Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

2024-25 Semester 2

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Outline

- Definition of Systems
- Instrumentation System: Definitions and Basic Concepts
- Overview of Control Systems
- **Static Characteristics of Sensor Performance**
- Dynamic Characteristics of Sensor Performance

Sensors vs Transducers

- The term sensor is used for an element which produces a signal related to the quantity being measured, i.e., electrical resistance temperature element.
- The term transducer is often used in place of the term sensor. Transducers are defined as elements that when subject to some physical change experience a related change.

Thus sensors are transducers.

Sensors vs Transducers

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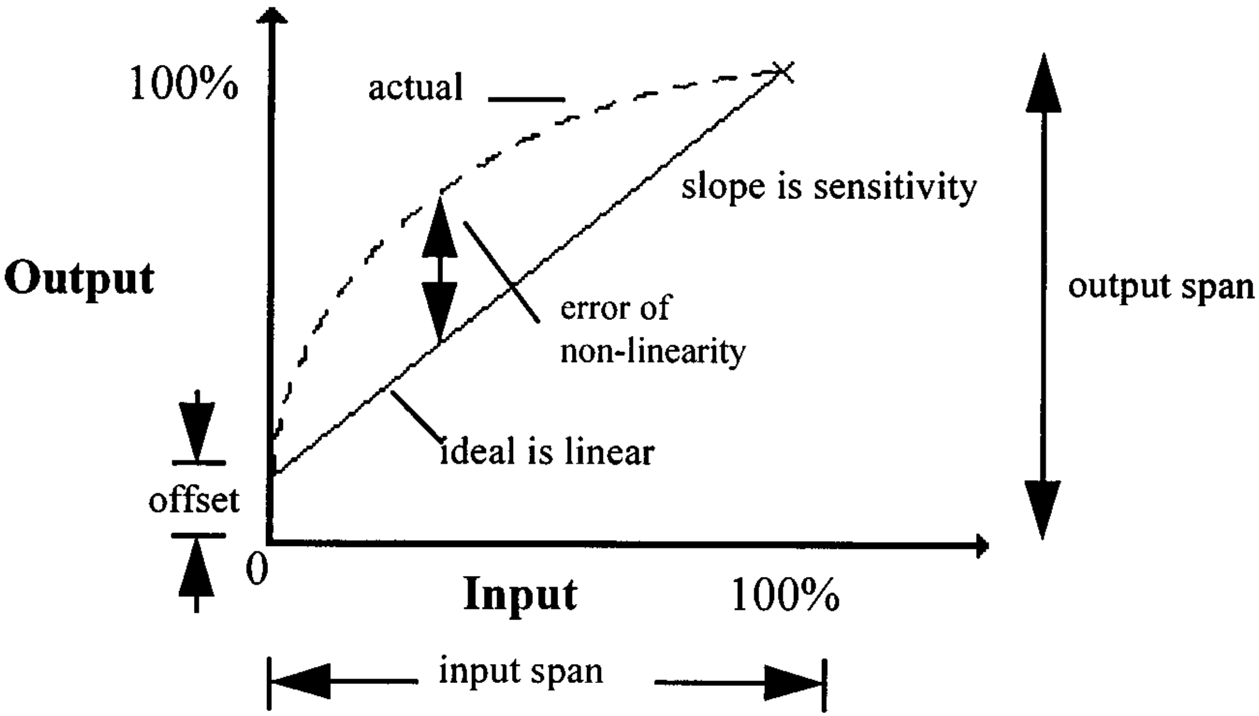
Thus sensors are transducers.

A measurement system may use transducers, in addition to the sensors, in other parts of the system, to covert signals in one form to another form.

Static Characteristics of Sensor Performance



- Range / span
- Error
- Accuracy
- Precision
- Sensitivity
- Resolution
- Hysteresis error
- Non-linearity error
- Repeatability/ reproducibility
- Dead band / time
- Etc.

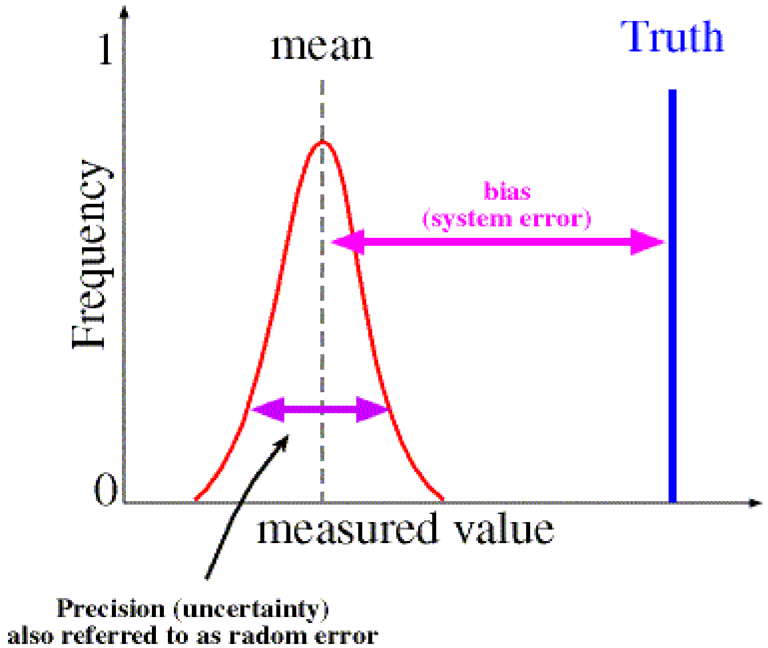
Factors Affecting Accuracy

- Transducer placement: the transducer must be located at an appropriate position and with an appropriate orientation to measure the measurand accurately;
- The introduction of a transducer may affect the measurand;
- The interconnection of the system may cause electrical loading effects;
- Other physical parameters may interact with the system and affect the measurement;
- The transducers themselves introduce a source of error.

Measurement Error: Systematic Error

- **Systematic Error (bias)** sources:
  - usually those that change the input–output response of a sensor resulting in mis-calibration
  - aging, damage or abuse of the sensor
  - measurement process itself changes the intended measurand
  - the transmission path
  - human observers

✓ Systematic error can be corrected by some methods if the error source is known.

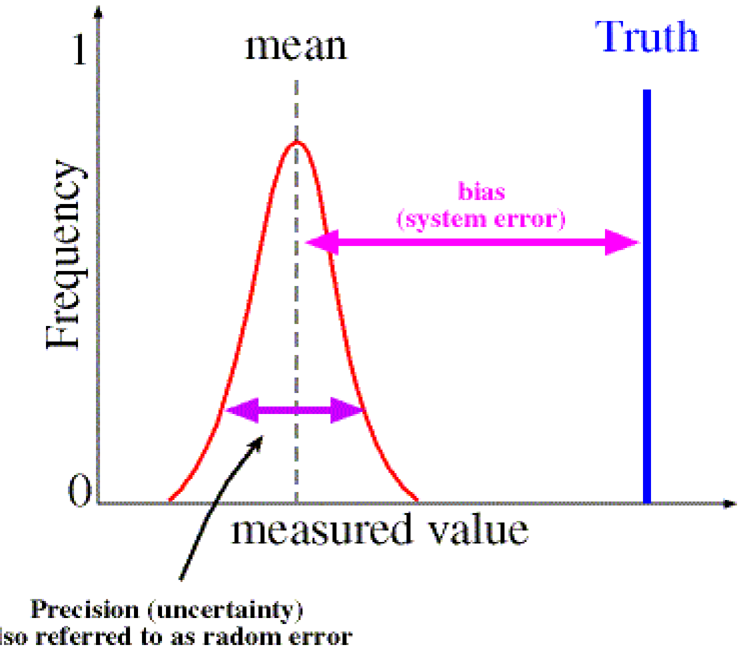


Measurement Error: Random Error

- **Random Error (noise)** sources:
  - usually unknown and unpredictable changes in the measurement
  - may occur in the measuring instruments or in the environmental conditions

Random error is often referred to as noise, and exhibit a ***Gaussian distribution*** when repeating a large number of measurements.

◆ Random error can NOT be completely eliminated.



Measurement Uncertainty

Accuracy:

- defined as the difference between the true value of the measurand and the measured value indicated by the instrument;
- determined by systematic error;
- usually expressed as a percentage of the full-scale deflection (FSD) of the transducer or system.

For example:

A system might have an accuracy of $\pm 1\%$ of FSD. If the FSD=10A, then the accuracy is

$$10 \times \pm 1\% = \pm 0.1\text{A}$$

Measurement Uncertainty

Accuracy:

- defined as the difference between the true value of the measurand and the measured value indicated by the instrument;
- determined by systematic error;
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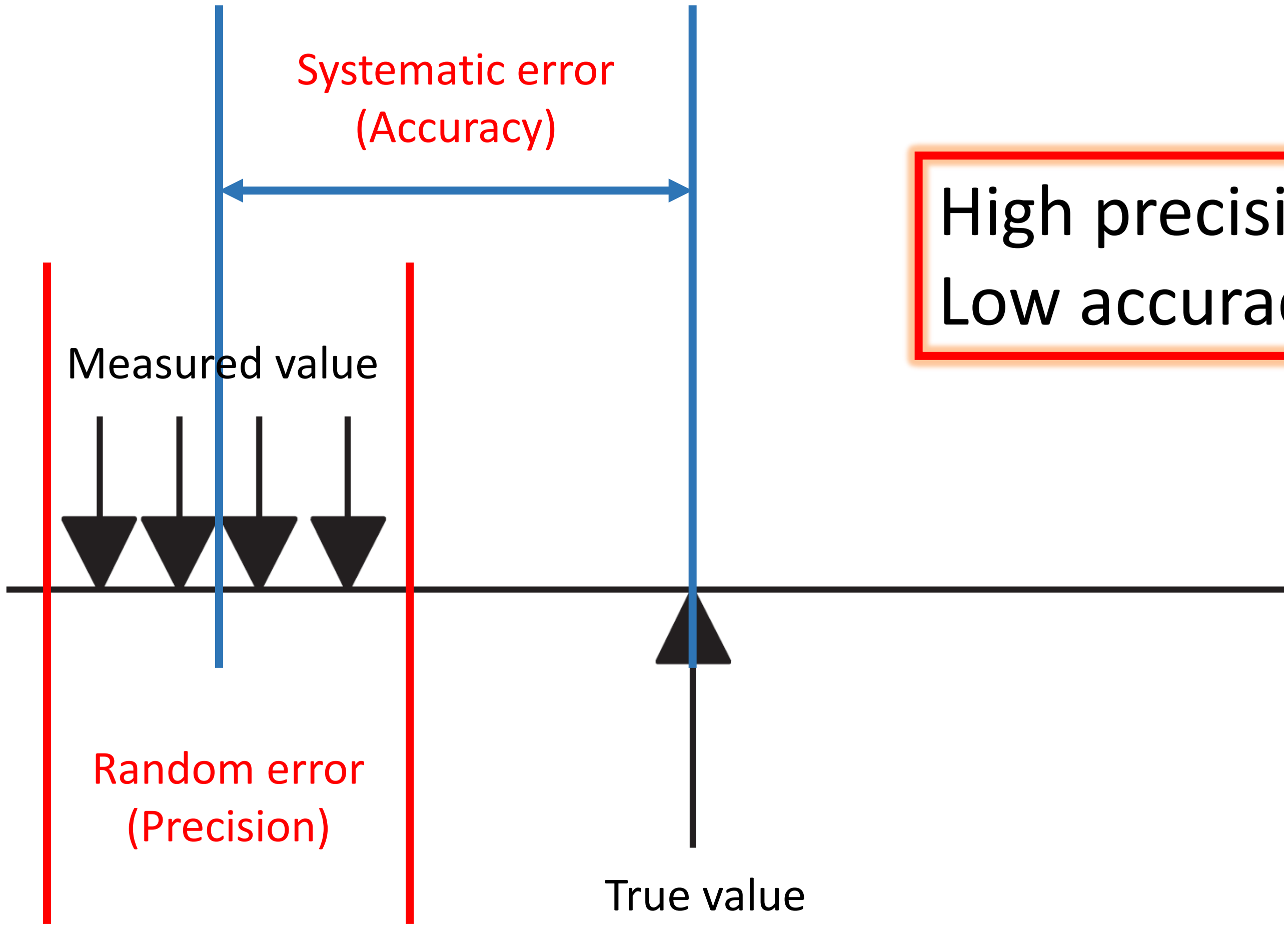
Precision:

