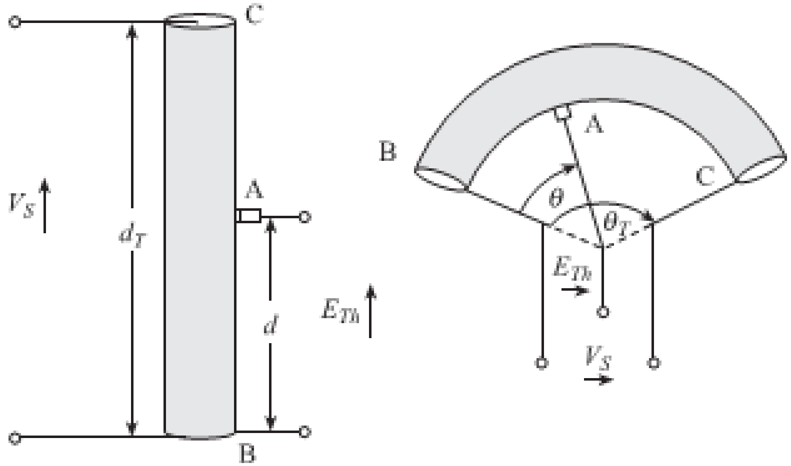
# SENSING ELEMENTS

Adam Schiffer, PhD

| | Input measured variable / Physical principle | Temperature | Heat/light flux | Pressure | Force | Torque | Level | Density | Flow rate | Flow velocity | Displacement/strain | Velocity | Acceleration | Gas composition | Ionic concentration | Humidity | Magnetic field |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrical output passive | Resistive | 8.1<br>15.5 | 15.5 | 8.6 | 8.6 | 8.6 | | | | 14.3 | 5.1<br>8.1 | | 8.6<br>4.4 | 8.1<br>14.4 | | 8.1 | |
| | Capacitive | | | 8.2 | | | 8.2 | | | | 8.2 | | | | | 8.2 | |
| | Inductive | | | | | | | | | | 8.3 | | | | | | |
| | Piezoresistive | | | 8.8 | | | | | | | | | | | | | |
| | Photovoltaic | | 15.5 | | | | | | | | | | | | | | |
| | Photoconductive | | 15.5 | | | | | | | | | | | | | | |
| | FET | | | | | | | | | | | | | 8.9 | 8.9 | | |
| | Hall effect | | | | | | | | | | | | | | | | 8.10 |
| Electrical output active | Electromagnetic | | | | | | | | 12.4 | | | 8.4 | | | | | |
| | Thermoelectric | 8.5<br>15.5 | 15.5 | | | | | | | | | | | | | | |
| | Piezoelectric | | | 16.2 | 8.7 | | | | | | | | 8.7 | | | | |
| | Electrochemical | | | | | | | | | | | | | 8.9 | 8.9 | | |
| | Pyroelectric | 15.5 | 15.5 | | | | | | | | | | | | | | |
| Mechanical output | Elastic | | | 8.6<br>9.4<br>9.5 | 4.1<br>8.6<br>9.5 | 8.6 | 9.4 | 9.5 | | | | | 8.6 | | | | |
| | Differential pressure | | | | | | | | 12.3 | 12.2 | | | | | | | |
| | Turbine | | | | | | | | 12.3 | | | | | | | | |
| | Vortex | | | | | | | | 12.3 | | | | | | | | |
| | Pneumatic | | | 13.1 | 13.1 | | 13.1 | | | | 13.1 | | | | | | |
| | Coriolis | | | | | | | | 12.4 | | | | | | | | |
| Thermal output | Heat transfer | | 15.5 | | | | | | | 14.3 | | | | 14.4 | | | |
| Optical output | Various | | 15.6 | 15.6 | 15.6 | | 15.6 | | | | 15.6 | 15.6 | | 15.6 | | | |

## Potentiometers for linear and angular displacement measurement




(a) Linear (rectilinear) displacement

(b) Angular (rotary) displacement

$$\frac{E_{Th}}{V_S} = \frac{\text{voltage across AB}}{\text{voltage across CB}} = \frac{\text{resistance across AB}}{\text{resistance across CB}}$$

where:

resistance of CB = total resistance of potentiometer = $R_P$
resistance of AB = fractional resistance = $R_P d/d_T = R_P x$
$x$ = fractional displacement = $d/d_T$.

$$E_{Th} = V_S x = V_S d/d_T \qquad E_{Th} = V_S \theta/\theta_T = V_S x$$

# Resistive sensing elements

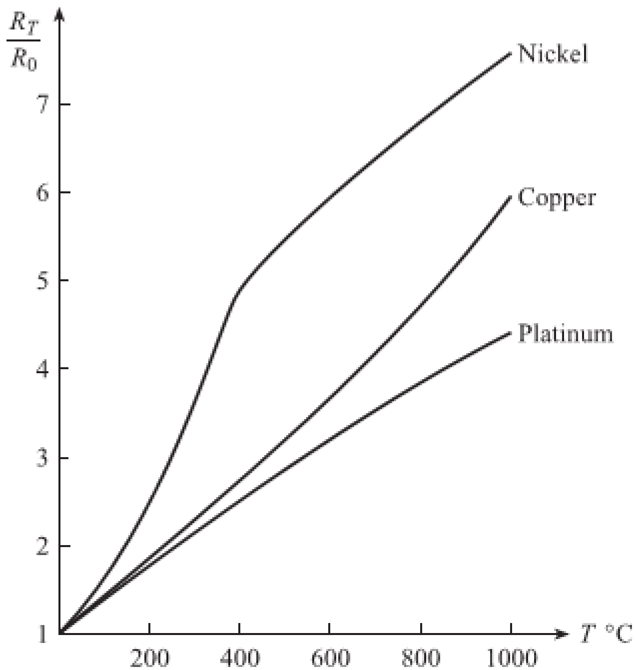
## Resistive metal and semiconductor sensors for temperature measurement

- The resistance of most **metals** increases reasonably linearly with temperature in the range −100 to +800 °C.
- Although relatively expensive, platinum is usually chosen for industrial resistance thermometers; cheaper metals, notably nickel and copper, are used for less demanding applications.
- The general relationship between the resistance $RT$ Ω of a metal element and temperature $T$ °C is a power series of the form:

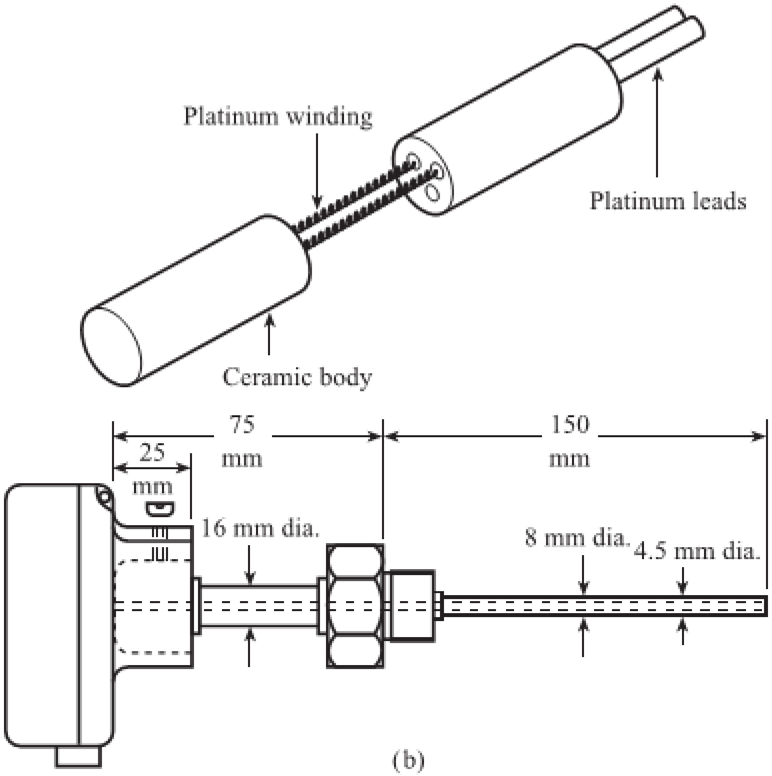
  $$RT = R0(1 + \alpha T + \beta T2 + \gamma T3 + \ldots),$$

