Ch4: Sensors – Part 1

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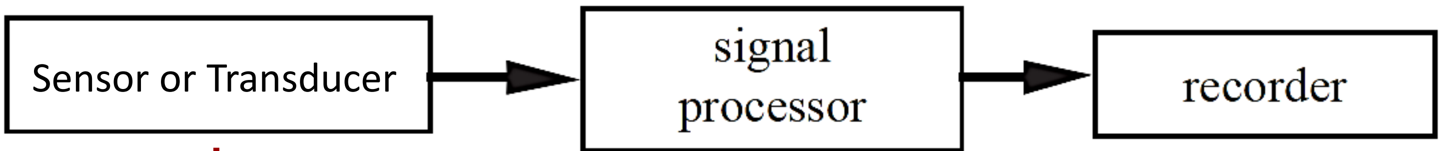
Introduction

Measurement Systems

A fundamental part of many mechatronic systems is a measurement system composed of the three basic parts.



A sensing device that converts a physical input into an output (usually a voltage)

For filtering, amplification, or other signal conditioning

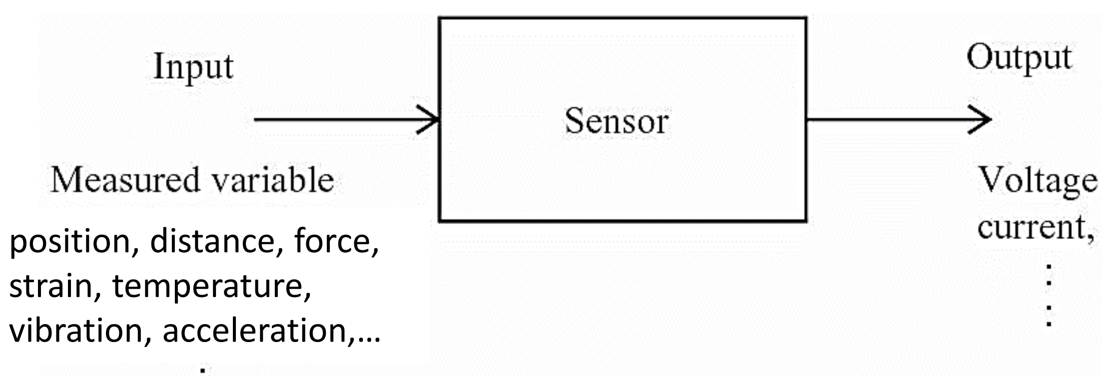
An instrument, a computer, a hard-copy device, or simply a display that maintains the sensor data for online monitoring or subsequent processing.

Sensors and Transducers

A **Transducer** is a device that **converts** energy from one form to another. This conversion is known as Transduction. Therefore, it is an energy converter (Ex.: Loudspeakers, Actuators).

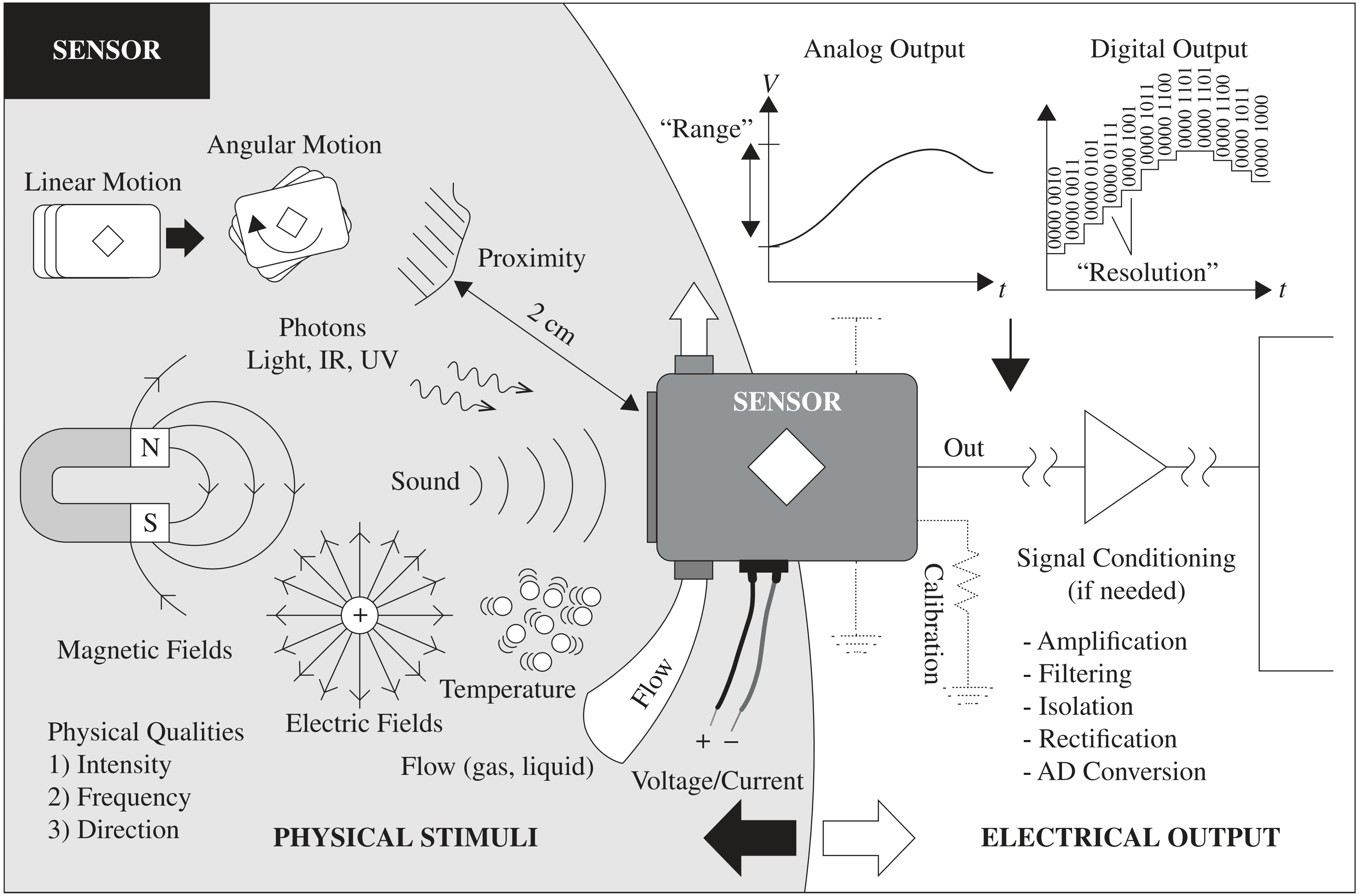
A **Sensor** is a device that **react** to a physical, chemical, or biological input in any form. It senses and can be considered as a **detector** (Ex.: Thermistor).

However, often, both these terms are used **interchangeably**.



Sensors and transducers are usually design based on **laws or principles of physics or chemistry**.

Sensors and Transducers



Sensors and Transducers Classifications

- **Analog Sensors** convert the input physical phenomenon into an analog output which is a continuous function of time. For example, an LVDT.
- **Digital Sensors** convert the input physical phenomenon into an electrical output which may be in form of pulse.

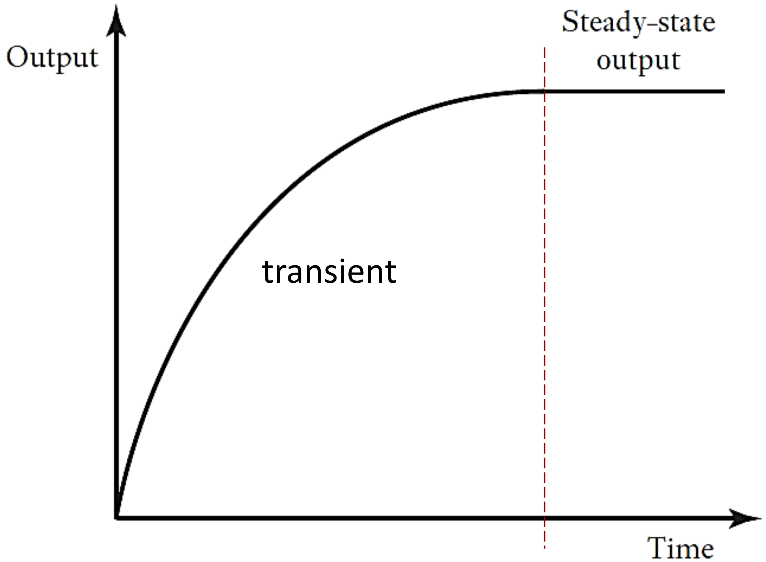
- **Passive Sensors** **require** an external power source to operate, which is called an excitation signal. The signal is modulated by the sensor to produce an output signal. For example, a thermistor does not generate any electrical signal, but by passing an electric current through it, its resistance can be measured by detecting variations in the current or voltage across the thermistor.
- **Active Sensors** **generate** an electric current in response to an external stimulus which serves as the output signal without the need of an additional energy source. Such examples are photodiodes, piezoelectric sensors, piezoelectric sensors, and thermocouples.

Sensor Characteristics and Performance

Static and Dynamic Characteristics

Sensors are identified by **static** and **dynamic** characteristics.

- **Static Characteristics** relate to steady-state behavior (when the sensor has settled down after having received some input).
- **Dynamic Characteristics** relate to the transient behavior (before when the sensor has settled down after having received some input).



Static Performance Characteristics:
Range, Span, Absolute Error, Accuracy, Sensitivity, Hysteresis Error, Nonlinearity Error, Repeatability/Reproducibility, Stability, Drift, Dead Band, Dead Time, and Resolution.

Dynamic Performance Characteristics:
Time Constant, Rise Time, and Settling Time, Peak Time, Maximum Overshoot.

Range, Span, and Absolute Error

- **Range** defines interval in which the input can vary.

$$[-40,50]\ ^\circ\mathrm{C}$$

- **Span** is difference between the limits of the interval.

$$50-(-40)=90\ ^\circ\mathrm{C}$$

- **Absolute Error** is the difference between the measured and true value.

$$\text{Absolut Error} = \text{Measured Value} - \text{True Value}$$

$$\text{Measured} = 30\ ^\circ\mathrm{C}, \qquad \text{True} = 32\ ^\circ\mathrm{C} \quad \Rightarrow \quad \text{Absolut Error} = -2^\circ\mathrm{C}$$

Accuracy & Sensitivity

- **Accuracy** is the extent to which the value indicated by sensor can be wrong.

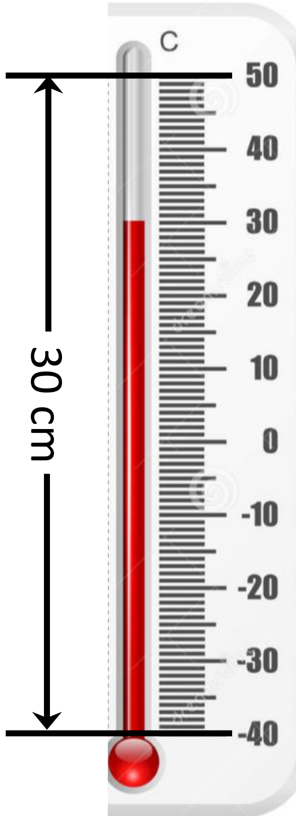
$$\text{Measured}=30\ ^\circ\text{C, Accuracy} = \pm 2\ ^\circ\text{C} \Rightarrow \text{True} \in [28,32]^\circ\text{C}$$

Accuracy is also expressed as a percentage of the full range output:

$$\text{Measured}=30\ ^\circ\text{C, Accuracy} = \pm 5\%\ \text{Span} \Rightarrow \text{True} \in [25.5,34.5]^\circ\text{C}$$
$$(\text{Accuracy} = \pm 4.5\ ^\circ\text{C})$$

- **Sensitivity** is the relationship indicating how much output there is per unit input, i.e., output/input.

$$30\ \text{cm} \equiv (50+40)^\circ\text{C} \Rightarrow \text{Sensitivity} = \frac{90\ ^\circ\text{C}}{30\ \text{cm}} = 3\ ^\circ\text{C/cm}$$

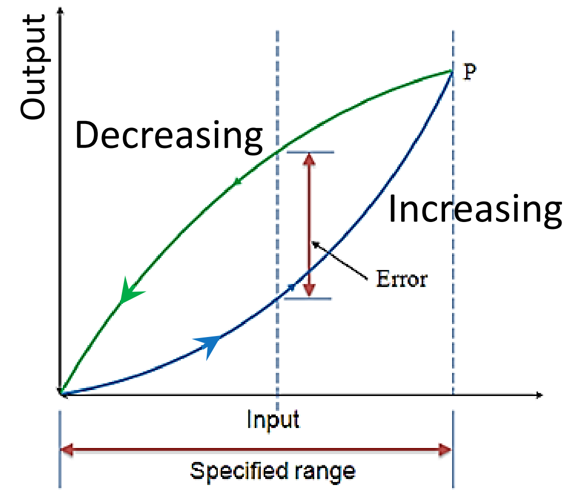


Note: This term is also used to indicate the sensitivity to inputs other than that being measured, i.e., environmental changes. For example, a pressure sensor may have a temperature sensitivity of 0.1% of the reading per °C change in temperature.

