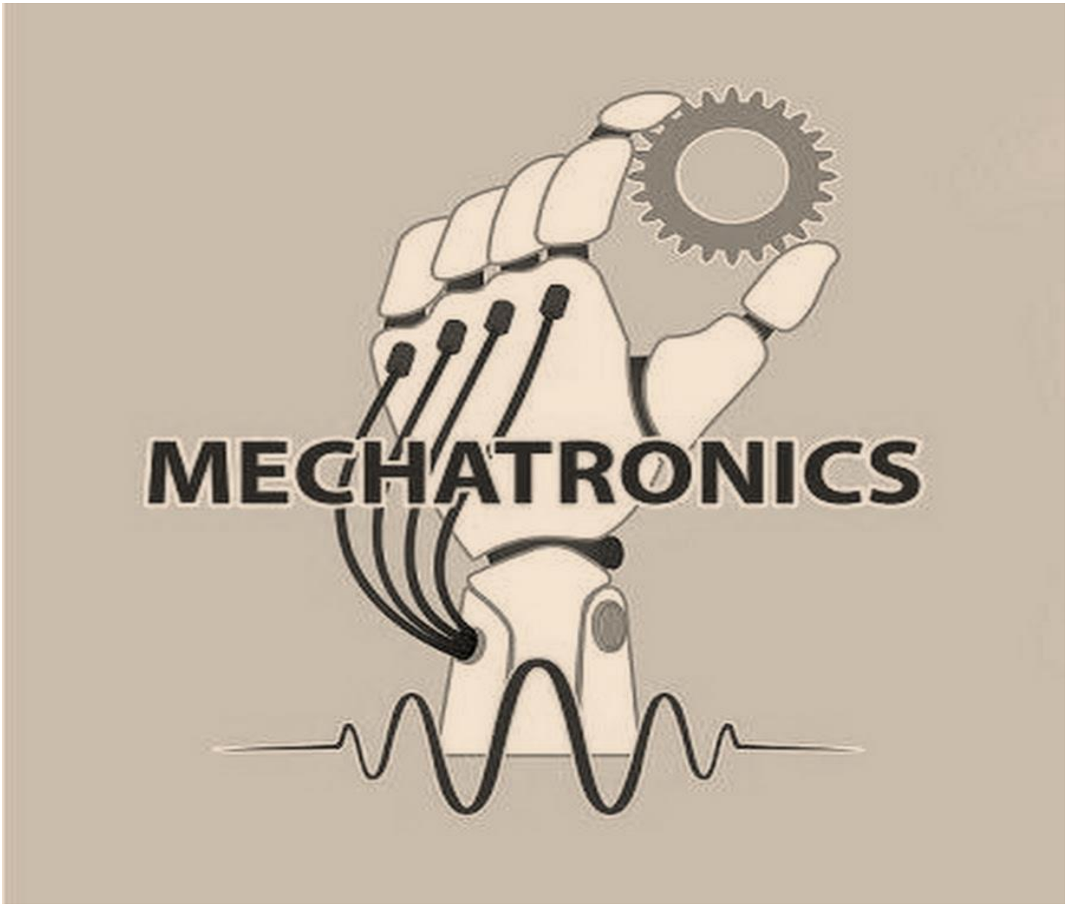

Mechatronics systems and applications

Code- ARA 204

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Faculty, USAR, GGSAIPU

Syllabus

S. No.	Contents
1	**Introduction**: Definition of mechatronics, measurement system, control systems, microprocessor based controllers, mechatronics approach.
2	**Sensors and Transducers**: Sensors and transducers, performance terminology, photoelectric transducers, flow transducers, optical sensors and transducers, semiconductor lasers, selection of sensors, mechanical / electrical switches, inputting data by switches.
3	**Actuators**: Actuation systems, pneumatic and hydraulic systems, process control valves, rotary actuators, mechanical actuation systems, electrical actuation systems.
4	**Signal Conditioning**: Signal conditioning, filtering digital signal, multiplexers, data acquisition, digital signal processing, pulse modulation, data presentation systems.
5	**Microprocessors and Microcontrollers**: Microcomputer structure, microcontrollers, applications, programmable logic controllers.
6	**Modeling and System Response**: Mathematical models, bond graph models, mechanical, electrical, hydraulic and thermal systems, dynamic response of systems, transfer function and frequency response, closed loop controllers.
7	**Design and Mechatronics**: Input/output systems, computer based modular design, system validation, remote monitoring and control, designing, possible design solutions, detailed case studies of mechatronic systems used in photocopier, automobile, robots.

Unit I [12]

Introduction: Introduction to Mechatronics System, Elements of mechatronics system, mechatronics in manufacturing, product and design, Measurement Systems, Control System, comparison between traditional and mechatronics approach.

Sensors and Transducers: Introduction, Performance terminology, static and dynamic characteristics of transducers, Displacement Measurement: Transducers for displacement, displacement measurement, potentiometer, LVDT. Strain Measurement: Theory of Strain Gauges, Bridge circuit, Strain gauge based load cells and torque sensors, Velocity and Motion: Electromagnetic tachometer, photoelectric tachometer, variable reluctance tachometer, Digital Encoders. Vibration and acceleration: Eddy current type, piezoelectric type; Accelerometer: Principle of working, practical accelerometers, strain gauge based and piezoelectric accelerometers. Pressure Measurement: Elastic pressure transducers viz. Bourdon tubes, diaphragm, bellows and piezoelectric pressure sensors. Flow Measurement: Bernoulli flowmeter, Ultrasonic flowmeter, Magnetic flow meter, Rotameter. Miscellaneous Sensors: Leak detector, Flame detector, Smoke detector, pH sensors, Conductivity sensors, Humidity sensors, Potentiometric Biosensors and Proximity sensors. Selection of sensors

Unit II [10]

Mechanical Actuation System: Cams, Gear trains, Ratchet and Pawl, Belt and chain drives, Bearings.

Hydraulic and Pneumatic Actuation System: Introduction to Hydraulic and Pneumatic Systems, Directional Control valves, Flow control valves.

Electrical Actuation System: Electrical systems, Solid State Switches, Solenoids, D.C. motors, A.C. motors, Stepper motors.

Unit III [12]

Microprocessors: Microprocessor systems, Microcontrollers, applications.

Programmable logic controllers: Programmable logic controllers (PLC) Structure, Input / Output Processing, principles of operation, PLC versus computer, Programming Languages, programming using Ladder Diagrams, Logic Functions, Latching, Sequencing, Timers, Internal Relays And Counters, Shift Registers, Master and Jump Controls, Jumps, Data Movement, Code Conversion, Data handling and manipulation, selecting a PLC.

Unit IV [8]

System Models: Mathematical models, Mechanical, Electrical, hydraulic and Thermal Systems, Modelling of dynamic systems.

Design of Mechatronics systems: Stages in designing mechatronics system, Traditional and Mechatronic design.

Case studies of Mechatronics system: Mechatronic approach to design, Boat Auto pilot, Pick and place robots, high speed tilting train, automatic car park system, coin counter, engine management system, automated guided vehicle, autonomous mobile system, antilock brake system control, Auto-Focus Camera, Printer, Domestic Washing Machine, Optical Mark Reader, Bar Code Reader

Books

- Mechatronics: Bolton, W., Longman
- Introduction to Mechatronics: D.G. Alciatore & Michael B. Histand; Tata Mc Graw Hill
- Mechatronic system Design; Shetty Dedas, Kolk and Richard
- Mechatronic handbook: Bishop; CRC press
- Intelligent Mechatronic Systems: Modeling, Control and Diagnosis, R. Merzouki, A. K. Samantaray, P. M. Pathak, B. Ould Bouamama, Springer, London

Unit 1: Introduction of Mechatronics

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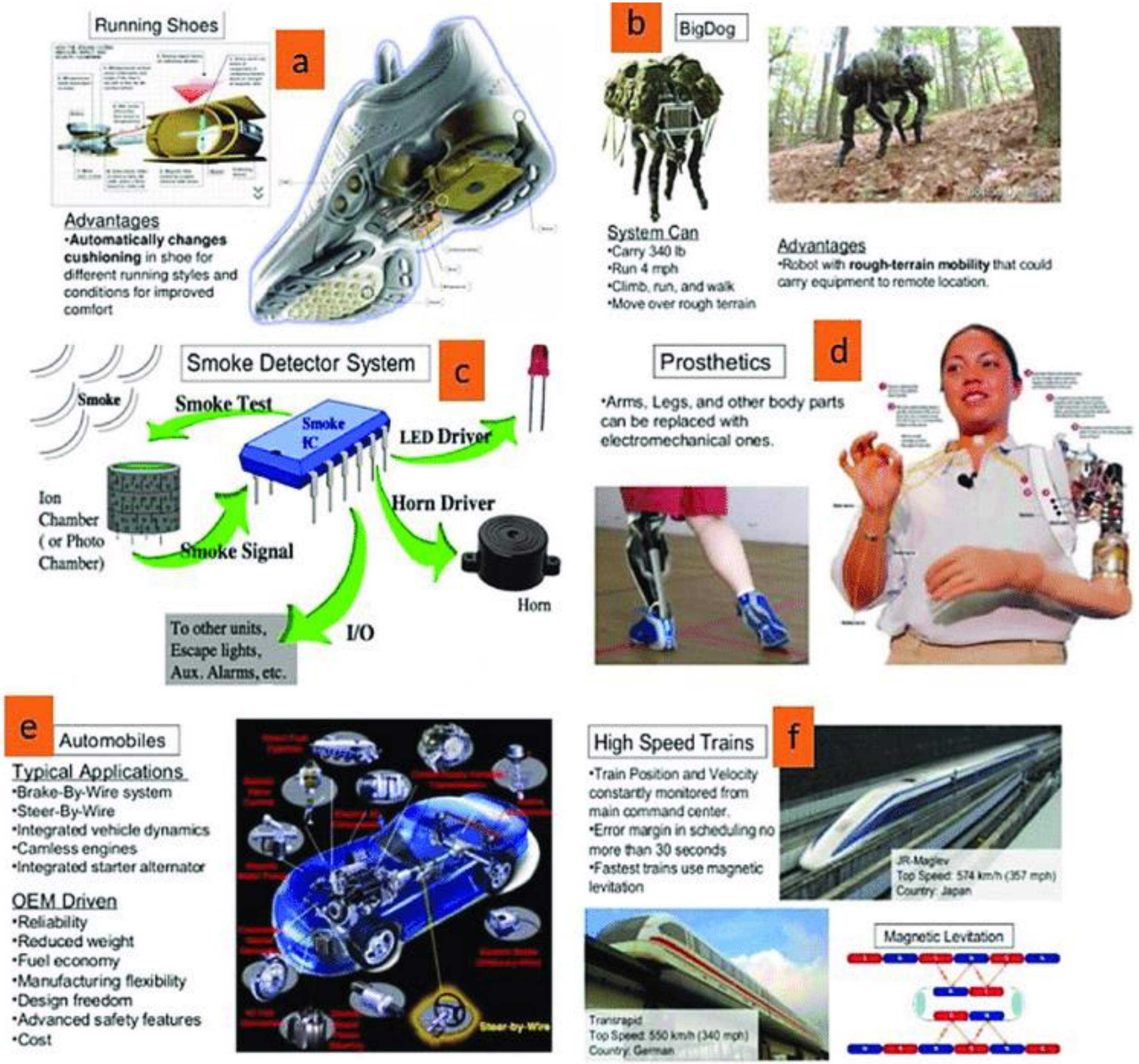
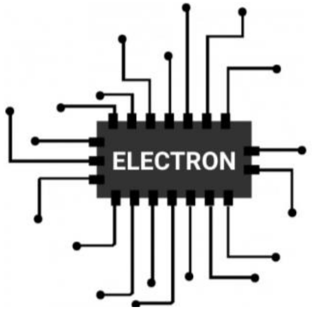
USAR



MECHAnics + elecTRONICS



- The word **Mechatronics** originated in Japanese-English and was created by **Tetsuro Mori,** an engineer of **Yaskawa Electric Corporation**. [**1969**]

- ***The general definition of Mechatronics can be…***
- Mechatronics is the **synergetic integration** of sensors, actuators, signal conditioning, power electronics, decision and control algorithms and computer hardware & software to manage complexity, uncertainty and communication in engineer system.

Some other Book definitions of mechatronics.

"Integration of electronics, control engineering, and mechanical engineering."

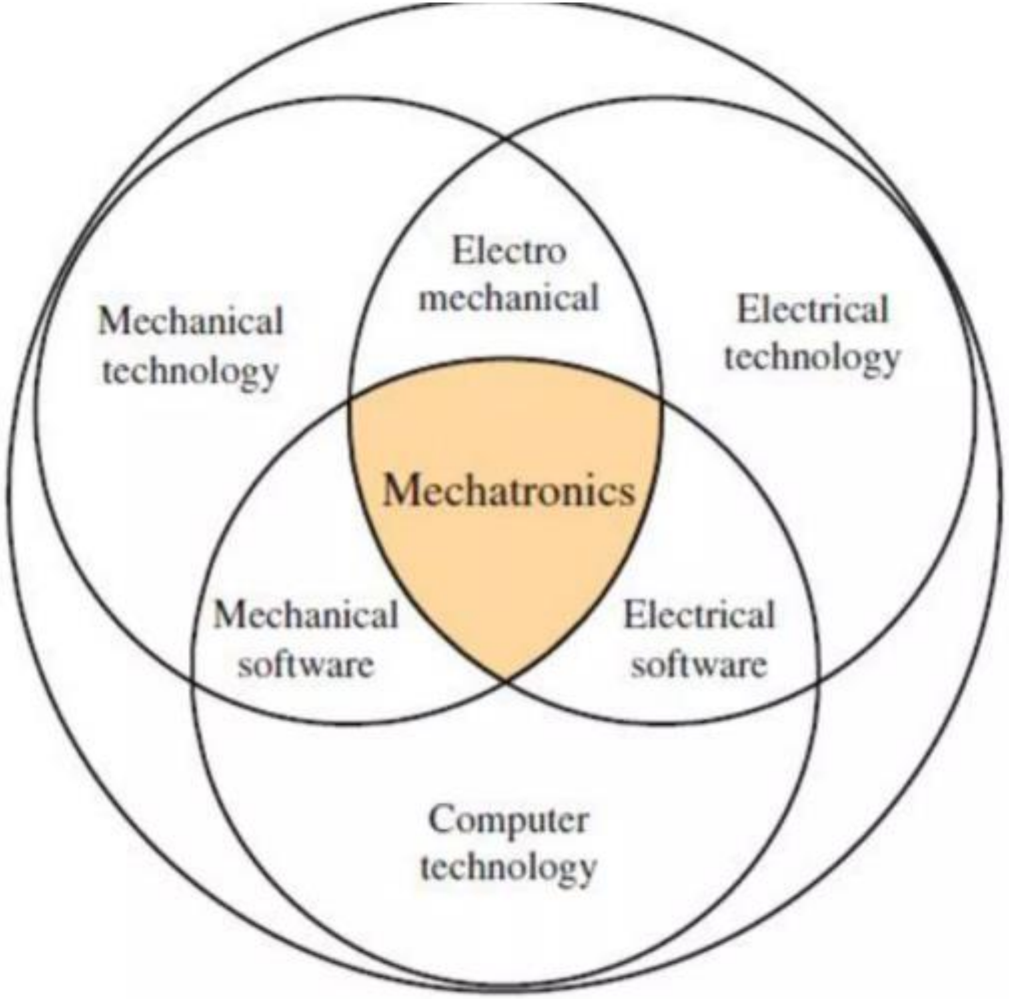
- W. Bolton, *Mechatronics: Electronic Control Systems in Mechanical Engineering*, Longman, 1995.

"Application of complex decision making to the operation of physical systems."

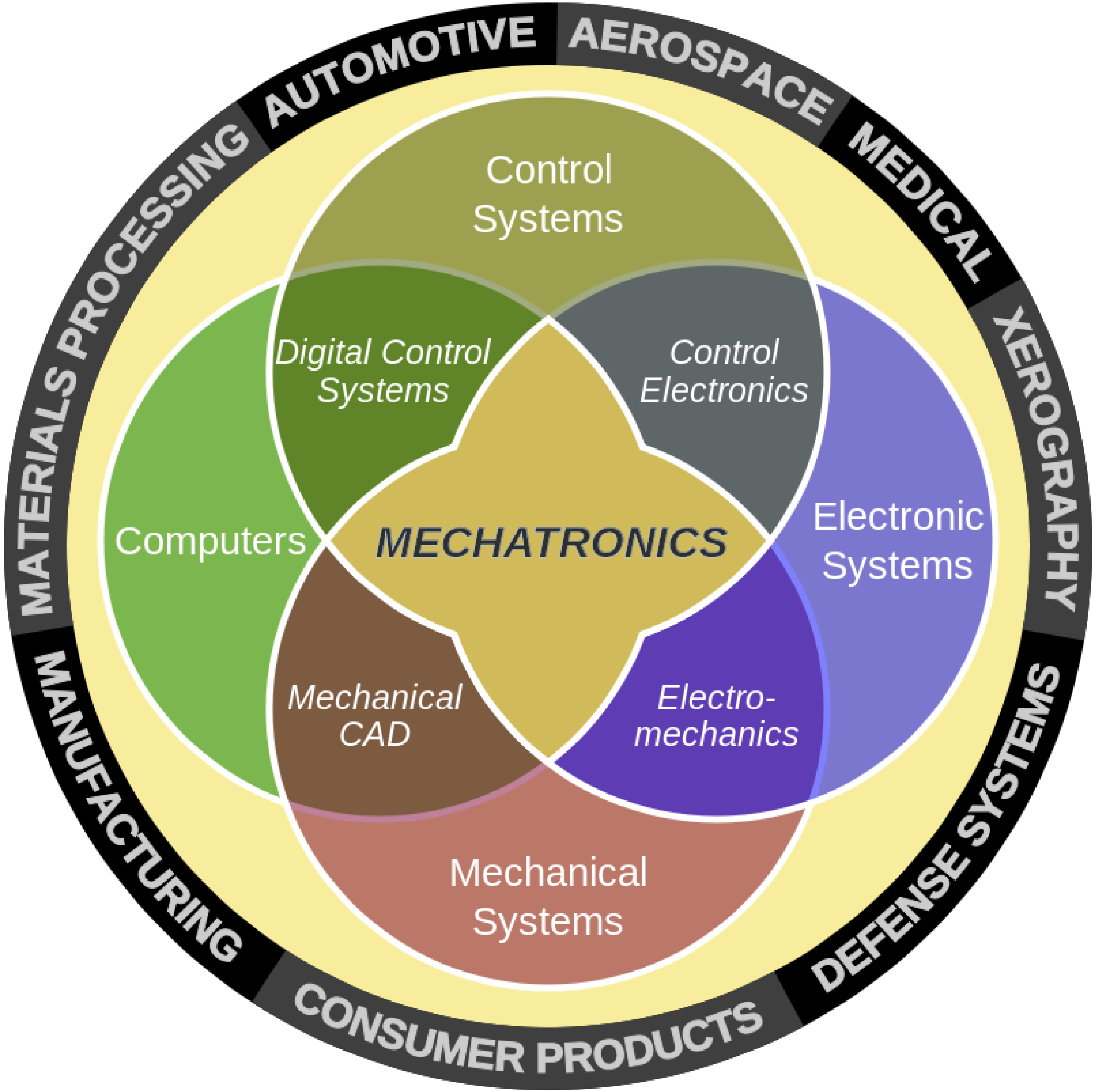
- D. M. Auslander and C. J. Kempf, *Mechatronics: Mechanical System Interfacing*, Prentice-Hall, 1996.

"Synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes."

- F. Harshama, M. Tomizuka, and T. Fukuda, "Mechatronics-what is it, why, and how?-and editorial," *IEEE/ASME Trans. on Mechatronics*, 1(1), 1-4, 1996.



A mechatronics engineer unites the principles of mechanics, electrical, electronics, and computing to generate a simpler, more economical and reliable system



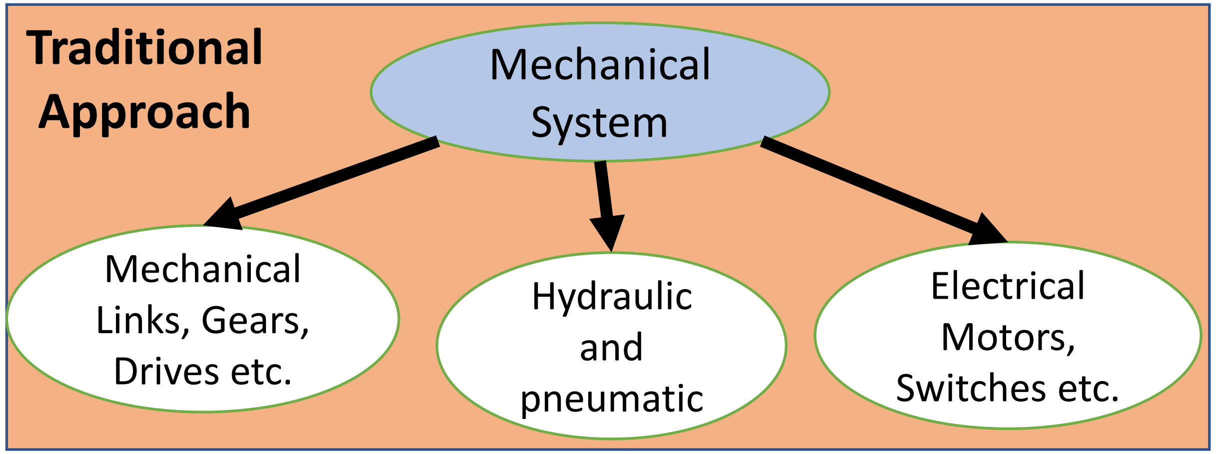
Need of Mechatronics.

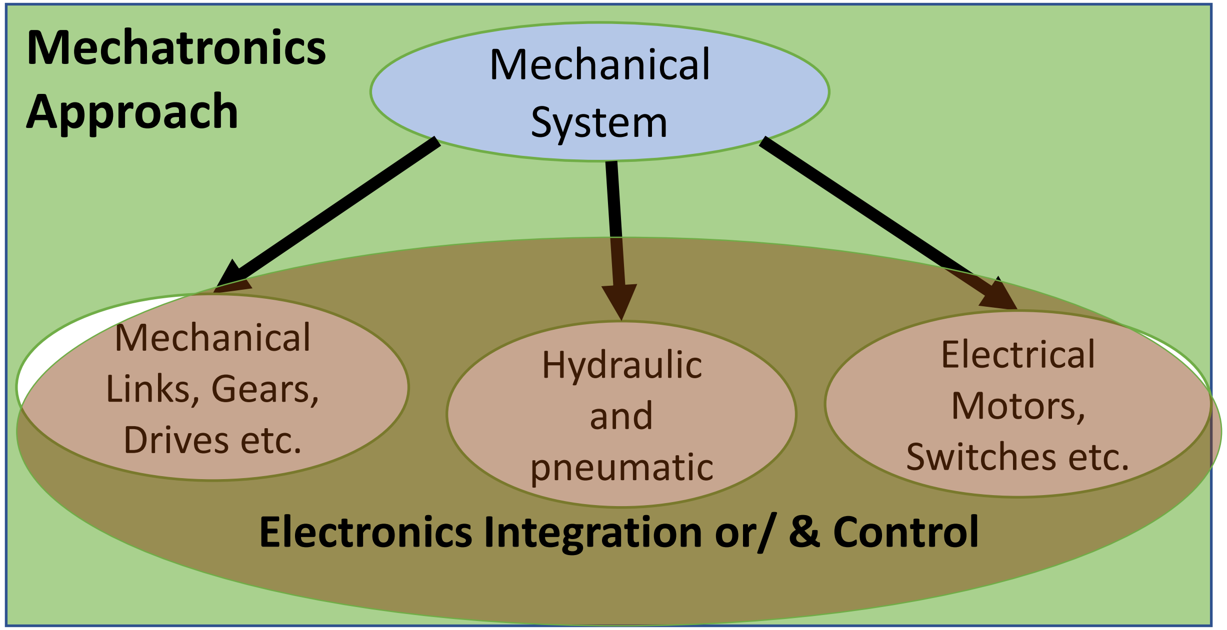
Mechatronics?

- Implementing electronics control in a mechanical system.
- Enhancing existing mechanical design with intelligent control.
- Replacing mechanical component with a electronic solution.



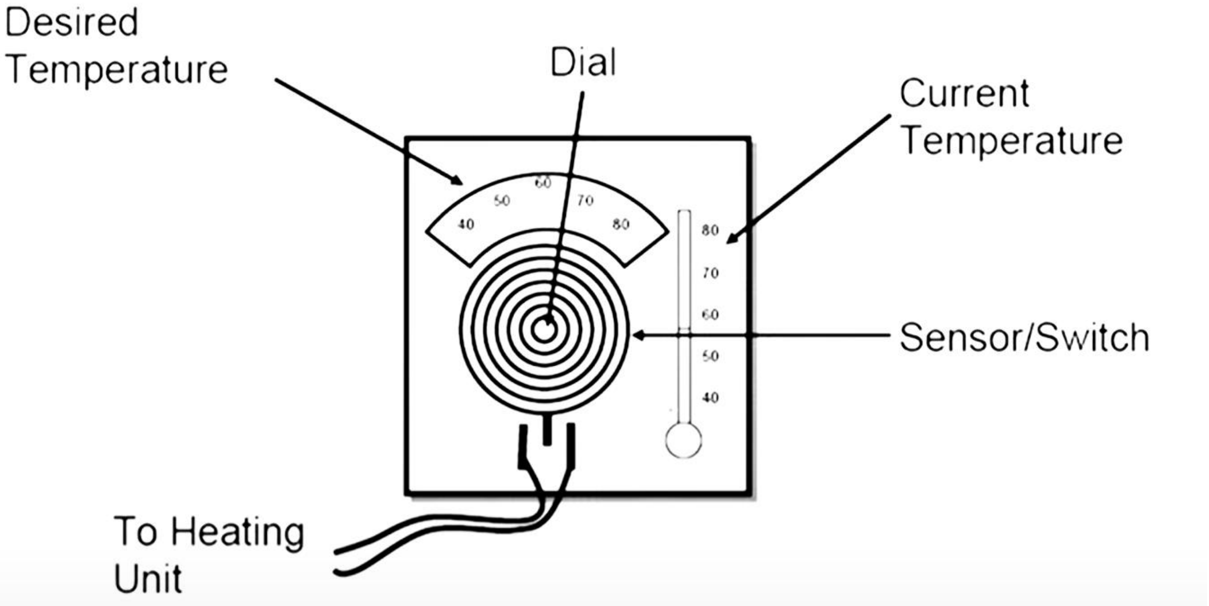

Comparison of traditional and mechatronics design

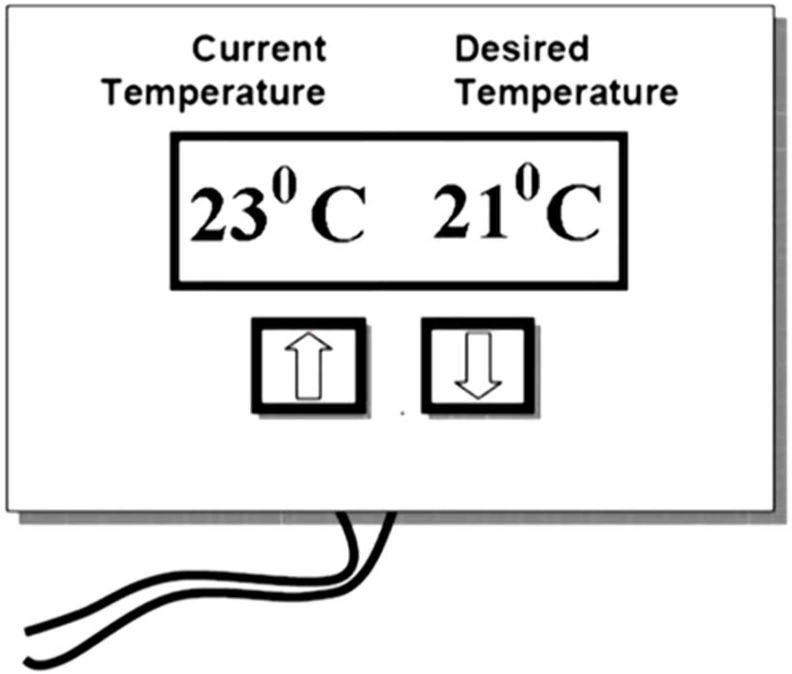




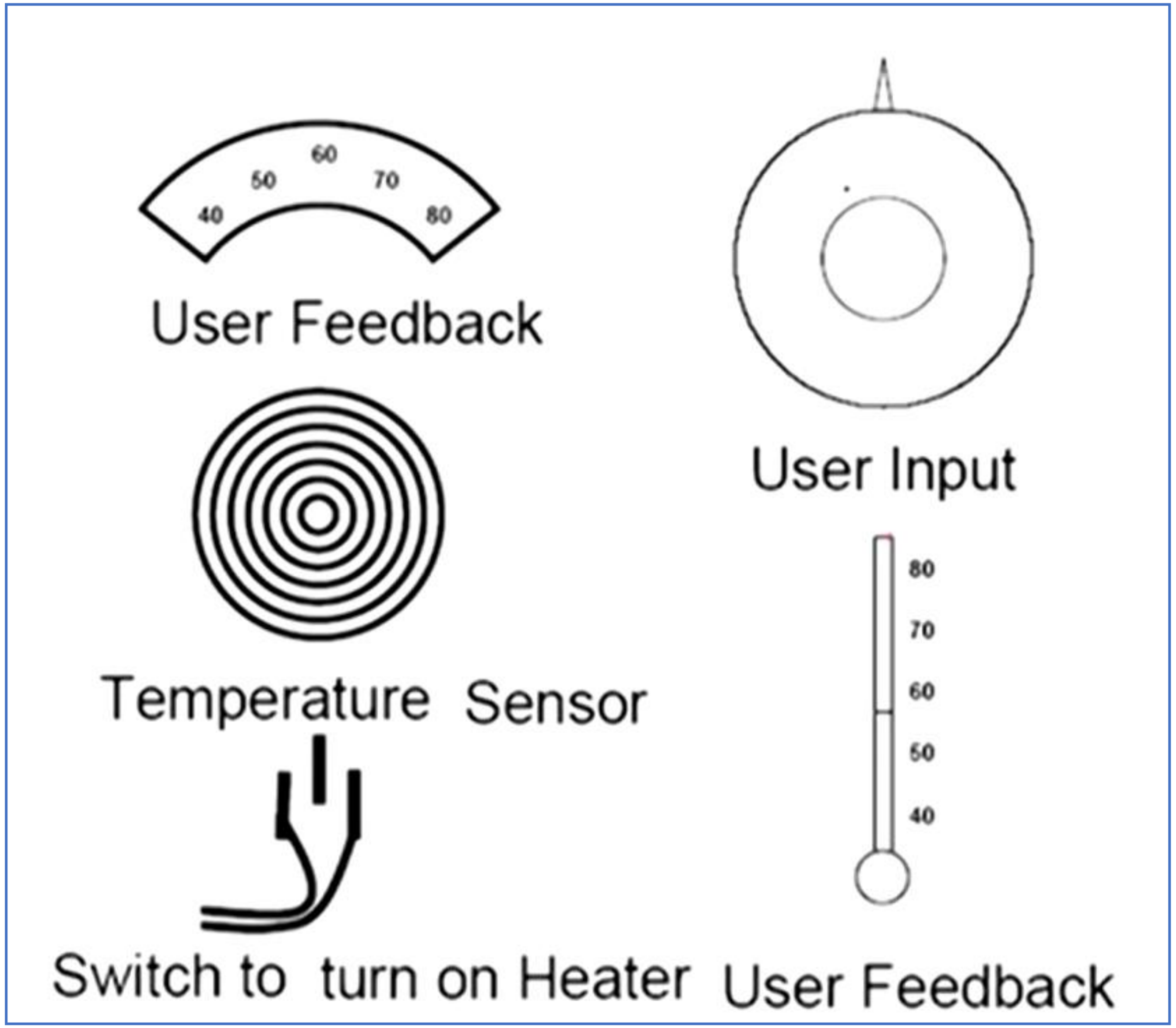
S.No	Traditional design	Mechatronics design
1	It is based on a traditional systems such as mechanical, hydraulic and pneumatic systems.	It is based on mechanical, electronics, computer technology and control engineering.
2	Less flexible.	More flexible.
3	Less accurate.	More accurate.
4	More complicate mechanism in design.	Less complicate mechanism design.
5	It involves more components and moving parts.	It involves fewer components and moving parts.

