# Sensors

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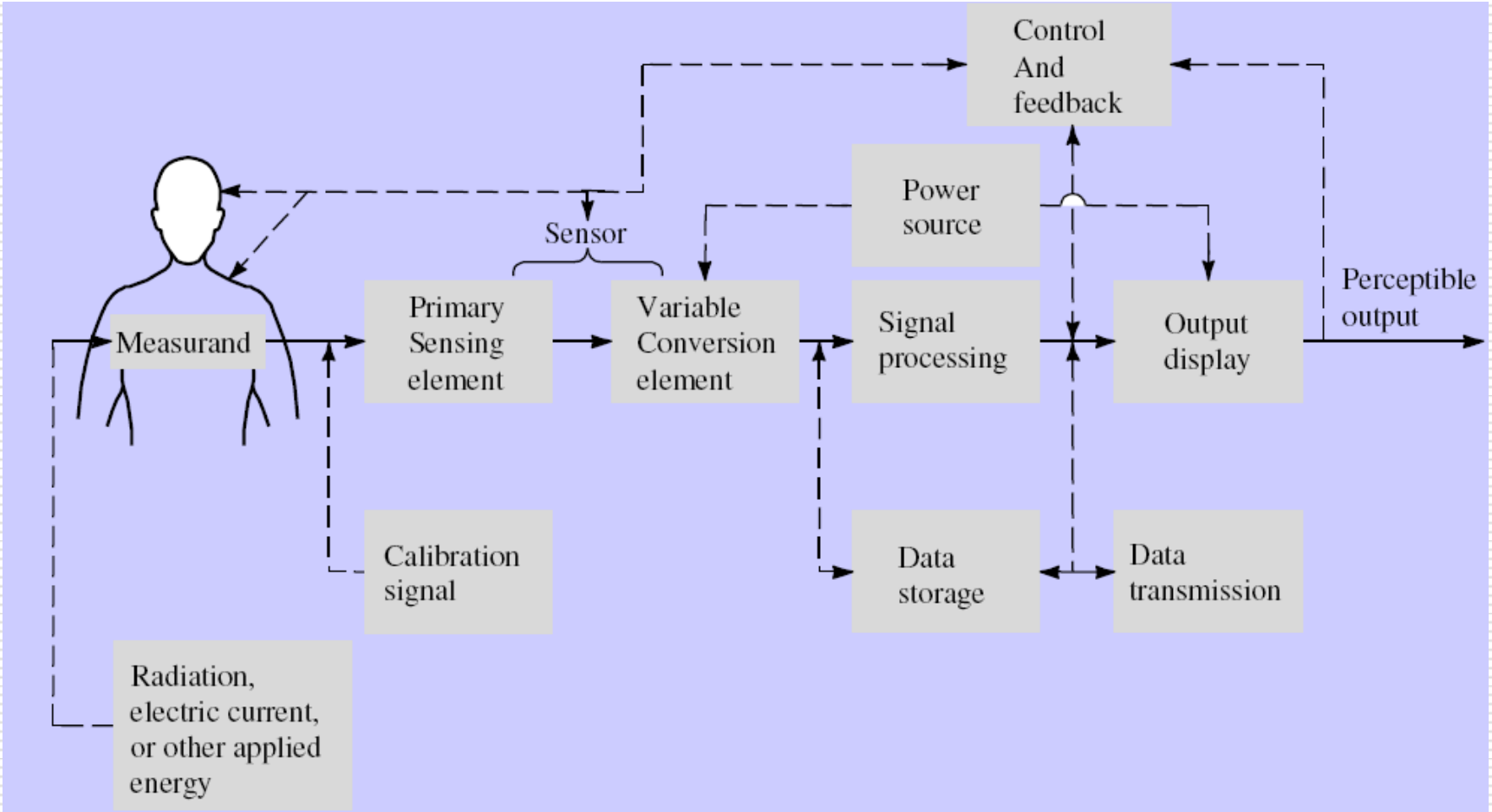
MEKATRONİK MÜHENDİSLİĞİ BÖLÜMÜ

# INTRODUCTION

- Basic mechanisms and principles of the sensors used in a number of medical instruments are discussed.



# Transducer, Sensor, and Actuator

- Transducer:
  - a device that converts energy from one form to another
- Sensor:
  - converts a physical parameter to an electrical output (a type of transducer, e.g. a microphone)
- Actuator:
  - converts an electrical signal to a physical output (opposite of a sensor, e.g. a speaker)

# Type of Sensors

- Displacement Sensors:
  - resistance, inductance, capacitance, piezoelectric
- Temperature Sensors:
  - Thermistors, thermocouples
- Electromagnetic radiation Sensors:
  - Thermal and photon detectors

# Transducer, Sensor, and Actuator

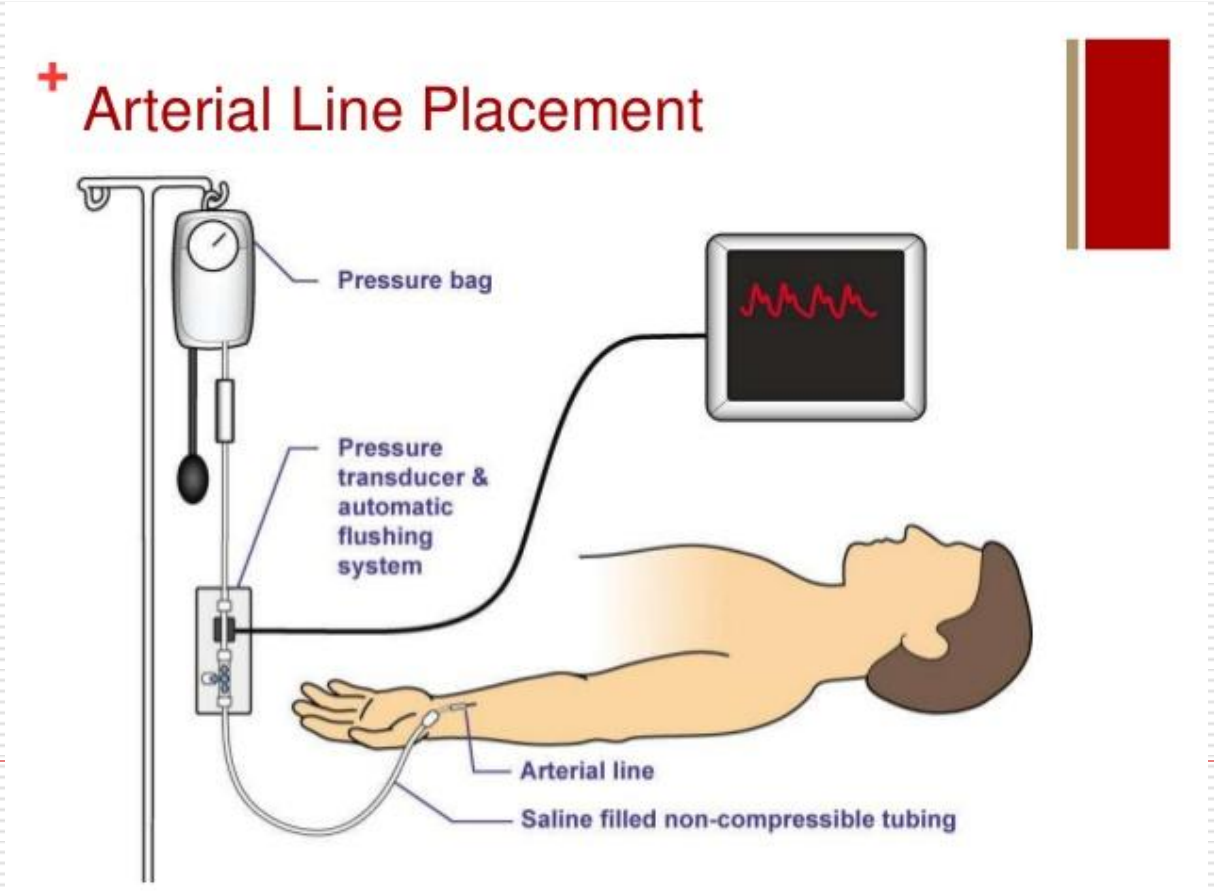
- **A transducer** is a device that converts energy from one form to another.
  - Energy: electrical, mechanical, chemical, thermal, optical, electromagnetic and others
- **A sensor** converts a physical parameter to an electric output.
  - Example: digital thermometer
- **An actuator** converts an electric signal to a physical output.
  - Example: heater

# 2.1 Displacement Measurements

- The physican and biomedical researcher are interested in measuring the size, shape and position of the organs and tissues of the body.
- Variations in these parameters are important in discriminating normal from abnormal function
- Displacement sensors can be used in both types of the measurement.
  - direct and
  - indirect systems

# Direct Method

- Direct measurements of the displacement are used to determine, blood pressure,  the change in diameter of blood vessels and the changes in volume and shape of cardiac chambers.



# Indirect Method

- Indirect measurements of displacement are used to quantify movements of liquids through heart valves. An example is the movement of a microphone diaphram that detects the movement of the heart indirectly and the resulting heart murmurs.

# Displacement-sensitive measurement

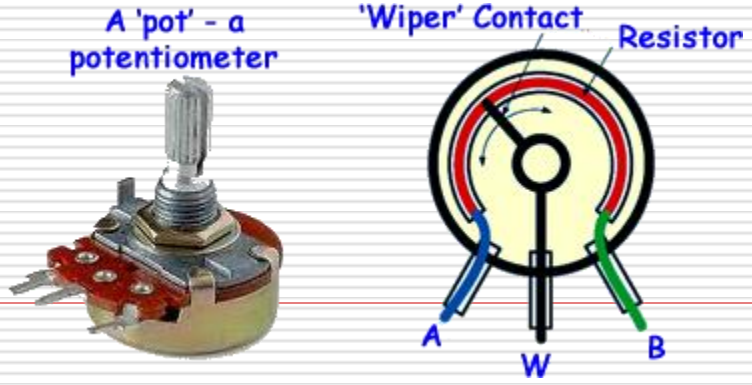
- Dimensonal changes may be measured by variations in
  - Resistance
  - Inductance
  - Capacitance
  - Piezoelectric effect

# Potentiometer

- A potentiometer is a manually adjustable variable resistor with 3 terminals. Two terminals are connected to both ends of a resistive element, and the third terminal connects to a sliding contact, called a wiper, moving over the resistive element.
- The position of the wiper determines the output voltage of the potentiometer.

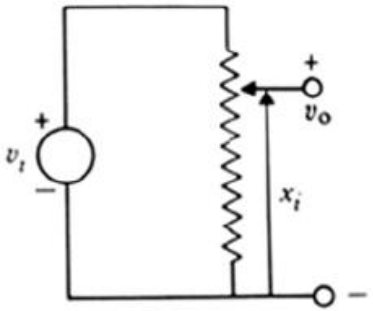
$$\Delta V = I \, \Delta R$$

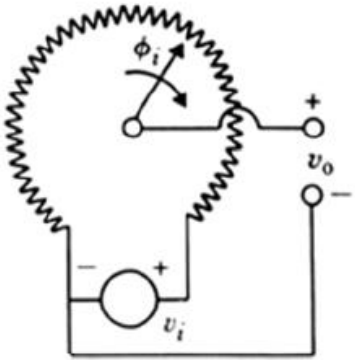
- It produces linear output (0.01% of full scale) in response to displacement.
- Resolution is a function of construction.

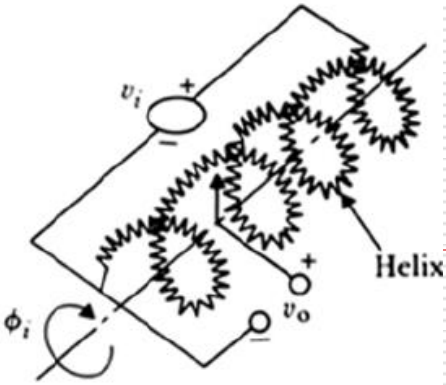


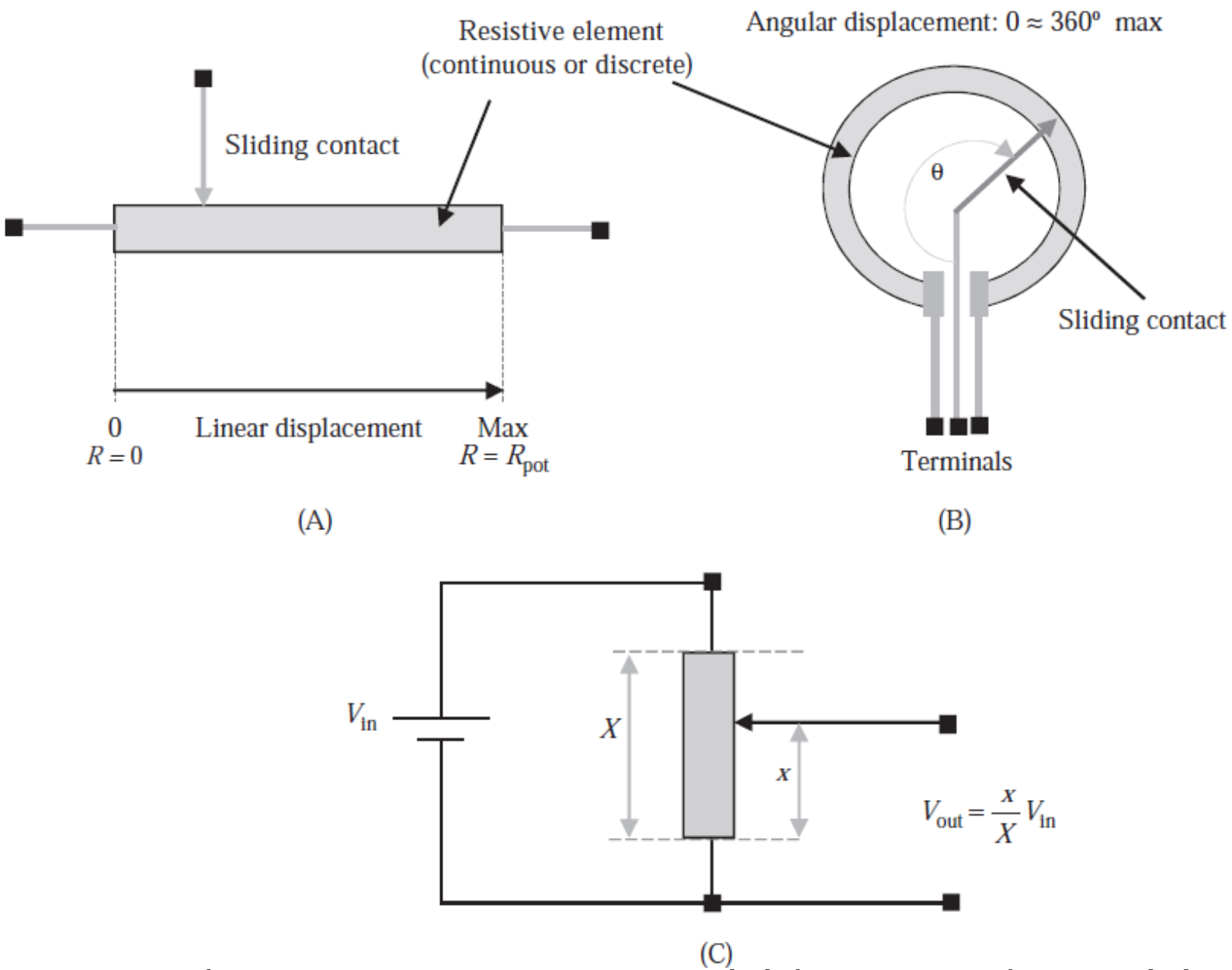
# Potentiometer

- The potentiometer shown in Figure 2.1(a) measures translational displacements from 2 to 500 mm.
- Rotational displacements ranging from 10° to more than 50° are detected as shown in single-turn pot and multi-turn pot (mostly 5, 10 or 20).
- Multi-turn pots are used where high precision and resolution is required.





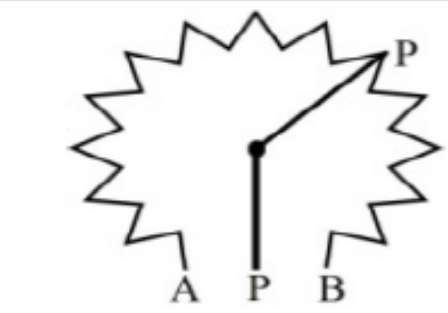

Resistive transducers type potentiometers (A) linear translation; (B) angular translation (single turn rotational). They usually respond to a linear or angular displacement with a linearly proportional output voltage (C).

# Example: RotaryPotentiometer

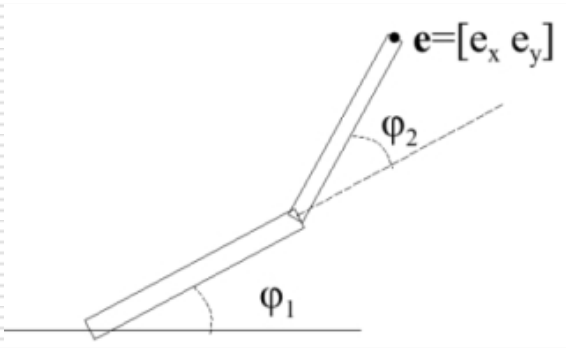
- Figure shows the rotary potentiometer. The changed resistance of the rotary potentiometer with respect to angular displacement is mathematically represented as,

$$R_{PB}=(R_{AB}/(P_{max.}-P_{min.})) \times P$$

- $R_{PB}$=Resistance between P and B,
- $R_{AB}$= Resistance between A and B,
- Pmax= Maximum angular displacement of potentiometer
- Pmin= Minimum angular displacement of potentiometer.
- The output voltage ($V_{PB}$) at the potentiometer output is given by,
- $V_{PB}=(R_{PB}/R_{AB}) \times Vcc$,
- $V_{PB}$ = Voltage between points P and B,
- Vcc= Exciting DC voltage across the potentiometer.
- Potentiometer is placed inside a robotic arm's joint. Pmin=30° and Pmax =180°. $R_{AB}$=1500Ω. $V_{CC}$=5V. If you measure 3V at the PB terminals. What is the joint angle?

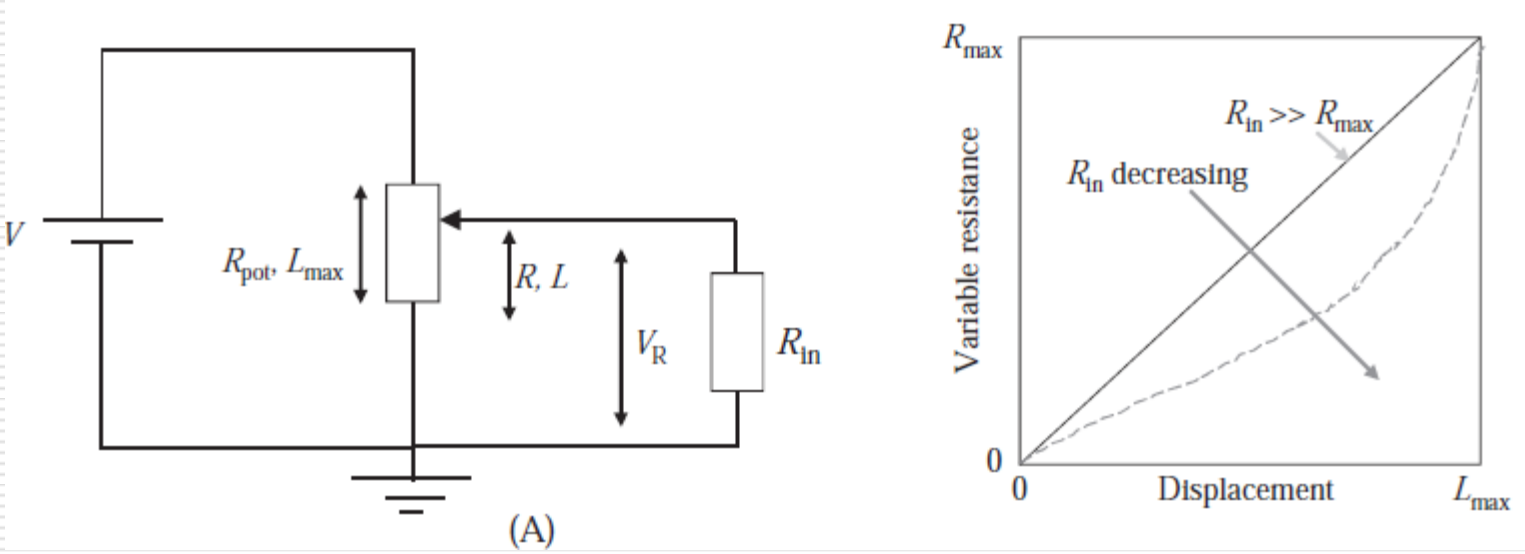


Rotary potentiometer.



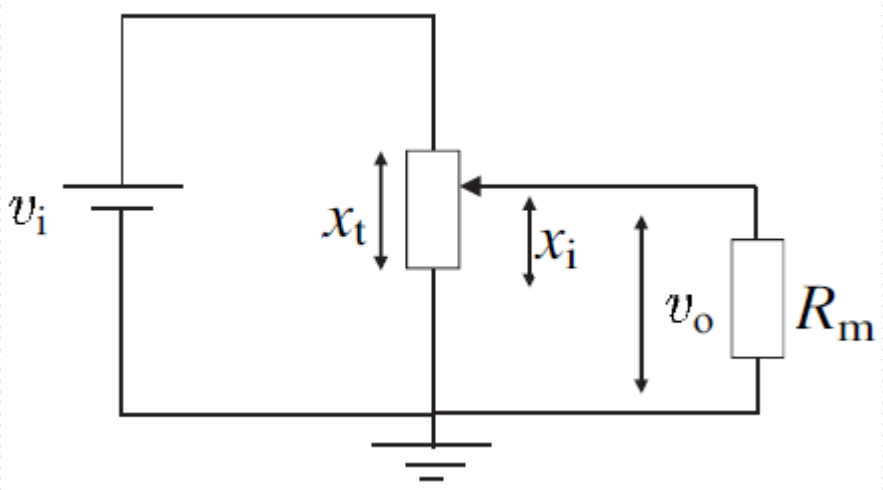
# Nonlinearity error

- For biomedical applications, the linearity error should be maintained below 1% to avoid nonlinearity distortion in the value being read. The device that reads the variable resistance value must have input impedance several times larger than the transducer output impedance, otherwise, it can load the transducer causing distortion.



# Example

**2.1** For Figure P2.1, plot the ratio of the output voltage to the input voltage $v_o/v_i$ as a function of the displacement $x_i$ of a potentiometer with a total displacement $x_t$ for ranges of $R_m$, the input resistance of the meter. Show that the maximal error occurs in the neighborhood of $x_i/x_t = 0.67$. What is the value of this maximal error?



Let the wiper fraction $F = x_i/x_t$

$$v_o/v_i = \frac{R_m \| F\,R_p}{R_m \| F\,R_p + (1-F)R_p}$$

$$= \frac{\dfrac{R_m\,F\,R_p}{R_m + F\,R_p}}{\dfrac{R_m\,F\,R_p}{R_m + F\,R_p} + (1-F)R_p}$$

$$= \frac{1}{1 + \dfrac{R_m\,F\,R_p}{R_m + F\,R_p}\,(1-F)R_p}$$

$$= \frac{1}{\dfrac{R_m F + R_m + F\,R_p - F\,R_m - FFR_p}{R_m F}}$$

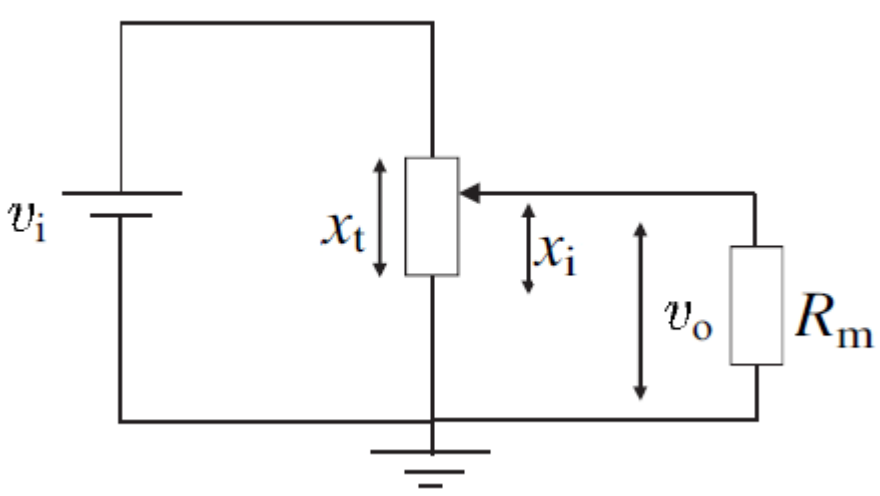
$$= \frac{1}{\dfrac{1 + F\,R_p/R_m - FFR_p/R_m}{F}}$$

$$= \frac{1}{\dfrac{1}{F} + \dfrac{R_p}{R_m}\,(1-F)}$$

Let $\varepsilon = R_p/R_m$

error $= F - v_o/v_i$

$$= F - \frac{1}{1/F + \varepsilon(1-F)}$$



$$= F - \frac{F}{1 + \varepsilon F - \varepsilon F^2}$$

$$= F - (F)\,(1 + \varepsilon F - \varepsilon F^2)^{-1}$$

$$d/dF(\text{error}) = 0 = 1 - (1)\,(1+\varepsilon F-\varepsilon F^2)^{-1} - (F)\,(-1)\,(1+\varepsilon F-\varepsilon F^2)^{-2}(\varepsilon - 2\varepsilon F)$$

multiply by $(1+\varepsilon F-\varepsilon F^2)^2$

$$0 = (1+\varepsilon F-\varepsilon F^2)^2 - (1+\varepsilon F-\varepsilon F^2) + (F)\,(\varepsilon - 2\varepsilon F)$$

expand, ignoring terms of $\varepsilon^2$, $\varepsilon^3$, ...

$$0 = 1 + 2\varepsilon F - 2\varepsilon F^2 - 1 - \varepsilon F + eF^2 + \varepsilon F - 2\varepsilon F^2$$

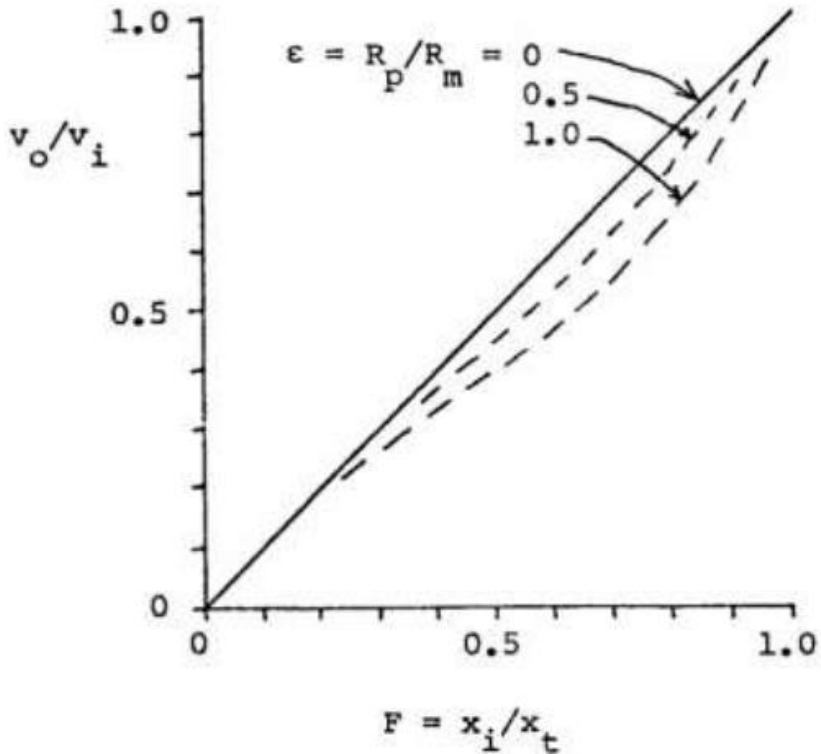
$$0 = -3\varepsilon F^2 + 2\varepsilon F = (\varepsilon)\,(F)\,(2-3F)$$

$$F = 0,\ 2/3$$

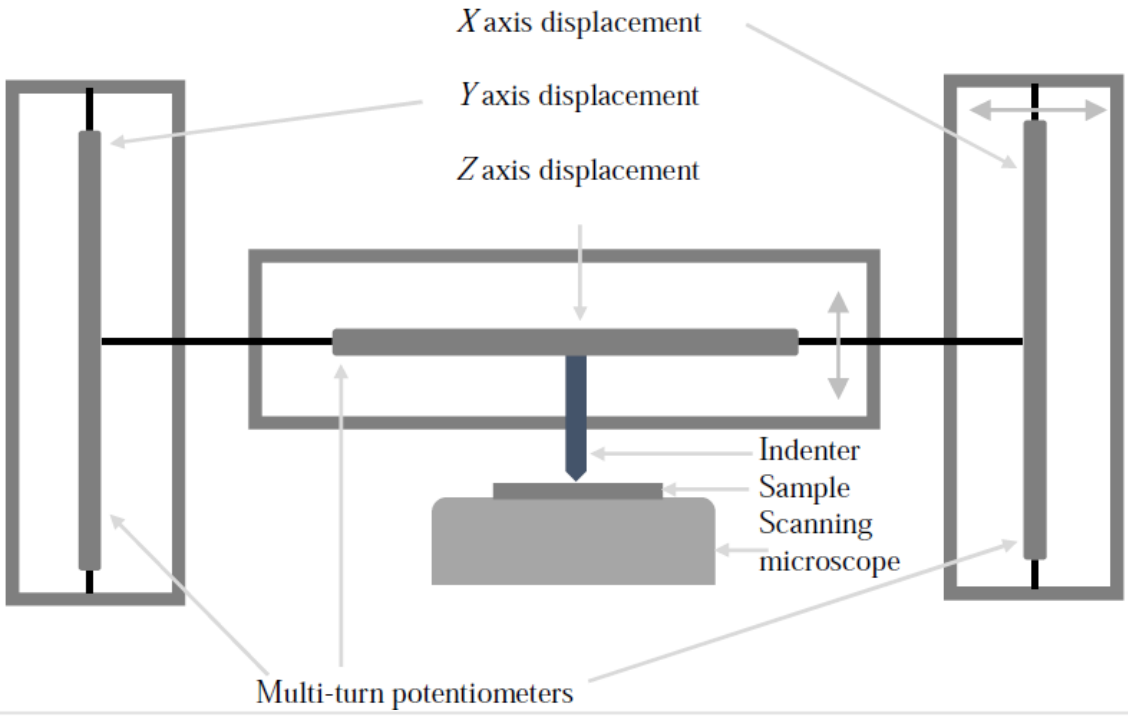
$$\text{error} = 0.67 - \frac{1}{1/0.67 + \varepsilon(1 - 0.67)}$$

$$= 0.67 - \frac{1}{1.5 + 0.33\varepsilon}$$

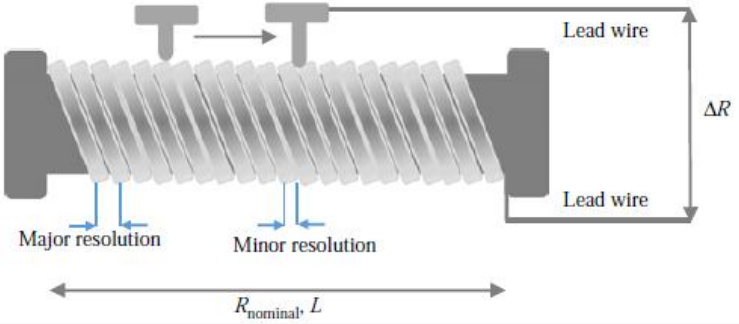
$$= \frac{0.22\varepsilon}{1.5 + 0.33\varepsilon} \approx 0.15\varepsilon = 0.15\ R_p/R_m$$



- A XYZ micropositioner with resolution of 0.0004” and linearity error equal to ±0.3% along a 2” full-scale displacement can be constructed with a multi-turn potentiometer.
- This type of micropositioner helps locating microelectrodes during Parkinson’s disease surgery.




The better resolution that can be achieved is 20 μm with a 500 turns/cm potentiometer



# STRAIN GAGES

- When a fine wire (25 μm) is strained within its elastic limit, the wire's resistance changes because of changes in the
  - diameter,
  - length,
  - and resistivity.
- The resulting strain gages may be used to measure extremely small displacements, on the order of nanometers.

# STRAIN GAGES

- R of a wire with resistivity $\rho$ (ohm.meter), length $L$ (meters), and cross-sectional area $A$ (meter squared) is given by:

$$R = \frac{\rho L}{A} \tag{2.1}$$

- The total differential change in R is found by summing the differential changes resulted in R due to differential changes in $\rho$, $L$ and $A$.

$$dR = \frac{\rho dL}{A} - \rho A^{-2} L\, dA + L\frac{d\rho}{A} \tag{2.2}$$

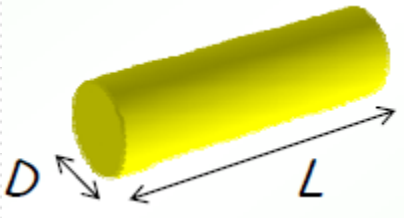
- Divide 2.2 by 2.1 results in

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \tag{2.3}$$

# STRAIN GAGES

- Poisson's ratio $\mu$ relates the change in diameter D to the change in length L:

$$\Delta D/D = -\mu\,\Delta L/L$$




- Substitute this formula in (2.3)

$$\frac{\Delta R}{R} = \underbrace{(1+2\mu)\frac{\Delta L}{L}}_{\text{Dimensional effect}} + \underbrace{\frac{\Delta \rho}{\rho}}_{\text{Piezoresistive effect}} \qquad (2.4)$$

- the change in resistance is a function of changes in dimension length, $(\Delta L/L)$
- plus the change in resistivity due to strain-induced changes in the lattice structure of the material, $\Delta\rho/\rho$

# STRAIN GAGES

- The gage factor G, found by dividing (2.4)by ΔL/L, is useful in comparing various strain-gage materials.

$$G = \frac{\Delta R/R}{\Delta L/L} = (1 + 2\mu) + \frac{\Delta \rho/\rho}{\Delta L/L}$$

- In practical existence, there is a metal strain gauge and also semiconductor strain gauge.
- The gage factor for semiconductor materials is approximately 50 to 70 times that of the metals.
- Gage factor for metals is primarily a function of dimensional effects.

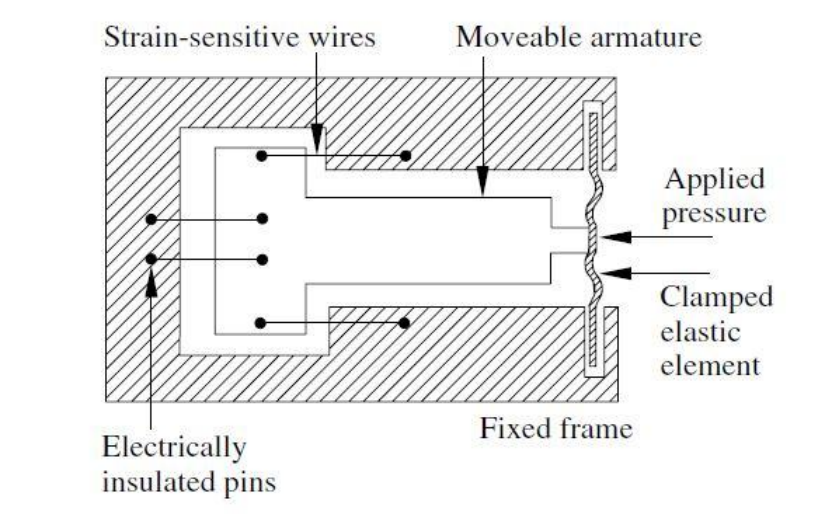
  For most metals, μ=0.3 and thus G is at least 1.6
- For semiconductors, the piezoresistive effect is dominant.
- The desirable feature of higher gage factors for semiconductor devices is offset by their greater resistivity-temperature coefficient.
- Designs for instruments that use semiconductor materials must incorporate temperature compensation.

# Table 2.1 Properties of Strain-Gage Materials

| Material | Composition (%) | Gage Factor | Temperature Coefficient of Resistivity ($°C^{-1} - 10^{-5}$) |
|---|---|---|---|
| Constantan (advance) | $Ni_{45}$, $Cu_{55}$ | 2.1 | ±2 |
| Isoelastic | $Ni_{36}$, $Cr_8$ $(Mn, Si, Mo)_4$ $Fe_{52}$ | 3.52 to 3.6 | +17 |
| Karma | $Ni_{74}$, $Cr_{20}$, $Fe_3$ $Cu_3$ | 2.1 | +2 |
| Manganin | $Cu_{84}$, $Mn_{12}$, $Ni_4$ | 0.3 to 0.47 | ±2 |
| Alloy 479 | $Pt_{92}$, $W_8$ | 3.6 to 4.4 | +24 |
| Nickel | Pure | −12 to −20 | 670 |
| Nichrome V | $Ni_{80}$, $Cr_{20}$ | 2.1 to 2.63 | 10 |
| Silicon | (*p* type) | 100 to 170 | 70 to 700 |
| Silicon | (*n* type) | −100 to −140 | 70 to 700 |
| Germanium | (*p* type) | 102 | |
| Germanium | (*n* type) | −150 | |

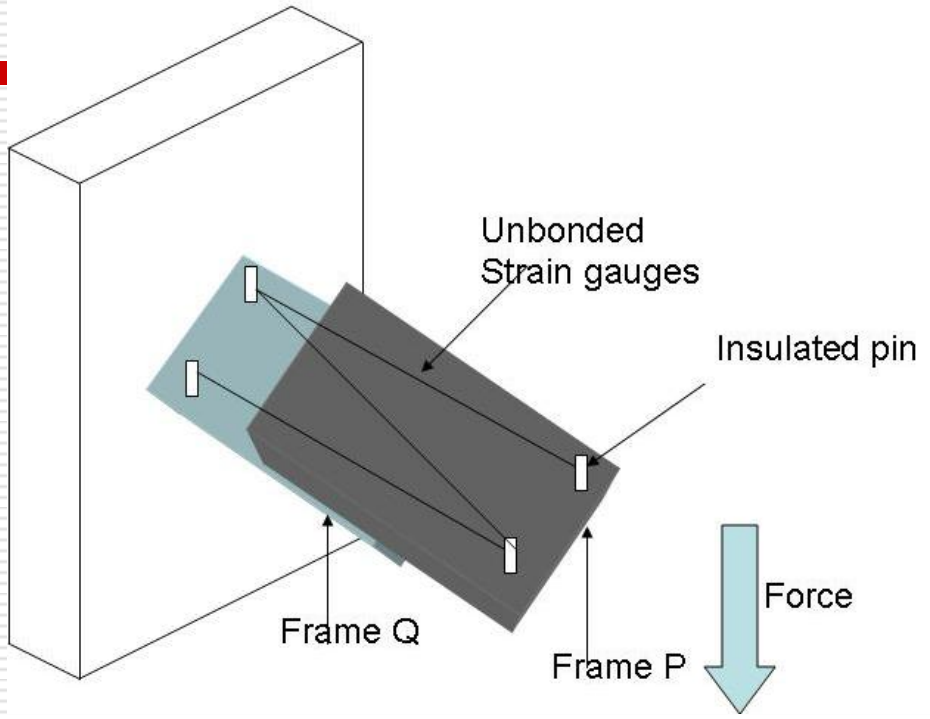
# Unbonded Strain Gage

- Strain gages can be classified as either unbonded or bonded.
- The unbonded strain gauge on the left consists of two wires connected to a fixed frame and two wires connected to a movable armature.
- When pressure is applied to the diaphragm , the armature moves, and two wires stretch while the other two contract. The resulting change in electrical resistance reflects the pressure applied.




- This type of sensor may be used for converting blood pressure to diaphragm movement, to resistance change, then to an electric signal.

