1.1. The term Measurement and Methods of Measurement

Definition and concept of Measurement

"The **measurement** of a given quantity is an act or the result of quantitative comparison between the unknown quantity and a quantity of a same kind chosen as a standard or unit".

- The result of measurement is expressed by a number representing the ratio of the unknown quantity to the adopted unit of measurement.
- The measurement is the process by which one can convert physical parameters to meaningful numbers.

Basic Requirements of Measurement

- The standard used for comparison purposes must be accurately defined and should be commonly accepted.
- The apparatus used and the method adopted must be provable.

Measuring Instrument

- It may be defined as a device for determining the value or magnitude of a quantity or variable.

Methods of Measurement

- The methods of measurement can be classified as direct methods and indirect methods.

  1) Direct Method
     - The unknown quantity is determined by direct comparison with a standard of the given quantity.
     - The result is expressed in terms of a chosen unit for the standard and a numerical multiplier.
     - For example, a length can be measured in terms of meter and a numerical constant. Thus a 5 m length means a length of 5 times of meter.

  2) In-direct Method
     - The direct comparison methods are simple but it is not always possible, feasible and practicable to use them.
     - The involvement of a person in these methods make them inaccurate and less sensitive. Hence, direct methods are not preferred and are rarely used.
     - In engineering applications, use of measurement systems which are indirect methods of measurement, is made.
     - For example, sometimes measurement of dc power is done by using measurement of voltage and current and then power is calculated by using product of them.

1.2. Standard

The "Standard"

- A **standard** (or etalon) is an object, system, or experiment that bears a defined relationship to a unit of measurement of a physical quantity.
- Standards are the **fundamental reference** for a system of weights and measures, against which all other measuring devices are compared.

- Modern measurements are defined in relationship to internationally standardized reference objects, which are used under carefully controlled laboratory conditions to define the units of length, mass, electrical potential, and other physical quantities.
- The standards can be classified in major four types as per following.

The "International Standard"

- International standards are standards developed by international standards organizations.
- International standards are available for consideration and use worldwide.
- The most prominent organization is the International Organization for Standardization (ISO).

The "Primary Standard"

- Primary standards are used to calibrate other standards referred to as working standards.
- Primary standards are defined via other quantities like length, mass and time.
- **An example** of a primary standard is the international prototype kilogram (IPK) which is the master kilogram and the primary mass standard for the International System of Units (SI).
- The IPK is a one kilogram mass of a platinum-iridium alloy maintained by the International Bureau of Weights and Measures (BIPM) in Sèvres, France.
- **Another example** is the unit of electrical potential, the volt. Formerly it was defined in terms of standard cell electrochemical batteries, which limited the stability and precision of the definition.

The "Secondary Standard"

- Secondary standards are calibrated with reference to a primary standard.
- Secondary reference standards are very close approximations of primary reference standards.
- **For example**, major national measuring laboratories such as the US's National Institute of Standards and Technology (NIST) will hold several "national standard" kilograms, which are periodically calibrated against the IPK and each other.

The "Secondary Standard"

- A Standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials.
- A working standard is usually calibrated against a reference standard.
- Working standards are used for the calibration of commercial and industrial measurement equipment.
- Working standards are expected to deteriorate, and are no longer considered traceable to a national standard after a time period or use count expires.

