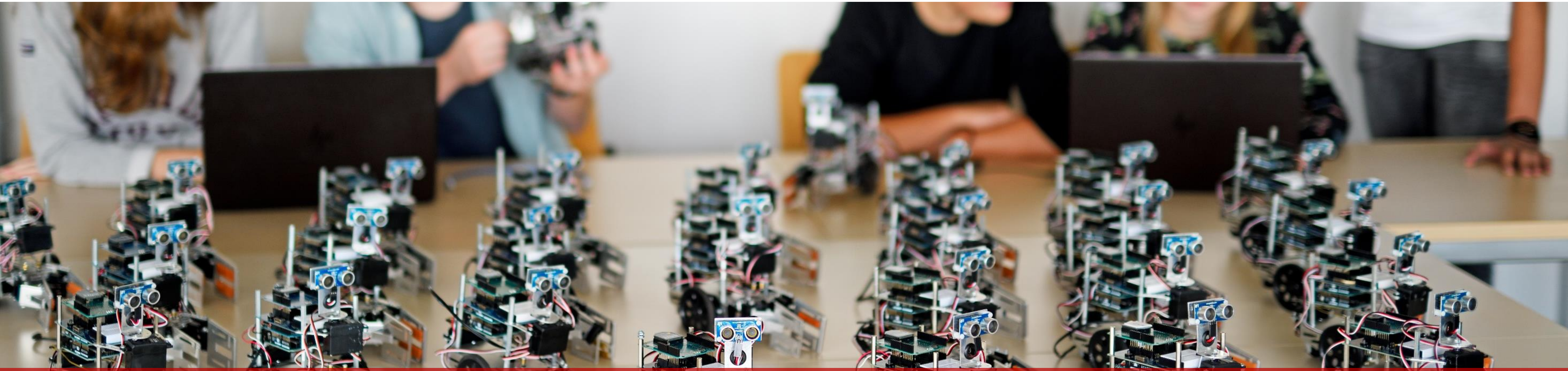


Sensing, Computing, Actuating

Sander Stuijk (s.stuijk@tue.nl)

ACOUSTIC SENSORS AND ACTUATORS

(Chapter 5.7)

Animal senses

bats

ultrasound (mechanical)

shark

electrical field

snake

thermal radiation

rats

touch (mechanical)

fish

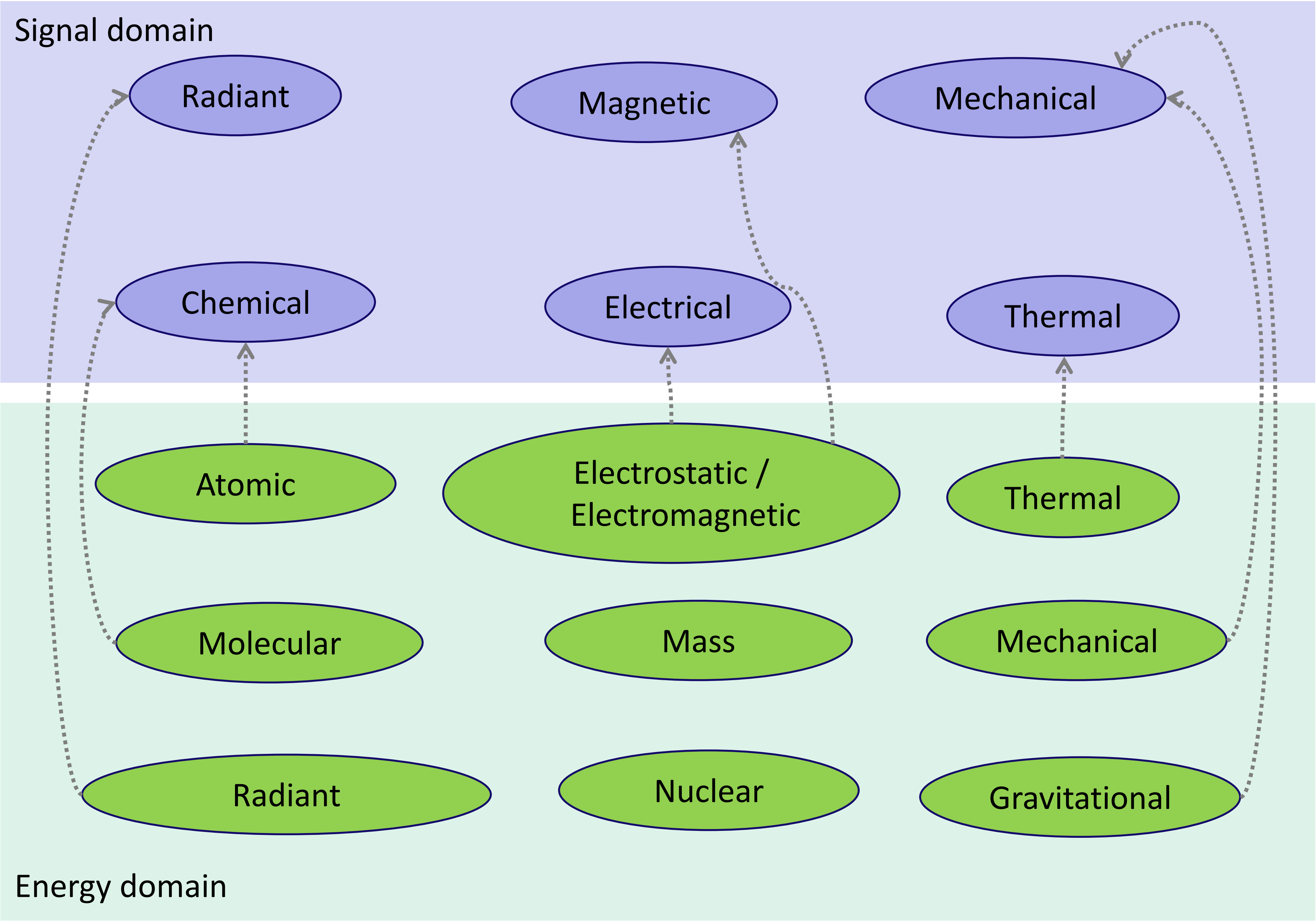
sound vibrations (mechanical)

birds

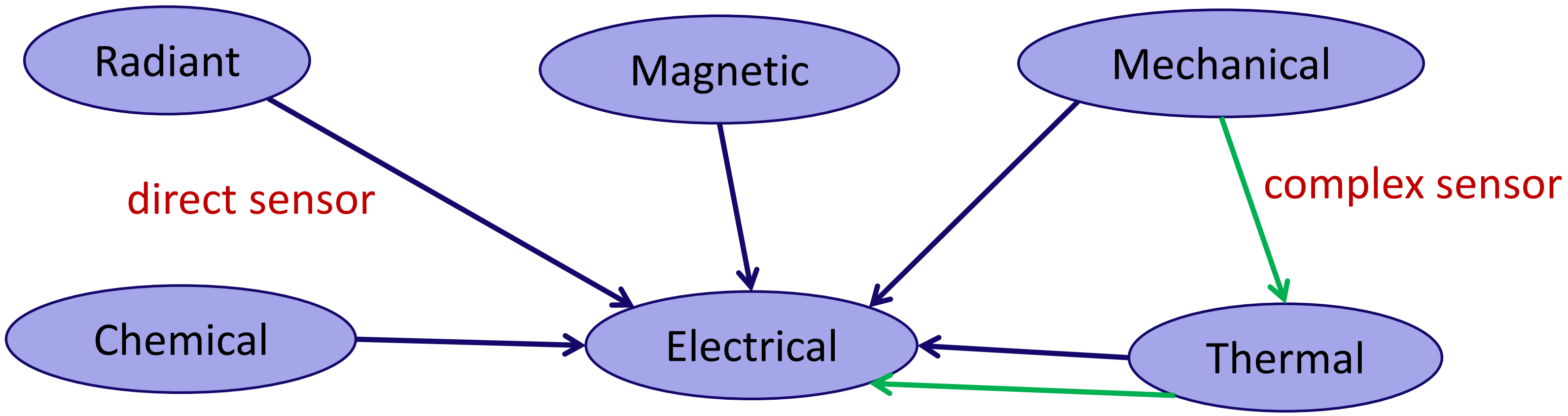
magnetic field

Signals-carrying energy

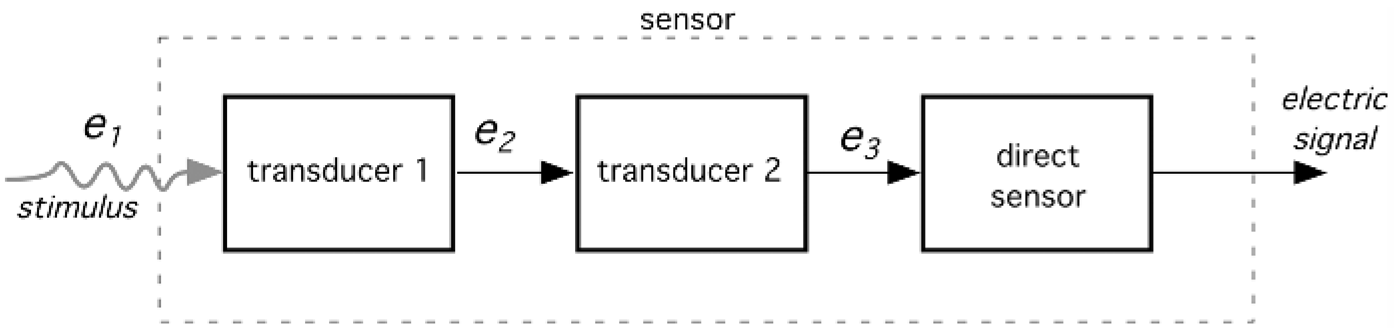
TU/e



Sensors, transducers and actuators

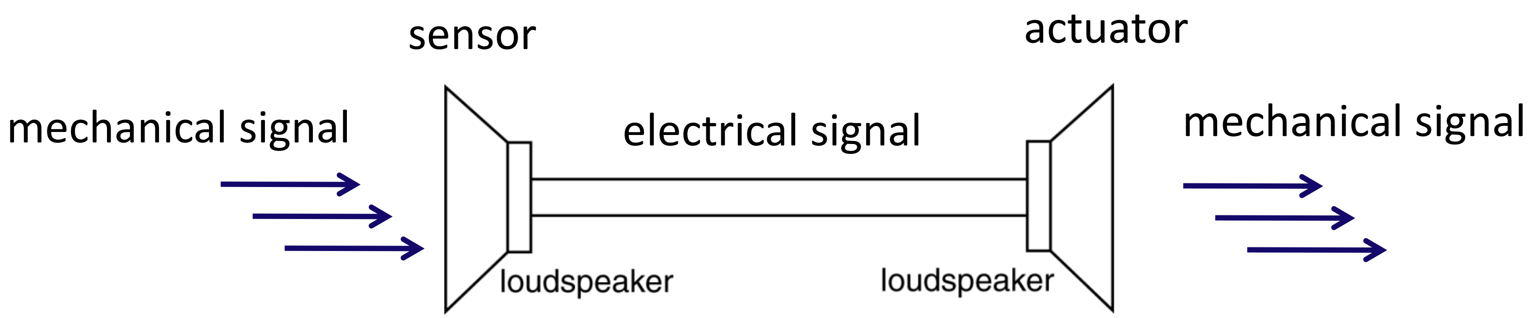


- a transducer converts a stimulus from a signal domain to another signal domain
- a sensor receives a stimulus and responds with an electrical signal

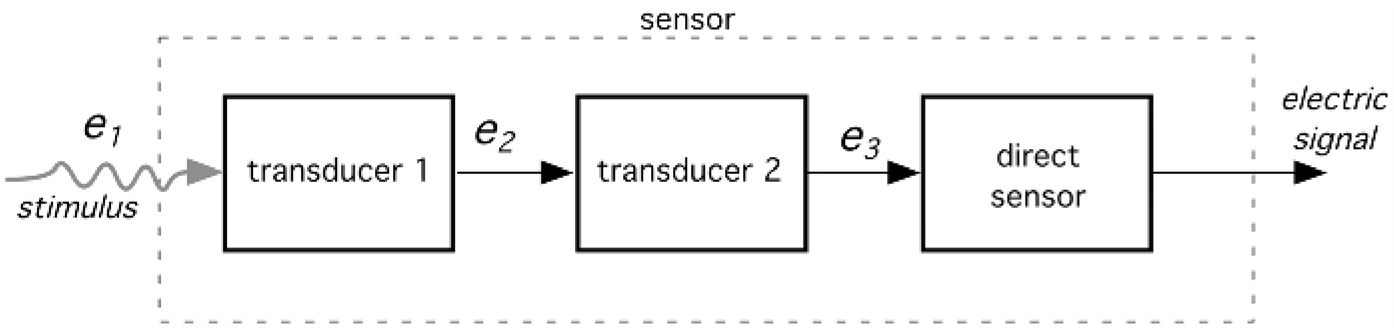


- an actuator converts an electrical signal to another signal domain

Example - loudspeaker system



- a transducer converts a stimulus from a signal domain to another signal domain
- a sensor receives a stimulus and responds with an electrical signal



