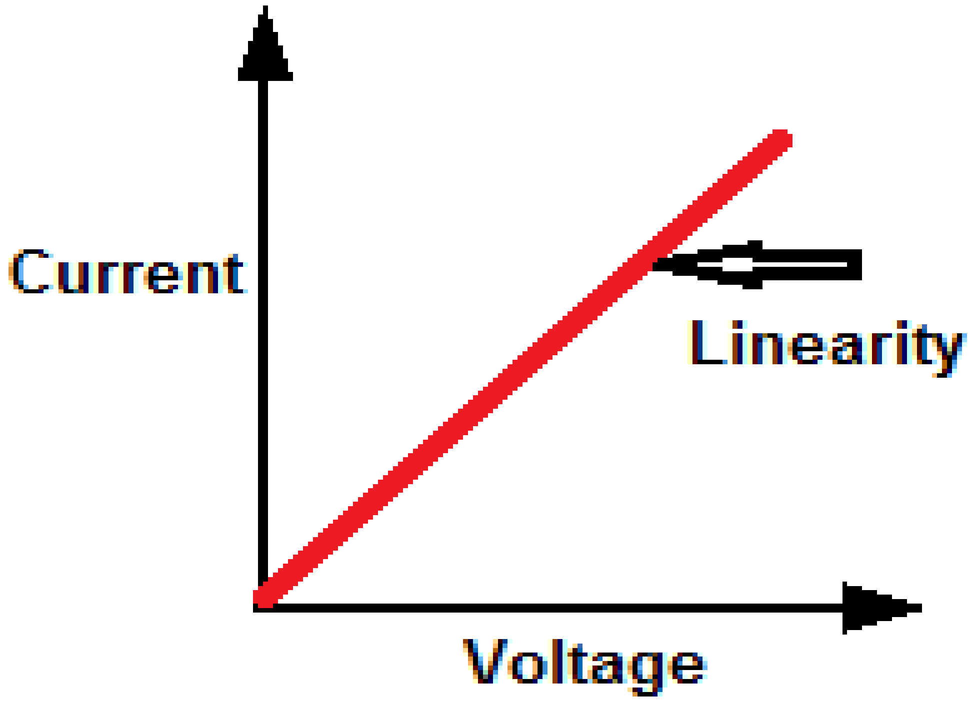
INC 102 Fundamental of Instrumentation and Process Control

Instrument Characteristics

Dr. Tanagorn Jennawasin
tanagorn.jen@kmutt.ac.th



Topics

- **Measurement**

  - Unit of measure

  - Measurement standards

- **Instruments**

  - Types of instruments

  - Static characteristics

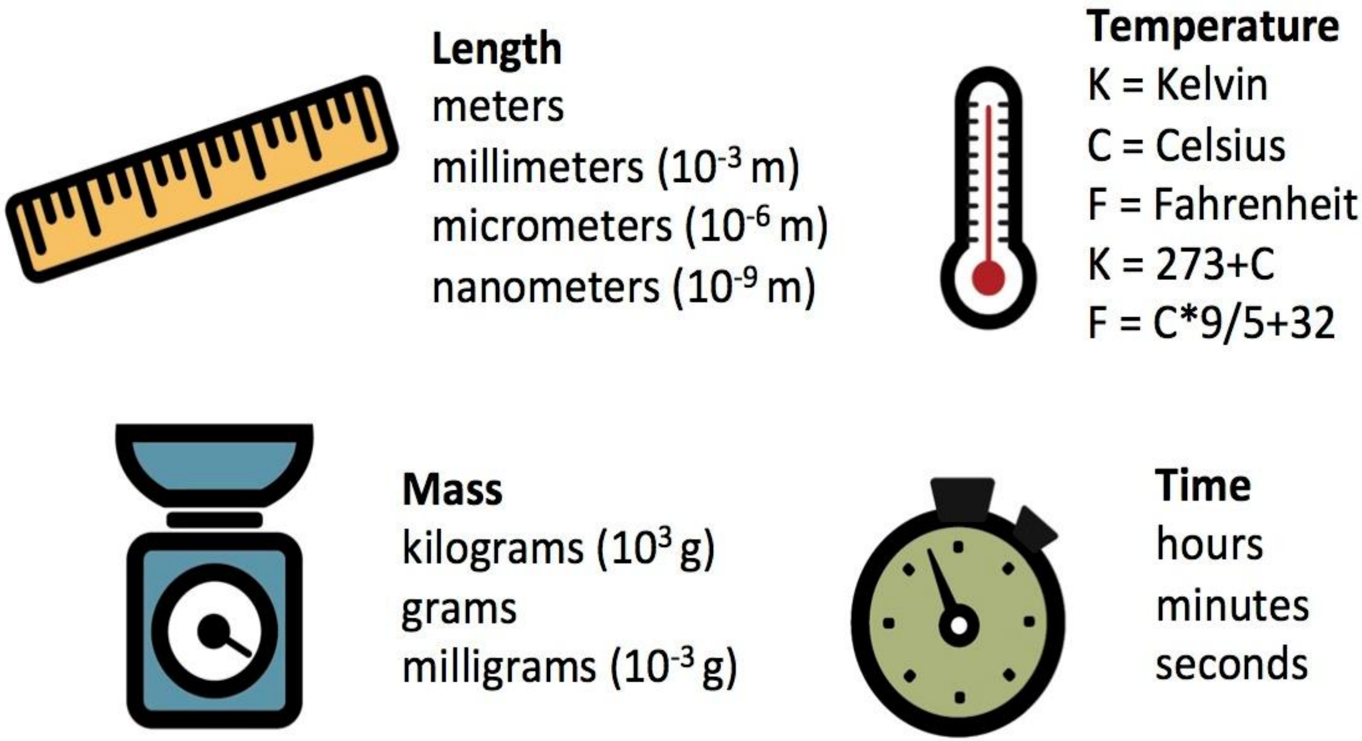
  - Dynamic characteristics

Introduction

- Measurement is the experimental process of acquiring any quantitative information. When doing a measurement, we compare the measurable quantity – measurand - with another same type of quantity. This other quantity is called measurement unit
- Measurand is a physical quantity, property, or condition which is measured

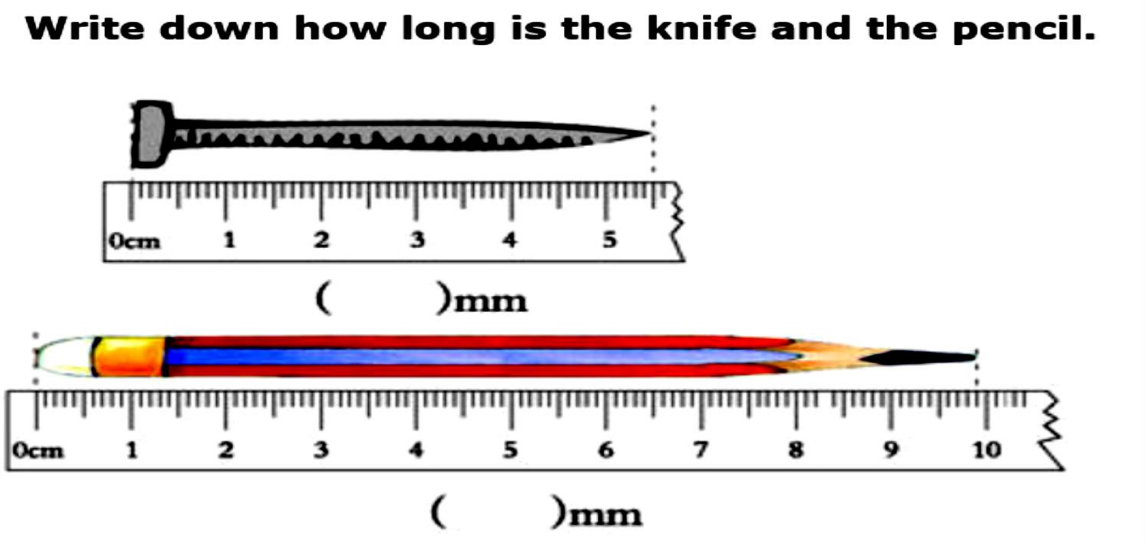
Units of Measure

- Magnitudes of measurements are typically given in terms of a specific unit. In surveying, the most commonly used units define quantities of length (or distance), area, volume, and horizontal or vertical angles.



