INTRODUCTION TO SENSORS

Content:

Sensors and measurement instruments
Sensors and electronics
Sensors parameters
Electronics for sensors

Measurement instruments

- Human senses as primary measurement instruments.
- The length is the most simple measurable quantity
  - Ruler
- Other quantities can be indirectly measured through suitable instruments that convert them into a measure of length.
  - noteworth exception: color
- Measurement instruments need calibration
  - a procedure assigining to each value of the primary quantity the corresponding value of the quantity under measurement.

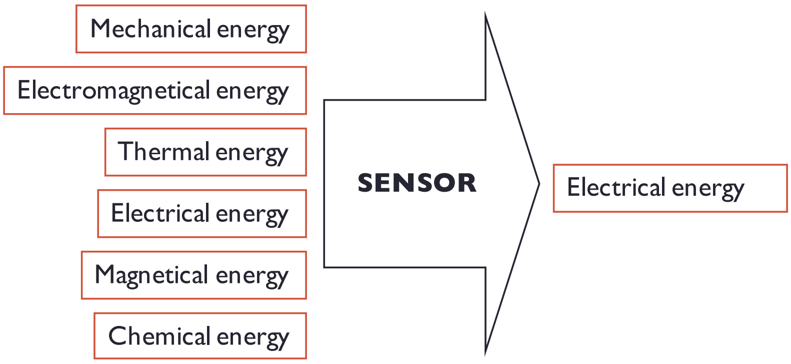
Thermal expansion: $\Delta T \rightarrow \Delta L$

Photochemical reaction: $\Delta pH \rightarrow \Delta colore$

Equilibrium between the gravity and spring elastic force: $\Delta M \rightarrow \Delta$✓

Transducers, Sensors, and Electronics

- Measurement instruments are based on **transducers**: devices transforming a quantity from a form of energy into something measurable.
- To measure means to acquire a quantitative information.
- This information is stored, transmitted and/or processed
  - Processing: to merge measures with models generating novel informations.
- Currently, electronics is the technology where all these operations are optimally performed.
- **Sensors** are a class of transducers that transform the quantity of interest into a measurable electric quantity.
- The measurable electric quantities are: magnitude, frequency and phase of voltage.



What is electronics? A functional definition

1952 PROCEEDINGS OF THE I.R.E. 899

Let Us Re-Define Electronics

W. L. Everitt

The passing years modify the nature and scope of all human activities. This has been notably the case for the fields of activity of The Institute of Radio Engineers. There is presented below a keenly analytic consideration of this evolutionary trend in the communications and electronics field. It is a stimulating and thought-provoking treatment of a difficult subject, and includes as well an interesting and constructive semantic proposal.

The author of the following guest editorial is a Fellow and Past President of the IRE, and Dean of the College of Engineering of the University of Illinois. He is widely recognized as one of the leading communications and electronics engineers of this age, and is the author of certain outstanding technical texts.—*The Editor*.

All of us are continually asked, "What is electronics?" In defining a word, it must be remembered that language, like science and industry, is dynamic and constantly changing. As an example, consider the word "football." It started out denoting a game in which the manipulation of the ball was done largely with the feet. As any fan knows, the word now denotes a complicated sport involving strategy, mass movements in attack and defense, and the foot is in contact with the ball only occasionally. Similarly, the word "chivalry" is derived from the word "cheval," or horse. However, it brings to mind a whole code of conduct stemming from the day when knighthood was in flower and the knight was on a horse while the common man went afoot.

Understandably, in defining "electronics" the lexicographer thus far has been too greatly influenced by the etymology—by the meaning of the word "electron." But current definitions are not immutable. The lexicographer follows rather than determines common usage. In defining a word for a dictionary he records how the word is most commonly used by the expert. Therefore it is appropriate that the Institute of Radio Engineers should, from time to time, write its own definition of this word "electronics."

One definition has been, "Electronics is the science and technology of systems using devices in which electrons flow in a gas, no matter how dense or tenuous." This definition is too narrow in 1952. The field of electronics should be considered in terms of its broad concepts; it should not be limited by the devices which it employs. The electron tube has given its name to, but should not determine the boundaries of, electronics. DeForest with his grid introduced a method of continuous control of the flow of current in a circuit, made the amplifier possible, and opened the way to a whole new group of ideas. But control is only one of the many important contributions of electronics.

Fundamentally, electronics is interested primarily in extending man's senses in space, as by the radio, television, and radar; in acuity, as by the electron microscope; in visual or audible range, as by the infrared sniperscope and "ultrasound" detectors; and in speed, as by computers. It is also interested in supplementing man's brain, both by acting as a switchboard and by making comparisons and judgements, for example, servomechanisms and photoelectric inspection systems, and by solving mathematical problems.

Modern industry is founded on the use of mechanical and electrical power to replace man's muscles; electronics more and more provides the routine brain power and nervous system for its control. Man, too, has found need for the extension of his own brain power and sensory organs for his enjoyment and studies.

I would suggest therefore the definition:

> *"Electronics is the science and technology which deals primarily with the supplementing of man's senses and his brain power by devices which collect and process information, transmit it to the point needed, and there either control machines or present the processed information to human beings for their direct use."*

Such a definition will recognize the dynamic character of electronics and its broad scope. When a new device such as the transistor appears, it fits logically into the pattern, even though no electrons flow in an evacuated envelope. When the feedback principle is utilized in a hydraulic servomechanism, we find it also is part of the family.

At the same time, because electronics is so intimately interwoven with other sciences and techniques, we will always expect many byproducts such as the fluorescent light, the high power rectifier, and the atom smasher.

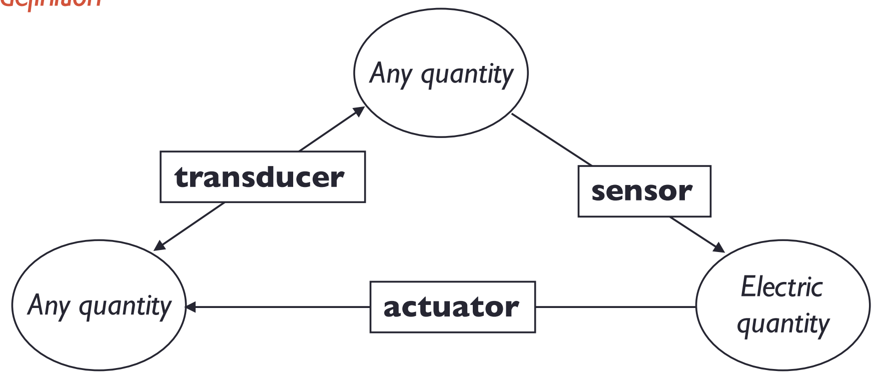
It is probable that the boundaries of this science can only be defined temporarily. Like other dynamic words, "electronics" will need to be re-defined as its expansion continues.

> *"Electronics is the science and technology which deals primarily with the supplementing of man's senses and his brain power by devices which collect and process information, transmit it to the point needed, and there either control machines or present the processed information to human beings for their direct use."*

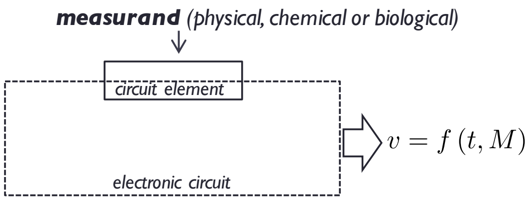
- Electrons are the tool of electronics
  - *"Electronics is the study of the physics of electron and its motion under different conditions"* (E. Gatti, Enciclopedia del Novecento, 1989)