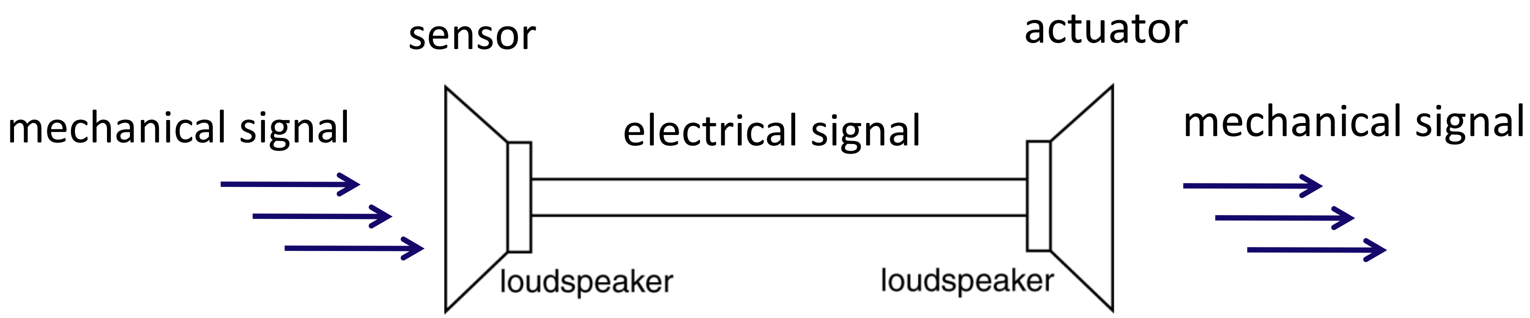
- an actuator converts an electrical signal to another signal domain

Electrical signal domain

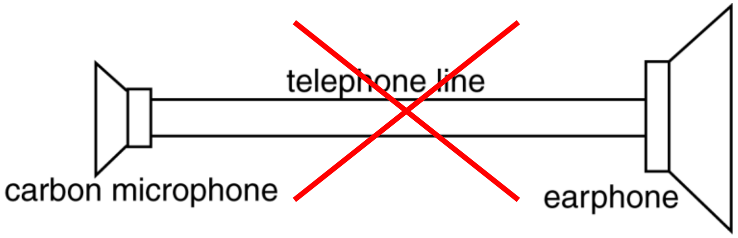
why do we prefer a transducer that produces a signal in the electrical domain?

- a signal in any domain can be converted to a signal in the electrical domain
- energy does not have to be drained from the processes being measured, instead an amplifier can be used
- many electrical signal conditioners exist
- many options exist to process, display and store electrical information
- it is easy to communicate electrical signals

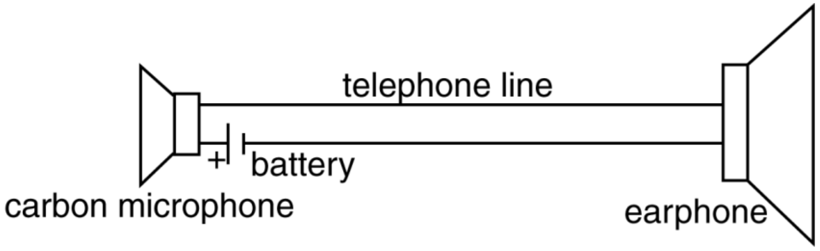
Example - telephone



- a telephone works in a different way

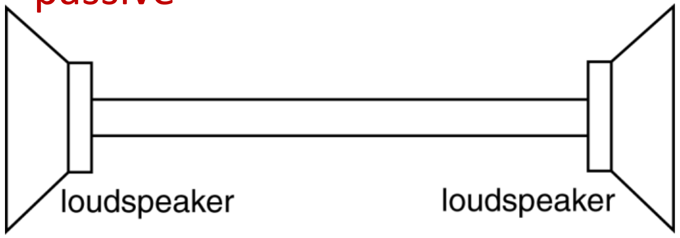


- microphone converts sound to change of resistance
- no transduction takes place (no change of energy)
- power source must be added to affect transduction

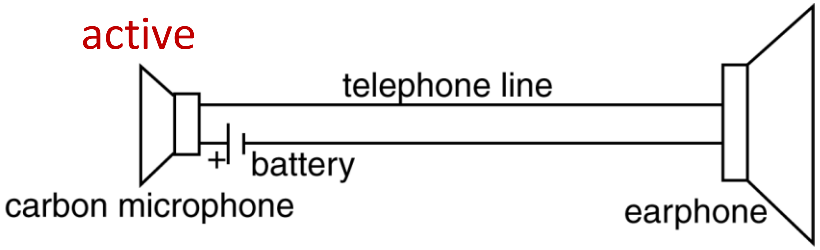


Sensor classification - excitation

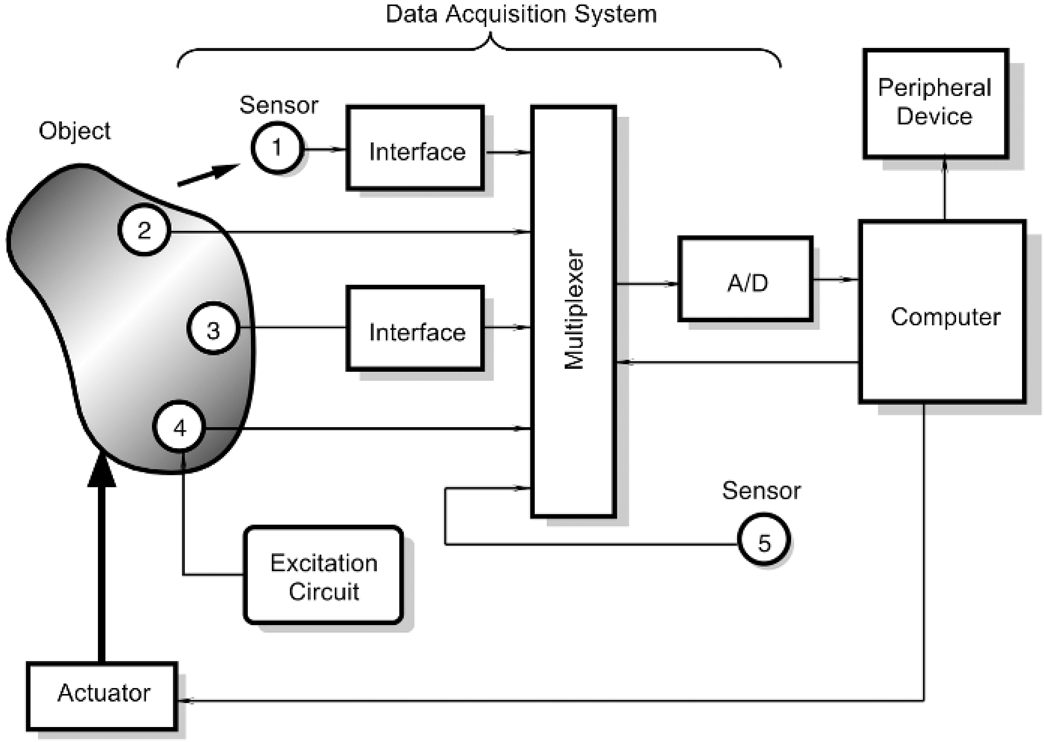
passive



active



- an active sensor requires external power to operate
- a passive (self-generating) sensor generates its own electrical signal



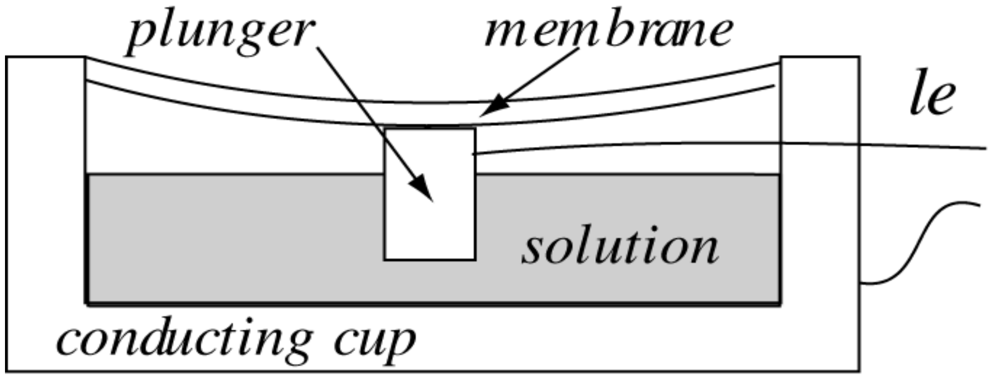
sensor classification	
1	passive
2	passive
3	passive
4	active
5	passive

Sensors and Actuators

- microphones are sound sensors sensing change in pressure
- speakers are sound actuators

- first microphones and speakers were devised and patented for use in telephones
- Alexander Graham Bell patented the first variable resistance microphone in 1876

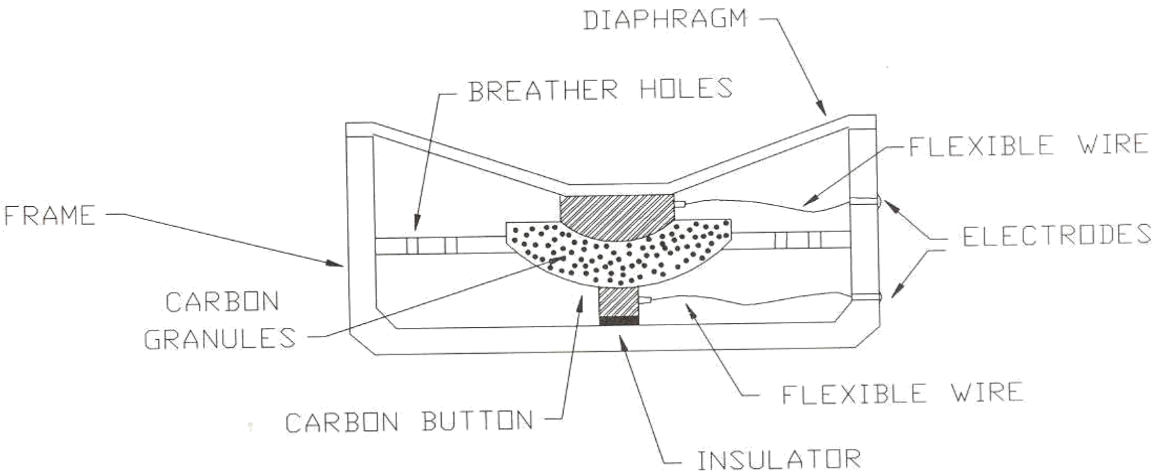
- operation
  - Pressure pushes membrane and plunger down in solution
  - Resistance between plunger and body of the microphone (cup) changes



Resistive microphones

- first practical microphone invented by Thomas Edison in 1878
- solution in Bell's microphone is replaced with carbon or graphite particles
- bulk resistivity of the powder is sensitive to pressure

- variable resistive microphones have poor performance
  - limited dynamic range
  - poor frequency response
  - high noise floor

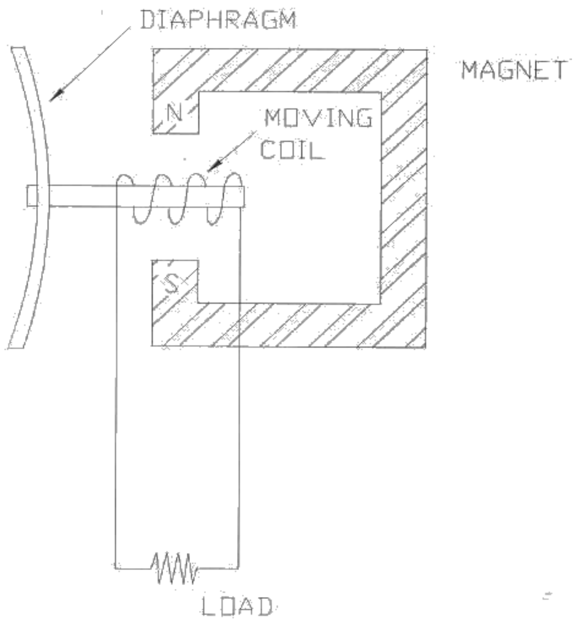


Moving coil microphone

- first microphone to produce the whole range of the human voice
- still in use today, although simpler devices have been developed

