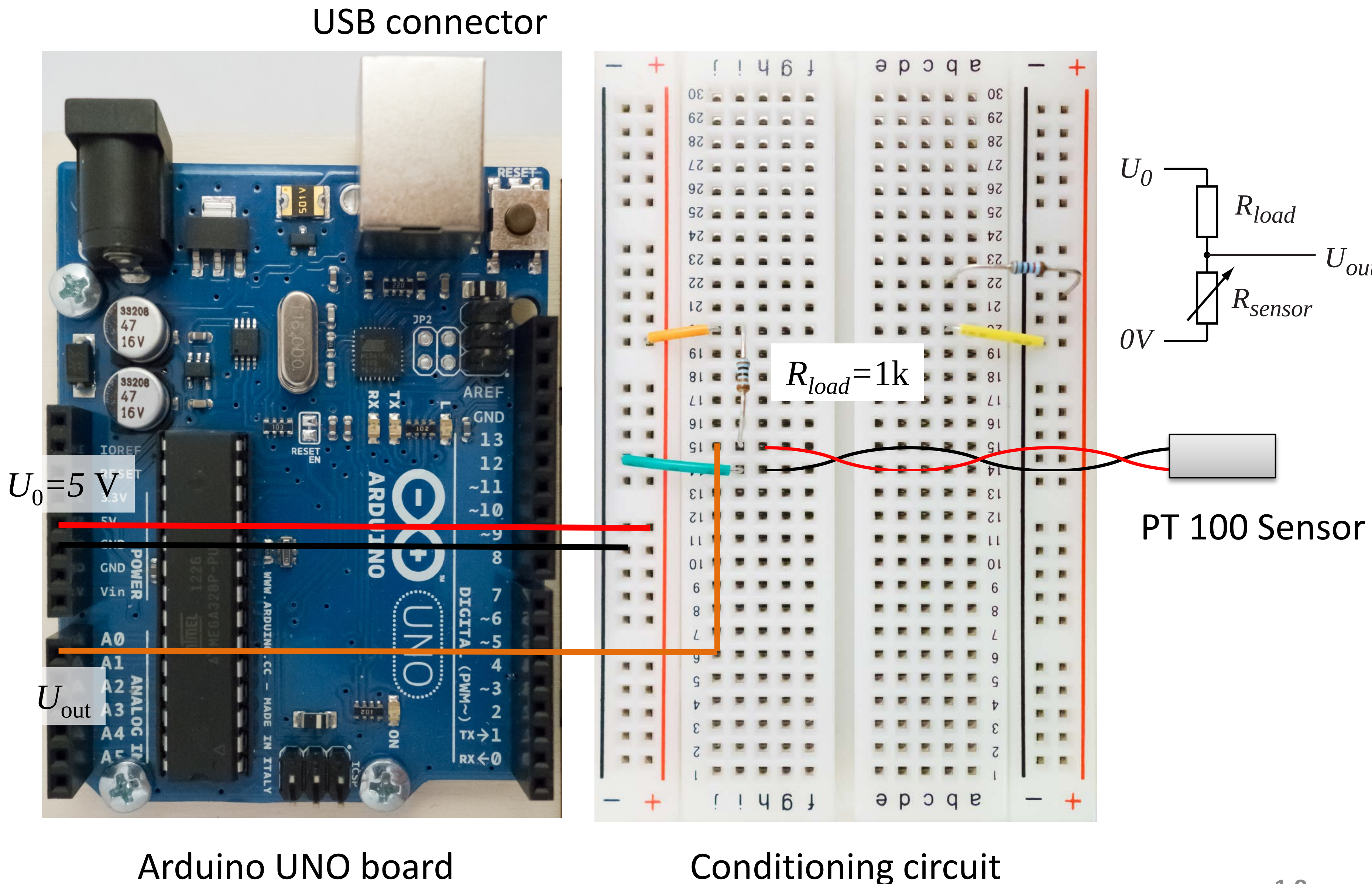
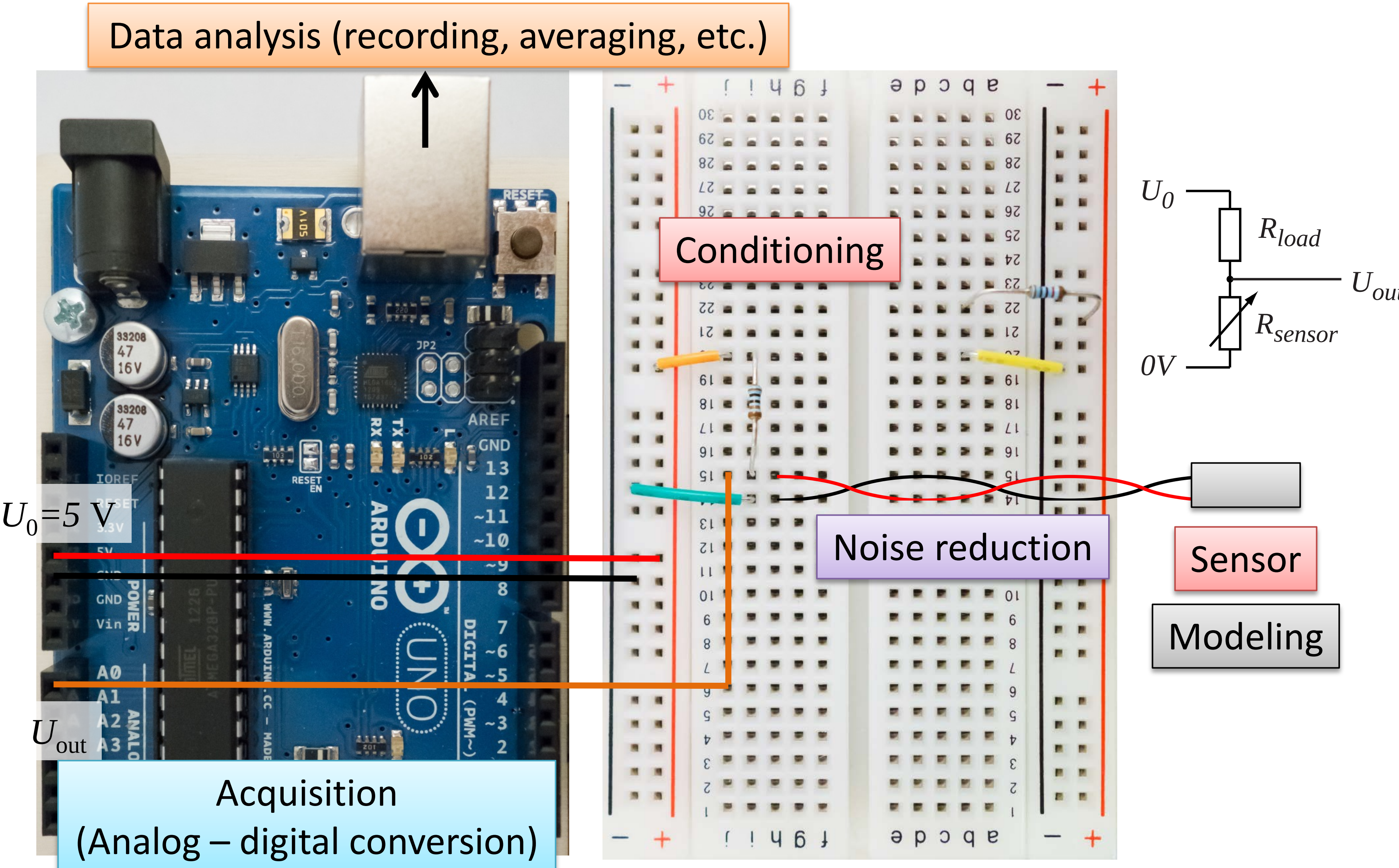
Measuring systems

Lecturer: Andras Kis

In class demo: RTD and photodetector



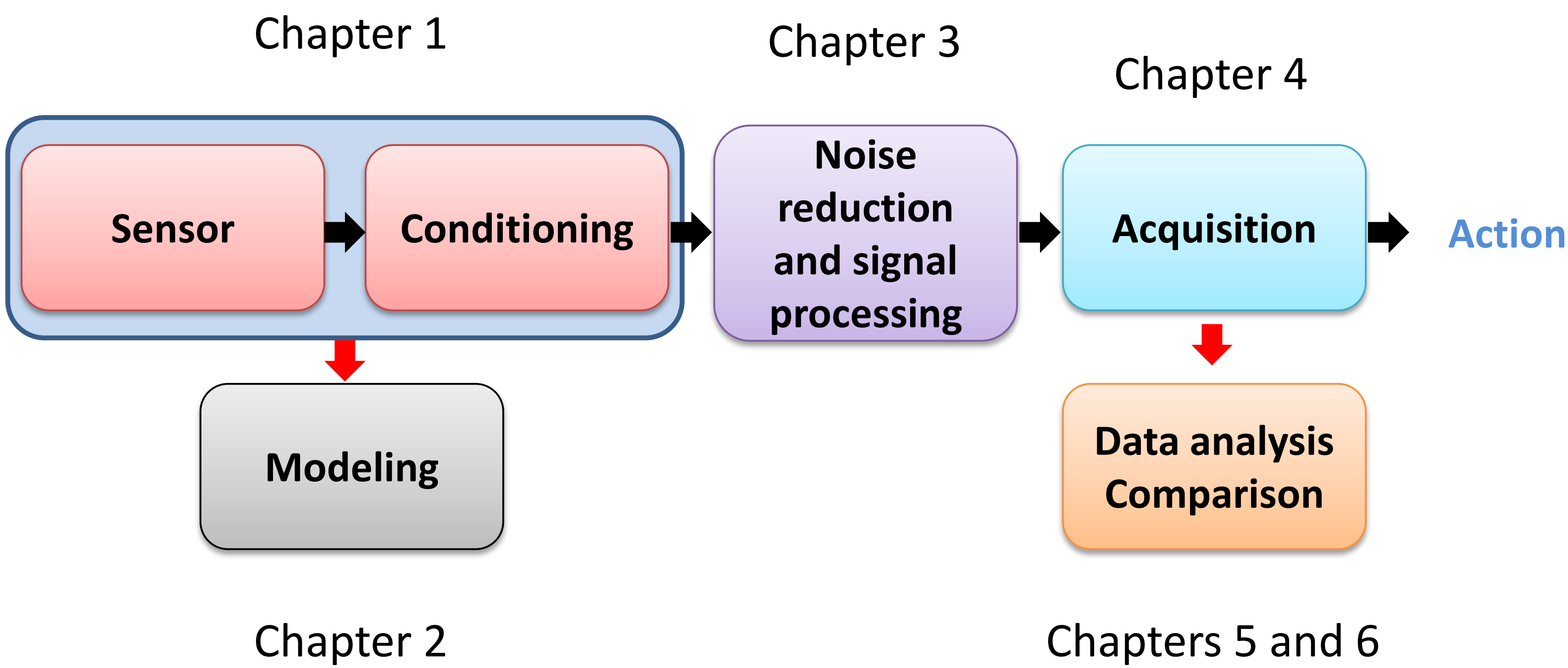
In class demo: RTD and photodetector



Arduino UNO board

Conditioning circuit

Measurement chain



Measuring systems

- Sensors and their conditioning
- Modeling sensors
- Noise estimation and reduction
- Data acquisition
- Data analysis and treatment
- Comparison betweeen different measurement results

References

- Georges Asch, Acquisition de données, Dunod, 2003
- Ph. Robert, TE vol 17, Systèmes de mesure

- Transparencies
- Exercises + solutions

Organisation

- Room BC 01
- Exercises
  - 11 problem sets
  - Discussions during the exercises
  - Work at home
- Written mock exam (end November or early December) – bonus (max +1 on the final exam)
- Written exam
- Prerequisits: Electrotechnique 1 and 2
- Needed for: TP Measuring systems

Expected work load

- 1 credit = 30 work hours (source: EPFL, CRAFT)
- 3 credits x 30 = 90 hours total

  - 10 h preparation for the exam

  =80h

  -3x14 lectures + exercises

  =38 h for individual work at home

  = **2.5-3 h/week**

Chapter 1: Sensors and conditioning circuits

Sensors and conditioning circuits

- Introduction
  - Transducer: sensor, actuator
- Passive sensors and their conditioning
  - Temperature – RTD (resistance temperature detector)
  - Displacement – capacitive sensors
  - Displacement – inductive sensors
  - Light intensity – photoconductors
- Active sensors and their conditioning
  - Temperature – thermocouple (thermoelectric effect)
  - Light intensity – photovoltaic cell photovoltaic effect
  - Displacement - piezoelectric gauge

