Measurement Systems

2. Sensors

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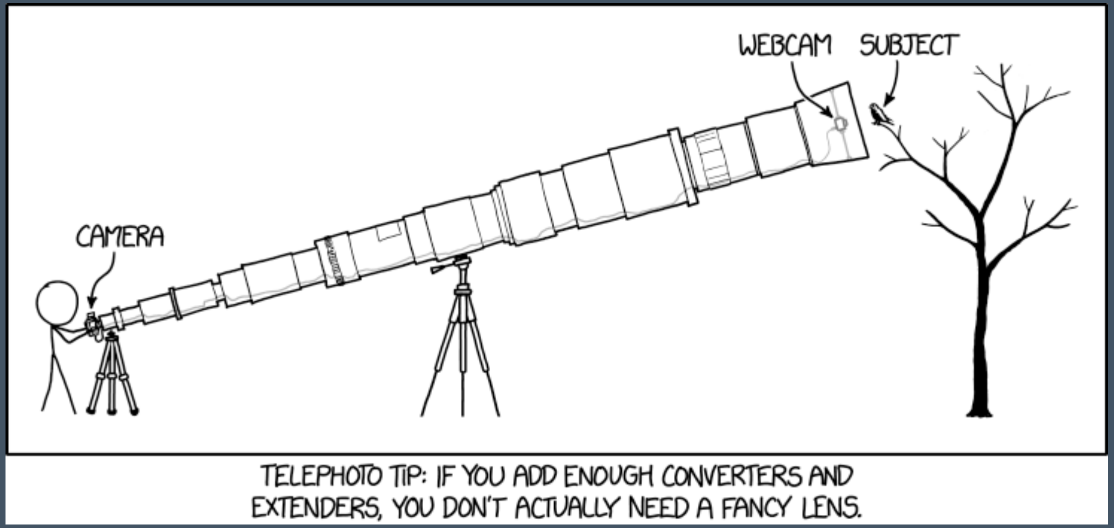

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Section 1 – Recap

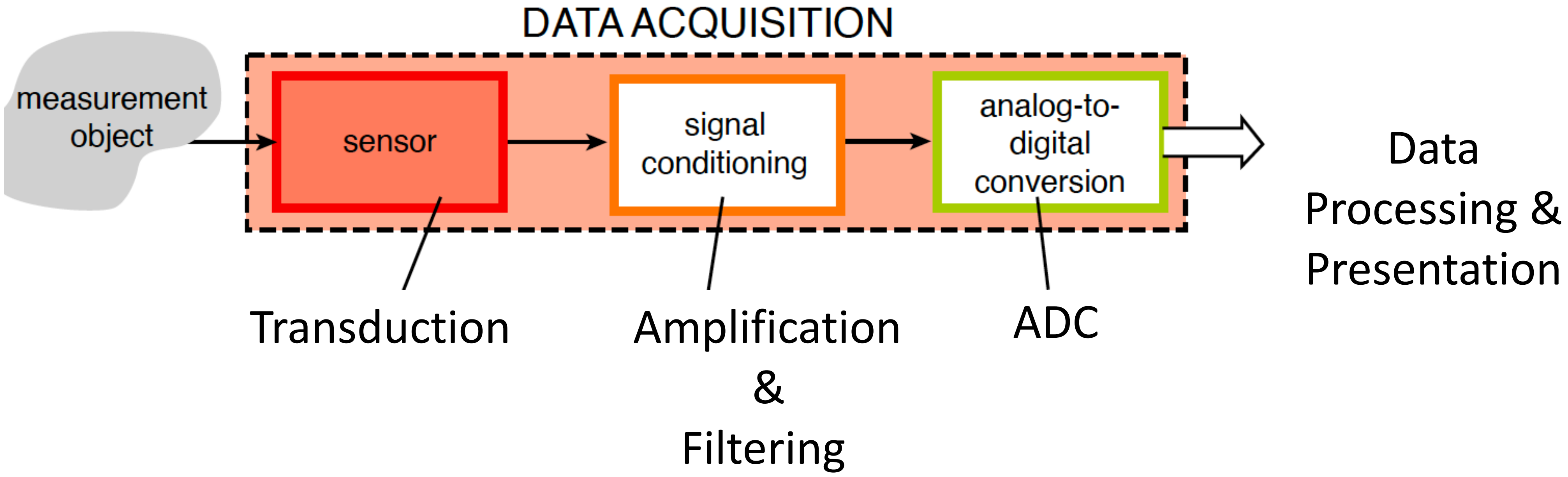
- Measurements are quantitative (determinable) and qualitative (distinguishable)

- The transfer function describes the relationship between an quantity x and measurement y

- Error and uncertainty are not the same!

- Calibration and understanding the sources of error can get us more accurate data

Overview of measurement systems



Transduction

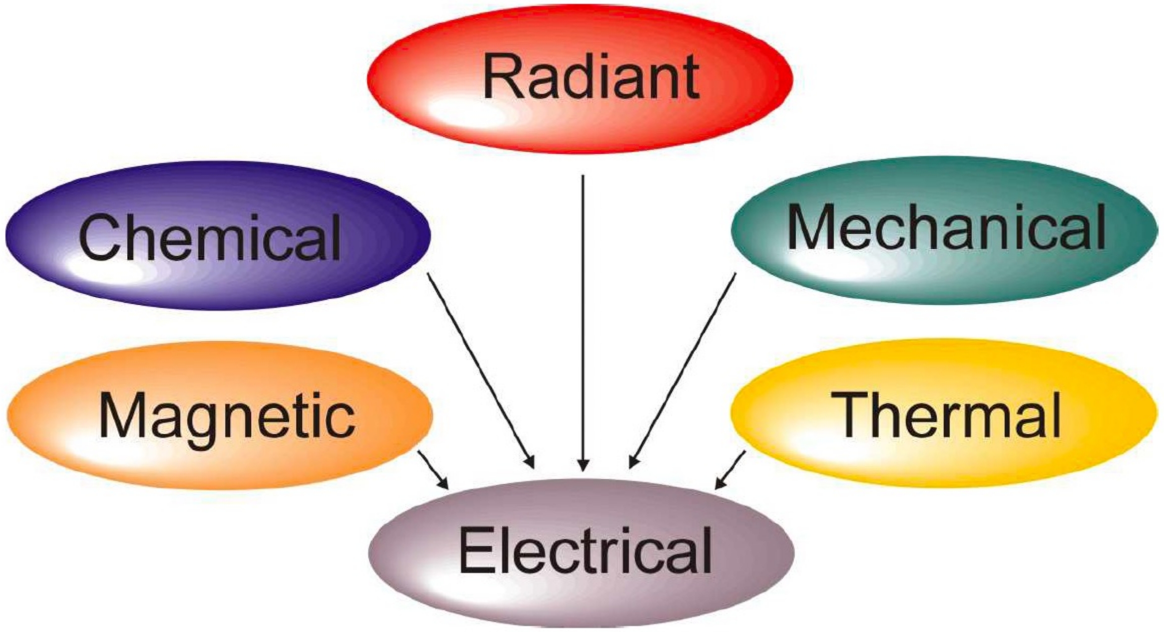
- All sensors transduce other forms of energy to electrical energy

- The ideal sensor:

  1. Imposes no “load”

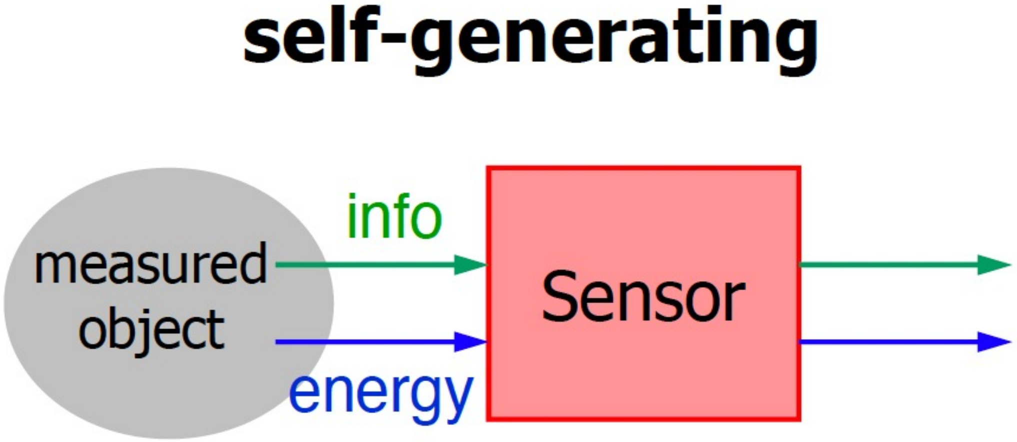
  2. Does not add noise

  3. Is selective



Self-generating Sensors

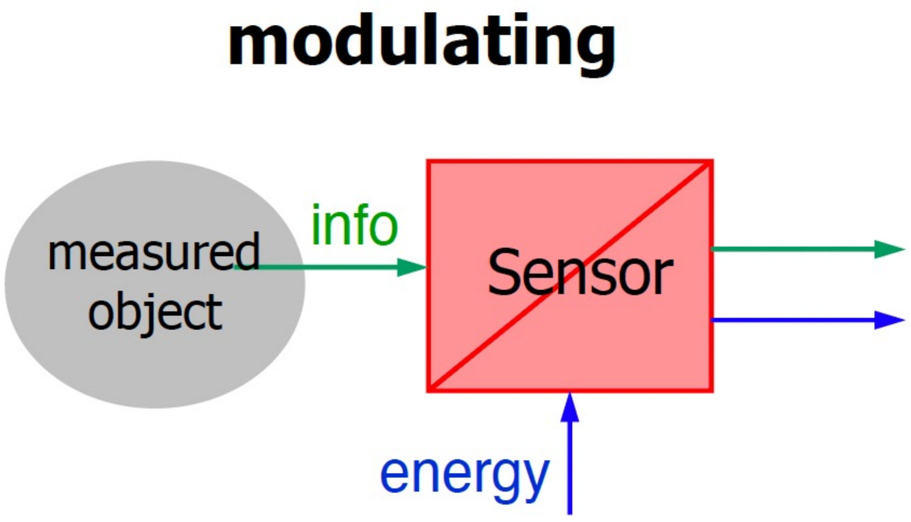
- Sensors can transduce information and energy directly from an object
- Good: minimal error
- Bad: load is imposed on the source



