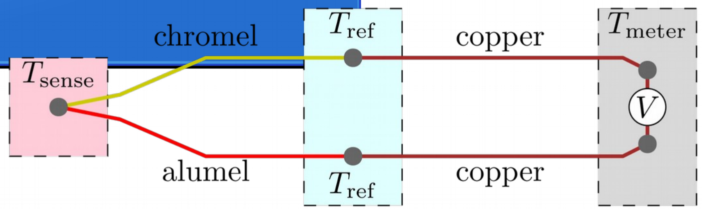
Jacobs University Bremen

Sensors 3

Thermocouple
Capacitive sensing
Accelerometer

Automation
CO23-320203

Thermocouple (and thermopile)



- Another sensor and an actuator in on (=transducer)! This time: from temperature to voltage
- Again, physical chemistry of the metals is responsible for the effect, or actually three effects:

Seebeck effect: generation of electrical potential by temperature difference

$$\mathbf{E}_{\mathrm{emf}} = -S\nabla T,$$

where: E_{emf} – local electromotive force (think of it as a voltage!) [V], S – Seebeck coef., T – temperature [K]

Peltier effect: heating/cooling by current flowing between dissimilar metals

$$\dot{Q} = (\Pi_{\mathrm{A}} - \Pi_{\mathrm{B}})I,$$

where: Q_f – heat [J], ∏ – Peltier coeficients for both metals, I – current [A]

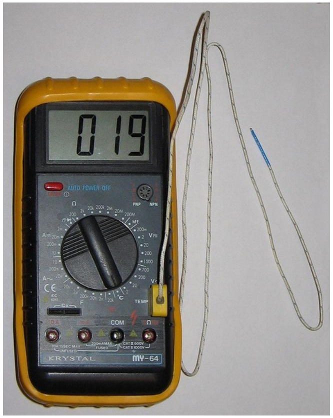
Thomson effect: combination of the two above in some special conditions

$$\dot{q} = -\mathcal{K}\mathbf{J} \cdot \nabla T,$$

where: q – heat [J] per unit volume, *K* – Thomson coeficient, J – current density [A/mm^2]

Thermocouple (and thermopile)

Not really a part of the thermocouple effect, but cannot be excluded of the picture: **Joule heating,** i.e. heating of the conductor due to the flowing electricity:



$$P \propto I^2 R$$

(it affects all wires, not only junctions)

Total:

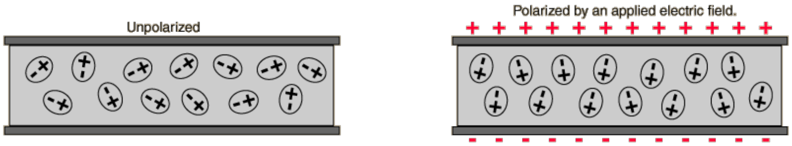
$$-\dot{q}_{\text{ext}} = \nabla \cdot (\kappa \nabla T) + \mathbf{J} \cdot \left(\sigma^{-1} \mathbf{J}\right) - T\mathbf{J} \cdot \nabla S.$$

Bonus: The coefficients are interconnected!

$$\mathcal{K} = T \frac{dS}{dT} \qquad \Pi = TS.$$

Capacitive sensing

- A capacitor can be a sensor, and not an actuator. It can be very useful nevertheless.
- The capacitor: two conductors separated by a non-conductive space (void or isolator)



- Mobile charges carriers (here: electrons) move to find an equilibrium of attraction and repulsion due to Coulomb force:

$$F = k_e \frac{q_1 q_2}{r^2}$$

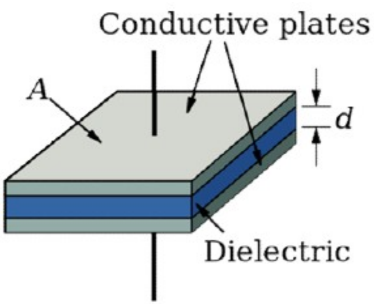
- where k_e - Coulomb's constant [k_e ≈ 9×109 Nm^2/C^2], q_1 and q_2 - signed magnitudes of the charges [C] and r - distance between the charges [m]

(visual recap how a capacitor works: https://www.youtube.com/watch?v=f_MZNsEqyQw)

