Aalto-yliopisto
Sähkötekniikan korkeakoulu

ELEC-E5710 - Sensors and Measurement Methods

Teachers:

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Course contents

- Introduction to sensors and measurement methods
- SI-system and uncertainty in measurements
- Measurement of electrical signals and quantities
- Measuring non-electrical quantities and applicable sensors
  - Temperature and humidity
  - Light
  - Mass
  - Pressure and flow
  - Force and acceleration
  - Displacement

Schedule

- Lectures on Tuesdays 8:30 – 10:00 in Teams
  Exercises on Tuesdays 10:15 – 12:00 Teams
  ~~Two Excursions: Aalto Metrology and VTT Mikes~~

	Date	Lecture 8:30 - 10:00	Exercise 10:15 - 12:00
8:30-10:00	2.3.	Introduction to sensors	
8:30-10:00	9.3.	SI-system of units, Uncertainty in measurements	Exercise 1
8:30-12:00	16.3.	Electrical measurements: U, I, C, L, R, F	Exercise 2
8:30-10:00	23.3	Measuring low signal levels, noise	Exercise 3
8:30-12:00	30.3.	Temperature and humidity	Exercise 4
8:30-12:00	6.4.	Light	Excercise 5
No lecture	13.4.	-	-
8:30-10:00	20.4.	Pressure and Flow	Exercise 6
8:30-12:00	27.4.	Displacement, position, proximity, touch	Exercise 7
8:30-10:00	4.5	Mass, force, acceleration	Exercice 8
8:30-12:00	11.5.	Velocity, Distance	Exercise 9
9:00-12:00	18.5.	Spectroscopy	-
12:00-15:00	26.5	Exam	-

Homeworks

- By making 5 homeworks, you can replace assignments in the exam.
- Homework are not compulsory, but highly recommended.
- Each homework consists of 1-2 assignments.
- Return your solutions before the deadline in MyCourses (16.3., 30.3., 20.4., 4.5., and 18.5. at 10:00)
- Solutions for the homework will be reviewed in exercise sessions.

Grading

- Exam: 5 assignments, you will need ~50 % of maximum points to pass
  - Types of questions: explain briefly, operation principles of sensors, pros and cons or uncertainty sources of a certain measurement method, measurement methods or sensors for a certain quantity or situation, calculation exercises, derivation of measurement equation, …
- By making homework, you can replace assignments in the exam
  - 50 % of homework points → 1 assignment in exam
  - 80 % of homework points → 2 assignments in exam
  - If you do whole exam, 1 – 2 worst assignments will be replaced

Course material

- Slides and exercise solutions in MyCourses.
- Books:
  - J. Fraden, *Handbook of Modern Sensors - Physics, Designs and Applications (3rd Edition)*, 2004. http://www.kelm.ftn.uns.ac.rs/literatura/si/pdf/HandbookOfModernSensorsPhysicsDesignAndApplications.pdf
  - J. S. Wilson, *Sensor Technology Handbook*, 2005. http://www.kelm.ftn.uns.ac.rs/literatura/si/pdf/Sensor%20Technology%20Handbook.pdf
  - Keithley, *Low Level Measurements Handbook – 7th Edition.* *https://www.tek.com/document/handbook/low-level-measurements-handbook*
- Books used selectively.

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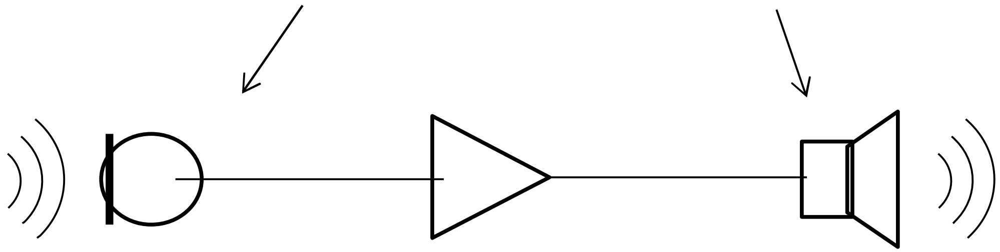
Introduction to sensors

ELEC-E5710 Sensors and Measurement Methods

J. Fraden, *Handbook of Modern Sensors,* Chapters 1, 2
J. S. Wilson, *Sensor Technology Handbook,* Chapter 1

Terminology

- **Sensor** is a device that receives a measurand /stimulus and responds with an electrical signal.
- **Transducer** is a device that transmits energy from one system to another in same or different format.
  - Transducers can be both sensors and actuators.



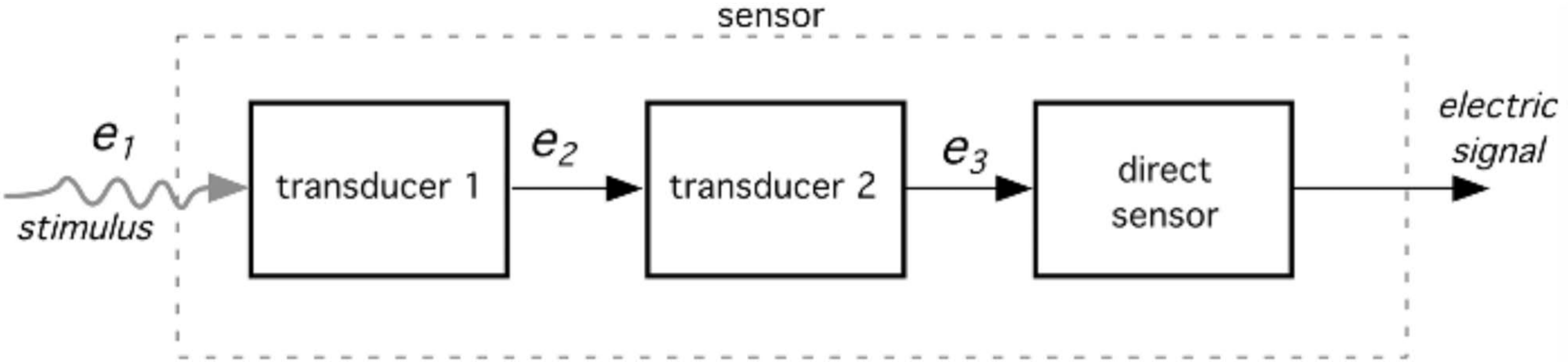
- **Actuator** (opposite to a sensor) converts electrical signal into generally nonelectrical energy.