# Unbonded Strain Gage

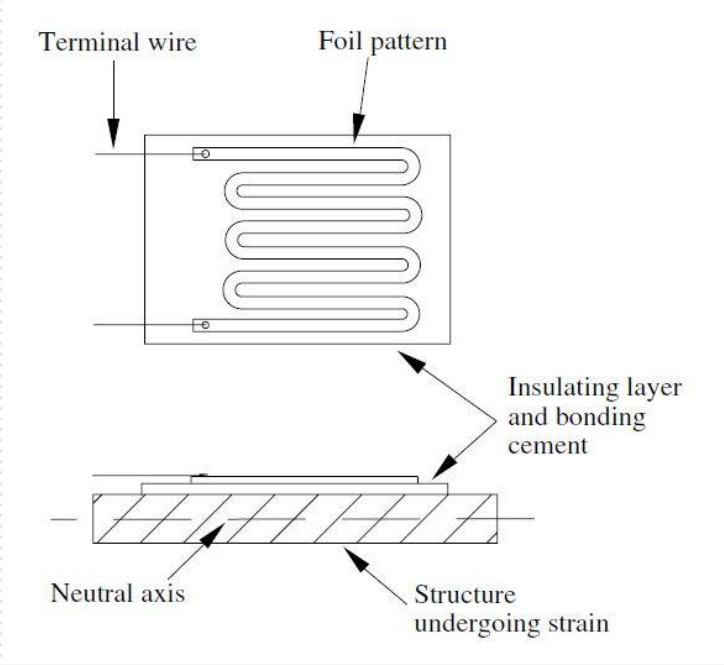


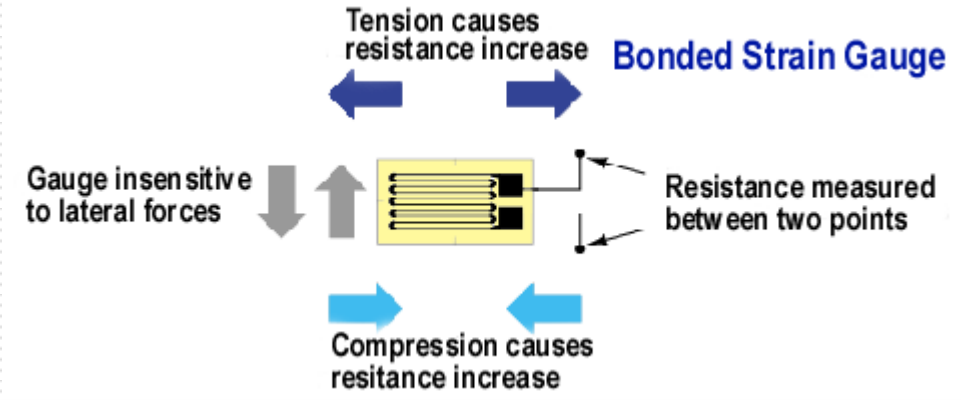

The strain gauge is not directly bonded or pasted onto the surface.

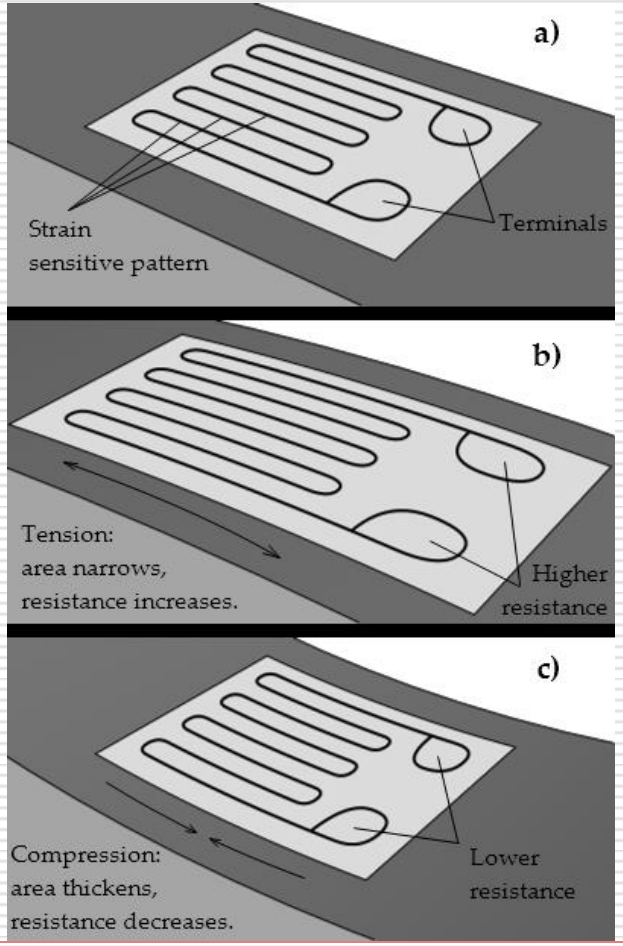
http://instrumentationandcontrollers.blogspot.com/2010/11/unbonded-strain-gauges.html

# Bonded Strain Gage

- In bonded strain gauges, the wire filament is embedded in cloth, paper, plastic, or resin and is mounted onto a flexible plate. When pressure is applied to the flexible plate, the filament wires stretch or contract. The resulting change in resistance reflects the pressure applied.



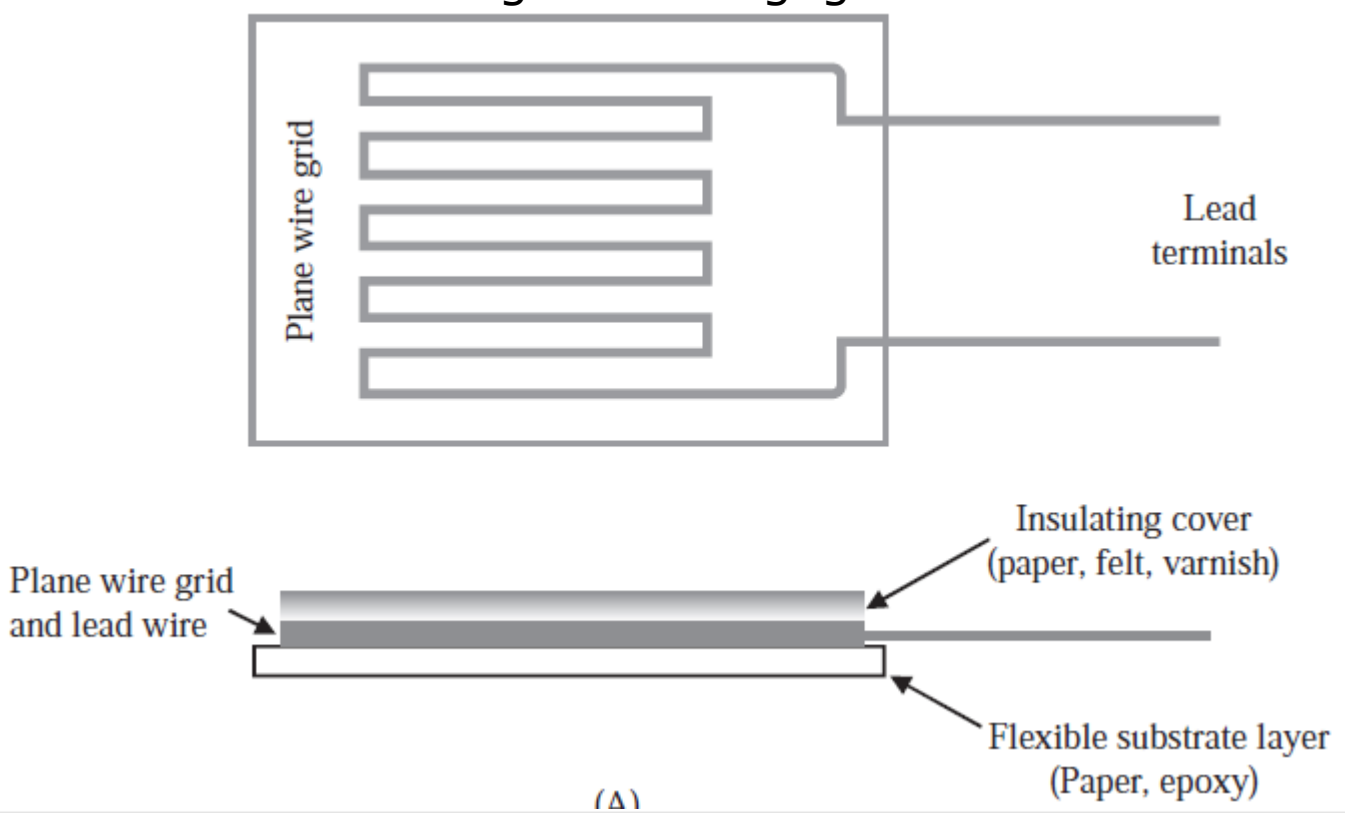




a)
Strain
sensitive pattern
Terminals
b)
Tension:
area narrows,
resistance increases.
Higher
resistance
c)
Compression:
area thickens,
resistance decreases.
Lower
resistance

# Types of Bonded strain gages

- Plane grid strain gages were developed in the end of the 1930s. The resistance wire is formatted like a plane grid; then the grid is bonded to a flexible substrate (paper or epoxy (reçine) ) and receives a thin layer of insulating material (paper, felt (keçe), or varnish (vernik)).

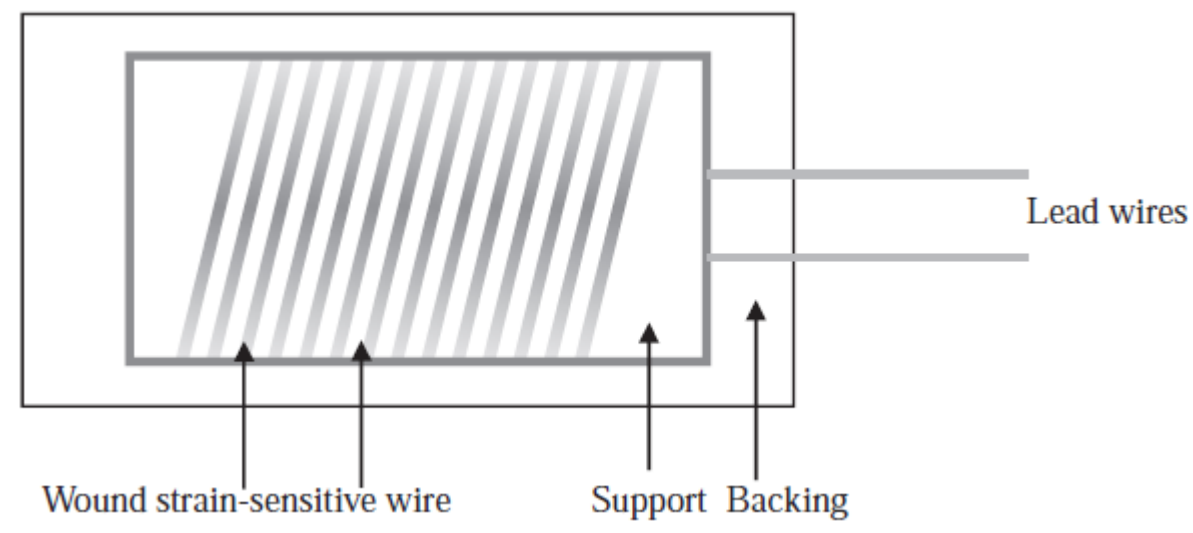
Plane grid strain gages



# Types of Bonded strain gages

- Wound grid strain gages are constructed by winding the strain-sensitive metal wire around a support made of paper, for instance, and then recovering the set with an insulating material

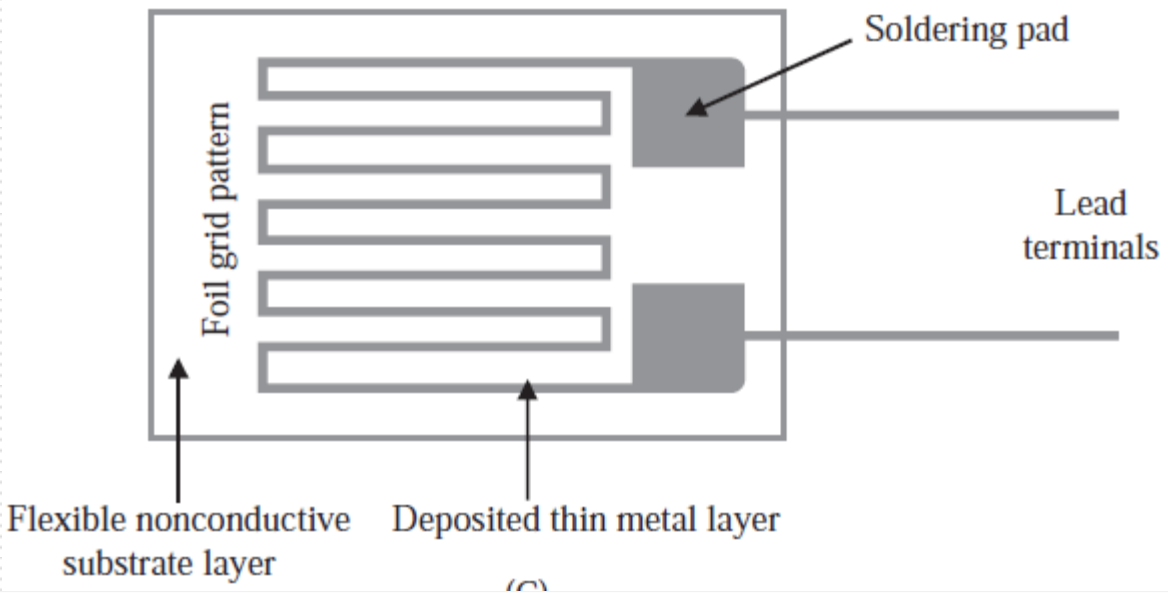
Wound grid strain gages



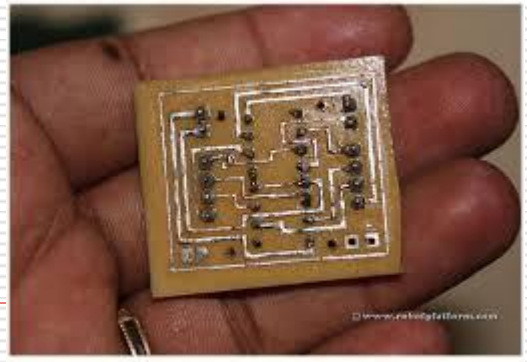
# Types of Bonded strain gages

- Foil grids can be fabricated with printed circuit technique (etching (oyma)), allowing complex and varied metallic grid formats that can be bonded to a proper substrate material, called the carrier, for instance, a thin layer of ceramic; alternatively thin strips of metallic film are deposited on a nonconducting substrate without the need of using any cement or glue.
- They are the most used strain gages since 1950, when they were developed. They are constructed with lengths varying from 20 μm to 10 mm and grid thickness ~25 μm, to get nominal resistance values from a few tens of Ω to a few units of kΩ

Foil grids strain gages

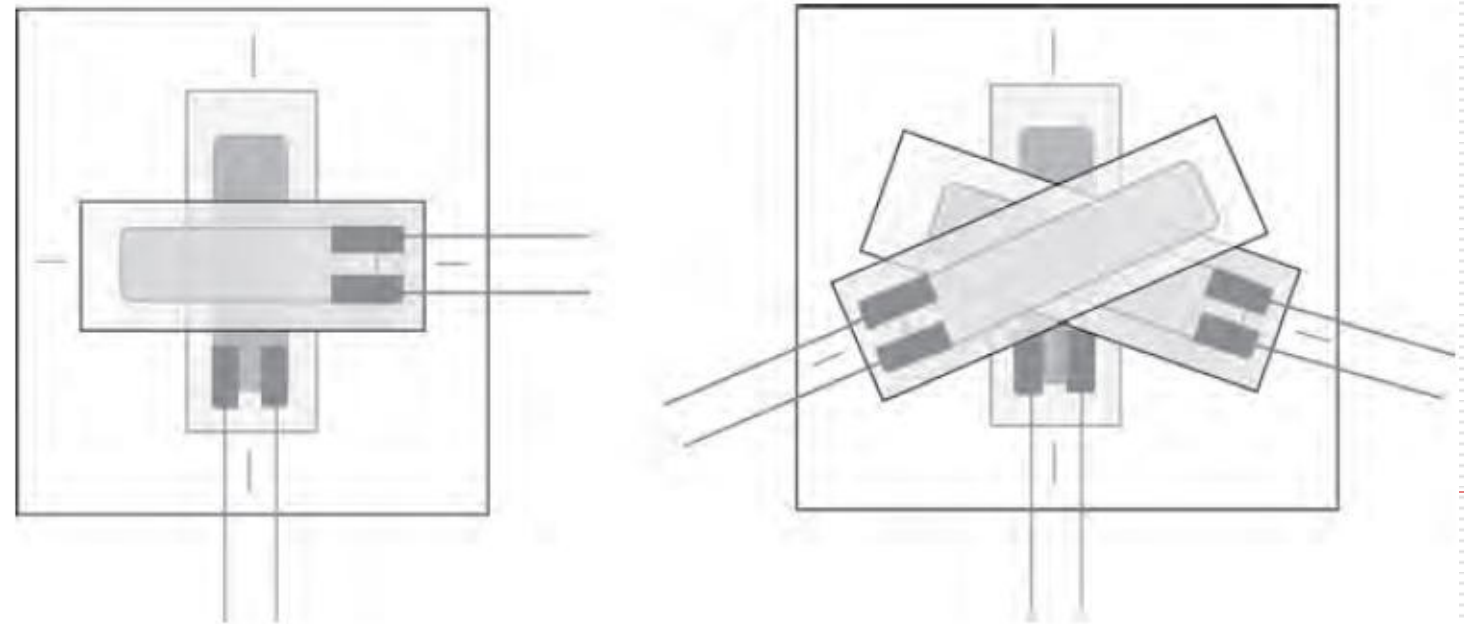


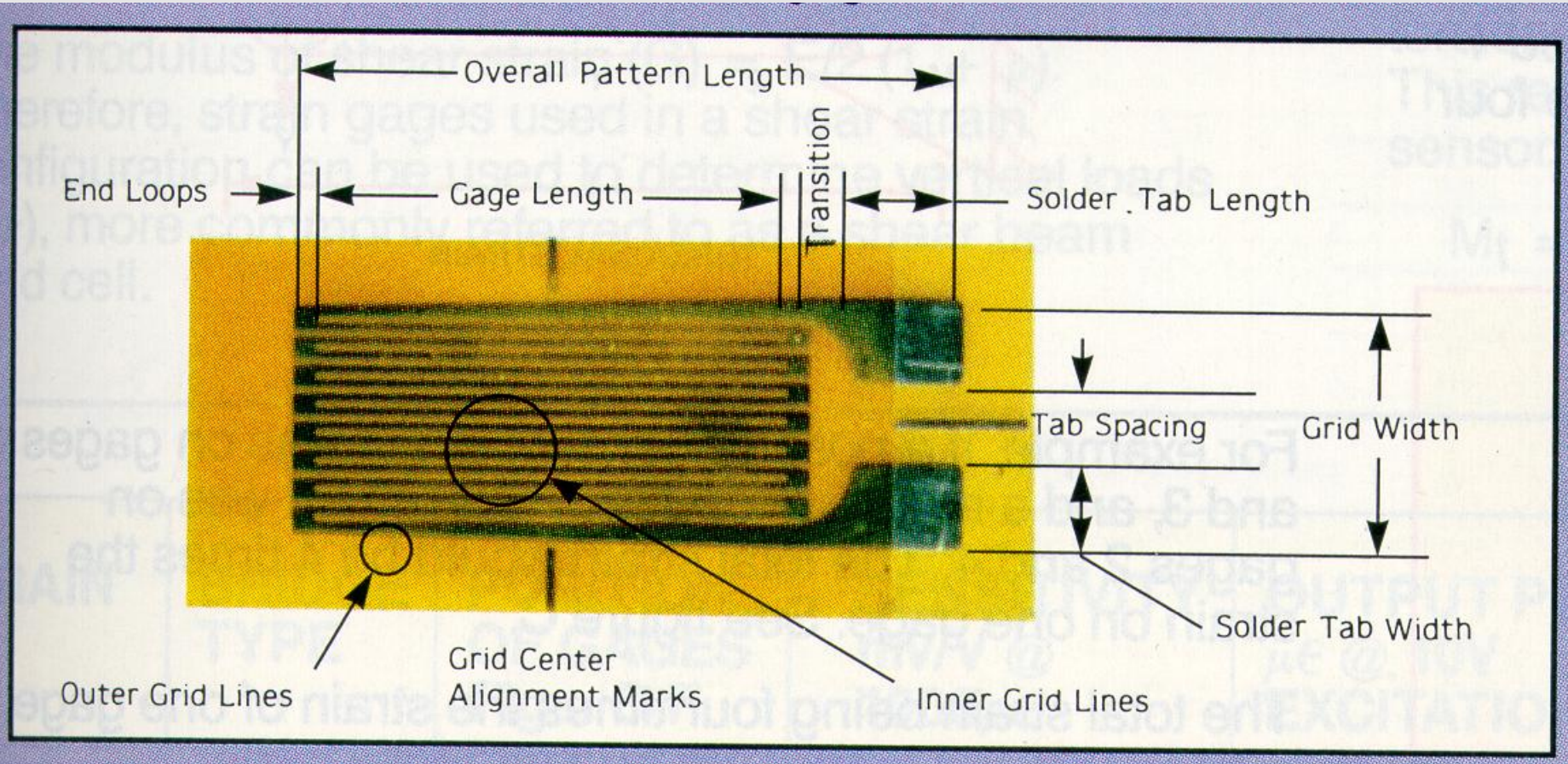

etching (oyma)

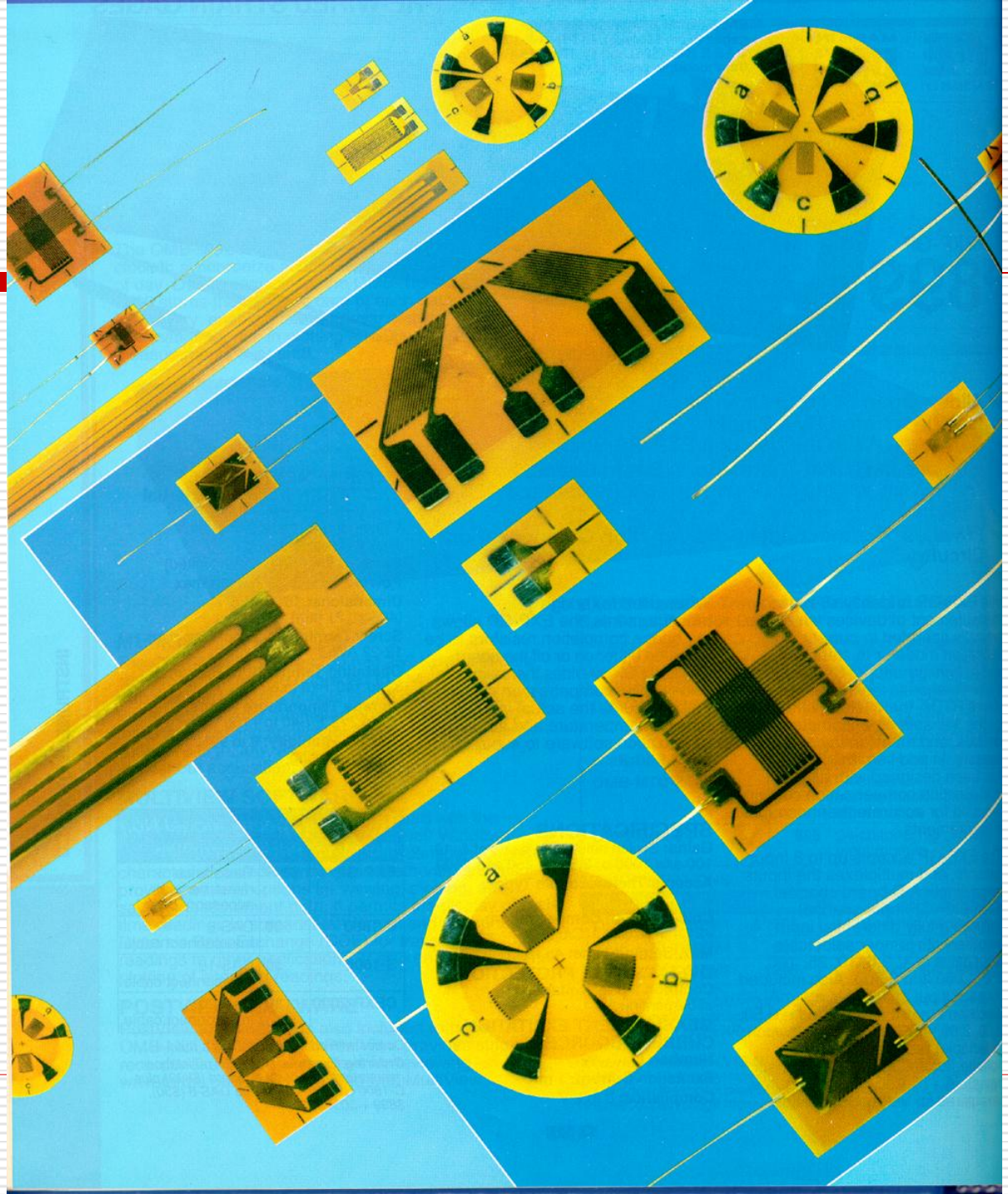


# Bonded Strain Gage

- They can be used to do static and dynamic measurements with very low hysteresis;
- They are relatively **low cost** and **temperature insensitive**;
- Their **accuracy** is better than ±0.10% and are constructed with nominal resistances ranging from 100 Ω to 1 kΩ in sizes small as a few millimeters and ΔLmax as large as a few μm.
- If deformation occurs in two main directions, and these directions are known, a two-direction rosette (çiçeksi rozet) can be used. Both strain gages are constructed on the same substrate.
- If the main deformation directions are unknown, multiple direction rosettes can be used.




Overall Pattern Length
End Loops
Gage Length
Transition
Solder Tab Length
Tab Spacing
Grid Width
Solder Tab Width
Outer Grid Lines
Grid Center
Alignment Marks
Inner Grid Lines



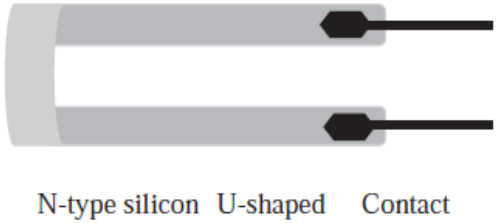
# Semiconductor Integrated Strain Gages

- Strain-gage technology advanced in the 1960s with the introduction of the semiconductor strain-gage element, which has the advantage of having a high gage factor.

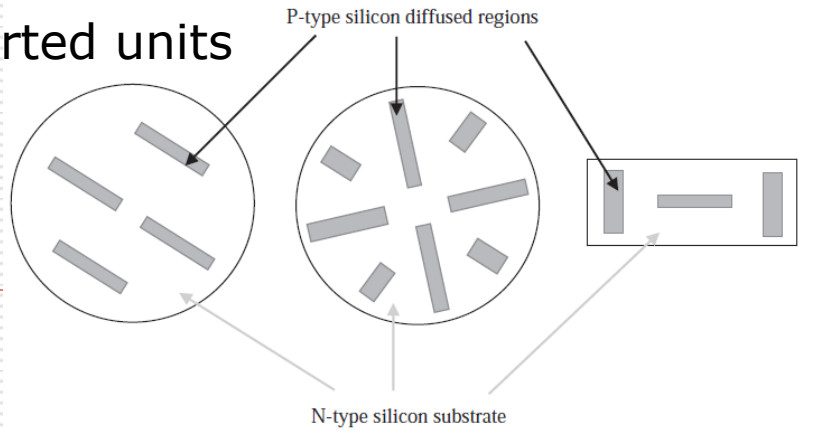
$$G = \frac{\Delta R/R}{\Delta L/L} = (1 + 2\mu) + \frac{\Delta \rho/\rho}{\Delta L/L}$$

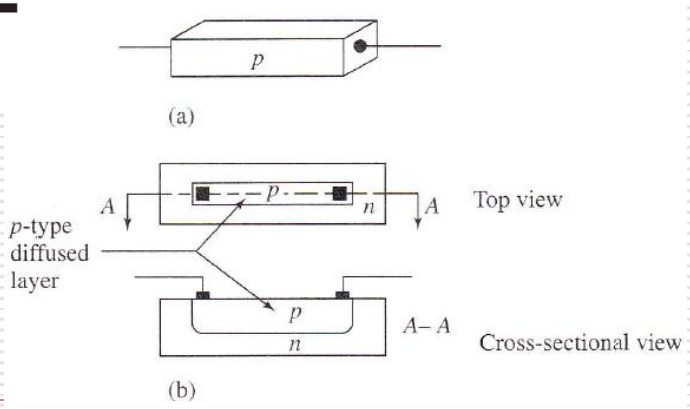
- Semiconductor strain gages are fabricated as loose units, usually of P Silicon, and as inserted units, which are P Silicon regions diffused in a larger N Silicon substrate (wafer) or vice versa.
- Loose units have different formats as bar (strait and thin strips) and U shape (Figure 5.10A). P diffused regions of inserted units can have the most variable formats, as complex rosettes or simple squares

loose units




inserted units




(a) unbonded, uniformly doped, (b) diffused p-type gage

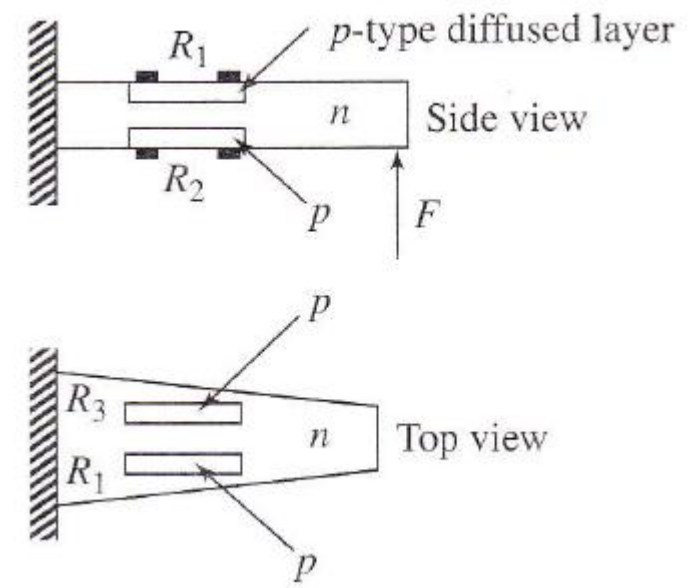
# Semiconductor Integrated Strain Gages

- Linearity error of loose semiconductor strain gages is in the range 10-20% while inserted gages have linearity error 1%.
- Semiconductor strain gages use the same principles as the wire/foil gages.
- Foil gages are selected over semiconductor gages only for macroscopic applications where significant pressure or displacement/velocity must be recorded.
- Semiconductor strain gages are more temperature sensitive and inherently more nonlinear than metal strain gages because the piezoresistive effect varies with strain.

| Strain gage characteristic | Metal | Semiconductor |
|---|---|---|
| Strain range ($\varepsilon = \Delta L/L$) | $(1 \times 10^{-1} - 40 \times 10^{3}) \times 10^{-6} \times \varepsilon$ | $(1 \times 10^{-3} - 3 \times 10^{3}) \times 10^{-6} \times \varepsilon$ |
| Sensitivity (G) | 2.0–12 | 100–170 |
| Nominal value ($\Omega$) | 120, 350, . . . , 5,000, 10,000 | 1,000–5,000 |
| Resistance tolerance | 0.1–0.2% | 1–2% |
| Linearity error | 1–5% | 10–20%—loose<br>≈ 1% inserted |
| Size (mm) | 3–6 (smaller and larger sizes available) | 1–5 (smaller sizes available) |

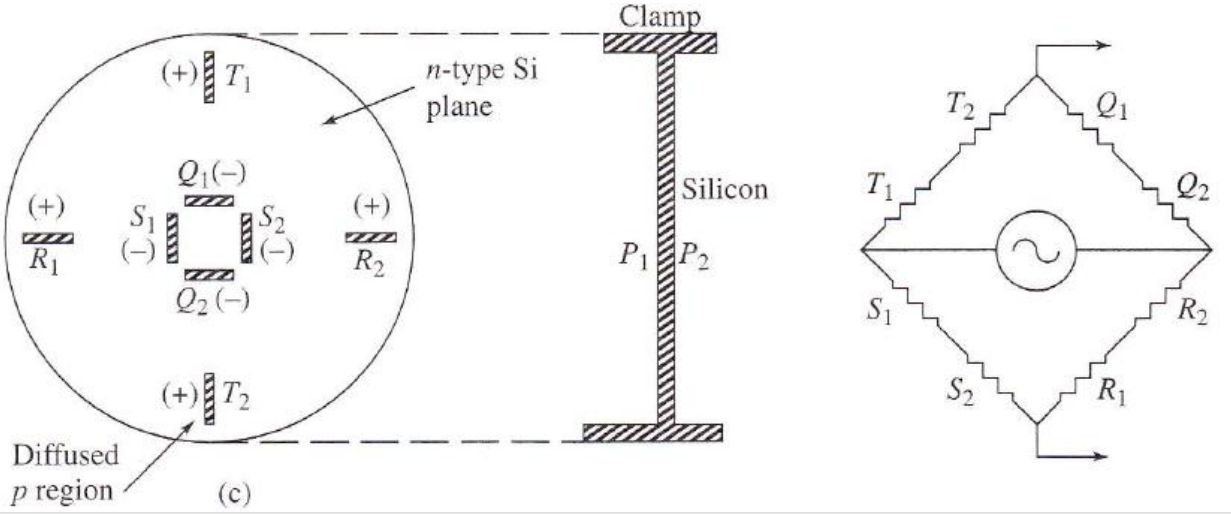
# Semiconductor Integrated Strain Gages

- Integrated cantilever-beam force sensor



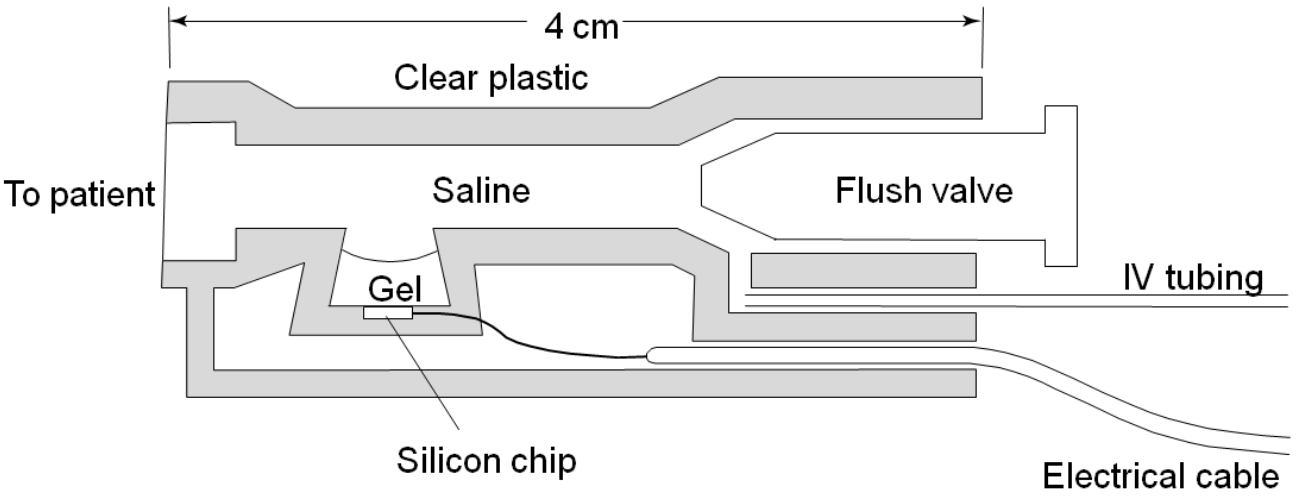
# Semiconductor Integrated Strain Gages

- The integrated-type sensor has an advantage in that a pressure sensor can be fabricated by using a silicon substrate for the structural member of the diaphragm. The gages are diffused directly onto the diaphragm.
- When pressure is applied to the diaphragm, a radial stress component occurs at the edge. The sign of this component is opposite to that of the tangential stress component near the center.
- The placement of the eight diffused strain-gage units shown in Figure (c) gives high sensitivity and good temperature compensation (Cobbold, 1974).

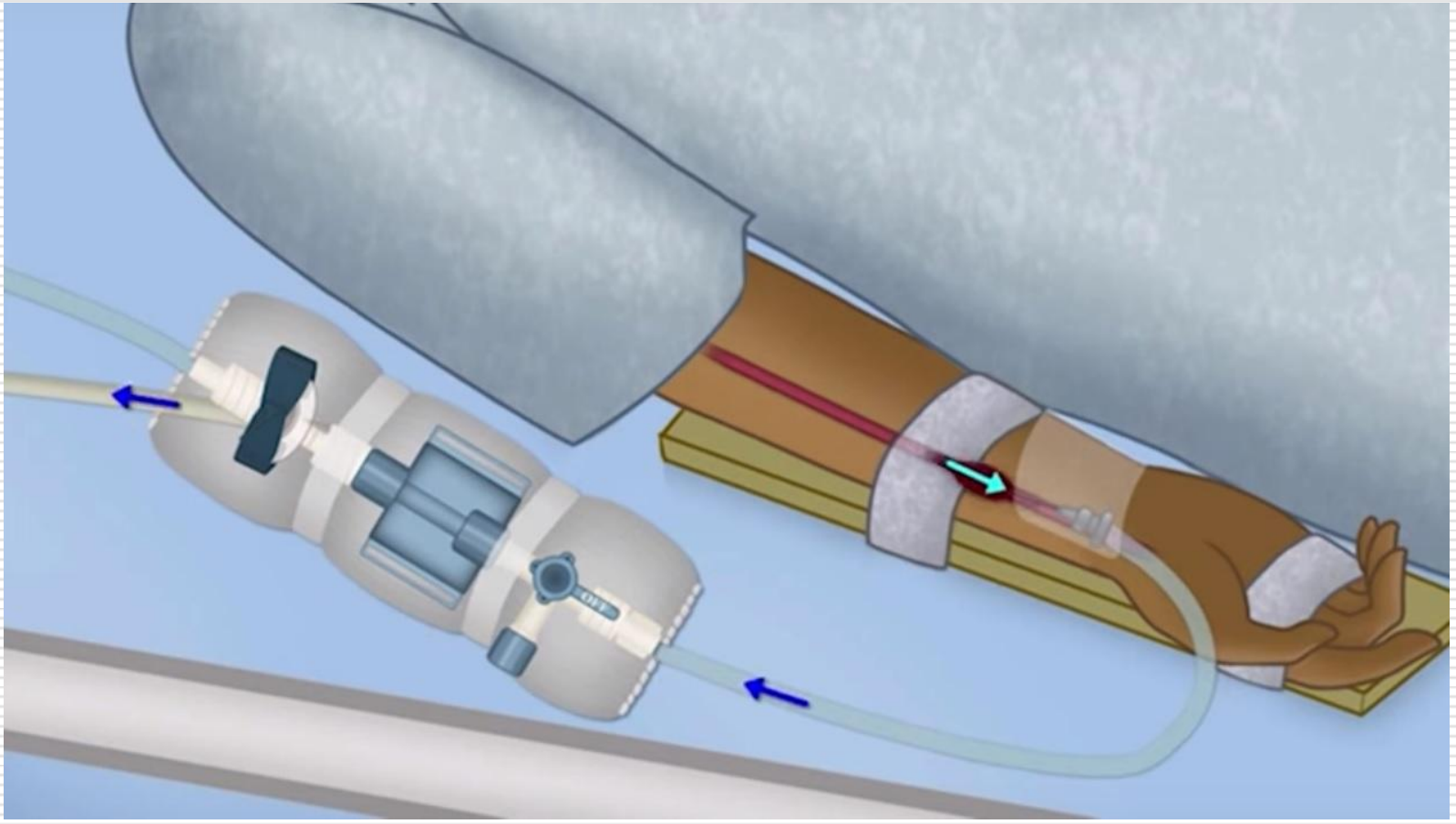


# Example:
# Isolation in a disposable blood-pressure sensor

- Below figure shows a disposable blood-pressure sensor that uses an integrated silicon chip. Silicon strain-gage pressure sensors can be placed on the tip of a catheter and inserted directly into the blood, resulting in more accurate measurements and faster response times
- Disposable blood pressure sensors are made of clear plastic so air bubbles are easily seen. Saline flows from an intravenous (IV) bag through the clear IV tubing and the sensor to the patient. This flushes blood out of the tip of the indwelling catheter to prevent clotting. A lever can open or close the flush valve. The silicon chip has a silicon diaphragm with a four-resistor Wheatstone bridge diffused into it. Its electrical connections are protected from the saline by a compliant silicone elastomer gel, which also provides electrical isolation. This prevents electric shock from the sensor to the patient and prevents destructive currents during defibrillation from the patient to the silicon chip.