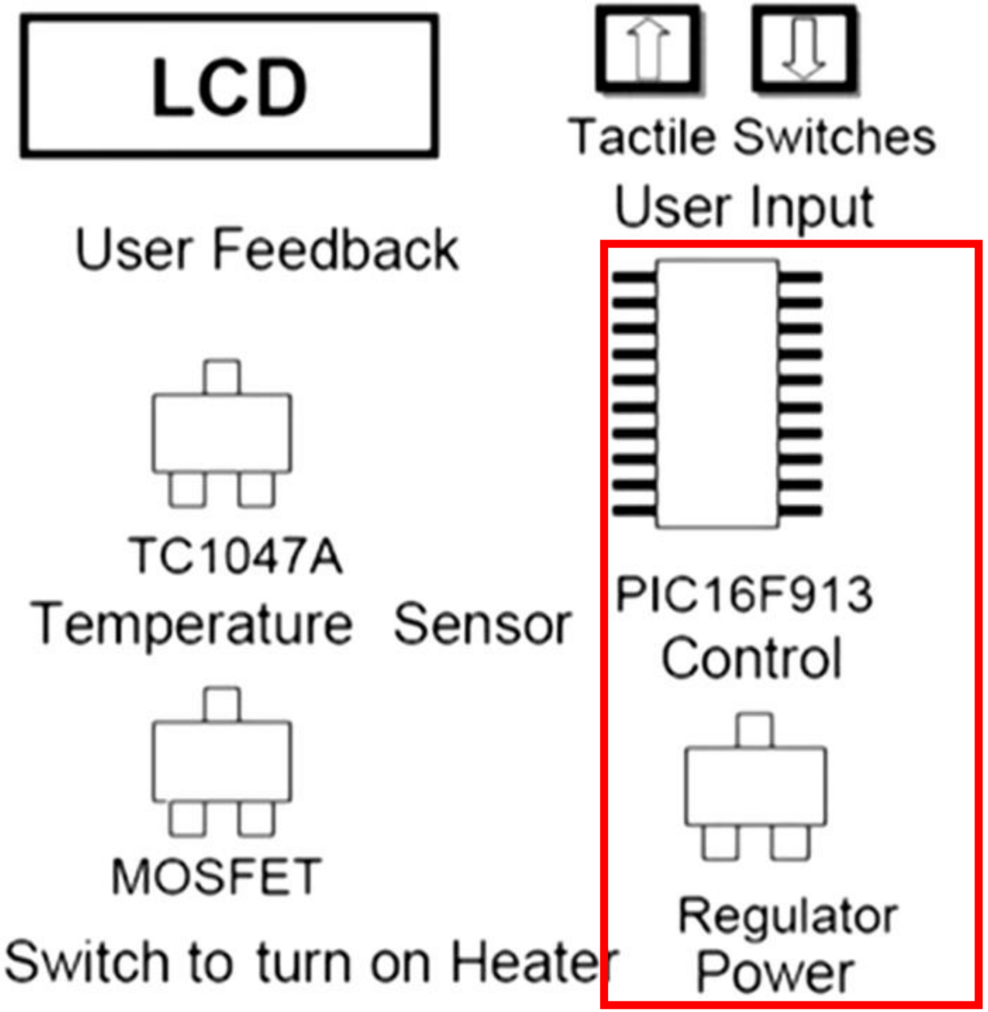
Fundamental comparison on traditional and modern **thermostat**





Thermostat components: Conversion to Mechatronic Design



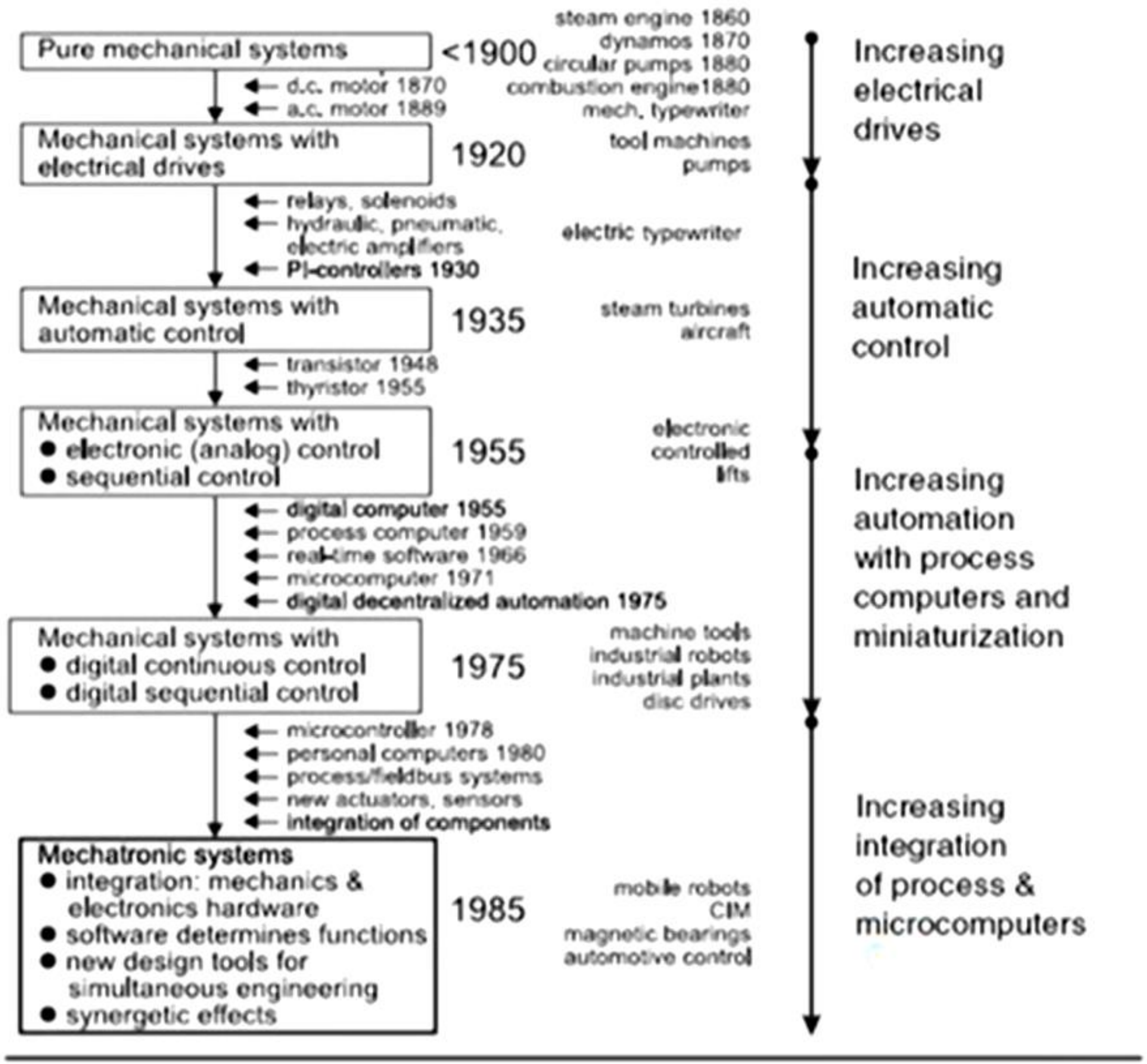


Classification of Mechatronics Products

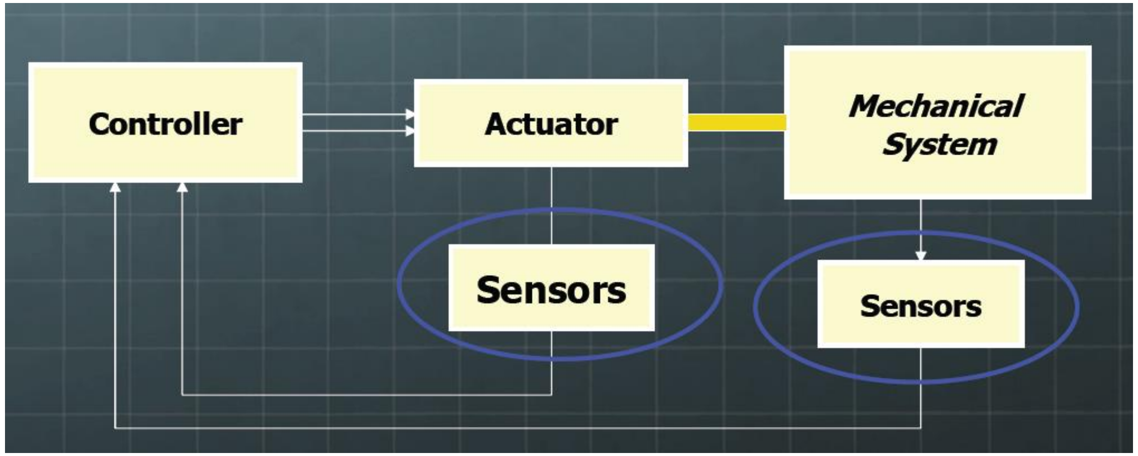
- In the late 1970s, the Japan Society for the Promotion of Machine Industry (JSPMI) classified mechatronic products into
- Class I:
  - Primarily mechanical products with electronics incorporated to enhance functionality.
  - Examples include numerically controlled machine tools and variable speed drives in manufacturing machines.
- Class II:
  - Traditional mechanical systems with significantly updated internal devices incorporating electronics. The external user interfaces are unaltered.
  - Examples include the modern sewing machine and automated manufacturing systems.

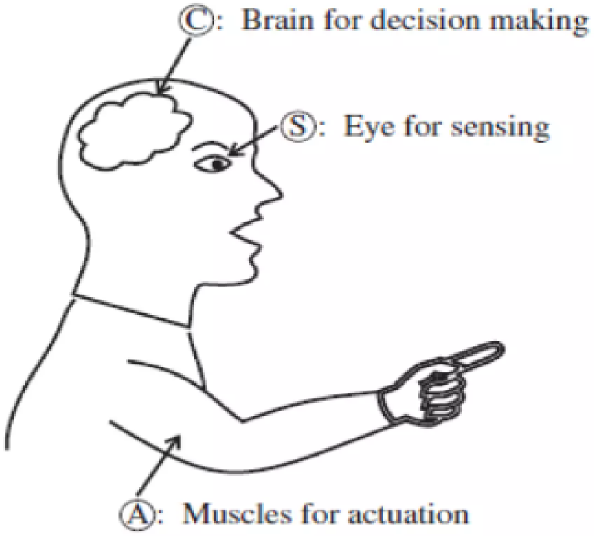
- Class III:
  - Systems that retain the functionality of the traditional mechanical system, but the internal mechanisms are replaced by electronics.
  - An example is the digital watch.
- Class IV:
  - Products designed with mechanical and electronic technologies through synergistic integration.
  - Examples include photocopiers, intelligent washers and dryers, and automatic ovens.

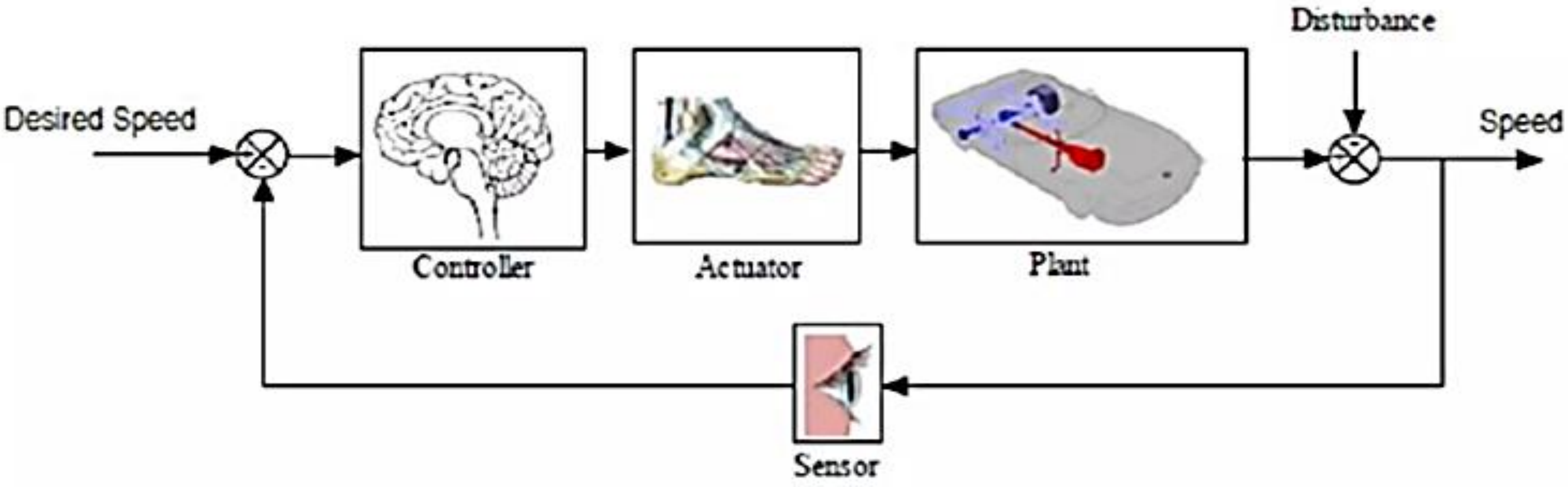
Historical Development of Mechanical, Electrical, and Electronic Systems



Elements of the Mechatronics System







Vehicle Speed Control

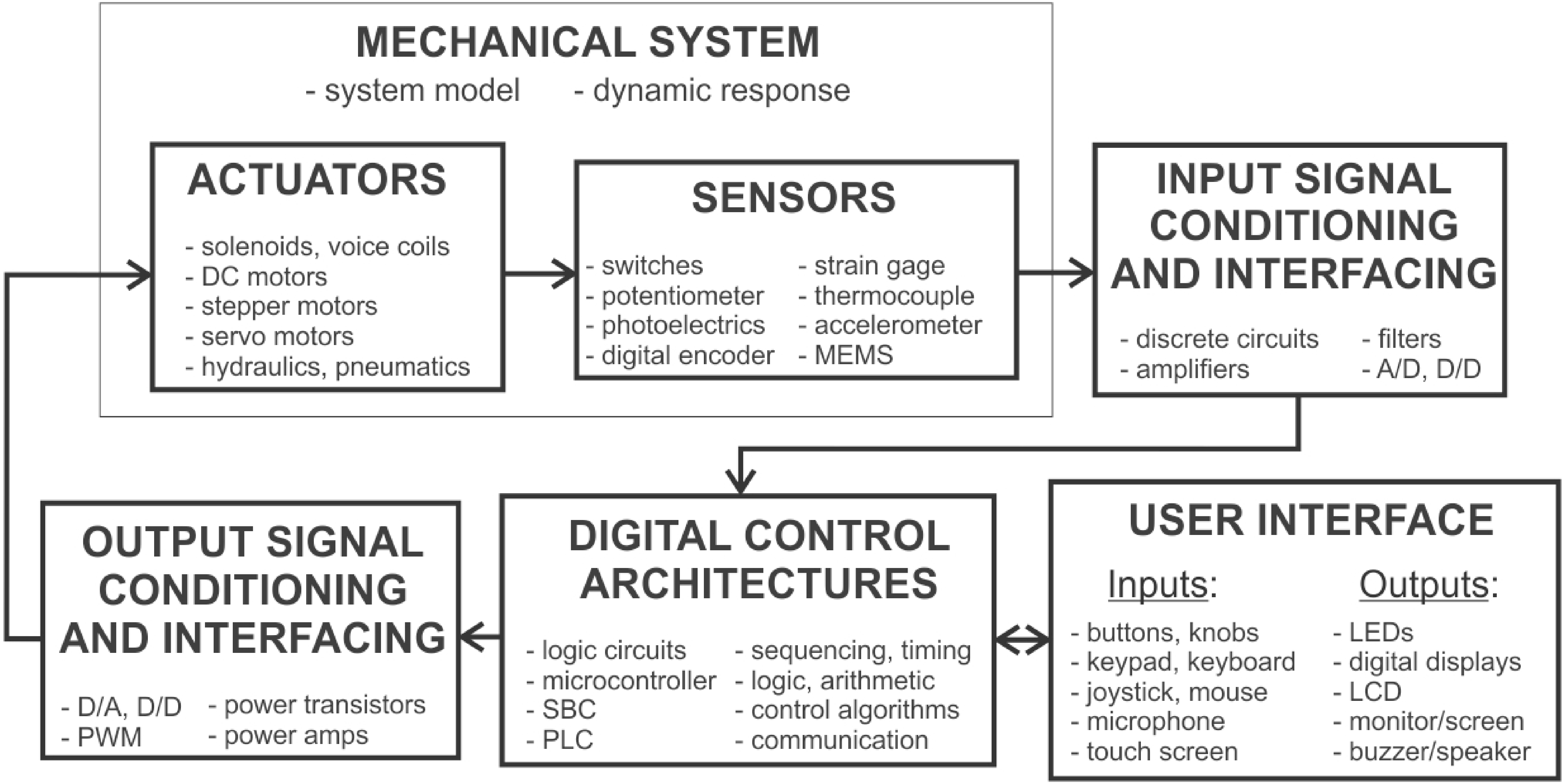
Examples of Mechatronic Systems

- Antilock Brake System (ABS)
- Electronic Fuel Injection (EFI)
- Traction Control System (TCS)
- Adaptive Cruise Control (ACC)
- Automatic Camera
- Scanner
- Hard Disk Drive
- Industrial Robots
- Mobile Robots (Wheeled Robots, Legged Robots)

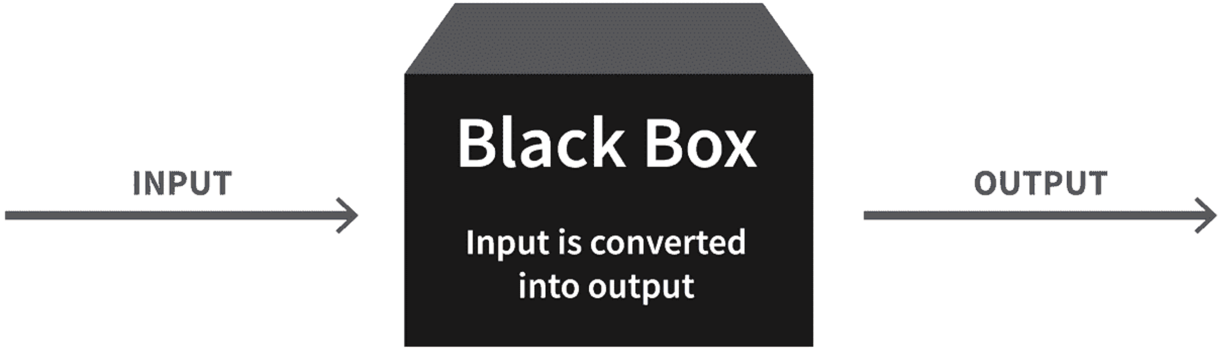
Benefits of Mechatronics

- More features
- Higher precession
- User friendly
- More flexible
- Lower cost, Efficient
- Environment friendly
- Smaller geometry
- More reliable
- Safer

Mechatronics system components

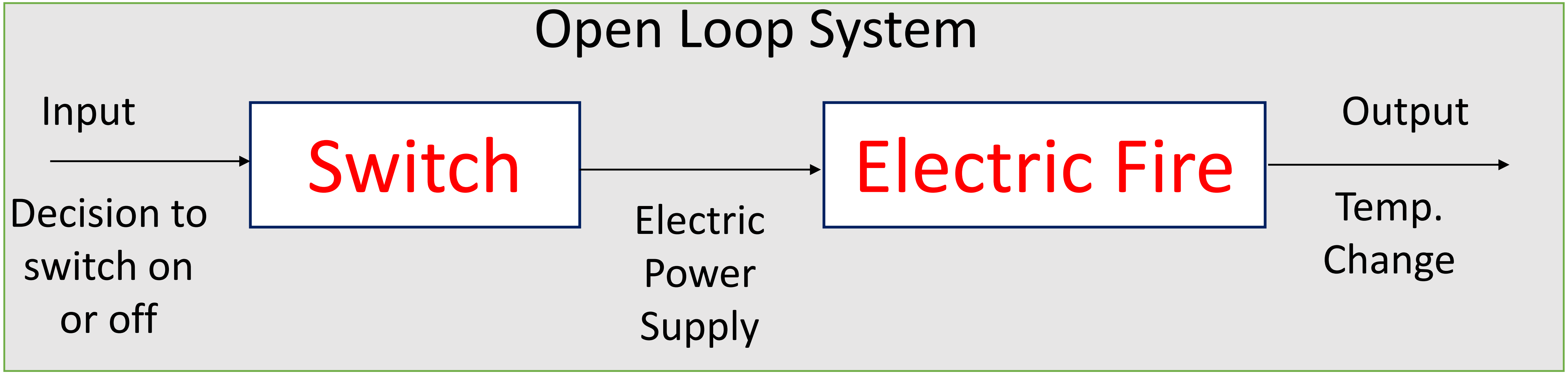


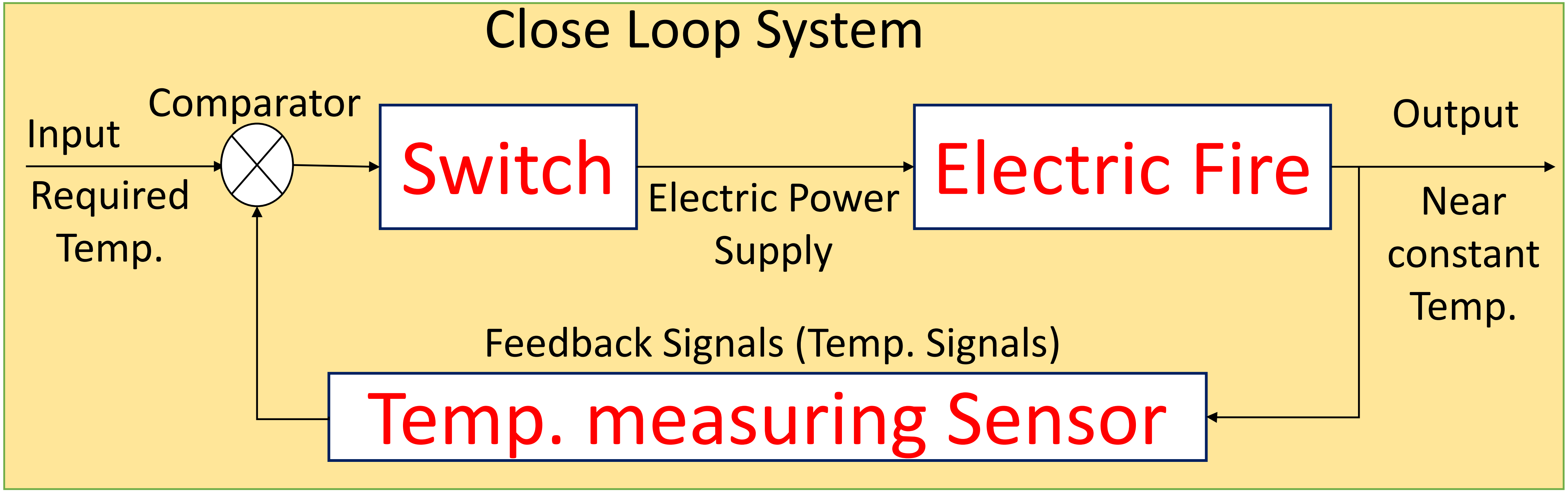
MEASUREMENT SYSTEM

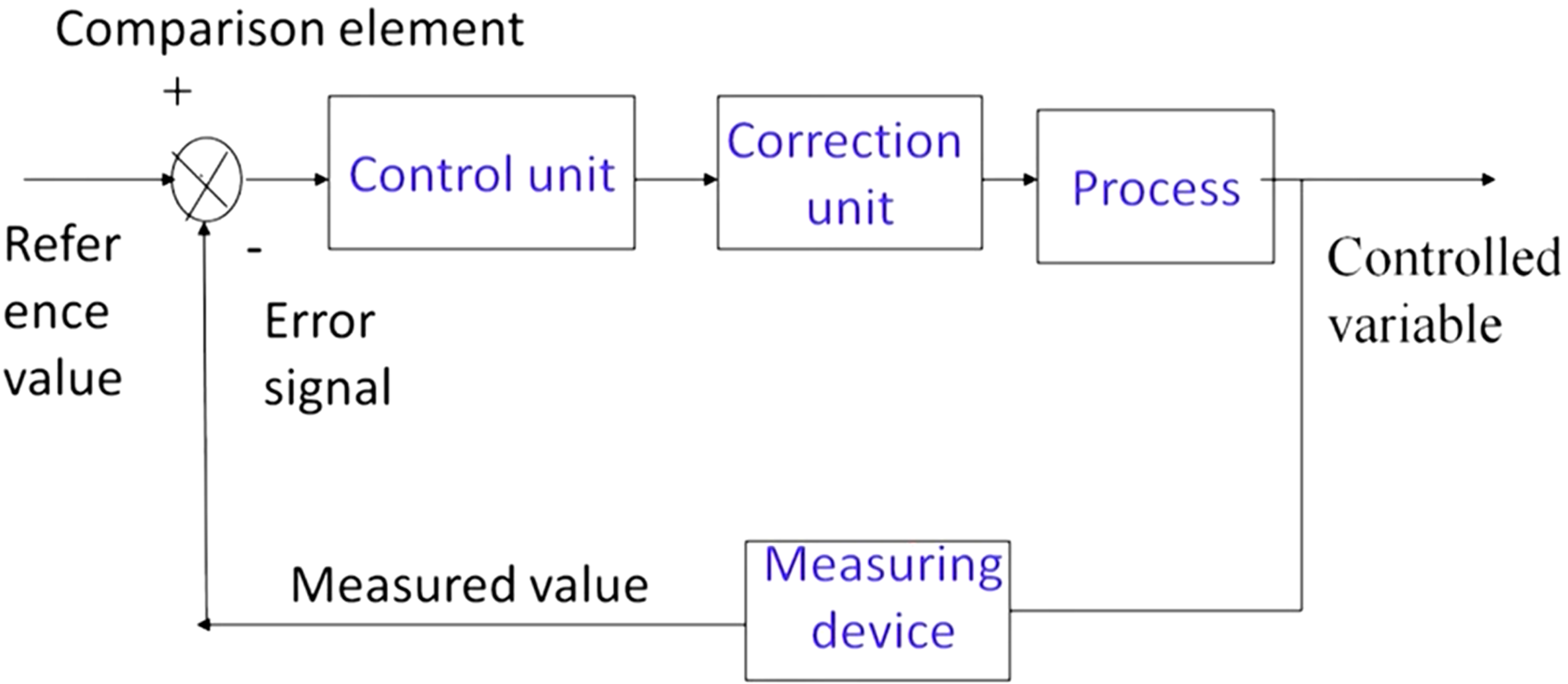


Measurement system consists of the following three elements.