Transformation of signal / energy

In \ *Out*	**Radiation**	**Mechanical**	**Thermal**	**Electrical**	**Magnetic**	**Chemical**
Radiation	Photo-luminescence	Radiation pressure	Absorption of radiation	Photoelectric effect	Photomagnetism	Photosynthesis
Mechanical	Piezo-luminescence	Preservation of momentum	Warming due to friction	Piezoelectric effect	Villari effect	Pressure induced explosion
Thermal	Glowing	(Thermal) expansion	Thermal conductivity	Seebeck effect	Curie-Weiss effect	Endothermic processes
Electrical	Electrical luminescence	Piezoelectric effect	Peltier effect	Semiconductors	Ampère’s law	Electrolysis
Magnetic	Faraday effect	Magnetostrictive	Ettinghausen effect	Hall effect		
Chemical	Chemical luminescence	Explosion	Exothermical processes	Volta effect		Chemical reaction

Sensor classification

- Direct sensor converts a stimulus into an electrical signal or modifies an electrical signal
- Complex sensor needs one or more transducers of energy before a direct sensor can be employed to generate an electrical output.



- Also Passive vs. Active (needs electricity)
- Absolute vs. Relative

A perfect sensor

- Sensitive for the measurand, Insensitive for other effects
- Does not affect the measured quantity or target.
- Sensitivity is linear and signal has no offset.
  - Can be compensated with calibration and electronics

Transfer function of a sensor

- The dependence of sensor signal S on the stimulus s.
  - Linear $S = a + bs$
  - Logarithmic $S = a + b \ln(s)$
  - Exponential $S = a\, e^{ks}$
  - Power function $S = a_0 + a_1 s^k$

- More complicated transfer functions can be modelled with a higher order polynomial function.

Sensor characteristics

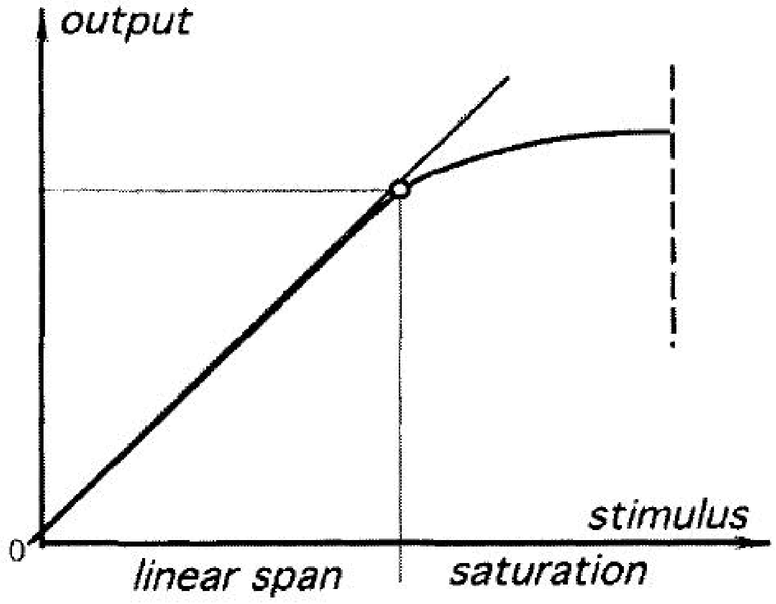
- Sensitivity
- Span / Dynamic range
- Accuracy / Uncertainty / Precision
- Resolution
- Linearity / Nonlinearity
- Hysteresis
- Noise
- Dynamic properties

Sensitivity

- Sensitivity is the derivative of the transfer function

$$b = S'(s)$$

- Also called Responsivity
- With linear detector, sensitivity is constant
- Not to be confused with that the sensor would be likely to break
- High sensitivity not always preferred



Span / Dynamic range

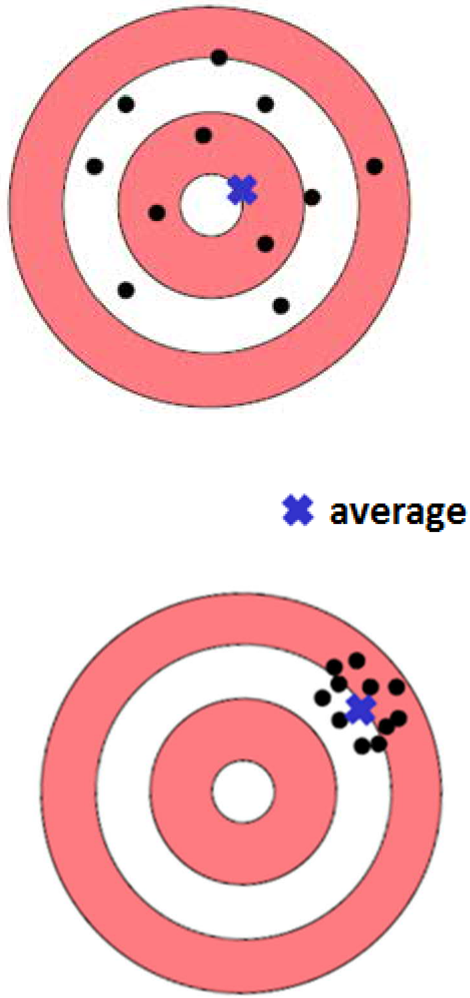
- Span is the range of stimuli which may be converted by a sensor (also known as Range, or Full scale)
- For example, an acceleration sensor may have a span of ±2g
- Dynamic range is the ratio of highest measurable stimulus to the lowest measurable stimulus, often given in decibels:

$$DR = 10 \log P_{max} / P_{min} = 20 \log S_{max} / S_{min}$$

- To think: Measurement range of a Voltmeter is given as 0 – 1000 V. Is this *span* or *dynamic range*?