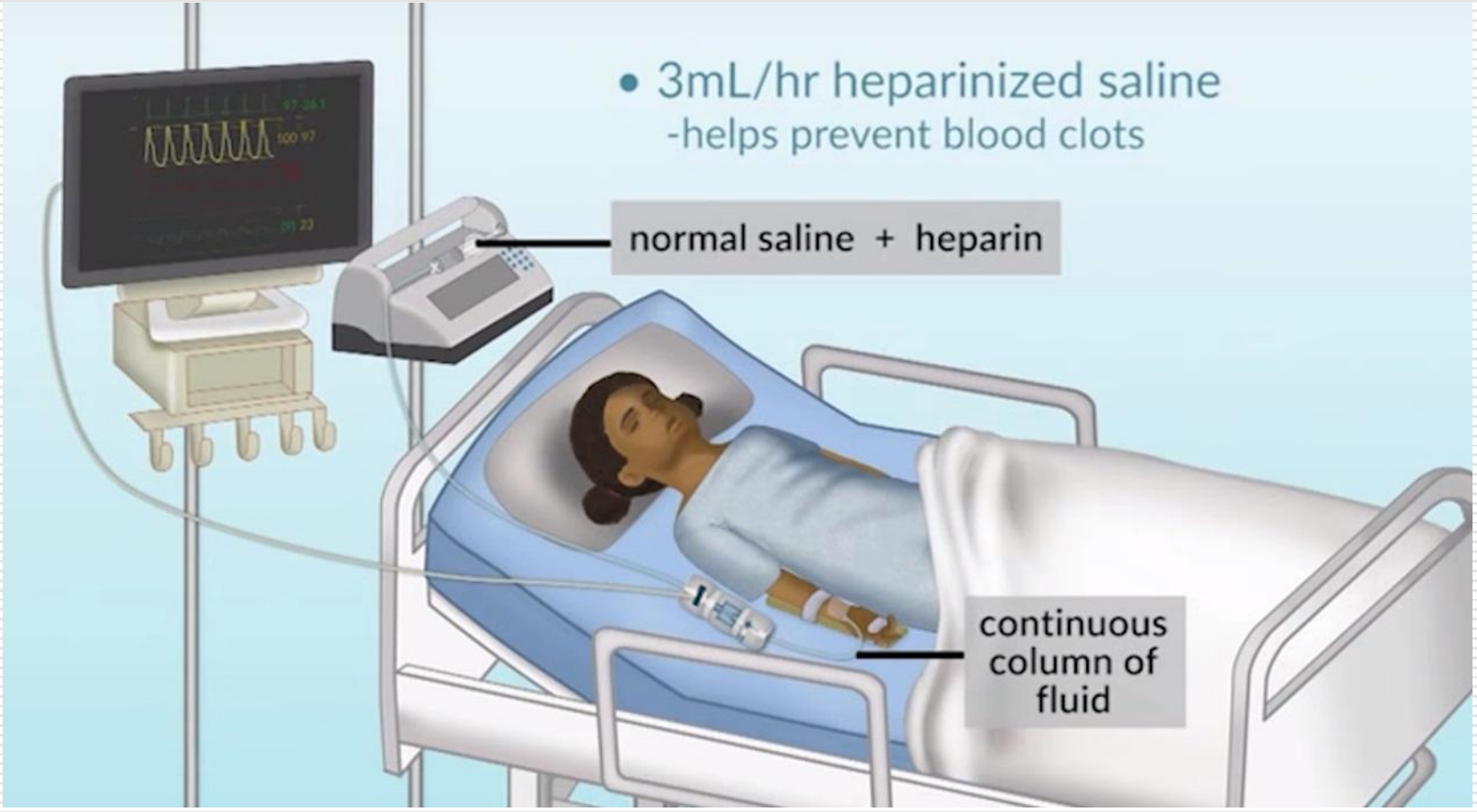
# Invasive Blood Pressure Measurement



https://www.youtube.com/watch?v=aJmQepDWVqw

"Transducers in Invasive Pressure Monitoring" by James DiNardo, MD for OPENPediatrics

# Invasive Blood Pressure Measurement



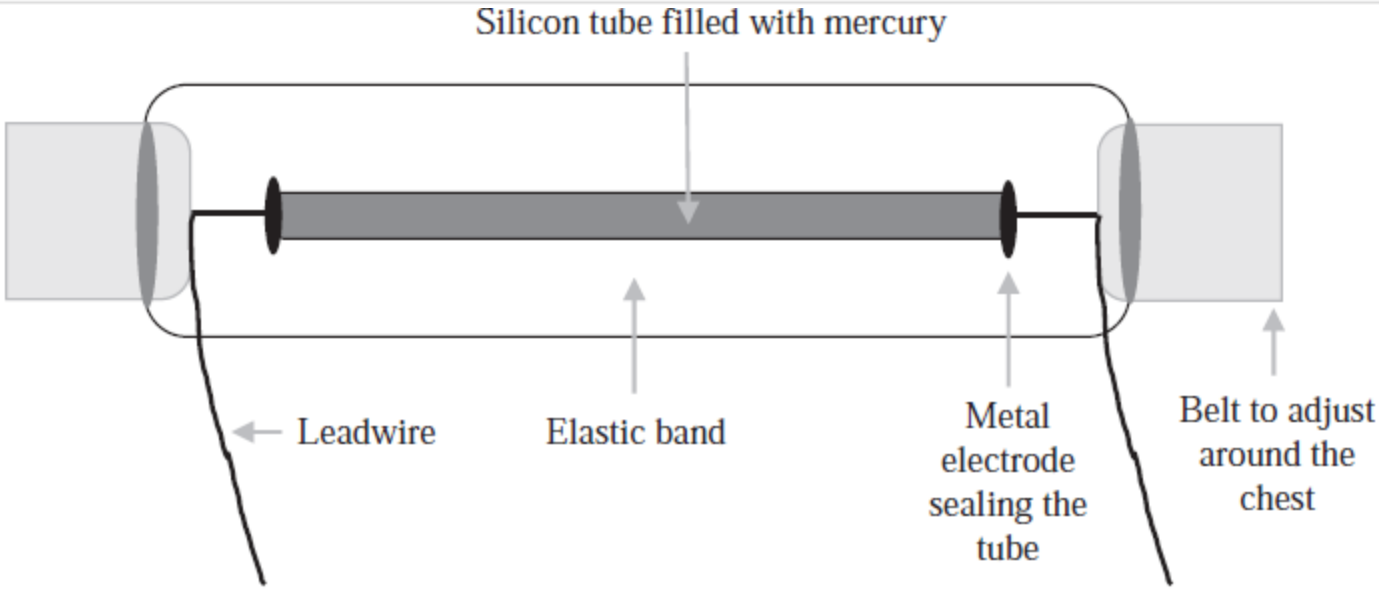

https://www.youtube.com/watch?v=aJmQepDWVqw

"Transducers in Invasive Pressure Monitoring" by James DiNardo, MD for OPENPediatrics

# Elastic-Resistance Strain Gages

- Elastic-resistance strain gages are extensively used in biomedical applications, especially in cardiovascular and respiratory dimensional and plethysmographic (volume-measuring) determinations.
- These systems normally consist of a narrow silicone-rubber tube [0.5 mm inner diameter (ID), 2 mm outer diameter (OD)] from 3 to 25 cm long and fillled with mercury or with an electrolyte or conductive paste. The ends of the tube are sealed with electrodes (amalgamated copper, silver, or platinum). Resistance values from 0.02 to 2 Ω/cm
- If the conductive fluid inside the elastic tube is liquid mercury, which is essentially incompressible, a tensile force applied between the extremities of the tube stretches it (as in the blood income in the limb during cardiac systole) and reduces the tube diameter, with the volume remaining constant.
- These units measure much higher displacements than other gages.
- Such devices were replaced by solid state strain gage or other modern technology instruments.

$$R = \left(\frac{\rho L^2}{V}\right)$$




**V** is the volume of mercury inside the elastic tube
**L** is the length of the tube
**A=V/L** is the cross-sectional area of the tube filled with mercury

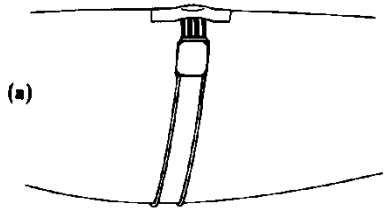
The variation in mercury resistance to a length stretching can be approximated by

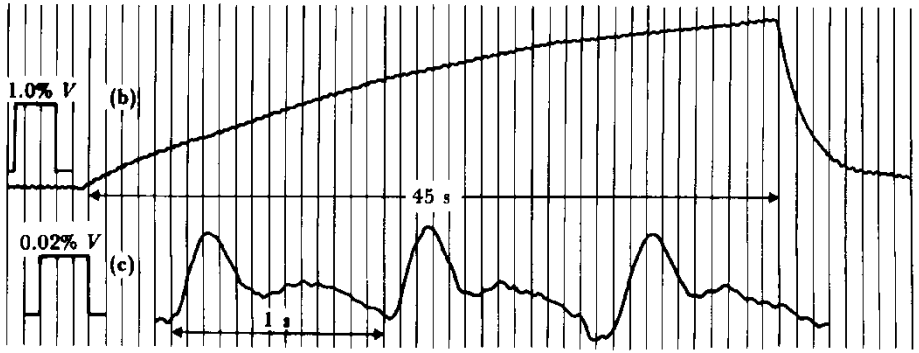
$$\frac{\Delta R}{\Delta L} = \frac{2\rho L}{V} = \frac{2R}{L}$$

# Elastic-Resistance Strain Gages

- The nonlinearity error varies with the distension percentage with regard to the original length: for deformations up to 10%, the error is in the range ±1% of full scale; above 30% of the resting value, the error is ± 4%.
- They respond well to frequencies ,10 Hz; frequency components above 30 Hz are considerably distorted
- Elastic displacement transducers are also used to monitor, typically in neonates, the displacement of the chest during breathing, which is useful to avoid death by respiratory arrest of the sleep apnea test that typically affects premature neonates.

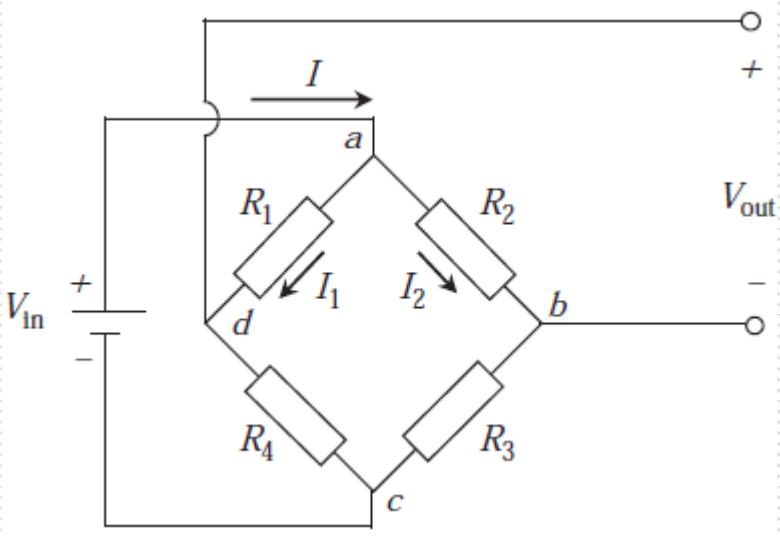
Mercury-in-rubber strain-gage plethysmography (a) Four-lead gage applied to human calf, (b) Bridge output for venous-occlusion plethysmography. (c) Bridge output for arterial-pulse plethysmography.



# The Wheatstone bridge

- When the bridge is balanced: Vout=0, Vad = Vab, and Vdc = Vbc, the potential drops in the branches adc and abc are equal to Vin



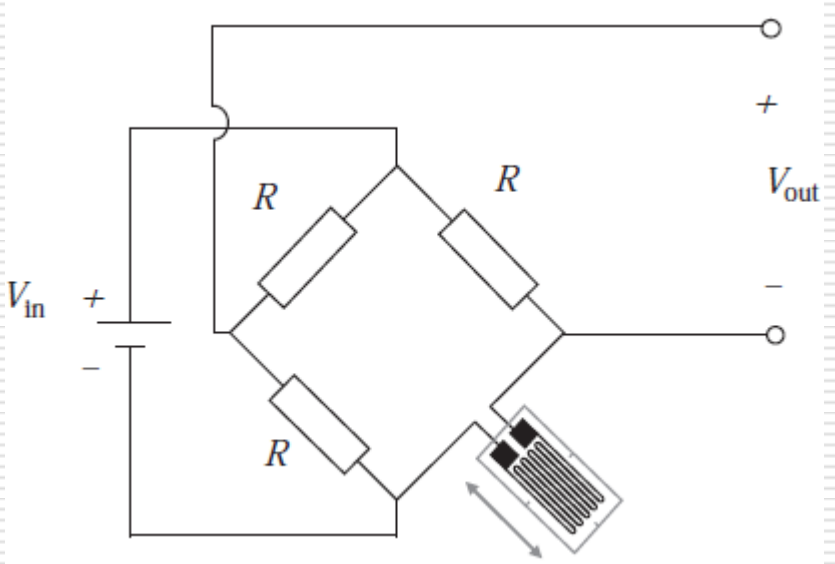

$$I_1 = \frac{V_{in}}{R_1 + R_4} \quad \text{and} \quad I_2 = \frac{V_{in}}{R_2 + R_3}$$

$$V_{out} = R_4 I_1 - R_3 I_2 = 0$$

$$V_{out} = \left( \frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3} \right) V_{in}$$

# The Wheatstone bridge one-quarter bridge

- Making all resistances in the bridge equal to R and replacing one of them by a strain gage with nominal unstressed resistance also equal to R, for example, R3, the configuration is called one-quarter bridge
- In the balance, the output of the bridge is null. If the strain gage resistance R changes to (R+ΔR), the voltmeter indicates V0≠0, that is proportional to the strain experienced by the strain gage.




$$V_{out} = \left(\frac{R+\Delta R}{2R+\Delta R} - \frac{R}{2R}\right) V_{in}$$

$$I_1 = \frac{V_{in}}{R_1 + R_4} \quad \text{and} \quad I_2 = \frac{V_{in}}{R_2 + R_3}$$

$$V_{out} = R_4 I_1 - R_3 I_2 = 0$$

$$V_{out} = \frac{\Delta R}{2(2R+\Delta R)} V_B \cong \frac{\Delta R}{4R} V_B$$

$$G = \frac{\Delta R/R}{\Delta L/L} = (1+2\mu) + \frac{\Delta \rho/\rho}{\Delta L/L}$$

$$\varepsilon = \frac{\Delta L}{L} = \frac{\Delta R}{GR}$$

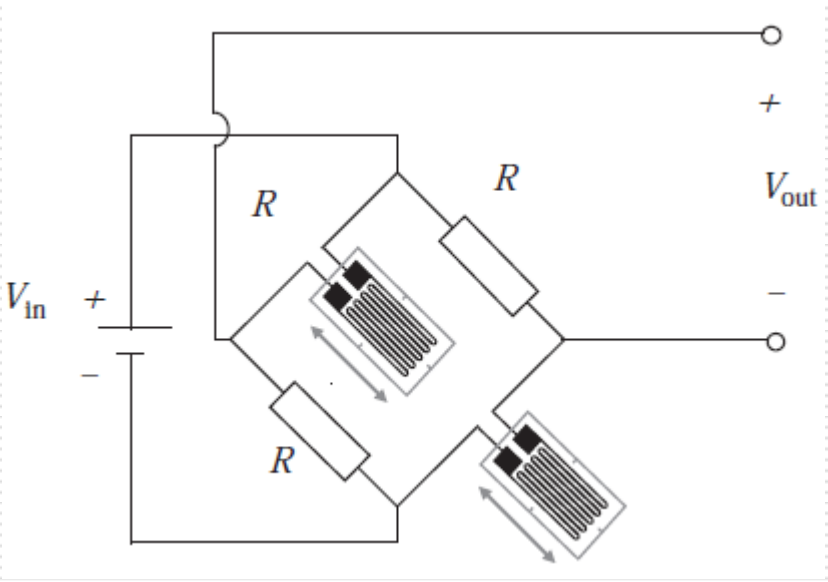
$$V_{out} = \frac{G\varepsilon}{4+2G\varepsilon} V_{in}$$

$$V_{out} = \left(\frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3}\right) V_{in}$$

# The Wheatstone bridge half bridge

- Replacing two resistors by strain gages, the configuration is called half-bridge and the resulting equation depends on which resistors are replaced and the direction of sensitivity of the gages.
- If two resistors are in opposed arms of the bridge, for example, R1 and R3, by active strain gages, both sensitive to tension or compression (same direction forces) the output voltage is calculated by

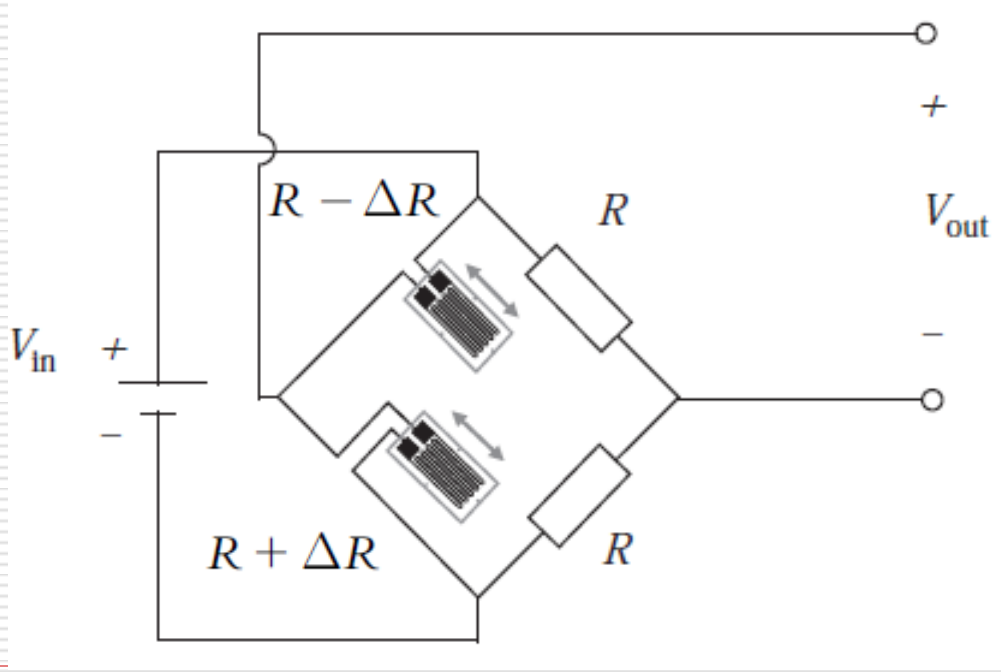
$$V_{out} = \frac{G\varepsilon}{2 + G\varepsilon} V_{in}$$



# The Wheatstone Bridge: Half Bridge

- If active strain gages replace two resistors, but in adjacent arms (R1 and R4) one sensitive to **tension** and the other to **compression** (opposite direction forces), the unbalanced output voltage is

$$V_{out} = \frac{G \cdot \varepsilon}{2} V_{in}$$



# The Wheatstone bridge half bridge ???

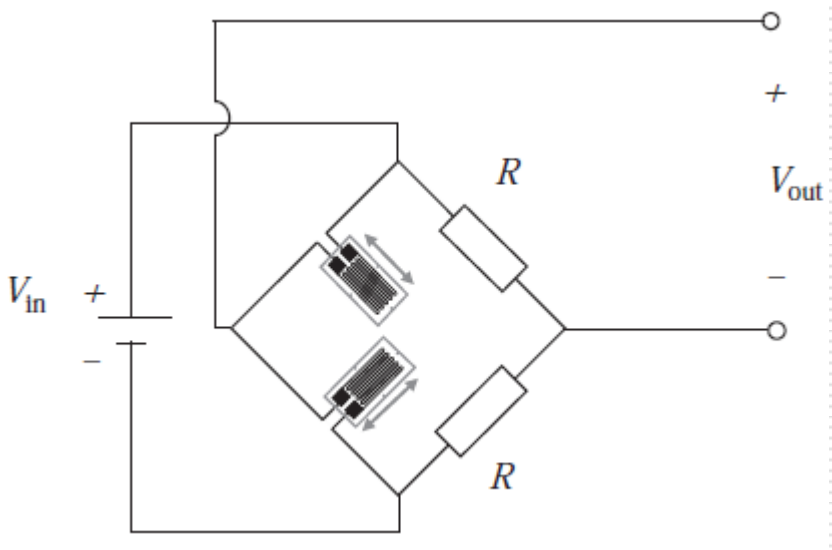
- Replacing R1 and R4 by active strain gages sensitive to tension or compression, but in perpendicular directions, the unbalanced output voltage is

$$V_{\text{out}} = \frac{G\varepsilon(1-\nu)}{2 + G\varepsilon(1-\nu)} V_{\text{in}}$$

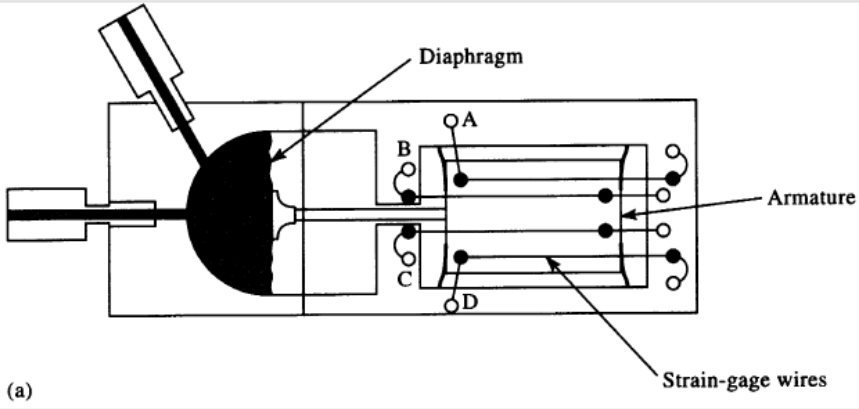
- where ***v*** is the Poisson's coefficient:

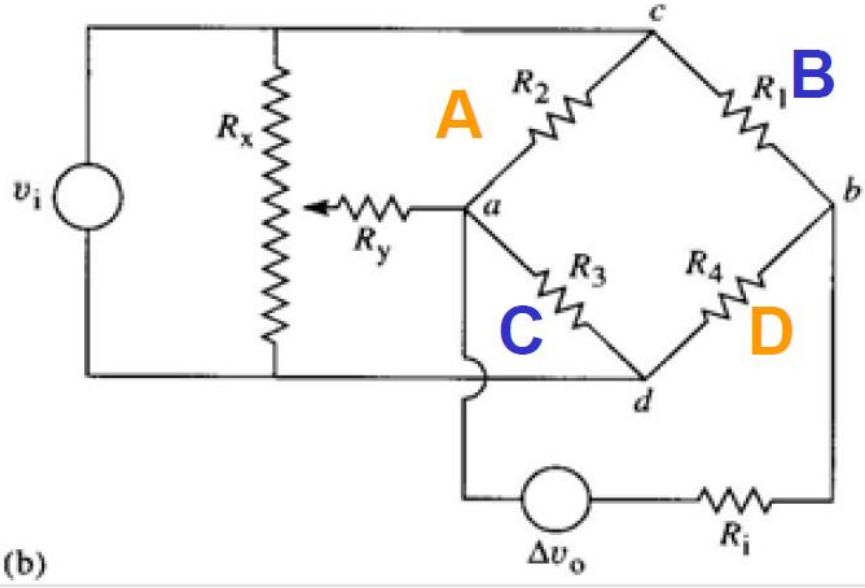
$$\nu = -\varepsilon_{\text{L}} / \varepsilon_{\text{T}}$$

- $\varepsilon_L$ and $\varepsilon_T$ are the strains in lateral and longitudinal directions, respectively.



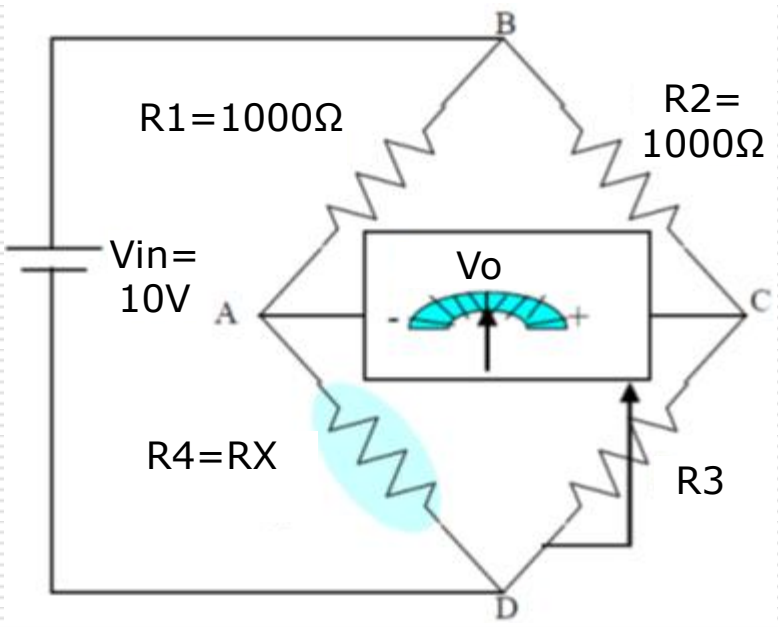
- Full bridge configuration: all bridge elements are variable (sensors).
- The four sets of strain-sensitive wires, A, B, C and D are connected to form a Wheatstone bridge.
- The diaphragm is directly coupled by an armature to an unbonded strain-gage system.
- With increasing pressure, the strain on gage pair B and C is increased, while that on gage pair A and D is decreased.
- Wheatstone bridge with four active elements. *R1=A, R2=B, R3=D, and R4=C.*
- When the unbonded strain gage is connected for translation motion. Resistor *Ry* and potentiometer *Rx* are used to initially balance the bridge.
- $v_i$ is the applied voltage and $v_0$ is the output voltage on a voltmeter or similar device with an internal resistance of *Ri*.



# Example: *Static Balanced Mode*

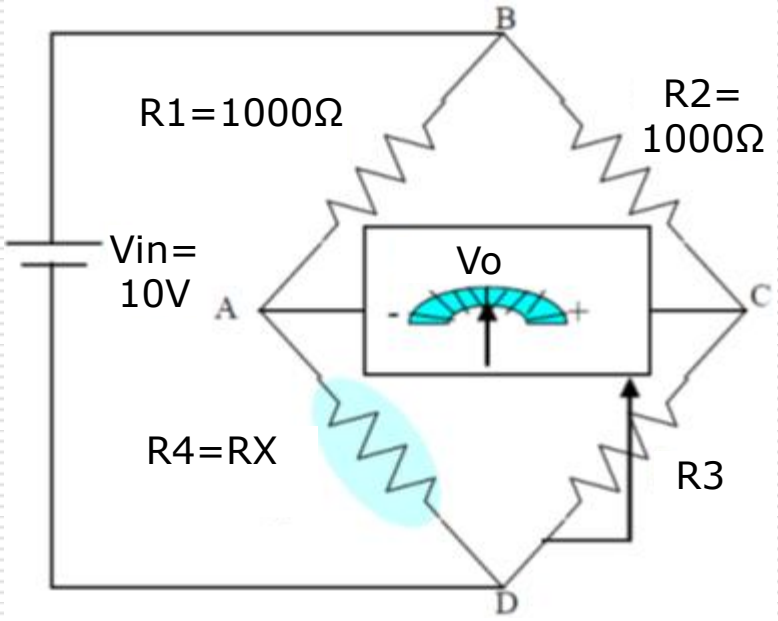
- Assume that the bridge shown in figure is used to determine the resistance of an unknown strain gage, R4=Rx. The variable resistance is set until voltmeter reads 0A. Calculate the unknown resistance R4, if the variable resistance setting indicates 1000Ω.
- Assume that after a stress applied on strain gage R4=Rx, voltmeter has started reading a voltage value≠0V. By readjusting the R3=1020Ω, brigde is balanced and no voltage is measured by voltmeter. What is the new value of R4 and ΔR4?



# Example

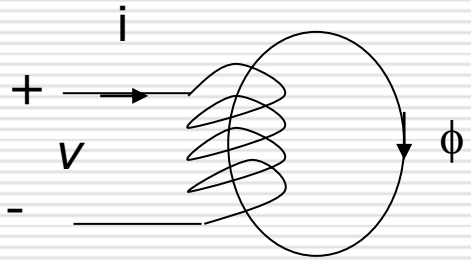
- The bridge will be balanced if R1/R4 = R2/R3 .
- Hence, R4 = Rx = R1/(R2/R3) = 1000x1000/1000 = 1000Ω

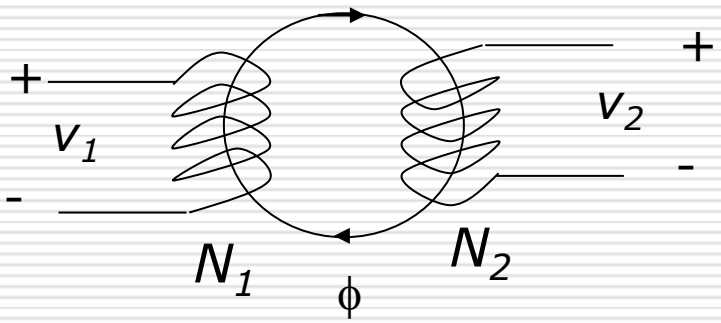
- After rebalancing bridge R3 becomes 1020Ω, then R4 = Rx = R1/(R2/R3) = 1000x1020/1000 = 1020Ω.
- ΔR4= 1020-1000=20Ω
- As you might notice, ΔR3= ΔR4=20Ω



# Inductive Sensors

- **Ampere's Law**: flow of electric current will create a magnetic field
- **Faraday's Law**: Electromagnetic induction is the process by which a current can be *induced* to flow due to a changing magnetic field.




$$v = N\frac{d\Phi}{dt}$$

$$v_1 = \frac{N_1}{N_2}v_2$$

# Inductive Sensors

- Inductive Sensors are non-contact type of devices used for precision measurement of a target position if the target is conductive in nature.
- Capacitive sensors make use of electric field for sensing the surface of a conducting target. Inductive sensors make use of electromagnetic field that penetrates through the target.
- An inductive sensor has an advantage in not being affected by the dielectric properties of its environment.
- However, it may be affected by external magnetic fields due to the proximity of magnetic materials.
- Unlike capacitive sensors, inductive sensors are independent of the material in the gap between the probe and the target. Hence, they can be used in hostile environment where oil or other liquids may appear in the gap.

# Inductive Sensors

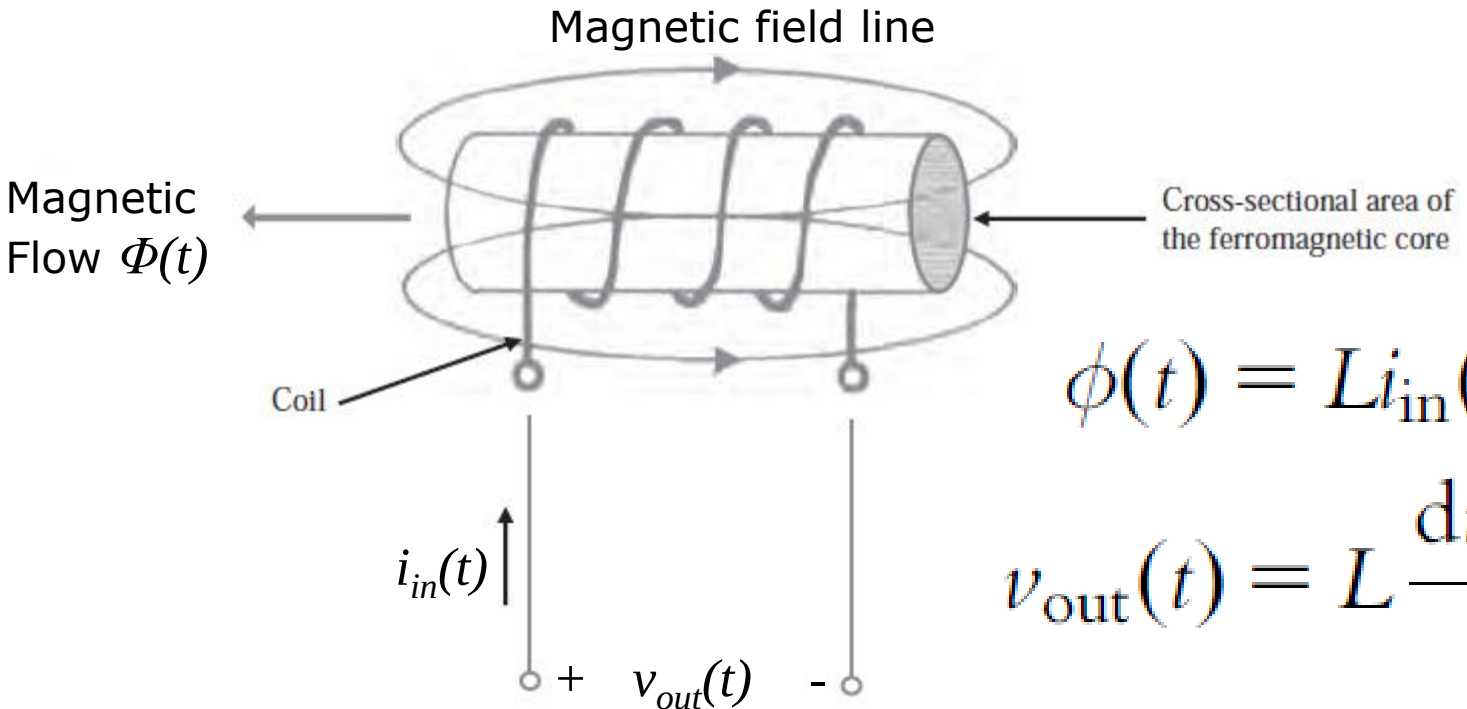
- Inductive transducers of displacement show linearity, long life of use, high sensitivity, and good dynamic response.
- Environment conditions, as humidity and temperature, have little effect on their performance.
- The principle of operation of the inductive displacement transducer is the variation of the self-inductance or auto-inductance (L) of an inductor or the mutual inductance (M) of two inductors

- Inductance L measures displacement by varying any three of the coil parameters.
  - n : Number of turns of coil
  - G : Geometric form factor
  - μ : Effective permeability of medium

$$L = n^2 G \mu$$

- Each parameter can be changed by mechanical means.
- G depends on *k* is a fabrication constant, *r* is the coil radius, and *l* is the coil length

$$G = k\pi r^2 / l$$

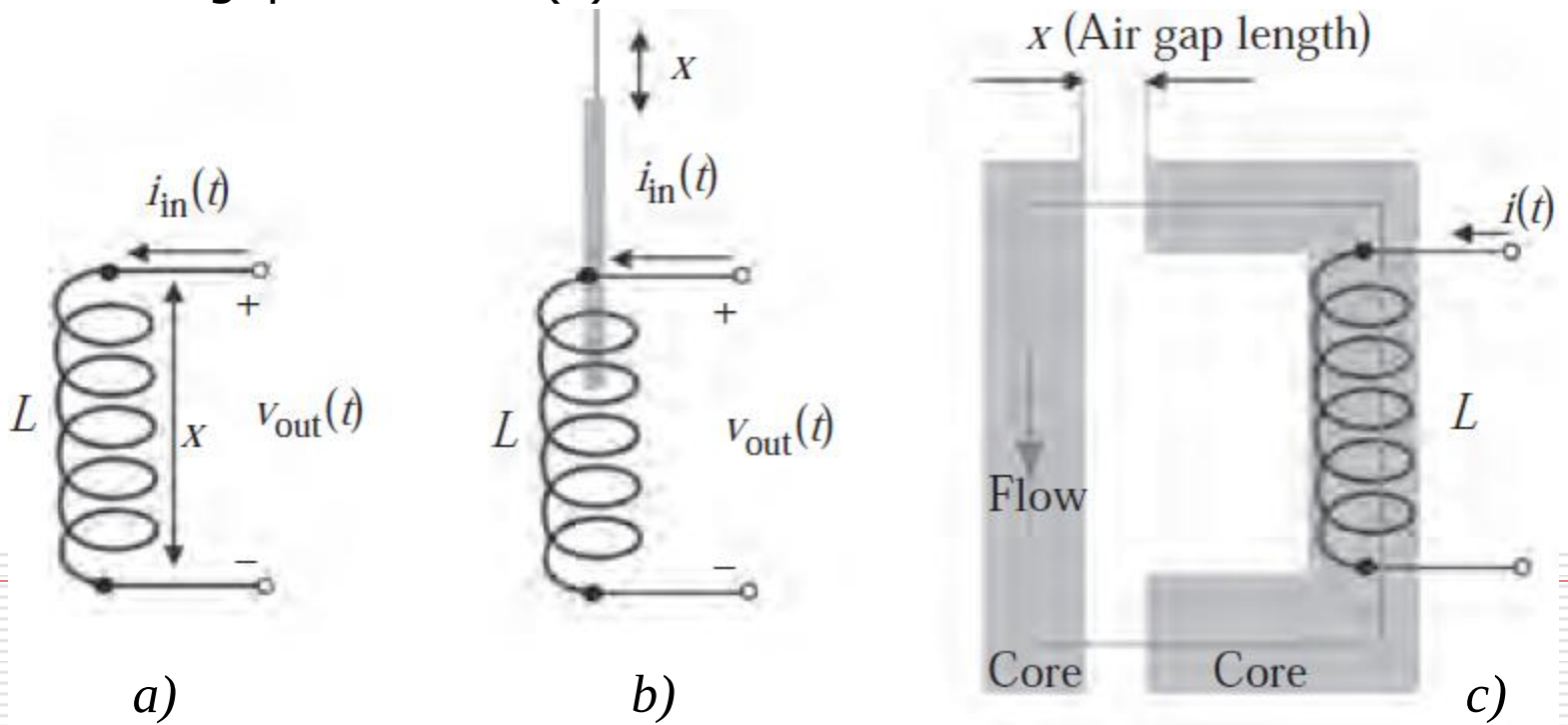



$$\phi(t) = L i_{\text{in}}(t)$$

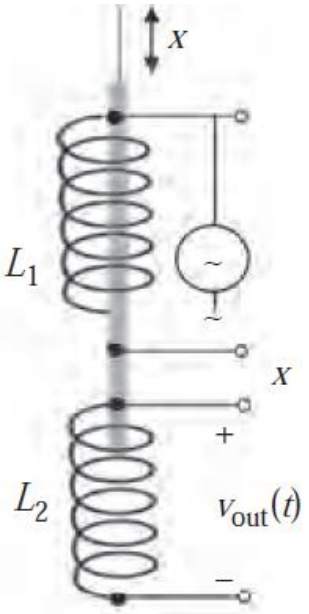
$$v_{\text{out}}(t) = L \frac{\mathrm{d}i_{\text{in}}(t)}{\mathrm{d}t}$$

# Types of Inductive Sensors

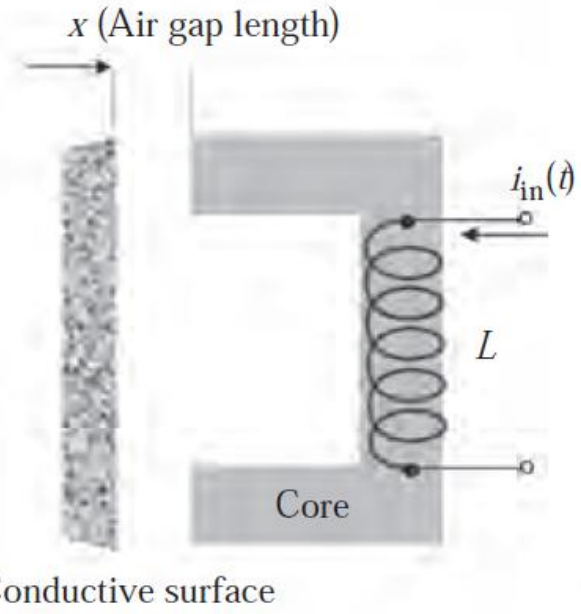
- Displacement is related to the variation of inductance.
- Usually the inductor is part of an electronic circuit and the voltage or current output signal is processed to obtain the displacement value.
- **Self-Induction**: The inductance modification occurs because the displacement ***x*** changes
  - the coil geometry (a);
  - the permeability (or reluctance) due to core displacement (b)
  - the air gap variation (c)