An example

- the measurand is the length of some object
- the measurement is the number of units (meters, inches, etc.) that represent the length



Measurement standards

- Measurement standards are devices, artifacts, procedures, instruments, systems, protocols, or processes that are used to define (or to realize) measurement units and on which all lower echelon (less accurate) measurements depend.

The Need for Standards

- Standards define the units and scales in use, and allow comparison of measurements made in different times and places.
- **A Historical Perspective**
  - to serve needs of commerce, trade, land division, taxation and scientific advances.
  - The earliest standards were based on the **human body**, and then attempts were made to base them on “**natural**” **phenomena**.

Examples

- Length
  - a fraction of the circumference of the earth but maintained by the use of a platinum/iridium bar.
  - Now, the meter is the distance that light travels in a vacuum in an exactly defined fraction (1/299,792,458) of a second.
- Time
  - defined as a fraction of the day but maintained by a pendulum clock.
  - the *second* is maintained by atomic clocks

The SI Base Units

TABLE A.1 The SI Base Units

Base quantity	Name of Base Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

The International Definitions of the SI Base Units

- **Unit of length (meter)**
  - The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second
  - Note: The original international prototype, made of platinum-iridium, is kept at the BIPM.
- **Unit of mass (kilogram)**
  - The kilogram is the unit of mass: it is equal to the mass of the international prototype of the kilogram.

The International Definitions of the SI Base Units(cont.)

- **Unit of time (second)**
  - The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom
- **Unit of electric current (ampere)**
  - The ampere is that constant current which, if maintained in 2 straight parallel conductors of infinite length, of negligible cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2x10–7 N/m.

The International Definitions of the SI Base Units (cont.)

- **Unit of thermodynamic temperature (kelvin)**
  - The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
- **Unit of luminous intensity (candela)**
  - The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540x1012 Hz and that has a radiant intensity in that direction, of 1/683 W/sr.

The International Definitions of the SI Base Units (cont.)

- **Unit of amount of substance (mole)**
  - 1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon-12.
  - 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
  - In the definition of the mole, it is understood that unbound atoms of carbon-12, at rest, and in their ground state, are referred to.

SI Derived Units with Special Names

TABLE A.3 SI Derived Units with Special Names[a]

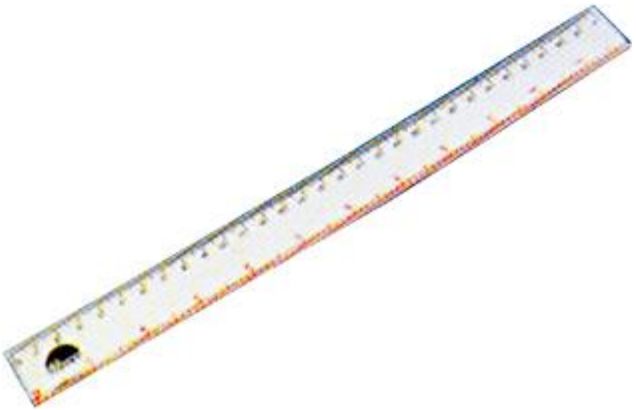
Derived quantity	Name	Symbol	Expressed in Terms of Other Units	Expressed in Terms of SI Base Units
Plane angle	radian	rad		$m\ m^{-1}$
Solid angle	steradian	sr		$m^2\ m^{-2}$
Frequency	hertz	Hz		s^{-1}
Force	newton	N		$m\ kg\ s^{-2}$
Pressure, stress	pascal	Pa	$N\ m^{-2}$	$m^{-1}\ kg\ s^{-2}$
Energy, work, quantity of heat	joule	J		$m^2\ kg\ s^{-2}$
Power, radiant flux	watt	W		$m^2\ kg\ s^{-3}$
Electric charge, quantity of electricity	coulomb	C		s A
Electric potential, potential difference, electromotive force	volt	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
Capacitance	farad	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
Electric resistance	ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
Electric conductance	siemens	S	A.V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
Magnetic flux	weber	Wb	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
Magnetic flux density	tesla	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
Inductance	henry	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
Celsius temperature	degree Celsius	°C		K
Luminous flux	lumen	lm	cd sr	$cd\ m^2\ m^{-2} = cd$
Illuminance	lux	lx	$m^{-2}\ cd\ sr$	$m^{-2}\ cd$
Activity (referred to a radio nuclide)	becquerel	Bq		s^{-1}
Absorbed dose, specific energy imparted, kerma	gray	Gy	J/kg	$m^2 s^{-2}$
Dose equivalent, ambient dose equivalent, organ equivalent dose	sievert	Sr	J/kg	$m^2 s^{-2}$

[a] Note that when a unit is named after a person the *symbol* takes a capital letter and the *name* takes a lowercase letter.

Measurement can be divided into direct or indirect measurements

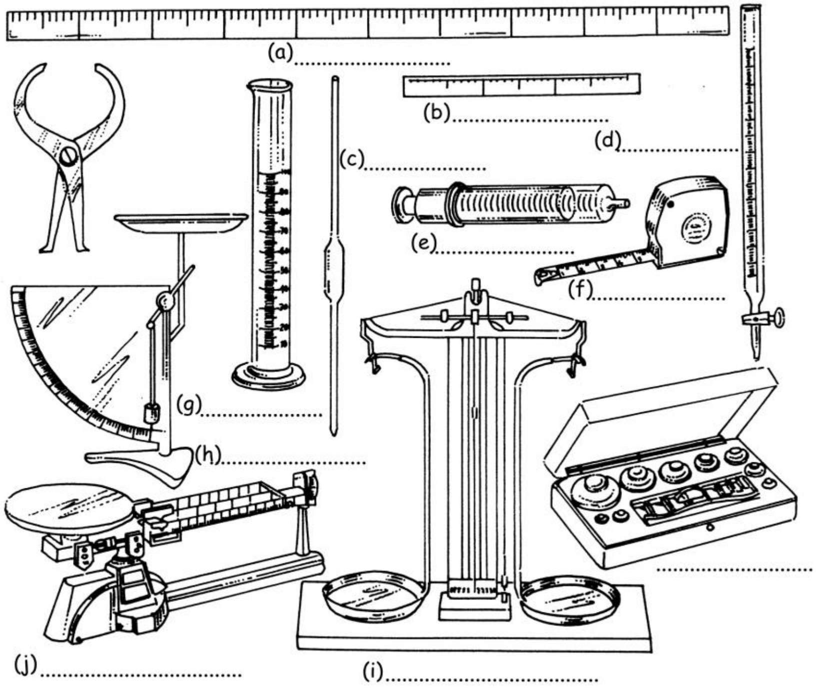
- Direct measurement – measured quantity is registered directly from the instruments display.
- Measuring voltage with voltmeter
- Measuring length with ruler
- Indirect measurement – result is calculated (using formula) from the values obtained from direct measurements

What is instrument?

