



**MCT151: Introduction to Mechatronics**  
**Lecture 10:**  
**Sensors & Transduction Mechanisms**

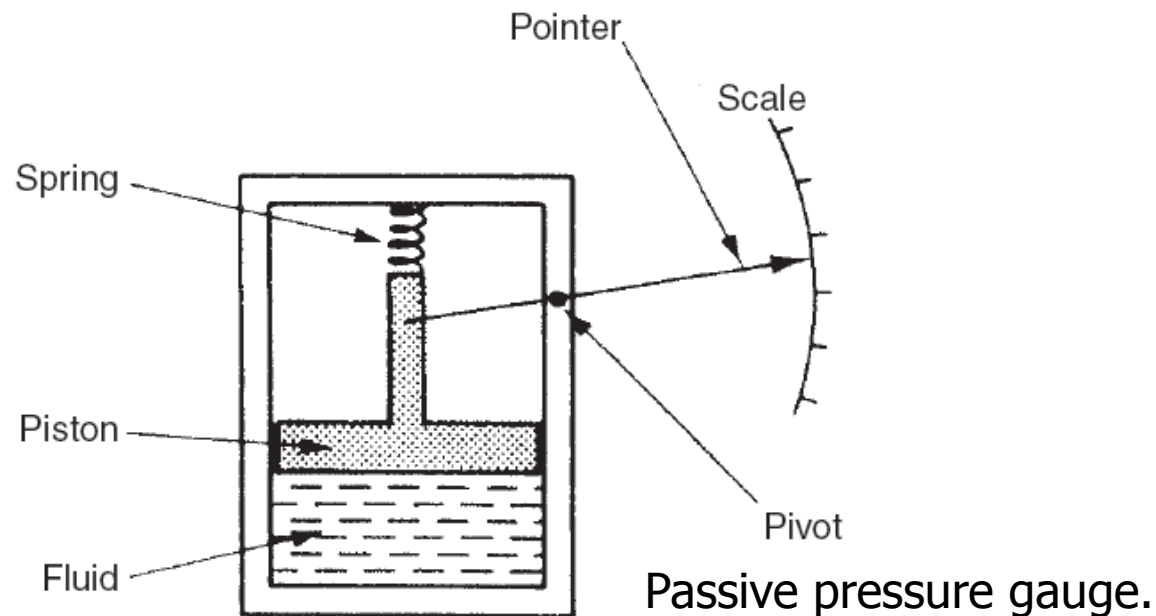
Slides are borrowed from Dr. Mohamed Elshiekh lectures

# Types of sensors

- Sensors are considered as transducers that convert input energy of one form into output energy of another form.
- In many cases, it converts the input energy from many forms into output energy in a form of electrical energy to be signal processed.
- Sensors could be mainly **active/passive** and **analog/digital**.

# Types of sensors: Passive

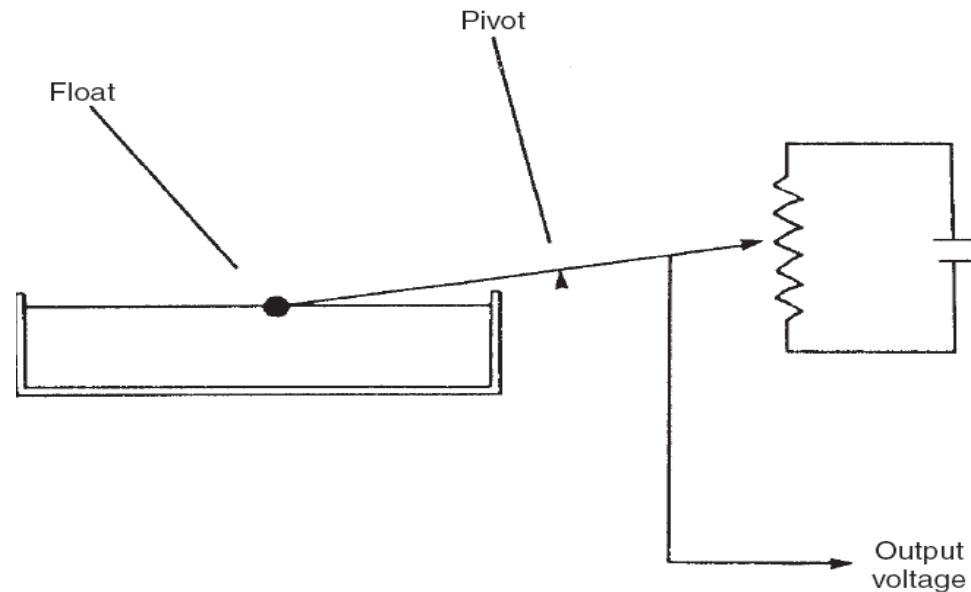
- Do not add energy as part of the measurement process.
- The output power is almost entirely provided by the measured signal without an external power supply.
- Example: pressure gages



# Types of sensors: Active

- Require an external source of power that provides the majority of the output power of the signal
- In other words, external energy is added to the measurement environment as part of the measurement process.
- **Better resolution** control by the adjustment of the magnitude of the external energy input.