Sensors, Transducers, and Actuators

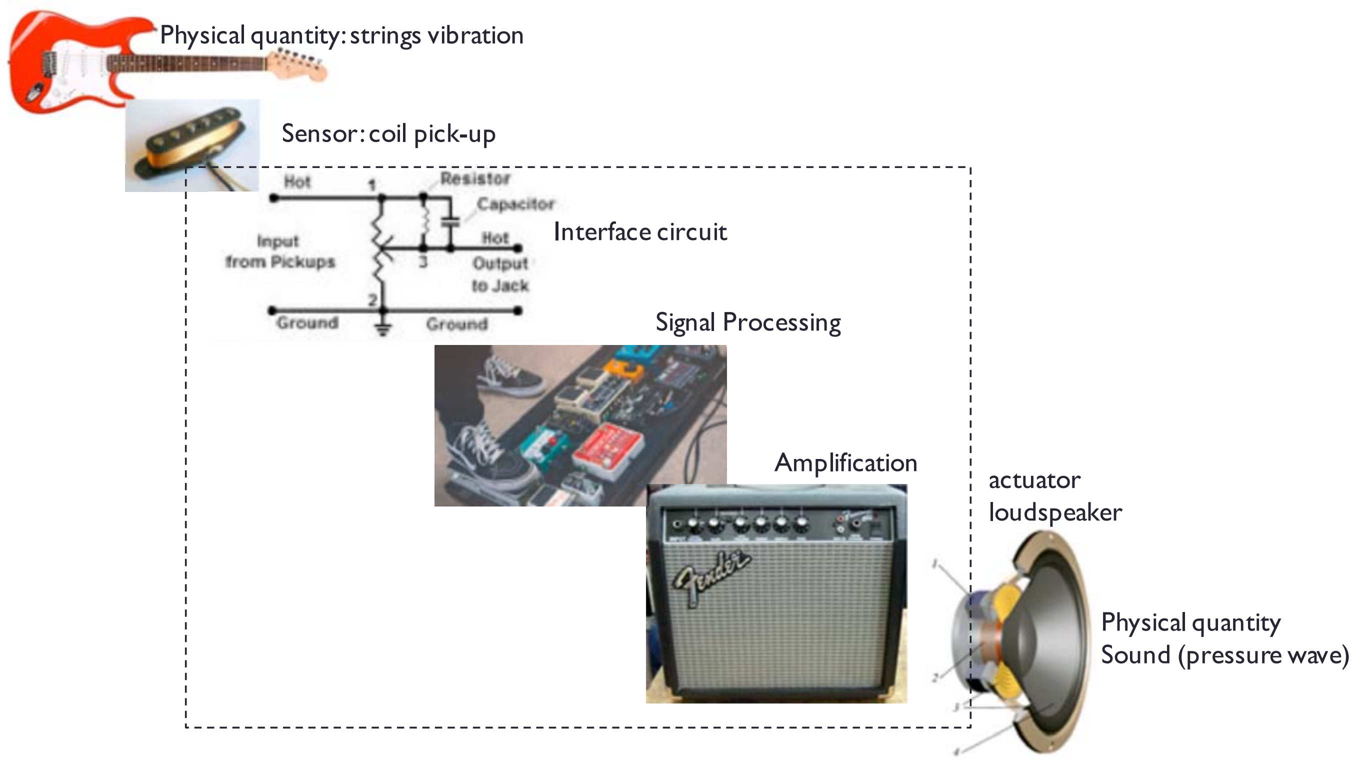
a practical definition



- Sensor: device that converts a physical, a chemical or a biological quantity into an electric signal.
  - Clinical thermometer: temperature → length= transducer
  - Thermistor: temperature→ electric resistance= sensor
- Sensors are components of electronic circuits. Due to sensors, the quantities of the circuit (current and voltage) become function of environmental quantities.



Sensor – Electronics – Actuator chain



Classification of sensors: as electronic devices

- **Resistors**
  - *Thermistor, photoconductor, magnetoresistance, strain gauge, gas sensor…*
- **Inductors**
  - *Position, fluxgate magnetometer,…*
- **Capacitors**
  - *Position, pressure, …*
- **Diodes**
  - *Photodiode, magnetic field sensors,…*
- **MOSFET**
  - *Magnetic field, ions in solution…*
- **Voltage**
  - *Hall probe (magnetic field sensors), ion selective electrodes,…*
- **Electromotive force (emf)**
  - *Thermocouple, Photovoltaic, electrochemical cells (ions and gas sensors)…*

Classification of sensors: sensed quantity and measurement principle

- **the measured quantity**
  - Sensors of physical quantities
    - Temperature
    - Electromagnetic radiation
      - antennas, infrared sensors, visible light, UV, X, γ
    - Magnetic field
      - compasses, position sensors
    - Mechanical quantities
      - Position, strain, acceleration, pressure, flux
  - Sensors of chemical quantities
    - Concentration of chemicals in air
      - gases and vapours
    - Concentration of chemicals in solutions
      - ions and neutral species
  - Sensors of biological quantities
    - Concentrations of compounds in corporeal fluids
      - ions, antibodies, proteins, DNA analysis, viruses and bacterias

- **the sensing principle**
  - Physical sensors
    - Sensors based on physical principles (mechanic or electric) to measure any quantity even non physical
      - e.g. oxygen sensing with magnetic field.
  - Chemical sensors
    - Sensors that uses the properties of molecules to measure any quantity even non chemical
      - e.g. molecular thermometer
  - Biosensors
    - Sensors that uses the properties of biomolecules (e.g. enzymes, peptides, proteins, nucleobases, DNA, cells…) to measure any quantity even non biological
      - e.g. immunosensors to detect pesticides

this course
"sensori chimici e biosensori" Laurea Specialistica in Ingegneria Elettronica (6 CFU)

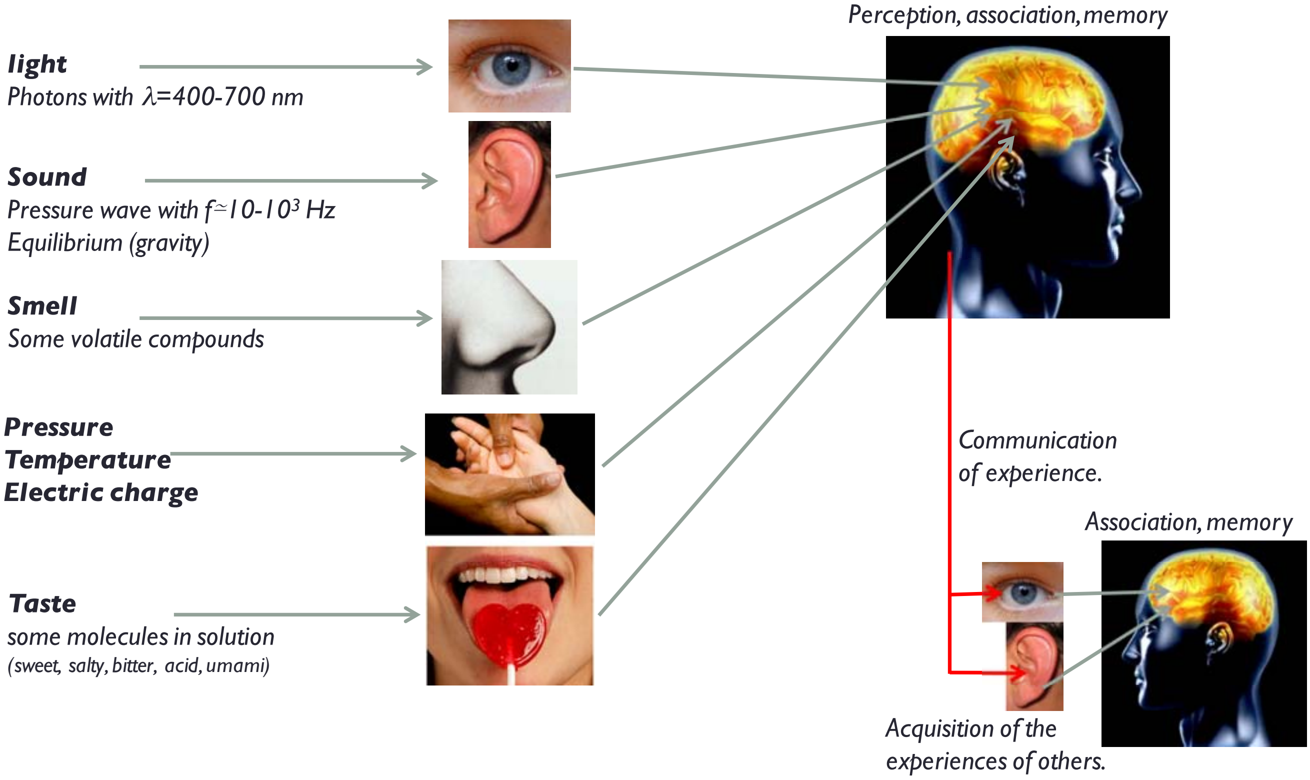
The sensorial paradigm: the living systems

- Living beings interact with their environment through sensorial receptors.
- Two main kinds of receptors:
  - **Physical**: tactile sense, temperature, optic (sight), acustic (hearing)……
  - **Chemical**: olfaction (smell), taste (flavour)
- The signals of receptors (*sensations*) are processed and integrated to form the knowledge (*perception*).
- On the other hand, living beings act in the environment through the actuators
  - Towards outside: mechanical (muscles), acoustic (sounds),…
  - Towards inside: e.g. The organs influence each other with biochemical actuators (hormones)

Jan Bruegel the elder & Peter Paul Rubens
Allegory of the five senses (1617-1618)
Museo del Prado, Madrid