Hysteresis & Nonlinearity Error

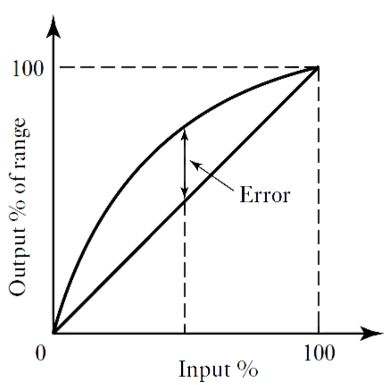
- **Hysteresis Error** is the maximum possible difference between the measurements of a quantify during an increase and a decrease.

- **Nonlinearity Error** for sensors with a linear relationship between the input and output is the maximum possible difference of the input-output relation from a straight line. This is usually expressed as percentage of the span.

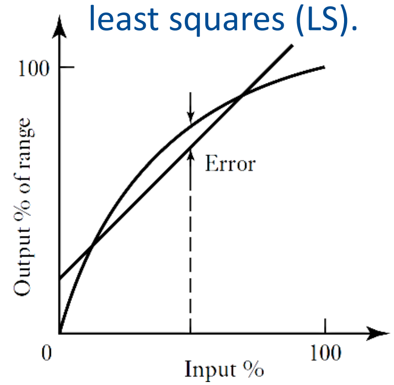


The straight line can be defined in different ways:

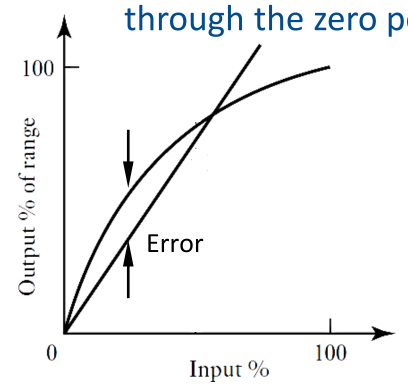
The straight line based on end-range values



The best straight line for all values using the method of least squares (LS).



The best straight line using the method of least squares through the zero point



Repeatability/Reproducibility

- **Repeatability/Reproducibility** is the ability of a sensor to give the same output for repeated applications of the same input value.

$$\text{Repeatability} = \frac{\text{max. values} - \text{min. values}}{\text{span}} \times 100$$

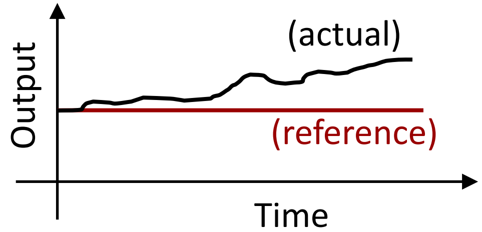
Example: 10 measurements of the same quantity.

#	Temp [°C]
1	28
2	30
3	31
4	31
5	30
6	28
7	30
8	30
9	28
10	29

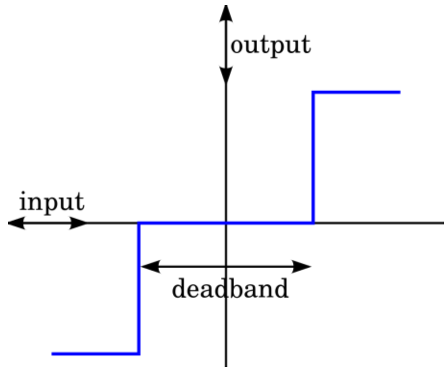
$$\text{Repeatability} = \frac{31 - 28}{90} \times 100 = 3.3\ \%$$

Stability, Drift, Dead Band, and Dead Time

- **Stability** is the ability to give the <u>same output</u> when used to measure a <u>constant input</u> **over a period of time**.
- **Drift** refers to the gradual change in the sensor output over time (e.g., days, months, or years) due to aging, temperature, humidity, or other environmental factors.



- **Dead Band** (or **Dead Zone**) is the range of input values for which there is no output. For example, due to mechanical friction in sensor there is no output until the input has reached a particular threshold.



- **Dead Time** is the duration from the application of an input until the output begins to respond and change.

Resolution

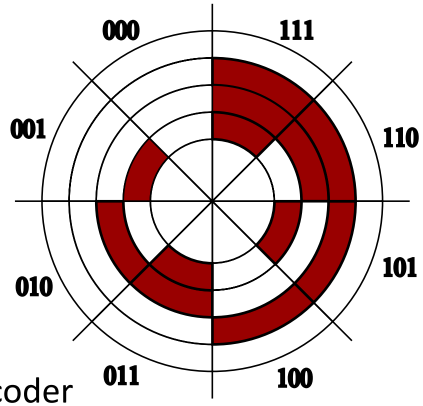
- **Resolution** is the smallest change in the input value that will produce an observable change in the output. In some sensors, when the input varies continuously over the range, the output signals may change in small steps.

For Example:

- In a wire-wound potentiometer, the output changes in steps as the potentiometer wiper moves from one wire turn to the next (say, 0.5°)

- For a sensor giving a digital output, the smallest change in output signal is 1 bit. Thus, for an N-bit sensor (i.e., a total of 2^N bits) the resolution is generally expressed as $1/2^N$.

$$\text{Resolution} = \frac{1}{2^3} \equiv 45\,°$$



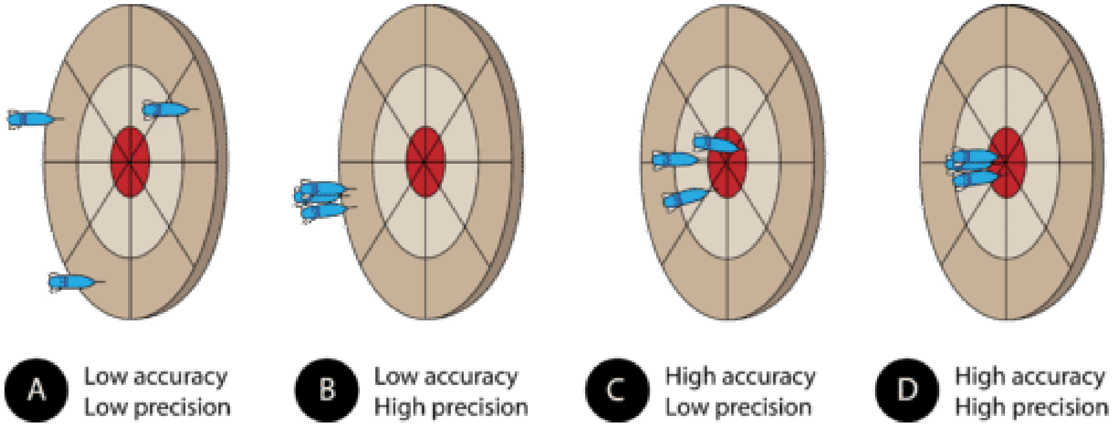
A 3-bit Absolute Encoder

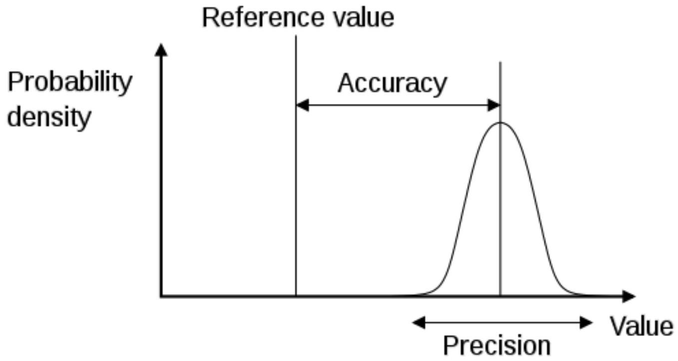
Accuracy and Precision in Measurements

Accuracy and **Precision** indicate the **quality** of a measurement.

Accuracy refers to how close the measured value is to the true value.

Precision (or repeatability) refers to how repeatable the independent measurement of a particular value is.

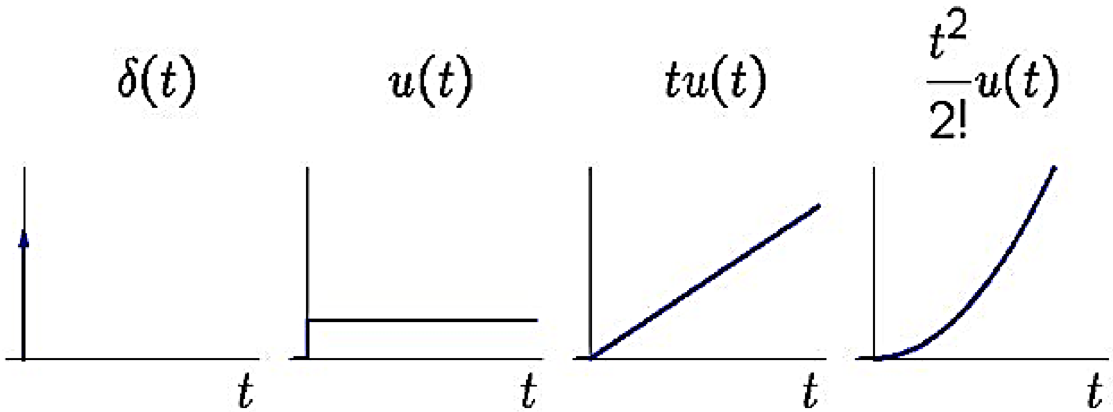


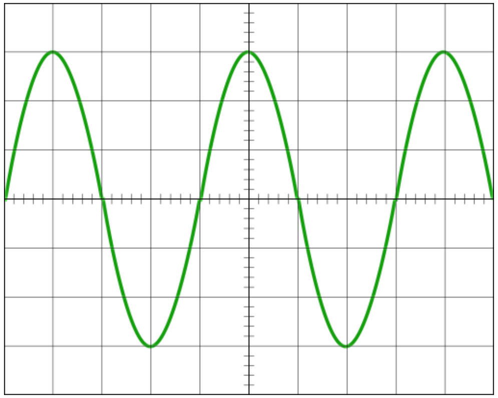


Mean value can be used to evaluate **Accuracy**, while **Variance** can be used to evaluate **Precision**.

Dynamic Characteristics: Test Inputs

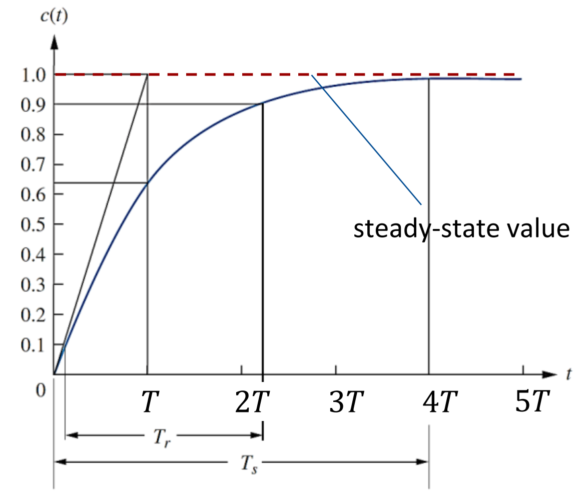
Dynamic Characteristics are stated in terms of the response of the sensor to inputs in particular forms (e.g., impulse, step when the input is suddenly changed from zero to a constant value, or a ramp when the input is changed at a steady rate, parabolic, or sinusoidal with a specified frequency).