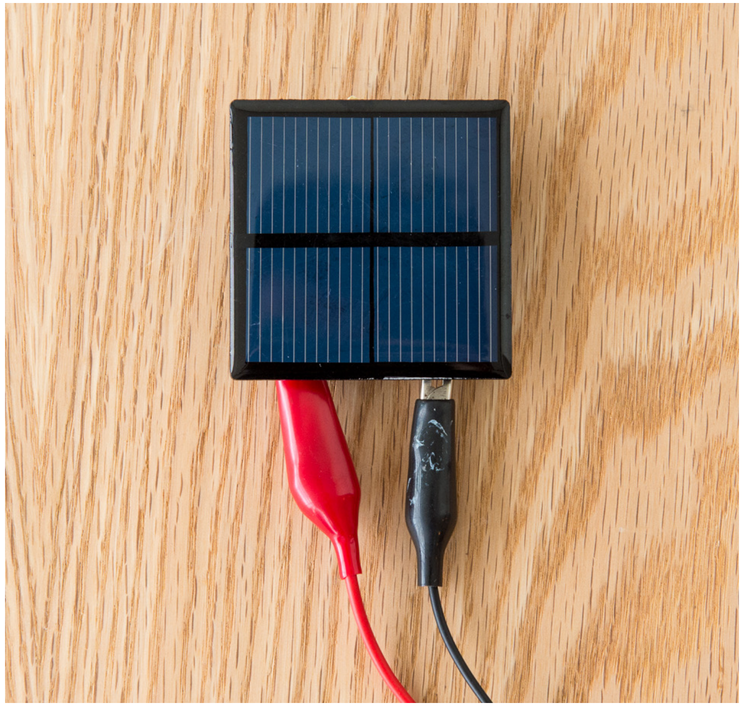
Modulated Sensors

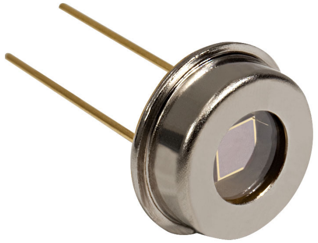
- If energy cannot be directly converted, we can modulate a signal to gain information

- Good: minimal load on source
- Bad: more sources of error



Examples

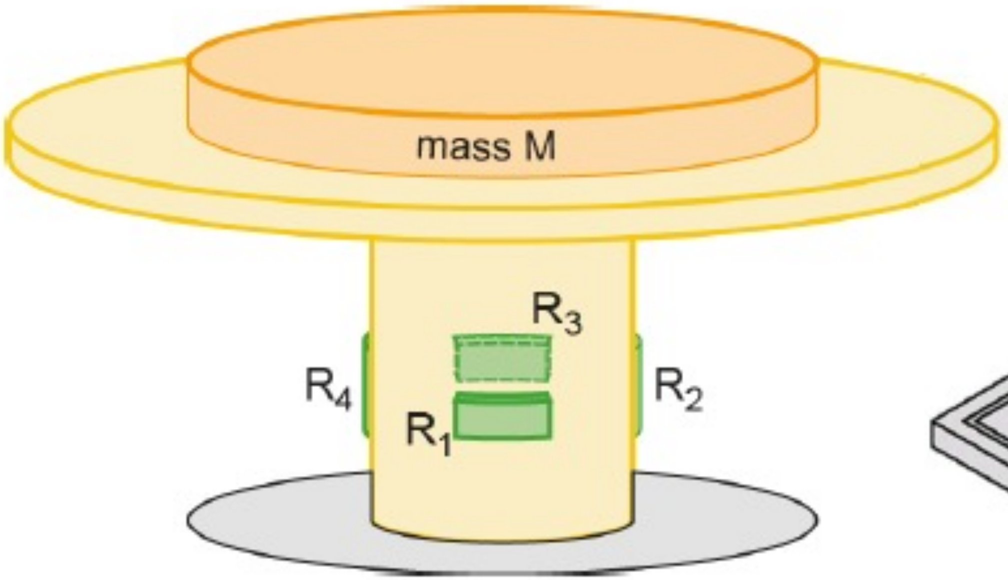




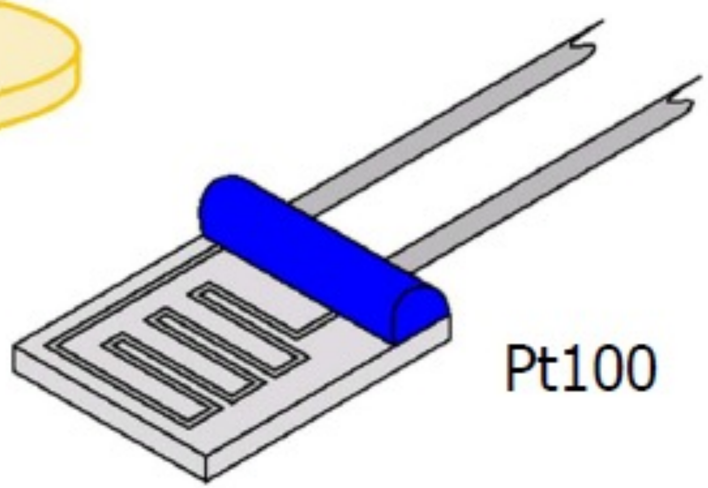
Self-Generating

Modulating

Self-Generating or Modulating?



Modulating



Modulating

Types of Sensors

- The electrical processes a sensor uses varies from application to application.

- Some examples:

- Resistive
- Capacitive
- Inductive
- Thermoelectric
- Piezoelectric
- Semiconducting
- …

Resistive Sensors

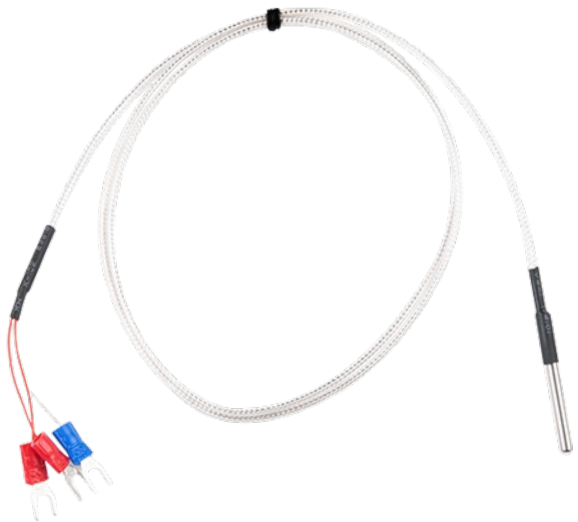
- Resistivity is given by:

$$R = \frac{\rho l}{A}$$

- For constant A, $R \propto \rho$ and $R \propto \ell$

$$V = RI$$

- If we pass a constant current through, then we get a voltage proportional to resistance and vice versa



- Therefore we can detect a change of either length or area as a change in voltage or current.

Resistive Temperature Dependance

- Linear thermal expansion of a wire is given by:

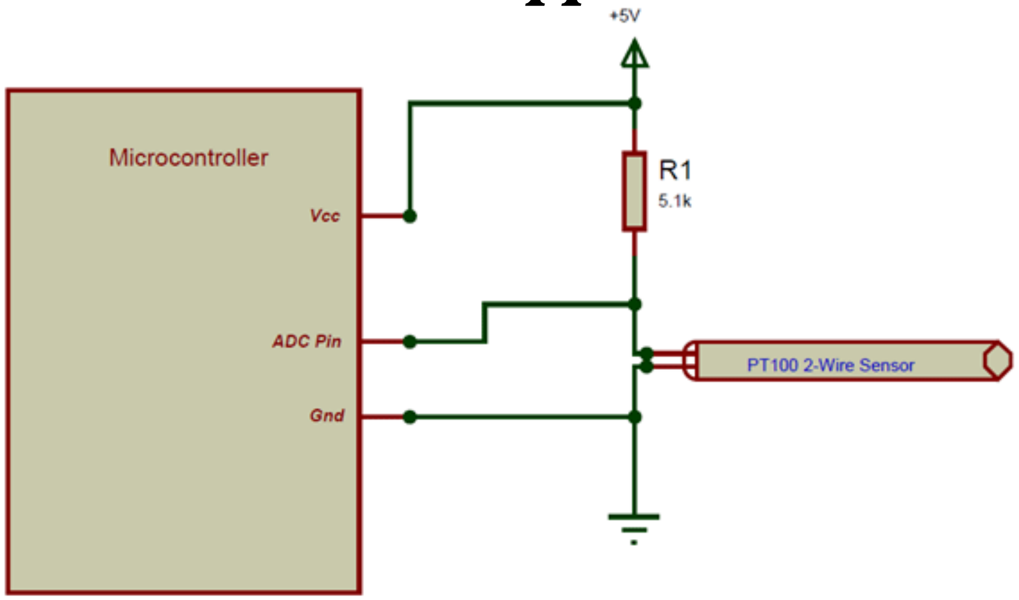
$$\frac{\Delta \ell}{\ell_0} = \alpha \Delta T$$

