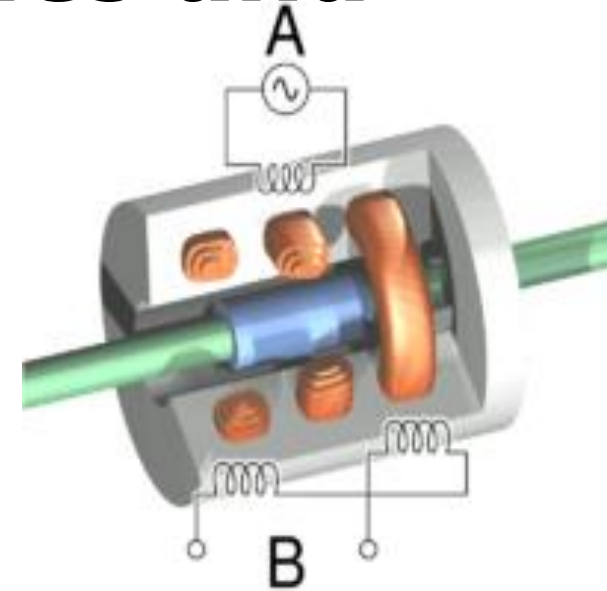
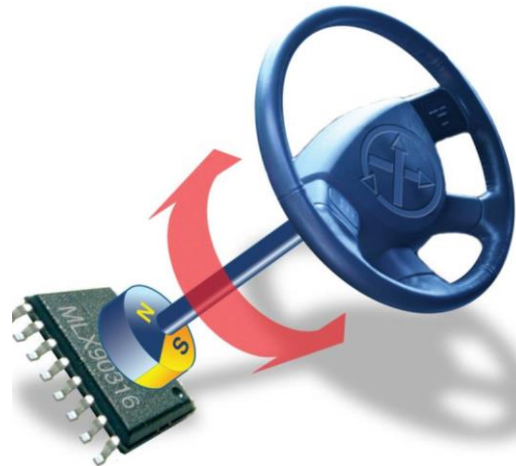
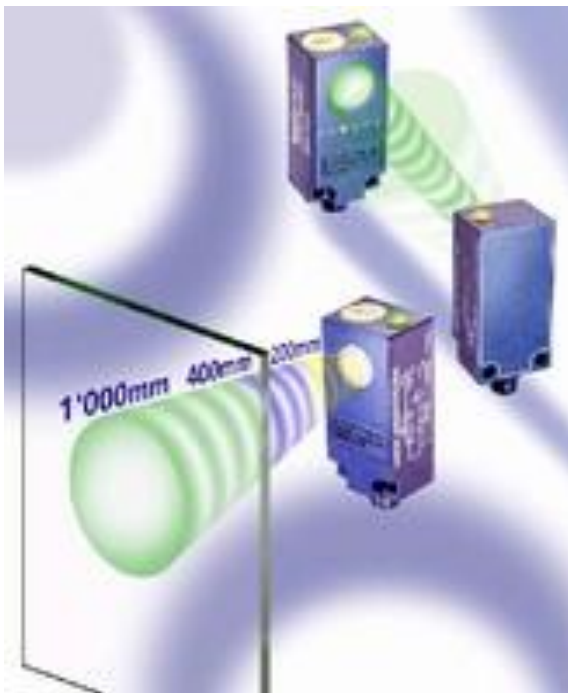


L6- Sensor Technologies and Sensors



Sensor/Transducer Technologies

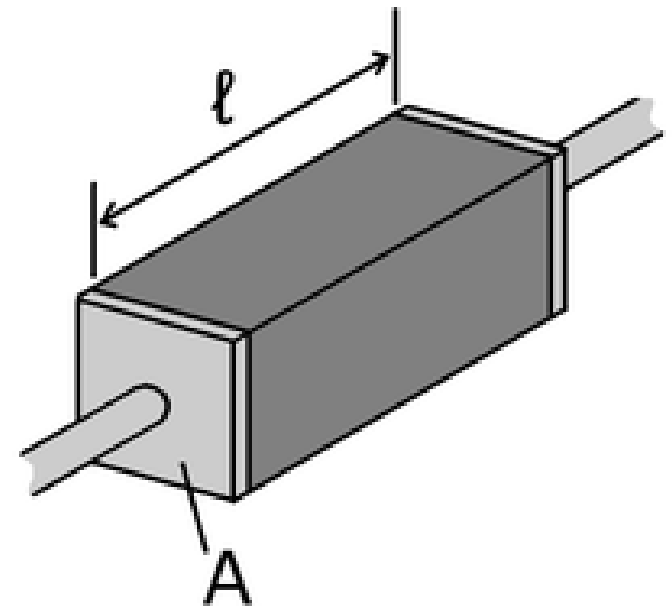
- **Resistive sensors**
- **Piezoresistive sensors**
- **Capacitive sensors**
- **Magnetic Sensors**
- **Hall Effect Sensors**
- **Piezoelectric transducers**
- **Light sensors**
- **Photo Interrupts**
- **Optical Sensors**
- **Infrared Sensors**
- **Ultrasonic Transducers**
- **Translational Motion Transducers**
- **Temperature Transducers**

1. Resistive sensors

- ❑ Resistive sensors rely on the variation of the resistance of a piece of material when the measured variable is applied to it.
- ❑ Many resistors and conductors have a uniform cross section and their resistance, R , is given by:

$$R = \rho(l/A)$$

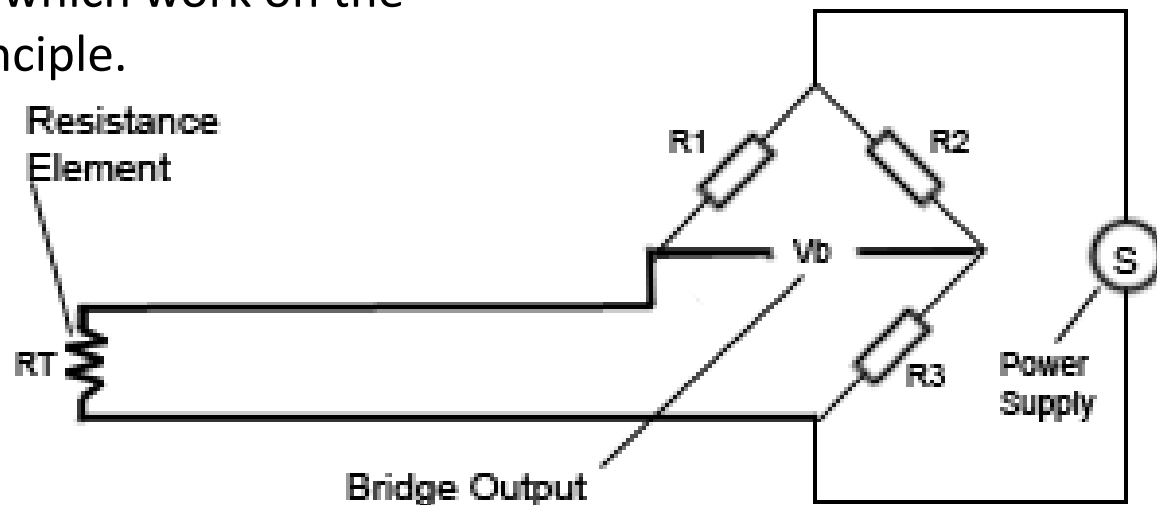
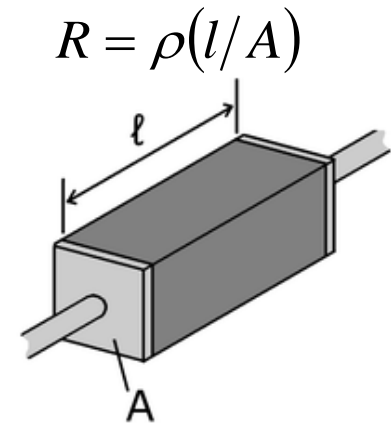
where ρ is the resistivity of the element's material, l is its length and A is its cross sectional area.



Resistive sensors:

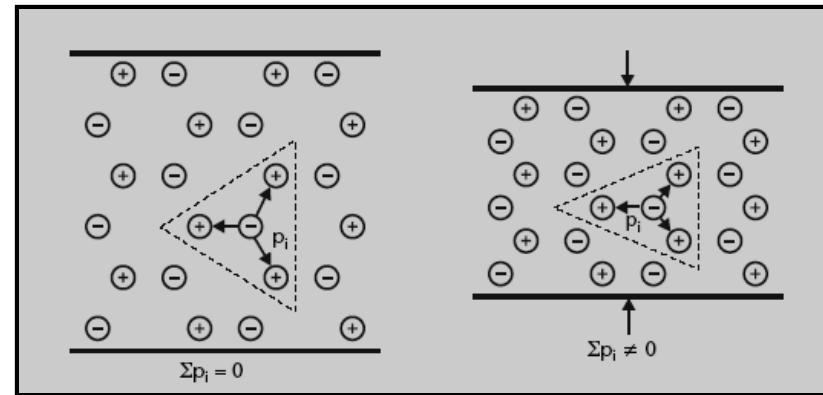
❑ Many resistive sensors rely on the **variation of the resistivity of the element's material** when measured variable is changed. Common application of this principle is found in:

- ❑ Resistance thermometers or resistive temperature detectors (RTDs)
- ❑ Piezoresistive sensors and Piezoresistive strain gauges.
- ❑ Some moisture meters which work on the resistivity-variation principle.



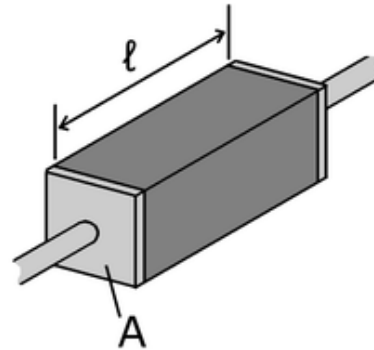
Piezoresistive sensors

- ❑ A piezoresistive sensor is made from semiconductor material in which a p-type region has been diffused into an n-type base. The resistance of this varies greatly when the sensor is compressed or stretched.
- ❑ This is frequently used as a strain gauge, where it produces a significantly higher gauge factor than that given by metal wire or foil gauges. Also, measurement uncertainty can be as low as $\pm 0.1\%$.
- ❑ It is also used in semiconductor pressure sensors and in semiconductor accelerometers.

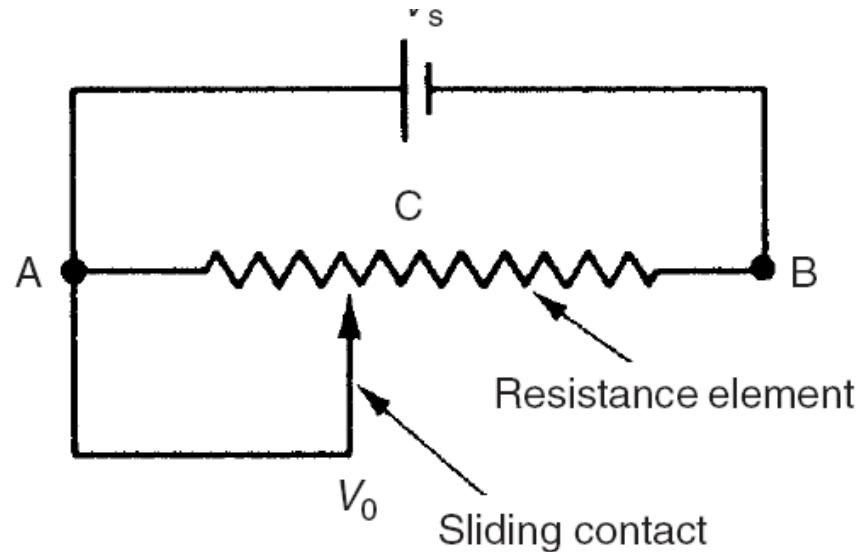


Resistive sensors: Potentiometers

- ❑ The resistive potentiometer is perhaps the best-known displacement-measuring device.
- ❑ It relies on changing the length /along which of the resistor is measured
- ❑ A linear relationship exists between the length and the resistance.

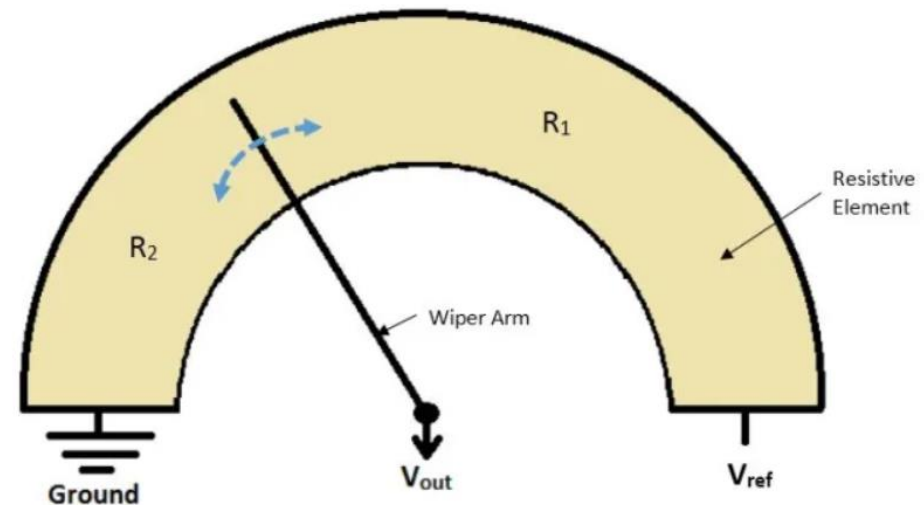


$$R = \rho(l/A)$$



Example : Electronic Throttle Control (ETC)

- ❑ In ETC systems, a vehicle's electronic control unit uses information from the throttle position sensor (TPS), accelerator pedal position sensor (APP sensor), wheel speed sensors, vehicle speed sensor and a variety of other sensors to determine how to adjust throttle position.
- ❑ TPS and APP sensors are very simple. The accelerator pedal position sensor and the throttle position sensor work together to translate user input into throttle plate movement.
- ❑ Until recently, these sensors have utilized potentiometers that worked as voltage dividers.
- ❑ The "divided" voltage is sent to a computer (ECU), which uses it to adjust the position of the throttle.



Example : Electronic Throttle Control (ETC)

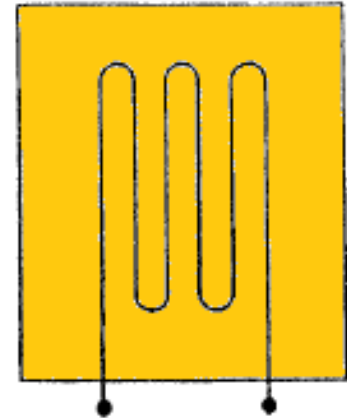
- The ECU takes in this signal, and sends an appropriate signal to a throttle actuator, which moves the throttle plate.
- The throttle position sensor works in a similar way. The potentiometer wiper is connected to the butterfly valve spindle. As the butterfly valve opens and closes, it varies the output voltage from 0 to the reference voltage. This output voltage is sent to the ECU. This is how the ECU knows the position of the throttle plate.
- The problem with potentiometer-based sensors is that, as the wiper arm and the resistive element rub against one another, they eventually wear out.
- Newer accelerator pedal position sensors use Hall effect as their basic operating principle.

<https://jalopnik.com/how-electronic-throttle-control-works-499966101>

https://www.infineon.com/dgdl/AppNote_Pedal_Position_Sensing_Rev.1.0.pdf?fileId=db3a30432313ff5e0123a38779c5262f

Resistive sensors: Metal Strain Gauges

- ❑ Strain gauges are devices that experience a change in resistance when they are stretched or strained.
- ❑ They are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm.
- ❑ The traditional metal strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet.
- ❑ The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area.
- ❑ As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance.
- ❑ The input–output relationship of a strain gauge is expressed by the gauge factor, which is defined as the change in resistance (R) for a given value of strain (S).



$$R = \rho(l/A)$$

$$\text{gauge factor} = \frac{\delta R}{\delta S}$$

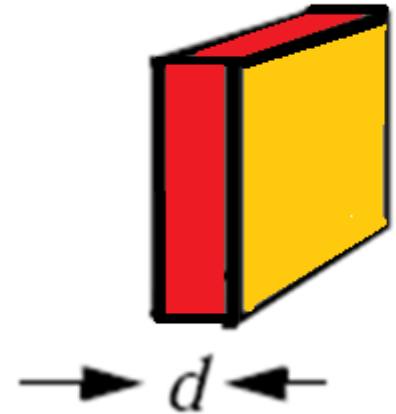
Strain gauges

- Strain gauges are manufactured to various nominal values of resistance, of which 120, 350 and 1000 are very common.
- The typical maximum change of resistance in a 120 device would be 5 at maximum deflection.
- Semiconductor strain gauges also are available with piezo-resistive elements, which are considered in greater detail in the next section.
- Compared with metal gauges, semiconductor types have a much superior gauge factor (up to 100 times better) but they are more expensive.
- Also, whilst metal gauges have an almost zero temperature coefficient, semiconductor types have a relatively high temperature coefficient

2. Capacitive sensors

- Capacitive sensors consist of two parallel metal plates in which a dielectric is between the plates. A dielectric is an electrical insulator that can be polarized by an applied electric field. is either air or some other medium.
- The capacitance C is given by:

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

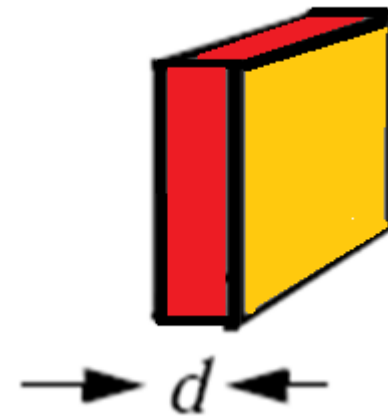


where ϵ_0 is absolute permittivity, ϵ_r is the relative permittivity of the dielectric medium between the plates, A is the area of the plates and d is the distance between them.

