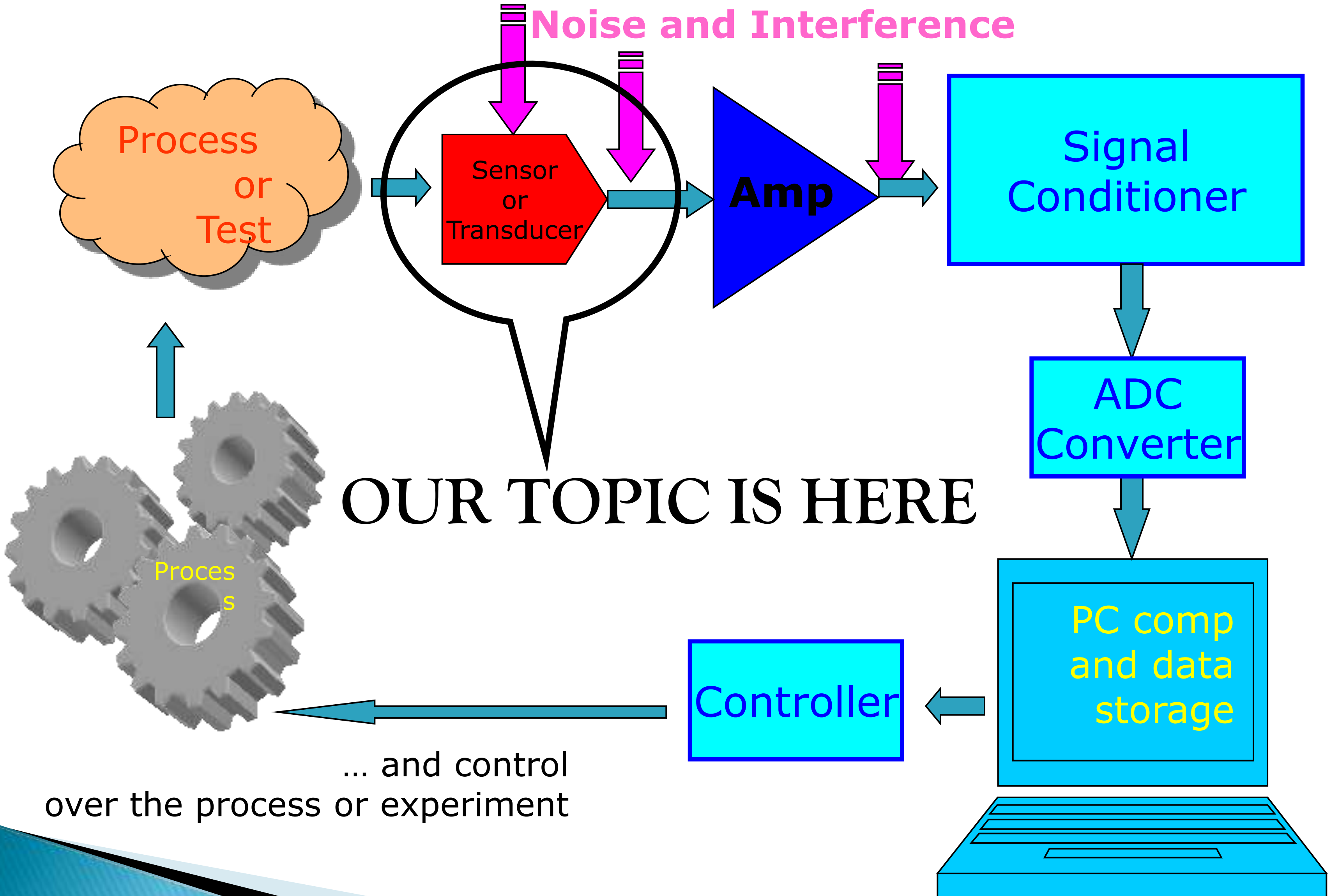
Introduction to Sensors

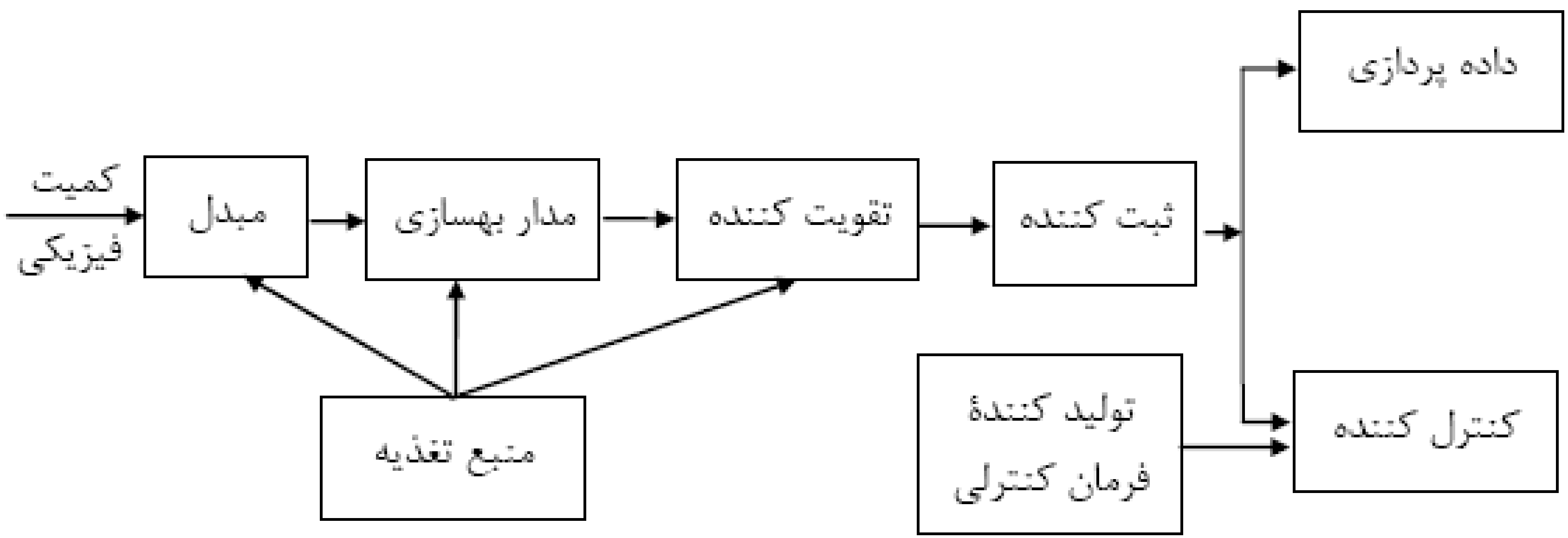
فصل اول:

حساسه ها و اساس کار آنها

Typical Measurement System Architecture



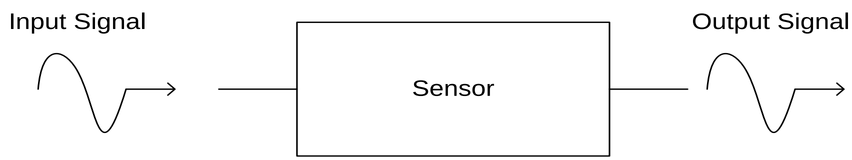
بلوك دياگرام عمومي يك سيستم ابزار دقيق



- **مبدل(سنسور)** : این وسیله کمیت فیزیکي مورد اندازه گیري را به کمیت الکتریکي تبدیل مي کند.
- **منبع تغذیه** : انرژی الکتریکي لازم براي تحریك مبدل ، مدار بهسازي و تقویت کننده را تولید مي کند. با توجه به نوع مبدل و مدار بهسازي مي توان از منابع تغذیة AC . یاDC استفاده نمود.
- **مدار بهسازي** : این مدارهاي الکتریکي وظیفة تبدیل ، جبرانسازي و تغییر سیگنال خروجي ازمبدل را به کمیتي الکتریکي که قابلیت استفادة مناسب در سایر بخشهاي سیستم را داشته باشد به عهده دارد.
- **تقویت کننده**: این بخش از سیستم زماني بکار گرفته مي شود ، که ولتاژ خروجي مبدل بقدر کافي قوي نباشد . گاهًا این مدار با مدار بهسازي ترکیب مي شود و در غالب یك بلوك نیز سیستم ابزار دقیق قابل نمایش است. در
- **ثبت کنند ه** : وسایل اندازه گیري ولتاژ الکتریکي که کمیت مورد اندازه گیري را به نحومقتضي در معرض نمایش کاربران قرار مي دهند.