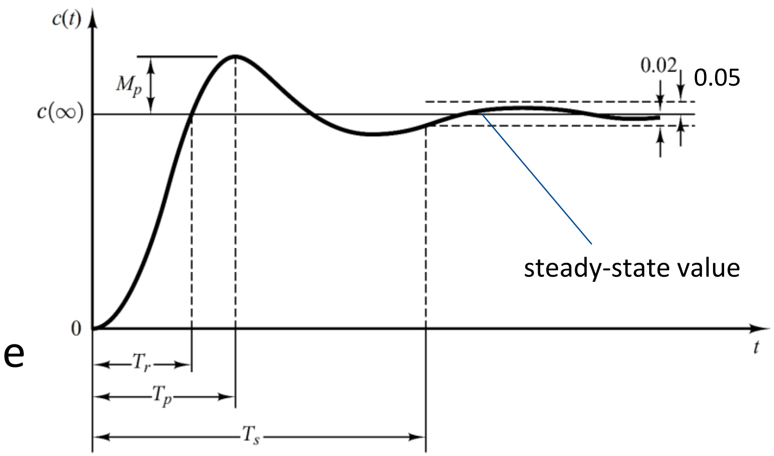


Dynamic Characteristics: Time Response to a Step Input

- **Time Constant** T: The time it takes for the response to rise to 63% of the steady-state value.
- **Rise Time** T_r: The time required for the response to go from 0% to 100% (or 10% to 90%) of the steady-state value.
- **Settling Time** T_s: The time required for the response to **reach and stay** within 2% (or 5%) of the steady-state value.
- **Peak Time** T_p: The time required for the response to reach the **first** (or maximum) peak.
- **Maximum Overshoot** M_p: The percentage of the steady-state value that the response overshoots the steady-state value at the peak time T_p.



(1st order sensor)



(2nd order sensor)

Sensor/Transducer Types

- Displacement, Position, and Proximity
- Velocity and Acceleration
- Stress, Strain, and Force
- Light Sensors
- Temperature
- …

For a complete list of sensors refer to:

https://en.wikipedia.org/wiki/List_of_sensors

Displacement, Position, and Proximity

Displacement, Position, and Proximity

- **Displacement Sensors** measure the amount by which an object is moved.
- **Position Sensors** measure the position of an object in relation to a reference point.
- **Proximity Sensors** determine when an object has moved to within a particular distance of the sensor (on/off outputs) like detecting the presence of an object (e.g., a man in front of a public urinal), counting moving objects (e.g., passing by on a conveyor belt), etc.

Displacement and position sensors can be grouped into two basic types:

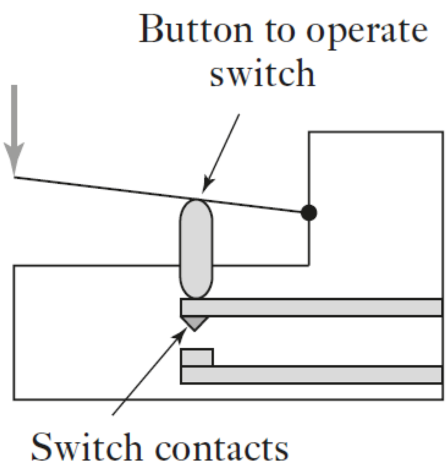
- **Contact Sensors**: The measured object comes into physical contact with the sensor.
- **Non-Contact Sensors**: There is no physical contact between the measured object and the sensor.

Note: Linear motion can often be easily converted to rotary motion (e.g., with a belt, gear, or wheel mechanism), allowing the use of rotary position sensors in linear motion applications.

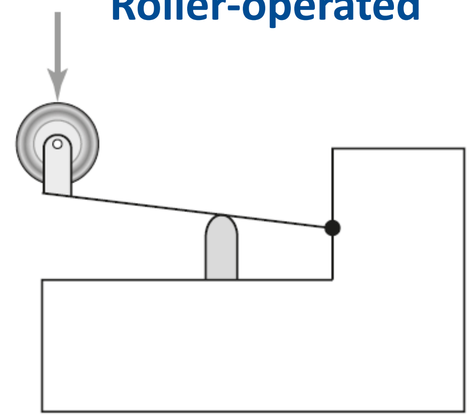
Limit Switch

Limit Switch (Microswitch or Snap Switch) is a **contact** switch which is opened or closed by the displacement of an object and it is also used to indicate the limit of object displacement (e.g., detecting the end of travel of a slider or joint in a mechanism).

Lever-operated

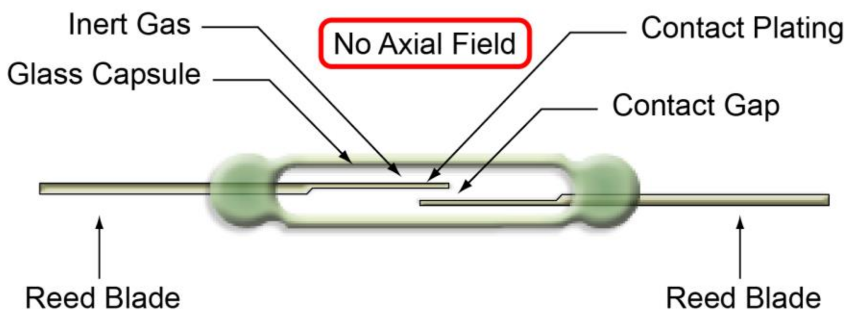


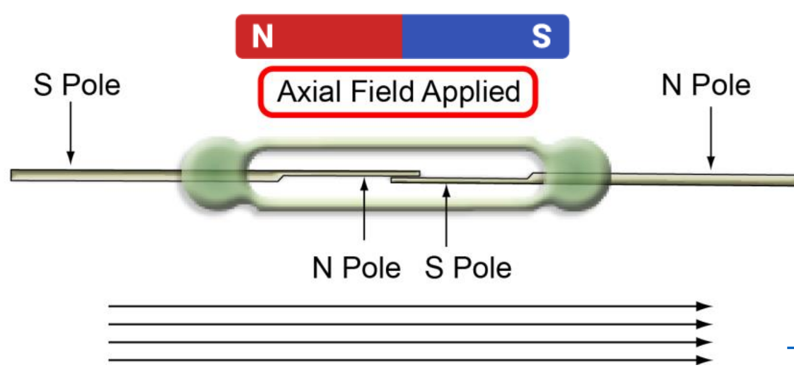
Roller-operated



Reed Switch

Reed Switch is a **non-contact** proximity switch which consists of two **ferromagnetic** metal reeds 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.

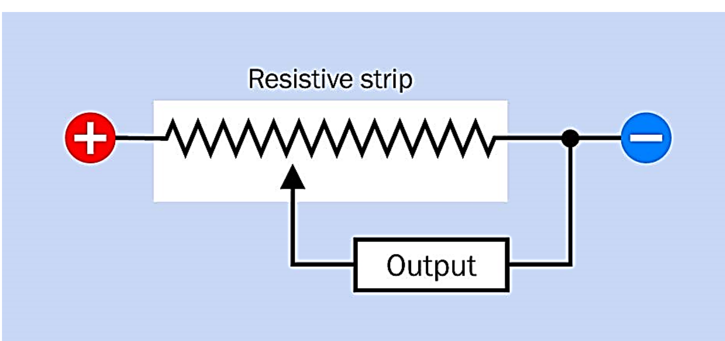


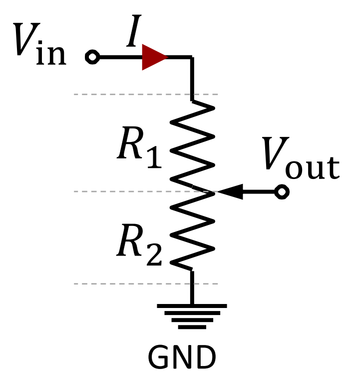


Slider Potentiometer

There are two types of **Slider Potentiometers**: **Linear** and **Logarithmic**

It consists of a straight-shape resistance element with a sliding contact as **wiper**. The potentiometer is wired as a **voltage divider** and a fixed potential is applied across its full **length**. By sliding the wiper along the resistance element, a voltage that varies linearly or logarithmically with the wiper's **position** varies. Output from the wiper can be used directly to control an **analog** indicator/meter or can be processed by an **analog-to-digital** converter.



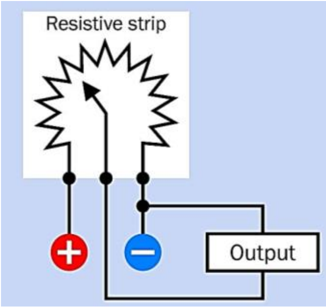


$$V_{\text{out}} = R_2 I = \frac{R_2}{R_1 + R_2} V_{\text{in}}$$

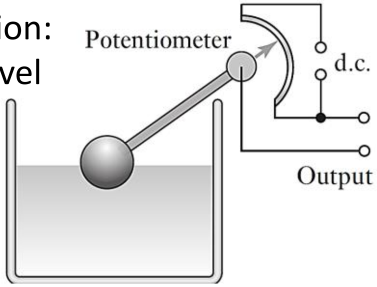
Rotary Potentiometer

There are two types of **Rotary Potentiometers**: **Linear** and **Logarithmic**. They can be **Single-Turn** (**Arc-Segment**) which is more common or **Multiturn**

A **Single-Turn** (**Arc-Segment**) potentiometer consists of an arc-shape resistance element with a sliding contact as **wiper**. This potentiometer works similar to Slider Potentiometer.



Application: Liquid level



A **Multiturn** potentiometer consists of a **spiral-shape** resistance element with a sliding contact as **wiper**. A potentiometer can be calibrated in degrees (a 10-turn pot covers 3,600 degrees).

Advantages and Disadvantages of Potentiometers:

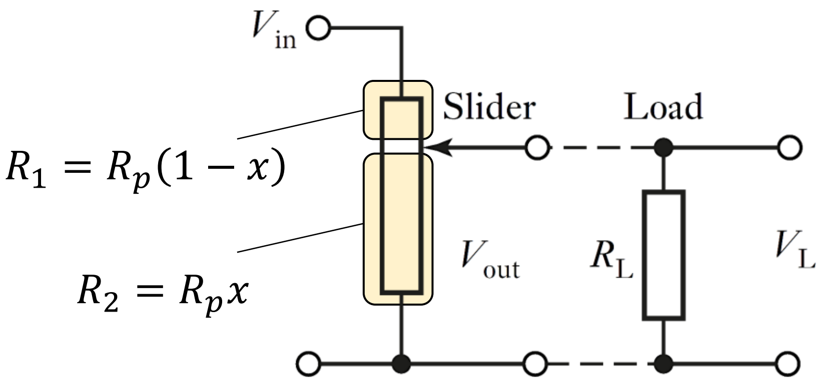
- They are simple, inexpensive, compact, and require few additional components.
- Wear due to friction, vibration, and contamination with dirt or moisture reduce its useful life.

Potentiometer - Load Effect

An important effect to be considered with a potentiometer is the effect of a load R_L connected across the output.

Consider a potentiometer with resistance R_p.
In the absence of a load:

$$V_{\text{out}} = \frac{R_2}{R_1 + R_2} V_{\text{in}} = x V_{\text{in}}$$



In the presence of a load R_L: $$V_{\text{out}} = V_L = \frac{x}{1 + \frac{R_p}{R_L} x(1-x)} V_{\text{in}}$$

Thus, the load R_L can create **nonlinearity**.

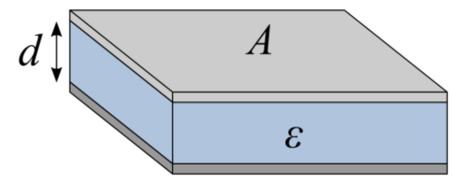
If the load is of infinite resistance ($R_L \to \infty$), then $V_L = V_{\text{out}} = x V_{\text{in}}$

Capacitive Sensors

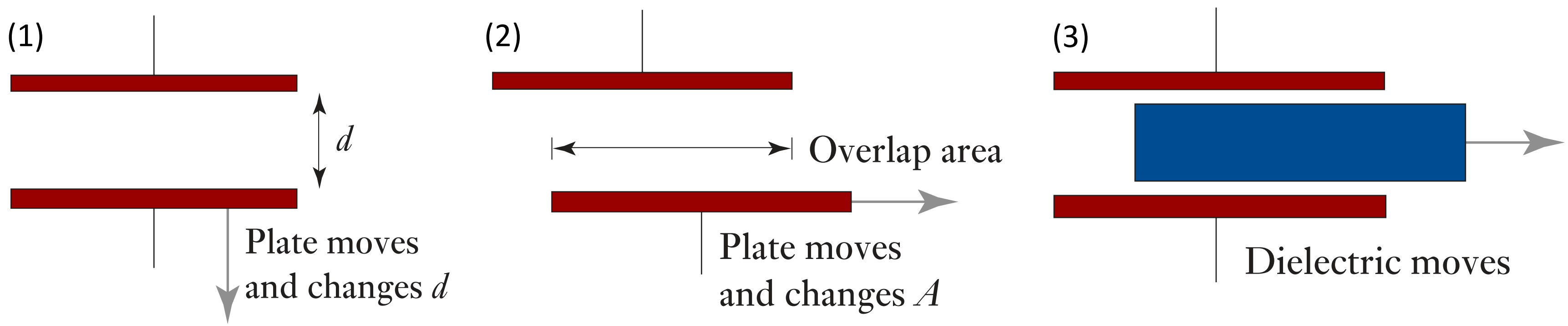
Capacitance C of a parallel plate capacitor:

ε_r: permittivity of the dielectric between the plates
ε_0: permittivity of free space

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$



Capacitive sensors for the monitoring of linear displacements can take one of the following forms, i.e., **changing capacitance with separation**, **area**, or **dielectric constant**.