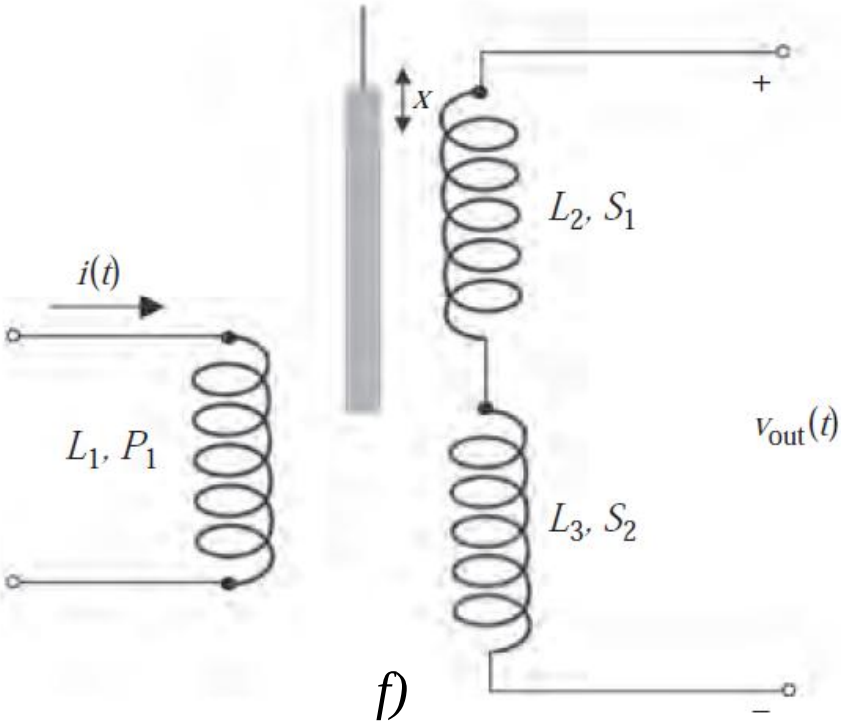
- The inductance modification occurs because the displacement ***x***
  - modifies the mutual magnetic coupling between inductors by changing the position of a common core (d) or the distance between the coils.
  - changes the distance between a conductive material and the coil's magnetic field, inducing eddy currents on the material (e)
  - modifies the mutual magnetic coupling between the primary and two secondary coils by the displacement of the common core (f). This arrangement is known as LVDT (linear variable differential transformer).




d)



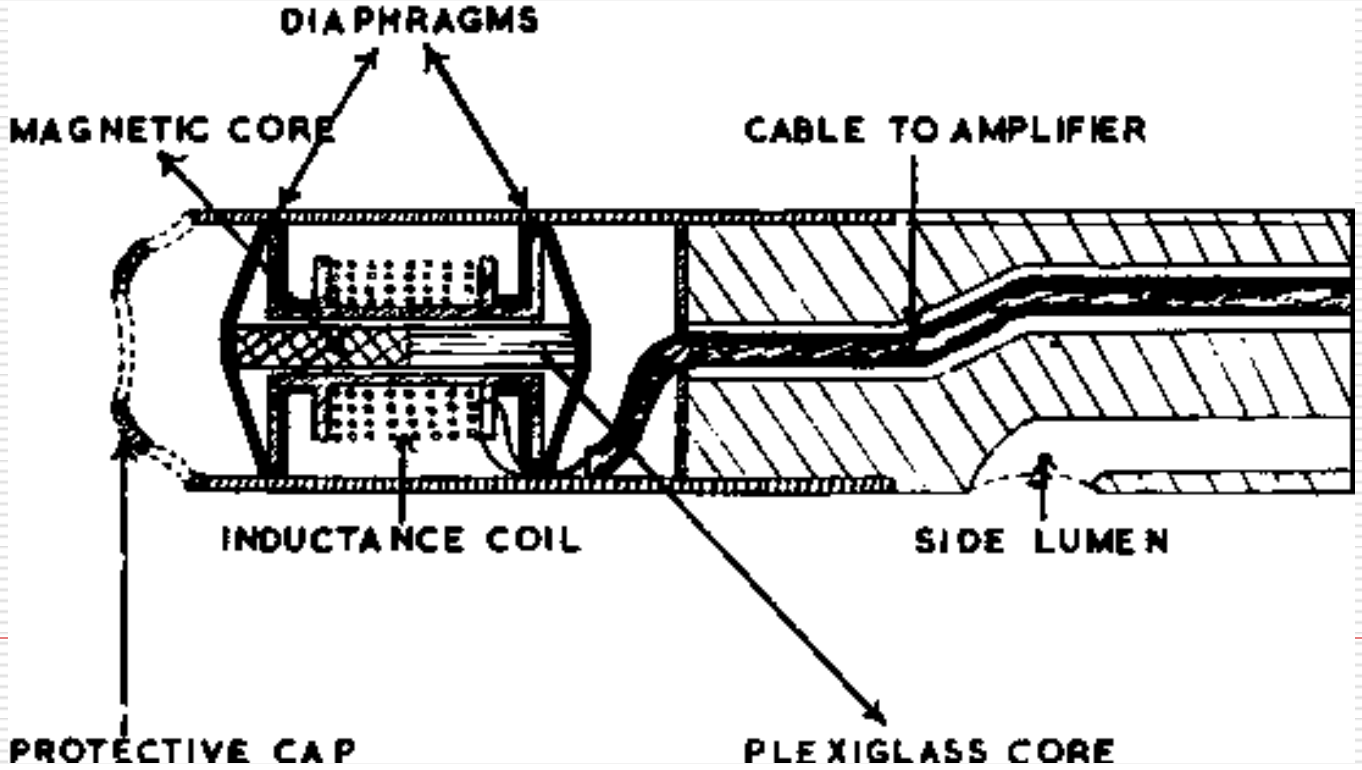

e)




f)

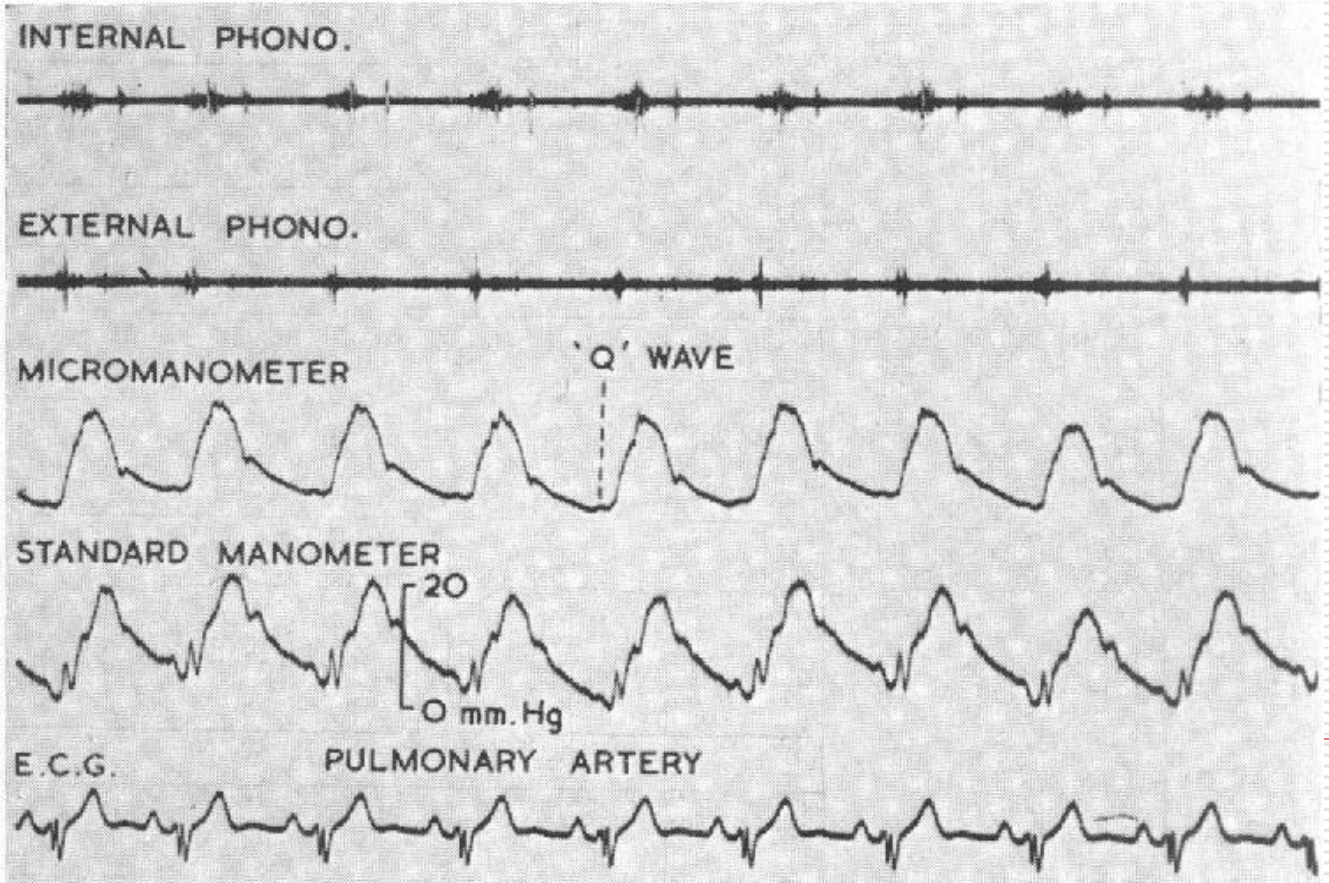
# The micromanometer of Allard –Laurens, 1962

- It is placed at the tip of a catheter and is carried to the interior of the heart chambers, allowing the simultaneous capture of the pressure wave and heart sounds.
- The variable coil is part of an LC oscillating circuit and the movable core is placed between two diaphragms;
- The first diaphragm moves together with the blood flux, pushing the core against the second diaphragm and changing the inductance value.



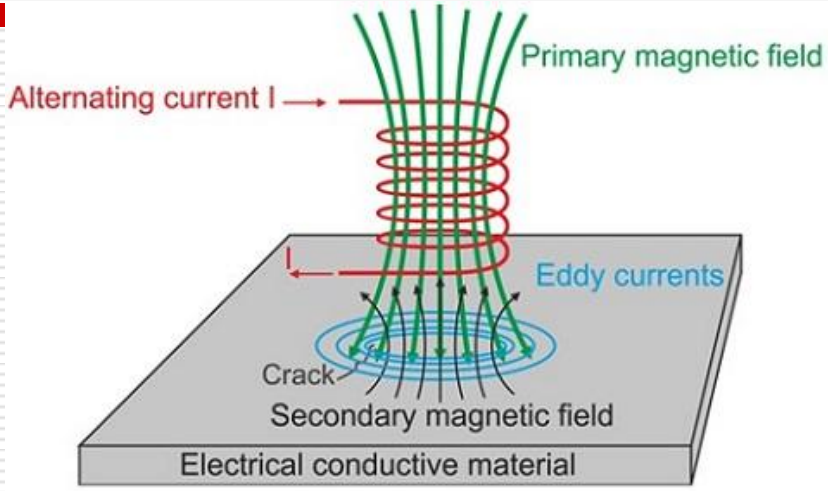
# The micromanometer of Allard -Laurens

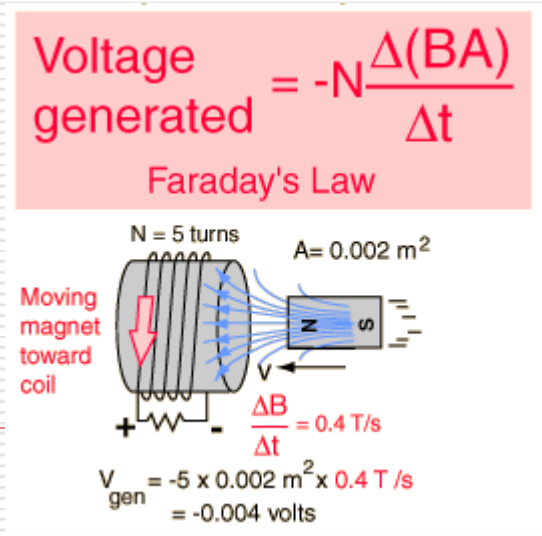
- The output signal frequency changes according to the blood pressure. A low pass filter separates the frequency components of the blood pressure curve and the phonocardiogram is obtained at the output of a high pass filter ( f.50 Hz).

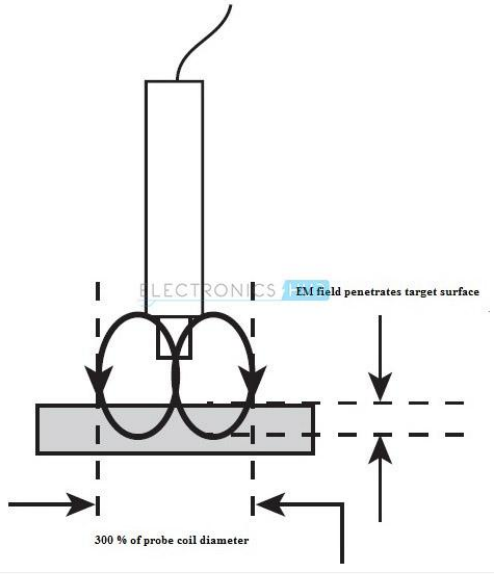


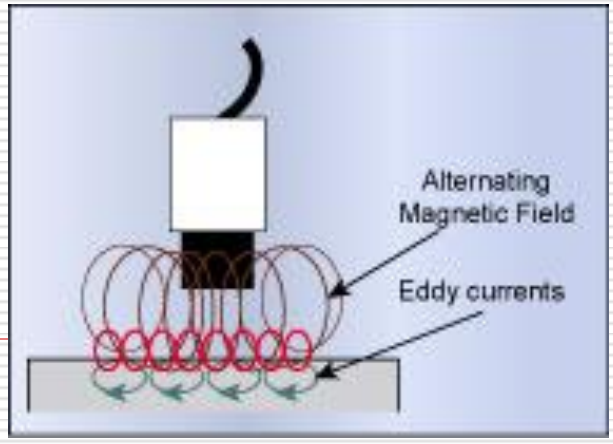
# Mutual-Induction Transducer Using Eddy Current

- When a coil is placed near to coil carrying alternating current, a circulating current is induced in it which in turn produces its own flux which try to reduce the flux of the coil carrying the current and hence inductance of the coil changes. Nearer the plate is to the coil, higher will be eddy current and higher is the reduction in inductance and vice versa. Thus inductance of coil varied with the variation of distance between coil and plate. Thus the movement of the plate can be calibrated in terms of inductance change to measure the quantity like displacement.



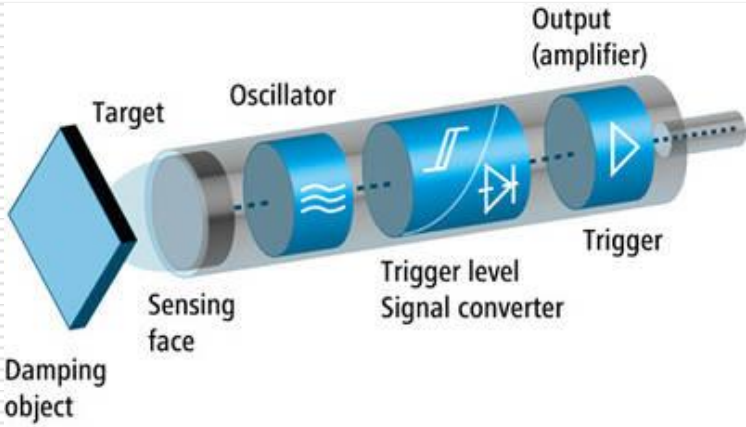



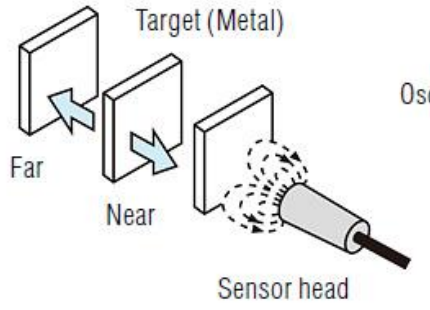



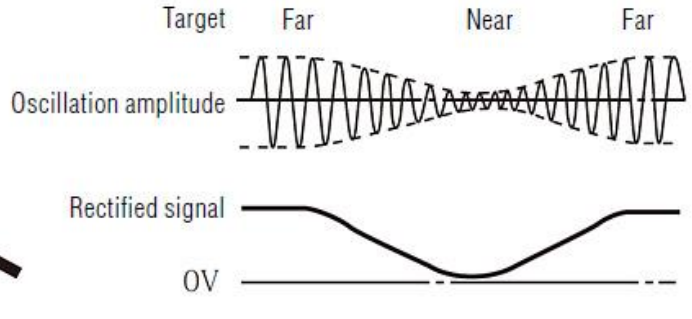



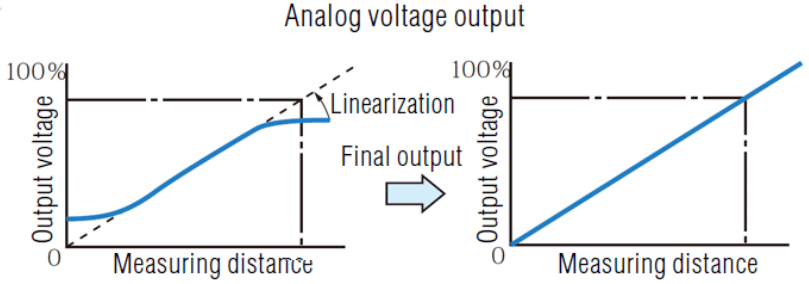
# Mutual-Induction Transducer Using Eddy Current

- An inductive sensor probe consists of an oscillator that generates a high frequency electromagnetic field. This field is radiates from the sensing face of the probe.
- When this field contacts a conducting metal target, a small current is induced within the metal target. These currents will generate their own electromagnetic field that interferes with the field originating from the probe. This causes a change in the amplitude of the oscillations of the signals from the probe.
- As the target approaches the sensor head, the eddy current loss increases and oscillation amplitude becomes smaller accordingly. This oscillation amplitude is rectified to obtain DC voltage variations.
- The rectified signal and distance have an approximate proportional relationship. The linearization circuit corrects the linearity to obtain a linear output that is proportional to the distance.

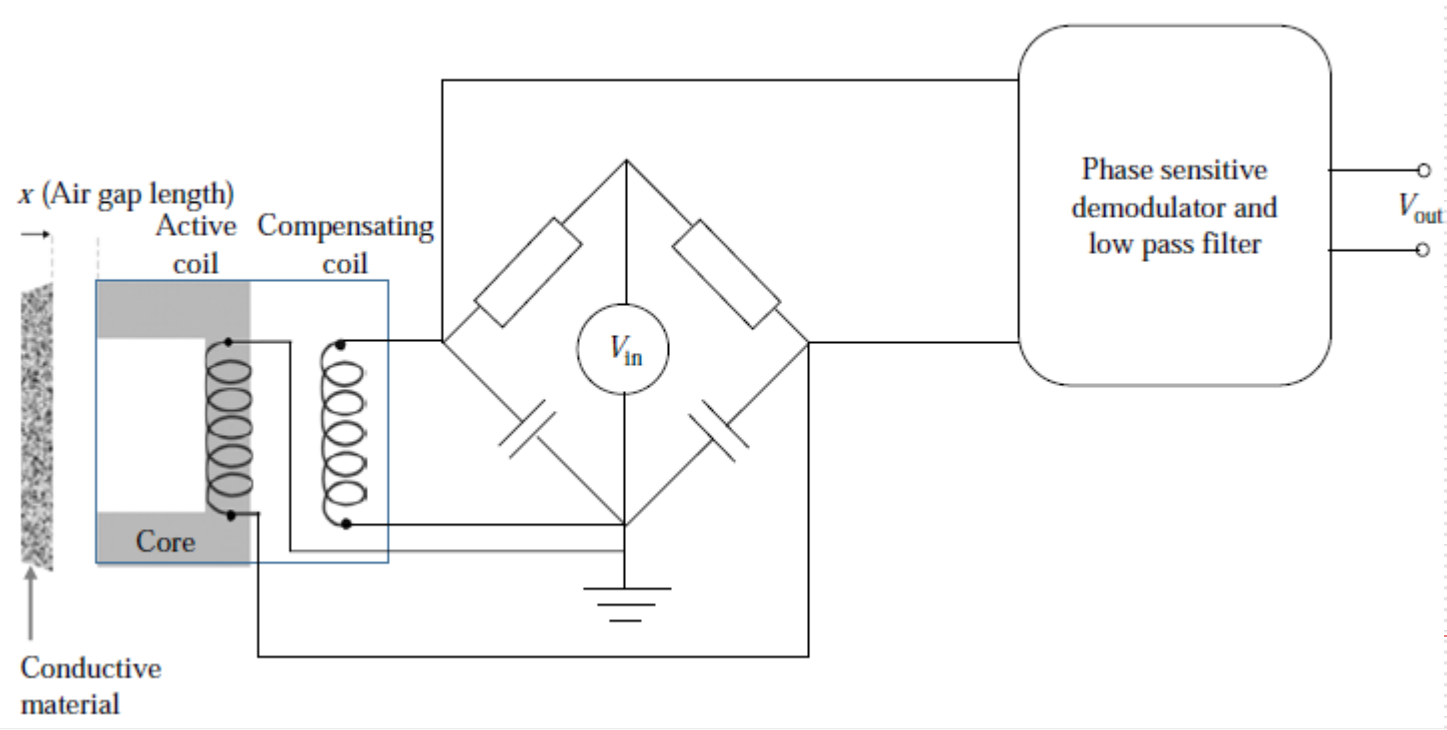


- When the distance between the target and the probe changes, the impedance of the coil changes correspondingly. This change in impedance can be detected by a Wheatstone bridge circuit (excitation signal frequency 50 kHz to 10 MHz) and processed to determine the displacement or position of the conductive material with regard to the core



# Eddy-Current Sensor Advantages

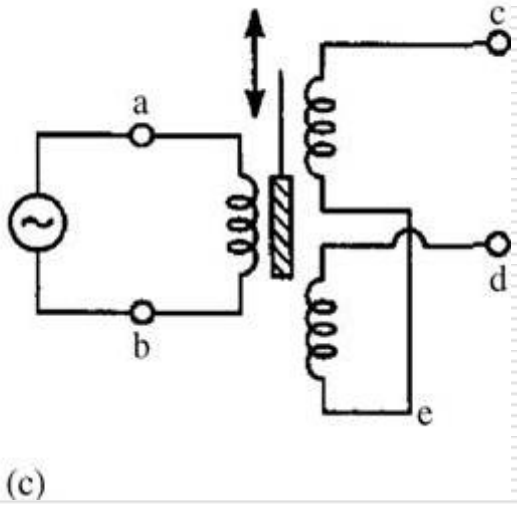
- Compared to other noncontact sensing technologies such as optical, laser, and capacitive, high-performance eddy-current sensors have some distinct advantages.
  - Tolerance of dirty environments
  - Not sensitive to material in the gap between the probe and target
  - Less expensive and much smaller than laser interferometers
  - Less expensive than capacitive sensors
- Eddy-Current sensors are not a good choice in these conditions:
  - Extremely high resolution (capacitive sensors are ideal)
  - Large gap between sensor and target is required (optical and laser are better)

**EX-V Series**

http://www.lionprecision.com/eddy-current-sensors/index.html

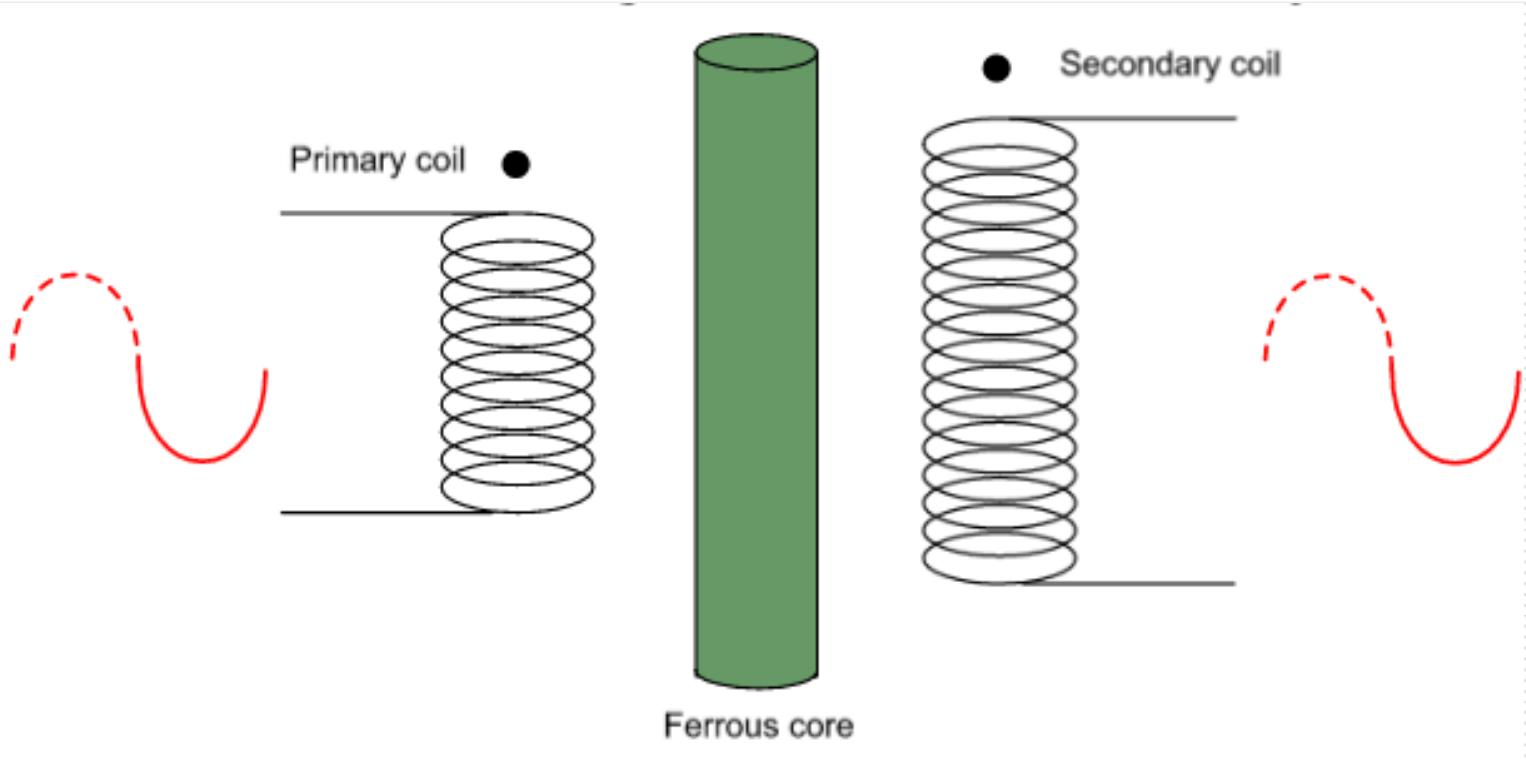
# Linear Variable Differential Transformer (LVDT)

- The linear variable differential transformer (LVDT) is widely used in physiological research and clinical medicine to measure pressure, displacement,and force.
- Primary coil (terminals a-b) and two secondary coils (c-e and d-e) connected in series.
- The coupling between these two coils is changed by the motion of a high-permeability alloy slug between them.
- The two secondary coils are connected in opposition in order to achieve a wider region of linearity.
- Primary coil is sinusoidally excited, with a frequency between 60 Hz and 20 kHz.



(c)

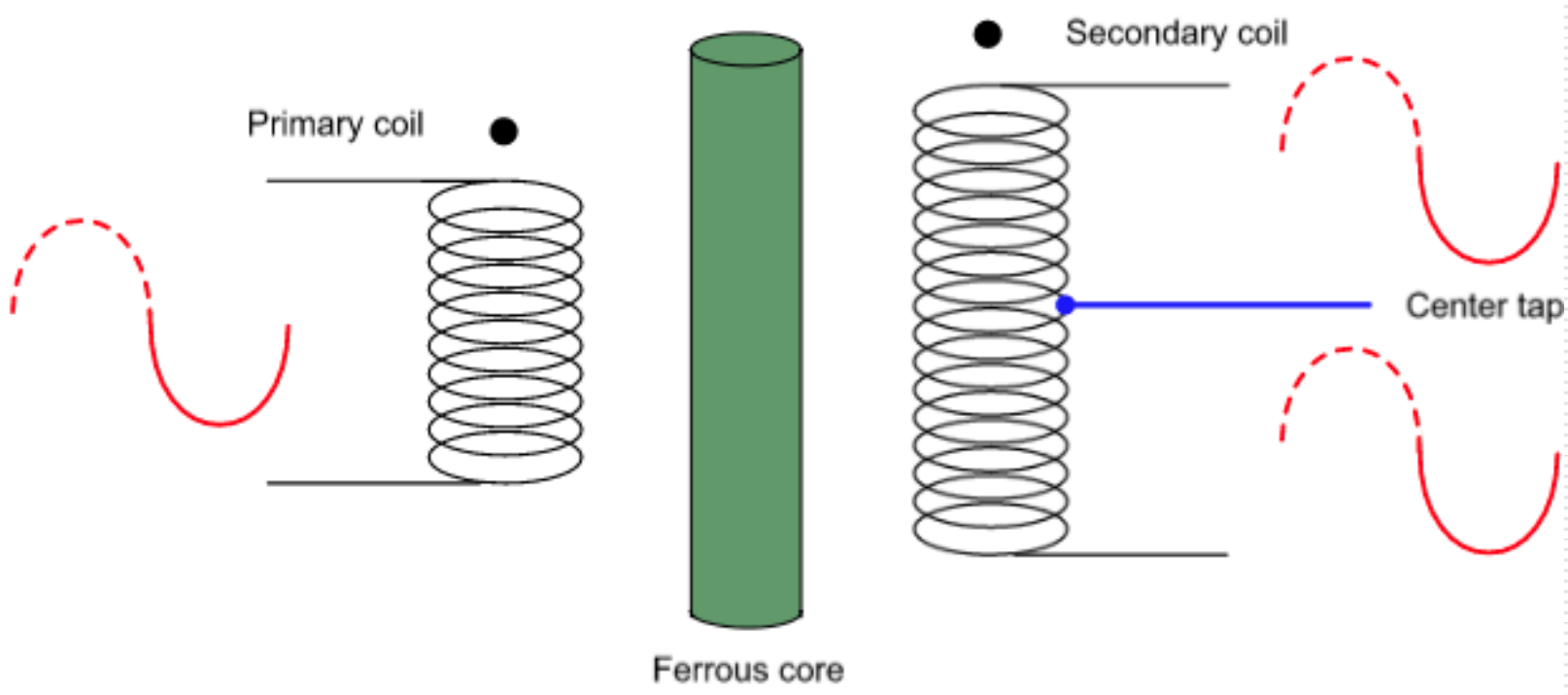
# AC voltage induced in secondary coil




https://www.wisc-online.com/learn/career-clusters/stem/iau7807/the-lvdt-a-linear-voltage-differential-transf

# Adding a center tap

- Create 2 separate coils
- Two separate voltages

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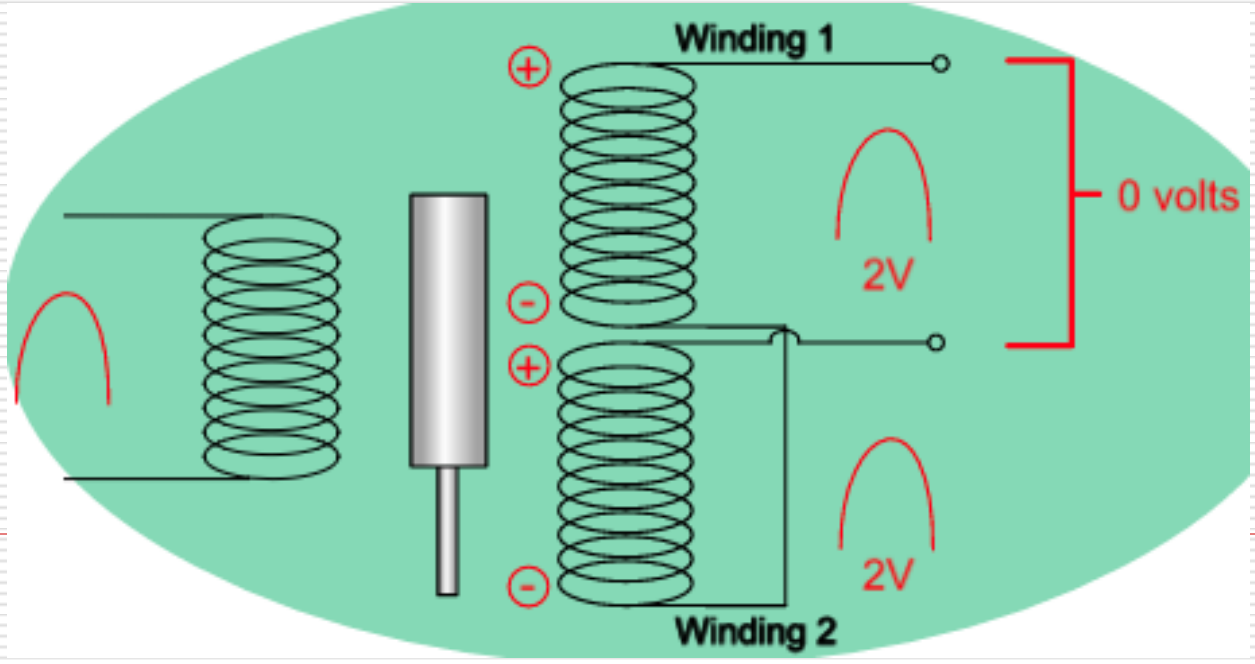
https://www.wisc-online.com/learn/career-clusters/stem/iau7807/the-lvdt-a-linear-voltage-differential-transf

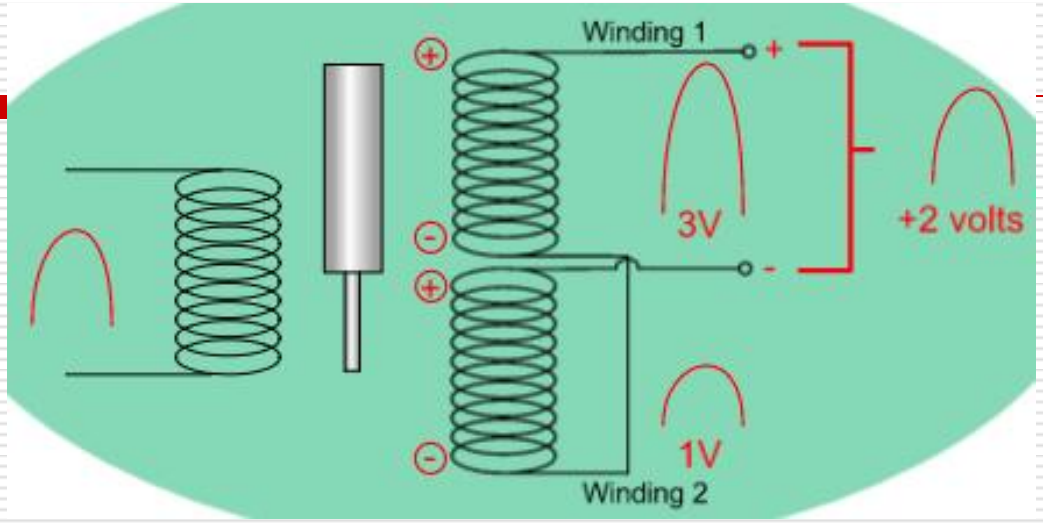
-Two secondary coils of LVDT are in series opposing

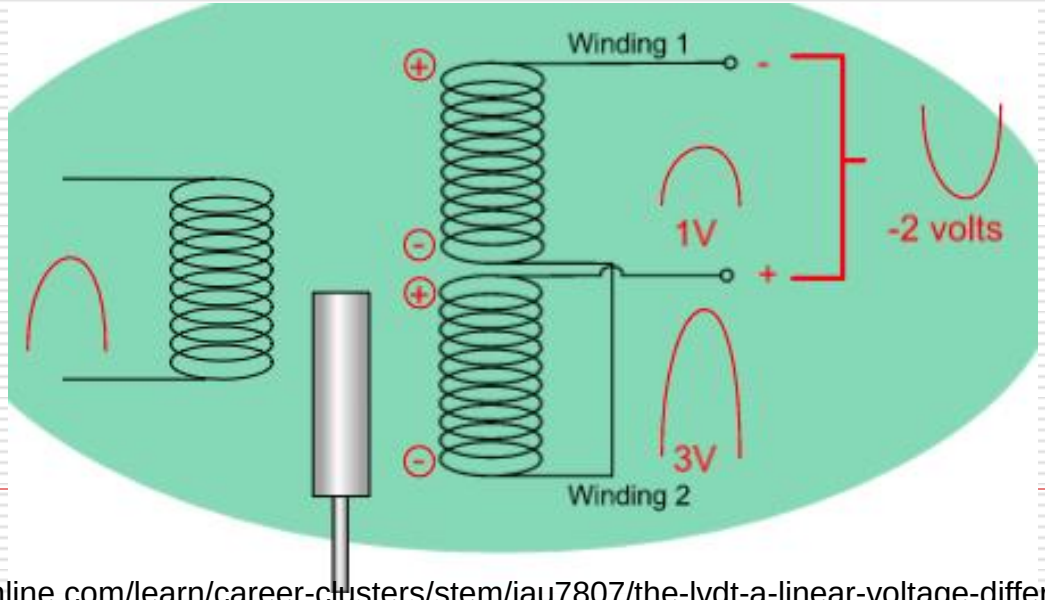
-The core is centered

-Primary coil's magnetic field is induced equally in both secondary coils



# Moving the core up and down




https://www.wisc-online.com/learn/career-clusters/stem/iau7807/the-lvdt-a-linear-voltage-differential-transf

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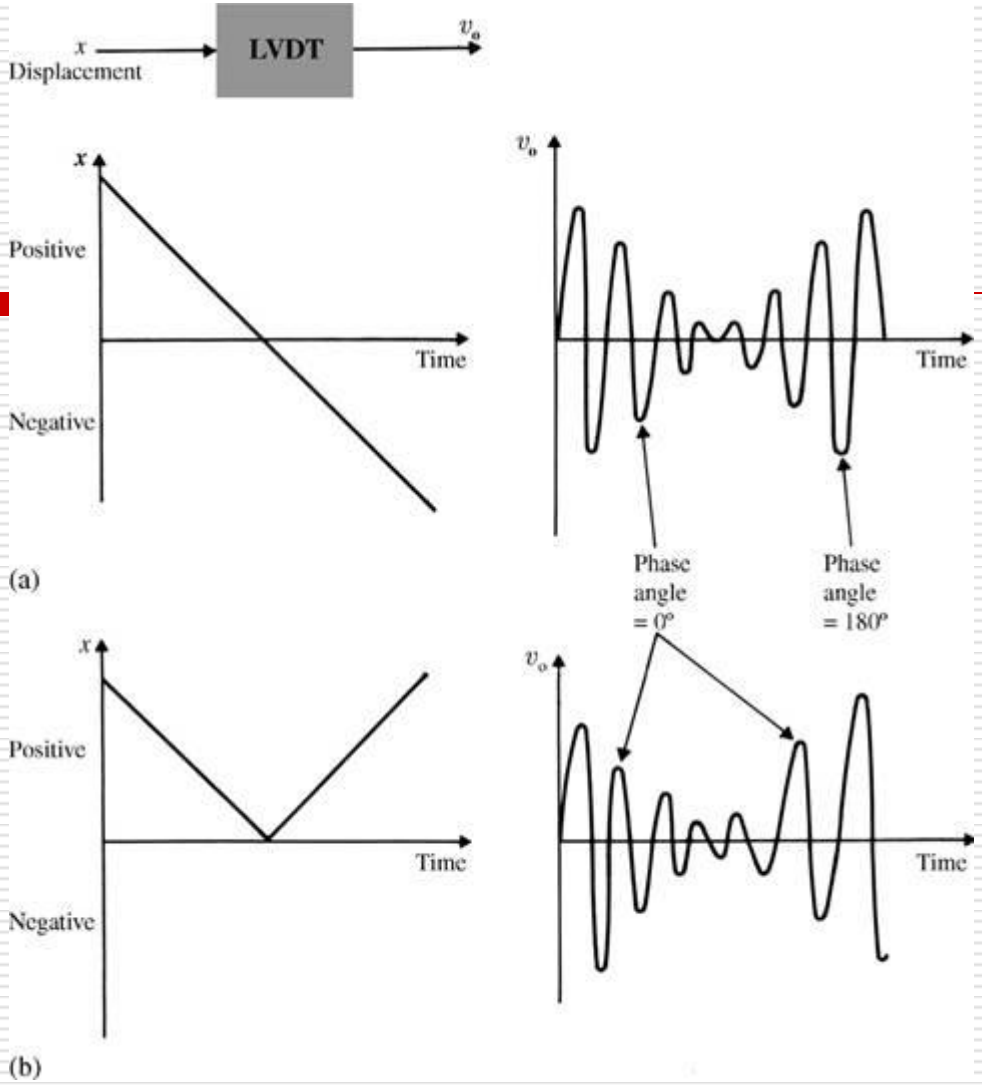