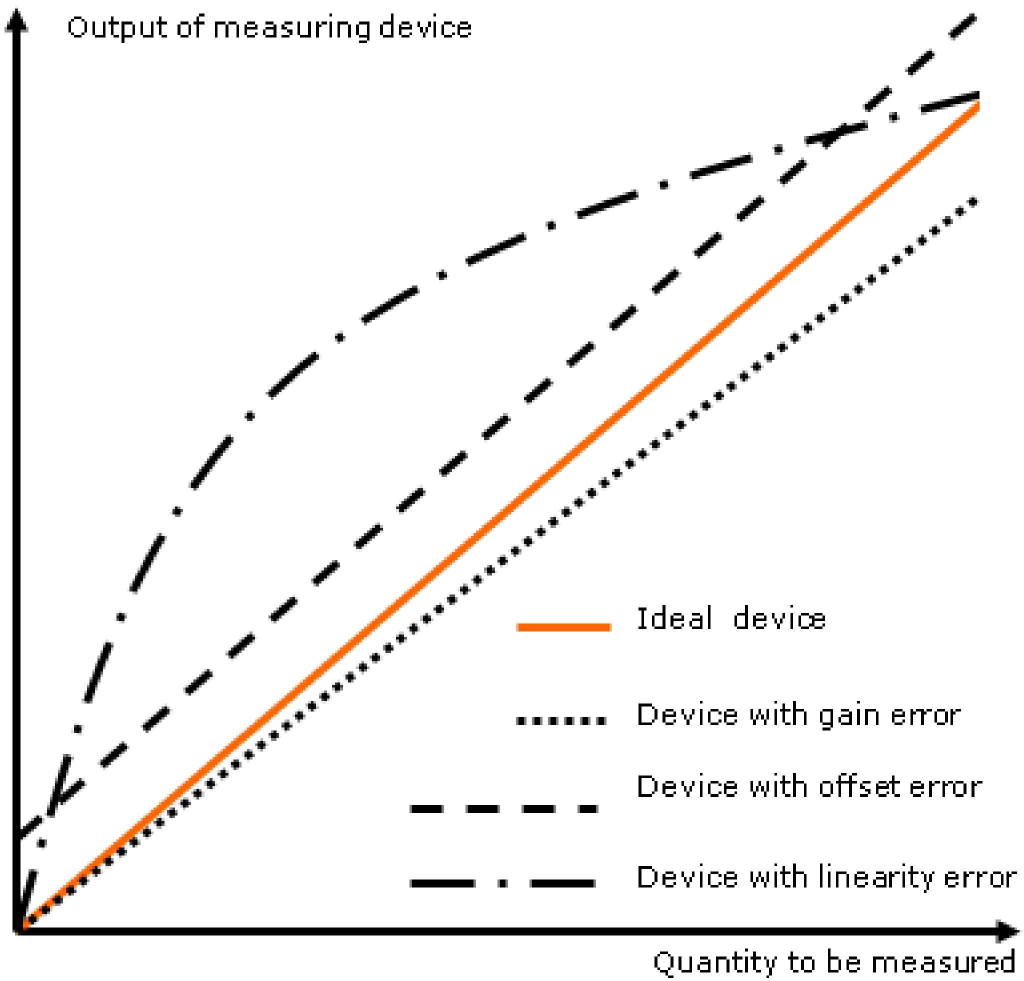
What does an accuracy mean?

- **Accuracy** is the agreement between the result of a measurement and the true value being measured.
  - Improves by calibrating
- **Precision** (Repeatability) is the ability of the sensor to output the same value for the same input over a number of trials.
  - Improves by averaging
- Often misunderstood! Also Resolution, the lowest measurable stimulus, is sometimes called accuracy