For case (1), if the separation d is increased by a displacement x:

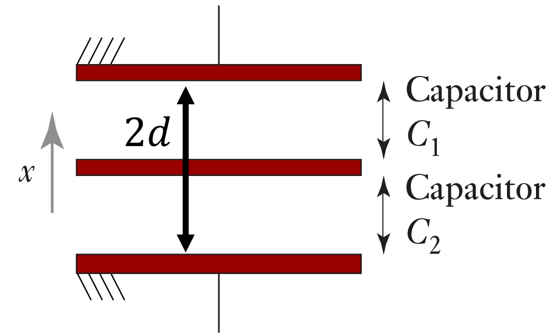
$$\frac{\Delta C}{C} = \frac{C_{d+x} - C_d}{C_d} = -\frac{x/d}{1 + (x/d)} \Rightarrow$$

Nonlinear relationship between ΔC and x.

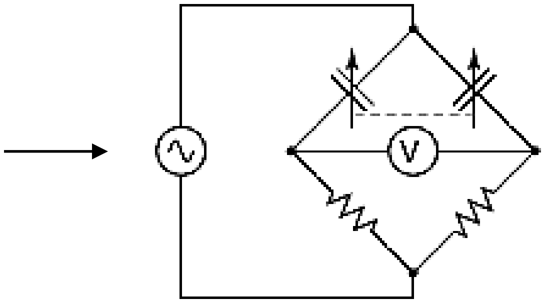
Capacitive Sensors: Push-pull Displacement Sensor

Push-pull displacement sensor is used to overcome this **nonlinearity**. A pare of capacitors that its **central common plate** is movable.

$$C_1 = \frac{\varepsilon_r \varepsilon_0 A}{d + x}, C_2 = \frac{\varepsilon_r \varepsilon_0 A}{d - x}$$

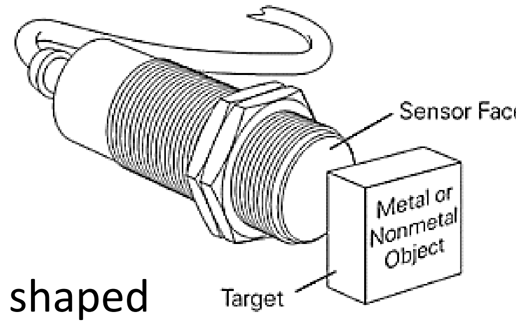


If C_1 and C_2 are in arms of an **AC bridge**, the out-of-balance voltage V is proportional to x.



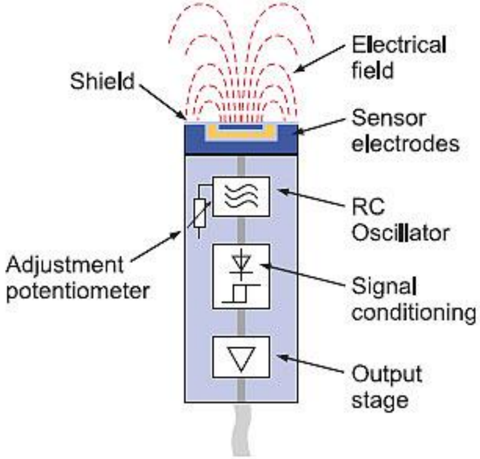
- The sensor is used for measuring a few to hundreds of millimeters.

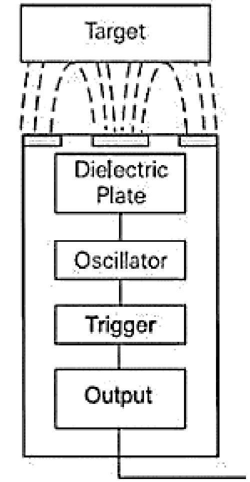
Capacitive Proximity Sensor



Capacitive Proximity Sensor is a **non-contact** sensor that can detect both metallic and nonmetallic (e.g., water, wood, and plastic) targets and are popular for liquid-level detection.

The sensing surface of this sensor is formed by two concentrically shaped **metal electrodes** of an unwound capacitor. When a **metal or nonmetal object** approaches the sensing surface, it enters the electrostatic field of the electrodes and **changes the capacitance**.

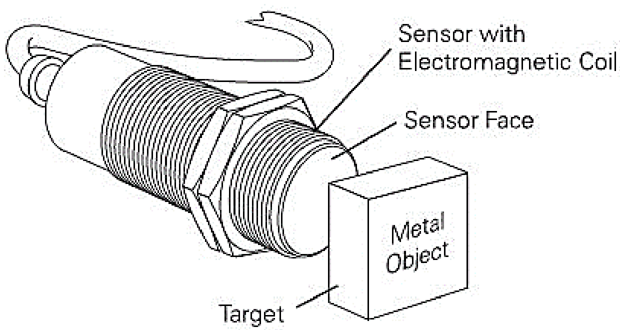


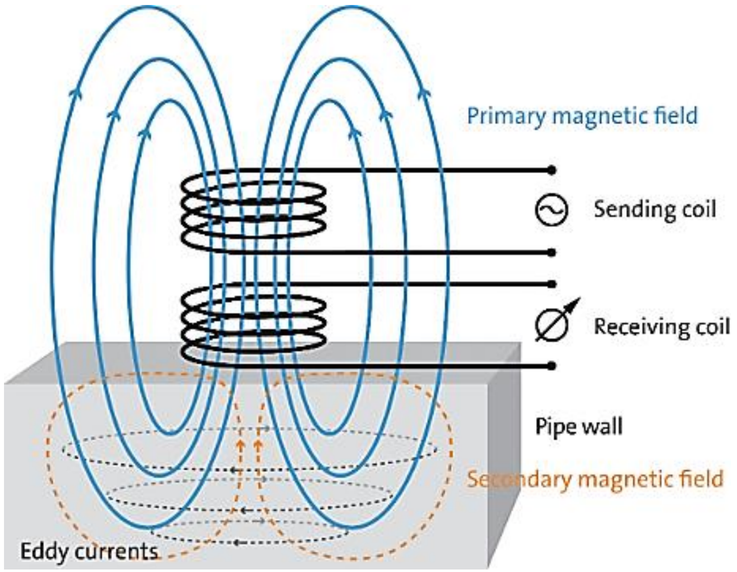


Inductive (or Eddy Current) Proximity Sensor

Proximity Sensor is a **non-contact** sensor and can only be used for the detection of **metal** objects and is best with **ferrous metals**.

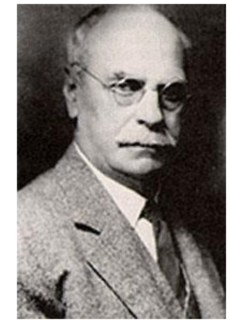
If a coil is supplied with an alternating current, an alternating magnetic field is produced. If there is a **conductive** (and non-magnetic) object in close proximity to this alternating magnetic field, **eddy currents** are induced in it. The eddy currents themselves produce a magnetic field. This field distorts the magnetic field responsible for their production. As a result, the impedance of the coil and the amplitude of the alternating current changes.



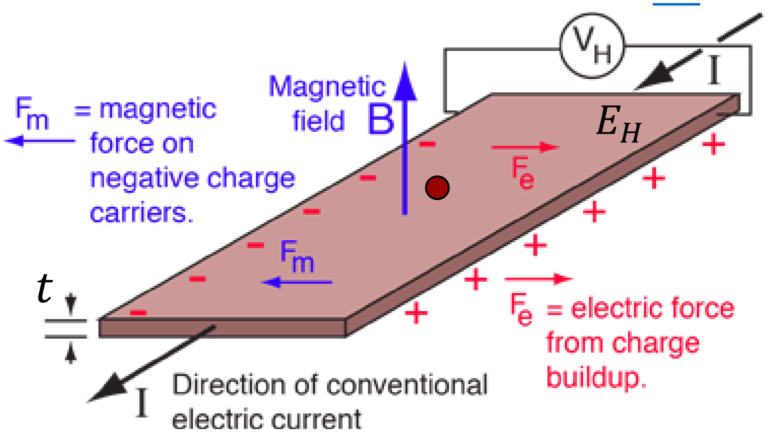


Hall Effect Sensor

Hall Effect: If an electric current flows through a (thin flat) conductor in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage (Hall voltage V_H) between the two sides of the conductor.



Discovered by
Edwin Hall in 1879



Due to **B**, (-) charges are forced to move until equilibrium is reached:

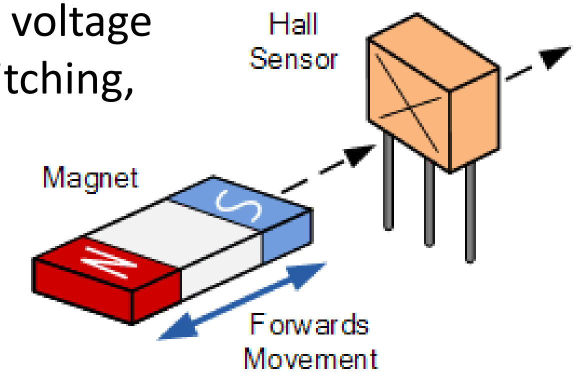
$$eE_H = ev_dB$$

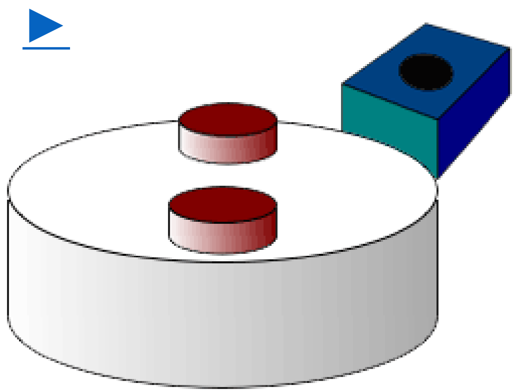
(Electric Force)=(Magnetic Force)

$$V_H = \underbrace{K_H}_{\text{Hall coefficient}} \frac{BI}{t}$$

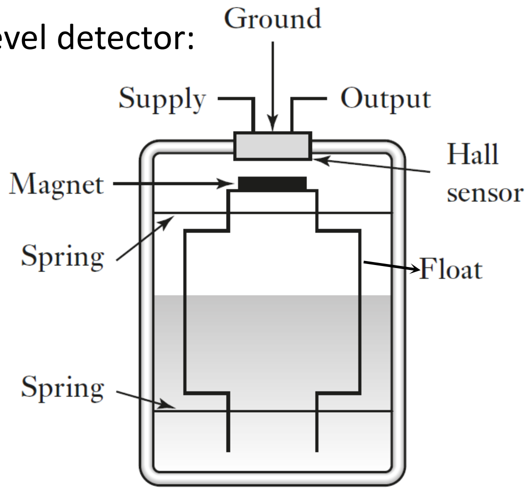
Hall Effect Sensor

Hall Effect Sensor is a **non-contact** sensor that varies its output voltage in response to a magnetic field. They are used for proximity switching, positioning, speed detection, and current sensing applications.