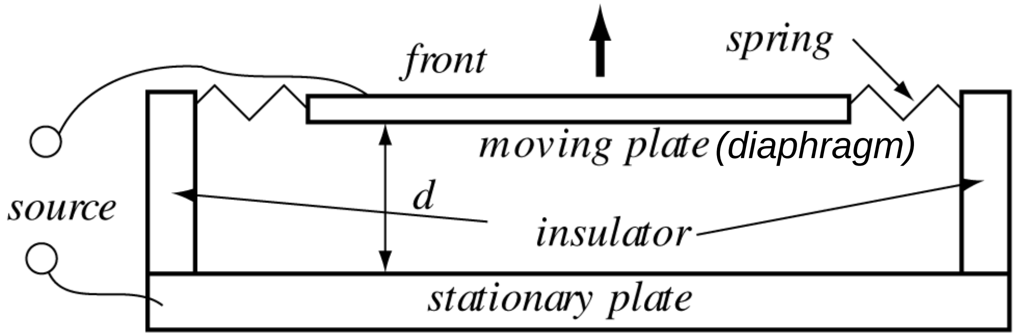
- device is fundamentally the same as a common loudspeaker
  - any small loudspeaker can serve as dynamic microphone
  - moving coil microphone is dual device capable of serving as loudspeaker or microphone (sensor and actuator)

- moving coil microphone offers
  - large dynamic range
  - good frequency response
  - relatively low noise level
  - high sensitivity



Capacitive microphone

- Operation
  - allow sound to move a plate in a capacitor
  - sense the change in capacitance



- operation based on basic equations for plate capacitor

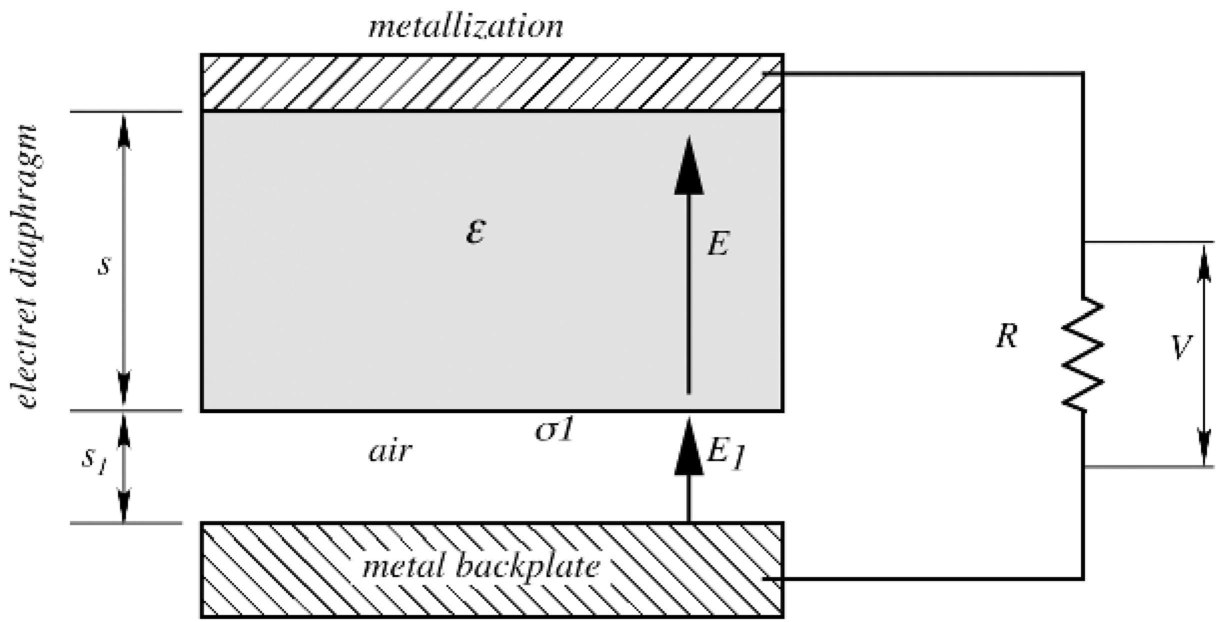
$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \qquad C = \frac{Q}{V} \longrightarrow V = Q\frac{d}{\varepsilon_o \varepsilon_r A}$$

  - output voltage proportional to distance between plates
  - magnitude of electric charge source Q determines sensitivity

Electret microphone

- electret microphone is a capacitive microphone used in many devices (e.g., phones)
- top plate consist of a thin film of electret material on which a metal payer is deposited
- thin film allows the flexibility and motion required in the microphone

- metal layers (top and bottom) are connected to a resistor
- output voltage across resistor used as output signal

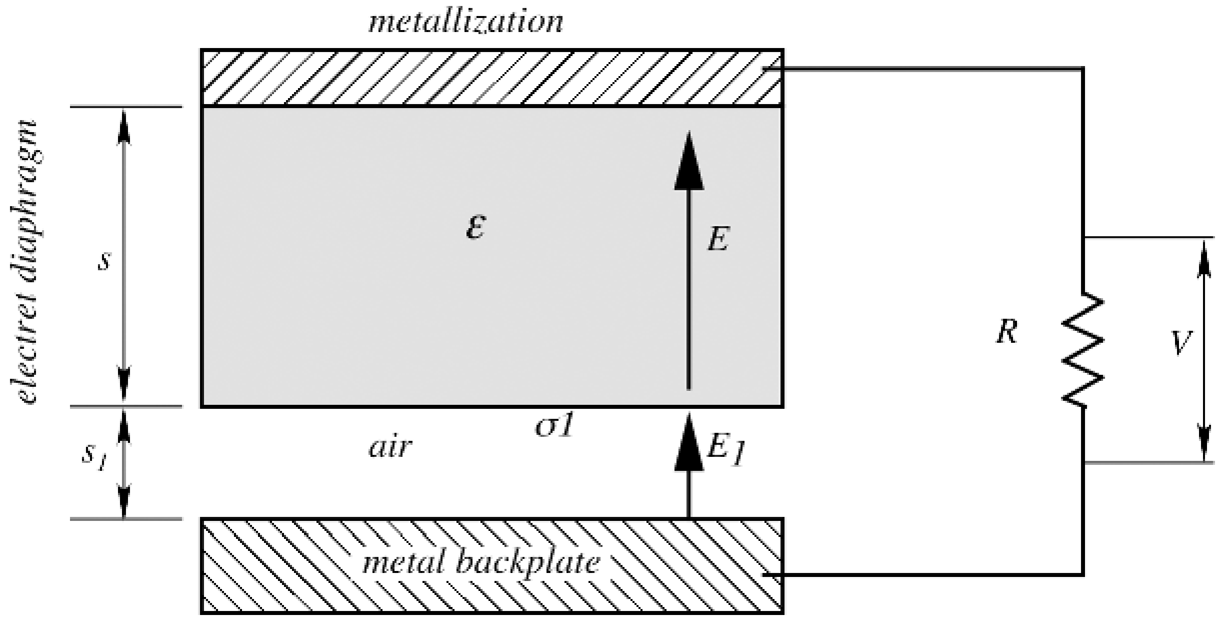


Electret microphone

- electret has a constant charge density σ_1 on its surface
- charge density sets electric field E_1 in air gap
- acoustic wave on diaphragm reduces size of air gap from s_1 to s_1-Δs
- when no circuit is connected, the difference in output voltage is equal to:

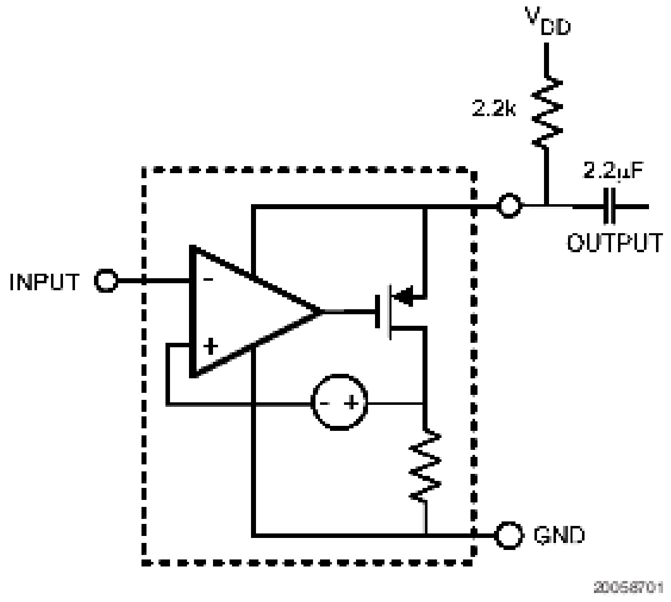
$$\Delta V = \frac{s\Delta s}{\varepsilon_o(s + \varepsilon s_1)}$$

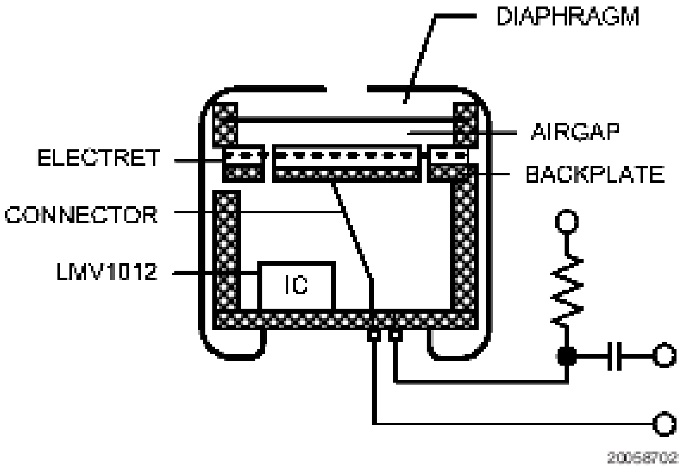
  - ε – electret constant of material



Electret microphone

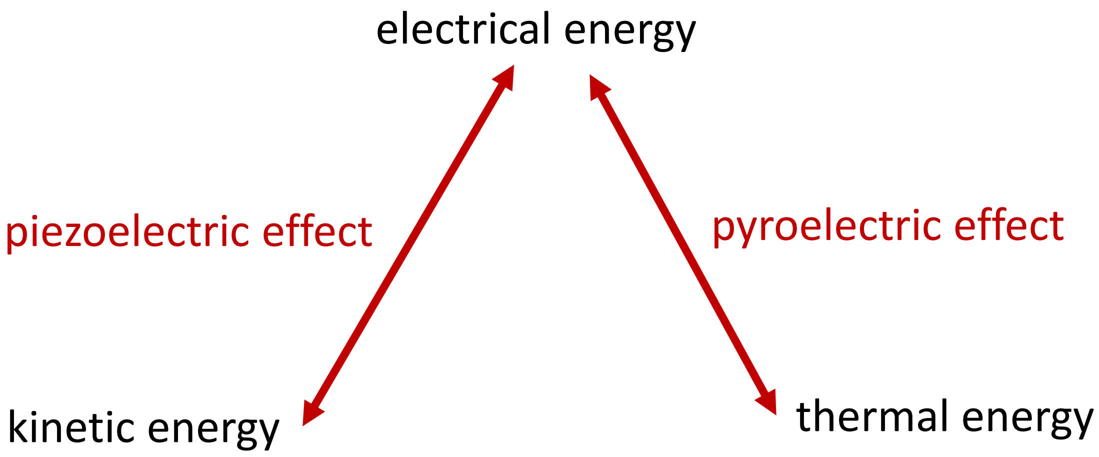
- electret microphones are very popular
  - simple and inexpensive
  - do not require a voltage source
- their impedance is very high
  - circuit is needed to match high impedance to low impedance of processing circuit
  - FET pre-amplifier or amplifier can be used for this purpose





Piezoelectric effect

- crystalline materials generate electric charge when subjected to stress (piezoelectric effect)
- pyroelectric effect closely related to piezoelectric effect
- both effects are reversible