What are Sensors?

- American National Standards Institute (ANSI) Definition
  - A device which provides a usable output in response to a specified measurand



- A sensor acquires a physical parameter and converts it into a signal suitable for processing (e.g. optical, electrical, mechanical)

- A transducer
  - Microphone, Loud Speaker, Biological Senses (e.g. touch, sight,…ect)

General Ideas about Sensors

- Sensor are truly systems!
- Sensors systems consist of three separable ideas:
  - Informational sources: physically measurable data sources (light beams, audio beams, electrical fields, etc)
  - Detector areas: Devices that react to changes in the informational sources
  - Data Interpreters: devices (hard or soft based) that convert informational changes into useful information

Sensor Performance Characteristics Definitions

- **Sensitivity: The sensitivity is the relationship indicating how must output you get per unit input**

Example: A resistance thermometer may have a sensitivity of 0.5

$\Omega/\,^{\circ}C$

- **Span or Dynamic Range :The range of input physical signals which may be converted to electrical signals by the sensor**

A load cell may measure forces in the range 0 to 50kN.

- **Error** :The difference between the true value of the quantity being measured and the result of the measurement. Units are those of the quantity being measured.

Errors in measurements

An example of gross error and its catastrophic results: Napoleon's retreat from Moscow,

Example of Limited Resolution of The Measurement System

Error classification

- Gross errors or Mistakes. Typically very large, can be fatal, but can be avoided
- System errors (experimental errors caused by functional and “good” instruments). System can be optimized to minimize those errors

Error classification: Gross Error

An example of gross error

A few definitions from the error heory

- Each measurement has a numerical value and a degree of uncertainty
- Error is the uncertainty in measurements that nothing can be done about (i.e. occurring even in the optimized measurement system)
- Error in the n^{th} measurement:

  X_n is n^{th} measured value, X is a "true" value; it is assumed that it exists. One can argue that "true" value can never be known. In reality X is defined using a high resolution *primary standard*.
- Precision and *sample mean.*

$$\varepsilon_n \equiv X_n - X$$

Percentile error

$$\%\varepsilon \equiv \left|\frac{\varepsilon_n}{X}\right| \times 100\%$$

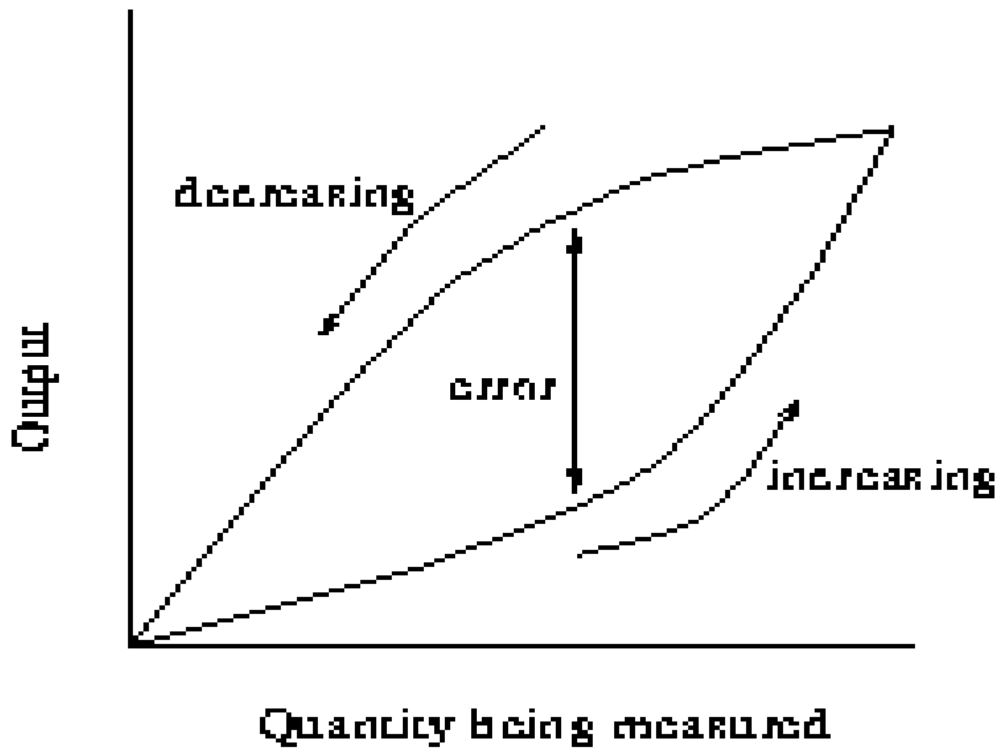
$$P_n \equiv 1 - \left|\frac{\langle X \rangle - X_n}{\langle X \rangle}\right|$$

$$\langle X \rangle \equiv \frac{\sum_n^N X_n}{N}$$

- **Accuracy**: Generally defined as the largest expected error between actual and ideal output signals
- if a sensor is specified as having accuracy of +/- 5% of full range output and the range of the sensor is **0** to **2000kN** then the measurement can be expected to be within + or **-100kN** of the true reading.

- **Hysteresis** : A sensor may give a different reading when measuring the same quantity depending on what ``direction" the value has been approached from

Hysteresis

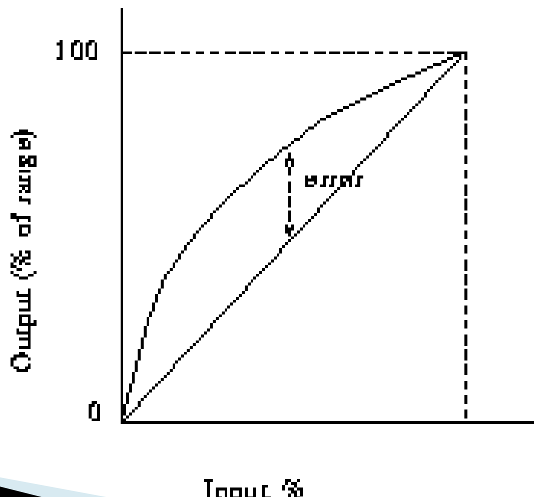


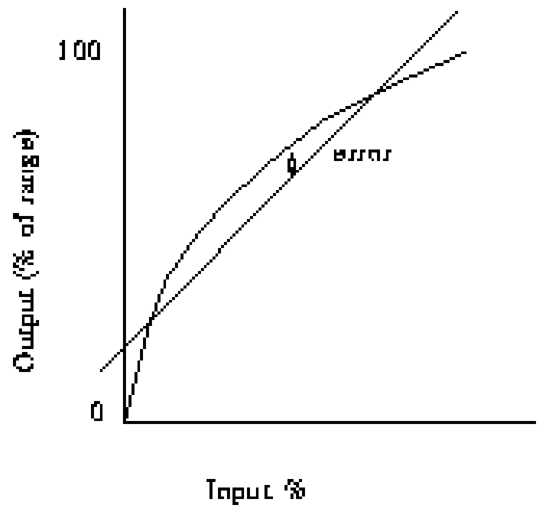
The maximum width of the expected error in terms of the measured quantity is defined as the hysteresis.