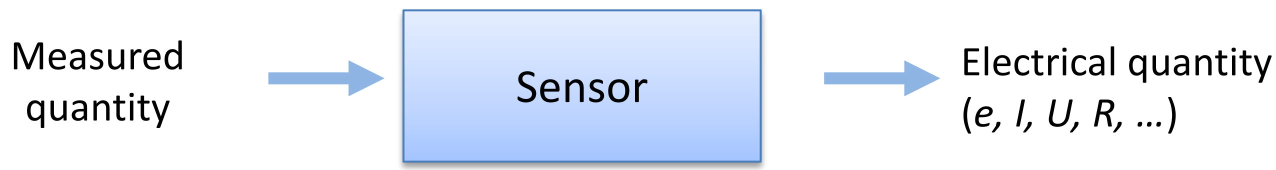
Transducer

A **transducer** is an element that converts one physical quantity into another physical quantity

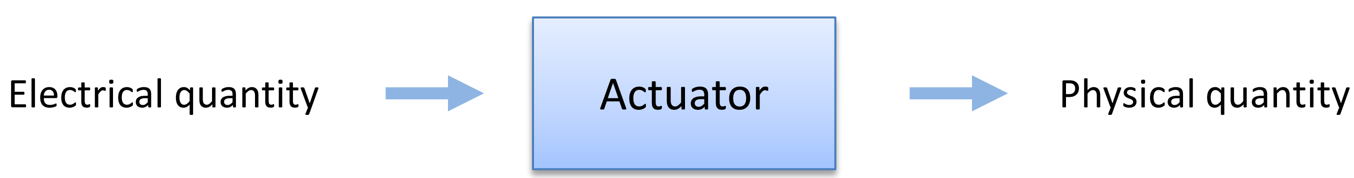
- Mercury thermometer (temperature – displacement)
- Accelerometer (acceleration – voltage)
- Electrode in a battery (ion – electrical charge)
- Motor (electrical current – mechanical moment)
- LED (electrical current – light)

Sensor - actuator

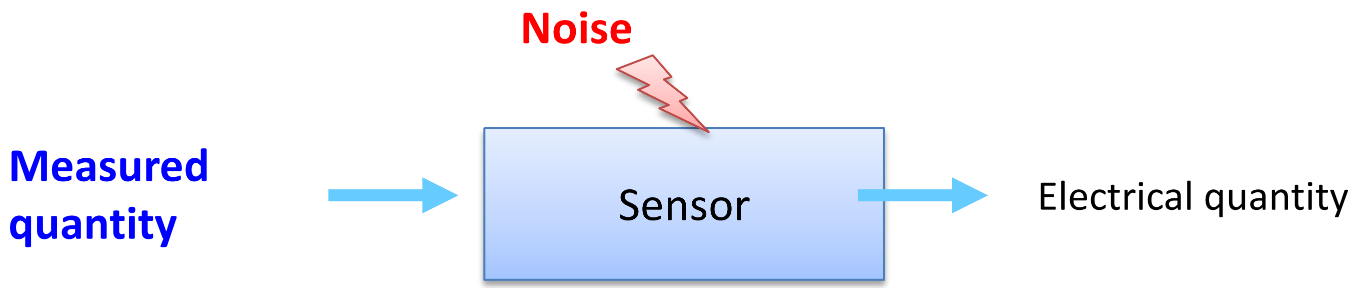
- A sensor is a transducer that converts a physical quantity into an electrical quantity:
  - Resistance thermometer (temperature - resistance)
  - Photodetector (light - current)



- An actuator is a transducer that converts an electrical quantity into a non-electrical quantity
  - Piezo actuator (charge - displacement)
  - Resistive heater (current - heat)
  - LED (current - light)



Sensors



x

$y = f(x)$

Ex: temperature T
Accelleration a

Sensitivity $S = \frac{dy}{dx}$

Ex: Resistance R
Voltage V

- Sensitivity ***S***: response in magnitude
- Transfer function: frequency response
- Noise: sensitivity to perturbations (internal and external)

Passive and active sensors

- **Passive sensors** - require an external power source

  Examples:

  - Resistive thermometer
  - Capacitive displacement sensor

- **Active sensors** - generate the electrical signal from the measured quantity

  Examples:

  - Thermocouples – thermoelectric effect
  - Accelerometers – piezoelectric effect

Passive sensors

Passive sensors

Measured quantity	**Sensitive characteristic**	**Device**
Temperature	Resistance	RTD (resistance temperature detector)
Mechanical (Force, pression, acceleration, vibrations, sound level, displacement)	Resistance, capacitance, inductance	potentiometer, microphone LVDT (linear variable differential transformer), accelerometer, strain gauge
Light intensity	Resistance	photoconductor phototransistor

Resistive temperature sensors (RTD)

- Resistance of a metal as a function of temperature:

$$R = R_0 \cdot f\left(T - T_0\right)$$

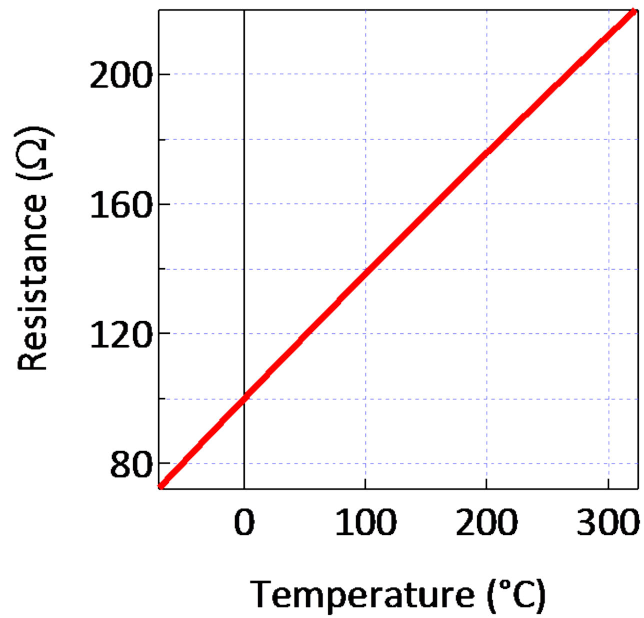
R – Resistance at temperature T
R_0 – Resistance at temperature T_0

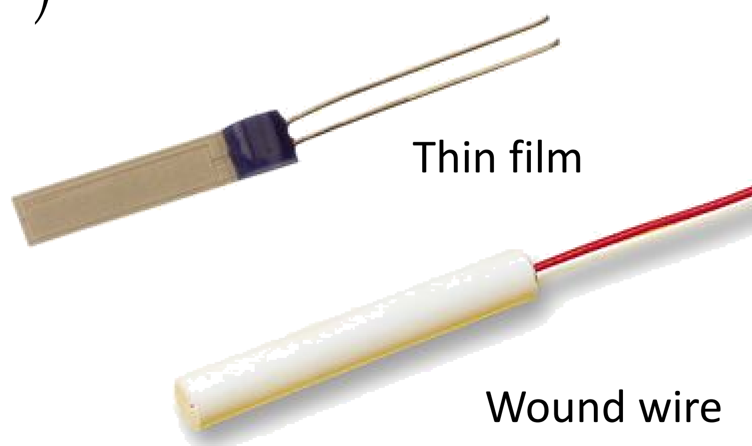
- For platinum (PT100):

$$R(T) = R_0\left(1 + A(T - T_0) + B(T - T_0)^2\right)$$

T – temperature in °C
T_0 = 0°C
R_0 = 100 Ω
A = 3.9×10^{-3} °C^{-1}
B = -5.775×10^{-7} °C^{-2}

- Linear but low sensitivity





Resistive temperature sensors (Thermistors)

- Ceramics or polymers
- Generally described by Steinhart-Hart equation:

$$\frac{1}{T} = A + B\left[\ln(R)\right] + C\left[\ln(R)\right]^3$$

T – Temperature in Kelvin

- Example: Omega 44006

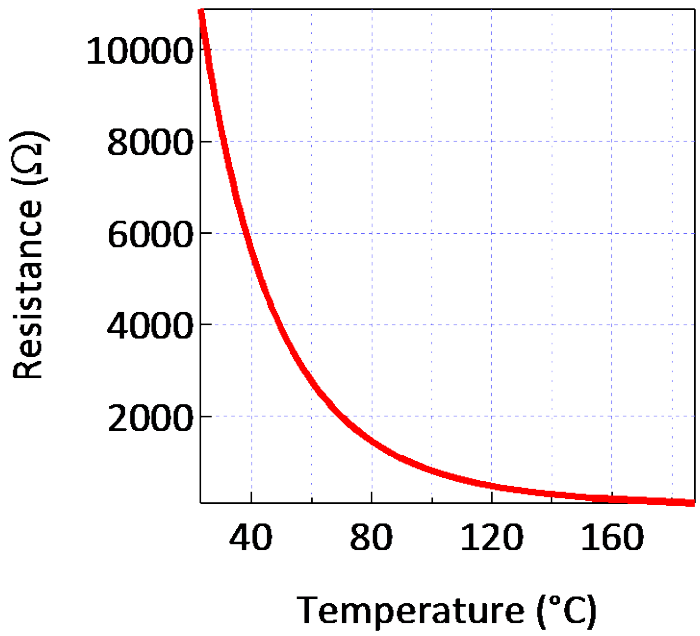
$R_{T=25°C} = 10000\ \Omega$

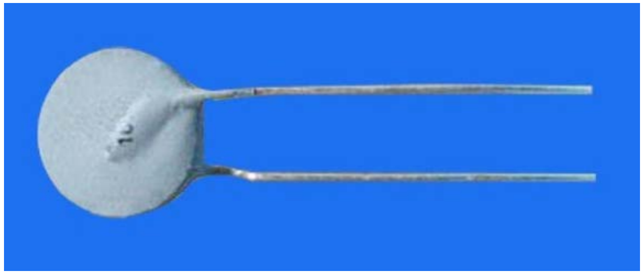
A = 1.032×10^{-3} °C^{-1}

B = 2.208×10^{-4} °C^{-1}

C = 1.276×10^{-7} °C^{-1}

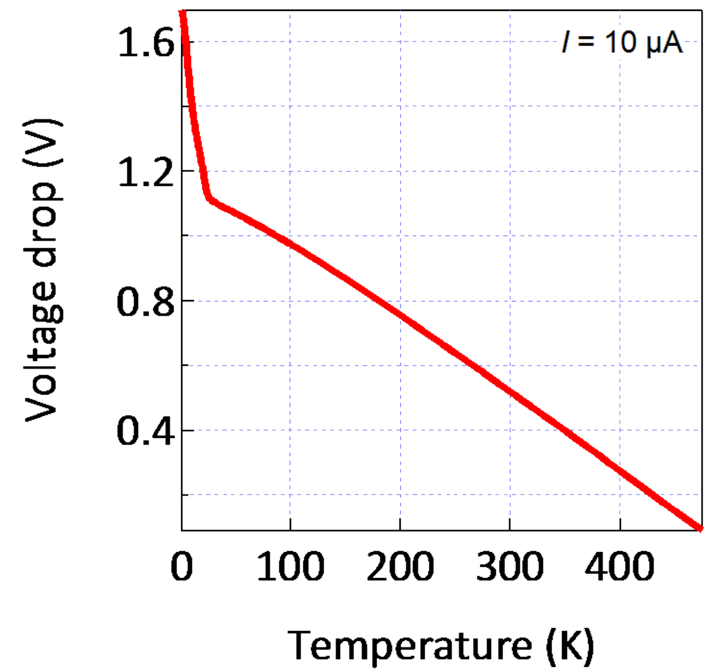
- Non-linear but high sensitivity

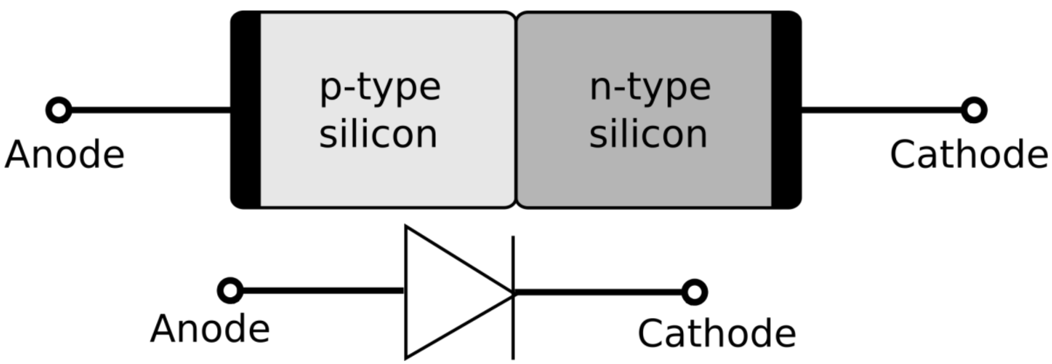


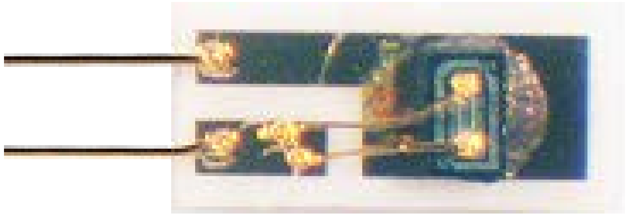


Semiconducting diode thermometers

- Si, Ge, etc.
  - pn junctions
  - Inexpensive and (mostly) linear
  - Limited temperature range (-50 – 150 °C)



