Measurement Systems: ELEN4006A

2019

by

Lesedi Masisi

Who am I?

- **Research area**: Electric Machines and Drives, Power Electronics, Electrification of transportation

- Applications:
  - Renewable energy (Wind energy, PV)
  - Electrification of transportation (Electric vehicles, trains, etc)

- Current Projects:
  - Retaining the integrity of the dc bus voltage due to supply fault
  - Comparison of Induction and Reluctance machine for heavy haul mining electric vehicles

- Future Projects:
  - Conversion/replacement of city buses to electric buses
  - Development of a low cost position sensor for drives applications

Course Out-Line

- Lectures 2 periods/week
- Project 40 % [Groups of two]
- Labs 10% (Will announce dates)
- Exam 50%
- Textbook Principles of Measurement Systems, Bentley

Course Homepage

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Course Home Page

https://cle.wits.ac.za/portal/site/ELEN4006A_2019

Project Plan

- Proposed measurement system — Google form [time stamped]
  - Brief description
  - Primary sensor
- Project proposal — 1 page [Max 2 pages]
- Pairs of two
- One Report
- Oral presentations

Lecture 1

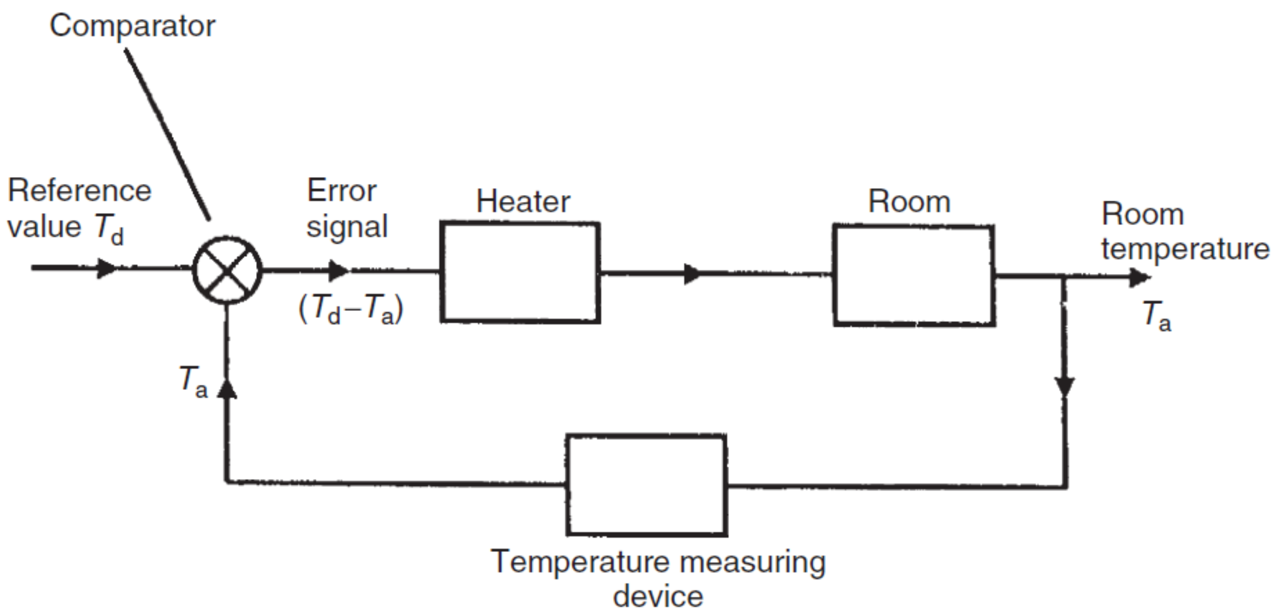
Definitions of Standard Units

Physical Quantity	Standard Unit	Definition
Length	Meter	Length of path traveled by light in an interval of 1/299,792,458 seconds
Mass	Kilogram	Mass of a platinum-iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second	9.192631770×10^9 cycles of radiation from vaporized cesium 133 (an accuracy of 1 in 10^{12} or one second in 36,000 years)
Temperature	Degrees	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Amphere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of 2×10^{-7} newtons per meter length of conductor
Luminous intensity	Candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz (Hz $\times 10^{12}$) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole	Number of atoms in a 0.012-kg mass of carbon 12

Find out new definition of mass, 2019 definition???

Applications

- Three main categories of measuring
  - Regulating trade (length, volume and mass in terms of standard units)
  - Monitoring (heat, pressure, speed, etc)
  - Calibration of instruments (use of automatic feedback system)

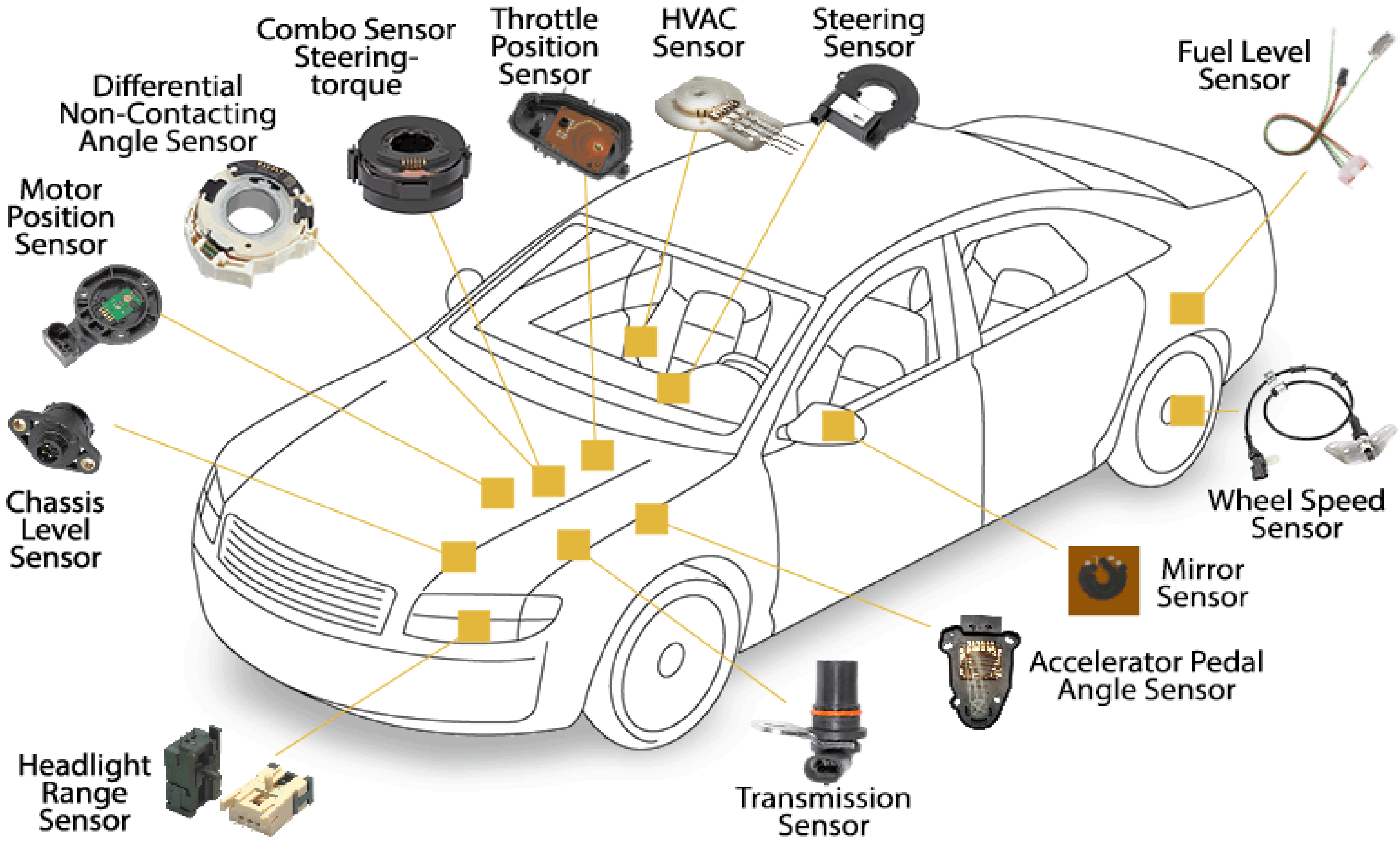


Ta is compared with the reference temperature

Applications….cont

Anything strange with this situation?

Sensing Elements



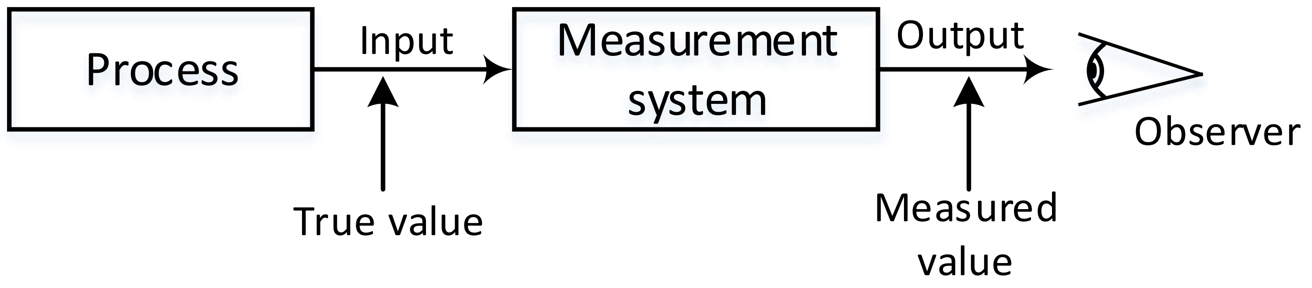
Sensing Elements…cont

- Criteria*
  - Accuracy
  - Environmental condition (Humidity & Temperature)
  - Range
  - Calibration (Initial conditions change)
  - Resolution (smallest incremental sample step)
  - Sensitivity
  - Dynamic performance
  - Cost
  - Reliability