Active level sensor.



# Types of sensors: Analog/Digital

□ Analog sensors produce a signal which is continuous over time and proportional to the measurand.

□ **Example:** bulb thermometer.



□ Digital sensors provide a signal that is a direct digital representation of the measurand. Digital sensors are basically binary ("on" or "off") devices.

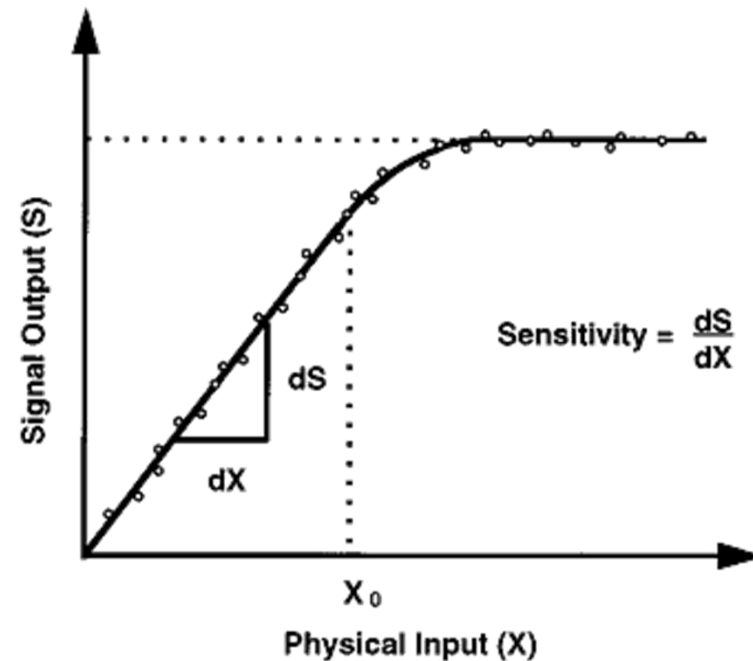
□ Example: A revolutionary counter.



# Sensor Sensitivity

- The sensitivity of measurement system is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount.
- Sensitivity is also named **amplification factor** or **gain** (if greater than one) and **attenuation** (if less than one).
- Measured in the linear/nonlinear region of the curve.

$$\text{Sensitivity} = \frac{dS}{dx}$$



# Outline

- Capacitive Transducers
- Inductive Transducers
- Resistive Transducers
- Piezoresistive Transducers
- Piezoelectric Transducers

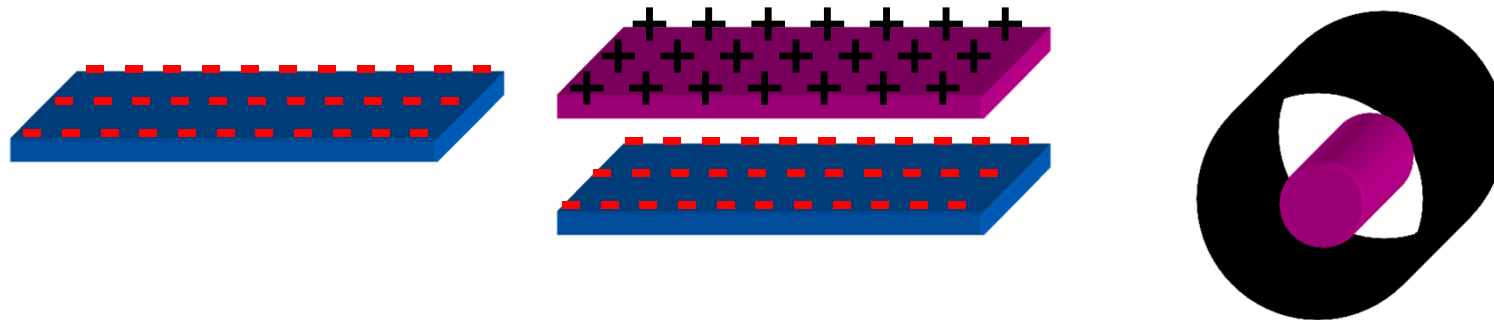
# Capacitive Transducers

- ❑ What is a capacitance ?
- ❑ How to have a capacitive transducer ?
- ❑ Capacitor transduction configurations
- ❑ Capacitor transducer applications
- ❑ How to interface a capacitor transducer ?