Nonlinearity (sometimes called Linearity)

- Often the relationship between input and output is assumed to be linear over the working range
- This assumption produces errors as sensors typically do not have such a linear relationship

- The error is the maximum deviation from a linear transfer function over the specified dynamic range





Resolution

- The resolution of a sensor is defined as the minimum detectable signal fluctuation

Repeatability

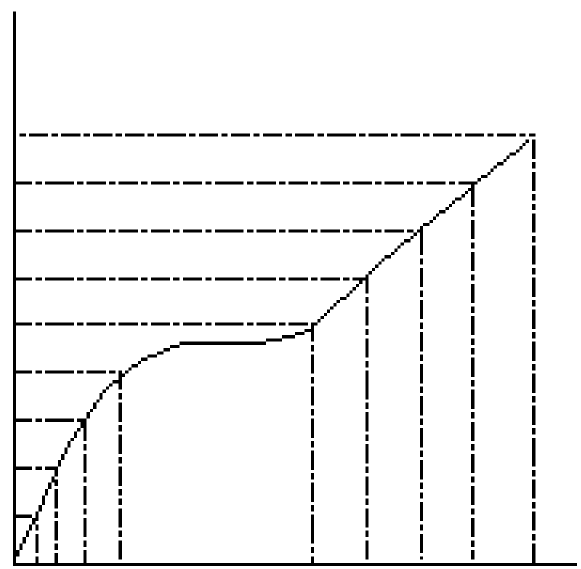
- The ability of the sensor to give the same output when measuring a constant input, measured on a number of occasions (i.e. with the sensor being disconnected between measurements).

Stability

- The ability of the sensor to give the same output when measuring a constant input, measured over a period of time.
- The term *drift* is often used to describe the change that occurs

Dead band

- This is a region for which the sensor input–output relationship has a small or zero slope



Dynamic terms

Response time

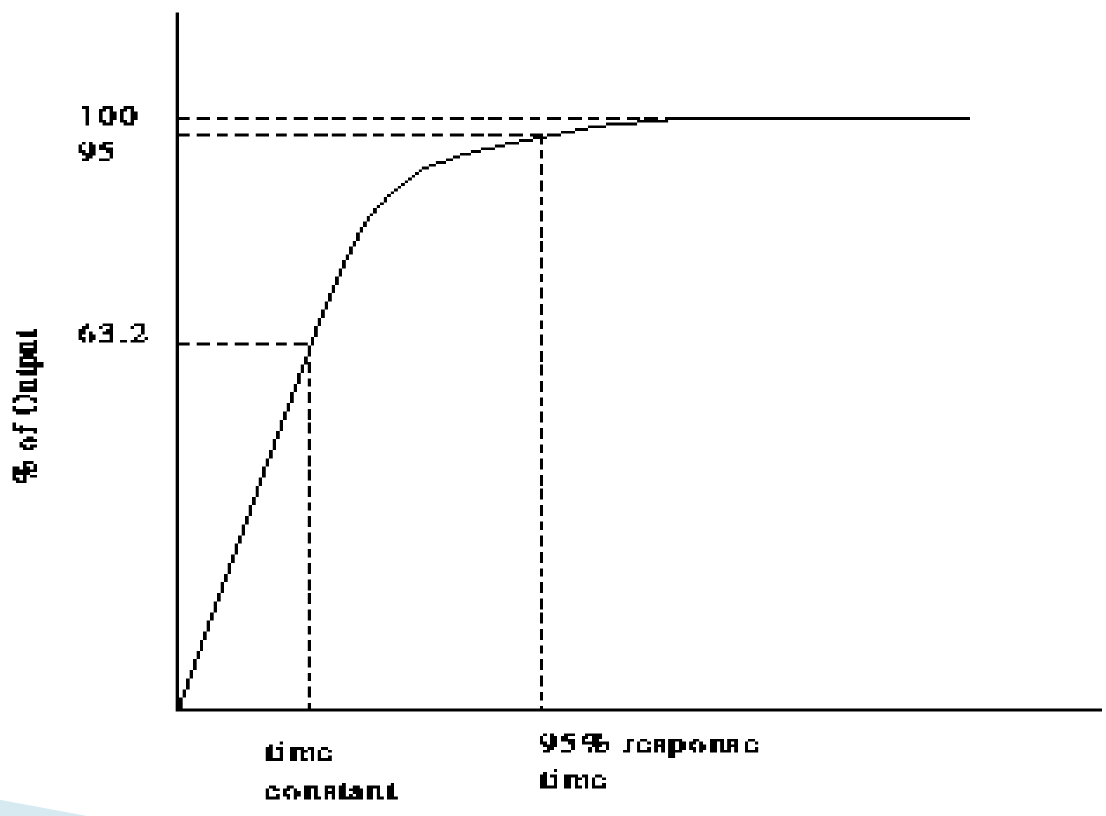
- The time that elapses after a constant input (step) up to the time the sensor give output that has reached some percentage (say 95%) of the value of the input

Time Constant

- 63.2% response time

Rise Time

- Time taken to rise to some specified percentage of the steady state value. Often the time to rise from 10% to 90 or 95% of the steady state value


100
95
63.2
% of Output
time
constant
95% response
time

Error

Gross errors or mistakes

- “Dynamic” error. Measurement "at first glance" for unsteady state. Often caused by inappropriate time constant.

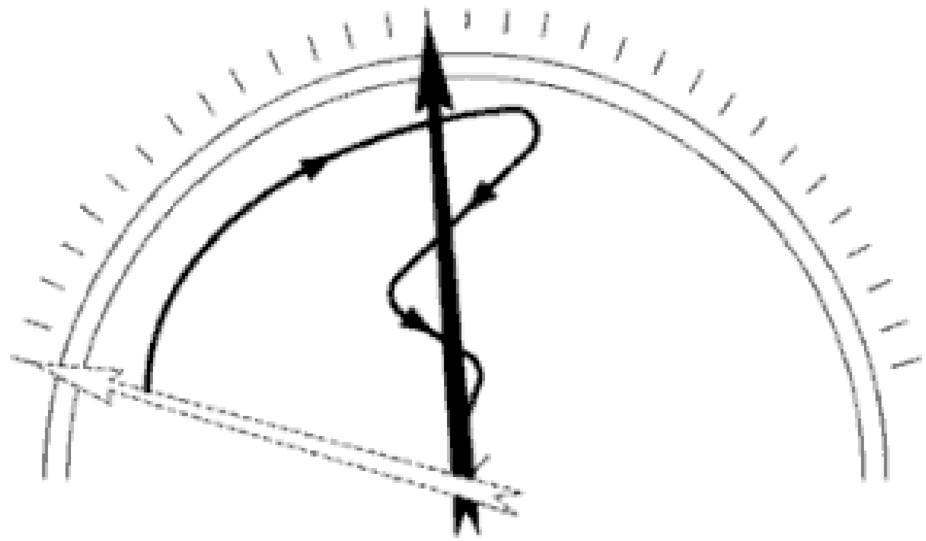


Figure 3.3. The movement of the pointer after connection of the device to the measured current