- This change of length will result in a corresponding change in Resistance of the wire

$$R = \frac{\rho l}{A}$$

- RTDs are also called PT100's

- Commonly found in industry for conta thermal measurements, e.g. pharma a bioprocessing



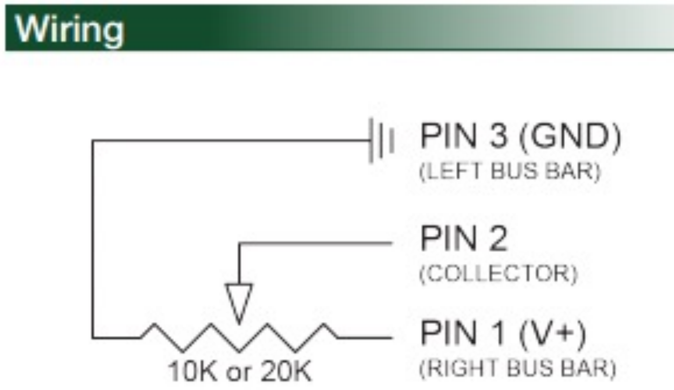
Linear Potentiometer

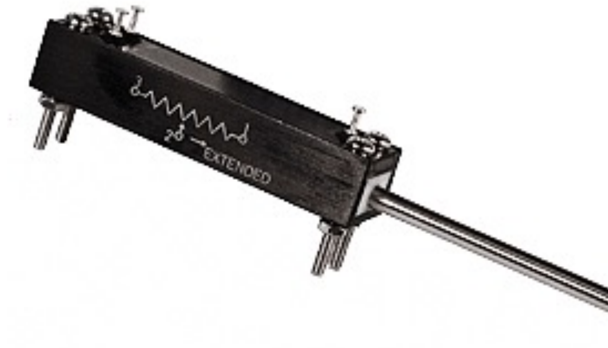
- Linear potentiometers have a moveable wire, in contact with a resistive element

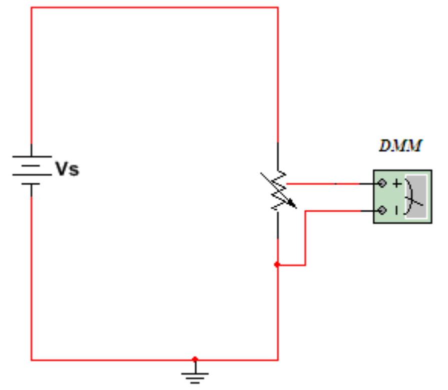
- The total resistance is proportional to the length along the wire

- The detected output voltage is given by

$$V_o = V_s \frac{d}{d_T} = v_s x$$





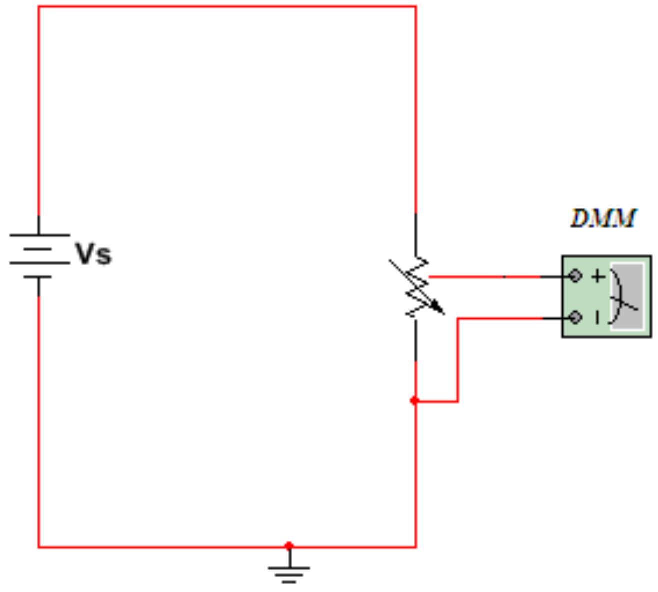


Linear Potentiometer

$$V_o = V_s \frac{d}{d_T} = V_s x$$

where $x = \dfrac{d}{d_T}$ is the Fractional Linear Displacement

- Linear potentiometer are used for:
  Automotive and aerospace suspension monitoring

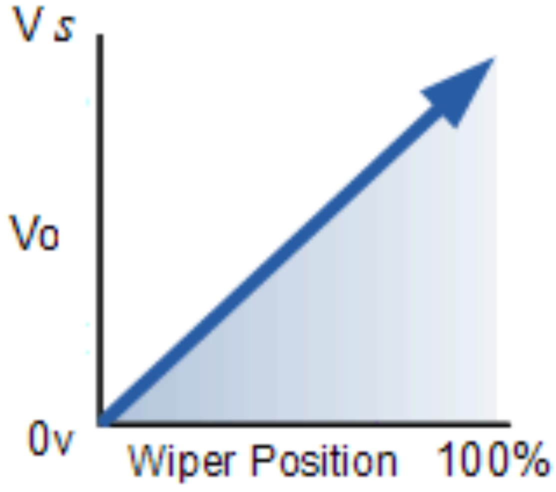


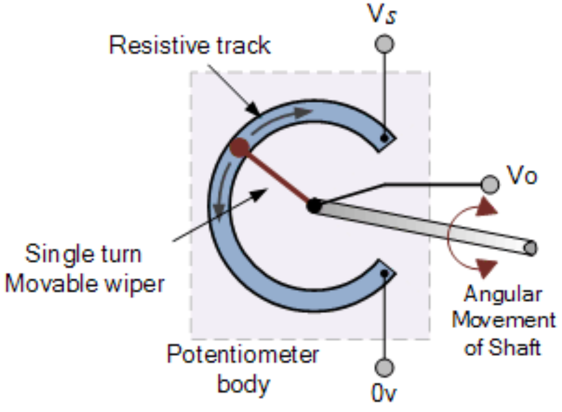
The choice of potentiometer depends on

- 1. Maximum displacement dT,
- 2. The supply voltage VS set by the required output voltage
- 3. The total resistance of the potentiometer (it should be sufficiently small compared to RL so that the maximum non-linearity is acceptable).
- 4. Power Rating

Angular Potentiometer

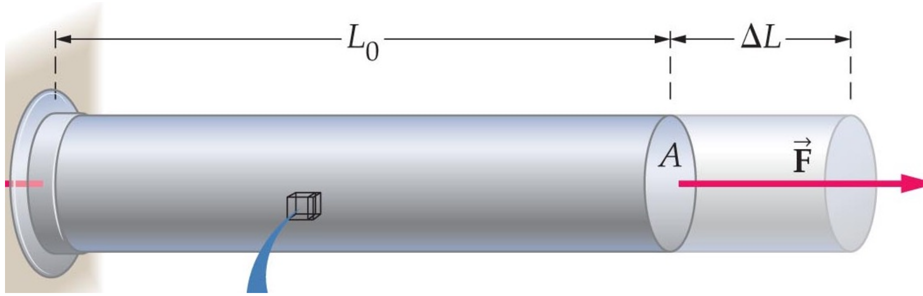
- Angular potentiometers have a moveable wire, in contact with a circular resistive element
- The total resistance is proportional to the angle movement of the contact along the element
- Commonly used in automotive sectors for throttle and gearbox control





Resistive Strain Gauges

- When a load or force is applied to a solid rod, the rod increases in length by an amount