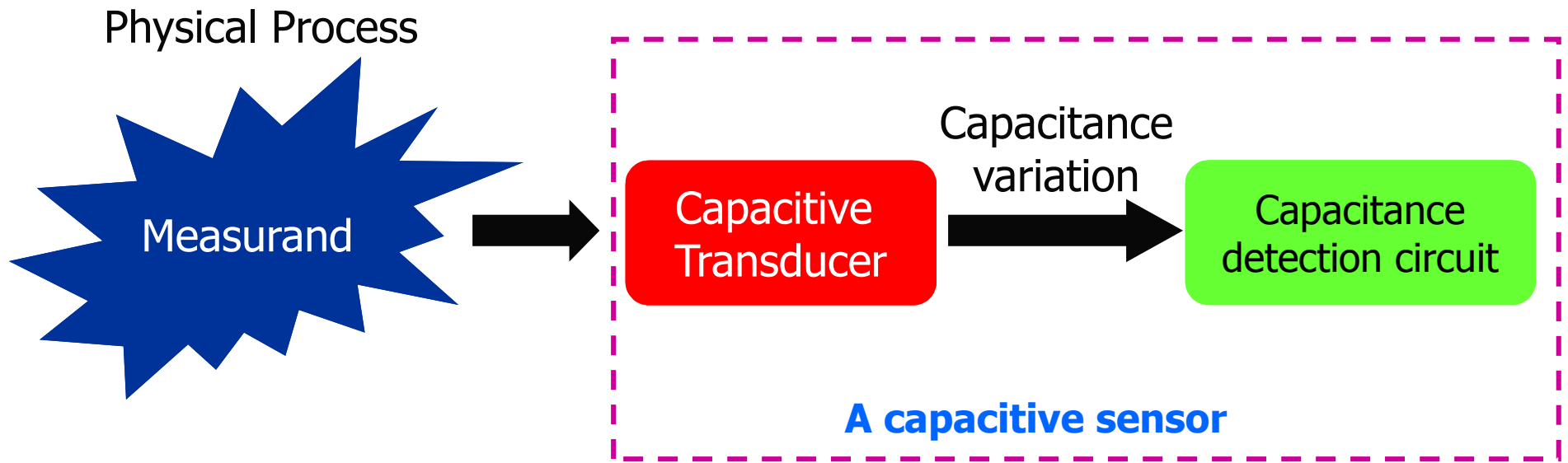


# What is a capacitance ?

- ❑ It is the property of a conductor that permits it to store charges on its surface.
- ❑ It is the proportionality constant between the **charge developed** on a conductor surface and the **potential difference** needed to get these charges .



# What is a capacitive transducer ?



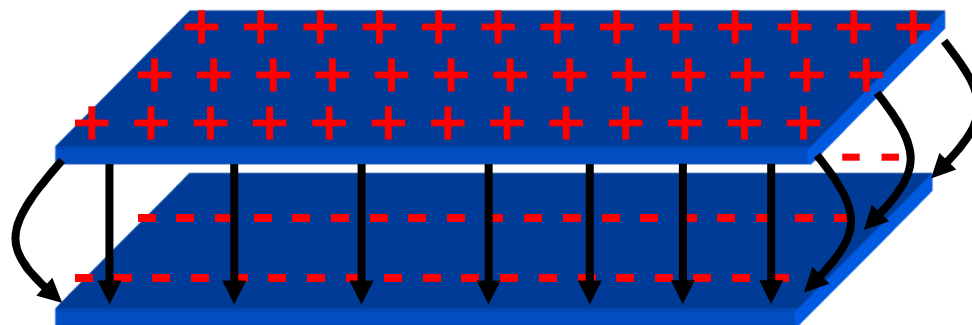
# Capacitor Transduction Configurations

$$C = f(\epsilon_r, A, g)$$

□ Where:

- $\epsilon_r$  is the relative permittivity of the dielectric enclosed.
- $A$  is the conductor electrode area
- $g$  is the gap between the conductor electrodes

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



# Variable Gap Capacitive Transducer

- The gap is changing by the physical parameters.
- **Example:** Displacement or Pressure measurement