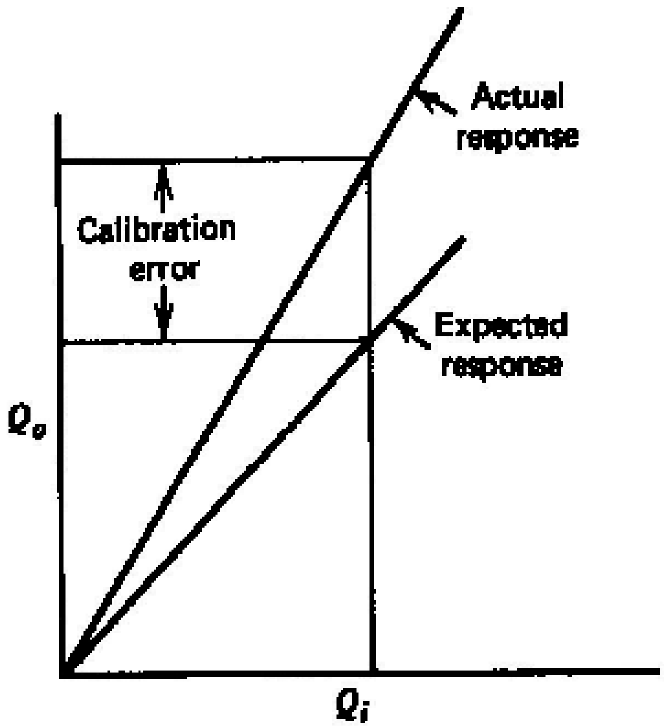
contact)

System (or experimental) errors

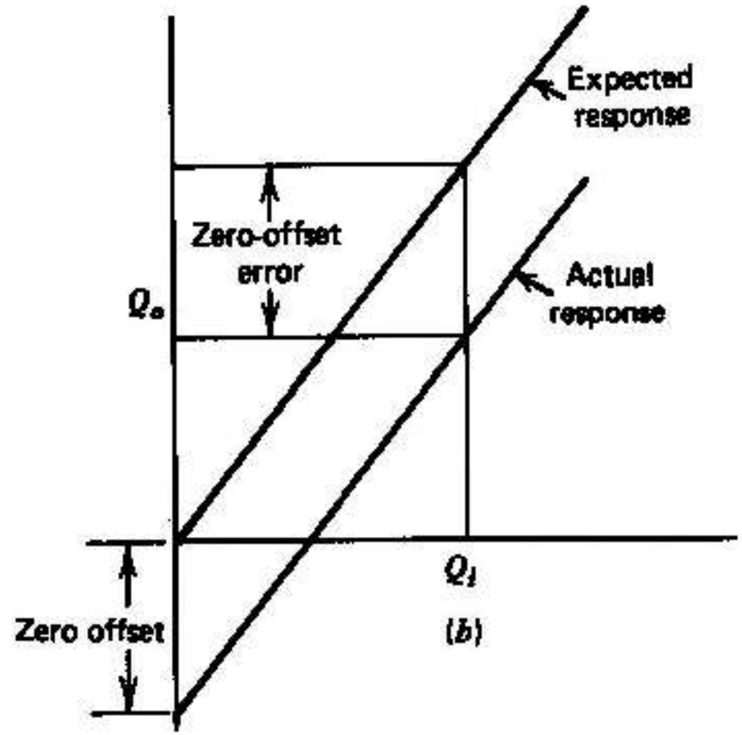
Errors which are inherent to the measurement process (related to both sensors and instrumentation):

- Calibration (gain) errors due to changing ambient conditions change (temperature, humidity) or aging
- Zero offset errors caused by ambient conditions change
- Range errors saturation, nonlinearity
- Reading uncertainty errors due to noise
- Drift errors. Affects static measurands the most
- Hysteresis errors result depends on the direction
- Repeatability errors different readings for the same input applied in the same fashion
- Resolution (A to D conversion) errors
- Dual sensitivity errors

Calibration and Zero Offset Errors

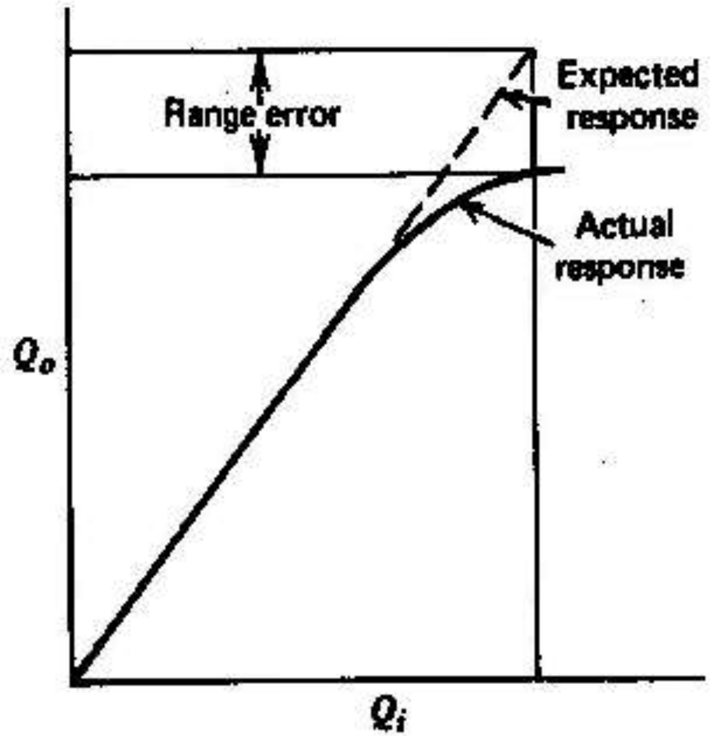


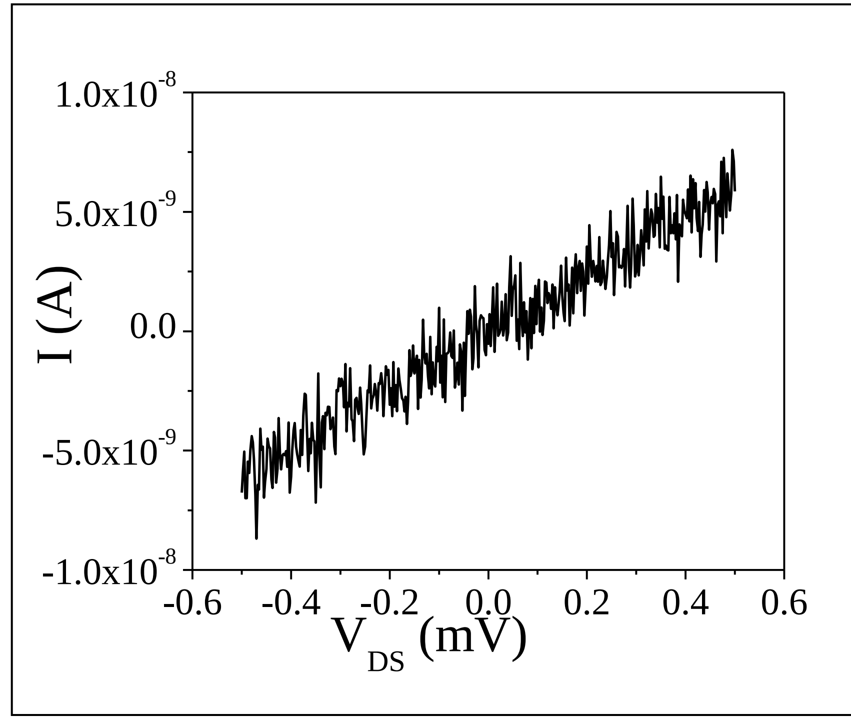
- Calibration or gain error. Instrument has to be calibrated vs known standard or at least vs another reasonably good instrument



- This is common cause of errors in DC measurements. One should know what to be called zero. Beware of the drifts!