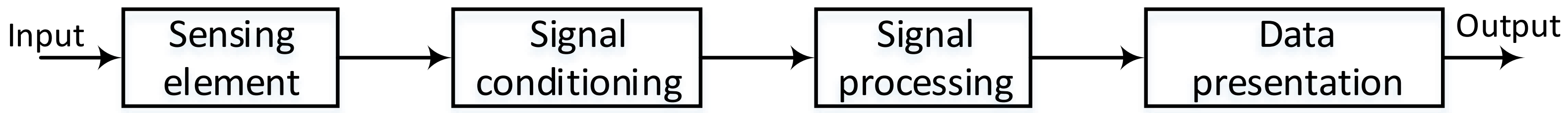
- Classification
  - Temperature: Thermistors, thermocouple, …
  - Pressure: Fibre optic, vacuum, elastic liquid,…
  - Flow: Electromagnetic, differential pressure,…
  - Proximity and displacement – LVDT, photoelectric,…
  - Etc…
- Look at a data sheet…

*https://www.engineersgarage.com/articles/sensors

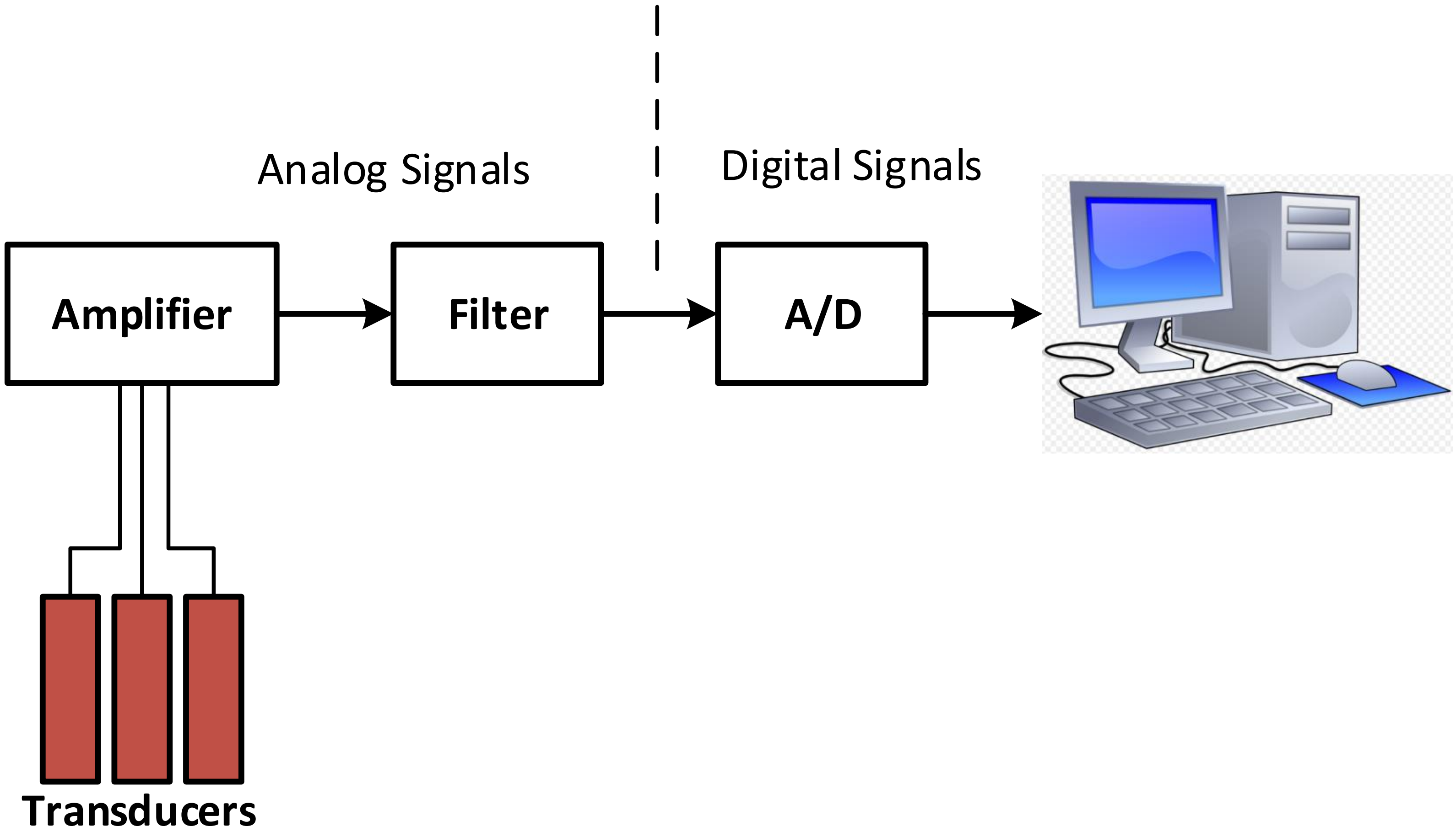
Structure of Measurement System



Elements of a measurement system



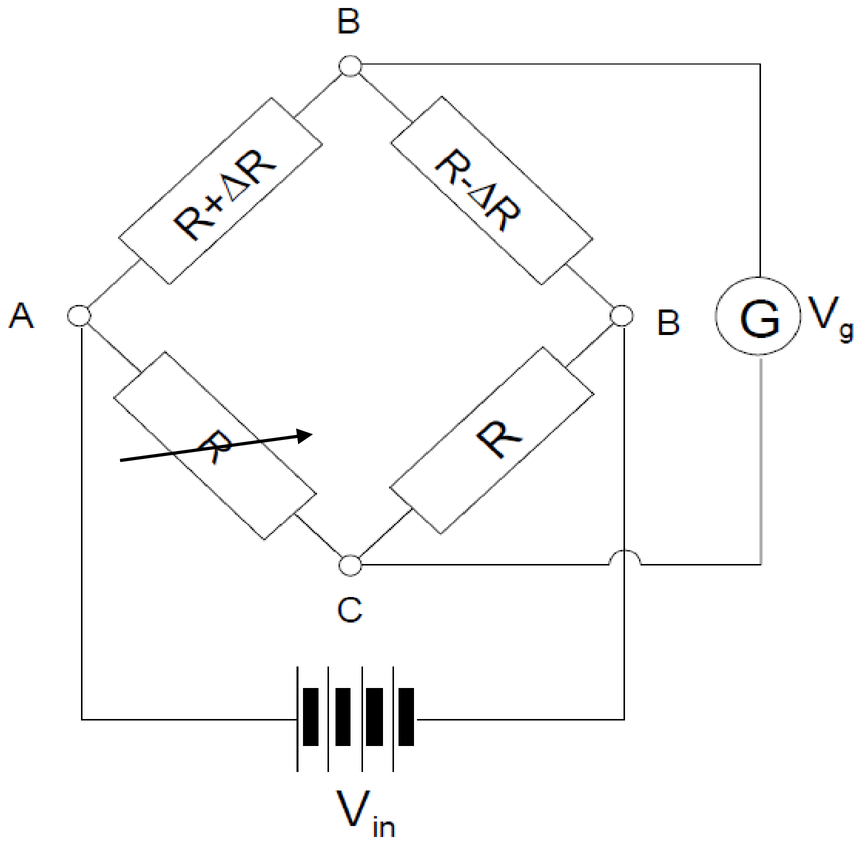
Structure of Measurement System



e.g. Strain gauge

Sensor Signal Conditioning

- Strain gauge example
  - Wheatstone half bridge (only two resistors strain gauges
  - …ΔR is change in resistance due to elongation of the strain
  - Vg is the signal

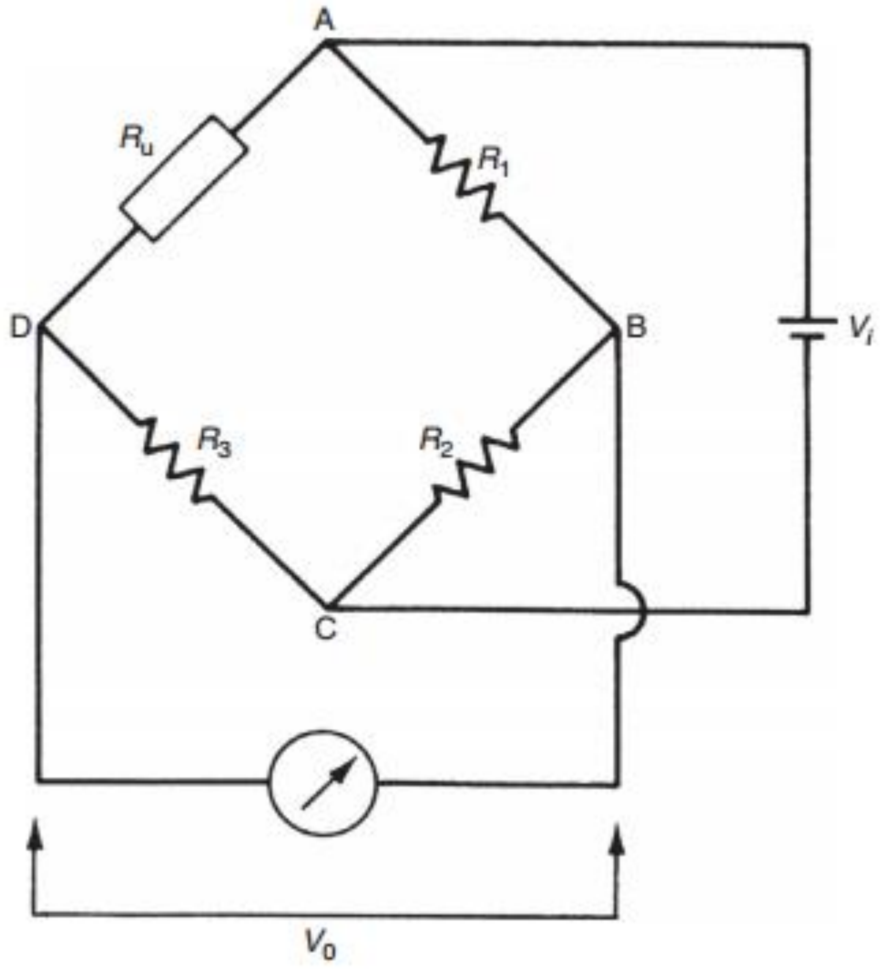


- Calibration
  - Relating the output voltage to the physical entity
  - Measurement to a known reference level
  - Excitation voltage
  - Amplification factor