- Stress is defined as the Force per unit Area

$$stress = \frac{Force}{Area} = \frac{F}{A}$$

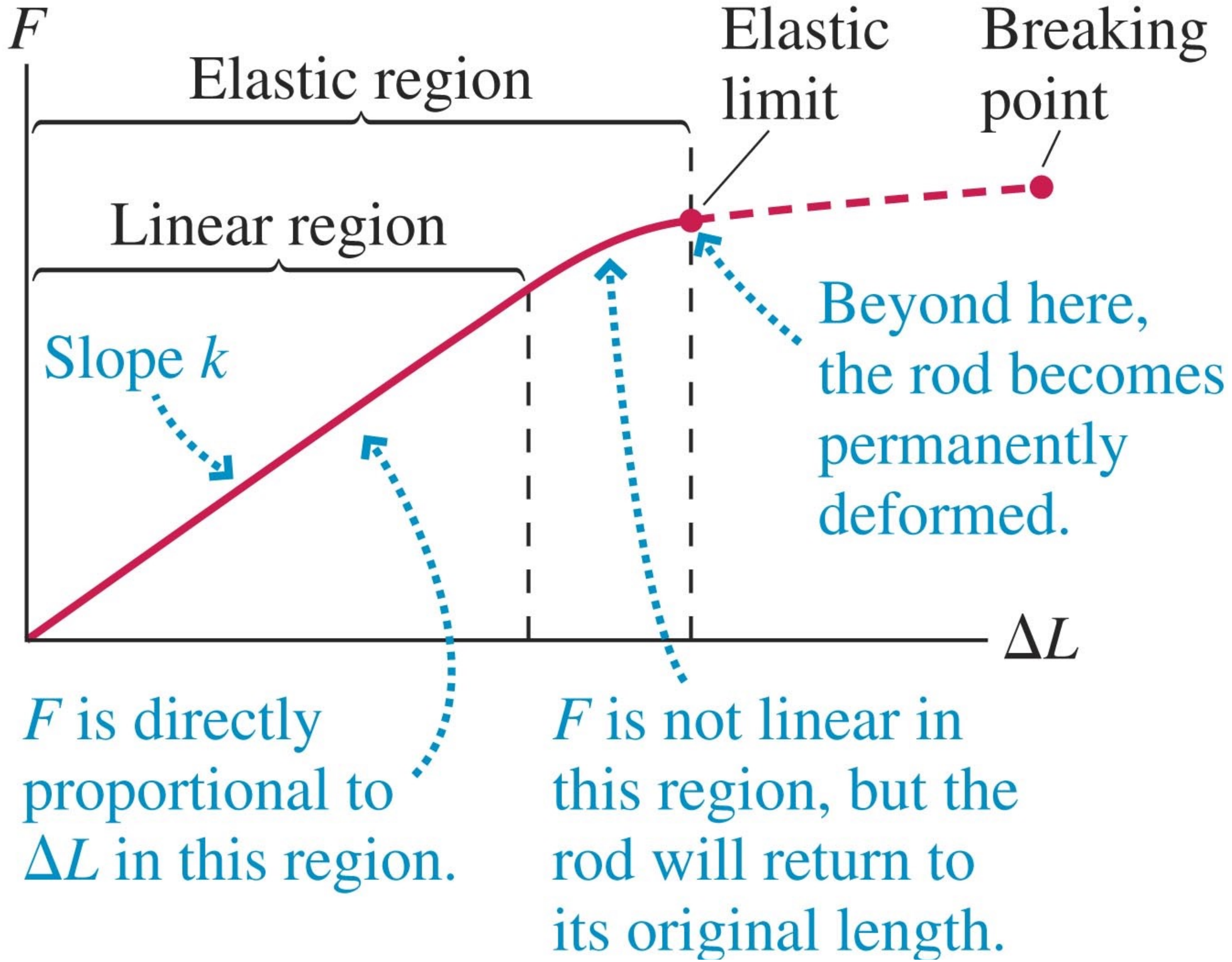
SI Units $\quad$ N/m^2

- Strain which is defined as the extension produced per unit length

$$strain = \frac{extension / compression}{original\ length} = \frac{\Delta L}{L_0}$$

No SI Units

Resistive Strain Gauges

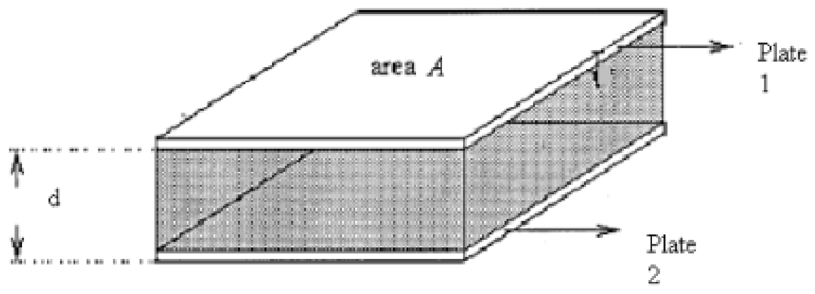


Capacitive Sensors

- A capacitor consists of two conducting plates (usually metallic) separated by an insulator. One typical type is a parallel plate capacitor where the two plates are flat and parallel. When a voltage is applied across the metal plates equal and opposite charges appear on the plates and the capacitance is given by:

$$C(\text{Capacitance in Farads}) = \frac{\text{Q(Charge in Coulombs that appears on each plate)}}{\text{V(voltage in Volts apllied across the plates)}}$$

For a parallel plate capacitor



The capacitance is given by: $C = \dfrac{\varepsilon A}{d}$

Capacitive Sensors

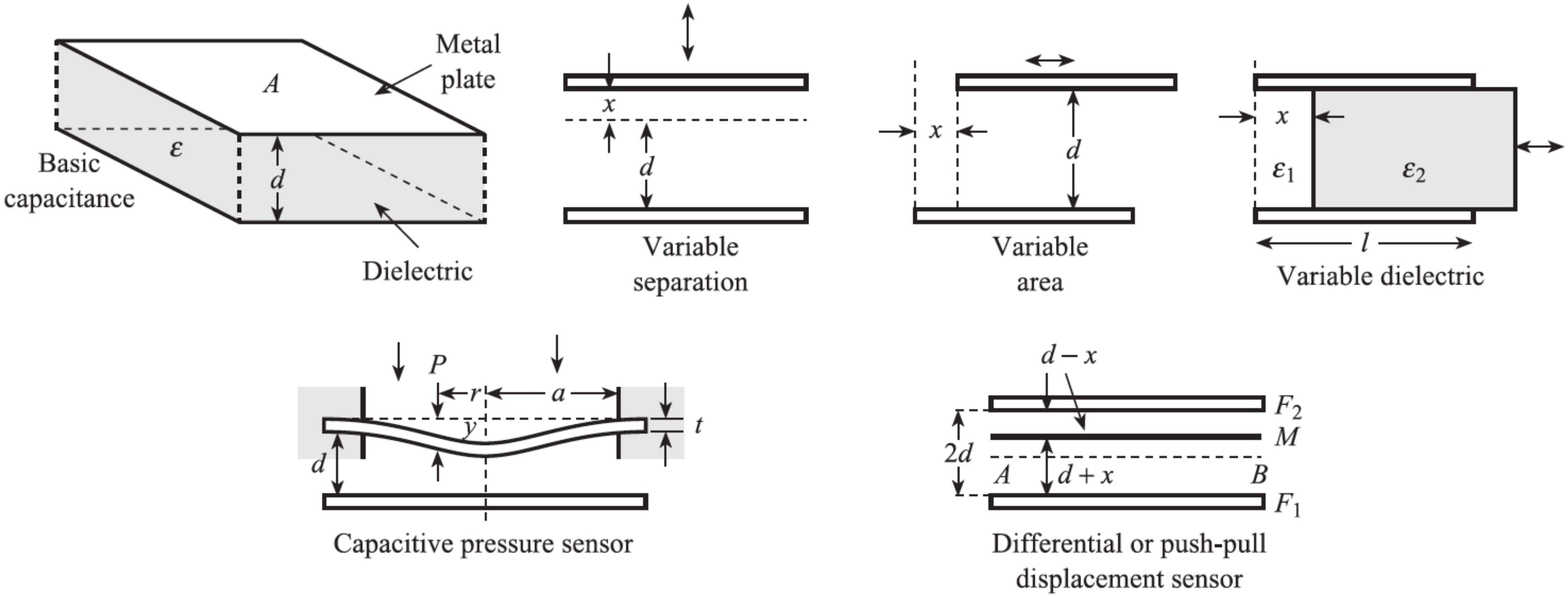
- Capacitance is also inversely proportional to Voltage such that:

$$C = \frac{q}{V}$$

- This allows us to measure a change in area or distance and detect it as a voltage

- Alternatively, the insulating medium can chance, which also allows us to detect a chance in the Capacitance via Voltage

Capacitive Sensors

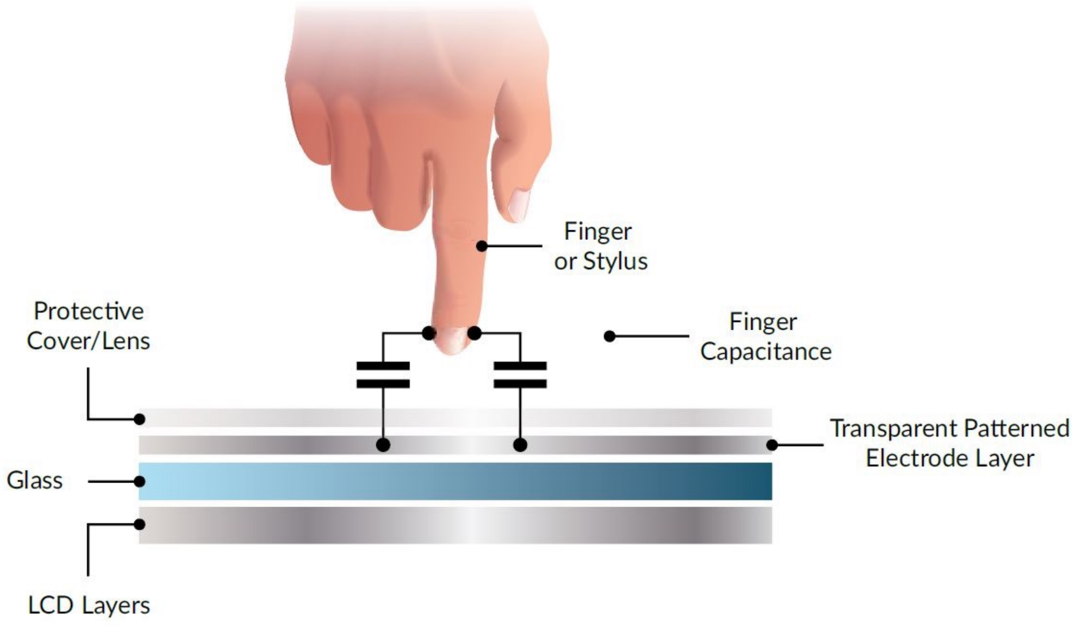


Capacitive Sensors

- Capacitive Proximity Sensing is the use of a capacitive sensor tuned to detect the presence of nearby objects with or without any direct physical contact.