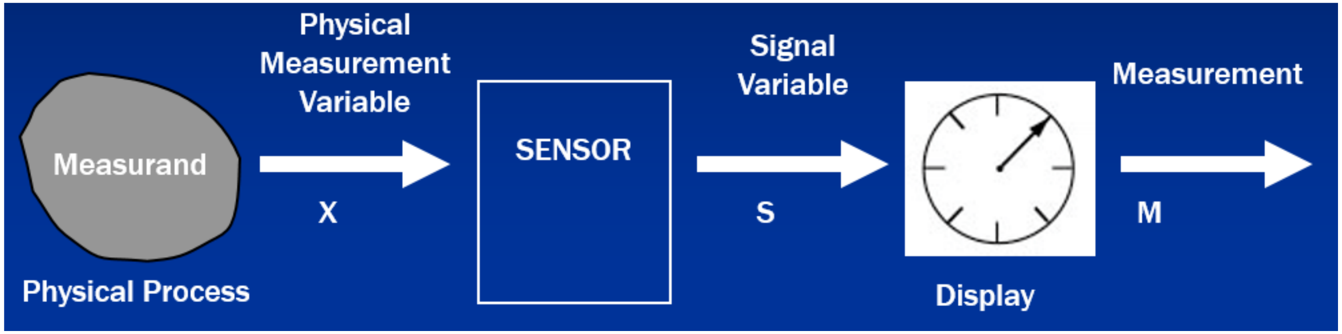


Measuring instrument

- Instrument is a device that transforms a physical variable of interest (the measurand) into a form that is suitable for recording (the measurement)

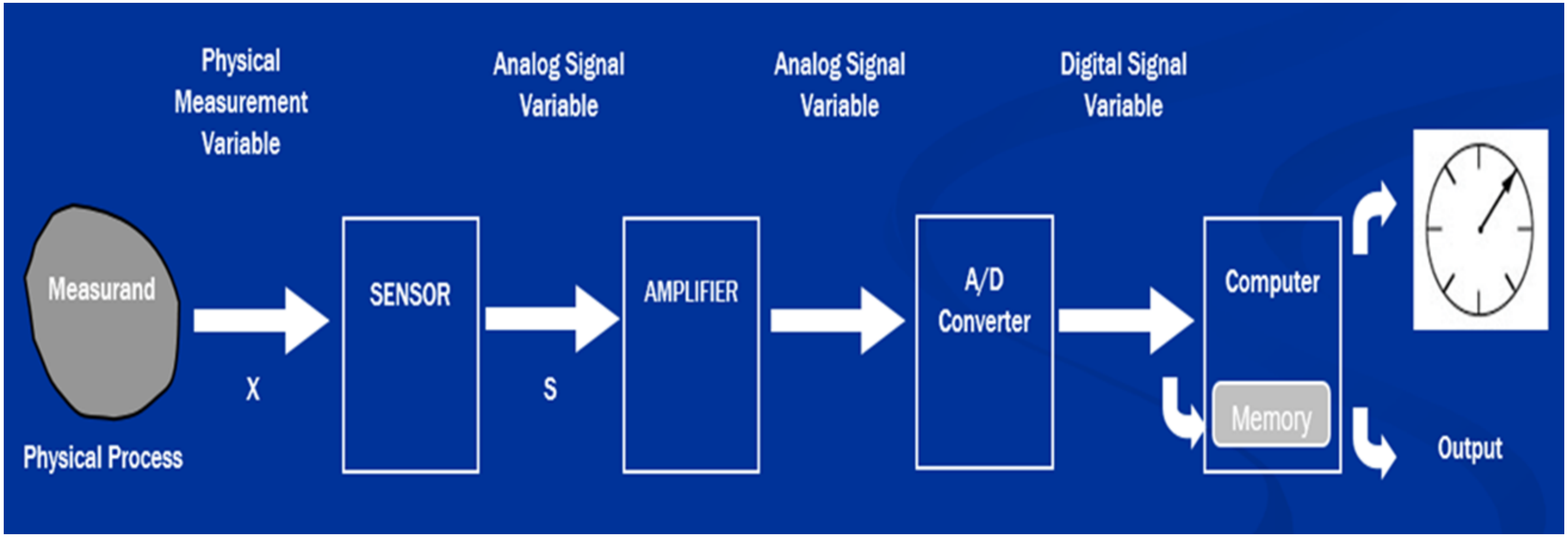


Simple Instrument Model



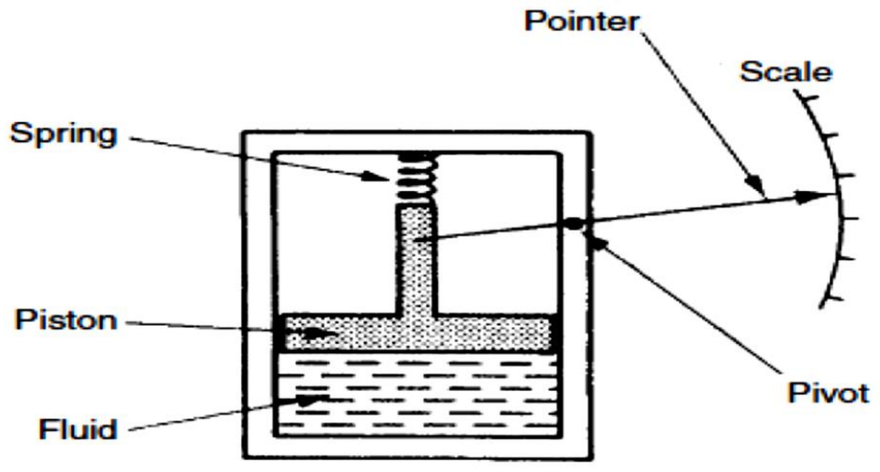
- The key functional element of the instrument model is the sensor, which has the function of converting the physical variable input into a signal variable output
- Due to the property that signal variables can be manipulated in a transmission system, such as an electrical or mechanical circuit, they can be transmitted to a remote output or recording device
- In electrical circuits, voltage is a common signal variable

- **If the signal from Sensor output is small, it is needed to be amplified. In many cases it is also necessary for the instrument to provide a digital signal output for connection with a computer-based data acquisition systems.**



Instrument types and performance characteristics

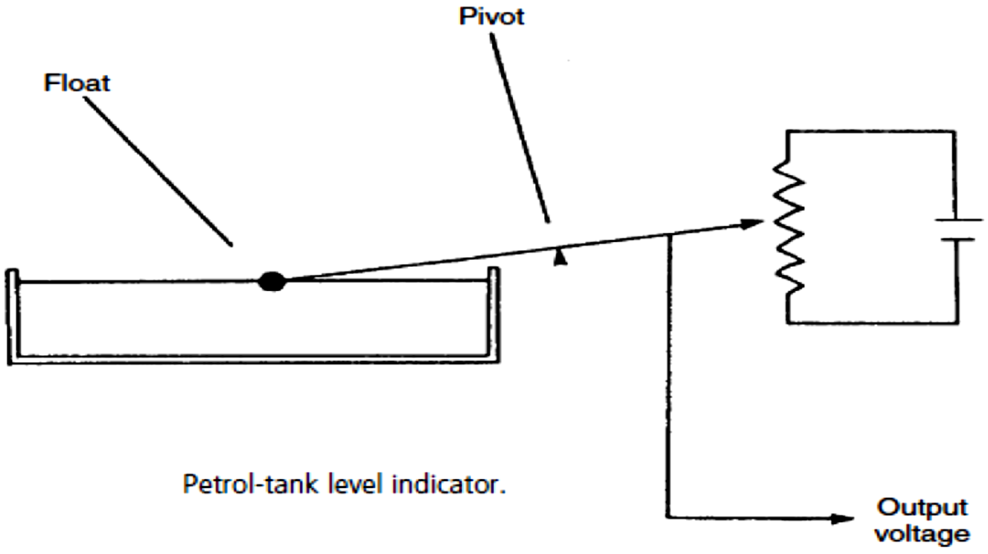
- **Passive Instruments**



Passive pressure gauge.

An example of a passive instrument is the pressure-measuring device. The pressure of the fluid is translated into a movement of a pointer against a scale.