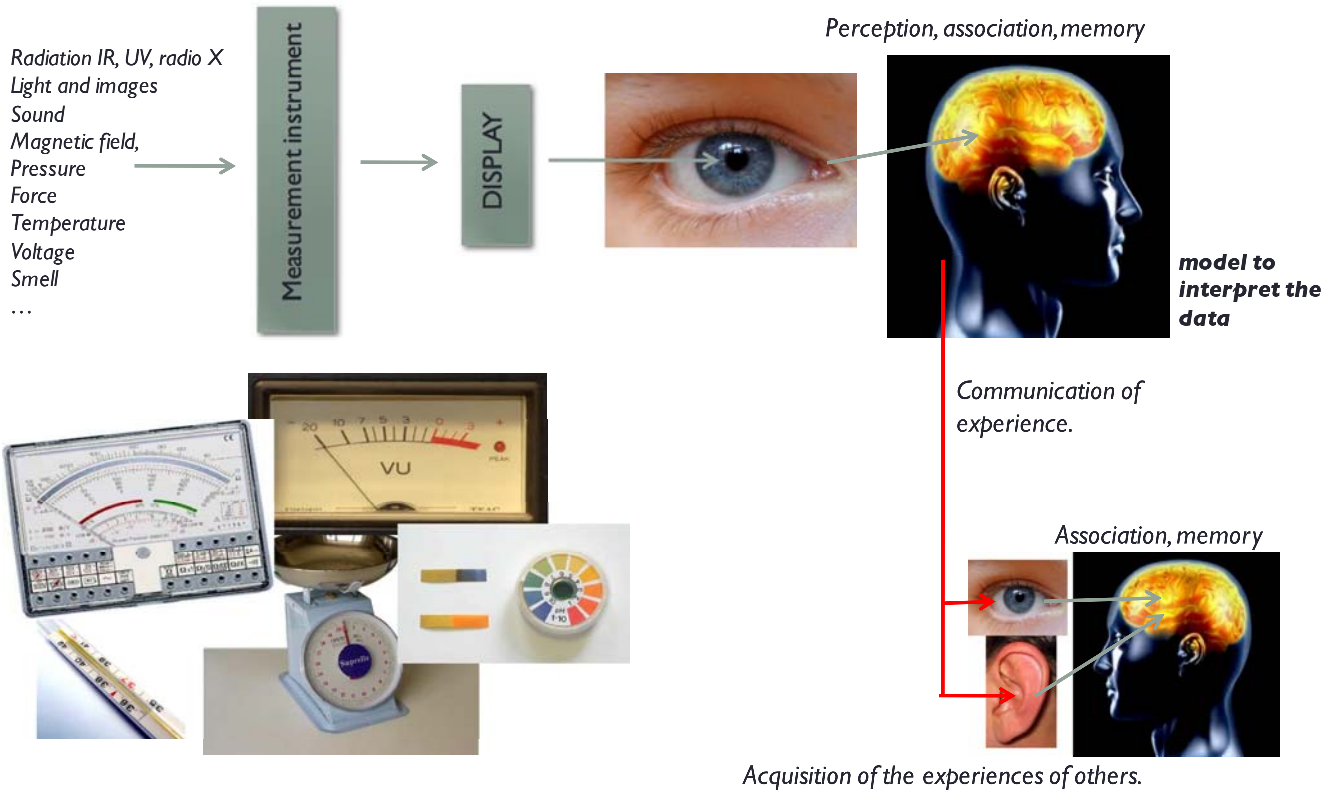
The natural senses

"Nihil est in intellectu nisi prius fuerit in sensu" (St. Thomas Aquinas)
There is nothing in the mind which was not first in the senses



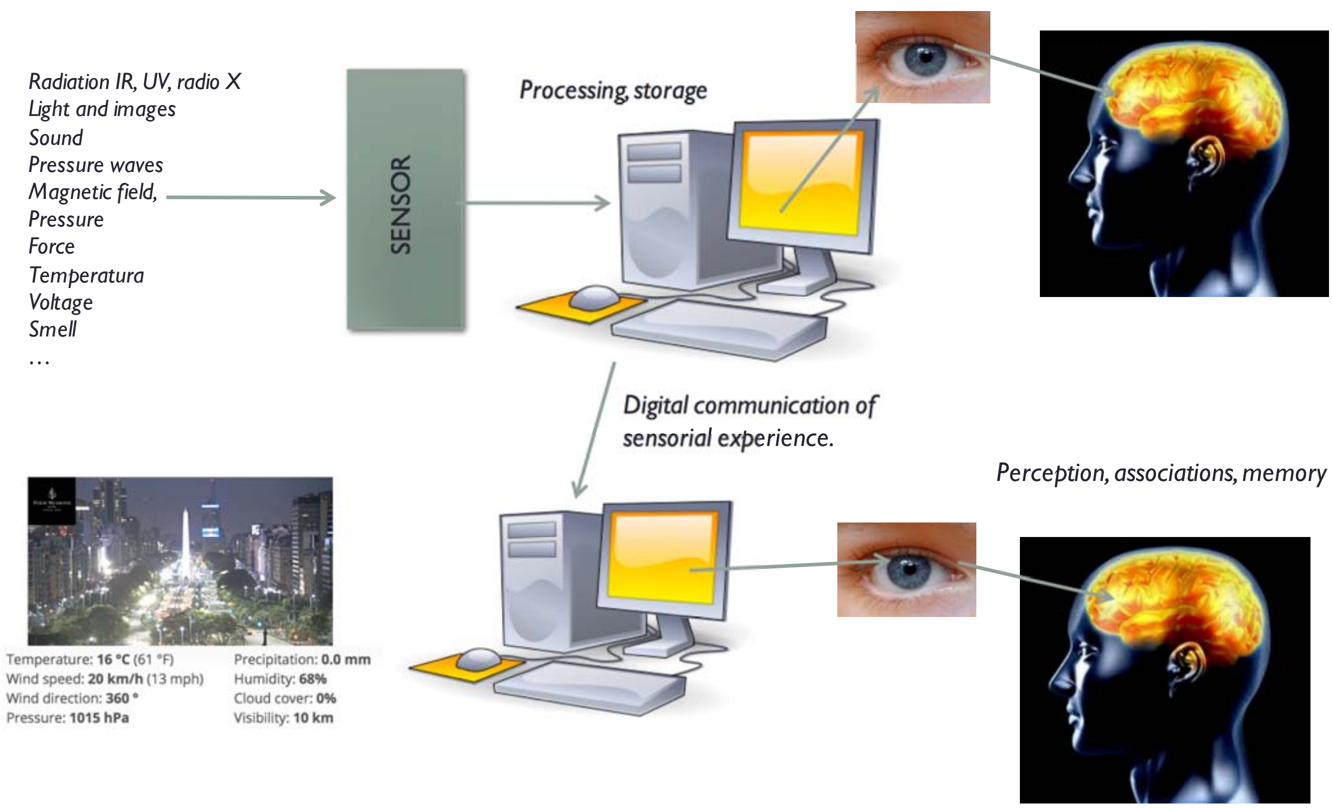
Beyond humans senses

*Measurement instruments make **visible** the imperceptible*



Electronics instrumentation

The measure is independent from the observer, the experience is automatically communicated

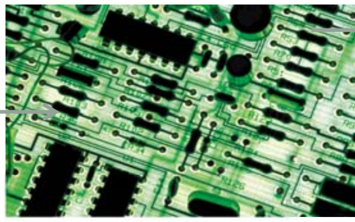


Beyond the senses interface

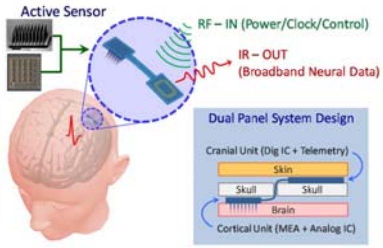
neurons-electronics interface

Radiation IR, UV, radio X
Light and images
Sound
Pressure waves
Magnetic field,
Pressure
Force
Temperatura
Voltage
Smell
...

SENSOR

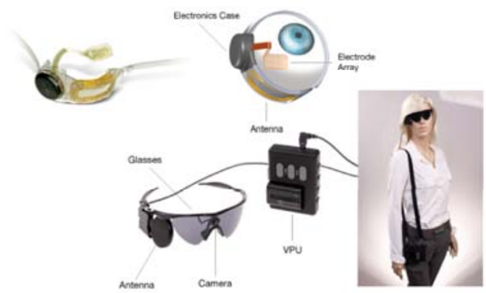


brain-machine interface



http://donoghue.neuro.brown.edu/

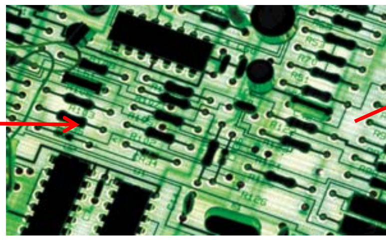
retinal prosthesis: Argus II



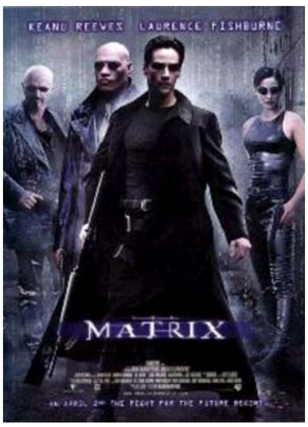
http:\\2-sight.eu

Artificial reality

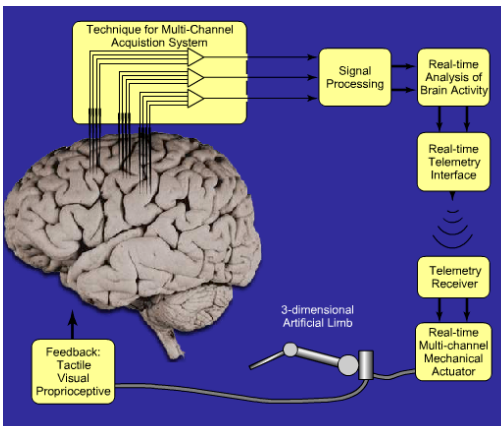
Generator of synthetic sensorial signals