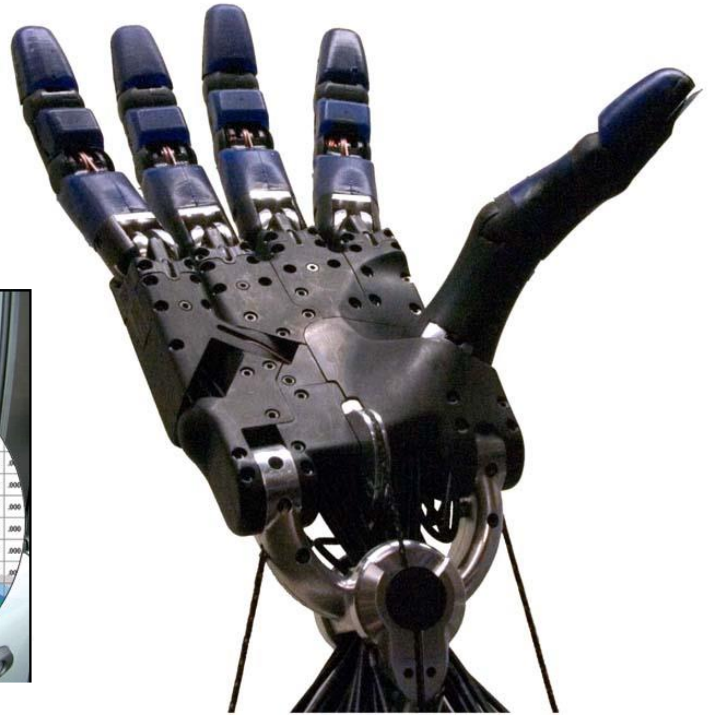


- piezoelectric effect exists in
  - natural crystals (e.g. quartz - SiO_2)
  - artificially polarized (poled) ceramics and polymers

Piezoelectric actuator

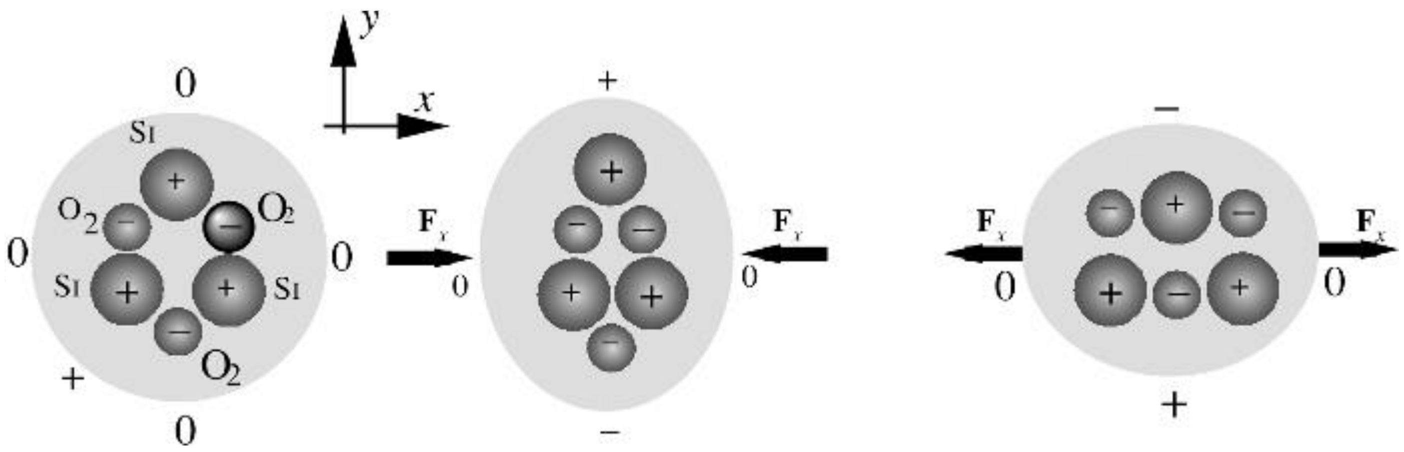
common rail injection system

Piezoelectric and pyroelectric sensors



Piezoelectric effect – explanatory model

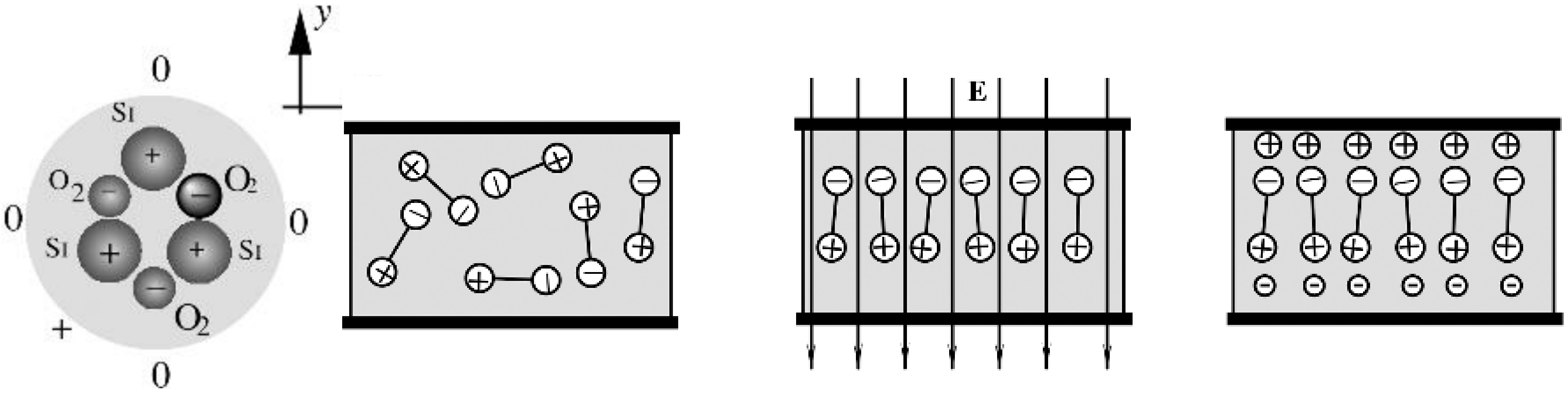
- quartz crystal model as helix
  - one silicon and two oxygen atoms alternating around helix
  - single cell (slice of helix) contains 3 Si atoms and 6 O atoms
  - Si has 4 positive charges, O has 2 negative charges
  - cell is electrically neutral
- compressing force in X direction leads to positive charge at top
- stretching force in Y direction leads to negative charge at top



Thermal poling of piezoelectric material

- crystal cells can be considered electrical dipoles
  - cells may be naturally oriented along crystal axes (e.g. quartz)
  - dipoles may be oriented randomly, but dipoles can be “poled” into required orientation

- thermal poling is most commonly used technique for poling
  - warm up crystalline material till just below Curie temperature
  - apply strong electrical field to align dipoles
  - cool material down
  - remove electrical field
  - orientation of dipoles is “frozen” in direction of the electrical field

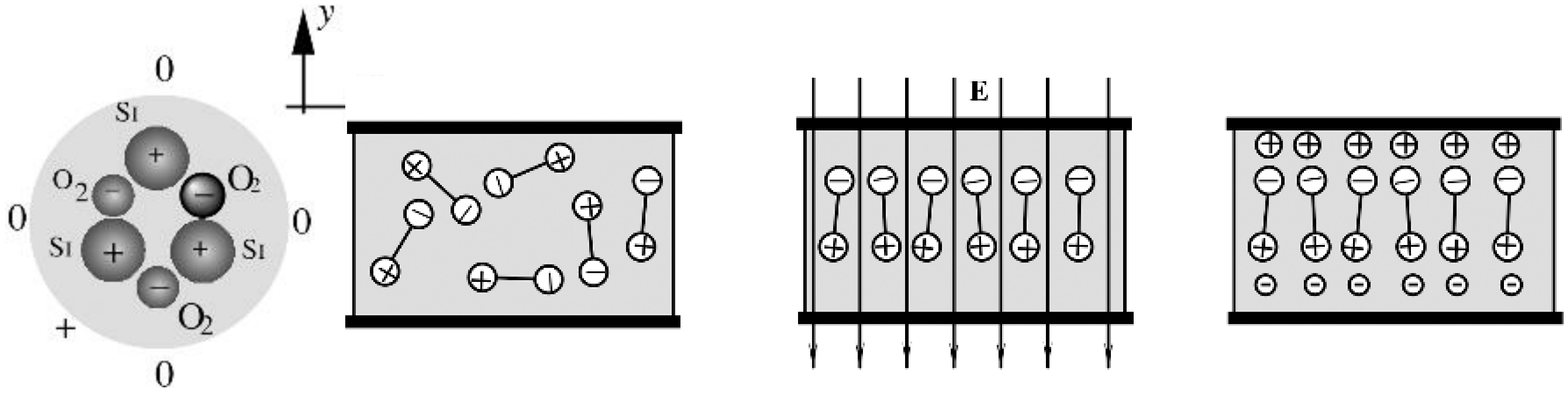


Piezoelectric sensor

- thermal poling creates small charge on the plates
  - quickly dissipated by free charges from the surrounding atmosphere which are attracted to the plates
  - after a very short time, there will be no charge on the plates

- stress disturbs balanced state
  - charge will appear on the plates

- internal leakage will neutralize charge when stress is maintained
  - piezoelectric sensor is sensitive to change, not to steady-state



Piezoelectric sensor

- charge on electrodes due to force F

$$Q = d\frac{F}{l \cdot h}(w \cdot l)$$

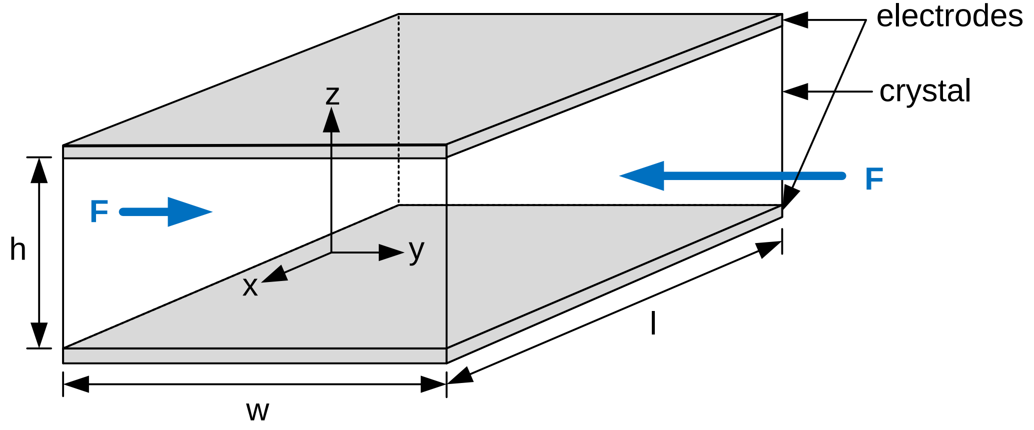
  - d – piezoelectric charge constant (pC/N)

- charge constant depends on position of force and electrodes
- capacitor relates charge and voltage

$$\left.\begin{array}{l} Q = CV \Rightarrow V = \dfrac{Q}{C} \\ C = \varepsilon_0\varepsilon_r\dfrac{w \cdot l}{h} \end{array}\right\} \Rightarrow V = d\frac{F}{l \cdot h}(w \cdot l)\frac{h}{\varepsilon_0\varepsilon_r \cdot w \cdot l} = d\frac{F}{l \cdot \varepsilon_0\varepsilon_r}$$

- crystal has conductive properties
- resistive path between electrodes

$$R = \rho\frac{h}{w \cdot l}$$



Piezoelectric sensor

- electrical equivalent circuit for sensor

1) force generates voltage

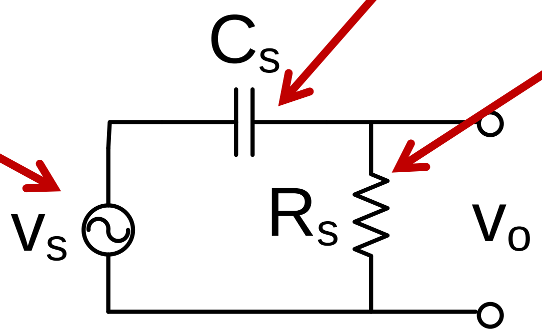
$$V = d\frac{F}{l \cdot \varepsilon_0 \varepsilon_r}$$