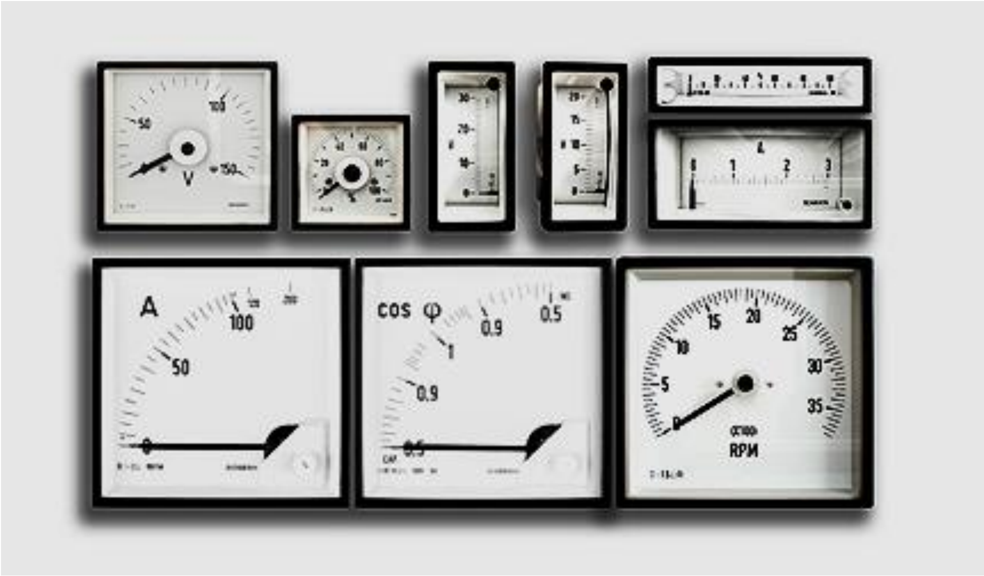
Active instruments

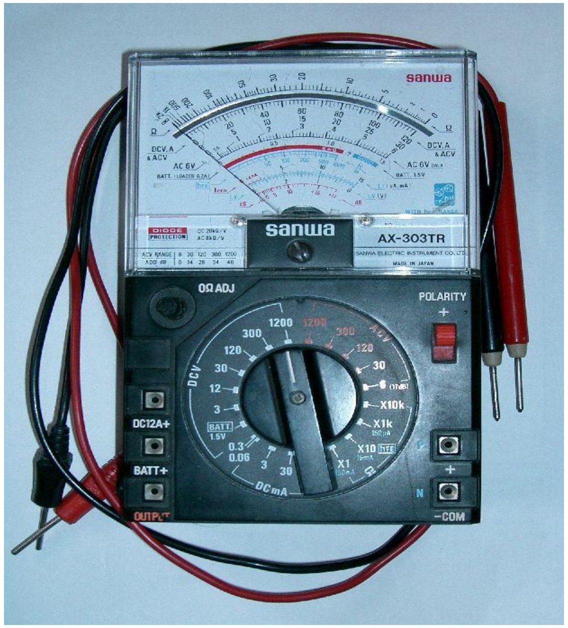


An example of an active instrument is a float-type petrol tank level indicator as sketched. Here, the change in petrol level moves a potentiometer arm, and the output signal consists of a proportion of the external voltage source applied across the two ends of the potentiometer.

Analog Instruments

- **An analog instrument gives an output that varies continuously as the quantity being measured changes.**





Digital Instruments

A digital instrument has an output that varies in discrete steps and so can only have a finite number of values.

Static characteristics of instruments

- If we have a thermometer in a room and its reading shows a temperature of 20°C, then it does not really matter whether the true temperature of the room is 19.5°C or 20.5°C. Such small variations around 20°C are too small to affect whether we feel warm enough or not.
- If we had to measure the temperature of certain chemical processes, however, a variation of 0.5°C might have a significant effect on the rate of reaction or even the products of a process. A measurement inaccuracy much less than ±0.5°C is therefore clearly required.

The various static characteristics

- Accuracy
- Precision
- Reproducibility
- Repeatability
- Resolution
- Sensitivity
- Linearity
- Tolerance
- Range or span

Accuracy

Accuracy is the degree of closeness with which the reading approaches the true value of the quantity to be measured. The accuracy can be expressed in following ways:

- Point accuracy: Such accuracy is specified at only one particular point of scale. It does not give any information about the accuracy at any other Point on the scale.

- Accuracy as percentage of full scale or span:

When an instrument as uniform scale, its accuracy may be expressed in terms of scale range.

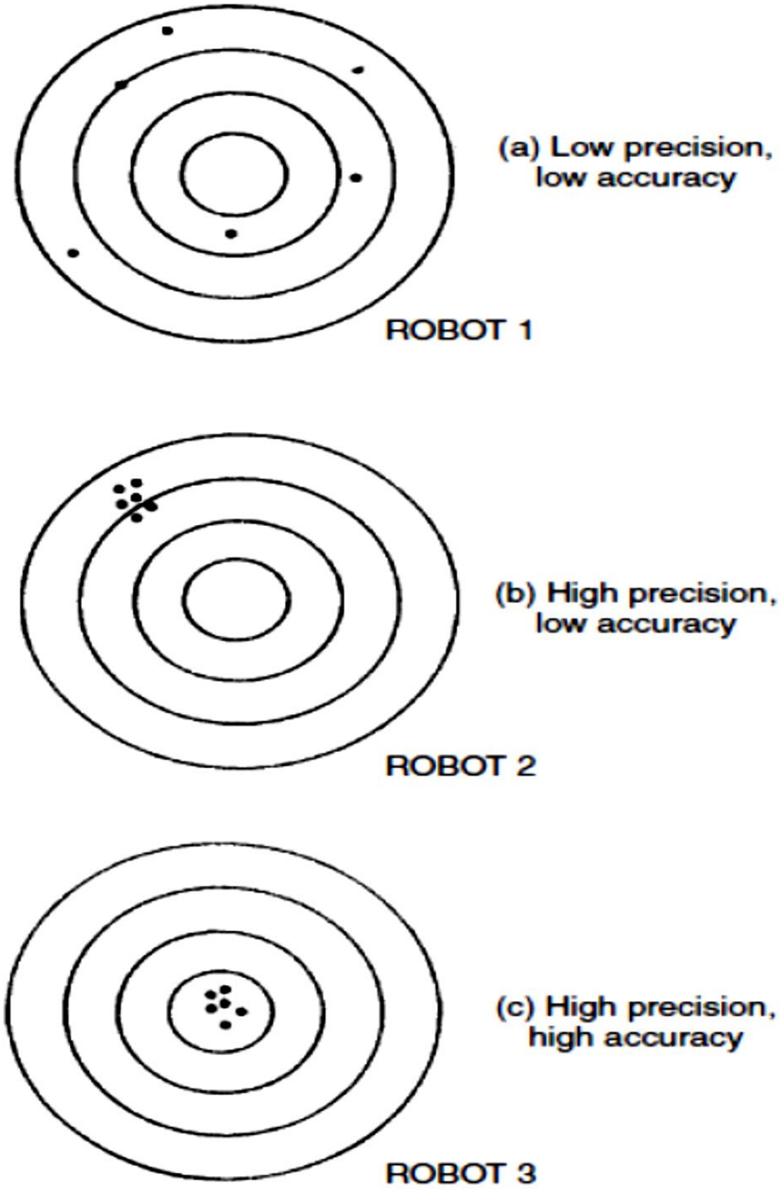
- Accuracy as percentage of true value: The best way to conceive the idea of accuracy is to specify it in terms of the true value of the quantity being measured. Precision: It is the measure of reproducibility i.e., given a fixed value of a quantity, precision is a measure of the degree of agreement within a group of measurements. The precision is composed of two characteristics.