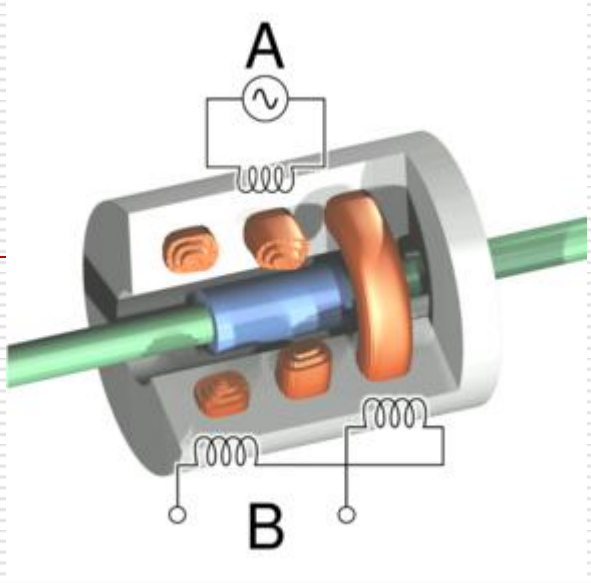

**Figure 2.8 (a) As *x* moves through the null position, the phase changes 180°, while the magnitude of vo is proportional to the magnitude of *x*. (b) An ordinary rectifier-demodulator cannot distinguish between (a) and (b), so a phase-sensitive demodulator is required.**

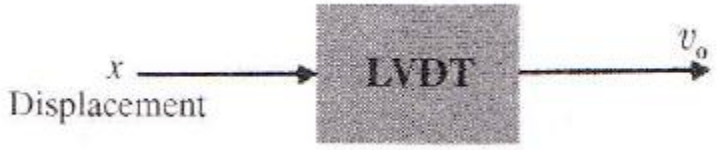
# LVDT

- Commercially available LVDTs include sensitivities on the order of 0.5 to 2 mV for a displacement of 0.01 mm/V of primary voltage
- Full-scale displacement of 0.1 to 250 mm, and
- linearity of ±0.25%
- Sensitivity for LVDTs is much higher than that for strain gages
- A phase-sensitive demodulator is used to determine the direction of displacement.
- A disadvantage of the LVDT is that it requires more complex signal processing instrumentation

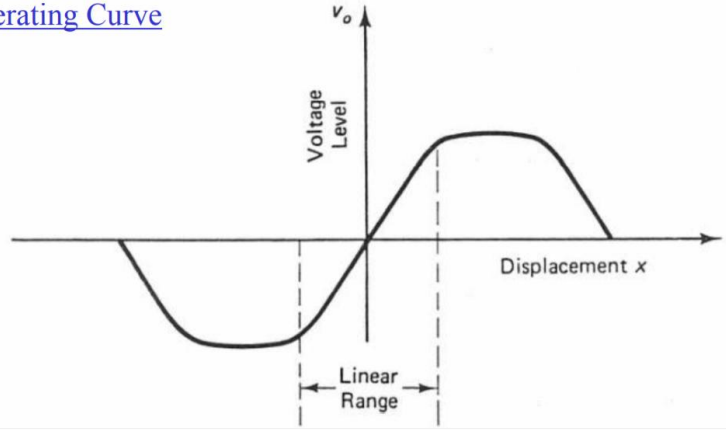
# Linear Variable Differential Transformer

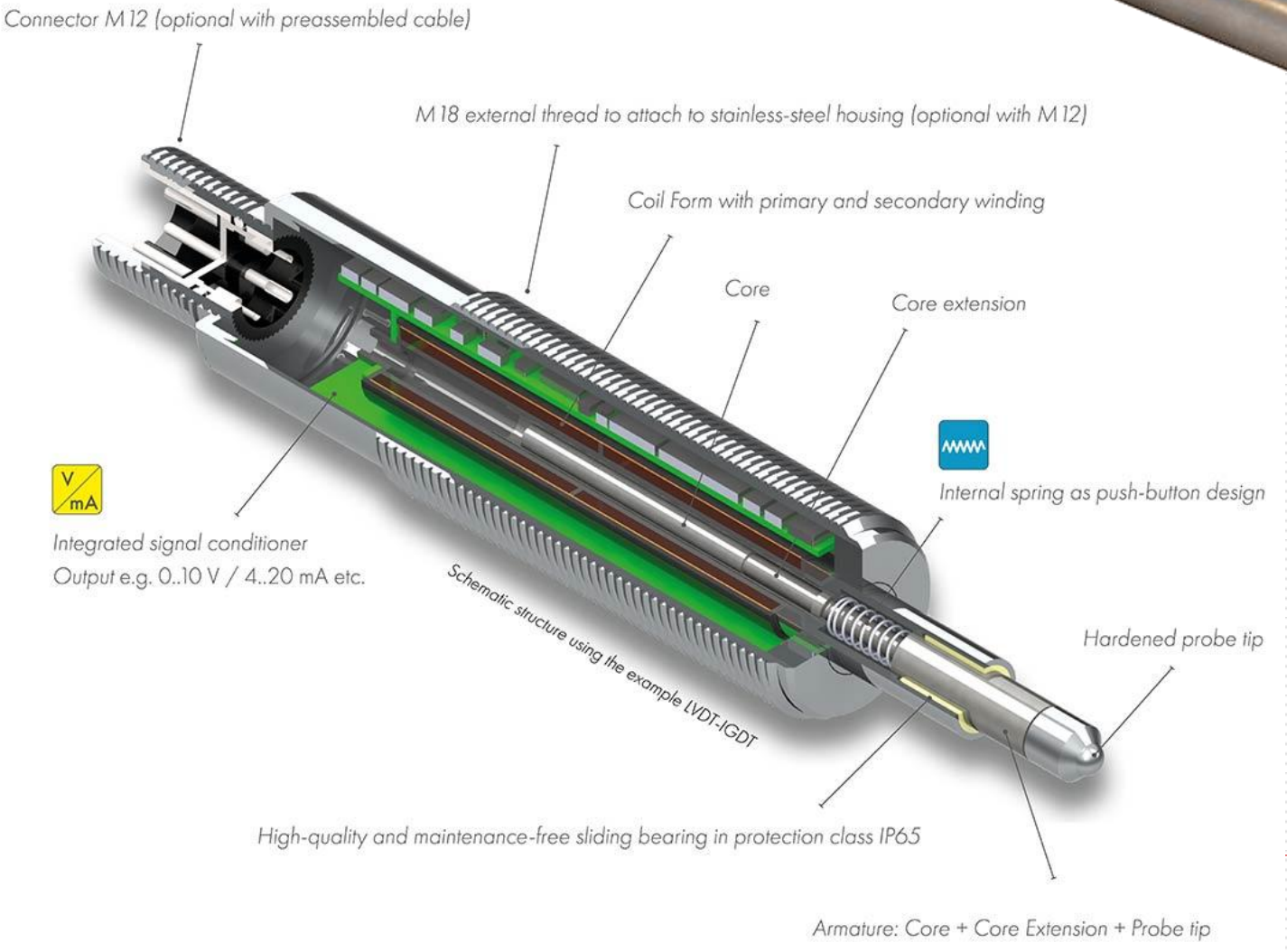
- Linear variable differential transformer characteristics include linearity over a large range, a change of phase by 180° when the core passes through the center position, and saturation on the ends.
- Specifications of commercially available LVDTs include sensitivities on the order of 0.5 to 2 mV for a displacement of 0.01 mm/V of primary voltage, full-scale displacement of 0.1 to 250 mm, and linearity of ±0.25%.
- Sensitivity for LVDTs is much higher than that for strain gages.




Typical LVDT Operating Curve



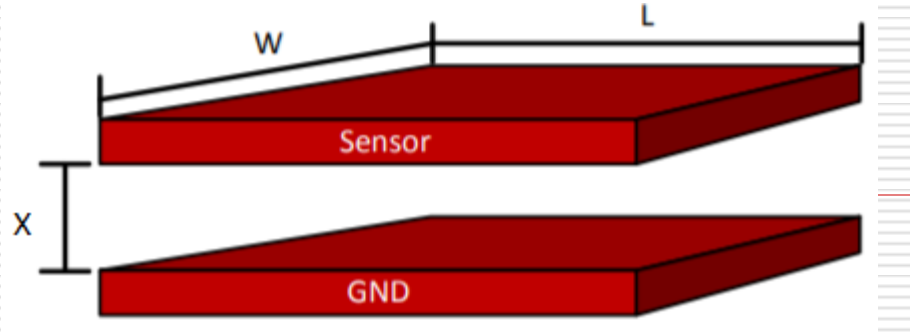

Connector M12 (optional with preassembled cable)
M18 external thread to attach to stainless-steel housing (optional with M12)
Coil Form with primary and secondary winding
Core
Core extension
Internal spring as push-button design
V
mA
Integrated signal conditioner
Output e.g. 0..10 V / 4..20 mA etc.
Schematic structure using the example LVDT-IGDT
Hardened probe tip
High-quality and maintenance-free sliding bearing in protection class IP65
Armature: Core + Core Extension + Probe tip

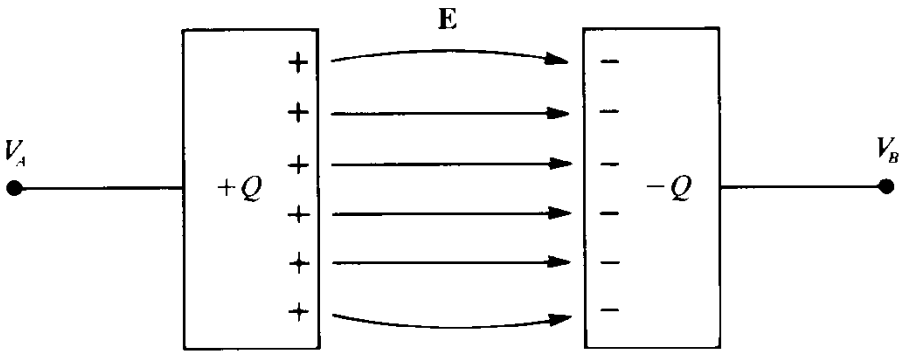
# Capacitive Sensors

- The capacitance between two parallel plates of area A separated by a distance x is:

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

- $\varepsilon_0$ = dielectric constant of free space
- $\varepsilon_r$ = relative dielectric constant of the insulator
- In principle it is possible to measure change in displacement by changing 3 parameters $\varepsilon_r$ , A or x.
- The most practical is by changing separation between the plates.
- Displacement is commonly sensed with a capacitor by measuring capacitance changes as the plate separation is changed.



- The sensitivity K of a capacitive sensor to changes in plate separation $\Delta x$ is found by differentiating;

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

$$K = \frac{\Delta C}{\Delta x} = -\varepsilon_0 \varepsilon_r \frac{A}{x^2}$$

- By substituting (2.8) into (2.9), the percent change in C about any neutral point is equal to the per-unit change in x for small displacements.

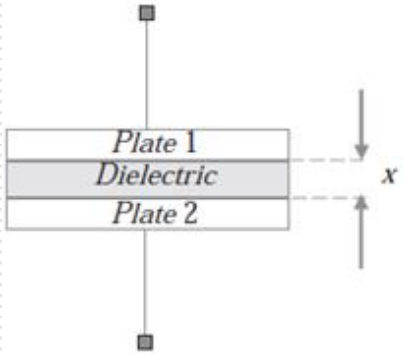
$$\frac{dC}{dx} = \frac{-C}{x} \qquad \frac{dC}{C} = \frac{-dx}{x}$$

- For a 1 $cm^2$ capacitance sensor, $R$ is 100 MΩ. Calculate $x$, the plate spacing required to pass sound frequencies above 20 Hz.
- Answer:
- From the corner frequency, $C = 1/2\pi fR = 1/(2\pi 20\times 10^8) = 80$ pF.
- $x$ can be calculated as follows:

$$x = \varepsilon_0 \varepsilon_r \frac{A}{C} = \frac{(8.854\times 10^{-12})(1\times 10^{-4})}{80\times 10^{-12}}$$

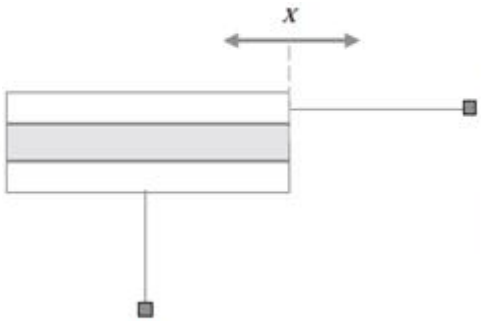
$$x = 1.11\times 10^{5}\ \text{m} = 1.11\ \mu\text{m}$$

- Figure shows some of the possibilities of varying the parameters of the plane plates capacitor to measure linear displacement.



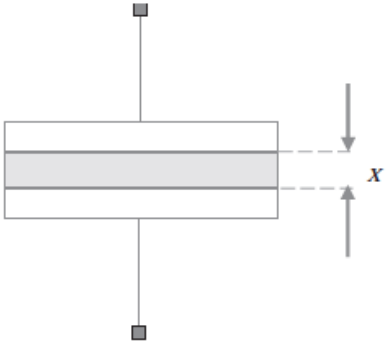

(A)

*Capacitance C changes if the distance between the plates varies, moving longitudinally one or two plates*



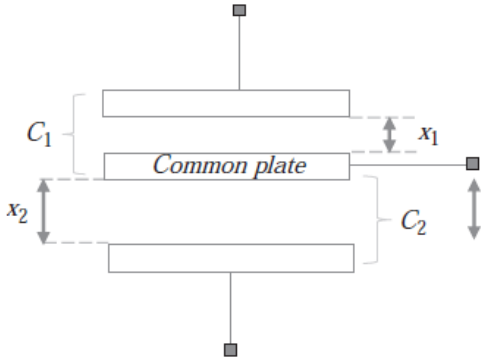

(B)

*Capacitance C changes if the common area between the plates varies, moving laterally one of the plates, the dielectric or the two plates*




(C)

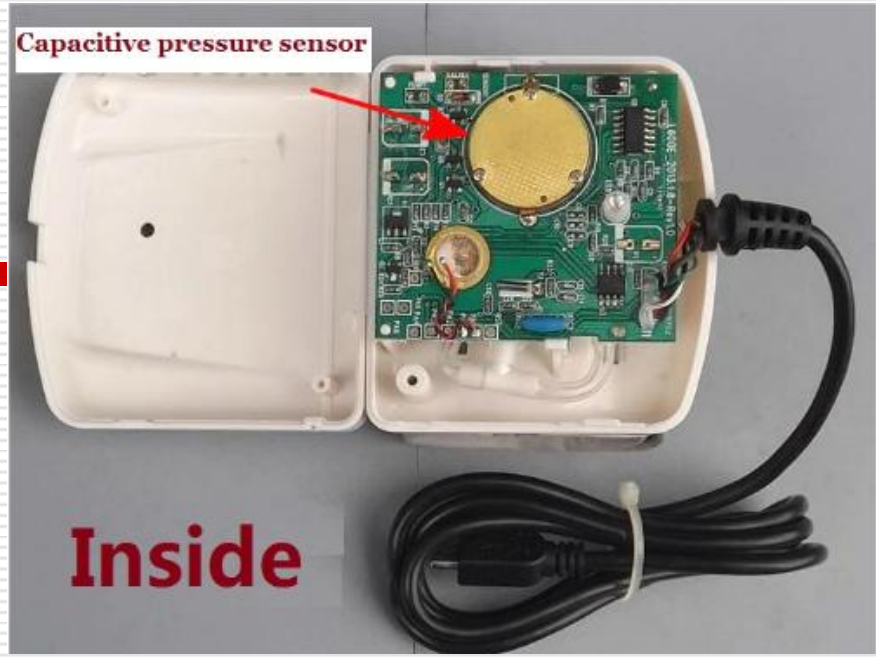
*Capacitance C changes if the value of the dielectric between the plates varies, for instance, when dielectric adsorbs humidity, is compressed or partially replaced by air*




(D)

*Capacitances $C_1$ and $C_2$ change when the distances between the common plate and the other plate vary. If $C_1$ increases, then $C_2$ decreases and vice versa*

- DIY Electronic Blood Pressure Monitor Kit / Miniature Inflatable Pump / Drain Valve / Capacitive Pressure Sensor
- A parallel plate capacitor in which one metal plate is fixed and the other plate is a thin, flexible diaphragm. The diaphragm is deformed with the variation of arterial blood pressure by varying the distance between the capacitor plates and thus the capacitance. The variable capacitance is typically used in an electronic circuit with high gain amplifier and powered by sinusoidal voltage with frequency of tens of kHz. The output voltage obtained is directly proportional to the separation of the capacitor plates. This distance varies in a range of lower frequencies (heartbeat) than that of the excitation frequency of the circuit and is determined by demodulation and filtering.
- $10.35



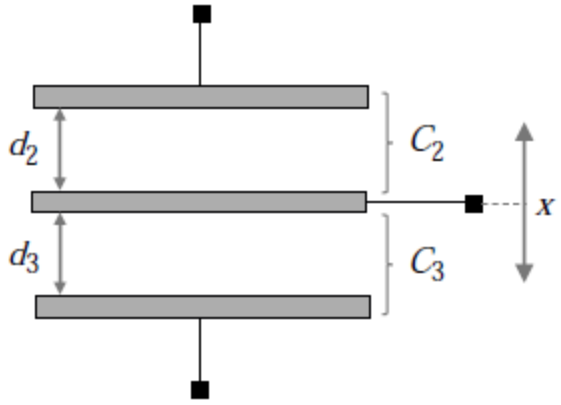
- Another example of biomedical capacitive displacement transducer is the measurement of the wall displacement of the heart or blood vessel, with similar electronic circuit, but with a shielded parallel plate capacitor, in which the movable plate is the conductive surface of the biological tissue (or target plate). Shielding the fixed plate (or sensor head) increases the response linearity (Dally et al., 1993)

- If differential capacitors are used, then the Wheatstone bridge is the indicated measuring circuit usually with one fixed capacitor, the two variables capacitors of the transducer, and one adjustable capacitor used to balance the bridge
- At the balance

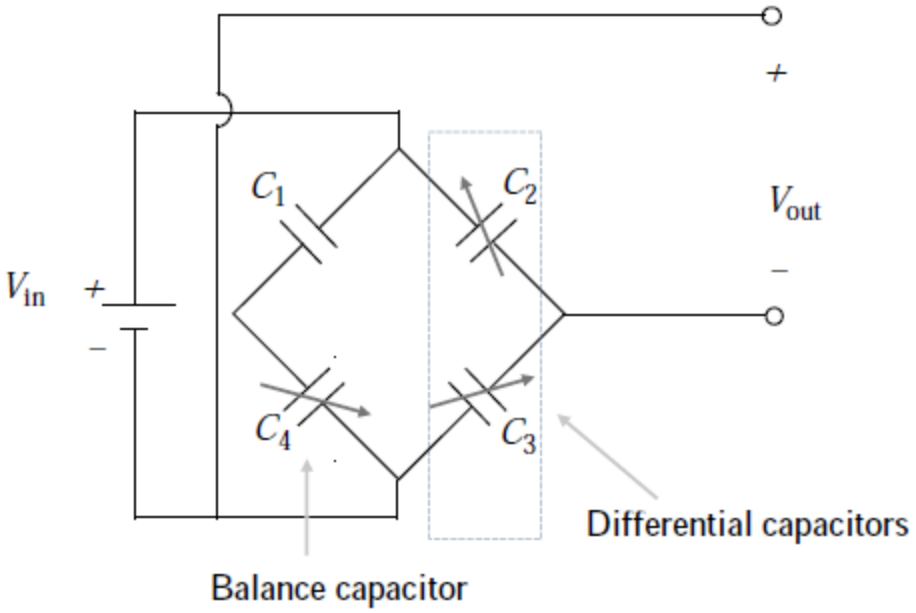
$$C_1 = C_2 = C_3 = C_4 \quad d_2 = d_3 = d$$

- When the central plate moves upward, the differential capacitances are

$$C_2 = \frac{[\varepsilon A]}{[d - x]} \qquad C_3 = \frac{[\varepsilon A]}{[d + x]}$$




(A)




(B)

$$C_2 - C_3 = [\varepsilon A][1/(d-x) - 1/(d+x)] = [\varepsilon A][2x/(d^2 - x^2)]$$

$$C_2 + C_3 = [\varepsilon A][1/(d-x) + 1/(d+x)] = [\varepsilon A][2d/(d^2 - x^2)]$$

$$\frac{(C_2 - C_3)}{(C_2 + C_3)} = \frac{2x}{2d} = \frac{x}{d}$$

- The output voltage for a displacement x is calculated as

$$V_{\text{out}}(j\omega) = V_{C_4}(j\omega) - V_{C_3}(j\omega)$$

- The voltage drop in C4 is

$$V_{C_4}(j\omega) = \frac{(V_{\text{in}}(j\omega)/j\omega C_4)}{[(1/j\omega C_1) + (1/j\omega C_4)]} \qquad V_{C_4}(j\omega) = \left[\frac{C_4}{(C_1 + C_4)}\right] V_{\text{in}}(j\omega)$$

- The voltage drop in C4 is similarly

$$V_{C_3}(j\omega) = \left[\frac{C_3}{(C_2 + C_3)}\right] V_{\text{in}}(j\omega)$$

- Then Vout is

$$V_{\text{out}}(j\omega) = \left\{ \left[\frac{C_4}{(C_1 + C_4)}\right] - \left[\frac{C_3}{(C_2 + C_3)}\right] \right\} V_{\text{in}}(j\omega)$$

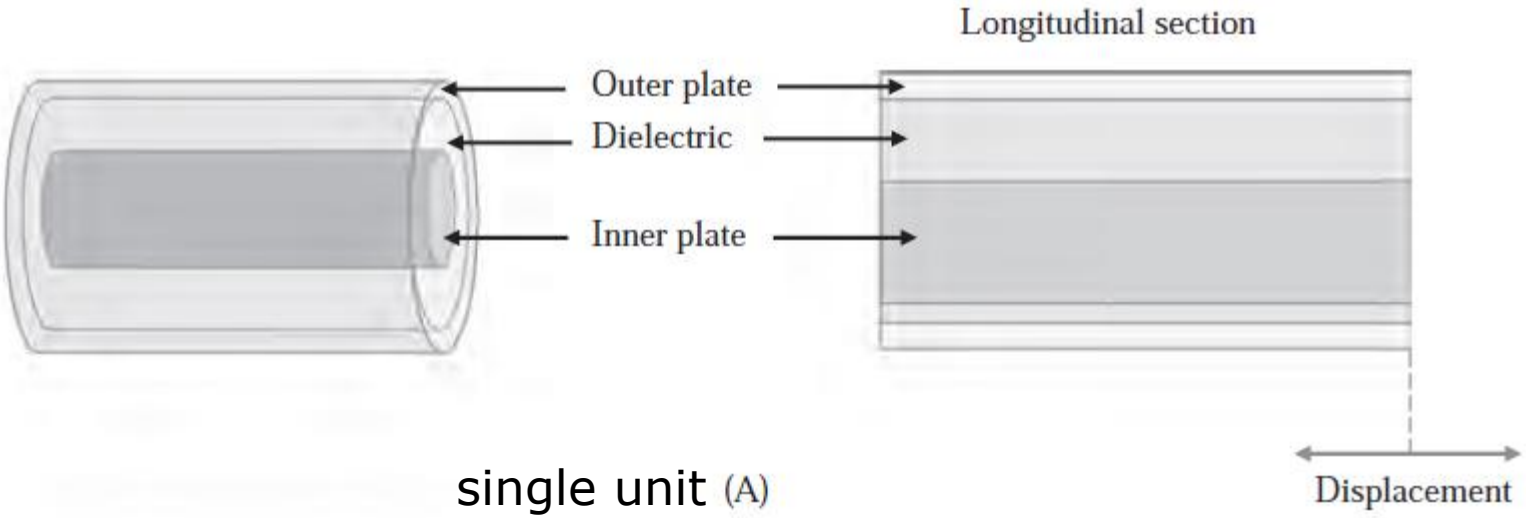
- In the balance, C4 is adjusted to be equal to C1. Then

$$V_{out}(j\omega) = \left\{\frac{1}{2} - \left[\frac{C_3}{(C_2 + C_3)}\right]\right\} V_{in}(j\omega) \qquad V_{out}(j\omega) = \frac{(C_2 - C_3)}{2(C_2 + C_3)} V_{in}(j\omega)$$

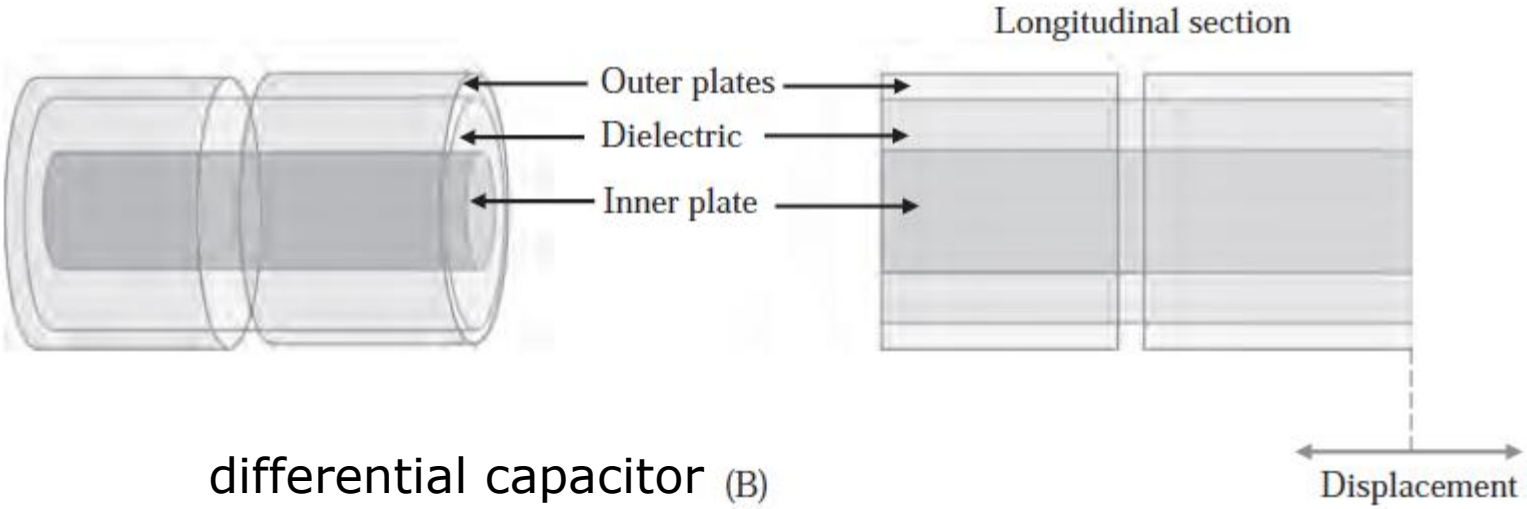
$$V_{out}(j\omega) = \frac{x}{2d} V_{in}(j\omega)$$

- shows that the output differential capacitive transducer is independent of the capacitors area A and dielectric permittivity ε

- Another possibility of obtaining a linear displacement capacitive transducer is to use a capacitor with cylindrical plates, instead of plane plates
- Rotational displacement also can be measured with capacitive transducers implementedwith plane or cylindrical plates. Usually the rotary object is attached to amoving plate in a way to change the common area of the plates of the capacitor, and the capacitance variation is used to calculate the object displacement.




single unit (A)

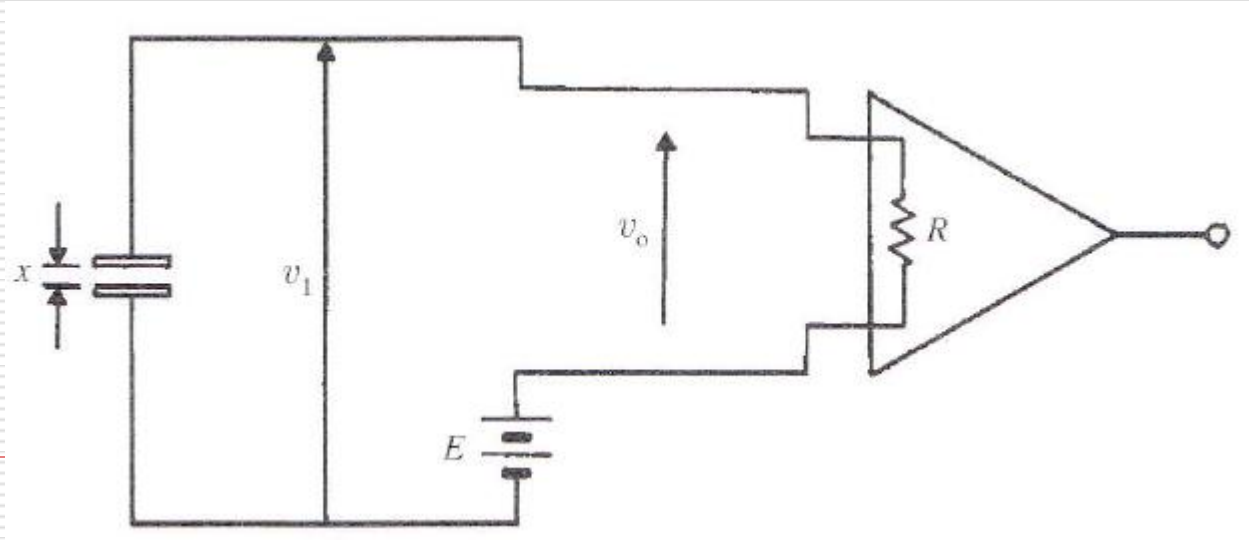



differential capacitor (B)

- This is a dc-excited circuit, so no current flows when the capacitor is stationary (with separation $x_0$), and thus V1=E.
- A change in position $\Delta x = x_1 - x_o$ produces a voltage $v_o = v_1 - E$.

$$\frac{V_o(j\omega)}{X_1(j\omega)} = \frac{(E/x_o)j\omega\tau}{j\omega\tau + 1}$$

$$\tau = RC = R\varepsilon_0\varepsilon_r A/x_0$$

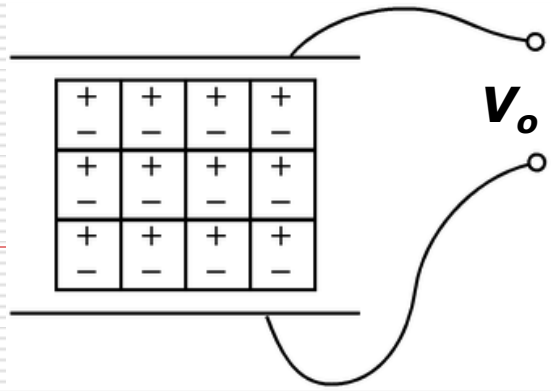


# Applications

- Compliant plastics of different dielectric constants may be placed between foil layers to form a capacitive mat to be placed on a bed. Patient movement generates charge, which is amplified and filtered to display respiratory movements from the lungs and ballistographic movements from the heart (Alihanka et al,1982).
- A capacitance sensor can be fabricated from layers of mica insulators sandwiched between corrugated metal layers. Applied pressure flattens the corrugations and moves the metallic plates closer to each other, thus increasing the capacitance. The sensor is not damaged by large overloads, because flattening of the corrugations does not cause the metal to yield. The sensor measures the pressure between the foot and the shoe (Patel et aL.,1989).
- Tsoukalas et al. (2006) describe micromachined silicon capacitive sensors and their electronic interfaces.

# PIEZOELECTRIC SENSORS

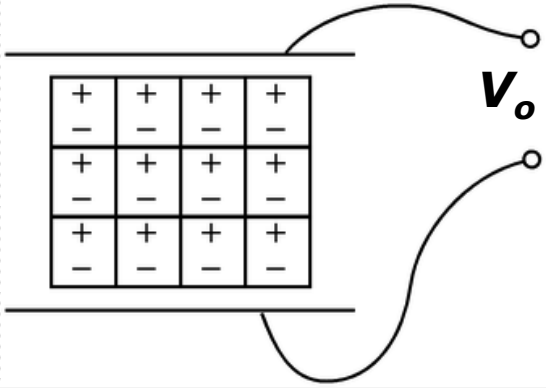
- Piezoelectric sensors are used to measure physiological displacements and record heart sounds.
- Piezoelectric materials generate an electric potential when mechanically strained, and conversely an electric potential can cause physical deformation of the material.
- The principle of operation is that when an asymmetrical crystal lattice is distorted, a charge reorientation takes place, causing a relative displacement of negative and positive charges.
- The displaced internal charges induce surface charges of opposite polarity on opposite sides of the crystal.
- Surface charge can be determined by measuring the difference in voltage between electrodes attached to the surfaces.
- The total induced charge *q* is directly proportional to the applied force *f*.




$$q = kf$$

$$k = \text{piezoelectric constant, C/N}$$

- The change in voltage can be found by assuming that the system acts like a parallel-plate capacitor where the voltage $V_O$ across the capacitor is charge $q$ divided by capacitance $C$ .

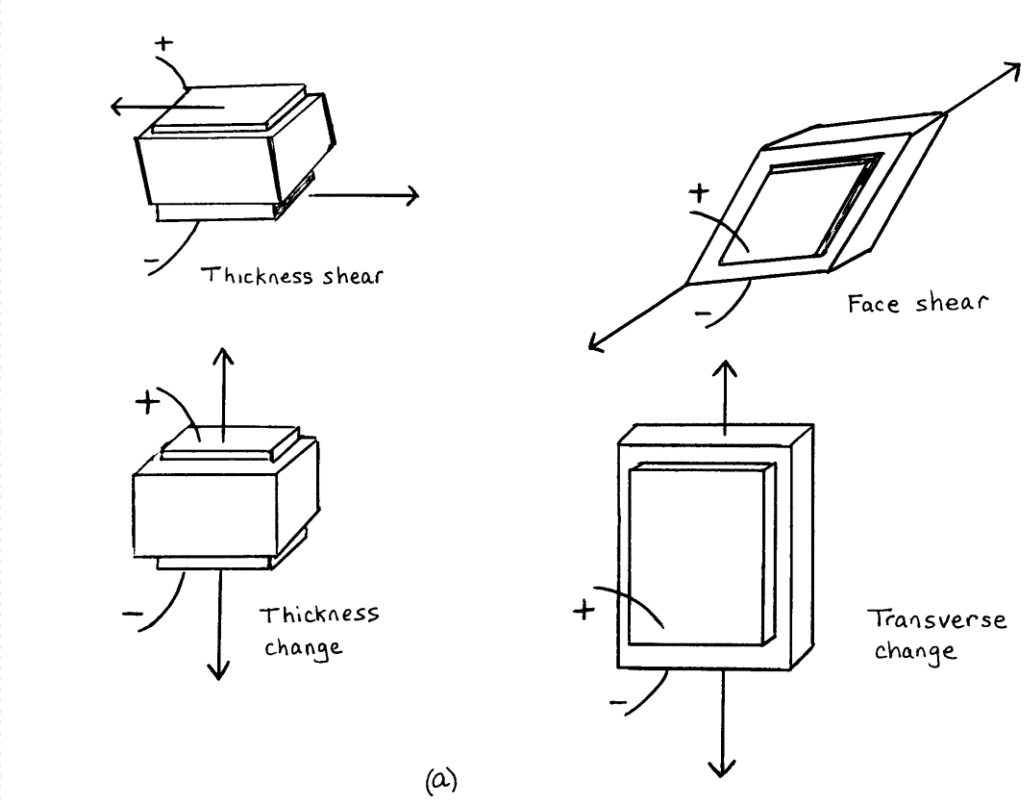



$$V_o = \frac{q}{C} = \frac{kf}{C} = \frac{kfx}{\varepsilon_0 \varepsilon_r A} \qquad C = \varepsilon_0 \varepsilon_r \frac{A}{x}$$

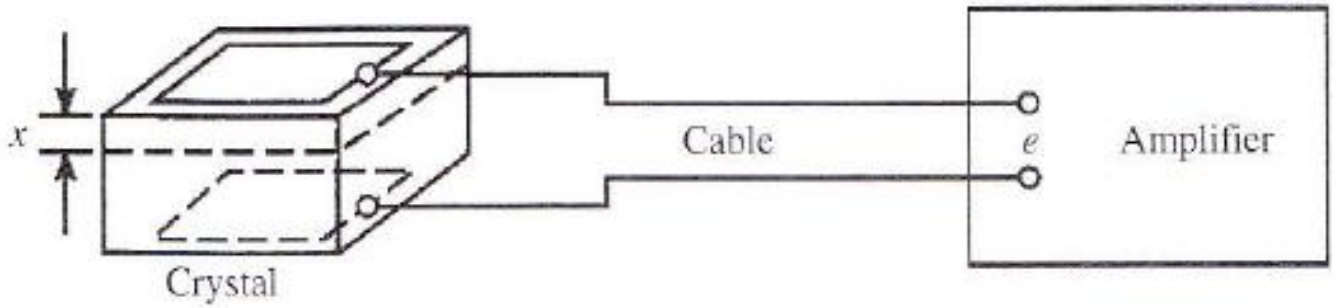
- Typical values for $k$ are 2.3 pC/N for quartz and 140 pC/N for barium titanate.
- For a piezoelectric sensor of 1 $cm^2$ area and 1 mm thickness with an applied force due to a 10 g weight, the output voltage $V_O$ is 0.23 mV and 14 mV for the qrtartz and barium titanate crystals, respectively.

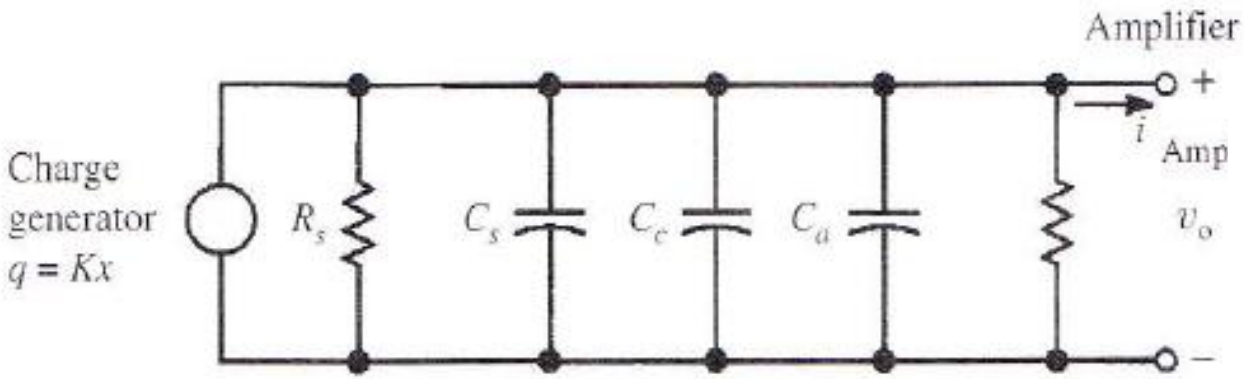
# Modes Of Operation Of Piezoelectric Sensors

- There are various modes of operation of piezoelectric sensors, depending on the material and the crystallographic orientation of the plate



- Piezoelectric materials have a high but finite resistance. If a static deflection x is applied, the charge leaks through the leakage resistor (on the order of 100 GΩ)).
- The input impedance of the external voltage-measuring device be an order of magnitude higher than that of the piezoelectric sensor.
- It would be helpful to look at the equivalent circuit for the piezoelectric sensor is required in order to quantify its dynamic-response characteristics.
- This circuit has a charge generator $q=Kx$ where K is proportionality constant C/m and x is deflection.