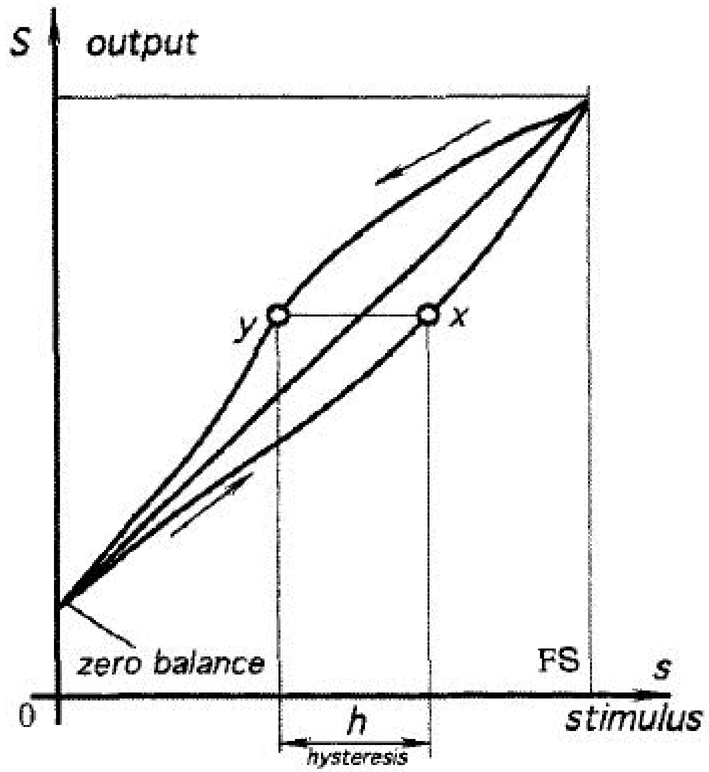


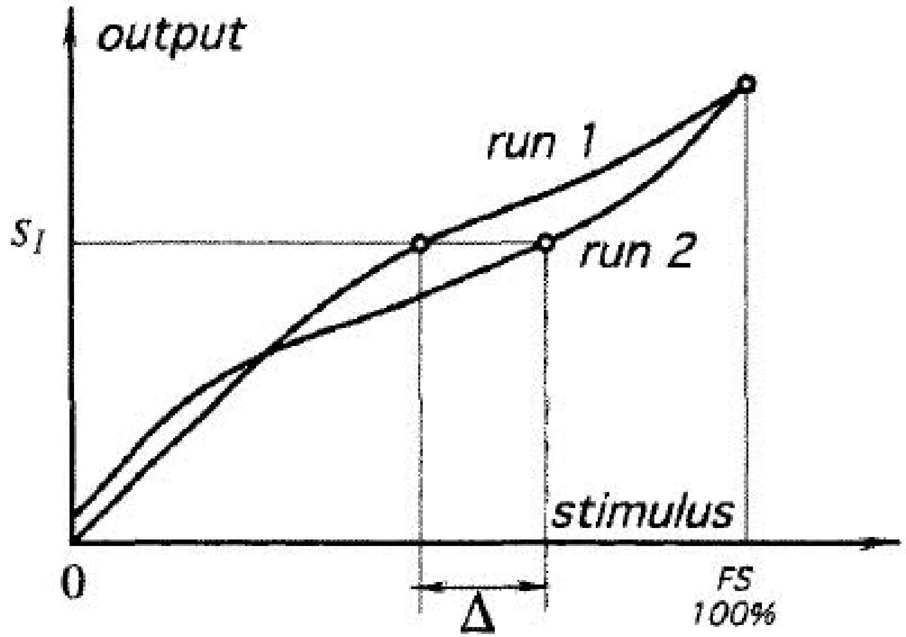
Error factors

- Non-linearity
- Offset
- Gain error
- Drift
- Can be corrected for with Calibration



Hysteresis and repeatability





Dynamic properties of sensors

- Sensitivity of a sensor with a variable stimulus
  - It takes some time for a temperature sensor to reach the target temperature -> time constants
  - Inductances, masses, thermal and electrical capacitances etc.
  - Dynamic response restricts frequency band.

Zeroth order sensors

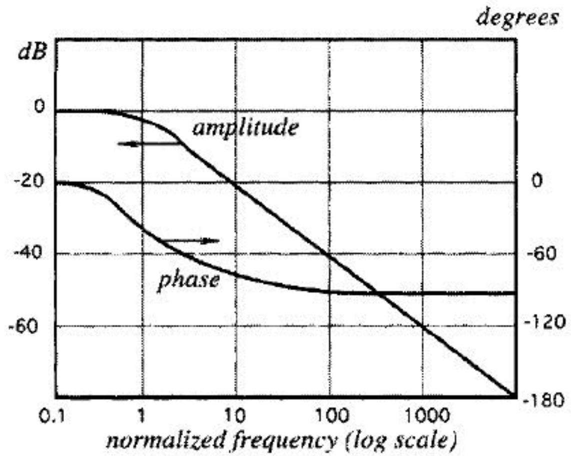
$$S(t) = a + bs(t)$$

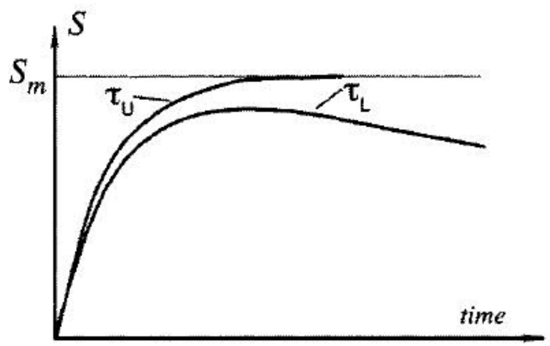
- *S*(*t*) is a sensor signal, *s*(*t*) is stimulus, *b* is static (linear) sensitivity, *a* is offset.
- Sensor has neither capacitance nor mass.
- The sensitivity of sensor follows stimulus without delay.
- E.g. potentiometric transitional sensor.

First order sensors

$$b_1 S'(t) + b_0 S(t) = s(t)$$

- Includes a single component storing energy.
- Temperature sensor is a first order sensor (temperature capacity).
- Step response: $S = S_m(1 - e^{-1/\tau})$.
- τ is time constant (dynamic response), S_m is static response.

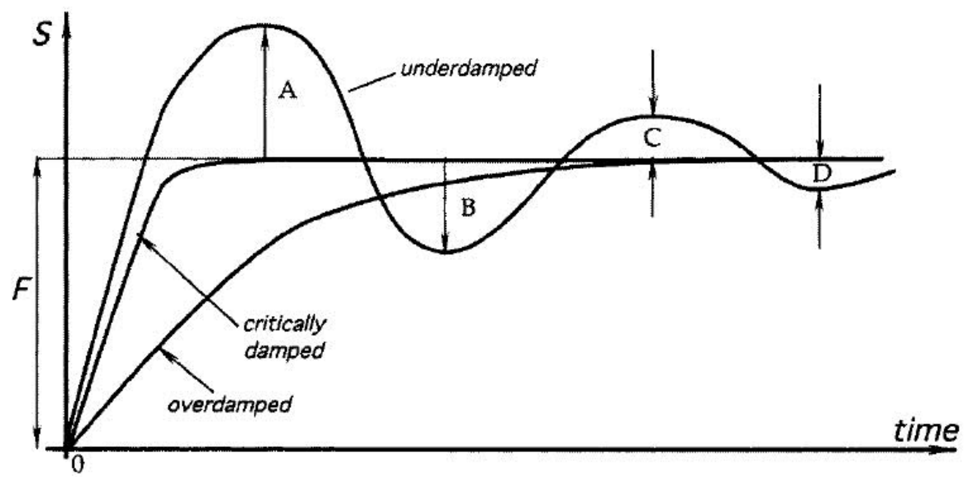




Second order sensors

$$b_2 S''(t) + b_1 S'(t) + b_0 S(t) = s(t)$$

- Include two components storing energy
- Acceleration sensor is a second order sensor (mass and spring)
- Characterized at resonance frequency (natural frequency)



The effect of environmental factors

- Storage and operation conditions are often specified
  - Effect especially on long term stability
- Transfer function varies due to environmental factors
- The most important factor is temperature
  - Does not only affect temperature measuring but also nearly everything
- Relative humidity
- EM-fields
- Varying these factors *during measurements* causes inaccuracies

Classification of sensors

- By the measured phenomenon
  - E.g. temperature, pressure, flow, etc.