- Zero level
  - Output signal from unloaded transducer is set to zero
  - **First option:** Balancing the measurement bridge by adjusting the variable resistances
  - **Second option:** At reference condition (unloaded), whatever is measured is subtracted from all the measurements

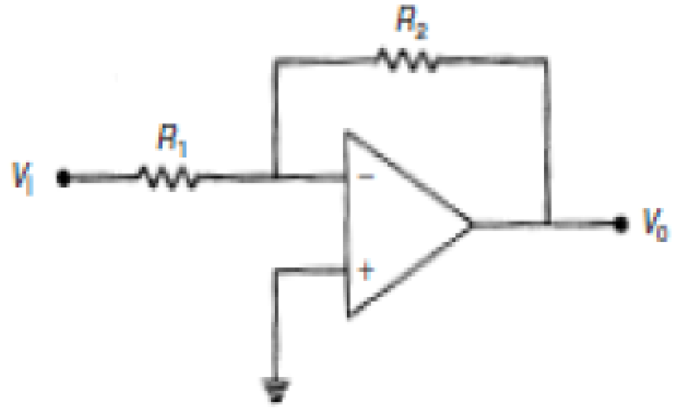
Sensor Signal Conditioning

- Voltage output (Using point B as reference)
  - $V0 = Vi(Ru/(Ru+R3) - R1/(R1+R2))$

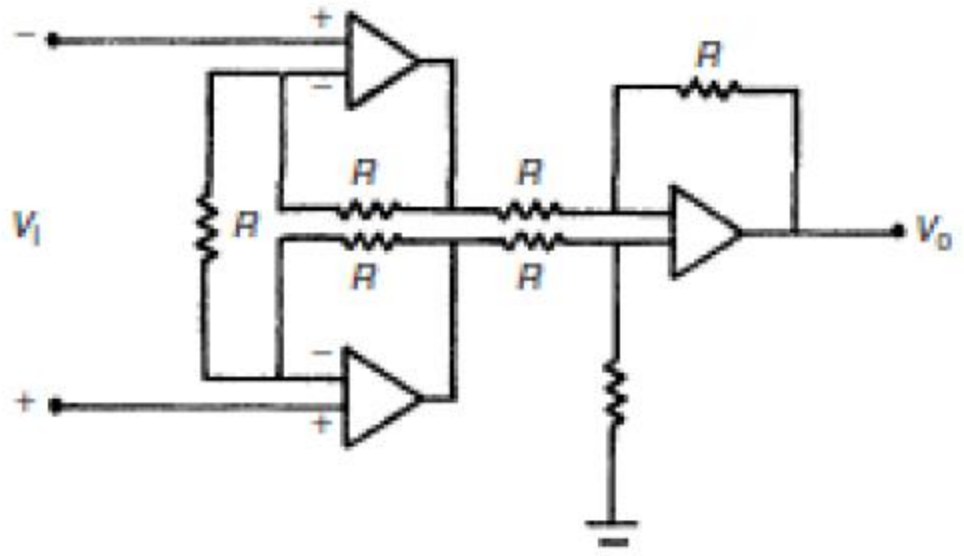


Signal Conditioning: Amplifiers

- Different types
  - DC
  - AC
  - Charge amplifiers (e.g. for piezo-electric sensors)



- Instrumentation amplifier



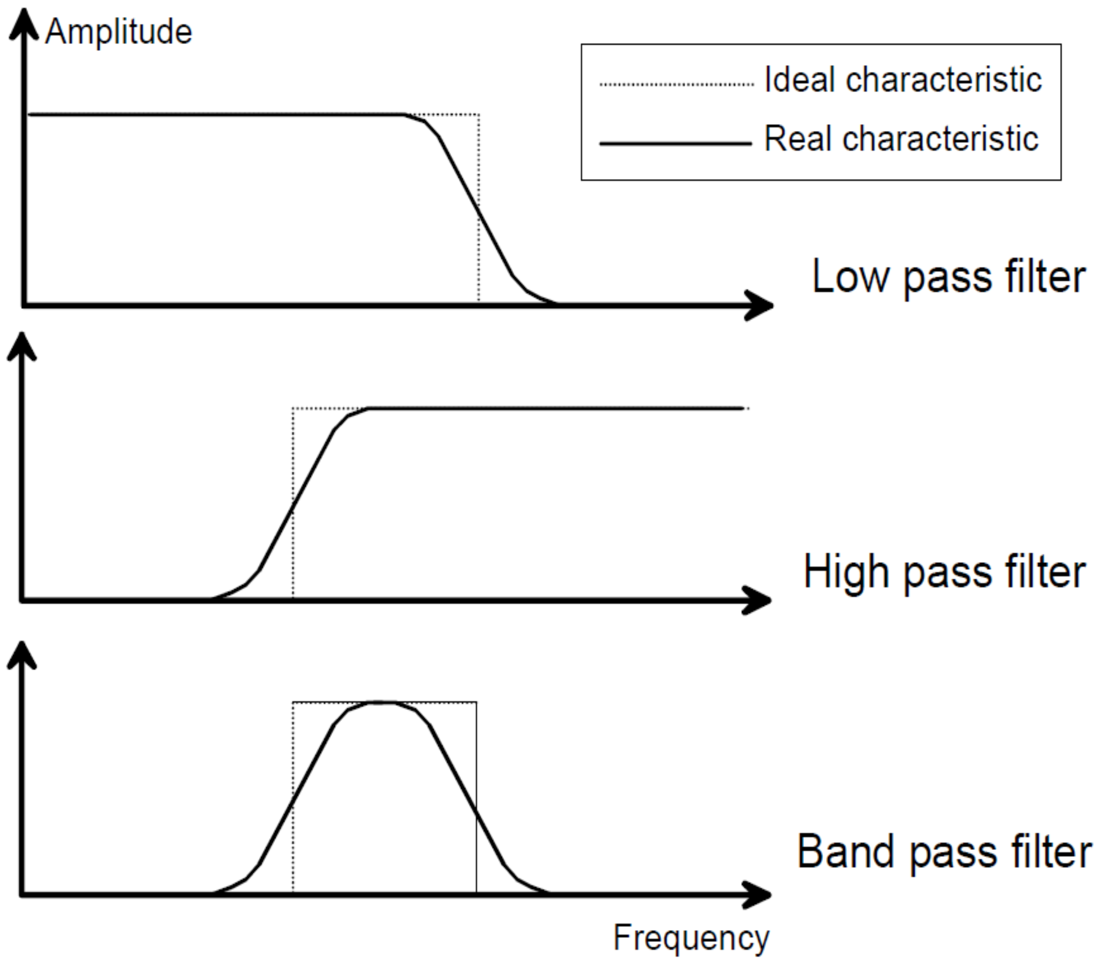
Filters, Sampling Frequency and A/D: Signal Conditioning

- Filters
  - Introduce phase delay
- ADC
  - Sampling (should be set at least 5-10X low pass filter cut off)
  - High sampling also means increased file size
  - Accuracy number of bits representing a number
  - $2^4 = 16$, only 16 different values possible
  - $2^8 = 256$, more values can be represented

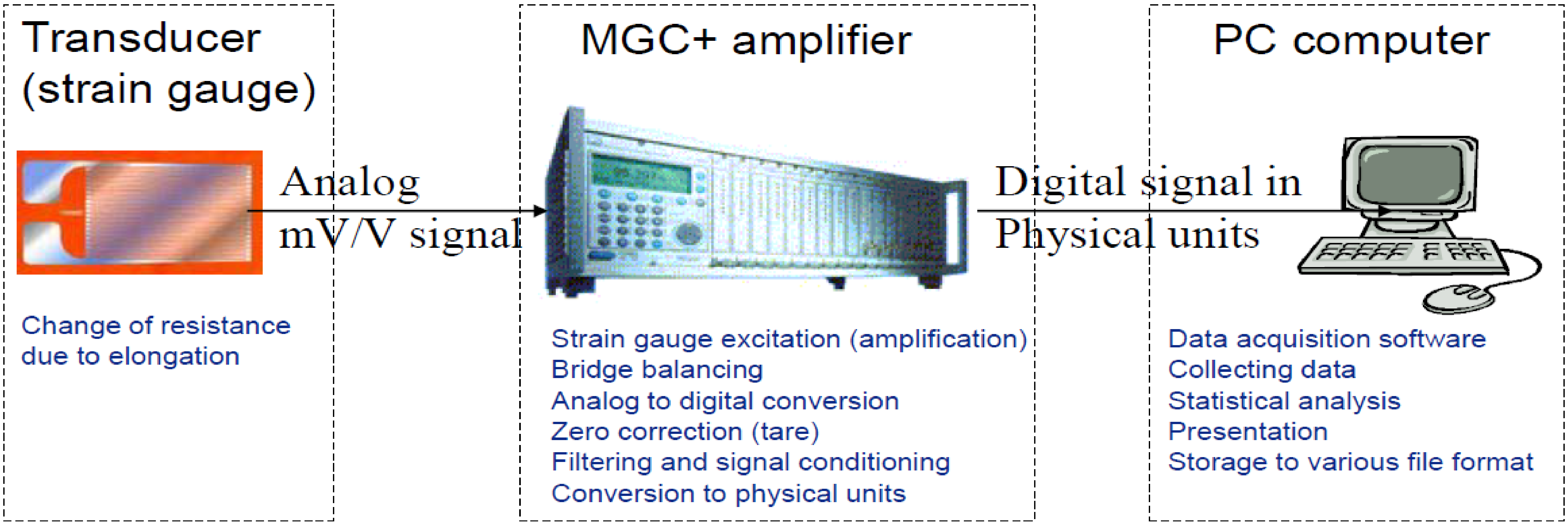
E.g. (Resolution) recording angle position ranging from 0-360deg