$R_s$: sensor leakage resistance
$C_s$: sensor capacitance
$C_c$: cable capacitance
$C_a$: amplifier input capacitance
$R_a$: amplifier input resistance

- The circuit may be simplified by converting the charge generator to a current generator, $i_S$

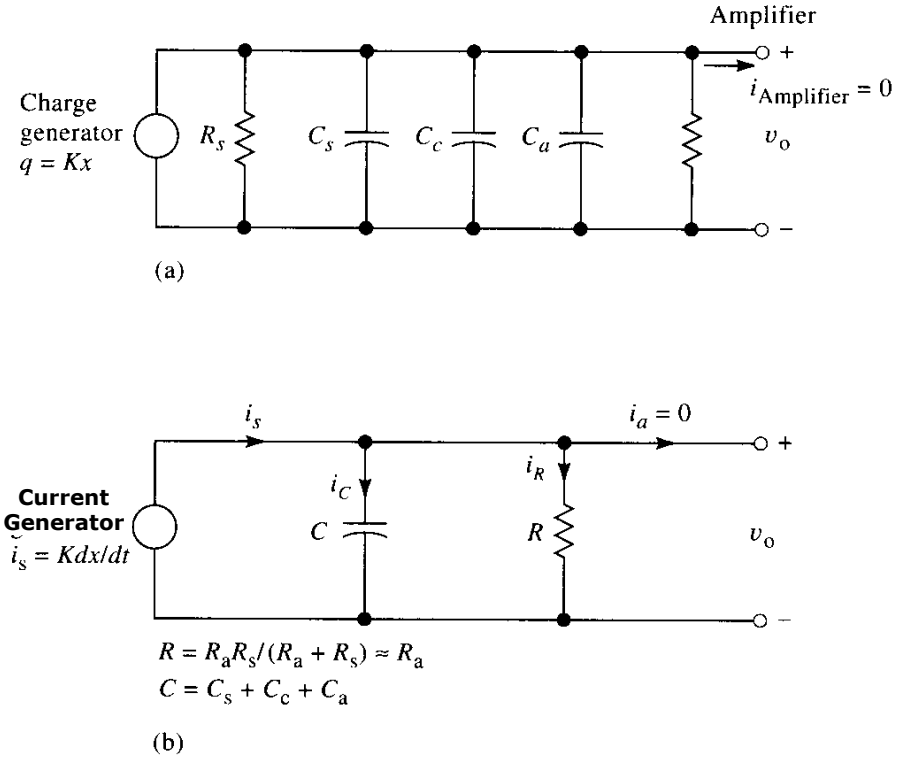
$$q = Kx \qquad i_s = \frac{dq}{dt} = K\frac{dx}{dt}$$

- Assuming that amplifier does not draw any current

$$i_s = i_C + i_R$$

$$v_o = v_C = \left(\frac{1}{C}\right)\int i_C dt$$

$$i_s - i_R = C\left(\frac{dv_o}{dt}\right) = K\frac{dx}{dt} - \frac{v_o}{R}$$




$$\frac{V_o(j\omega)}{X(j\omega)} = \frac{K_s j\omega\tau}{j\omega\tau + 1}$$

High Pass Filter

$K_s = K/C$ (sensitivity, V/m)

$\tau = RC$ (time constant)

# A capacitor in the s domain

- *iv*-relation in the time domain

$$i(t) = C \cdot \frac{d}{dt} v(t).$$

- By operational Laplace transform:

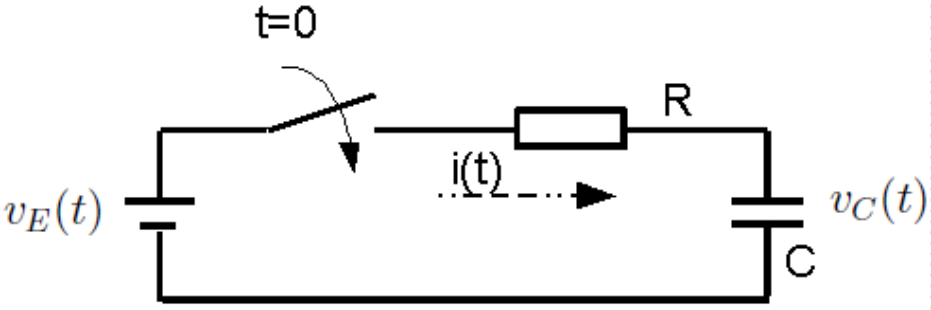
$$L\{i(t)\} = L\{C \cdot v'(t)\} = C \cdot L\{v'(t)\},$$

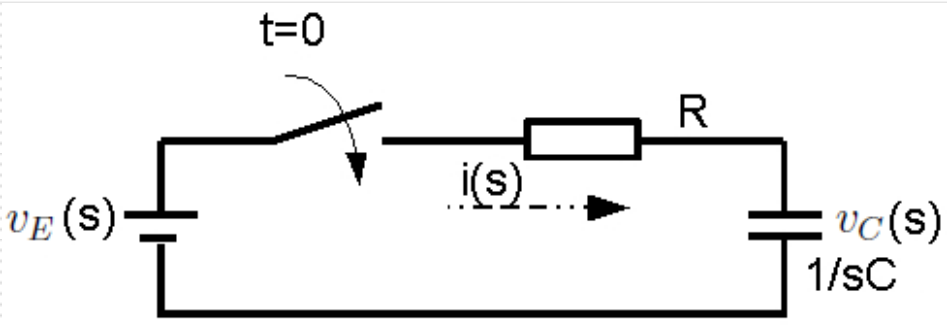
$$\Rightarrow I(s) = C \cdot [sV(s) - V_0] = sC \cdot V(s) - CV_0.$$

initial voltage

# Step Response of First Order Circuit

- We want to investigate the behavior of the circuit when the switch is closed at a time called t = 0. In order to do it, in time domain, the step function is used
- It is assumed that at time t < 0 the value of $v_C(t^-) = 0$.




$$v_E(t) = R \cdot C\frac{dv_c(t)}{dt} + v_C(t)$$

- Having Laplace transform of equation then obtain transfer function

$$\mathcal{L}\{f(t)\} = F(s) = \int_0^\infty f(t)e^{-st}dt \qquad H(s) = \frac{v_C(s)}{v_E(s)} \qquad H(s) = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} = \frac{1}{sRC + 1}$$

- As step function appears at input

$$v_C(s) = H(s) \cdot v_E(s) = \frac{1}{sRC + 1} \cdot \frac{1}{s} = \frac{1}{s} - \frac{1}{s + \frac{1}{RC}}$$

- Then, next task is to find the inverse Laplace's transform in order to determine the charging transient in time domain.

$$f(t) = \frac{1}{j2\pi}\int_{c-j\infty}^{c+j\infty} F(s)e^{st}ds \qquad t > 0$$

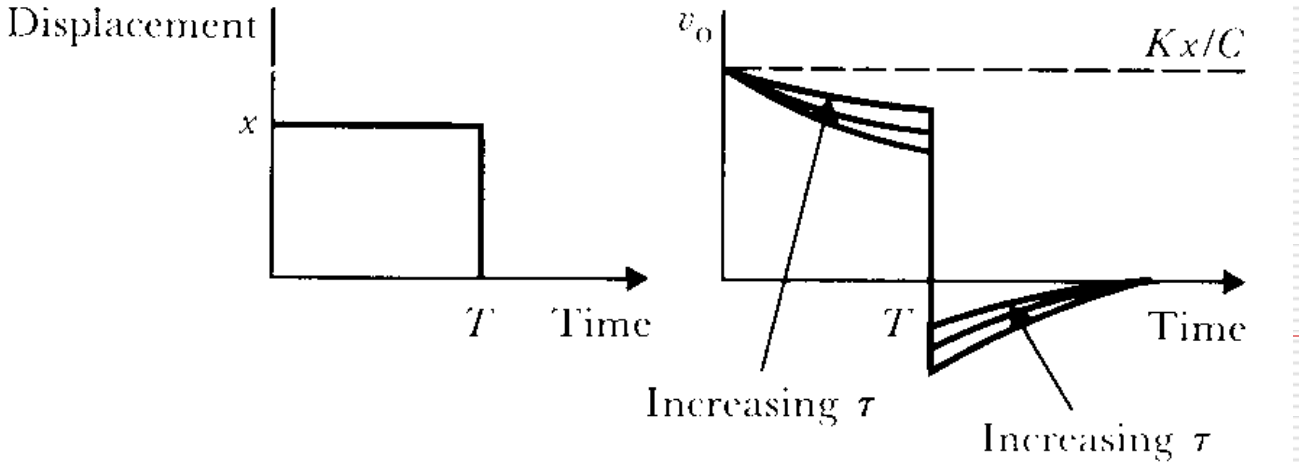
$$\mathcal{L}\left[e^{at}\right] = \frac{1}{s-a} \qquad \mathcal{L}^{-1}\left[\frac{1}{s-a}\right] = e^{at}$$

$$\mathcal{L}\left[u(t)\right] = \frac{1}{s} \qquad \mathcal{L}^{-1}\left[\frac{1}{s}\right] = u(t)$$

$$\mathcal{L}^{-1}\{v_C(s)\} = \mathcal{L}^{-1}\{\frac{1}{s} - \frac{1}{s+\frac{1}{RC}}\}$$

$$v_C(t) = v_E\left(1 - e^{\frac{-t}{RC}}\right)$$

- Figure shows the voltage-output response of a piezoelectric sensor to a step displacement x. The output decays exponentially because of the finite internal resistance of the piezoelectric material.
- At time equal to T, the force is released, and a displacement restoration results that is equal to and opposite of the original displacement. This causes a sudden decrease in voltage of magnitude Kx/C, with a resulting undershoot equal to the decay prior to the release of the displacement.
- The decay and undershoot can be minimized by increasing the time constant, $\tau$=RC. The simplest approach to increasing $\tau$ is to add a parallel capacitor.
- However, doing so reduces the sensitivity in the midband frequencies according to (2.20).

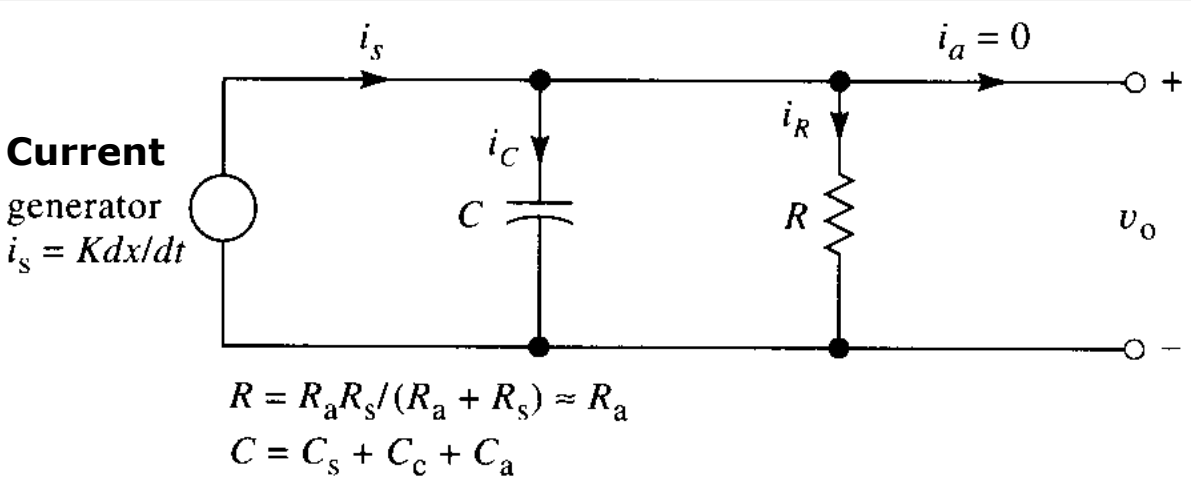


# Example

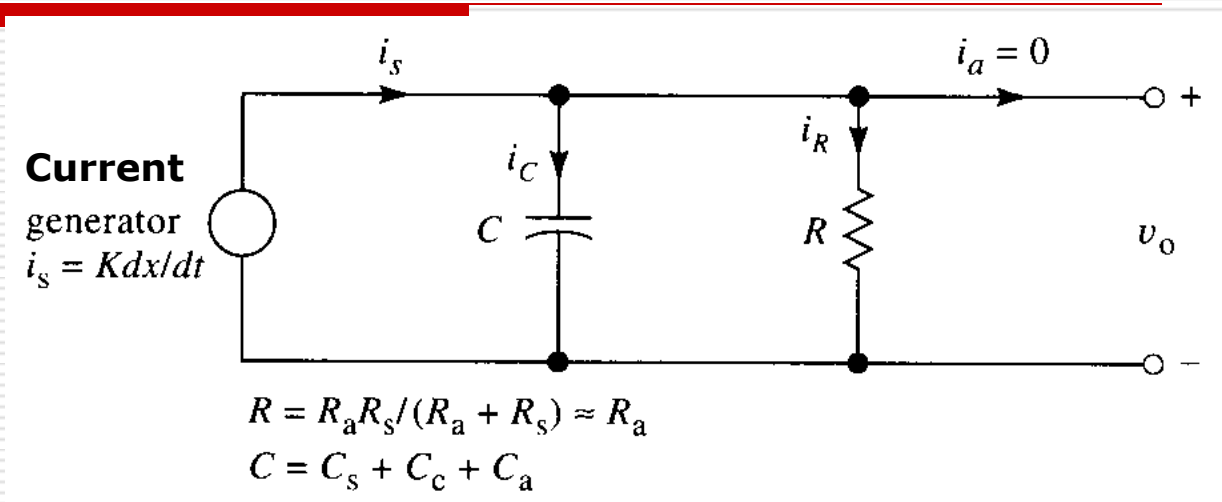
- A piezoelectric sensor has C = 500 pF. Sensor leakage resistanse is 10 GΩ. The amplifier input impedance is 5 MΩ. What is the low corner frequency?

High Pass Filter

$$\frac{V_o(j\omega)}{X(j\omega)} = \frac{K_s j\omega\tau}{j\omega\tau + 1}$$



$C$ = 500 pF
$R_{leak}$ = 10 GΩ
$R_a$ = 5 M Ω
What is $f_{c,low}$ ?




$$f_{c,low} = \frac{1}{2\pi RC} = \frac{1}{2\pi(5\times10^{6})(500\times10^{-12})} = 64\ \text{Hz}$$

*If input impedance is increased 100 times:* ($R_a$ = 500 M Ω), then

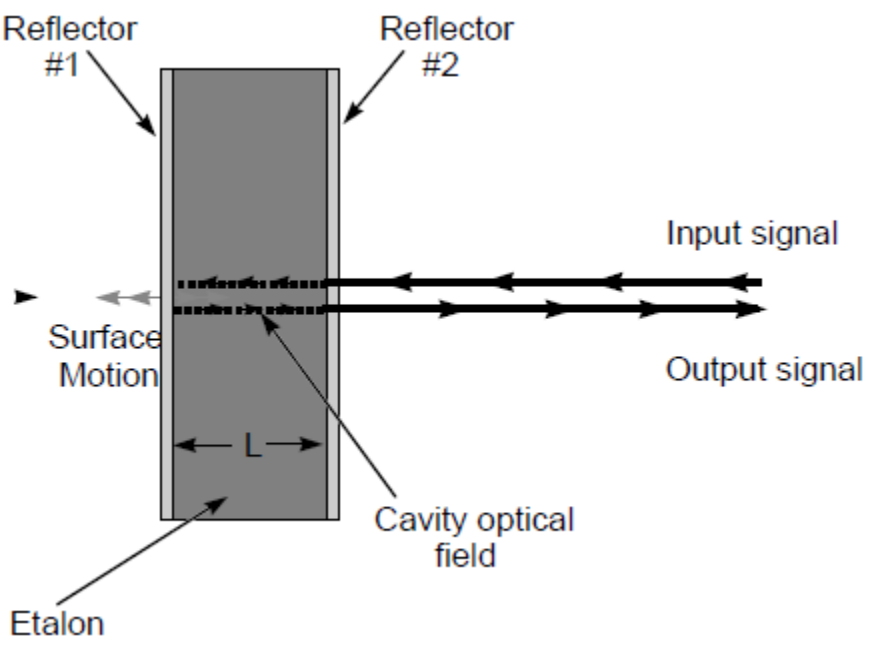
$$f_{c,low} = \frac{1}{2\pi(500\times10^{6})(500\times10^{-12})} = 0.64\ \text{Hz}$$

# Piezoelectric Sensor Applications

- Piezoelectric sensors are used quite extensively in cardiology for external (body-surface) and internal (intracardiac) phonocardiography.
- They are also used in the detection of Korotkoff sounds in blood-pressure measurements (Chapter 7).
- Additional applications of piezoelectric sensors involve their use in measurements of physiological accelerations. A piezoelectric sensor and circuit can measure the acceleration due to human movements and provide an estimate of energy expenditure (Servais et al., 1984).
- Section 8.4 describes ultrasonic blood-flow meters in which the piezoelectric element operating at mechanical resonance emits and senses high-frequency sounds.
- Li and Su (2006) describe piezoelectric sensors as sensitive mass sensors to detect and measure a broad variety of biomedical analytes in both gas and liquid phases based on the adsorption (*yüzeye tutma*) and/or desorption (*yüzeyden bırakma*) of target analyte(s) on the sensor surface.

# Fiber Optic Displacement Sensors

- An optical etalon (i.e., resonator) is formed with two reflecting mirrors placed on opposite surfaces of a transparent medium.
- An incident laser source illuminates the resonator.
- As the front surface of the resonator displaces with respect to the back surface, the cavity thickness changes and the output intensity changes
- Very high resolution measurements can be made with this system, but only over the limited operating range (i.e., dynamic range) of the resonance curve.
- Such sensors are used in high frequency applications such as optical microphones.

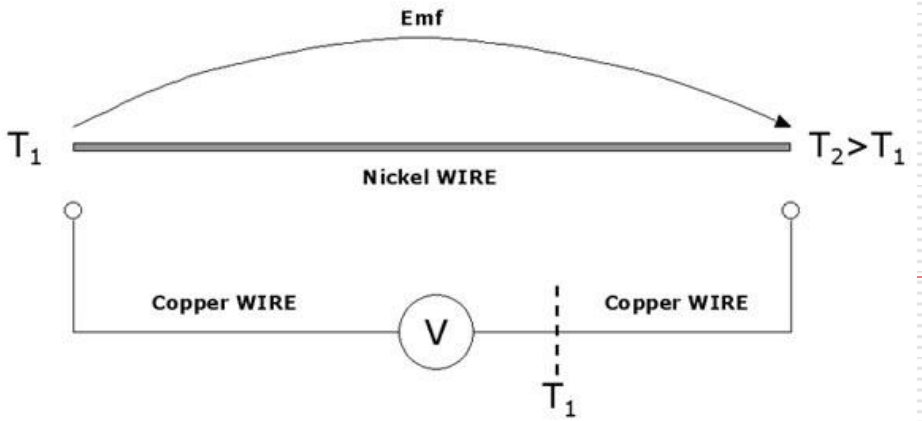


# 2.7 TEMPERATURE MEASUREMENTS

- A patient's body temperature gives the physician important information about the physiological state of the individual.
- External body temperature is one of many parameters used to evaluate patients in shock, because the reduced blood pressure of a person in circulatory shock results in low blood flow to the periphery. A drop in the **big-toe temperature** is a good early clinical warning of shock.
- Infections, on the other hand, are usually reflected by an increase in body temperature, with a hot, flushed skin and loss of fluids.
- Increased ventilation, perspiration, and blood flow to the skin result when high fevers destroy temperature-sensitive enzymes and proteins.
- Anesthesia decreases body temperature by depressing the thermal regulatory center. In fact, physicians routinely induce hypothermia in surgical cases in which they wish to decrease a patient's metabolic processes and blood circulation.
- In pediatrics, special heated incubators are used for stabilizing body temperature of infants.
- In the study of arthritis (*kireçlenme*), physicians have shown that temperatures of joints are closely correlated with the amount of local inflammation (*iltihap*). The increased blood flow due to arthritis and chronic inflammation can be detected by thermal measurements.
- Temperature sensors type
  - Thermocouples
  - Thermistors
  - Radiation and fiber-optic detectors
  - *p-n* junction semiconductor (2 mV/$^{o}$C)

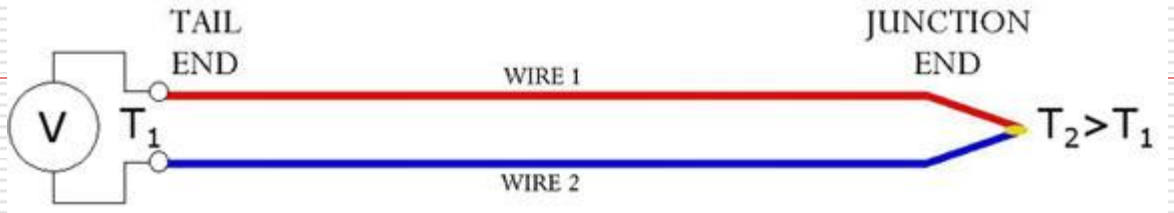
# 2.8 THERMOCOUPLES

- When a temperature difference is applied between the two ends of a single Ni wire, a voltage drop is developed across the wire itself. The end of the wire at the highest temperature, $T_2$, is called hot end, while the end at the lowest temperature, $T_1$, is called cold end.
- When a voltmeter, with Cu connection wires, is used to measure the voltage drop across the Ni wire, two junctions need to be made at the hot and cold ends between the Cu wire and the Ni wire; assuming that the voltmeter is at room temperature $T_1$, one of the Cu wires of the voltmeter will experience along it the same temperature drop from T2 to T1 the Ni wire is experiencing. In the attempt to measure the voltage drop on the Ni wire a Ni-Cu thermocouple has been made and so the measured voltage is in reality the voltage drop along the Ni wire plus the voltage drop along the Cu wire.
- The Emf along a single thermoelement cannot be measured: the Emf measured at the tail end in previous figure is the sum of the voltage drop along each of the thermoelements. As two thermoelements are needed, the temperature measurement with thermocuoples is a **differential measurement**.
- Note: if the wire in figure was a Cu wire a null voltage would have been measured at the voltmeter.



# 2.8 THERMOCOUPLES

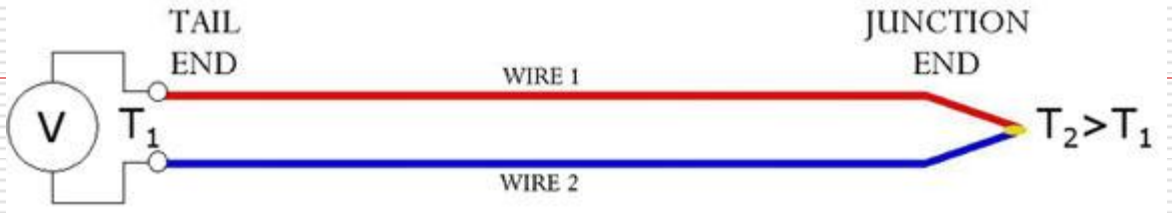
- A thermocouple is a device made by two different wires joined at one end, called **junction end** or **measuring end**. The two wires are called **thermoelements** or legs of the thermocouple: the two thermoelements are distinguished as positive and negative ones. The other end of the thermocouple is called **tail end** or **reference end** (Figure). The junction end is immersed in the enviroment whose temperature $T_2$ has to be measured, which can be for instance the temperature of a furnace at about 500°C, while the tail end is held at a different temperature $T_1$, e.g. at ambient temperature.
- Because of the temperature difference between junction end and tail end a voltage difference can be measured between the two thermoelements at the tail end: so the thermocouple is a temperature-voltage transducer.



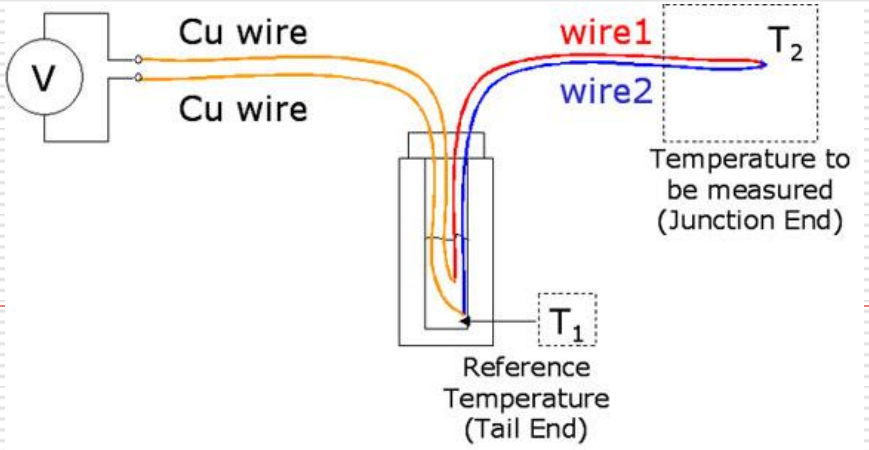
- The temperature vs voltage relationship is given by:

$$Emf = \int_{T_1}^{T_2} S_{12} \cdot dT = \int_{T_1}^{T_2} (S_1 - S_2) \cdot dT$$

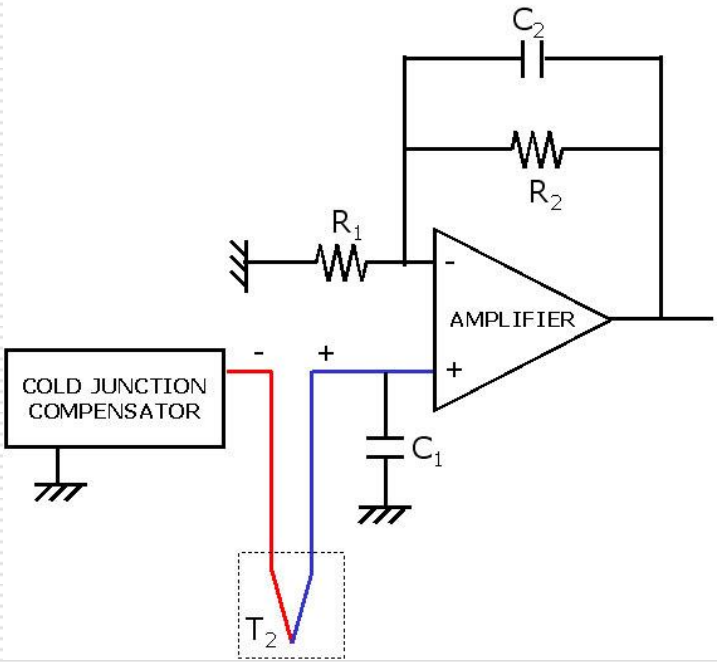
- where Emf is the Electro-Motive Force or Voltage produced by the thermocople at the tail end, $T_1$ and $T_2$ are the temperatures of reference and measuring end respectively, $S_{12}$ is called Seebeck coefficient of the thermocouple and $S_1$ and $S_2$ are the **Seebeck coefficient** of the two thermoelements; the **Seebeck coefficient** depends on the material the thermoelement is made of.
- Looking at equation it can be noticed that:
  - a null voltage is measured if the two thermoelements are made of the same materials: different materials are needed to make a temperature sensing device,
  - a null voltage is measured if no temperature difference exists between the tail end and the junction end: a temperature difference is needed to operate the thermocouple,
  - the Seebeck coefficient is temperature dependent.



- The temperature measurement with thermocouples is also a **differential measurement** because two different temperatures, $T_1$ and $T_2$, are involved. The desired temperature is the one at the junction end, $T_2$. In order to have a useful transducer for measurement, a monotonic "Emf versus junction end temperature $T_2$ relationship" is needed, so that for each temperature at the junction end, a unique voltage is produced at the tail end.
- However, from the integral in Equation1 it can be understood that the Emf depends on both $T_1$ and $T_2$: as $T_1$ and $T_2$can change independently, a monotonic "Emf vs $T_2$ relationship" cannot be defined if the tail end temperature is not constant. For this reason the tail end is maintained in an ice bath made by crushed ice and water in a Dewar flask: this produces a reference temperature of 0°C. All the voltage versus temperature relationships for thermocouples are referenced to 0°C.



- The ice bath is usually replaced in industrial application with an integrated circuit called **cold junction compensator**: in this case the tail end is at ambient temperature and the temperature fluctuations at the tail end are tolerated; in fact the cold junction compensator produces a voltage equal to the thermocouple voltage between 0°C and ambient temperature, which can be added to the voltage of the thermocouple at the tail end to reproduce the voltage versus temperature relationship of the thermocouple.
- It should be underlined that the cold junction compensation cannot reproduce exactly the voltage versus temperature relationship of the thermocouple, but can only approximate it: for this reason the cold junction compensation introduces an error in the temperature measurement.
- Figure shows also the filtering and amplification of the thermocouple. Being the thermocouple voltage a DC signal, removal of AC noise through filtering is beneficial; furthermore the thermocouples produce voltage of few tens of mV and for this reason amplification is required.

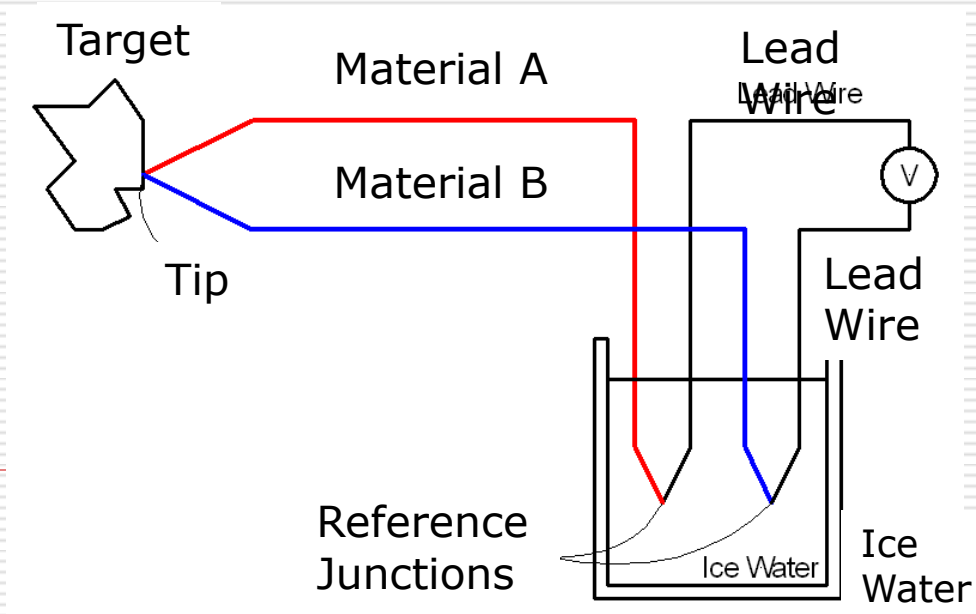


# Implementation

- A typical thermocouple consists of wires made from the two materials and a method of measuring the potential difference
- The reference temperature $T_{ref}$ is usually supplied by an ice-water bath or in the field the ambient temperature is used

$$T_{tip} = T_{ref} + \frac{V_{out}}{\alpha_{SA} - \alpha_{SB}}$$

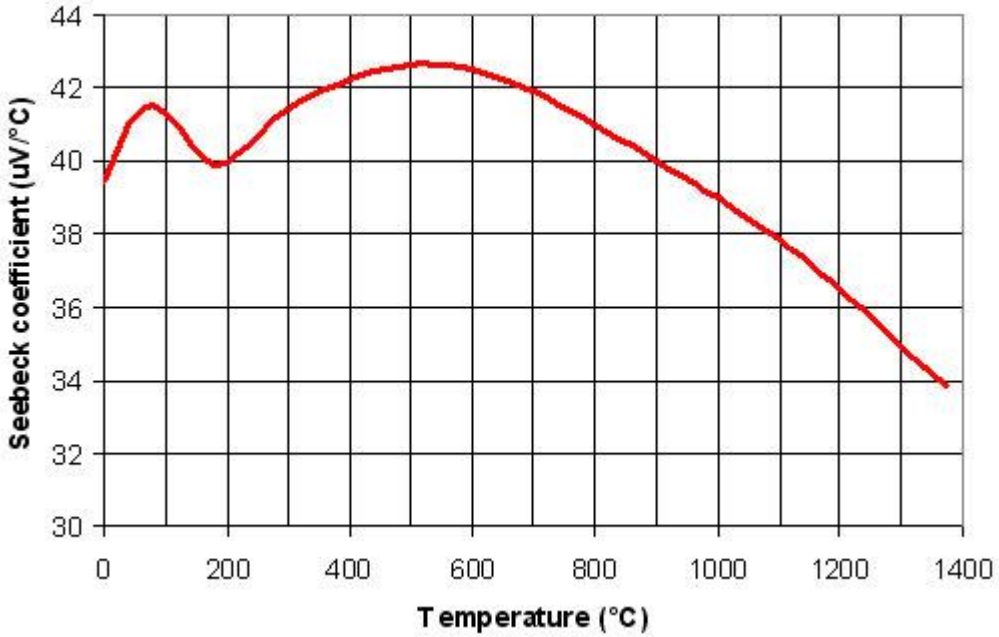
where $\alpha_{SA}$ and $\alpha_{SB}$, are the thermoelectric coefficients of the two materials



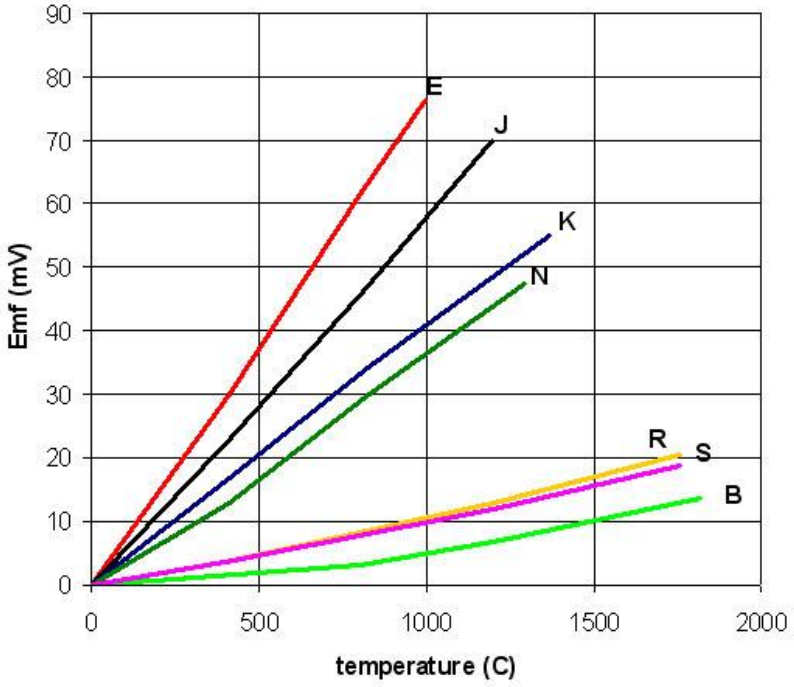
- The small voltage range for some of the most common thermocouples (**letter designated thermocouples**) is shown in Figure, where their voltage versus temperature relationship is reported.
- All the voltage-temperature relationships of the letter designated thermocouples are monotonic, but not linear. For instance the type N thermocouple voltage output is defined by the following 10 degree polynomials

| Thermocouple type | Positive Thermoelement | Negative Thermoelement |
|---|---|---|
| B | Pt-30%Rh | Pt-6%Rh |
| R | Pt-13%Rh | Pt |
| S | Pt-10%Rh | Pt |
| K | Ni-10%Cr | Ni-5% other elements |
| N | Ni-14%Cr-1.5%Si | Ni-4.5%Si-0.1%Mg |
| E | Ni-10%Cr | 45%Ni-55%Cu |
| J | Fe | 45%Ni-55%Cu |

Table1: Approximate composition for thermoelements of letter-designated thermocouples




Type K Seebeck coefficient vs Temperature

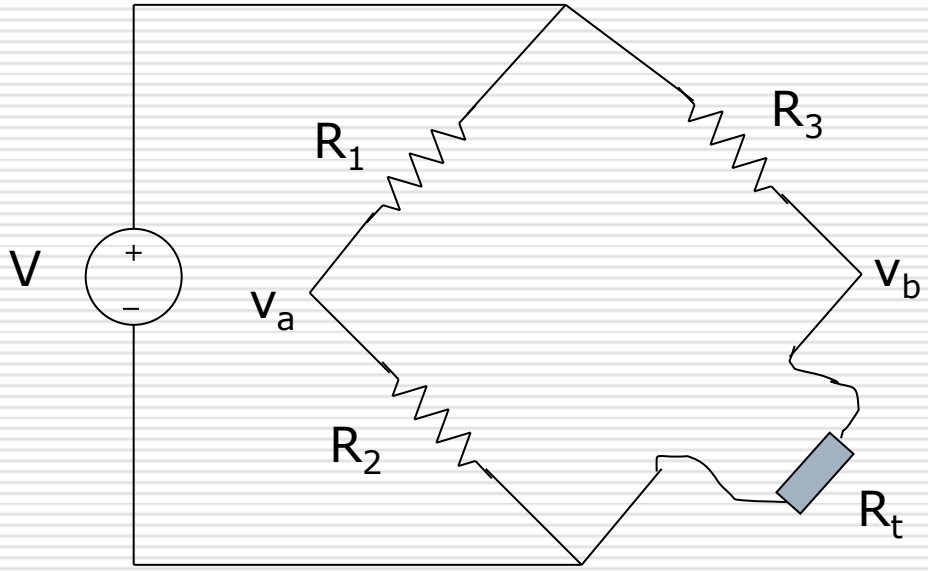


# Thermistors

- Thermistors are semiconductors made of ceramic materials whose resistance decreases as temperature increases.
- **Advantages**
  - Small in size (0.5 mm in diameter)
  - Large sensitivity to temperature changes (-3 to -5% /$^{o}$C)
    - Blood velocity
  - Temperature differences in the same organ
  - Excellent long-term stability characteristics ($\Delta$R=0.2% /year)
- **Disadvantages**
  - Nonlinear portion exists in
  - Self heating occurs after a certain amount of current passes
  - Limited range but suitable for biomedical applications

# Circuit Connections of Thermistors

- Bridge Connection to measure voltage




- Operational-amplifier circuits may be used to measure the current in a thermistor as a function of temperature. In essence, this circuit applies a constant voltage to the thermistor and monitors its current with a current-to voltage converter.

- Relationship between Resistance and Temperature at zero-power resistance of thermistor.

$$R_t = R_0 e^{[\beta(T_0 - T)/TT_0]} \qquad 2.23$$

- $\beta$ = material constant for thermistor, increases slightly with temperature but not a problem for the limited temperature spans for biomedical work (10°C to 20°C).

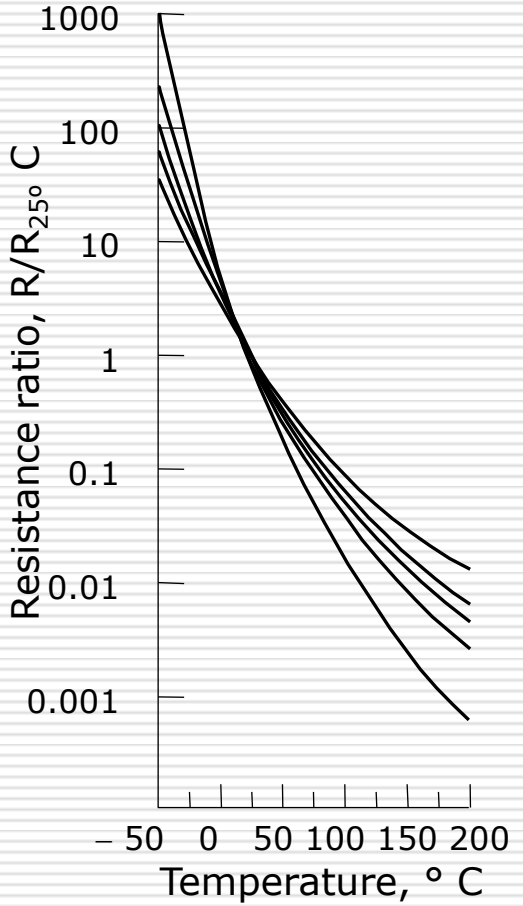
  $T_o$ = standard reference temperature, K

  $T_o$ = 293.15 K = 20C = 68F

- The temperature coefficient $\alpha$ can be found by differentiating eq. 2.23 with respect to T and dividing by $R_t$

$$\alpha = \frac{1}{R_t}\frac{dR_t}{dT} = -\frac{\beta}{T^2} \qquad (\%/K)$$

$\alpha$ is a nonlinear function of temperature which causes nonlinearity in the figure.