Fluid-level detector:

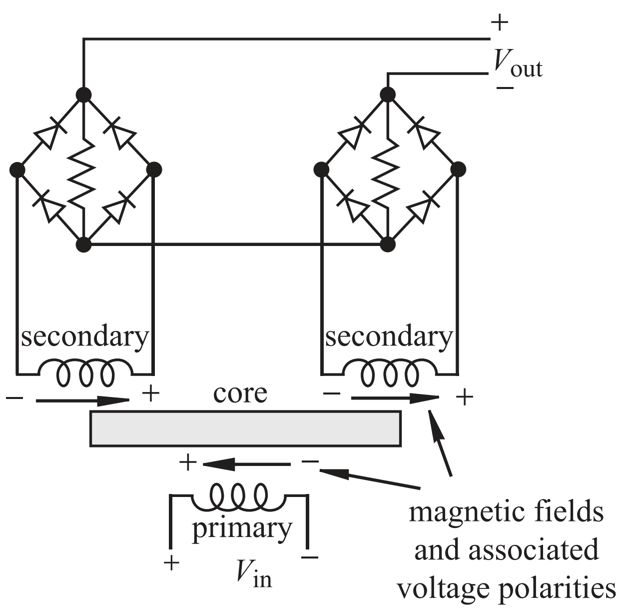


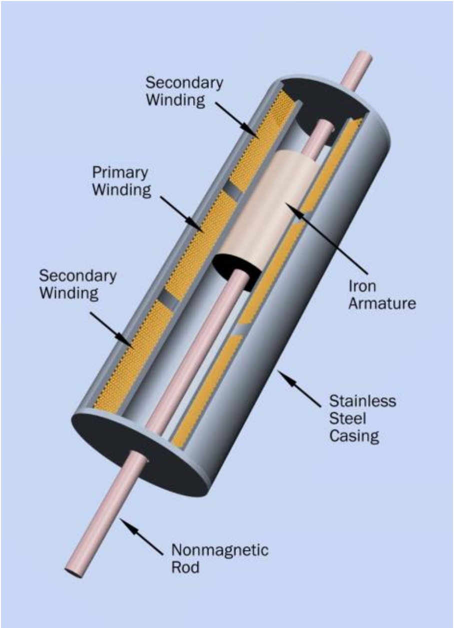
Advantages:

- They are immune to environmental contaminants and can be used under severe service conditions.
- They can operate as switches which can operate up to 100 kHz repetition rate.

Linear Variable Differential Transformer (LVDT)

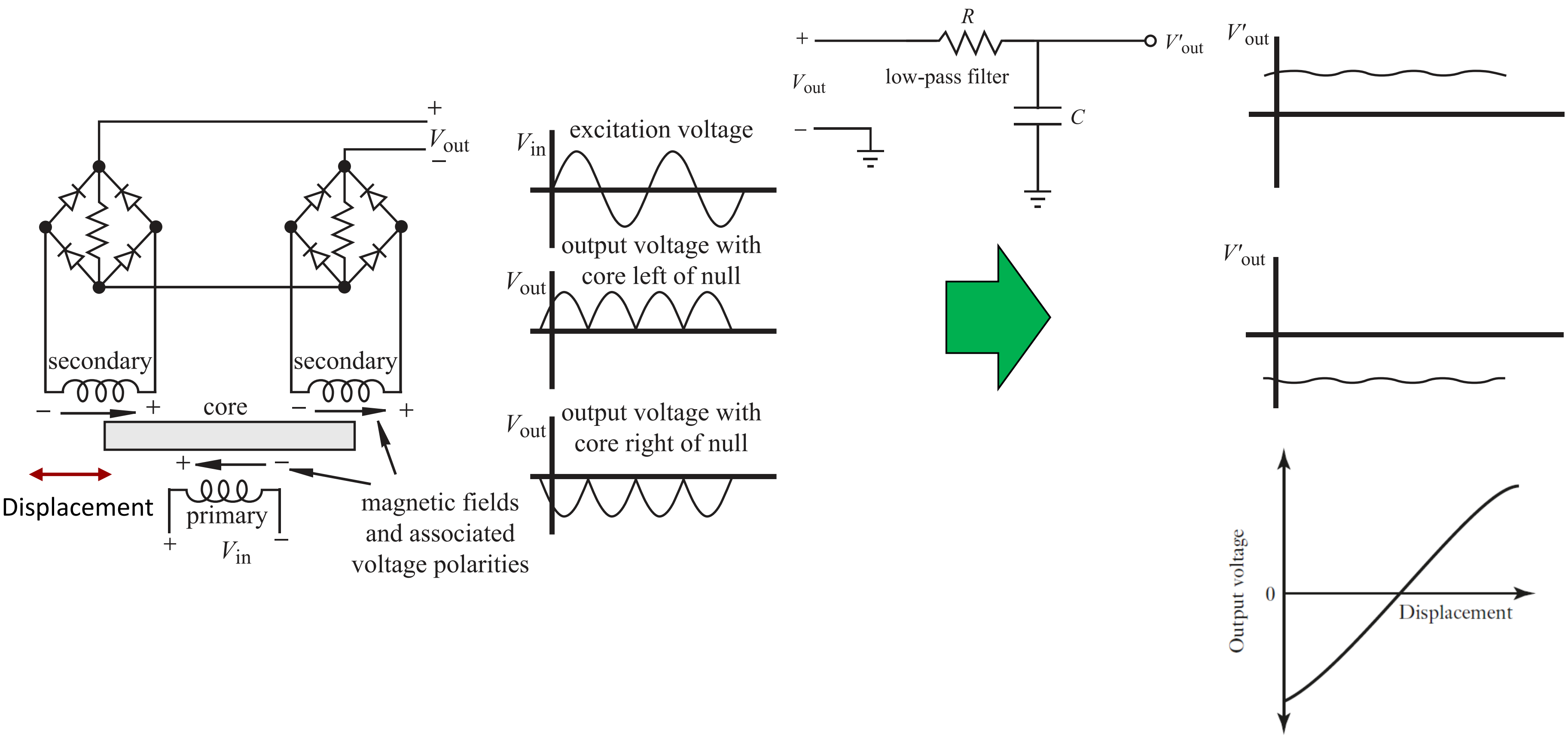
LVDT consists of **three coils** symmetrically spaced along an insulated tube. The central coil is the **primary coil** and the other two are identical **secondary coils**. When there is an **alternating voltage** input to the primary coil, alternating EMFs are induced in the secondary coils. When the magnetic core is displaced from the central position, there is a greater amount of magnetic core in one coil and a greater EMF is induced in that coil.





Linear Variable Differential Transformer (LVDT)

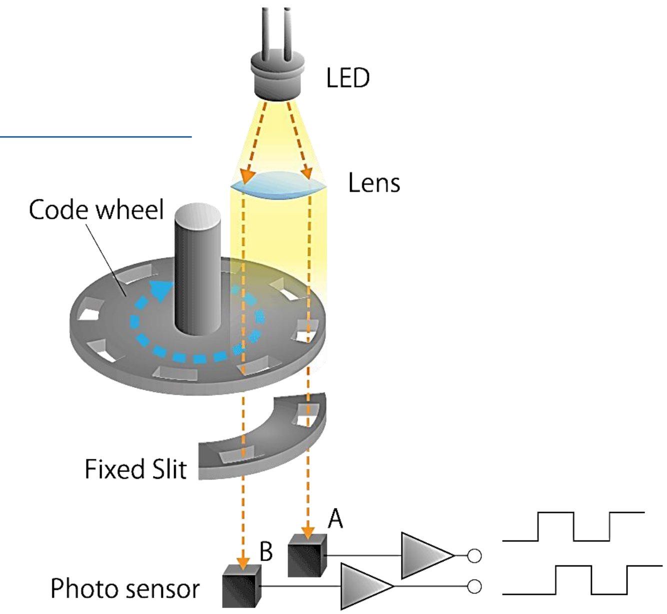
To convert the output into a **DC voltage** which gives a unique value for each displacement, the secondary output signal is processed by a phase-sensitive **demodulator** and after **rectification** (using diodes) and **filtering** (using low-pass filter), gives DC voltage.



Digital Optical Encoder

A **Digital Optical Encoder** is a device that converts **motion** into a sequence of **digital pulses**. By **counting a single bit** or **decoding a set of bits**, the pulses can be converted to **relative** or **absolute** position measurements.

A beam of light passes through slots in a disc and is detected by a light sensor to produce pulses when the disc is rotated.

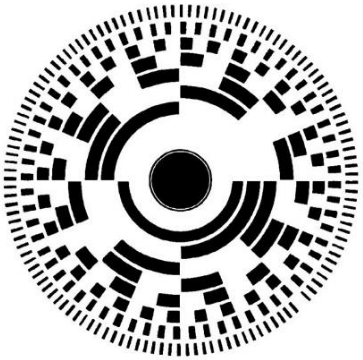


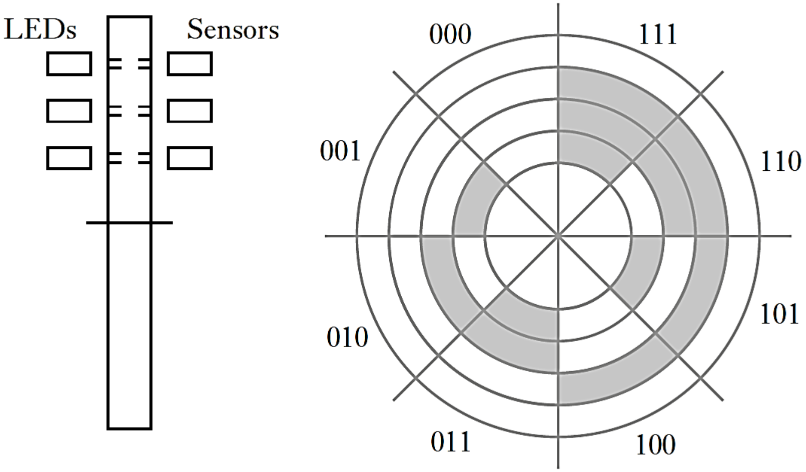
Encoders can be **Linear** or **Rotary**. Basic forms of **Rotary** encoders:

- **Absolute Encoder**
- **Incremental Encoder (or Relative Encoder)**

Absolute Encoder

The optical disk of the **Absolute Encoder** is designed to produce a unique digital word that distinguishes N distinct rotational positions of the shaft, e.g., an eight-track encoder can measure 256 (2^8) distinct positions and its angular **resolution** is 1.406° (360°/256).



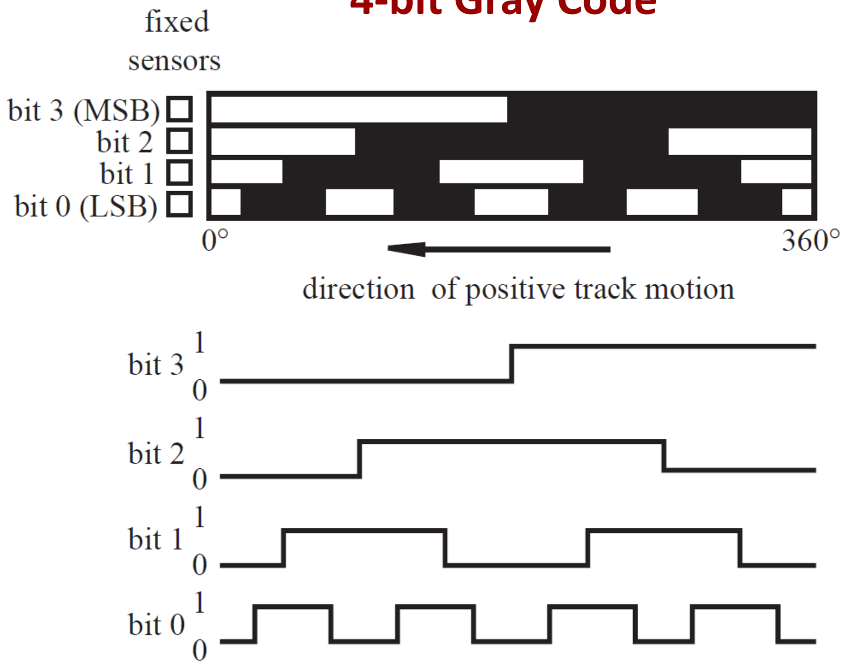


3-bit (three-track) Absolute Encoder

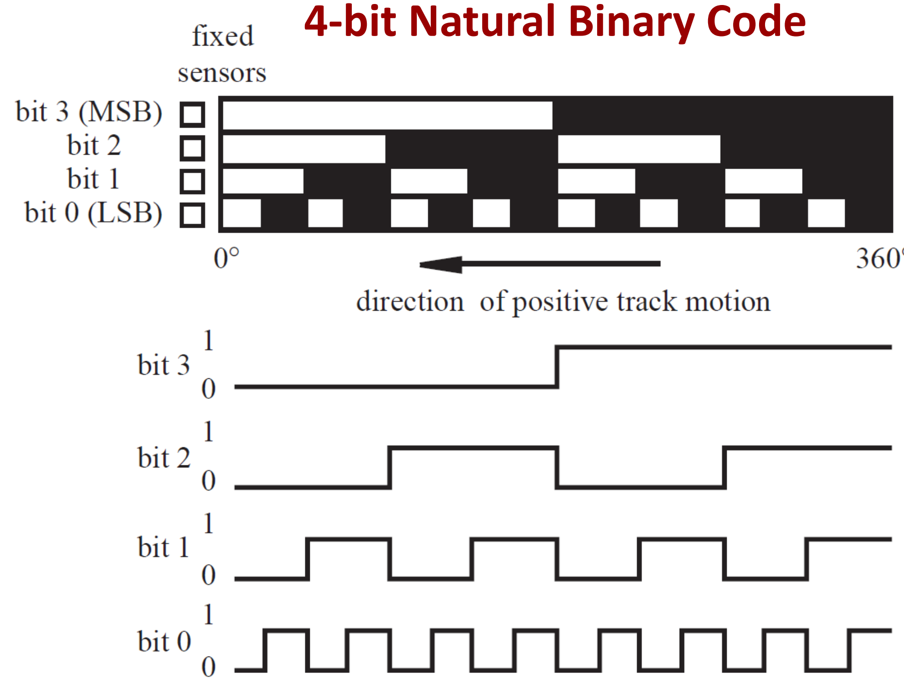
Two of common numerical encoding are **Gray Code** and **Natural Binary Code**.