Example

- A pressure gauge of range 0–10 bar has a quoted inaccuracy of ±1.0% f.s. (±1% of full-scale reading), then the maximum error to be expected in any reading is 0.1 bar.
- This means that when the instrument is reading 1.0 bar, the possible error is 10% of this value.

- Precision is a term that describes an instrument’s degree of freedom from random errors.
- Repeatability 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 describes the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument, location, conditions of use and time of measurement.

The figure shows the results of tests on three industrial robots that were programmed to place components at a particular point on a table.



Comparison of accuracy and precision.

Calculation of Absolute Error

ϵ_i = Measured value – True value

$$\epsilon_i = X_i - X_T$$

measured value at ith-time

Calculation of Relative Error (in percent)

$$E_i = \left|\frac{\epsilon_i}{X_T}\right| \times 100 = \left|\frac{X_i - X_T}{X_T}\right| \times 100$$

Calculation of Accuracy

$$A_i = 1 - \left|\frac{X_i - X_T}{X_T}\right|$$

Calculation of Accuracy (in percent)

$$A_i = \left(1 - \left|\frac{X_i - X_T}{X_T}\right|\right) \times 100$$

$$A_i = 100 - E_i$$

Calculation of Precision

$$P_i = 1 - \left| \frac{X_i - \bar{X}}{\bar{X}} \right|$$

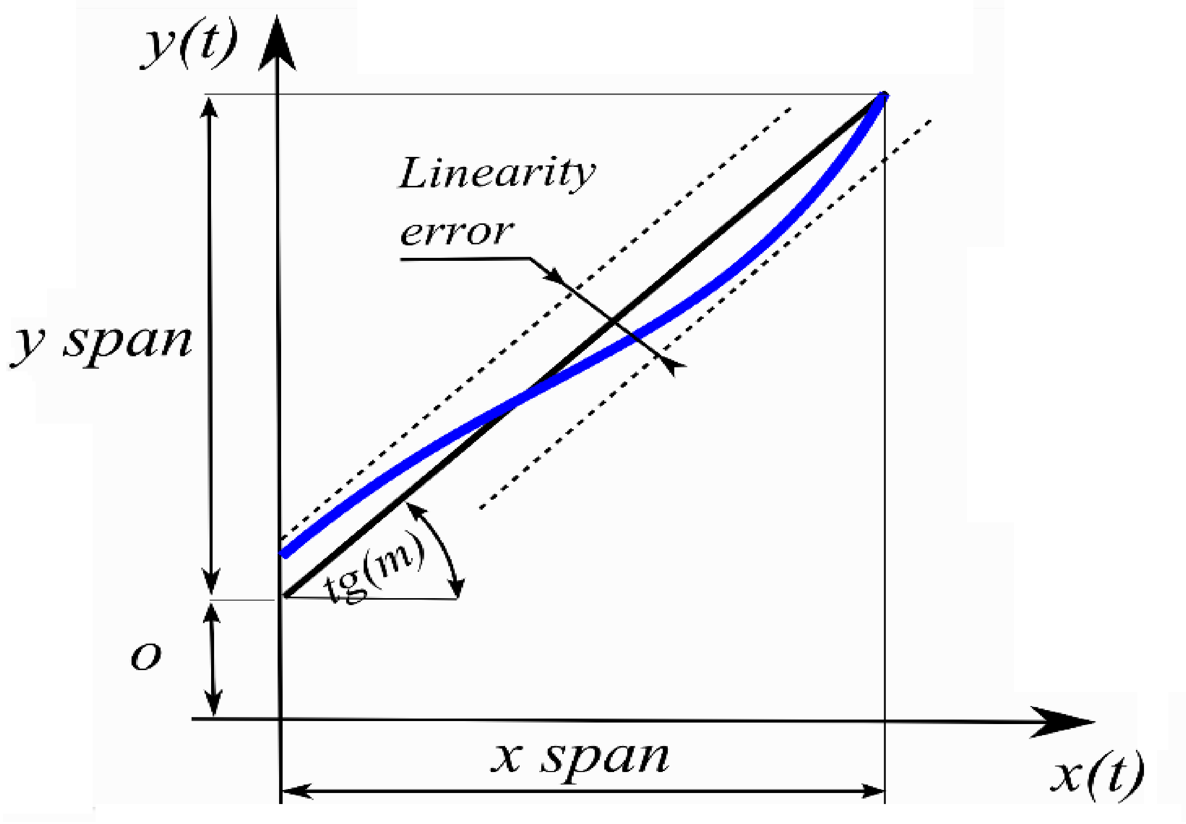
$$P_i = \left(1 - \left| \frac{X_i - \bar{X}}{\bar{X}} \right| \right) \times 100$$ **(in percent)**

Where $\bar{X} = \frac{\sum X_i}{n}$ is the average of the measured values

Resolution

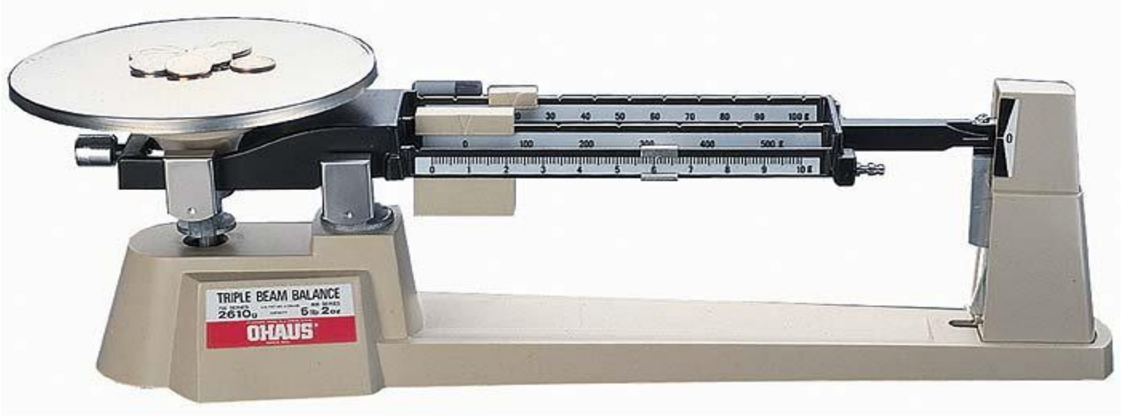
When an instrument is showing a particular output reading, there is a lower limit on the magnitude of the change in the input measured quantity that produces an observable change in the instrument output. Like threshold, resolution is sometimes specified as an absolute value and sometimes as a percentage of f.s. deflection.

- Linearity is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured.



- The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount. Thus, sensitivity is the ratio:

$$\frac{\text{scale deflection}}{\text{value of measurand producing deflection}}$$

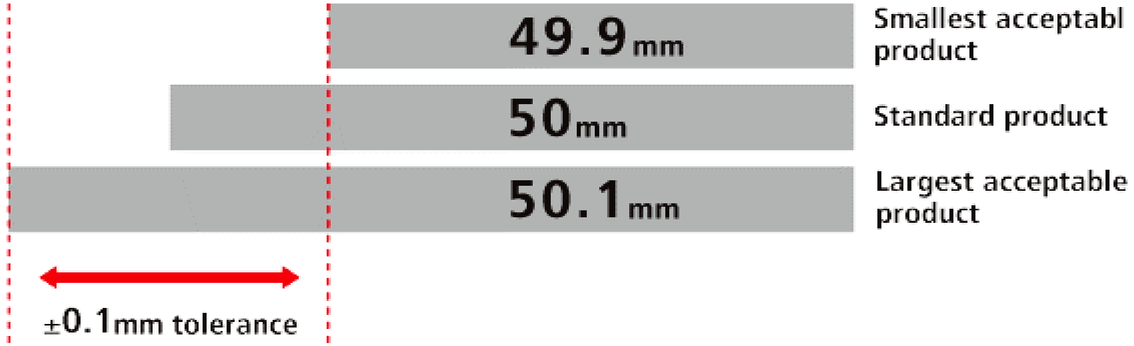


Example

- The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in ohms/°C.