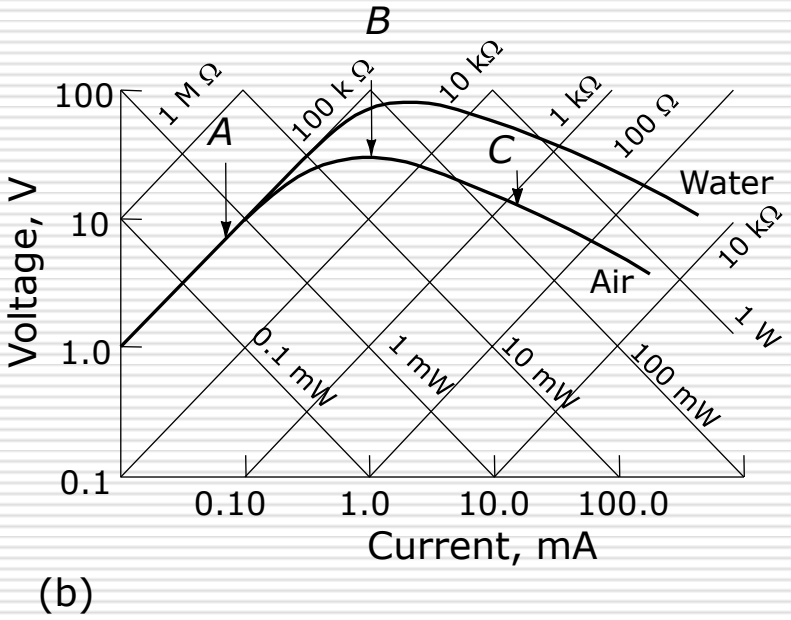



(a)

(a) Typical thermistor zero-power resistance ratio-temperature characteristics for various materials

# Voltage-Versus-Current Characteristics

- The voltage-versus-current characteristics of thermistors, as shown in Figure are linear up to the point at which self-heating becomes a problem.
- The temperature of the thermistor is that of its surroundings. However, above specific current, current flow generates heat that make the temperature of the thermistor above the ambient temperature.
- (b) Thermistor voltage-versus-current characteristic for a thermistor in air and water. The diagonal lines with a positive slope give linear resistance values and show the degree of thermistor linearity at low currents. The intersection of the thermistor curves and the diagonal lines with the negative slope give the device power dissipation. Point A is the maximal current value for no appreciable self-heat. Point B is the peak voltage. Point C is the maximal safe continuous current in air.




(b)

# Semiconductor Thermal Sensors

- A semiconductor PN junction of a diode or transistor exhibits a strong temperature dependence.
- If the junction is connected to a constant current source, the voltage becomes a measure of the junction temperature.
- This relationship is very linear, and is therefore used for accurate three terminal temperature sensing integrated circuits
- The LM35Z temperature sensor has a linear output internally trimmed for the Celsius scale with a sensitivity of 10mV per °C and a nonlinearity error confined within +/-0.1°C.

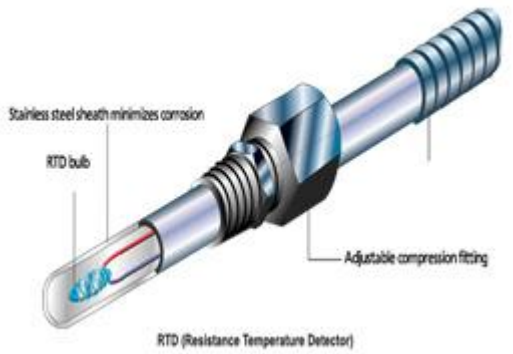
$$V_{out} = V_0 + \alpha T$$

# Resistance Temperature Detection (RTD) Thermometers

- Most other thermometer types are based on materials whose electrical properties change with temperature.
- Possibly the most accurate of these are resistance temperature detectors (RTD).
- Standard platinum RTDs can be manufactured with accuracies of +/- 0.0001°C, while simple industrial RTDs are generally accurate to about +/-0.1°C.

# Implementation

- The sensitive portion of an RTD is a coil of high-purity wire or a thin film deposited onto a ceramic substrate
- The metal used is usually platinum, copper or nickel depending on the temperature range and accuracy.
- Platinum is the material of choice because it doesn't oxidise even when subjected to very high temperatures.
- In operation, a constant current (0.8mA to 1mA typically) is passed through the coil.
- As the temperature increases, the resistance will increase (the temperature coefficient is positive), and the voltage that is developed across the coil will reflect this.
- An accurate voltmeter calibrated to measure temperature can be used to display this value



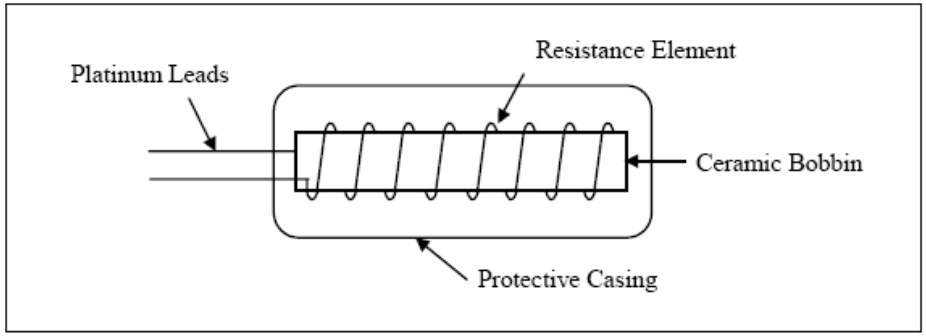




Figure 7-14. Typical RTD – resistance temperature detectors

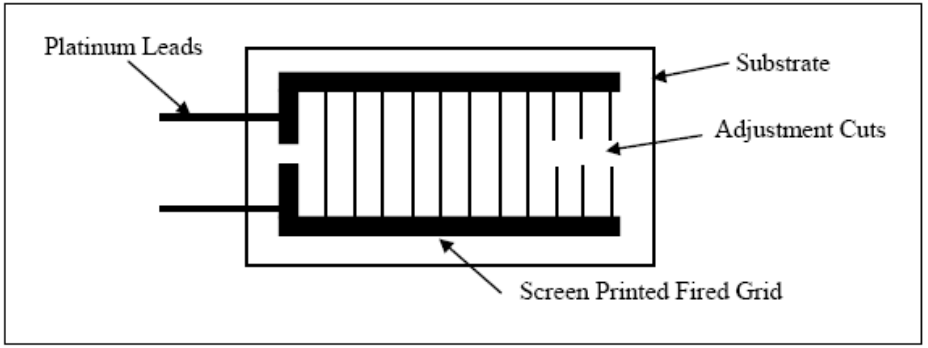


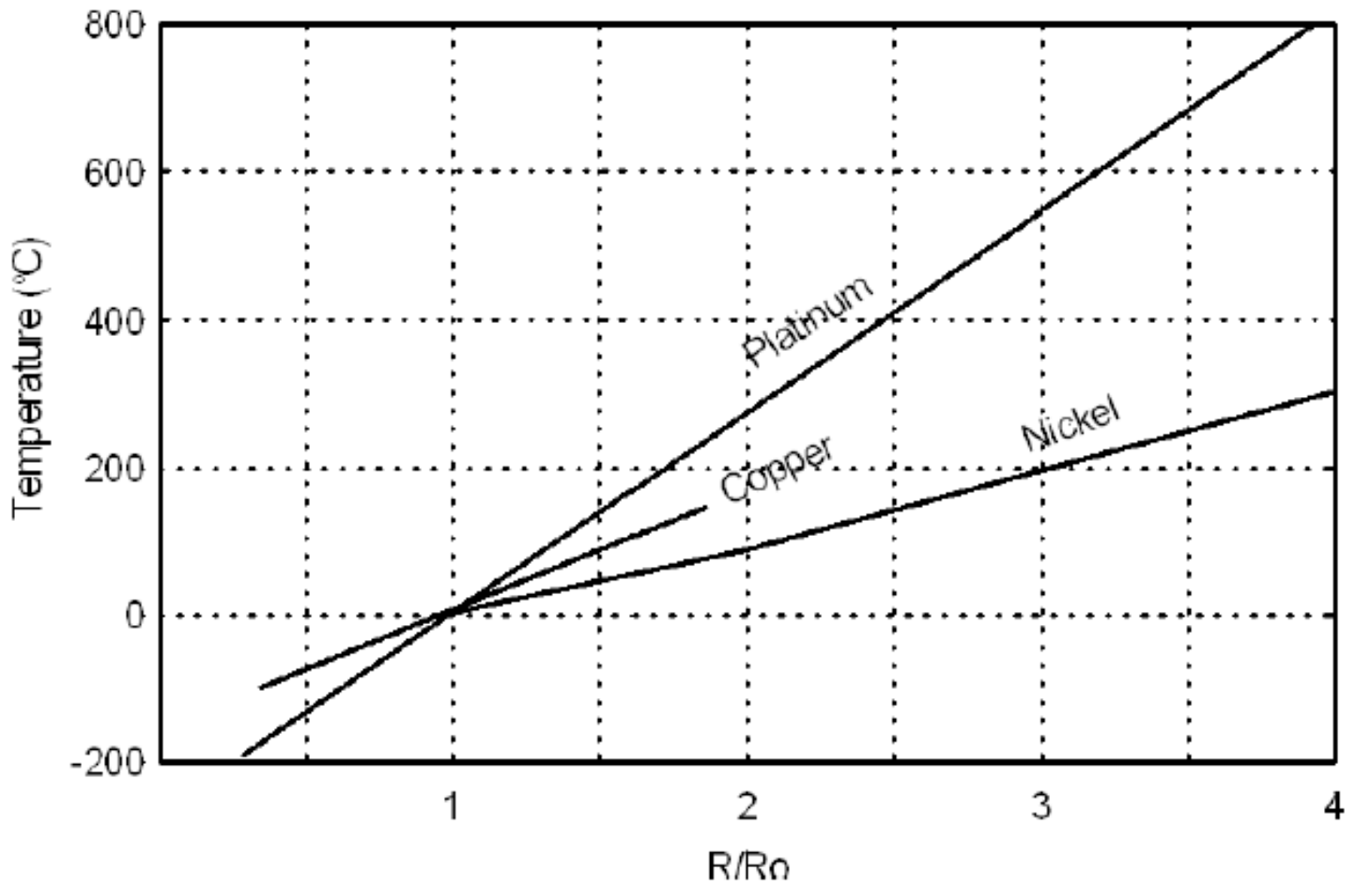

Figure 7-15. Metal-film RTD

# Performance Considerations

- The temperature coefficient of resistance $\alpha$ is defined as the change in resistance per degree C per ohm over the range from 0°C to 100°C
- Considerations:
  - Copper - 0.00427
    - Good linearity
    - Limited temperature range - oxidises at 150°C
  - nickel - 0.00672
    - Best sensitivity
    - Very nonlinear above 300°C
  - platinum - 0.003902
    - Widest temperature range -184°C to +649°C
    - Good linearity
    - Good repeatability
    - Long life

$$\alpha = \frac{R_{100} - R_0}{100 R_0}$$

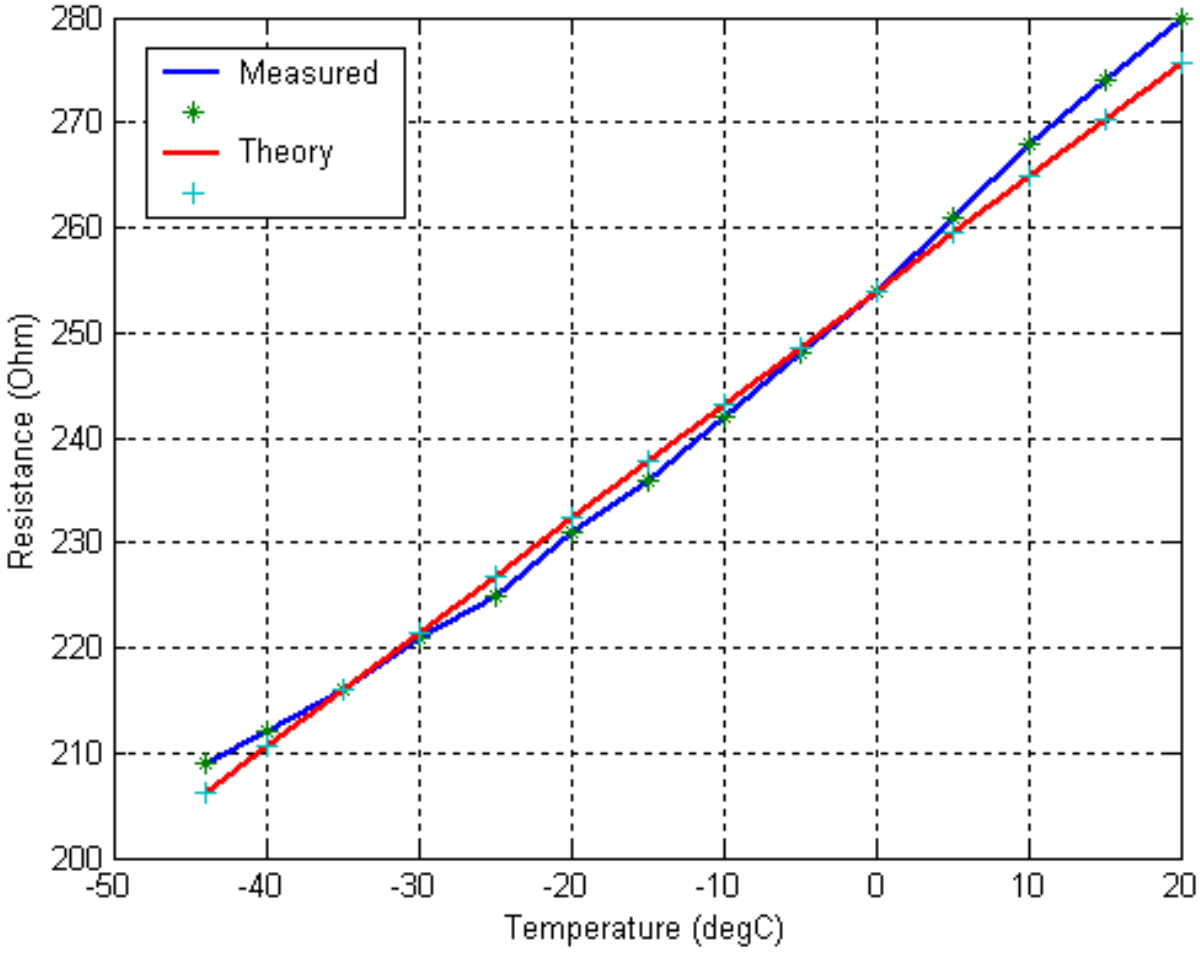
# Operational Range & Sensitivity




$$\alpha = \frac{R_{100} - R_0}{100 R_0}$$

$R_o$ is the resistance at 0°C

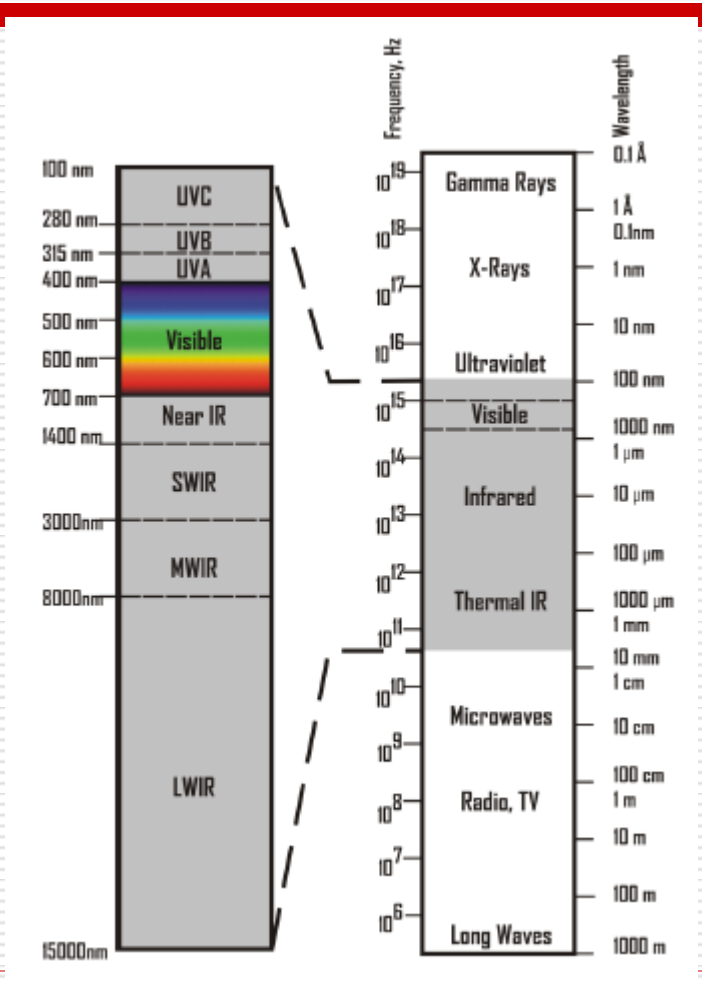
# Copper RTD – Theory and Measured Data



# Radiation Thermometry

- Radiation thermometry uses the relationship between the surface temperature of an object and its radiant power to measure the temperature of a body without physical contact with it.
- Medical thermography is a technique whereby the temperature distribution of the body is mapped with a sensitivity of a few tenths of a kelvin. It is based on the recognition that skin temperature can vary from place to place depending on the cellular or circulatory processes occurring at each location in the body.
- The higher the temperature of a body the higher is the electromagnetic radiation (EM).
- Electromagnetic Radiation Transducers convert energy in the form of EM radiation into an electrical current or potential, or modify an electrical current or potential.
- Application
  - Breast cancer, determining location and extent of arthritic disturbances,
  - measure the depth of tissue destruction from frostbite and burns,
  - detecting various peripheral circulatory disorders (venous thrombosis (toplar damarda pıhıtılaşma)
  - carotid artery occlusions (şah damarı tıkanıklığı))

- All bodies above absolute zero emit thermal radiation.
- The quantity of power emitted is measured by the radiative intensity.
- Energy is distributed across the electromagnetic spectrum and the intensity of emission and the shape of the distribution is dependent on the temperature.
- Conversely, the temperature of a body can be measured by the quantity and spectral distribution of energy it emits.




- Radiation thermometers measure radiation in the ultra-violet (UV), visible, and infra-red (IR) ranges of the electromagnetic spectrum. These comprise the regions in the spectrum from about 0.1 to 5000 µm.

# Radiation Temperature Measurement

- By measuring the radiation intensity or distribution, the temperature of a blackbody or black surface can uniquely be obtained.
- This is the basic principle of radiation temperature measurement.
- A blackbody is an ideal thermal radiator; as such, it absorbs all incident radiation and emits the maximal possible thermal radiation.
- The intensity and distribution of energy is governed by Planck's law and is determined by the wavelength of light, $\lambda$ and the temperature, T.

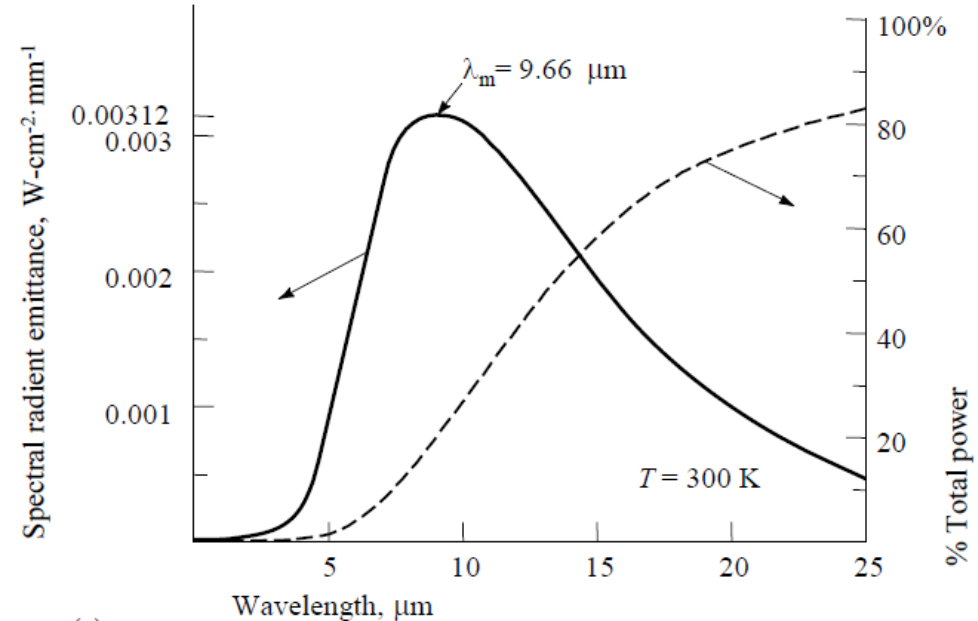
$$W_\lambda = \frac{\varepsilon C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1\right)}$$

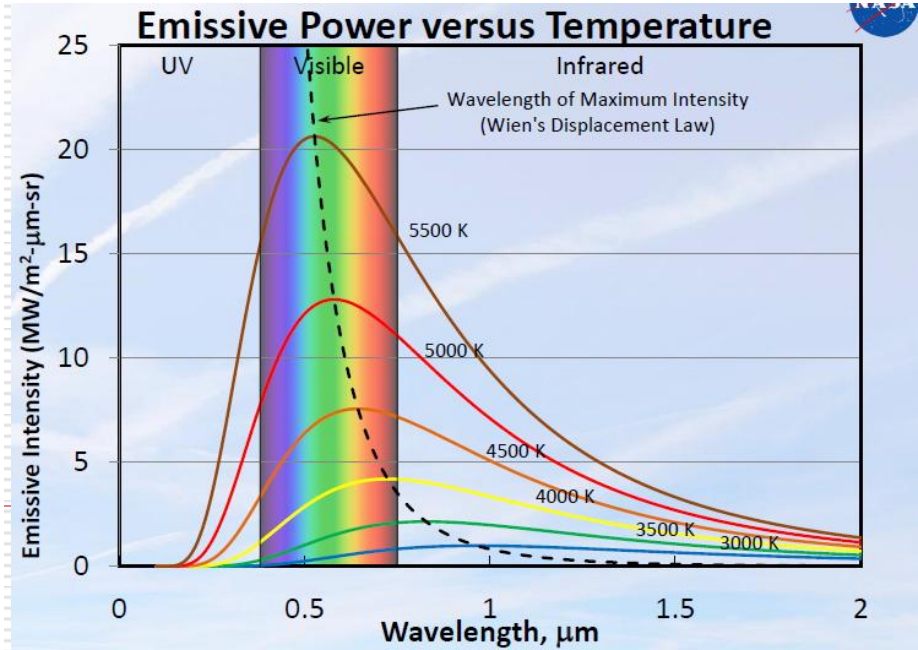
$$C_1 = 3.74 \times 100 \ (\mathrm{W \cdot \mu m^4/cm^2})$$

$$C_2 = 1.44 \times 10^4 \quad (\mu \mathrm{m \cdot K})$$

- $\varepsilon$ is the relative emissivity (i.e., the extent which a surface deviates from a black body - for a true black body, $\varepsilon$=1).

- For a given temperature such as room temperature, the wavelength at which a black body maximally radiates is about 9.66 mm, in the infrared range.

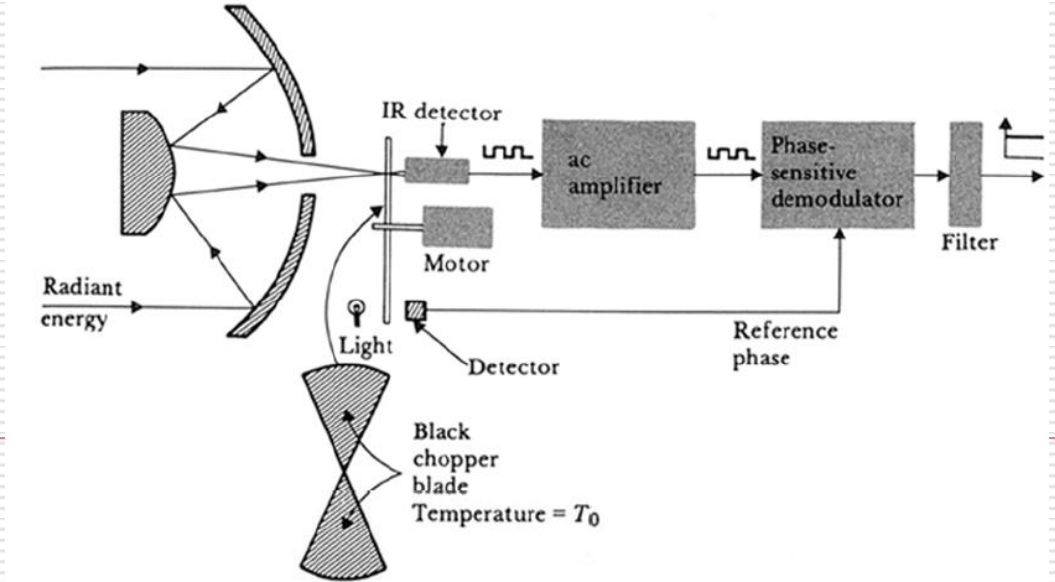


- Real surfaces do not emit radiation like an idealized blackbody
- Instead, real surfaces emit at a lower rate
- The fraction of radiation a surface emits relative to a blackbody is known as the emissivity
- The emissivity of a surface varies with direction, wavelength, and temperature.
- Determining the effect of changes in surface emissivity with wavelength is important to accurately determine the temperature of a given source.
- For example, at 300 °K and $\lambda$=3$\mu$m, a 5% change in $\varepsilon$ is equivalent to a temperature change of about 1 °C.
- To detect IR emissivity for an object, IR cameras are used.

# Chopped-Beam Radiation-Thermometer System

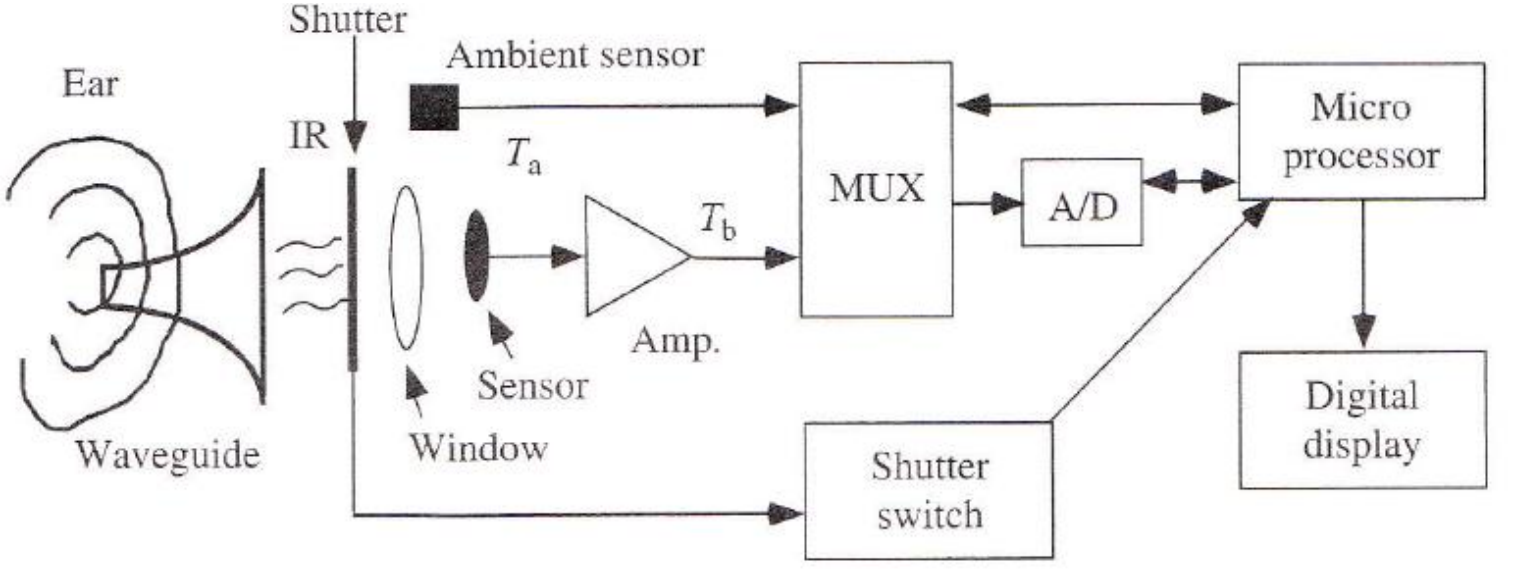
- A typical IR camera system used for temperature sensing is illustrated in the figure below.
- A mirror focuses the radiant energy from the source onto a photodiode detector.
- The output of the detector circuit is a series of pulses with amplitude dependent on the strength of the radiation source. This ac signal is amplified, while the mean value, which is subject to drift, is blocked.
- A reference-phase signal, used to synchronize the phase-sensitive demodulator, is generated in a special circuit consisting of a light source and detector. Phase-sensitive detection is performed for optimal sensitivity.
- The signal is then filtered to provide a dc signal proportional to the target temperature.
- This signal can then be displayed or recorded. Infrared microscopes have also been designed using these techniques.



NASA/IPAC
93.4
90
85
80
75
73.6

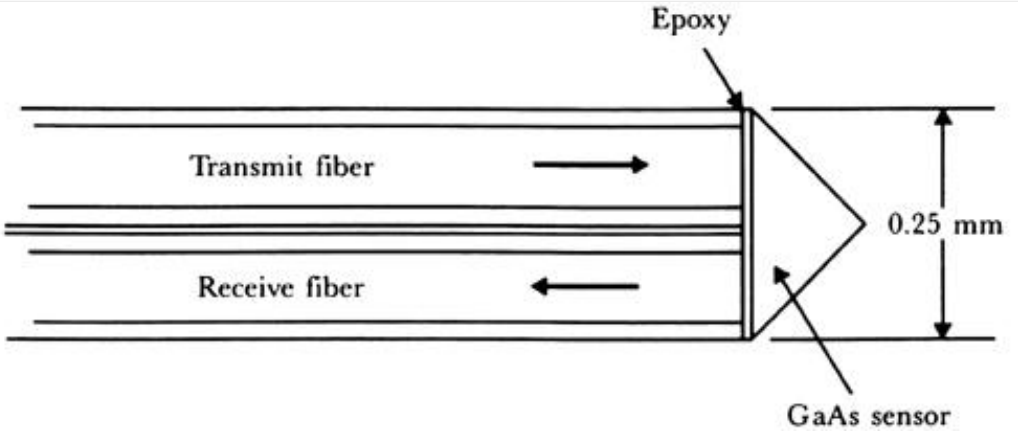
# The Infrared Thermometer

- Figure shows one application of radiation thermometry is an instrument that determines the internal or core body temperature of the human by measuring the magnitude of infrared radiation emitted from the tympanic membrane and surrounding ear canal.
- The tympanic membrane is in close relation with hypothalamus which is body's main thermostat regulating the core body temperature.
- This approach has advantages over using mercury thermometers, thermocouples, or thermistors.
- The other type of thermometers must be in contact with the patient long enough for its temperature to become the same as, or close to, that of the subject
- Infrared thermometry device measures almost instantly and does not require contact with the patient.



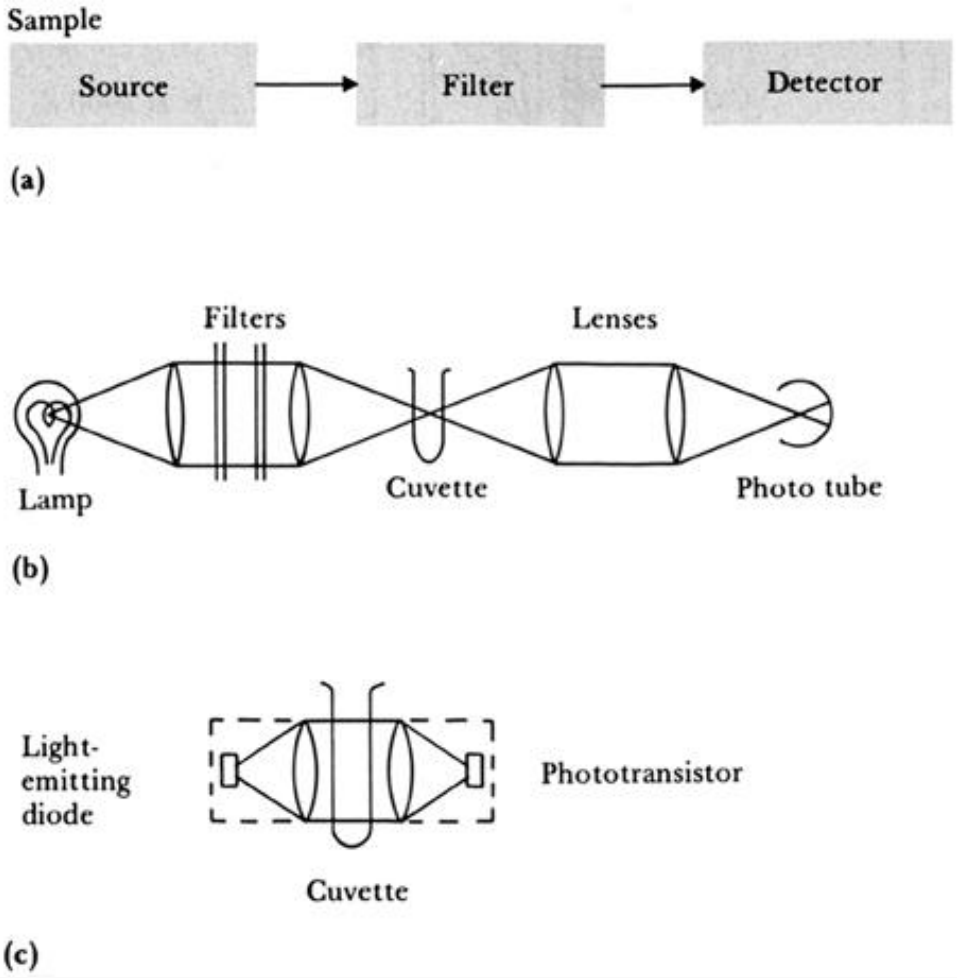
# 2.11 FIBER OPTIC TEMPERATURE SENSORS

- Figure below light is coupled from an input fiber into an output fiber through a double mirror constructed from a III-IV semiconductor (typically GaAs).
- One fiber transmits light from a light-emitting diode source to the sensor, where it is passed through the GaAs and collected by the other fiber for detection in the readout instrument.
- Some of the optical power traveling through the semiconductor is absorbed, by the process of raising valence-band electrons, across the forbidden energy gap into the conduction band.
- Because the forbidden energy gap is a sensitive function of the material's temperature, the amount of power absorbed increases with temperature.
- By monitoring changes in the transmitted intensity, the temperature of the medium in thermal contact with the GaAs sensor is measured.
- This nonmetallic probe is particularly suited for temperature measurement in the strong electromagnetic heating fields used in **heating tissue for cancer therapy** or **in patient rewarming.**



# 2.12 Optical Measurements

- All optical sensors have the same 3 general components: optical source, filter, optical detector.
- The filter is the primary sensing element, where some optical property is changed in response to a physical or chemical characteristic of the system.
- Applications:
  - Clinical-chemistry lab (analyze sample of blood and tissue)
  - Cardiac Catheterization (measure oxygen saturation of hemoglobin and cardiac output)



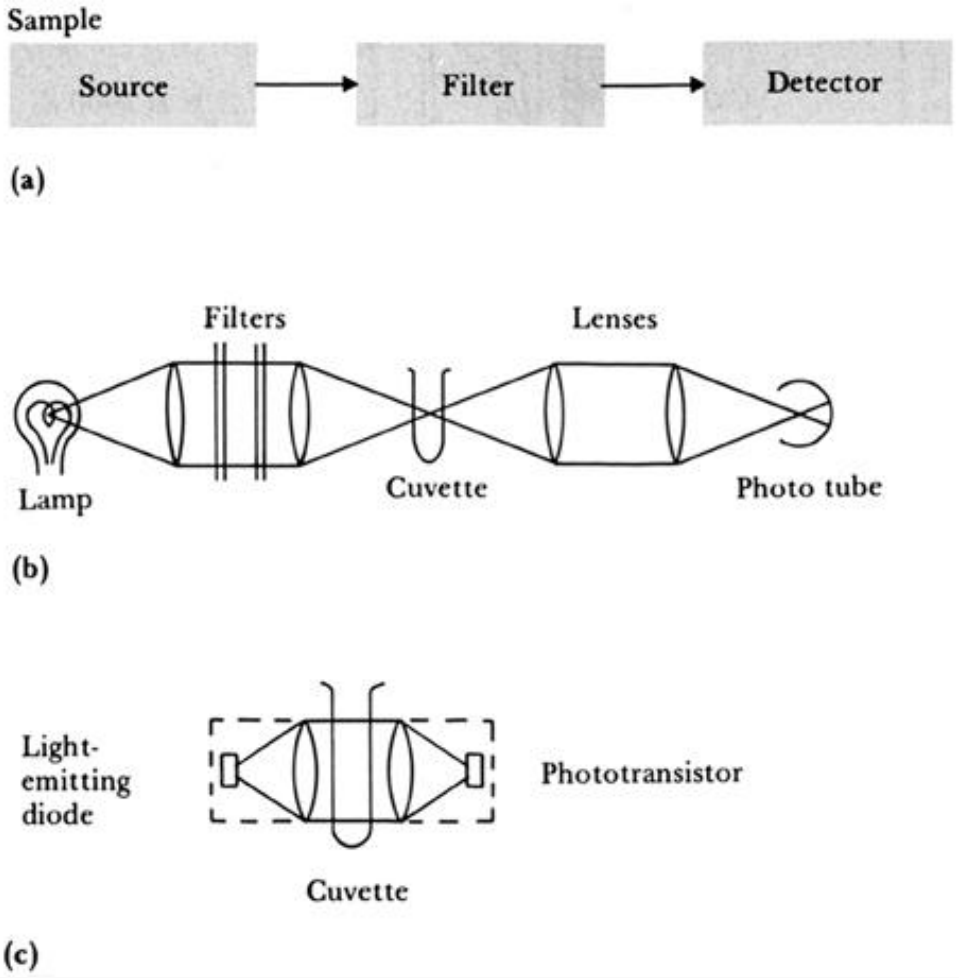

(a) General block diagram of an optical instrument.
(b) Highest efficiency is obtained by using an intense lamp, lenses to gather and focus the light on the sample in the cuvette, and a sensitive detector.
(c) Solid-state lamps and detectors may simplify the system.

# 2.12 Optical Measurements

- (a) General block diagram of an optical instrument.

- b)Highest efficiency is obtained by using an intense lamp, lenses to gather and focus the light on the sample in the cuvette, and a sensitive detector

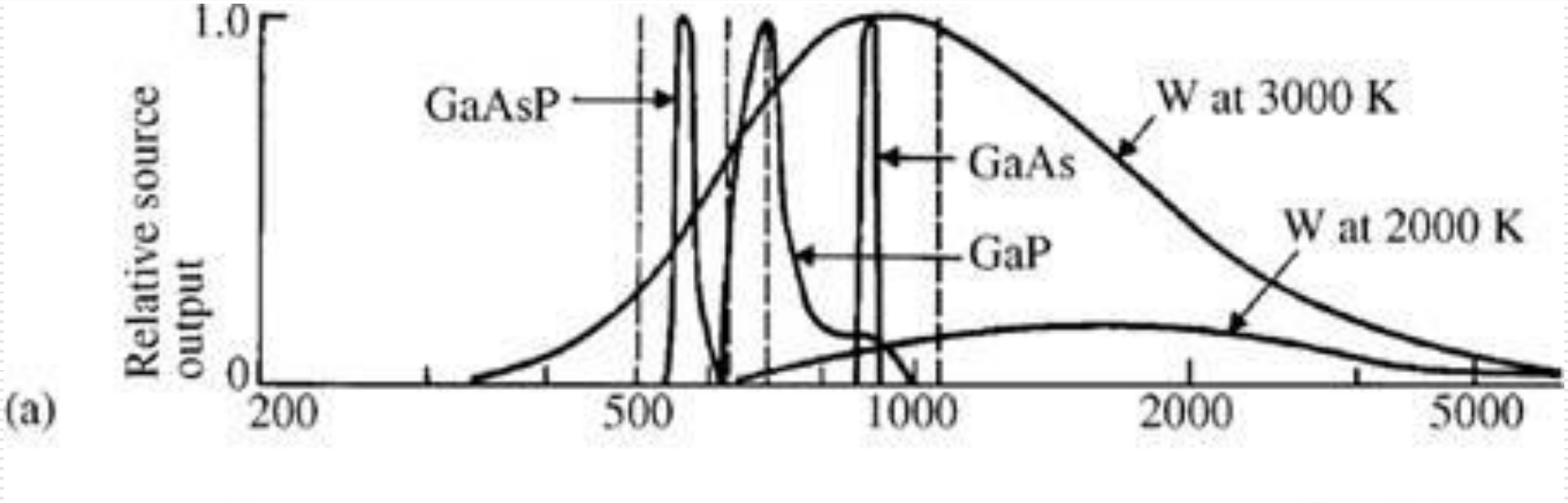
- c) Solid-state lamps and detectors may simplify the system.