  where $R0$ Ω is the resistance at 0 °C and α, β, γ are temperature coefficients of resistance.
- A typical platinum element has $R\,0 = 100.0$ Ω, $R100 = 138.50$ Ω, $R200 = 175.83$ Ω, $\alpha = 3.91 \times 10-3$ °C$^{-1}$ and $\beta = -5.85 \times 10^{-7}$ °C$^{-2}$.

## Resistive metal and semiconductor sensors for temperature measurement

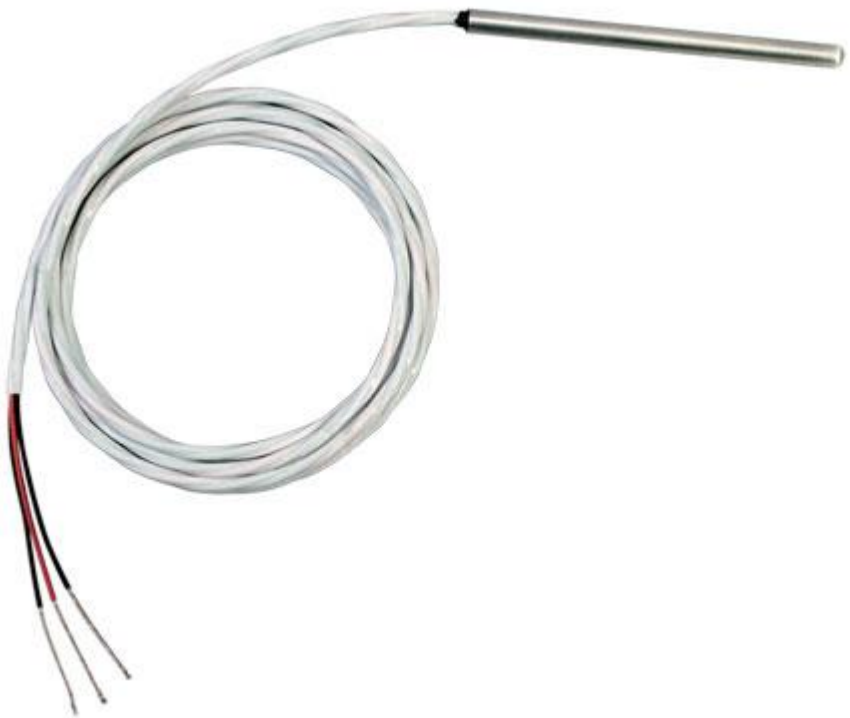



(a)




(b)

# Resistive sensing elements



RTD

Advantages:

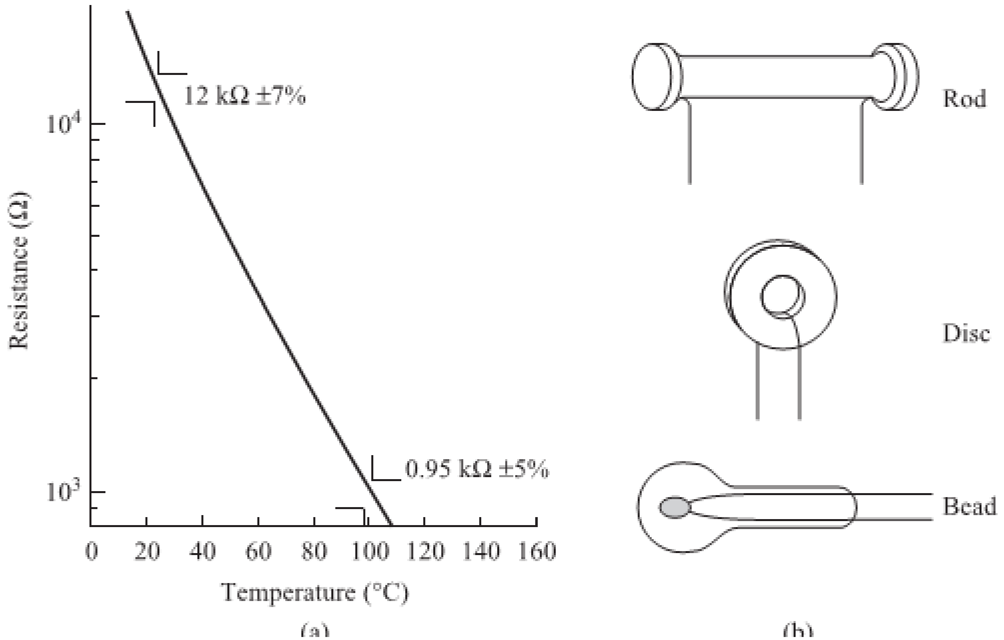
- Stabe
- Very accurate
- Linear

Disadvantages

- Expensive
- Current source required
- Small change in resistance
- Self heating

## Semiconductors (Thermistors)

The resistance of these elements decreases with temperature – in other words there is a negative temperature coefficient (NTC) – in a highly non-linear way.



# Resistive sensing elements

## Semiconductors (Thermistors)

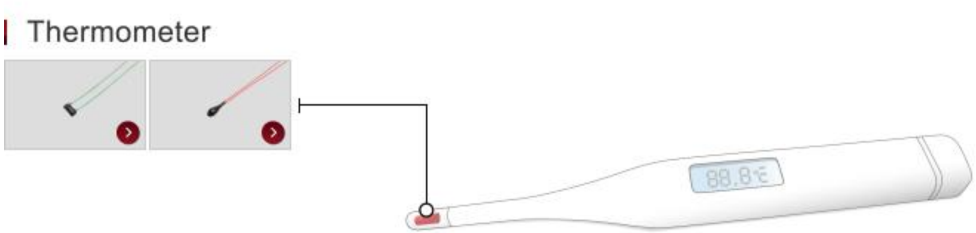
Thermistor

Advantages:

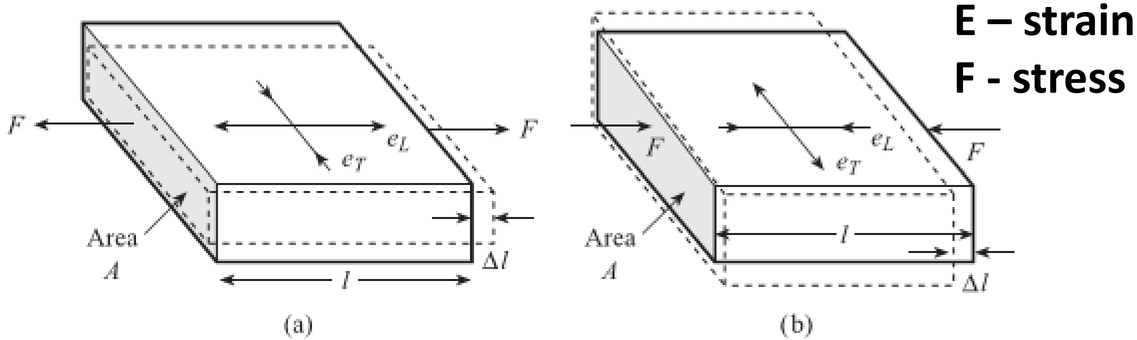
- Very sensitive
- Quick response
- Best accuracy