2) charge collects on plates

$$C_s = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{h}$$

3) charge leaks through internal resistance

$$R_s = \rho \frac{h}{w \cdot l}$$

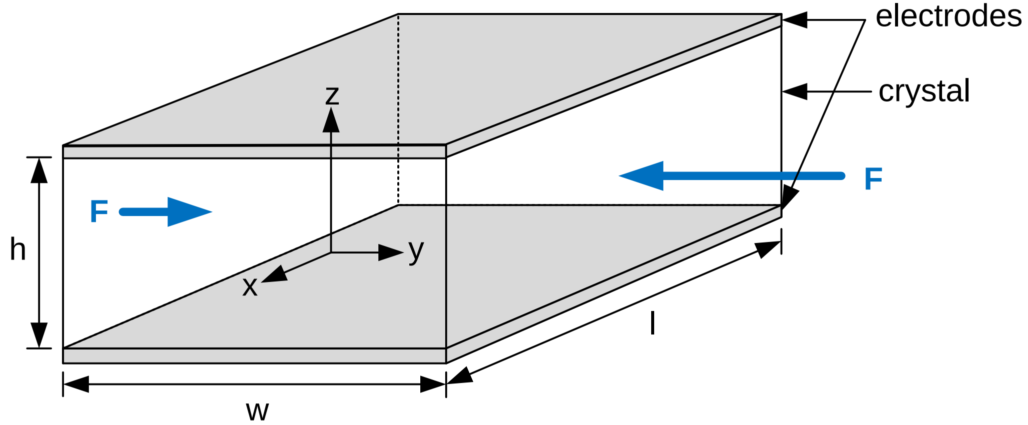


- capacitor and resistor form HPF

$$\left|\frac{v_o}{v_s}\right| = \left|\frac{j\omega R_s C_s}{1 + j\omega R_s C_s}\right| = \frac{\omega R_s C_s}{\sqrt{1 + (\omega R_s C_s)^2}}$$

- cut-off frequency

$$\omega_c = \frac{1}{R_s C_s}$$



Piezoelectric sensor

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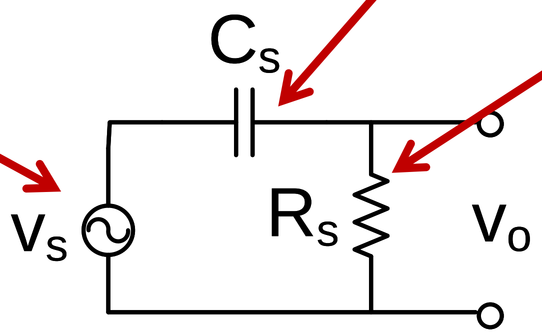

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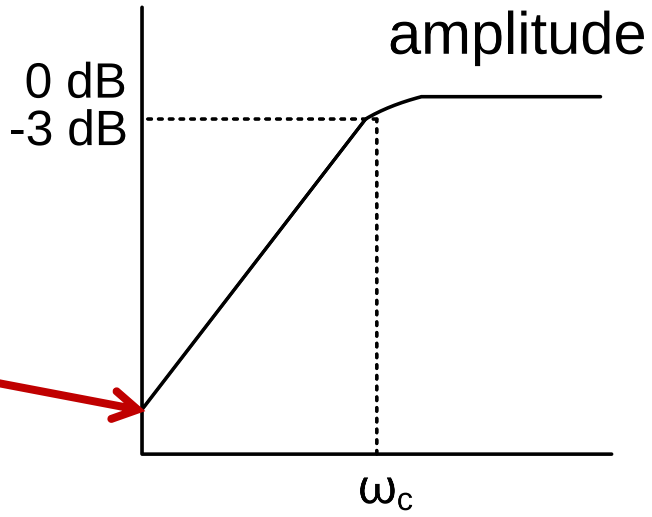
- cut-off frequency

$$\omega_c = \frac{1}{R_s C_s}$$

- sensor only sensitive to changing force

sensor has no DC response



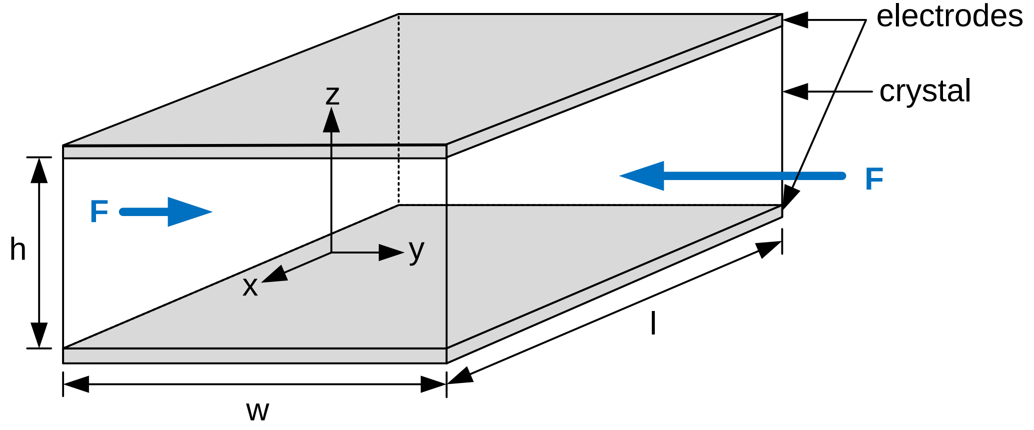
Piezoelectric sensor

example – piezoelectric sensor

- h = 52 µm, l = 10 cm, w = 10 cm
- d = 23 pC/N, ε_r = 12, ε_0 = 8.85 pF/m, ρ = 10 TΩ·m

what is the force generated voltage when a weight of 40 kg is applied to the sensor?

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?



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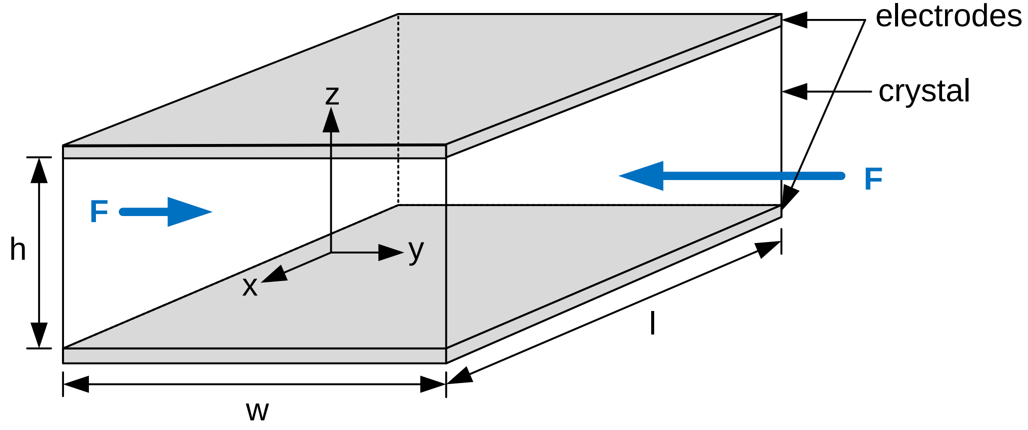
what is the force generated voltage when a weight of 40 kg is applied to the sensor?

$$V = d\frac{F}{l \cdot \varepsilon_0 \varepsilon_r} = (23pC/N)\frac{40 \cdot 9.8N}{(0.1m) \cdot (12 \cdot 8.85pF/m)} = 849V$$

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?

constraint: $$\left|\frac{v_o}{v_s}\right| = \frac{\omega R_s C_s}{\sqrt{1 + (\omega R_s C_s)^2}} = \frac{1}{\sqrt{1 + \left(\frac{\omega_c}{\omega}\right)^2}} > 0.95$$



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- d = 23 pC/N, ε_r = 12, ε_0 = 8.85 pF/m, ρ = 10 TΩ·m

what is the minimal frequency of a dynamic compression for an allowed amplitude error of 5%?

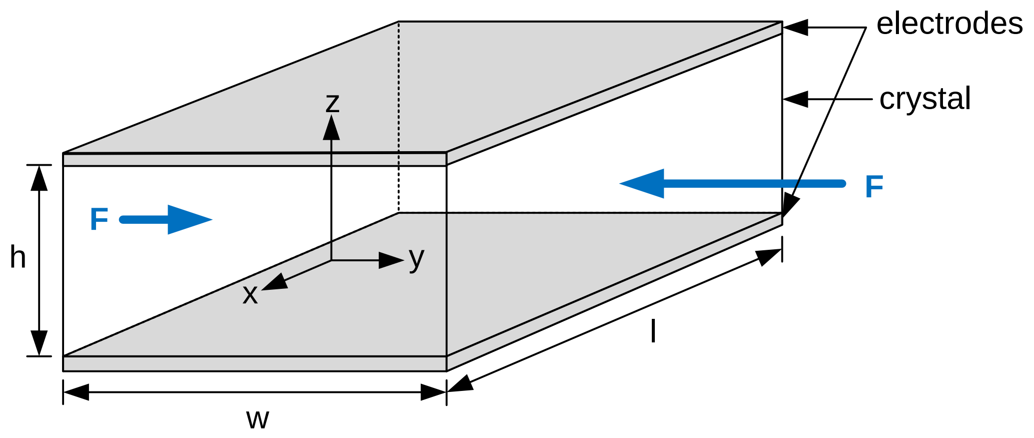
$$R_s = \rho \frac{h}{w \cdot l} = (10 \cdot 10^{12} \Omega m) \frac{52\mu m}{0.1m \cdot 0.1m} = 52G\Omega$$

$$C_s = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{h} = 12 \cdot 8.85pF/m \cdot \frac{0.1m \cdot 0.1m}{52\mu m} = 20.4nF$$

$$\Rightarrow \omega_c = \frac{1}{R_s C_s} = 1 \cdot 10^{-3} rad/s$$

constraint: $$\frac{1}{\sqrt{1 + \left(\frac{\omega_c}{\omega}\right)^2}} > 0.95$$

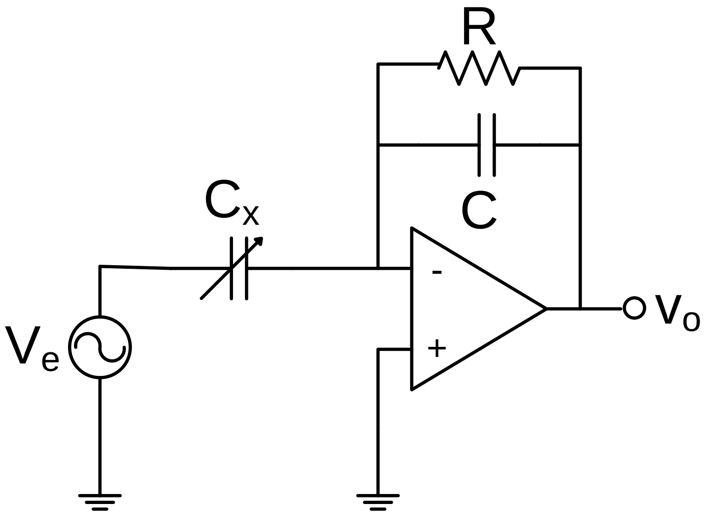
$$\Rightarrow \omega > 0.003 rad/s \Leftrightarrow f > 0.02Hz$$



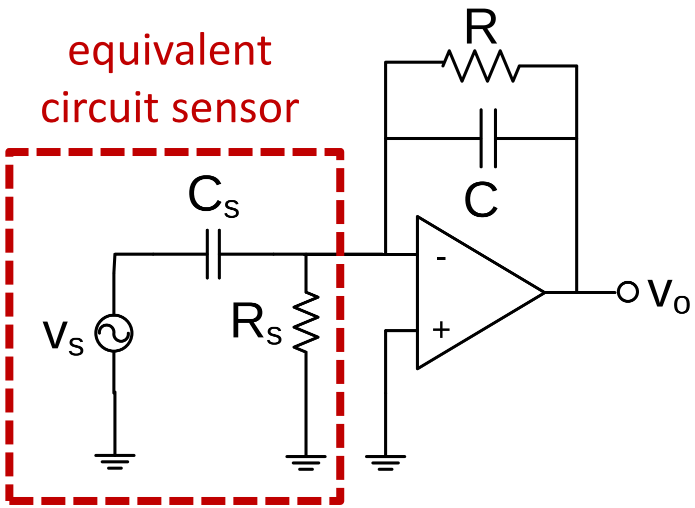
Signal processing

- charge amplifier circuit
  - R provides bias current path
  - output voltage

$$v_o = -\frac{C_x}{C} v_e$$



- charge amplifier can be used to get charge of piezoelectric sensor



$$\left.\begin{aligned} v_o &= -\frac{C_s}{C} v_s \\ v_s &= \frac{Q_s}{C_s} \end{aligned}\right\} \Rightarrow v_o = -\frac{C_s}{C}\frac{Q_s}{C_s} = -\frac{Q_s}{C}$$