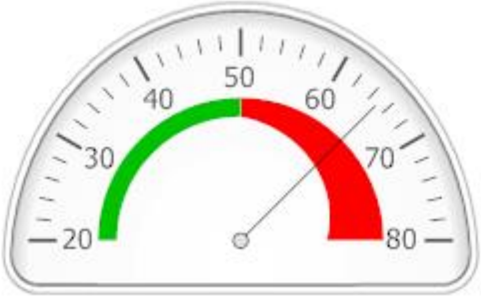
Resistance (Ω)	Temperature (°C)
307	200
314	230
321	260
328	290

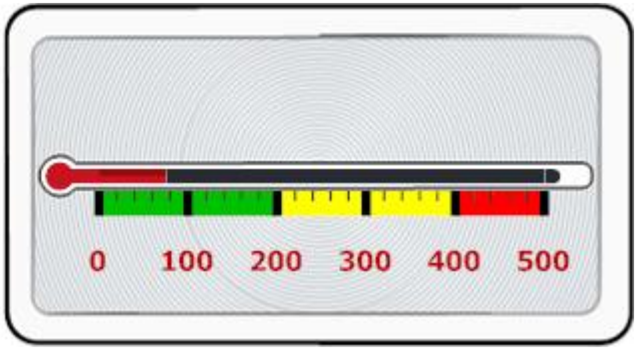
- Tolerance is a term that is closely related to accuracy and defines the maximum error that is to be expected in some value.



- For example one resistor chosen at random from a batch having a nominal value 100 ohms and tolerance 5% might have an actual value anywhere between 95 and 105 ohms.

- The range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure

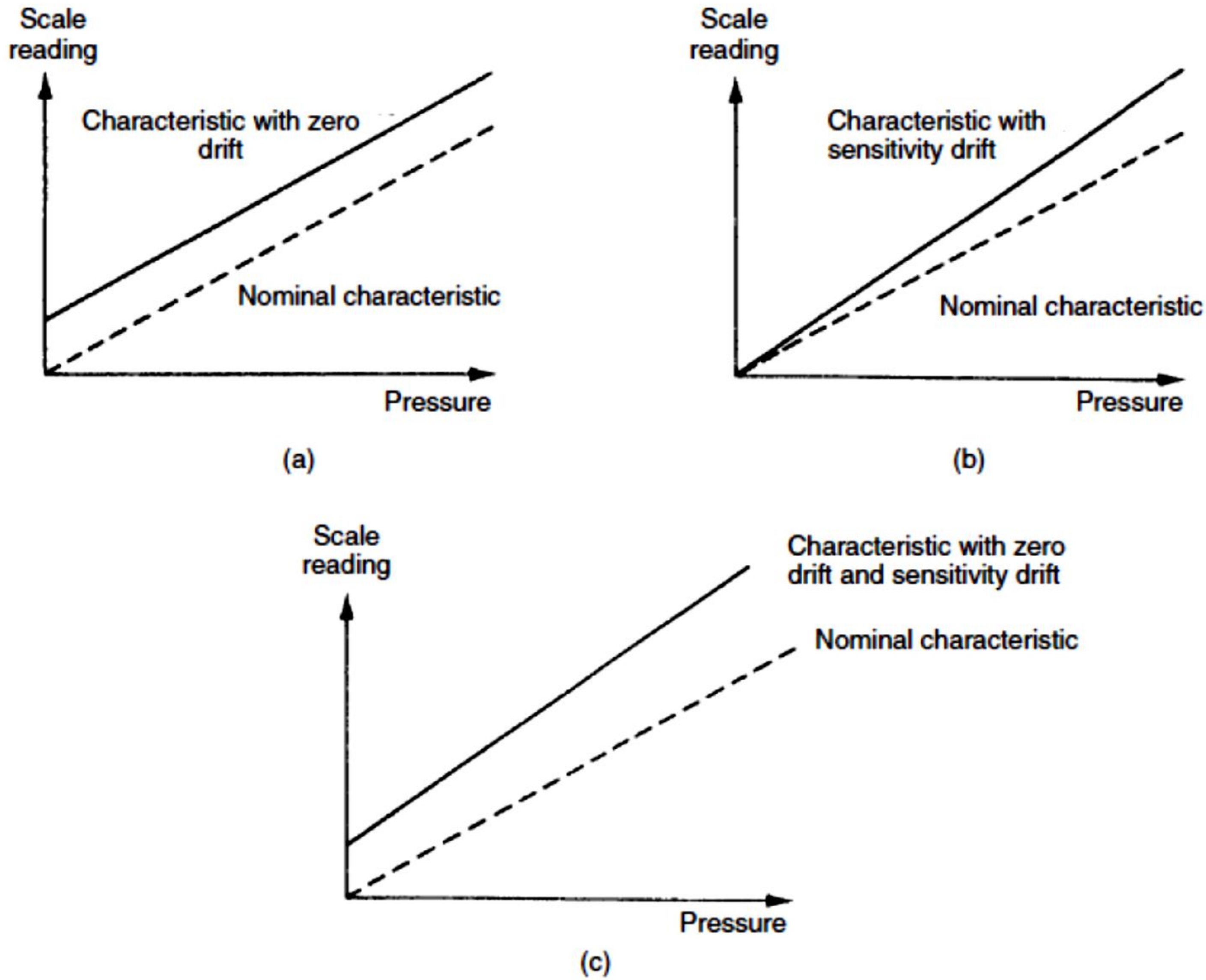




Sensitivity to disturbance

- All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure etc. These standard ambient conditions are usually defined in the instrument specification.
- As variations occur in the ambient temperature etc., certain static instrument characteristics change.

- The sensitivity to disturbance is a measure of the magnitude of this change. Such environmental changes affect instruments in two main ways, known as zero drift and sensitivity drift.
- Zero drift or bias describes the effect where the zero reading of an instrument is modified by a change in ambient conditions.
- Sensitivity drift (also known as scale factor drift) defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change.



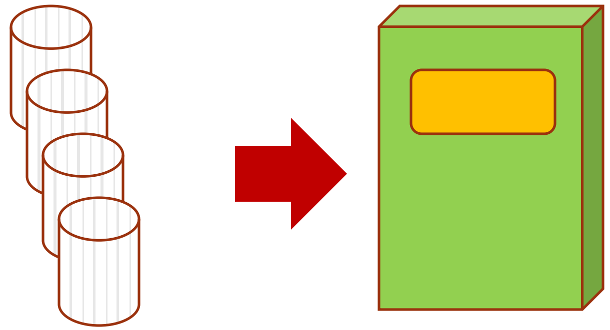
Effects of disturbance: (a) zero drift; (b) sensitivity drift; (c) zero drift plus sensitivity drift.