$$\frac{dC(x)}{dx} = \frac{C_o / g_o}{(1 - x / g_o)^2}$$

**Transducer Sensitivity**

$$C(x) = \frac{\epsilon_o \epsilon_r A}{g_o - x} = \frac{C_o}{1 - x / g_o}$$



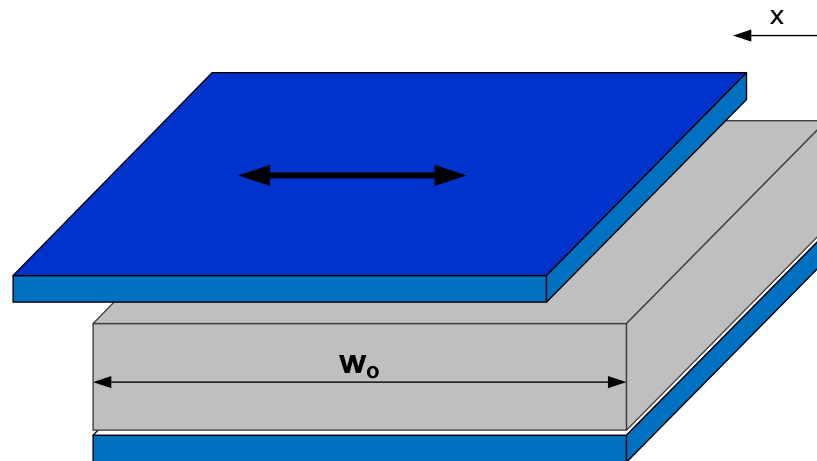
# Variable Area Capacitive Transducer

- The overlap area is changing by the physical parameters.
- **Example:** Displacement or Pressure measurement

$$\frac{dC(x)}{dx} = C_o / w_o$$

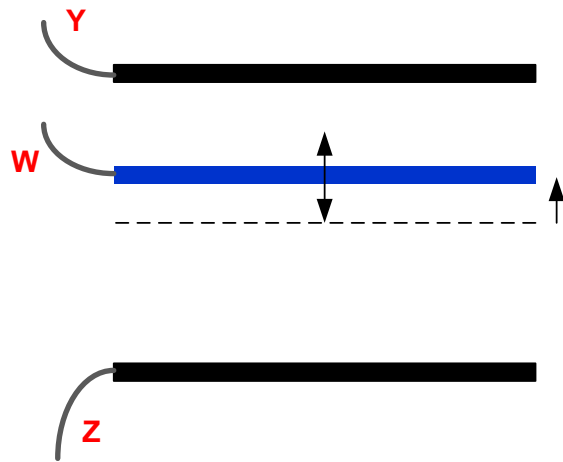
**Transducer Sensitivity**

$$C(x) = \frac{\epsilon_o \epsilon_r t (w_o - x)}{g_o} = C_o (1 - x / w_o)$$

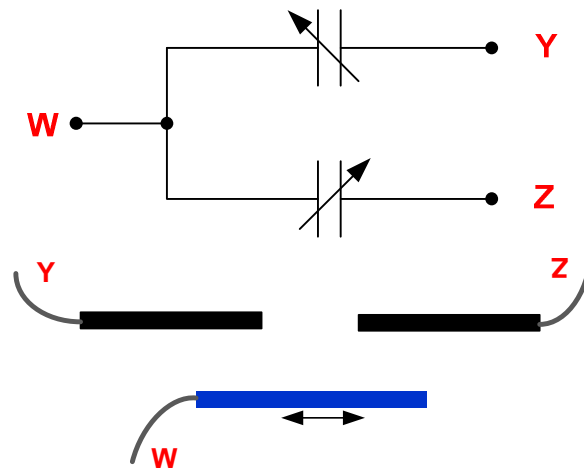


# Differential Capacitive Transducer

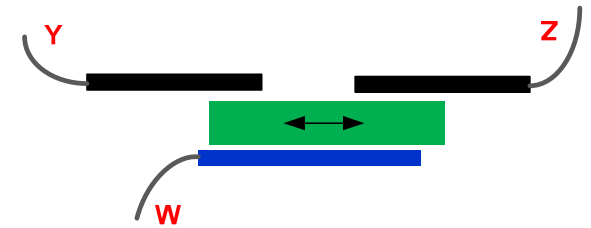
- The idea is to use a middle electrode to produce a differential capacitor variation through a three terminal device