science fiction

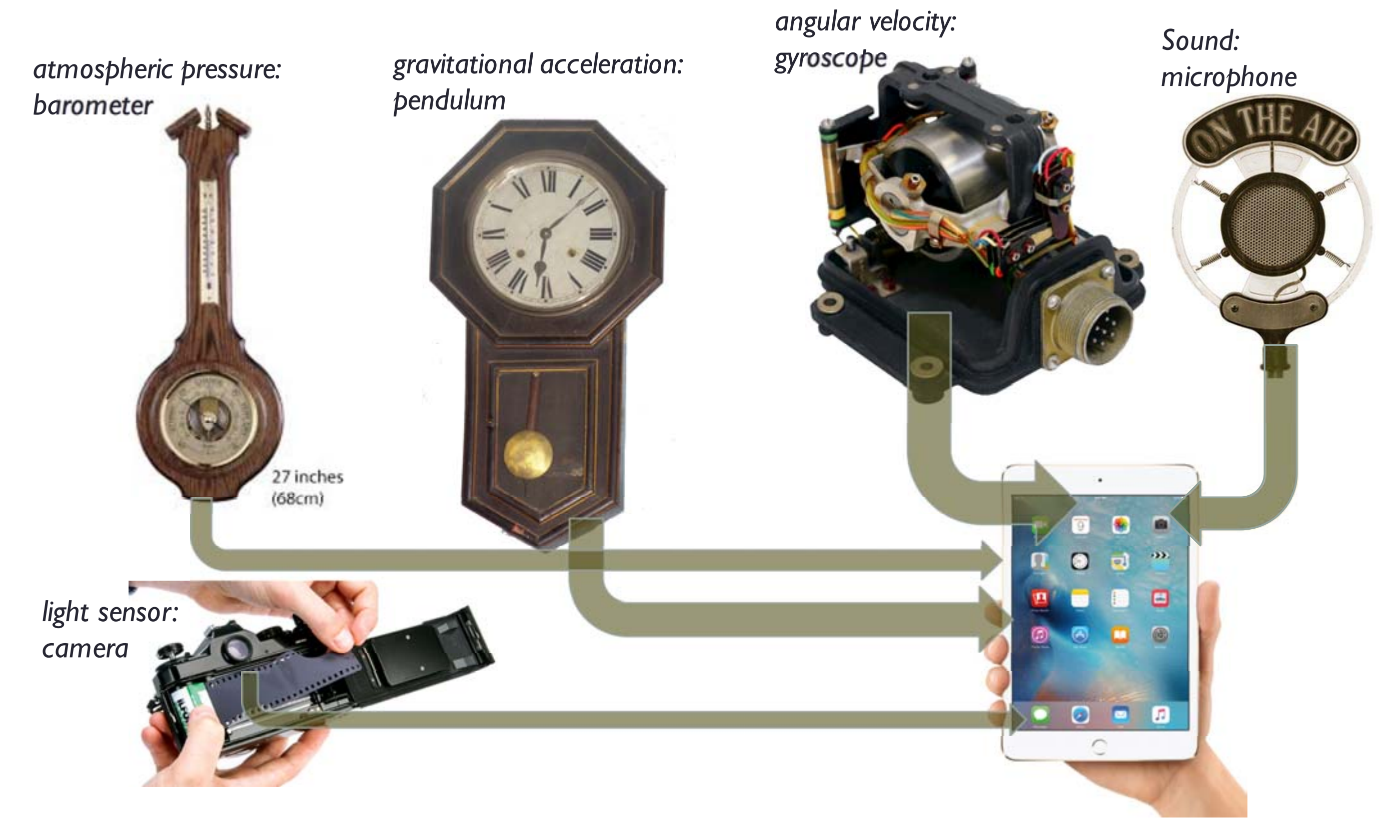


science



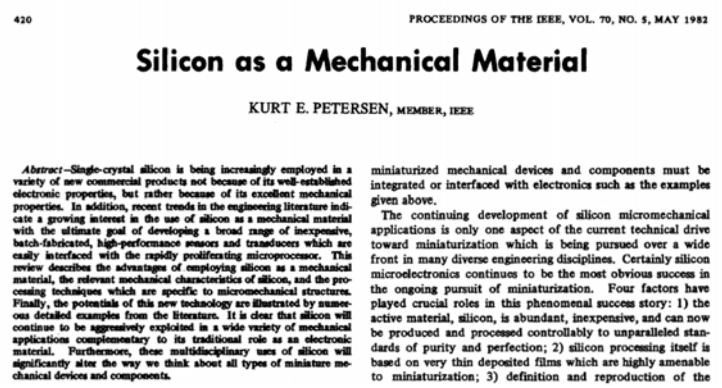
http://www.nicolelislab.net/

From measurement instruments to sensors



Microsensors

- Integrated sensors
  - Silicon technology (microelectronics) enables the fabrication of integrated systems where both the sensitive element and the electronics are integrated in the same chip. MEMS (Micro Electro Mechanical Systems)


420 PROCEEDINGS OF THE IEEE, VOL. 70, NO. 5, MAY 1982

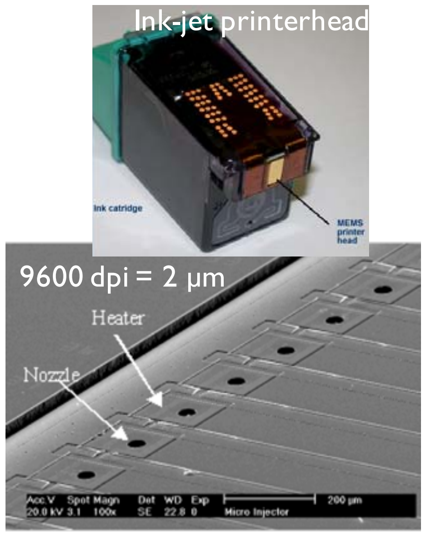
Silicon as a Mechanical Material

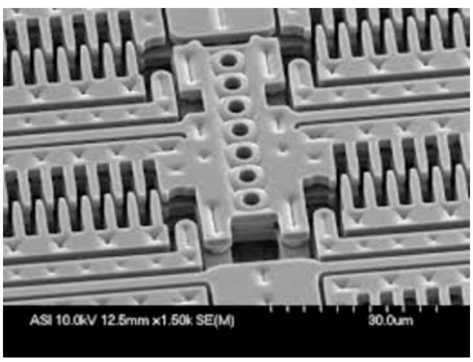
KURT E. PETERSEN, MEMBER, IEEE

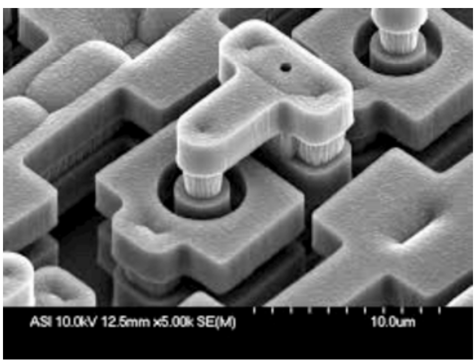
Abstract—Single-crystal silicon is being increasingly employed in a variety of new commercial products not because of its well-established electronic properties, but rather because of its excellent mechanical properties. In addition, recent trends in the engineering literature indicate a growing interest in the use of silicon as a mechanical material with the ultimate goal of developing a broad range of inexpensive, batch-fabricated, high-performance sensors and transducers which are easily interfaced with the rapidly proliferating microprocessor. This review describes the advantages of employing silicon as a mechanical material, the relevant mechanical characteristics of silicon, and the processing techniques which are specific to micromechanical structures. Finally, the potentials of this new technology are illustrated by numerous detailed examples from the literature. It is clear that silicon will continue to be aggressively exploited in a wide variety of mechanical applications complementary to its traditional role as an electronic material. Furthermore, these multidisciplinary uses of silicon will significantly alter the way we think about all types of miniature mechanical devices and components.

miniaturized mechanical devices and components must be integrated or interfaced with electronics such as the examples given above.

