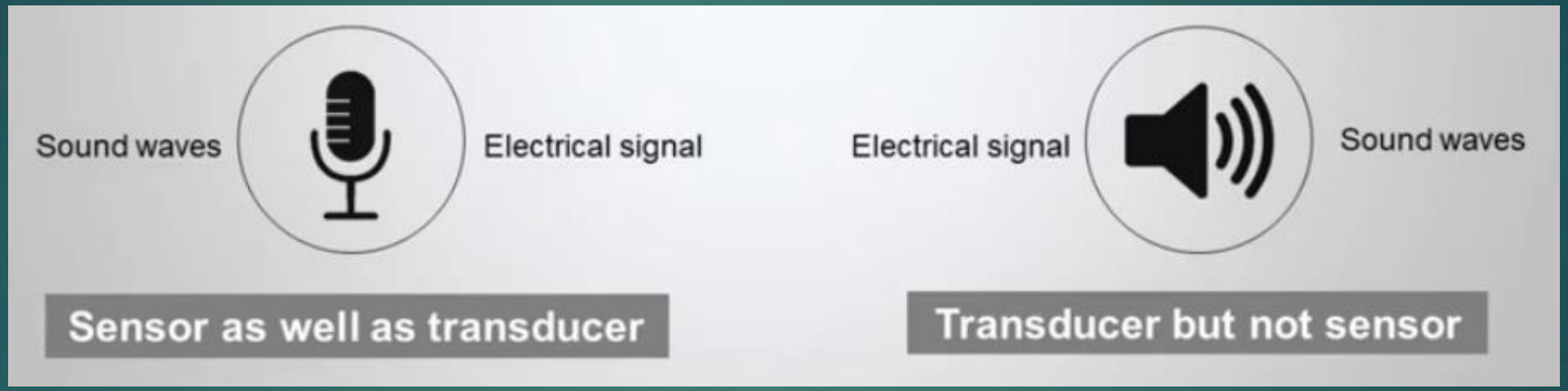
Sensors, Transducers, and Actuators

Sensors and Transducers

- Sensors and transducers are both devices which react to a change in a physical quantity (temperature, heat, speed, etc.) in their surroundings.
- A transducer is an electronic device which takes measurement in one form and converts it to another form. For example, a measurement which is not electrical and converts it into an electrical signal. This is known as transduction principle.
- There are two transducer types:
  - Input transducer take some sort of physical energy and converts it into a signal that can be read. Example is microphone which converts sound energy to electrical energy.
  - Output transducer takes in electrical signals and converts them into other forms of physical energy. Example is loudspeaker which converts electrical signal to sound wave.

Sensors and Transducers

- Sensor is a device that senses the change in the environment they are exposed to and gives an output in the same format. An example is the thermistor. A thermistor is a temperature sensitive resistor. A change in temperature will result to a change in resistance value.
  - A thermistor on its own is a sensor but, when incorporated with appropriate electrodes and attached to input-output mechanisms, it becomes a transducer. Example is when a thermistor is used to produce output voltage with the variations in ambient temperature.

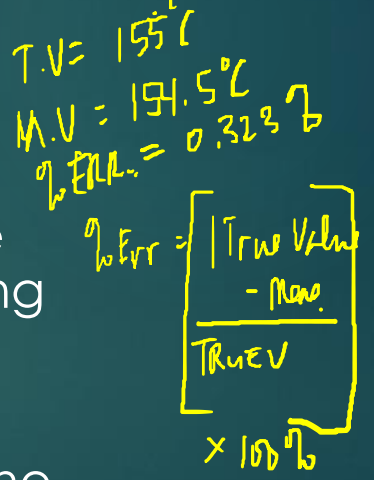

Sound waves
Electrical signal
Sensor as well as transducer
Electrical signal
Sound waves
Transducer but not sensor

Sensors and Transducers

	Sensor	Transducer
Principle	Senses a physical measurement and makes it readable for the user but keeps it in the same format.	Senses a physical measurement and converts the measured quantity to another form, e.g., non-electrical to electrical
Examples	Thermistor, motion sensor	Microphone, loudspeaker

Sensor/Transducer Specifications:

1) Range – The range of a sensor indicates the limits between which the input or measured quantity can vary. Example, a certain thermistor can measure -55°C to +150°C
2) Span – The is the difference between maximum and minimum values of the input. The thermistor from the example above will have a span of 205°C.
3) Error – Error is the difference between the result of the measurement and the true value of the quantity being measured.
4) Accuracy – Accuracy defines the closeness of the agreement between the actual measurement and the true value of the measured quantity. It is often expressed in percentage of the full range.



Sensor/Transducer Specifications:

5) Sensitivity – Sensor sensitivity is defined as the ratio of change in output value to the per unit change in input value that causes the output change. Example, device sensitivity of 25μV/°C
6) Nonlinearity – The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve.
7) Resolution – Resolution is the smallest detectable incremental change of input parameter that can be detected.
8) Stability - Stability is the ability of a sensor device to give same output when used to measure a constant input over a period of time.

Sensor/Transducer Specifications:

9) Repeatability – It specifies the ability of a sensor to give same output for repeated applications of same input value. It is usually expressed as a percentage of the full range output.
10) Response time – Response time describes the speed of change in the output in response to the input.

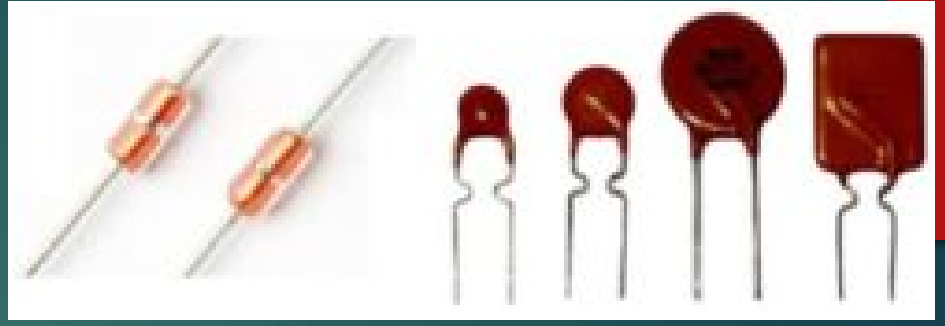
Classification of Sensors Based on Property

- Temperature:
  - Thermistors
  - Thermocouples
  - **Resistance Temperature Detectors (RTD)**
  - **Thermo-diodes**
  - **Thermo-transistors**
- Light:
  - Photo diodes
  - Photo resistors
  - **Photo transistors**
- Liquid Level
  - Float switch
- Liquid Flow
  - **Rotating vane flow meter**
  - Turbine flow meter
- Force
  - Strain gauge load cell

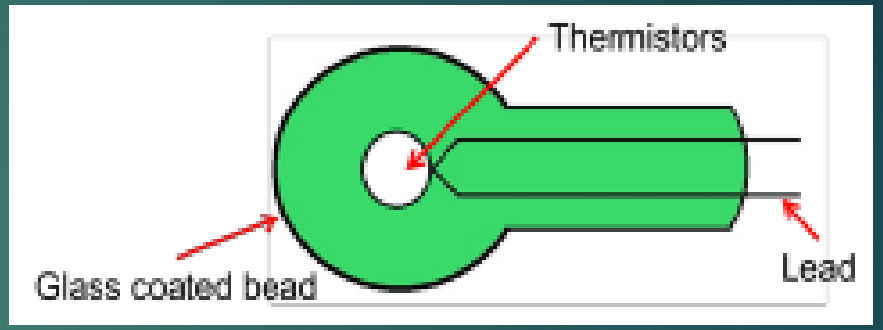
Classification of Sensors Based on Property

- Displacement, position, and proximity:
  - Potentiometer
  - Pneumatic sensors
  - Proximity switches
  - Optical Encoder
  - Hall effect sensors
- Velocity and motion:
  - Tachogenerator
  - Pyroelectric sensors
- Image
  - Charge-coupled device (CCD)
  - Active pixel sensor
- Sound
  - microphone