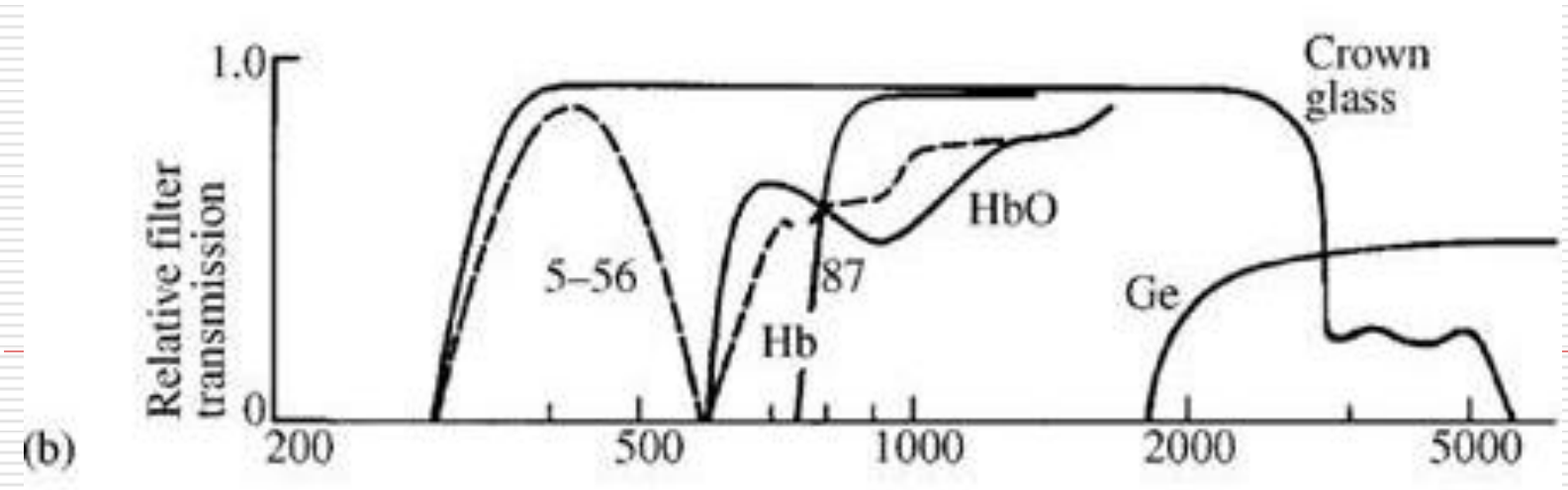
# 2.13 RADIATION SOURCES

- Spectral characteristics of (a) Light sources

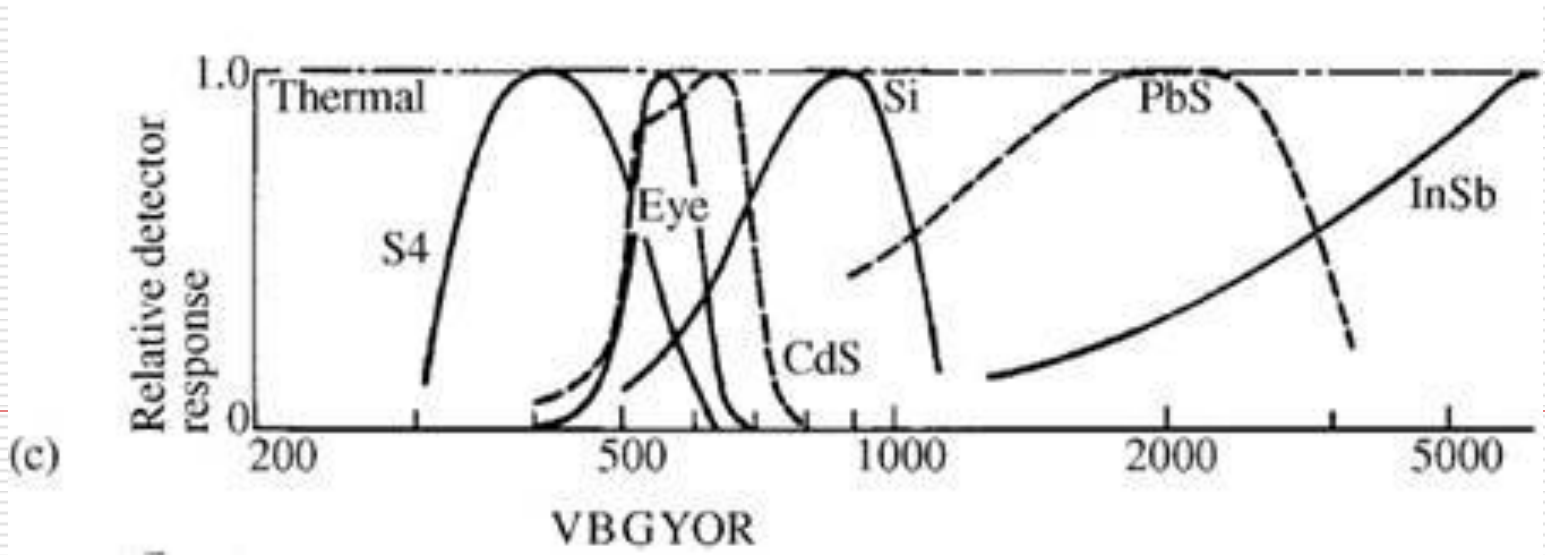
- Tungsten (W) at 3000 K has a broad spectral output. At 2000 K, output is lower at all wavelengths and peak output shifts to longer wavelengths.
- Light-emitting diodes yield a narrow spectral output with GaAs in the infrared, GaP in the red, and GaAsP in the green.
- Monochromatic outputs from common lasers are shown by dashed lines: Ar, 515 nm; HeNe, 633 nm; ruby, 693 nm; Nd, 1064 nm; CO2 (not shown), 10,600 nm



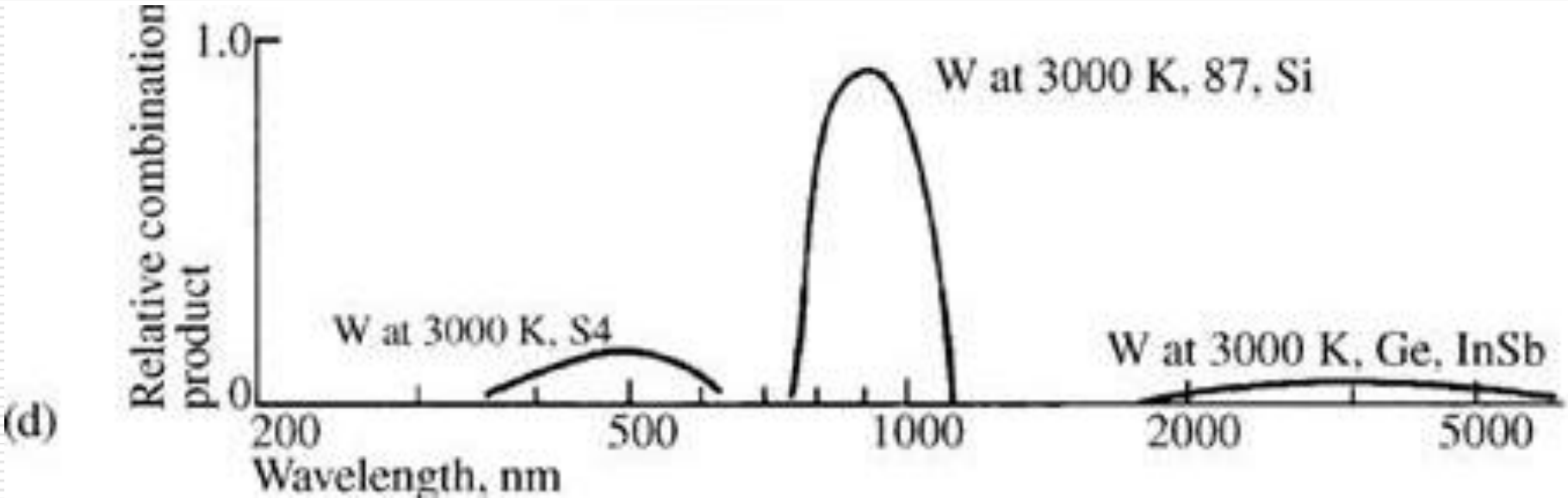
- Spectral characteristics of (b) Filters.
- A Corning 5-56 glass filter passes a blue wavelength band.
- A Kodak 87 gelatin filter passes infrared and blocks visible wavelengths.
- Germanium lenses pass long wavelengths that cannot be passed by glass.
- Hemoglobin Hb and oxyhemoglobin HbO pass equally at 805 nm and have maximal difference at 660 nm.



- Spectral characteristics of (c) Detectors.
- The S4 response is a typical phototube response.
- The eye has a relatively narrow response, with colors indicated by VBGYOR.
- CdS plus a filter has a response that closely matches that of the eye.
- Si *p-n* junctions are widely used.
- PbS is a sensitive infrared detector. InSb is useful in far infrared.

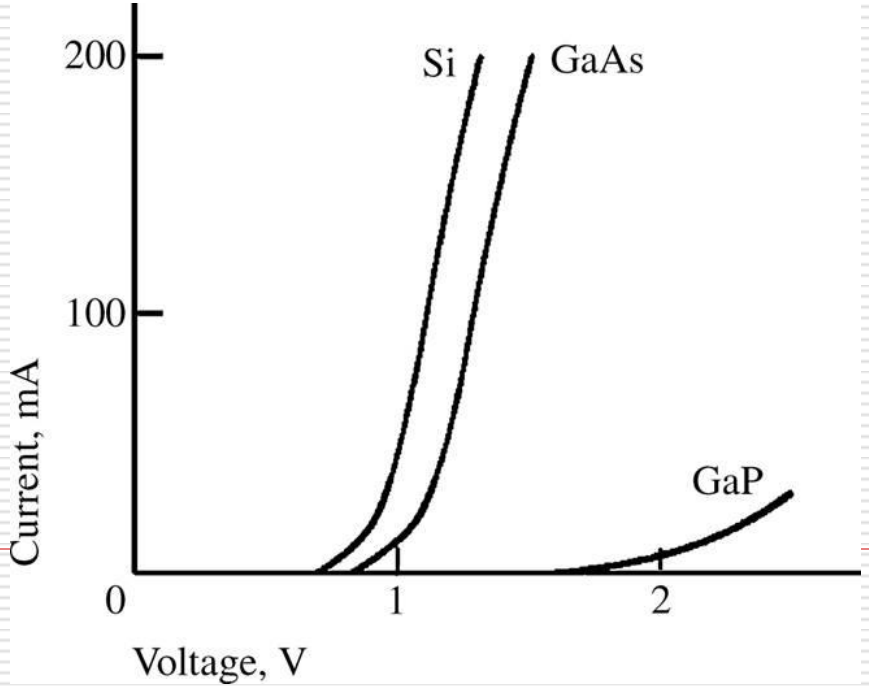


- Spectral characteristics of (d) Combination.
- Indicated curves from (a), (b), and (c) are multiplied at each wavelength to yield (d), which shows how well source, filter, and detector are matched



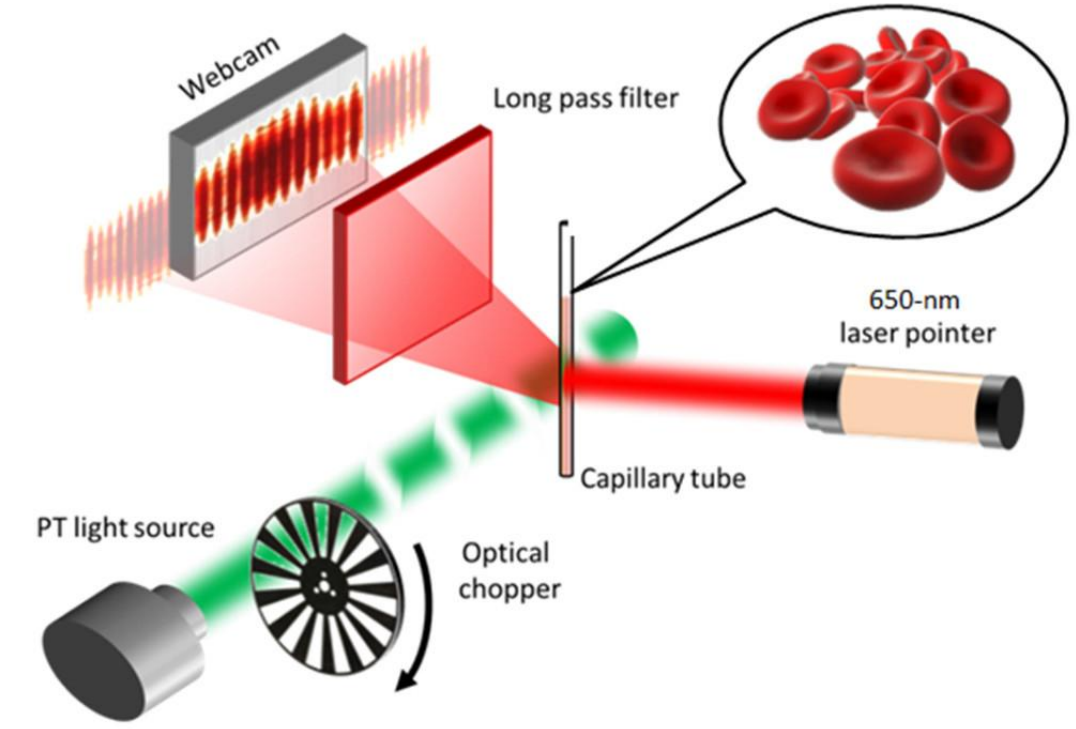
- Forward characteristics for *p-n* junctions emits radiant power when a current (typically 20 mA) passes in the forward direction
- Ordinary silicon diodes have a band gap of 1.1 eV and are inefficient radiators in the near-infrared.
- GaAs has a band gap of 1.44 eV and radiates at 900 nm.
- GaP has a band gap of 2.26 eV and radiates at 700 nm (bright red light).

the electronvolt (**eV**) is a unit of energy equal to approximately $1.6\times10^{-19}$ joules



# A photothermal optical sensor enables measurement of hemoglobin concentration in unprocessed, nanoliter blood sample.

- Fig. 1. Schematic of the PT-AS sensor for rapid and direct [Hb] measurement. 650-nm probe light from a commercial laser pointer is directed to a blood-containing capillary tube. The interference of the scattered light from the tube produces a distinct pattern on a webcam. Under the illumination of 532nm light, where Hb exhibits high absorption, Hb absorbs the light energy and converts it into heat, leading to a change in the refractive index of blood. This photothermal change in refractive index results in a shift in the scattering pattern. Quantification of this shift in the scattering pattern enables high-accuracy [Hb] measurement in unprocessed blood sample.



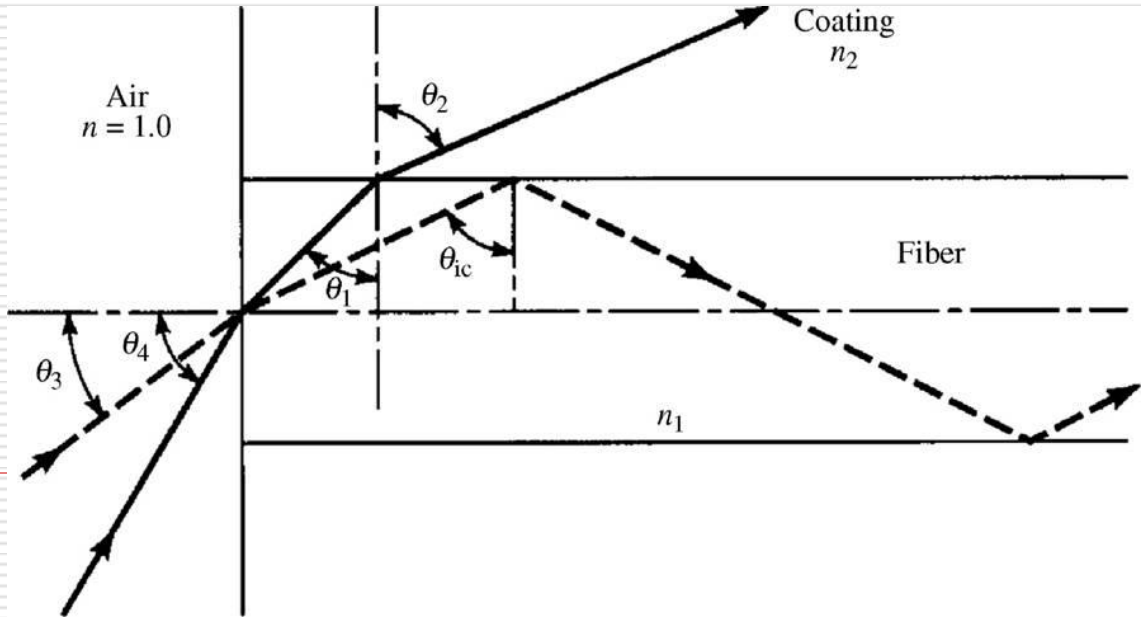

https://atlasofscience.org/a-photothermal-optical-sensor-enables-measurement-of-hemoglobin-concentration-in-unprocessed-nanoliter-blood-sample/

# Fiber Optics

- For applications where space is a major issue (e.g., catheter-based instruments), fiber delivery and collection systems are most efficient.
- Fibers consist of a plastic or glass core with refractive index n1 surrounded by a cladding of lower refractive index n2.
- According to Snell's Law, because n1 > n2, sinθ2 > sinθ1 . This means for a certain value θ1=θic<90°, θ2=90° and sin θ2=1.0. If θ1> θic than the ray is internally reflected.
- θ3 is the angle of light ray entering from air that enable ray reflect in the fiber with angle θic.
- Rays entering the end of the fiber at larger angles (θ4) are not transmitted down the flber; they escape through the walls.

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$

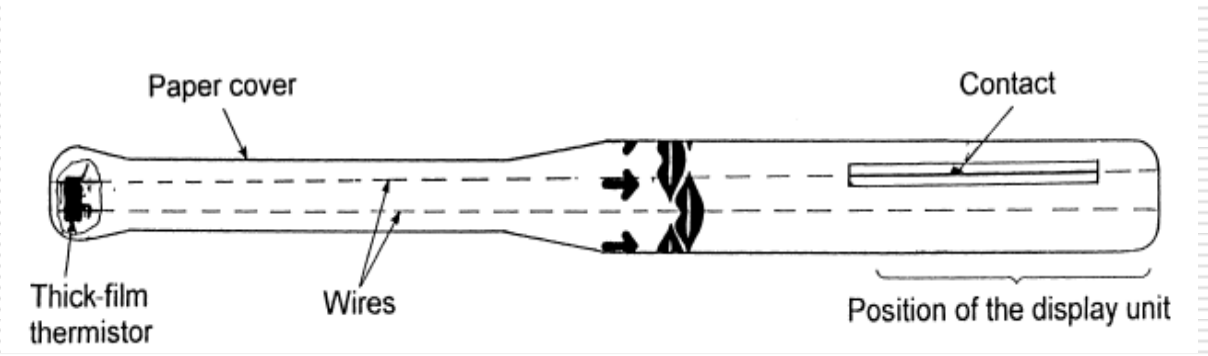
$$\sin\theta_{ic} = \frac{n_2}{n_1}$$



- Fiber optics can be used in two ways:
  - Noncoherent: There is no correlation between a fiber's spatial position at the input and at the output. These fibers are useful only for transmitting radiation.
  - Coherent (*uyumlu*): the fibers occupy the same relative position at both end faces. An image at one end is faithfully transmitted to the other end.
- Noncoherent applications:
  - Light transmissions for viewing internal organs
  - Measuring blood oxygen saturation by transmitting radiation at two wavelengths down one bundle and analyzing backscattered radiation through a second bundle by the red-blood cells
- Coherent Applications:
  - Endoscope: A small lens focuses the image of the lining onto the end of a coherent bundle, which transmits the image in such a way that it may be viewed or photographed.

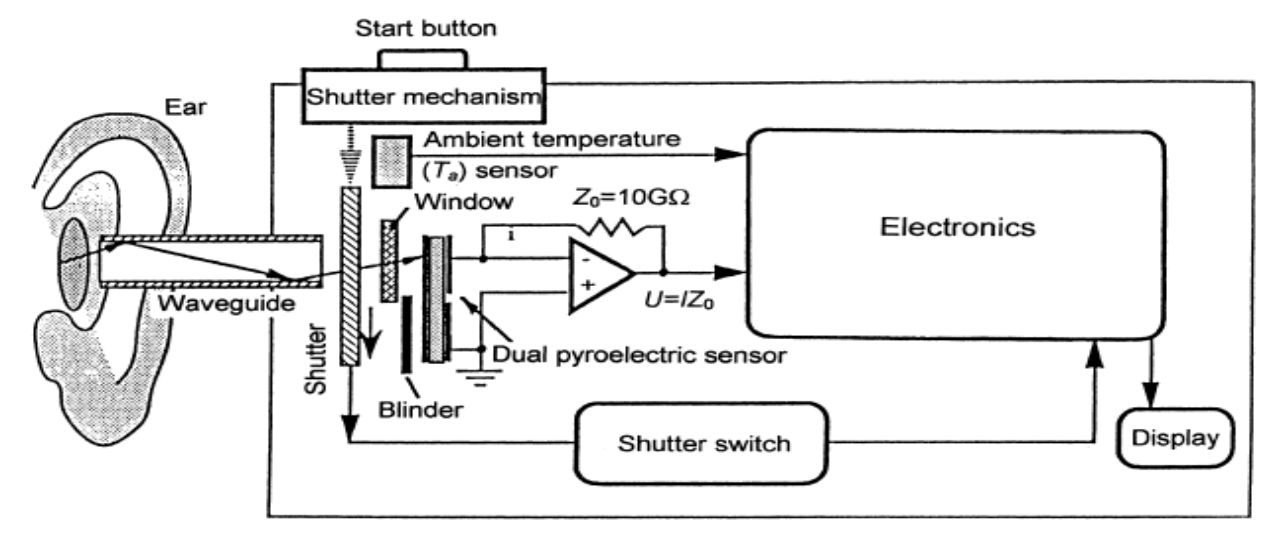
# Electronic thermometers

They generally contain diodes as temperature-sensing elements with a special package design that can assure small thermal capacity and good thermal conductivity to the environment. They have relatively short response times and good visible display units



Structure of a disposable oral thermometer.

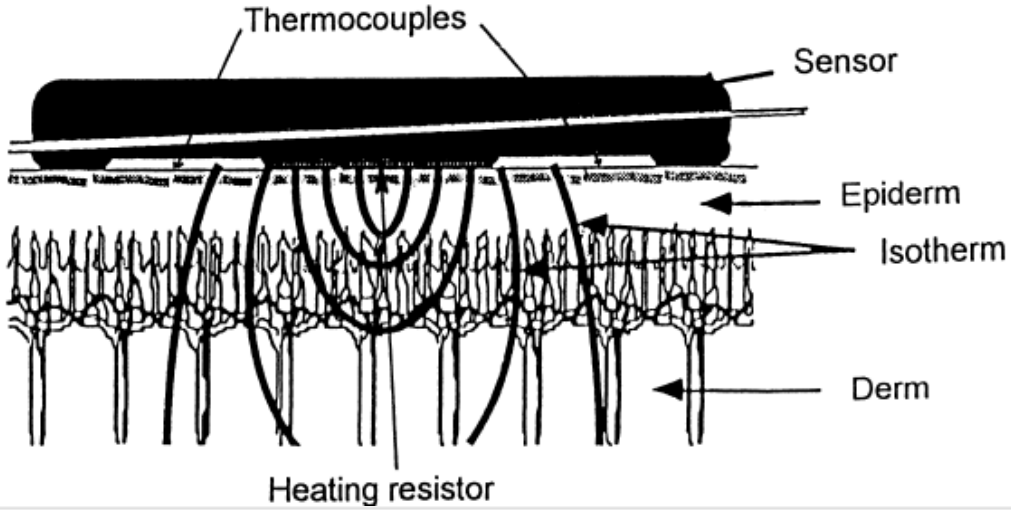
# Radiation Ear Thermometer




This version is based on a pyroelectric sensor. Thermal radiation flux from the auditory canal is channeled by the optical waveguide toward the pyroelectric sensor. When pressing the start button, the shutter opens momentarily, exposing the sensor to thermal radiation and replacing the radiation coming from the shutter itself. An ambient temperature sensor element is behind the shutter. The radiation reaches the sensor where it is converted into electric current impulse due to the pyroelectric effect

# Skin Blood-Flow Sensor

*Skin blood flow* (SBF) or skin perfusion is a complex phenomenon that occurs in capillaries. In perfused tissue, thermal conductivity depends not only on the thermal conductivity of the tissue materials, but also on the heat convection transferred by the blood flow in capillaries. Thus, thermal conductivity of the skin can vary within a wide range; its minimum value, 2.5 mW/(cm°C)

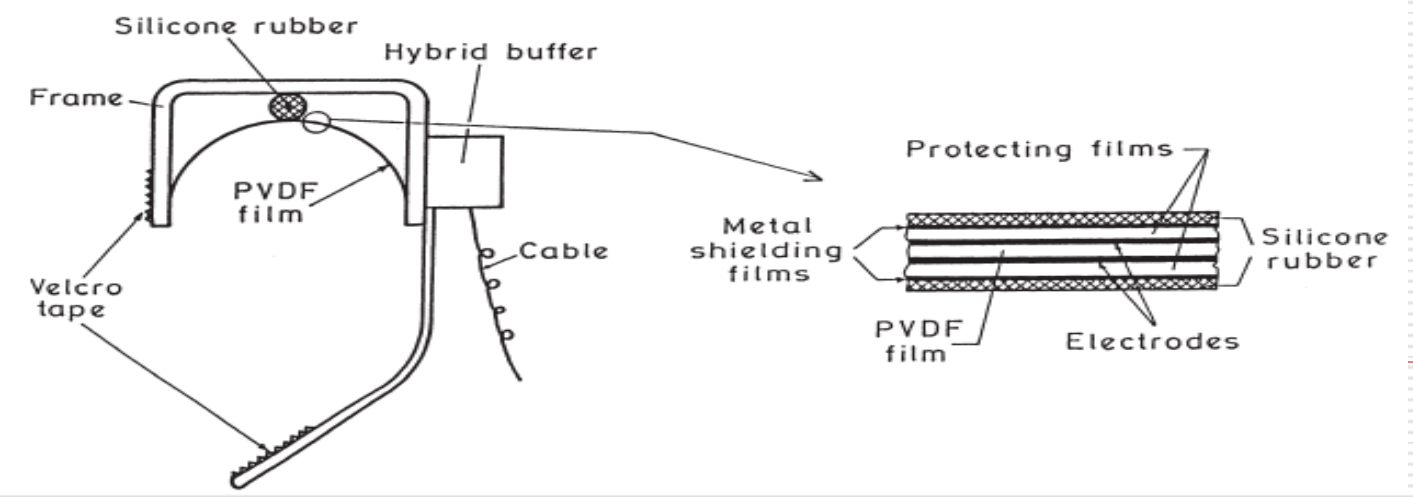



A Thermal Conductivity Sensor for the Measurement of Skin Blood Flow

# Sensors for Pressure Pulses and Movement

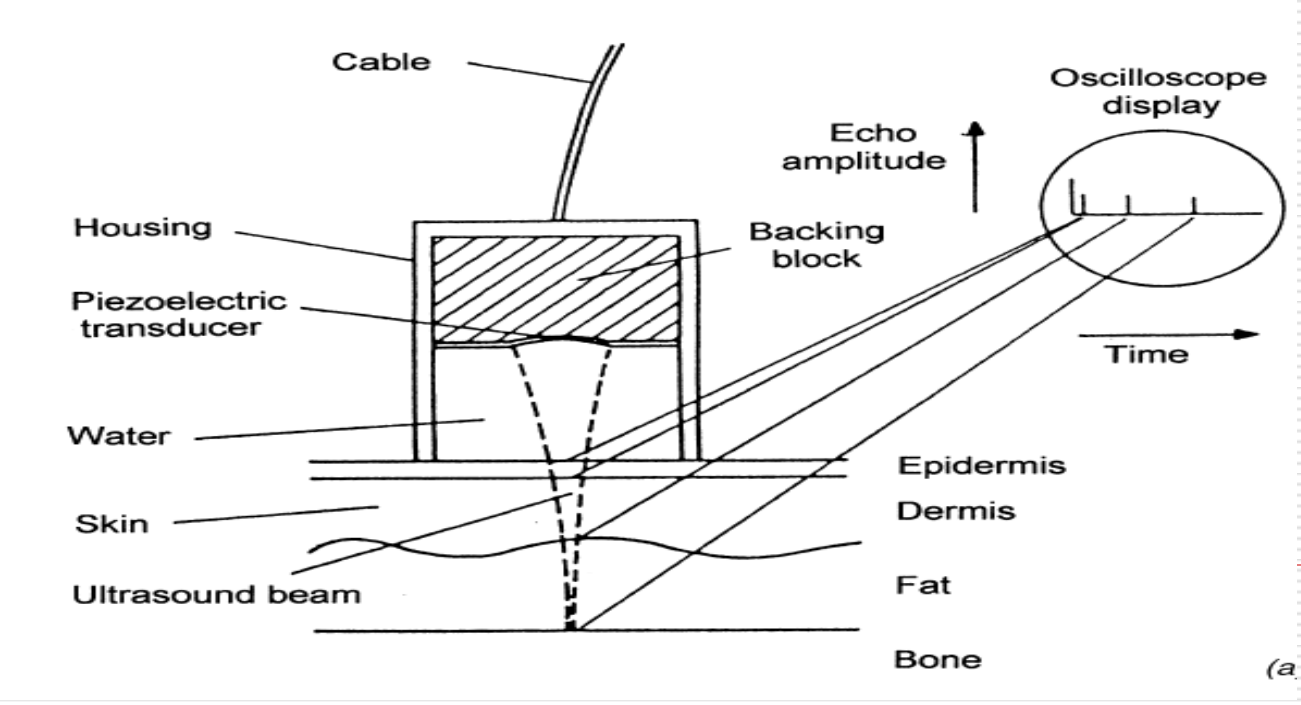
Pulse sensing is a convenient and efficient way of acquiring important physiological information concerning the cardiovascular system. Finger pulse pickups can be employed in systems that measure blood pressure, heart rate, and blood flow

The pulse-wave signal is sent through the buffer to the signal-processing electronics. The PVDF film is in direct contact with the finger therefore, its metallized surfaces have to be shielded on both sides with thin metallized protecting polymer films and sealed with highly insulating silicone rubber to avoid damage to the surface electrodes



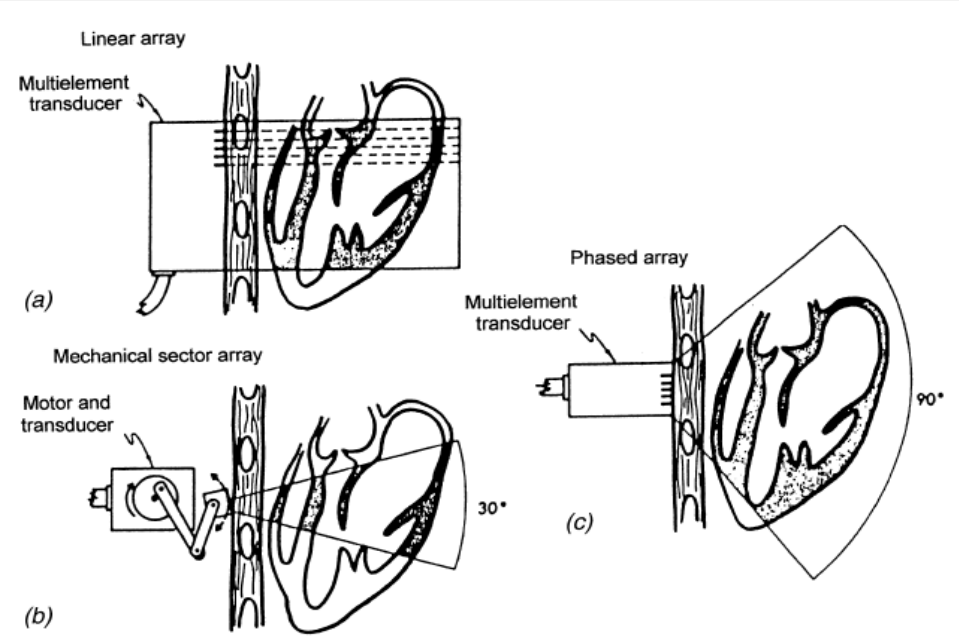
# SENSORS IN ULTRASOUND IMAGING

The first and simplest ultrasound imaging systems applied the *A-mode (amplitude modulation)* imaging illustrated in Figure



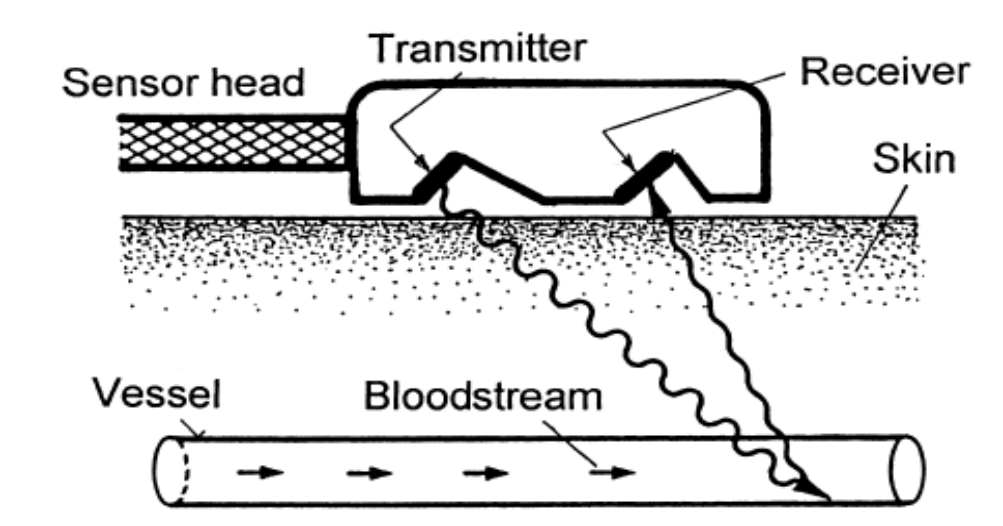
# ULTRASOUND IMAGING

In *B-mode (brightness modulation)* imaging, all echo impulses are represented by a pixel on the display, and the brightness corresponds to the amplitude of the echo. To get a two-dimensional cross-sectional image, an appropriate scanning of the desired cross section is necessary




Scanning methods in B-mode ultrasound imaging: (a) sequential linear array scanner, (b) mechanical sector scanner, and (c) phased array sector scanne

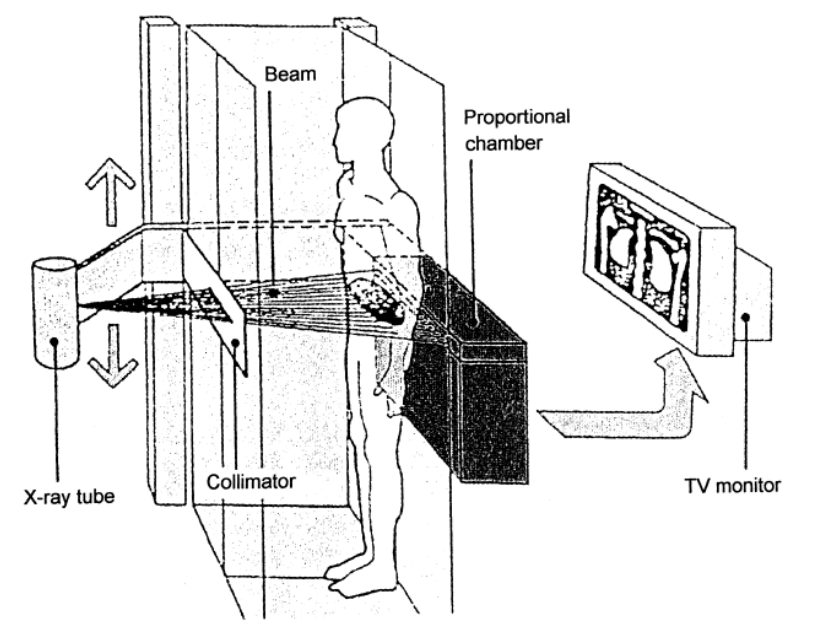
# The Doppler Blood-Flow Measurement




Doppler blood flow detectors operate by means of continuous sinusoidal excitation. The frequency difference calibrated for flow velocity can be displayed or transformed by a loudspeaker into an audio output.

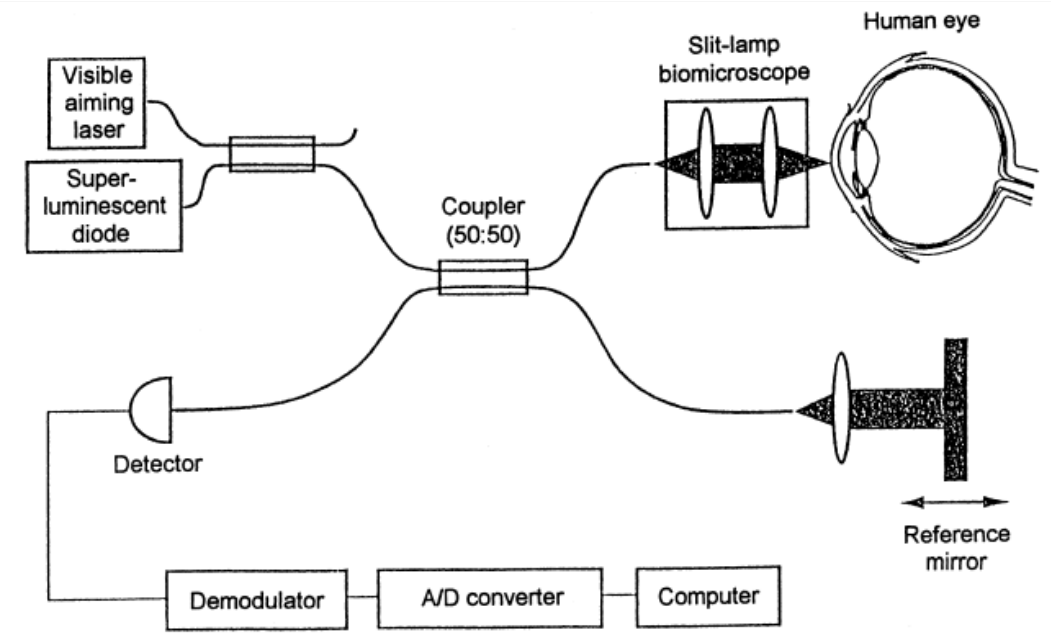
# X-ray Imaging System

*In optically coupled CCD X-ray imaging system,* X rays are impinged into a fluorescent screen and the image produced is then transferred onto the surface of an individual CCD by optical lenses



# Optical Coherence Tomography

The technique of *optical coherence tomography (OCT)* provides a micronscale resolution cross-sectional image from the overall eyeball, not only from the retina. OCT is similar to B-scan ultrasonic imaging




Schematic diagram of optical coherence tomography instrumentation