4 bit: 22.5deg resolution (360/16)

8 bit: 1.41deg resolution (360/256)



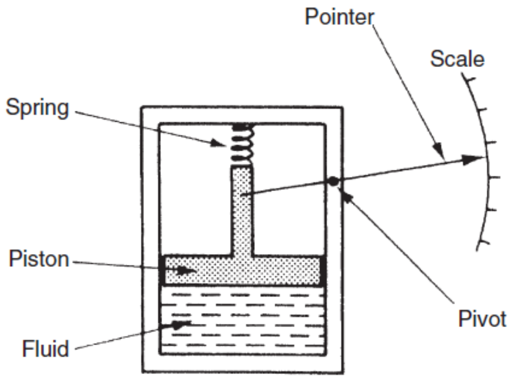
Measurement System



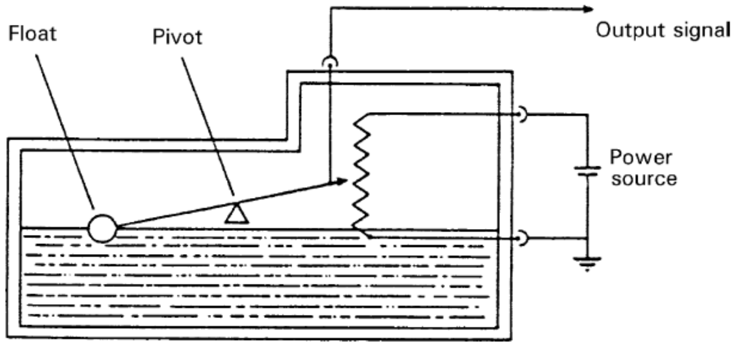
Lecture 2

Instrument Types

- Passive
  - Instrument output produced entirely by quantity being measured
  - Easy to manufacture



- Active
  - Makes use of an external source
  - Tend to get better resolution
  - Tend to be expensive



- Analog
  - Prone to human error
- Digital
  - Automatic systems

Static Characteristics

- Static characteristics: Only in steady sate conditions
- A diff of +/-0.5deg Celsius too small to affect how we feel
  - But for a chemical process could affect chemical reaction

- Accuracy
  - A measure of how close the output reading is to the correct value
  - This could be referred to as measurement uncertainty (Extent to which a reading might be wrong)
  - This is dependent on the Full Scale (f.s) of the measurement system capability
  - E.g. if expected values to be measured is between 0 and 1 pa, and instrument with range 0 – 10 pa will lead to increased accuracies

Example:

A pressure gauge with a measurement range of 0–10 bar has a quoted inaccuracy of $\pm$1.0% f.s. ($\pm$1% of full-scale reading).

(a) What is the maximum measurement error expected for this instrument?

(b) What is the likely measurement error expressed as a percentage of the output reading if this pressure gauge is measuring a pressure of 1 bar?

Solution:

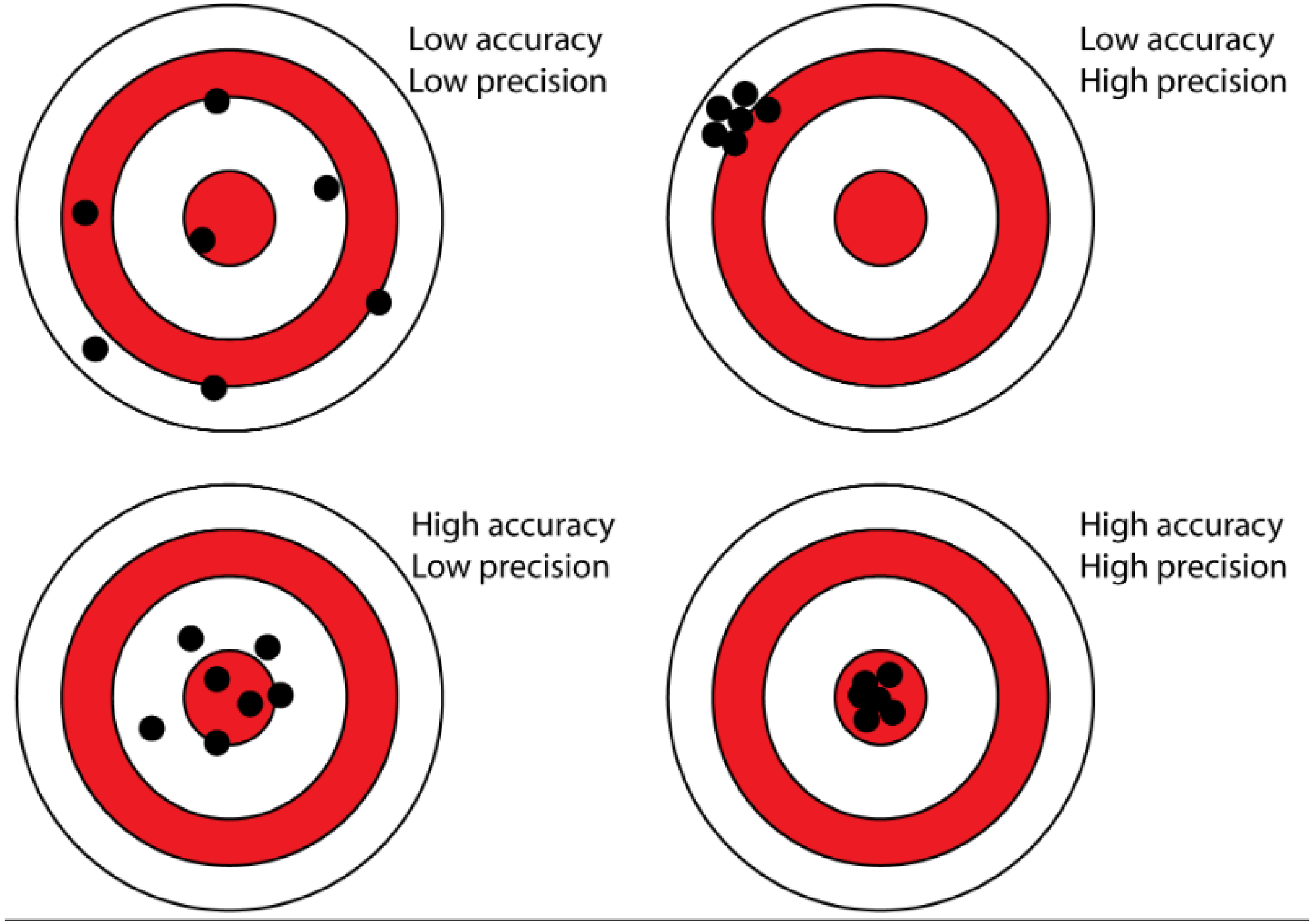
(a) The maximum error expected in any measurement reading is 1.0% of the full-scale reading, which is 10 bar for this particular instrument. Hence, the maximum likely error is $1.0\% \times 10$ bar $= 0.1$ bar.

(b) The maximum measurement error is a constant value related to the full-scale reading of the instrument, irrespective of the magnitude of the quantity that the instrument is actually measuring. In this case, as worked out earlier, the magnitude of the error is 0.1 bar. Thus, when measuring a pressure of 1 bar, the maximum possible error of 0.1 bar is 10% of the measurement value.

Measurements taken at lower range values will have higher error

Static Characteristics…cont

- Precision/Repeatability/Reproducibility
  - Describes instruments degree of freedom from random errors



Static Characteristics…cont

- Tolerance
  - Closely describes the maximum error to be expected
  - Describes the maximum deviation of a manufactured component from a specified value
  - Resistors have tolerances of approximately 5%, screw hole may have tolerance of 0.1mm, etc.

Example:

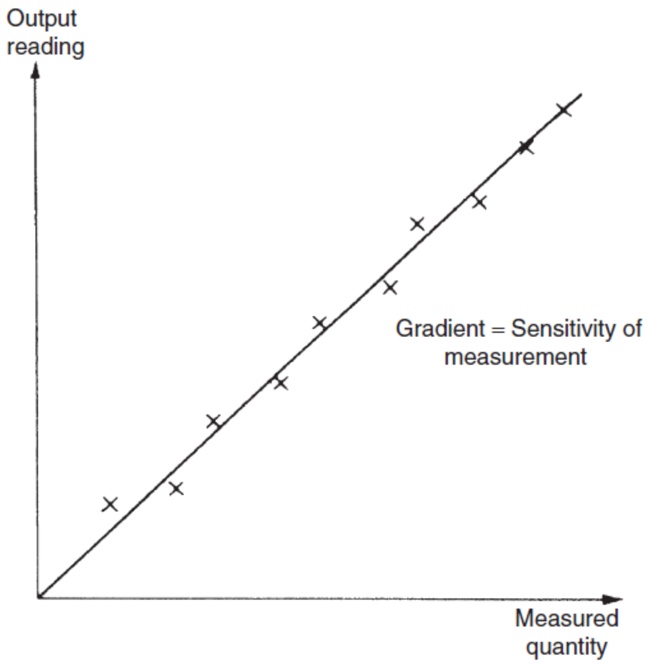
A packet of resistors bought in an electronics component shop gives the nominal resistance value as 1000 Ω and the manufacturing tolerance as ±5%. If one resistor is chosen at random from the packet, what is the minimum and maximum resistance value that this particular resistor is likely to have?

Solution:

The minimum likely value is $1000\ \Omega - 5\% = 950\ \Omega$.
The maximum likely value is $1000\ \Omega + 5\% = 1050\ \Omega$.