Capacitive sensors

- ❑ Capacitive devices are often used as displacement sensors, **in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance.**
- ❑ Often, the measured displacement is part of instruments measuring pressure, sound or acceleration.
- ❑ Alternatively, **fixed plate capacitors** can also be used as sensors, in which the capacitance value is changed by causing the measured variable **to change the dielectric constant** of the material between the plates in some way.
- ❑ **This principle is used in devices to measure moisture content, humidity values and liquid level.**
- ❑ **Also Capacitive proximity sensors exist**

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

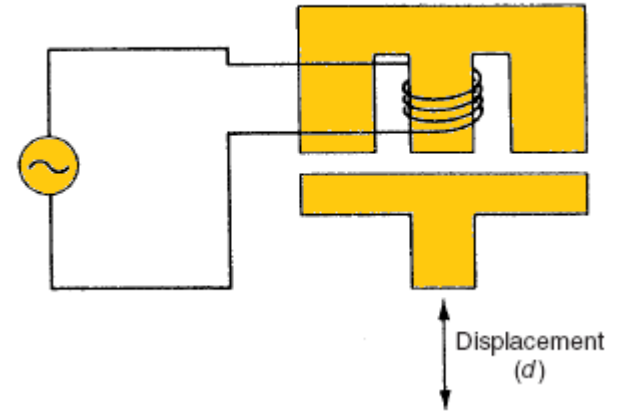


3. Magnetic Sensors

- **Magnetic sensors utilize the magnetic phenomena of:**
 - inductance,
 - reluctance
 - eddy currents
- **Used to indicate the value of the measured quantity, which is usually some form of displacement.**

Inductive Sensors

- ❑ In the inductive displacement transducer, the single winding on the central limb of an 'E'-shaped ferromagnetic body is excited with an alternating voltage.
- ❑ The displacement to be measured is applied to a ferromagnetic plate in close proximity to the 'E' piece.
- ❑ Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding. The current-voltage relationship in the winding is given by:
- ❑ For fixed values of ω and V , I depends only on L , which in turn, depends on the displacement d applied to the plate.
- ❑ The relationship between L and d , is a non-linear one, and hence the output-current/displacement characteristic has to be calibrated.



$$v = L \frac{di}{dt},$$

$$i = \frac{1}{L} \int v dt = \frac{V}{L} \int \cos \omega t dt$$

$$= \frac{V}{\omega L} \sin \omega t$$

$$I = \frac{V}{\omega L}$$

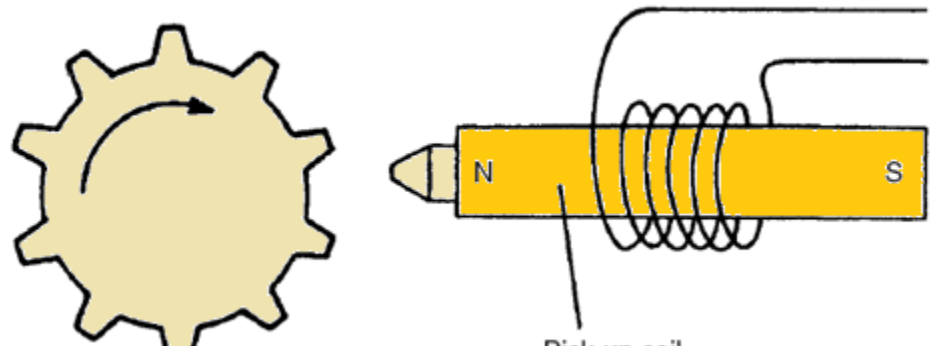
Magnetic Reluctance

- Magnetic Reluctance is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy).
- An electric field causes an electric current to follow the path of least resistance,
- **A magnetic field causes magnetic flux to follow the path of least magnetic reluctance**
- The definition can be expressed as: $\mathcal{R}=F/\Phi$
where
 - (" \mathcal{R} ") is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.
 - ("F") is the magnetomotive force (MMF) in ampere-turns
 - Φ ("Phi") is the magnetic flux in webers.

Variable Reluctance Sensors

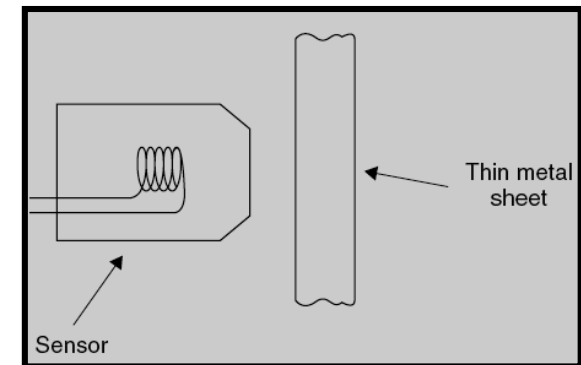
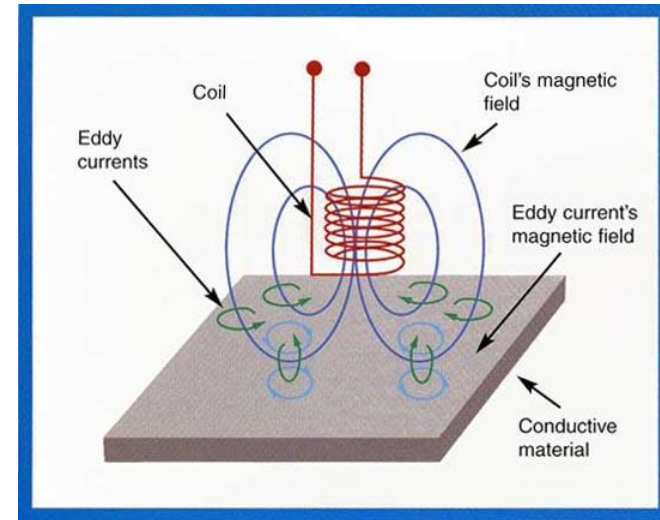
- ❑ Variable reluctance sensors are a class of magnetic sensors in **which a coil is wound on a permanent magnet** rather than on an iron core as in variable inductance sensors.
- ❑ Such devices are commonly used to measure rotational velocities.
- ❑ In a typical instrument a ferromagnetic gearwheel is placed next to the sensor.
- ❑ As the tip of each tooth on the gearwheel moves towards and away from the pick-up unit, the changing magnetic flux in the pick-up coil causes a voltage **to be induced in the coil** whose magnitude is proportional to the rate of change of flux.
- ❑ Thus, the output is a sequence of positive and negative pulses whose frequency is proportional to the rotational velocity of the gearwheel.

<https://www.youtube.com/watch?v=37oJtcUTpL8>



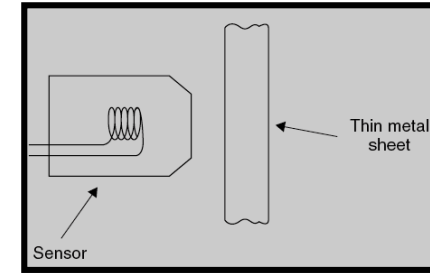
Eddy Current Sensors

- ❑ Eddy current sensors are a third class of magnetic sensors and **consist of a probe containing a coil that is excited at a high frequency, which is typically 1MHz.**
- ❑ This is used to measure the displacement of the probe relative to a moving metal target.
- ❑ Because of the high frequency of excitation, eddy currents are induced in the surface of the target and the current magnitude reduces to almost zero a short distance inside the target.
- ❑ This allows the sensor to work with very thin targets, such as the steel diaphragm of a pressure sensor.

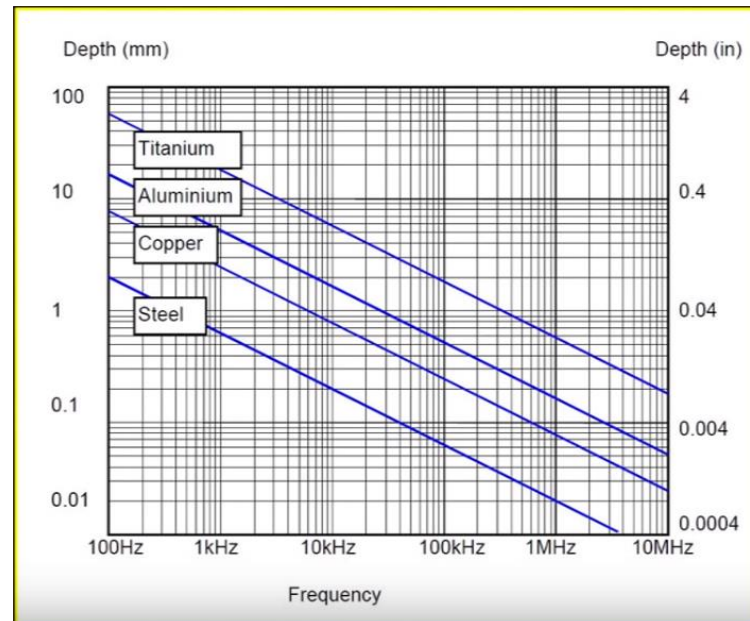


<https://www.youtube.com/watch?v=T0DMHIbaPnc>

Eddy Current Sensors



- ❑ The eddy currents alter the inductance of the probe coil, and this change can be translated into a d.c. voltage output that is proportional to the distance between the probe and the target.
- ❑ Measurement resolution as high as $0.1\ \mu\text{m}$ can be achieved.
- ❑ A signal conditioning circuit can be used to measure change in dc voltage/current as a function of distance

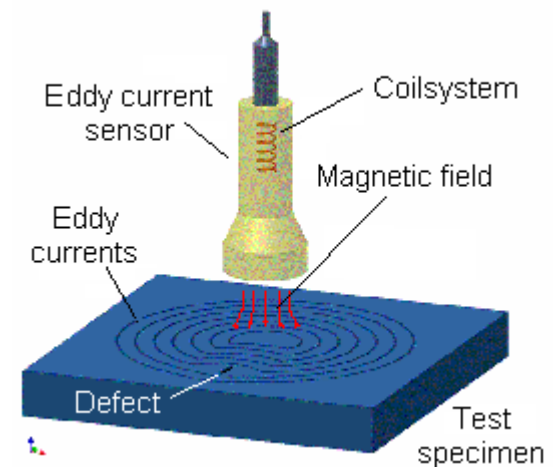
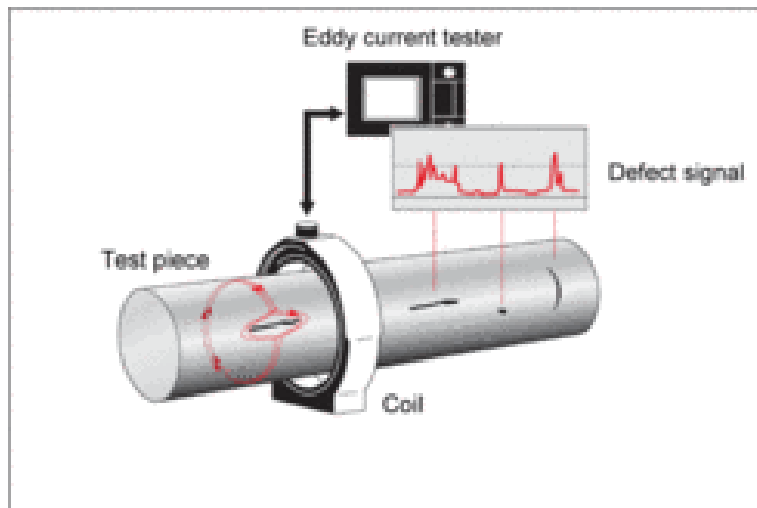


Eddy Current sensor applications

- The sensor can also work with a non-conductive target if a piece of aluminum tape is fastened to it.

Distance measurement

For product testing



Hall Effect Sensors

The Hall effect refers to the potential difference (Hall voltage) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current. Edwin Hall discovered this effect in 1879.

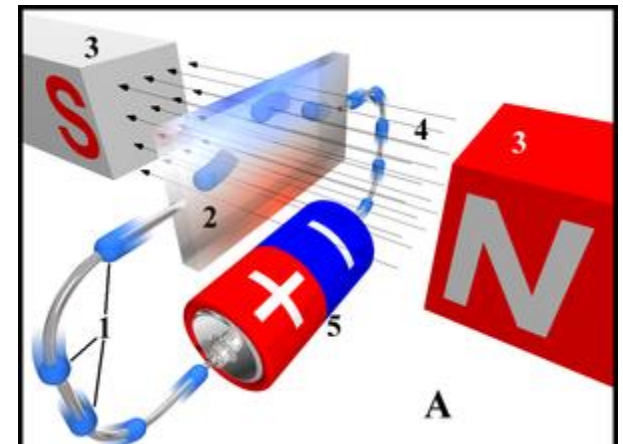
Hall effect diagram, showing electron flow (rather than conventional current).

Legend:

1. Electrons
2. Hall element, or Hall sensor
3. Magnets; 4. Magnetic field ;
5. Power source

Description:

In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color).



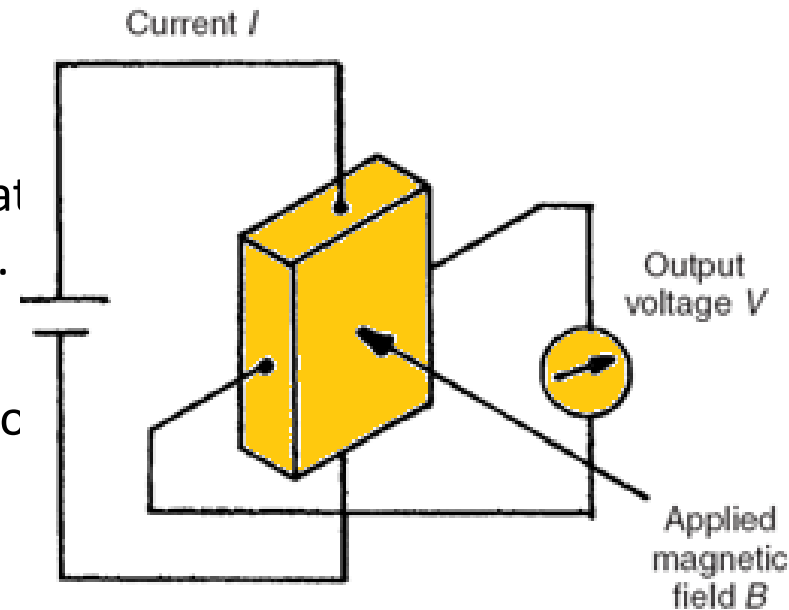
Hall-effect sensors

- ❑ A Hall-effect sensor is a device that is used to measure the magnitude of a magnetic field.
- ❑ It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field.
- ❑ This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength.
- ❑ For an excitation current I and magnetic field strength B , the output voltage is given by

$$V = KIB,$$

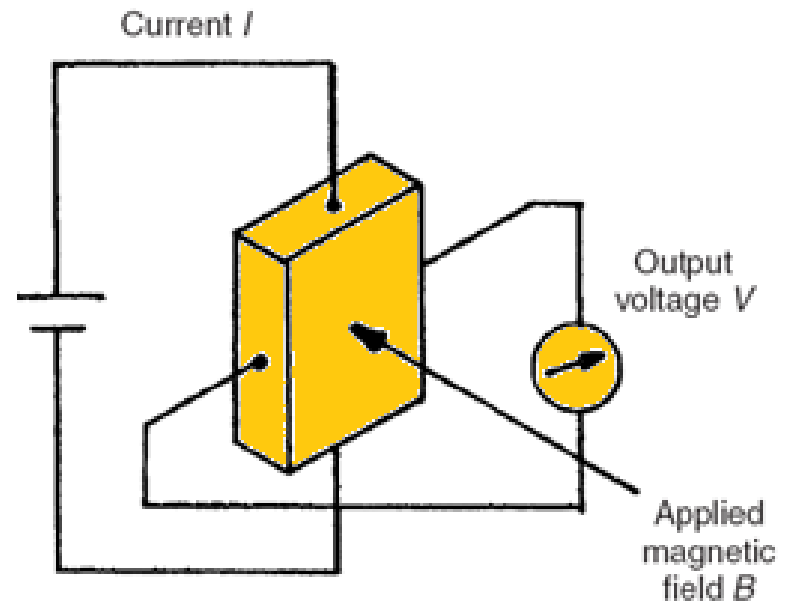
where K is known as the Hall constant.

- ❑ The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size.



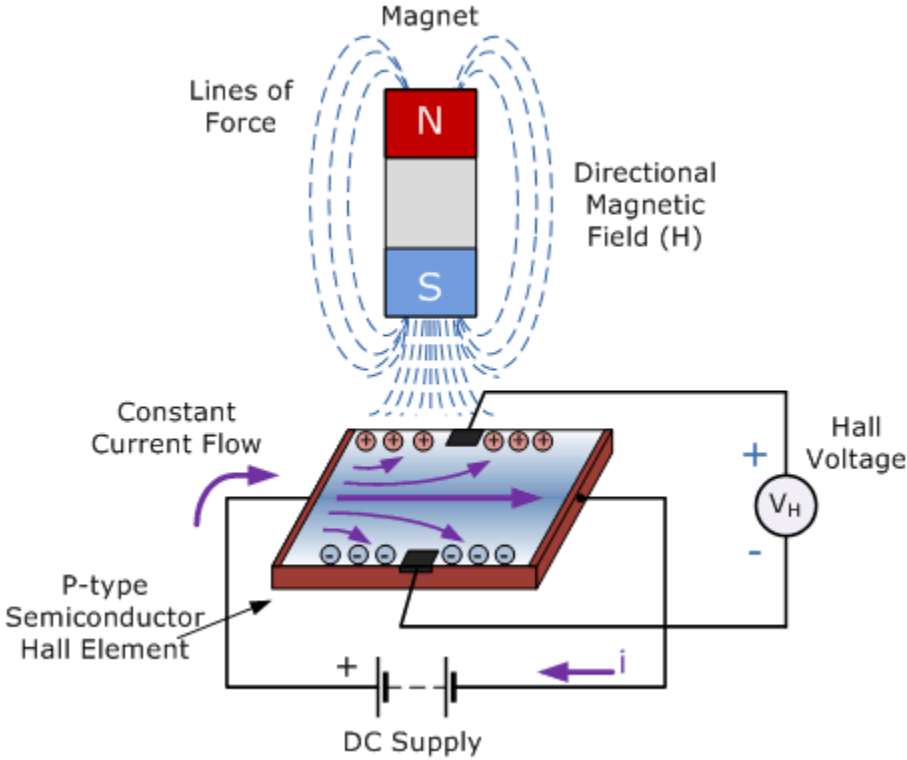
Hall-effect sensors

- ❑ In one common use of the device as a **proximity sensor**, the magnetic field is provided by a permanent magnet that is built into the device.
- ❑ The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary.
- ❑ **The Hall effect is also commonly used in keyboard pushbuttons**, in which a magnet is attached underneath the button.
- ❑ When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. **Such pushbutton switches can operate at high frequencies without contact bounce.**



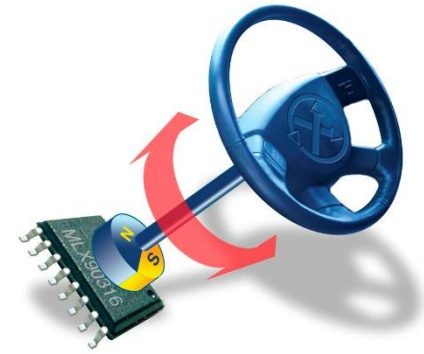
<https://www.youtube.com/watch?v=wpAA3qeOYiI>

Hall Effect Current Sensor



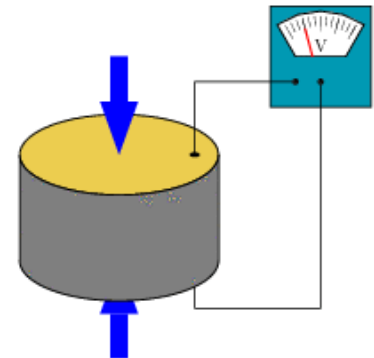
Example : Electronic Throttle Control (ETC)

- Newer accelerator pedal position sensors and throttle position sensors use Hall effect as their basic operating principle.
- These sensors contain transducers that convert external magnetic fields into voltage.
- Using magnets placed on the pedal and throttle shaft as reference points, Hall effect sensors output a different voltage depending on the intensity of the magnetic field.
- As the pedal or throttle moves, so does the magnet. This movement changes the magnetic field strength and thus alters output voltage from the sensor to the ECU.
- MLX90316 Non-contact absolute non-contacting rotary sensor IC allows simple implementation of rugged 360 degree position indicators.
- Applications include Throttle position sensing, pedal position drive by wire sensors, ride height, shaft position and other 0 to 360 degree absolute rotary position indication applications.
- The IC is fully programmable to allow the user to set the angular range to any value and still have rail to rail signal for the chosen angular displacement

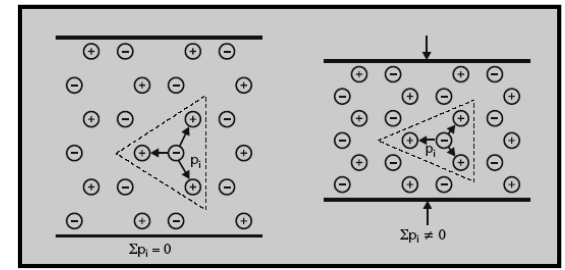


Piezoelectricity

- **Piezoelectricity** is the ability of some materials (**notably crystals and certain ceramics**) to generate an electric potential in response to applied mechanical stress.
- This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material.
- The word is derived from the Greek *piezein*, which means to squeeze or press.
- **The piezoelectric effect is reversible in that materials exhibiting the direct piezoelectric effect (the production of electricity when stress is applied) also exhibit the converse piezoelectric effect (the production of stress and/or strain when an electric field is applied).**
- For example, lead zirconate titanate crystals will exhibit a maximum shape change of about 0.1% of the original dimension.