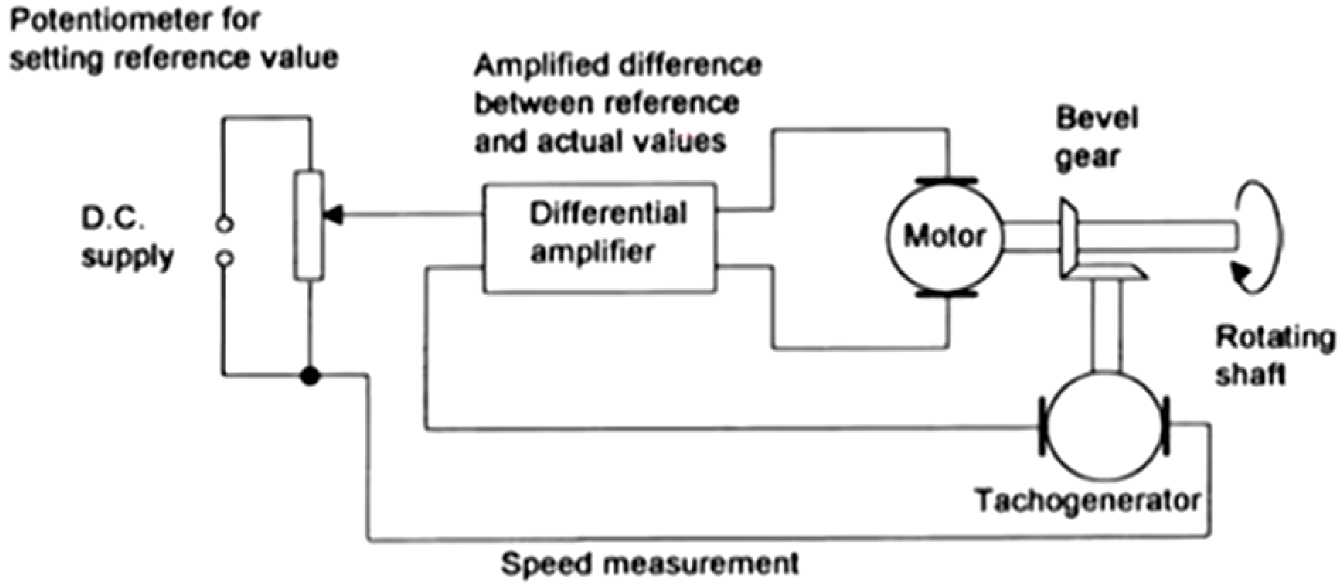
a) Sensor **b)** Signal conditioner **c)** Display System

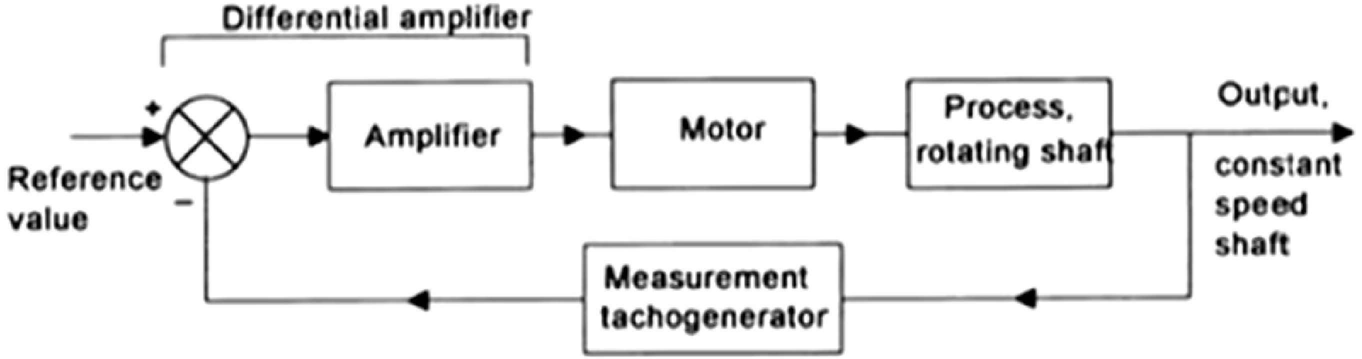

Open Loop System
Input
Decision to switch on or off
Switch
Electric Power Supply
Electric Fire
Output
Temp. Change


Close Loop System
Input
Required Temp.
Comparator
Switch
Electric Power Supply
Electric Fire
Output
Near constant Temp.
Feedback Signals (Temp. Signals)
Temp. measuring Sensor


Comparison element
+
-
Refer
ence
value
Control unit
Correction
unit
Process
Controlled
variable
Error
signal
Measured value
Measuring
device

Shaft Speed Control (Closed loop system)





Sensors and transducers

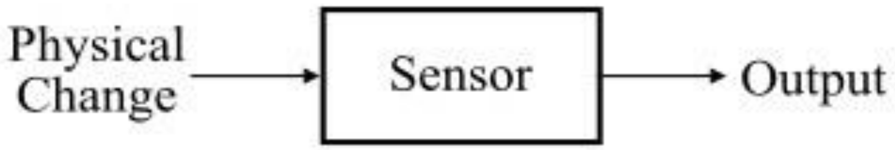


Figure - Sensor

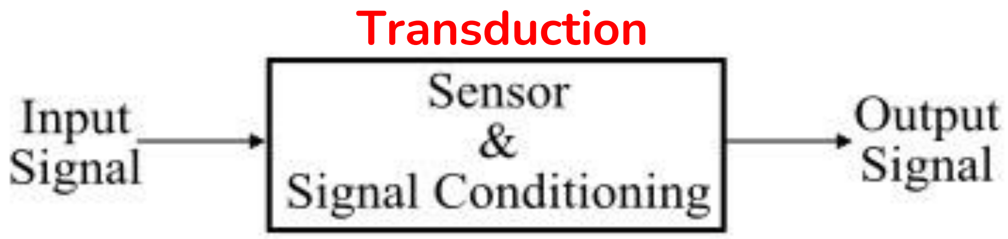


Figure - Transducer

A **sensor** is a device that detects any physical quantity such as pressure, light, heat, temperature, humidity, etc. from the outside environment

Some common examples of sensors are temperature sensor, pressure sensor, humidity sensor, proximity sensor, photo sensor, motion sensor, etc.

A device that is used for transforming energy from one form to another form is known as **transducer**.

Basis of Difference	Sensor	Transducer
Definition	A sensor is a device which converts the physical parameter of a quantity into corresponding electrical output.	A transducer is a device that transforms energy from one form to another, such as speed into electrical signal.
Main components	A sensor does not have any other component except itself.	The components of a transducer are − input device (sensor), processing device (signal conditioning), and output device.
Dependency	All the sensors are not transducers.	A sensor is the part of all the transducers.
Complexity	A sensor is less complicated in its construction and processing.	Transducer is a relatively more complex device because it involves the transformation of energy from one form to another.
Function	A sensor detects the change in the physical parameter of quantity to produce corresponding electrical signal.	Transducer converts the energy into a different form.
Feedback	Sensor does not provide any feedback to the system. Which means, it only measures the change in the physical quantity and cannot give input to the system on its own.	Transducer generally provides a feedback to the system through the output device after processing.
Examples	Common examples of sensor are: temperature sensor, photo sensor, proximity sensor, etc.	Examples of transducers are: strain gauge, microphone, loud speaker, piezoelectric element, etc.

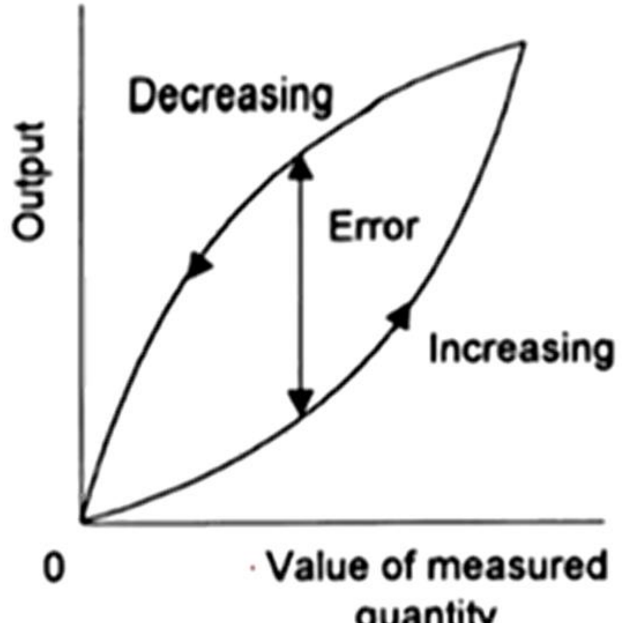
Performance Terminology

- Range
  - limits between which the input can vary
- Span
  - maximum value-minimum value
  - For a load cell measurement of forces might have a range of 0 to 50 kN and a span of 50 kN
- Error
  - measured value – true value
  - A sensor might give a resistance change of 10.2 Ω when the true change is 10.5 Ω . The error is thus -0.3 Ω.

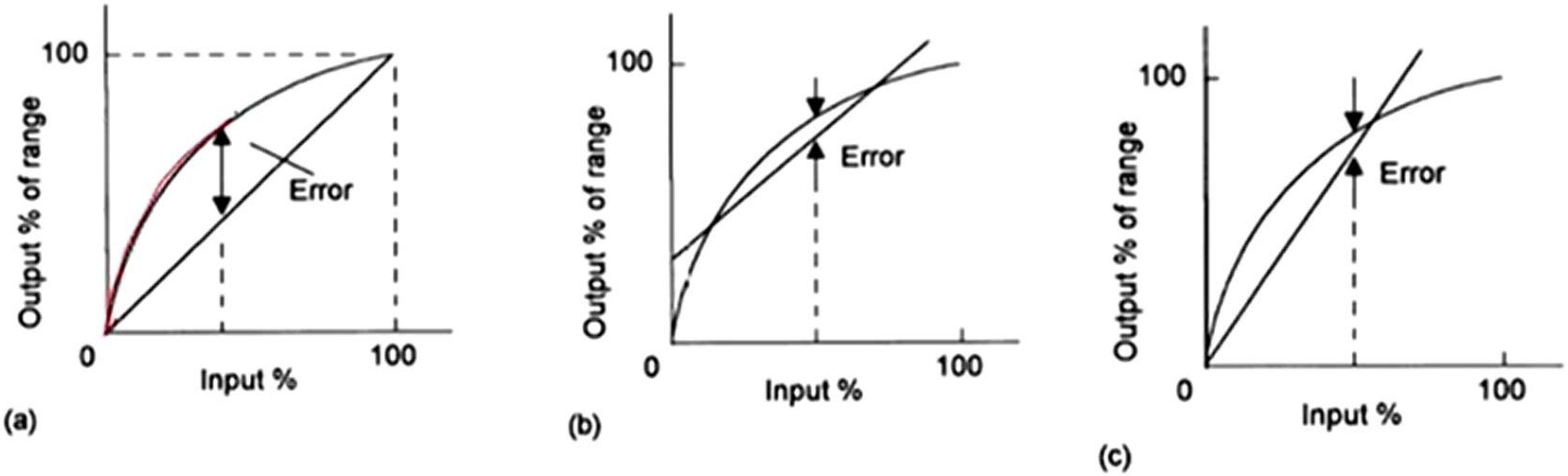
- Accuracy
  - Extent to which the value indicated might be wrong.
  - Accuracy of $\pm 2^{\circ}C$ means reading of instrument may lie + or $-2^{\circ}C$.
  - Also expressed as % of full range output.
  - Range 0 to $200^{0}C$, accuracy $\pm 5\%$, means result is expected to lie within + or $-10^{0}C$

- Sensitivity
  - Relation ship indicating how much output one gets per unit input.
  - A resistance thermometer may have a sensitivity of 0.5 Ω/ ˚C.
  - Many times sensitivity is expressed for input which is not being measured.

- Hysteresis Error
  - Different output for the same value of the input
  - depending upon whether it has been got for increasing value or for decreasing value.



- Non Linearity Error
- For many transducers a linear relationship between the input and output is assumed over the working range.
- Various methods are used for the numerical expression of the non linearity error.
- These method differ by the way straight line relationship against which the error is specified.



a- End range values

b- best straight line for all values (using least square)

c- best straight line through zero point

- Repeatability/reproducibility:
  - ability to give same output for repeated application of same input.
  - = [(max-min value given)/full range]x100
- Stability:
  - same output when used to measure a constant input over a period of time.
  - Drift is used to define the change of output over time.
  - The term zero drift is used for changes that occur in output when there is zero input.

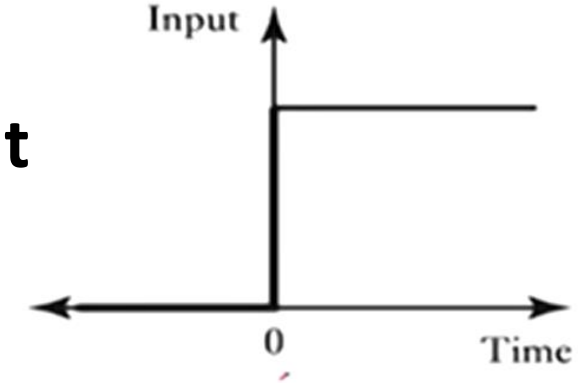
- Dead Band
  - range of input values for which no output.
- Dead Time :
  - length of time from the application of an input until the output begins to respond the change.
- Resolution:
  - smallest change in input value that will produce an observable change in output values.

- Output Impedance
  - it is important to know this as sensor is either connected in series or parallel in circuit.

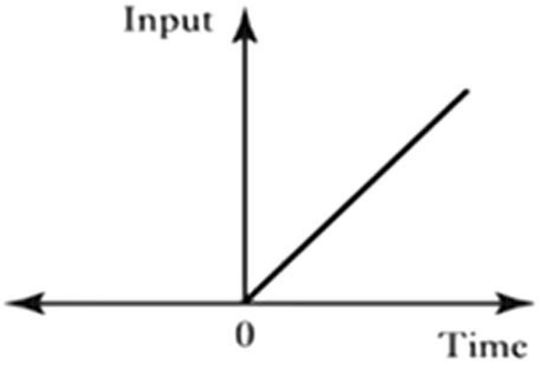
Static & Dynamic Characteristics

- Static Characteristic
  - Values given when steady state condition occurs i.e., values settle down after receiving the input.
- Dynamic Characteristic
  - behavior between the time that the input values changes and the time the values given by transducers settle down.

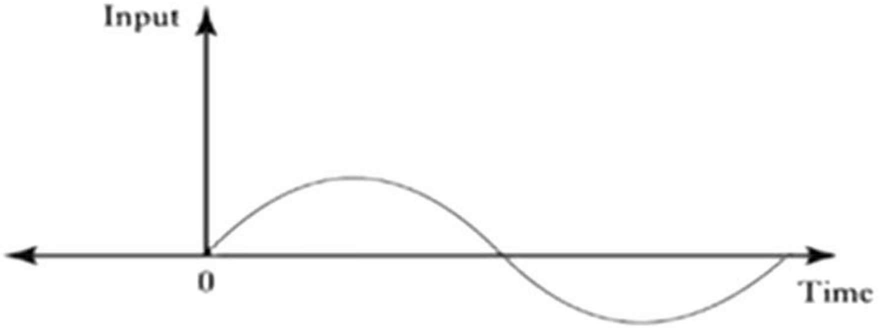
Input



Step input (0 to a constant value)



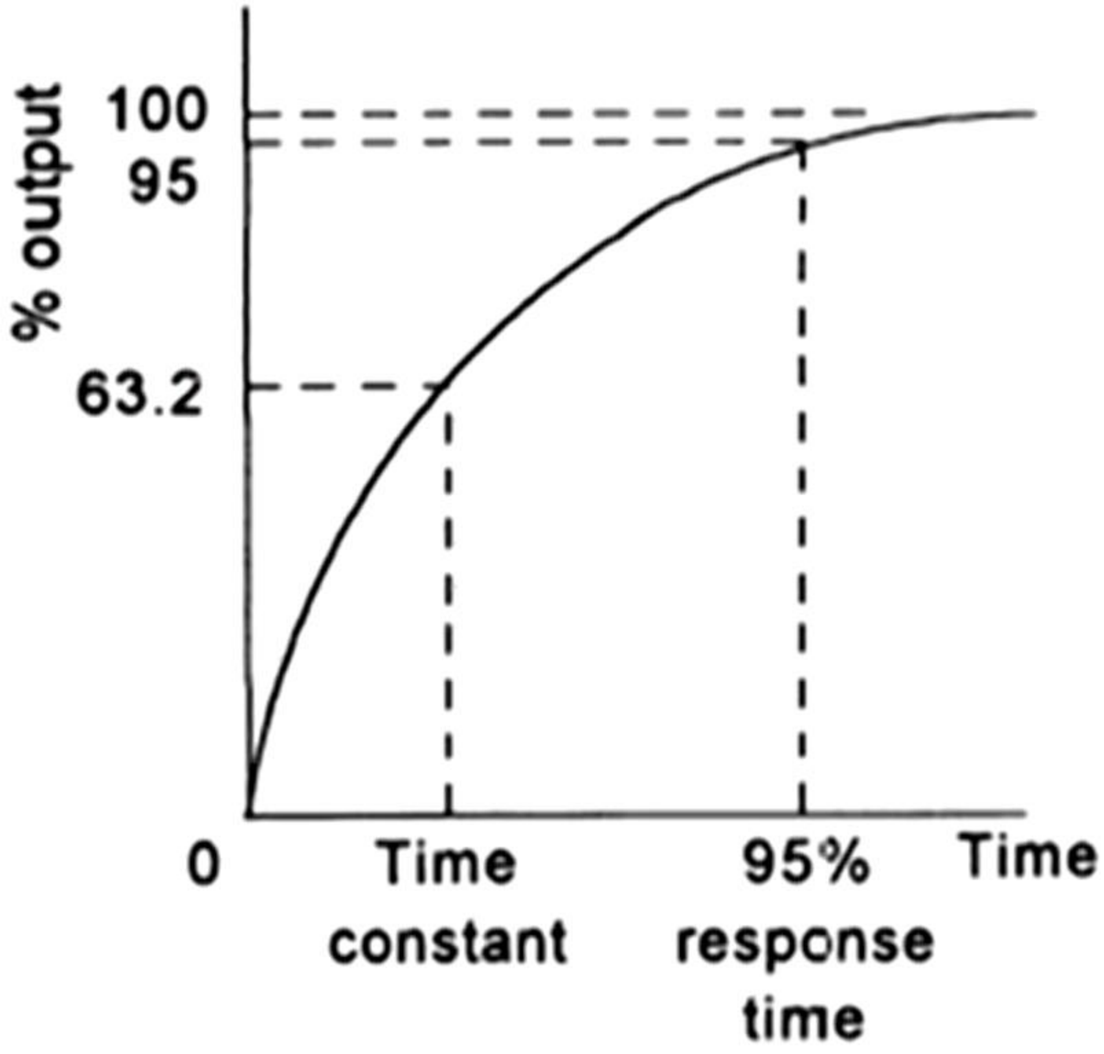
Ramp i/p – i/p changed at steady rate.

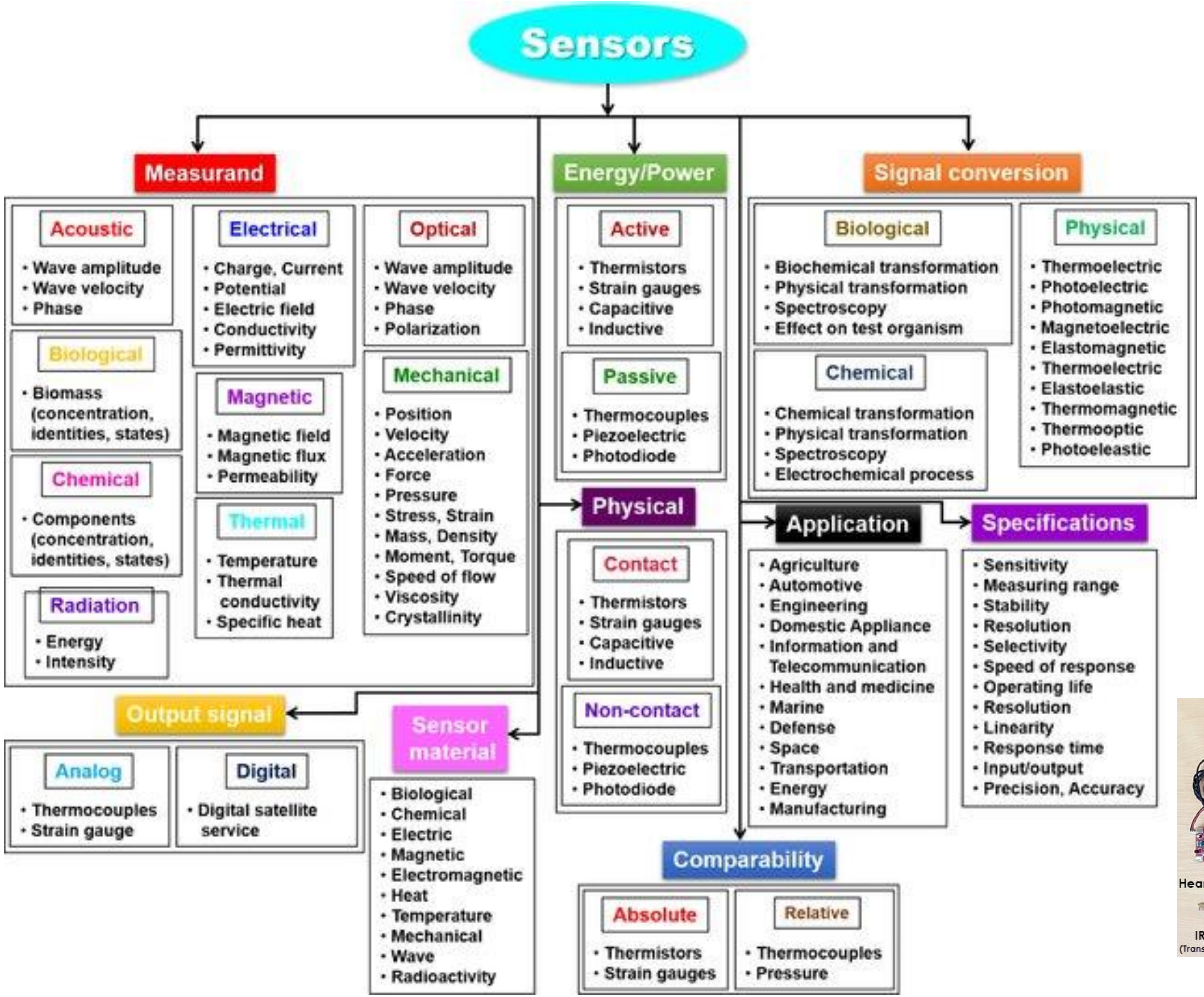


Sinusoidal input of a specified frequency

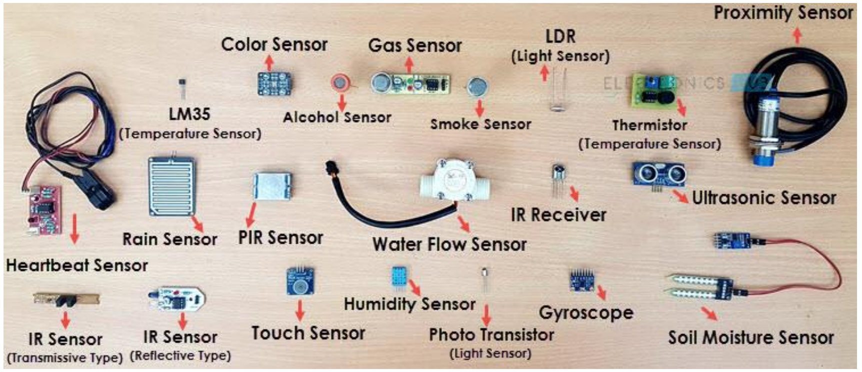
- Response time
  - time which elapse after a constant input is applied up to the point at which transducer gives values corresponding to some specific % of the value of the output. (say 95%)
- Time constant
  - time corresponding to 63.2% of output
  - Measures inertia of the sensor and so how fast it will react to changes of input.
- Rise time
  - Time taken for the output to rise to some specific % of steady state output (10% to 90 or 95%).
- Settling time
  - Time taken for the output to settle to within some % (2% of steady state value)

- Response to a
  - step input





- Displacement Measurement
- Strain Measurement
- Velocity and Motion
- Vibration and Acceleration
- Pressure Measurement
- Flow Measurement

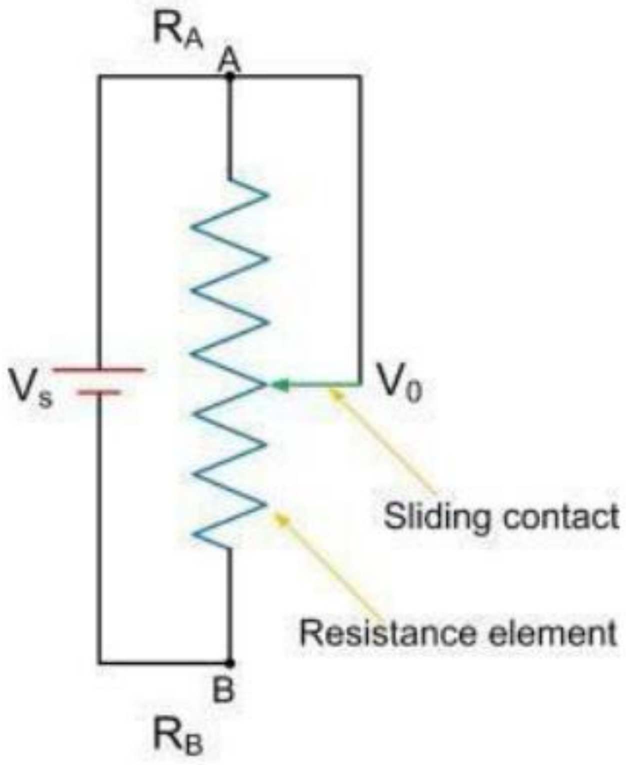


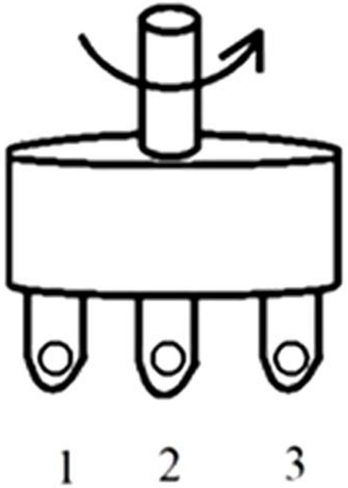
Displacement, Position & Proximity Sensors

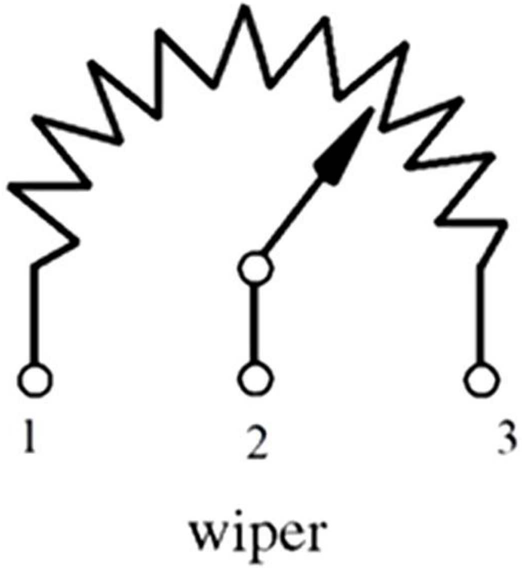
- Displacement:
  - Measures amount by which the object has moved.
- Position:
  - Measures position of the some object with respect to some reference position.
- Proximity:
  - Tells whether object has moved within some particular distance or not.

Potentiometer

- Potentiometer is a displacement measuring device.
- It is a variable resistance device whose output resistance changes as the wiper connected to a moving object moves across a resistive surface.
- This can be used for linear or rotary displacements.
- Here the displacement is converted into a potential difference.