1.3. Generalized Measurement System

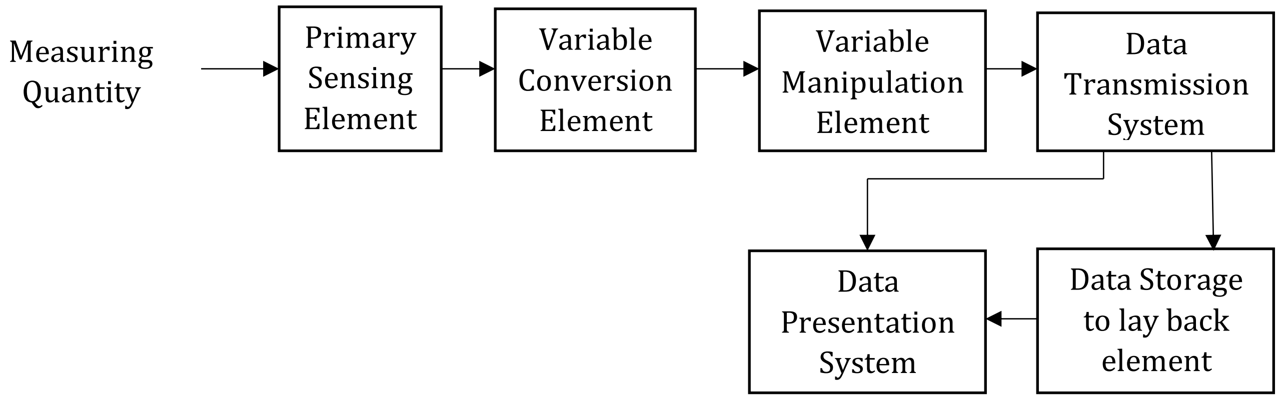

Figure 1.1 Block Diagram of Generalized Measurement System

- The measurement system have mainly five elements as described below.

Primary Sensing Element (Detector stage)

- The quantity under measurement makes its first contact with the primary sensing element of a measurement system. i.e., the measurand- (the unknown quantity which is to be measured) is first detected by primary sensor which gives the output in a different analogous form.
- This output is then converted into an electrical signal by a transducer - (which converts energy from one form to another).
- The first stage of a measurement system is known as a detector.

Variable Conversion Element (Transducer stage)

- The output of the primary sensing element may be electrical signal of any form; it may be voltage, a frequency or some other electrical parameter.
- For the instrument to perform the desired function, it may be necessary to convert this output to some other suitable form.

Variable Manipulation Element (Signal conditioning stage)

- The function of this element is to manipulate the signal presented to it preserving the original nature of the signal.
- It is not necessary that a variable manipulation element should follow the variable conversion element.
- Some non-linear processes like modulation, detection, sampling, filtering, chopping etc., are performed on the signal to bring it to the desired form to be accepted by the next stage of measurement system.
- This process of conversion is called signal conditioning'.
- The term signal conditioning includes many other functions in addition to Variable conversion & Variable manipulation. In fact the element that follows the primary sensing element in any instrument or measurement system is called signal conditioning element'.

Data Transmission Element

- When the elements of an instrument are actually physically separated, it becomes necessary to transmit data from one to another. The element that performs this function is called a data transmission element'.

Data Presentation Element

- The information about the quantity under measurement has to be conveyed to the personnel handling the instrument or the system for monitoring, control, or analysis purposes. This function is done by data presentation element.
- In case data is to be monitored, visual display devices are needed. These devices may be analog or digital indicating instruments like ammeters, voltmeters etc.
- In case data is to be recorded, recorders like magnetic tapes, high speed camera & TV equipment, CRT, printers may be used.
- For control & analysis purpose microprocessor or computers may be used. The final stage in a measurement system is known as terminating stage.

1.4. Classification of instrument system

The instrument system mainly classified in following manners.

1) Absolute and Secondary Instruments
2) Direct measuring and Comparison Instruments
3) Active and Passive Instruments
4) Deflection and Null type Instruments
5) Monitoring and Control Instruments
6) Analog and Digital Instruments

1) Absolute and Secondary Instruments

Absolute Instruments

- This type of instrument give the magnitude of the quantity to be measured in terms of instrument constant and its deflection.
- Such instrument do not require any comparison with any other standard instrument.
- Such instruments are not widely used in practice.
- **Example:** Tangent Galvanometer ……… which gives value of current in terms of tangent of the angle of deflection produced, the horizontal component of the earth's magnetic field, the radius and the number of turns of wire used.

Secondary Instruments

- In this instrument, the measurand can be measured by observing the output indicated by the instrument.
- These instruments are required to be calibrated by comparison with an absolute instrument.
- Such instruments are widely used in practice.
- **Example:** ammeters, voltmeters, wattmeters, glass thermometers, pressure gauges etc.

Table 1.1 Comparison of Absolute and Secondary Instruments

Instrument	Absolute	Secondary
Result	In terms of physical constant of instruments	Result displayed on dial
Time required	Time consuming	Quick measurement can be done
Usage	In standard institutions	Everywhere
Examples	Tangent Galvanometer	Voltmeter, Pressure gauge

2) Direct measuring and Comparison Instruments

Direct measuring Instruments

- This type of instrument convert the energy of the unknown quantity directly into energy that deflects the moving element of the instrument, the value of the unknown quantity being measured by reading the resulting deflection.
- These instruments are widely used in engineering practice.
- **Example:** Ammeters, voltmeters, wattmeters.

Comparison Instruments

- This type of instrument measure the unknown quantity by comparing it with a standard that is often contained in the instrument case such as resistance measuring bridges.
- These instruments are used in cases when a higher accuracy of measurement is needed.
- **Example:** Wheatstone bridge, Maxwell's bridge etc.