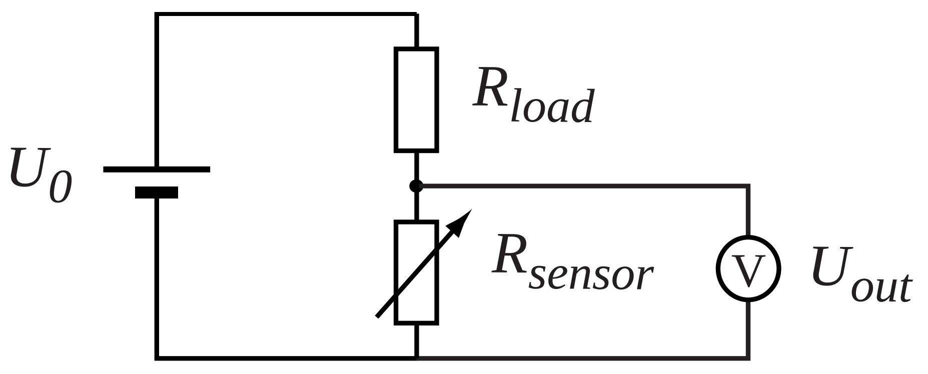




Lakeshore DT 400

Conditioning circuits for resistive sensors

Voltage divider



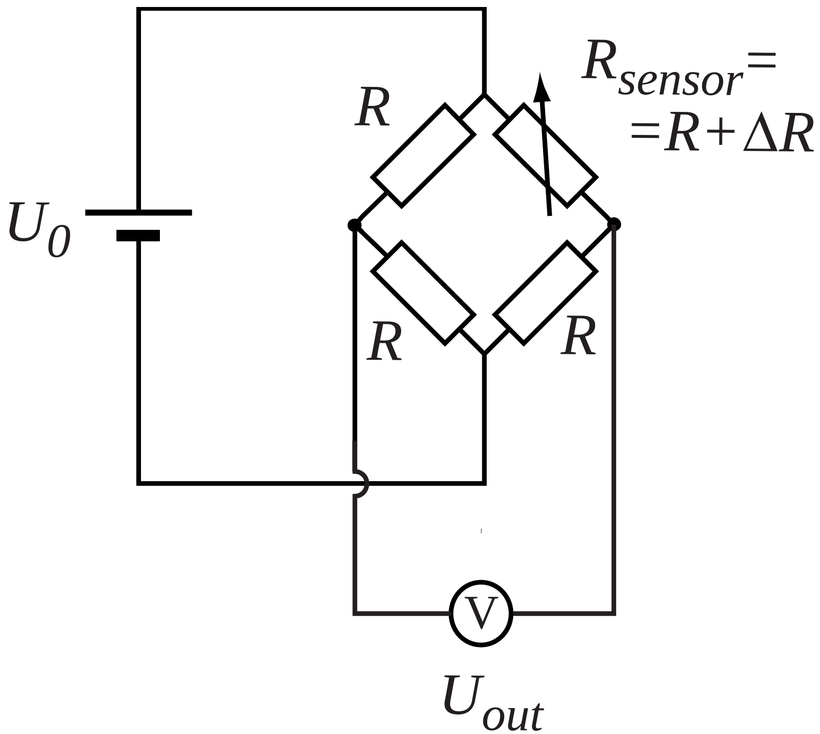
$$U_{out} = U_0 \frac{R_{sensor}}{R_{load} + R_{sensor}}$$

For $R_{load} = R_{sensor} = R$:

$$U_{out} = \frac{U_0}{2}$$

Conditioning circuits for resistive sensors

Wheatstone bridge



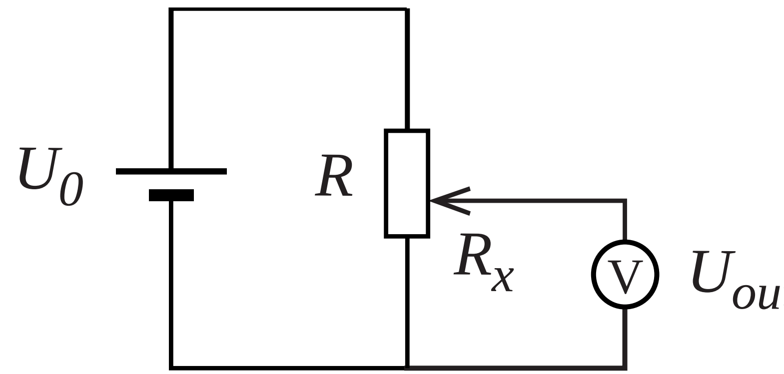
$$U_{out} = \left[\frac{R_{sensor}}{R_{sensor} + R} - \frac{R}{2R} \right] U_0$$

For $R_{sensor}=R$:

$$U_{out} = 0$$

Displacement sensor - resistive

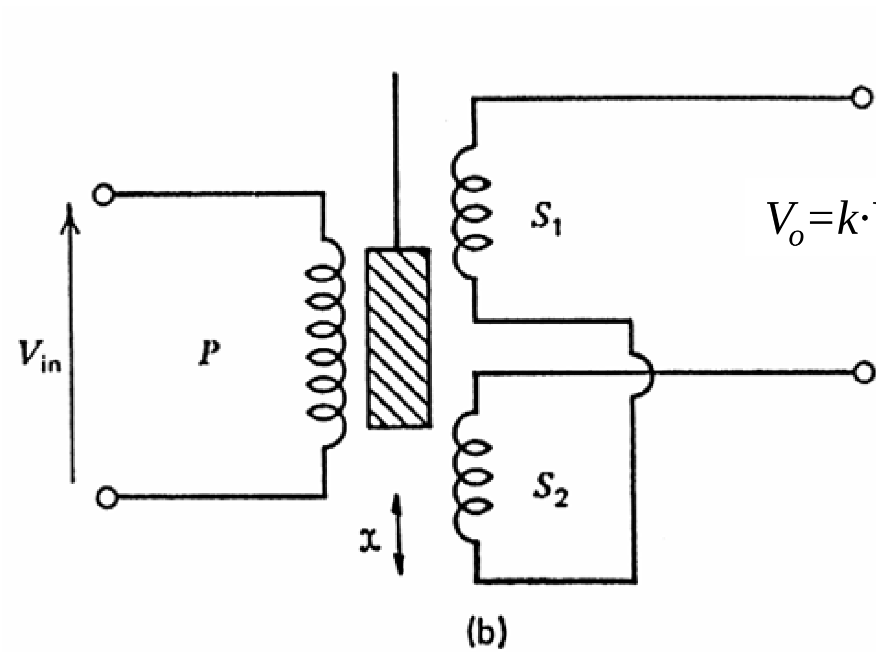
- Potentiometer
  - Resistor with a sliding contact
  - Acts as a voltage divider



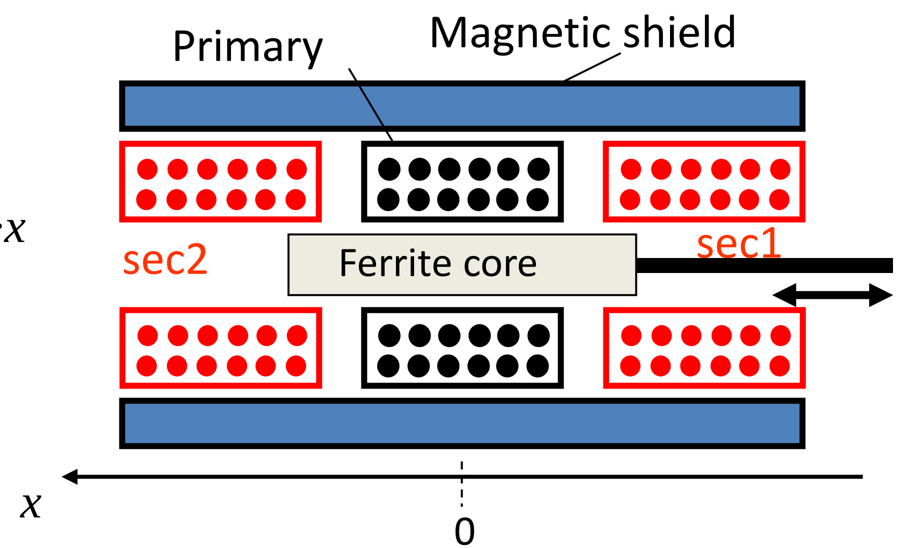
$$U_{out} = \frac{R_x}{R} U_0$$

Displacement sensor - inductive

- LVDT (Linear Variable Differential Transformer)



$$V_o = k \cdot V_{in} \cdot x$$



Mutual inductance – differential transformer

$$u_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + (M''-M')\frac{di_2}{dt}$$

$$u_2 = -(R_2^{'} + R_2^{''})i_2 - (L_2^{'} + L_2^{''})\frac{di_2}{dt} + (M''-M')\frac{di_1}{dt}$$

$$\underline{U}_1 = (R_1 + j\omega L_1)\underline{I}_1 + j\omega(M''-M')\underline{I}_2$$

$$\underline{U}_2 = -(R'_2 + R''_2 + j\omega L'_2 + j\omega L''_2)\underline{I}_2 + j\omega(M''-M')\underline{I}_1$$

Voltage on L_2' due to current i_2:

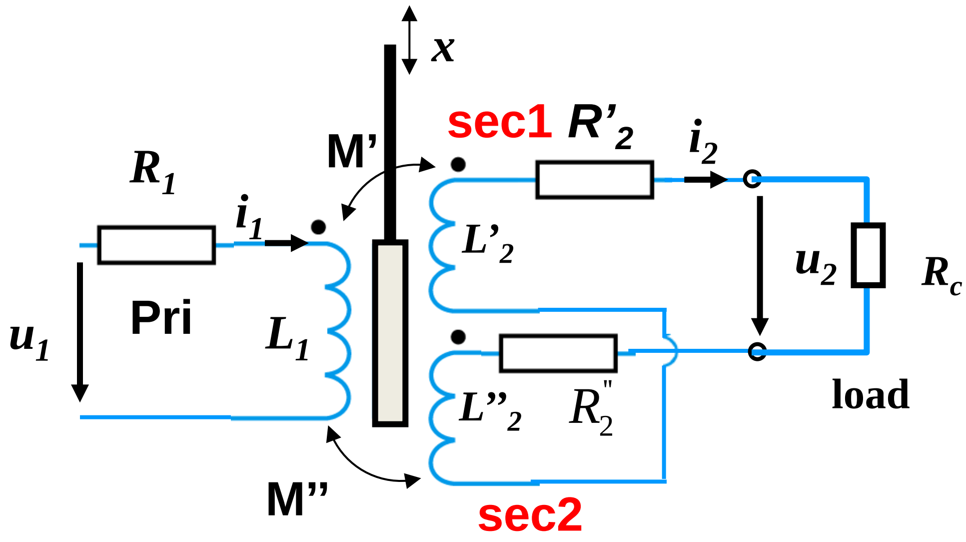
$$L_2{}' \frac{di_2}{dt}$$

Voltage on L_2' due to current i_1:

$$M' \frac{di_1}{dt}$$

For R_c >> , $i_2 \approx 0$

$$\underline{U}_2 = \frac{j\omega[M''(x) - M'(x)]}{R_1 + j\omega L_1}\underline{U}_1$$