Absolute Encoder

4-bit Gray Code



4-bit Natural Binary Code



Resolution: $360°/2^4 = 22.5°$

Gray Code Advantage: Only one track (one bit) changes state for each count transition, unlike the binary code where multiple tracks (bits) can change during count transitions. Thus, the **uncertainty** during a transition is only one count. This is useful for dealing with misalignment errors.

Absolute Encoder

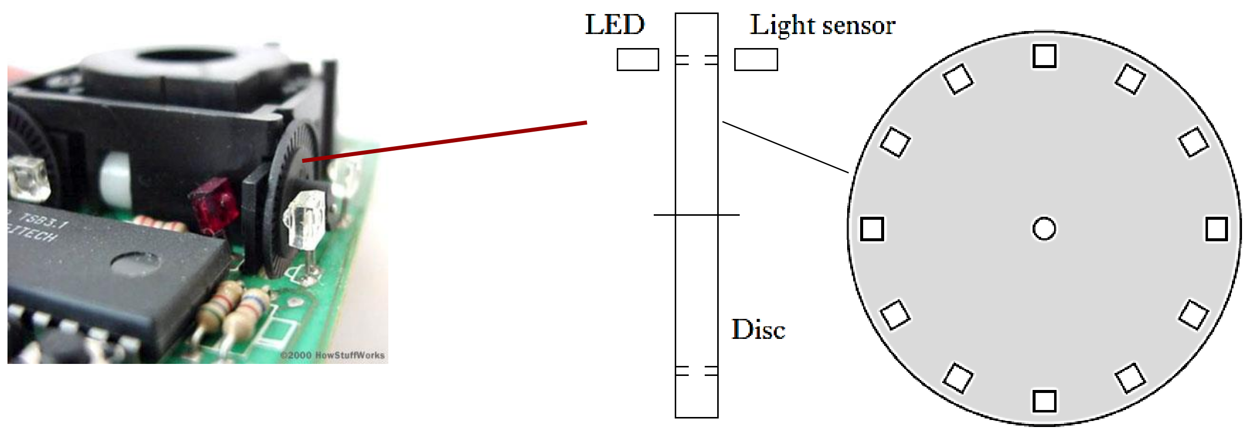
For direct interface to digital devices, a circuit to convert from **gray** to **binary** code is required.

Decimal Code	Rotation Range (°)	Natural binary code ($B_3B_2B_1B_0$)	Gray code ($G_3G_2G_1G_0$)
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	157.5–180	0111	0100
8	180–202.5	1000	1100
9	202.5–225	1001	1101
10	225–247.5	1010	1111
11	24 7.5–270	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

4-bit (four-track) Absolute Encoder

Incremental Encoder (or Relative Encoder)

Incremental Encoder: Digital pulses are produced as the shaft rotates to measure the **relative** displacement of the shaft.



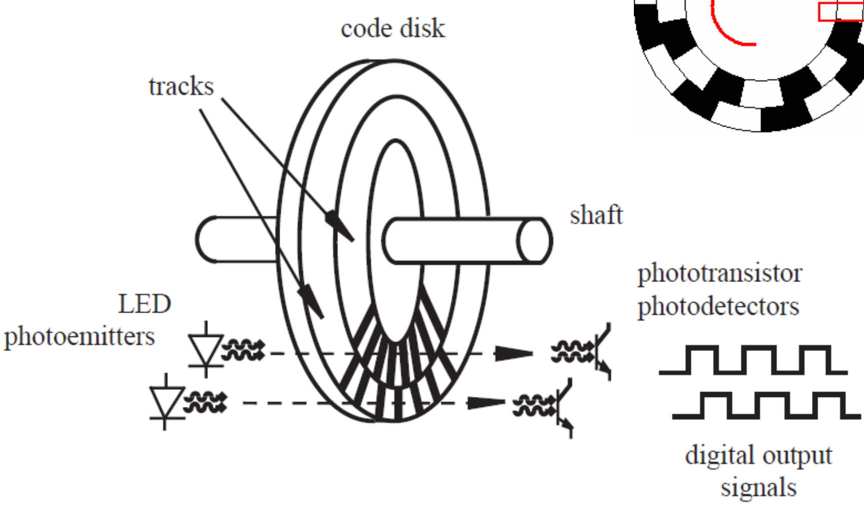
The disc with slots through which the light can pass

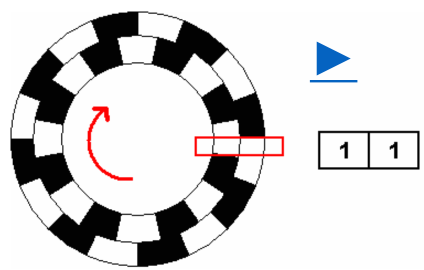
- A **single-track** incremental encoder is simple and cheap to manufacture. However, it is impossible to determine the **direction** of rotation.
- **Resolution** is determined by the number of slots on the disc (60 slots in 1 revolution $\Rightarrow$ resolution is 360°/60=6°).

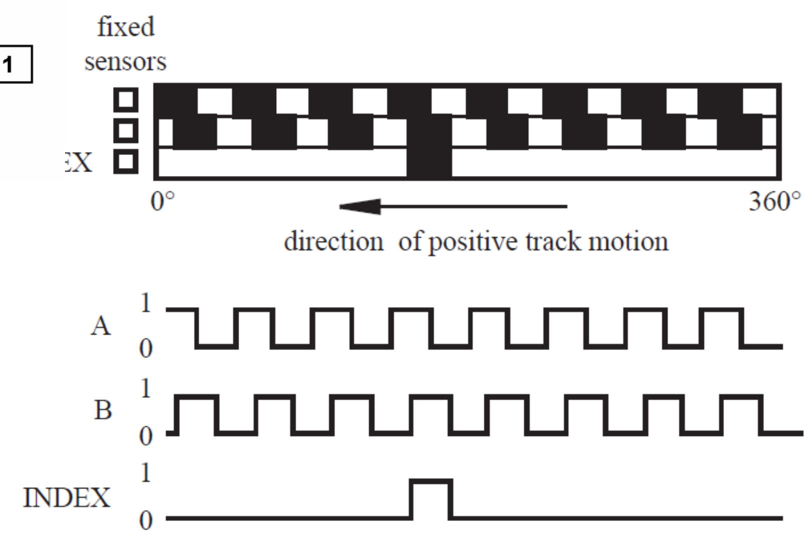
Incremental Encoder (or Relative Encoder)

A two-track **Incremental Encoder** consists of two sensors whose outputs are designated **A** and **B**. These signals indicate both the <u>occurrence</u> of and <u>direction</u> of movement.

- **A** and **B** are 1/4 (a quarter) cycle out of phase with each other and are known as **quadrature signals**.
- Often a third output, called **Index**, yields one pulse per revolution, which is useful in **counting full revolutions** or defining a **reference** or **zero** position.







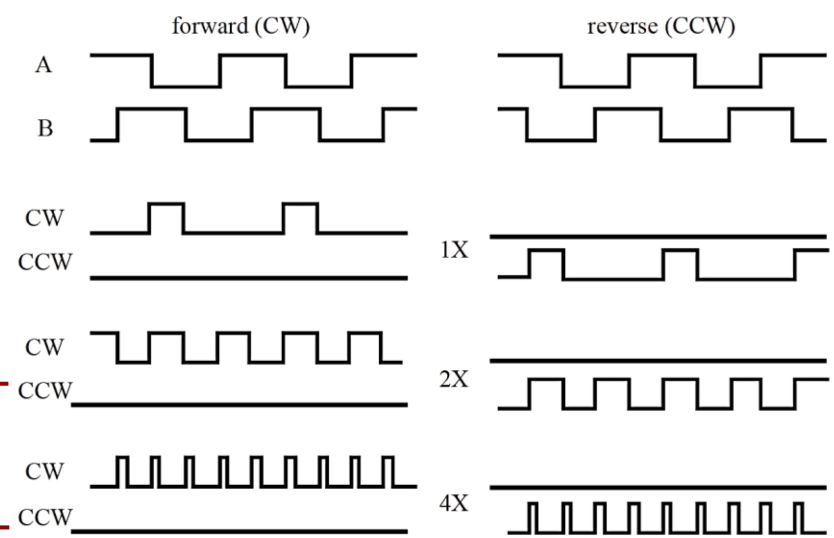
Incremental Encoder

- The **quadrature signals** A and B need to be **decoded** to yield angular displacement and the direction of rotation.
- Quadrature decoding can be done with **software** (on a microcontroller) or **hardware** (using sequential logic circuits or ICs like HCTL-2016) to provide three different **resolutions**: 1X, 2X, and 4X.

An output pulse at each negative edge of signal A or B.

An output pulse at every negative or positive edge of signal A or B.

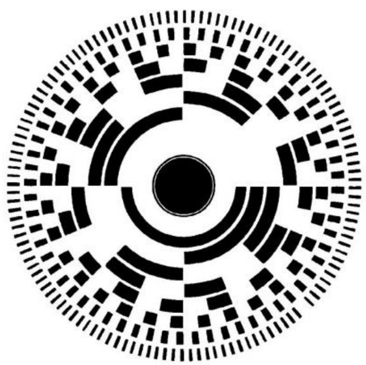
An output pulse at every positive and negative edge of signal A and B.

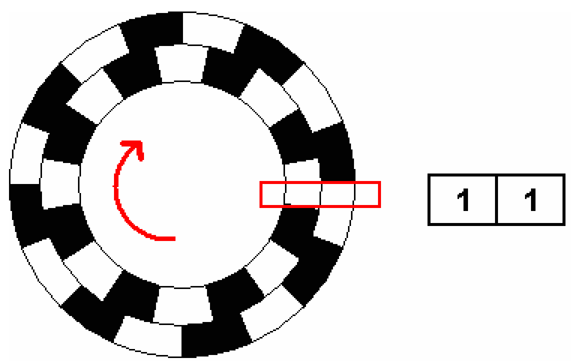


Direction of rotation is determined by assessing which channels "leads" the other or by the level of one quadrature signal during an edge transition of the second quadrature signal. For example, in the 1X mode, A=↓ with B =1 implies a clockwise pulse, and B=↓with A=1 implies a counter-clockwise pulse.

Absolute vs Incremental Encoder

- Incremental encoders provide **more resolution at lower cost** than absolute encoders.
- Incremental encoders measure only relative motion and do not provide absolute position directly.
- Incremental encoder can be used in conjunction with a limit switch to define absolute position relative to a reference position defined by the switch.
- Absolute encoders are chosen in applications where establishing a reference position is impractical or undesirable.