3) Active and Passive Instruments

- Instruments are either active or passive according to whether the instrument output is entirely produced by the quantity under measurement or the quantity under measurement simply modulates the magnitude of some external power source.
- **Example:** Active ----- Petrol tank level indicator

  Passive ---- Pressure gauge

Table 1.2 Comparison of Active and Passive Instruments

Instrument	Active	Passive
Energy source	No external energy source	External energy source required
Resolution	Less	High
Design	Simple	Complicated
Examples	Analog Voltmeter, Ammeter	Flow indicator, LVDT

4) Deflection type and Null type Instruments

Deflection type Instrument

- In this, the quantity under measurement produces some physical effect which deflects or produces a mechanical displacement of the moving system of the instrument.
- An opposing effect is built in instrument which tries to oppose the deflection.
- The opposing effect increases until a balance is achieved, at which point the 'deflection' is measured and value of measured quantity inferred from this.
- **Examples –** PMMC meters.

Null type Instrument

- A null type instrument attempts to maintain deflection at zero by suitable application of an effect opposing that generated by the quantity under measurement.
- Necessary to such an operations are a detector of unbalance and a means of restoring balance.
- **Example –** DC Potentiometer.

Table 1.3 Comparison of Active and Passive Instruments

Instrument	Deflection type	Null type
Accuracy	Low	High
Sensitivity	Less	High
Dynamic measurement	Suitable	Not suitable
Examples	PMMC, Moving Iron	Potentiometer

5) Analog and Digital Instruments

Analog Instruments

- An analog instrument provides an output which varies continuously as the quantity under measurement changes. The output can have infinite number of values within the range that the instrument is designed to measure.
- **Example** - Deflection type pressure gauge, analog ammeters

Digital Instruments

- A digital instrument has an output which varies in discrete steps and so can only have a finite number of values.
- **Example –** Digital Multimeter.

Table 1.4 Analog and Digital Instruments

Instrument	Analog	Digital
Loading effect	More	Negligible
Programming facility	Not available	Available
Frictional error	High	Low
Reading	Difficult	Easy
Size	Large	Compact
Examples	Pressure gauge	DMM

6) Monitoring and Control Instruments

Monitoring Instruments

- It is used to monitor a physical quantity.
- Instruments which only provide an audio or visual indication of the magnitude of quantity under measurement, such as liquid-in-glass thermometer.
- This class normally includes null type instruments and most passive transducers.

Control Instrument

- For an instrument to be suitable for inclusion in an automatic control system, its output must be in a suitable form for direct input to the controller.
- Usually, this means that an instrument with an electrical output is required, although other forms of output such as optical or pneumatic signals are used in some systems.

1.5. Functions of Instruments and measuring systems

The instruments and measuring systems have mainly three different functions as per following.

1) Indicating Instruments

- An instrument that supplies the information in form of deflection of pointer.
- **Example:** Pressure gauges, speedometers, ammeters, voltmeters

2) Recording Instruments

- This instrument keep a continuous record of variations of the magnitude of an unknown quantity to be observed over a definite period of time.
- **Example:** Temperature and Pressure recorders / data loggers

3) Controlling Instruments

- In this, the information is used to control the original measured quantity.
- **Example:** Thermostat, Float type level control

1.6. Types of measurement errors

Measurement Error

- It is the difference between measured value and true value.

Error = Measured value – True value

- It is impossible to made measurement with perfect accuracy.

1) Gross Error

- Errors due to human carelessness.
- It can be avoided by two means: a) Great care in reading and recording data, b) More observations of measurement to avoid same error
- **Example** – misleading of instrument or using wrong range.

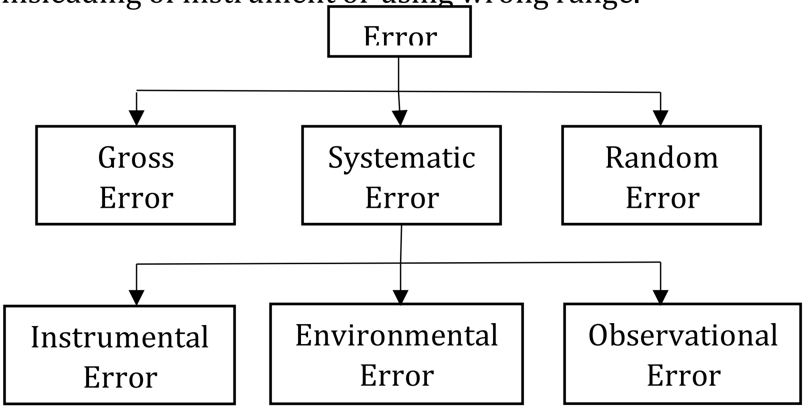

Figure 1.2 Classification of measurement errors

2) Systematic Errors (Bias)