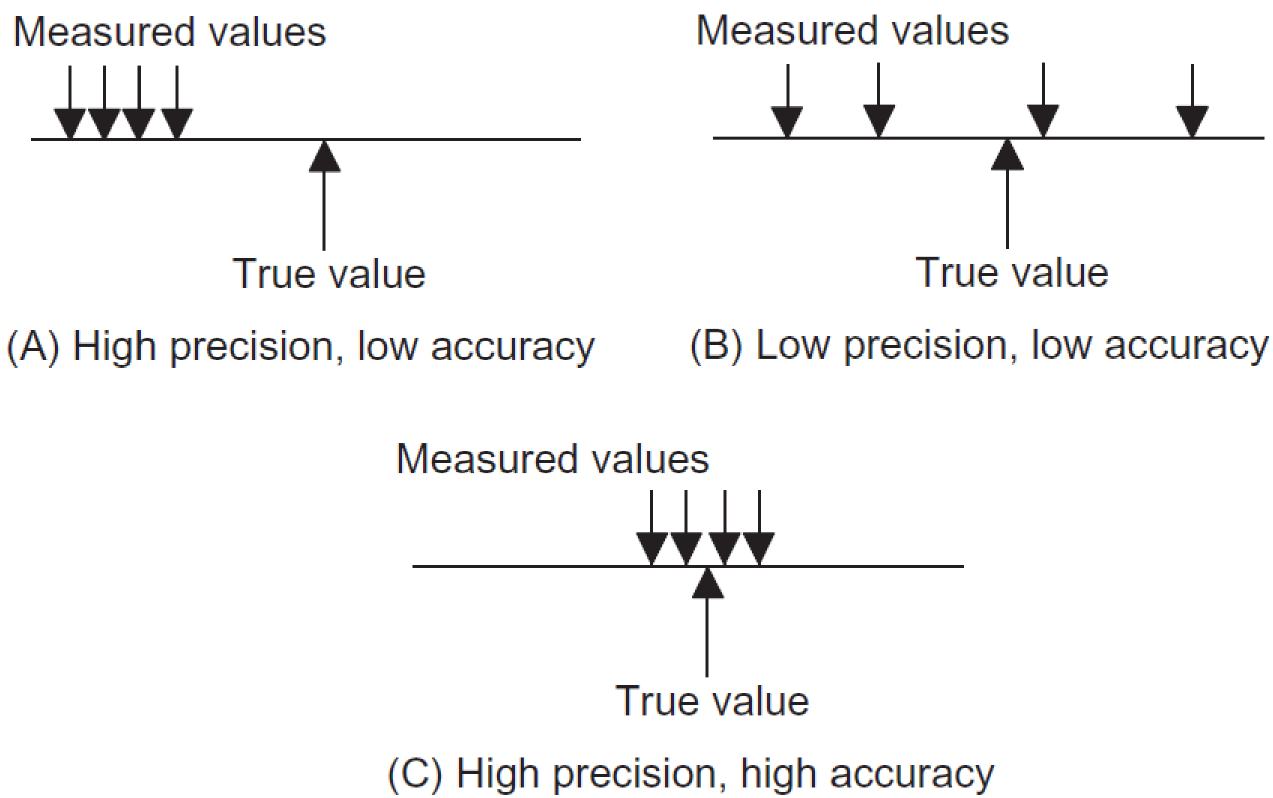
- a term that describes an instrument's degree of freedom from random errors;
- normally quantified by the standard deviation δ that indicates the width of the Gaussian distribution;
- The smaller the standard deviation, the more precise the measurement.