Piezoelectric transducers



- ❑ Piezoelectric materials have an asymmetrical lattice of molecules that distorts when a mechanical force is applied to it.
- ❑ This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges.
- ❑ The charge displacement induces surface charges on the material of opposite polarity between the two sides. By implanting electrodes into the surface of the material, these surface charges can be measured as an output voltage. For a rectangular block of material, the induced voltage is given by:

$$V = \frac{kFd}{A}$$

where F is the applied force, A is the area of the material, d is the thickness of the material and k is the piezoelectric constant. The polarity of the induced voltage depends on whether the material is compressed or stretched.

Piezoelectric Materials

- Materials exhibiting piezoelectric behavior:

- Natural materials: **quartz**,
- **Synthetic materials** : **lithium sulphate**
- **Ferroelectric ceramics**: **barium titanate**.

$$V = \frac{kFd}{A}$$

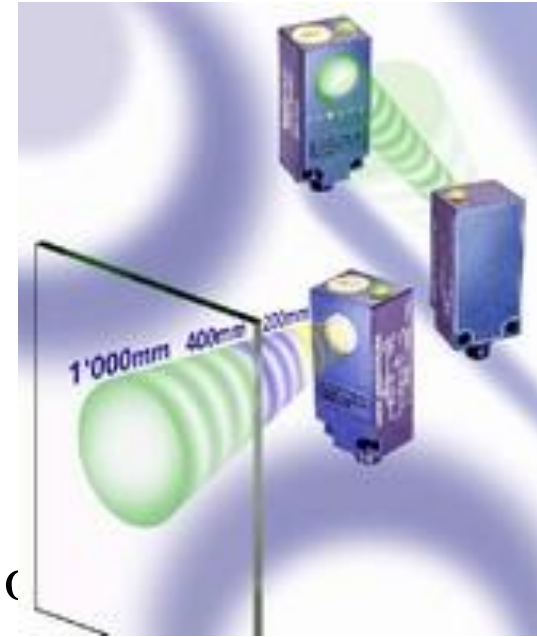
- The piezoelectric constant “k” varies widely between different materials. Typical values of k are 2.3 for quartz and 140 for barium titanate.
- Applying equation for a force of 1 g applied to a crystal of area 100 mm² and thickness 1 mm gives an output of 23 μV for quartz and 1.4 mV for barium titanate.
- They are frequently used as **ultrasonic receivers** and also as **displacement transducers**, particularly as part of devices measuring **acceleration, force** and **pressure**.

<https://www.youtube.com/watch?v=ACsy6xSIBm8>

4 min video

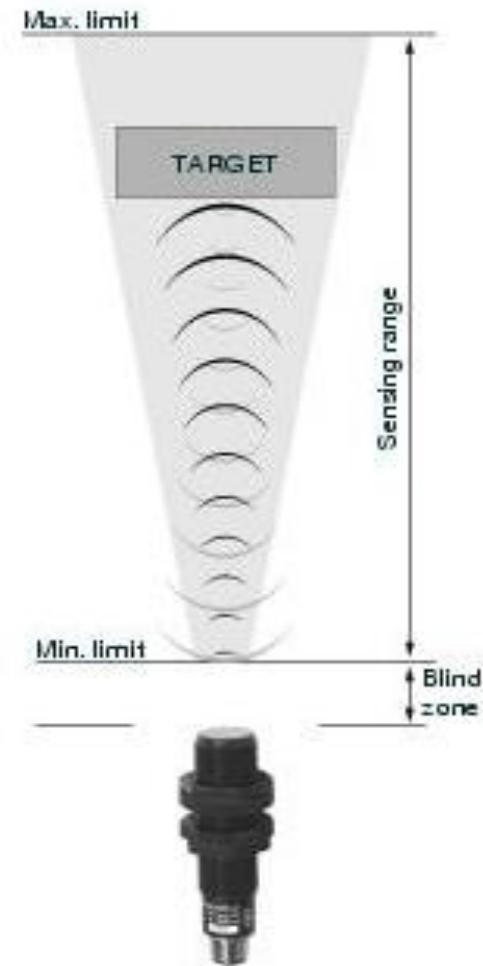
Ultrasonic transducers

- ❑ Ultrasonic devices are used for measuring of different physical quantities
- ❑ Ultrasound is a band of frequencies in the range above **20 kHz up to 15 MHz**, that is, above the sonic range that humans can usually hear.
- ❑ Measurement devices that use ultrasound consist of one device that transmits (Tx) an ultrasound wave and another device that receives (Rx) the wave
- ❑ Changes in **the measured variable** are determined either by measuring the change **in time taken** for the ultrasound wave **to travel between the transmitter and receiver**, or, alternatively, by measuring the **change in phase or frequency** of the transmitted wave.



Ultrasonic transducers

- ❑ The most common form of ultrasonic element is a piezoelectric crystal contained in a casing.
- ❑ Such elements can operate interchangeably as either a transmitter or receiver. These are available with operating frequencies that vary between 20 kHz and 15 MHz.
- ❑ As a piezoelectric crystal, it generates an ultrasonic wave when an alternating voltage is applied.
- ❑ It also works in reverse. When it receives a sound wave, it generates an alternating voltage.



- Also capacitive ultrasonic elements exist.
- These consist of a thin, dielectric membrane between two conducting layers.
- Elements with resonant frequencies in the range between 30 kHz and 3MHz can be obtained.

Factors affecting Ultrasonic waves

- When transmitted through air, **the speed of ultrasound** is affected by environmental factors such as **temperature, humidity and air turbulence**.
- Temperature has the largest effect. **The velocity of sound through air varies with temperature according to:**

$$V = 331.6 + 0.6T \text{ m/s}$$

where T is the temperature in ° C.

- Thus, even for a relatively small temperature change of 20 degrees from 0° C to 20° C, the velocity changes from 331.6 m/s to 343.6 m/s.

Table 13.1 Transmission speed of ultrasound through different media

<i>Medium</i>	<i>Velocity (m/s)</i>
Air	331.6
Water	1440
Wood (pine)	3320
Iron	5130
Rock (granite)	6000

Other factors affecting Ultrasonic waves

- Humidity changes have a much smaller effect. If the relative humidity increases by 20%, the corresponding increase in the transmission velocity of ultrasound is 0.07% (corresponding to an increase from 331.6m/s to 331.8m/s at 0° C).
- Changes in air pressure itself have negligible effect on the velocity of ultrasound.
- Similarly, air turbulence normally has no effect (though note that air turbulence **may deflect ultrasound waves away from their original direction of travel**).
- However, if turbulence involves currents of air at different temperatures, then random changes in ultrasound velocity occur according to equation (6.2).

Ultrasound Range Sensor (distance sensor)

- $X = v_{\text{sound}} \cdot t$

- Where:

- v_{sound} is known

- $t = 0.5$ (time of flight)

- X is distance between sensor head and object

- Range of sensor varies between 5 cm to 20 m

- Sensor is not appropriate for very short distance measurements

- Frequency response (distance measurement update rate) varies with distance measured

- In general, it is about 100 Hz

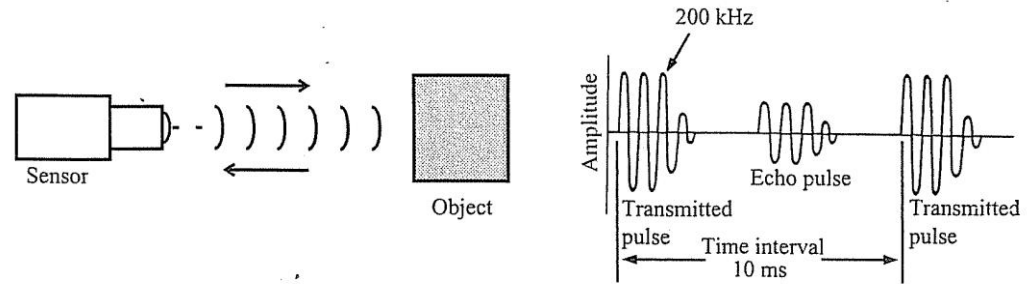


FIGURE 6.26: Operating principle of a sonic distance sensor.

Temperature Effect

- An obvious difficulty in applying this equation is the variability of v with temperature .
- One solution to this problem is to include an extra ultrasonic transmitter/ receiver pair in the measurement system in which the two elements are positioned a known distance apart.
- This allows measurement of transmission time of energy between this fixed pair which provides compensation of temp effects

Ultrasound Technology Applications

- **Translational Displacement (motion in straight line)**
- **Wind speed and direction (anemometer),**
- **Speed through air or water**
- **Fluid flow rates.**
- **Level (amount) of liquid in tank**
 - sensor **measures distance to surface of fluid.**
- **Other applications include:**
 - in robots for **obstacle avoidance**
 - Burglar alarms
 - Non-destructive testing, and etc

Wavelength, frequency and directionality of ultrasound waves

- The frequency and wavelength of ultrasound waves are related according to:

$$\lambda = v/f$$

- where λ is the wavelength,
- v is the velocity and
- f is the frequency of the ultrasound waves.
- v is also affected by Humidity and temperature

Attenuation of ultrasound waves

- Ultrasound waves suffer attenuation in the amplitude of the transmitted energy according to the distance traveled.
- The amplitude X_d of the ultrasound wave at a distance d from the emission point can be expressed as:

$$\frac{X_d}{X_0} = \frac{\sqrt{e^{-\alpha d}}}{fd}$$

- where X_0 is the magnitude of the energy at the point of emission, f is the nominal frequency of the ultrasound
- and α is the attenuation constant that depends on frequency, medium and pollution such as dust

Resolution and Accuracy

- Best resolution of ultrasonic ranging system is equal to wavelength of the transmitted wave

$$\lambda = v/f$$

- High frequency elements seem to be preferable since λ is smaller, but range is less for higher frequency due to higher attenuation of the wave as it travels from Tx to Rx
- Here frequency choice is a compromise between resolution and range.

Ultrasonic Imaging

- The main applications of ultrasound in imaging are found in medical diagnosis and in industrial testing procedures.
- In both of these applications, a short burst of ultrasonic energy is transmitted from the ultrasonic element into the medium being investigated and the energy that is reflected back into the element is analyzed using advanced signal processing techniques.
- Ultrasound is reflected back at all interfaces between different materials, with the proportion of energy reflected being a function of the materials either side of the interface.
- The principal components inside a human body are water, fat, muscle and bone, and the interfaces between each of these have **different reflectance** characteristics.
- Measurement of the time between energy transmission and receipt of the reflected signal gives the depth of the interface.

Ultrasound in medical diagnosis procedures

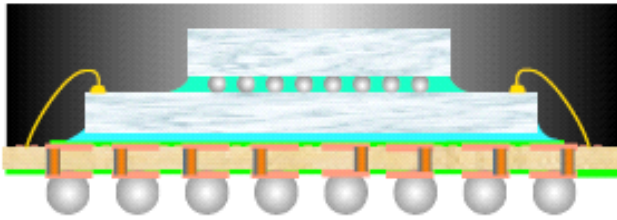
■ **Diagnosis procedures:**

- 1) The reflected energy appears as a series of peaks, with the magnitude of each peak corresponding to the type of interface that it is reflected from
- 2) The time of each peak corresponding to the depth of the interface in the body.
- 3) Thus, a 'map' of fat, muscle and bone in the body is obtained. A fuller account can be found elsewhere (Webster, 1998).

■ **Applications in industrial test procedures usually involve detecting internal flaws (defects) within components.**

Identifications of Solder Bump Defects in Chip Packages

Examples of Emerging Microelectronic Packages:



3-D Packaging: Stacked Die



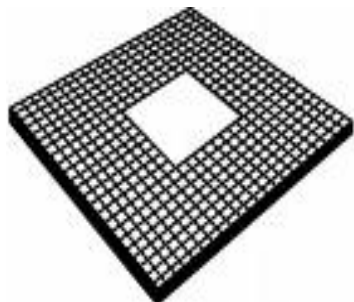
Chip Scale Package



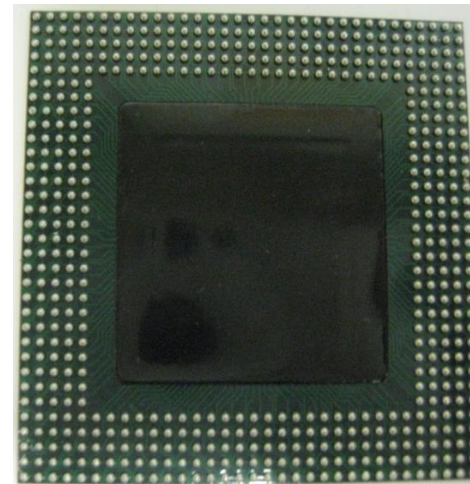
Quad Flat Package (QFP)



Flip Chip



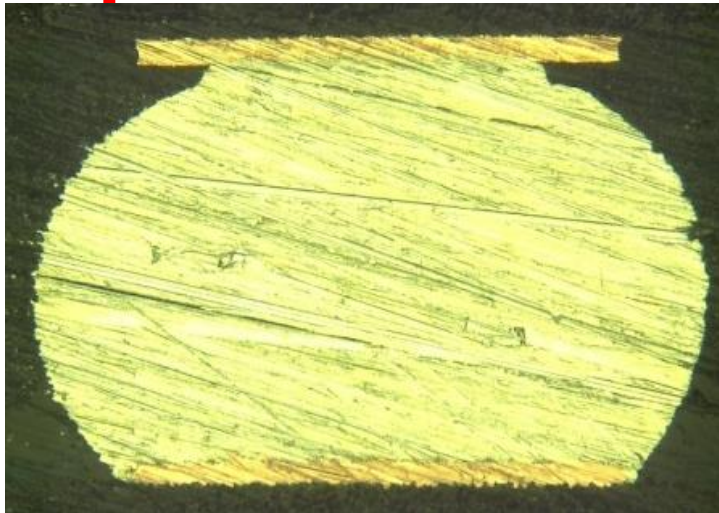
Ball Grid Array (BGA)



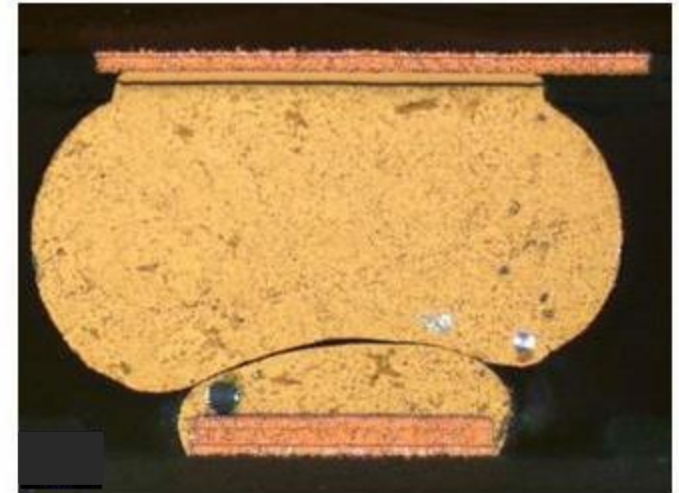
Amkor Super BGA



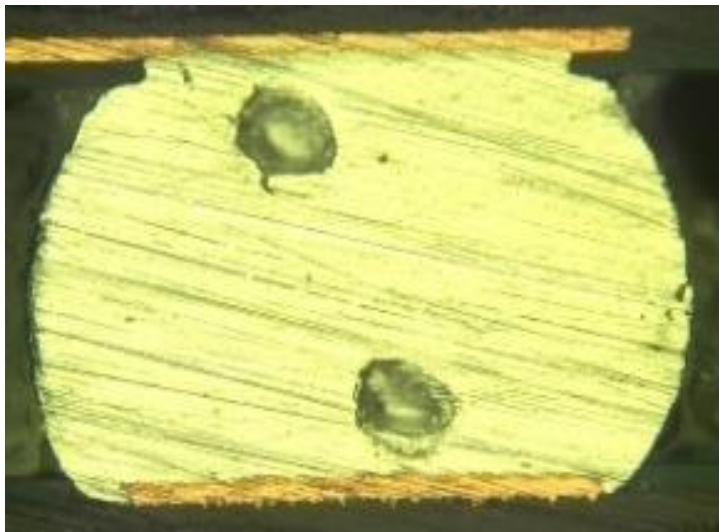
Optical Micrographs of Good and Bad Solder Bump Cross Sections