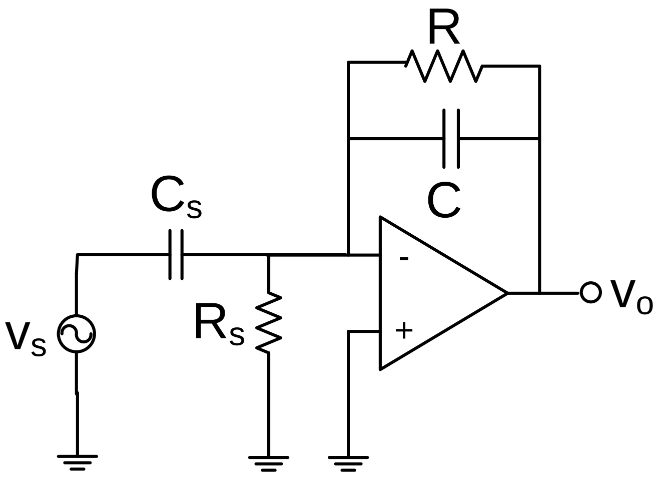
$$\left.\begin{aligned} &\Leftrightarrow v_o = -\frac{Q_s}{C} \\ &Q_s = d\frac{F}{l \cdot h}(w \cdot l) \end{aligned}\right\} \Rightarrow v_o = -d\frac{F}{l \cdot h}(w \cdot l)\frac{1}{C}$$

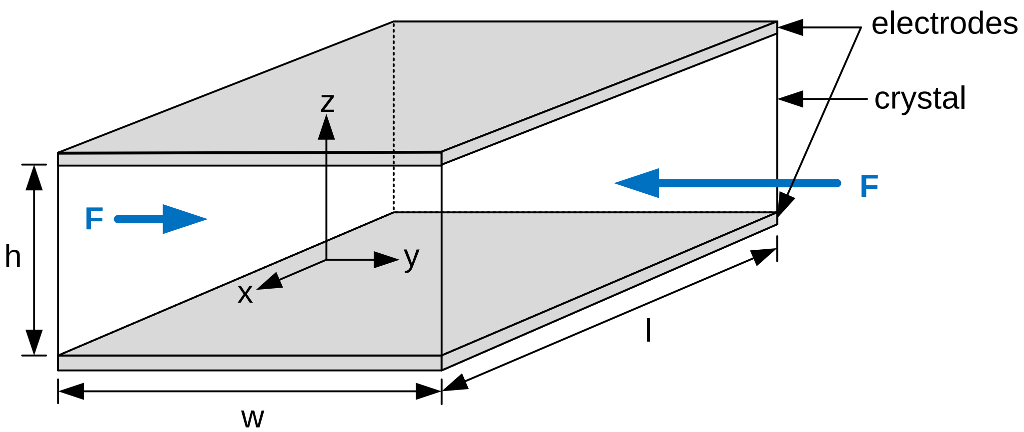
example – piezoelectric sensor

- h = 52 µm, l = 10 cm, w = 10 cm
- d = 23 pC/N, ε_r = 12, ε_0 = 8.85 pF/m, ρ = 10 TΩ·m
- C_s = 20.4 nF, R_s = 52 GΩ

what value should the capacitor C have to get an output sensitivity of -10 mV/Pa?

$$v_o = -d\frac{F}{l \cdot h}(w \cdot l)\frac{1}{C} \quad \Rightarrow -10mV = -23pC/N(1N/m^2)(0.1m \cdot 0.1m)\frac{1}{C} \quad \Rightarrow C = 23pF$$





Piezoelectric sensor/actuator

- piezoelectric speakers (actuator)
  - used in many electronics devices (e.g., computer, watch)
  - piezoelectric speakers are resistant to overloads
  - provide direct conversion of electrical to mechanical energy
    - other speaker use magnetic field to move cone
  - their frequency response is inferior to that of other technologies
    - generally used in single frequency (beeper) applications

- piezoelectric speaker can also be used to convert mechanical energy (sound) to electrical energy
- actuator (speaker) can be used as sensor (microphone)

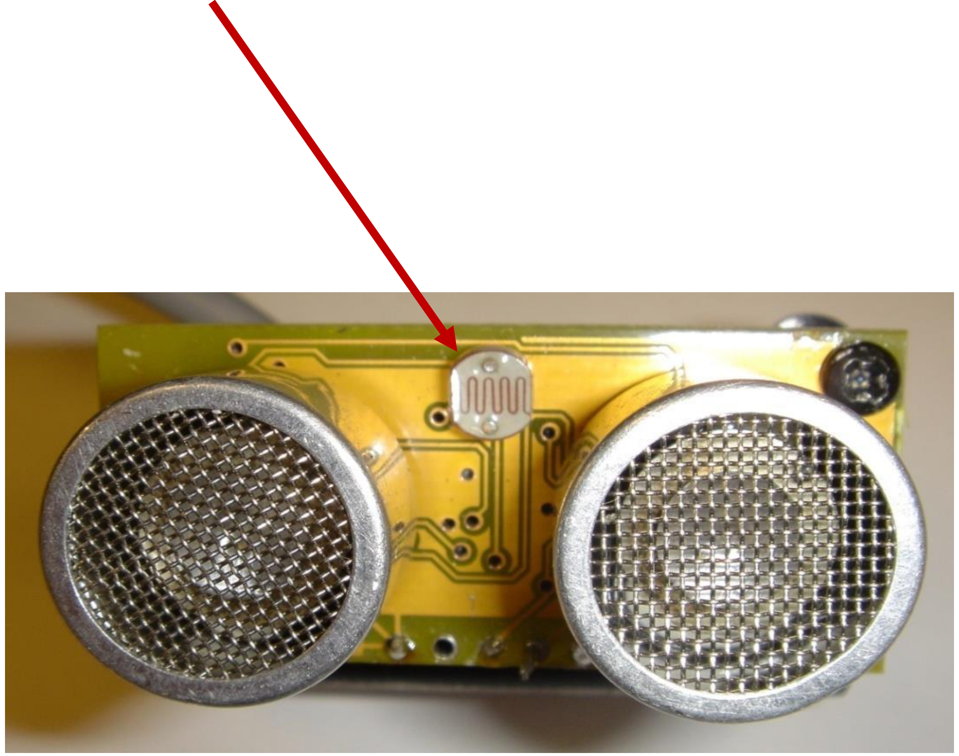
Ultrasonic sensors and actuators

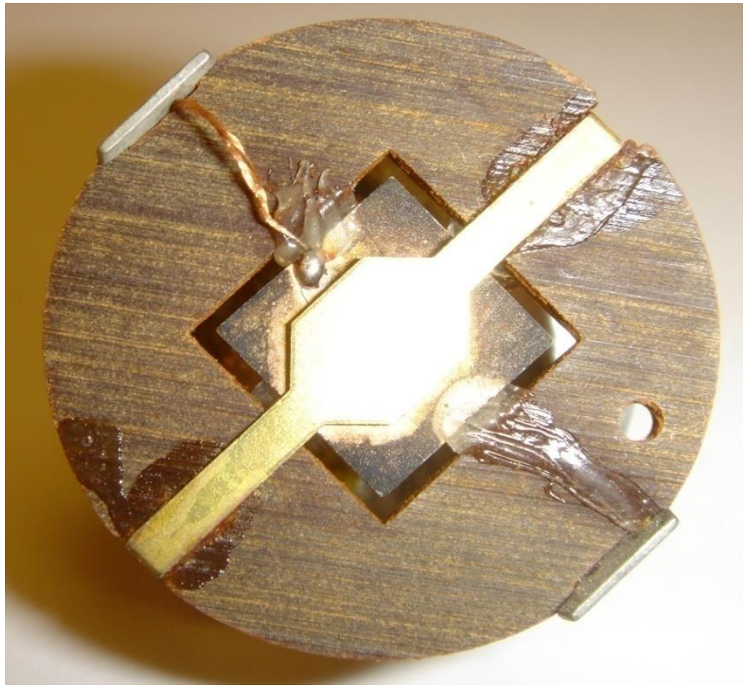
- ultrasonic range starts where audible range ends
- basic principles of ultrasound sensors identical to acoustic sensors
- therefore ultrasound sensors for the near ultrasound range are quite similar to acoustic sensors
- construction, materials used, and frequency range are different

- example: 40kHz UT transmitter and receiver
  - transmitter and receiver have essentially the same construction
  - both use an identical piezoelectric disk
  - only difference is in the construction of the cone

Ultrasonic sensors and actuators

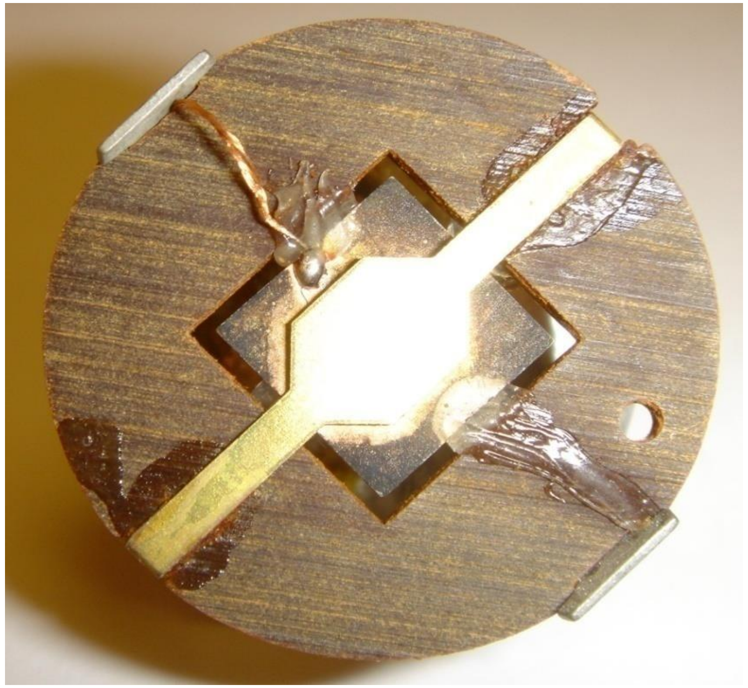
- example: 40kHz ultrasonic sensor
  - sensor contains piezoelectric element (square in center)
  - one electrode connected to top of piezoelectric element
  - other wire is connected underneath brass element which supports sensor
  - can be used in pair to measure distance (range finding)
    - notice the thermal sensor (speed of sound is highly temperature dependent)





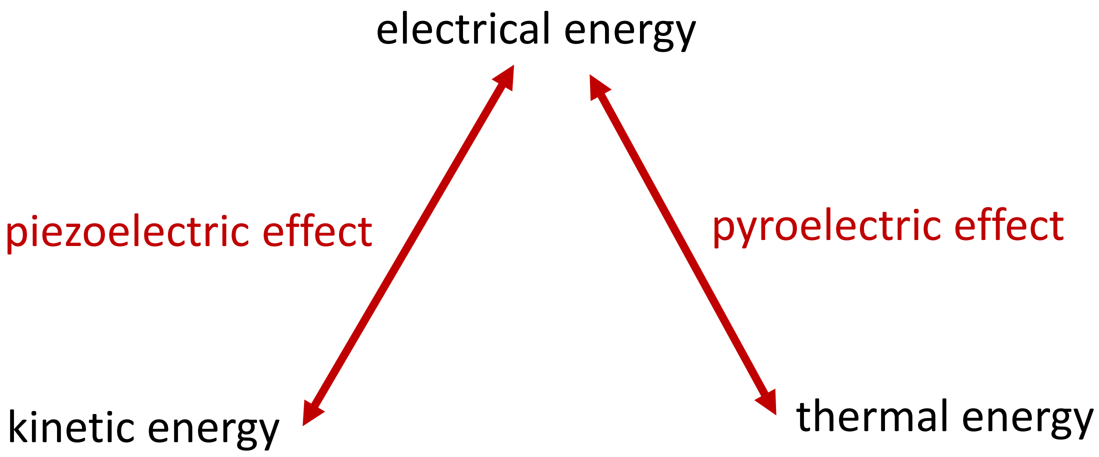
Ultrasonic sensors and actuators

- example: 40kHz ultrasonic actuator
  - actuator contains piezoelectric element (square in center)
  - piezoelectric materials can oscillate at a fixed, sharply defined frequency (resonant frequency)