**Variable gap**

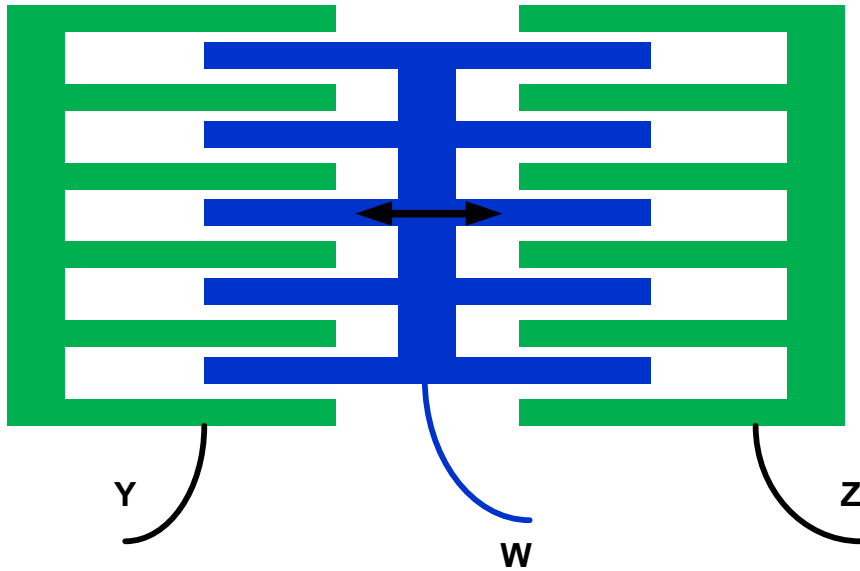


**Variable area**



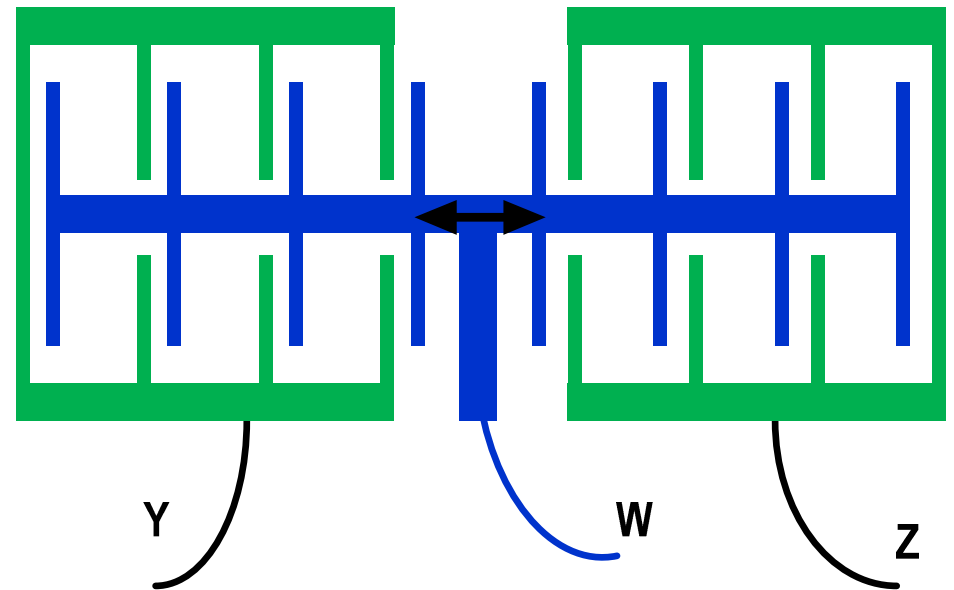
**Variable dielectric**

# Practicable differential implementation

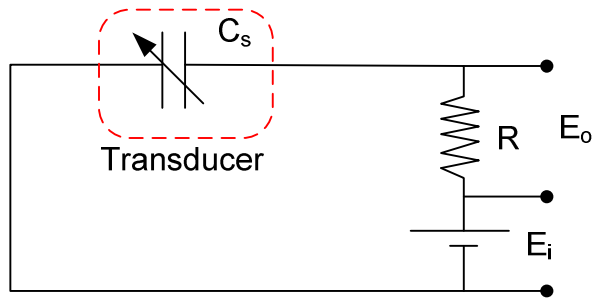


**Overlap Comb-finger Capacitor**

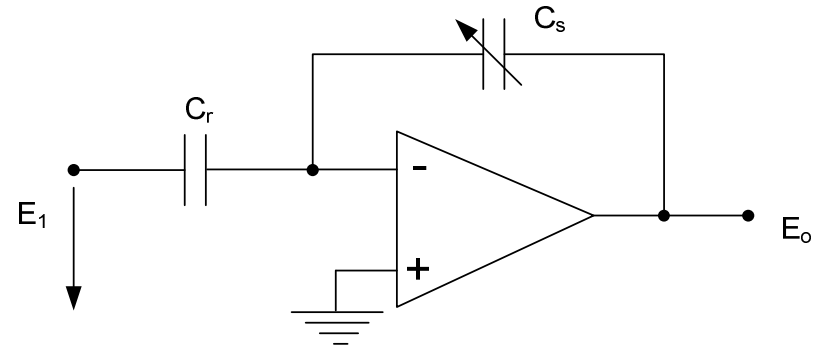
**Gap closing Comb-finger Capacitor**



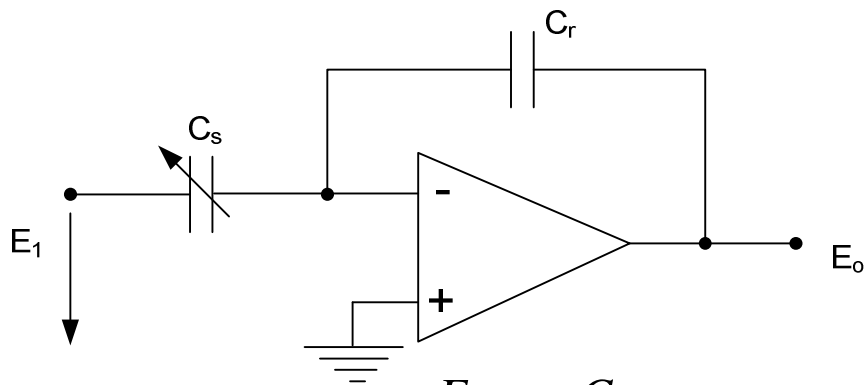
# Capacitive Transducer circuits (C2V)