Range and Uncertainty Errors

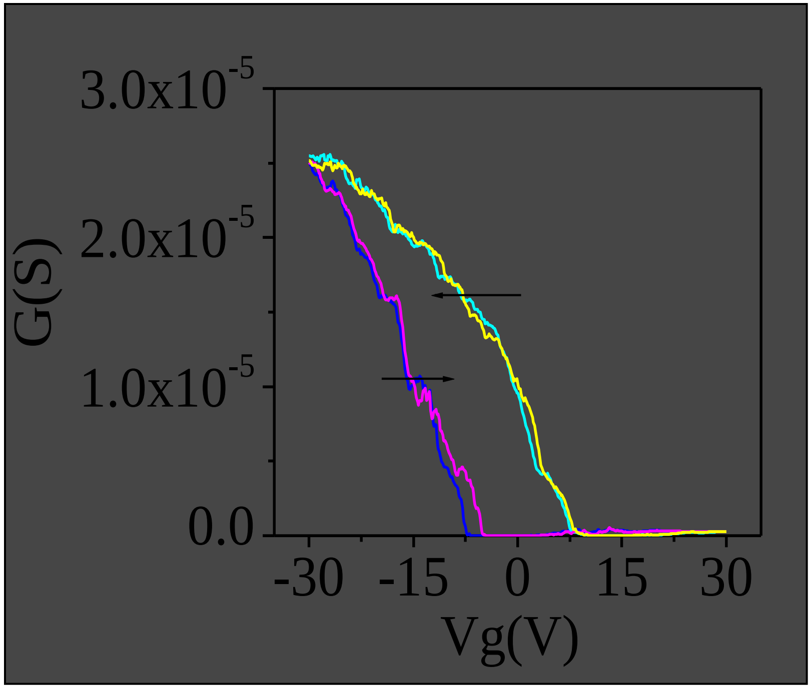


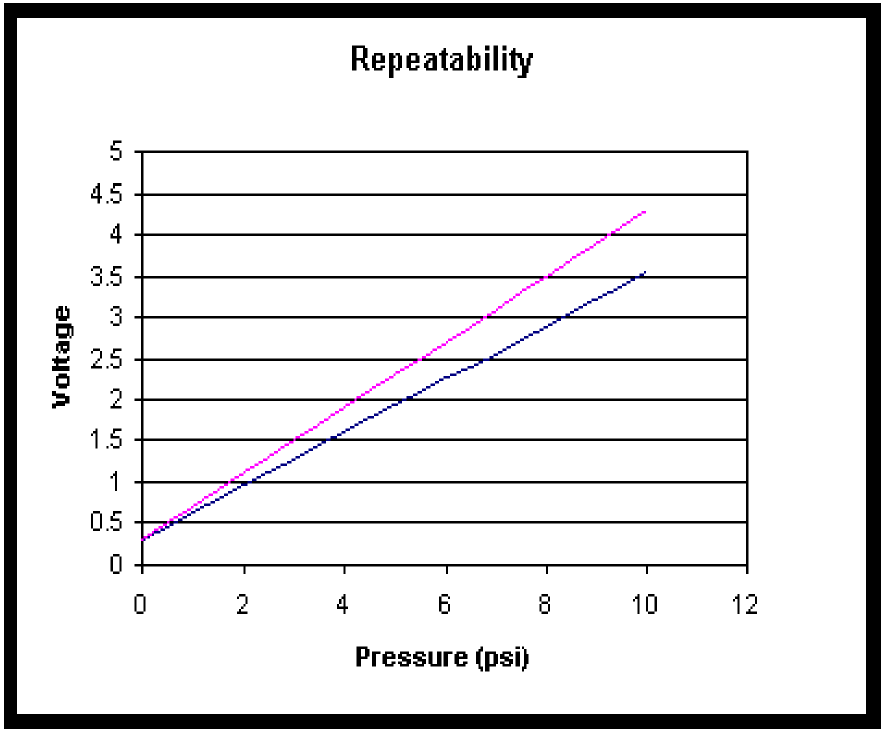


- Each instrument has finite dynamic range. Beware of saturation and too small signals!
- Linearity is an idealization. Know the range where it works!

- Noise limits the accuracy and resolution. Beware of too small signals!