- Main application in capacitive touchscreens

- Touchscreens require transparent conductors such as Indium Tin Oxide (ITO) arranged in arrays

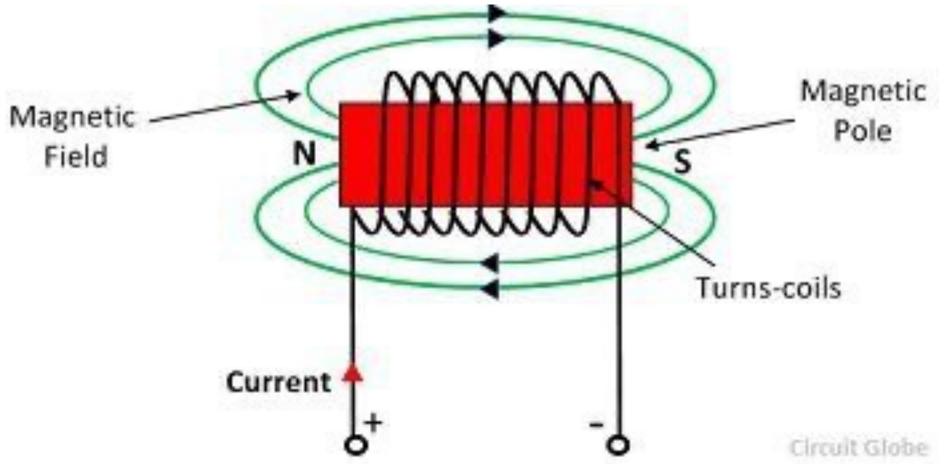


Inductive Sensors

- Variable inductive sensors detect a chance in the magnetic field strength around the sensor

- Just as for an electrical circuit the electromotive force $\mathrm{F}_{\mathrm{emf}} = I \times R$, for a magnetic circuit, the magnetomotive force is the Flux times Reluctance

$$F = \phi \times \mathcal{R}$$



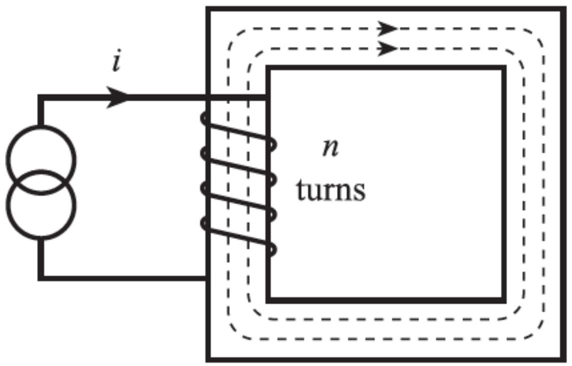
Inductive Sensors

- Reluctance in a magnetic circuit is given by:

$$\mathcal{R} = \frac{\ell}{\mu\mu_0 A}$$

where ℓ is the length of the magnetic circuit, A is the cross-sectional area,

and μ and μ_0 is the permeability of the circuit and permeability of free space ($4\pi \times 10^{-7}$ H.m^{-1}) respectively.



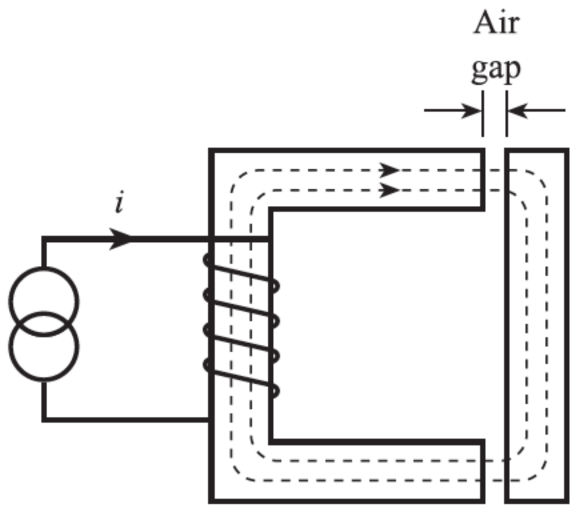
(a)

Inductive Sensors

- In a variable-inductive sensor, Reluctance is given by:

$$\mathcal{R}_T = \mathcal{R}_1 + \mathcal{R}_{air} + \mathcal{R}_2$$

- This any movement in the circuit will change $\mathcal{R}_{air}$ allowing a distance ℓ to be detected



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Inductive Sensors

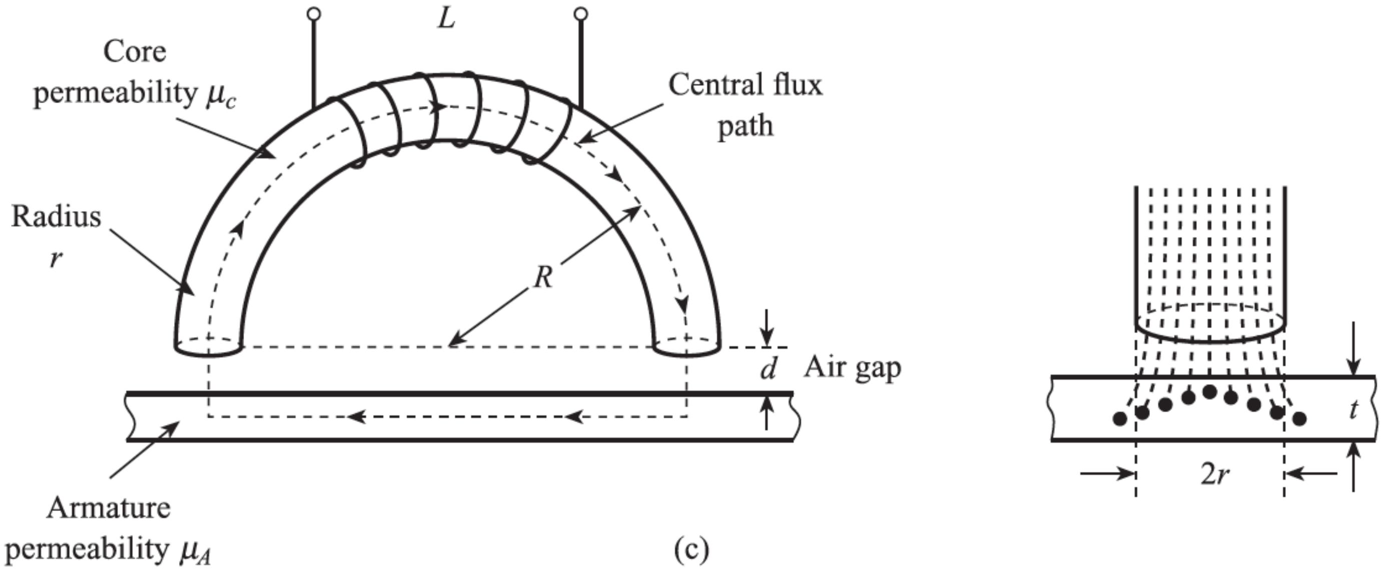
- Examples:

  Inductive loop metal detectors

  Nuclear Magnetic Resonance / Magnetic Resonance Imaging

  Magnetic anomaly detection

  Real-time traffic monitoring



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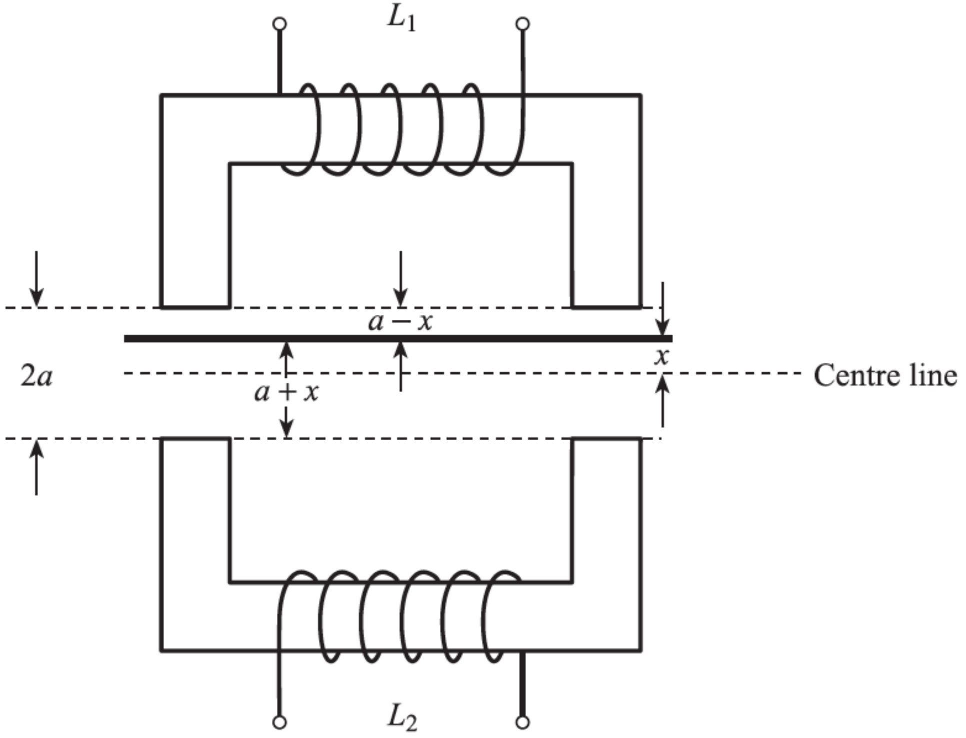