Target Analogy of Measurement – 1D

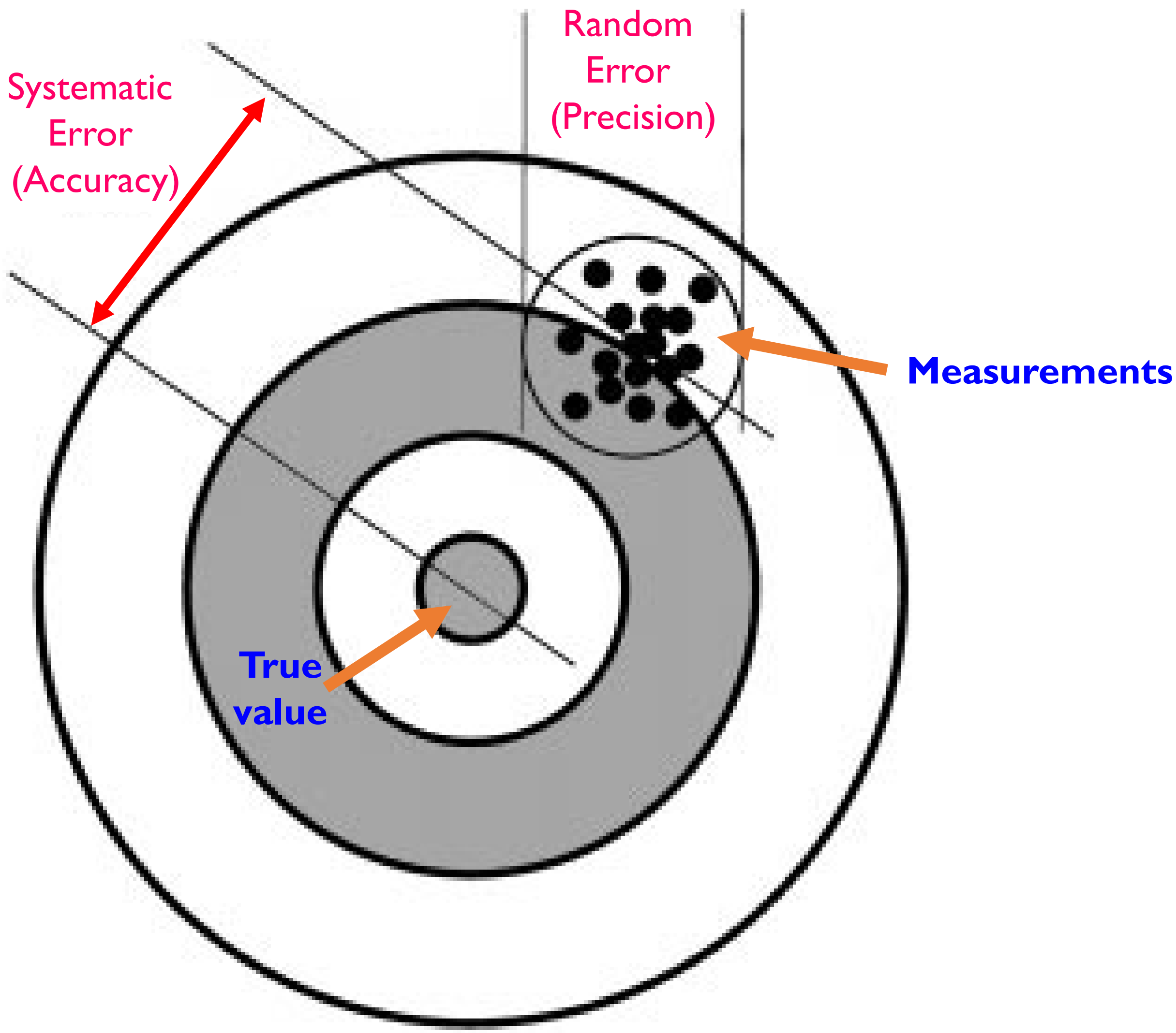


High precision
Low accuracy

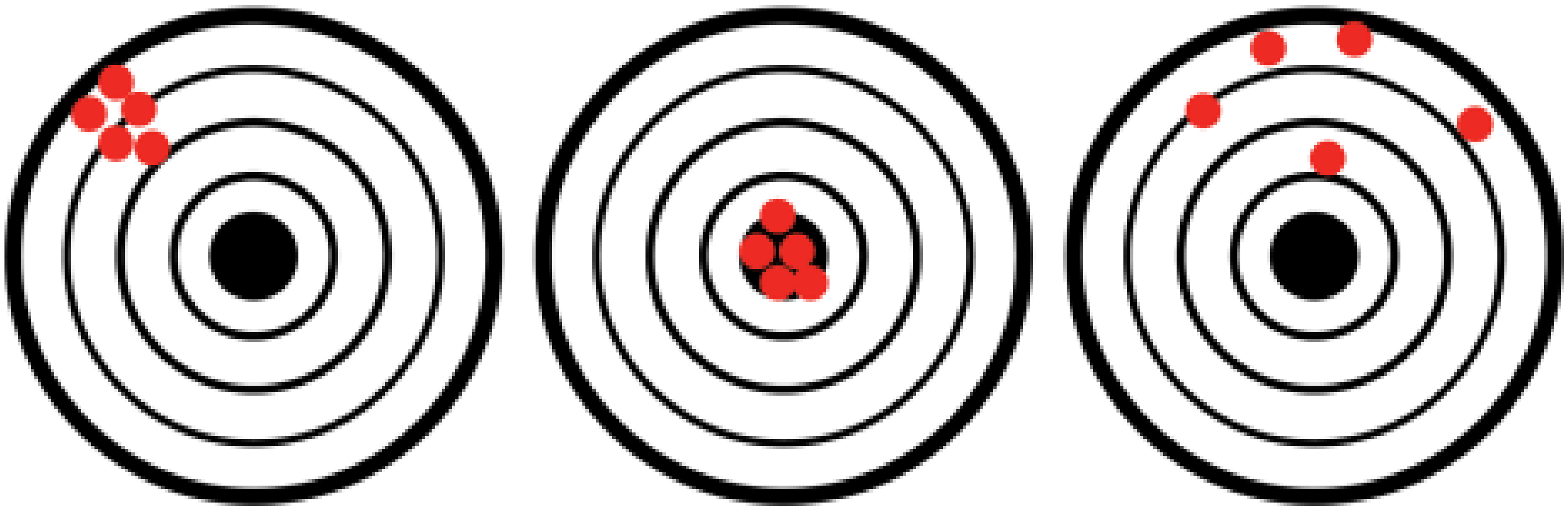
Accuracy vs. Precision – 1D



Target Analogy of Measurement – 2D



Accuracy vs. Precision – 2D



Poor accuracy but good precision

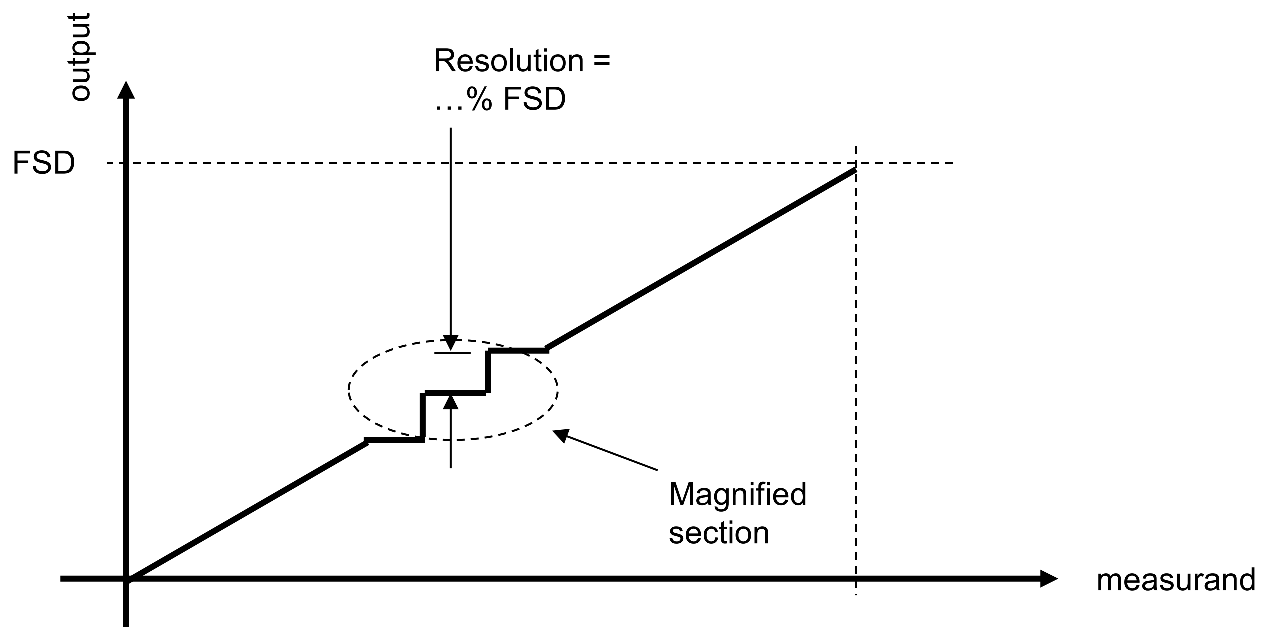
Good accuracy and good precision

Poor accuracy and poor precision

Resolution

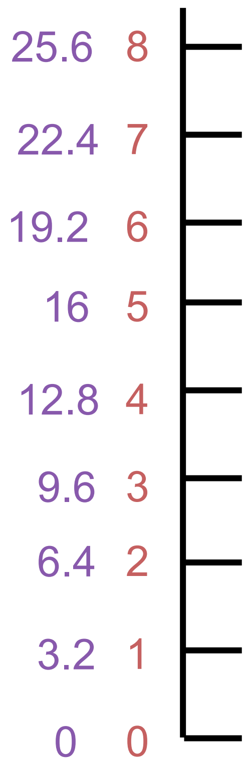
Resolution:

- is the smallest change in the measurand that can be measured;
- the resulting maximum error is **half** the resolution of the measurement.



FSD: Full Scale Deflection

Resolution and Maximum Error



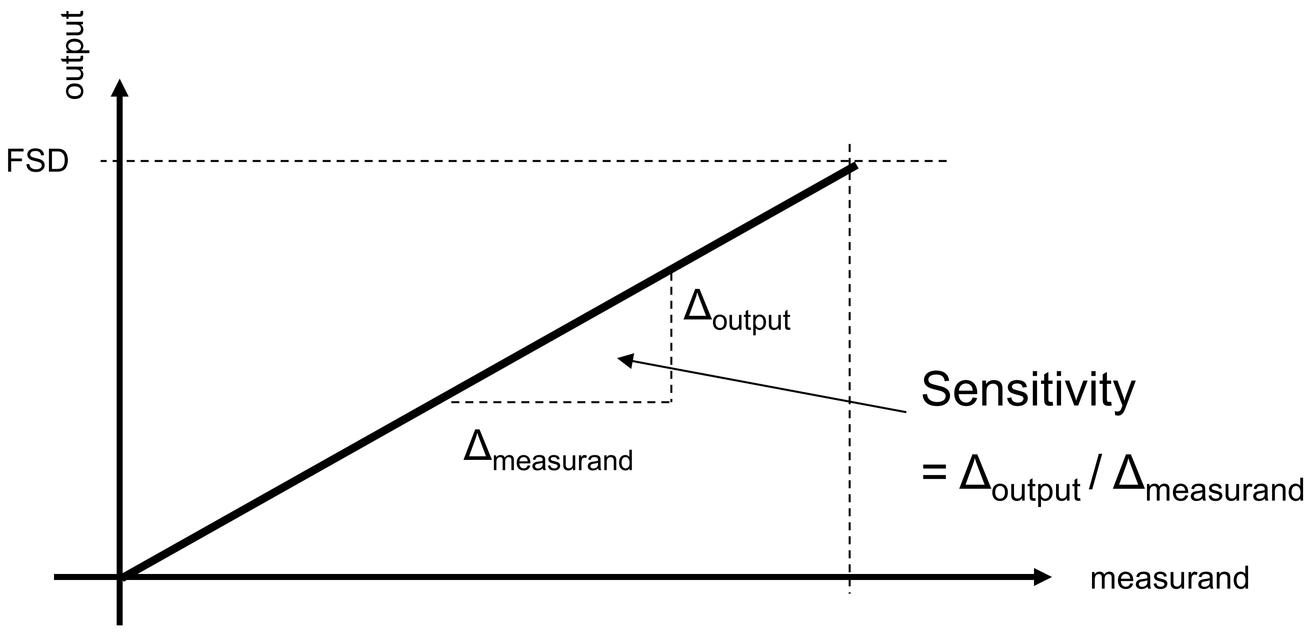
Unit (mm, ^{o}C, Volt etc.)

Resolution	True Value	Measurement	Error	
1	1.2	1	0.2	≤ 0.5
	3.6	4	0.4	
	7.5	7 or 8	0.5	
	…	…	…	
3.2	2.8	3.2	0.4	≤ 1.6
	17.5	16	1.5	
	24.8	25.6	0.8	
	…	…	…	

Sensitivity

Sensitivity:

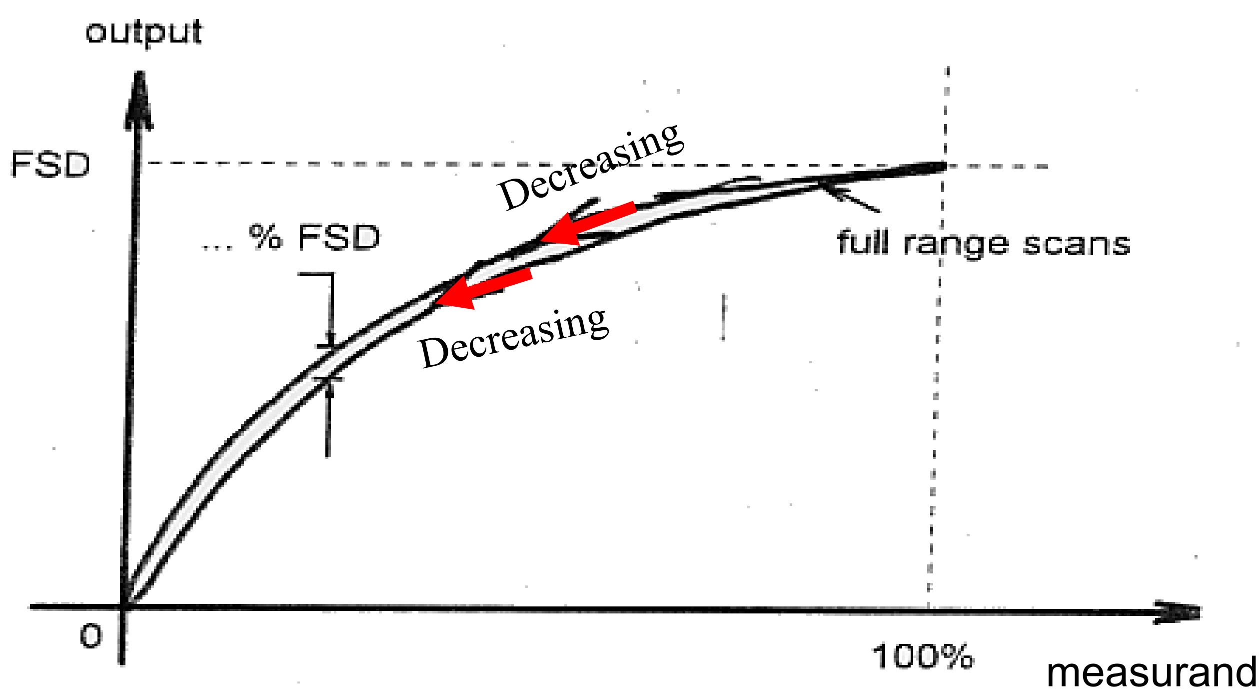
- is the slope of the output vs input (measurand) in the graph;
- note the difference between sensitivity and resolution.



Repeatability

Repeatability:

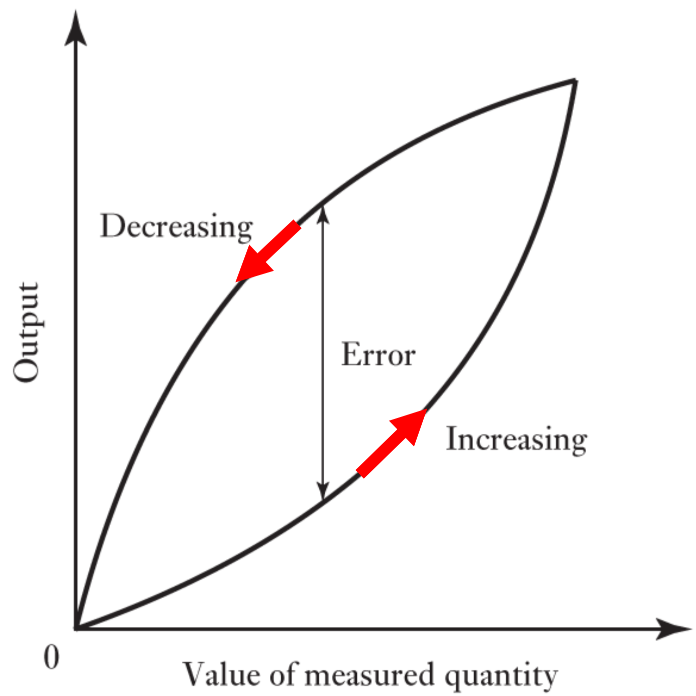
- relates to the maximum difference between any two output values at the same value of measurand taken during full range traverses of the measurand and approached from the same direction.



Hysteresis Error

Hysteresis error:

- the difference in transducer output obtained when any measurement point is approached from different directions during a full range scan of the transducer.



Example

Thermometer measuring the same temperature

- Reached by warming up to the measured temp;
- Reached by cooling down to the measure temp.

Non-linearity Error

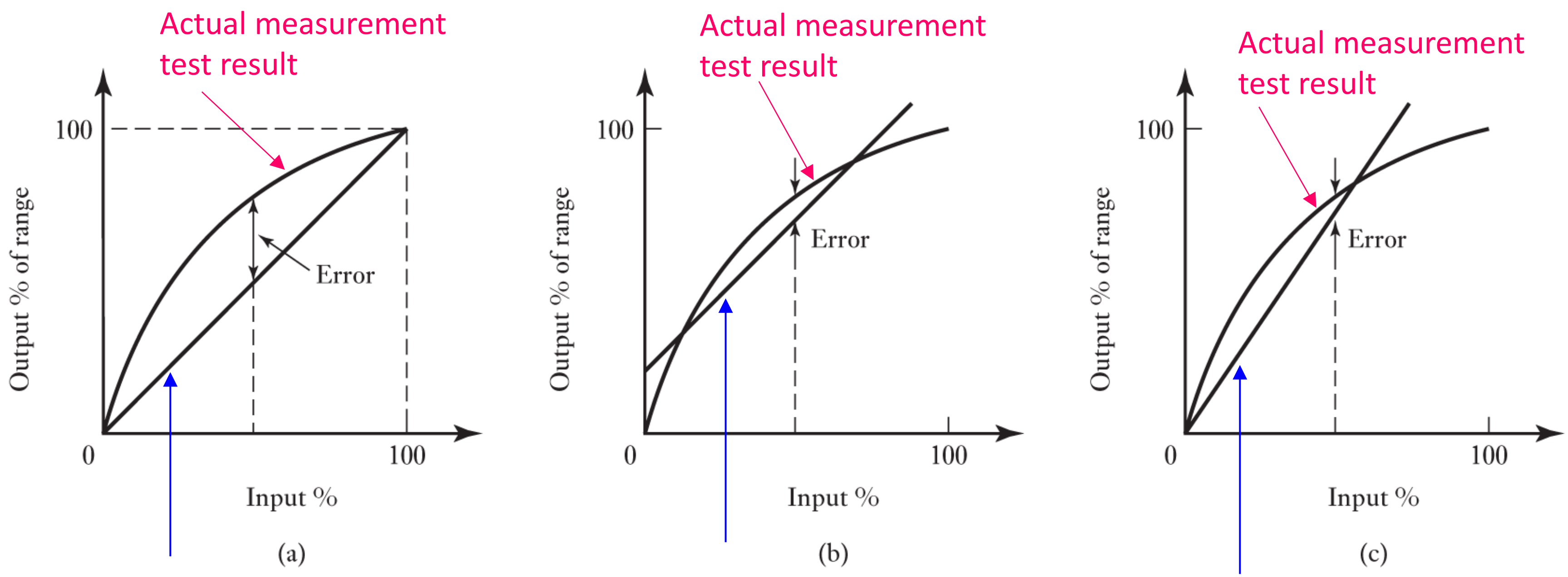
Non-linearity error:

- For many transducers a linear relationship between the input and output is assumed over the working range, i.e., a graph of output plotted against input is assumed to give a straight line. Errors occur as a result of the assumption of linearity.
- Non-linearity is not necessarily a source of error at all. It only becomes one if the transducer is assumed to have a linear output (most are).