Static Characteristics…cont

- Range/Span
  - Defines the minimum and maximum values of a quantity instruments is designed to measure
- Linearity
  - Normally output is linearly proportional to the quantity being measured
  - Procedure is to draw a good fit straight line through the Xs
  - Nonlinearity is then the maximum deviation of the X from the straight line
    (usually expressed as a percentage of full-scale reading)
- Sensitivity
  - It is the measure of a change in instrument output when measured quantity
    changes by given amount
  - It a ratio, slope/gradient of the straight line, see figure.



Static Characteristics...cont

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

Solution:

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.

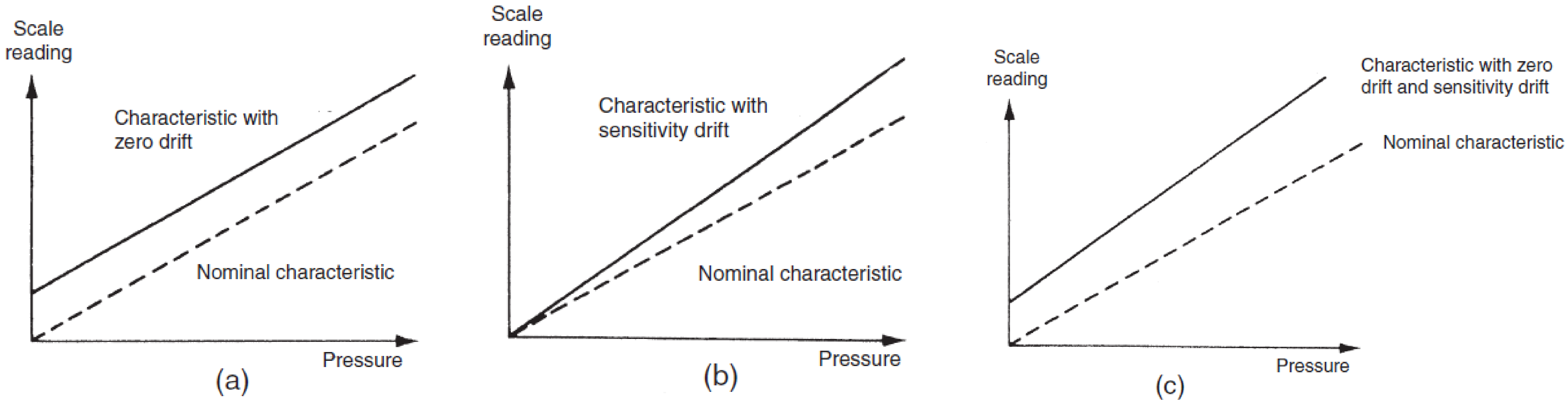
For a change in temperature of 30°C, the change in resistance is 7 Ω. Hence the measurement sensitivity $= 7/30 = 0.233$ Ω/°C.

Static Characteristics…cont

- Threshold
  - The minimum input before the change in the instrument output reading
  - E.g. typically the vehicle speedometer has threshold of 15 km/h (no output speed measured until 15 km/h is reached)
- Resolution
  - The lowest limit in magnitude of what is being measured that produces and observable change in instruments output
  - Vehicle speedometer has subdivisions of 5 km/h (cannot estimate speed inbetween)
  - 5km/h is the resolution of the instrument

Static Characteristics...cont

- Sensitivity to disturbance
  - Variations in the external conditions such as ambient temperature can affect the static characteristics
  - Sensitivity to disturbance is a measure of the magnitude of this change
  - These environmental changes affect instrument in two ways: zero drift and sensitivity drift/bias
  - Zero drift is usually issue of calibration (e.g. a mass scale has a thumb wheel to zero the scale)
  - Sensitivity drift indicates the amount by which an instruments sensitivity of measurement varies due to environmental temperature changes (measured in: $V/bar/^{0}C$ as due to temperature changes)



Example: The following table shows output measurements of a voltmeter under two sets of conditions:

(a) Use in an environment kept at 20°C which is the temperature that it was calibrated at.
(b) Use in an environment at a temperature of 50°C.

Voltage readings at calibration temperature of 20°C (assumed correct)	Voltage readings at temperature of 50°C
10.2	10.5
20.3	20.6
30.7	40.0
40.8	50.1

Determine the zero drift when it is used in the 50°C environment, assuming that the measurement values when it was used in the 20°C environment are correct. Also calculate the zero drift coefficient.

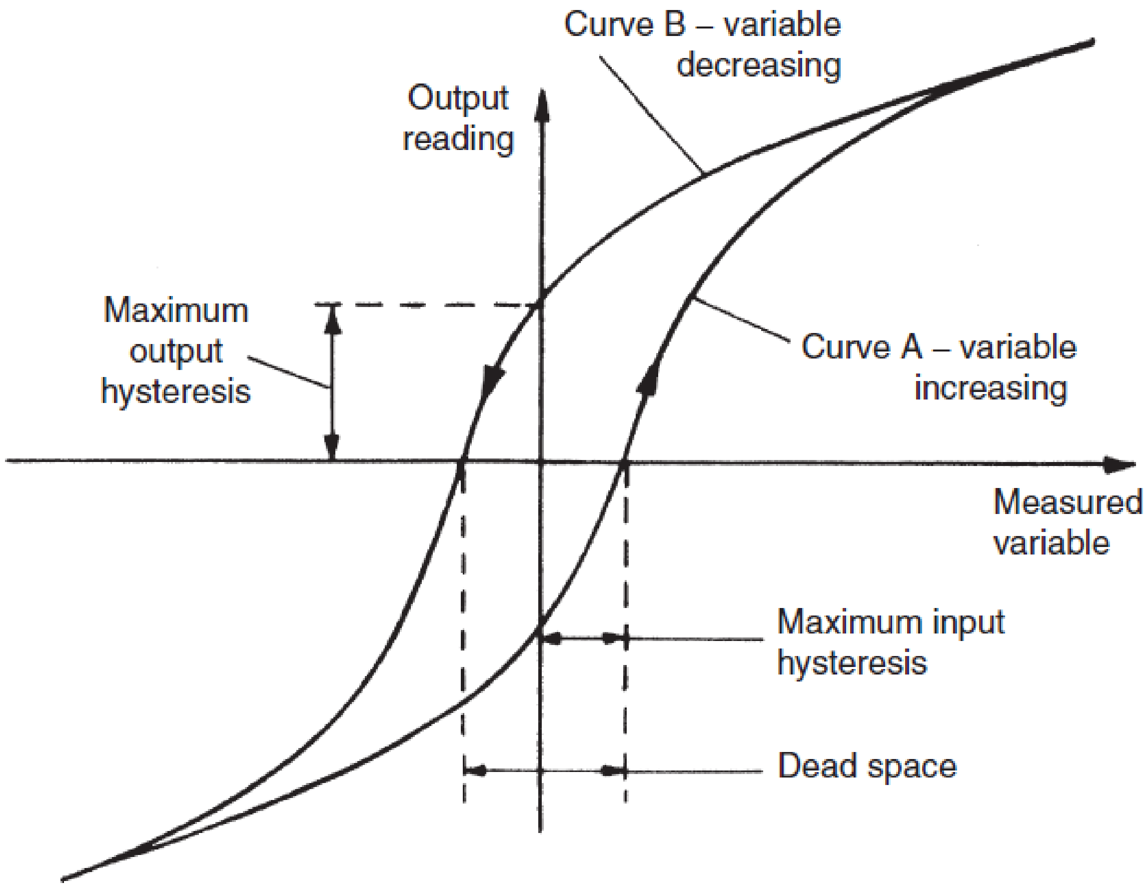
Solution:

Zero drift at the temperature of 50°C is the constant difference between the pairs of output readings, that is, 0.3 volts.

The zero drift coefficient is the magnitude of drift (0.3 volts) divided by the magnitude of the temperature change causing the drift (30°C). Thus the zero drift coefficient is $0.3/30 = 0.01$ volts/°C.

Static Characteristics...cont

- Hysteresis Effects
  - Increasing input measured quantity results in output reading varying in the manner shown in A
  - Decreasing input variable results in output reading as shown in curve B
  - Electrical winding around iron core, magnetic hysteresis, variable inductance displacement transducers, friction forces, etc