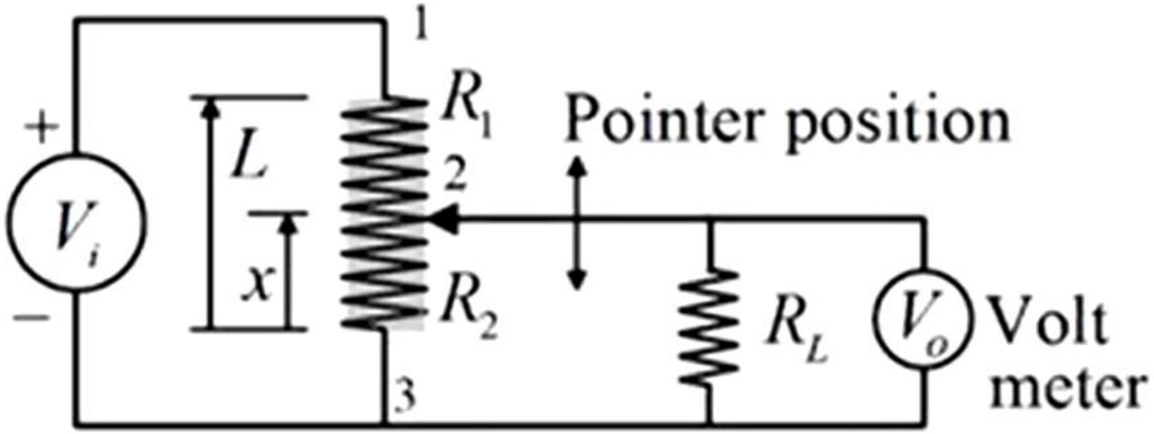






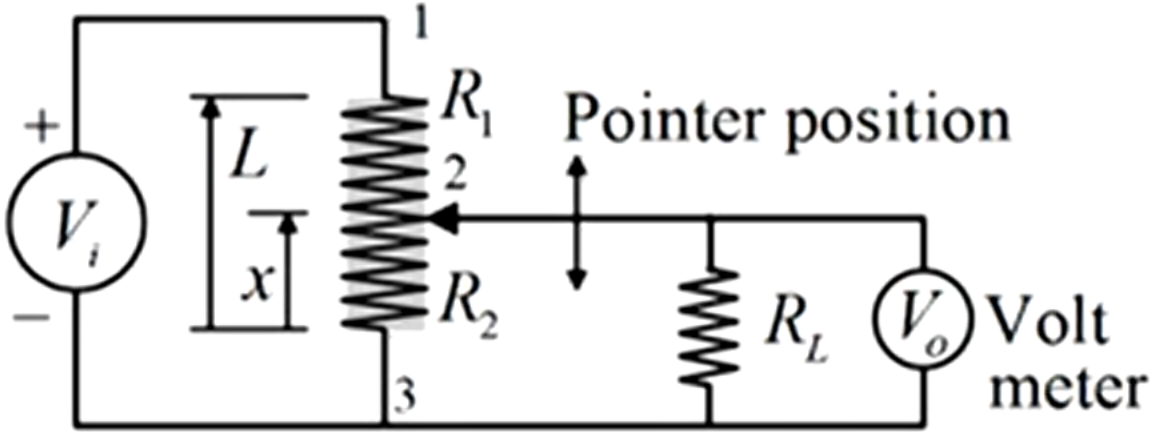
- Constant input voltage V_i between terminal 1 and 3
- Output voltage V_o between terminal 2 and 3.

- V_i is the input voltage, V_o is the output voltage, R_1 and R_2 are variable resistances, and R_L is the internal resistance of the voltmeter.
- Potentiometer calibration
- when x = 0, $R_1 = R_{max}$; $R_2 = 0$
- when $x = x_{max}$, $R_2 = R_{max}$, $R_1 = 0$.



Thus, $R_1 = \left(1 - \frac{x}{x_{max}}\right) R_{max}$

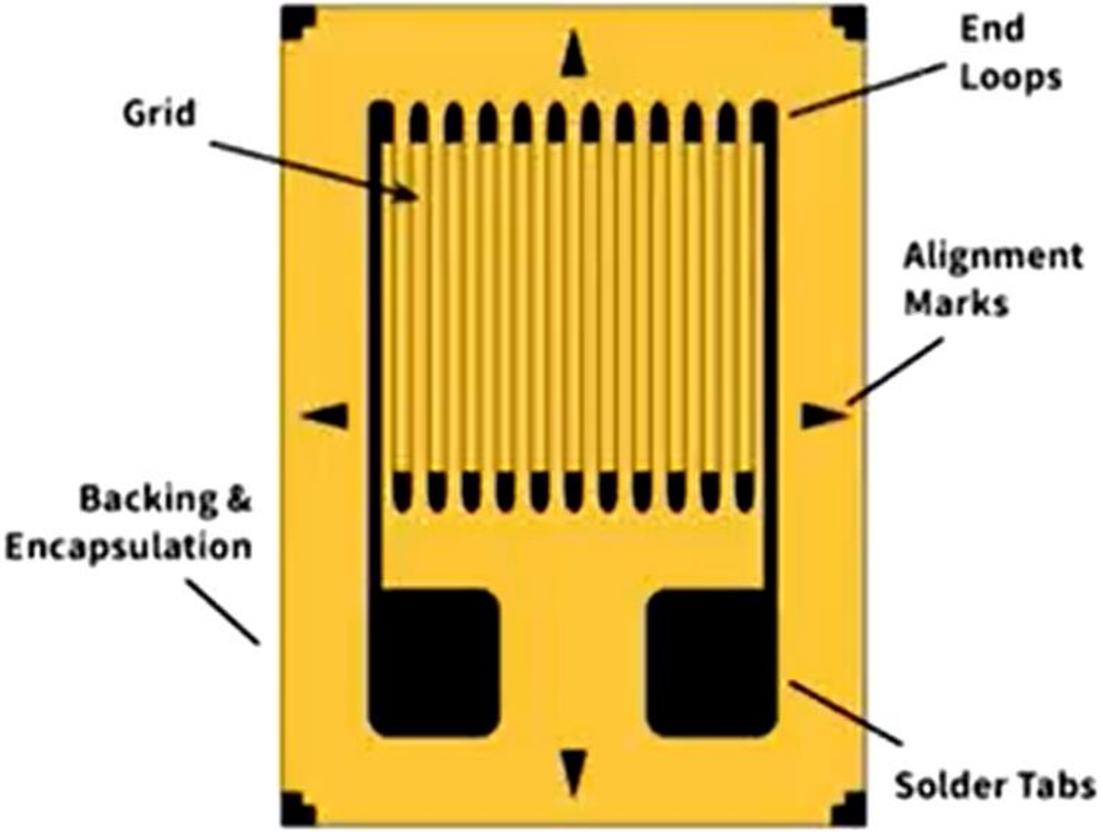
$$R_2 = \frac{x}{x_{max}} R_{max}$$

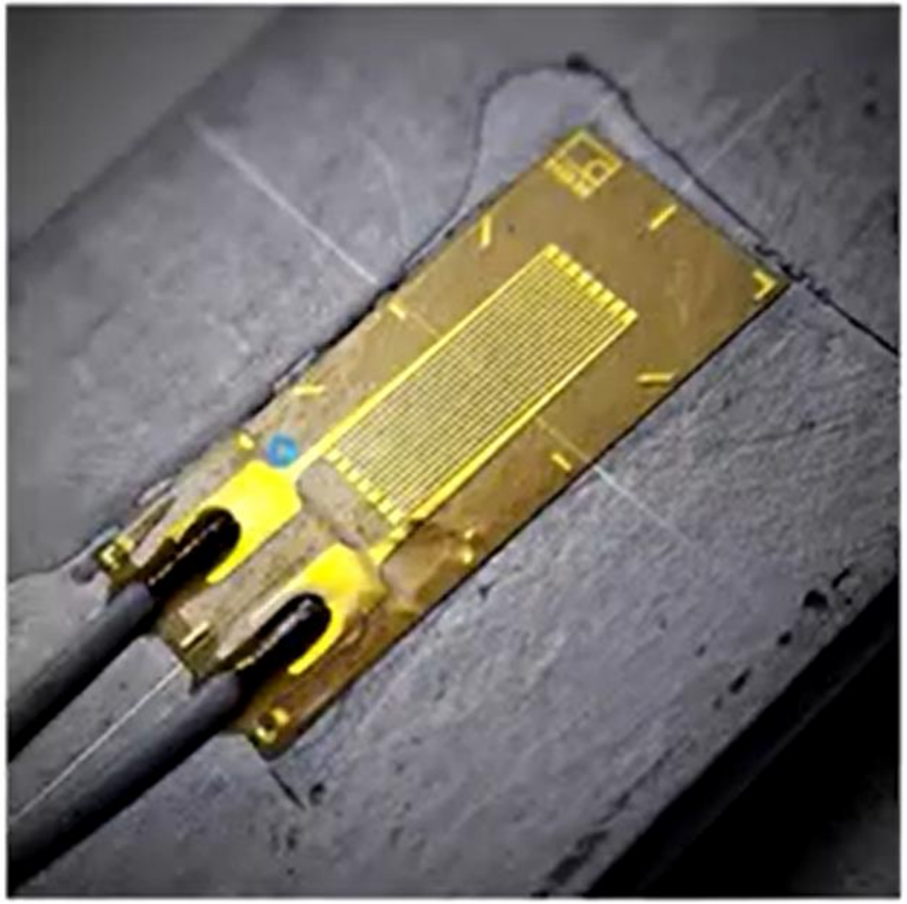


- $V_i - V_o = iR_1$ so $i = \frac{V_i - V_o}{R_1}$
- $V_o = iR_2 = \frac{V_i - V_o}{R_1} R_2$
- $V_o = \frac{R_2}{R_1 + R_2} V_i = \frac{R_2}{R_{max}} V_i = \frac{x}{x_{max}}$
- $V_o = \left(\frac{V_i}{x_{max}}\right) x$

Strain Gauge

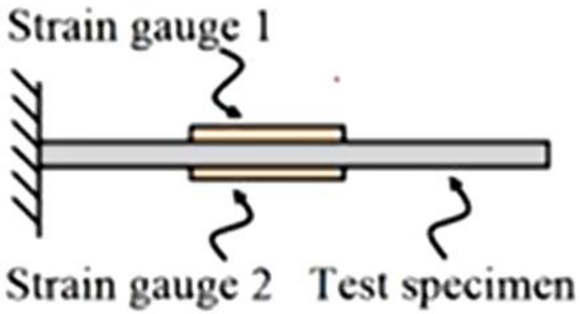
- The electrical resistance strain gauge is a metal wire, metal foil strip or a strip of semiconductor material which can be pasted on surfaces.
- When subjected to strain, its resistance *R* changes.
- The fractional change in resistance ($\frac{\Delta R}{R}$) is proportional to strain ε i.e., $\frac{\Delta R}{R} = G\varepsilon = \frac{\Delta l}{l} = \frac{\text{Change in length}}{\text{original length}}$
- G is constant of proportionality called gauge factor.

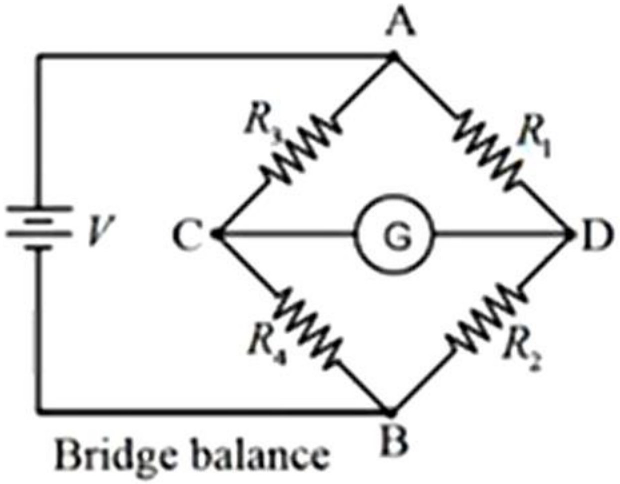




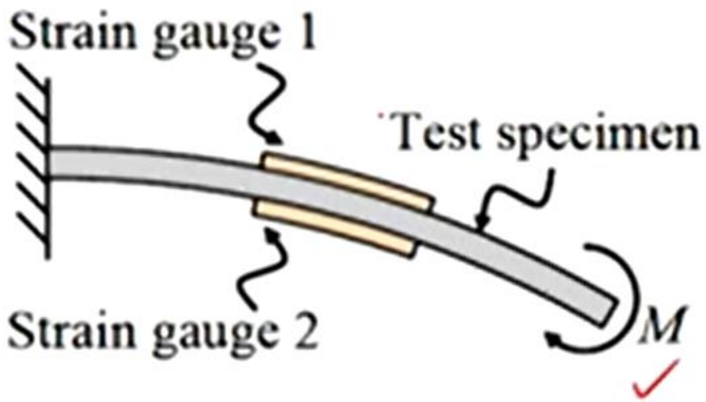
Commercially available form: Metal foil

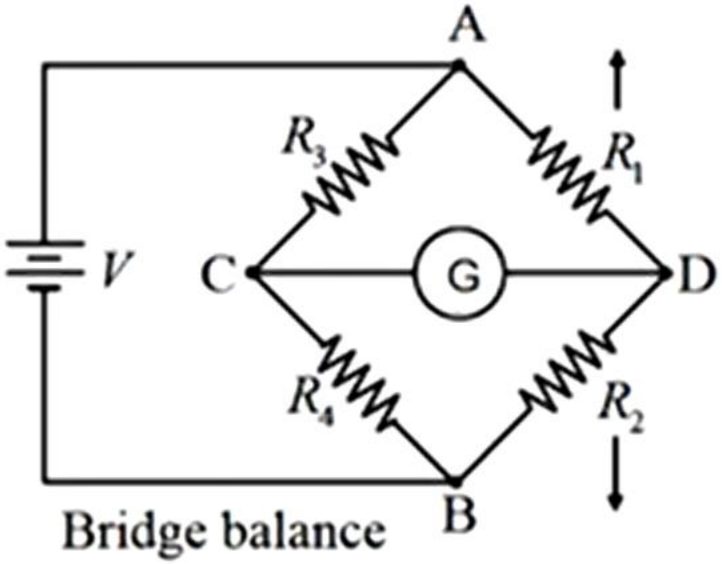
- Strain gauges are put at the top and bottom portions of a cantilever beam.
- In the undeflected beam position, these strain gauges when connected as the arms of the Wheatstone bridge circuit cause the bridge to be balanced with no reading in the Galvanometer





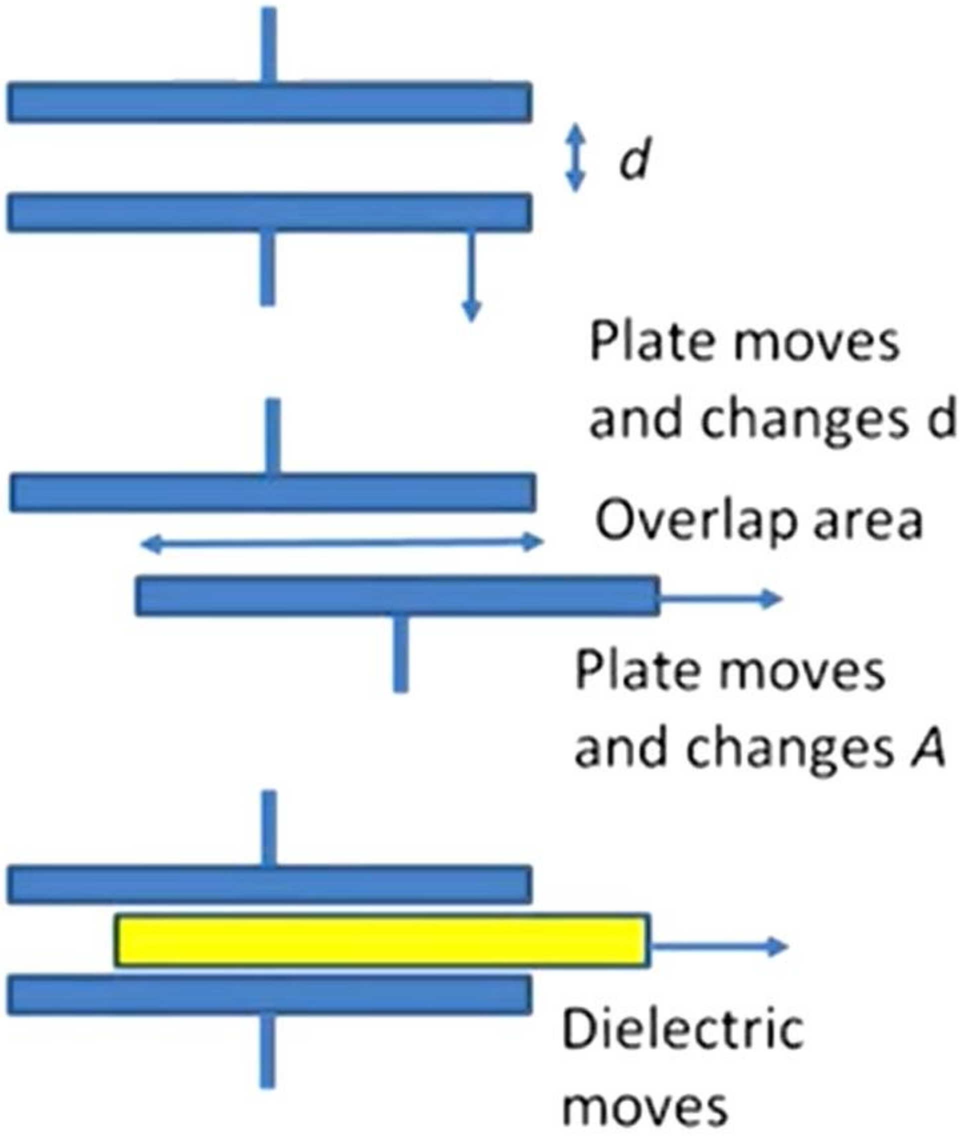
- Case when an end load (pure moment or pure bending load) has been applied on the cantilever causing the bending of the cantilever with strain gauge 1 subjected to stretching whereas strain gauge 2 is subjected to compression.





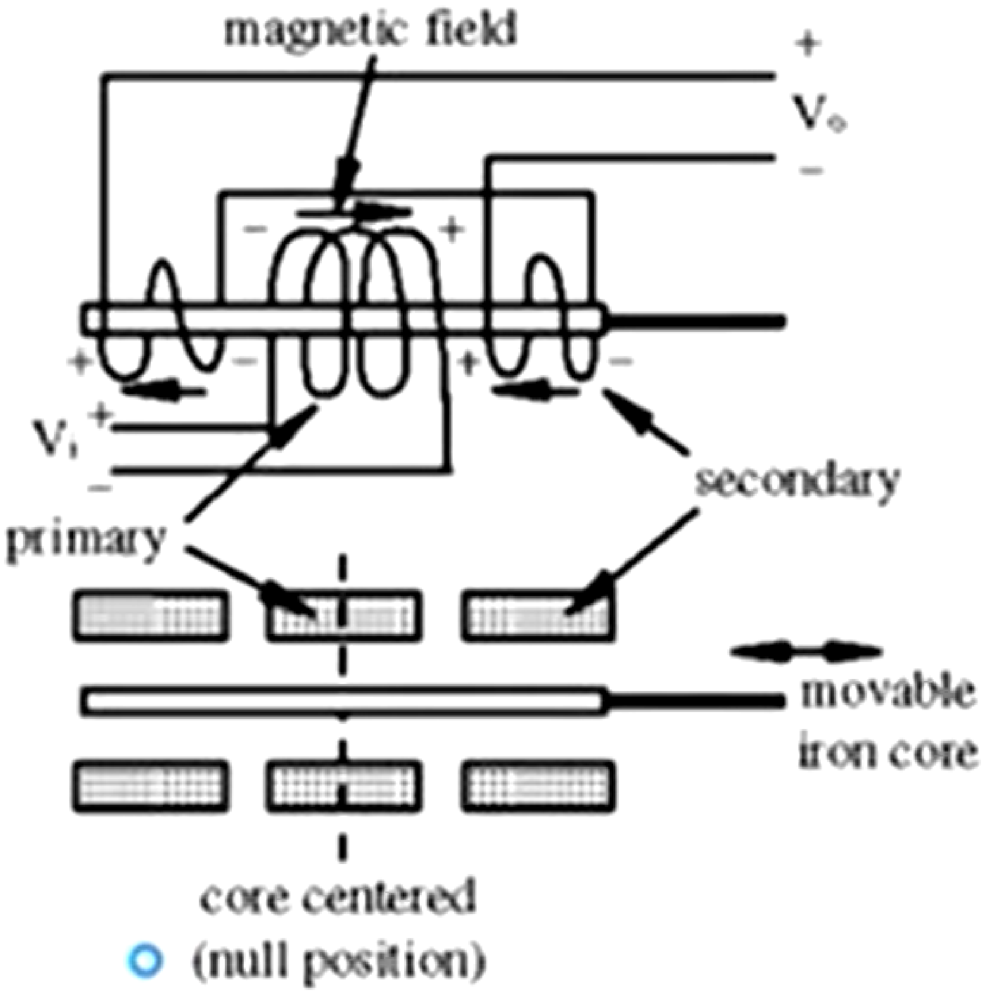
Capacitive Elements

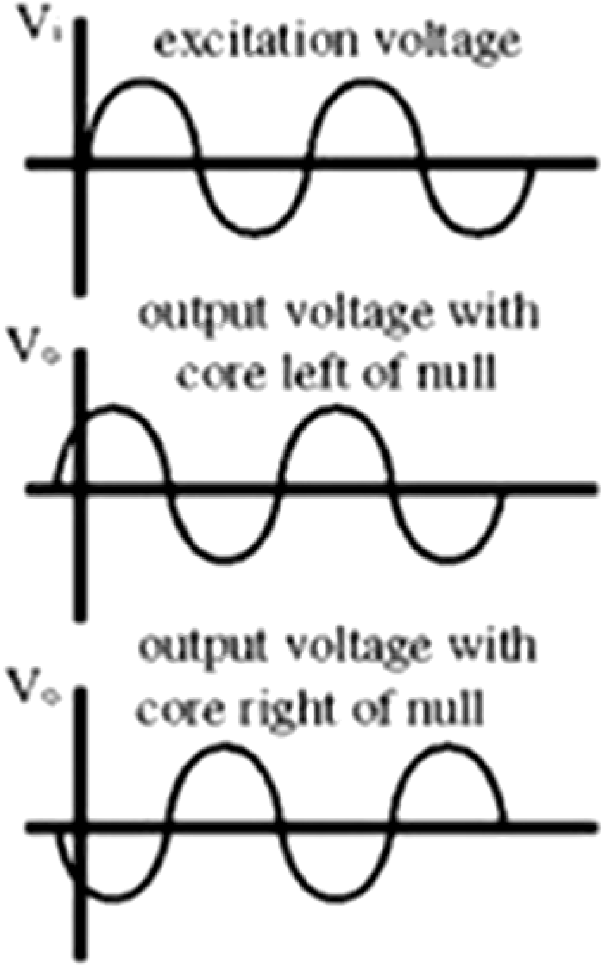
- The capacitance C of a parallel plate capacitor is given by $C = \frac{\varepsilon_r \varepsilon_0 A}{d}$
- ε_r is relative permittivity of the dielectric between the plates
- ε_0 is a constant called permittivity of free space
- *A* is the area of overlap between the two plates
- *d* is plate separation.

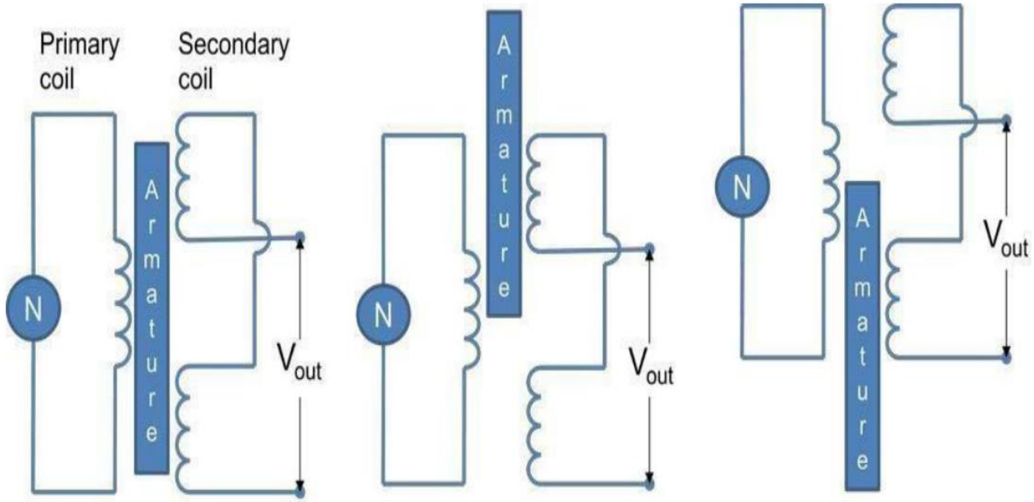



棕
黑
Load:300

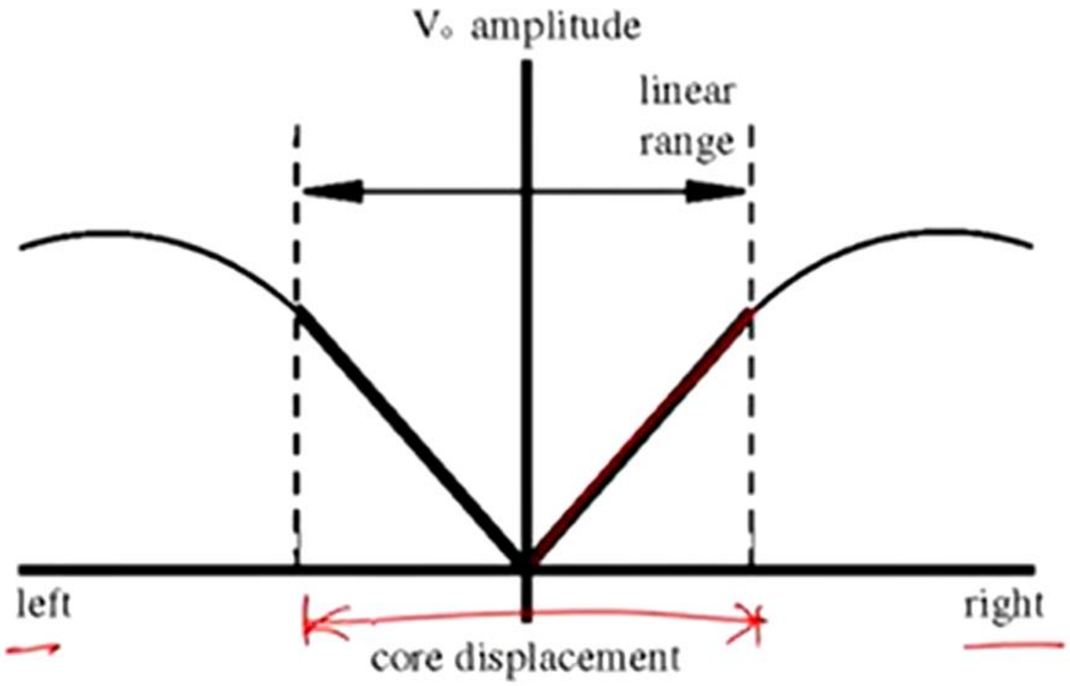
Linear variable differential transformer(LVDT)



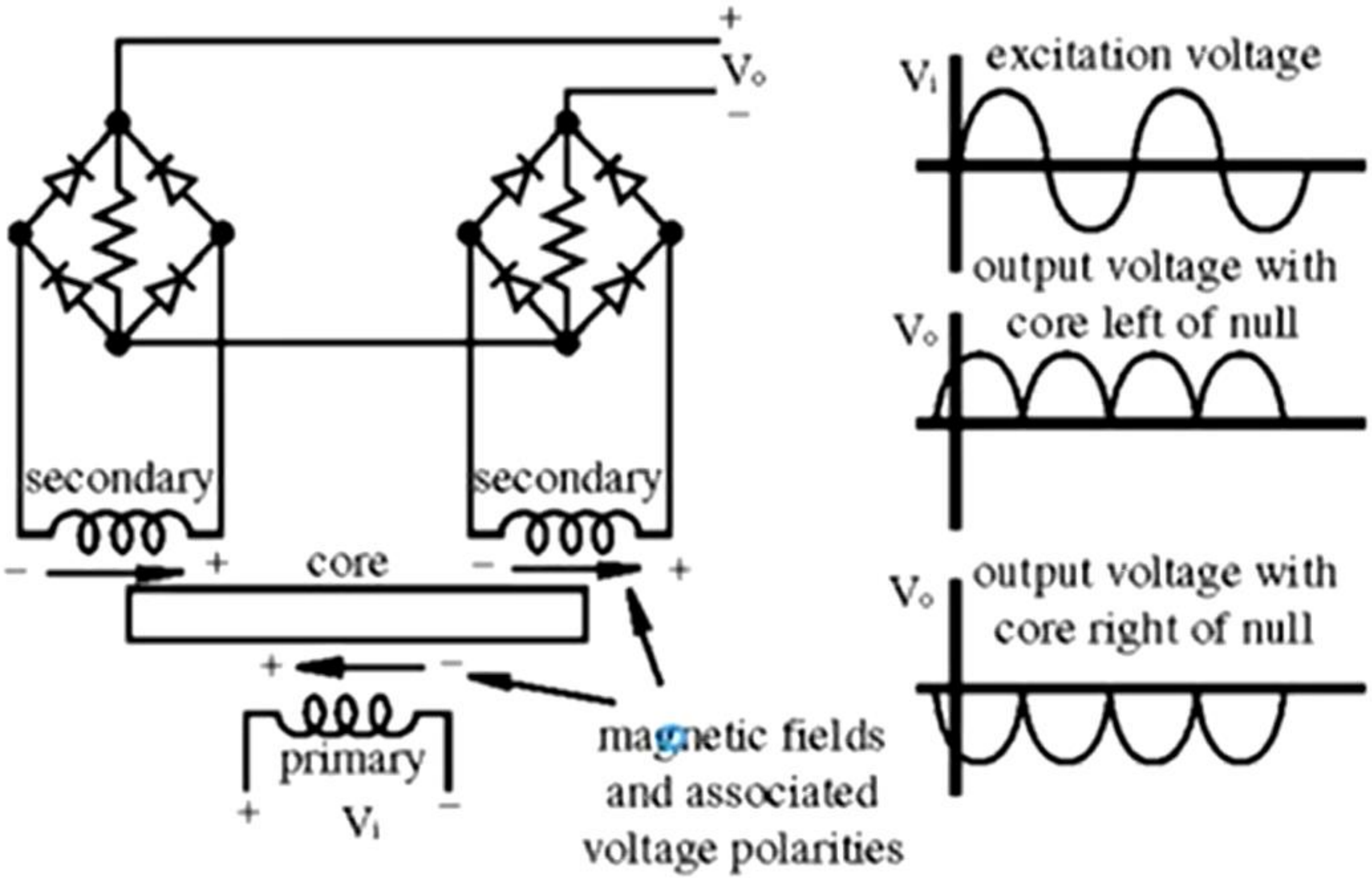




- As the core moves from the null position, the output amplitude increases a proportional amount over a linear range around the null
- Therefore, by measuring the output voltage amplitude, we can easily and accurately determine the magnitude of the core displacement