Disadvantages

- Non-linear
- Small temperature range
- Current source required
- Self heating



# Metal and semiconductor resistive strain gauges




Effect of tensile stress

Effect of compressive stress

$$\text{Elastic modulus} = \frac{\text{stress}}{\text{strain}}$$

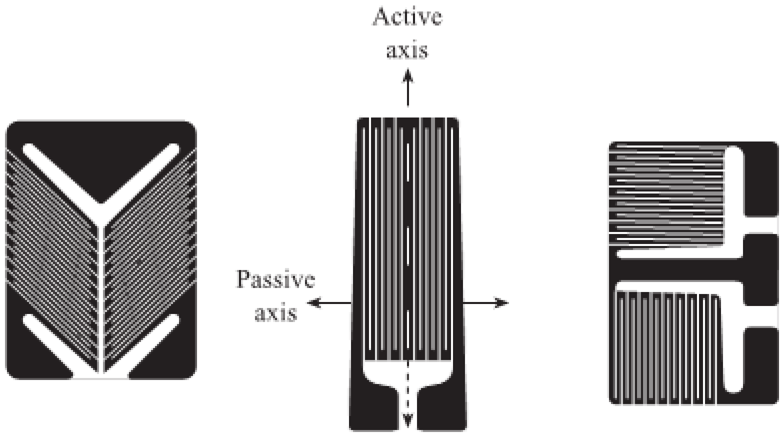
A **strain gauge** is a metal or semiconductor element whose resistance changes when under strain.

We can derive the relationship between changes in resistance and strain by considering the factors which influence the resistance of the element. The resistance of an element of length *l*, cross-sectional area *A* and resistivity ρ is given by:

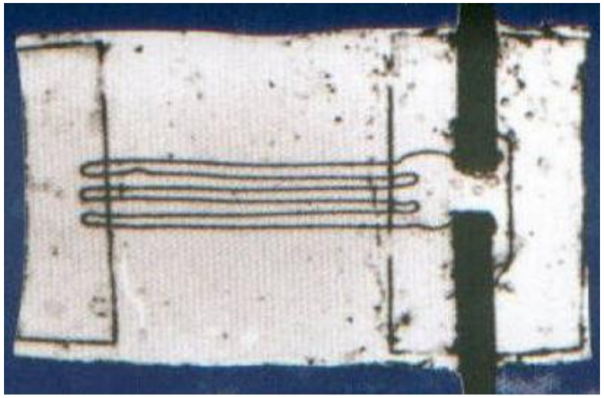
$$R = \frac{\rho l}{A}$$

$$\Delta R = \left(\frac{\partial R}{\partial l}\right)\Delta l + \left(\frac{\partial R}{\partial A}\right)\Delta A + \left(\frac{\partial R}{\partial \rho}\right)\Delta \rho$$