The error is defined as the **maximum difference** of the actual input-output curve from a straight line. Various methods are used for numerical expression of the nonlinearity error, depending on how to define the reference straight line.

Non-linearity Error

There are many ways to define non-linearity error, all depend on how to define the straight line.



(a) Straight line defined as the linear line connects the end points (**End-point nonlinearity**);

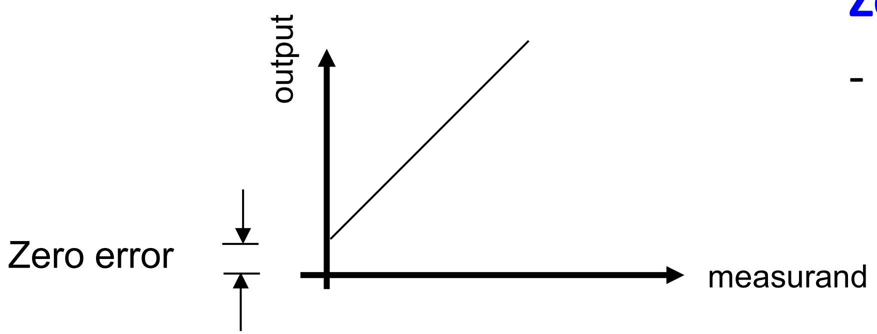
(b) Straight line defined as the best fit linear line based on all measurement data;

(c) Straight line defined as the best fit linear line based on all measurement data and also passes through the zero point.

In addition, analytical linear line: the straight line is the response that the transducer should have as given by theory.

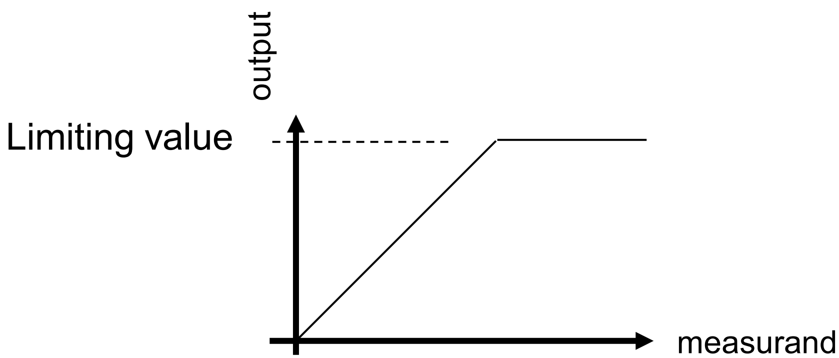
Inherent Error

Error resulted from the characteristic of the sensor



Zero error:

- self explanatory – may be specified as …% FSD or as a specified output value.



Limiting value:

- occurs due to the transducer being taken outside its calibrated operating range;
- often results in abrupt levelling off or saturation of the output.

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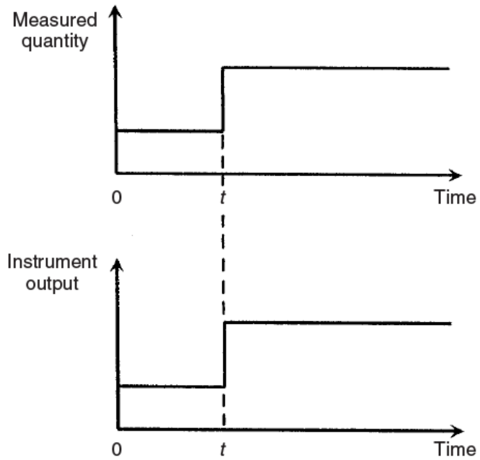
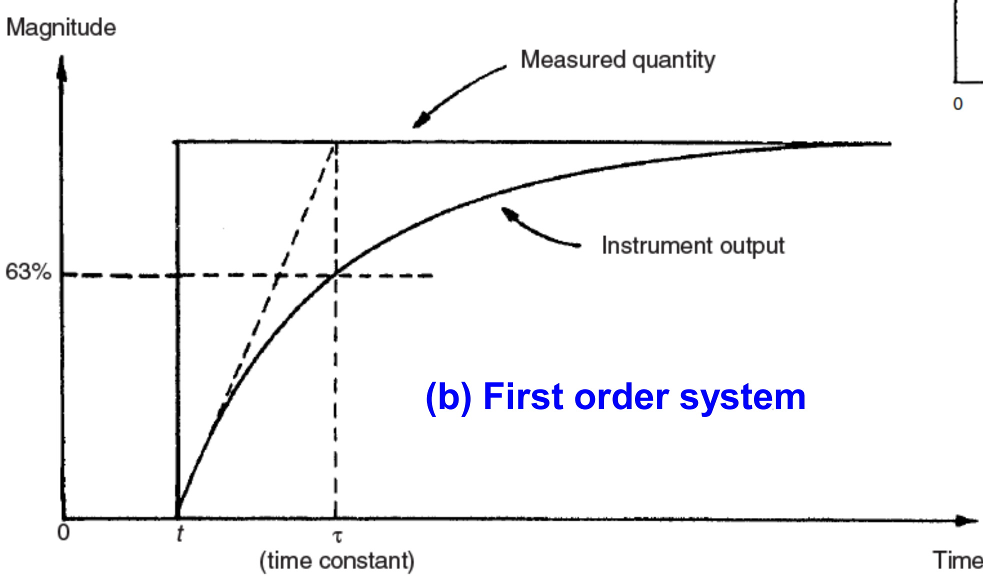
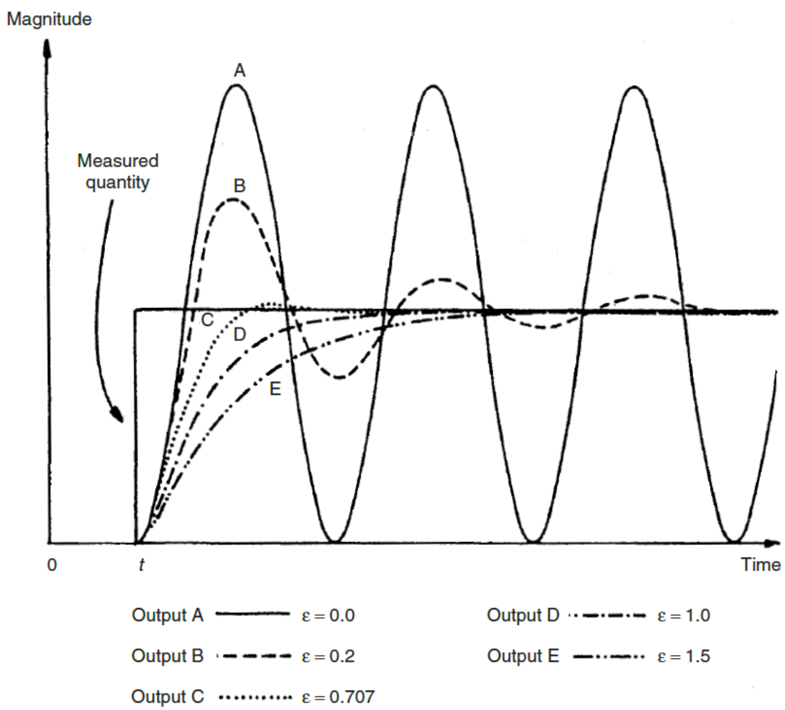
Dynamic Characteristics of Sensor Performance



(a) Zero order system

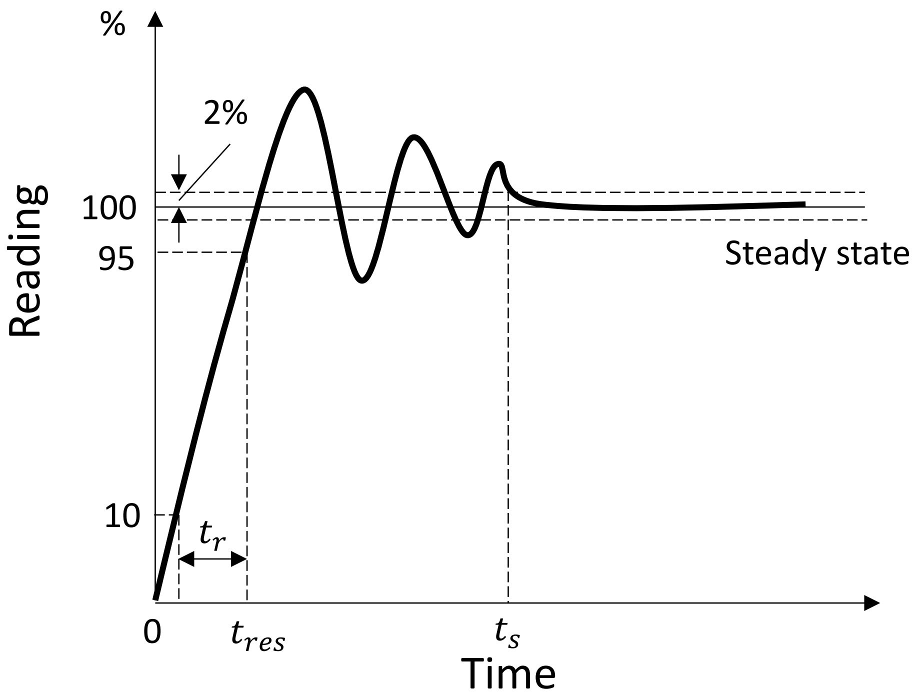


(b) First order system



(c) Second order system

Dynamic Characteristics of Sensor Performance



Settling time t_s:

- is the time taken for the output to settle to within some percentage, e.g., 2% of the steady-state value.

Response time t_{res}:

- is the time which elapses after the input to a system element is abruptly increased from zero to a constant value up to the point at which the system or element gives an output corresponding to some specified percentage, e.g. 95% of the value of the input.

Rise time t_r:

- is the time take for the output to rise to some specified percentage of the steady-state output, usually the duration of output to rise from 10% to 90% or 95% of the steady state.