Temperature

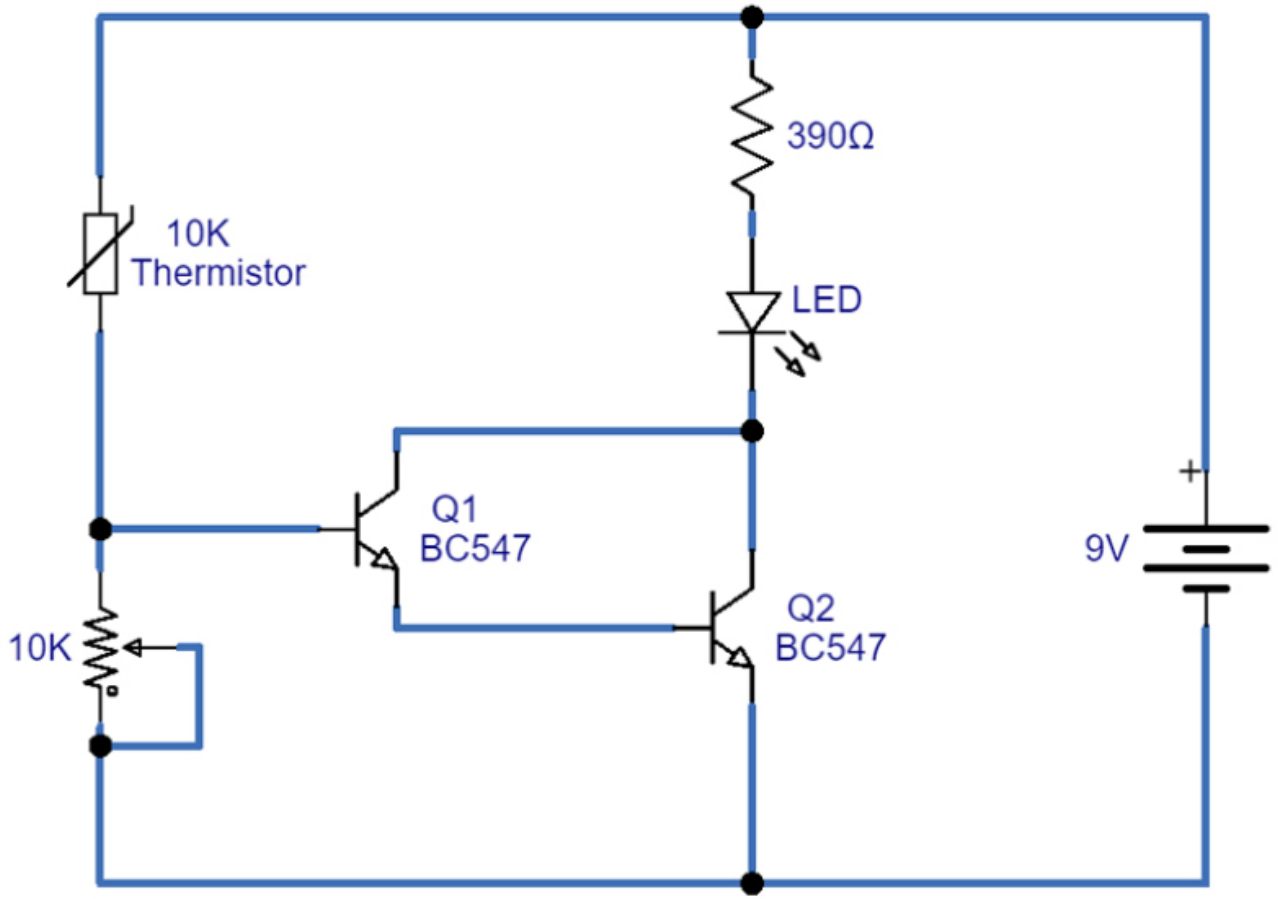


- **Thermistors** follow the principle of decrease in resistance with increasing temperature.
- The material used in thermistor is generally a semiconductor material.
- As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance.
- Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics



- Applications:
  - To monitor the temperature of incubator, battery packs while charging, hot ends of 3D printers
  - To maintain correct temperature in food handling and processing industry equipment
  - To control the operation of toasters, coffee makers, freezers, refrigerators, etc.

Temperature Sensor Circuit



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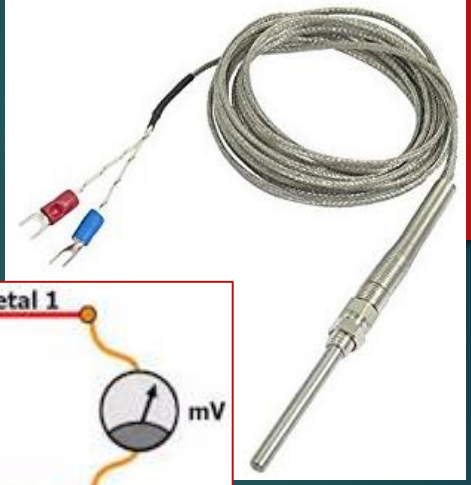
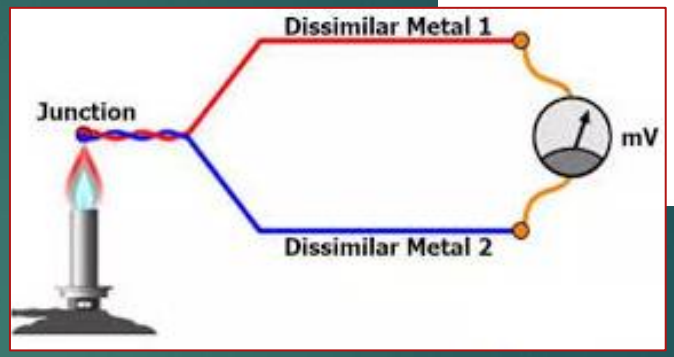
The circuit operates at 9 volts. Initially, when there is no heat, the circuit will remain turned off. When the thermistor receives heat its resistance will decrease and it will let the current flow. This will activate both the transistors (Darlington configuration) and the current will flow through the LED and it will light up. A variable resistor of 10-20K ohms is used to adjust the circuit for activation of LED on the required temperature or heat.

This device is ideal to use where you don't want any device or equipment to be overheated, the circuit is compact so it can fit anywhere.

Temperature

- **Thermocouple** comprises of two different metals connected on one end and open on the other.
- Thermocouple works on the fact that when a junction of dissimilar metals is heated, it produces an electric potential related to temperature. This is called thermoelectric effect.
- The physical structure is very strong
- To protect the device from various environmental factors, it is covered with plastic and ceramic sheaths.





- Applications:
  - Testing temperatures in chemical production and petroleum refineries
  - Testing of heating appliance safety
  - Temperature measurement of gas turbine
  - Monitoring of temperatures in the production and smelting process in the steel, iron, and aluminum industry

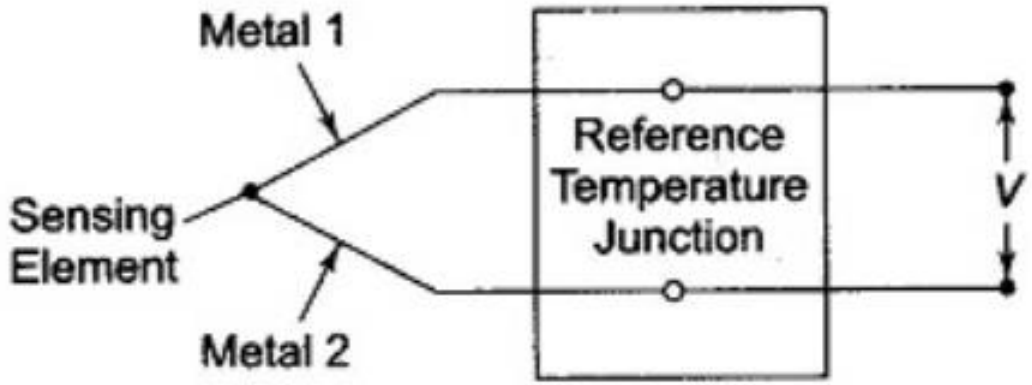


Fig. 13.41 Basic Thermocouple Connection

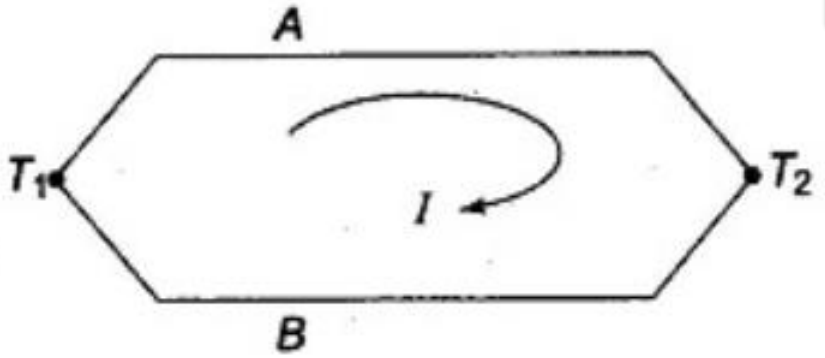


Fig. 13.42 Current through Two dissimilar Metals

One of the most commonly used methods of measurement of moderately high temperature is the thermocouple effect. When a pair of wires made up of different metals is joined together at one end, ***a temperature difference between the two ends of the wire produces a voltage between the two wires of Thermocouple Connection.***

Temperature measurement with Thermocouple Connection is based on the ***Seebeck effect***. A current will circulate around a loop made up of two dissimilar metal when the two junctions are at different temperatures.

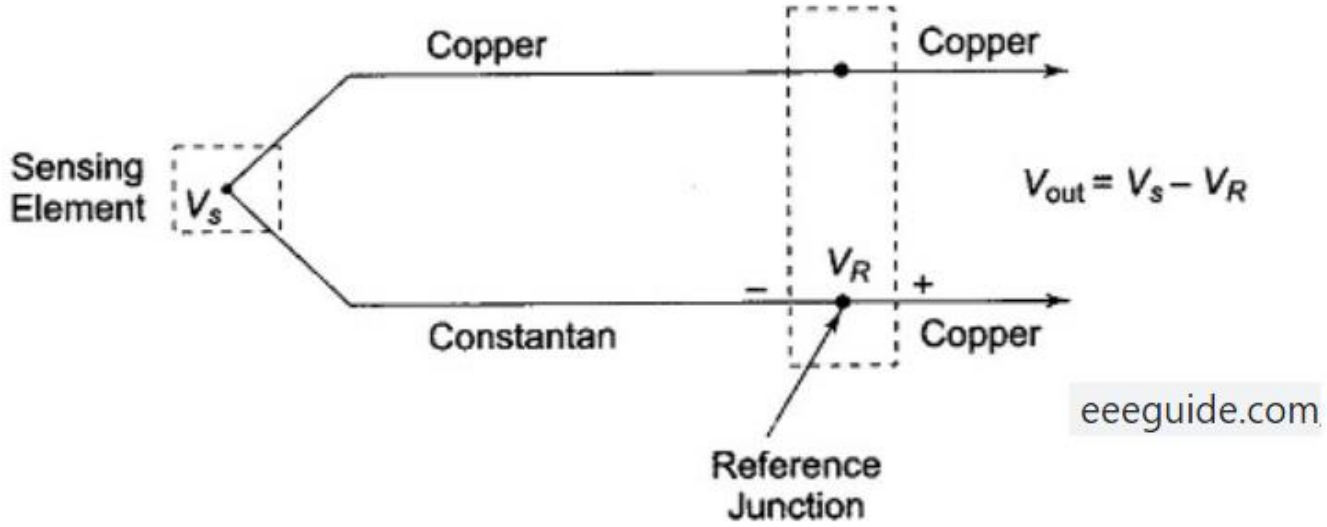


Fig. 13.44 A Type T Thermocouple with Reference Junction

For accurate measurement of hot junction temperature, the cold junction or the reference junction should be kept at 0°C. If the reference junction is kept at the ambient temperature, then a voltage corresponding to this temperature must be added to the measurement to obtain accurate reading.