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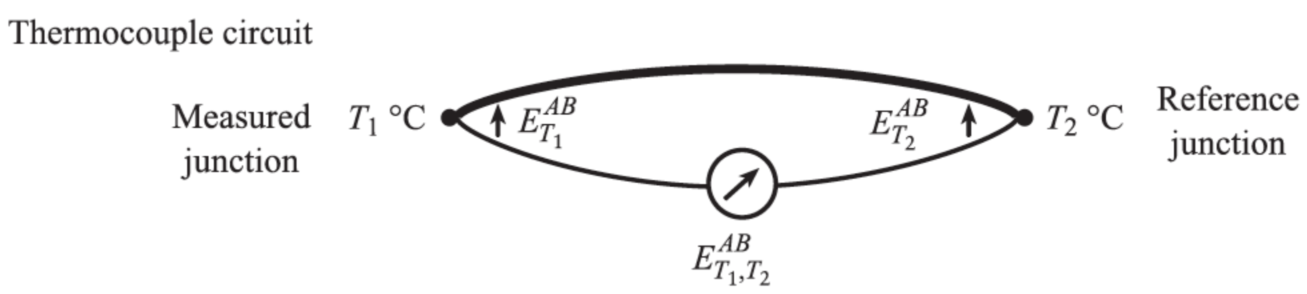
Thermoelectric Sensors

- Thermoelectric or thermocouple sensors are a common temperature measurement tool
- If two metals A and B are joined, a potential difference forms across the junction of the two known as the ”Junction Potential”
- This potential depends on both the types of metals used, and the temperature of the circuit

$$E_T^{AB} = a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + \ldots$$

where a_1, a_2,... are constants depending on the metal choice

Thermoelectric Sensors

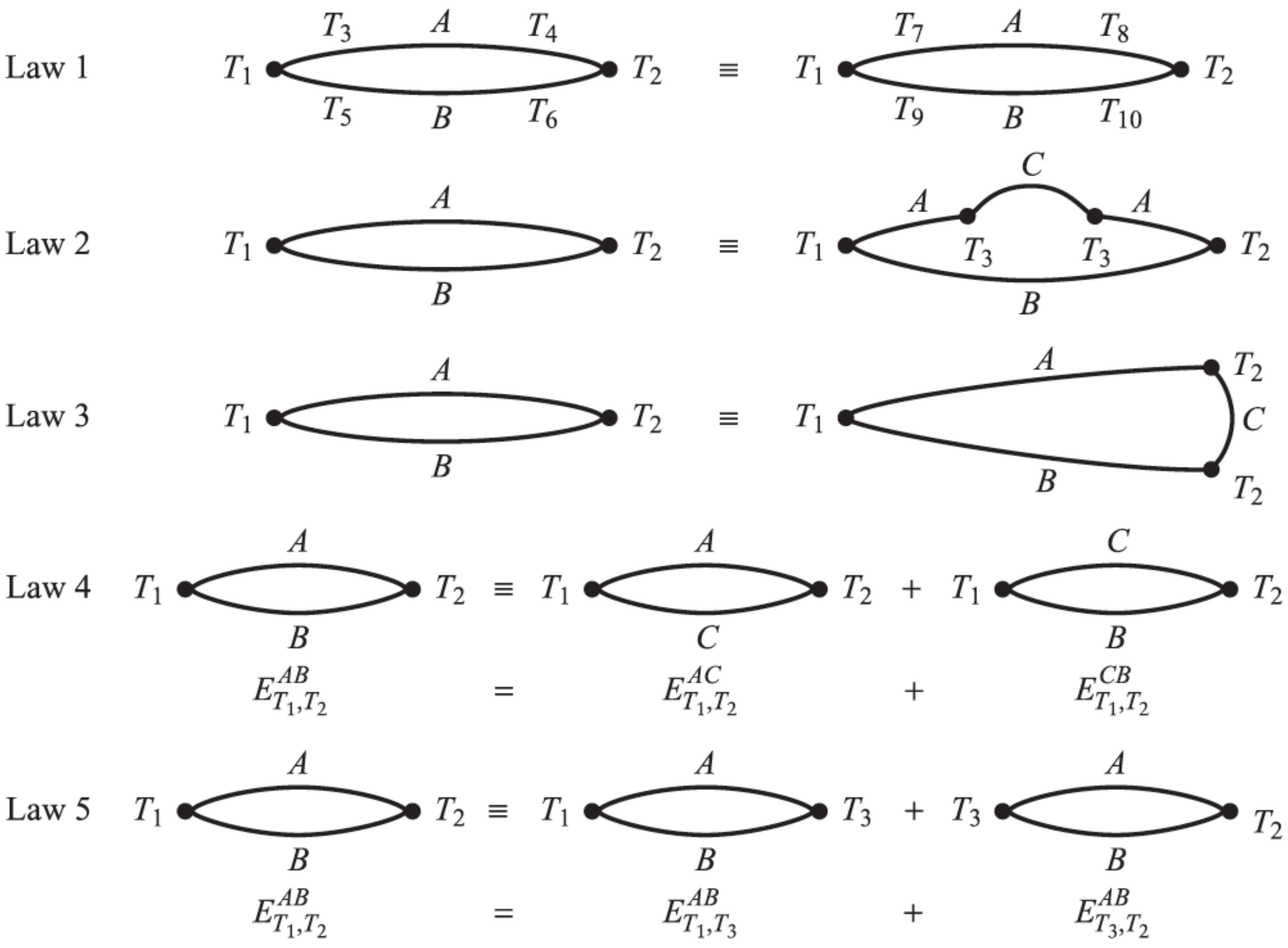


- Thermocouple have two junctions – the measurement junction and a reference junction
- How they are used is governed by five "laws"

1. The emf only depends on the thermocouple behaviour
2. If a third metal C is introduced, the emf is unchanged if it is at the same temperature at the junctions
3. If the AC and CB are is at the measurement junction the emf is unchanged
4. The emf of AB and BC can be used to calculate CA ($E_{AB} = E_{AC} + E_{CB}$)
5. The emf due to a change in temp at the junction can be used to calculate the change at the others $E_{T_1,T_2} = E_{T_1,T_3} + E_{T_3,T_2}$

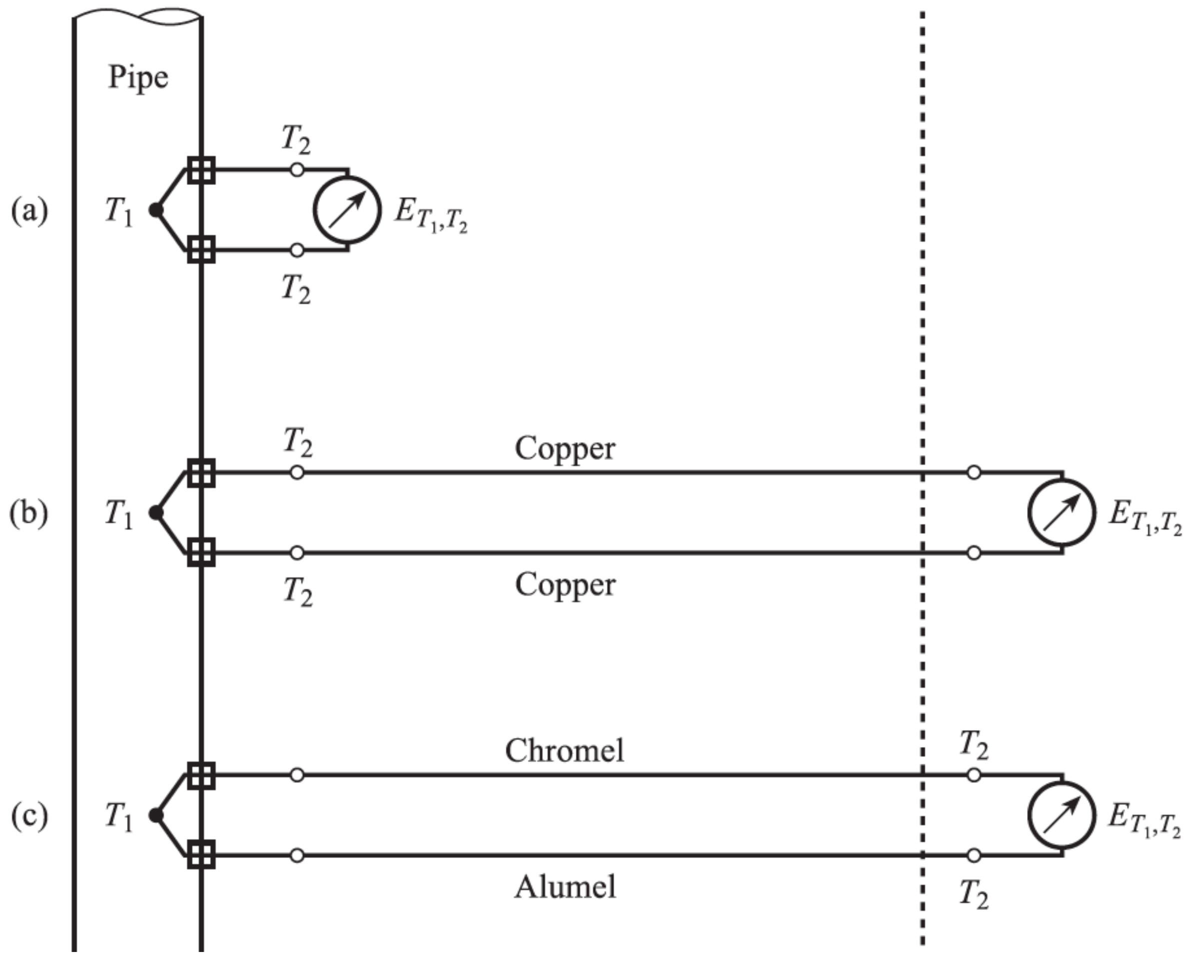
Thermoelectric Sensors

Thermocouple laws



Thermoelectric Sensors

- Installation is very important
- Any meter must be far away from heat source
- Measurement junction must be at the heat source
- Reference junction should be at a known temperature
- Automatic referencing can be used if reference junction cannot be placed at known temperature –most common approach