Dynamic Characteristics

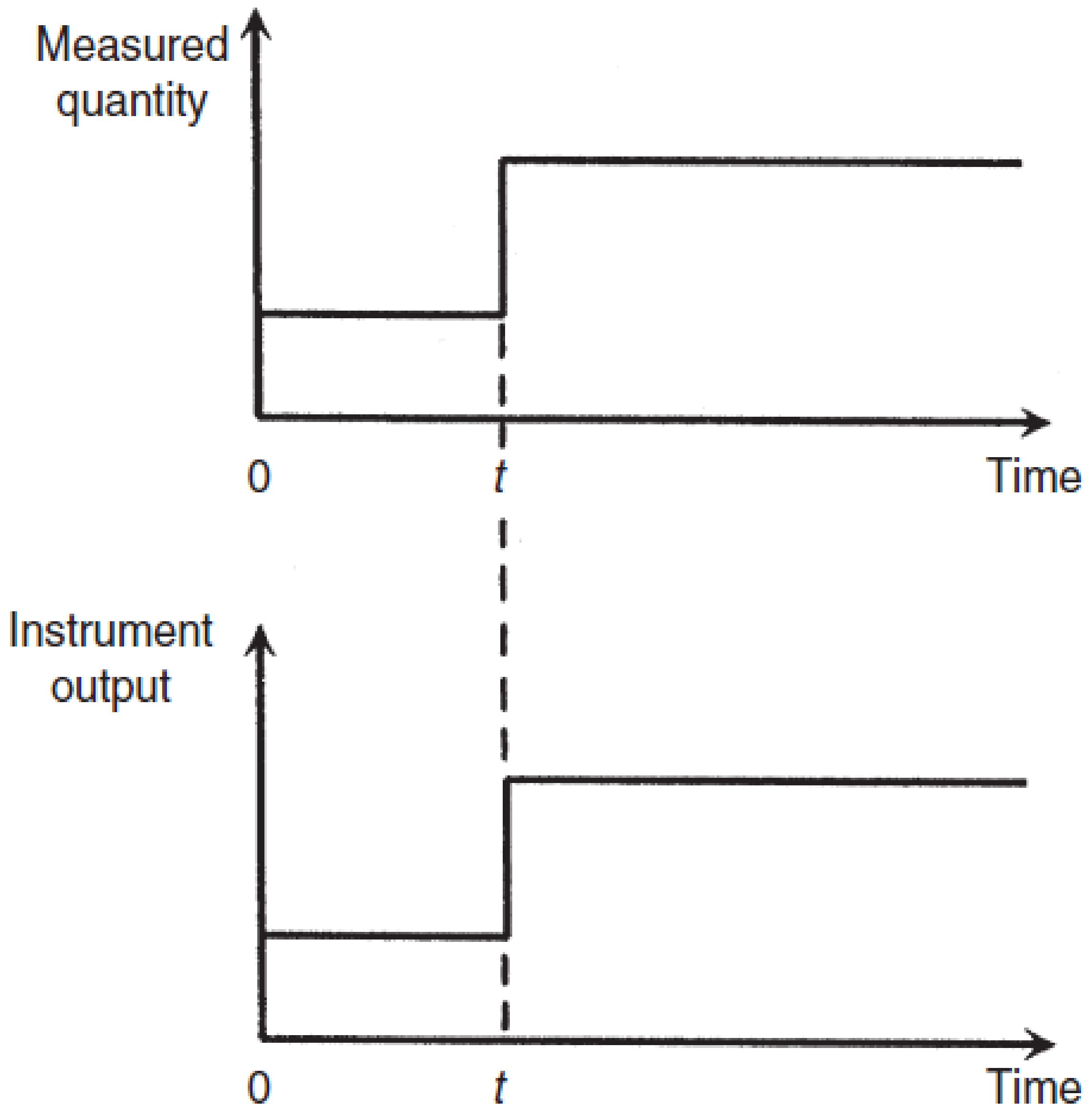
- Dynamic characteristics
  - Describe its behavior between the time a meas ıtput reaches steady value
- For step changes (linear, time-invariant me

$$a_n \frac{d^n q_0}{dt^n} + a_{n-1} \frac{d^{n-1} q_0}{dt^{n-1}} \dots + a$$

where q_0 is the out reading, q_i is the measured q

- Zero-Order Instrument
  - Set coefficients in (1), $a_1 \dots \dots a_n$ to zero, then:

$$q_0 = \frac{b_0 q_i}{a_0} = \mathrm{k} q_i$$



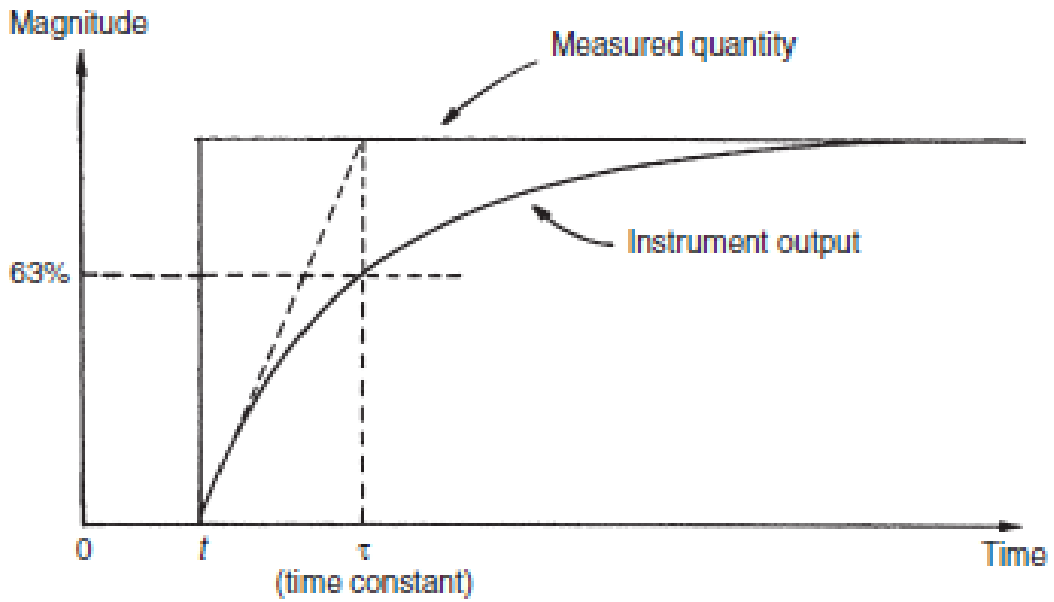
Dynamic Characteristics…cont

- First order system

$$a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i \qquad (1.1)$$

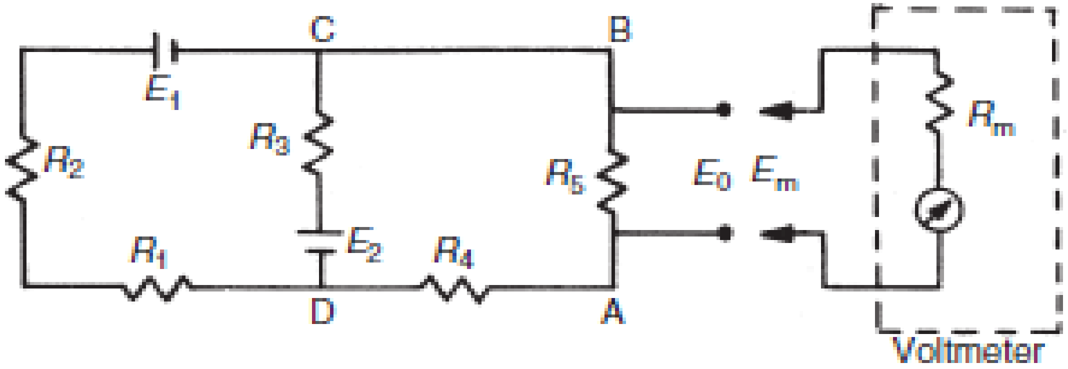
Any instrument that behaves according to (1.1) is first order system

$$q_0 = \frac{(b_0/a_0)q_i}{1+(a_1/a_0)s} = \frac{kq_i}{1+\tau s} \qquad (1.2)$$



Measurement Uncertainty: Sources of systematic error

- System disturbance due to measurement
  - Common source of systematic error
  - Taking a thermometer initial at room temperature to measure water temperature (introduces relatively cold mass)
  - Process of measurement disturbs the system and alters the values of the physical quantity being measured
  - Orifice plate placed into a fluid-carrying pipe to measure the flow rate
  - During instrument design important to reduce disturbance of measurement system

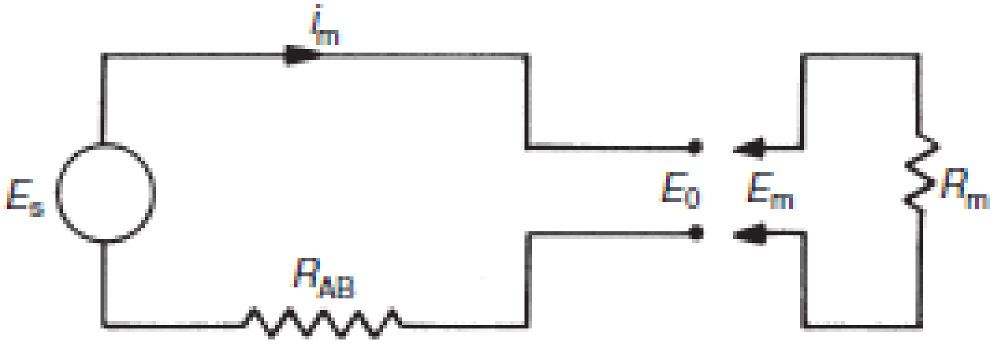


  - Voltage across R5 is to be measured by voltmeter with resistance Rm (acts as a shunt resistance across R5)
  - Will cause a decrease in resistance between point AB (disturbing the circuit)
  - Thus voltage Em is not the same value as Eo that existed prior the measurement

How would you determine the extent of the disturbance?

Measurement Uncertainty: Sources of systematic error…cont

- The use of Thevinin theorem



$$E_m = \frac{R_m E_o}{R_{AB} + R_m}$$

By making $\boldsymbol{R_m \gg R_{AB}, E_m \approx E_o}$

Measurement Uncertainty: Sources of systematic error…cont

- Errors due to environmental inputs
  - Static and dynamic characteristics only valid for particular environmental conditions
  - During calibration exercises same environmental conditions must be reproduced
  - Environmental induced variation can be quantified by two constants:

Sensitivity drift and zero drift [usually specified in data sheets]

  - E.g. given a small closed box and informed that it may contain a mouse or a rat
    - The box weighs 0.1 kg when empty
    - Placing the box on the bathroom scale we observe a reading of 1.0 kg
    - **What is in the box?**

(a) A 0.9 kg rat in the box (real input)
(b) An empty box with a 0.9 kg bias on the scale due to temperature change
(c) A 0.4 kg mouse in the box together with a 0.5 kg bias (real + environmental inputs)

- Measurement designers should quantify the of the environmental inputs and minimize their effects

Measurement Uncertainty: Sources of systematic error…cont

- Wear of instruments
  - Systematic errors can develop over a period of time due to wear/aging of instrument
  - Recalibration often provides a full solution

- Connecting leads
  - Not taking into account the resistance of connecting leads
  - E.g. A typical of resistance thermometer (can be separated from other parts by 100 meters)
  - A 20-gauge copper wire is 7 Ohms, has temperature coefficient of 1 $m\Omega/°C$
  - Should be of adequate cross sectional area to minimize their resistance
  - Routing of cables also needs careful planning (measure parameters can be affected by environmental signals)

Measurement Uncertainty: Sources of systematic error…cont

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Project

Primary sensor: **Bandwidth or frequency response**

Project

Hazardous area zones and equipment categories

Hazardous places are classified in terms of zones on the basis of the frequency and duration of the occurrence of an explosive atmosphere.