Mutual inductance – differential transformer

$$\underline{U}_2 = \frac{j\omega\left[M''(x) - M'(x)\right]}{R_1 + j\omega L_1}\underline{U}_1$$

$$M'(x) = M(0) + ax + bx^2 + \ldots \text{ for } x > 0$$

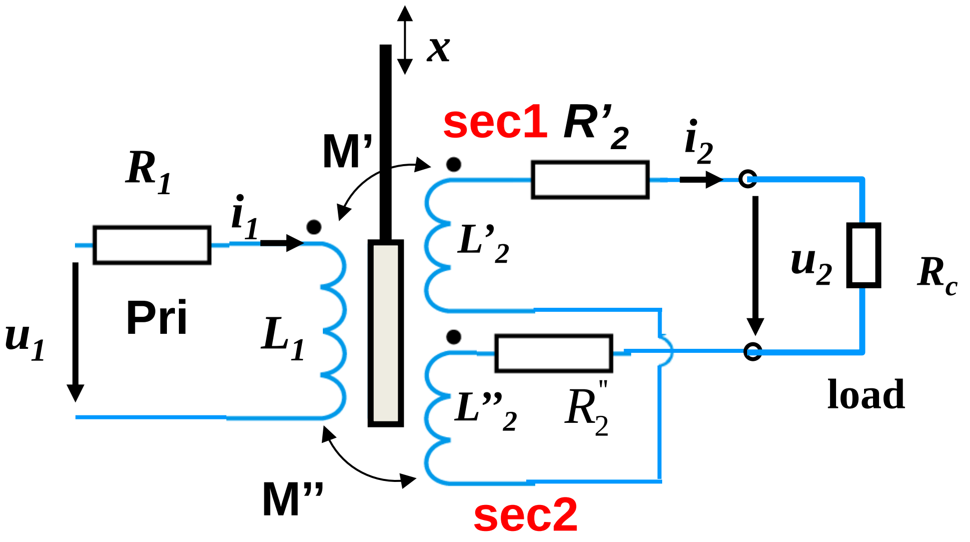
$$M''(x) = M(0) - ax + bx^2 + \ldots \text{ for } x < 0$$

2nd order approximation:

$$M''(x) - M'(x) = -2ax$$

We get a linear relationship:

$$\underline{U}_2 = \frac{-2j\omega \cdot a\underline{U}_1}{R_1 + j\omega L_1}\underline{X}$$

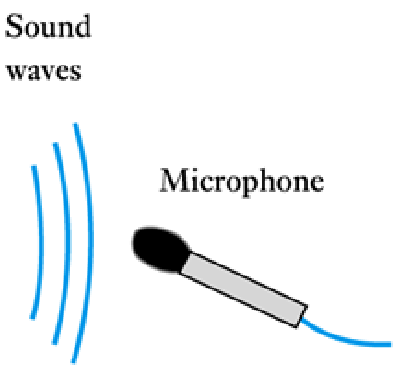


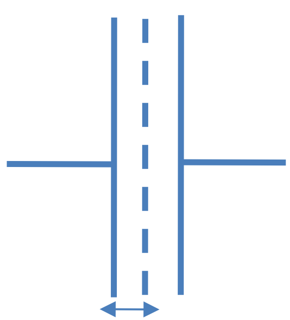
Capacitive displacement sensor

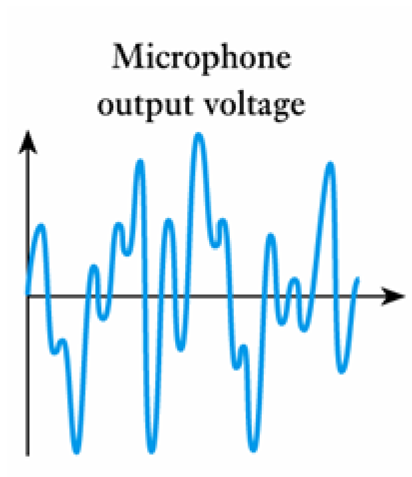
- Capacitance

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

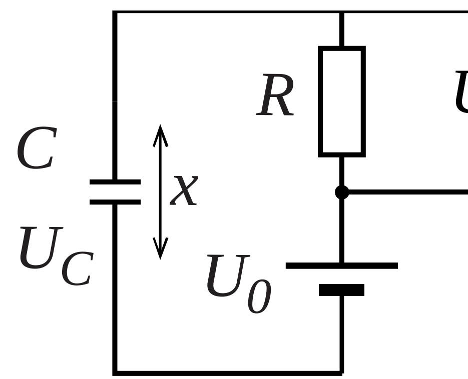
- Microphone: sound (external pressure variations) cause the membrane to vibrate (displacement dx)