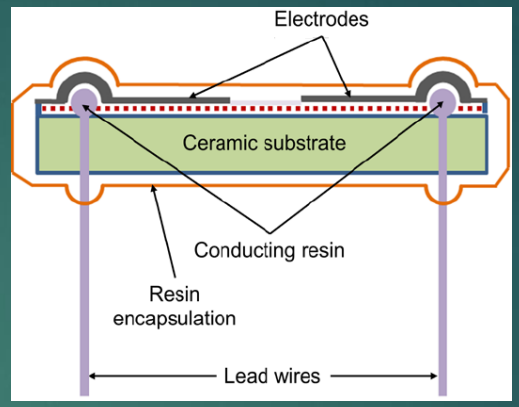
The magnitude of the output voltage depends on the material used for the wires and the amount of temperature difference between the joined ends and the other ends. The junction of the wires of the Thermocouple Connection is called the **sensing junction**, and this junction is normally placed on the unit under test.

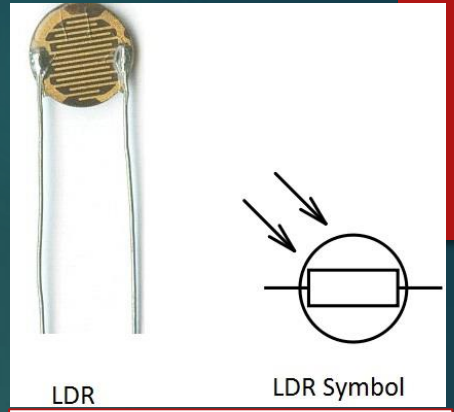
Table 13.3 Different Types of Thermocouples

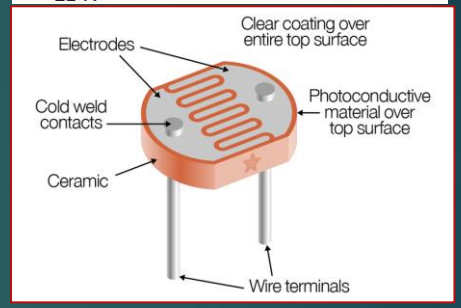
Thermocouple type	*Materials used*	*Temperature range/ °C*	*Sensitivity μV/°C*
Type T	Copper/Constantan	–200–400	15–60
E	Chromel/Constantan	0–850	40–55
J	Iron / Constantan	–200–900	45–57
K	Chromel/Alumel	–200–1250	40–55
R	Platinum/Platinum 13% Rhodium	0–1600	5–12
S	Platinum/Platinum 10% Rhodium	0–1500	5–12
B	Platinum 6% Rhodium/ Platinum 30% Rhodium	30–1800	0.3–0.8
G	Tungsten/Tungsten 26% Rhenium	15–2800	3–20
C	Tungsten 5% Rhenium/ Tungsten 25% Rhenium	0–2750	10–20

Light

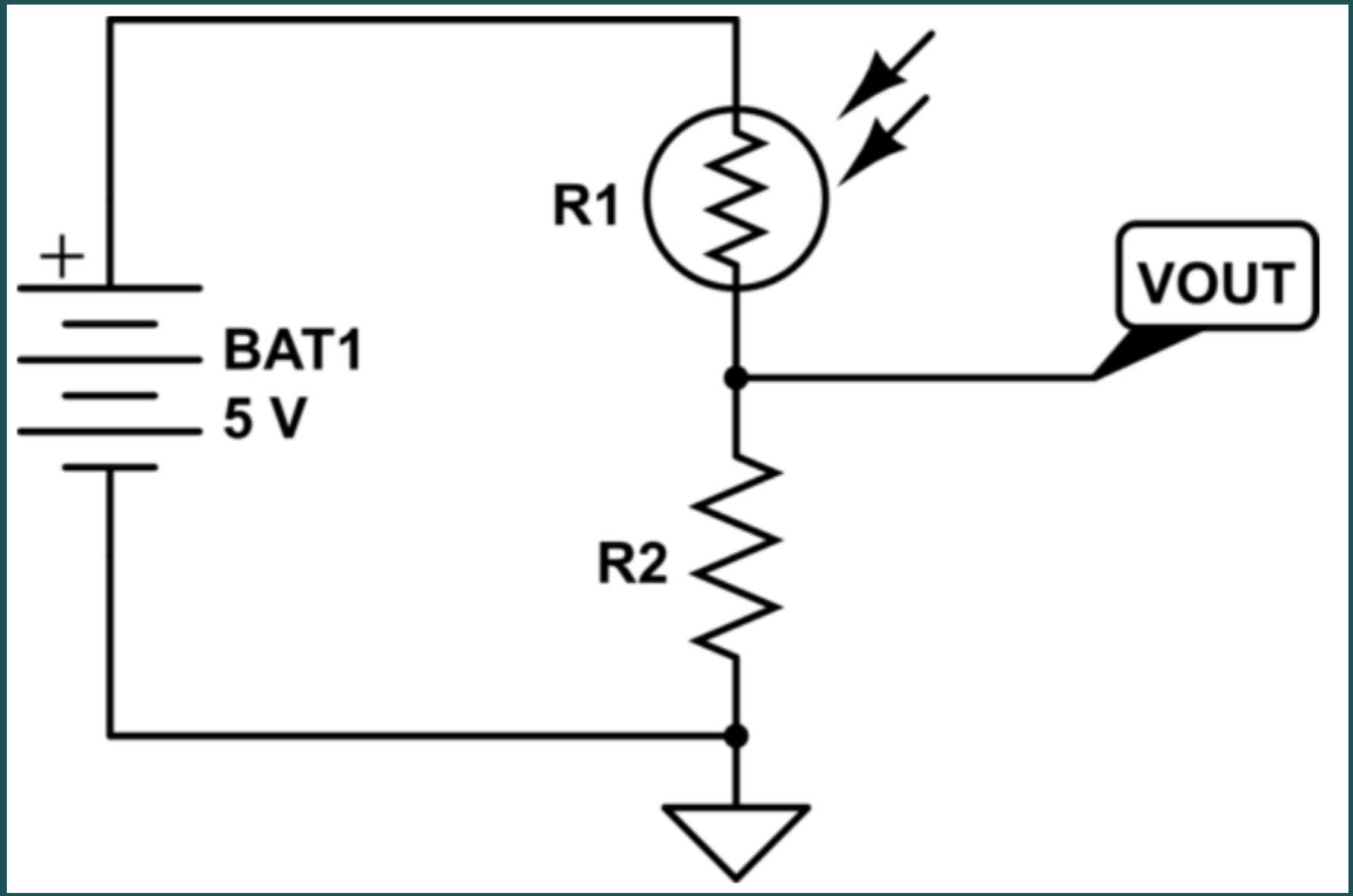
- **Photoresistor** is also called Light Dependent Resistor (LDR).
- On incidence of high intensity light on the electrodes, the resistance of resistor coil decreases.
- It is made of a high resistance semiconductor material, cadmium sulfide (CdS), which is mounted on a ceramic substrate.
- The assembly is encapsulated by a resin material.



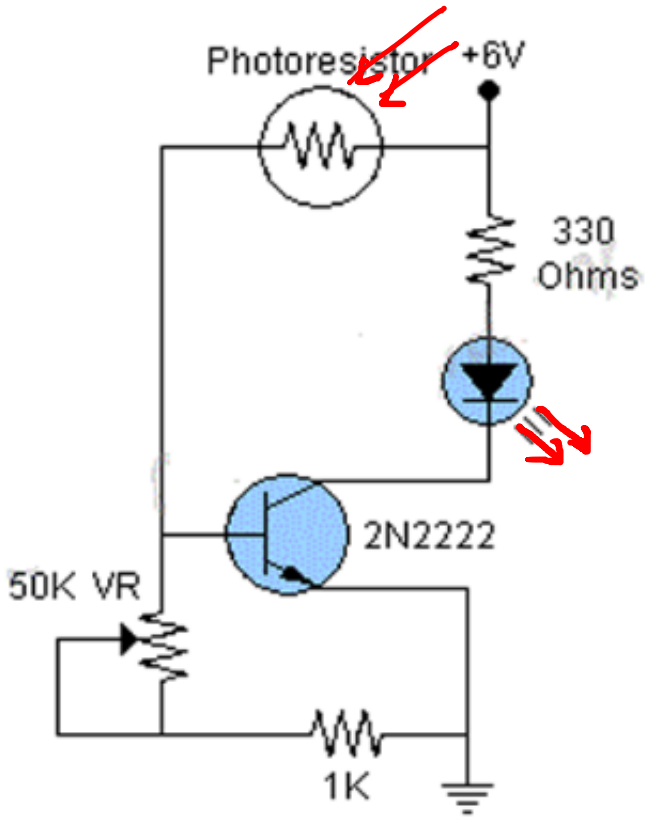




- Applications:
  - Computers, mobile phones, and televisions, use ambient light sensors to automatically control the brightness of the screen
  - Auto flash for camera
  - Industrial process control
  - Robotics. Robots can be programmed to have a specific reaction if a certain amount of light is detected.