# Metal and semiconductor resistive strain gauges



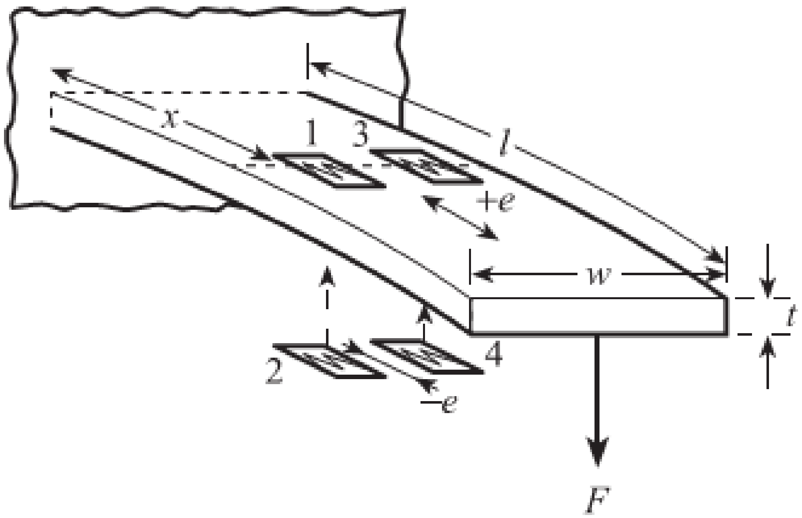

First Strain Gauge, Ruge, 1938

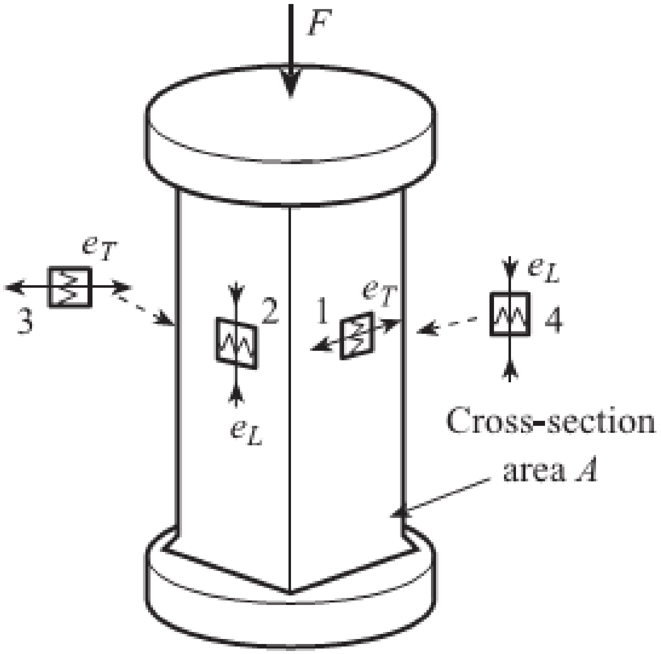


We now define the **gauge factor** *G* of a strain gauge, hence

$$\frac{\Delta R}{R_0} = Ge$$

# Metal and semiconductor resistive strain gauges



# Capacitive sensing elements

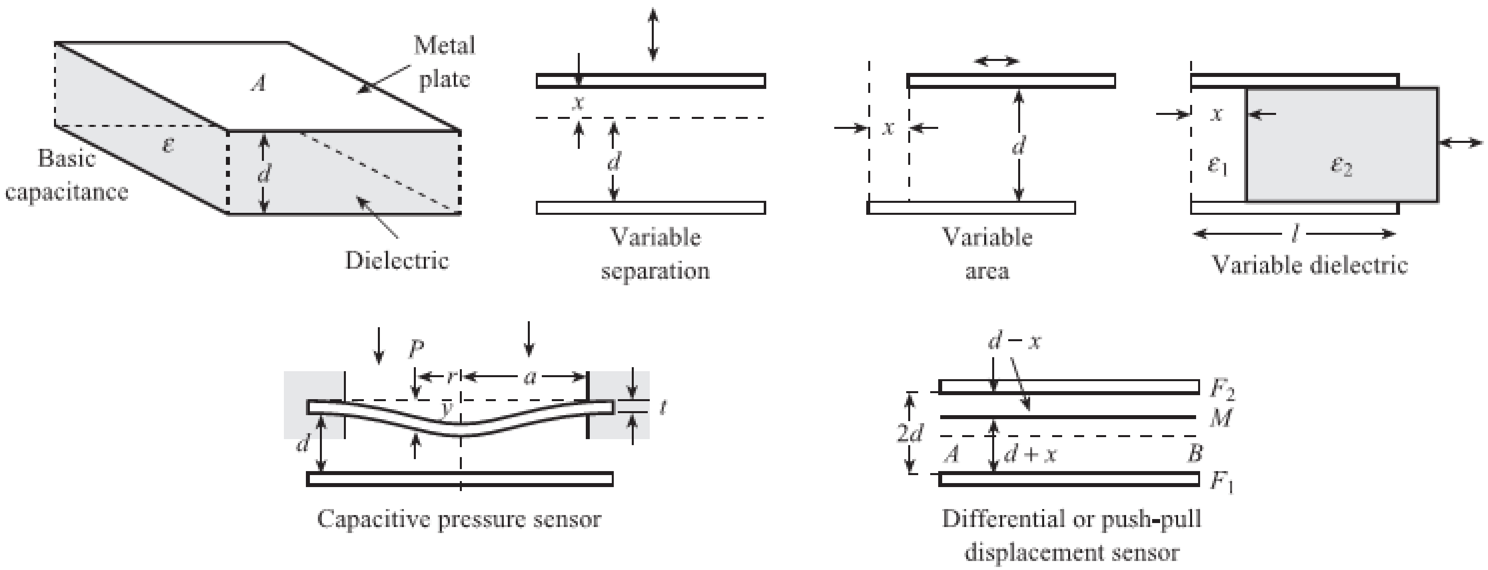
Most alloys have a low **temperature coefficient of resistance** ($2 \times 10^{-5}$ °C $^{-1}$) and a low **temperature coefficient of linear expansion**.

A typical gauge has:

- Gauge factor 2.0 to 2.2
- Unstrained resistance 120 ± 1 Ω
- Linearity within ±0.3%
- Maximum tensile strain +2 × 10−2
- Maximum compressive strain −1 × 10−2
- Maximum operating temperature 150 °C.

# Capacitive sensing elements

The simplest capacitor or condenser consists of two parallel metal plates separated by a dielectric or insulating material

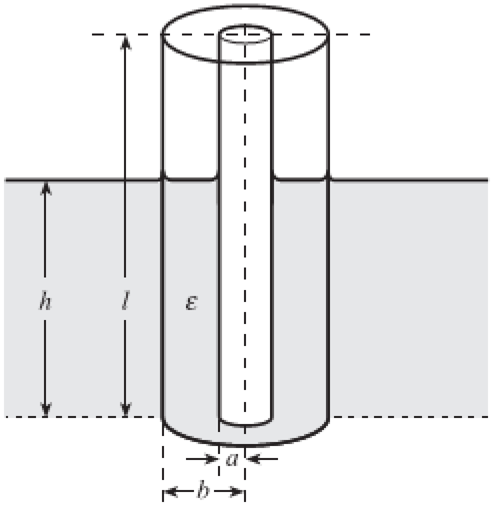



The capacitance of this parallel plate capacitor is given by:

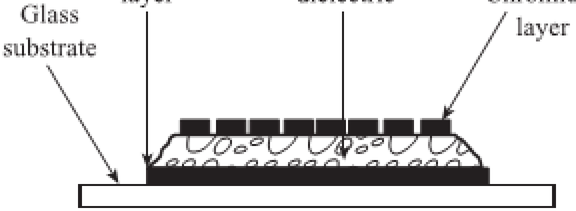
$$C = \frac{\varepsilon_0 \varepsilon A}{d}$$

where ε0 is the permittivity of free space (vacuum) of magnitude 8.85 pF $m^{-1}$, ε is the relative permittivity or dielectric constant of the insulating material, *A* $m^2$ is the area of overlap of the plates, and *d* m is their separation

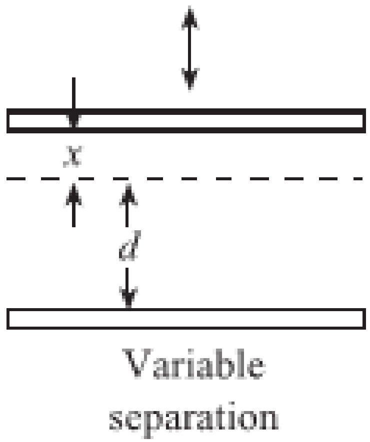
# Capacitive sensing elements




Capacitive level sensor




Capacitive humidity sensor




**EXAMPLE:**

**capacitive displacement sensors** using each of these methods. If the displacement *x* causes the plate
separation to increase to $d + x$ the capacitance of the sensor is:

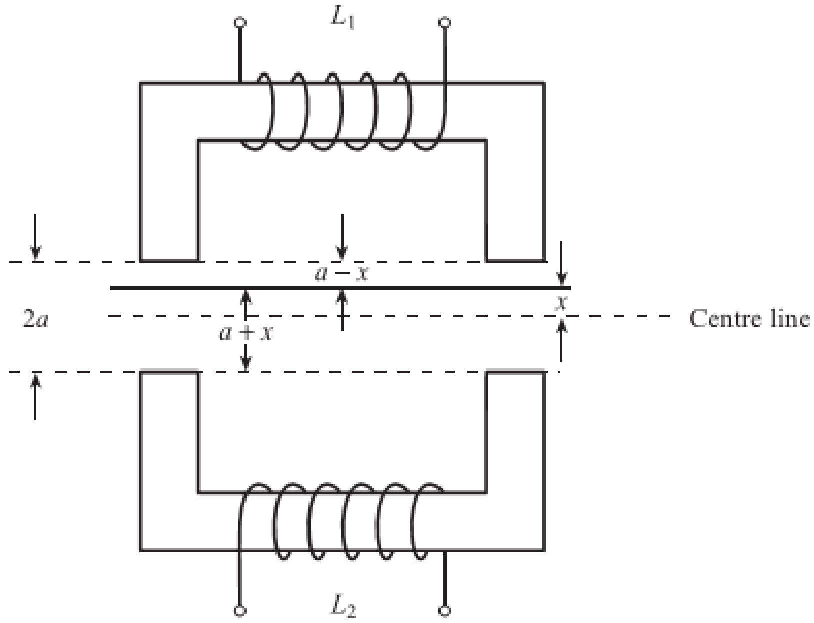
$$C = \frac{\varepsilon_0 \varepsilon A}{d + x}$$

# Inductive sensing elements

In order to discuss the principles of these elements we must first introduce the concept of a **magnetic circuit**. In an electrical circuit an electromotive force (e.m.f.) drives a current through an electrical resistance and the magnitude of the current is given by