Piezoelectric effect

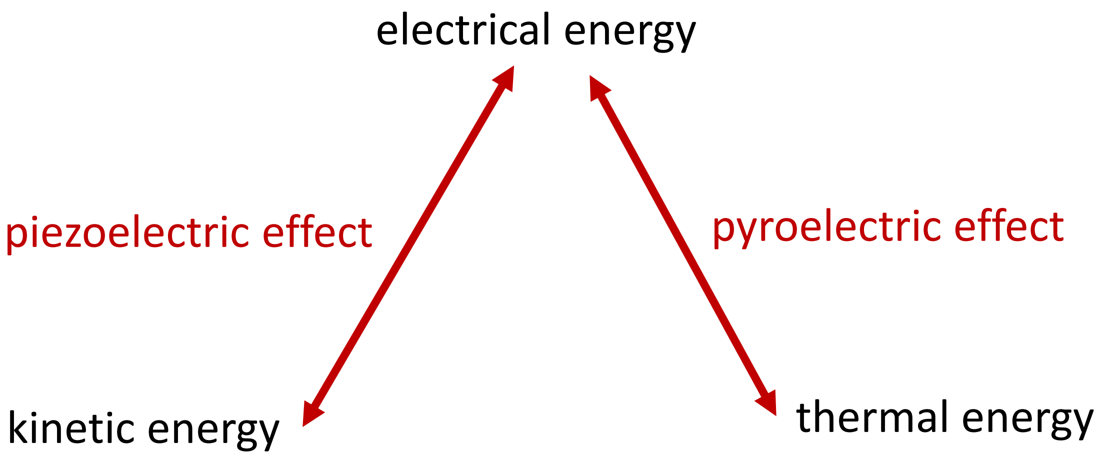
- crystalline materials generate electric charge when subjected to stress (piezoelectric effect)
- pyroelectric effect closely related to piezoelectric effect
- both effects are reversible



- piezoelectric effect exists in
  - natural crystals (e.g. quartz - SiO_2)
  - artificially polarized (poled) ceramics and polymers

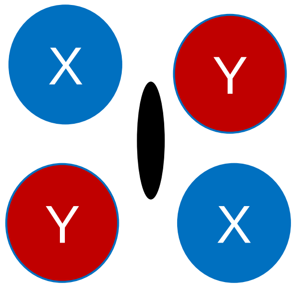
Pyroelectric effect

- pyroelectricity is the ability of certain materials to generate an electrical charge in response to heat flow
- pyroelectric effect is closely related to piezoelectric effect

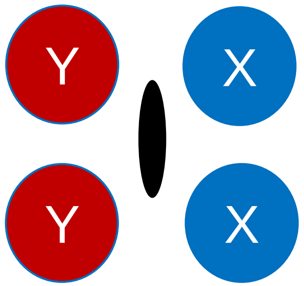


Pyroelectric material

- material has center of symmetry when each atom in an imaginary unit cell has an exact twin opposite to it on a line through an imaginary center point

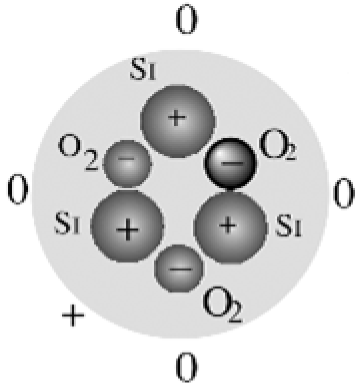


symmetric cell



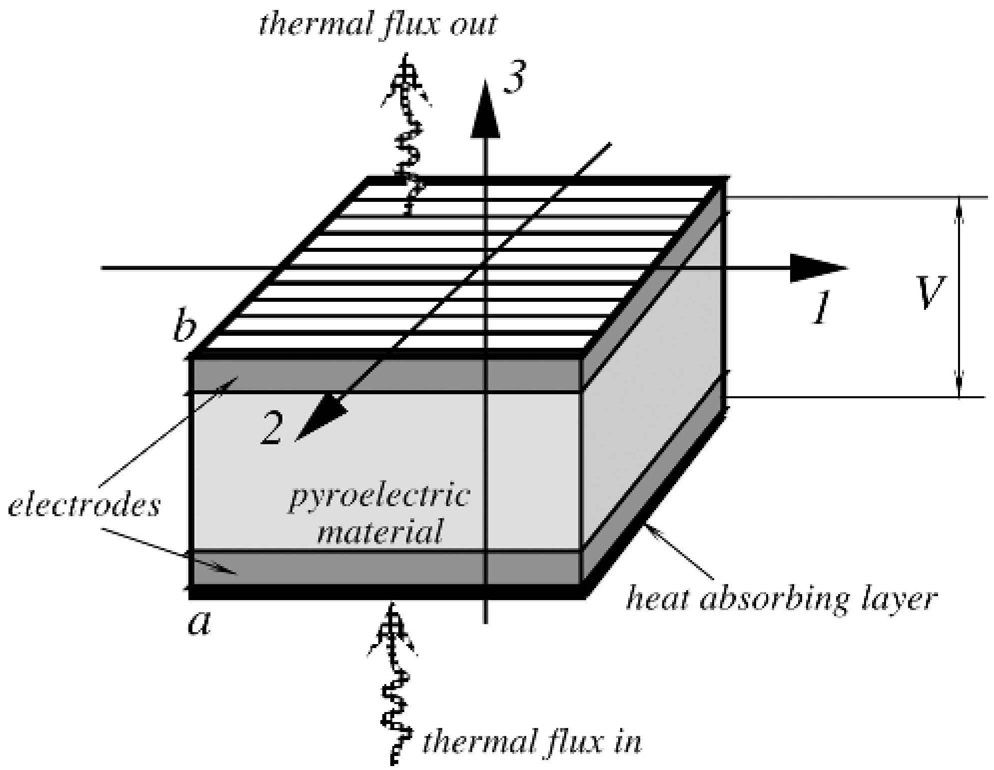
non-symmetric cell

- force on symmetric cell will never cause a dipole to appear
- piezoelectric materials have no center of symmetry
  - some piezoelectric materials show temperature dependent polarization
  - these materials are called pyroelectric



Operation of a pyroelectric sensor

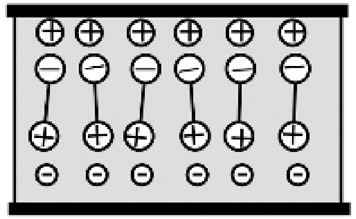
- pyroelectric sensor
  - same construction as piezoelectric sensor
  - passive (self-generating) sensor
  - responds to change in temperature (dynamic)
  - no response to temperature (steady-state)

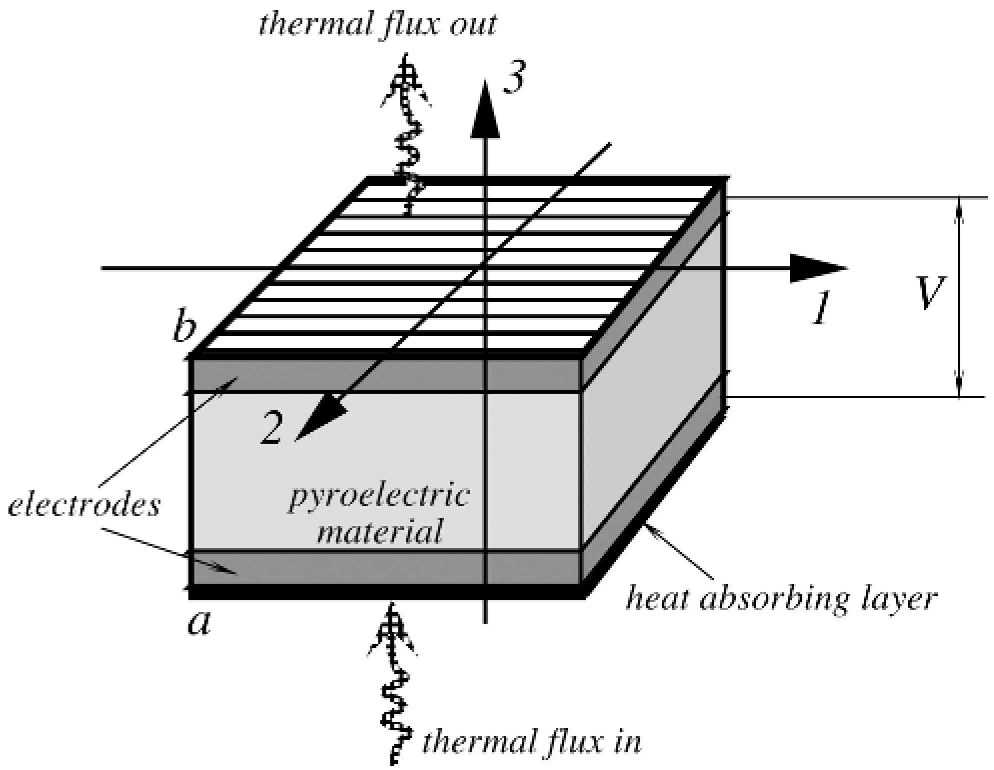


Operation of a pyroelectric sensor

- pyroelectricity is the ability of certain materials to generate an electrical charge in response to heat flow

- pyroelectricity caused by two mechanisms
  - mechanism 1: temperature changes cause
    - shortening or elongation of individual dipoles
    - randomness of dipole orientation changes due to thermal agitation

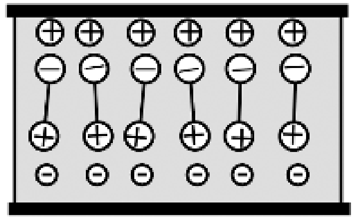


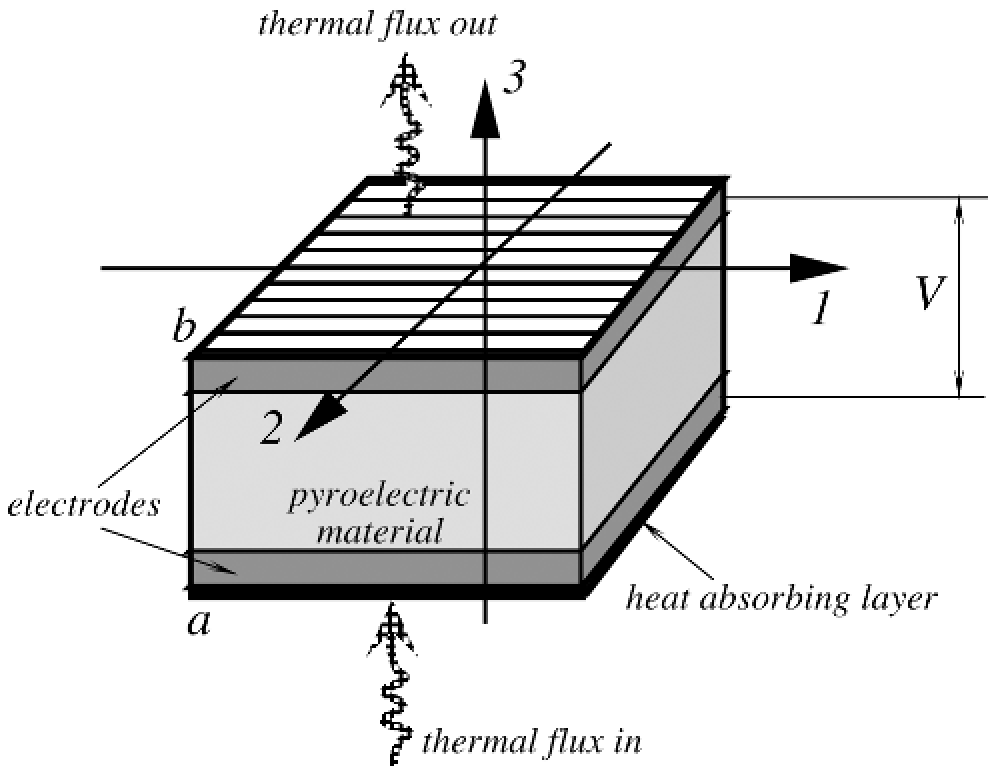


Operation of a pyroelectric sensor

- pyroelectricity is the ability of certain materials to generate an electrical charge in response to heat flow