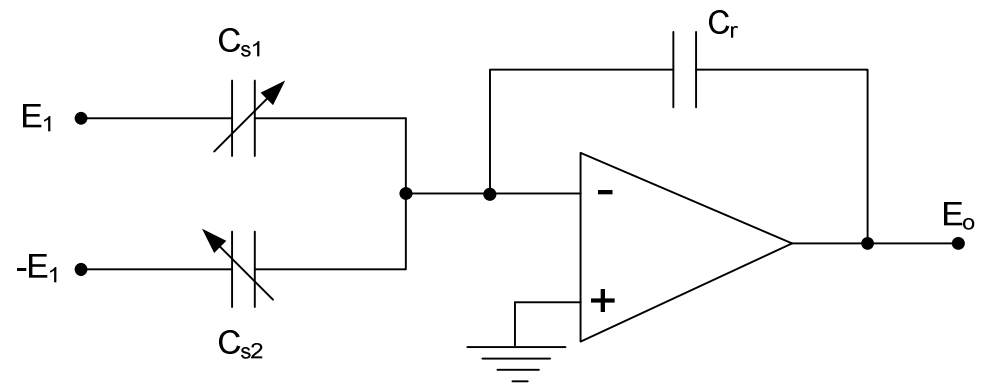
$$\frac{E_o}{E_i} = \frac{sC_s R}{1 + sC_s R}$$



$$\frac{E_o}{E_i} = -\frac{C_r}{C_s}$$



$$\frac{E_o}{E_i} = -\frac{C_s}{C_r}$$



$$\frac{E_o}{E_i} = ??$$



# Outline

- Capacitive Transducers
- Inductive Transducers
- Resistive Transducers
- Piezoresistive Transducers
- Piezoelectric Transducers

# Inductive Transducers

- ❑ An **inductive transducer** is designed such that the measurand alters the (self) inductance of the sensor's coil to produce either a change in current through the coil or a change in the voltage across the coil.
- ❑ The **(self) inductance**  $L$  is an indication of the ability of a coil to oppose any change in current flowing through the coil. The inductance  $L$  of a cylindrical coil is given by:

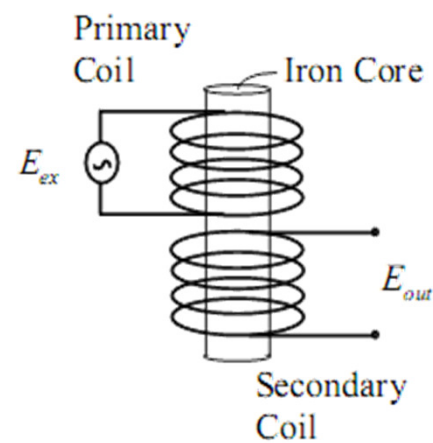
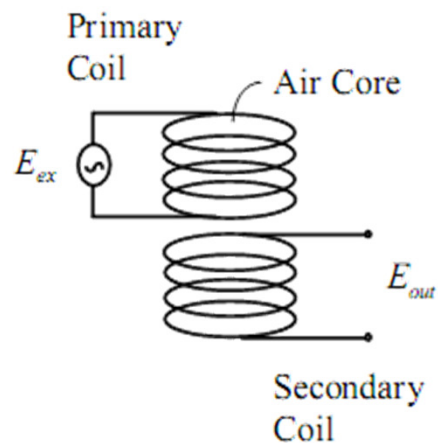
$$L = \mu \frac{n^2 A}{l}$$

where

- $L$  is the inductance [Henry, H]
- $\mu$  is the permeability of the core [Wb/A-t-m]
- $n$  is the number of turns of coil
- $A$  is the cross sectional area of core [m<sup>2</sup>]
- $l$  is the length of core [m]