- By the operation mechanism
  - E.g. resistive, capacitive, MEMS (micro-electro-mechanical system), electricity generating

Resistive sensors

Operating principles:

- Ohm’s Law
- Light resistive effect
- Piezoresistive effect
- Thermal resistive effect of metals and semiconductors
- Bioelectrical impedance

Resistive sensors

- Resistance depends on resistivity ρ [Ωm] and geometry of a wire (cross-sectional area *A* and length l):

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

- Resistivity depends on the electric field strength E [V/m] and current density j [A/m^2]:

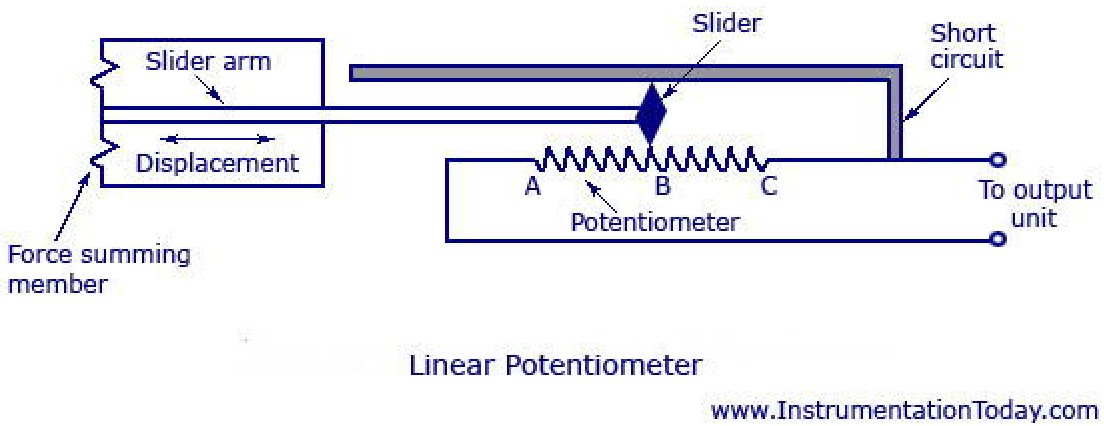
$$\rho = \frac{E}{j}$$

- Resistivity of metals depends nearly linearly on temperature:

$$\rho = \rho_0[1 + \alpha(t - t_0)]$$

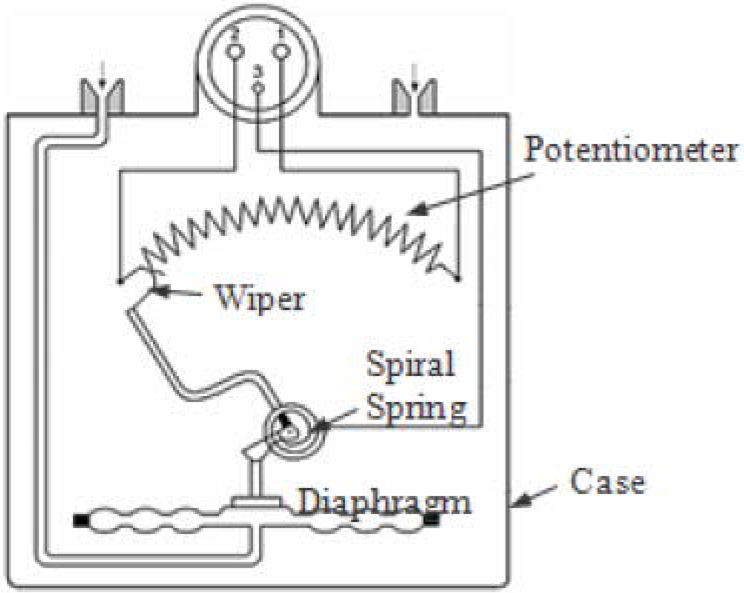
Potentiometric sensors (Ohm's law)

- Mounted potentiometer has a moving contact
- The contact of the potentiometer is either sliding or rotatable
  - Linear or angular position sensor

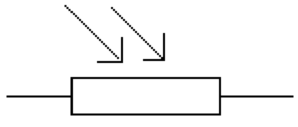


Potentiometric pressure sensor

- Pressured fluid/gas changes the foil when the lever moves and thus changes the resistance.



Light resistive sensors

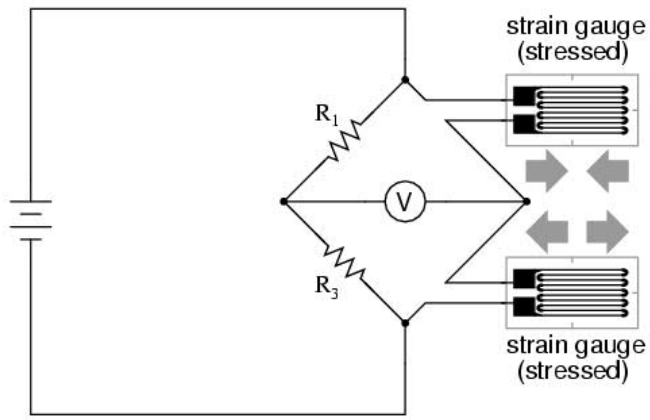


- The resistance of a photoresistor decreases when the amount of light increases.
- Photoresistor can be called LDR (light dependent resistor), photoconductor, or photo cell
  - It is made of semiconductor with high resistance
  - Photon absorbed by a semiconductor generates an electron which has enough energy to jump to conduction band. Generated free electron conducts electricity and thus decreases resistance.
  - CdS is the most sensitive to visible light. PbSe is the most effective to near infrared light.

Piezoresistive sensors

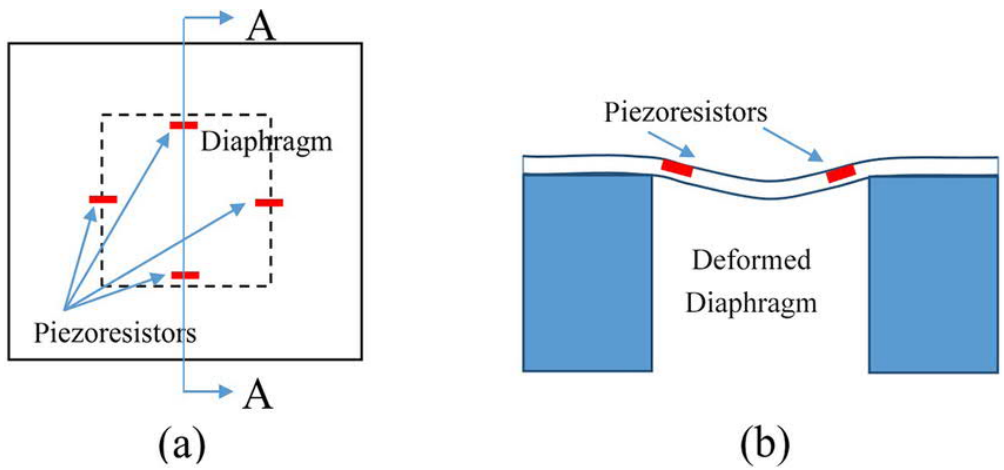
- The resistance of a material changes in consequence of mechanical strain.
- Resistance of conductor: $R = \rho \frac{l}{A}$
- Resistance changes because geometry (metal strain gauge) or resistivity (semiconductor strain gauge) changes.