Gases, vapours and mists

For gases, vapours and mists the zone classifications are:

Zone 0	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is present continuously or for long periods or frequently.
Zone 1	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is likely to occur in normal operation occasionally.
Zone 2	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

Dusts

For dusts the zone classifications are:

Zone 20	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is present continuously, or for long periods or frequently.
Zone 21	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is likely to occur in normal operation occasionally.
Zone 22	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

Notes:

1. Layers, deposits and heaps of combustible dust must be considered as any other source which can form an explosive atmosphere.

2. "Normal operation" means the situation when installations are used within their design parameters.

Measurement Uncertainty: Reduction of systematic errors

Measurement Uncertainty: Reduction of systematic error…cont

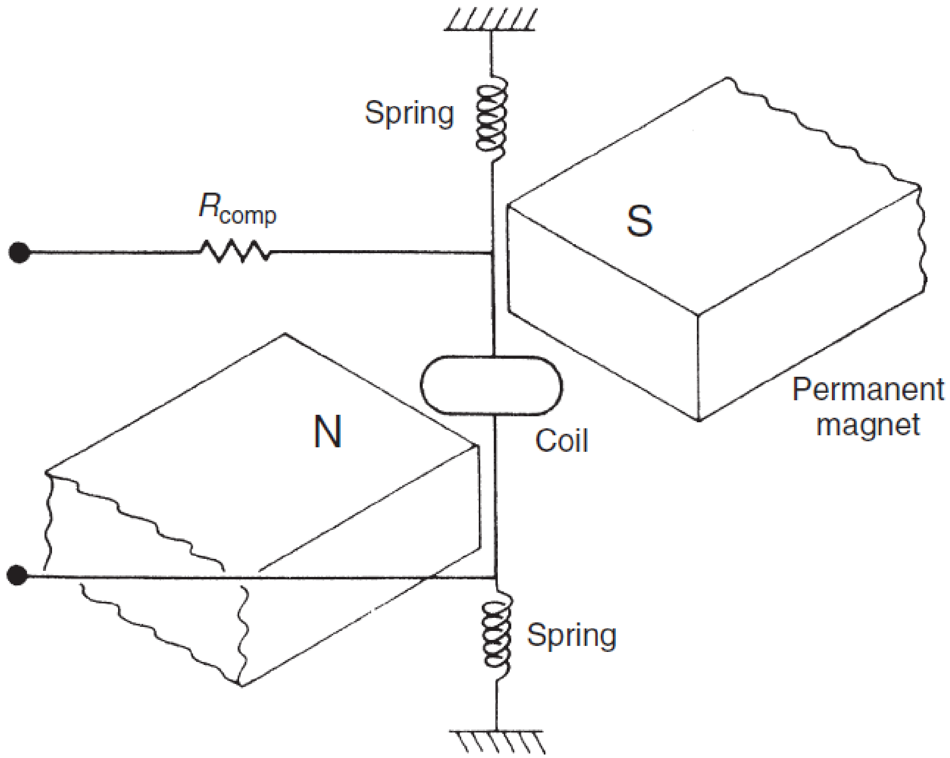
- Complete analysis of the measurement system
  - Simple faults: bent needle and poor cabling practices
  - Other error sources require more detailed analysis and treatment

- Careful instrument design
  - Reduce impact of environmental inputs
  - E.g. in a strain gauge, use material whose resistance has a low temperature coefficient
  - Cost implications, low cost design and high cost design: Trade off over performace

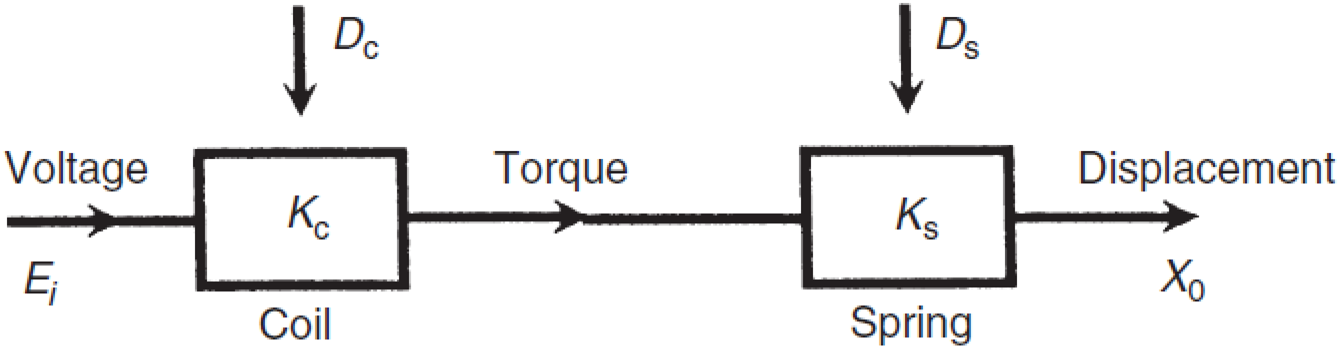
- Calibration
  - Instruments suffer drift
  - Calibration error grows as instruments drift increases over use

Measurement Uncertainty: Reduction of systematic error…cont

- Using opposing inputs
  - Rcoil increases due to temperature increase
  - Rcom decreases due to temperature increase (opposite temperature coefficient to that of Rcoil)



- High gain feedback
  - Makes the overall system insensitive to the environmental effects



  - Dc and Ds are the environmental effects on the measurement system

$$X_o = K_c K_s E_i \text{ (ignoring } D_c \text{ and } D_s\text{)}$$

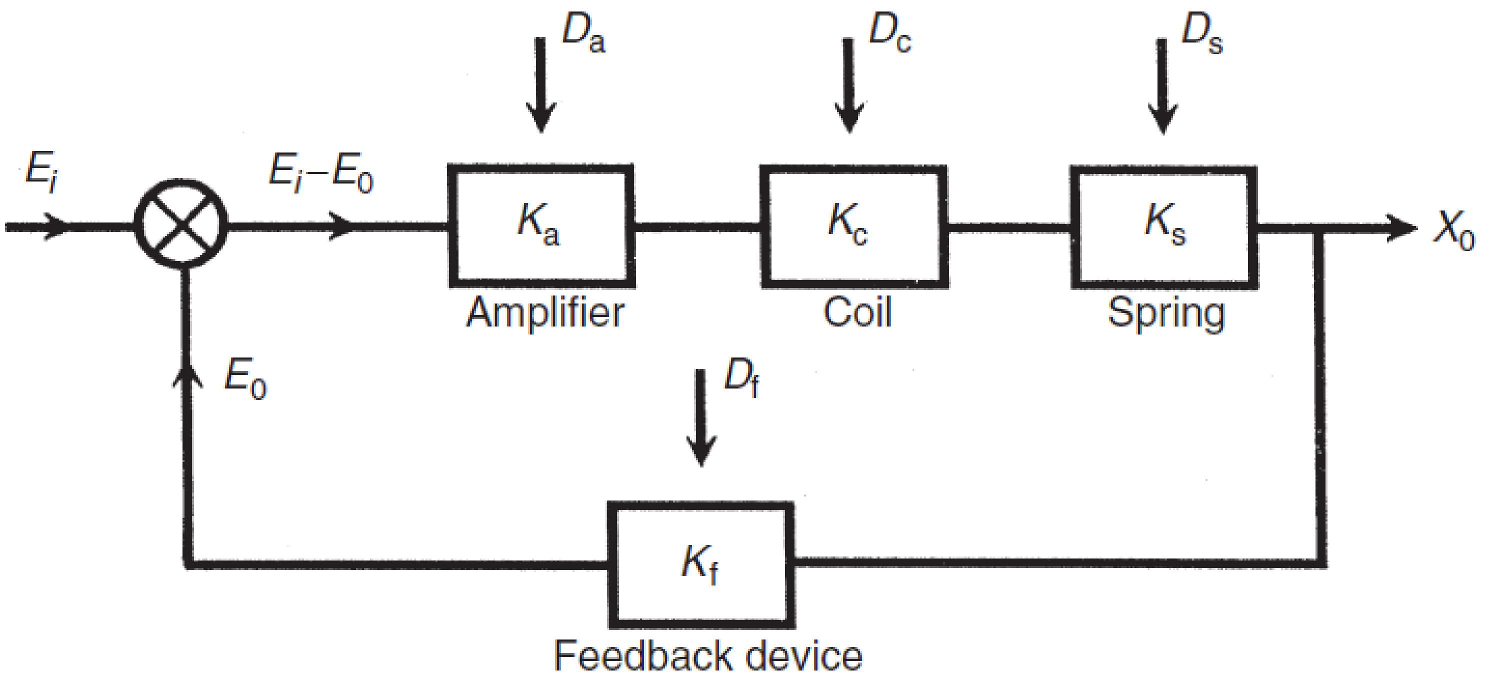
In the presence of environmental effects K_c and K_s are affected greatly

(resulting in increased error and deformed X_o)

Measurement Uncertainty: Reduction of systematic error…cont

- Adding an amplifier with high gain ()
  - With gain K_a and feedback device K_f
  - Sensitivity of K_a, K_c and K_s to the environment can be reduced
  - Only concerned with one environmental input (D_f)

- Easier to design feedback device that is insensitive to environmental inputs
  - Better than trying to make a motor and spring insensitive