Static calibration

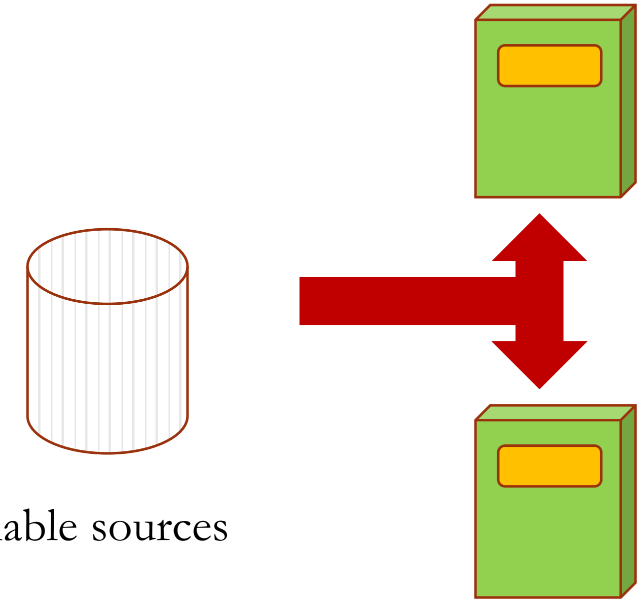
- All inputs except one are kept at some constant values. Then the input under study is varied over some range of constant values.
- The input-output relationship is valid under the stated constant conditions of all the other inputs.
- Measurement method: ideal situation
  - “all other inputs are held constant”
- Measurement process: physical realization of the measurement method

Calibration Methods

- Standard source



- Standard meter

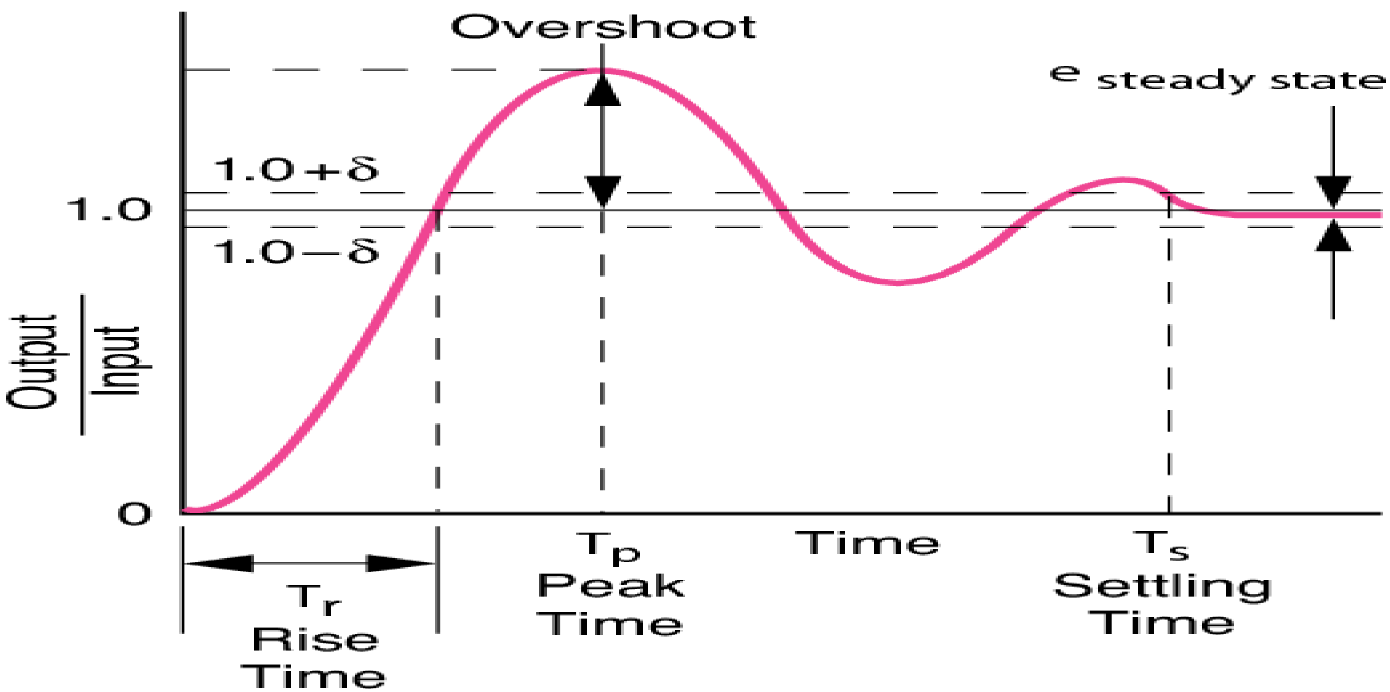


Example: Thermometer Calibration

- Standard source: Fixed points
  - calibrated by measurements at a series of temperature fixed points: e.g. freezing/melting points, triple points, vapor pressure points.
- Standard meter: comparison

Dynamic characteristics of instruments

- The dynamic characteristics of a measuring instrument describe its behavior between the time a measured quantity changes value and the time when the instrument output attains a steady value in response.



Dynamic Characteristics

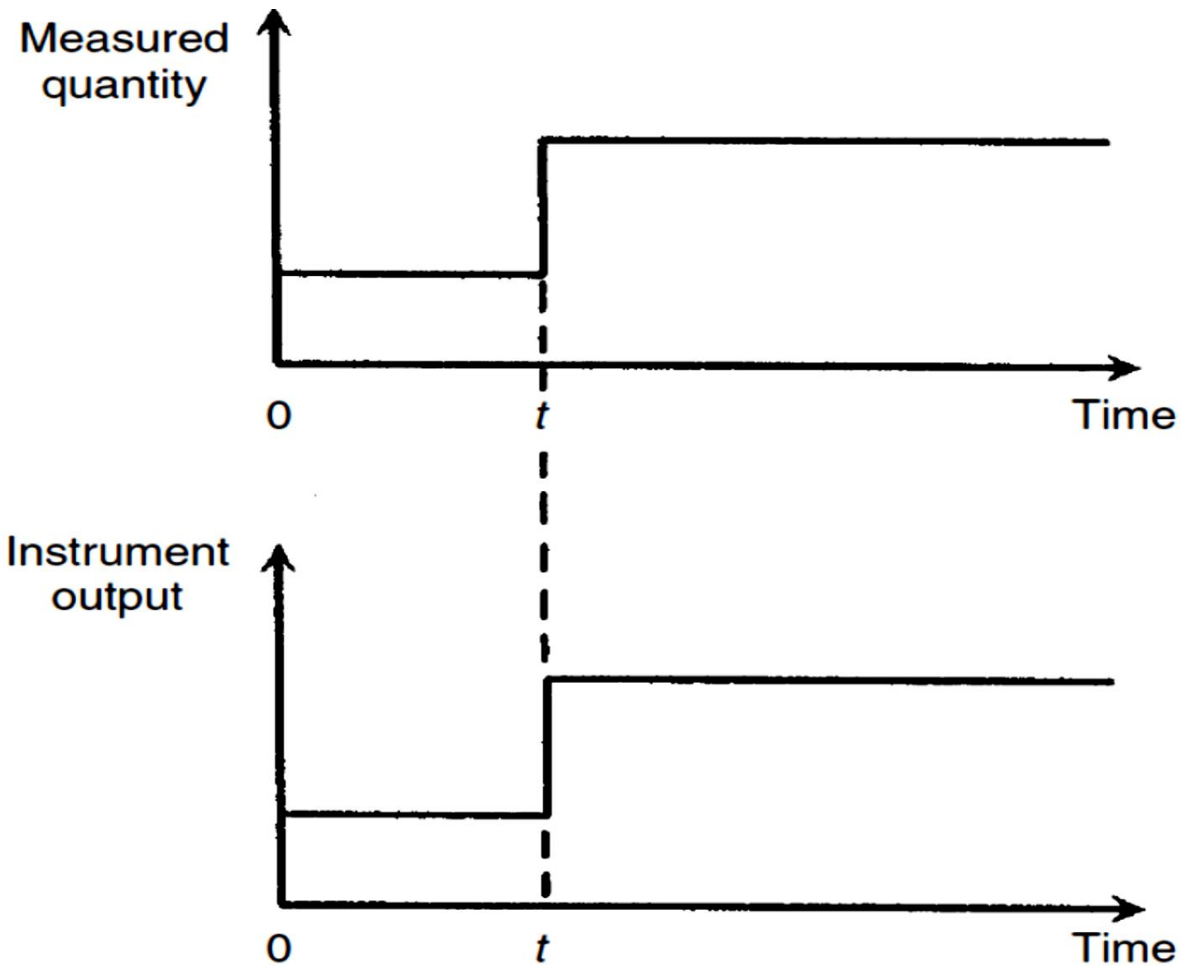
- **Time constant** characterize the speed of response of a first-order system. It is a measure of the time necessary for a process to adjust to a change in the input.
- **Rise time** is the time the output takes to first reach the new steady state value
- **Settling time** is the time required for the output to reach within ±5% of the new steady state value.
- **Dead time** is the delay from when a controller output (CO) signal is issued until when the measured process variable (PV) first begins to respond.