The continuing development of silicon micromechanical applications is only one aspect of the current technical drive toward miniaturization which is being pursued over a wide front in many diverse engineering disciplines. Certainly silicon microelectronics continues to be the most obvious success in the ongoing pursuit of miniaturization. Four factors have played crucial roles in this phenomenal success story: 1) the active material, silicon, is abundant, inexpensive, and can now be produced and processed controllably to unparalleled standards of purity and perfection; 2) silicon processing itself is based on very thin deposited films which are highly amenable to miniaturization; 3) definition and reproduction of the

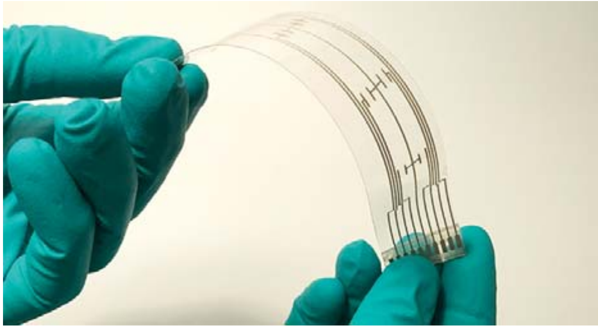






Novel technologies

- Flexible



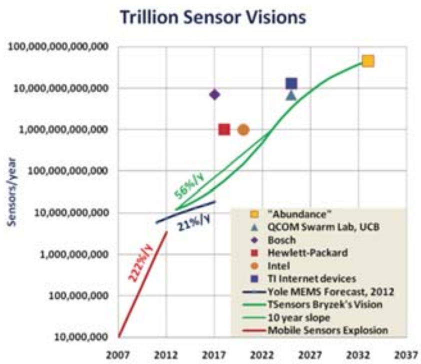
- wearable

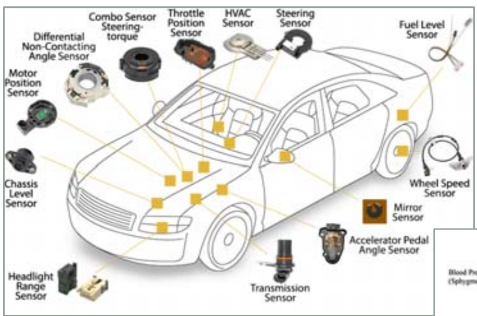
- Electronic skin

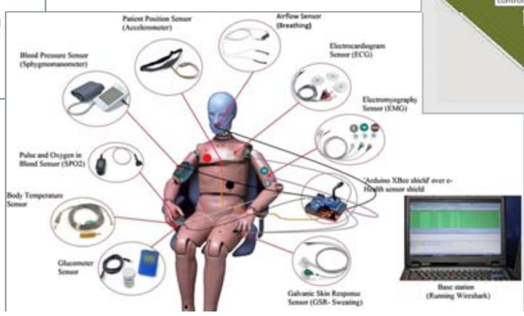
Ubiquitous sensing

- I computer sono sempre più potenti, più piccoli e pervasivi.
- La rete rende il dato disponibile ovunque e a chiunque.
- 10^{12} sensori connessi.
- Big Data

- *microphone*
- *2 image sensors*
- *3D accelerometer*
- *3D gyroscope*
- *Pressure sensor*
- *3D compass*
- *Ambient light sensor*
- *Proximity sensor*



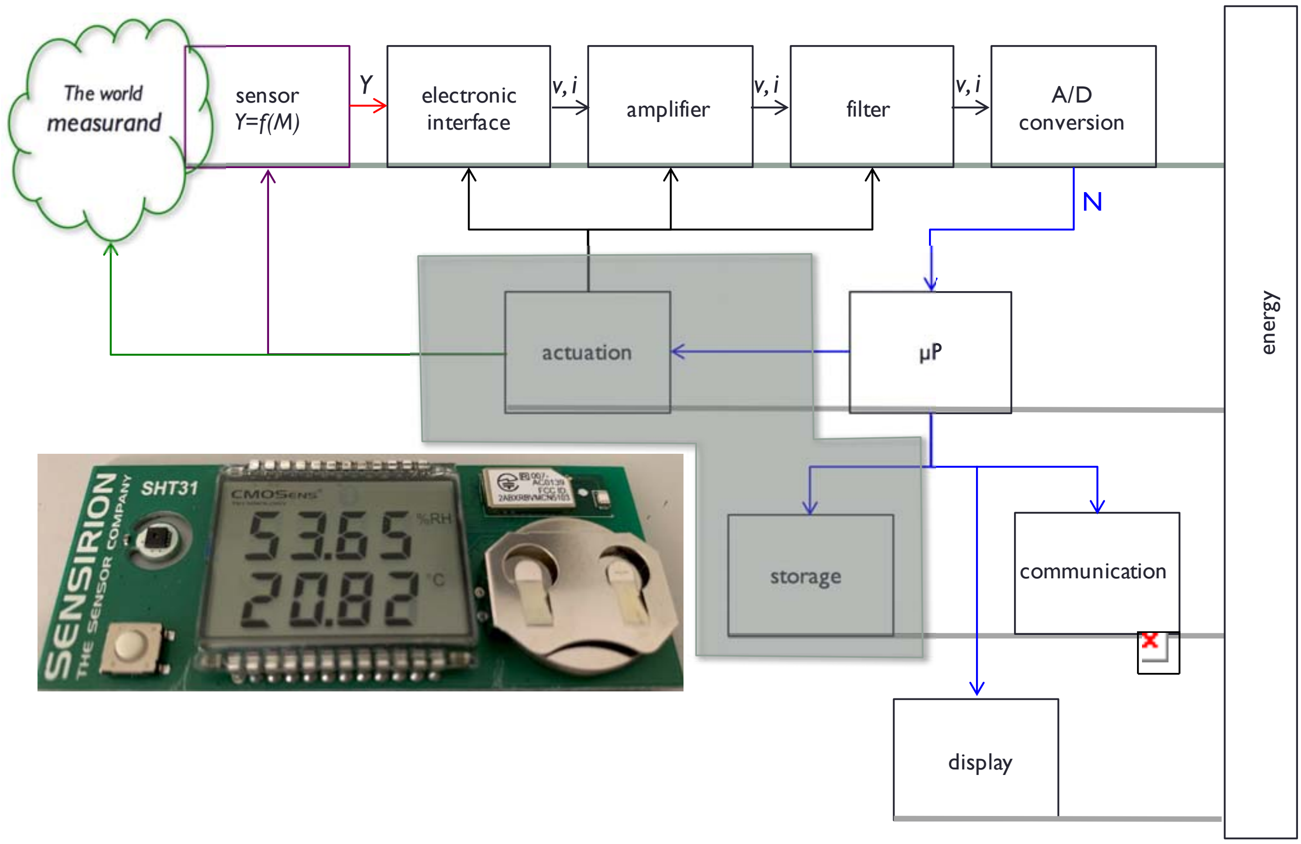




Artificial intelligence

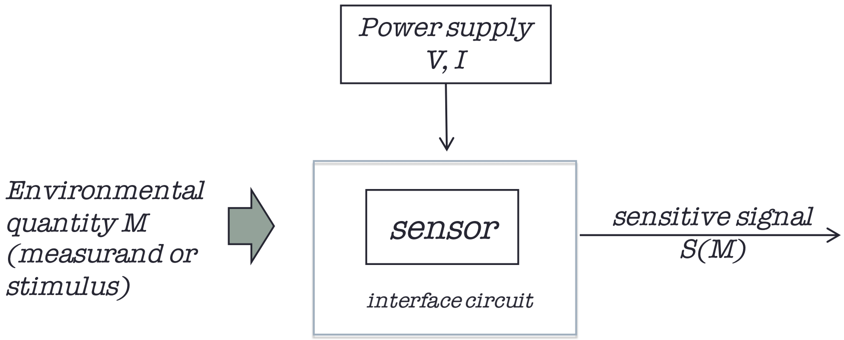
If mind acquires knowledge from sensory experience can sensory experience creates knowledge without the mind?

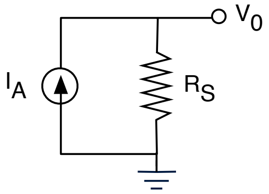
Sensor systems



General parameters of sensors

- Sensor signal
  - A measurable quantity that depends on the sensor itself
  - Except few cases, Most sensors are passive devices: a circuit is necessary to generate the signal.





$R_S(M)$ is the sensor: a resistance whose value depends on some "ambiental" quantity (e.g. Temperature, light, magnetic field, gas, mechanical stress,…)
$V_0(M)$ is the sensor signal whose value depends on R_S and the circuit used to generate the signal.
The circuit is designed to optimize some property of $V_0(M)$

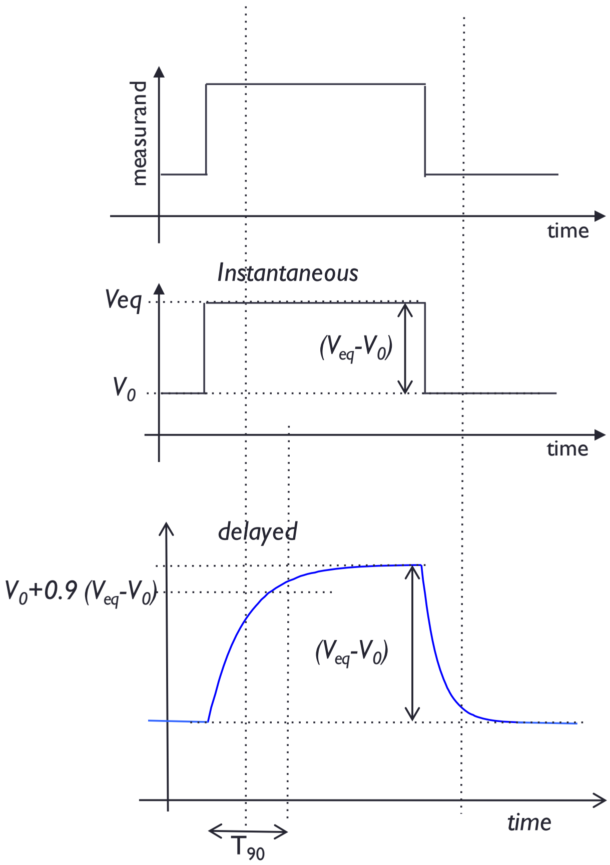
- The actual sensor is *$R_S(M)$, but its value can be evaluated only from the measure of $V_0(M)$.*