Measurement Uncertainty: Reduction of systematic error…cont

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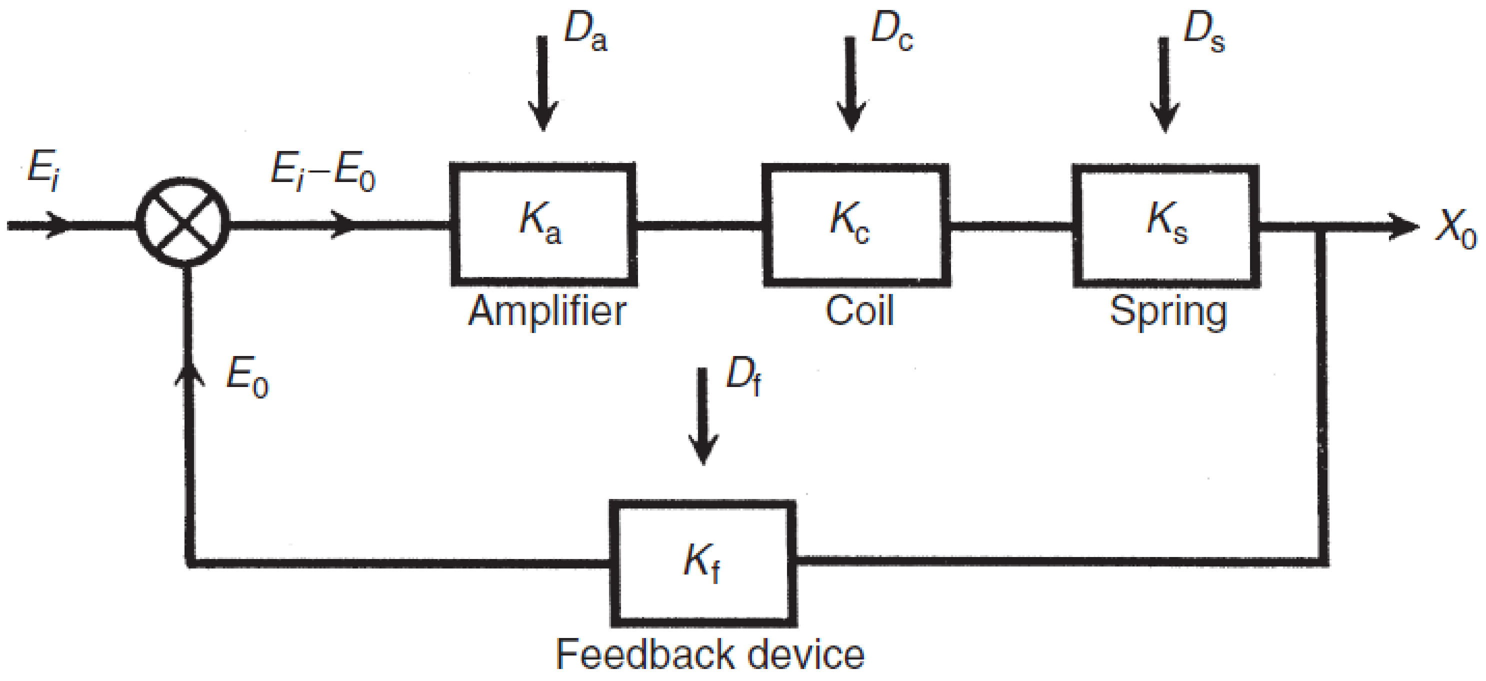
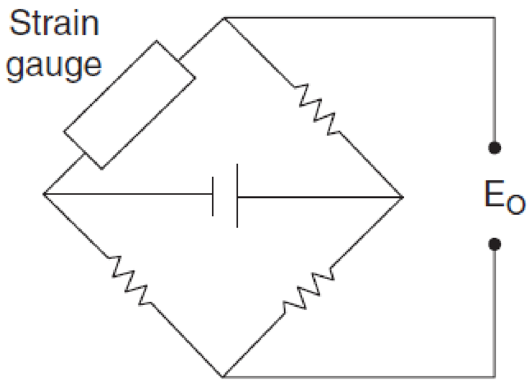
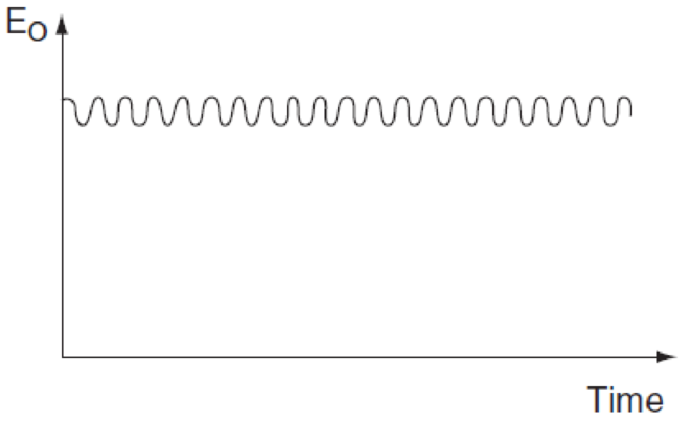


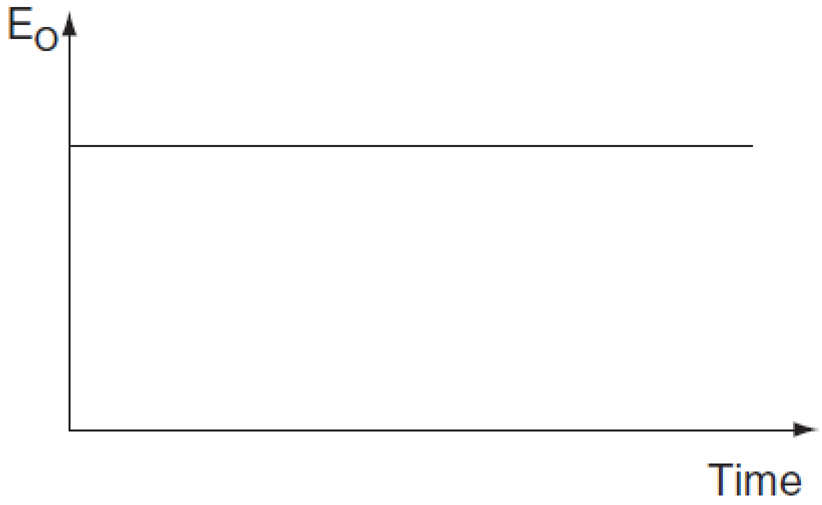
- What is the one potential problem?? **Instability**

Measurement Uncertainty: Reduction of systematic error…cont

- Signal filtering
  - Corruption of the output reading
  - Periodic noise







Quantification of Individual Errors

- Calibration Errors
  - Drift causing a bias

- Overall systematic error

Three separate sources of systematic error are identified in a measurement system and, after reducing the magnitude of these errors as much as possible, the magnitudes of the three errors are estimated to be

System loading: $\pm 1.2\%$
Environmental changes: 0.8%
Calibration error: 0.5%

Calculate the maximum possible total systematic error and the likely system error by the root-mean-square method.

Quantification of Individual Errors

- Solution:

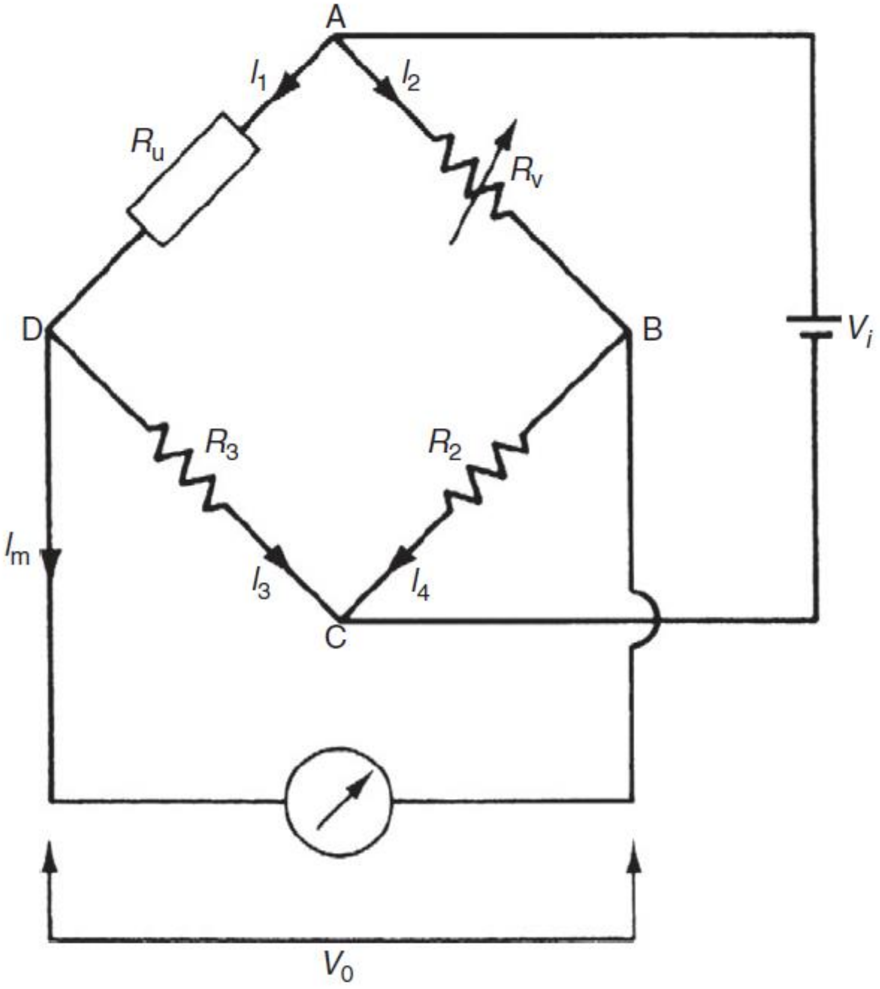
The maximum possible system error is $\pm(1.2 + 0.8 + 0.5)\% = \pm 2.5\%$

Applying the root-mean-square method,

$$\text{likely error} = \pm\sqrt{1.2^2 + 0.8^2 + 0.5^2} = \pm 1.53\%.$$

Quantification of Individual Errors

Rv is a decade resistance box with specified inaccuracy +/-2% and $R_2 = R_3 = 500$ Ohms +/0.1%. If the value of R_v at the null position is 520.4Ohm, determine the error band for R_u expressed as a percentage of its nominal value.



Calibration