Zero order instrument

- If all the coefficients $a_1 \ldots a_n$,other than a_0 in equation are assumed zero, then:

$$a_0 q_0 = b_0 q_i \quad \text{or} \quad q_0 = b_0 q_i / a_0 = K q_i$$

- where K is a constant known as the instrument sensitivity as defined earlier.



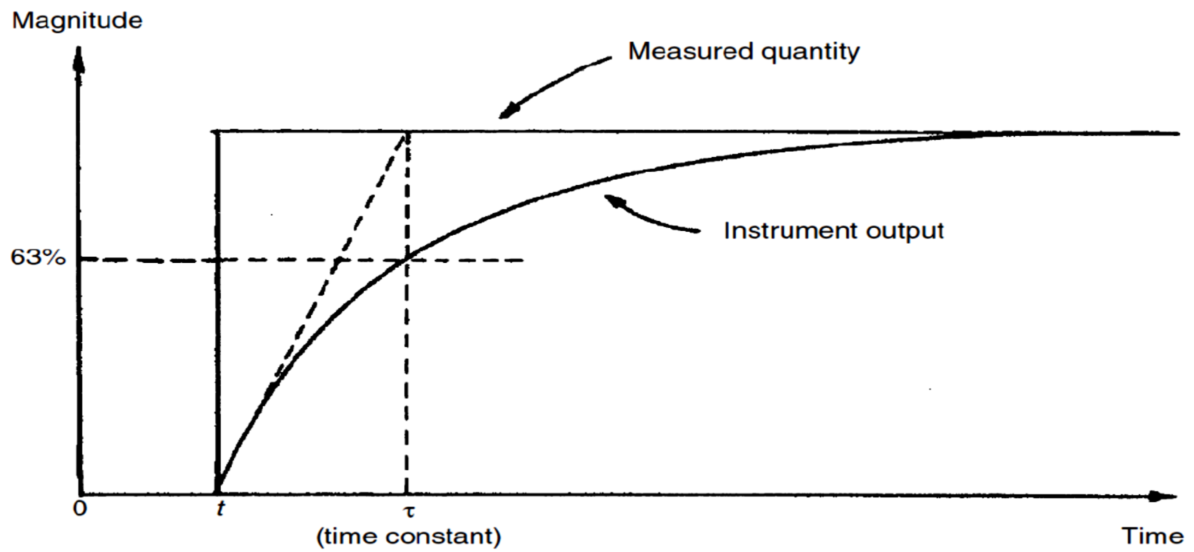
Zero order instrument characteristic.

First order instrument

- If all the coefficients $a_2 \ldots$ an except for a_0 and a_1 are assumed zero in equation then:

$$a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

- If equation is solved analytically, the output quantity q_0 in response to a step change in q_i at time t varies with time in the manner.



First order instrument characteristic.

Second order instrument

- If all coefficients $a_3 \ldots a_n$ other than a_0, a_1 and a_2 in equation are assumed zero, then we get:

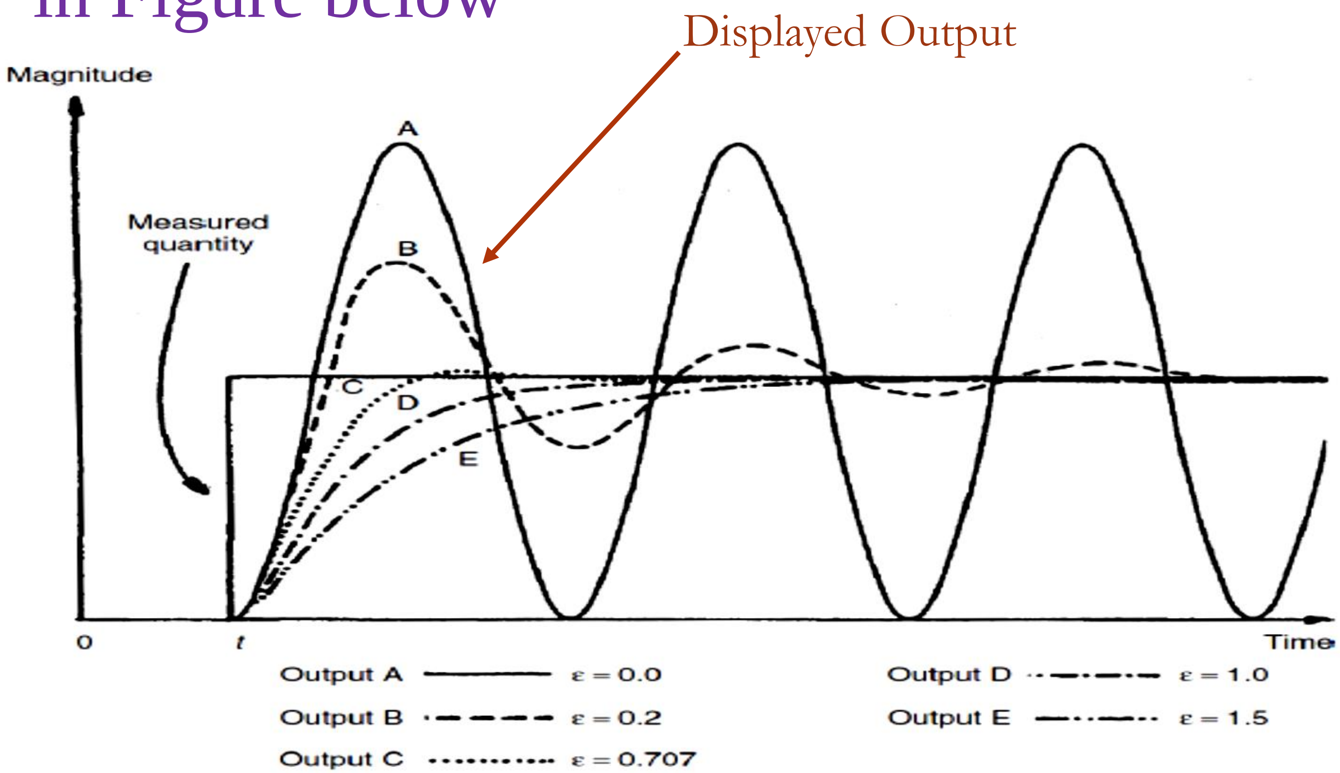
$$a_2 \frac{d^2 q_0}{dt^2} + a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

It is convenient to re-express the variables a0, a1, a2 and b0 in equation in terms of three parameters K (static sensitivity), ω (undamped natural frequency) and ξ (damping ratio), where:

$$\frac{1}{\omega^2}\frac{d^2 q_0}{dt^2} + \frac{2\xi}{\omega}\frac{dq_0}{dt} + q_0 = Kq_i$$

$$K = \frac{b_0}{a_0} \quad , \quad \omega^2 = \frac{a_0}{a_2} \quad , \quad \xi = \frac{a_1 \omega}{2a_0}$$

- The output responses of a second order instrument for various values of following a step change in the value of the measured quantity at time t are shown in Figure below



Response characteristics of second order instruments.