Measurement Errors and Uncertainty:

The “Error” in a measurement is the difference between the measured value and the true value of the measurand. However, the error in a measurement is not known since the true value of the measurand is not normally known. But, “estimates” of the nature and the magnitude of the error can be given.

If one wishes to assign a value to the estimate of the measurement error, it is commonly referred to as “Uncertainty”.

Types of Errors:

Errors may be originated from different sources and are usually classified as:

1. Gross Errors
2. Systematic (Fixed) Errors (Bias):
3. Random Errors
Gross Errors: Largely human errors originating from misreading instruments, incorrect adjustment or improper use of instruments, computational mistakes. This type of errors can be minimized by proper training and experience of the personnel involved in measurement processes.

Systematic Errors: They are originated from either
- instruments
or
- their environments

Typical instrumental based systematic errors are due to the effects of inherent characteristics of instrument structures like friction, irregular spring tension, or improper calibration.

Typical environmental based systematic errors are effects of changes in surrounding temperature, humidity, barometric pressure, magnetic or electrical fields which can be minimized by proper conditioning of the environment and/or isolating/shielding the instrument from its environment.

Systematic errors can be overcome by applying correction factors after determining the amount of the error or by instrument calibration under in-service conditions.

Random Errors: They are mostly due to unknown causes and therefore are very difficult to predict. The only way to offset them is to increase the size of the data and to use statistical techniques so that the best estimate of the true value of the measured is obtained.
Calibration:

Every measuring system must be tested before using in measurements in terms of its ability to measure reliably. The procedure to demonstrate this by determining the system’s scale is called “Calibration”.

During an ideal calibration process, all inputs to the measuring system are kept constant (or as near constant as the calibration conditions allow in reality) except the measurand which is varied in a controlled manner.

The measurand (input to the measurement system) may be static or dynamic, depending on the application. However, quite often the dynamic performances of measurement systems are based on a “Static Calibration”, simply because a practical dynamic source is not available.

Since the “Calibration Standards” with respect to which calibrations are performed are themselves physical devices and thus are imperfect (i.e., incapable of telling us the “true” value), the following rule of thumb is often used in actual practice:

“A calibration standard should, if possible, be about 10 times more accurate than the instrument being calibrated.”
Accuracy:

Degree of closeness of measurements to the true value of the measurand.

It should be noted that only a careful calibration can reveal the correct level of accuracy of a given instrument; that is, the quality of accuracy determination of a device is as good as its calibration.

The accuracy of an instrument is expressed as either

- **absolute** or
- **relative**

manner.

The *relative* accuracy is defined with respect to either

- **actual reading** or
- **full scale reading**

of the instrument.

\[ \pm 1\% \text{ accuracy actually means } \pm 1\% \text{ inaccuracy} \]

Precision (Repeatability):

The degree of agreement between repeated measurements.

A *precise* data implies a small degree of dispersion (scattering) which may or may not be close to the true value of the measurand.
**Precision ≠ Accuracy**

<table>
<thead>
<tr>
<th>Instrument Readings</th>
<th>True Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accurate &amp; precise</td>
<td>Inaccurate but precise</td>
</tr>
</tbody>
</table>

**Bias:**

It is another name for “*systematic error*”.

Bias in measurement readings results in “*inaccuracy*” which can be corrected by an effective calibration.
**Resolution:**

The smallest increment of input signal (measurand) that a measuring system is capable of distinguishing.

The following table gives results of a measurement in which the true value of the measurand is changed from 10.48 to 10.56, incrementally.

<table>
<thead>
<tr>
<th>True Value</th>
<th>Measurement</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.48</td>
<td>10.50</td>
<td>0.02</td>
</tr>
<tr>
<td>10.49</td>
<td>10.50</td>
<td>0.01</td>
</tr>
<tr>
<td>10.50</td>
<td>10.51</td>
<td>0.01</td>
</tr>
<tr>
<td>10.51</td>
<td>10.52</td>
<td>0.01</td>
</tr>
<tr>
<td>10.52</td>
<td>10.53</td>
<td>0.03</td>
</tr>
<tr>
<td>10.53</td>
<td>10.53</td>
<td>0.02</td>
</tr>
<tr>
<td>10.54</td>
<td>10.53</td>
<td>0.01</td>
</tr>
<tr>
<td>10.55</td>
<td>10.55</td>
<td>≥0.02</td>
</tr>
<tr>
<td>10.56</td>
<td>10.55</td>
<td>?</td>
</tr>
</tbody>
</table>

As demonstrated above, the resolution of an instrument may vary from one value of the measurand to another value or it may well be constant for all values of the measurand.

**Threshold:**

When the value of the input signal (measurand) is slowly increased stating from zero value, it is the minimum signal level beyond which a change in the output is detected.

It can therefore be considered as the resolution at zero value.
**Hysteresis:**

If an instrument provides different readings for the same measurand values depending on whether measurand is increased or decreased, then the I/O characteristic of this instrument is said to have an hysteresis.

Hysteresis plays an important role in measurements in which the measurand is changed in a non-monotonic manner.

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**Span:**

The range of variable (measurand) that an instrument is designed to measure.

For example, thermometers used to measure body temperature have a span of 7 °C ranging from 35 °C to 42 °C.

**Dynamic range:**

Span of an instrument expressed in terms of ratio of the highest and the lowest values of the measurand.
**Static Sensitivity:**

Measure of the change produced in the instrument output for a change of its input (measurand).

The higher the sensitivity is the larger instrument outputs are produced for the same changes in the measurand.

The local rate of change (slope) in static I/O characteristic of a device determines its local sensitivity.

An instrument may have different sensitivity regions over its span.
Zero Drift & Sensitivity Drift:

Undesired inputs to a sensor can cause a calibration curve to shift its position causing errors.

A shift in calibration curve in vertical direction is called “Zero Drift”.

A shift in calibration curve to change the sensitivity is called “Sensitivity Drift”.

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**Linearity:**

An instrument is called "Linear" when its I/O relation (i.e., the calibration curve) is a straight line, indicating that the output is proportional to the input.

The most common method to find the "best fitted straight line" for a series of calibration data is the least squares.

Linearity is desirable in most applications. It eliminates the need of referring to a "calibration chart" or a "conversion data".

However, the linearity does not imply a better accuracy, a higher precision, or greater sensitivity.

A nonlinear instrument may even be desired in some cases. For example, a high quality voltmeter may have a logarithmic scale which is nonlinear (but linear in decibels, dB).
**Independent Linearity:**

An indication on the maximum deviation of any calibration point from the best fitted line expressed as \( \pm x \% \) of the full scale of the instrument.

**Proportional Linearity:**

An indication on the maximum deviation of any calibration point from the best fitted line expressed as \( \pm x \% \) of the actual reading of the instrument.