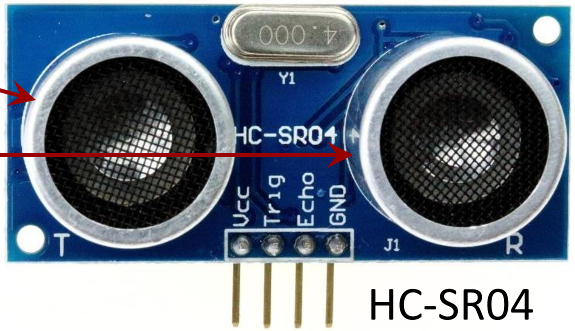




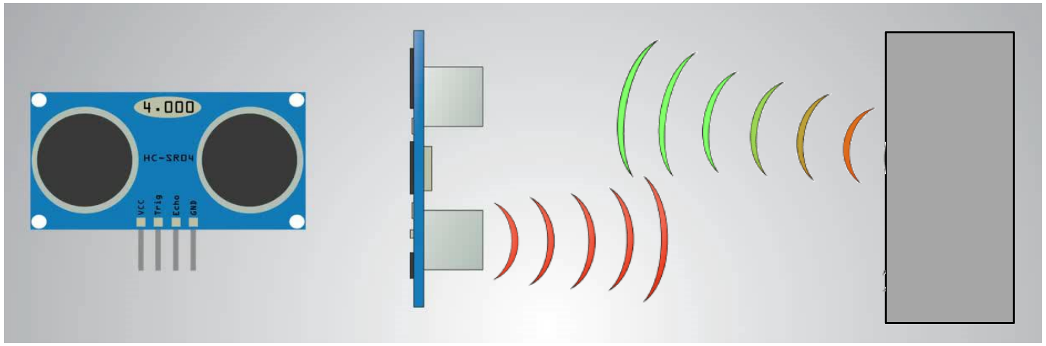
Ultrasonic Sensor

Ultrasonic Sensor is a non-contact sensor that use sonar to determine **distance** to an object like what bats or dolphins do.

The sensor includes ultrasonic **Transmitter**, **Receiver** and **Control Circuit**.



HC-SR04

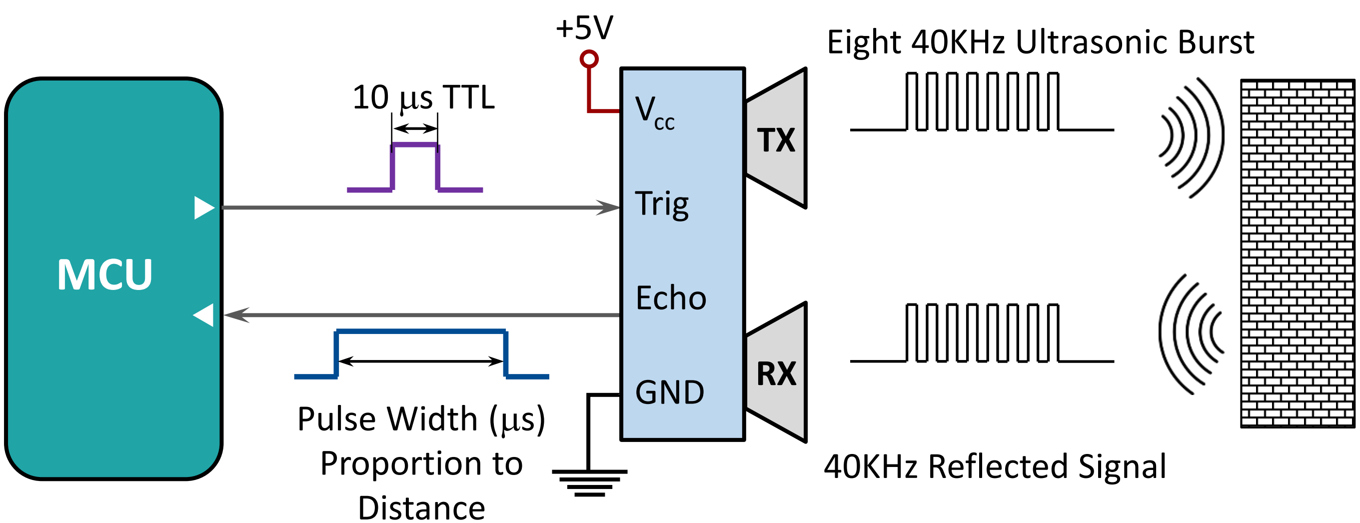


VCC: +5V
Trig: Trigger input of Sensor
Echo: Echo output of Sensor
GND: Ground

- Its operation is not affected by sunlight.
- Acoustically soft materials like cloth can be difficult to detect.
- The surface of object should be smooth.

Ultrasonic Sensor: How Does It Work?

To start measurement, you must send a pulse of HIGH (5V) for at least 10μs to **Trig** pin to **initiate the sensor**. Then, sensor transmit out 8 cycles of ultrasonic bursts at 40KHz and wait for the reflected signal. When the sensor detected ultrasonic from receiver, it will set the Echo pin to HIGH (5V) and delay for a period (width) which proportion to distance. To obtain the distance, measure the width of Echo pulse output.



(about 150 μs-25ms, 38ms if no obstacle)

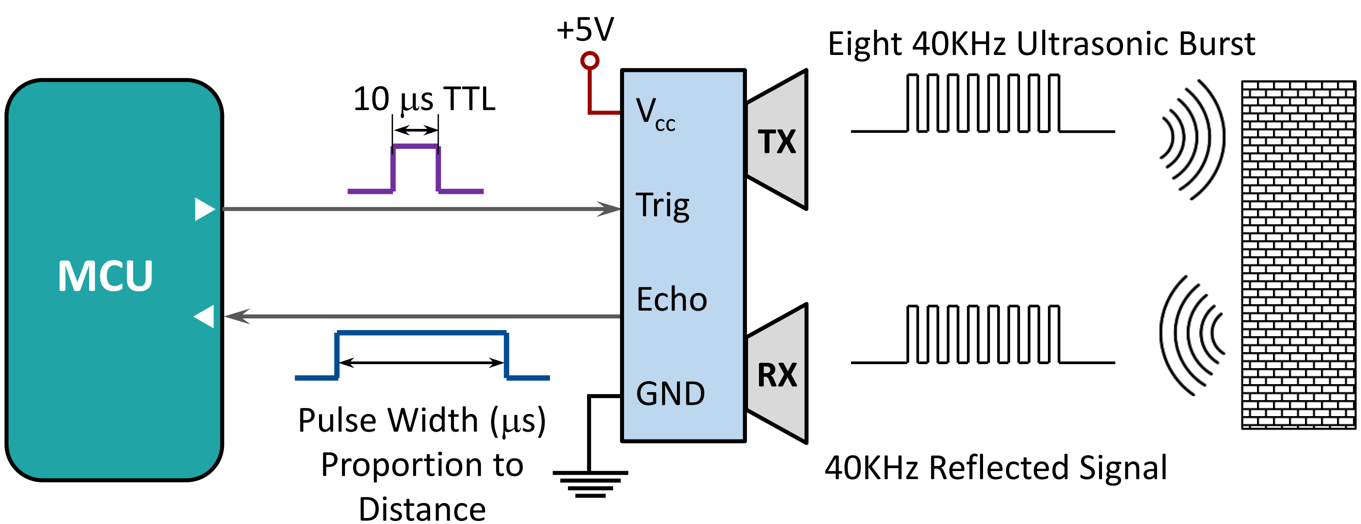
Ultrasonic Sensor: How Does It Work?

t: Time taken by the Ultrasonic Burst to Leave and Return the Sensor (= Width of Echo pulse, in μs)

x: Ultrasonic Burst Travel Distance

v: Speed of Sound $\rightarrow$ $v = 340\ \mathrm{m/s} = 0.034\ \mathrm{cm/\mu s}$ (in dry air at 20 °C)

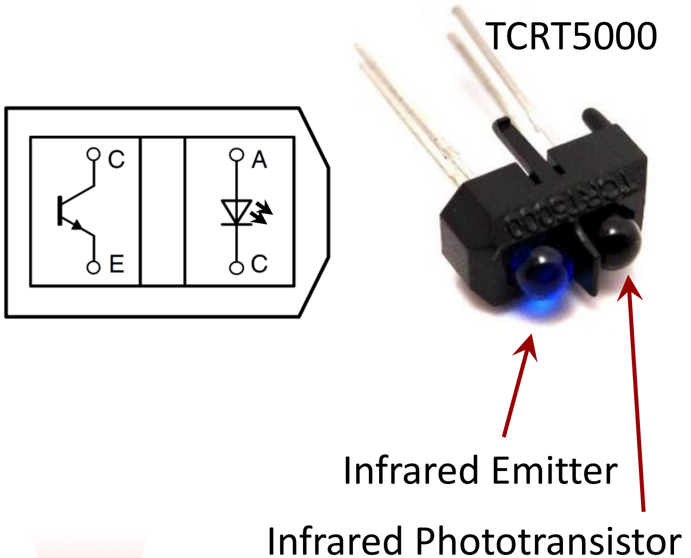
$$x = vt \xrightarrow[d:\ \text{Distance to Object}]{d = x/2} d = v\,t/2 \longrightarrow \underset{\text{(cm)}}{d} = (0.034/2)\,\underset{(\mu\text{s})}{t} \quad \text{or} \quad d = t/58.8 \ \text{(cm)}, \quad d = t/148 \ \text{(in)}$$

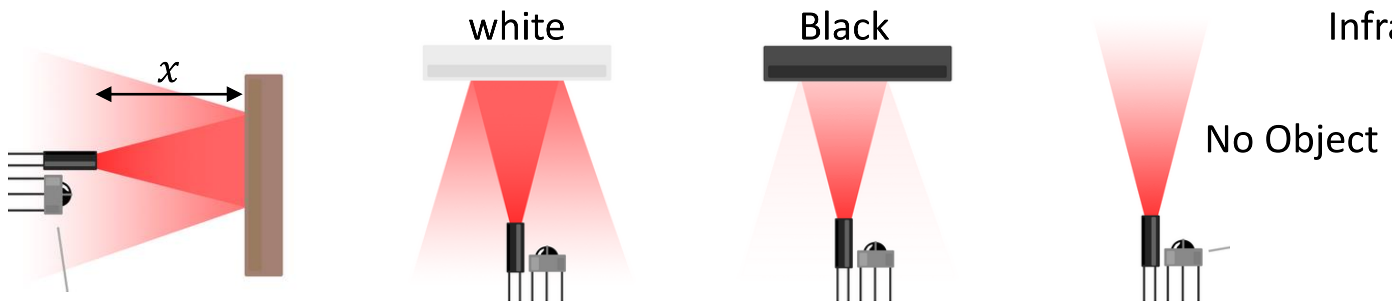


Reflective Optical Sensor

Reflective Optical Sensor is designed to sense the **distance** to an object using infrared (IR) light waves. It can also identify the difference between **white** and **black** based on the contrast of an object and its reflective properties.

The sensor includes an **Infrared Emitter** (IR LED) and **Infrared Phototransistor** in a leaded package.

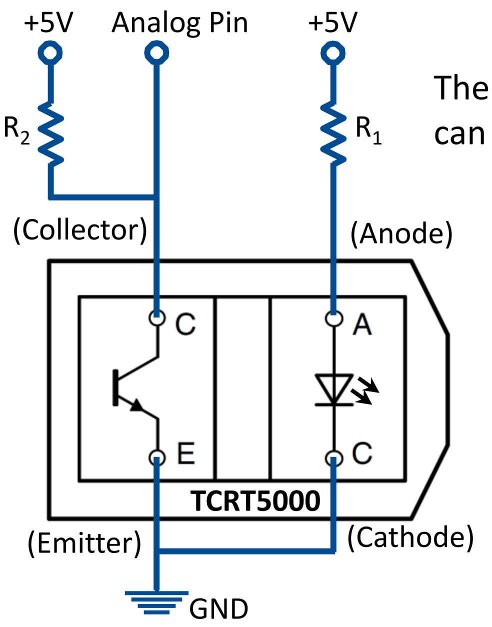




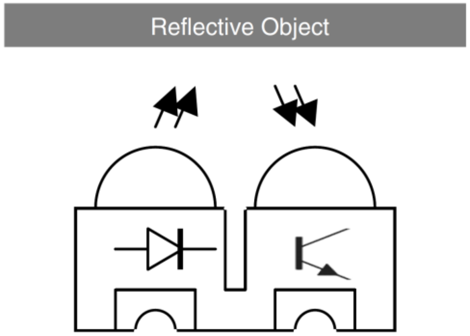
Reflective Optical Sensor

The IR LED **emits infrared light** (the light which is not visible to humans) and the phototransistor filters natural light and captures the infrared light retunes from objects to determine their reflectivity by measuring the **intensity** of the received light.

- **White** and **light-colored** objects return the IR light; hence, you can detect them.
- **Black** and **dark-colored** objects absorb the IR light; hence, you cannot detect them (like when nothing is in the way of the sensor).



The sensitivity of the sensor can be changed by changing R_2.