+
BAT1
5 V
R1
R2
VOUT

Light Activated LED using Photoresistor



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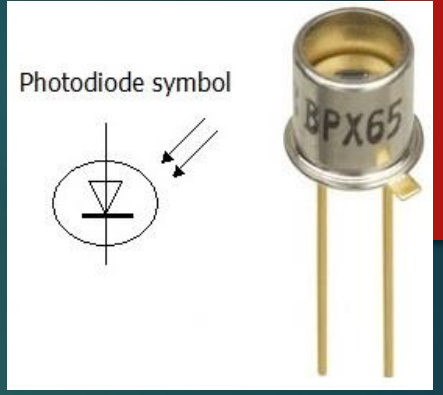
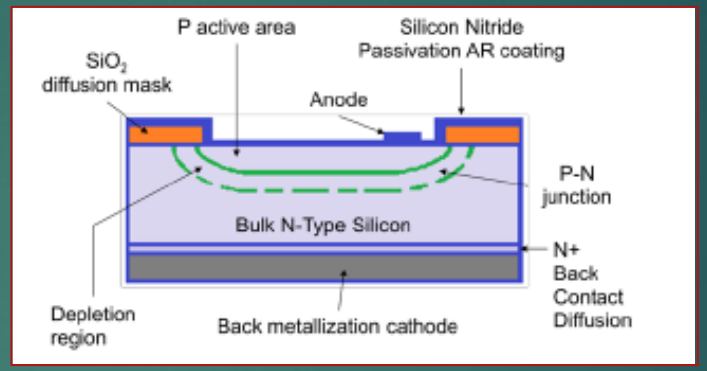
Light



- **Photodiode** is a solid-state device which converts incident light into an electric current.
- It is made of Silicon. It consists of a shallow diffused p-n junction, normally a p-on-n configuration. When photons of energy greater than 1.1eV (the bandgap of silicon) fall on the device, they are absorbed and electron-hole pairs are created.



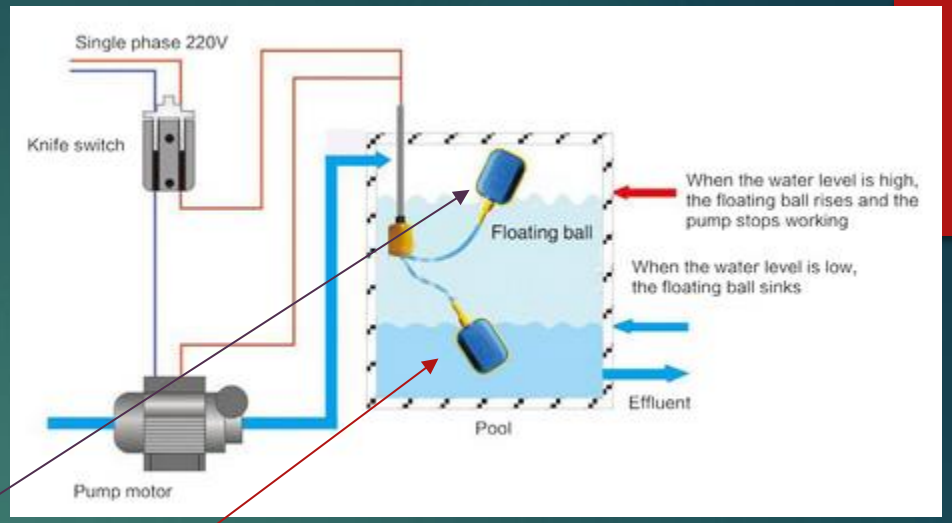
Photodiode

Applications

- **Applications of photo diodes**
- **Camera:** Light Meters, Automatic Shutter Control, Auto-focus, Photographic Flash Control
- **Medical:** CAT Scanners - X ray Detection, Pulse Oximeters, Blood Particle Analyzers
- **Industry**
  - Bar Code Scanners
  - Light Pens
  - Brightness Controls
  - Encoders
  - Position Sensors
  - Surveying Instruments
  - Copiers - Density of Toner
- **Safety Equipment**
  - Smoke Detectors
  - Flame Monitors
  - Security Inspection Equipment - Airport X ray
  - Intruder Alert - Security System
- **Automotive**
  - Headlight Dimmer
  - Twilight Detectors
  - Climate Control - Sunlight Detector
- **Communications**
  - Fiber Optic Links
  - Optical Communications
  - Optical Remote Control

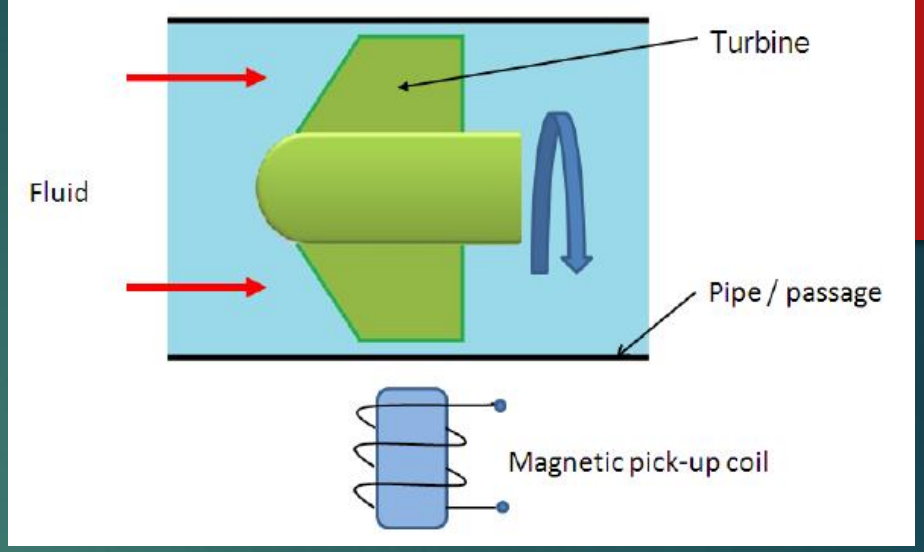
Liquid Level

- **Float switch** is a device which operates when a certain level is detected.
- When the water level is high, the floating ball rises and the water pump stops working
- When the water level is low, the floating ball sinks



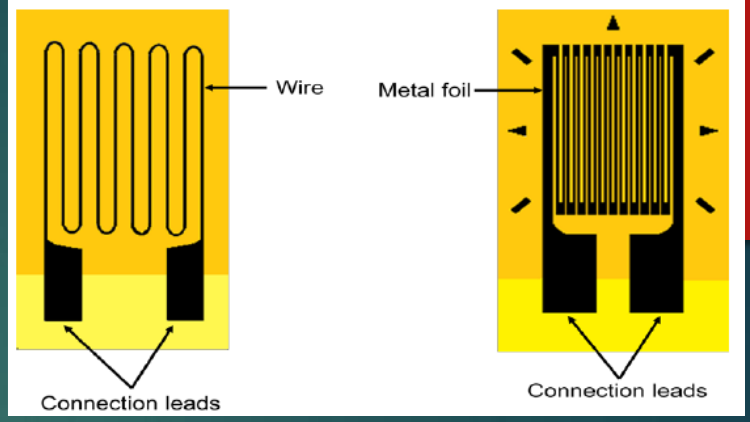
Flow

- **Turbine flow meter** is a volume sensing device. As liquid or gas passes through the turbine housing, it causes the freely suspended turbine blades to rotate. The velocity of the turbine rotor is directly proportional to the velocity of the fluid passing through the flow meter.
- The multi blade rotor is mounted centrally in the pipe along which the flow is to be measured.
- The fluid flow rotates the rotor. Accordingly the magnetic pick up coil counts the number of magnetic pulses generated due to the distortion of magnetic field by the rotor blades.
- The angular velocity of the rotor is proportional to the number of pulses and fluid flow is proportional to angular velocity.



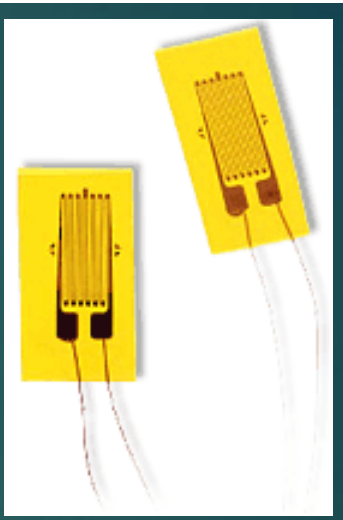
- Applications:
  - Water injection , chemical injection
  - Fuel flow measurement
  - Pill coating for medicines
  - Water metering
  - Liquids measurement for plant applications and truck deliveries
  - Engine testing
  - Monitor fuel supply to ship engines

Force



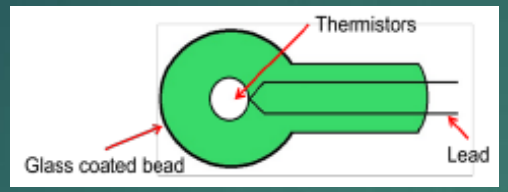
- A **Strain gauge** is a sensor whose resistance varies with applied force
- It converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured.
- When external forces are applied to a stationary object, stress and strain are the result. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur.

- Applications:
  - Experimental stress analysis and diagnosis on machines and failure analysis
  - Bending and deflection measurement
  - Force measurement in machine tools
  - Safety device in automotives

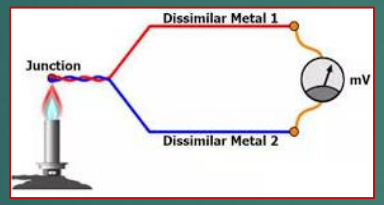


Review:

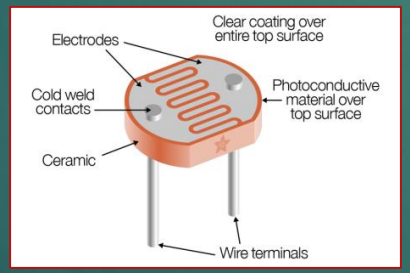
- Temperature:
  - Thermistors



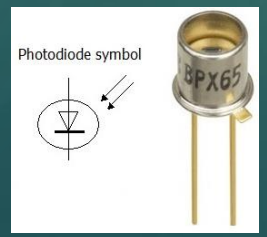
  - Thermocouples



- Light:
  - Photo resistors

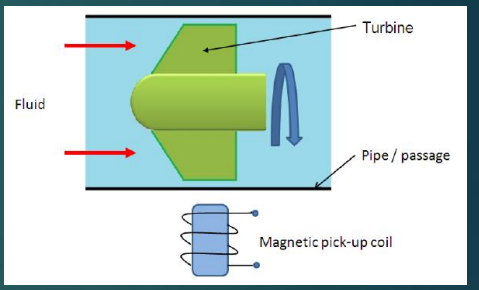


  - Photo diodes

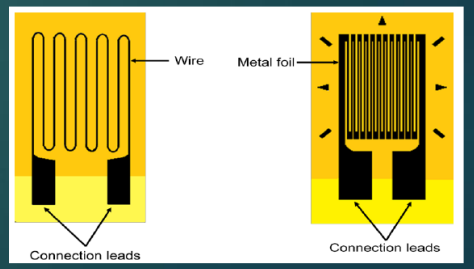


- Liquid Level
  - Float switch

- Liquid Flow
  - Turbine flow meter



- Force
  - Strain gauge

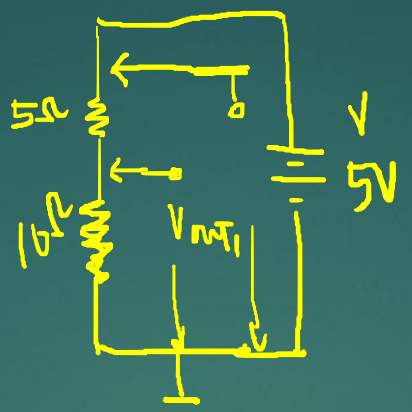


Displacement and Position

- Displacement sensors are basically used for the measurement of movement of an object.
- Position sensors are employed to determine the position of an object in relation to some reference point.
  - The location of an item is of primary concern in many servo control systems.
  - Automated assembly using robots demands precise positioning.
  - Milling, shaping, and drilling of machine parts as well as the movement of the head on a computer's disk drive or the pen on a plotter require control of position.