- To determine the direction of the core displacement, the secondary coils can be connected to a demodulation circuit.
- The diode bridges in this circuit produce a positive or negative rectified sine wave, depending on which side of the null position the core is located

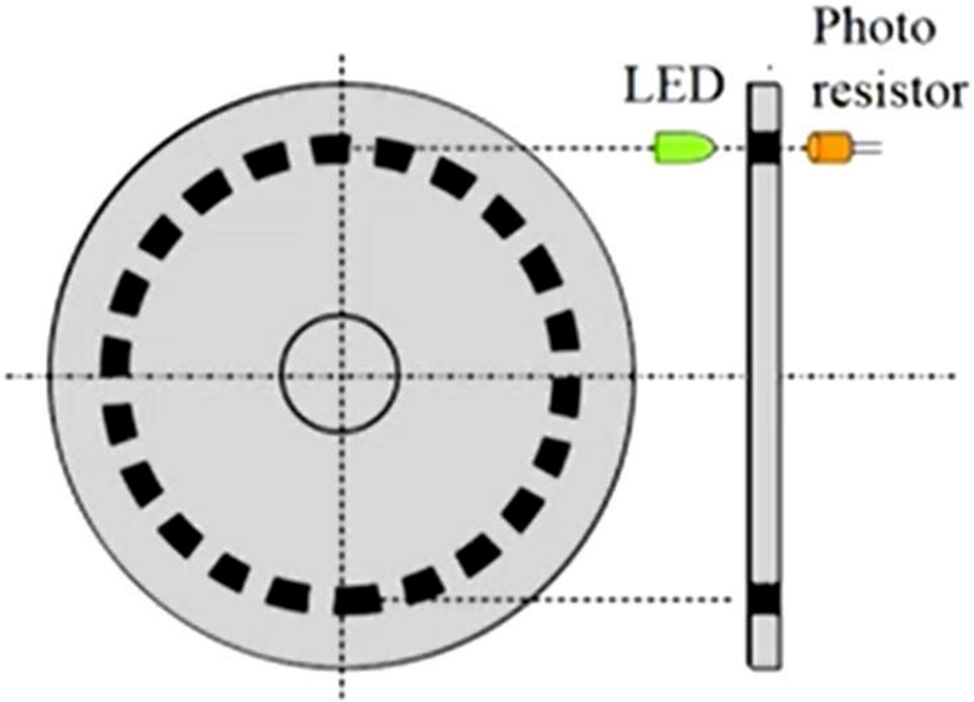


Optical Encoders

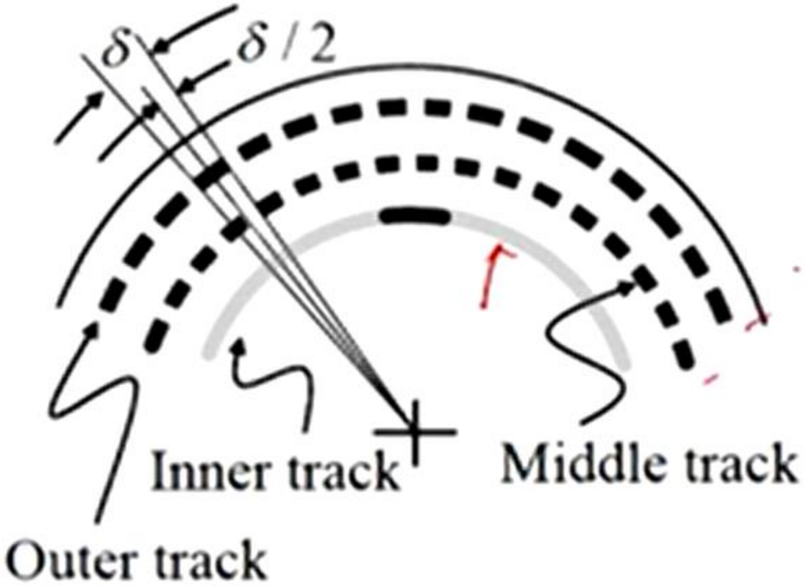
- An encoder is a device that converts a linear or angular displacement into a sequence of pulses.
- By counting these pulses we can obtain the linear or angular displacement.
- Encoders come in two basic forms, i.e., incremental encoders and absolute encoders.
- Incremental encoders give the rotation with respect to some reference position whereas absolute encoders give the actual position.

Incremental Encoder

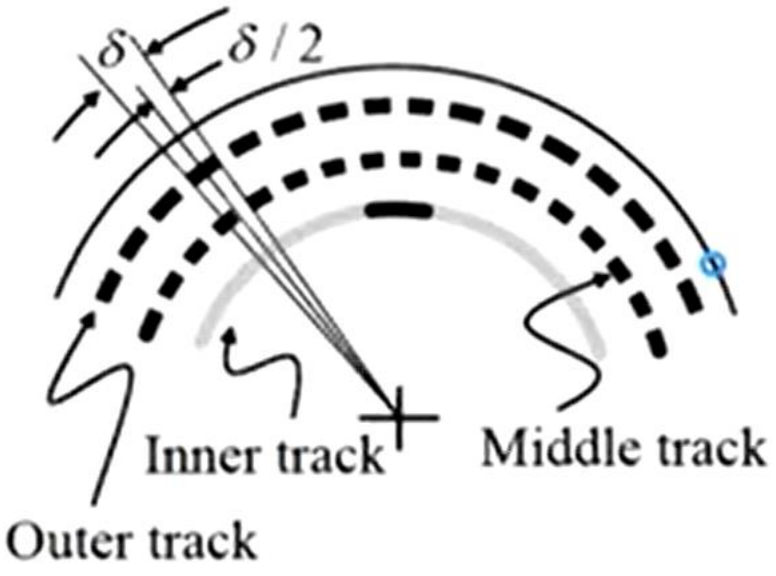
- A beam of light (from a LED) passes through slots in a disc. This beam of light is detected by a light sensor (photo resistor) placed at the other side of the disc.
- When the disc rotates, a pulsed output is produced by the photo resistor.
- The number of pulses received by photo resistor is proportional to the angle through which the disc has rotated.



- Actually, three concentric tracks with three sensors are used in incremental encoders where δ is the angle subtended by each hole.
- The inner track has one hole and it locates the home position of the disc.
- The middle and outer track have equally spaced holes around the periphery of the disc.
- Holes in the middle track are at an offset equal to half the width of a hole in comparison to outer track holes.



- If the shaft rotates in clockwise direction then the pulses in the outer track lead those in the middle track whereas if the shaft rotates in anti-clock wise direction the pulses in the outer track lag those in the middle track.
- This allows identification of the direction of rotation.

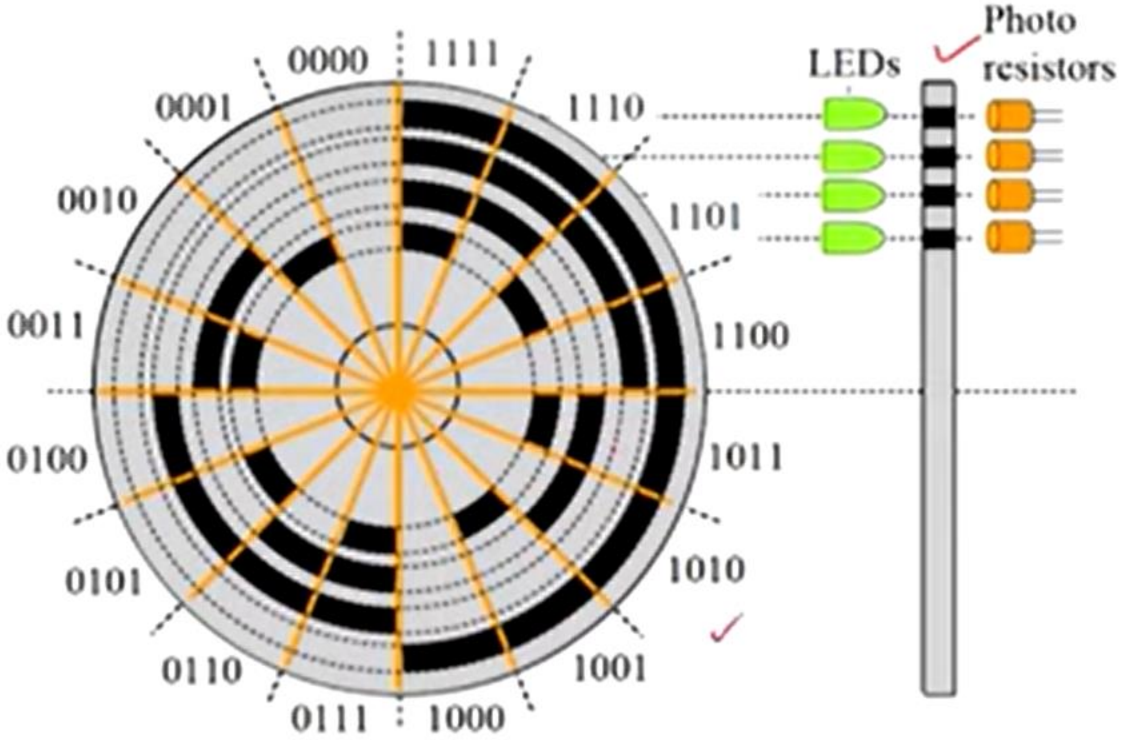


Absolute Encoder

- Absolute encoder are used for the measurement of angular displacement.
- Here we get the output in the form of a binary number of several digits.
- Here each number represents a particular angular position.

Absolute Encoder

- In four bit absolute encoder the rotating disc has four concentric circles of slots.
- There are four light emitting diodes (LEDs) to emit the light and four photo resistors to detect the light.

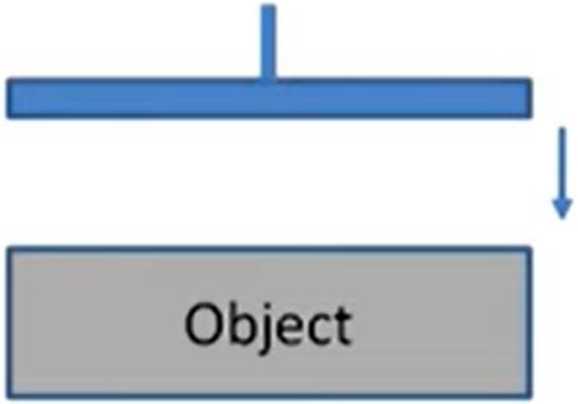


Four bit absolute encoder

Decimal code	Rotation range (deg.)	Binary code	Gray code
0	0-22.5	0000	0000
1	22.5-45	0001	0001
2	45-67.5	0010	0011
3	67.5-90	0011	0010
4	90-112.5	0100	0110
5	112.5-135	0101	0111
6	135-157.5	0110	0101
7	15.75-180	0111	0100
8	180-202.5	1000	1100
9	202.5-225	1001	1101
10	225-247.5	1010	1111
11	247.5-270	1011	1110
12	270-292.5	1100	1010
13	292.5-315	1101	1011
14	315-337.5	1110	1001
15	337.5-360	1111	1000

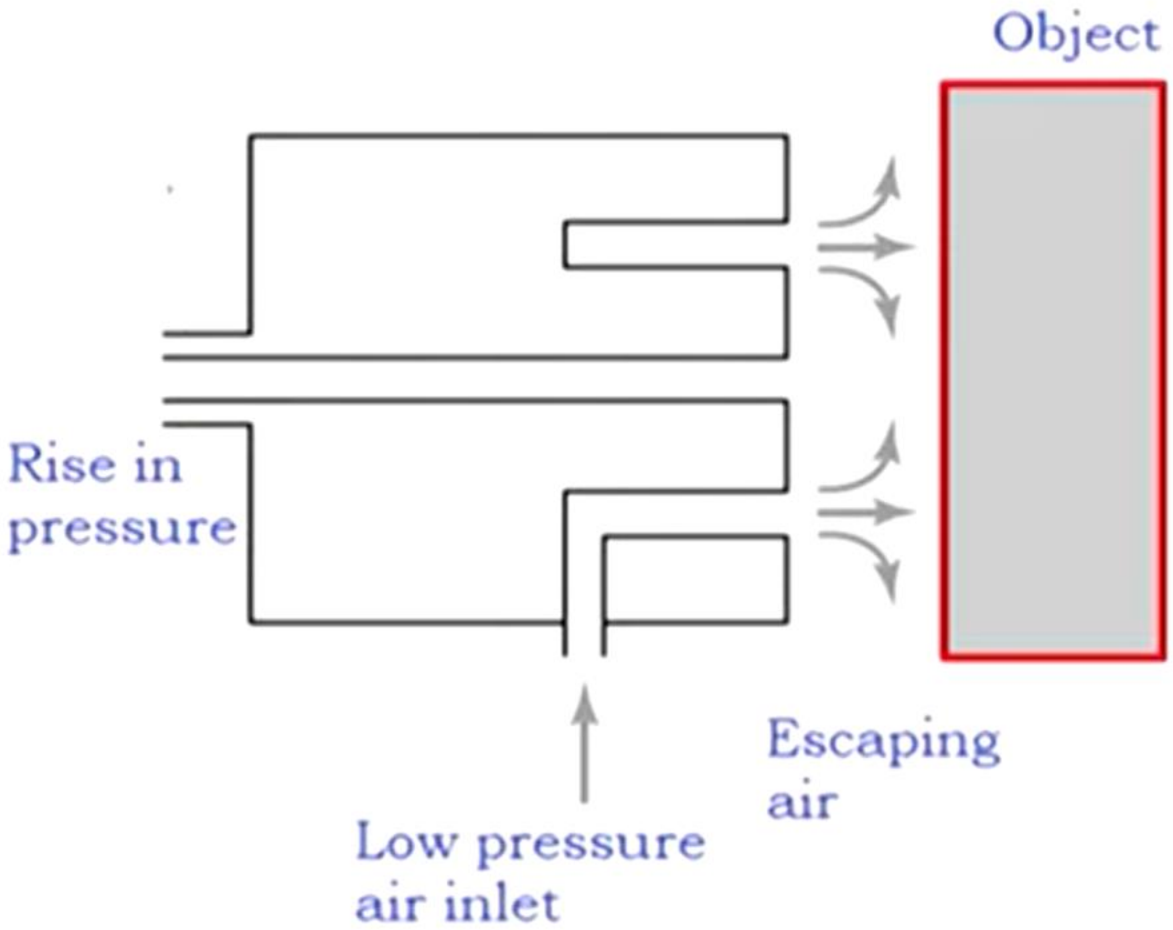
Capacitive Proximity Sensor

- One form of capacitive proximity sensor consists of a single capacitor plate probe with the other plate being formed by the object (metallic and earthed)
- As the object approaches the ‘plate separation’ of the capacitor changes.
- This is detectable when the object is close to the probe.



Pneumatic Sensors

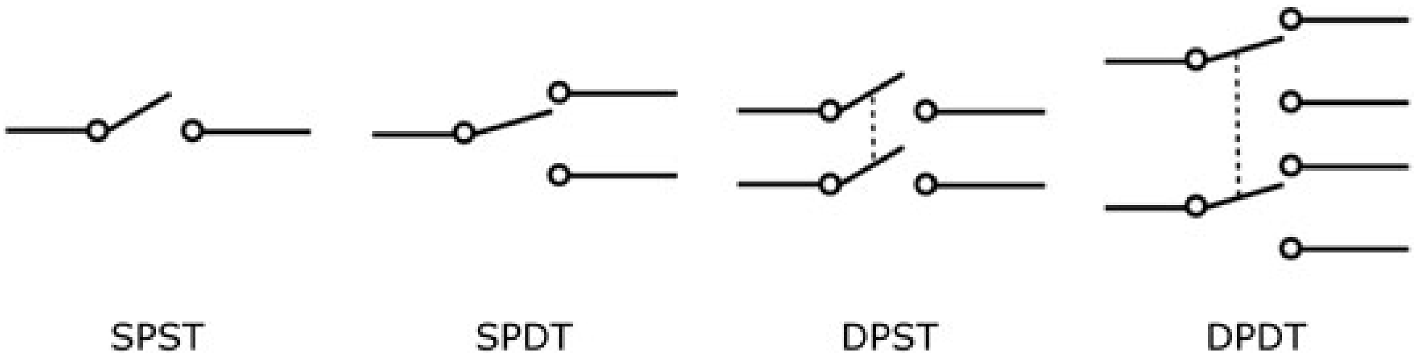
- Use compressed air
- Displacement or proximity of the object is transformed into change of pressure

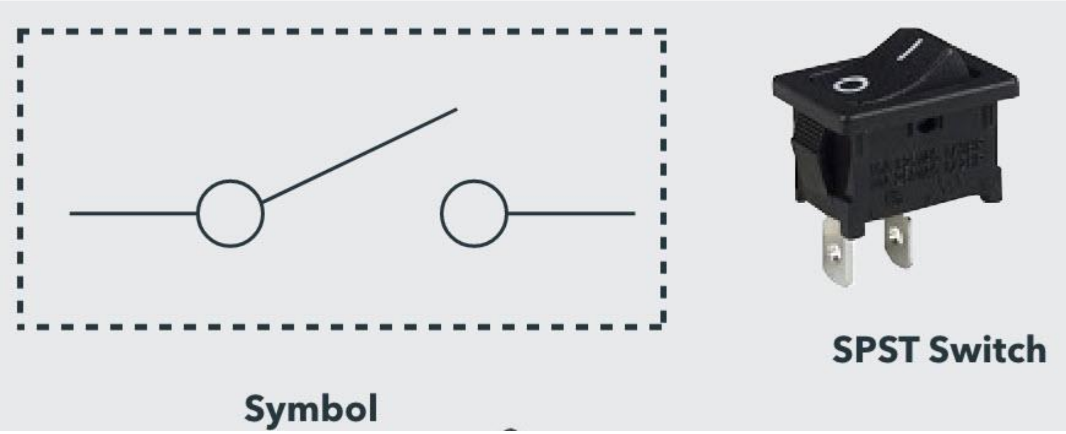


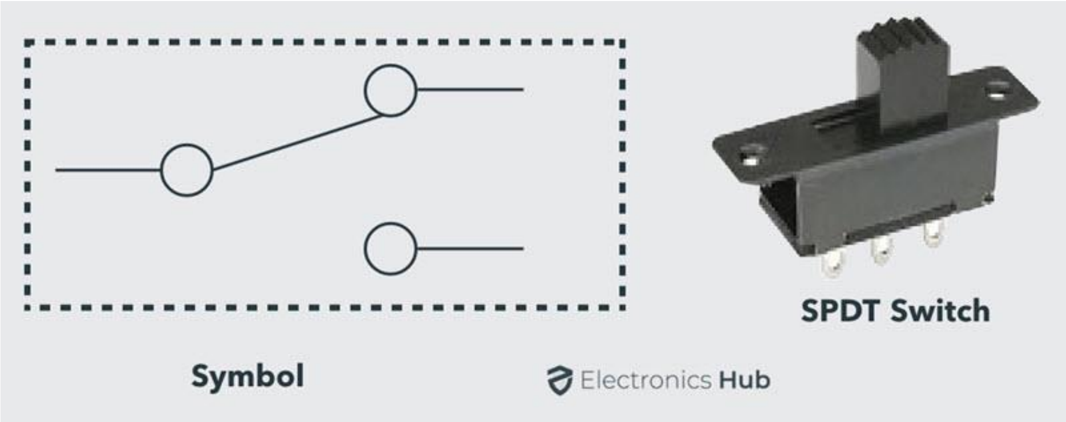
Switch

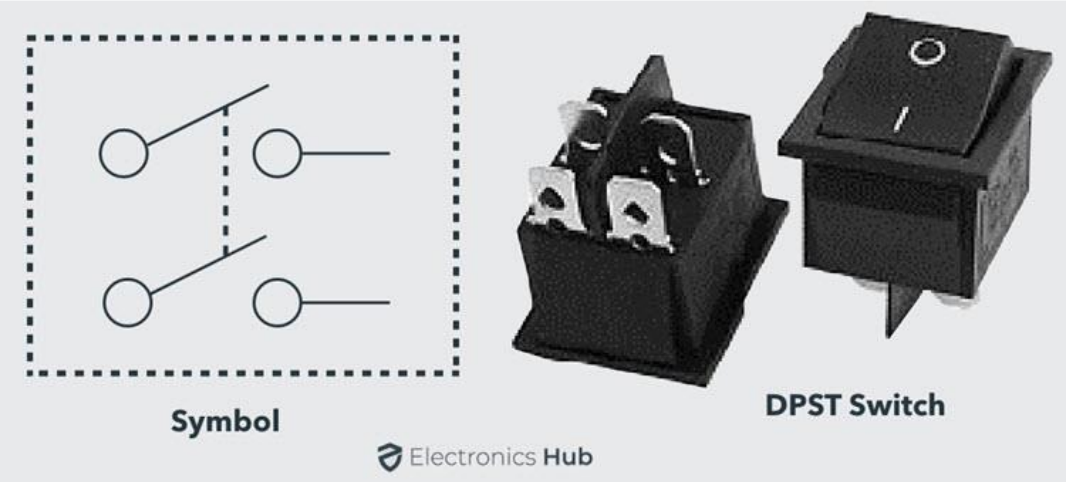
- A switch is a device that is used for making and breaking electrical connections in a circuit.
- Thus 0 or 1 signals can be transmitted by the act of opening or closing a switch.
- The term limit switch is used when the switches are opened or closed by the displacement of an object and used to indicate the limit of its displacement before action has to be initiated.

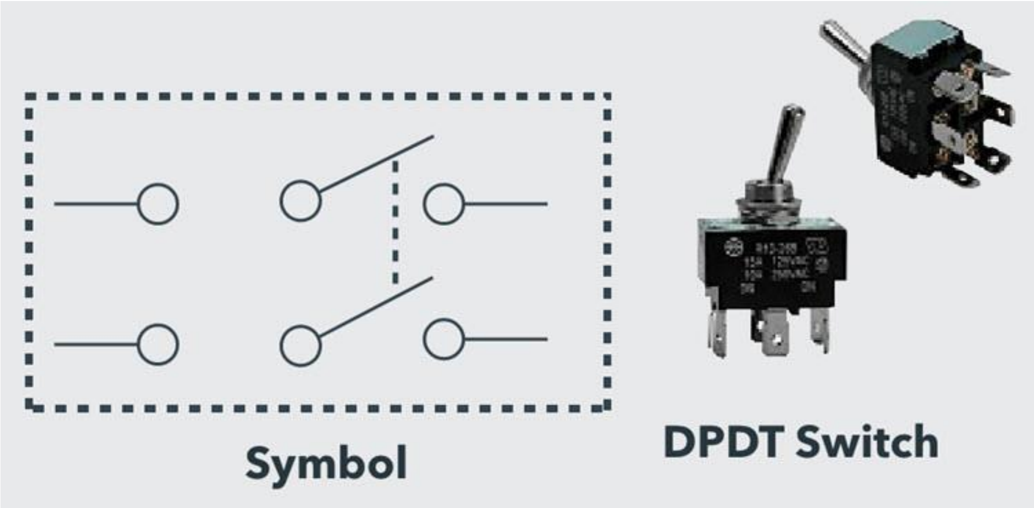
- Mechanical switches are specified in terms of their number of poles and throws.
- Poles are the number of separate circuits that can be completed by the same switching action
- Throws are the number of individual contacts for each pole.
- There are many types of these devices.
- Beside the general type of switch (toggle, slide, pushbutton, etc) there are many configurations of the contacts possible.
- Often you will see a switch in a schematic referred to as a SPST (Single Pole Single Throw) or DPDT (Double Pole Double Throw).