Thermoelectric Sensors

Type	Temperature ranges (°C)	e.m.f. values (μV)[a]	Tolerances	Extension leads	Characteristics
Iron v. constantan Type J	–20 to +700	$E_{100,0}$ = 5 269 $E_{200,0}$ = 10 779 $E_{300,0}$ = 16 327 $E_{500,0}$ = 27 393	Class 1 −40 °C to +375 °C ±1.5 °C	As for thermocouple	Reducing atmospheres have little effect. Should be protected from moisture, oxygen and sulphur-bearing gases
Copper v. constantan Type T	−185 to +400	$E_{-100,0}$ = −3 379 $E_{+100,0}$ = 4 279 $E_{200,0}$ = 9 288 $E_{400,0}$ = 20 872	Class 1 −40 °C to +125 °C ±0.5 °C	As for thermocouple	Recommended for low and sub-zero temperatures. Resists oxidising and reducing atmospheres up to approximately 350 °C. Requires protection from acid fumes
Nickel–chromium v. nickel–aluminium Chromel v. alumel Type K	0 to +1100	$E_{100,0}$ = 4 096 $E_{250,0}$ = 10 153 $E_{500,0}$ = 20 644 $E_{1000,0}$ = 41 276	Class 1 −40 °C to +375 °C ±1.5 °C	As for thermocouple	Recommended for oxidising and neutral conditions. Rapidly contaminated in sulphurous atmospheres. Not suitable for reducing atmospheres
Platinum v. platinum– 13% rhodium Type R	0 to +1600	$E_{300,0}$ = 2 401 $E_{600,0}$ = 5 583 $E_{900,0}$ = 9 205 $E_{1200,0}$ = 13 228	Class 1 0 to 1100 °C ±1.0 °C	Copper Copper–nickel	High resistance to oxidation and corrosion. Particularly susceptible to many metal vapours, therefore important that non-metal sheaths are used

Piezoelectric Sensors

- Piezoelectric effect is the ability of certain materials to generate an electric charge in response to an applied mechanical stress or dynamic changes in mechanical variables, such as mechanical shock, vibration and acceleration.

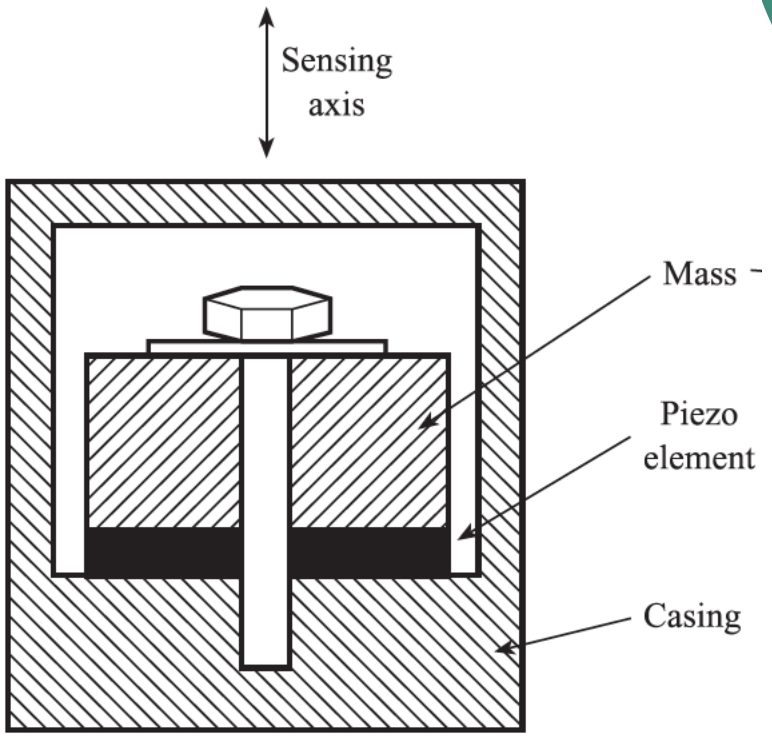
- This effect is reversable – materials only will exhibit this when under the applied force.

- When a force is applied, a shift in positive and negative charged within the material occur, resulting in an external electric field. When the force is removed, the material returns to it’s original state.

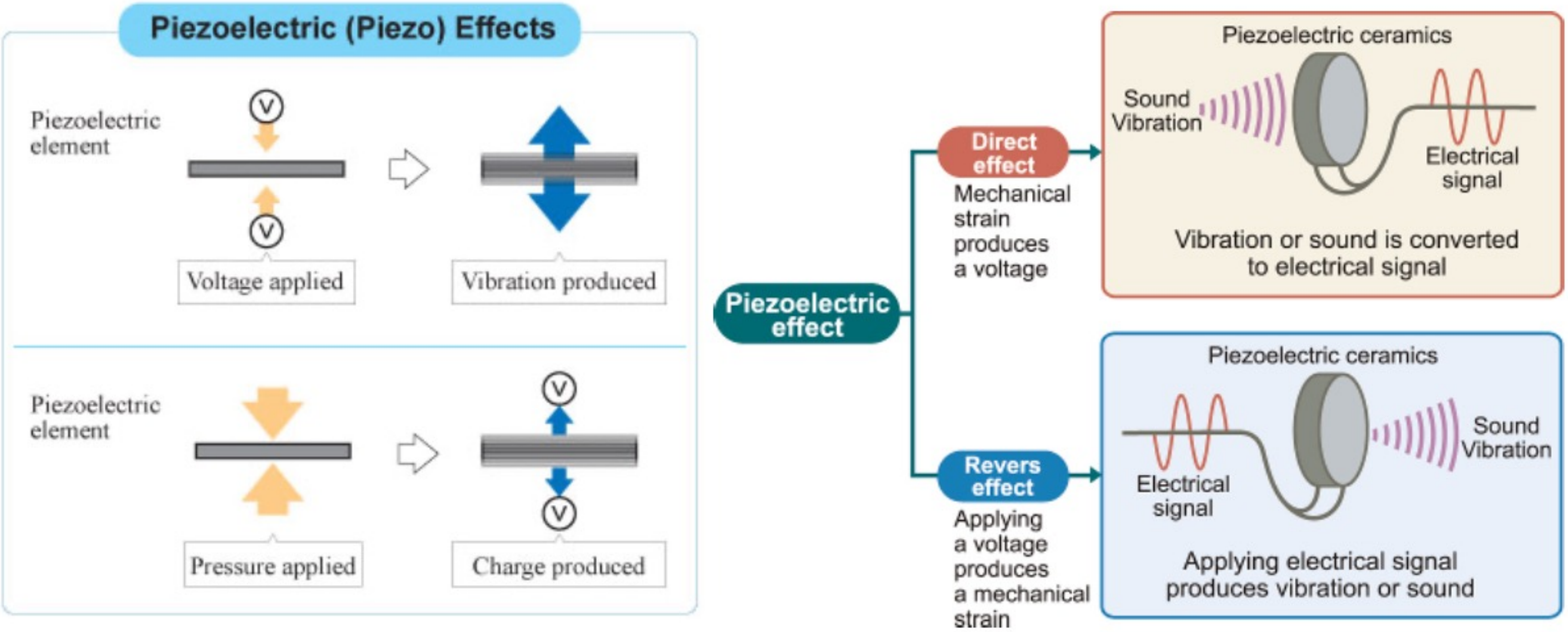
Piezoelectric Sensors

- The piezoelectric effect allows not only static measurements to be taken, but a time-dependent signal can produce a time-varying voltage across the piezo

Material	Charge sensitivity d pC N^{-1}	Dielectric constant ε	Voltage sensitivity $g \times 10^{-3}$ V m N^{-1}	Young's modulus $E \times 10^{9}$ N m^{-2}	Damping ratio ξ
Quartz	2.3	4.5	50	80	2×10^{-5}
PZT	110	1200	10	80	7×10^{-3}
$BaTi_2O_3$	78	1700	5.2	80	1×10^{-3}
PVDF	23	12	230	2	5×10^{-2}