- Errors from measurement system / instrument or due to wrong use of instrument.
- It occurs when there is a problem in the measurement system that affects all measurements in the same way.
- These are predictable, is typically proportional to true value.
- It can be generally measured / eliminated if the cause is known.
- **Example** – Offset error, Zero setting error, a clock that is 5 minutes slow

The systematic errors broadly classified in following three ways:

Instrumental Errors

- Inherent shortcoming of instruments
- Misuse of the instruments
- Loading effects of instruments

Environmental Errors

- Errors are due to conditions external to the measuring device including the atmospheric conditions such as temperature, pressure, humidity, dust, vibrations, external magnetic fields etc.

Observational Errors

- Errors due to Parallax
  Parallax is a displacement or difference in the apparent position of an object viewed along two different lines of sight.

3) Random Errors

- Random errors are caused by unpredictable variations in the measurement system.

- Random uncertainty comes from fluctuations in measurements that can be greater or less than the actual result.
- These often stem from the limitations of the equipment being used or limitations of the experimenter (e.g. how precisely you can read a scale).
- These errors can never be eliminated completely, but can be reduced by using repeats.
- Random errors are usually observed as small worries of the measurement around the correct value. i.e. positive and negative errors occur in approximately equal numbers for a series of measurements made of the same constant quantity.
- Therefore, random errors can be largely be eliminated by calculating the average or mean of a number of repeated measurements.
- **Examples** – Weighing a baby that is shacking, reading a measuring device wrong.

1.7. Statistical analysis of errors

- Statistical study is mainly concerned with precision of measurement and so it cannot remove systematic errors from set of data. So systematic errors should be small as compared with random errors.
- To make statistical methods and interpretations meaningful, a large number of measurements is usually required. Some of these methods (four methods) are described below.

1) Arithmetic Mean

- The most probable value of a measured variable is the arithmetic mean of the number of readings taken.
- The arithmetic mean is given by the following expression:

$$\bar{X} = \frac{x_1 + x_2 + x_3 + \cdots \ldots \ldots . . + x_n}{n}$$

Where $\bar{X}$ is arithmetic mean and $x_1, x_2, x_3, \ldots . . x_n$ are the readings taken and n is the number of readings taken.

2) Deviation from the Mean

- The deviation of a reading is the amount by which it differs from the mean.
- If we have a set of readings x_1, x_2, x_3, …. With mean $\bar{X}$, the deviations of the individual readings are

$$\text{Deviation of } x_1 = d_1 = x_1 - \bar{X}$$

$$\text{Deviation of } x_2 = d_2 = x_2 - \bar{X}$$

- Deviation from the mean may have a +ve or –ve value but the algebraic sum of all the deviations is always zero.

3) Average Deviation

- Average deviation is the sum of the scaler values of the deviations divided by the number of readings. It may be expressed as

$$D = \frac{|d_1| + |d_2| + \cdots + |d_n|}{n}$$

- Average deviation gives an indication of the precision of the instruments used in carrying out measurements. Low average deviation between readings shows that instruments used for measurements are highly precise.

4) Standard Deviation

- ➢ The standard deviation of an infinite number of data is the square root of the sum of all the individual deviations squared, divided by the number of readings.

$$\sigma = \sqrt{\frac{{d_1}^2 + {d_2}^2 + {d_3}^2 + .. + {d_n}^2}{n}}$$

- The standard deviation is also known as root mean square deviation. Reduction in this quantity effectively means improvement in measurement.
- In practice, the possible number of observations is finite. The standard deviation of a finite number of observations is given as

$$\sigma = \sqrt{\frac{{d_1}^2 + {d_2}^2 + {d_3}^2 + .. + {d_n}^2}{n-1}}$$

- Another expression for essentially the same quantity is the variance or mean square deviation, which is same as the standard deviation except that the square root is not extracted.

Variance, V = σ^2

1.8. Characteristics of instruments and measurement systems

The characteristics of instruments can be classified in major two ways:

Static characteristics and Dynamic characteristics.

1) Static Characteristics

- These are established by the process of calibration.
- By static calibration, the relationship between the output signal and the quantity under study is experimentally determined.