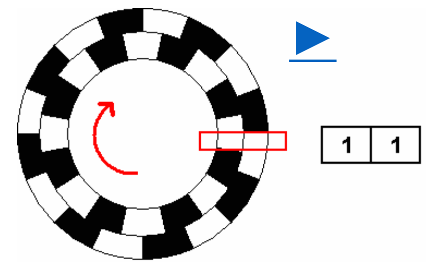
Applications:

- making a line follower robot,
- making an edge avoiding robot,
- making an encoder to calculate the RPM of a DC motors,
- measuring the small distance to an object,
- detecting if something has passed by the sensor.

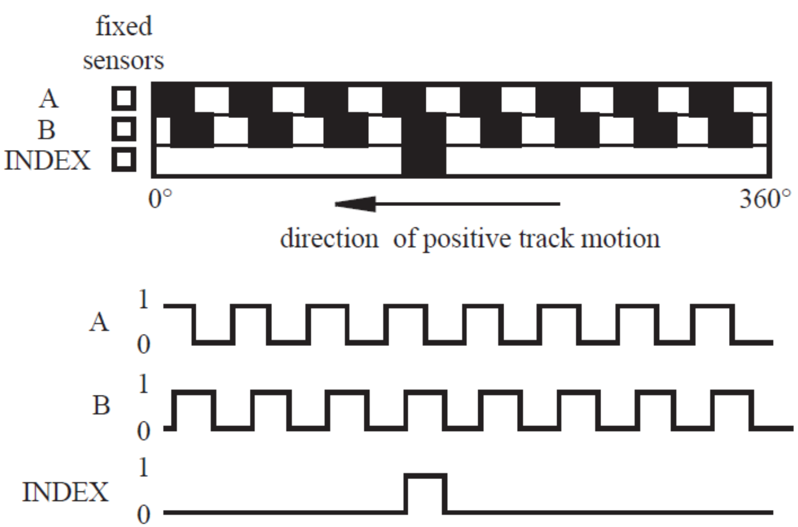
Velocity and Acceleration

Incremental Encoder

Incremental Encoder can be used for the measurement of **angular velocity**. By **counting the number of pulses per second** and **knowing the resolution of the disk**, the angular motion can be measured.



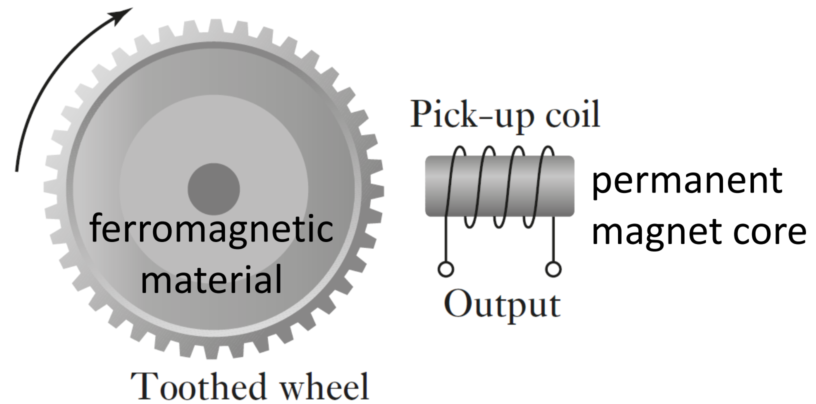
As the shaft rotates, digital pulse trains occur on A and B at a **frequency** proportional to the shaft **speed**, and the lead-lag phase relationship between the signals yields the direction of rotation.



Variable-Reluctance Tachometer

Variable-Reluctance Tachometer is used to measure **angular velocity**.

It consists of a toothed wheel of ferromagnetic material which is attached to the rotating shaft. A pick-up coil is wound on a permanent magnet.

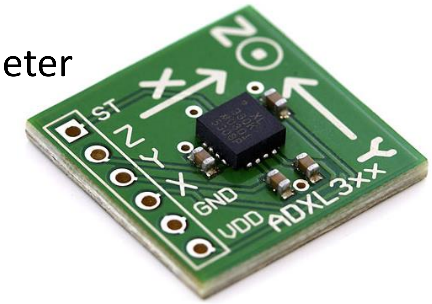


As the wheel rotates, the teeth move past the coil and the air gap between the coil and the ferromagnetic material changes. Each **teeth** positioned in **front** of the coil **decreases reluctance** (magnetic resistance) and **increases magnetic filed density** around the coil. Since we have a magnetic circuit with an air gap which periodically changes, the flux linked by a pick-up coil changes. This **change in the flux** produces an **alternating EMF** in the coil, whose **frequency** depends on the **angular velocity** and **number of teeth**.

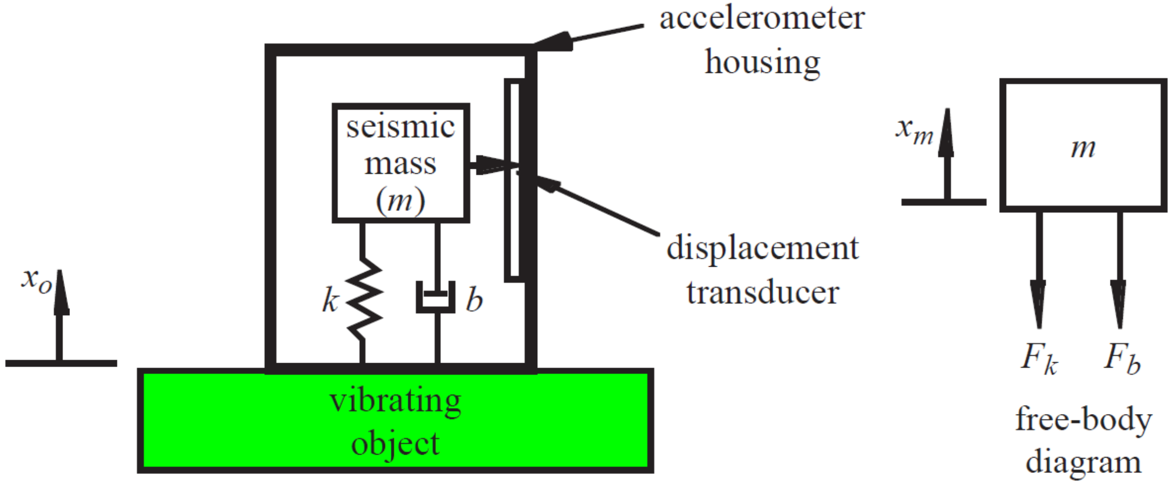
Accelerometer

Accelerometer is a sensor designed to measure acceleration (rate of change of speed) due to **motion** (e.g., in a video game controller), **vibration** (e.g., from rotating equipment), and **impact events** (e.g., to deploy an automobile airbag).

Triple Axis Accelerometer



Accelerometer is based on the inertial effects:

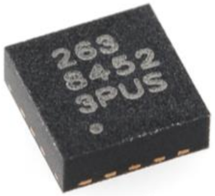


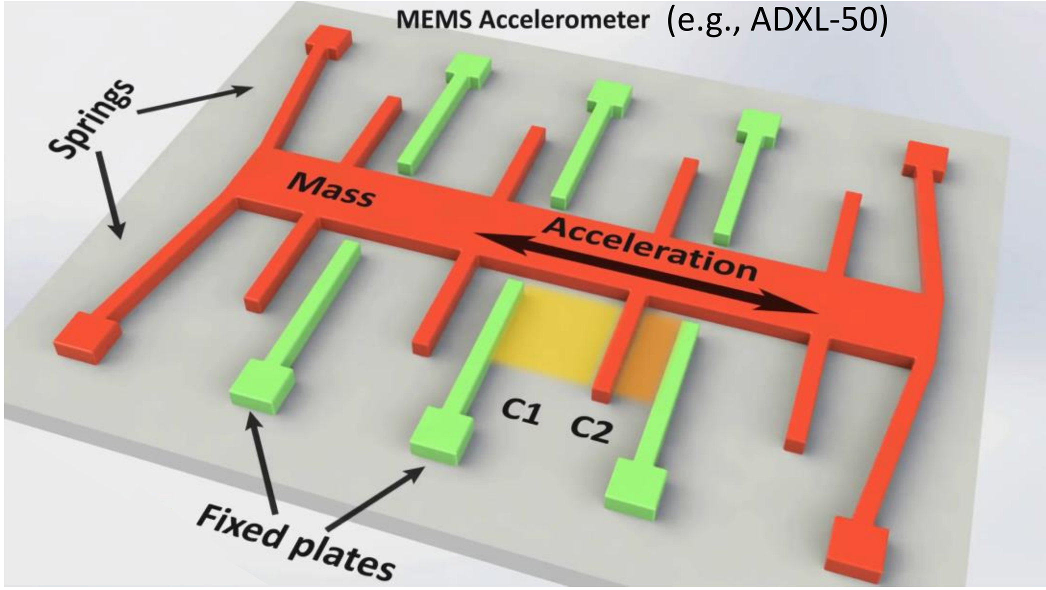
$$-kx_r - b\dot{x}_r = m\ddot{x}_m$$

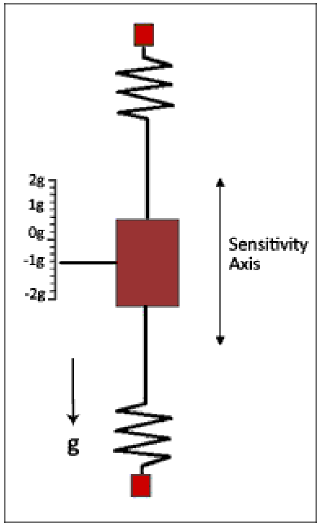
$$x_r = x_m - x_o$$

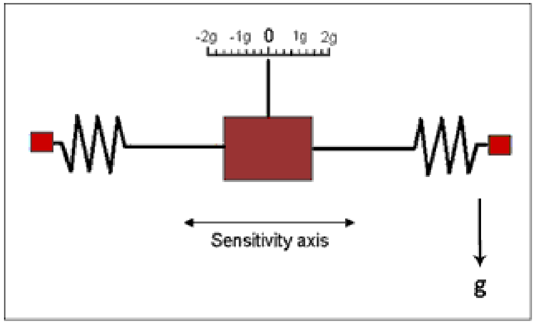
Capacitive Accelerometer

In a Capacitive Accelerometer, when mass moves, **capacitance** between mass and fixed plates changes. This change is measured and processed.





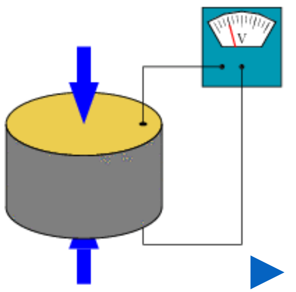




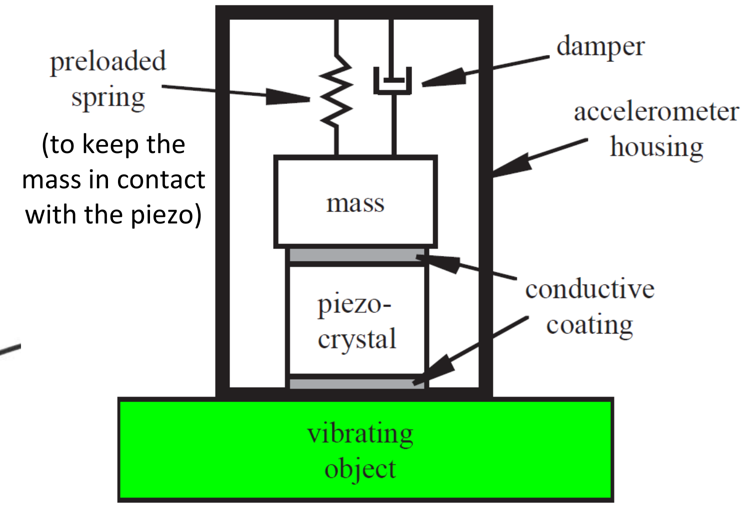
This accelerometer **detects** acceleration along **one axis** and is **insensitive** to motion in **orthogonal directions**. They can also detect **gravity**.

Piezoelectric Accelerometer

Piezoelectricity is the property of certain materials to produce an electrical charge when mechanically deformed. In a reciprocal manner, when they are placed in an electric field, they contracts or elongates.



When the mass moves, strain in the piezoelectric crystal causes a **displacement charge** between the crystal conductive coatings. This charge is converted to a voltage that can be measured by a charge amplifier.



- It requires no external power supply.
- It cannot measure constant or slowly changing motions.
- It is excellent for dynamic measurements such as vibration and impacts (e.g., bearing health monitor).