Displacement and Position

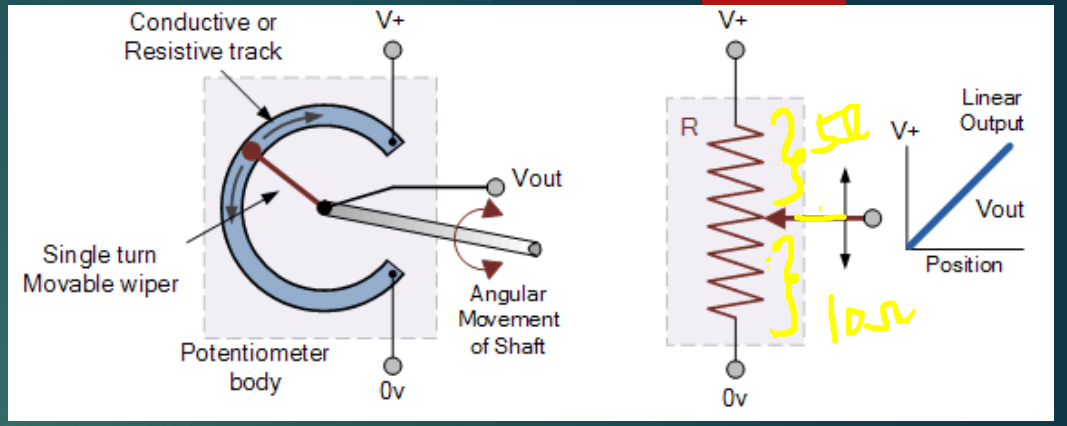
- A **potentiometer sensor** measures the distance or displacement of an object in a linear or rotary motion and converts it into an electrical signal.
- It has a wiper contact linked to a mechanical shaft that can be either angular (rotational) or linear (slider type) in its movement, and which causes the resistance value between the wiper/slider and the two end connections to change giving an electrical signal output that has a proportional relationship between the actual wiper position on the resistive track and its resistance value. In other words, resistance is proportional to position.



$I = \frac{5V}{15\Omega} = 0.33\,A$

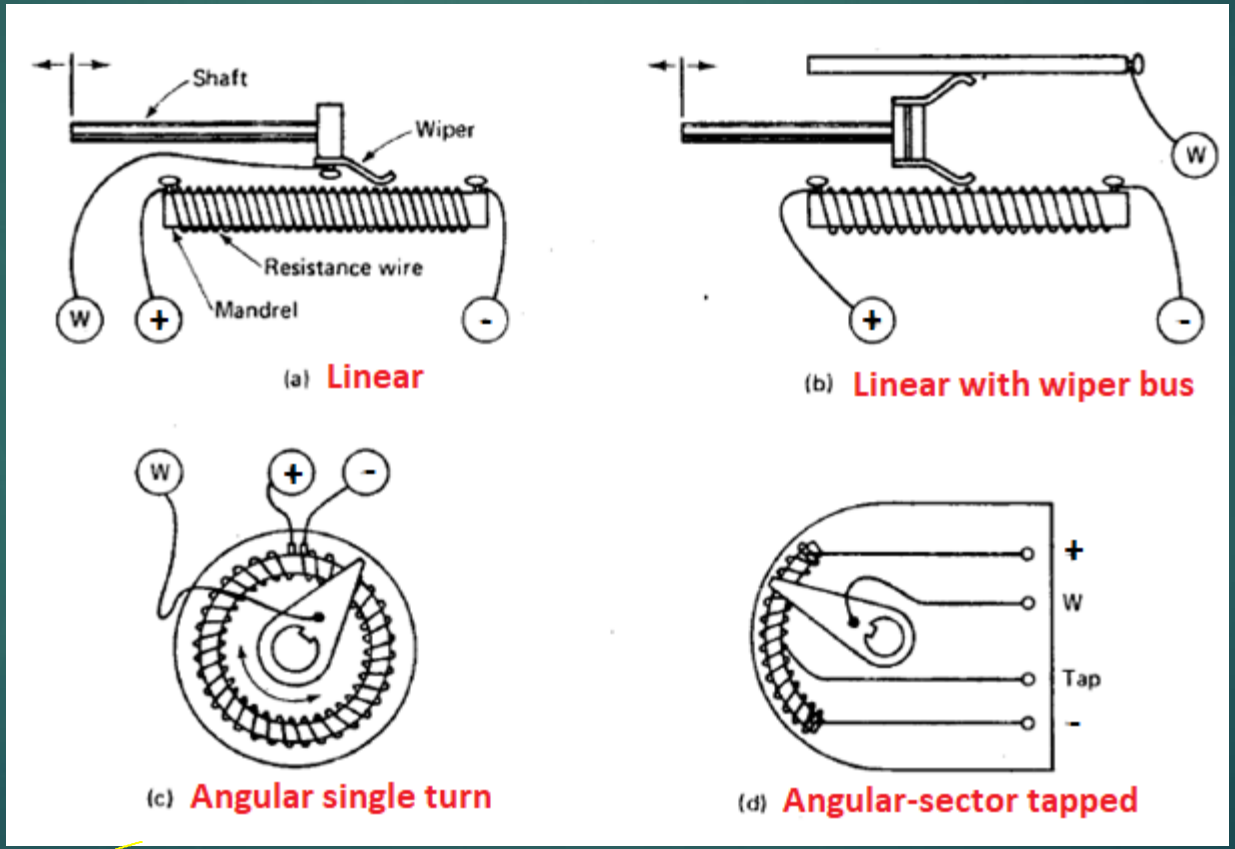
$V_{out_1} = V_{10\Omega} = 0.33A(10\Omega) = 3.33V$

$V_{out_2} = V_{15\Omega} = 5V$

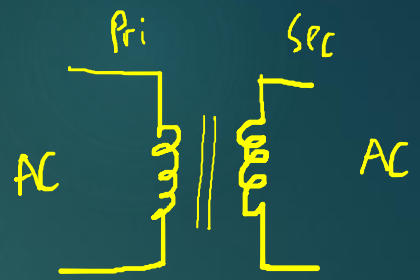


- Applications
  - control systems with a feedback loop to ensure that the moving member or component reaches its commanded position.
  - Elevators
  - Forklift trucks
  - Woodworking machinery
    - Printing
  - Spraying
  - Robotics
  - Liquid level assemblies