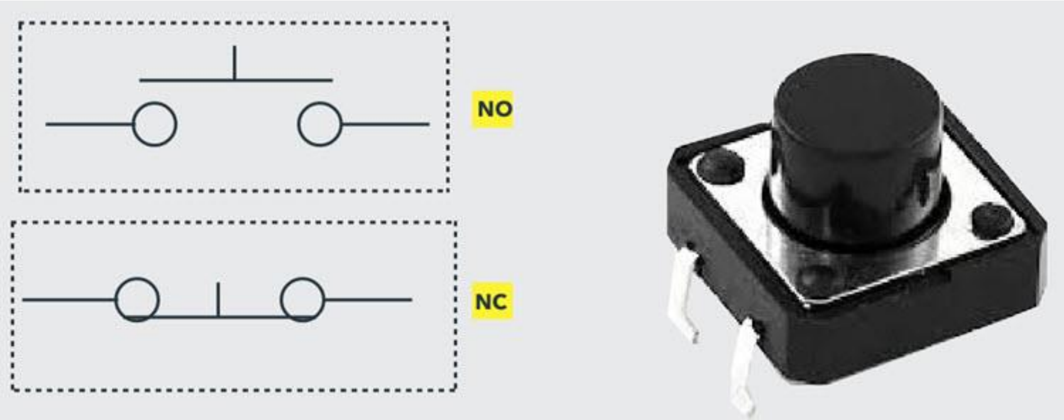



SPST Switch
Symbol

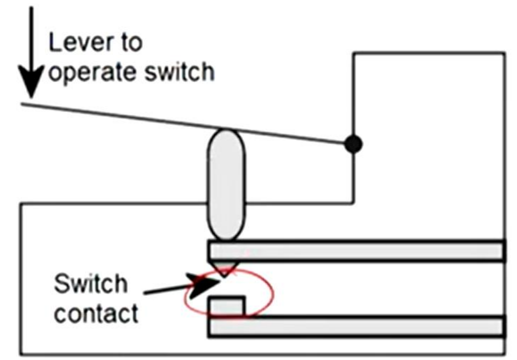

SPDT Switch
Symbol
Electronics Hub


DPST Switch
Symbol
Electronics Hub


DPDT Switch
Symbol

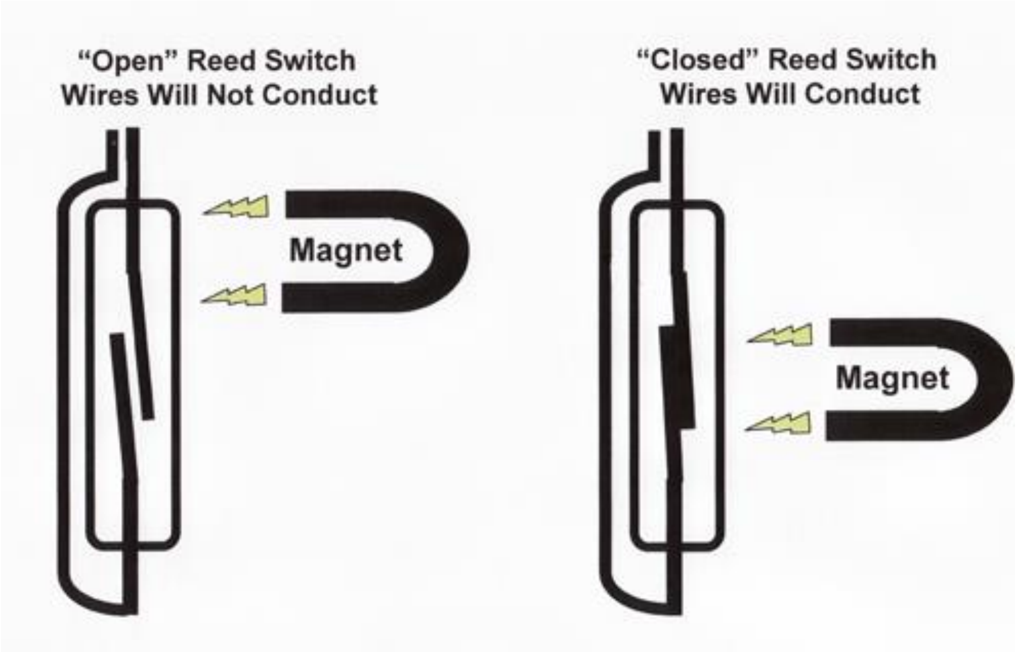

NO
NC

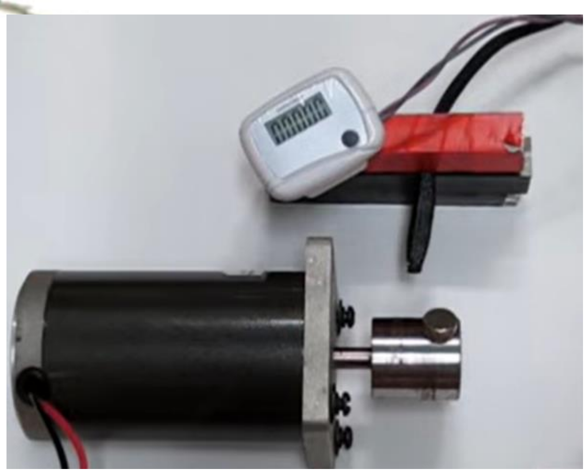

Normally Open
Limit Switch
Normally Closed
Limit Switch
Normally Open
Held Closed
Limit Switch
Normally Closed
Held Open
Limit Switch
Limit Switch


Lever to
operate switch
Switch
contact

Reed Switch

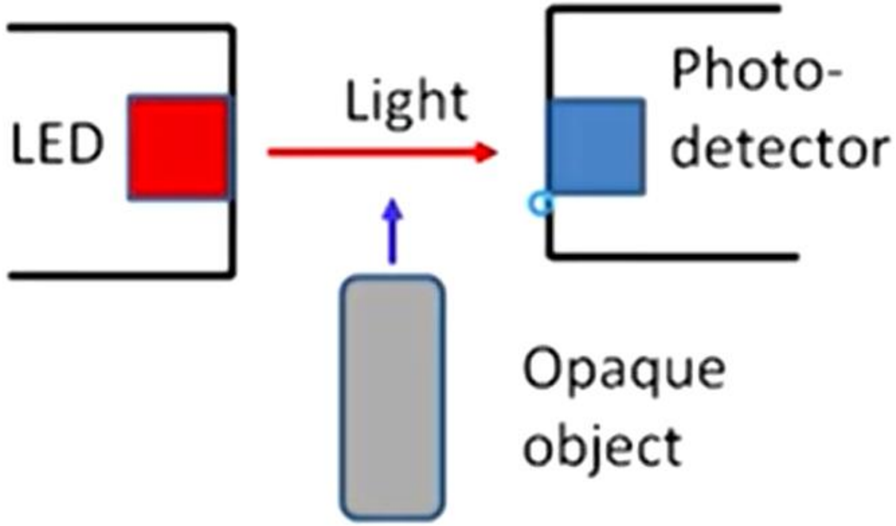
- It consists of two magnetic switch contacts sealed in a glass tube.
- When a magnet is brought close to the switch, the magnetic reeds are attracted to each other and close the switch contacts.
- It is a non-contact proximity switch.
- Used in
  - checking the closure of doors.
  - tachometers

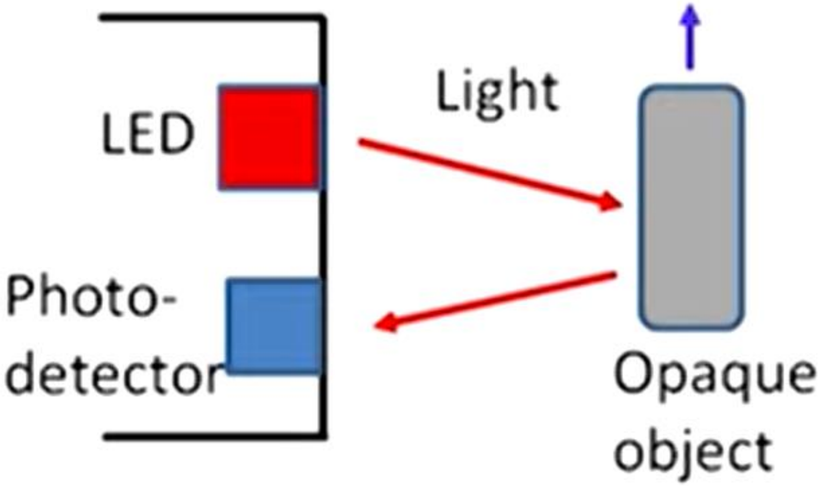




Photosensitive Devices

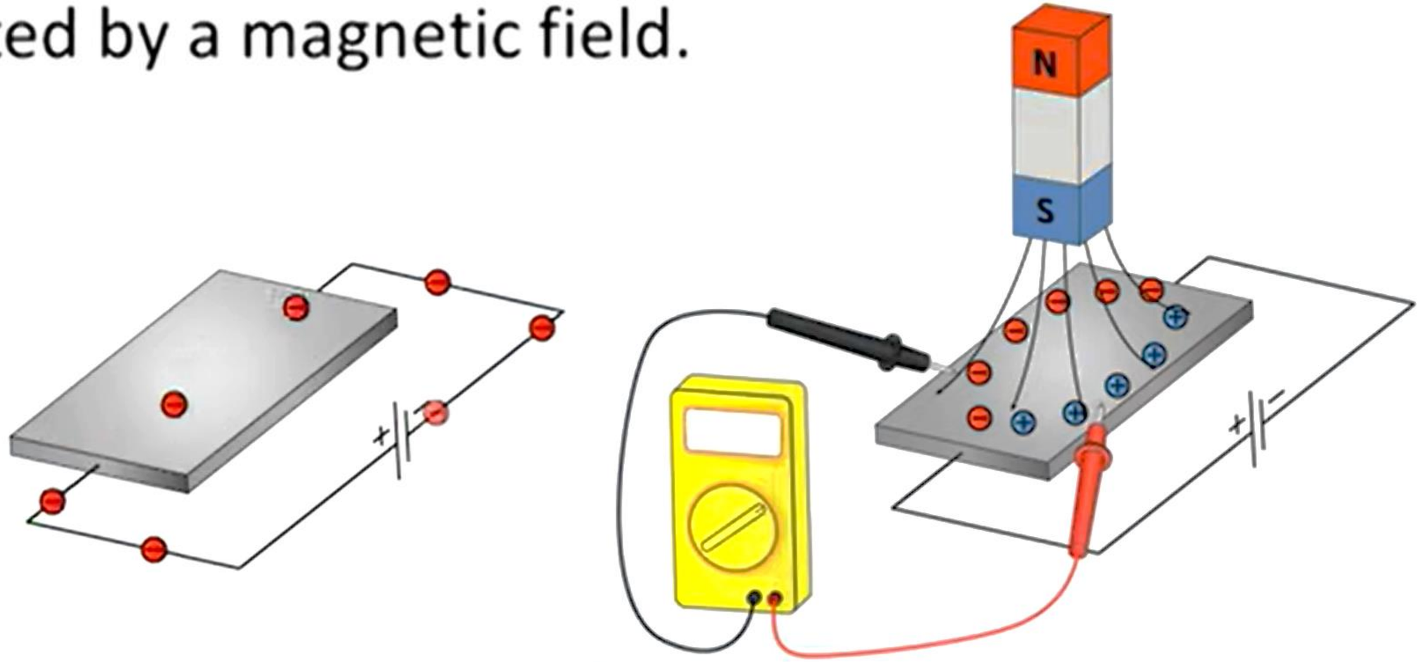
- Photosensitive devices can be used to detect the presence of an opaque object by its
  - breaking a beam of light, or infrared radiation, falling on such a device
  - or by detecting the light reflected back by the object

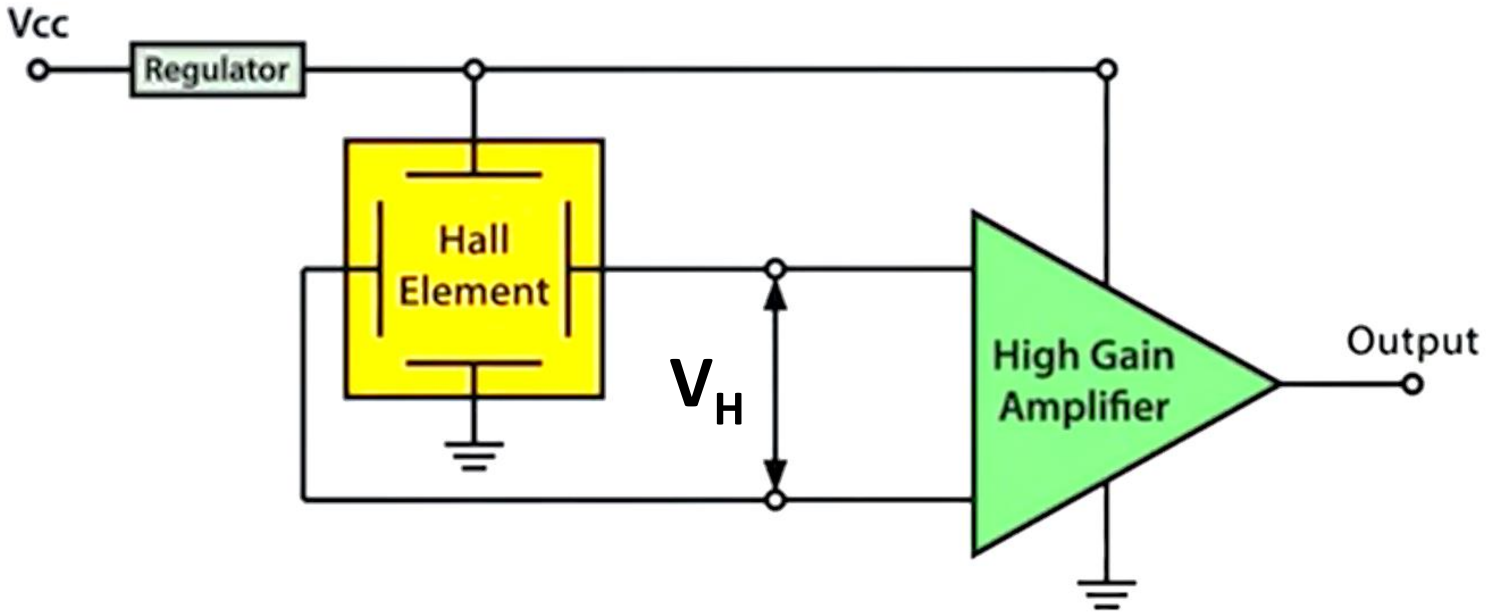




Hall Effect Sensors

- Working Principle (E.R. Hall, 1879):
- When a beam of charged particles passes through a magnetic field, forces act on the particles and the beam is deflected from its straight line path (Hall effect).
- A current flowing in a conductor is like a beam of moving charges and thus can be deflected by a magnetic field.





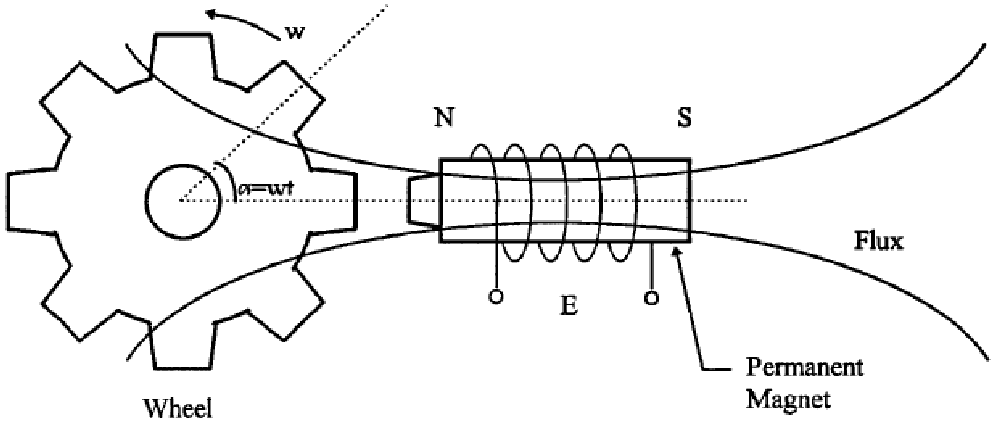
$$V_H = K_H . \frac{B.I}{t}$$

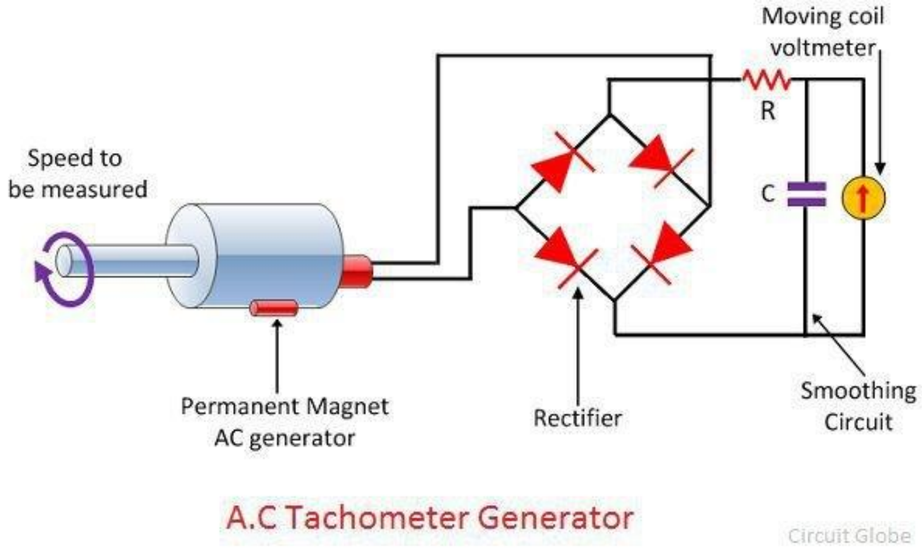
Where, K_H is a constant (Hall Coefficient), B = magnetic flux density, I = current, t = plate thickness

- So for constant I, V_H is a measure of B.

Velocity and Motion

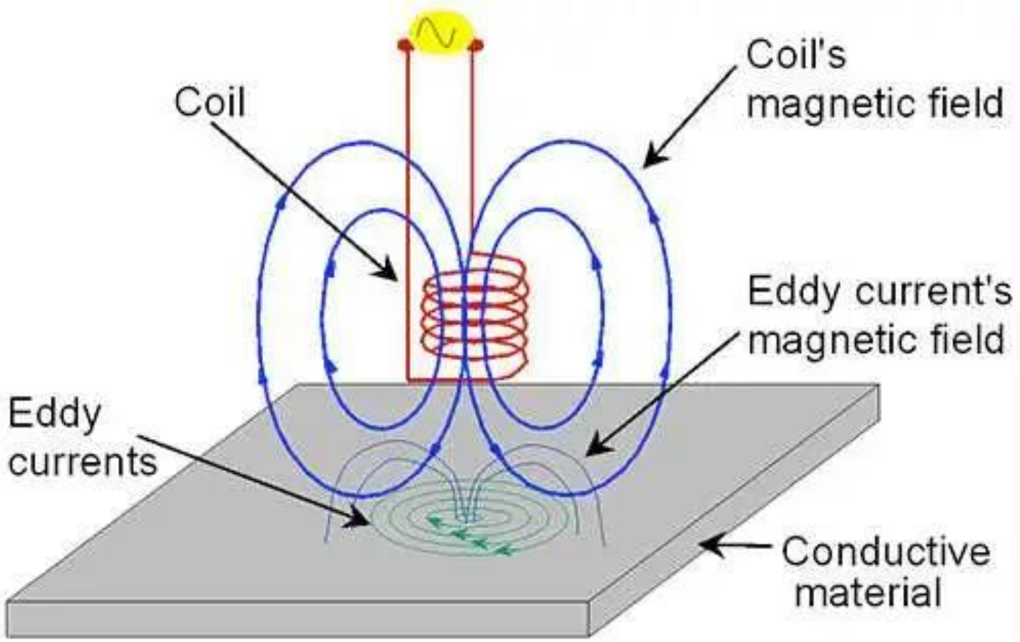
- Linear and angular velocity measurements and thus detect motion.
- Application of motion detectors are found in security systems to detect intruders.





A.C Tachometer Generator

Eddy current proximity sensors

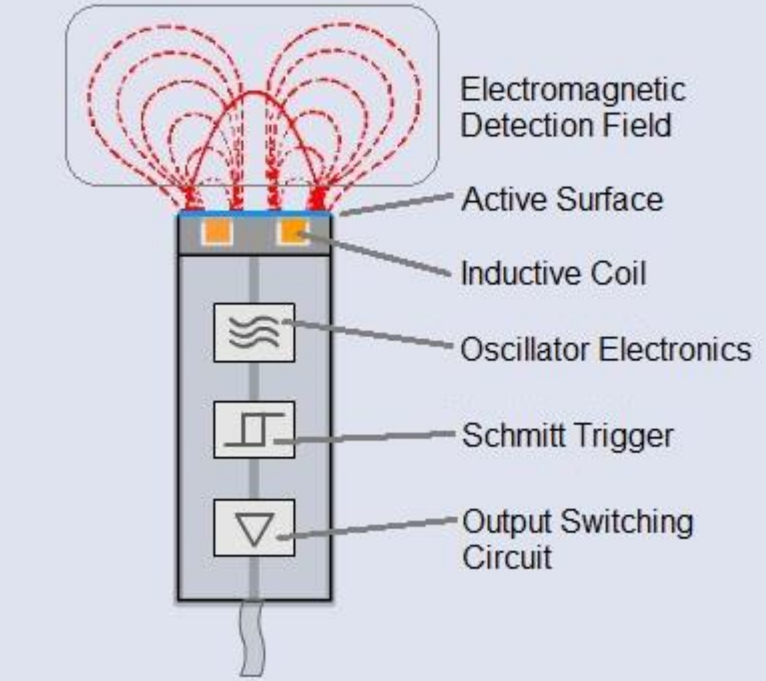


Applications of eddy current proximity sensors

- Automation requiring precise location.
- Machine tool monitoring.
- Final assembly of precision equipment such as disk drives.
- Measuring the dynamics of a continuously moving target, such as a vibrating element.
- Drive shaft monitoring.
- Vibration measurements.

Inductive proximity switch

- Inductive proximity switches are basically used for detection of metallic objects.
- Figure shows the construction of inductive proximity switch.
- An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit. An alternating current is supplied to the coil which generates a magnetic field. When, a metal object comes closer to the end of the coil, inductance of the coil changes.
- This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.



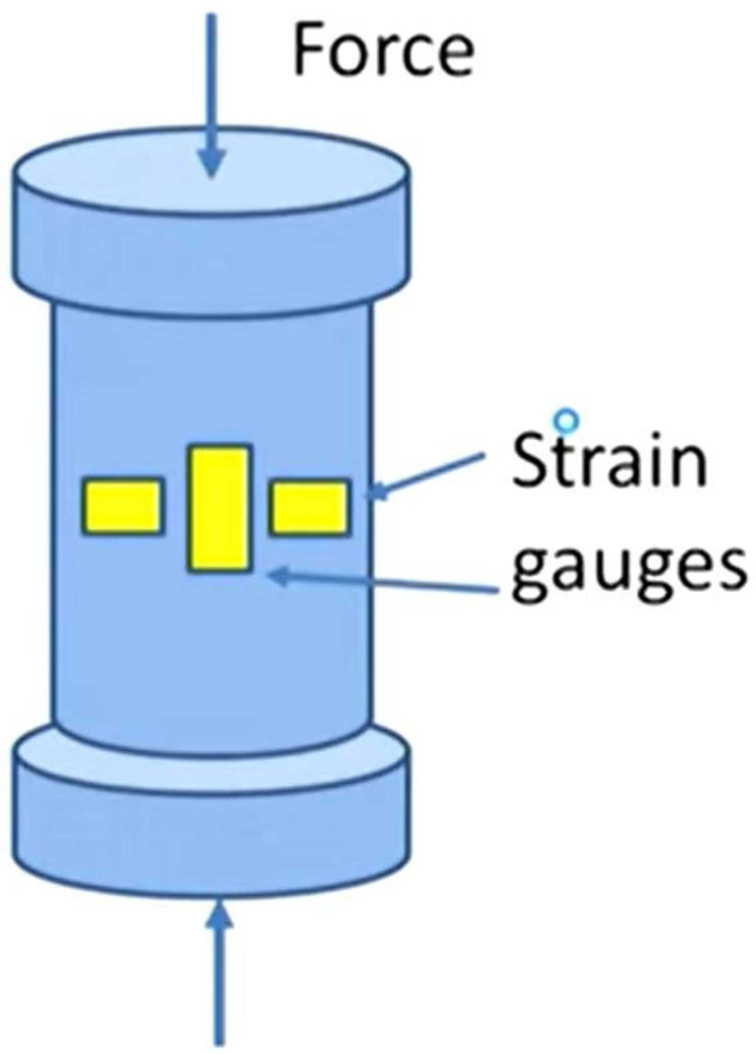
Internal Elements of an Inductive Proximity Sensor

Force Sensor

- Forces are commonly measured by the measurement of displacement.
- **Spring balance** is an example of force sensor.
- Force is proportional to displacement.
- The displacement is then a measure of the force

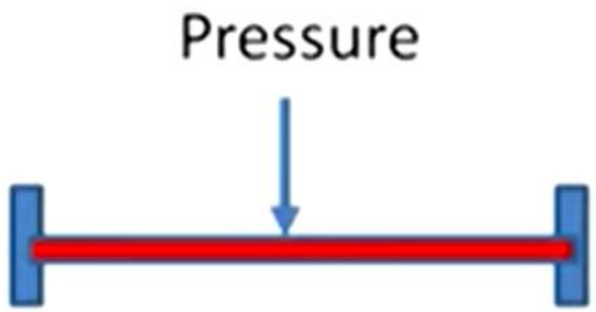
Spring balance

- When forces are applied to the cylinder to compress it, then the strain gauges give a resistance change.
- The resistance change is a measure of the strain and hence the applied forces.
- Typically such load cells are used for forces up to about 10 MN.
- Strain gauge load cells based on bending of a strain gauged metal element tend to be used for smaller forces (From 0 to 5N to 0 to 50 kN.)

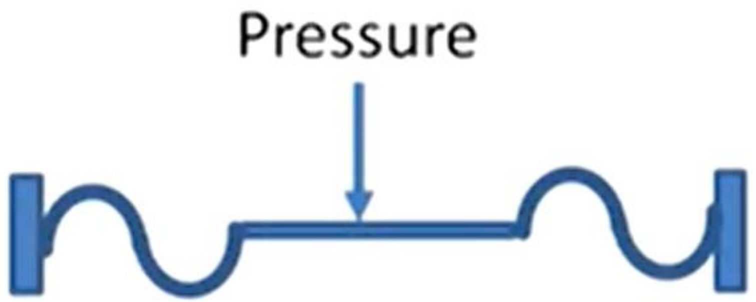


Fluid Pressure

- Fluid pressure is measured by elastic deformation of diaphragms, capsules, bellows, tubes etc.
- Type of pressure measurement
  - Absolute (with respect to vacuum)
  - Differential (pressure difference is measured)
  - Gauge (with respect to barometric pressure)

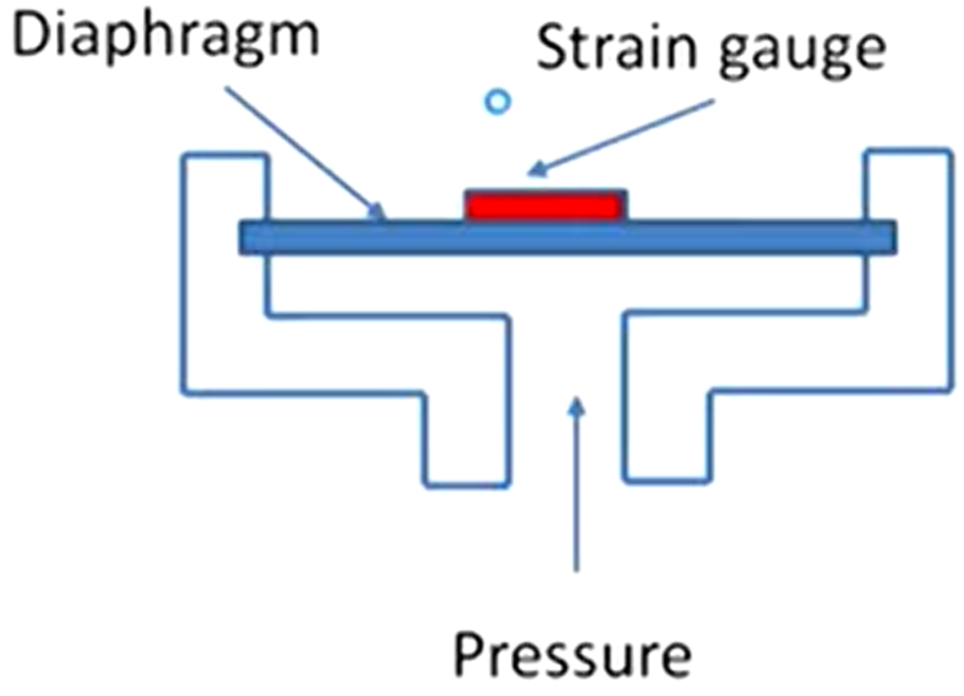


Flat diaphragms



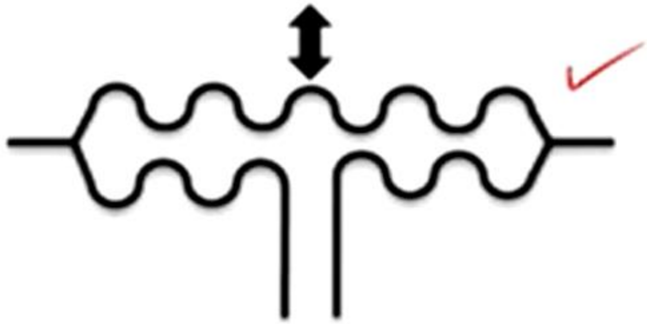
Corrugated diaphragms

- Diaphragm movement can be monitored by strain gauge,
- 4 strain gauges used
- 2 in radial direction
- 2 in circumferential direction.
- The four strain gauges are then connected to form the arms of a Wheatstone bridge.
- An use is in cars to monitor the inlet manifold pressure. Here a silicon diaphragm with the strain gauges as specially doped areas of the diaphragm.

