in value of $A+$ Percentage error in value of B.

3. In case of power functions

If $y=k\frac{A^l B^m}{C^n}$ then,

$$\frac{\Delta y}{y}=l\left(\frac{\Delta A}{A}\right)+m\left(\frac{\Delta B}{B}\right)+n\left(\frac{\Delta C}{C}\right)$$

$\Rightarrow$ (Percentage error in value of y) = l (Percentage error in value of A) + m (Percentage error in value of B) + n (Percentage error in value of C)

NOTE

1. The error in a measurement is always equal to the least count of the measuring instrument.
2. Errors never propagate in case of constants.
3. In general, if $y=kx^n$ then
   $$\frac{\Delta y}{y}=n\frac{\Delta x}{x}$$
   irrespective of value of k .

Example: Specific resistance p of a thin circular wire of radius r cm, resistance R ohm and length L is given by $\rho=\frac{\pi r^2 R}{L}$. If r = (0.26±0.1) cm, R = (30 ± 2) ohm and L=(75.00 ± 0.01) cm, find the percentage error in p.

Solution: From $\rho=\frac{\pi r^2 R}{L}$

$$\frac{\Delta\rho}{\rho}=2\frac{\Delta r}{r}+\frac{\Delta R}{R}+\frac{\Delta L}{L}=2\times\frac{0.01}{0.26}+\frac{2}{30}+\frac{0.01}{75}$$

=0.0769 + 0.0666 + 0.0001 = 0.1436

Percentage error, $\frac{\Delta\rho}{\rho}\times 100 = 0.1436\times 100 = 14.36\%$

1.4 LEAST COUNT, ACCURACY AND PRECISION OF MEASURING INSTRUMENT

1.4.1 Least count

The *least count* of any measuring equipment is the smallest quantity that can be measured accurately using that instrument. Thus Least Count indicates the degree of accuracy of measurement that can be achieved by the measuring instrument.

All measuring instruments used in physics have a least count. A meter ruler's least count is 0.1 centimeter; a vernier caliper has a least count of 0.02 millimeters, although this too may vary; and micrometer screw gauge's least count is 0.01 millimeter and of course a conventional ruler has .01m.

The least count is the discrimination of a vernier instrument. All measuring instruments used in the subject of physics can be used to measure various types of objects, but all do so without considering the detail of accuracy.

No measuring instrument used in physics is accurate and always has an error when readings are taken. Even the latest technology used in measuring objects also has an error where readings are concerned. Various names can be given to this error. The least count, uncertainty or maximum possible errors are the terms normally used in a physics course, although this may vary with different syllabuses.

The error made in an instrument can be compared with another by calculating the percentage uncertainty of each of the readings obtained. The one with the least uncertainty is always taken to measure objects, as all measurements are required with accuracy in mind. The percentage uncertainty is calculated with the following formula: (Maximum Possible error/Measurement of the Object in question) *100

The smaller the measurement, the larger the percentage uncertainty. The least count of an instrument is indirectly proportional to the accuracy of the instrument.

1.4.2 Accuracy of measurement

The accuracy of measurement is a measure of how close the measured value is to the true value of the quantity.

1.4.3 Precision

Precision tells us to what resolution or limit the quantity is measured by a measuring instrument. It is determined by the least count of the measuring instrument. Smaller the least count, greater is the precision.

Example: The concept of precision and accuracy can be understood with the help of this example.

Three different individuals with different skill levels are allowed to complete a round of target practice. The outcome of the event is shown in the figure. It is evident that the target at the left belongs to a highly skilled shooter. This is characterized by all the shots in the inner most circle. The result indicates good accuracy as well as good precision. A measurement made well must be like this case! The individual in the middle is precise but not accurate. Maybe it is due to a faulty bore of the gun. The individual at the right is an unskilled person who is behind on both counts. Most beginners will fall into this category. The analogy is quite realistic since most students performing a measurement in the laboratory may be put into one of the three categories. A good experimentalist has to work hard to excel in it!