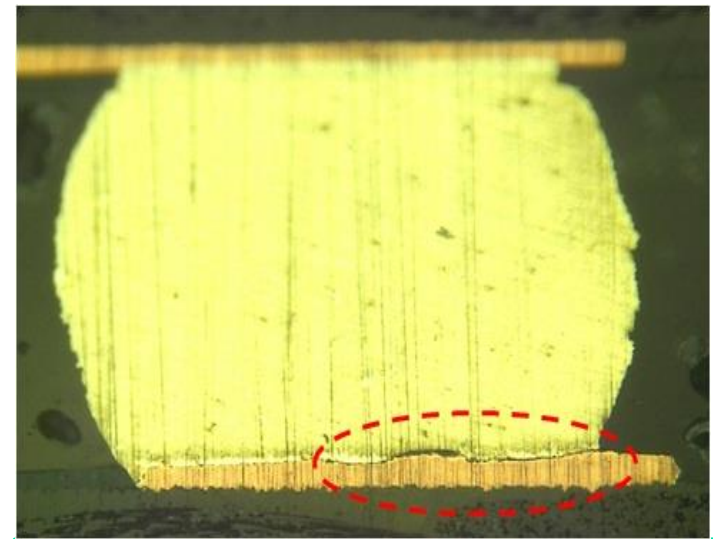
Good Solder Bump



Head-in-Pillow defects

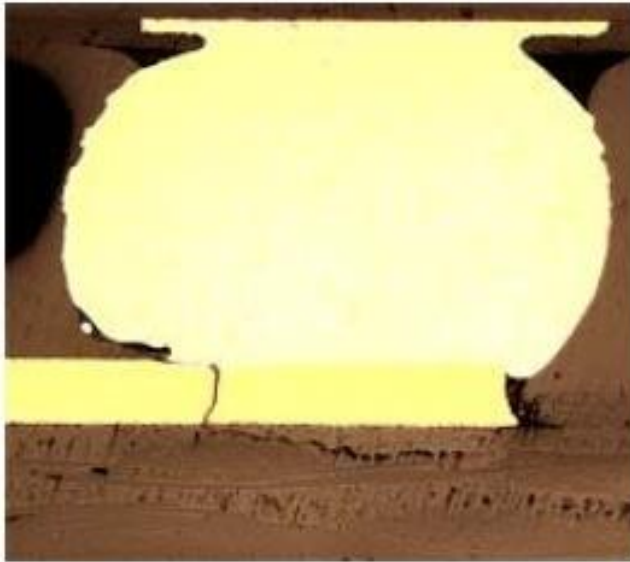


Two medium size voids near the interface

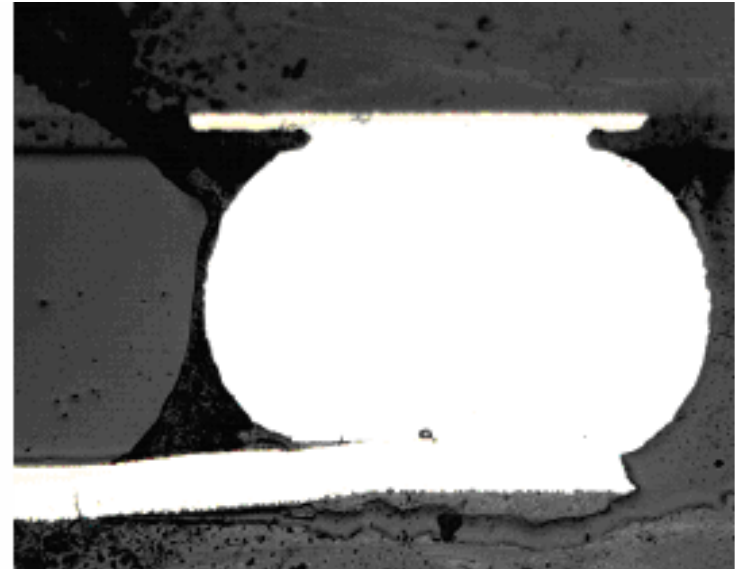


Poor wetting, an intermittent connection

Optical micrographs of Good and Bad Solder Bump Cross Sections



Pad crater with crack initiating at the trace



Crack initiates at the edge of the pad

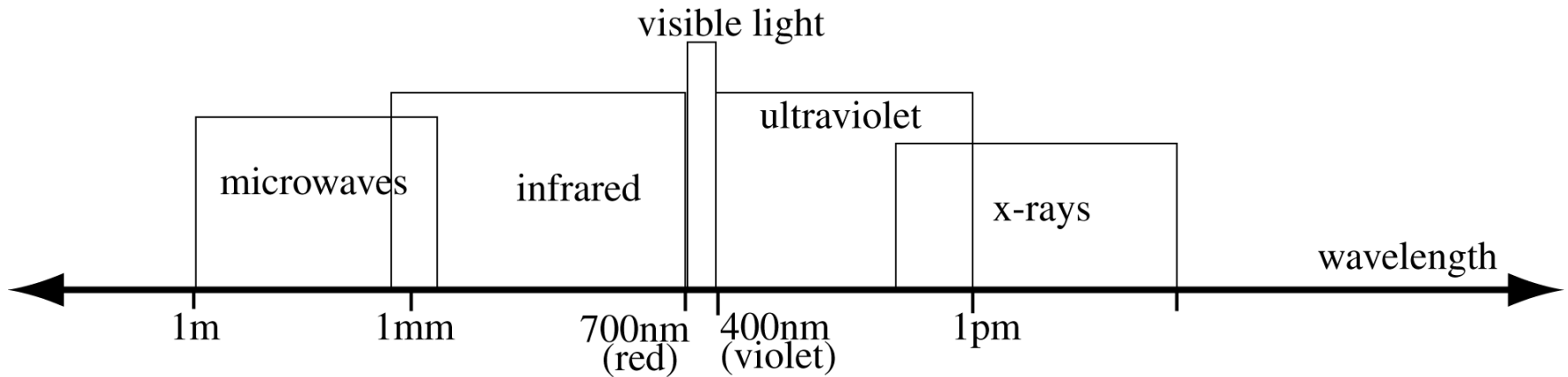
Inspection of solder bumps is crucial process in microelectronics manufacturing industry.

Optical sensors

- Optical sensors are those sensors that detect electromagnetic radiation in the broad optical range – from **far infrared** to **ultraviolet**
- Approximate range of wavelengths from **1mm** (3×10^{11} Hz or far infrared) to **1 nm** (3×10^{17} Hz or upper range of the ultraviolet range).
- **Direct methods** of transduction from light to electrical quantities (photovoltaic or photo-conducting sensors)
- **Indirect methods** such as conversion first into temperature variation and then into electrical quantities (PIR sensors).

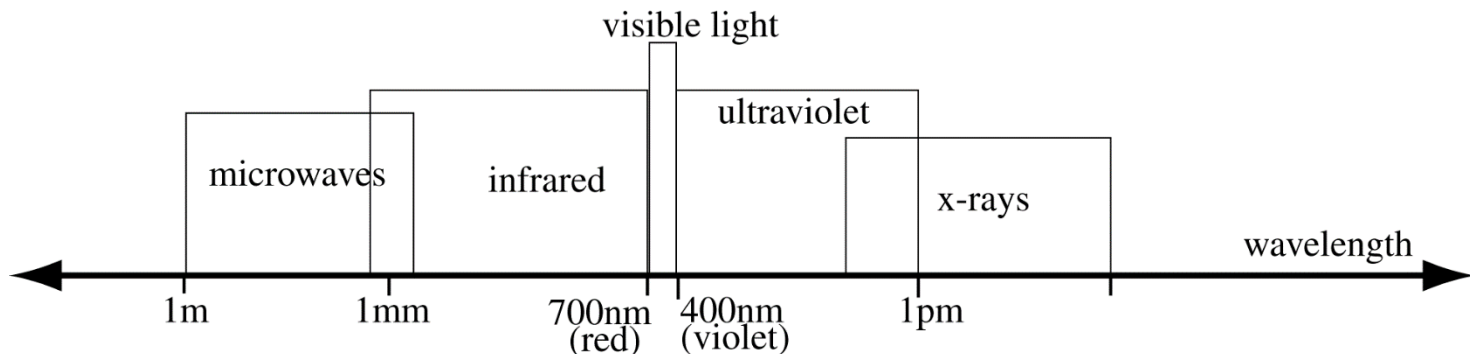
Spectrum of “optical” radiation

- Nomenclature: (المصطلحات)
 - Visible light
 - Infrared radiation (not infrared “light”)
 - Ultraviolet radiation (not UV “light”)



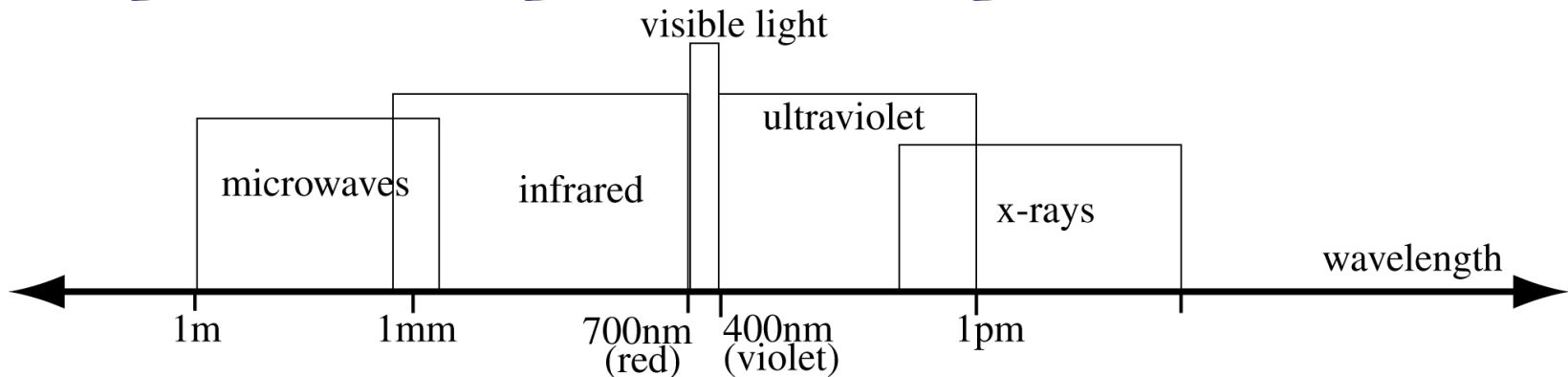
Infrared radiation

- Approximate spectrum
 - 1mm (300 GHz) to 700nm (430 THz)
- Meaning: **below red**
- Near infrared (closer to visible light)
- Far infrared (closer to microwaves)
- *Invisible radiation, usually understood as “thermal” radiation*
- $1\text{nm}=10^{-9}\text{m}$, $1\text{GHz}=10^9\text{ Hz}$, $1\text{THz}=10^{15}\text{ Hz}$



Visible light

- Approximate spectrum
 - 700nm (430 THz) to 400nm (750 THz)
- Based on our eye's response
- From red (low frequency, long wavelength)
- To violet (high frequency, short wavelength)
- Our eye is most sensitive in the middle (green to yellow)
- **Optical sensors may cover the whole range, may extend beyond it or may be narrower**

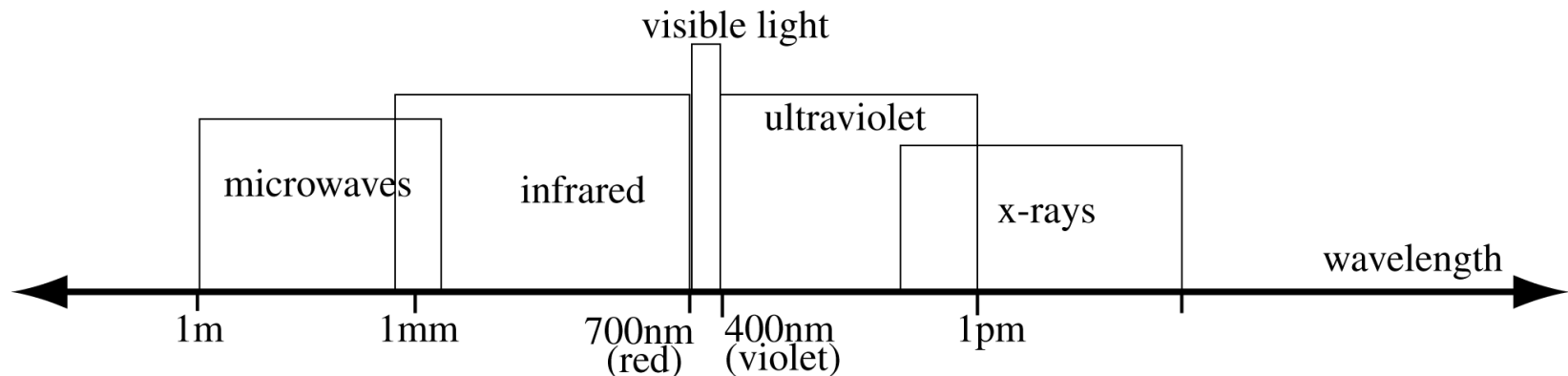


Light Power

- For a sensor, we're interested in the light power that falls on a unit area, and how well the sensor converts that into a signal.
- A common unit **is the lux** which measures apparent brightness (power multiplied by the human eye's sensitivity).
- Sunlight corresponds to about **50,000 lux**
- Artificial light typically **500-1000 lux**

Ultraviolet (UV) radiation

- Approximate spectrum
 - 400nm (750 THz) to 400pm (300 PHz)
- Meaning - above violet
- Understood as “penetrating” radiation
- Only the **lower end** of the UV spectrum is usually sensed
- Exceptions: radiation sensors based on ionization



The photoelectric effect

- Photons collide with electrons at the surface of a material
- The electrons acquire energy and this energy allows the electron to:
 - Release themselves from the surface of the material by overcoming the *work function* of the substance.
 - Excess energy imparts the electrons kinetic energy.

Photo-conducting effect

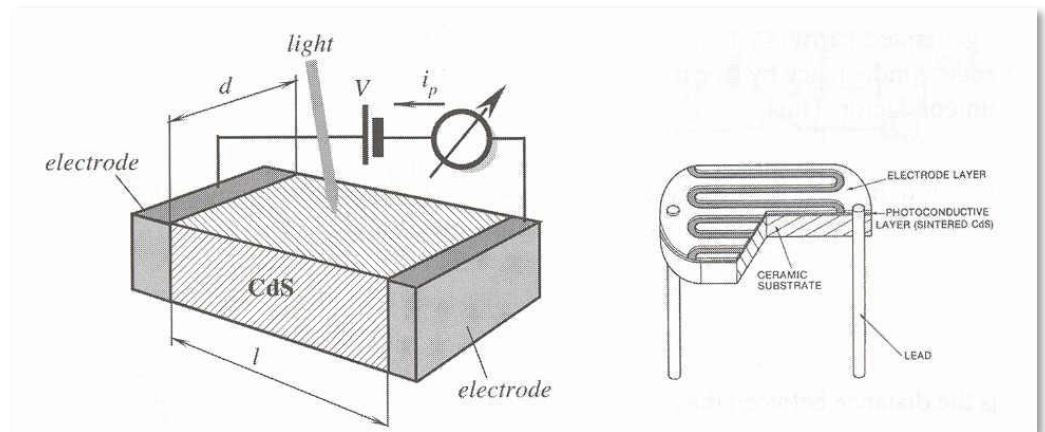
- Conductivity results from the charge, mobilities of electrons and holes and the concentrations of electrons, n and p from whatever source.
- In the absence of light, the material exhibits what is called **dark conductivity**, which in turn results in a **dark current**.
- Depending on construction and materials, the resistance of the device may be very high (a few MegaOhms ($M\Omega$) or a few $k\Omega$).
- When the sensor is illuminated, its conductivity changes depending on the change in carrier concentrations (excess carrier concentrations).

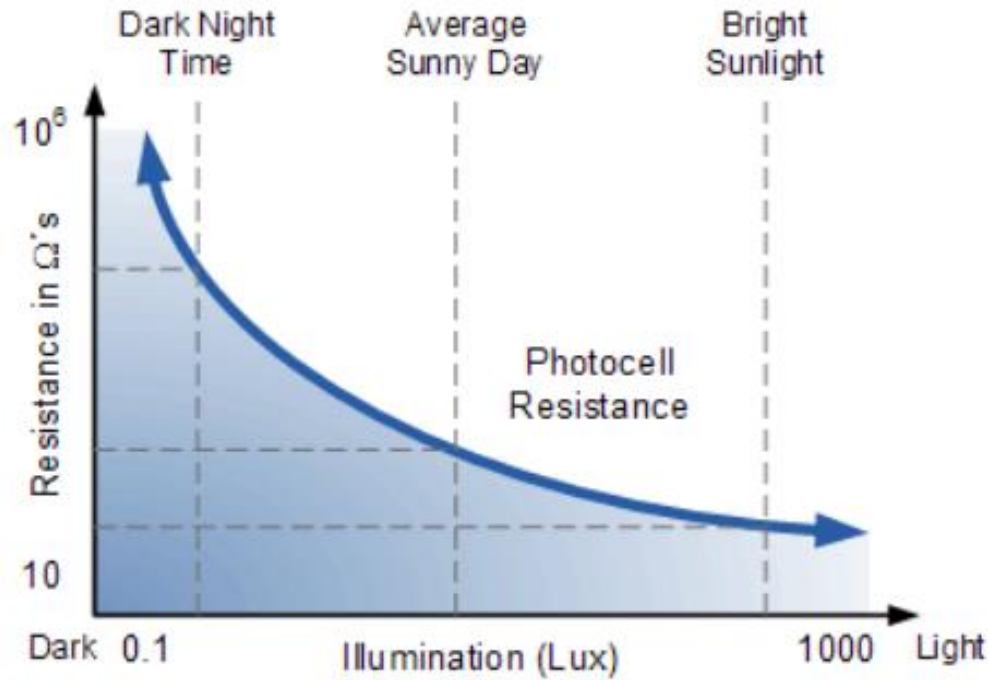
Light Sensors/Detectors

- Simplest light sensor is an LDR (Light-Dependent Resistor).
- Optical characteristics close to human eye.
- Common material is CdS (Cadmium Sulphide)
- Sensitivity:

Typical

dark $1\text{ M}\Omega$,
10 lux $40\text{ k}\Omega$,
1000 lux $400\ \Omega$.





Photodiodes

- **Semiconductor diode exposed to radiation**
- Excess carriers due to photons add to the existing charges in the conduction band exactly in the same fashion as for a pure semiconductor.
- The diode itself may be reverse biased, forward biased or unbiased
- **Forward biased mode is not useful as a photo-sensor**
 - Number of carrier in conducting mode is large
 - Number of carrier added by radiation small
 - Sensitivity is very low

Photodiode - two modes

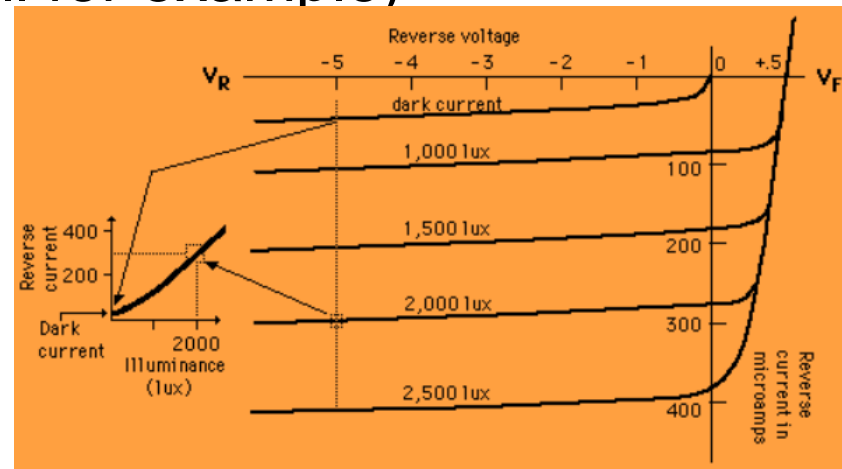
■ 1. Photoconductive mode

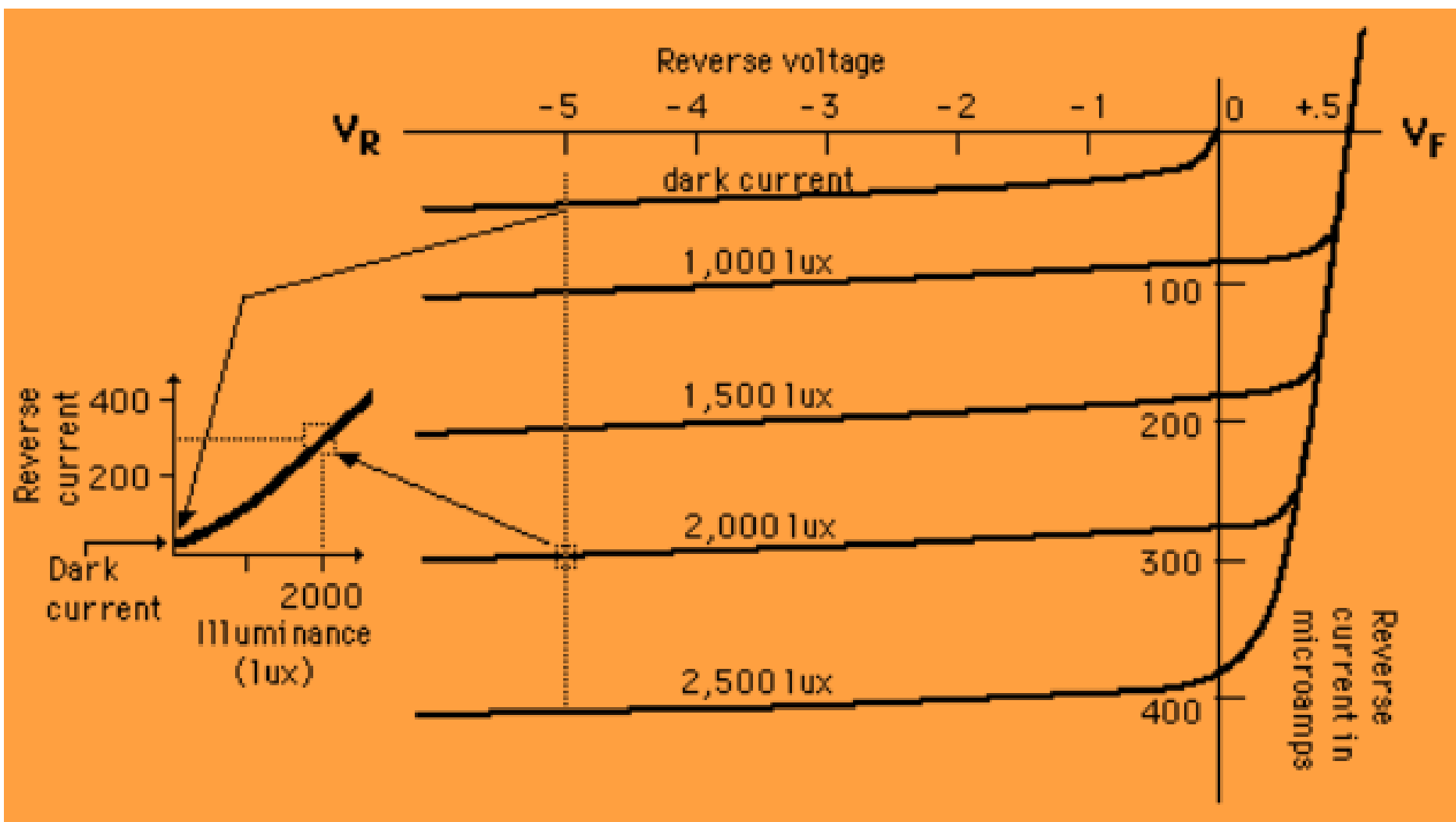
- Diode is reverse biased
- Operates similarly to a photoconductor
- The reverse voltage application will increase the depletion layer's width, which in turn decreases the response time & the junction capacitance. This mode is fast and displays electronic noise

■ 2. Photovoltaic mode

- Diode is not biased
- Operates as a source (solar cell for example)

- It gives a very small dynamic range & non-linear characteristic





Photodiode - construction

- Any diode can serve as a photodiode if:
 - n region, p region or pn junction are exposed to radiation
 - Usually exposure is through a transparent window or a lens
 - Sometimes opaque materials are used (IR, UV)
- Specific structures have been developed to improve one or more of the characteristics
 - PIN diode: Addition of the intrinsic p layer increases resistance
 - Reduces dark current
- Phototransistors and photo-Darlington transistors are also available.
- Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.