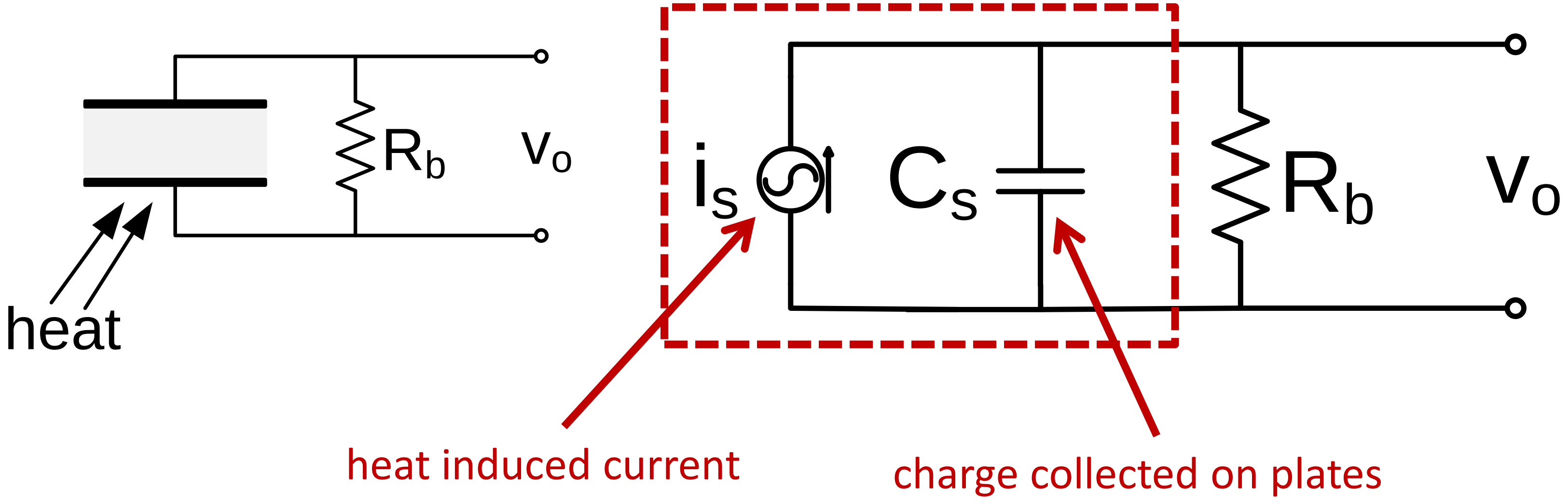
- pyroelectricity caused by two mechanisms
  - mechanism 2: strain due to thermal expansion creates piezoelectric effect
    - thermal radiation absorbed by sensor as heat
    - heat propagates to pyroelectric material
    - creates thermally induced stress



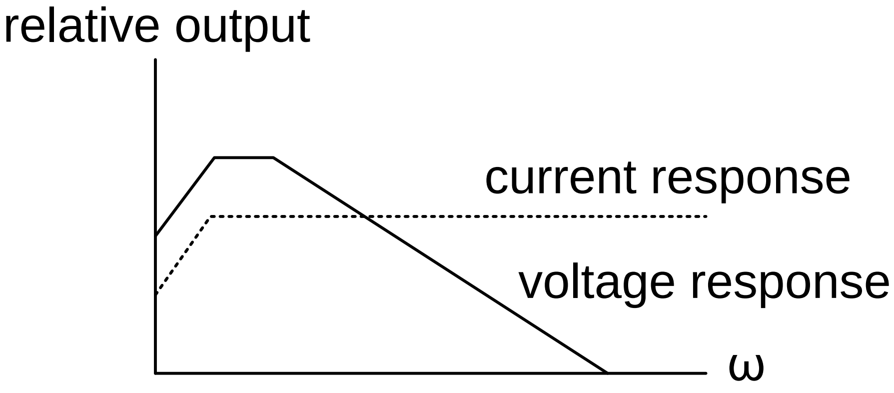


Pyroelectric sensor

- pyroelectric sensor connected to a resistor R_b



- ignore internal leakage since $R_b << R_s$
- capacitor discharged through R_b
- measure output of sensor as
  - current through R_b (flow of charge)
  - voltage across R_b (charge build-up)



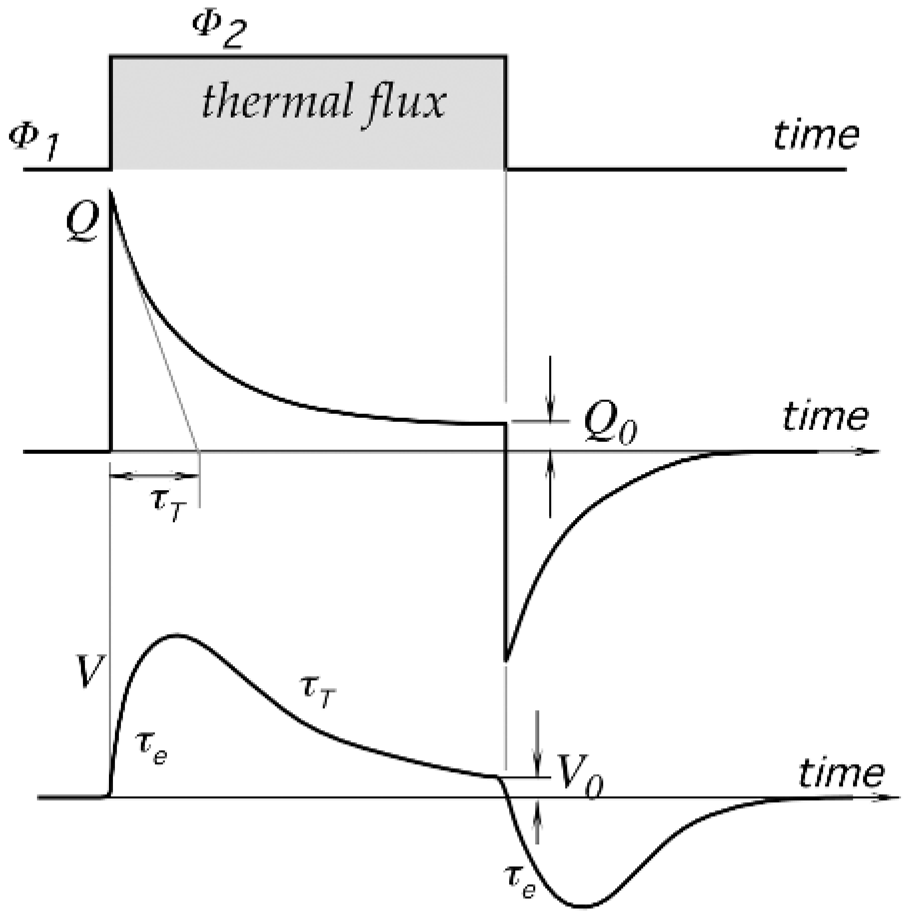
Pyroelectric sensor

- pyroelectric sensor exposed to step function of heat
- electric charge (Q) reaches peak value instantaneously

- thermal induced polarization occurs initially only at outermost layers
  - outer layers reach maximal temperature instantaneously
  - creates highest thermal gradient and maximal polarization

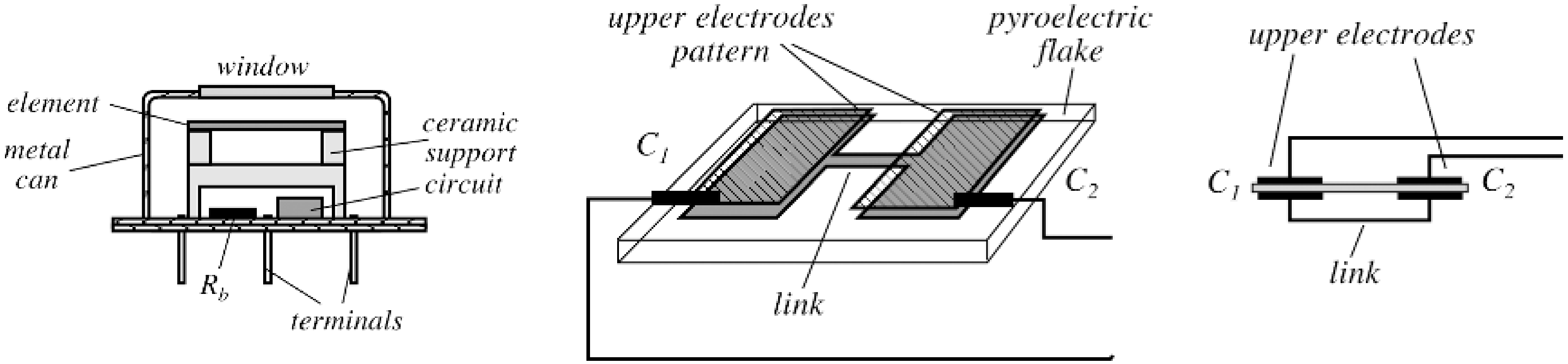
- electric charge decays as heat propagates through material

- part of heat lost to surrounding environment
  - result in voltage V_0
  - use sensor to measure (constant) heat flow



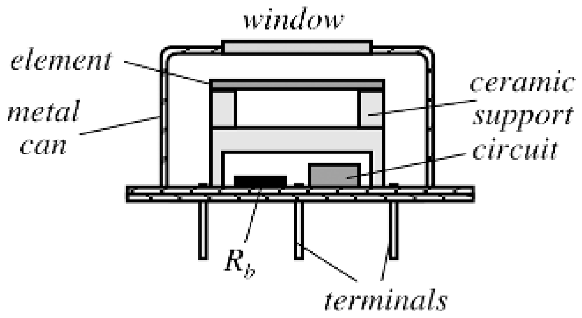
Construction of pyroelectric sensors

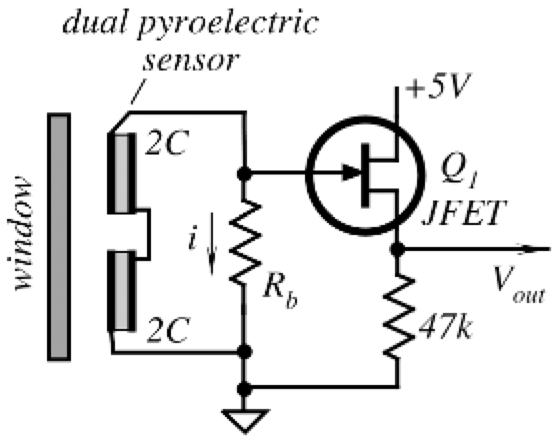
- pyroelectric sensors belong to class of passive infrared sensors
- thermal energy reaches sensor element through window
- often two sensor elements for compensation of mechanical stress

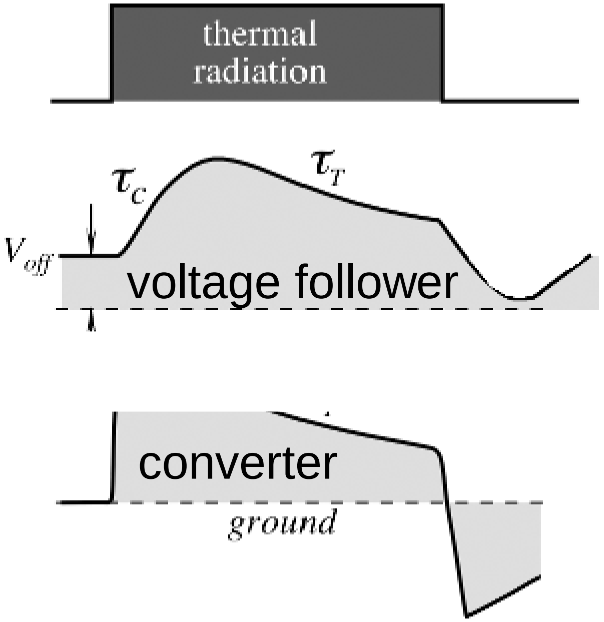


Signal processing

- solution 1: voltage follower
  - voltage across bias resistor R_b is followed by voltage V_{out}
  - response time depends on electrical time constant ($\tau_e = C \cdot R_b$)
    - typically 2 seconds
    - upper cut-off frequency around 0.08Hz
    - only suitable for slow moving objects (e.g. people)
  - offset voltage at output due output resistor







Signal processing

- solution 2: current-to-voltage converter
  - output voltage follows shape of current
    - faster response
    - insensitive to sensor capacitance
  - feedback forces output voltage of sensor to zero