Sensor response and feature extraction

- Sensors follows measurand with a proper dynamic. Then the signal always evolves in time.
  - In practice, a sensor is instantaneous when the response time is much shorter than the typical rate of variation of the measurand.
- Synthetic descriptors (features) are extracted from the time evolution of the sensor signal.
  - Absolute steady-state signal (V_{eq})
  - Differential or relative signal (with respect to a baseline V_0 (reference measurand condition)

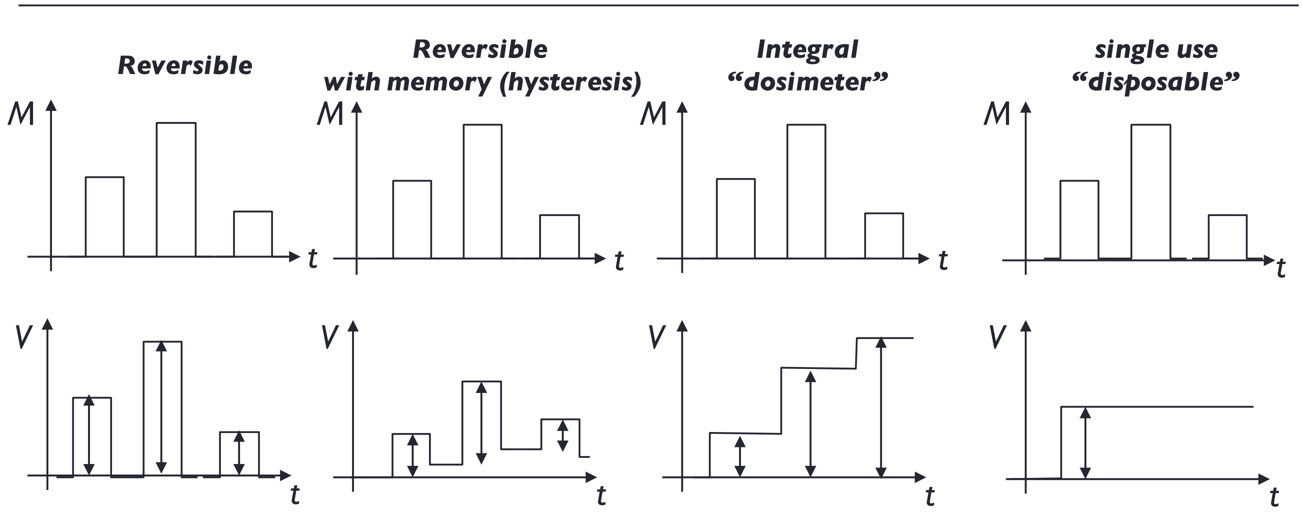
$$V_{eq} - V_0; \quad \frac{V_{eq}}{V_0}; \quad \frac{V_{eq} - V_0}{V_0}$$

  - for delayed sensors:
    - Response time (T_{90})
      - Interval of time necessary to achieve 90% of the steady-state signal.



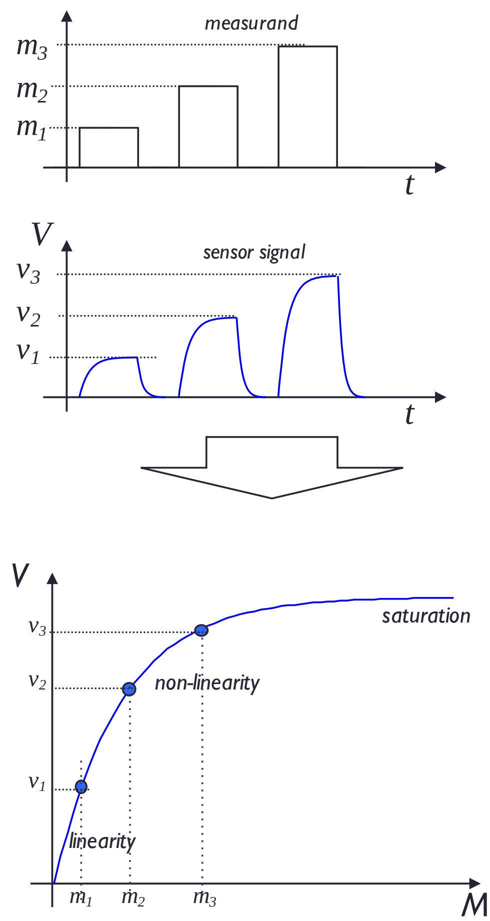
Sensors parameters: *Reversibility*

- *Reversibility* is the capability of a sensor to follow, with its own dynamics, the variations of the measurand.
- A sensor is reversible if, when the stimulus stops, the signal comes back to the pristine value.



Sensors parameters: the response curve

- Each sensor defines a mapping from the space of the measurand to the space of the signals.
- If both these spaces are one-dimensional, the sensor is represented by a function $V=f(M)$ called the *response curve*.
- This function allows utilizing the sensor as a measurement instrument: from the measurand signal, the measurand is estimated.
- Response curves are almost always made by a linear region, a non-linear region and a saturation region.
- The response curve is obtained measuring the sensor signal correspondent to known values of the measurand (*calibration)*
  - These conditions are provided by:
    - Standards: reference samples (e.g. masses) or known experimental conditions (e.g. melting point of ice)
    - Reference instruments: certified instruments used to measure the "true" values of the measurand
  - The performance of the sensor is limited by the goodness of the calibration.

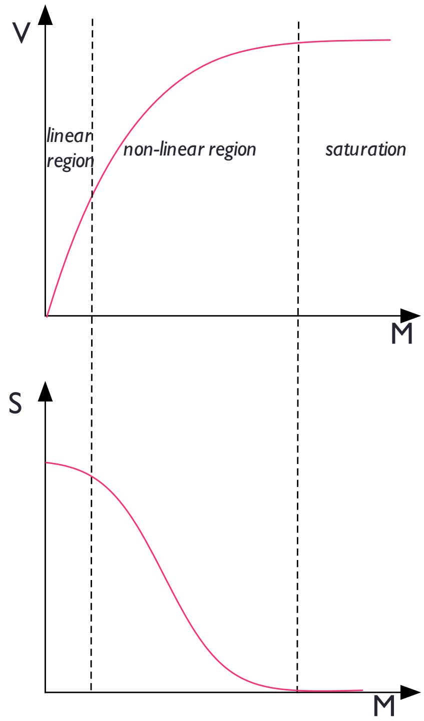


Sensors parameters
Sensitivity

- The sensitivity (S) describes the capability of the sensor to follow the variations of the measurand.
- Analytically, it is the derivative of the response curve

$$S = \frac{dV}{dM}$$

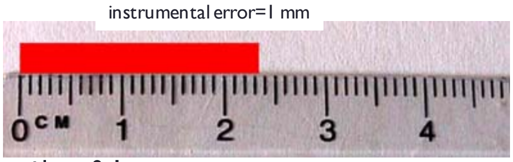
- In case of a non linear response curve, S is a function of the measurand.
- Largest values of S are found in the linear region close to the origin.



Instrumental errors and intrinsic fluctuations

- Every physical measure contains a part of uncertainty.
- This uncertainty comes from the limits of the measurement instrument and from the intrinsic statistical nature of the measured quantity.
- In case of electric quantities, the intrinsic statistical nature is the *electronic noise*.
- Which of the two sources prevail depends on the characteristics of the measurement instrument.

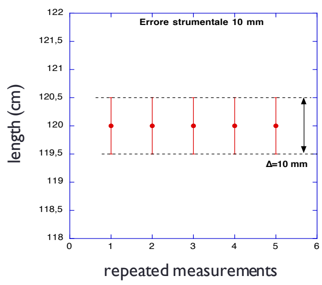
instrumental error=1 mm



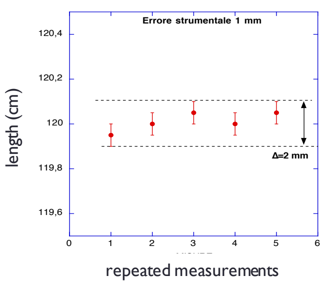
Δl_{min}=0.1 cm
L=(2.3 ÷ 2.4) cm ⇒ 2.35 ± 0.05 cm

Example: repeated measurements of the length of a rod performed with instruments with different measurement errors

Δl_{min}=0.1 cm
L=(2.3 ÷ 2.4) cm ⇒ 2.35 ± 0.05 cm



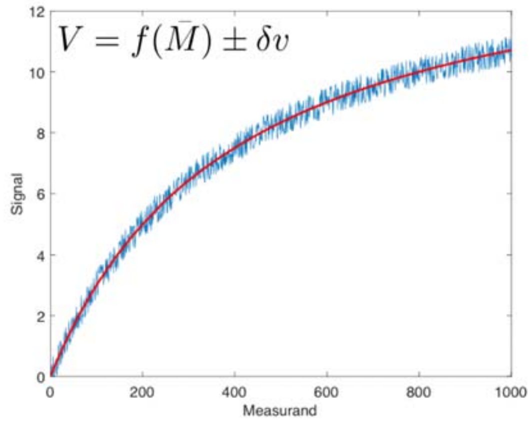
Measurement error hides the intrinsic fluctuation.