Capacitive sensing

- Capacitance of a capacitor:

$$C = \epsilon \frac{A}{d} = \frac{Q}{V}$$

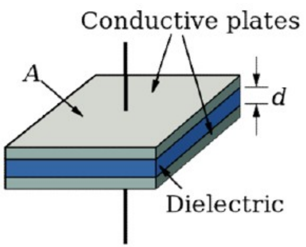


where: C - capacitance [F], ε – permittivity of the dielectric, A – area of the plates [m2], d – distance between them [m], Q – electrical charge [C], V – applied voltage [V]

$$\varepsilon = \kappa\, \varepsilon_0$$

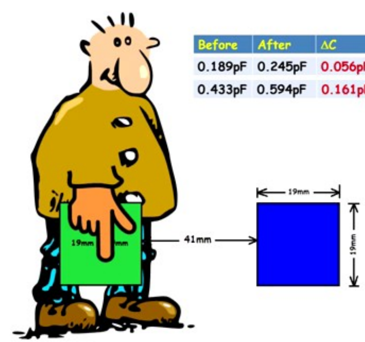
where: κ – medium's relative permittivity, ε_0 – permittivity of vacuum [8.85×10^{-12} F/m]

Capacitive sensing



- The capacitance $C = \epsilon \frac{A}{d}$ depends on several factors
  - we can potentially measure all of them if we can estimate the capacitance at instant *t*!
- Here is the basic intuition, which works well for turning our capactor into a presence sensor (or even… a button): https://www.youtube.com/watch?v=QItuf6lNvmI
- But how can we really quantify capacitance?

Before	After	ΔC	% change
0.189pF	0.245pF	0.056pF	30%
0.433pF	0.594pF	0.161pF	37%



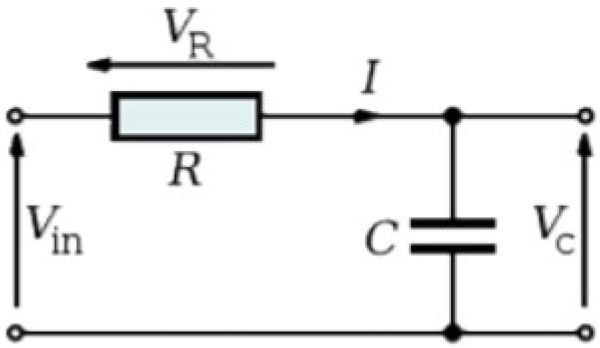
Capacitive sensing

- We need to employ some dynamics!
- A practical circuit to charge a capacitor:

$$\frac{V_c(s)}{V_{in}(s)} = \frac{1}{1 + RCs}$$

$$V_c(t) = V_{in}(t)(1 - e^{-t/\tau})$$

$$\tau = RC$$



- A good practical summary in a practical circuit: https://www.youtube.com/watch?v=bhspPkxOMxs

Example: capacitive digitiser

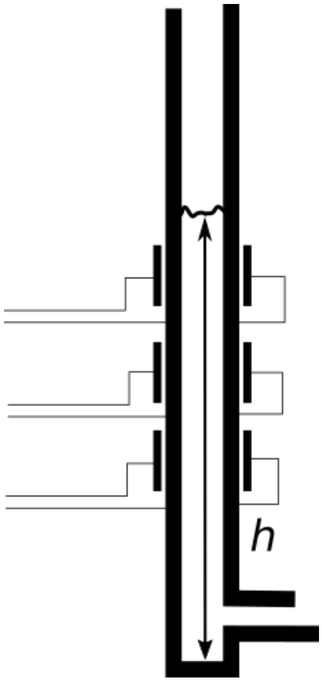
- Would you say you have it at your arm's length?

Capacitive sensing – ε modification

- Liquid level detection example revisited

Capacitive sensing – ε modification

- Liquid level detection example revisited



Capacitive sensing in an accelerometer

- Accelerometer measures acceleration – any acceleration, to be precise:
  - Acceleration due to accelerated motion
  - Acceleration due to gravity

  (and there is no way to distinguish the two!)
- Why? Because of how we measure acceleration: measure the (resultant) force acting on a body.
- Specifically, we use Newton’s laws. Here is the second law:

$$F = m\,a$$

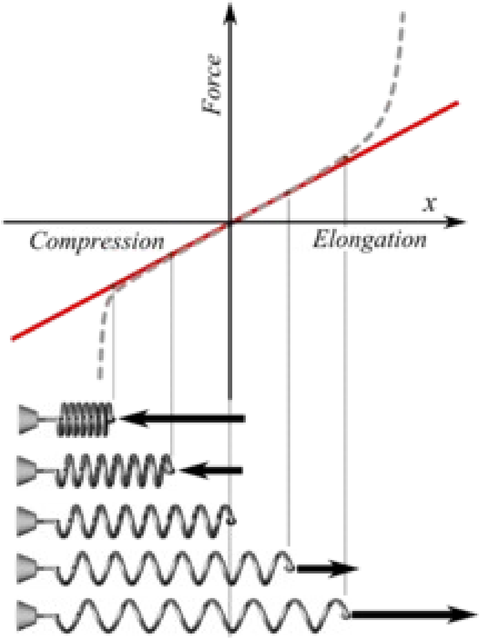
where: F – force applied to body [N], m – body mass [kg] and a – acceleration [m/s^2]