Half-bridge strain gauge circuit



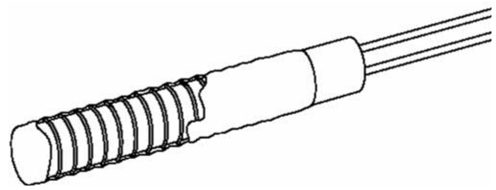
Piezoresistive sensors

- Are used in e.g. force, pressure, acceleration, and oscillation sensors.
- Good frequency response.
- Sensitive to temperature changes and mechanical interferences

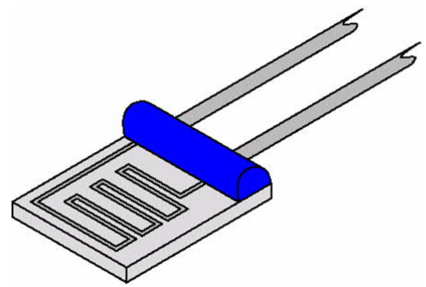


Thermal resistive sensors

- Metal resistance temperature detector (RTD)



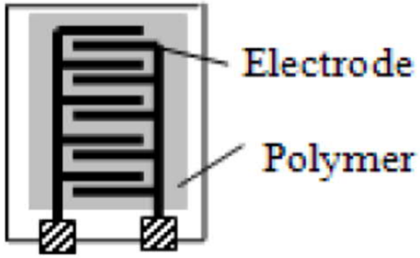
- Wire-wound resistor: a very thin wire spun around a substrate.
- Thin-film resistor: thin metal foil overlaid on a substrate using thin-film lithography.



- The most common metals: platinum, copper, nickel.
- Resistance has rather linear temperature dependency.

Resistive humidity sensors (humistor)

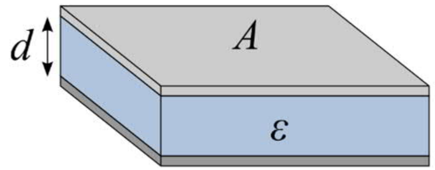
- Measure changes in resistance of a hygroscopic material
  - Heavily dependent of the concentration of absorbed water molecules.
  - Usually an exponential dependence to humidity.



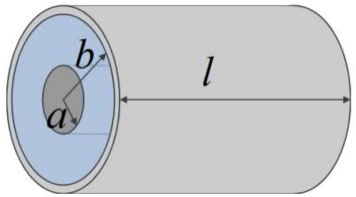
- Usually includes a substrate and two silk screen printed conducting electrodes

Capacitive measurements

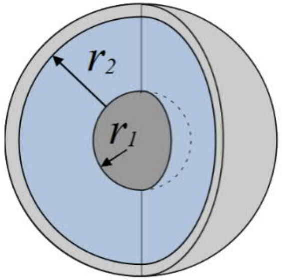
- Based on the change of capacitance when a specific condition changes.



- Capacitance: $C = \varepsilon_r \varepsilon_0 G$
  - where ε_r is the relative static permittivity of the material, ε_0 is the electric constant, and *G* the geometry factor.

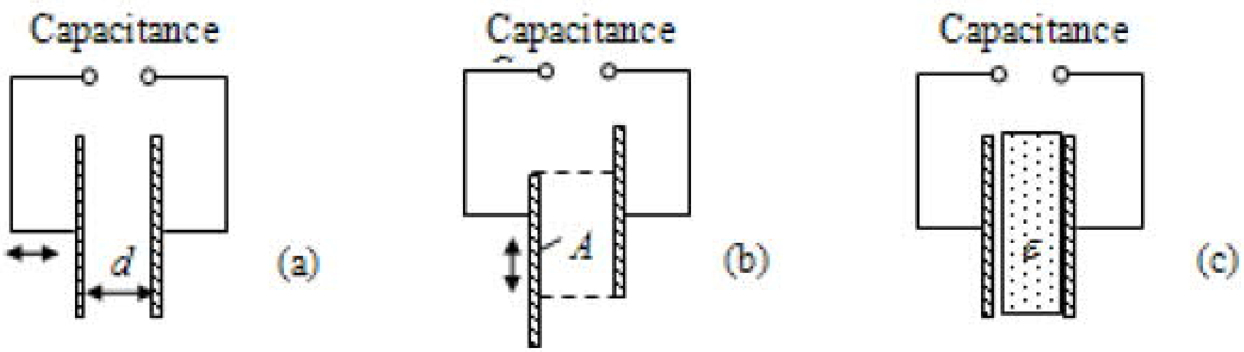


- *G* is dictated by the shape of the capacitor:
  - Plate capacitor: $G = A/d$
  - Cylinder capacitor: $G = 2\pi l/[\ln\left(\frac{b}{a}\right)]$
  - Spherical capacitor: $G = 4\pi r_1 r_2/(r_2 - r_1)$