Intrinsic fluctuation are observable.

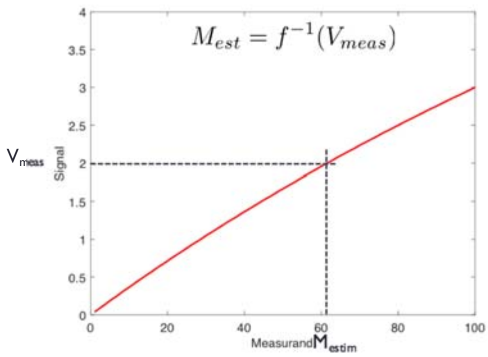
The actual response curve

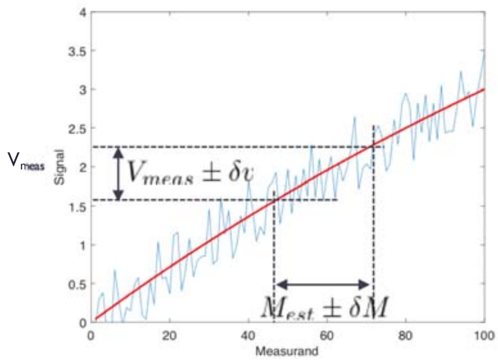
- Due to the fluctuation of the signal and the limited accuracy of the signal measurement, the response curve is modified in a deterministic part function of the average of the measurand [f(M)] and a stochastic part due to the fluctations (δv).



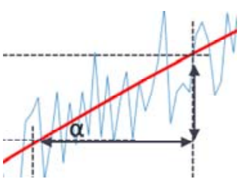
Sensors parameters: Resolution

- Due to the fluctations, the estimation of M is affected by an uncertainty. This uncertainty is quantified by the resolution.
- The resolution is the smallest change of M that produces a observable change of signals.
  - The signal change is larger than the fluctuation





Resolution and sensitivity



$$\delta M = \frac{\delta v}{tan\alpha}$$

$$tan\alpha = \left(\frac{dV}{dM}\right)_{M_{est}} = S(M_{est})$$

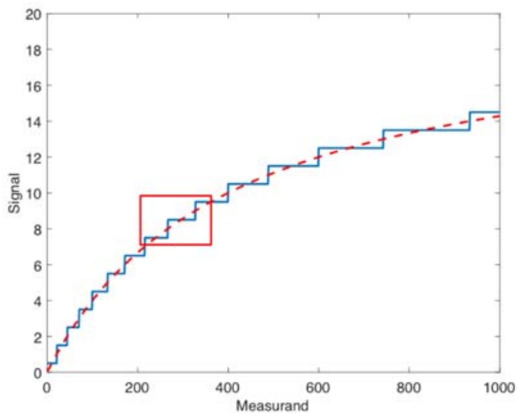
$$\boxed{\delta M = \frac{\delta v}{S(M_{est})}}$$

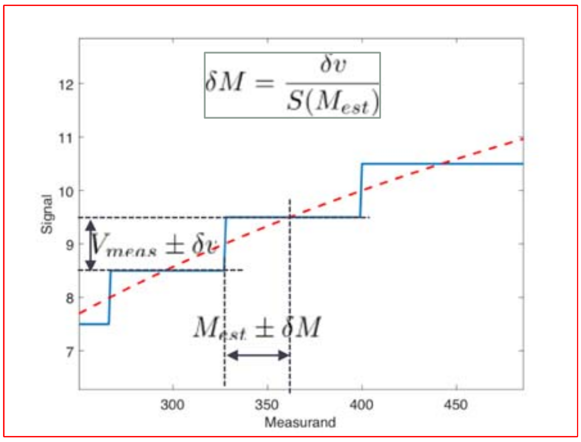
The resolution is inversely proportional to the sensitivity.

Resolution and measurement errors

- Fluctuations are sometimes small, in these cases the resolution is dominated by the measurement error of the instrument used to acquire the signal.
- In practice, the accuracy is defined by the number of bits of the Analog to Digital converter.
- Example: the measurement error due to a 10 bits ADC in a range of 10 V is

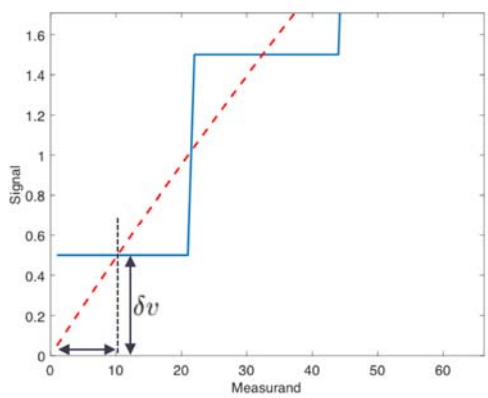
$$\delta v = \frac{10}{2^{10}} = 9.8\ mV$$





Sensors parameters
Limit of detection

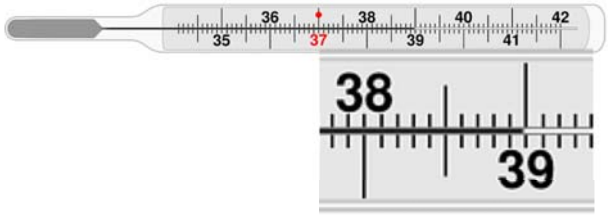
- The limit of detection (LOD) is the resolution evaluated as the signal approaches zero.
- The origin of the response curve is not accessible by a measurement but by the analytical extension of the response curve.
- When the resolution is determined by the noise, the LOD is the smallest theoretical measurable quantity.



$$M_{LOD} = \frac{\delta V}{S(M=0)}$$

Generalized sensitivity and resolution

- The concepts of sensitivity and resolution are valid for any input/output system
  - e.g. clinical thermometer



$$S = 10\ \frac{ticks}{°C}$$

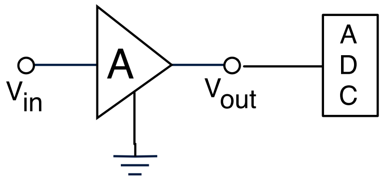
$$N_{tick,\ err} = \frac{1}{2}\ ticks$$

$$\Delta T_{ris} = \frac{N_{tick,\ err}}{S} = \frac{1}{2 \cdot 10} = 0.05°C$$

  - e.g. amplifier

$$S = A = \frac{V_{out}}{V_{in}}$$

$$V_{in,res} = \frac{\Delta V_{out}}{A}$$

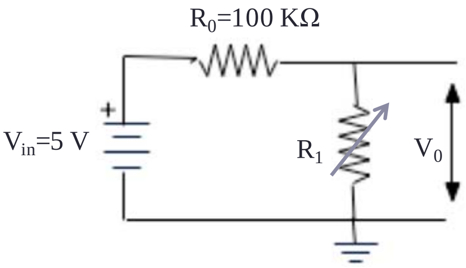


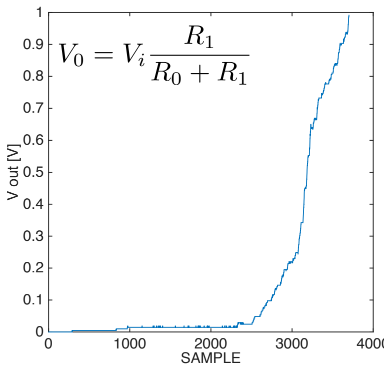
example:
$A = 100;\ V_{out} = [-12;\ +12]\ V;\ ADC_{res} = 10\ bit$

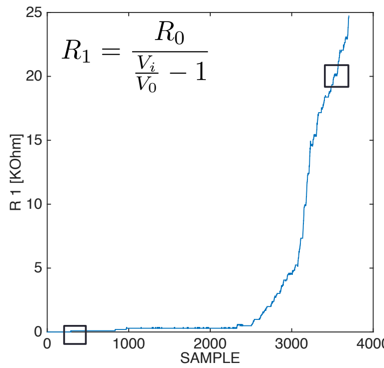
$$\Delta V_{out} = \frac{24}{2^{10}} = 23\ mV;$$

$$V_{in,res} = \frac{23}{100} = 230\ \mu V$$

Resistance measurement with a voltage divider







Response curve V_0=f(R_1) is not linear, then the resolution depends on R_1.

$$\Delta V_{0,err} = \frac{V_i}{2^{10}} = 4\ mV$$

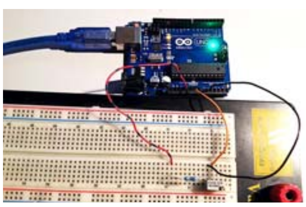
$$S = \frac{dV_0}{dR} = V_i \frac{R_0}{(R_0 + R_1)^2};$$

$$S_{R_1=0} = \frac{V_i}{R_0} = \frac{5}{100 \cdot 10^3} = 49\ \mu A$$

$$S_{R_1=20K\Omega} = 5\frac{100}{120^2} = 35\ \mu A$$

$$R_{1,LOD} = \frac{\Delta V_{0,err}}{S_{R_1=0}} = \frac{4 \cdot 10^{-3}}{49 \cdot 10^{-6}} = 81\ \Omega;$$