Quiz 1.1

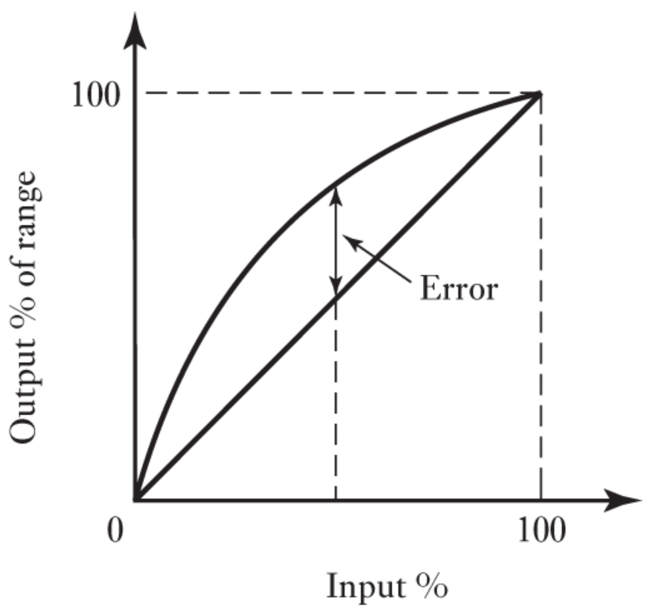
A pressure sensor has a range of 0 to 1,000 kPa and a non-linearity error of $\pm 0.15\%$ FSD and a hysteresis error of $\pm 0.05\%$ FSD. The error for a reading of 300kPa is

A. ± 0.3 kPa

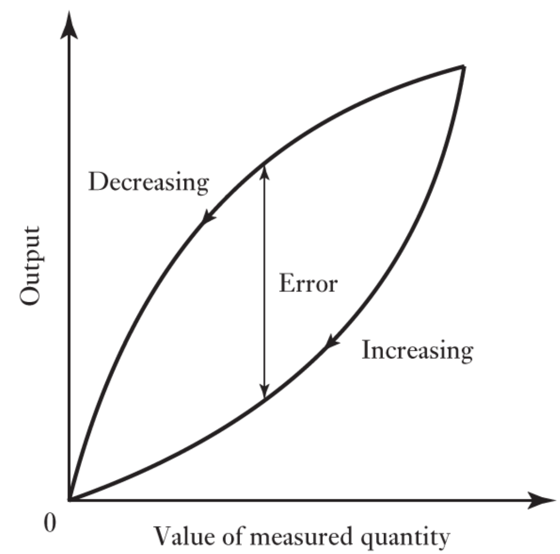
B. ± 0.6 kPa

C. ± 1.0 kPa

D. ± 2.0 kPa



non-linearity error



hysteresis error

Lecture 2

Outline

Sensors & Transducers

- **Temperature Sensors**
  - Bimetallic strips
  - Resistance temperature detectors (RTDs)
  - Thermistors
  - Thermocouples
- **Fluid Pressure Sensors**
  - Diaphragm sensor
  - Piezoelectric sensor

Temperature Transducers

Changes that are commonly used to monitor temperature are the expansion or contraction of solids, liquids or gases, the change in electrical resistance of conductors and semiconductors, and thermoelectric e.m.f. (electromotivative force).

Temperature Transducers

Changes that are commonly used to monitor temperature are the expansion or contraction of solids, liquids or gases, the change in electrical resistance of conductors and semiconductors, and thermoelectric e.m.f. (electromotivative force).

The following are some of the commonly used temperature sensors:

- *Bimetallic strips*
- *Resistance temperature detectors (RTDs)*
- *Thermistors* （热敏电阻）
- *Thermocouples* （热电偶）

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Sensors & Transducers

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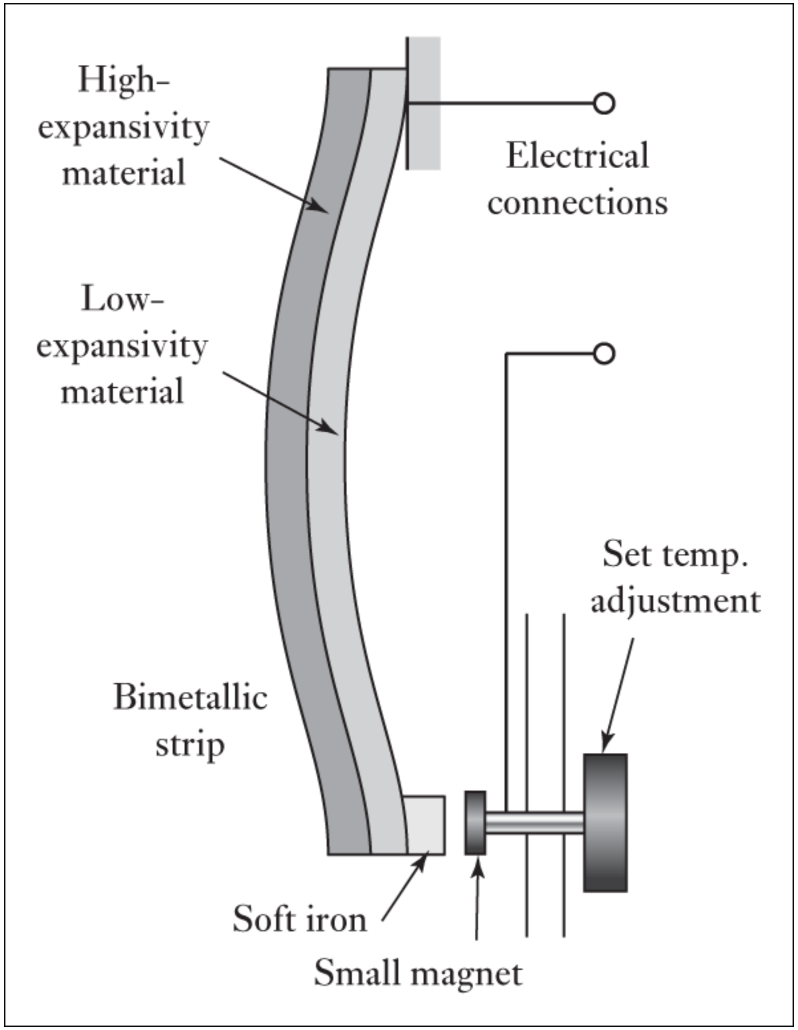
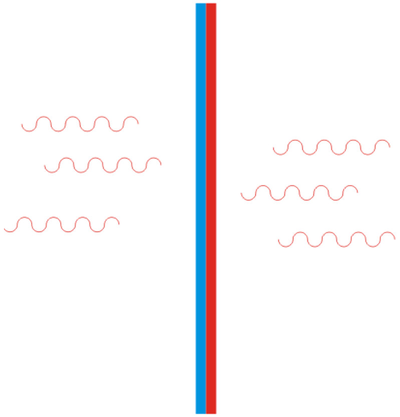
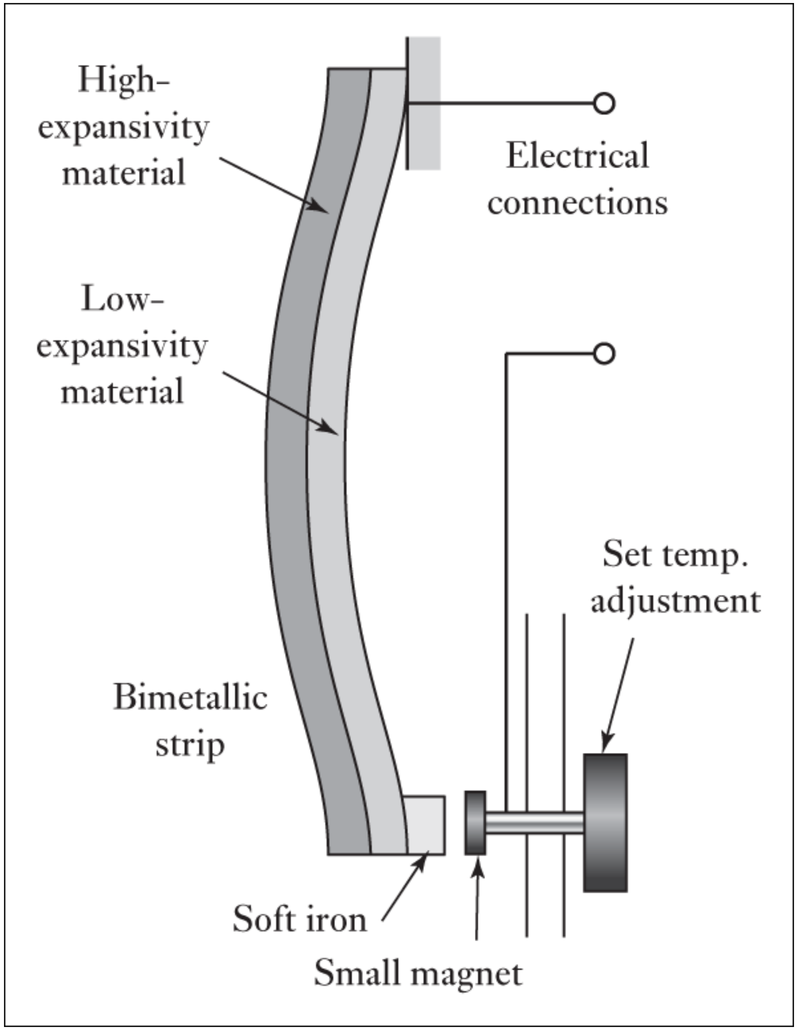
Bimetallic Strips



- The device consists of two different metal strips bounded together;
- The metals have different coefficients of expansion;
- When the temperature changes, the composite strip bends into a curved strip, with the higher coefficient metal on the outside of the curve;



Bimetallic Strips



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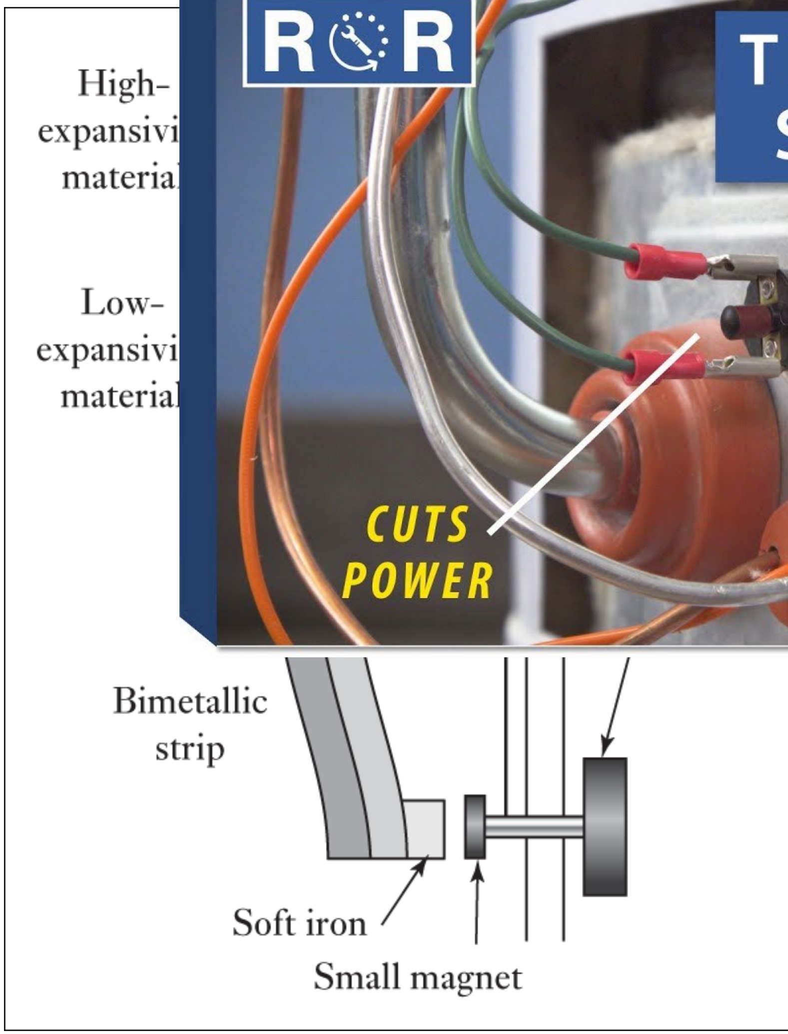
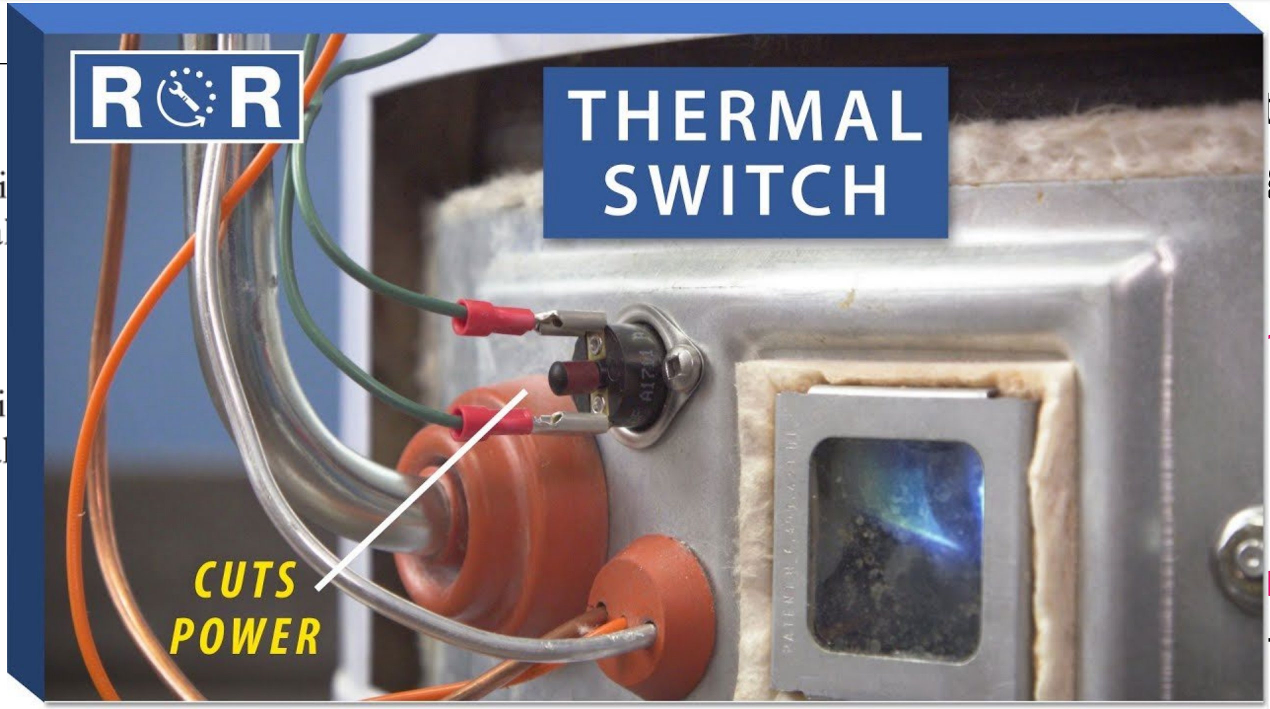
- This deformation may be used as a temperature-controlled switch.