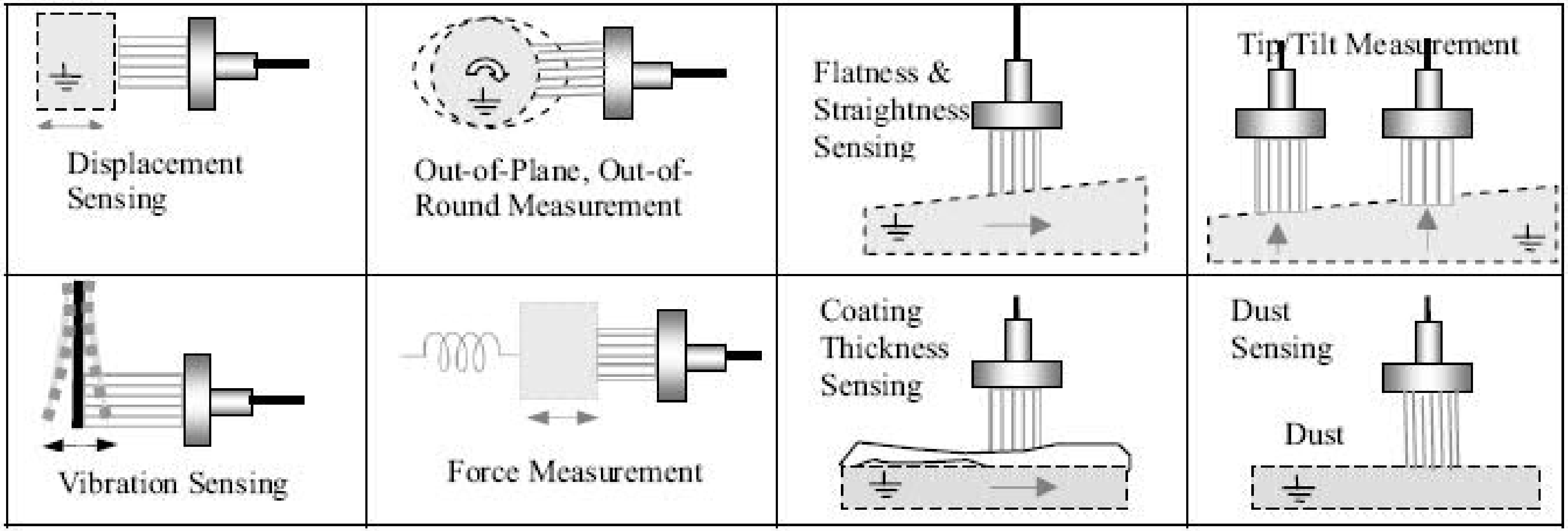


Capacitive way of measuring

- Can be used to recognise movement and to measure pressure, power and acceleration.
- The capacitance of a sensor changes when the distance (a), area (b), or permittivity (c) of two plates changes.

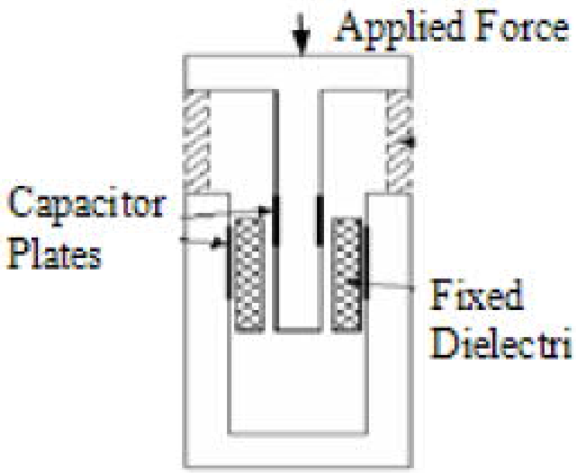


Applications of plate capacitor sensors



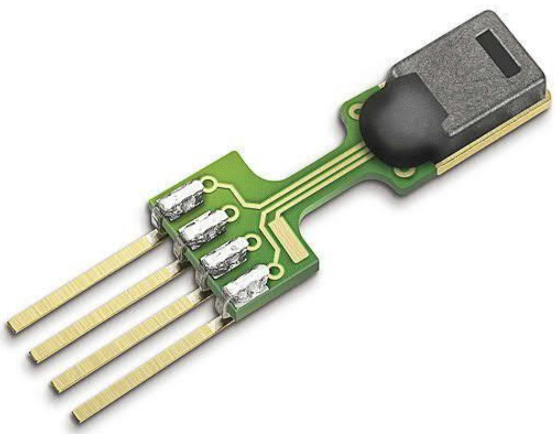
Coaxial capacitive sensor

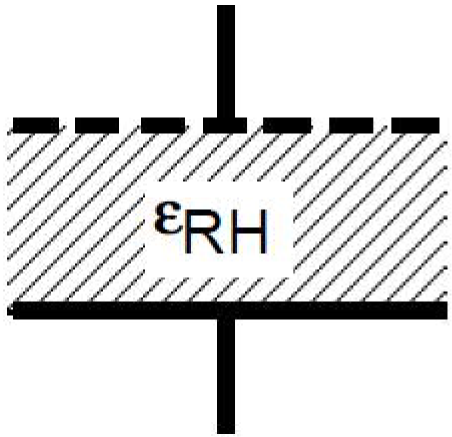
- Power sensor.
- A polymer used as a good insulator (e.g. polyvinylidene fluoride)
  - High capacitance.
- The capacitance of both capacitors change because of the movement of another electrode.
- Coaxial geometry allows better sensitivity than equivalent plate capacitor would.



Capacitive humidity sensor

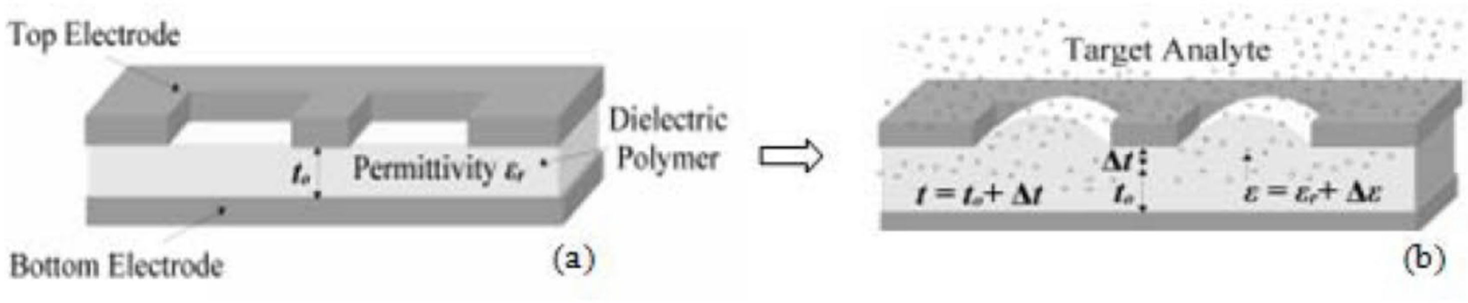
- Polymer between two electrodes.
- Permittivity depends on humidity.