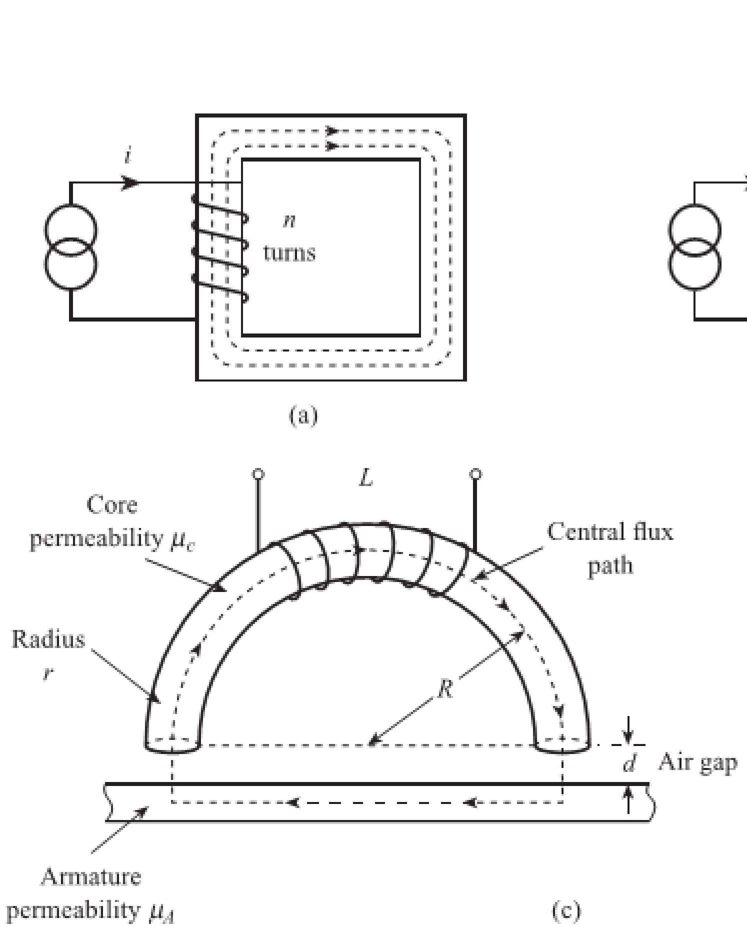
**e.m.f. = current × resistance**

Since the relative permeability of air is close to unity and that of the core material many thousands, the presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in flux and inductance. Thus a small variation in air gap causes a measurable change in inductance so that we have the basis of an **inductive displacement sensor**.



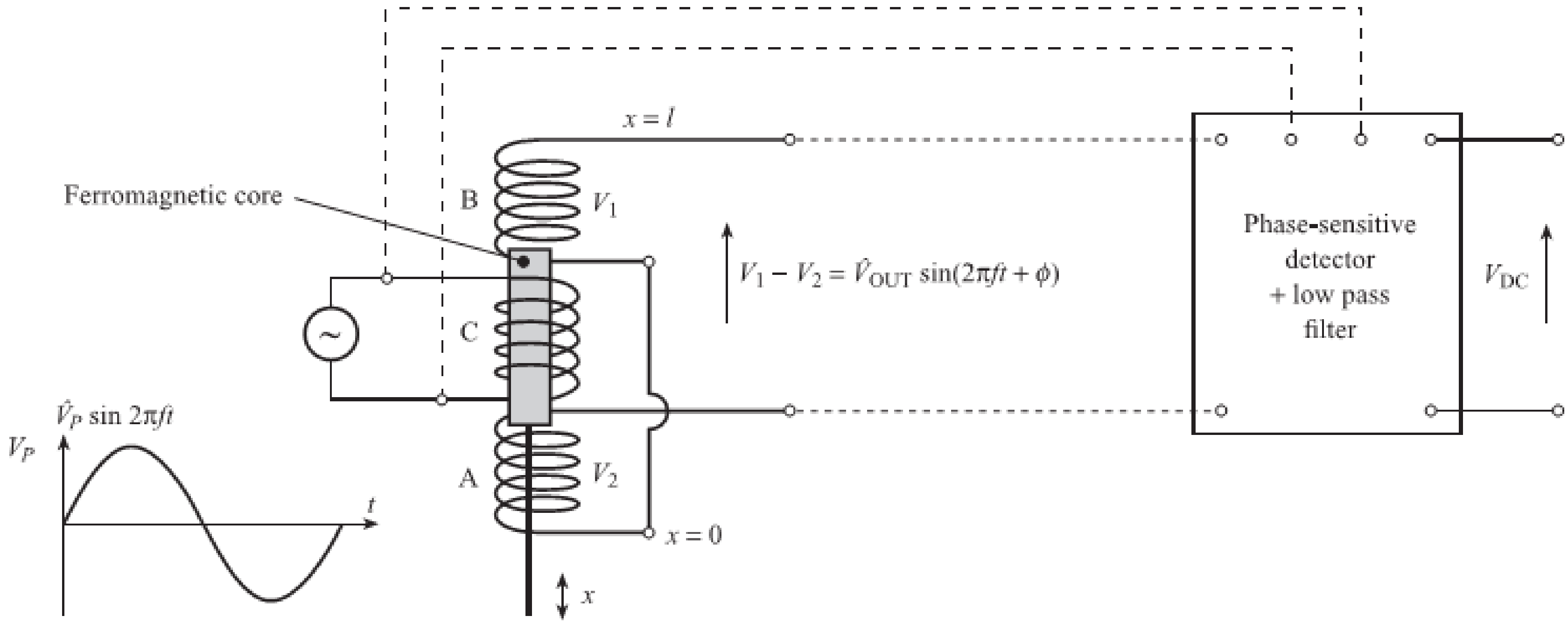
# Inductive sensing elements

(a)(b) Basic principle of reluctance sensing elements
(c) Reluctance calculation for typical element