Photodiodes - construction

- Available in various packages and for various applications
 - Individual diodes in cans with lenses
 - Surface mount diodes used in infrared remote controls
 - Arrays (linear) of various sizes for scanners
 - Infrared and UV diodes for sensing and control



- Photodiode as used in in a CD player



- Photodiode array used a scanner

Photovoltaic diodes

- The diode is not biased
- Serves as a generator
 - Carriers generated by radiation create a potential difference across the junction
 - Any photodiode can operate in this mode
 - Solar cells are especially large-surface photodiodes

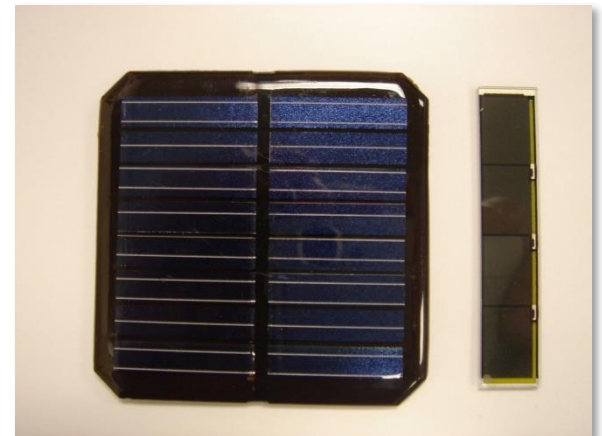


Photo Interrupt

- Uses emitter and detector photo diode pair
- With no obstruction detector is high
- When an object blocks the light the detector is low
- Advantages
 - Simple to interface
 - Inexpensive
 - Reliable

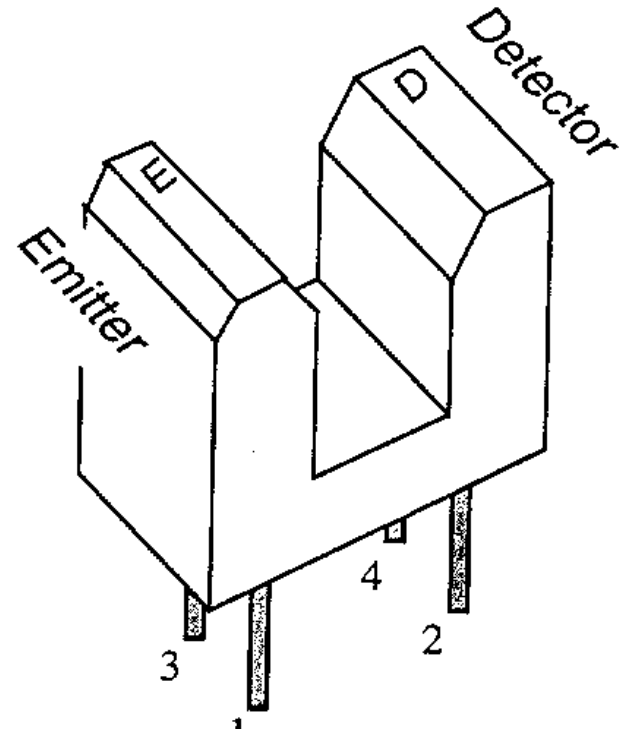
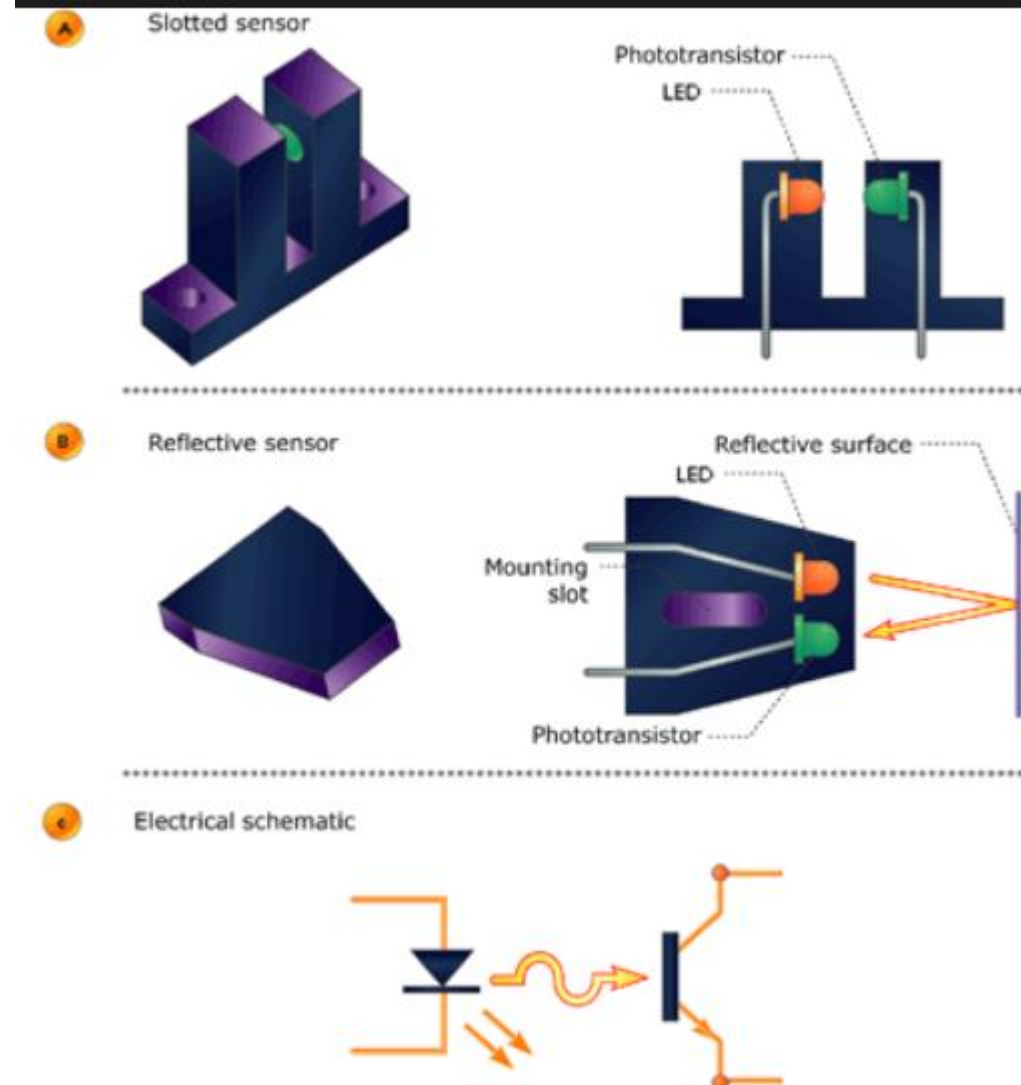


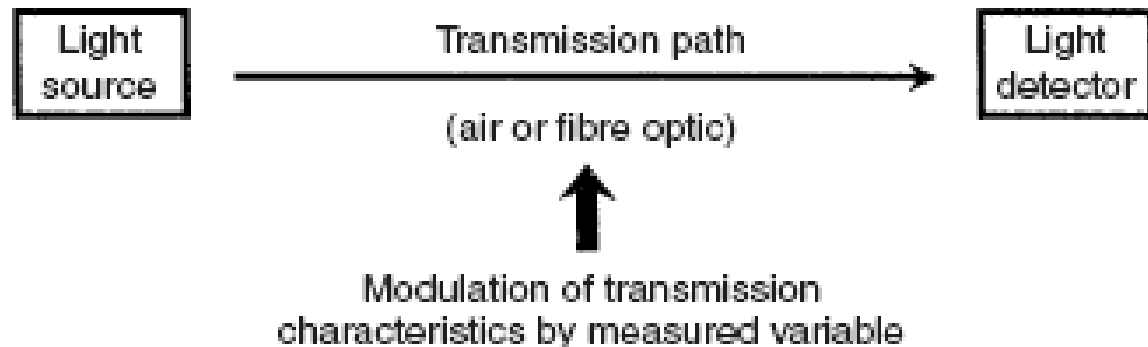
Photo Interrupt Types

- Wide variety of packages and orientations
- Types
 - Logic (digital ± 5 volts)
 - Transistor/diode (analog)
- Manufacturers
 - Fairchild
 - Honeywell



Optical sensors

- Optical sensors are based on the modulation of light travelling between a light source and a light detector.
- The transmitted light can travel along either an **air path** **or a fibre-optic cable.**
- Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in **hazardous environments.**



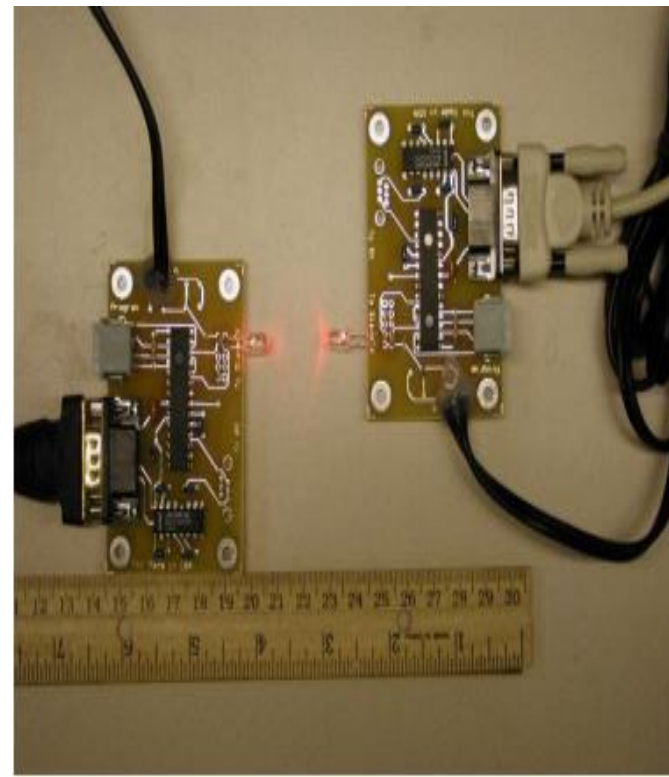
Optical Sensors: Advantages and applications

- ELECTROMAGNETIC IMMUNITY
- ELECTRICAL ISOLATION
- COMPACT AND LIGHT
- WIDE DYNAMIC RANGE

- Example Apps:
 - Temperature; Pressure; Flow; Liquid Level;
 - Displacement; Vibration; Rotation; Acceleration;
 - Magnetic Field; Humidity; Strain;

Optical sensors

- Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs).
- However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources.
- Hence, **infrared LEDs or infrared laser diodes are usually preferred.**
- These emit light in a narrow frequency band in the infrared region **and are not affected by sunlight**



- Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration

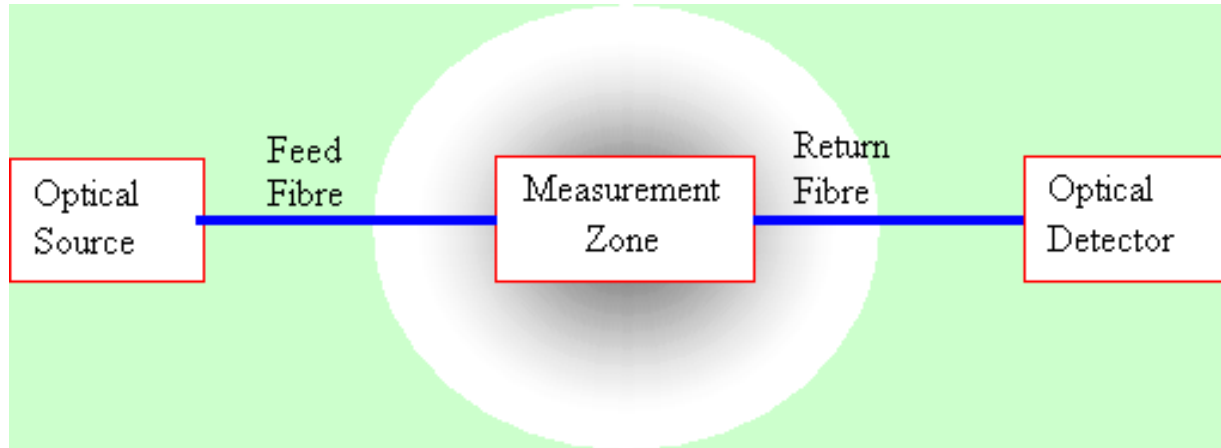
Fibre-Optic Sensors

- **As an alternative to using air as the transmission medium, optical sensors can use fibre-optic cable instead to transmit light between a source and a detector.**
- **In such sensors, the variable being measured causes some measurable change in the characteristics of the light transmitted by the cable.** The proportion of light entering the cable must be maximized
- The basis of operation of fibre-optic sensors is the translation of the physical quantity measured into a change in one or more parameters of a light beam.

Fibre-optic sensors characteristic

- Fibre-optic sensors characteristically
 - 1) Long life.
 - 2) Good accuracy : $\pm 1\%$
(for a fibre-optic pressure sensors)
 - 3) Simple, low cost, small size, high reliability
 - 4) Capability of working in many kinds of hostile environment.

WORKING PRINCIPLE

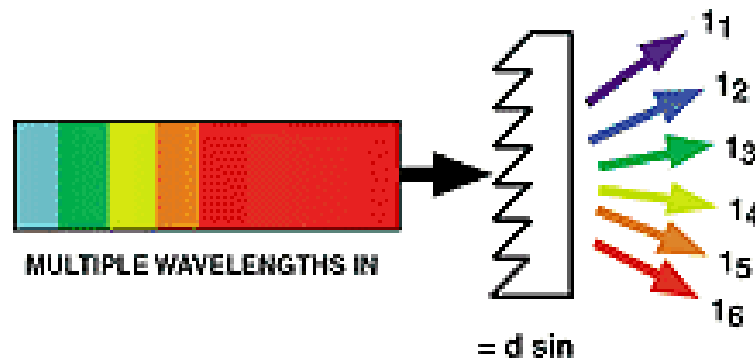


- **Light beam changes by the phenomena that is being measured**
- **Light may change in its five optical properties i.e intensity, phase, polarization , wavelength and spectral distribution**

SENSING DETAILS

$$E_p(t)\cos[\omega t + \theta(t)]$$

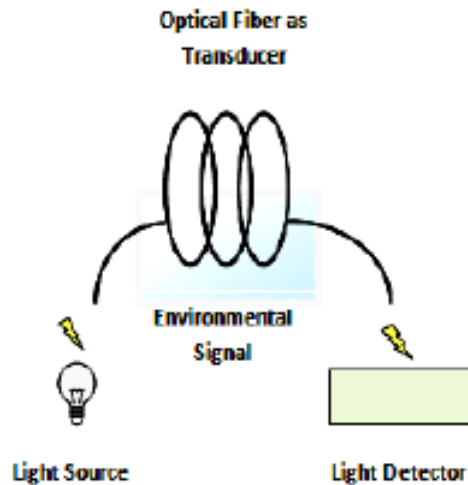
- Intensity based sensors – $E_p(t)$
- Frequency varying sensors - $\omega_p(t)$
- Phase modulating sensing- $\theta(t)$
- Polarization modulating fiber sensing



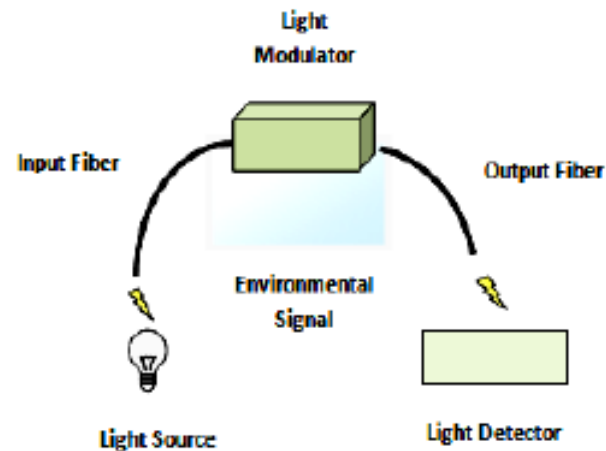
Fibre-optic sensors Classification

- Two major classes of fibre-optic sensor exist, **intrinsic** sensors and **extrinsic** sensors.
- In *intrinsic sensors*, the fibre-optic cable itself is the sensor,
- whereas in *extrinsic sensors*, the fibre-optic cable is only used to guide light to/from a conventional sensor.