Bimetallic Strips





two different
gether;

different
n;

changes, the
nto a curved
r coefficient
the curve;

- This deformation may be used as a <u>temperature-controlled switch</u>.
    - Example in water heater.

Outline

Sensors & Transducers

- **Temperature Sensors**
  - Bimetallic strips
  - *Resistance temperature detectors (RTDs)*
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  - Diaphragm sensor
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Resistance Temperature Detectors (RTDs)

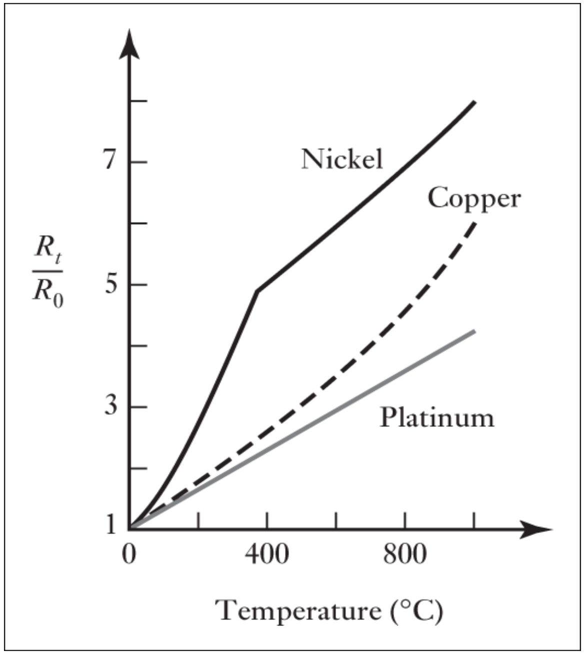


Fig. Variation of resistance with temperature for metals.

In practice, the linear equation is only approximately valid over a limited temperature range.

- The resistance of most metals increases, over a limited temperature range, in a reasonably linear way with temperature.
- RTDs are highly stable and give reproducible response over long periods of time; they tend to have response time of the order of 0.5 to 5s or more.
- For such a linear relationship,

$$R_T = R_0(1 + \alpha T)$$

where

- R_t is the resistance at a temperature $t(^oC)$,
- R_0 is the resistance at 0^oC,
- α is a constant for the metal termed the temperature coefficient of resistance.

RTDs (cont'd)

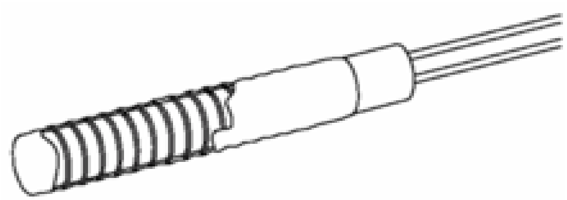
- Platinum detectors
  - high linearity, good repeatability, high long-term stability
  - accuracy of $\pm 0.5\%$ or better
  - measuring range about [-200 ºC , + 850 ºC]
  - can be used in a wide range of environments without deterioration
  - disadvantages: expensive than other materials
- Alternative alloys
  - cheaper
  - less stability
  - more prone to interaction with the environment
  - cannot be used over large temperature ranges

Specifications of commercially available platinum resistance thermometer:

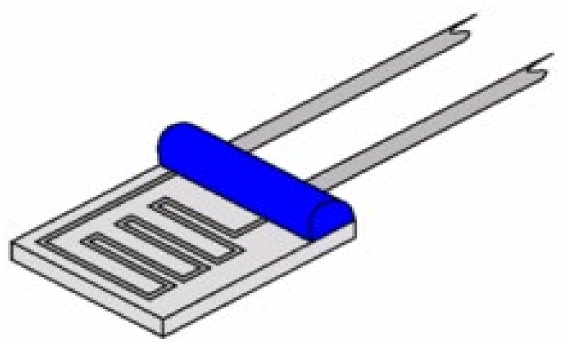
- Range: [-200,800] ºC
- Accuracy: $\pm$0.01 ºC
- Sensitivity: 0.4Ω/ ºC for 100Ω

RTDs (cont'd)

3 Forms of RTDs



Wire-wound



Thin-film

Coils of wires

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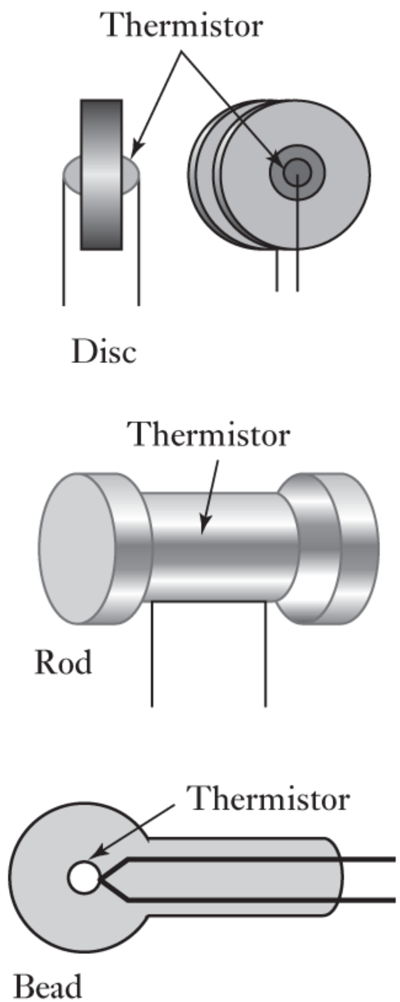
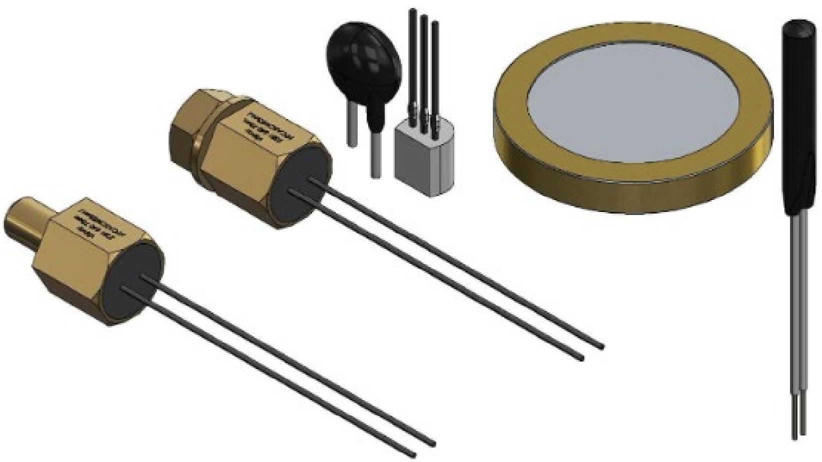
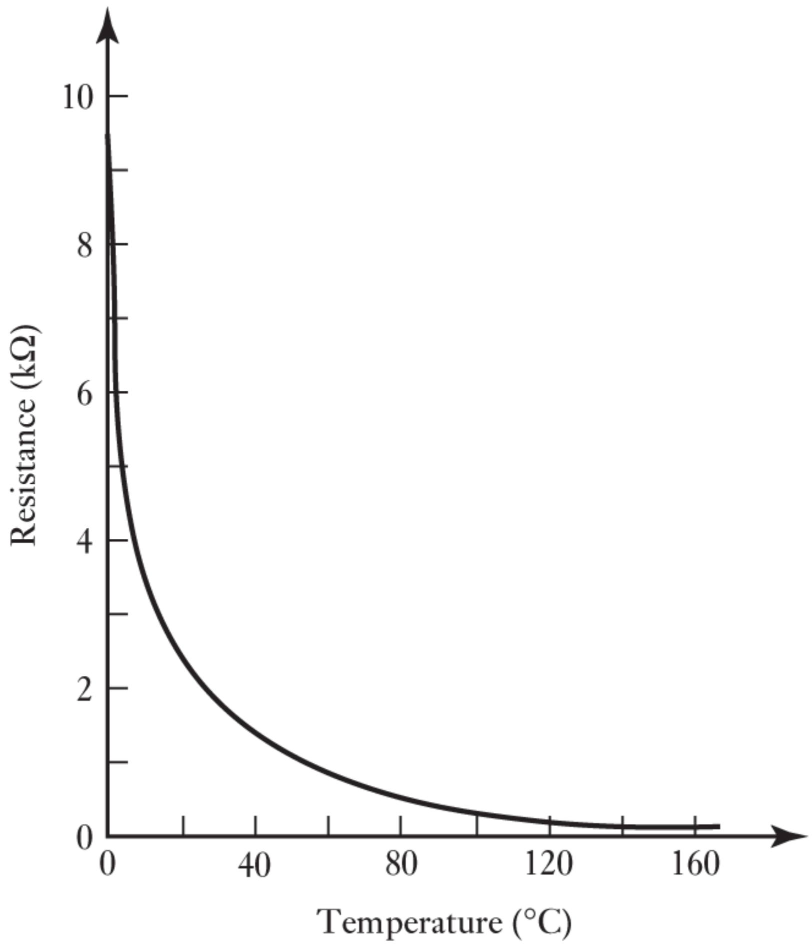
Thermistors



- Thermistors are small pieces of material made from mixtures of metal oxides, such as those of chromium, cobalt, iron, manganese and nickel. These oxides are semiconductors;