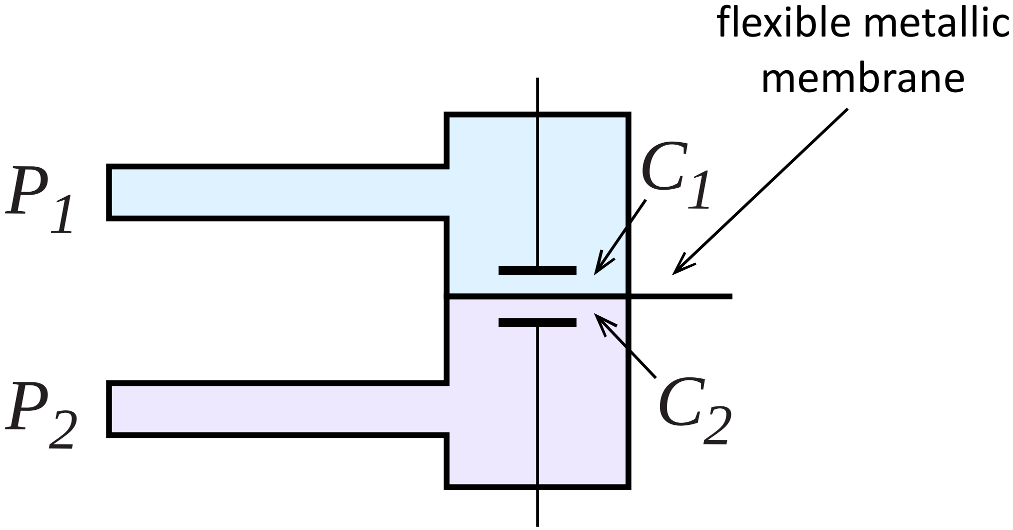
$$i = -\frac{dq}{dt}$$

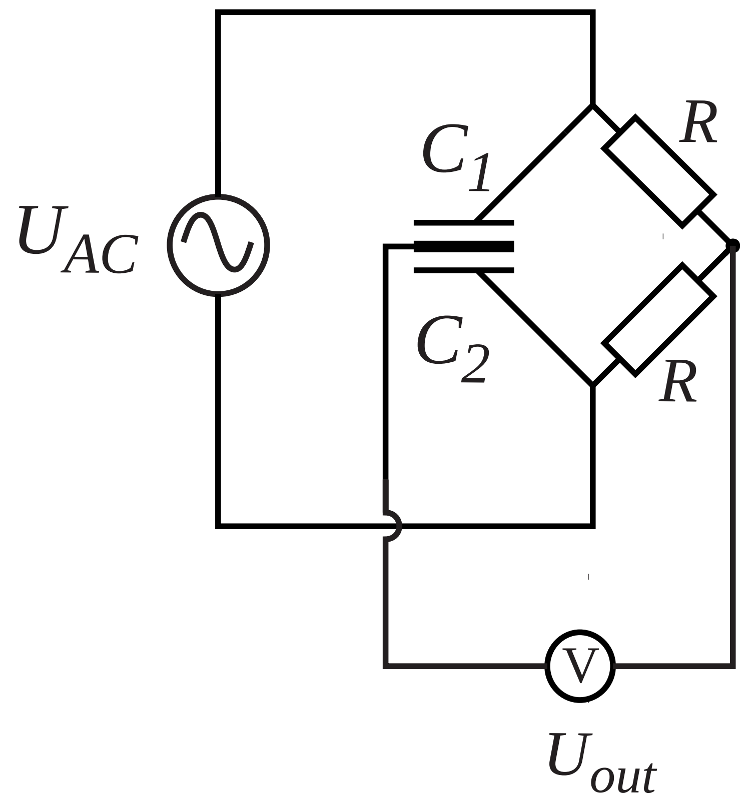


$$U = -R\frac{dq}{dt}$$

Conditioning for capacitive sensors

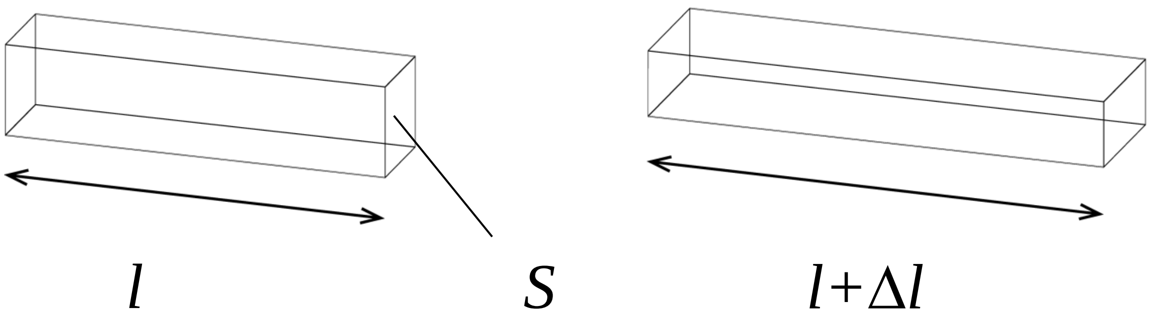
Pressure sensor





Strain gauge

- Principle: change in resistance upon mechanical deformation

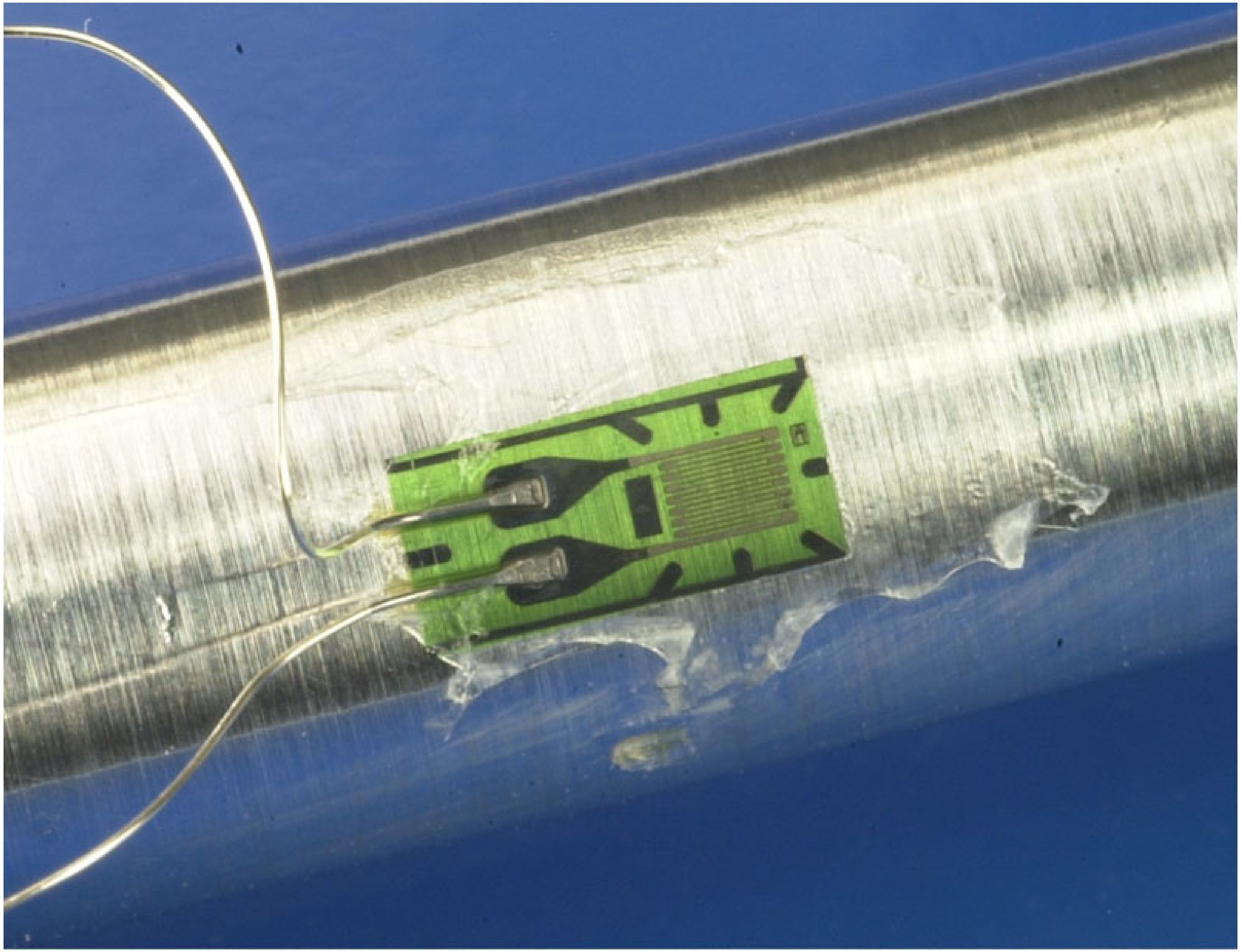


R resistance
ρ resistivity
l length
S cross-sectional area

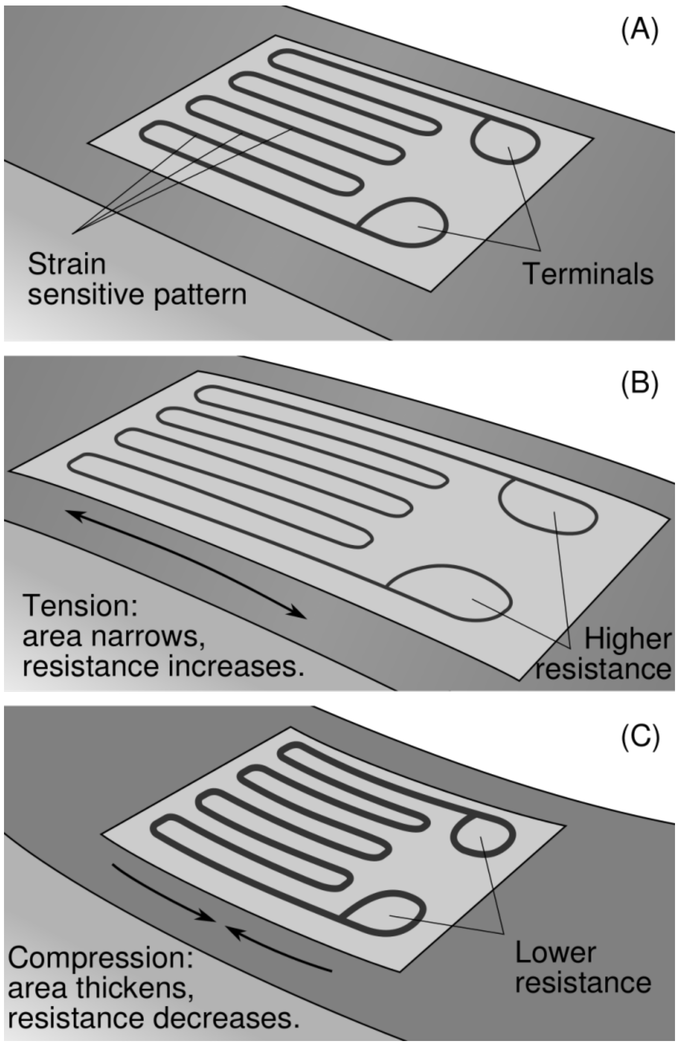
$$R_{initial} = \rho \frac{l}{S}$$

$$R_{strained} = (\rho + \Delta\rho)\frac{l + \Delta l}{S + \Delta S}$$

Strain gauge



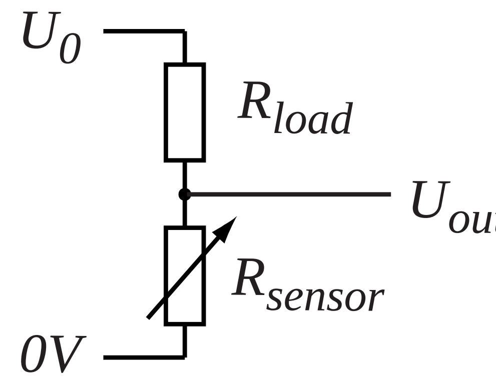
Strain gauge

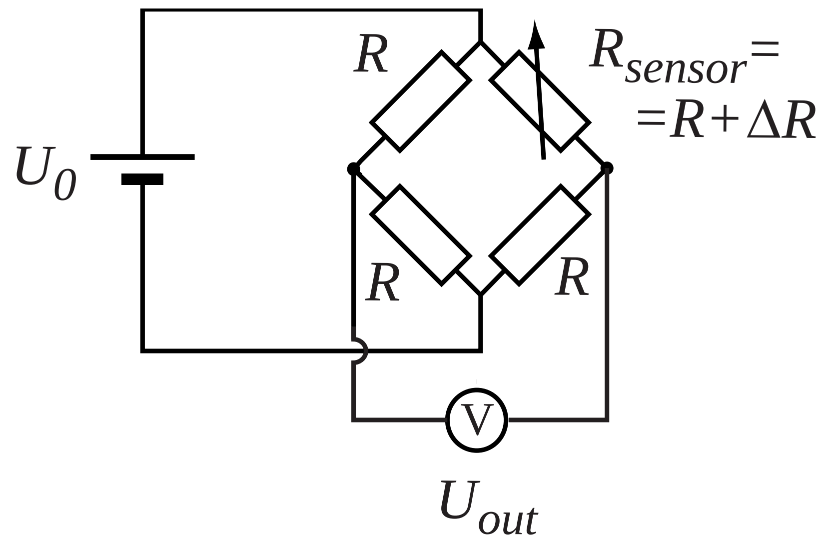


Source: Wikipedia

$$\frac{\Delta R}{R} = K \frac{\Delta l}{l}$$

$$K \sim 2 - 4$$





$U_{out} = f(U_0, \Delta R/R)$?

Strain gauge

- Let strain ε be the relative change in length and stress σ the force F per cross-sectional area S:

$$\varepsilon = \frac{\Delta l}{l} \qquad \sigma = \frac{F}{S}$$

- Strain and stress are related through the Young's modulus Y and Poisson ratio ν
  - In the direction parallel to the stress: $$\varepsilon_{\parallel} = \frac{\sigma}{Y}$$
  - Perpendicular to the stress: $$\varepsilon_{\perp} = -\nu\varepsilon_{\parallel} = -\nu\frac{\sigma}{Y}$$

Strain gauge

- Surface change:

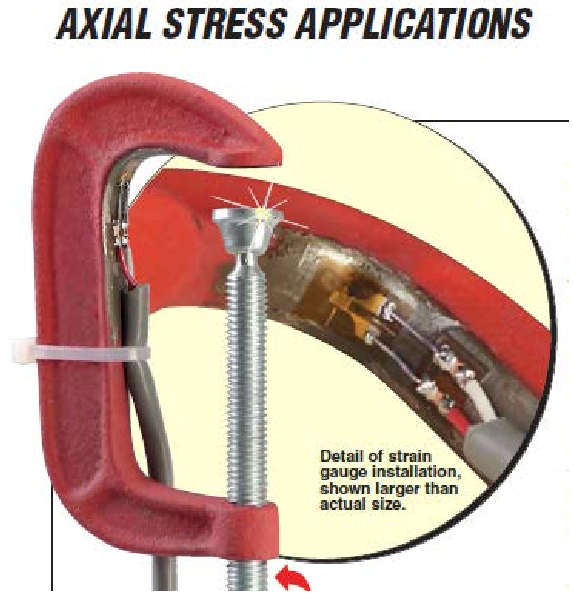
$$\frac{\Delta S}{S} = -2\nu \frac{\Delta l}{l}$$

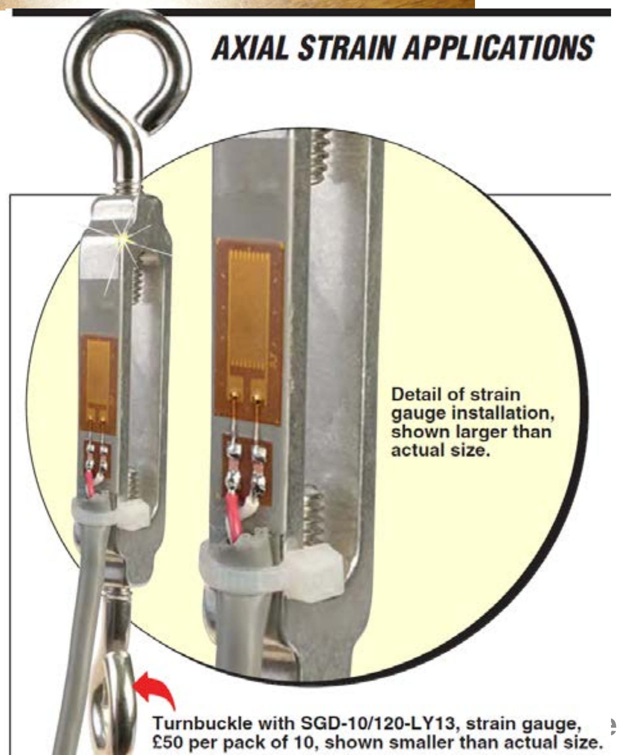
- Resistance change:

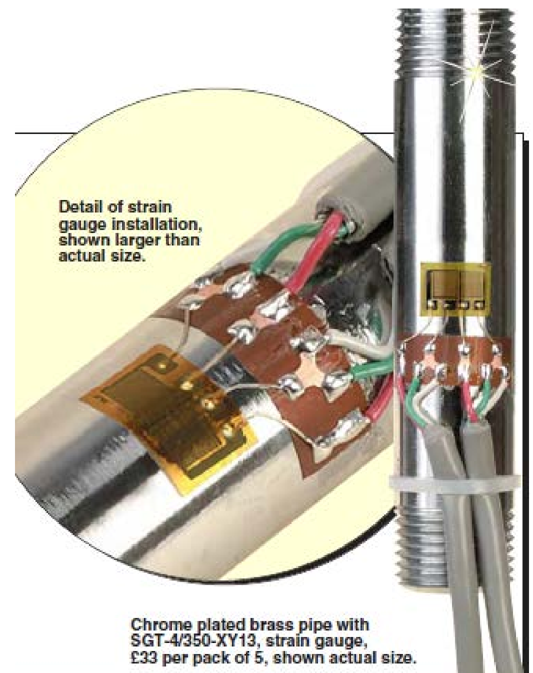
$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta l}{l} - \frac{\Delta S}{S}$$

$$\frac{\Delta R}{R} = \left(1 + 2\nu\right)\frac{\Delta l}{l} + \frac{\Delta \rho}{\rho}$$

Dominant terms
Metals: first term (geometry)
Semiconductors: second term

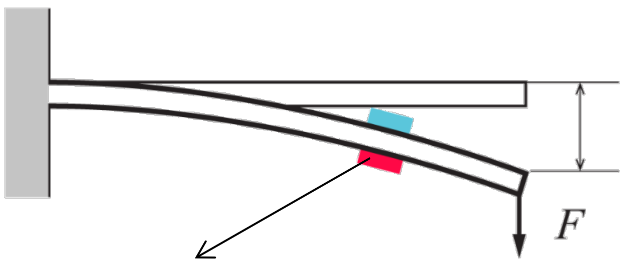

AXIAL STRESS APPLICATIONS
Detail of strain gauge installation, shown larger than actual size.


AXIAL STRAIN APPLICATIONS
Detail of strain gauge installation, shown larger than actual size.
Turnbuckle with SGD-10/120-LY13, strain gauge, £50 per pack of 10, shown smaller than actual size.

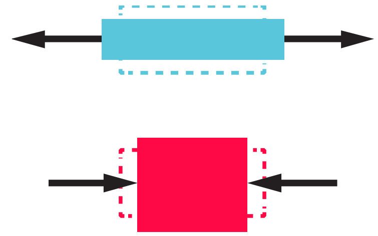

Detail of strain gauge installation, shown larger than actual size.
Chrome plated brass pipe with SGT-4/350-XY13, strain gauge, £33 per pack of 5, shown actual size.