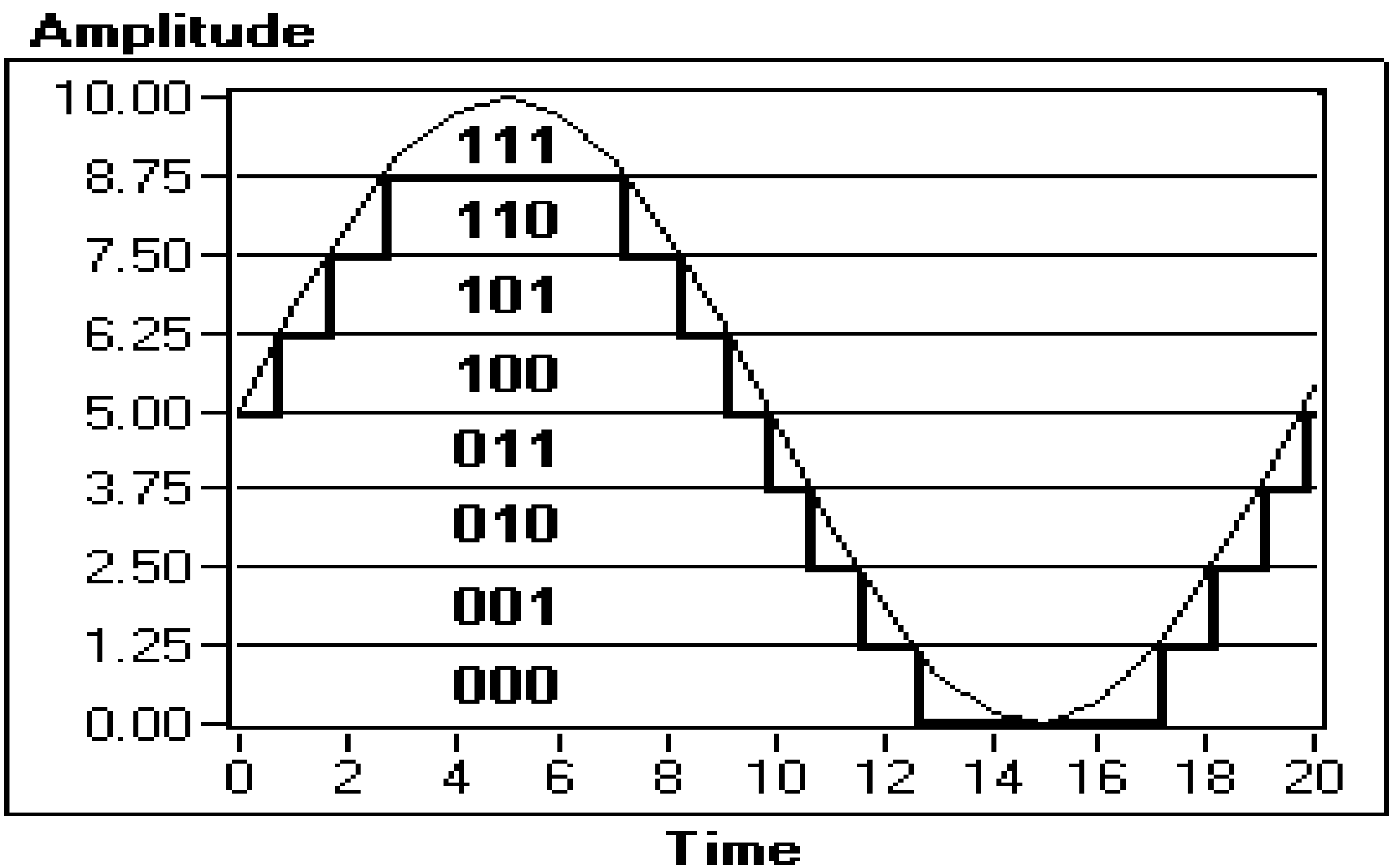
Hysteresis and Repeatability Errors





- Will cause error if used as a sensor

Resolution Error



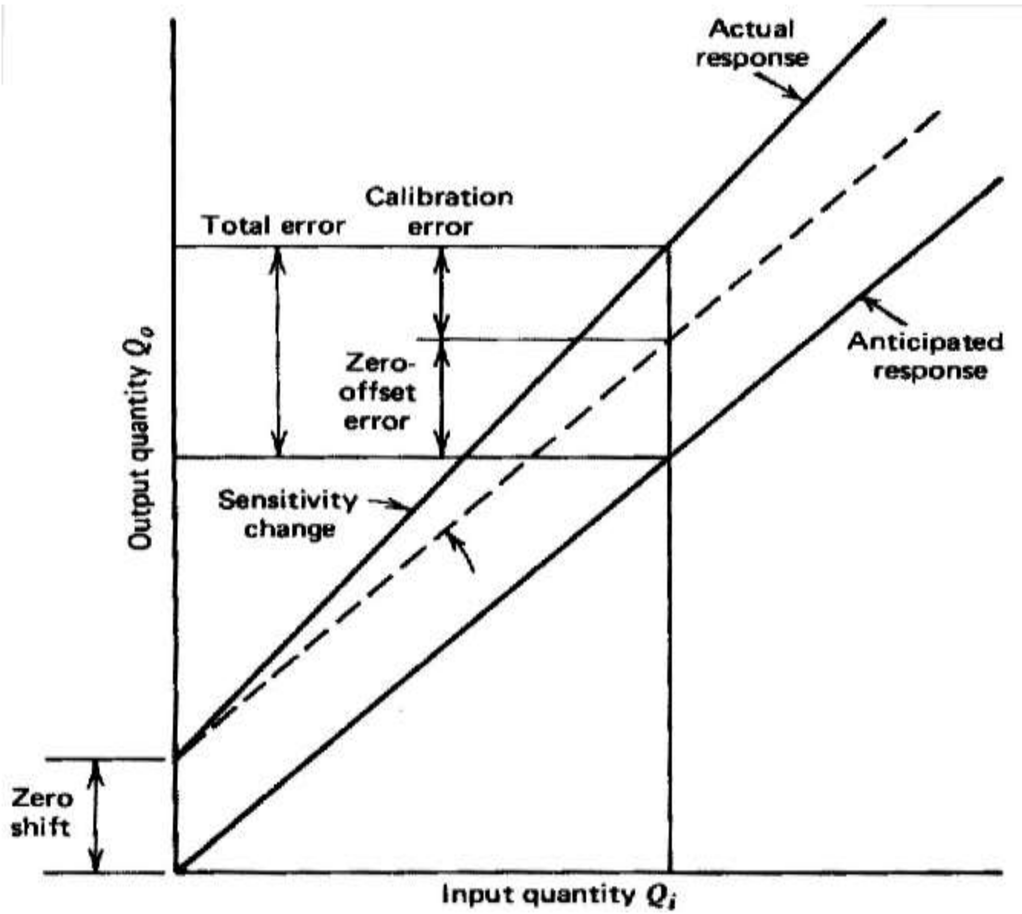
Dual Sensitivity and Back-action Errors

- An ideal sensor does not affect the process and is not supposed to react on any other changes rather than the quantity it is designed to react on.
- Real sensor are susceptible to various environmental changes which can change the sensitivity, offset etc.
- This is also applicable to the whole measurement process.
- Moreover, sometimes sensors themselves can affect the process/test.

Examples

- Examples of Dual Sensitivity Errors:
  - the resistivity of a strain gauge depends on the humidity
  - the sensitivity of a Single-Electron Transistor (SET) is strongly affected by temperature
- Example of Effect of Sensor on the Process
  - resistive thermometer can overheat the sample if the current used to measure resistance is too high
  - Single Electron Transistor creates noise which may affect a QCA cell nearby

The Result of Dual Sensitivity

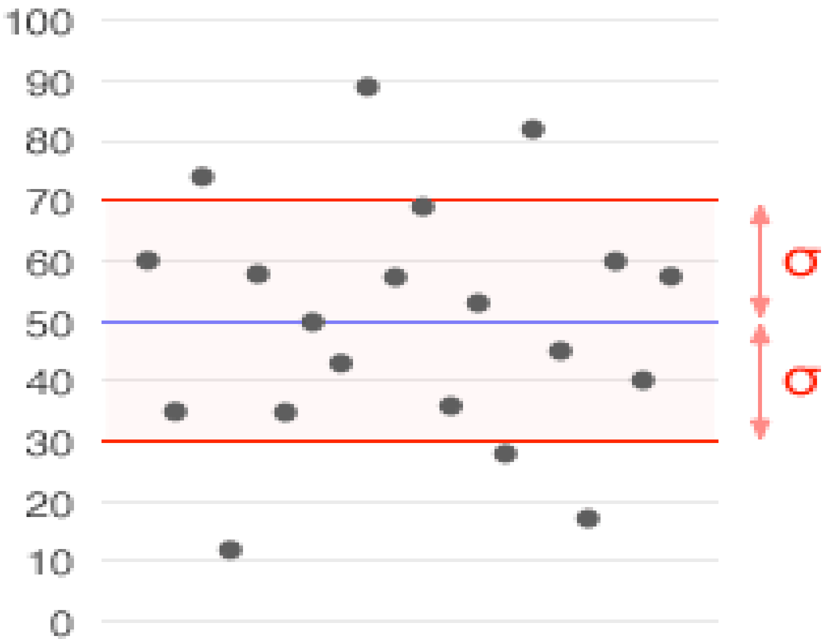


Don’t mix the dual sensitivity error with “Rooster in the magnet” gross error!

Here, due to change in temperature we got both the offset change and the change in the sensitivity (calibration and offset errors)

Important statistical definitions

- *Deviation* $$d_n \equiv X_n - \langle X \rangle$$
- *Average deviation* $$D_N \equiv \frac{\sum_{n}^{N} X_n - \langle X \rangle}{N}$$
- *Standard deviation* $$S_N \equiv \sqrt{\frac{1}{N}\sum_{n=1}^{N}(X_n - \langle X \rangle)^2} = \sigma_X$$
- *Signal-to-noise Ratio*



$$SNR \equiv \frac{\langle X \rangle}{\sigma_X} = \frac{\langle X \rangle}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}(X_n - \langle X \rangle)^2}} \propto \sqrt{N}$$

SNR improves as $$SNR \equiv \frac{\langle X \rangle}{\sigma_X} \propto \sqrt{N}$$