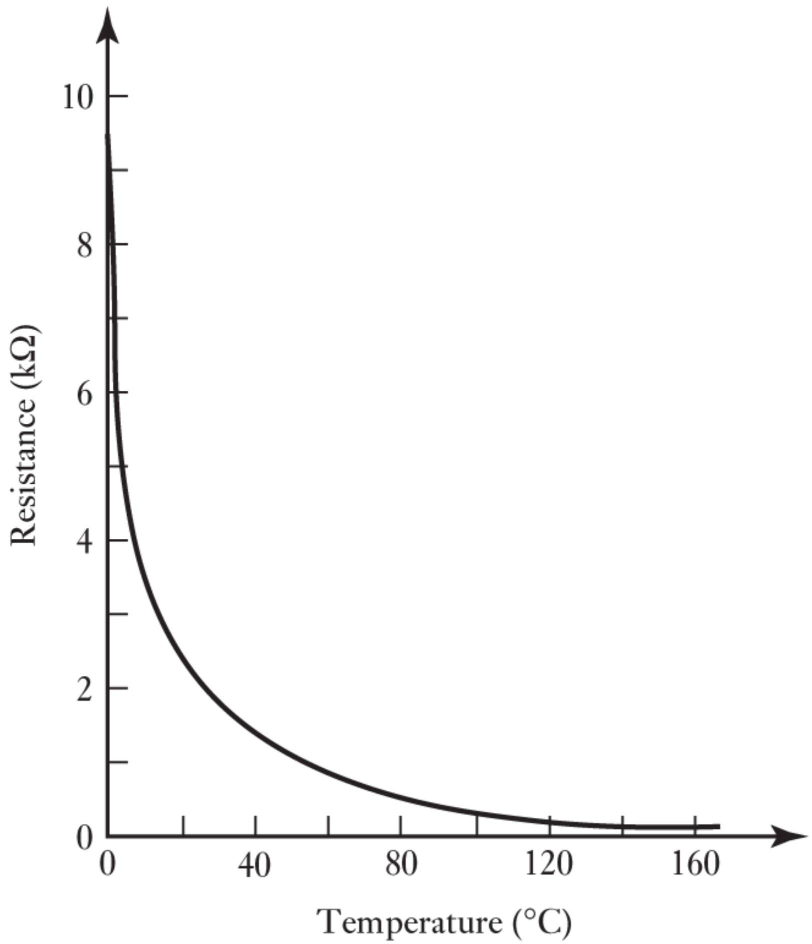


Thermistors



- Thermistors are small pieces of material made from mixtures of metal oxides, such as those of chromium, cobalt, iron, manganese and nickel. These oxides are semiconductors;
- The resistance of conventional metal-oxide thermistors decreases in a very nonlinear manner with an increase in temperature.
  - NTCs: Negative temperature coefficients
- Positive temperature coefficients (PTC) thermistors are also available.
- The change in resistance per degree change in temperature is considerably larger than the one occurs in metals.

Thermistors



- The resistance-temperature relationship for a thermistor can be described by

$$R_T = Ke^{\beta/T}$$

where

- R_T is the resistance at a temperature T,
- K and β are constants.

Thermistors (cont'd)

Advantages:

- Rugged and can be very small, enabling temperatures to be monitored at virtually a point
- Responds very rapidly to changes in temperature
- Gives very large changes in resistance per degree changes in temperature

Used as thermal switches

Main Disadvantage:

- Nonlinearity

Typical Resistance/Temperature Dependence.

T ºC	R_T ohms
0	350 000
25	100 000
50	34 000
100	6 000
150	1 600
200	550
250	240
300	110

Thermistors (cont'd)

Advantages:

- Rugged and can be very small, enabling temperatures to be monitored at virtually a point
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Used as thermal switches

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Main Disadvantage:

- Nonlinearity

Specifications of platinum thermometer:

- Range: [-200,800] °C
- Accuracy: ± 0.01 °C / $\pm 0.5\%$
- Sensitivity: 0.4Ω/ °C for 100Ω

Specification of a bead thermistor:

Range: [-40,+125] °C

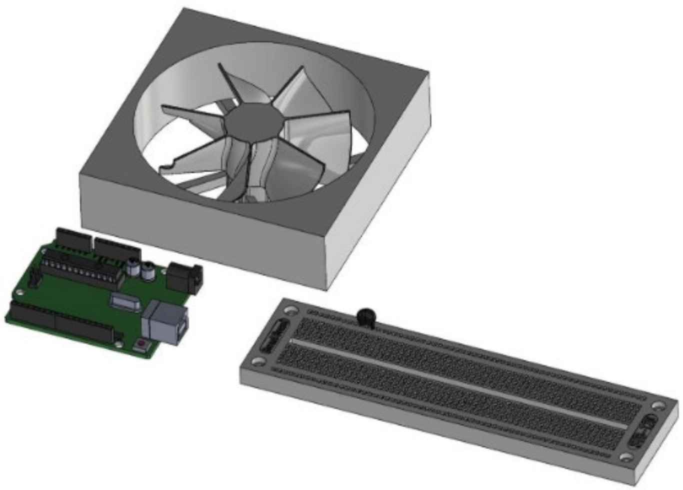
Accuracy: $\pm 5\%$

Maximum power: 250mW

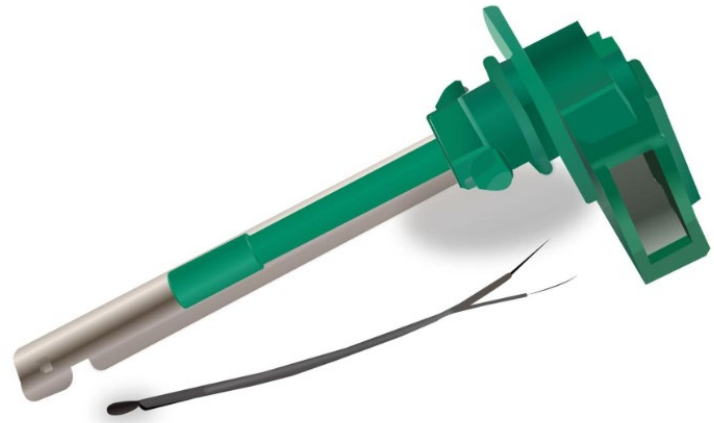
Response time: 1.2s

Applications of Thermistors

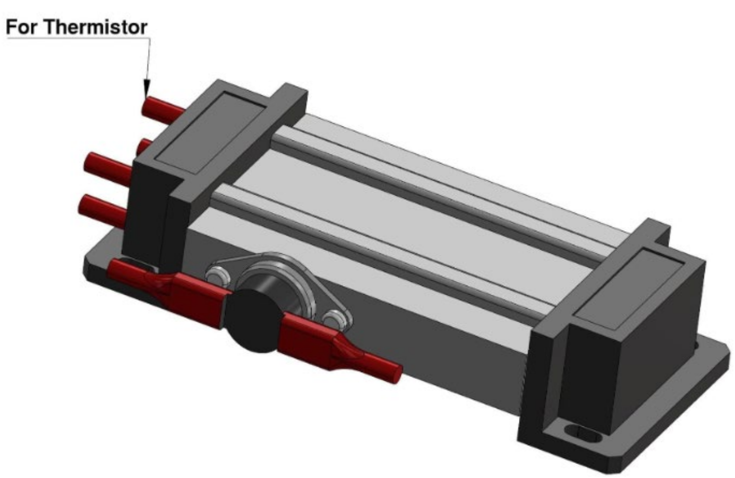
Thermistor Based HVAC System



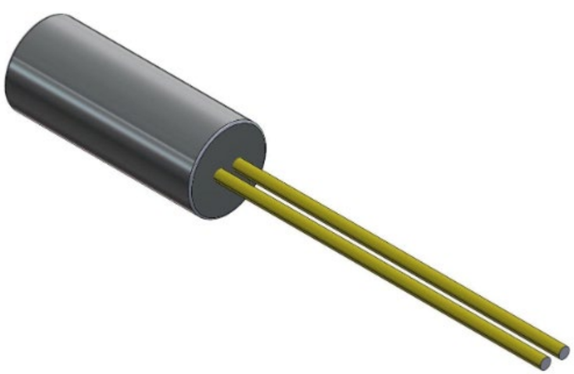
Thermal NTC Thermistor for Auto
Air Intake Systems



Battery Charger Thermistor



Cell Phone Thermistors



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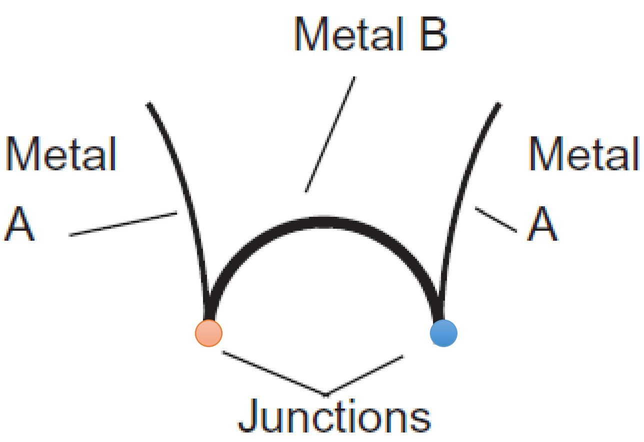
Thermocouples

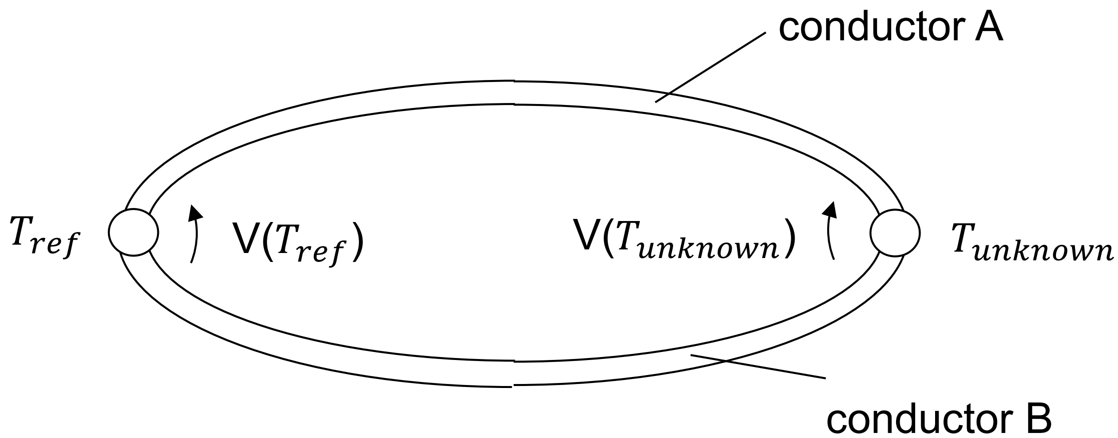
Physical principle:

When two different metals are joined together, a potential difference occurs across the junction. The potential difference depends on the two metals used and the temperature of the junction. A thermocouple involves two such junctions.



Thermocouples

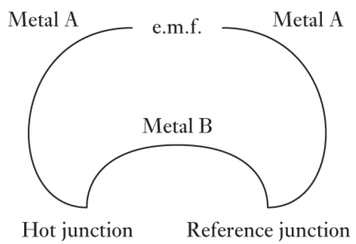
If both ends of conductors A and B are joined together, two inter-metallic contacts are formed.



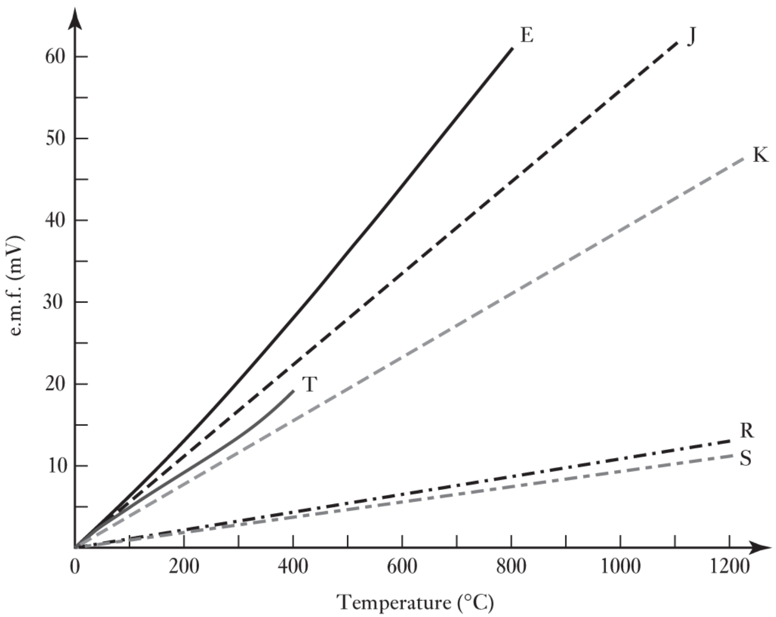
No net potential difference (net e.m.f. = 0) will be produced in the circuit provided: both junctions are at the same temperature.