Force sensor

- Based on a strain sensor attached to a test object



gauge



extension $\Delta l / l > 0$

compression $\Delta l / l < 0$

Force F → Deformation of the test object → Resistance change of the gauge → Voltage drop in the circuit

$$F$$

$$\frac{\Delta l}{l} = \frac{F}{A \cdot Y}$$

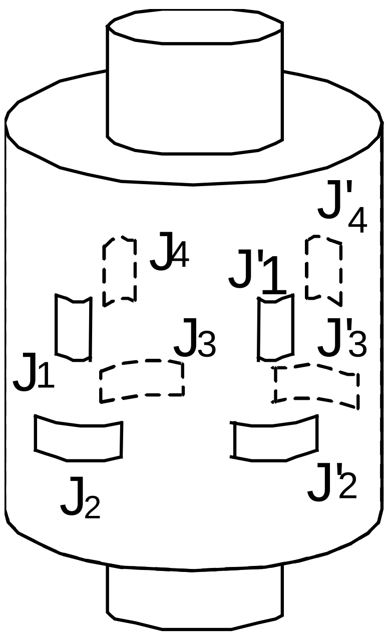
$$\frac{\Delta R}{R} = K \frac{\Delta l}{l}$$

$$\frac{\Delta U}{U} = \frac{\Delta R}{R} I$$

$$\frac{\Delta U}{U} = K \frac{F}{Y \cdot A} I$$

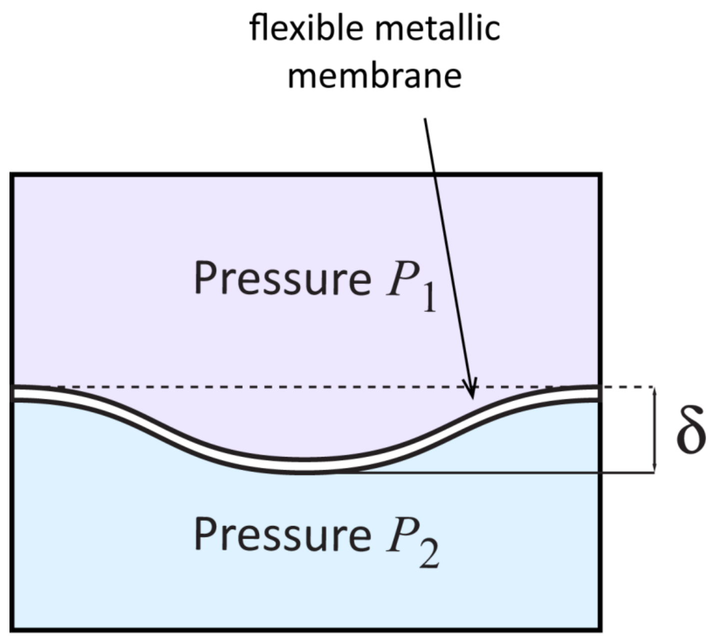
Sensors for force, pressure, acceleration

Force F



$$F = f(\varepsilon)$$

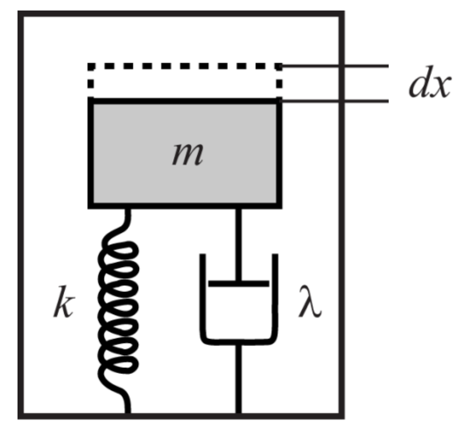
Pressure $P = P_1 - P_2$



$P_1 > P_2$

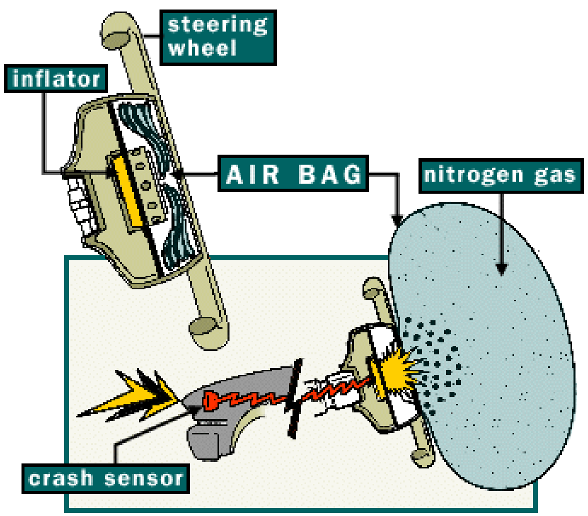
$$P = f(\varepsilon)$$

Acceleration a



$$a = \Delta x \cdot \frac{k}{m} = f(\varepsilon)$$

Some applications for accelerometers



Airbag

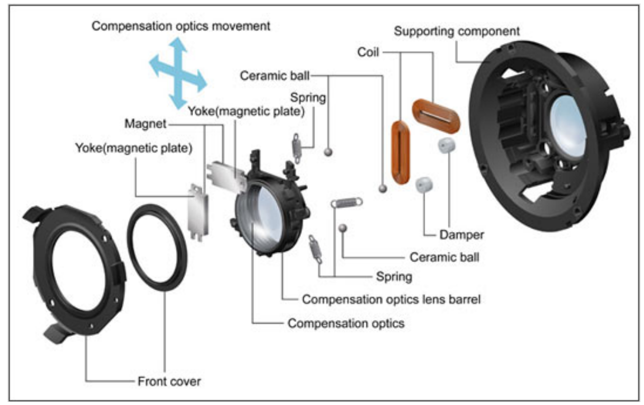


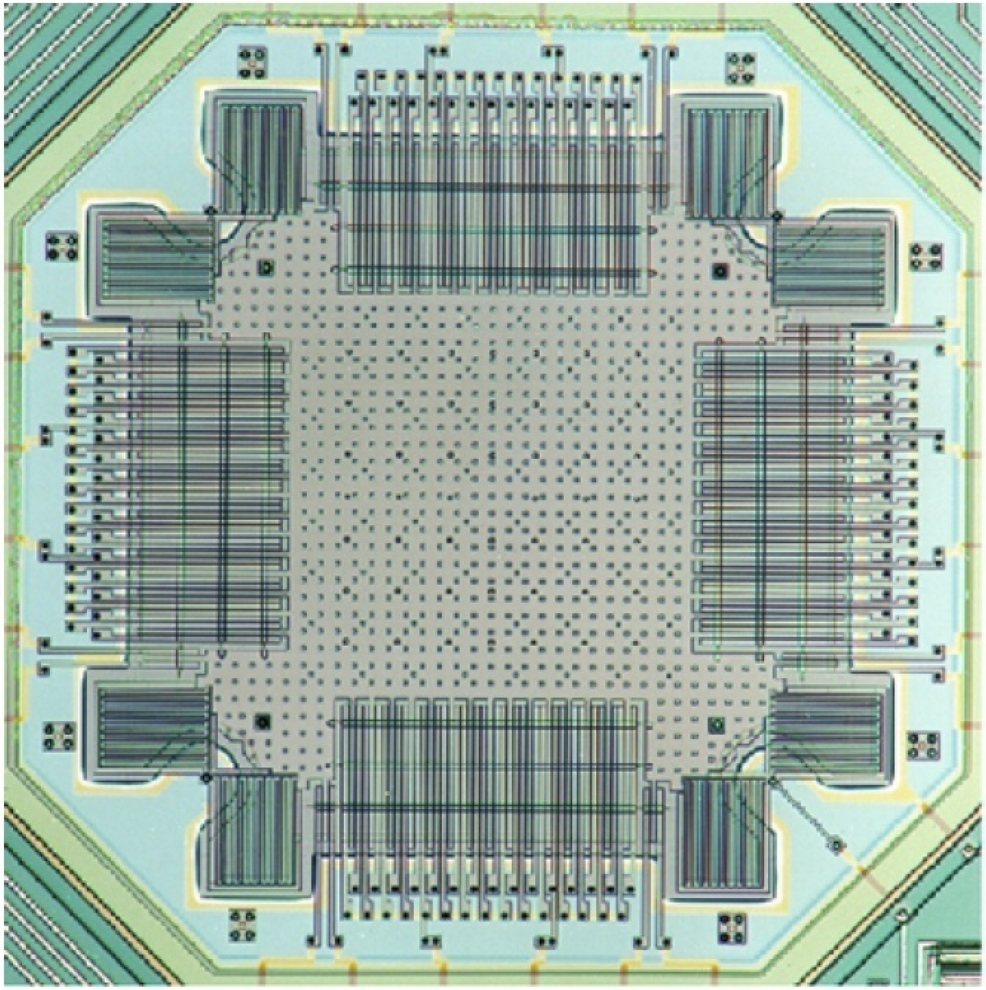
Image stabilisation

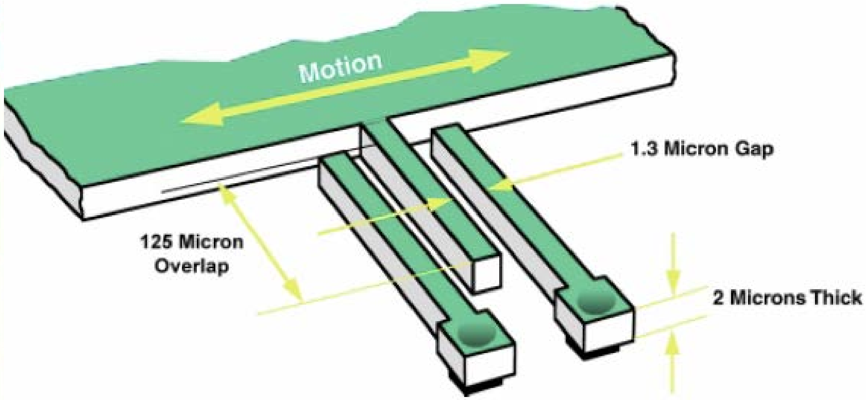
Nintendo Wii

iPhone etc.

MEMS-based accelerometer

- Micro-Electro-Mechanical systems: integration of electronics and mechanical elements: sensors and actuators



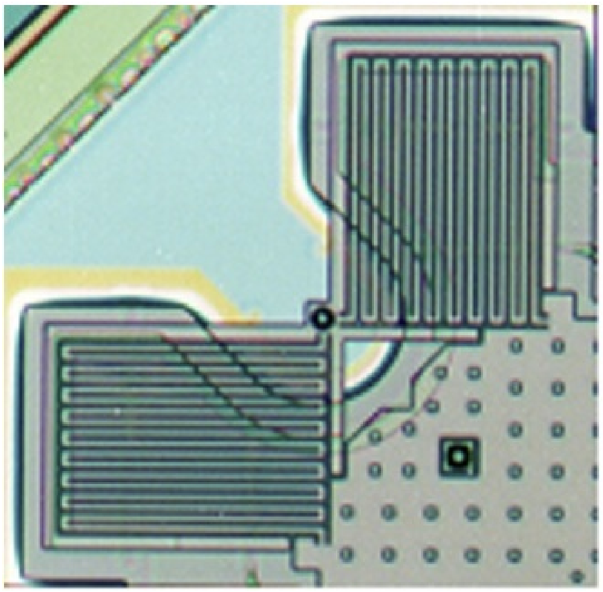


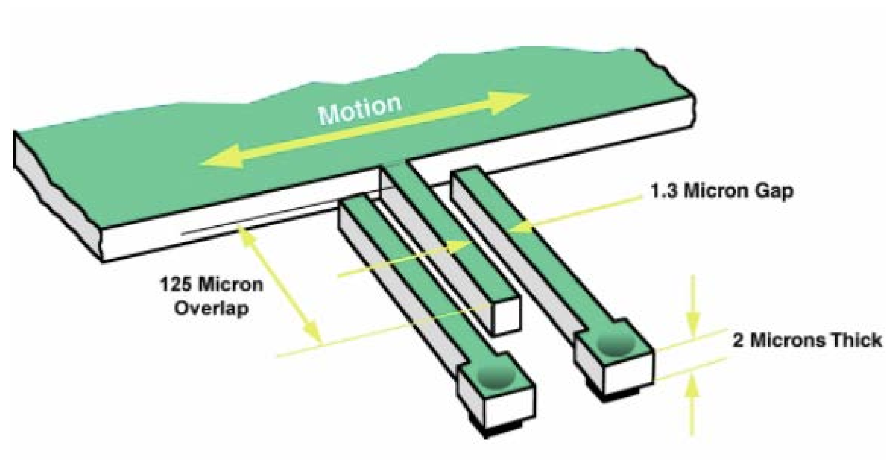
ADXL202 accelerometer
[Analog Devices website]