Piezoelectric Sensors



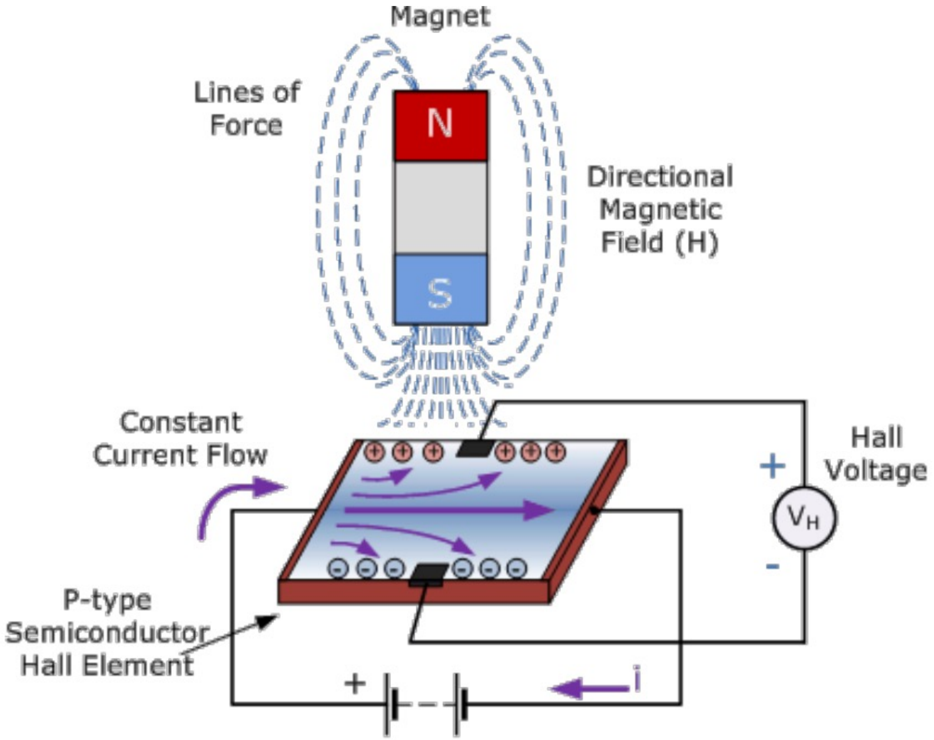
Piezoelectric Sensors

- Applications:
  Pressure sensors – in-cylinder combustion sensors
  Sound transducers
  Accelerometers

- Advantages:
  Wide frequency range
  No moving parts
  Linear sensor over range
  Low output noise
  Low load
  Self-generating

Semiconducting Sensors

- A Hall effect sensor consists of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), which has a continuous constant current flowing through it.
- When the device is placed in a magnetic field, the magnetic flux (strength of the magnetic field, B) exerts a force which deflects the charge carriers, electrons and holes, to either side of the semiconductor.



Semiconducting Sensors

- This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material. As these electrons and holes move a potential difference (the Hall voltage) is produced between the two sides of the semiconductor material by the build-up of these charge carriers.
- The effect of generating a measurable voltage by using a magnetic field is called the Hall effect after Edwin Hall.
- The output voltage, called the Hall voltage, (VH) is directly proportional to the strength of the magnetic field passing through the semiconductor material. This output Hall voltage is given as:

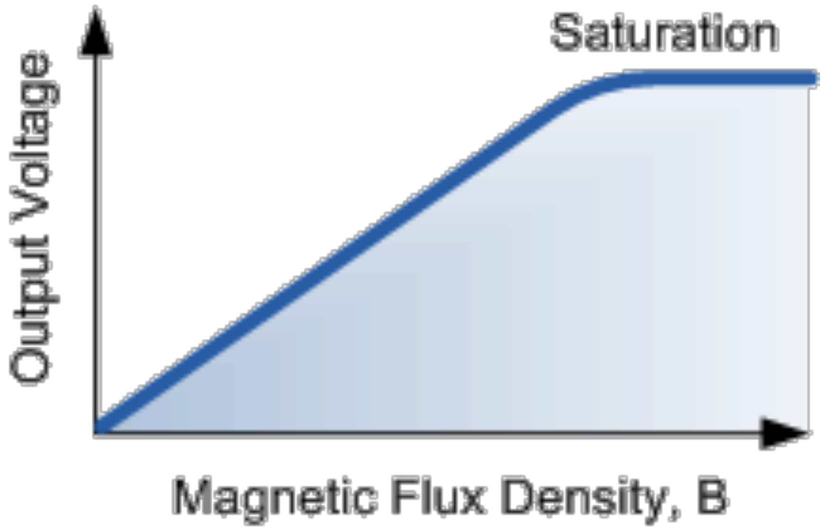
$$V_H = R_H \left(\frac{I}{t} \times B \right)$$

where R_H is the Hall coefficient, I is the current flow through the sensor in amps, t is the thickness of the sensor in mm and B is the Magnetic Flux density in Teslas

Semiconducting Sensors

- This output voltage can be quite small, only a few microvolts, even when subjected to strong magnetic fields so most commercially available Hall effect devices are manufactured with built-in DC amplifiers.

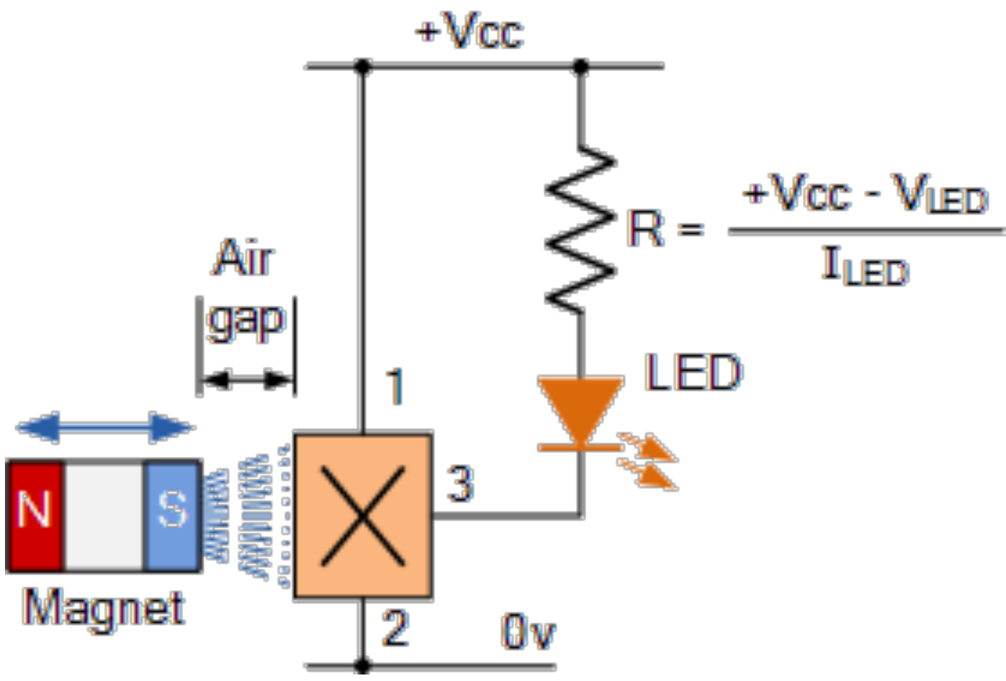
- In linear output Hall effect sensors, as the strength of the magnetic field increases the output signal from the amplifier will also increase until it begins to saturate by the limits imposed on it by the power supply.



Semiconducting Sensors

Positional detector / Safety Interlock:

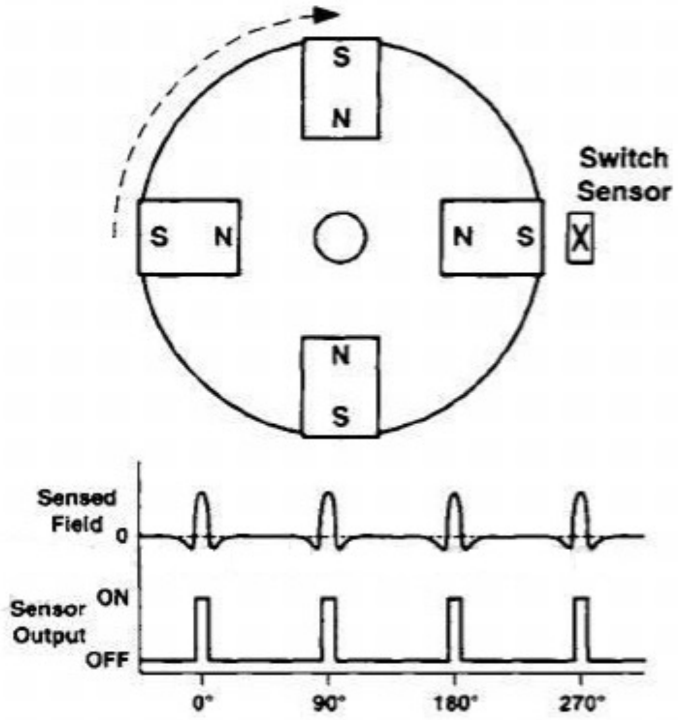
- This head-on positional detector will be “OFF” when there is no magnetic field present.
- When the permanent magnets south pole is moved perpendicular towards the active area of the Hall effect sensor the device turns “ON” and lights the LED.
- Once switched “ON” the Hall effect sensor stays “ON”.
- To turn the device and therefore the LED “OFF” the magnetic field must be reduced to below the release point for unipolar sensors or exposed to a magnetic north pole for bipolar sensors.



Semiconducting Sensors

Speedometer:

- Fixed hall senor, placed near spinning permanent magnets
- Resulting output becomes a series of pulses which can be detected by a change in the hall voltage.
- Pulses are generated each time a magnet passes the hall sensor
- Can be used to calculate speeds directly, or that of larger objects



(a)

Summary

- Various physical principles can be used to detect physical phenomenon

- Sensors can be modulated or self-modulated, and may impose a load on our quantity to be measured

- Transduction of a physical quantity to an electrical signal can be done using:
  Resistance
  Capacitance
  Inductance
  Semiconduction
  and other means