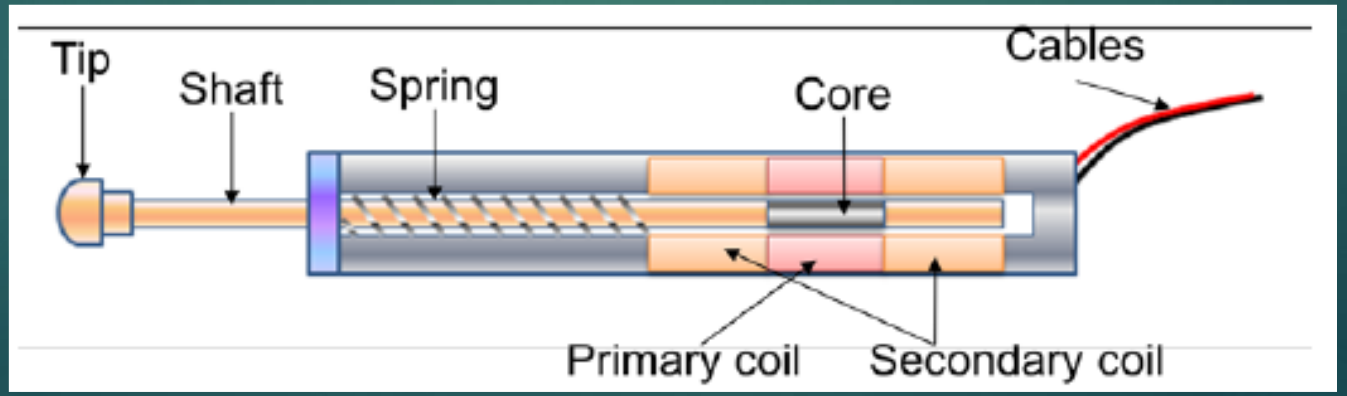
Potentiometer Sensor Construction

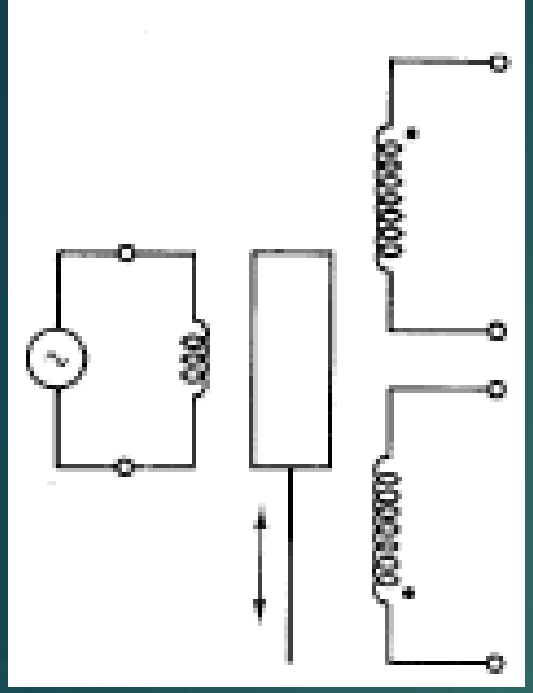


Displacement and Position



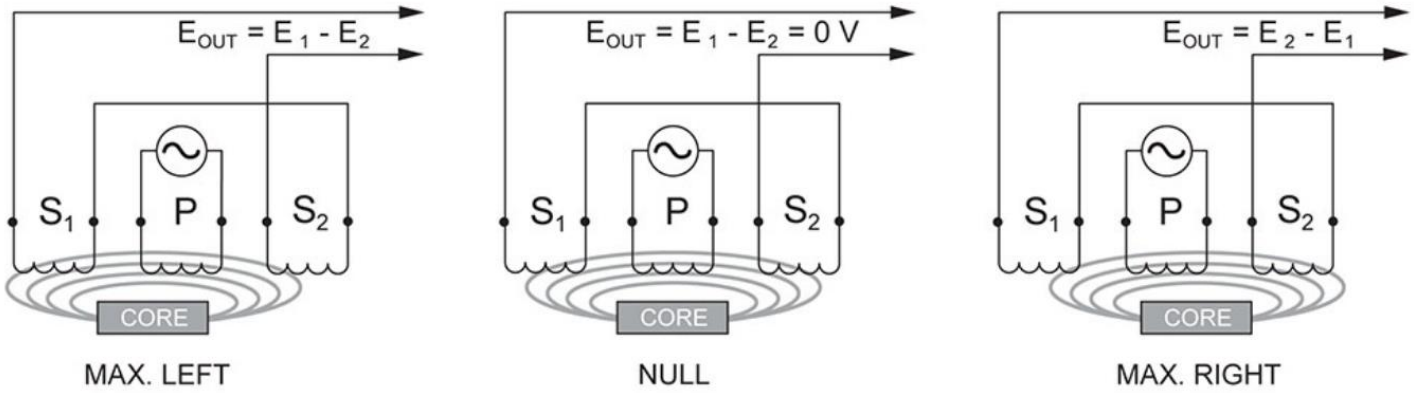
- **Linear variable differential transformer (LVDT)**
  - Electromechanical device that produces an electrical output proportional to the displacement of a separate movable core
  - It consists of a primary coil and two secondary coils symmetrically spaced on a cylindrical form
  - A free moving rod-shaped magnetic core inside the coil assembly provides a path for the magnetic flux linking the coils
  - Although an LVDT is an electrical transformer, it requires AC power of an amplitude and frequency quite different from ordinary power lines to operate properly (typically 3 Vrms at 3 kHz).
  - One of the most important features of an LVDT is its friction-free operation. In normal use, there is no mechanical contact between the LVDT's core and coil assembly, so there is no rubbing,





LVDT operation

- When the primary coil is energized by an external ac source, voltages are induced in the two secondary coils.
- These are connected in series opposing so the two voltages are opposite polarity
- The net output of the transducer is the difference between these voltages, which is zero when the core is at the center (null) position.
- Moving the core increases the induced voltage in the coil toward which the core is moved, and decreases the opposite coil, hence , a **differential voltage output that varies with changes in core position**



LVDT Applications

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously monitor fluid level as part of leak detection system
- To detect the number of currency bills dispensed by an ATM

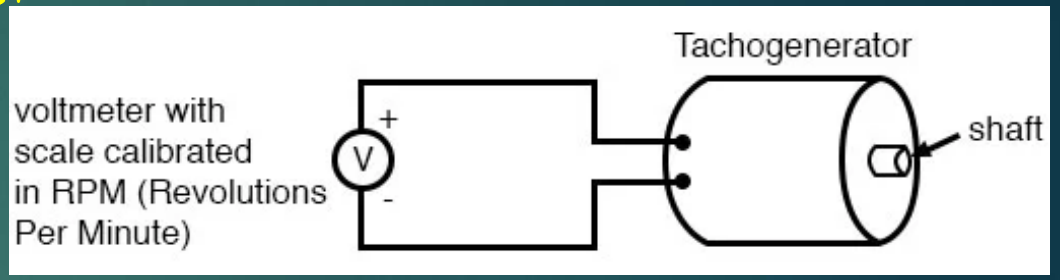
Velocity and Motion

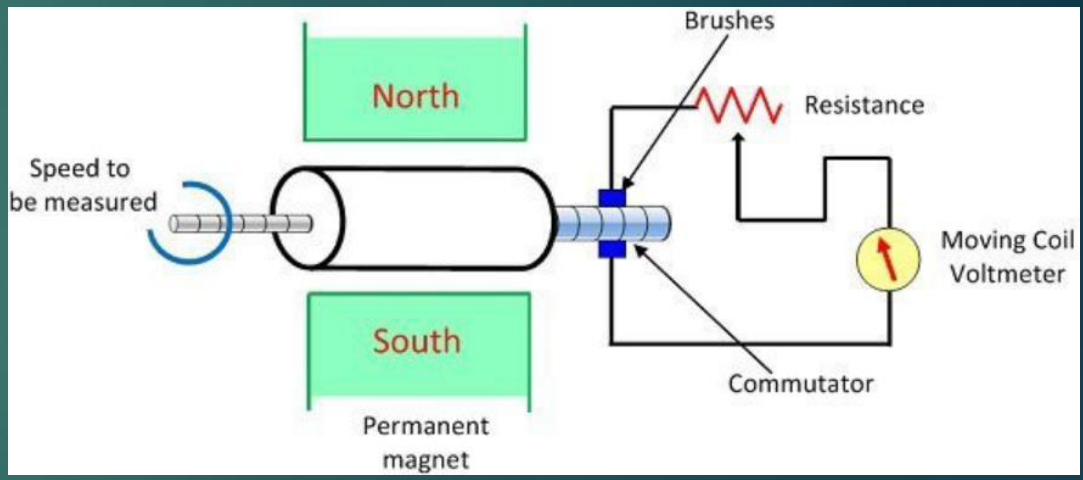
$V_o = k_t \omega_s$

k_t : tach constant

ω_s = angular speed

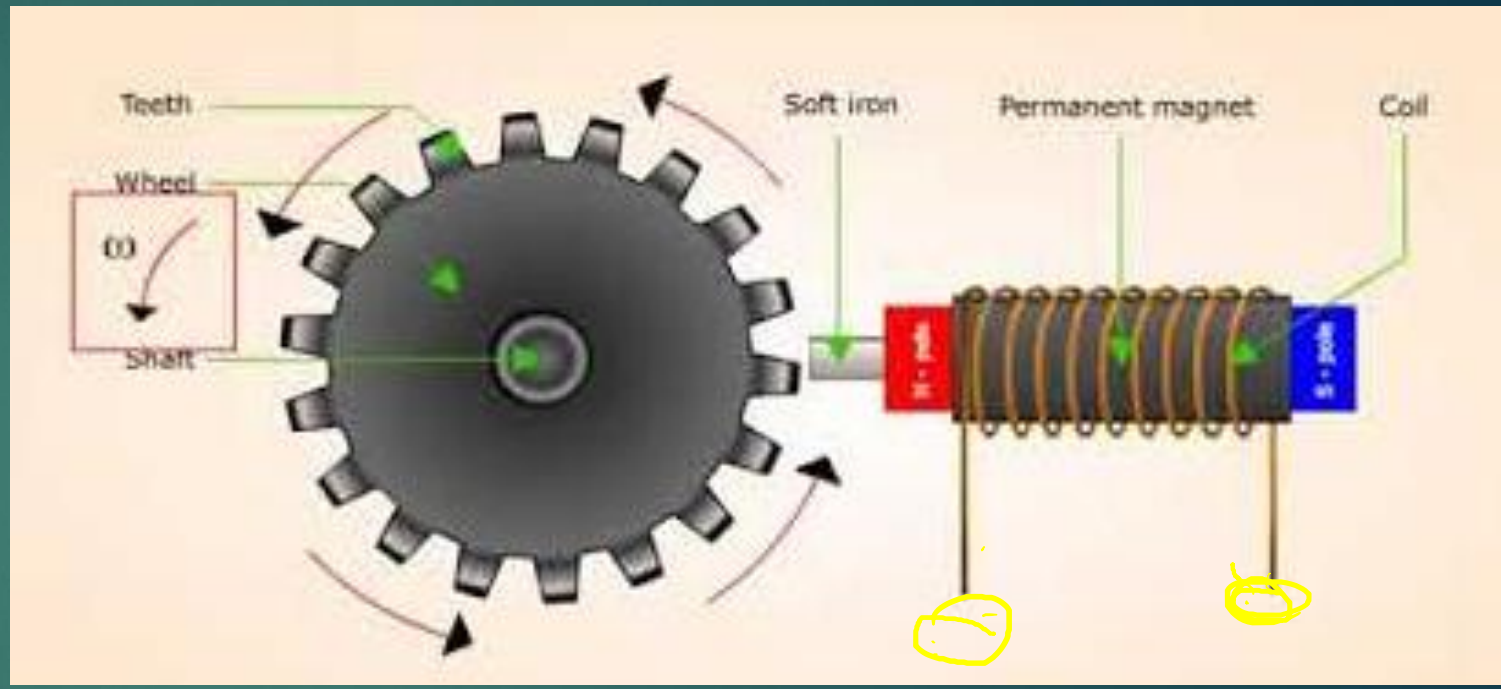
- **Tachogenerator or Tachometer generator or Tach** is an electromechanical device used to accurately measure the speed of engines and motors.
- A tachogenerator can measure the speed and direction of all manner of rotational devices once connected and will output a voltage proportional to the rotation around its own shaft. In other words, a tachogenerator can convert mechanical energy into electrical energy.
- When not connected to a load resistance, generators will generate voltage roughly proportional to shaft speed.
  - Applications:
    - For control or measurement applications which require directional indication
    - To measure engine and motor speed, as well as the corresponding speed of powered equipment such as conveyors, mixers, fans, and machine tools





Velocity and Motion

- **Toothed rotor tachometer is** a tachometer generator consisting of a metallic toothed rotor mounted on the shaft whose speed is to be measured
  - Magnetic pick-up responds to the movement of a toothed ferrous disk.
  - The pulse repetition frequency of the output is proportional to the angular velocity.
  - The frequency of the pulses of induced voltage will depend upon the number of teeth of the rotor and its speed of rotation. Since the number of teeth is known, the speed of rotation can be determined by measuring the frequency of pulses with an electronic counter. Suppose the rotor has "T" teeth, the speed of rotation is "n" rps and the number of pulses per second is"P".