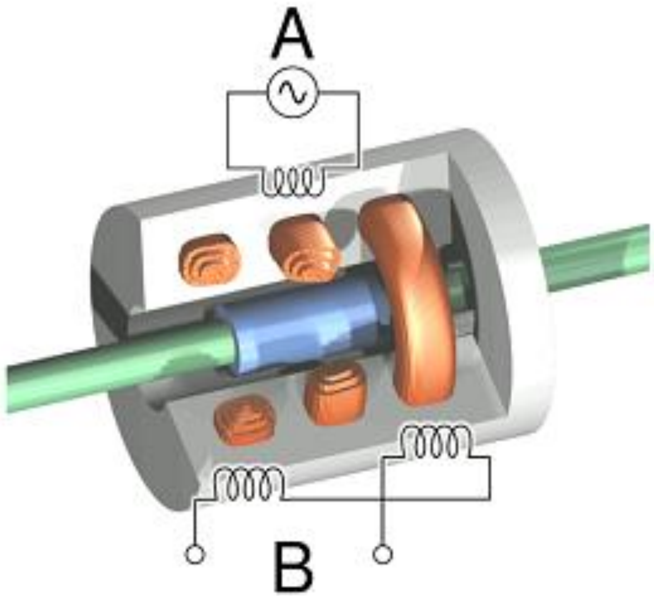


# Linear Variable Differential Transformer (LVDT) displacement sensor

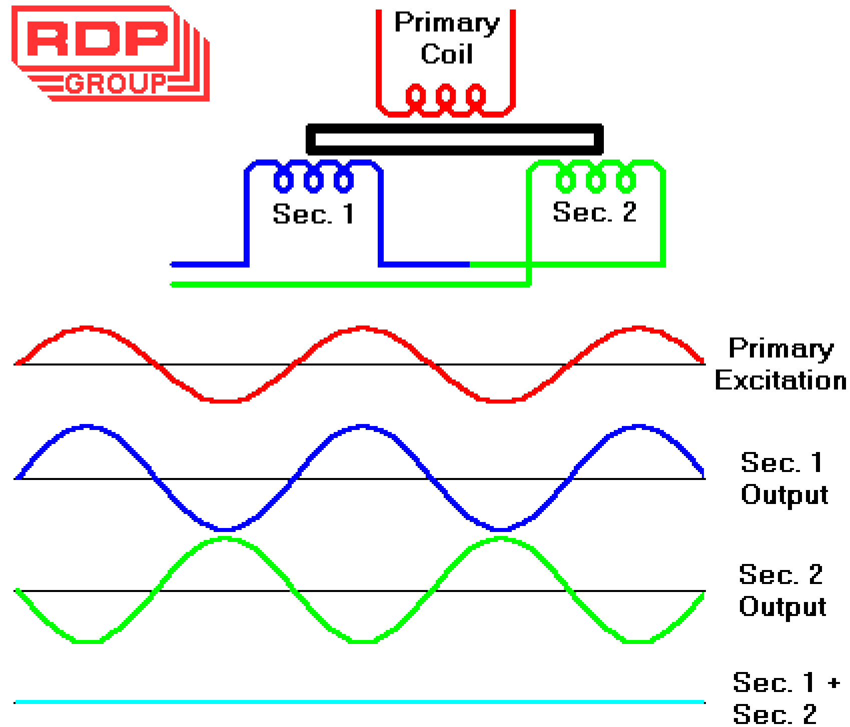
This sensor is a transformer with a single primary winding and two identical secondary windings wound on a tubular ferromagnetic former



# Linear Variable Differential Transformer (LVDT) displacement sensor



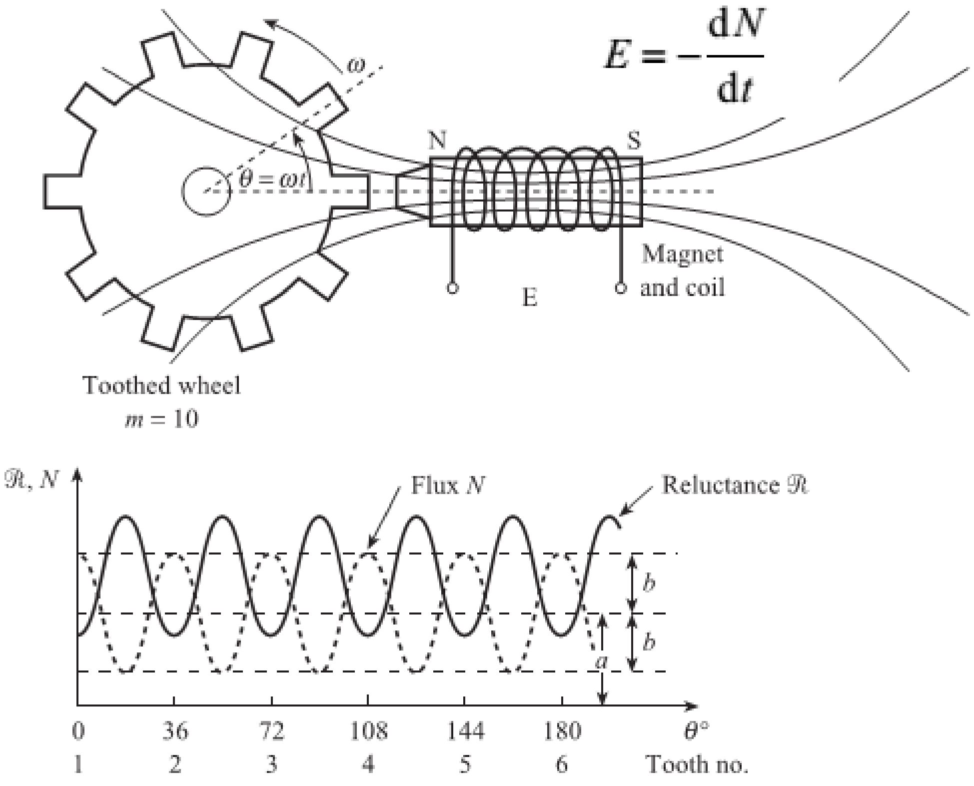




# Electromagnetic sensing elements

These elements are used for the measurement of linear and angular velocity and are based on Faraday's law of electromagnetic induction. This states that if the flux $N$ linked by a conductor is changing with time, then a back e.m.f. is induced in the conductor with magnitude equal to the rate of change of flux, i.e.

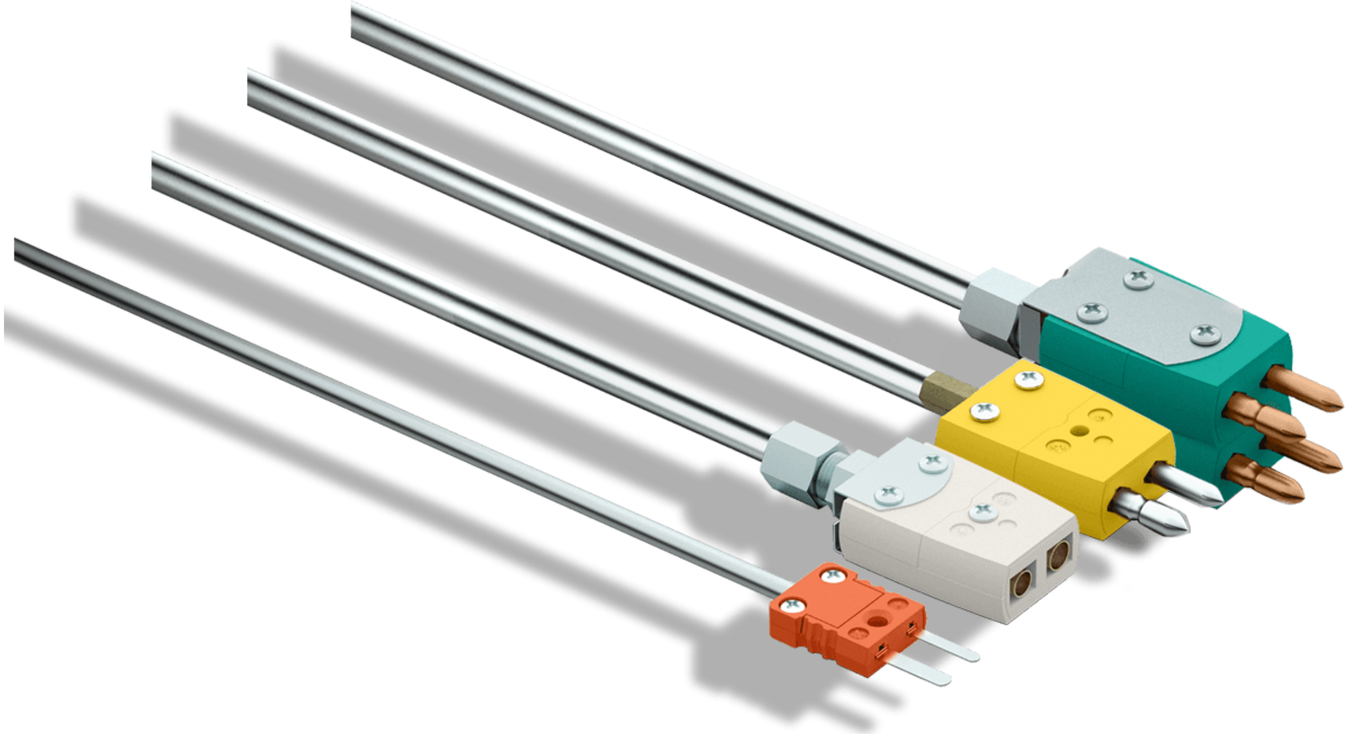
$$E = -\frac{dN}{dt}$$




Variable reluctance tachogenerator, angular variations in reluctance and flux.