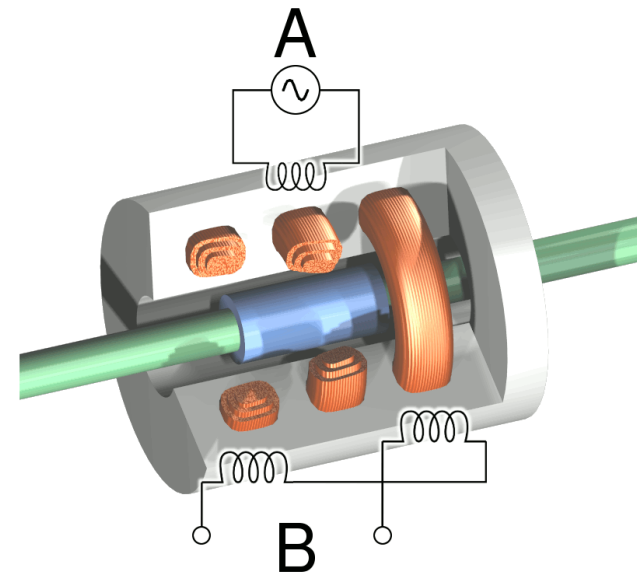
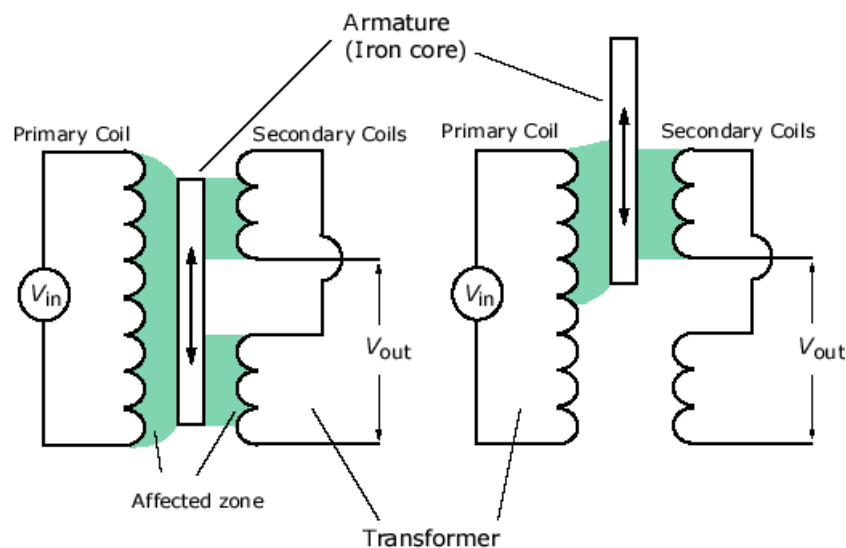
## How to make an Inductive Transducer ?

- ❑ One of the most common ways of producing such a change is to use a movable core which moves back and forth inside a coil, where the permeability is varied as the core is displaced within the coil.
- ❑ The core is usually made of a highly permeable material such as ferrite and iron.



# LVDT Transducer

- ❑ Linear Variable Differential Transformer (LVDT) transducer has two sets of coils, a primary coil and two secondary coils.
- ❑ The secondary coils are wound in opposite directions such that if the core moves to either direction, the voltage in one of the secondary coils increases while it decreases in the other, generating a nonzero voltage output. When the core is located at the center, the output is zero.



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# Resistive Transducers

- Resistance is a characteristic of a device. It depends on both the material and the geometry of the resistor.
- For a conductor:

$$R = \frac{\rho \cdot L}{A}$$

- Where:
  - $\rho = 1/\sigma$  is the resistivity of the material
  - $L$  is the length of the conductor
  - $A$  is the cross-sectional area of the conductor

# Temperature Measurement

- ❑ Resistivity, material property, has temperature dependence
- ❑ The temperature dependence determines the type of the sensor, RTDs or Thermistors.
- ❑ **Resistive temperature Detectors (RTD):**
  - They are made of metals and are characterized by positive temperature dependence.
  - Platinum is the best material because of its small resistivity and strong temperature dependence.

$$\rho = \rho_0 (1 + \sigma_1 (t - t_0) + \sigma_2 (t - t_0)^2)$$

## Temperature Measurement (2)

### □ Thermistors:

- Thermistors are resistors with large either negative (NTC) or positive (PTC) temperature coefficients.
- They are usually ceramic semiconductors commonly made of oxides of one or more of the following metals: nickel, manganese, cobalt, titanium, iron.
- Their resistances vary from a fraction of an ohm to many mega ohms.

$$R_t = R_{t0} e^{\beta(1/T-1/T0)}$$



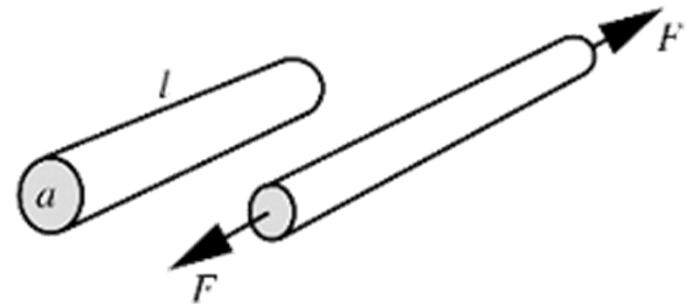
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# Piezoresistive Transducers: Stress Measurement