  Followings are the static characteristics.

- **True Value** – "Average of an infinite number of measured values, when the average deviation due to various contributing factors tends to zero".
- **Static Error** – "Difference between measured value and true value ($\delta A = A_m - A_t$)".
- **Static Correction** – "Difference between true value and measured value ($\delta C = A_t - A_m = -\delta A$)".
- **Scale Range** – "The range of instrument from minimum measurable value (X_{min}) to maximum measurable value (X_{max})".
- **Scale Span** – "The difference between maximum measurable value (X_{max}) and minimum measurable value (X_{min})".
- **Accuracy** – "The closeness with which an instrument reading approaches the true value".

- Accuracy is specified as Point accuracy, Percentage of true value, Percentage of full scale deflection
- Percentage of true value: Error = $\frac{Measured\ value - True\ value}{True\ value} \times 100$
- Percentage of full scale deflection: Error = $\frac{Measured\ value - True\ value}{True\ scale\ value} \times 100$

- **Precision** – "It is the consistency of the instrument output for a given value of input".
- **Bias** – "It describes a constant error which exists over the full range of measurement of an instrument".
- **Repeatability** – "It describes the closeness of output readings when the same input is applied repetitively over a short period of time, with the same measurement conditions, same instrument and observer, same location and same conditions of use maintained throughout".
- **Reproducibility** – "It is the closeness with which the same value of the input quantity is measured at different times, and under different conditions of usage of the instrument and by different instruments".
- **Tolerance** – "It is the term which is closely related to accuracy and defines the maximum error which is to be expected in some value".
- **Deviation** – "It is described as the difference between measured value and true value for a particular input value". The deviation is given a plus or minus sign.
- **Sensitivity** – "The ratio of the magnitude of the output and the magnitude of input of given instrument".
- **Drift** – "A change in an instrument's reading over extended periods due to factors such as time, line voltage, or ambient temperature effects".
- **Resolution or Discrimination** – "The Smallest measurable input change. The Smallest increment in input which can be detected with certainty by an instruments is its resolution".
- **Threshold** – "The Smallest measurable input. The Smallest input which can be detected with certainty by an instruments is its threshold value".
- **Dead Time** – "The time required by a measurement system to begin to respond to a change in the measurand".
- **Hysteresis** - Instrument does not show same result during loading and unloading of instruments. This effect is known as hysteresis effect : "non-coincidence between loading and unloading curves is known as hysteresis"

2) Dynamic Characteristics

- As we know that the instruments and measurement systems do not respond to the input immediately due to the presence of energy storage elements in the system. The system exhibits a characteristic sluggishness due to the presence of these elements.
- In measurement systems having inputs dynamic in nature, the input varies from instant to instant, so does the output. The behaviour of the system under such conditions is dealt by the dynamic response of the system, and its characteristics are given below.
- **Dynamic Error** – "It is the difference of true value of the quantity changing with time and the value indicated by the instrument provided static error is zero".

- **Fidelity** – "It is the ability of the system to reproduce the output in the same form as the input".

  In the definition of fidelity any time lag or phase difference is not included. Ideally a system should have 100% fidelity and the output appear in the same form as the input and there is no distortion produced by the system. Fidelity needs are different for different applications.
- **Bandwidth** – "It is the range of frequencies for which its dynamic sensitivity is satisfactorily".

  For measurement systems, the dynamic sensitivity is required to be within 2% of its static sensitivity.
- **Speed of response** – "Speed of response of a physical system refers to its ability to respond to sudden changes of amplitude of input signal".

  It is usually specified as the time taken by the system to come close to steady-state conditions, for a step-input function.
- **Time constant** – "It is associated with the behaviour of a first-order-system and is defined as the time taken by the system to reach 0.632 times its final output signal amplitude".

  A system having smaller time constant attains its final output amplitude earlier than the one with larger time constant and therefore, has higher speed of response.
- **Measuring Lag** – "It is defined as the delay in the response of an instrument to a change in the measurand".
- **Settling or Response Time** – "It is the time required by the instrument or measurement system to settle down to its final steady-state position after the application of the input".

  A smaller settling time indicates higher speed of response. Settling time is also dependent on the system parameters and varies with the condition under which the system operates.
- **Dynamic Range** – "It is the range of signals which the measuring system is likely to respond faithfully under dynamic conditions".

  This is generally expressed as the ratio of the amplitudes of the largest signal to the smallest signal to which the system is subjected and the system can handle satisfactorily.