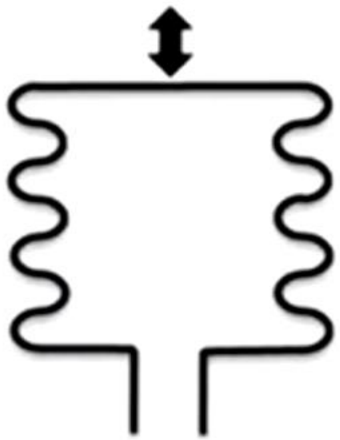


Diaphragm Pressure Gauge

- Capsules can be considered to be just two corrugated diaphragms combined and give even greater sensitivity.
- A stack of capsules is just a bellows and even more sensitive

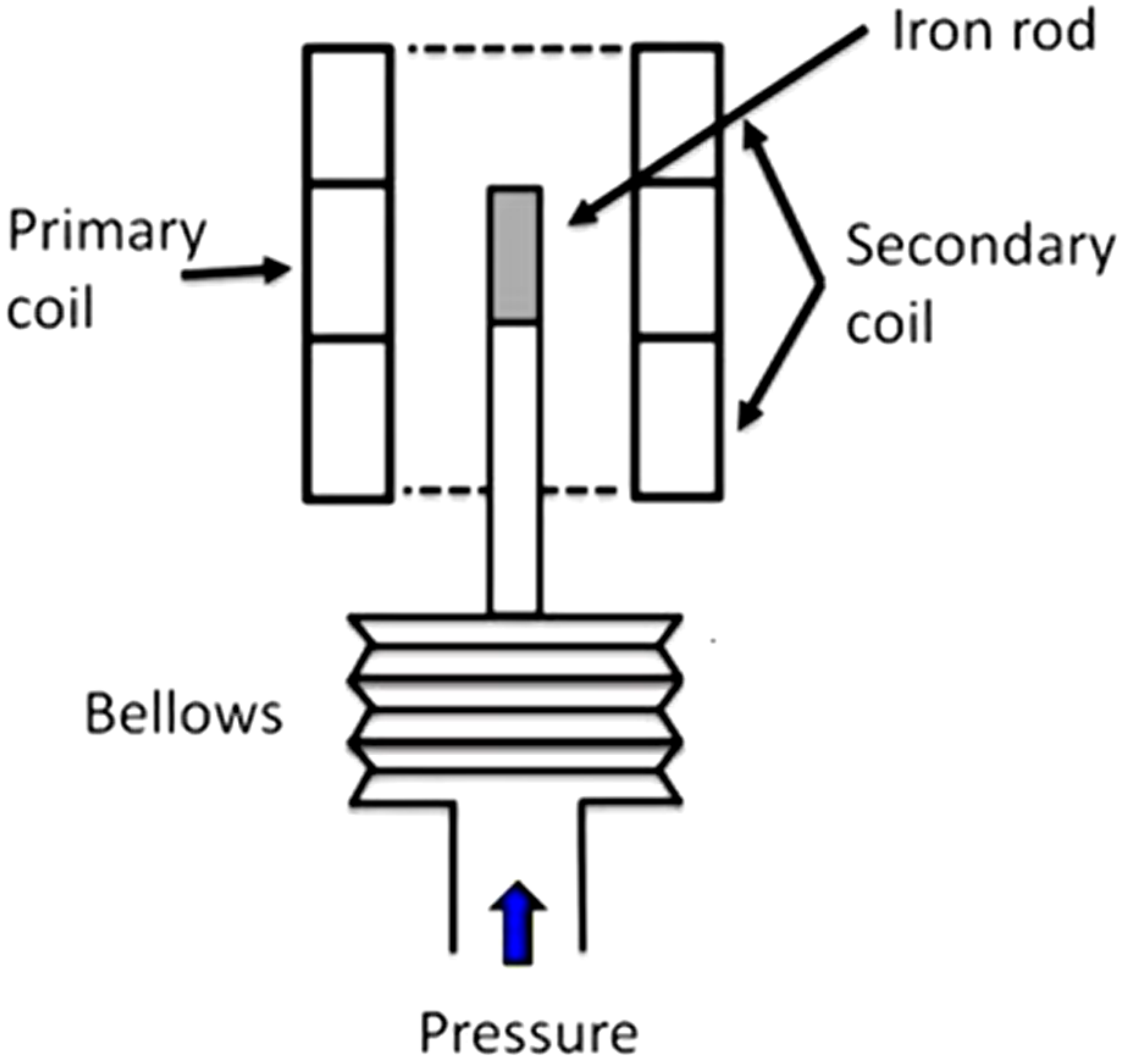


Capsule



Bellows

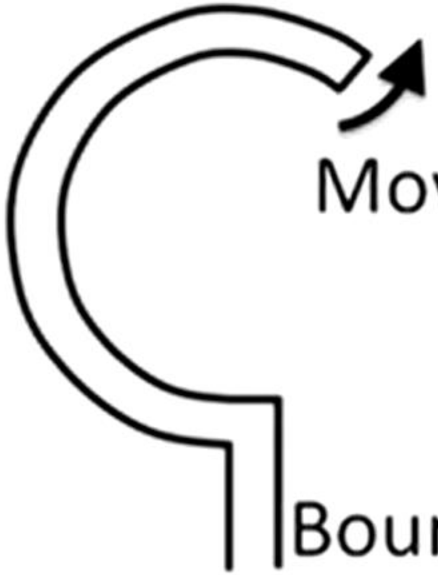
- A bellows can be combined with an LVDT to give a pressure sensor with an electrical o/p.
- Diaphragms, capsules and bellows are made from materials as stainless steel, phosphor bronze and nickel. Rubber and nylon also being used for some diaphragms.
- Can measure 10^3 to 10^8 Pa.



LVDT with bellows

- A deformation is obtained using a tube with an elliptical cross-section.
- Increasing the pressure in such a tube causes it to tend to a more circular cross-section.
- Such a tube is in the form of C shape, it is known as a Bourdon tube, the C opens up to some extent when the pressure in the tube increases.

Tube cross-section

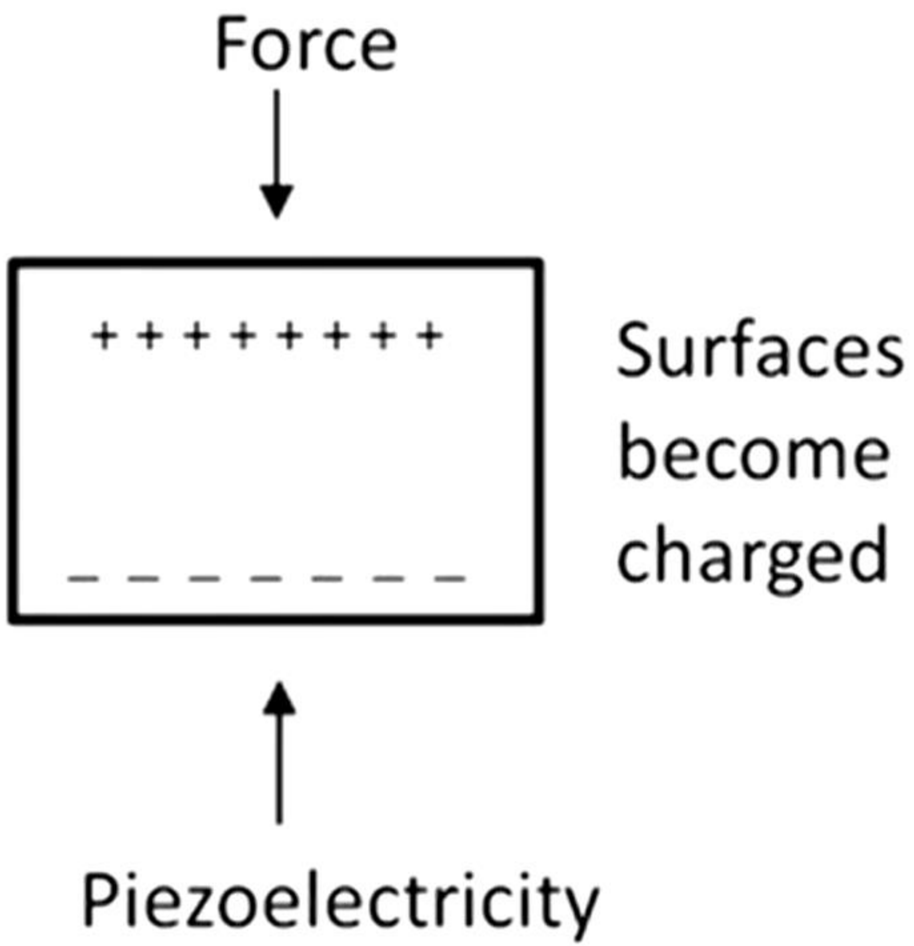


Bourdon tube

- A helical form of such a tube gives a greater sensitivity.
- Tube made of stainless steel or phosphor bronze
- Can measure 10^3 to 10^8 Pa

Piezoelectric Sensors

- Piezoelectric material are ionic crystals.
- When stretched or compressed, generate electric charges with one face of material becoming positively charged and the opposite face negatively charged.
- As a result a voltage is produced.



- The net charge q on a surface is proportional to the amount x by which the charges have been displaced, and since the displacement is proportional to the applied force F:

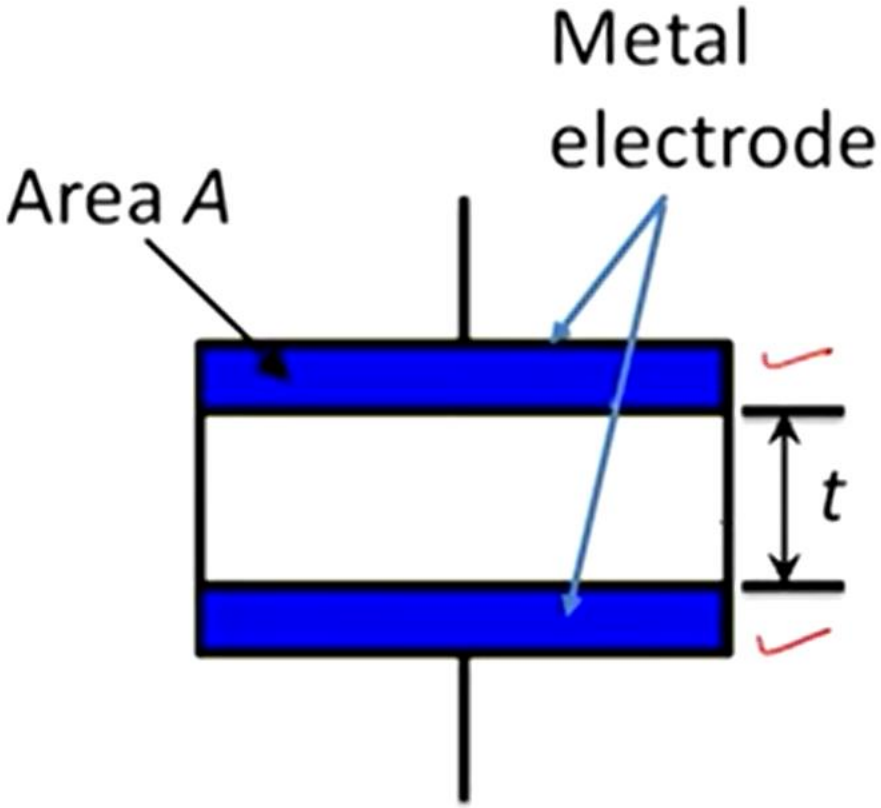
$$q = kx = SF$$

- where k is a constant and S a constant termed the charge sensitivity.
- The charge sensitivity depends on the material concerned and the orientation of its crystals.
- S= 2.2 pC/N for Quartz when the crystal is cut in one particular direction and the forces applied in a specific direction.

- Metal electrodes are deposited on opposite faces of the piezoelectric crystal.
- The capacitance C of the piezoelectric material between the plates is

$$C = \frac{\varepsilon_o \varepsilon_r A}{t}$$

- where ε_r is the relative permittivity of the material, A is area and t its thickness.



Piezoelectric Capacitor

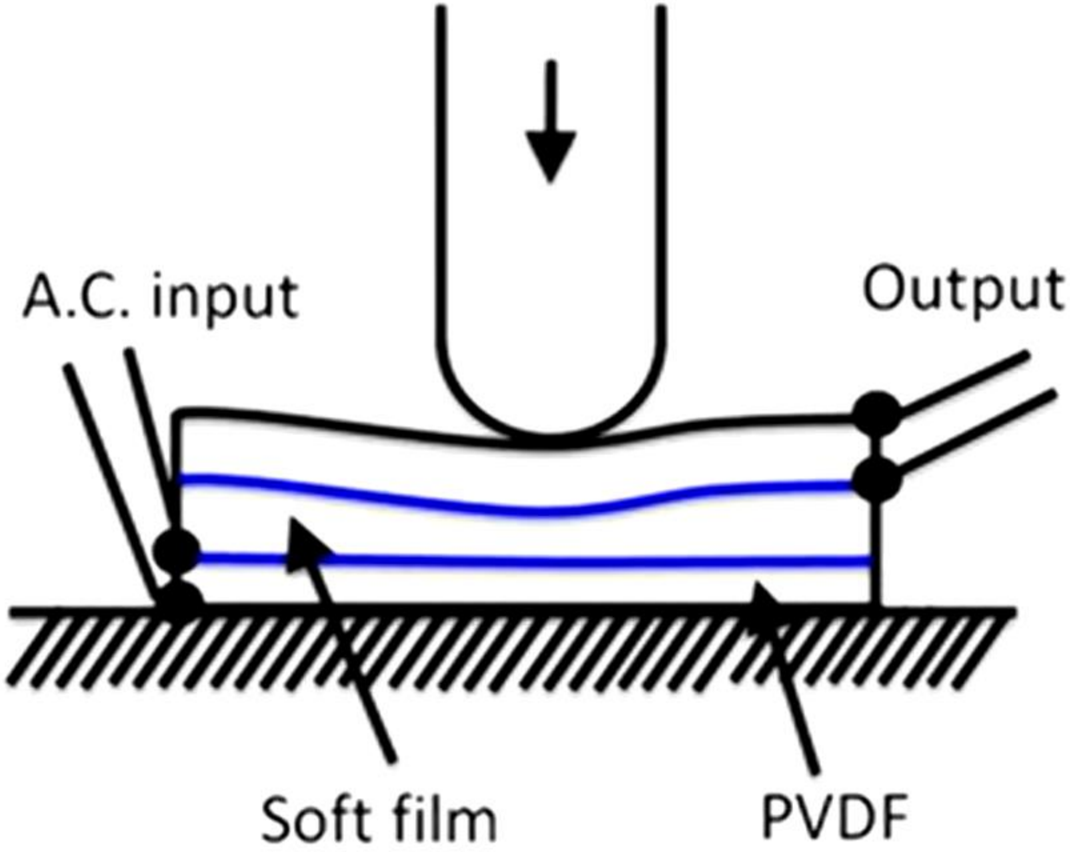
- $C = \frac{\varepsilon_0 \varepsilon_r A}{t}$
- $\frac{q}{V} = \frac{\varepsilon_0 \varepsilon_r A}{t}$
- $V = \frac{qt}{\varepsilon_0 \varepsilon_r A}$
- $V = \frac{SFt}{\varepsilon_0 \varepsilon_r A}$ (since $q=SF$)
- $V = \left(\frac{S}{\varepsilon_0 \varepsilon_r}\right)\frac{Ft}{A}$

- $V = S_v pt$
- S_v is voltage sensitivity factor
- p is pressure
- Thus, the voltage is proportional to the applied pressure.
- The voltage sensitivity for quartz is about 0.055 VmPa.
- For barium titanate it is about 0.011 Vm Pa

- Piezoelectric sensors are used for the measurement of
  - pressure,
  - force and
  - acceleration
- The applications have, however, to be such that the charge produced by the pressure does not have much time to leak off and thus tends to be used mainly for transient rather than steady pressures.

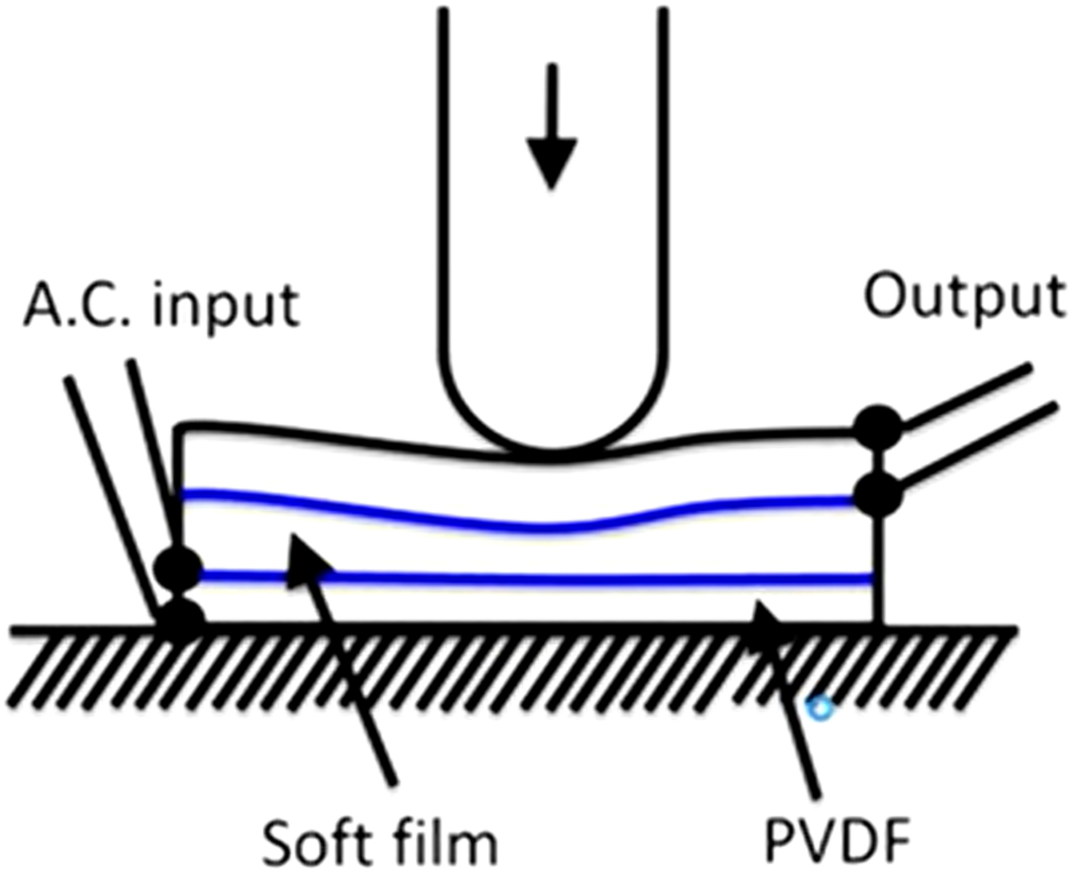
Tactile Sensors ✓

- Form of pressure sensor
- One form of tactile sensor uses piezoelectric polyvinylidene fluoride (PVDF) film.
- Reverse piezoelectric effect used here.
- Used in fingertip of robotic hand.
- Also in touch display screen
- Two layers of the film are used and are separated by a soft film which transmits vibrations



PVDF tactile sensor

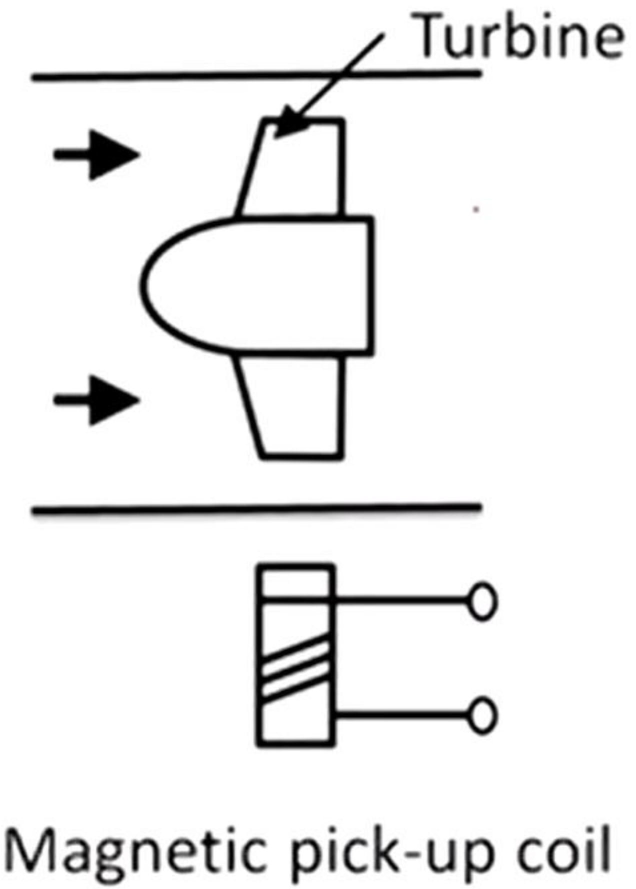
- The lower PVDF film has an alternating voltage applied to it and this results in mechanical oscillations of the film (reverse piezoelectric effect).
- The intermediate film transmits these vibrations to the upper PVDF film.



PVDF tactile sensor

Turbine Flowmeter

- It consists of a multi-bladed rotor that is supported centrally in the pipe along which the flow occurs.
- The fluid flow results in rotation of the rotor, the angular velocity being approximately proportional to the flow rate.
- The rate of revolution of the rotor can be determined using a magnetic pick-up.
- The pulses are counted and so the number of revolutions of the rotor can be determined.



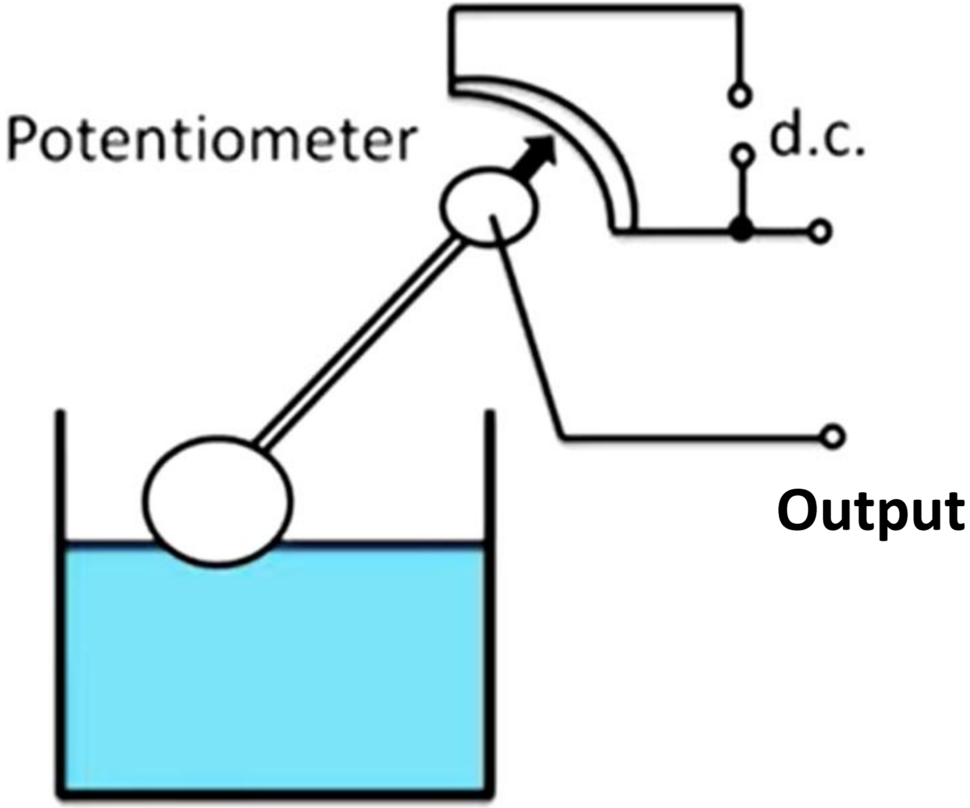
Turbine flowmeter

Liquid Levels

- Measured directly by monitoring the position of the liquid surface or indirectly by measuring some variable related to the height.
- Direct methods can involve floats; indirect methods include the monitoring of the weight of the vessel by, say, load cells.
- The weight of the liquid is $Ah\rho g$, i.e. $h \propto weight$, where A is the cross-sectional area of the vessel, h the height of liquid, ρ its density and g the acceleration due to gravity.
- Indirect methods also involve the measurement of the pressure at some point in the liquid, the pressure due to a column of liquid of height h being $h\rho g$,i.e., $h \propto pressure$

Float System

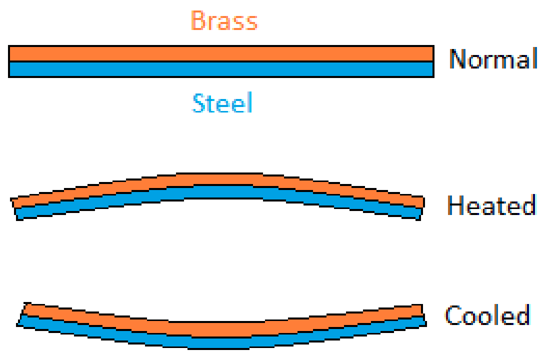
- The displacement of the float causes a lever arm to rotate and so move a slider across a potentiometer.
- The result is an o/p voltage related to the height of liquid.
- Other forms could be (i) the lever causing the core in an LVDT to become displaced, (ii) stretch or compress a strain-gauged element.



Float system

Temperature Sensor

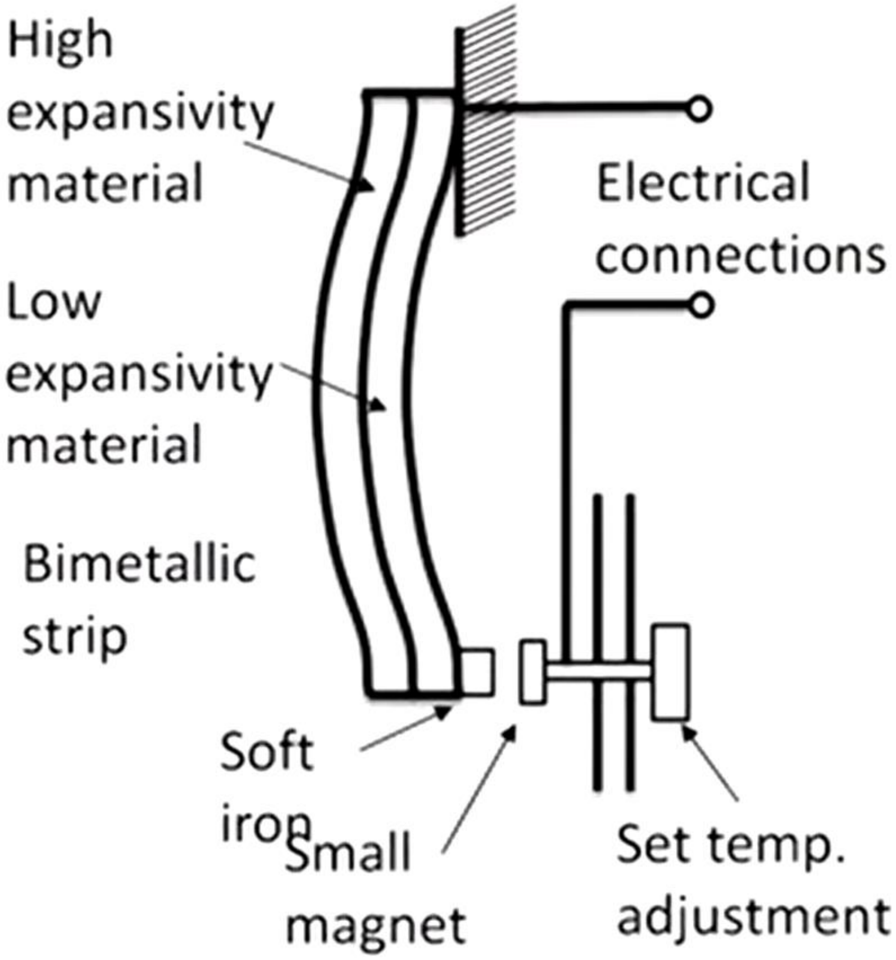
- Changes that are commonly used to monitor temperature are
  - the expansion or contraction of solids, liquids or gases
  - the change in electrical resistance of conductors and semiconductors and
  - thermoelectric e.m.f.s.



Bimetallic strip

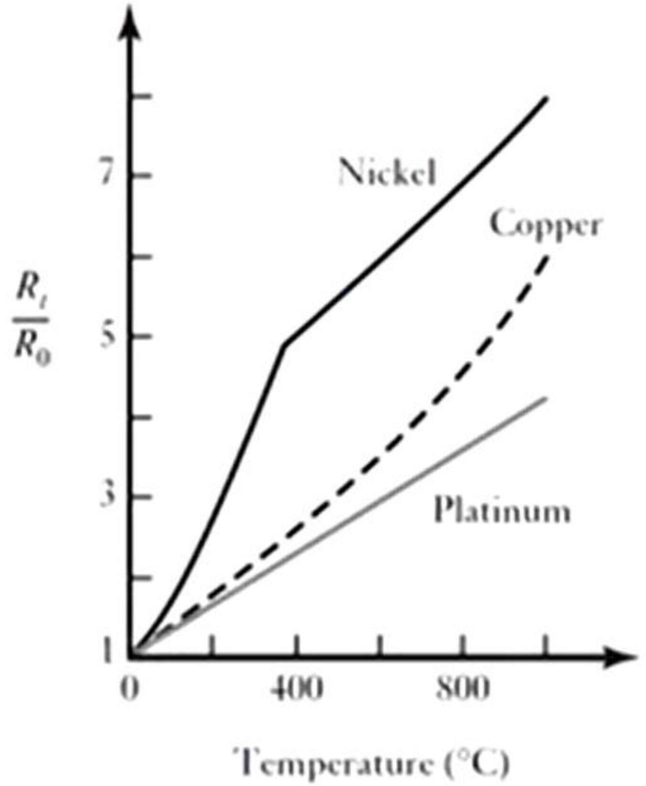
Bimetallic Strips

- This device consists of two different metal strips bonded together.
- The metals have different coefficients of expansion and when the temperature changes the composite strip bends into a curved strip, with the higher coefficient metal on the outside of the curve.
- This deformation may be used as a temperature-controlled switch
- Used with domestic heating system



Resistance Temperature Detectors (RTDs)

- The resistance of most metals increases, over a limited temperature range, in a reasonably linear way with temperature
- $R_t = R_0(1 + \alpha t)$
- α is a constant for the metal (temperature coefficient of resistance).
- RTDs are simple resistive elements in the form of coils of wire of such metals as platinum, nickel or nickel–copper alloys

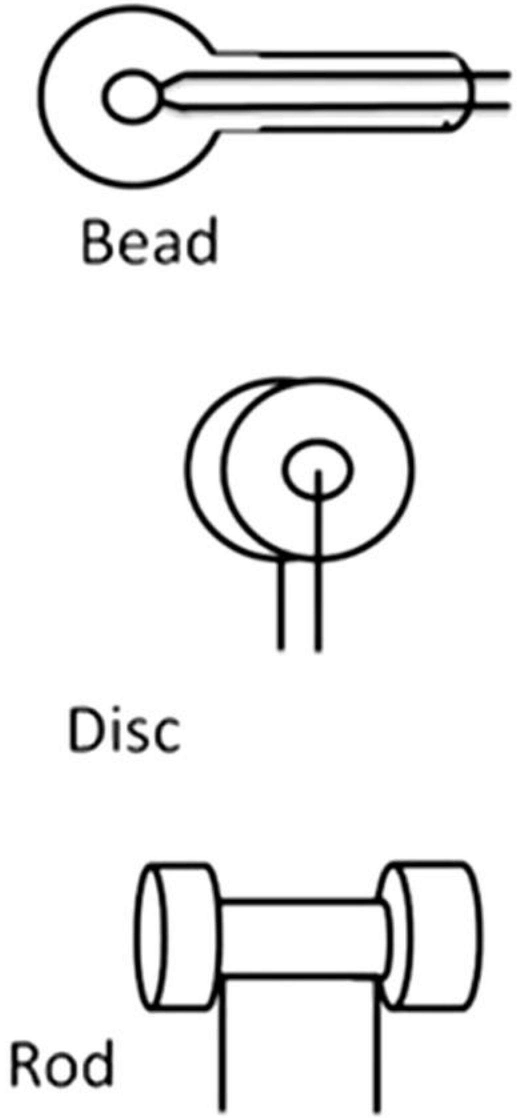


Variation of resistance with temperature for metal

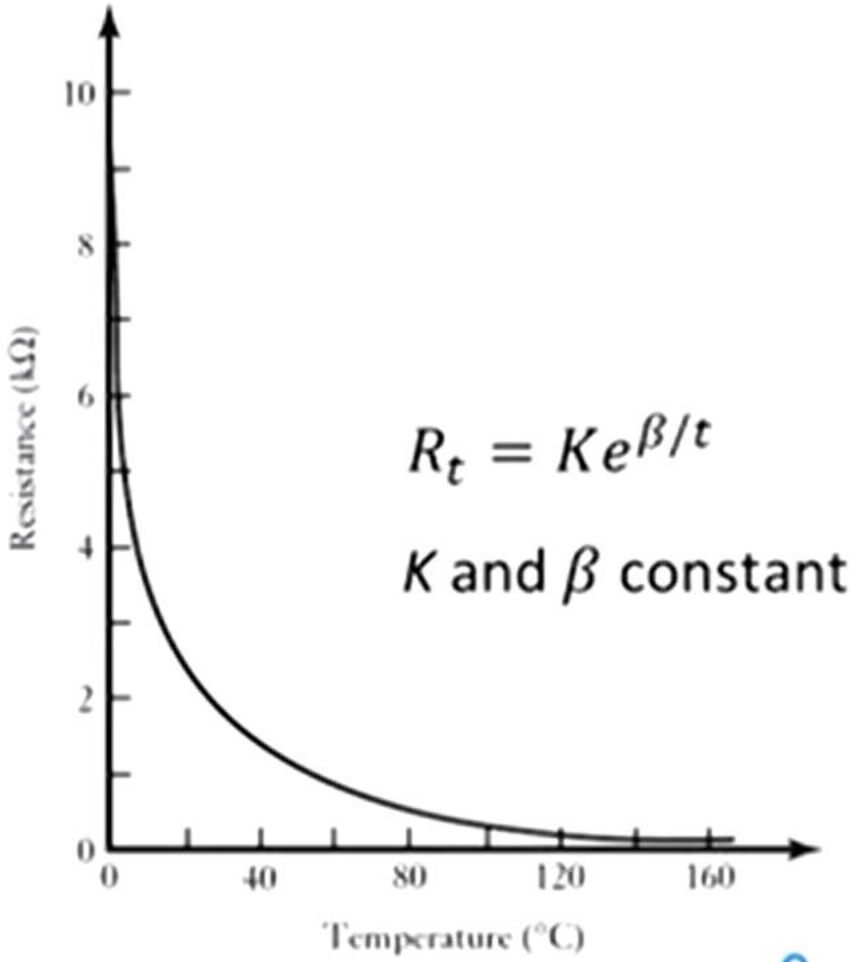
With the increase in temperature, the random motion of electrons increases. As a result, the number of collisions of electrons with the positive ions increases in a metal. Hence, the resistance of a metal increases with increase in temperature.