- www.analog.com

Microelectromechanical systems (MEMS)

- Micro-Electro-Mechanical systems: integration of electronics and mechanical elements: sensors and actuators





Movement of the beam controlled by springs with spring constant *k*

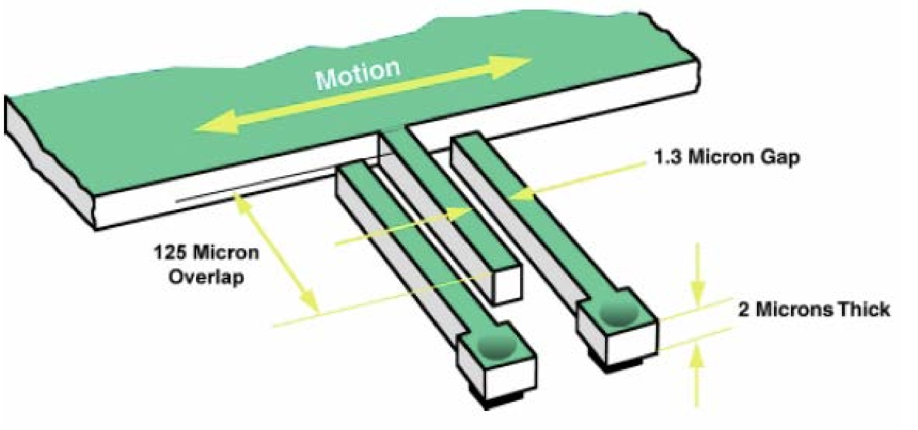
ADXL202 accelerometer
[Analog Devices website]

- www.analog.com

Microelectromechanical systems (MEMS)

Force on a mass *m* subject to acceleration *a*:

$$F = ma$$



Restoring force from the spring:

$$F = k \cdot \Delta x$$

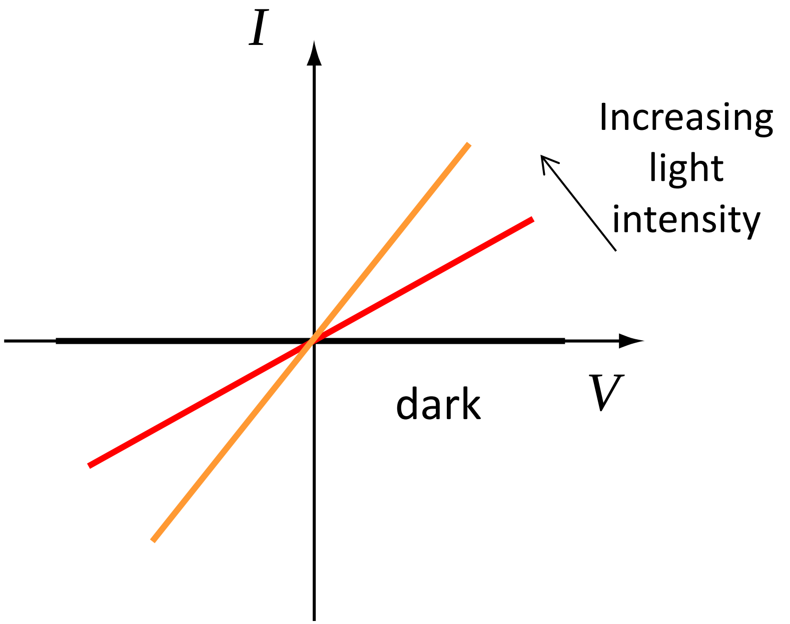
So the deflection is: $$\Delta x = \frac{m}{k} a$$

It is read out by measuring the electrical capacitace between the « fingers »

$$C = C\left(x\right)$$

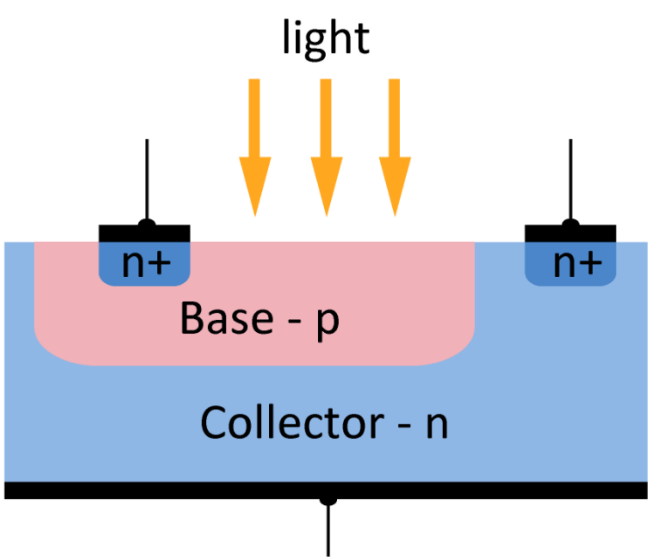
Light intensity measurements

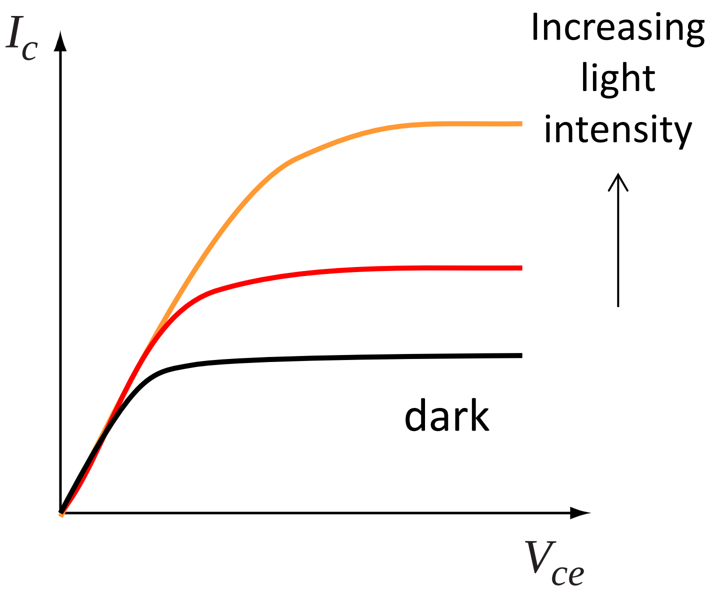
- Photoconductor
  - Highly resistive semiconductor (for example CdS)
  - Under illumination, electron-hole pairs are excited and the resistance decreases
  - Requires a voltage source to operate in a similar way to RTDs



Light intensity measurements

- Phototransistor
  - npn or pnp junction
  - Light absorbed in the base-collector junction generates electrons that are injected into the base and amplified by the transistor's current gain
  - Higher responsivity (A/W) but longer response time and higher dark currents than photodiodes

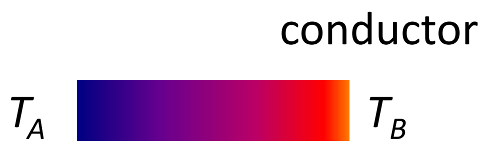




Active sensors

Temperature – Thermoelectric effect

- Seebeck effect – temperature difference results in a potential difference



$T_A < T_B \rightarrow$ e⁻ in B are more energetic than in A

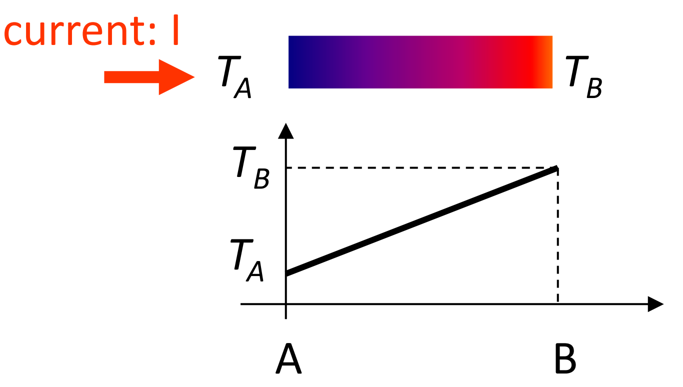
e⁻ move from B to A $\rightarrow$ more electrons in A

$\rightarrow$ $U_{AB} > 0$

- Thomson effect – heat transport due to electrical current

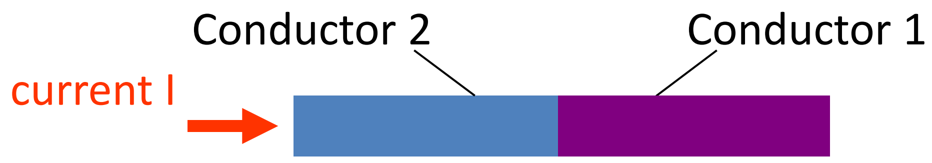
e⁻ move from B to A $\rightarrow$ energy loss $\rightarrow$ temperature increase in the middle of the conductor

e⁻ move from A to B $\rightarrow$ energy is absorbed $\rightarrow$ temperature decrease in the middle



Temperature – Thermoelectric effect

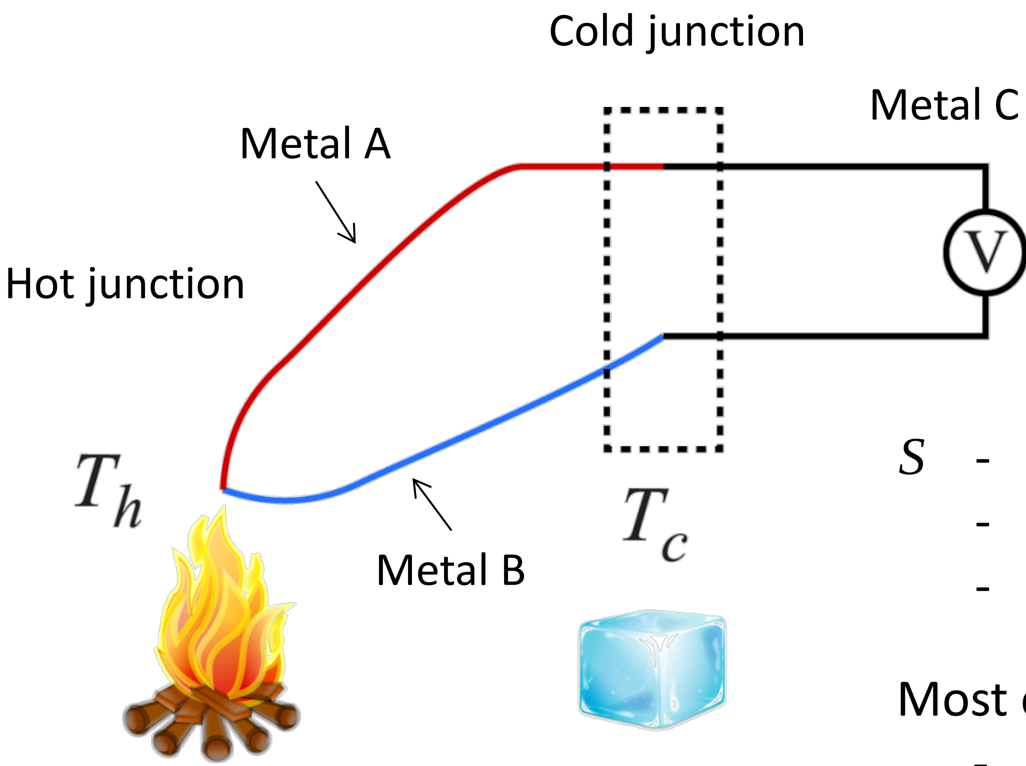
- Peltier effect



  - The energy of an electron depends on the temperature, work function (type of the conductor) and local electromagnetic field
  - By passing from 1 to 2, the energy of an electron is modified, resulting in heat being absorbed (cooling) or generated (heating)

- Thermoelectric effect - common name for these three effects
- Sensor: thermocouple
- Actuator: Peltier element

Thermocouple



$$V = S \cdot (T_h - T_c)$$

S - sensitivity
- characteristic of the AB metal pair
- typically 10-100 μV/K

Most common – type K:
- chromel (90% Ni, 10% Cr) / alumel (95% Ni, 2% Mn, 2% Al, 1% Si)
- S = 41μV/K at room temperature