Capacitive sensing in an accelerometer

- One way to measure force is indirectly, through Hooke's law governing springs:

$$F_s = -k\,x$$

where: F_s – restoring force acting on the spring [N], k – spring constant [N/m] and x – position [m]

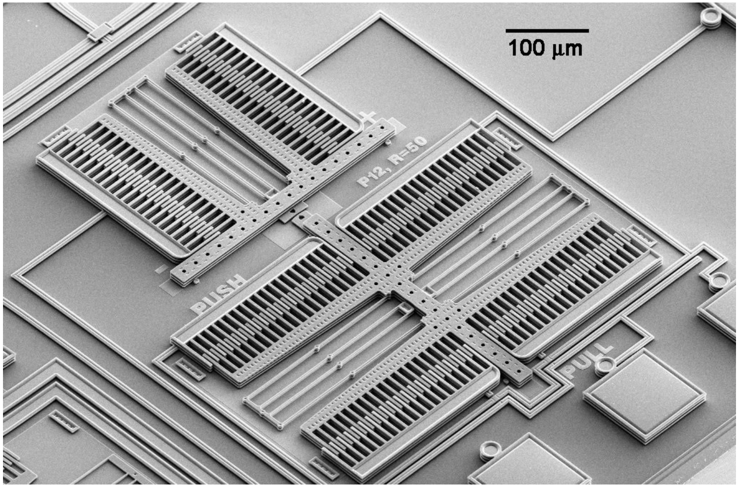


- It's an approximate law – it covers the zone where the material stays within its elastic limit (not even fully)

Capacitive sensing in an accelerometer

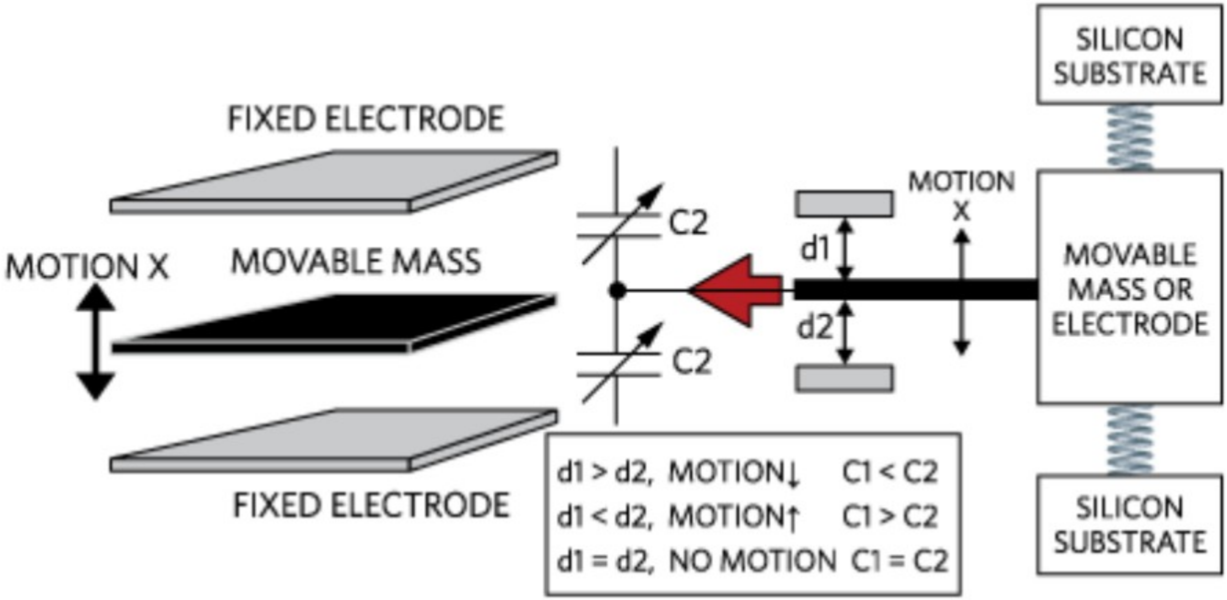
The simplest idea? (blackboard sketch)

- From a naïve device to a serious technology, let's just change the scale!
- MEMS (= Microelectromechanical systems) are made up of components between 1 and 100 micrometers in size
- We are used to manufacture circuits using silicon chip production methods – and that is exactly how MEMS came to life:



Capacitive sensing in an accelerometer

- Let's put everything together:



Capacitive sensing in an accelerometer

- How to improve the sensitivity and produce the signal?