Intrinsic Fiber Optic Sensor

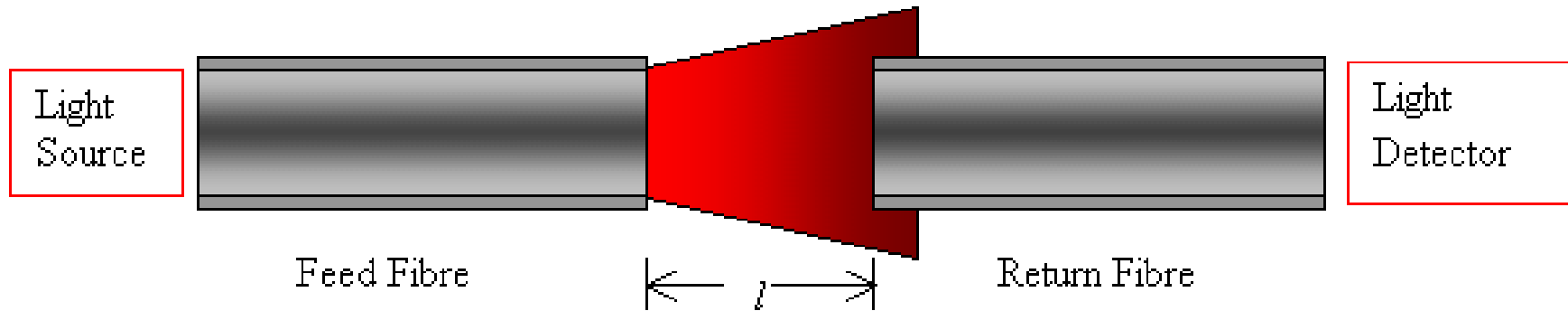


Extrinsic Fiber Optic Sensor



CLASSIFICATION

- Extrinsic sensors

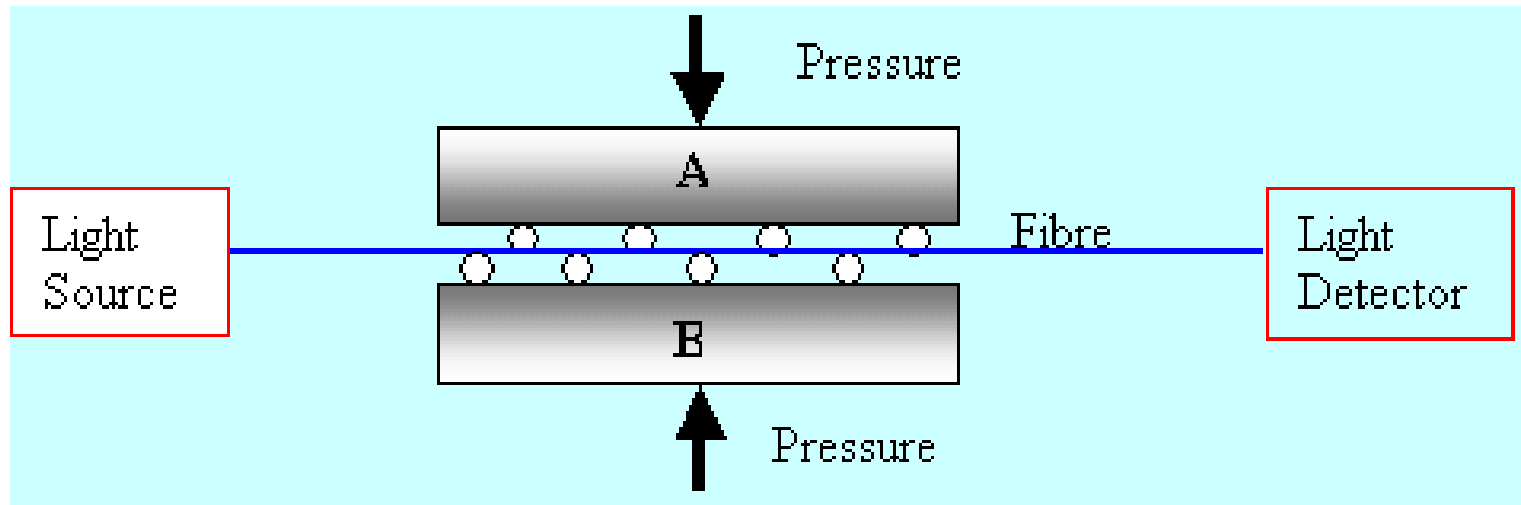


where the light leaves the feed or transmitting fiber to be changed before it continues to the detector by means of the return or receiving fiber



CLASSIFICATION (contd.)

- INTRINSIC SENSORS



intrinsic sensors are different in that the light beam **does not leave the optical fiber** but is changed whilst still contained within it.

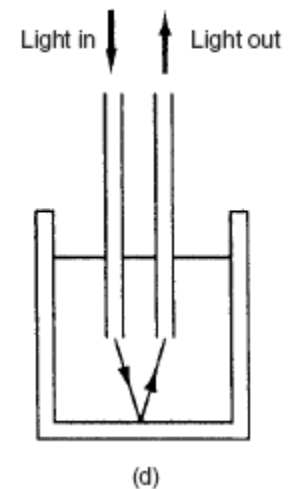
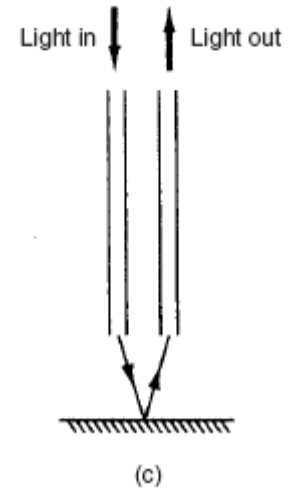
Fibre-optic sensors

- Proximity sensor

The amount of light reflected varies with the distance between the fibre ends and a boundary

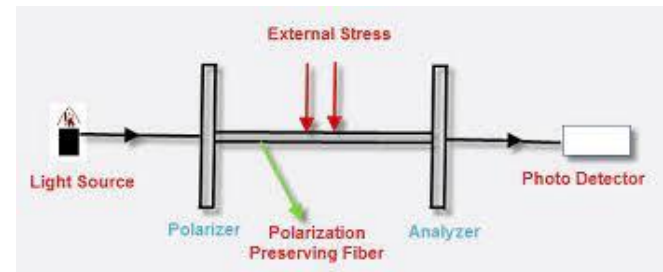
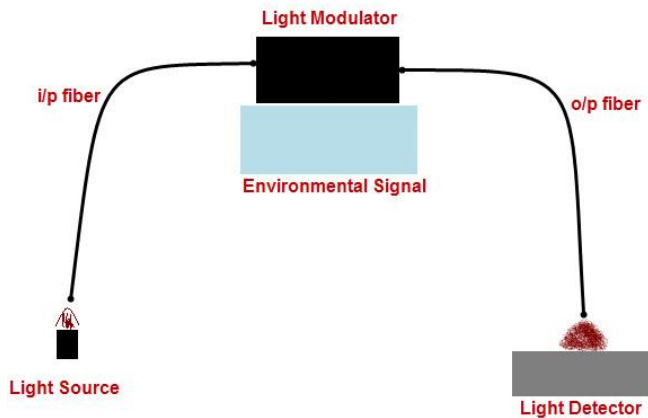
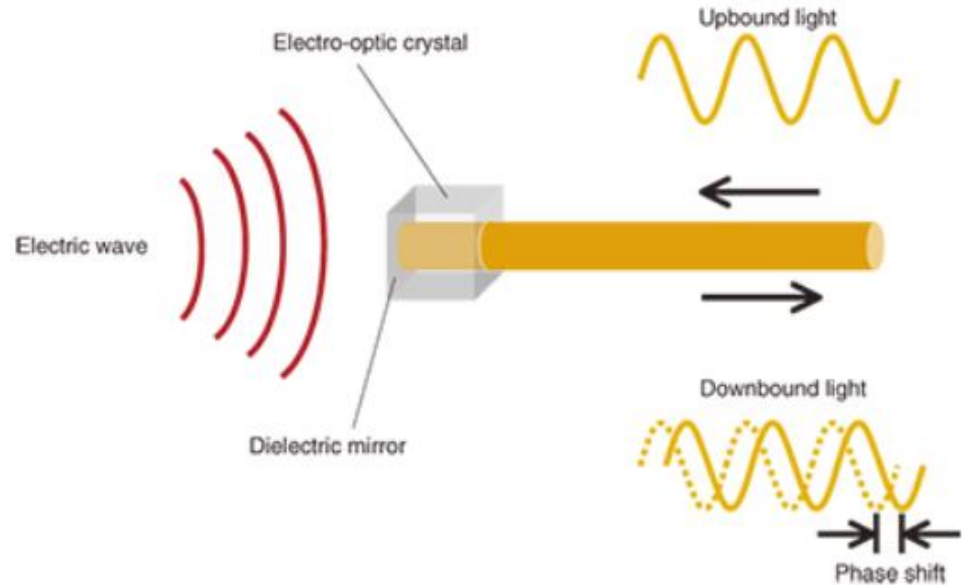
- pH sensor

The amount of light reflected back into the fibers depend on the pH-dependant color of the chemical indicator in the solution around the probe tip



- **Optical Fiber Electric Field Sensor for Antenna Measurement**

- **Phase Shift is the key output**



Infrared Sensors

- An infrared sensor is an electronic instrument that is used to sense certain characteristics of its surroundings by either emitting and/or detecting infrared radiation.
- It is also capable of measuring heat of an object and detecting motion.
- **Infrared waves are not visible to the human eye.**
- In the electromagnetic spectrum, infrared radiation is the region having wavelengths longer than visible light wavelengths, but shorter than microwaves.
- The infrared region is approximately demarcated from 0.75 to 1000 μm .
- The wavelength region from **0.75 to 3 μm** is termed as **near infrared**, the region from **3 to 6 μm** is termed **mid-infrared**, and the region **higher than 6 μm** is termed as **far infrared**.

Infrared Sensor

- Infrared technology is found in many of our everyday products.
- For example, **TV has an IR** detector for interpreting the signal from the remote control.
- **Key benefits of infrared sensors include low power requirements, simple circuitry, and their portable feature.**

Types of Infra-Red Sensors

- Infra-red sensors are broadly classified into two types:
- **Thermal infrared sensors** – These use infrared energy as heat. Their photo sensitivity is independent of wavelength. Thermal detectors do not require cooling; however, they have slow response times and low detection capability.
- **Quantum infrared sensors** – These provide higher detection performance and faster response speed. Their photo sensitivity is dependent on wavelength. Quantum detectors have to be cooled so as to obtain accurate measurements.

Working Principle

- A typical system for detecting infrared radiation using infrared sensors includes; **First:** the **infrared source** such as blackbody radiators, tungsten lamps, and silicon carbide.
- In case of active IR sensors, the sources are infrared lasers and LEDs of specific IR wavelengths.
- **Second:** is the transmission medium used for infrared transmission, which includes **vacuum**, the **atmosphere**, and **optical fibers**.

Working Principle

- **Thirdly:** optical components such as optical lenses made from quartz, CaF_2 , Ge and Si, polyethylene
- Fresnel lenses, and Al or Au mirrors, are used to converge or focus infrared radiation. Likewise, to limit spectral response, band-pass filters are ideal.
- **Finally**, the infrared detector completes the system for detecting infrared radiation.
- The output from the detector is usually **very small**, and hence **pre-amplifiers coupled with circuitry are added to further process the received signals**

Applications

- Tracking and art history
- Climatology, meteorology, and astronomy
- Thermography, communications, and alcohol testing
- Heating, hyper-spectral imaging, and night vision
- Biological systems, photo-bio-modulation, and plant health
- Gas detectors/gas leak detection
- Water and steel analysis, flame detection
- Anesthesiology testing and spectroscopy
- Petroleum exploration and underground solution
- Rail safety.

What is a Passive/Pyroelectric Infrared (PIR) Sensor?

- Used to detect motion
- Basically made up of pyroelectric sensors
 - Detect levels of infrared radiation
- Does not emit any radiation, only detects, hence passive
- Note: PIR sensors are slow with time constants ~ 1 sec
- Eltec two-element sensor, shown with matching fresnel IR lens and mounting:
- NAIS ultra-compact PIR sensor



Practical Applications

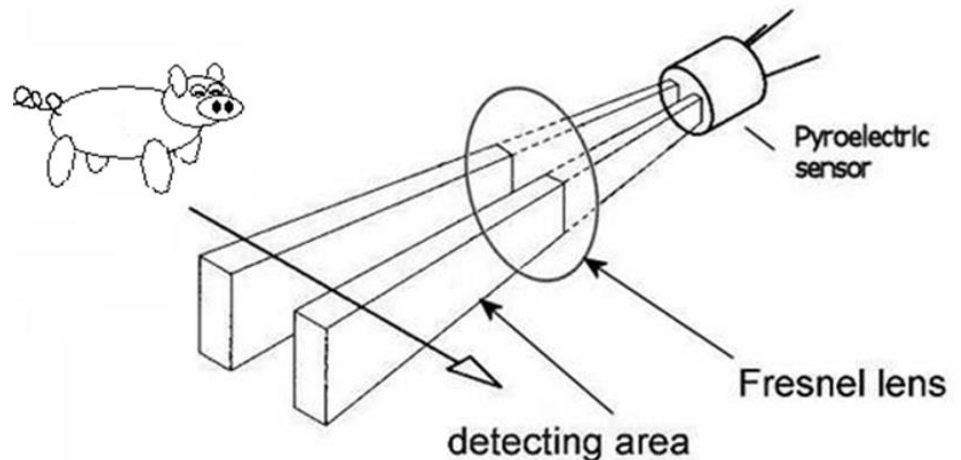
- Motion Detection
 - Automatic doors
 - Interactive Rooms
 - Activate when person enters room
 - Remote triggered cameras
 - Take photos/start recording when person enters room
- Measuring Temperature Differentials
 - Measure temperatures of remote objects

How It Works – Theory

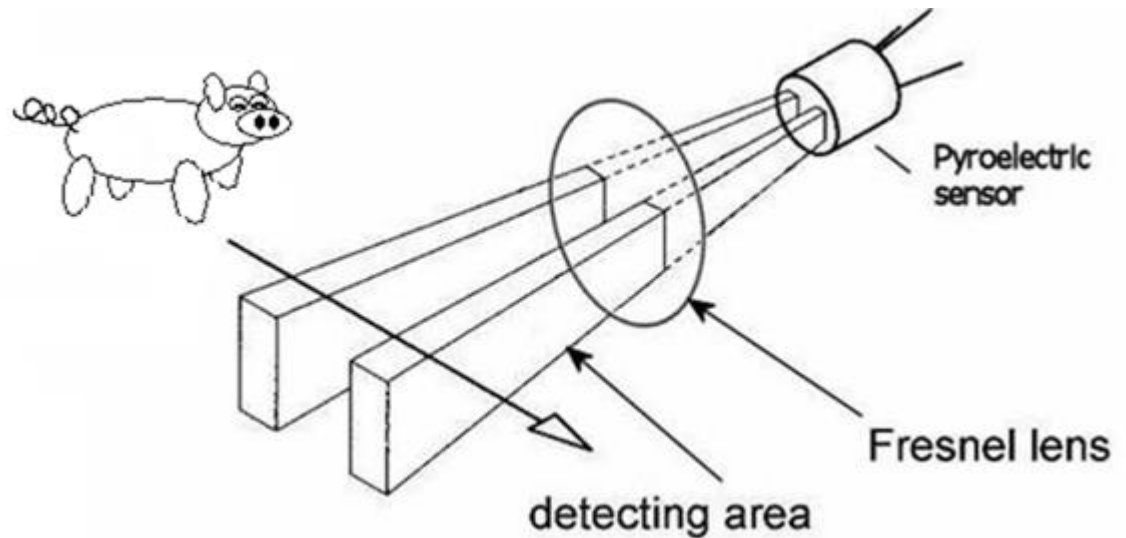
- Infrared radiation exists in the EM spectrum
 - Can't be seen, but can be detected
- Objects that generate heat also generate IR radiation
- PIR sensor consists of two sensing elements
 - One gives a frame of reference and the other detects the change
 - Can only detect the difference in temperatures between the two sensors

How It Works – Theory (cont.)

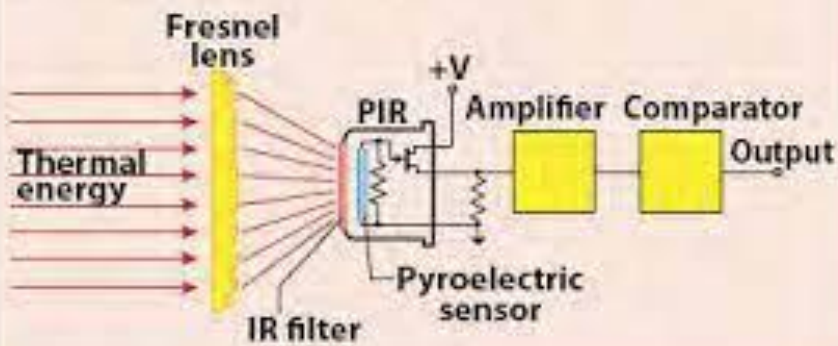
- **For example:** A PIR sensor is pointed into a room. An animal, with a temperature greater than the wall, walks into the room.
- As the animal crosses the first sensor, a positive pulse is produced.
- When the animal is in front of both sensors, there is no sensed change.
- As it crosses the second sensor, a negative pulse is emitted.
- These pulses are what is detected.



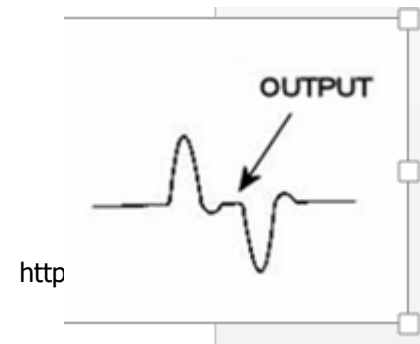
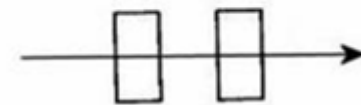
How It Works – Theory (cont.)



Passive infrared-motion sensor block diagram

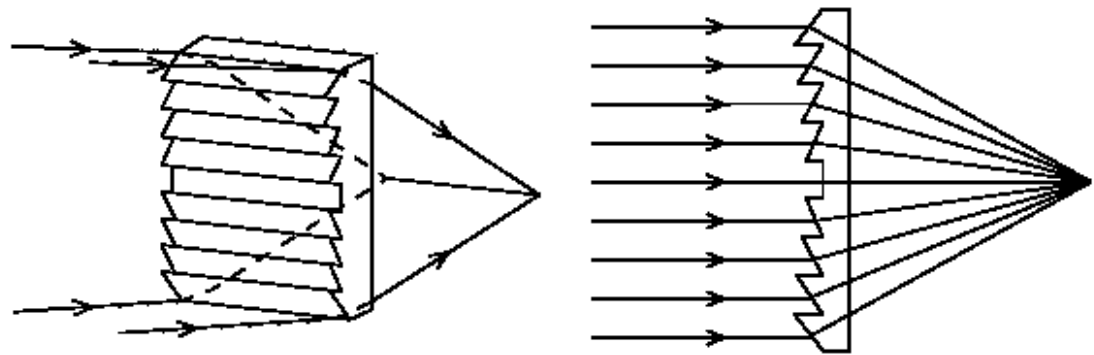


infrared source movement



How It Works – Fresnel Lens

- Captures more IR radiation
- Focuses the radiation into a smaller point
- Condenses the light and provides a larger range of IR to the sensor
- Made of material opaque to visible light
- Materials that pass visible light will not pass infrared radiation (e.g. glass, plastic, etc.)



<http://www.ladyada.net/learn/sensors/pir.html>

Major Specifications

- Power requirements
- Communication (Output):single bit high/low output
- Dimensions
- Operating Temperature
- Range and Detection Angle

Limitations

- Sensing can be confused
 - Motion too close to sensor
 - Motion is not passed through sensor one at a time
 - Cannot detect slow moving or stationary objects
 - Sensor is approached straight on
- Limited range in most sensors
- Temperature sensitive

Temperature Measurement

- Instruments to measure temperature can be divided into separate classes according to the physical principle on which they operate. The main principles used are:
- The thermoelectric effect → Thermocouples
- Resistance change → RTD's and Thermistors

Other Principles (FYI)

- Sensitivity of semiconductor device
- Radiative heat emission
- Thermography
- Thermal expansion
- Resonant frequency change
- Sensitivity of fibre optic devices
- Acoustic thermometry
- Color change
- Change of state of material.

Temp Sensors

<https://www.youtube.com/watch?v=w3Hfj2kMrGo>

Thermocouples- important

- Consist of a pair of dissimilar metal wires joined together at one end (sensing, hot junction) and terminated at the other end (reference, cold junction) which is kept at known constant temperature.
- emf (voltage) is produced when there is a difference in temperature between the two junctions, this is called the **thermocouple effect** or **Seebeck effect**.