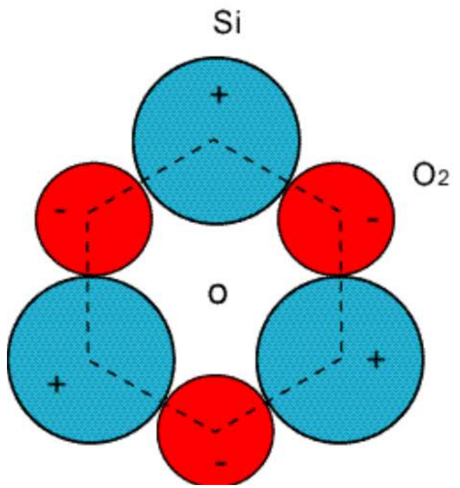
- Practical devices have built-in cold junction compensation

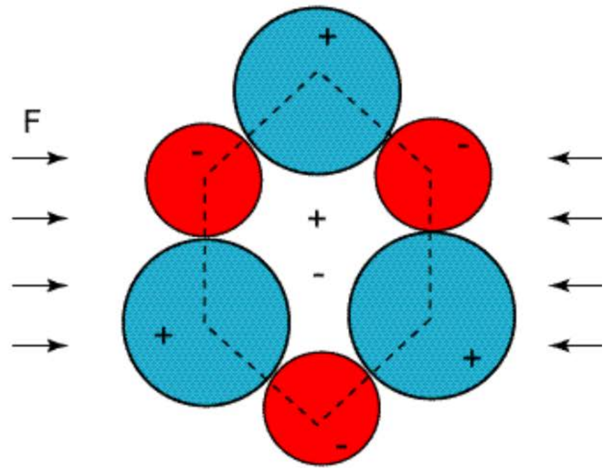
Thermocouples vs. RTD

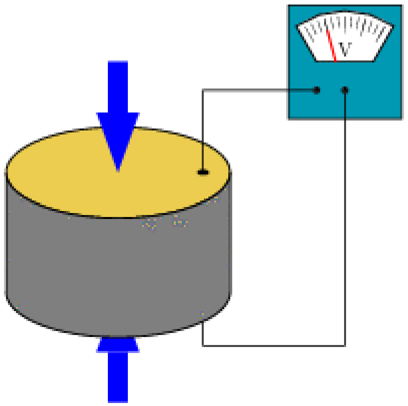
Characteristic	**Thermocouples**	**RTD**
Range	Up to 2300°C	Up to 500°C
Speed	Fast (<1 s)	Slow (>1 s)
Precision	Low (~1 °C)	High (<<1 °C)

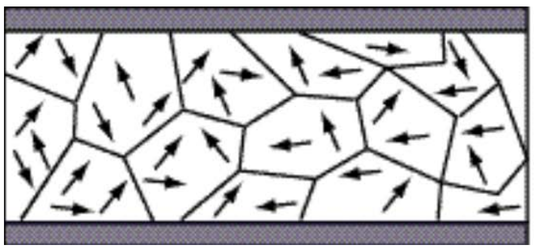
Displacement – Piezoelectric effect

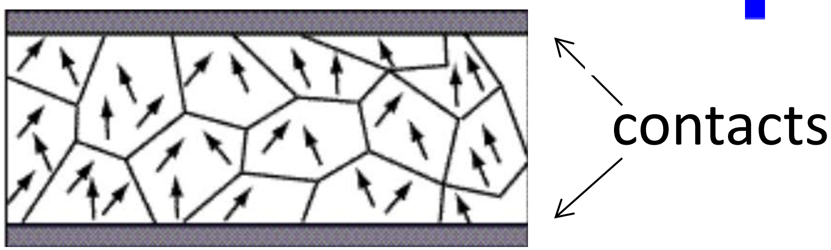
Occurs in materials with no inversion symmetry











Before polarisation

$q = d\sigma$ After polarisation

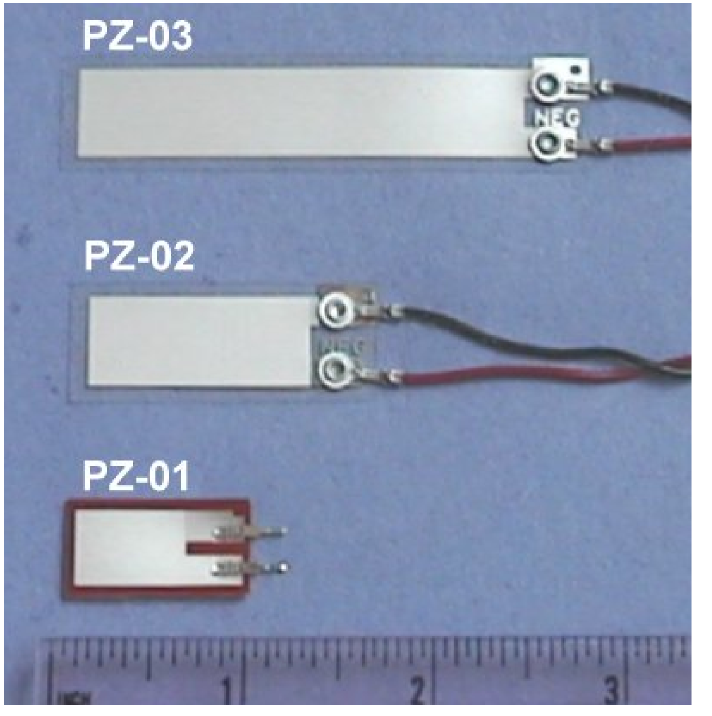
q – induced charge

d – piezoelectric coefficient

σ – mechanical stress

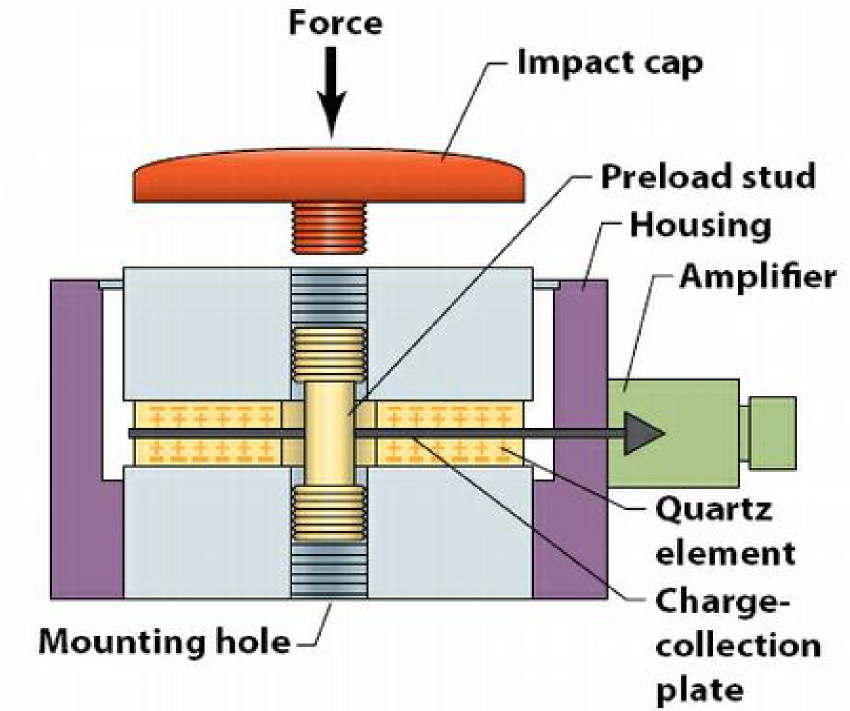
Displacement – Piezoelectric effect

- Sources of mechanical stress
  - Force, deformation, vibration, sound
- Materials
  - Quartz, ceramics (PZT), PVDF (Polyvinylidene fluoride)
- Applications
  - Force and pressure sensors
  - Accelerometers
  - Microphones

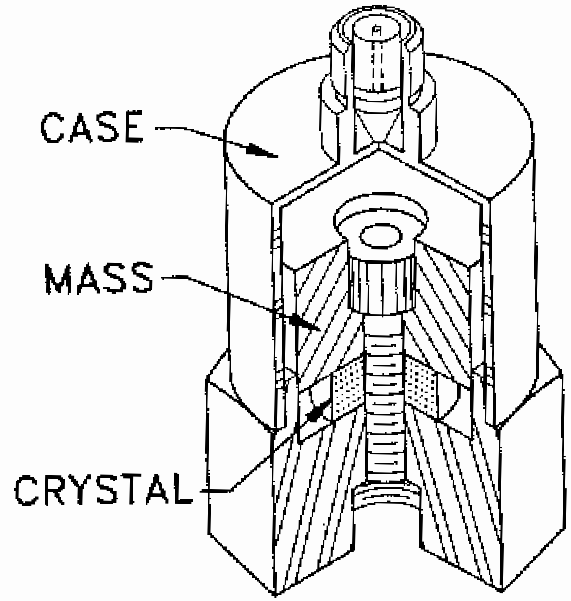


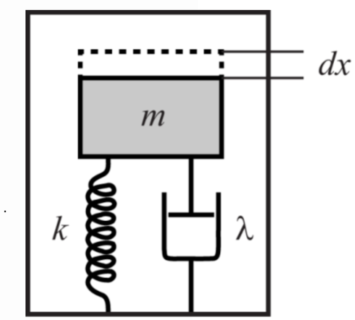
Displacement – Piezoelectric effect

Force sensor



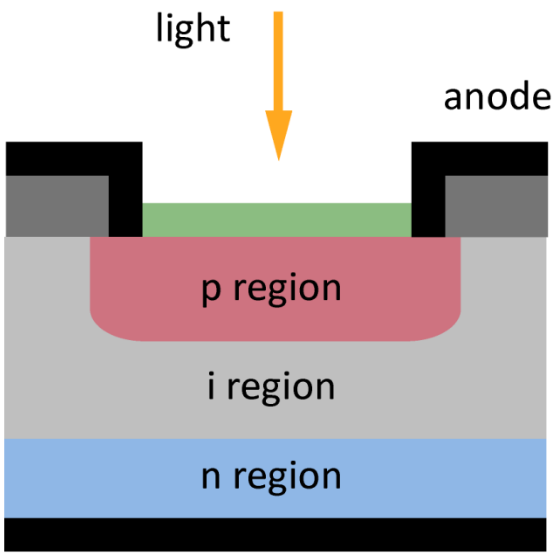
Accelerometer

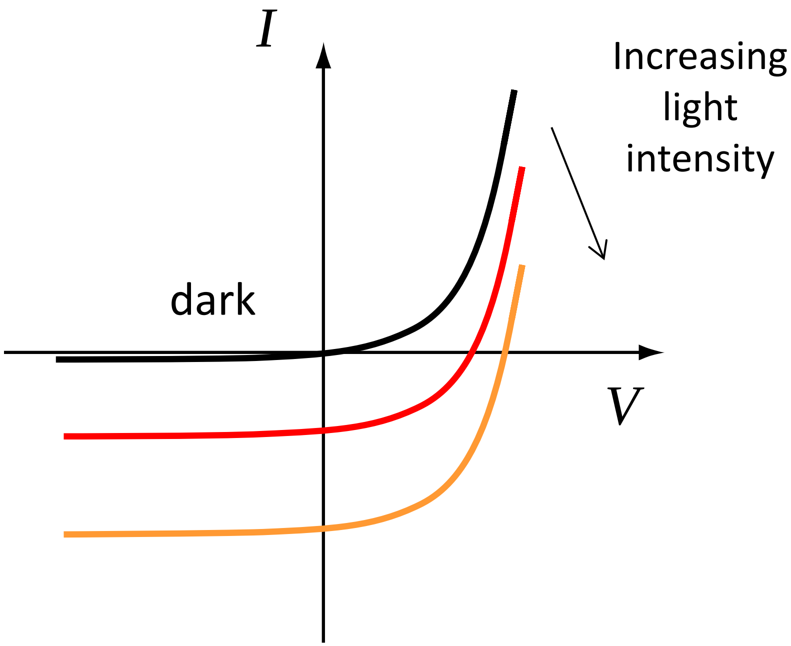




Light intensity measurements - Photodiode

- Light is absorbed in a pn junction
- Photoexcited charge carriers are separated in the internal electric field
- Voltage is generated
- Non-linear response





Key Points

- There is a large number of sensors and measurement principles
- Passive sensors - based on measurements of R, L, C; require a power supply
- Active sensors – directly use the measured quantity for generating the signal
- The signal is obtained with the use of a conditioning circuit
- When choosing an appropriate sensor, keep in mind the operating principle, the measurement range, possible sources of errors