However, if one is at a different temperature than the other ($T_{ref} \neq T_{unknown}$), a potential difference will occur and can be measured.

Different Types of Thermocouples



(a)



(b)

- The value of e.m.f. produced depends on the two metal concerned and the temperature of both junctions.
- Assume one junction is held at 0 °C, then the following relation holds

$$E = aT + bT^2$$

where a and b are constants for the metal used.

- Left figure shows how the emf varies with temperature for a number of commonly used pair of metals.

Different Types of Thermocouples

International standards have been established for thermocouple materials. These are covered by BS4937: 1973 - 74 International Thermocouple Reference Tables.

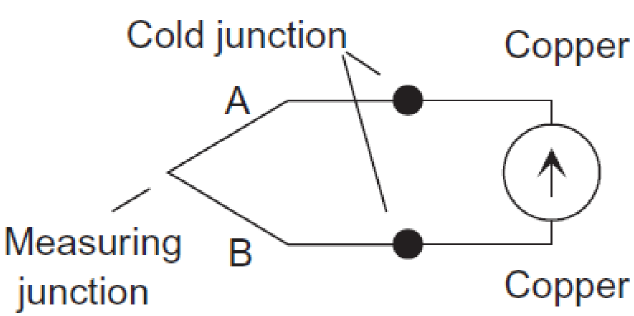
Ref.	Materials	Range (°C)	(μV/°C)
B	Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
E	Chromel/constantan	−200 to 1000	63
J	Iron/constantan	−200 to 900	53
K	Chromel/alumel	−200 to 1300	41
N	Nirosil/nisil	−200 to 1300	28
R	Platinum/platinum 13% rhodium	0 to 1400	6
S	Platinum/platinum 10% rhodium	0 to 1400	6
T	Copper/constantan	−200 to 400	43

- The left table shows the commonly used the thermocouples with temperature ranges and typical sensitivity.
- The commonly used thermocouples are given reference letters.
  - Among them, E, J, K, T are relatively cheap but low accuracy and deteriorate with age.
  - Nobel-metal thermocouples, e.g., R, are more expensive, but more stable with longer life and higher accuracy.

Law of Intermediate Metals

- Law of intermediate metals: a thermocouple circuit can have other metals in the circuit, and they will have no effect on the thermoelectric emf provided all their junctions are at the same temperature.

- How to measure emf?

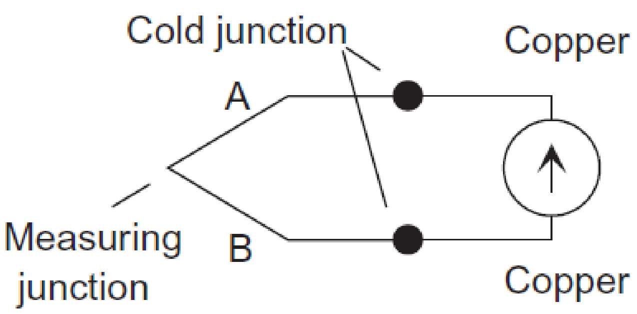


- When a thermocouple is connected to a measuring circuit, the other metals are involved.
- We can have as the 'hot' junction (or measuring junction) between metals A and B; and the 'cold' junction effectively extended by the introduction of copper leads and the measurement instrument.

Law of Intermediate Metals

- Law of intermediate metals: a thermocouple circuit can have other metals in the circuit, and they will have no effect on the thermoelectric emf provided all their junctions are at the same temperature.

- How to measure emf?



- Provided the junctions with the intermediate materials are at the same temperature, there is no extra emf. We still have the emf as due to the junction between A and B.
  - Ensure cold junctions are at the same temperature.

Law of Intermediate Temperature

- The standard table assumes that the reference junction is always at 0 ^{o}C
  - this is very inconvenient in practice
- When a thermocouple has reference junction not at 0 ^{o}C, a correction has to be applied before the tables can be used.
- Law of intermediate temperature:

$$E_{T,I} = E_{T,0} - E_{I,0}$$

  - $E_{T,I}$: emf at temperature T when the cold junction is at I ^{o}C
  - $E_{T,0}$: emf at temperature T when the cold junction is at 0 ^{o}C
  - $E_{I,0}$: emf at temperature I when the cold junction is at 0 ^{o}C

Example

- Consider a type E thermocouple with following data

Temp. (°C)	0	20	200
e.m.f. (mV)	0	1.192	13.419

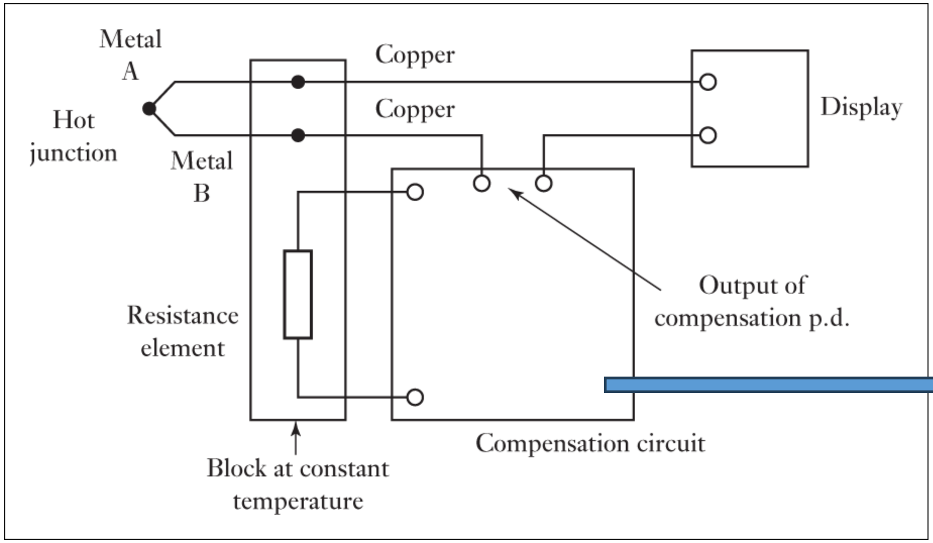
- Use the law of intermediate temperatures, the thermocouple emf at 200 °C with the cold junction at 20 °C is:

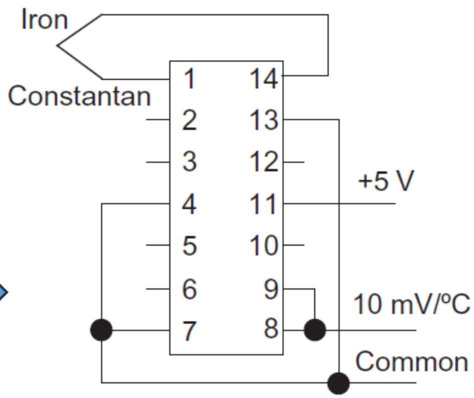
$$E_{200,20} = E_{200,0} - E_{20,0} = 13.419 - 1.192 = 12.227\, mV$$

- Note the is not the emf at 180 °C when cold junction is at 0 °C, namely 11.949 °C.

Cold Junction Compensation

- To maintain one junction of a thermocouple at 0°C, i.e. have it immersed in a mixture of ice and water, is often not convenient.
- A compensation circuit can, however, be used to provide an e.m.f. which varies with the temperature of the cold junction (reference temperature). This is called 'cold-junction compensator'.
  - In such a way, the thermocouple will always generates a combined e.m.f. which is the same as when the cold junction is held at 0°C.

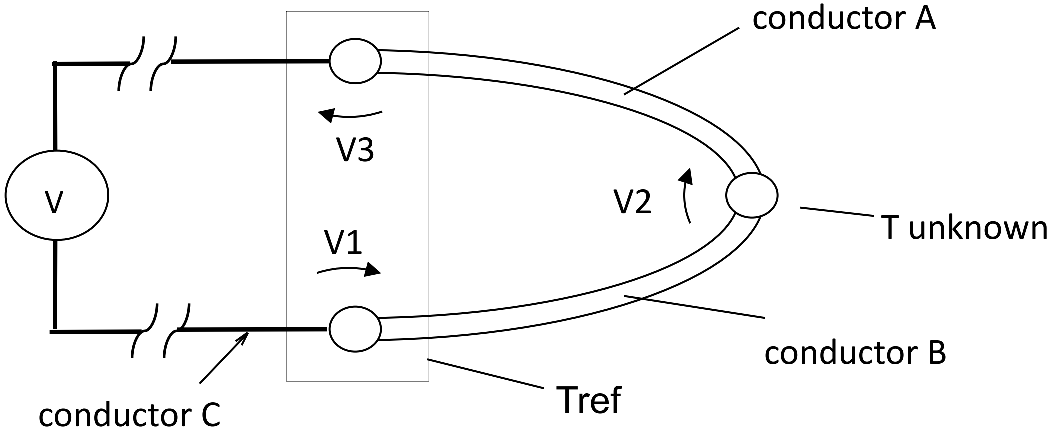




AD594

Thermocouple: Extension Wires

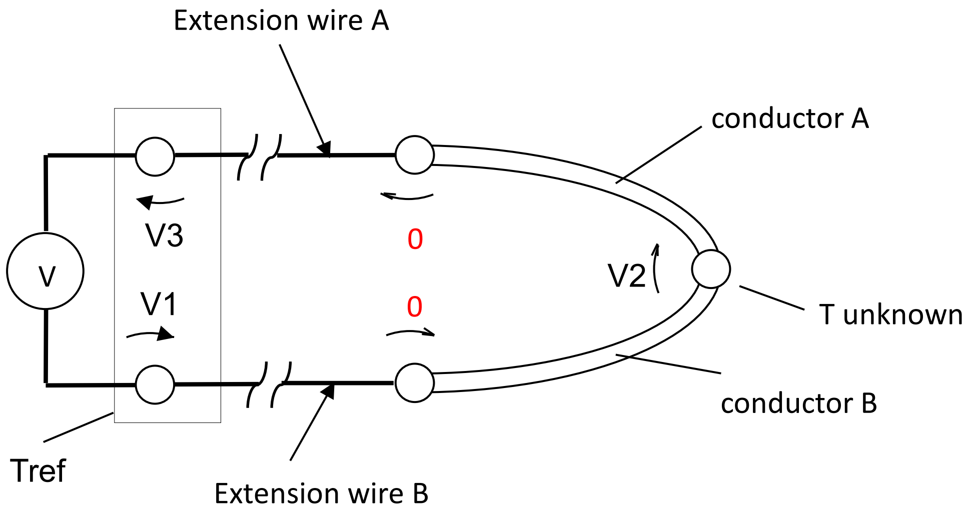
The measuring instrument or display is often required to be remote from the location of the unknown temperature being measured, the use of ordinary copper wires to connect the thermocouple would mean that those junctions become the new reference junction and its temperature would need to be known and the two junctions should be kept at the same temperature.



One solution is to use very long lengths of thermocouple wire.

This is very expensive!!

Thermocouple: Extension Wires



A lower cost alternative is to use extension wires of an appropriate composition such that no contact potentials are created at the junction with the actual thermocouple wires, but can be manufactured less expensively.

Quiz 2.1

A thermocouple is used to measure temperature between 0 and 200°C. The e.m.f. at 0°C is 0 mV, at 100°C it is 4.277 mV, and at 200°C it is 9.286 mV. What will be the nonlinearity error at 100°C? Please express it in %FSD. (Hint: use end-point nonlinearity)

Answer:

Quiz 2.2

A type E thermocouple is used to measure temperature of some car engine. The reference junction is placed at 35°C, the output voltage is 5.62 mV. What is the temperature of this car engine? (Please refer to the calibration table in previous slides)

Answer:

Thank You !