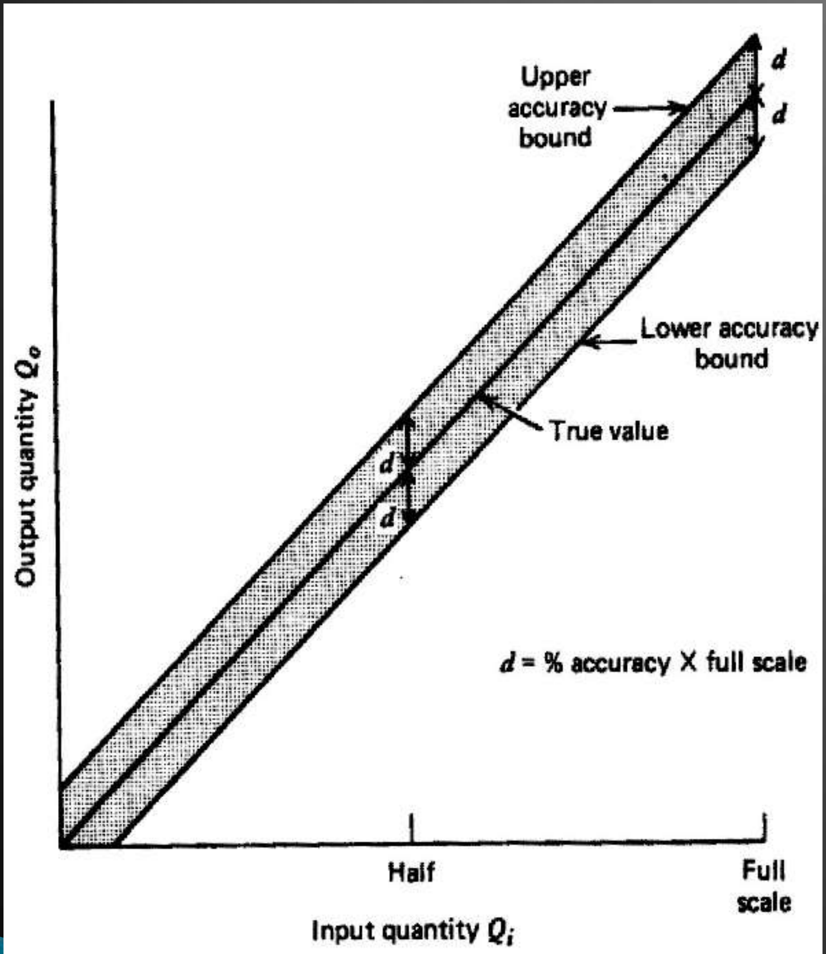
Accuracy and Instrument Deviation

- *Full scale accuracy A* $\equiv |\varepsilon$ / **Full scale** $|$
  - It is often quoted in units ppm (parts per million) or ppb (parts per billion) with a simple meaning of maximal acceptable error ε over a full scale.
  - Example: 1 ppm accuracy for 1V voltmeter – can measure accurately 1 μ V of signal on top of 1 V applied to the input. Sometimes term *limiting error* or *guaranteed error* is used instead of accuracy.
  - Example: a voltmeter with a 100 V scale has a guaranteed error of 2% of the full scale reading. Therefore, *guaranteed error* in volts around full scale is 2 V (meaning **no worse than 2%**)
- *Instrument Deviation* (**ID**) is defined as the product of the accuracy and the full scale value of the instrument:

$$\textbf{ID} = A \times \textbf{Full Scale} .$$

Gives you the corridor of manufacturer specifications

Accuracy Bounds for an Instrument



- The instrument can introduce larger percentile errors than the accuracy limits seem to imply
- At half scale the error is $\times 2$ (because **Instr. Deviation** remains the same, but we operate at only a half-scale)
- Error reaches 100% if the instrument is used close to zero of the scale
- Given: 1 mV full-scale voltmeter with accuracy 0.1% for full scale signal. What error in the measurement will one get if the reading fluctuates by 1 μV ?
  - For input signal of 1 μV, the error is 100%
  - For input signal of 1 mV, the error is 0.1%

Resolution

- *Resolution* stands for the smallest unit that can be detected. *Resolution* and *accuracy* are closely related. They are not the same, though *accuracy* can be equal to *resolution*.
- Not always! E.g.:
  - an ADC converter has resolution of 1/3 mV, but the last digit is so noisy, that accuracy is of the order of 1 mV.
  - Or an instrument can resolve 1 mV on top of 1 kV, but due to offset the result is inaccurate

Sensitivity, Span, Precision

- *Sensitivity* is a parameter extracted from the instrument response (based on the assumption that the response is linear). If *input quantity* changes by ΔQ_{INP}, resulting in the *output quantity* change of ΔQ_{OUT}, then the sensitivity is

$$S = \frac{\Delta Q_{out}}{\Delta Q_{inp}}$$

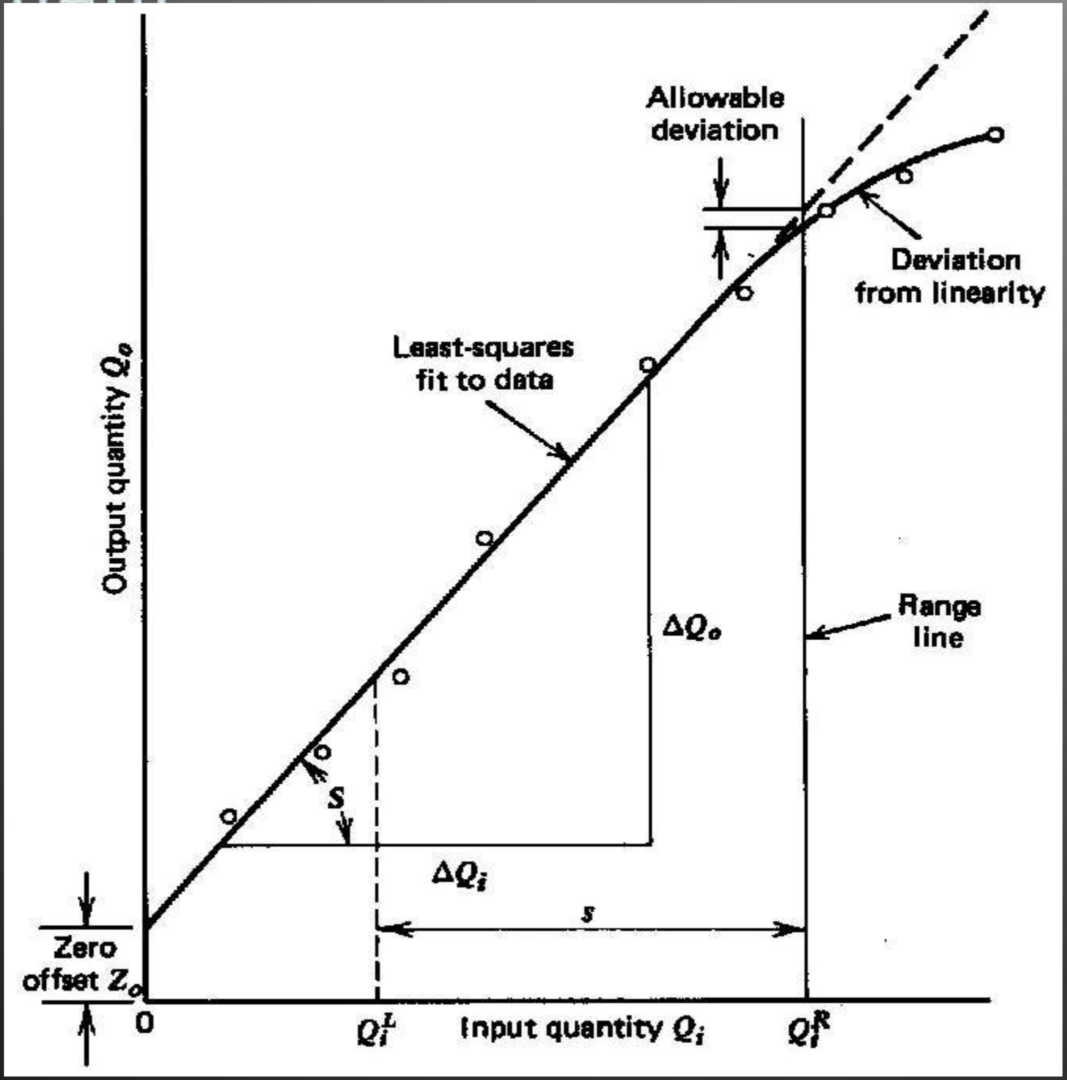
- *Span* of the Instrument is the difference between the upper and the lower limits of operation

  span = Upper – Lower

- *Precision Measurement* requires a measurement system capable of resolving very small signals, (say, one part in $10^{7)}$. In other words, the precise measurement is such for which