- $$e = a_1T + a_2T^2 + a_3T^3 + \dots + a_nT^n$$
 ← FYI

Which can be approximated for certain pairs of metals by

$$e \approx a_1T$$

- Thermal emf magnitude depends on the materials used and on temperature difference .
- Remember how to convert from degrees C to degrees F
- Many types of thermocouples exist which differ in the metals used to construct them,
- among these are type E,J,K and S which differ in the combination of the used materials and their temperature range and application

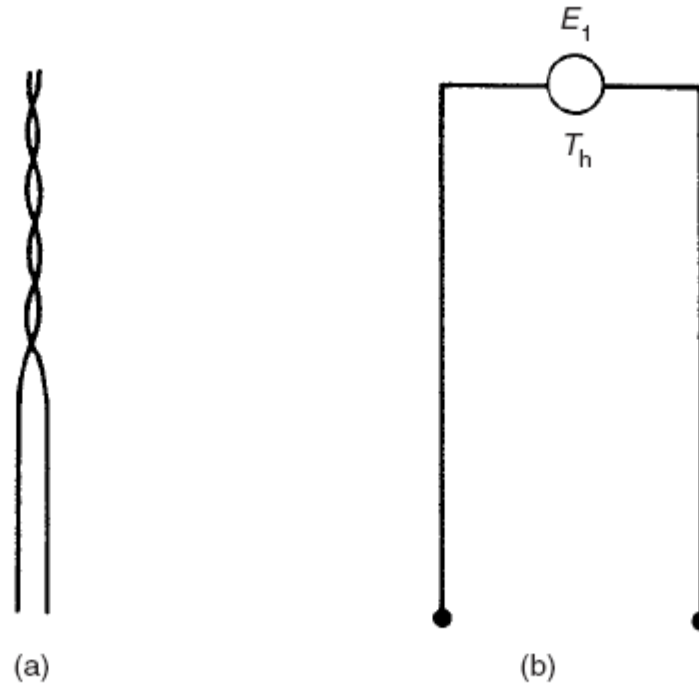
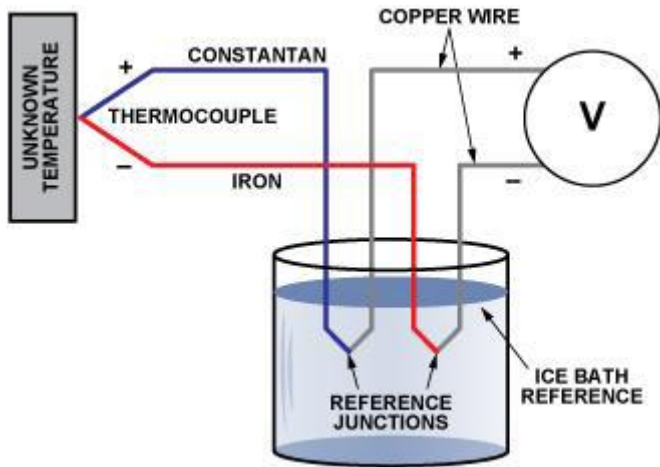
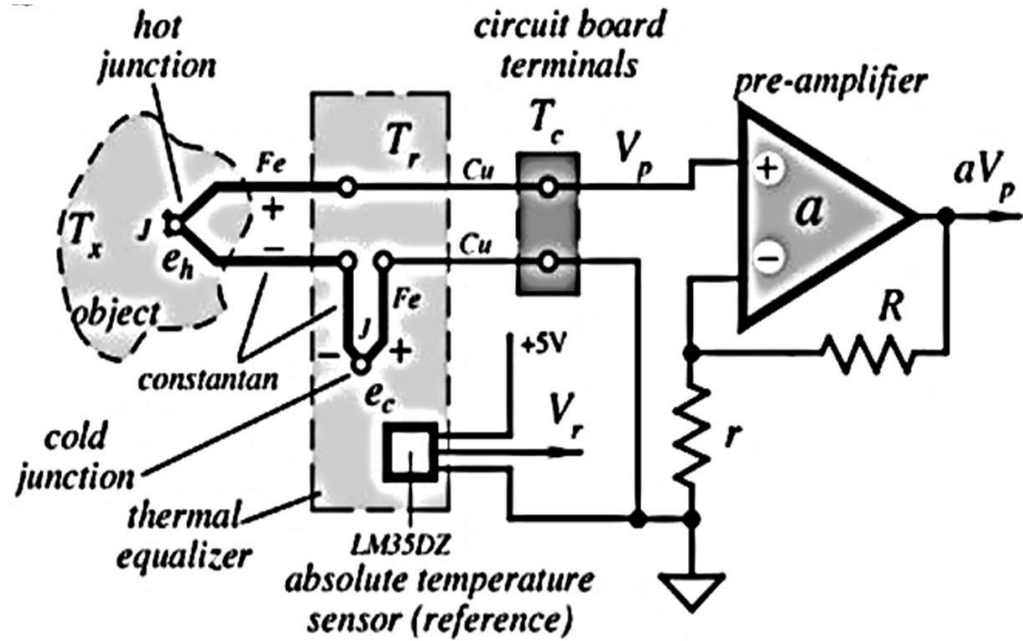
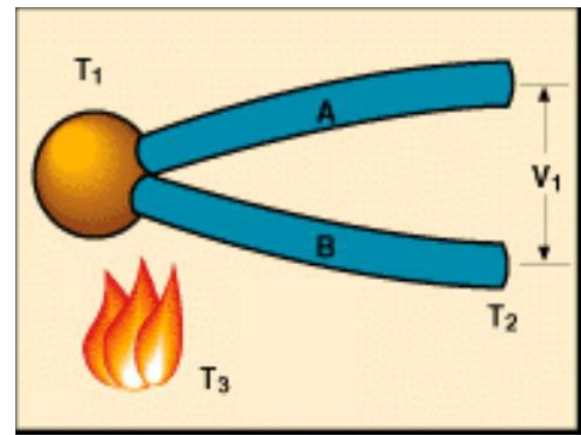


Fig. 14.2 (a) Thermocouple; (b) equivalent circuit.

- The emf generated at the hot junction is presented by E_1 and temperature is known as T_h
- E_1 is measured at the open ends of the thermocouple (known as reference junction)



Zero Temp reference



Temp reference measured by LM35 temp sensor

Thermocouple Types

- Type E → Chromel-Constantan
- Type J → Iron-Constantan
- Type K → Chromel-Alumel
- Type S → Platinum-Platinum/Rhodium

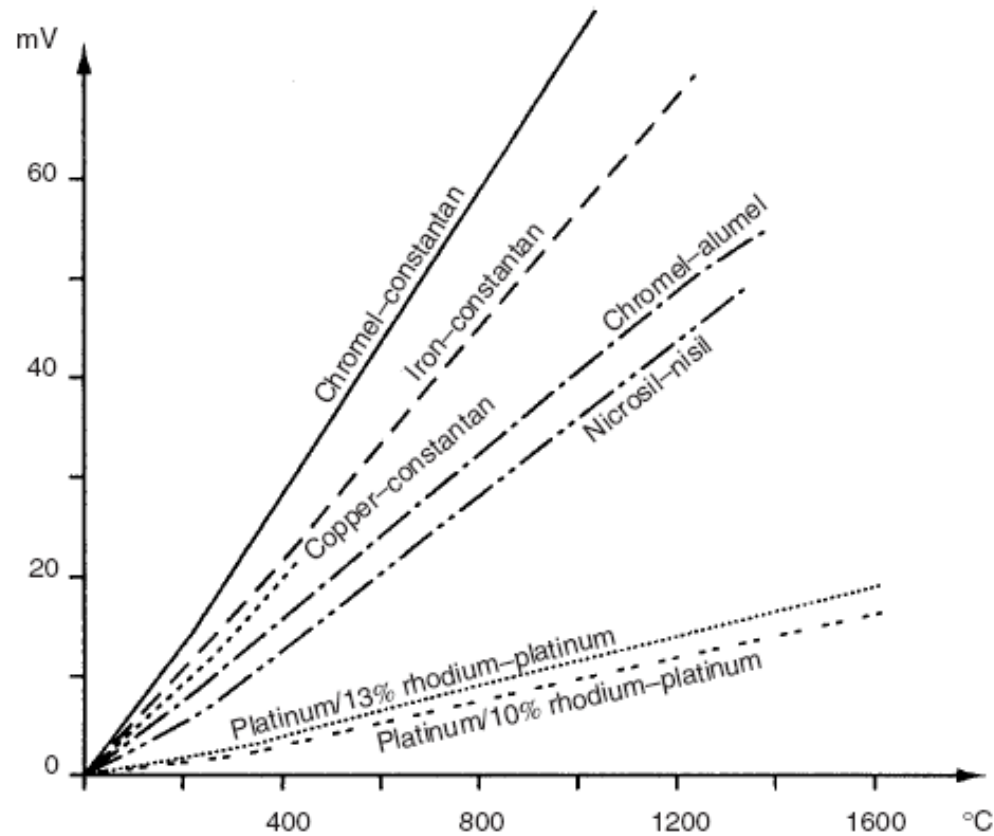
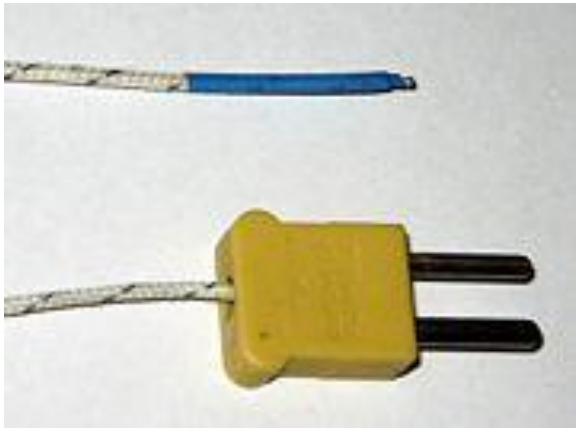
















Fig. 14.1 E.m.f. temperature characteristics for some standard thermocouple materials.

FYI



		United States Color Codes  ANSI MC96.1 1982	
		Thermocouple Grade	Extension Grade
Type K Thermocouple	KK 	KX 	
Type T Thermocouple	TT 	TX 	
Type J Thermocouple	JJ 	JX 	
Type N Thermocouple	NN 	NX 	
Type E Thermocouple	EE 	EX 	
Type S Thermocouple	None Established	SX 	
Type R Thermocouple	None Established	RX 	
Type B Thermocouple	None Established	BX 	

Thermistors / Important

- A **thermistor** is a type of resistor with resistance varying according to its temperature. The word is a combination of thermal and resistor.
- Thermistors are widely used as **inrush current limiters, temperature sensors, self-resetting overcurrent protectors, and self-regulating heating elements.**
- Assuming, as a first-order approximation, that the relationship between resistance and temperature is linear, then:

$$\Delta R = k\Delta T$$

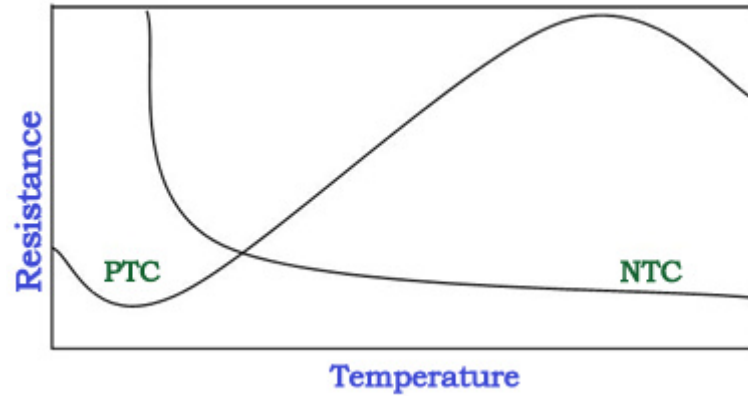
where

ΔR = change in resistance

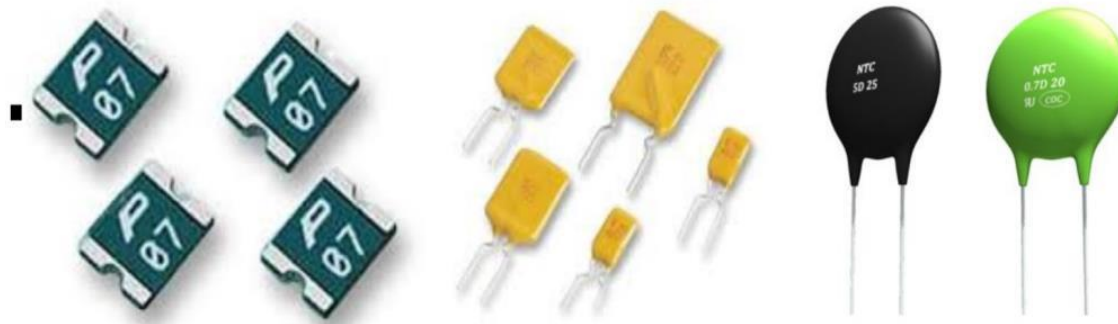
ΔT = change in temperature

k = first-order temperature coefficient of resistance





Thermistors



Thermistors / Important

- Thermistors can be classified into two types depending on the sign of k . If k is positive, the resistance increases with increasing temperature, and the device is called a positive temperature coefficient (PTC) thermistor, or **posistor**.
- If k is negative, the resistance decreases with increasing temperature, and the device is called a negative temperature coefficient (NTC) thermistor.
- Resistors that are not thermistors are designed to have the smallest possible k , so that their resistance remains nearly constant over a wide temperature range
- Thermistors differ from resistance temperature detectors (RTD) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges.

RTD's / Important

Resistance thermometers, which are alternatively known as *resistance temperature devices* (or RTDs), rely on the principle that the resistance of a metal varies with temperature according to the relationship:

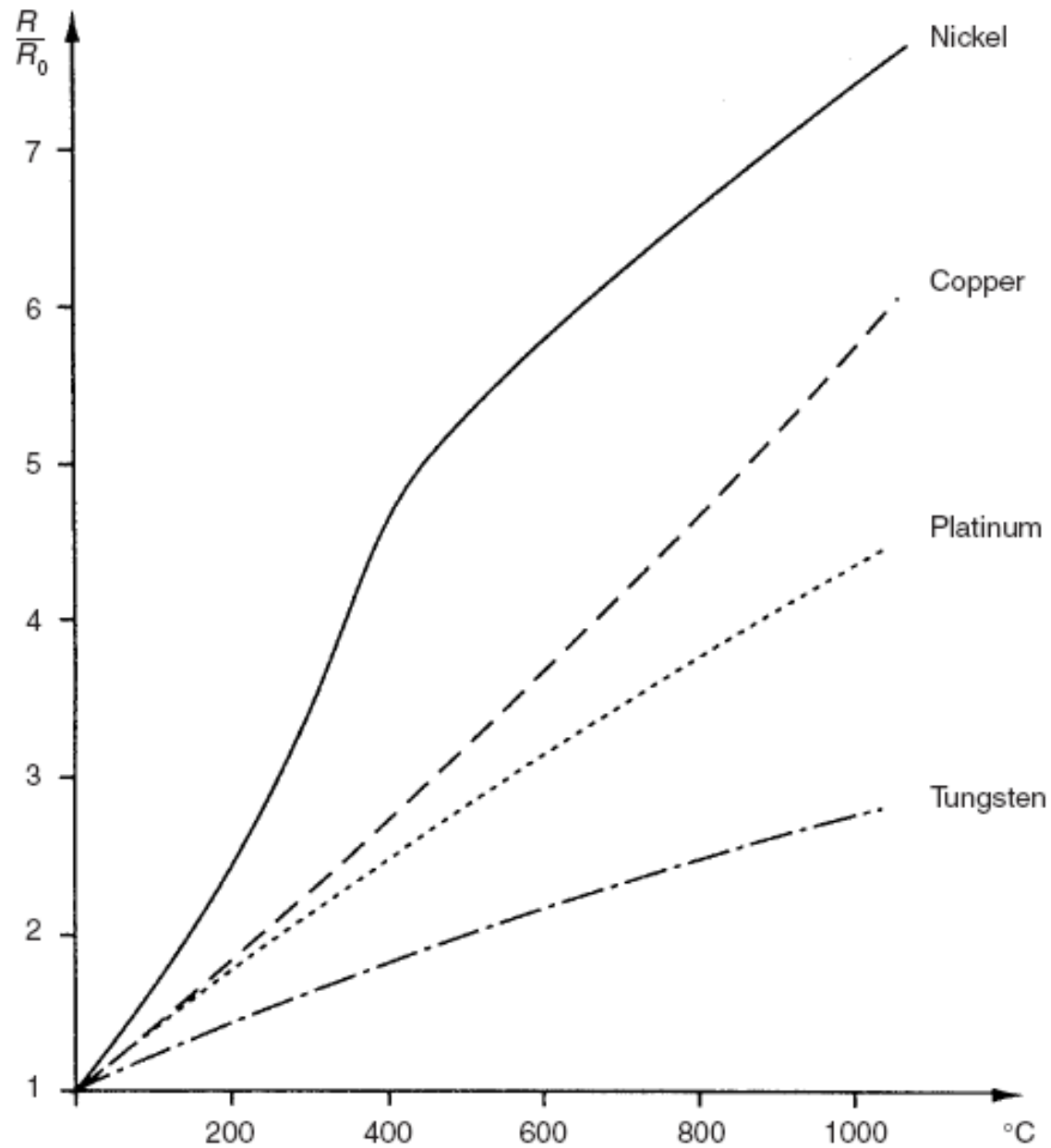
$$R = R_0 (1 + a_1T + a_2T^2 + a_3T^3 + \dots + a_nT^n) \quad (14.7)$$

This equation is non-linear and so is inconvenient for measurement purposes. The equation becomes linear if all the terms in a_2T^2 and higher powers of T are negligible such that the resistance and temperature are related according to:

$$R \approx R_0 (1 + a_1T)$$

This equation is approximately true over a limited temperature range for some metals, notably platinum, copper and nickel, whose characteristics are summarized in Figure 14.8. Platinum has the most linear resistance–temperature characteristic, and it also has good chemical inertness, making it the preferred type of resistance thermometer

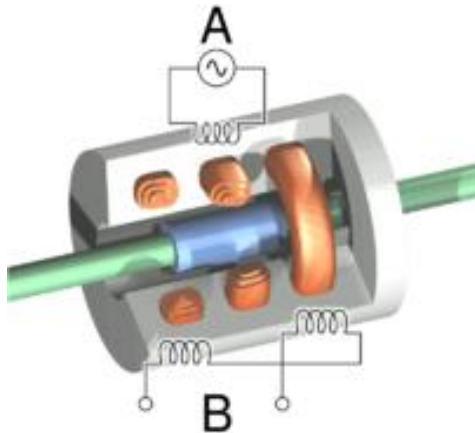
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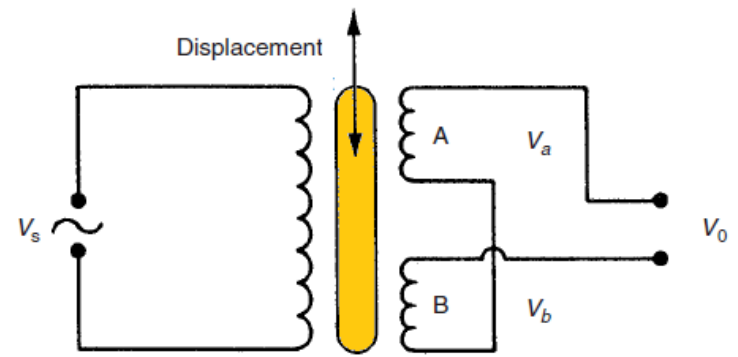
Typical resistance–temperature characteristics of metals.

Translational Motion Transducers

- Translational displacement is movement in a straight line between two points
- Translational Displacement transducers can be used as primary or secondary transducers
- Simple type as resistive potentiometer
- LVDT: linear variable differential transformer



Cutaway view of an LVDT. Current is driven through the primary coil at *A*, causing an induction current to be generated through the secondary coils at *B*.