- Stress measurement by using the piezoresistive phenomena.

$$R = \frac{\rho \cdot l^2}{v}$$
$$\frac{dR}{dl} = \frac{2 \rho \cdot l}{v}$$
$$\frac{dR}{R} = 2 \frac{dl}{l} = S_e \varepsilon$$



$$\sigma = E \frac{dl}{l} = E \varepsilon$$

- $S_e$  ranges between 2-6 in metals/alloys and 40-200 in semiconductors.
- Si and Ge has good piezoelectric properties

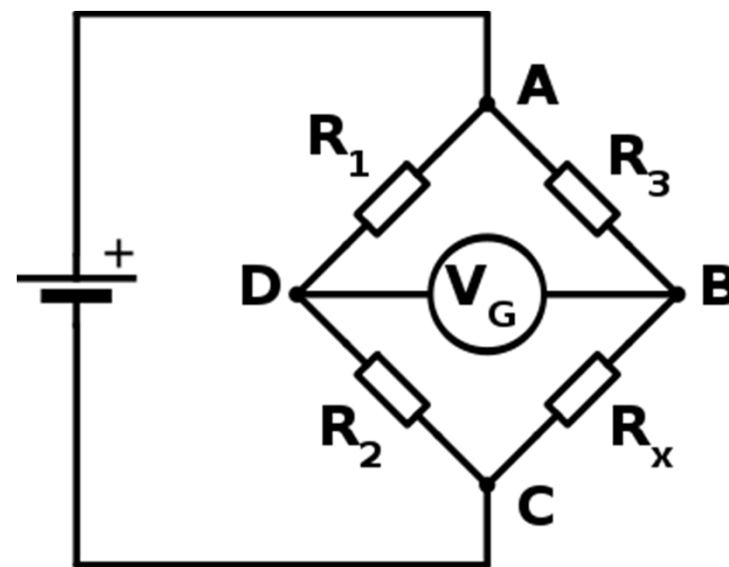
## Detection Mechanism

- A bridge is typically used to transfer  $\Delta R$  into  $\Delta V$ .
- Wheatstone bridge @ Null condition:

$$R_x = \frac{R_2}{R_1} R_3$$

- Without Null condition:

$$V_G = \left( \frac{R_x}{R_x + R_3} - \frac{R_2}{R_1 + R_2} \right) V_s$$

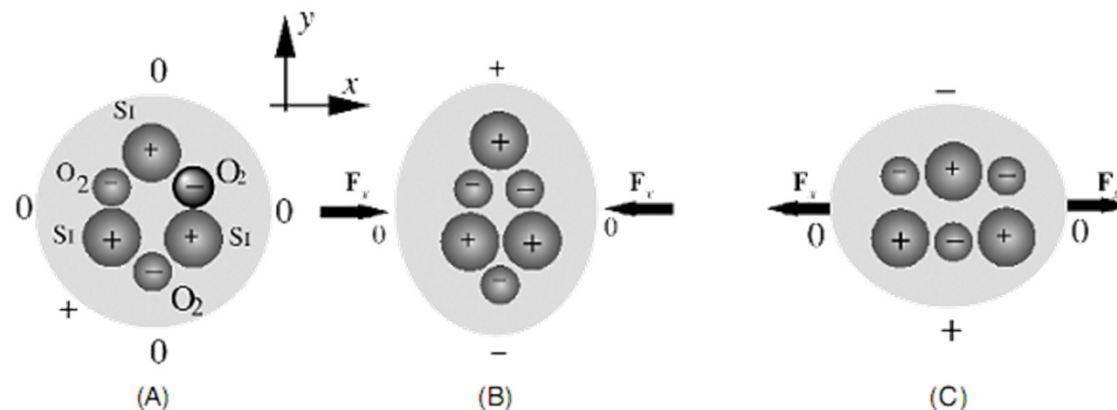


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# Piezoelectric Transducers

- ❑ The piezoelectric effect is the generation of electric charge by a crystalline material upon subjecting it to stress.
- ❑ The effect exists in natural crystals, such as quartz (chemical formula  $\text{SiO}_2$ ), and poled (artificially polarized) man-made ceramics and some polymers, such as polyvinylidene fluoride.
- ❑ The Curie brothers discovered the piezoelectric effect in quartz in 1880.



## Piezoelectric Transducers (2)

- ❑ The piezoelectric effect is a **reversible** physical phenomenon. That means that applying voltage across the crystal produces mechanical strain.
- ❑ To pick up an electric charge or apply a voltage , **conductive electrodes** must be applied to the crystal at the opposite sides of the cut.
- ❑ A piezoelectric sensor becomes a **capacitor** with a dielectric material which is a piezoelectric crystal.