  Span / Resolution » 1

Input-Output Response Curve for an instrument



- Generic Instrument response curve includes all previously discussed parameters

Calculations of Error for a Test with Multiple Variables

- In case the experiment is designed so that the outcome of the measurement, Q, is a function of multiple variables,

$$Q = f(x_1, \ldots, x_N)$$

- with uncertainty of ($\Delta x_1, \ldots, \Delta x_N$), the resulting error can be calculated using Taylor series. By dropping higher derivatives, the worst case uncertainty, or *limiting error* (all N sources of error pull the result in the same direction) is

$$\Delta f_{\max} = f(x_1, \ldots, x_N) - f(x_1 + \Delta x_1, \ldots, x_N + \Delta x_N) = \sum_{i=1}^{N} \left| \frac{\partial f}{\partial x_i} \Delta x_i \right|$$

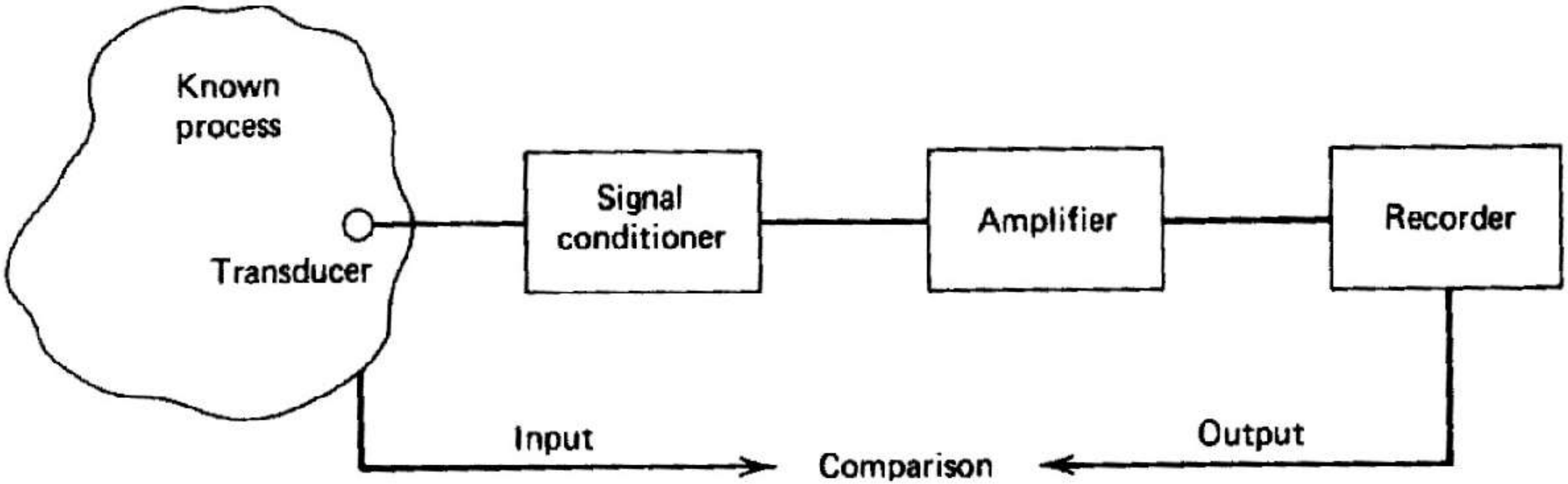
- Instrumentation system usually contains several elements with each element introducing error (even when it operates within specifications!), and error accumulates.
- Maximal accumulated error for the instrument system is given by (all sources of error assumed to be independent (uncorrelated)) :

$$\varepsilon_{\max} = \sqrt{\sum_{i=1}^{N} \varepsilon_i^2}$$

Minimizing experimental Errors

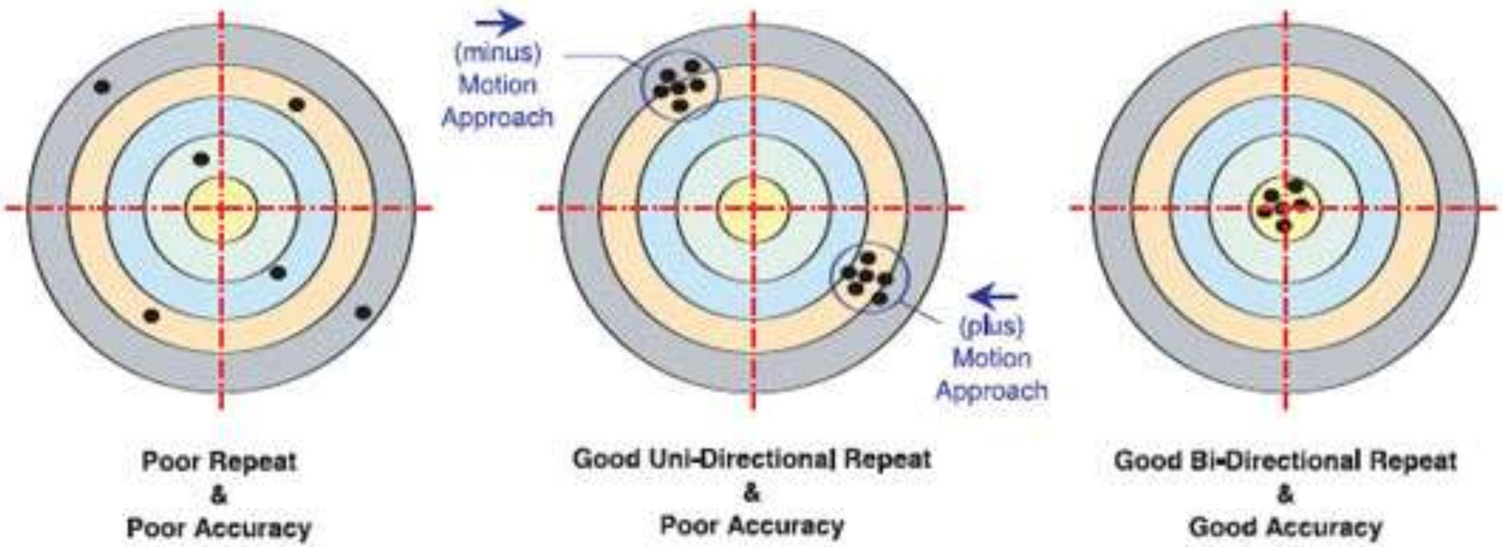
- Use the right sensor: The sensor should not affect the process and the process should not destroy the sensor.
- Check the accuracy of each element and determine the accumulated accepted error
- Calibrate each instrument
- Connect system with proper wires
- Check the system for electrical noise
- Estimate the total error in the system from all known sources
- Perform a system calibration by measuring the variable in a known process. This gives you a single calibration constant for the entire system. Example: scales

System Calibration (versus individual instruments calibration)



- Calibrate your measurement system vs known standard, so that your output (say, in volts) corresponds to known input quantity (say, in ohms)
- In this case you don't have to consider intermediate details of your measurement system for as long as
  - The system response is linear
  - There are no offset errors
  - The system is within the dynamic range
  - The system signal-to-noise ratio is satisfactory
  - The system does not change its parameters in time
- This approach allows to eliminate instrument calibration

System Calibration



- There are situations where it is impossible to calibrate parts of the entire system, but the system as a whole can be easily calibrated