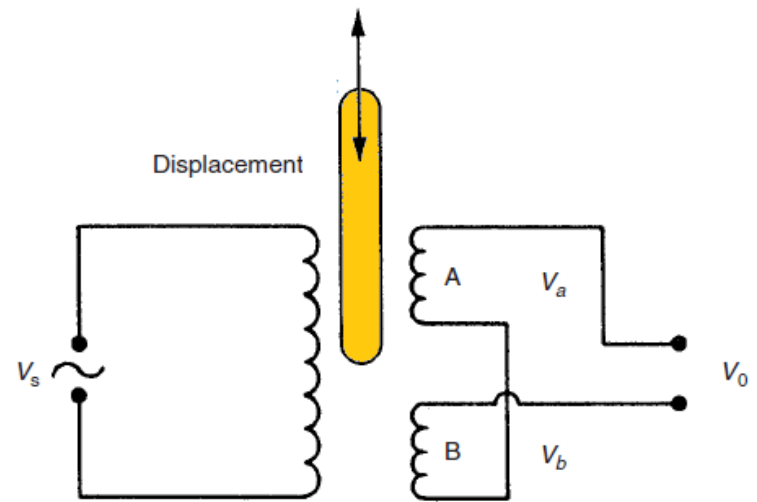
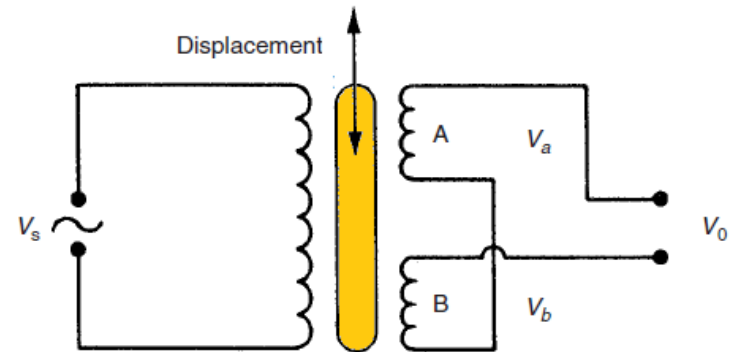
Linear Variable Differential Transformer

- ❑ LVDT has one primary and two secondary's (A and B) connected in series in opposing manner.
- ❑ The object moves the central iron core of the transformer.
- ❑ For an excitation voltage V_s given by

$V_s = V_p \sin(\omega t)$, the e.m.f.s induced in the secondary windings V_a and V_b are given by:

$$V_a = K_a \sin(\omega t - \varphi), V_b = K_b \sin(\omega t - \varphi)$$

- Parameters K_a and K_b depend on the amount of coupling between the respective secondary and primary windings and hence on the position of the iron core.

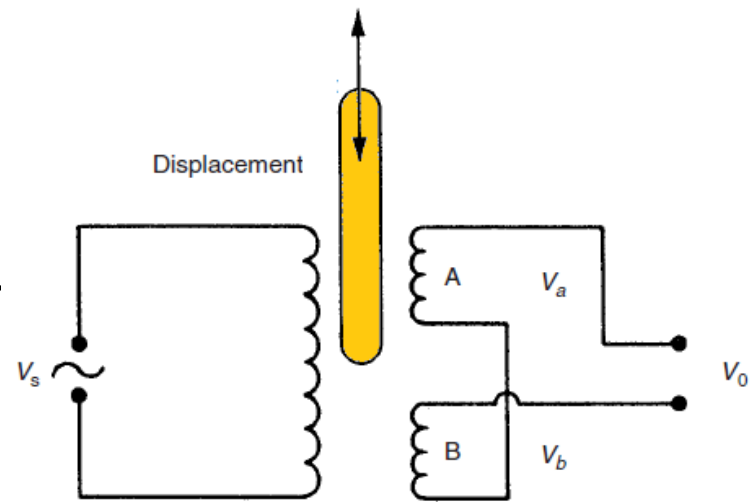
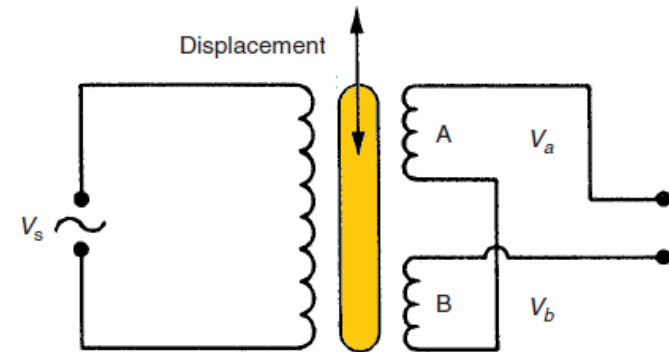


Linear Variable Differential Transformer

□ Because of the series opposition mode of connection of the secondary windings, the output voltage, V_o is the difference between V_a and V_b ,

□ With the core in the central position, $K_a = K_b$, and $V_o = 0$.

□ The relationship between the magnitude of V_o and the core position is approximately linear over a reasonable range of movement of the core on either side of the null position.



$$V_o = V_a - V_b = (K_a - K_b) \sin(\omega t - \varphi)$$

Linear Variable Differential Transformer

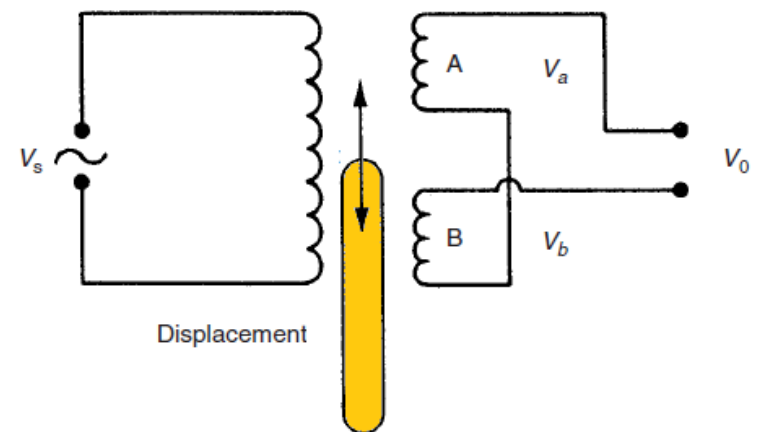
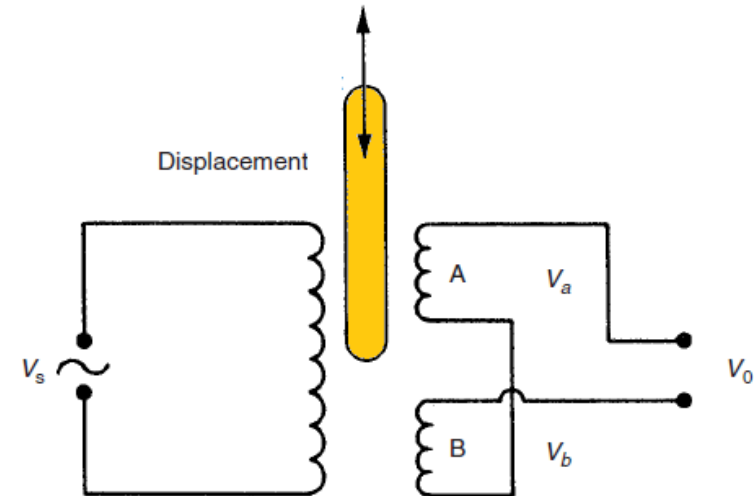
- Suppose that the core is displaced upwards (i.e. towards winding A) by a distance x . then K_a increases to become K_L and K_b decreases to become K_S . We thus have:

$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi)$$

- If, alternatively, the core were displaced downwards from the null position (i.e. towards winding B) by a distance x , then K_a decreases to become K_S and K_b increases to become K_L , and we would have:

$$V_o = V_a - V_b = (K_S - K_L)\sin(\omega t - \varphi)$$

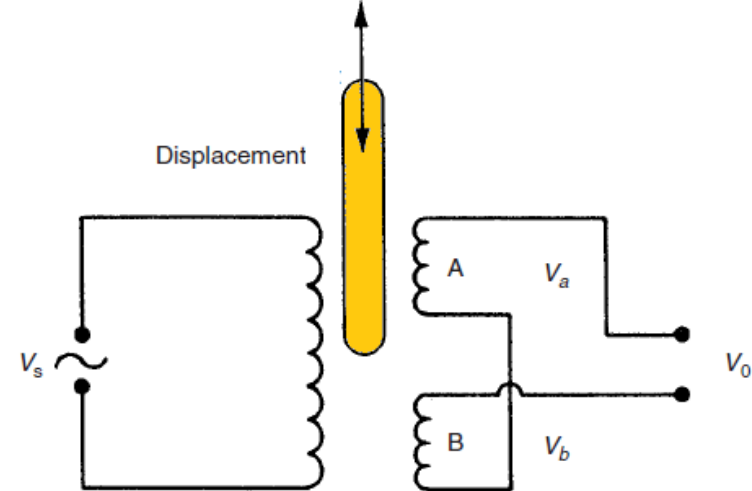
$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi + \pi)$$



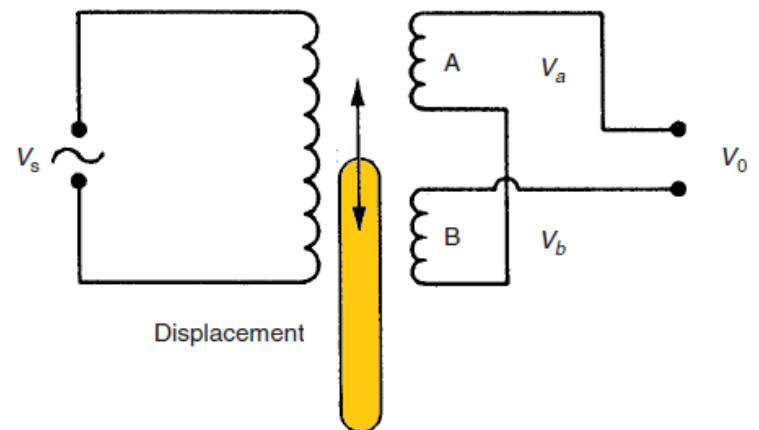
Linear Variable Differential Transformer

$$V_o = (K_L - K_S) \sin(\omega t - \varphi)$$

- Thus for equal magnitude displacements $+x$ and $-x$ of the core away from the central (null) position, the magnitude of the output voltage V_o is the same in both cases. The only information about the direction of movement of the core is contained in the phase of the output voltage, which differs between the two cases by 180° .



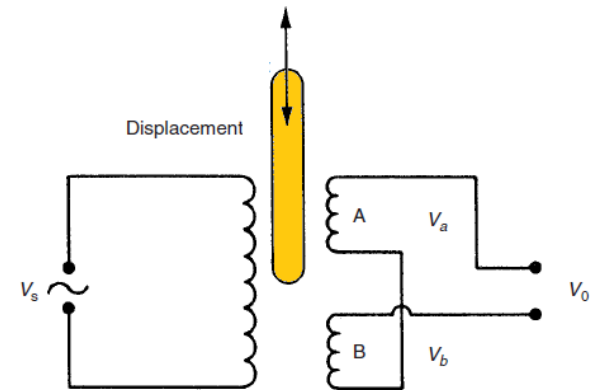
- If, therefore, measurements of core position on both sides of the null position are required, it is necessary to measure the phase as well as the magnitude of the output voltage.



$$V_o = (K_L - K_S) \sin(\omega t - \varphi + \pi)$$

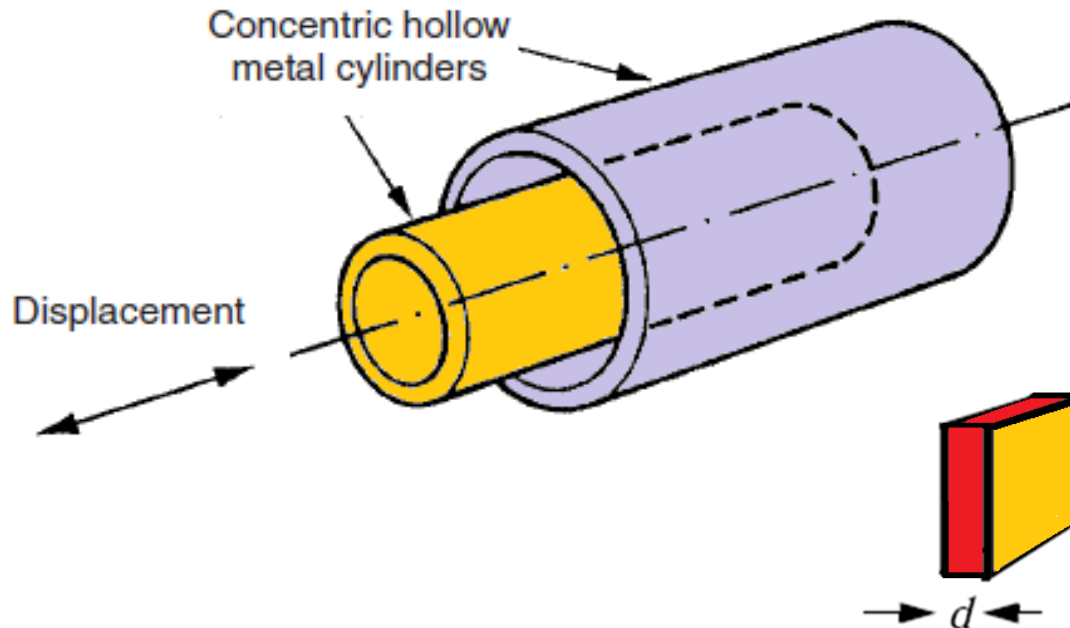
Linear Variable Differential Transformer

- ❑ Some problems that affect the accuracy of the LVDT are the presence of harmonics in the excitation voltage and stray capacitances, both of which cause a non-zero output of low magnitude when the core is in the null position.
- ❑ It is also impossible in practice to produce two identical secondary windings, and the small asymmetry that invariably exists between the secondary windings adds to this non-zero null output. The magnitude of this is always less than 1% of the full-scale output and in many measurement situations is of little consequence.
- ❑ Where necessary, the magnitude of these effects can be measured by applying known displacements to the instrument. Following this, appropriate compensation can be applied to subsequent measurements.



Variable Capacitance Transducers

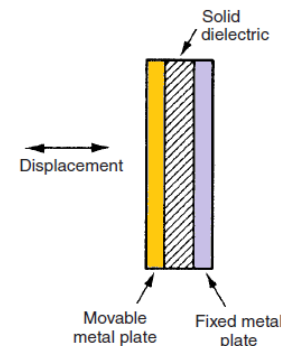
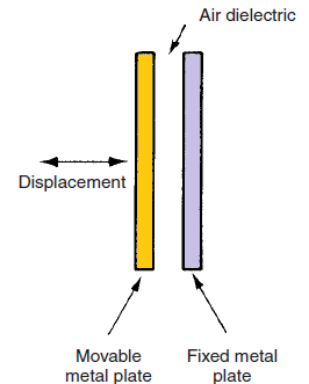
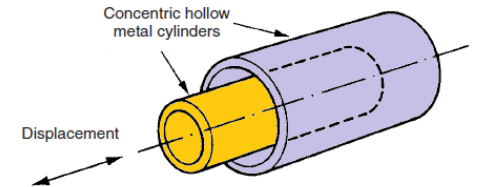
- ❑ In the concentric cylinders variable capacitance transducer, capacitance plates are formed by two concentric, hollow, metal cylinders.
- ❑ The displacement to be measured is applied to the inner cylinder, which alters the capacitance



$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

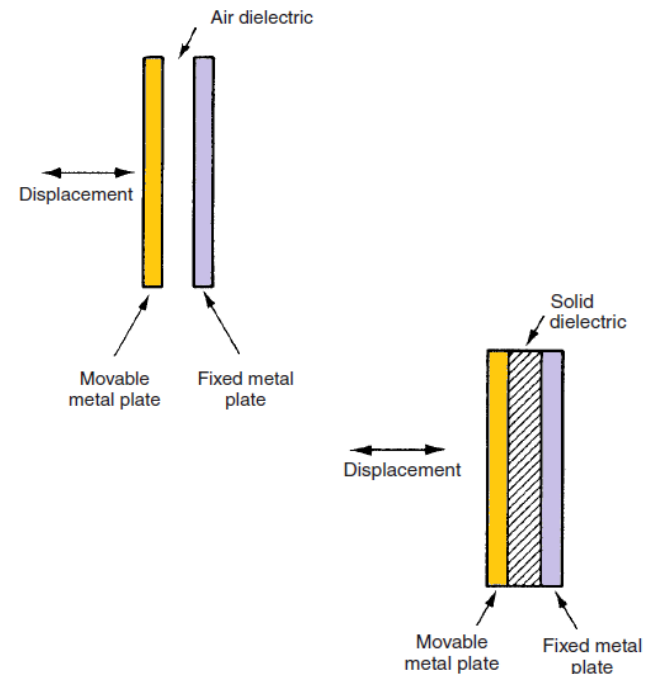
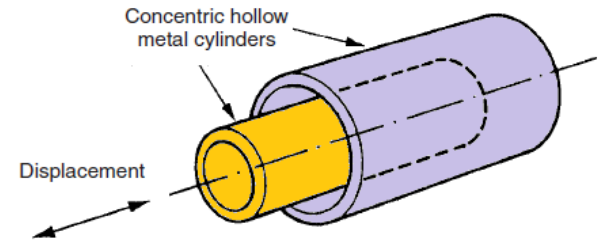
Variable Capacitance Transducers

- ❑ Inaccuracies as low as $\pm 0.01\%$ are possible with these instruments, with measurement resolutions of 1 micron. Individual devices can be selected from manufacturers' ranges that measure displacements as small as 10-11 μm or as large as 1m.
- ❑ The fact that such instruments consist only of two simple conducting plates means that it is possible to fabricate devices that are tolerant to a wide range of environmental hazards such as extreme temperatures, radiation and corrosive atmospheres.
- ❑ As there are no contacting moving parts, there is no friction or wear in operation and the life expectancy quoted is 200 years.



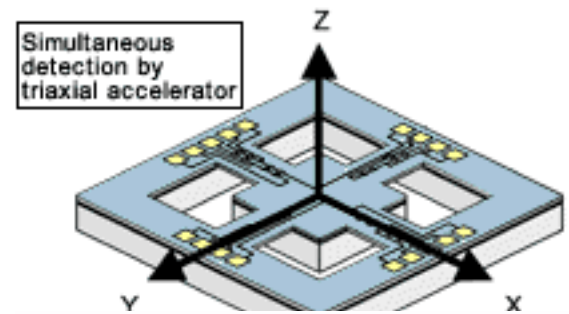
Variable Capacitance Transducers

- ❑ The major problem with variable capacitance transducers is their high impedance. This makes them very susceptible to noise and means that the length and position of connecting cables need to be chosen very carefully.
- ❑ In addition, very high impedance instruments need to be used to measure the value of the capacitance.
- ❑ Because of these difficulties, use of these devices tends to be limited to those few applications where the high accuracy and measurement resolution of the instrument are required.



Accelerometers

- Because of earth's gravity, the sensor will read 1 to 0 g as the sensor is rotated from being vertical to horizontal.
 - This can be used to measure angle of tilt
- Most have analog outputs that need amplification
 - Some have built-in amplifiers for direct connection into microcontroller



Accelerometers

Applications

- Can be used to sense orientation, vibration and shocks.
- Used in electronics like the Wii and iPhone for user input.
- Acceleration integrated once gives velocity, integrated a second time gives position.
 - The integration process is not precise and introduces error into the velocity and position.