Example: A tachometer has 180 teeth on its rotor and the speed of the shaft on which it is mounted is 1200 rpm. What is the frequency of the output pulses?

$T = 180$ teeth

$n = 1200 \frac{rev}{min}$

$P = Tn$

$= 180 \times 1200 \frac{rev}{min} \times \frac{1\,min}{60\,sec}$

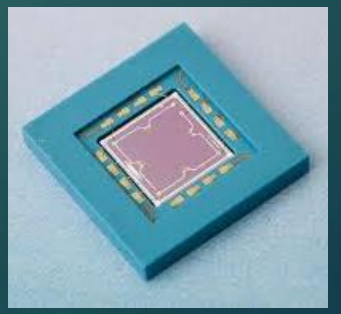
$P = 3600 \frac{pulse}{sec}$

Pressure

- Microswitch pressure sensor
  - Microswitch fitted with actuator mechanism and range setting springs.
  - Suitable for high-pressure applications.

- Differential pressure vacuum switch
  - Microswitch with actuator driven by a diaphragm.
  - May be used to sense differential pressure.
  - Alternatively, one chamber may be evacuated and the sensed pressure applied to a second input.

- Piezo-resistive pressure sensor
  - Pressure exerted on diaphragm causes changes of resistance in attached piezo-resistive transducers.
  - Transducers are usually arranged in the form of a four active element bridge which produces an analogue output voltage.



Differential pressure sensor

- This sensor measures the **difference between two pressures**, one connected to each side of the sensor.
- Differential pressure sensors are used to measure many properties, such as pressure drops across oil filters or air filters, fluid levels (by comparing the pressure above and below the liquid) or flow rates (by measuring the change in pressure across a restriction).
- Technically speaking, most pressure sensors are really differential pressure sensors; for example a gauge pressure sensor is merely a differential pressure sensor in which one side is open to the ambient atmosphere.

Proximity sensor

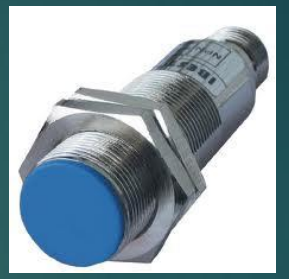
- A proximity sensor is a sensor able to detect the presence of nearby objects without any physical contact.
- A proximity sensor often emits an **electromagnetic field** or a beam of electromagnetic radiation (infrared, for instance), and looks for changes in the field or return signal.
- The object being sensed is often referred to as the proximity sensor's **target**.
- Different proximity sensor targets demand different sensors.
- For example, a **capacitive photoelectric sensor** might be suitable for a **plastic target**; an **inductive proximity** sensor always requires a **metal target**.

Proximity

- Electrical switch operated by an applied magnetic field.
- The **reed switch** contains a pair (or more) of magnetizable, flexible, metal reeds whose end portions are separated by a small gap when the switch is open.
- The reeds are hermetically sealed (airtight) in opposite ends of a tubular glass envelope.
- A magnetic field (from an electromagnet or a permanent magnet) will cause the reeds to come together, thus completing an electrical circuit.
- The stiffness of the reeds causes them to separate, and open the circuit, when the magnetic field ceases.
- Only effective over short distances.

Proximity

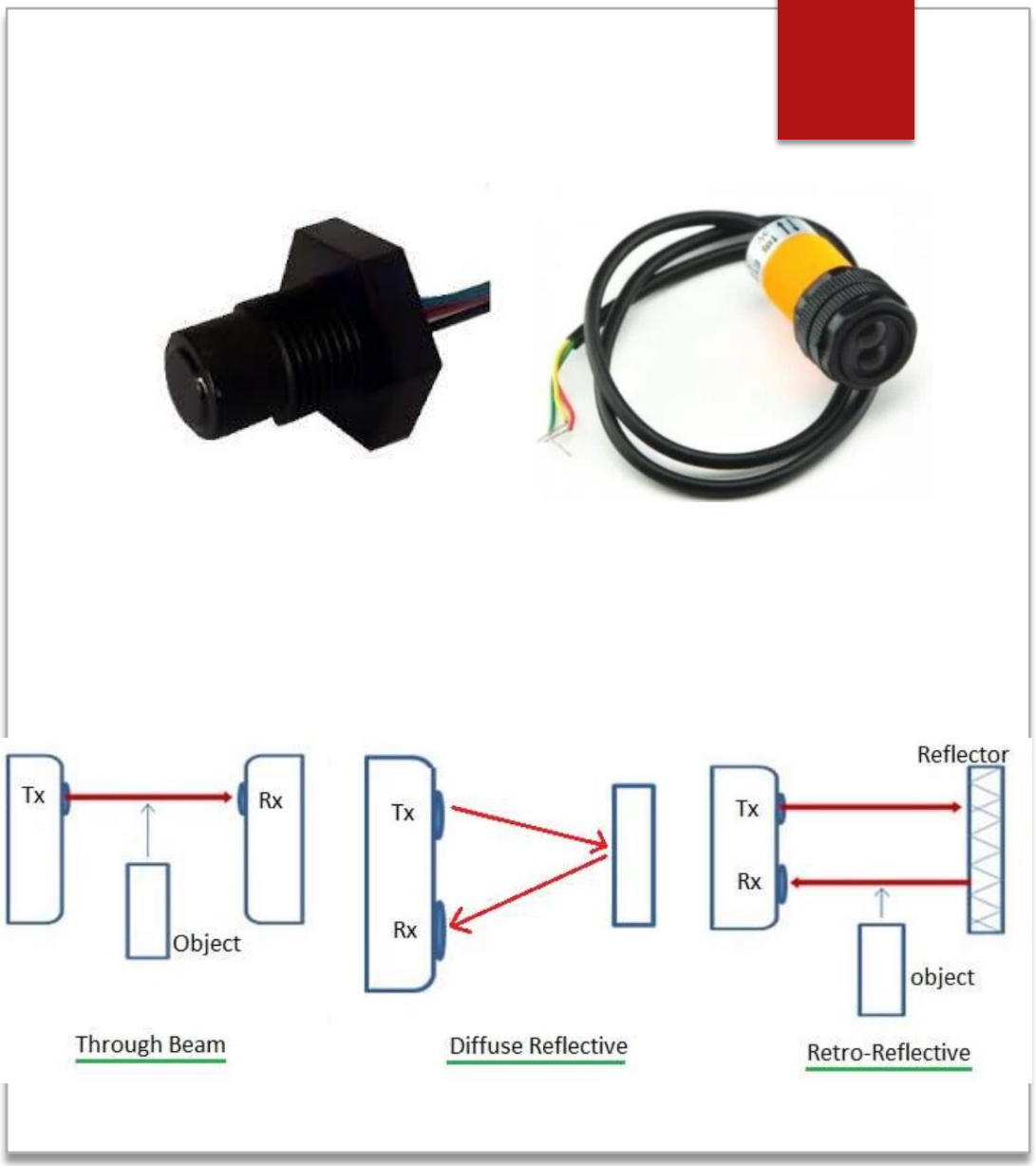
- **Inductive proximity switch**
  - The **inductive proximity sensors** are useful to detect the metallic object which is present next to their active side. This sensor operate under the electrical principal of inductance; where a fluctuating current induces an electromotive force(EMF) in a target object.
  - Target object modifies **magnetic field** generated by the sensor.



- **Capacitive proximity switch**
  - Target object modifies **electric field** generated by the sensor.
  - The capacitive proximity sensors use the variance in the capacitance of the sensor to concluded that an object has been detected.
  - Suitable for plastics, wood, and some liquids and powders.

Proximity

- **Optical proximity switch**
  - A complete optical proximity sensor includes a light source, and a sensor that detects the light. These sensors detect objects directly in front of them by the detecting the sensor's own transmitted light reflected back from an object's surface.
  - Available in Through Beam, Diffuse Reflective, and Retro-Reflective.
  - All types employ optical transmitters and receivers (usually infra-red emitting LEDs and photo-diodes or photo-transistors).
  - Digital input port required.

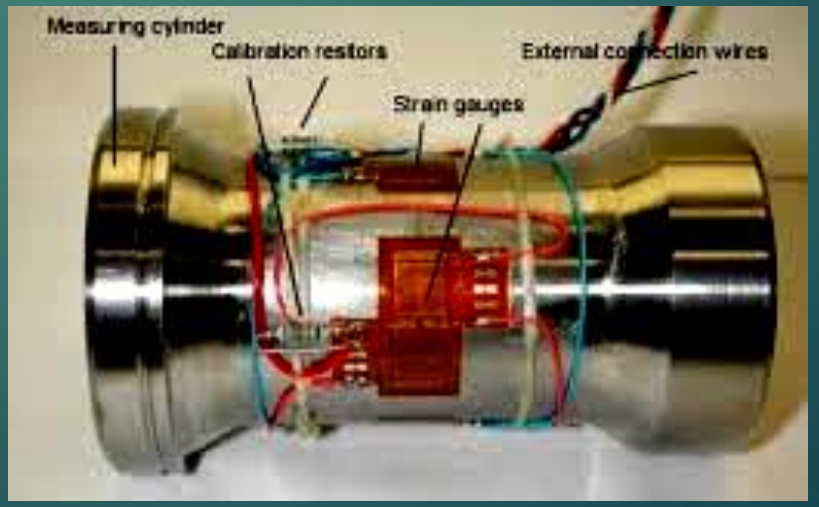


Proximity

- **Ultrasonic Proximity Sensor**
  - Ultrasonic sensors emit an ultrasonic pulse which is reflected by objects in its path and the reflected wave enters the sonic cone.
  - They employ sound waves to detect objects.