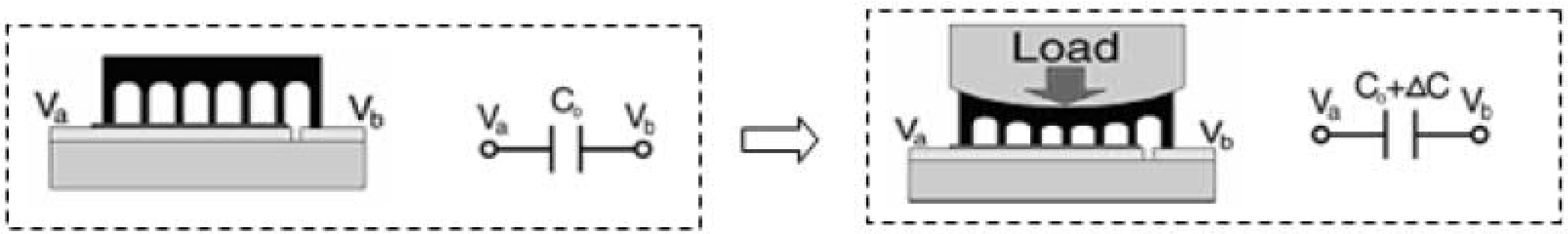
Chemical capacitive sensor

- A chemically sensitive polymer between two electrodes
- Polymer absorbs special chemical and then consequently expands. This increases the distance and permittivity between the electrodes => capacitance changes



Shrinking capacitive sensor

- Sensor has flexible, conducting elastomer as electrodes instead of ordinary hard metals.
- An electrode with large area and short distance => higher capacitance.
- Load bends elastomer and thus changes the geometry and capacitance

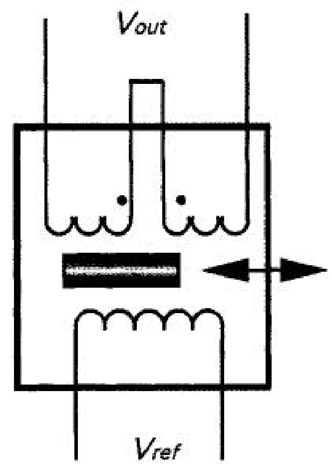


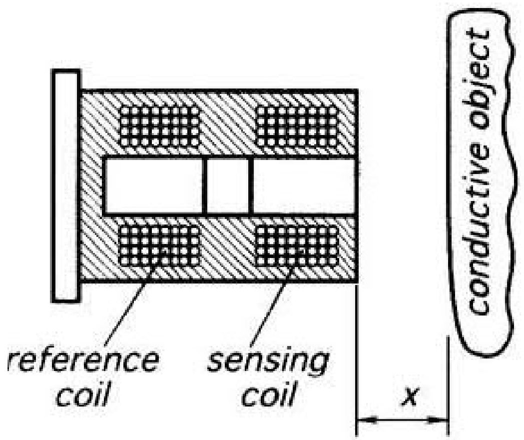
Piezoelectric effect

- Mechanical stress causes electric polarization and also other way round: electric field causes mechanical stress.
- Mechanic or acoustic signals can be transformed into electric ones.
- Power, acceleration, and pressure sensors, microphones etc…

Electromagnetic induction

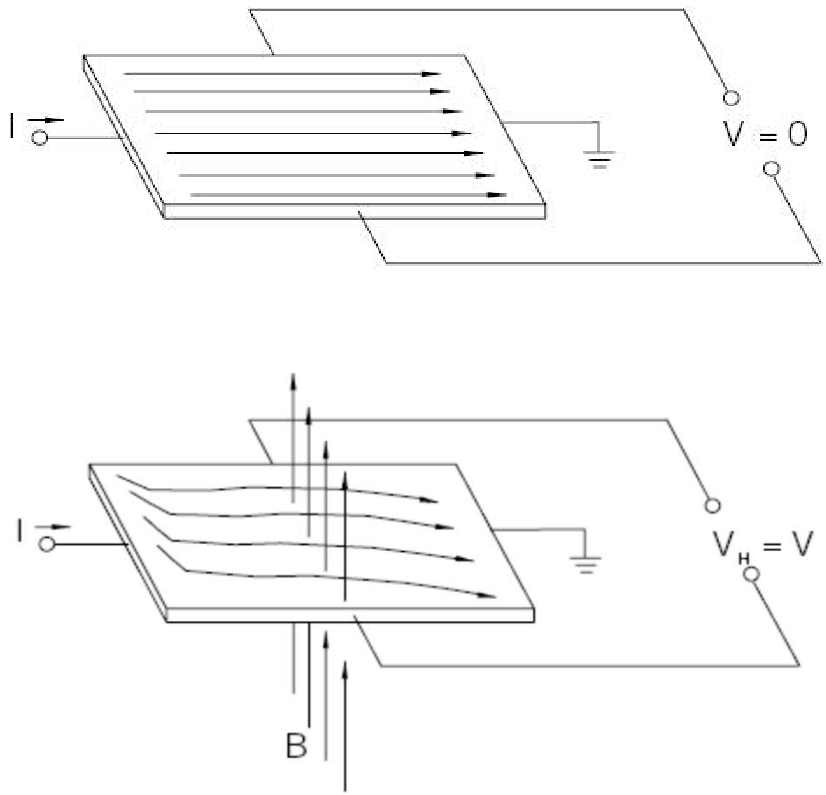
- Transitional sensors
  - Linear Variable Differential Transformer (LVDT)
- Distance sensors





Hall sensors

- Current flow in a thin semiconducting plate.
- Direction of the current changes when the plate is placed into a perpendicular magnetic field.
- Lorentz's force determines the direction of electrons



$$V_H \propto \mathbf{I} \times \mathbf{B}$$

Electrochemical ways of measuring

- Resistive chemical sensors measure the change in conductivity when the active part of the sensor interacts with a chemical
  - Semiconductors (metal oxides, conducting polymers).
  - Tin oxide resistor to detect gas.
  - Reducible gas decreases the resistance of the sensor and oxidizable gas increases it.