Thermistors

- Small piece of material made from mixture of metal oxides, such as those of chromium, cobalt, iron, manganese and nickel.
- These oxides are semiconductors.
- They give large change in resistance per degree change in temperature.
- Draw back is non linearity.
- The material is formed into various forms of element, such as beads, discs and rods



- Such thermistors have negative temperature coefficients (NTCs).
- The change in resistance per degree change in temperature is considerably larger than that which occurs with metals.
- Thermistors are rugged and can be very small.
- Used with the electronic systems for cars to monitor such variables as air temp. and coolant air temp.



$$R_t = Ke^{\beta/t}$$

K and β constant

The resistance of metal-oxide thermistors decreases in a very non-linear manner with an increase in temp.

Thermodiodes

- In a junction semiconductor diode when the temperature of doped semiconductor changes, the mobility of their charge carrier changes and this affects the rate at which the electrons and holes diffuse across p-n junction.
- Thus when a p–n junction has a potential difference *V* across it, the current *I* through the junction is
- $I = I_0\left(e^{eV/kT} - 1\right)$
- where *T* is the temperature on the Kelvin scale, *e* the charge on an electron, and *k* and I_0 are constants.

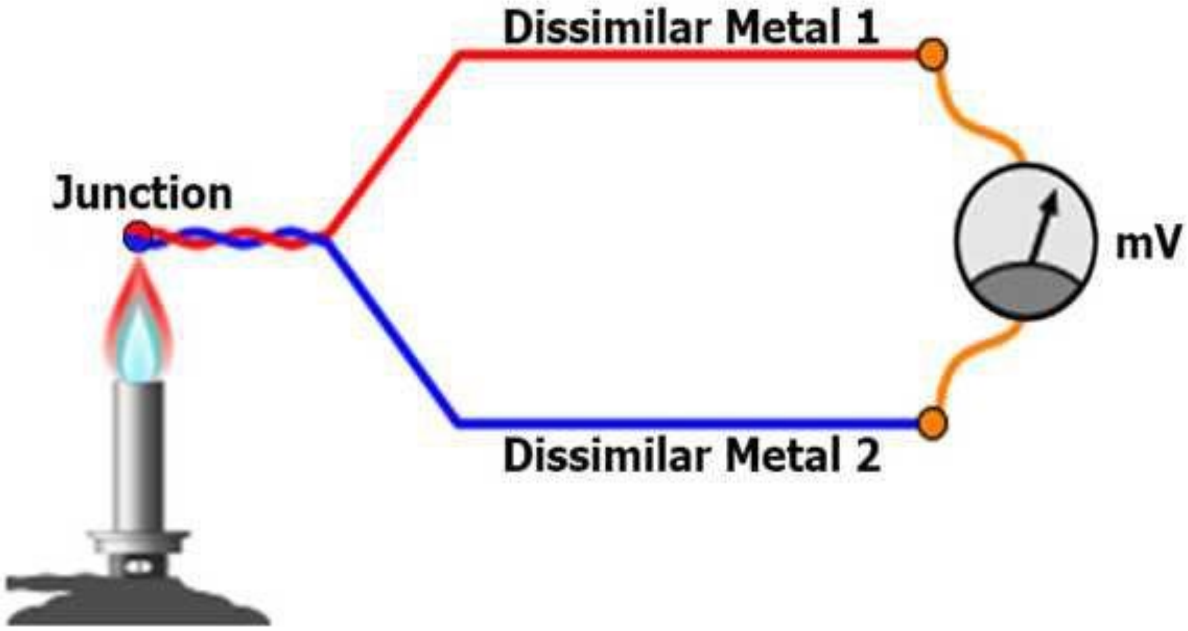
Thermotransistor

- In a thermo transistor the voltage across the junction between the base and the emitter depend upon the temperature and can be used as a measure of temperature.
- Example: LM35.
- This sensor can be used in the range -40 to 110°C and gives an output of 10 mV/°C.

Thermocouple

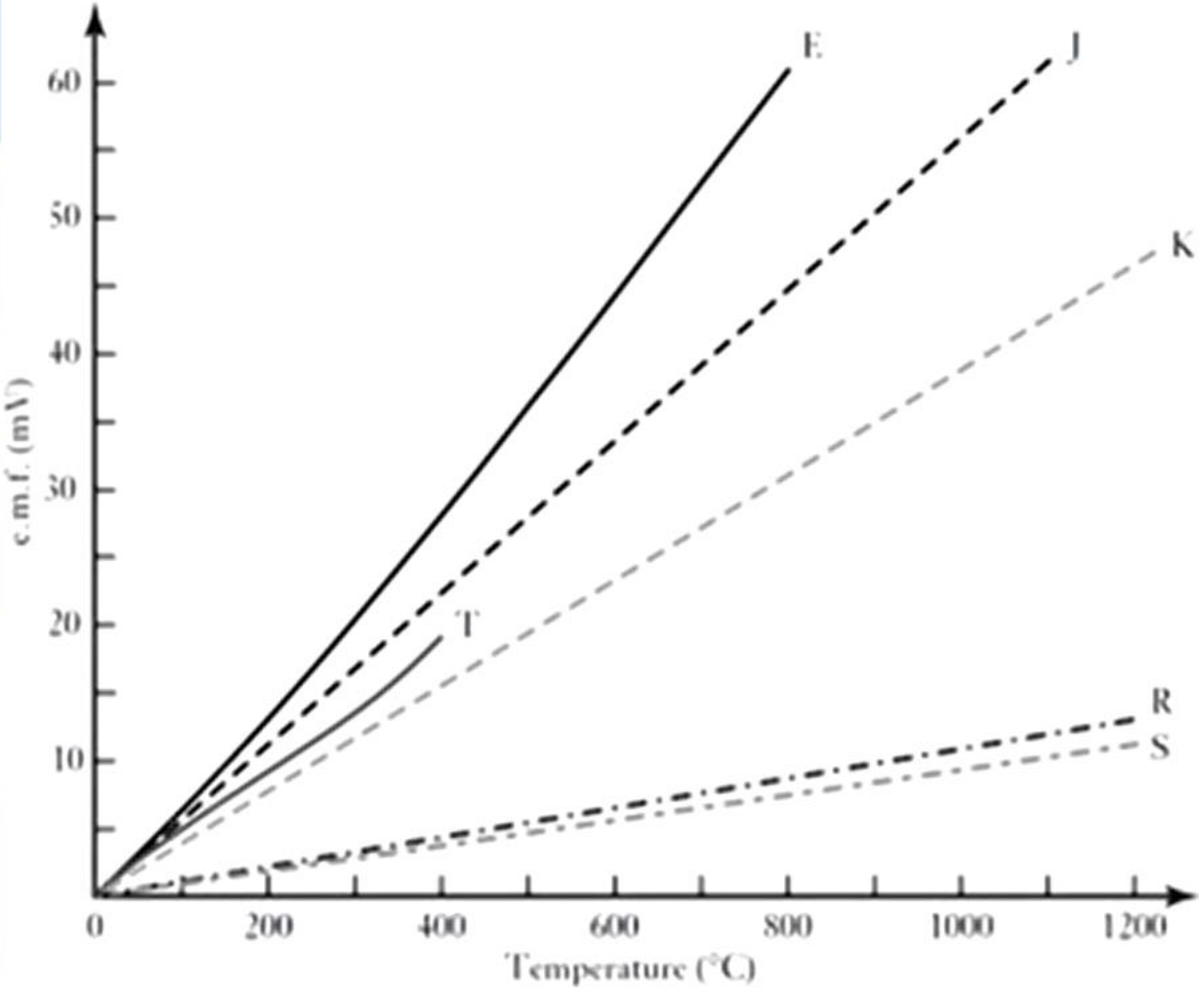
Seebeck effect

- If two different metals are joined together, a potential difference occurs across the junction.
- The potential difference depends on the metals used and the temperature of the junction.



Thermocouple

Ref.	Materials	Range (°C)	Sensitiviti (μV/°C)
E	Chromel/constantan	-200 to 1000	63
J	Iron/constantan	-200 to 900	53
K	Chromel/alumel	-200 to 1300	41
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



Light Sensors

- Photodiodes
- Semiconductor junction diodes connected into a circuit in reverse bias, thus giving high resistance, when light falls on the jn of diodes, extra hole–electron pairs are produced, the resistance drops and current rises appreciably.
- The reverse current is very nearly proportional to the intensity of the light.

Phototransistors

- Have light sensitive collector base pn jn.
- With no incident light there is very small collector to emitter current
- When light is incident a base current is produced that is directly proportional to light intensity
- This leads to production of collector current which is measure of light intensity.
- These are often available in a Darlington arrangement.

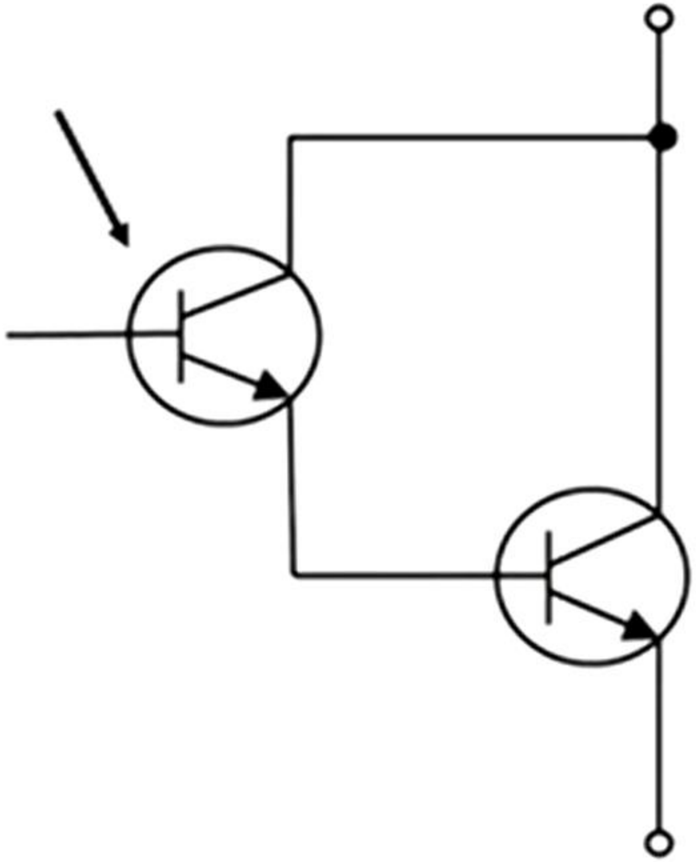


Photo Darlington

Photoresistors

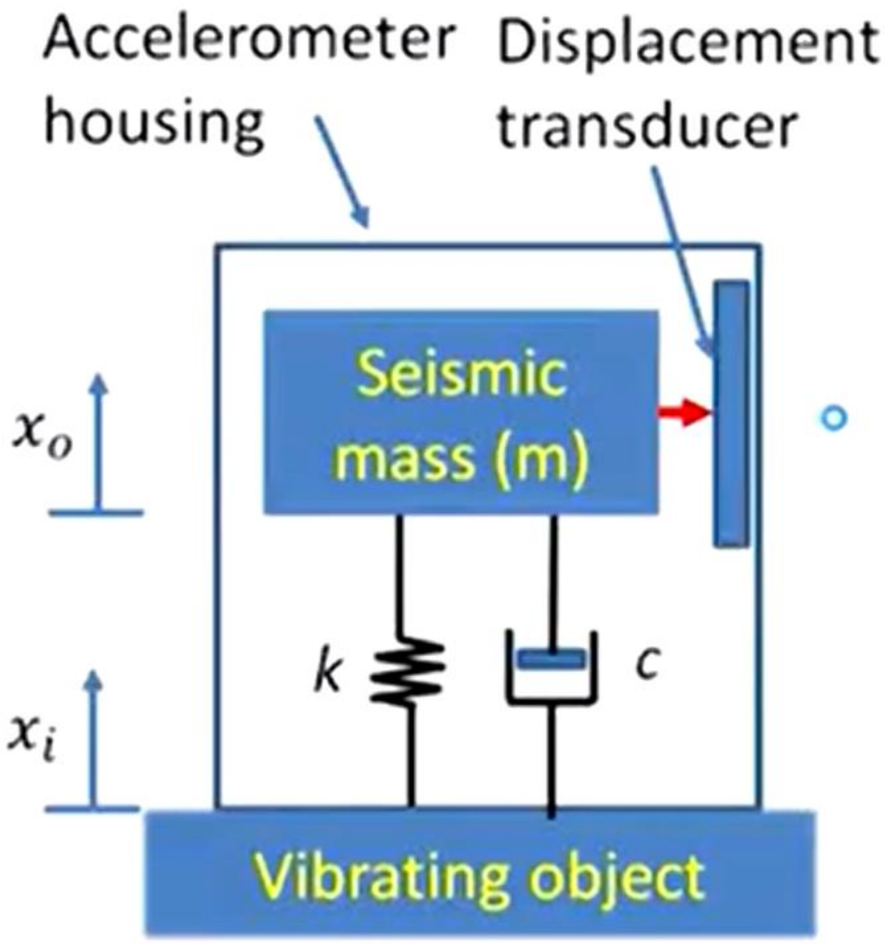
- Its resistance depends upon light falling on it.
- It decreases linearly as the intensity increases.
- Cadmium sulphide photo resistor is most responsive to light.

Introduction

- An accelerometer is a sensor designed to measure acceleration, or rate of change of speed, due to motion, vibration, and impact events.
- Accelerometers are normally mechanically attached or bonded to an object or structure for which acceleration is to be measured.
- The accelerometer detects acceleration along one axis and is insensitive to motion in orthogonal directions.
- Strain gages or piezoelectric elements constitute the sensing element of an accelerometer, converting acceleration into a voltage signal.

Vibration and Acceleration Measurement

- The design of an accelerometer is based on the inertial effects associated with a mass connected to a moving object through a spring, damper, and displacement sensor.
- As object accelerates, there is relative motion between the housing and the seismic mass.
- A displacement transducer senses the relative motion.
- From frequency response analysis one can relate the displacement transducer output to either the absolute position or acceleration of the object.



Frequency Response of the Accelerometer

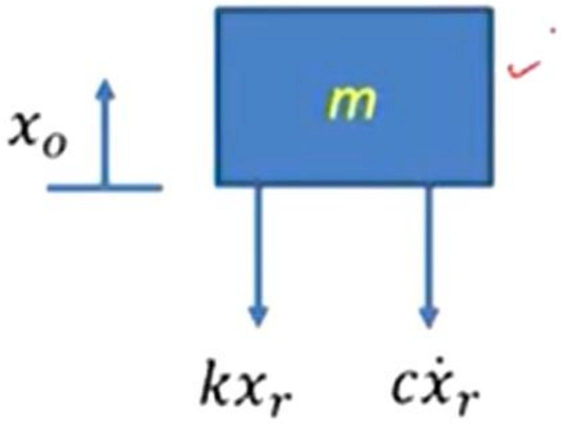
- Relative displacement (x_r) between the seismic mass and the object is $x_r = x_o - x_i$
- Using Newton's second law, the equation of motion for the seismic mass is

$$m\ddot{x}_o = -kx_r - c\dot{x}_r$$

$$m(\ddot{x}_r + \ddot{x}_i) = -kx_r - c\dot{x}_r$$

$$m\ddot{x}_r + c\dot{x}_r + kx_r = -m\ddot{x}_i$$

- This 2nd order differential equation relates the measured relative displacement x_r to the input displacement x_i



Free body diagram

$$\Sigma F = -kx - c\dot{x} + F_{external} = m\ddot{x}$$

- $m\ddot{x}_r + c\dot{x}_r + kx_r = -m\ddot{x}_i$
- $\ddot{x}_r + \frac{c}{m}\dot{x}_r + \frac{k}{m}x_r = -\ddot{x}_i$
- Let us define $\omega_n^2 = \frac{k}{m}$ and $\zeta^2 = \frac{c^2}{4mk}$ then $\zeta = \frac{c}{2\sqrt{mk}}$
- $\boxed{\ddot{x}_r + 2\zeta\omega_n\dot{x}_r + \omega_n^2 x_r = -\ddot{x}_i}$

Eq. of motion for seismic mass

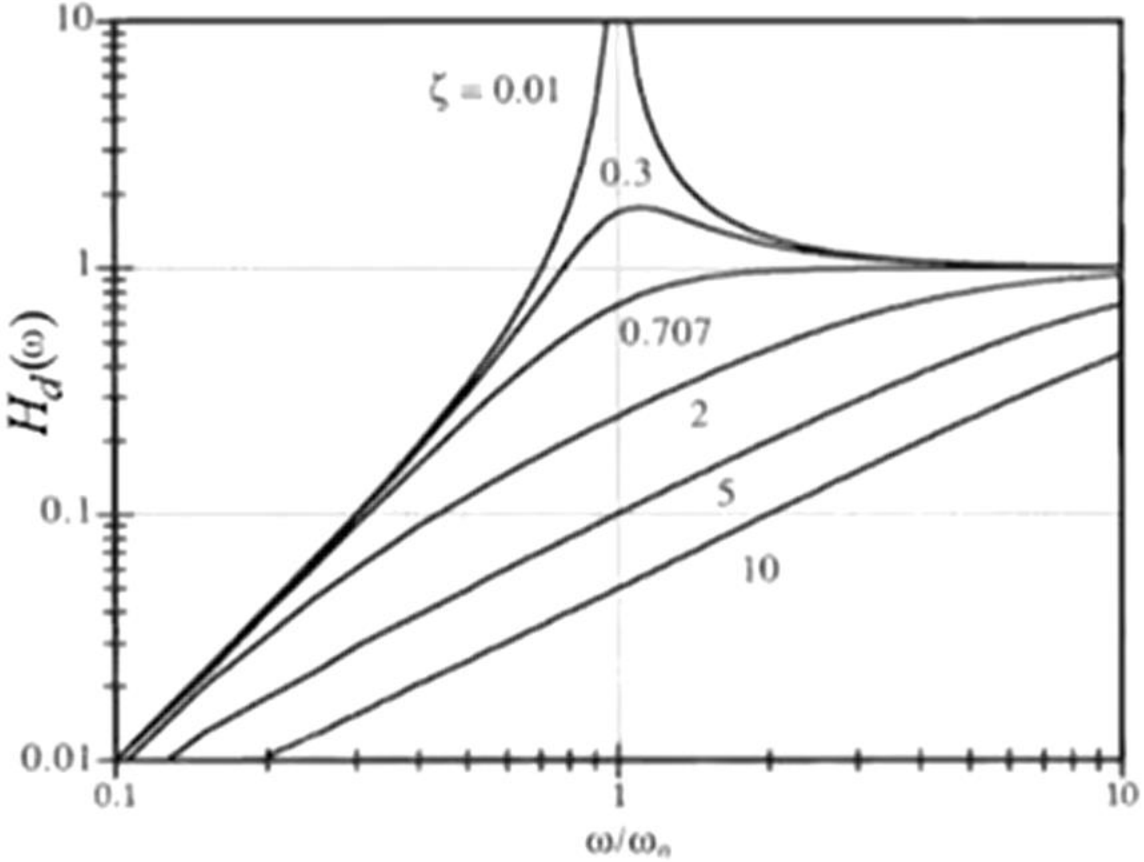
- For a frequency response analysis, let the i/p displacement is $x_i(t) = X_i \sin(\omega t)$ (of sinusoidal form)
- Since the system is linear, the resulting relative o/p displacement will be $x_r(t) = X_r \sin(\omega t + \phi)$ (sinusoidal of the same frequency but different phase)

ω_n is the undamped natural frequency and ζ is the damping ratio.

- To relate the relative output displacement signal x_r to the input acceleration $\ddot{x}_i$
- $x_i(t) = X_i \sin(\omega t)$
- $\ddot{x}_i(t) = -\omega^2 X_i \sin(\omega t)$
- So amplitude of input acceleration is $\omega^2 X_i$, so rewriting amplitude ratio expression as
- $\frac{X_r \omega_n^2}{X_i \omega^2} = \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + (2\zeta\omega/\omega_n)^2}} = H_a(\omega)$ so,

Vibrometer

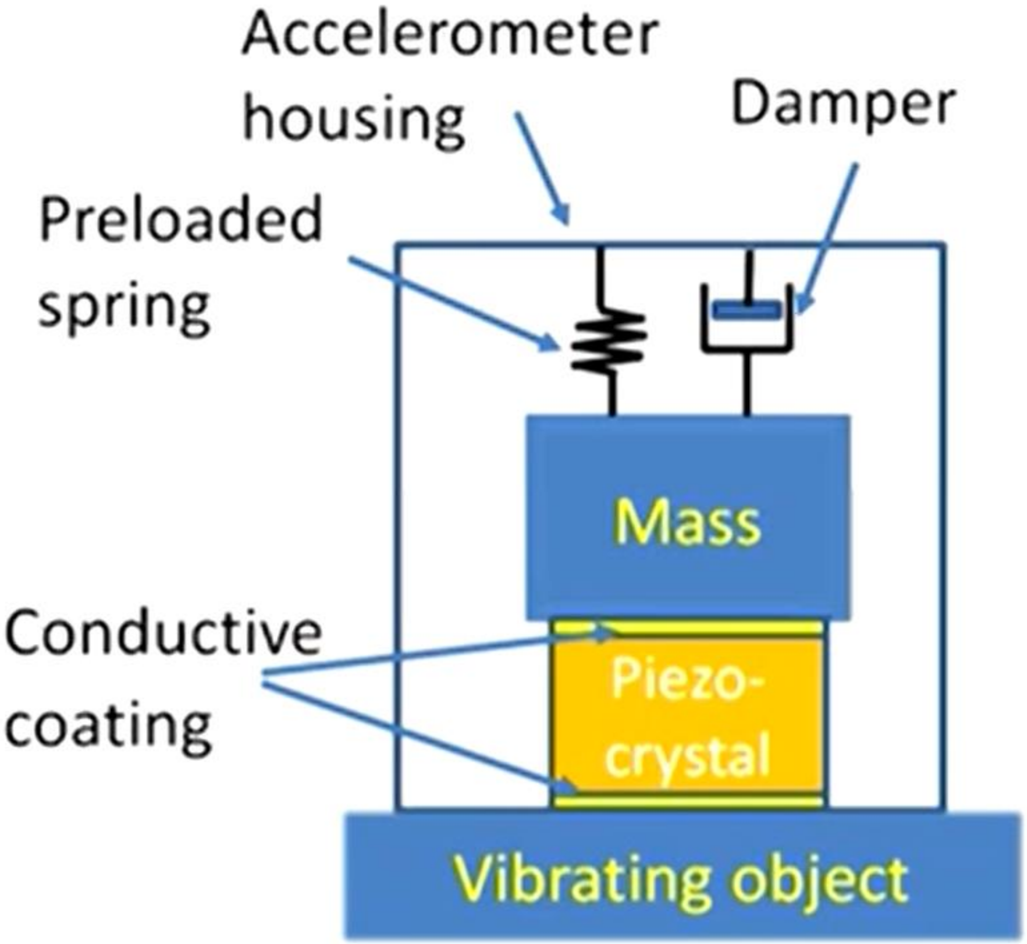
- The same spring-mass-damper configuration used to measure acceleration can also be designed to measure displacement.
- Let us define $H_d(\omega) = \frac{X_r}{X_i}$
- So $X_i = \frac{X_r}{H_d(\omega)}$
- If we design the vibrometer so that $H_d(\omega) \approx 1$ over a large frequency range, then $X_i = X_r$



Amplitude response of a Vibrometer

Piezoelectric Accelerometer

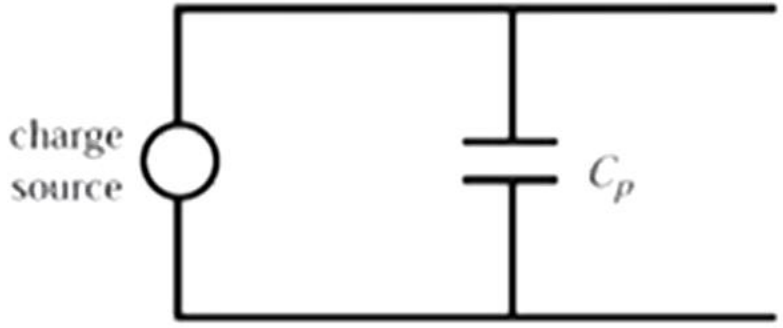
- The highest quality accelerometers use piezoelectric crystal.
- When the vibrating object experiences acceleration, relative displacement occurs between the object and the mass due to the inertia of the mass.



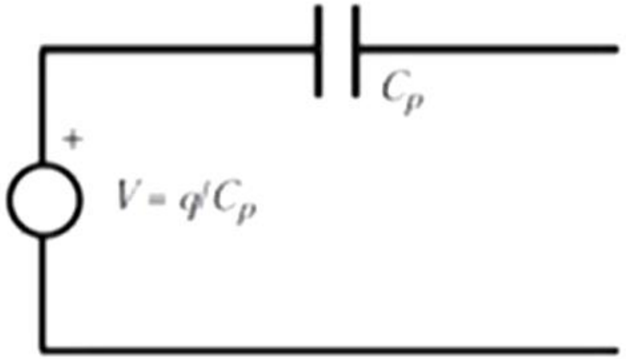
- The resulting strain in the piezoelectric crystal causes a displacement charge between the crystal conductive coatings as a result of the piezoelectric effect.
- This accelerometer requires no external power supply.
- It measures acceleration in the mounted direction (along the axis of spring)

Commercially available piezoelectric accelerometer

- Piezoelectric crystal is effectively a capacitor and a charge source that generates a charge q across the capacitor plates proportional to the deformation of the crystal.
- Representing the accelerometer by a Thevenin equivalent circuit the open circuit voltage V is $V = \frac{q}{C_p}$
- Typically q is in the picocoulomb range, and C_p in the picofarad range.



Equivalent circuit for piezoelectric crystal.



Thevenin equivalent of piezoelectric crystal.