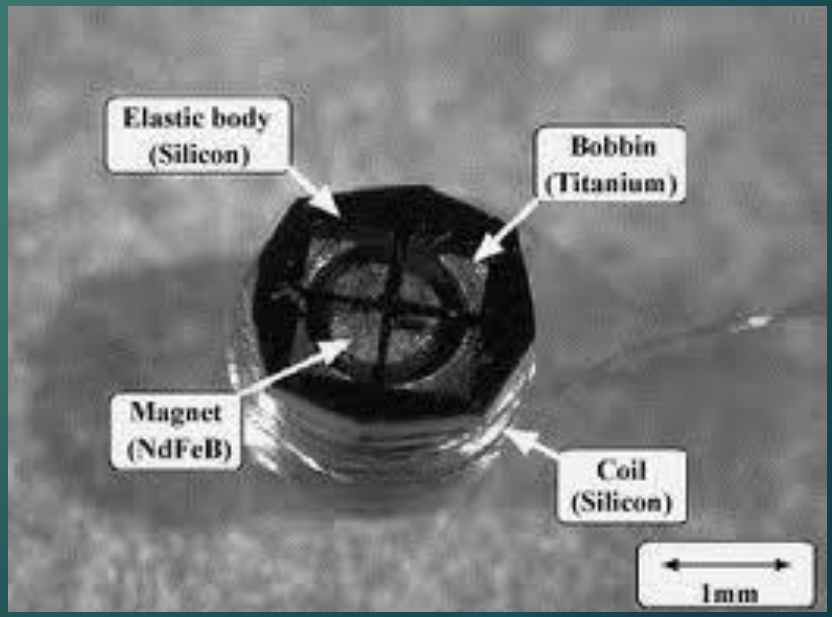
Weight

- **Load cell**
  - Usually comprises four strain gauges attached to a metal frame.
  - This assembly is then loaded, and the analog output voltage produced is proportional to the weight of the load.



Vibration

- **Electromagnetic vibration sensor**
  - Permanent magnet seismic mass suspended by springs within a cylindrical coil.
  - The frequency and amplitude of the analogue output voltage are respectively proportional to the frequency and amplitude of vibration.



ACTUATORS

Actuators

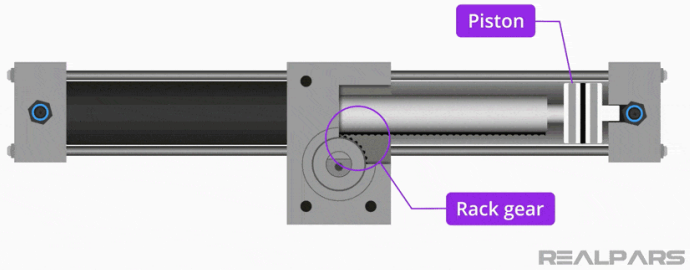
- An actuator is a device that converts energy into motion or mechanical energy. Therefore, an actuator is a specific type of a transducer.
- An actuator is a component of a machine that is responsible for moving and controlling a mechanism or system, for example by opening a valve. In simple terms, it is a "mover".
- Most of the actuators e.g., DC servo motors only accept analog signals. Therefore, in case the input to an actuator is still digital, the digital signal must be converted first into Analog form so that the required actuator can be operated accordingly. For this purpose, Digital to Analog Converters are used.

Type of Actuators

1) **Hydraulic actuator**

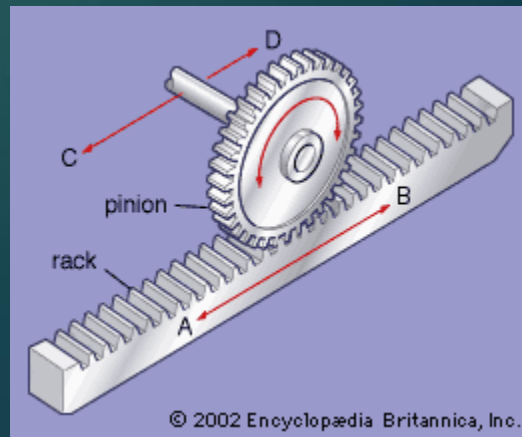
• This actuator converts mechanical motion into linear, rotary or oscillatory motion.
• The hydraulic actuator consists of cylinder or fluid motor which uses hydraulic power to help mechanical operation.
• Liquids are nearly impossible to compress, hydraulic actuator maintains considerable force. Limited acceleration of actuator restricts its usage.
• **Example:** Hydraulic brake in vehicle

Type of Actuators



2) **Pneumatic actuator**

- Pneumatic actuator converts energy formed by vacuum or compressed air at high pressure into linear or rotary motion.
- They are responsible to convert pressure into force.
- **Advantages:**
  1. Pneumatic energy responds quickly to start and stop signals.
  2. It does require power source to be stored in reserve for its operation.
  3. Pneumatic actuators produce large forces from relatively small pressure changes.
- **Examples:**
  - *Rack and Pinion actuators used for valve controls of pipes
  -Pneumatic brakes are very responsive to small pressure changes applied by the driver.



*Rack and pinion is a type of linear actuator that comprises a circular gear (the *pinion*) engaging a linear gear (the *rack*), which operate to translate rotational motion into linear motion.

Type of Actuators

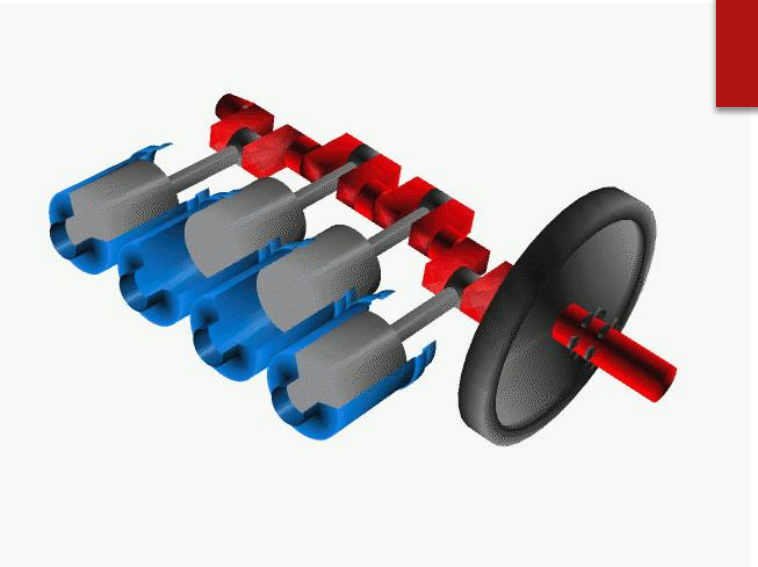
3) **Electrical actuator**

- It is powered by motor which converts electrical energy into mechanical torque.
- Electrical energy is used to actuate equipments (e.g. solenoid valves) which control water flow in pipes with response to electrical signals.
- **Advantages:** cheap, speedy type of actuator.
- **Examples:** Solenoid based electric bell ringing mechanism

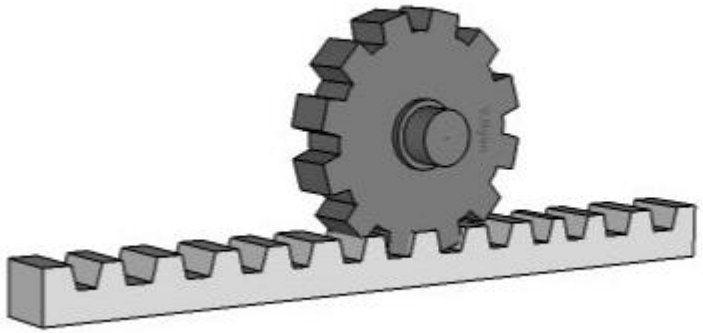
Type of Actuators

4) **Mechanical actuator**

- Coverts one kind of motion into another kind such as rotary motion into linear motion or vice versa.
- It consists of gears, pulleys, rails, chains and other devices for its operation.
- **Examples:** Rack and pinion mechanism and Crank shaft



Crank shaft – converts linear to rotational motion



Rack and pinion- converts rotational motion to linear motion

Type of Actuators

5) **Thermal or Magnetic actuator**

- This actuator can be actuated by application of thermal or magnetic energy.
- A magnetic actuator work on the principle of electromagnetism, it converts electrical energy into mechanical energy and vice versa
- Thermal actuator is a device that generates motion by thermal expansion
- **Examples:** thermostatic actuator, magnetic actuator

Type of Actuators

6) **Soft actuator**

• It is polymer based and are designed to handle fragile objects like fruit harvesting in agriculture or manipulating the internal organs in biomedicine.
• Examples: Shape Memory polymers, Photo polymers
  - Shape memory polymer functions similar to our muscles. It provides response to range of stimuli e.g. light, electrical, heat, magnetic, pH, moisture changes etc. The advantages of such polymers are low density, high strain recovery, bio-compatibility, bio-degradability etc.
  - Photo polymers are known as light activated polymers. They are special type of shape memory polymers which are activated by light stimuli.

Other Types of Actuators

- Following are the other types of Actuators.
  - Comb drive
  - Electric motor
  - Digital micromirror device
  - Electroactive polymer
  - Piezoelectric actuator
  - Screw Jack
  - Hydraulic Cylinder

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