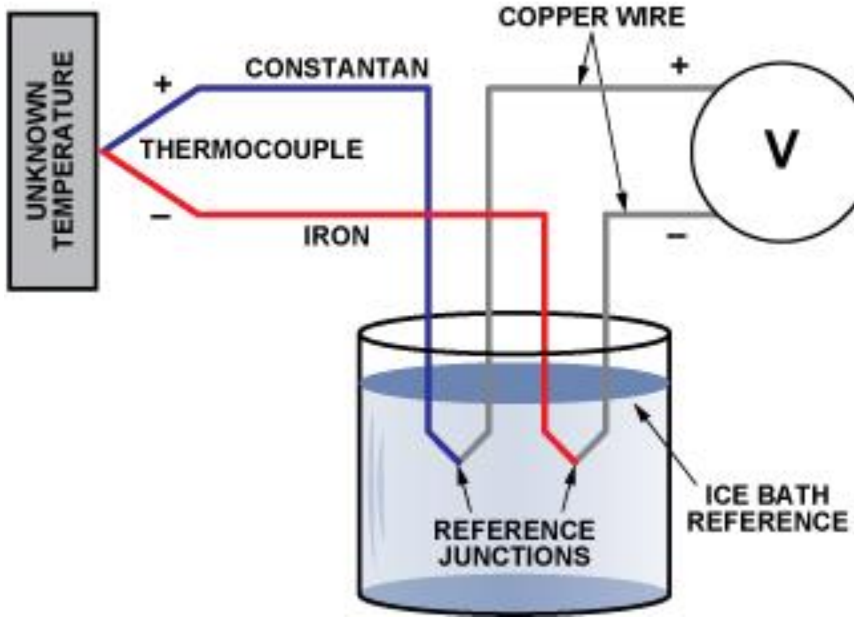
# Thermoelectric sensing elements

Thermoelectric or thermocouple  (TC) sensing elements are commonly used for measuring
temperature. If two different metals *A* and *B* are joined together, there is a difference in electrical potential across the junction called the **junction potential**



# Thermoelectric sensing elements

the **junction potential**




TC

Advantages:

- Self powered
- rugged
- Inexpensive
- simple

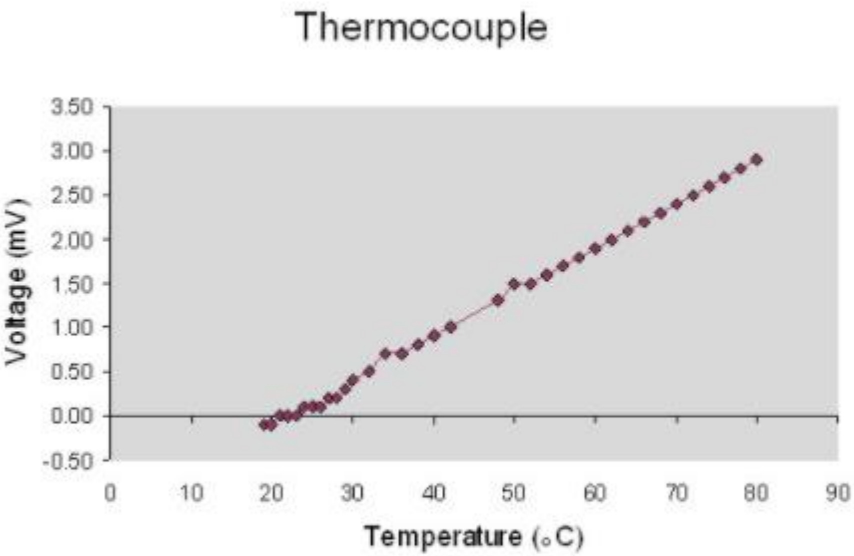
Disadvantages

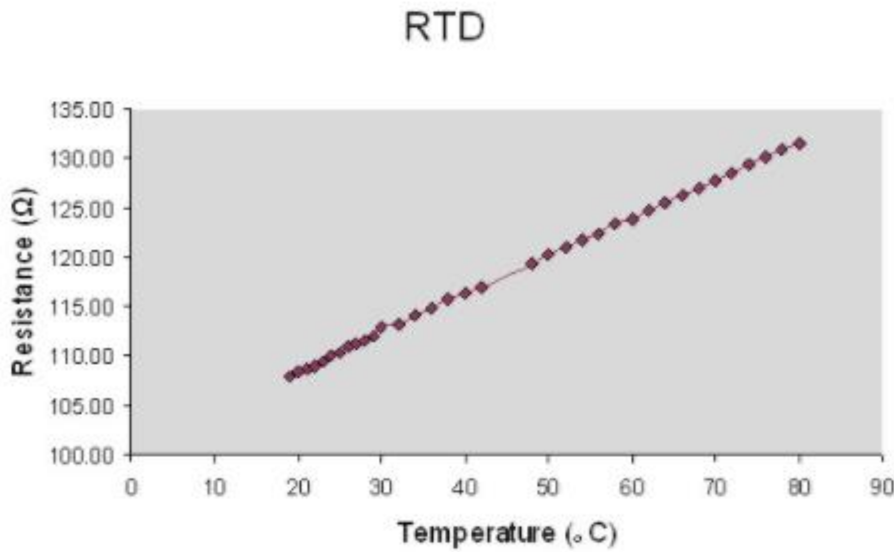
- Extremly low voltage output
- Not very stable
- Needs a reference point

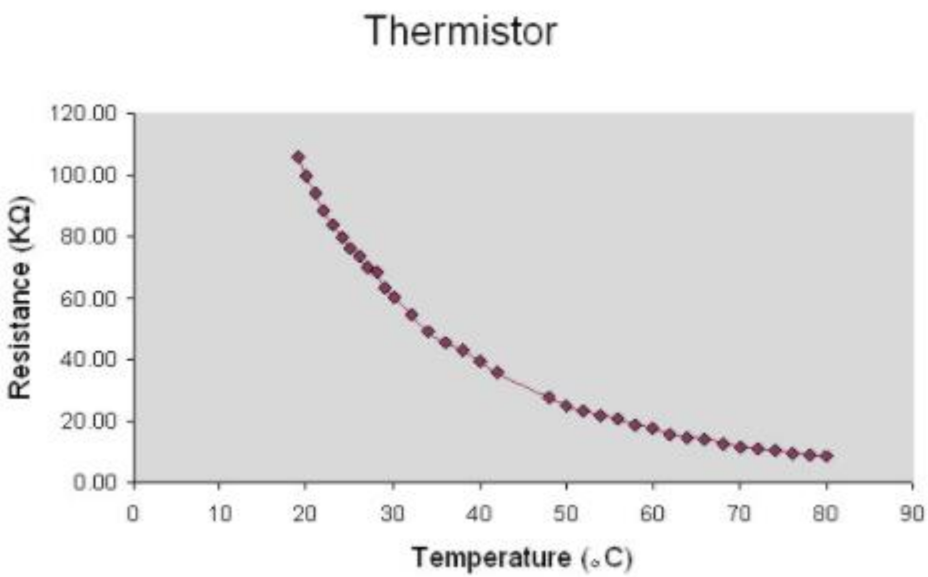
# Temperature sensing elements

| Temperature (degrees Celsius) | Thermocouple (mille-Volts) | RTD (ohms) | Thermistor (kilo-ohms) |
|---|---|---|---|
| 19 | -0.10 | 108.00 | 105.60 |
| 20 | -0.10 | 108.40 | 99.80 |
| 21 | 0.00 | 108.70 | 94.20 |
| 22 | 0.00 | 109.00 | 88.20 |
| 23 | 0.00 | 109.50 | 83.80 |
| 24 | 0.10 | 110.00 | 79.70 |
| 25 | 0.10 | 110.40 | 75.90 |
| 26 | 0.10 | 110.90 | 73.30 |
| 27 | 0.20 | 111.30 | 70.00 |
| 28 | 0.20 | 111.50 | 68.40 |
| 29 | 0.30 | 112.00 | 63.40 |
| 30 | 0.40 | 112.90 | 60.50 |
| 32 | 0.50 | 113.20 | 54.80 |
| 34 | 0.70 | 114.10 | 49.20 |
| 36 | 0.70 | 114.80 | 45.50 |

# Temperature sensing elements

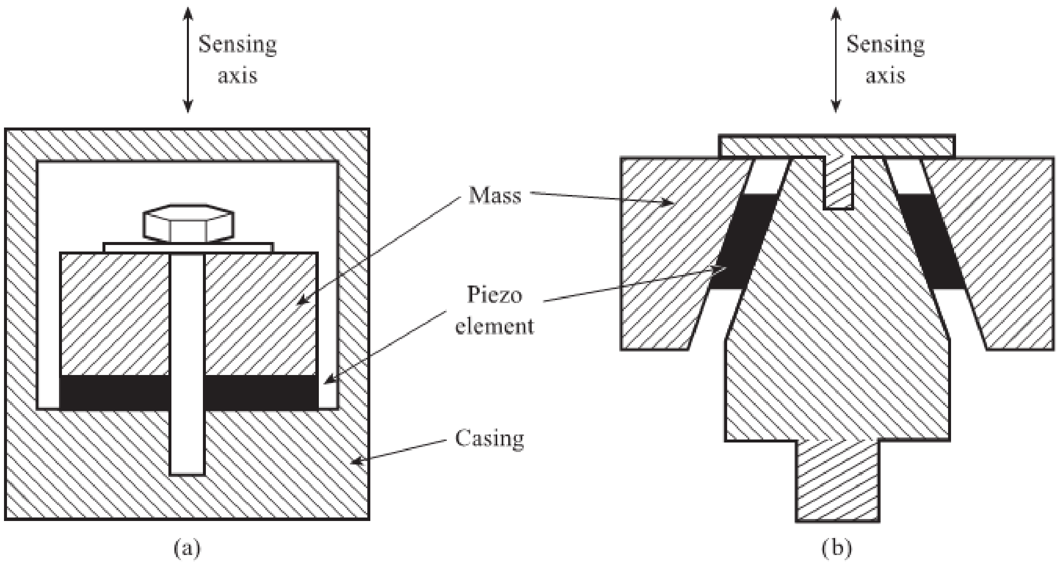


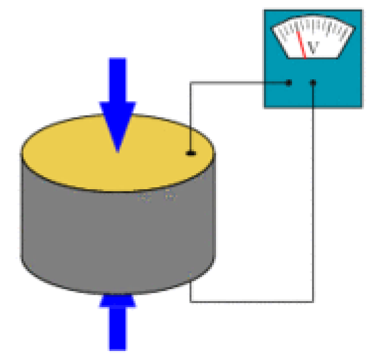



# Piezoelectric sensing elements

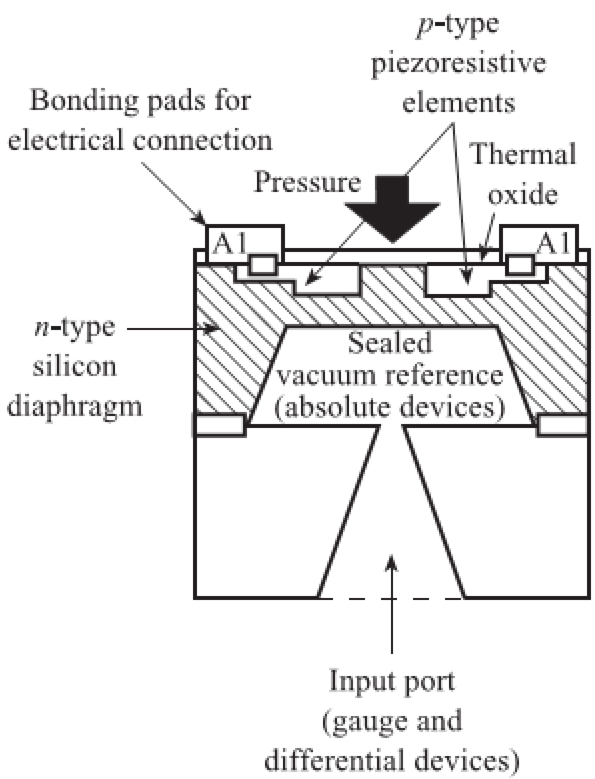
If a force is applied to any crystal, then the crystal atoms are displaced slightly from their normal positions in the lattice. This displacement $x$ is proportional to the applied force $F$: i.e., in the steady state,



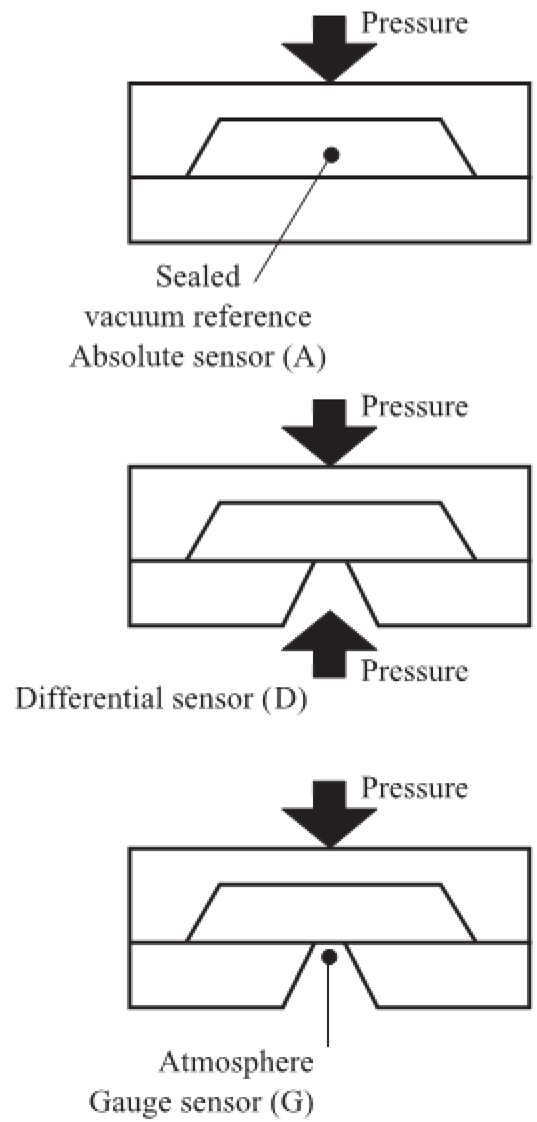



Piezoelectric accelerometers:
(a) Compression mode
(b) Shear mode

# Piezoelectric sensing elements



(a)



(b)