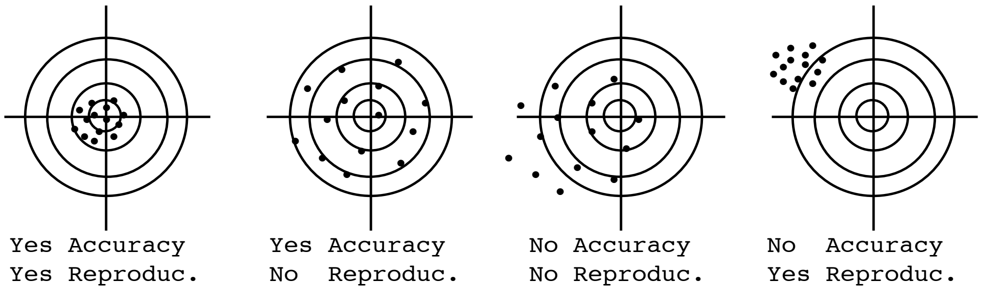
$$R_{1,res20K\Omega} = \frac{\Delta V_{0,err}}{S_{R_1=20K\Omega}} = \frac{4 \cdot 10^{-3}}{35 \cdot 10^{-6}} = 114\ \Omega;$$



Limit of detection and resolution: smallest measurable resistance
Arduino UNO ADC: 10 bit

Sensors parameters
Accuracy and Reproducibility

- Sistematic and random errors define the accuracy and the reproducibility of a sensor.
- **Accuracy** is the difference between estimated and "true" value of measurands.
  - the true value is not accessible because each measurement is always affected by an error. Accuracy is defined respect to a "reference" measurement system
- **Reproducibility** (or **precision**) is the dispersion of repeated measurements performed in the same conditions.
- Both terms are statistical quantities: given N measures, the accuracy is associated to the average and the reproducibility to the variance.



Electronic noise

- The electronic noise is the macroscopic manifestation of the statistical nature of the electric phenomena.
  - Current: collective motion of a large number of individual particles.
  - thermal and drift velocities are average quantities
- General properties of noise:
  - zero average
  - described by a probability function
  - frequency distribution (spectral density)
  - root means square value different from zero

Spectral density of noise

- The noise is described by a power spectral density

$$p_n = \frac{dP_n}{df} \left[\frac{W}{Hz}\right]$$

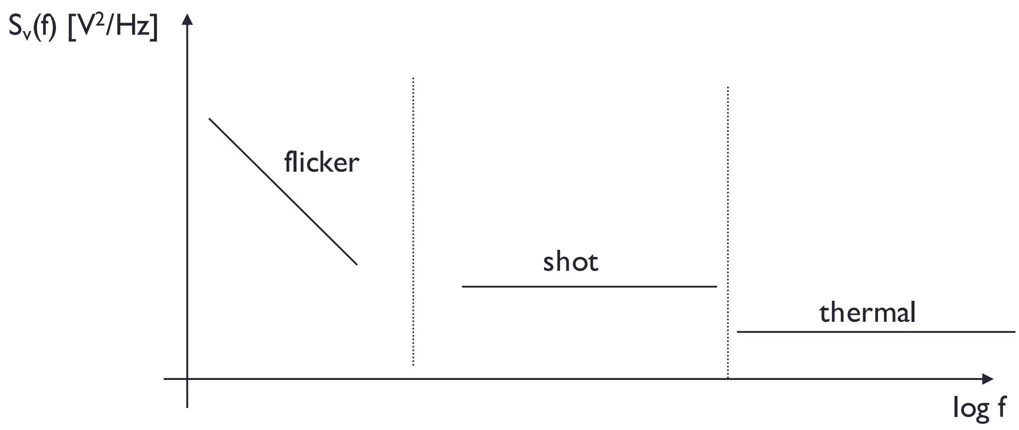
- Then, the spectral densities of voltage and current are:

$$v_n = \sqrt{\frac{dV_n^2}{df}} \left[\frac{V}{\sqrt{Hz}}\right]; \quad i_n = \sqrt{\frac{dI_n^2}{df}} \left[\frac{A}{\sqrt{Hz}}\right]$$

- Voltage and current are obtained from the respective spectral densities integrating the spectral density in a frequency interval defined by the measurement conditions:

$$V_n[f_1 \rightarrow f_2] = \sqrt{\int_{f_1}^{f_2} v_n^2\, df} \ [V]; \quad I_n[f_1 \rightarrow f_2] = \sqrt{\int_{f_1}^{f_2} i_n^2\, df} \ [A];$$

Spectral densities of typical noises



$$thermal: \ S(f) = 4kTR$$
$$shot: \ S(f) = 2aI_o$$
$$flicker: \ S(f) = \frac{K}{f^{\alpha}} \ [\alpha \approx 1]$$

Shot and flicker are excess noises: they can be observed only in biased materials.
Thermal noise is observed without bias.

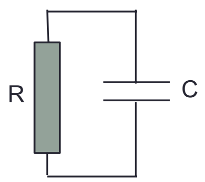
Thermal noise

(a.k.a. *Johnson noise* or *Nyquist noise*)

- Electrons, kept in movement by the thermal energy, are continuosly scattered by fixed atoms. Scattering ensures the thermal equilibrium between electrons and atoms.
- Thermal noise is the electric manifestation of the random motion of electrons. It was firstly observed by Johnson and theoretically explained by Nyquist (1928, Bell Lab)
- It is common to all conductors (0<R<∞) and it does not depend on the applied voltage.
  - thermal velocity is greater than drift velocity
- The spectral density of thermal noise is equally distributed in frequency for this reason it is also called *white noise*.
- Nyquist explained the thermal noise using statistical mechanics arguments, here a proof based on electric network is given (Van der Ziel, 1954)

Thermal Noise in a resistor

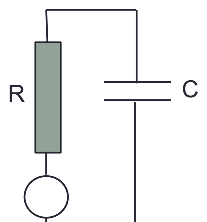
Van der Ziel, 1954



Let us consider a RC circuit.
The random motion of electrons charges the capacitance.
The average energy of a system in thermal equilibrium is kT/2 (for each degree of freedom)
Then the average energy stored in the capacitance is:

$$\frac{1}{2}C\cdot\overline{V}_C^2=\frac{1}{2}k\cdot T \Rightarrow \overline{V}_C^2=\frac{k\cdot T}{C} \quad (*)$$

thermal noise of a ideal capacitor

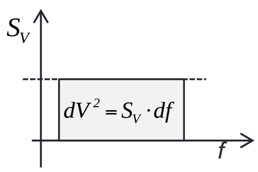


$dV=(S_V\cdot df)^{1/2}$

Let us add a voltage supplier whose power spectral density is equally distributed in frequency.
The voltage drop across the capacitance is:

$$d\overline{V}_C=\frac{1}{j\cdot\omega\cdot C}\frac{(S_V\cdot df)^{1/2}}{R+\frac{1}{j\cdot\omega\cdot C}}=\frac{(S_V\cdot df)^{1/2}}{j\cdot\omega\cdot C\cdot R+1};\qquad d\overline{V}_C^2=\frac{S_V\cdot df}{1+(\omega\cdot R\cdot C)^2}$$

$$\overline{V}_C^2=\int_0^\infty\frac{S_V\cdot df}{1+(2\cdot\pi\cdot f\cdot R\cdot C)^2}=\frac{S_V}{2\cdot\pi\cdot R\cdot C}\int_0^\infty\frac{dx}{1+x^2}=\frac{S_V}{2\cdot\pi\cdot R\cdot C}\left[\tan^{-1}x\right]_0^\infty=\frac{S_V}{2\cdot\pi\cdot R\cdot C}\frac{\pi}{2}=\frac{S_V}{4\cdot R\cdot C} \quad (*)$$



Equating the two expressions (*) the voltage source equivalent to the thermal noise is calculated:

$$\frac{k\cdot T}{C}=\frac{S_V}{4\cdot R\cdot C} \Rightarrow S_V=4\cdot k\cdot T\cdot R$$

Thermal noise

- The noise voltage across a resistance R is:

$$V_n = \sqrt{4 \cdot k \cdot T \cdot R \cdot B}\ [V]$$

- where B is the frequency interval defined by the measurement of V_n

examples at T=300 K:

$$B = 1\ KHz;\ R = 1\ K\Omega\ \Rightarrow V_n = 0.129\ \mu V$$
$$B = 1\ KHz;\ R = 100\ \Omega\ \Rightarrow V_n = 41\ nV$$

- At room temperature (T=300 K)

$$V_n = 0.129 \cdot \sqrt{R[M\Omega] \cdot B[Hz]}\ \mu V$$

- Thermal noise can also be expressed as a current source

$$I_n = \frac{V_n}{R} = 0.129 \cdot \sqrt{\frac{B[Hz]}{R[M\Omega]}}\ pA$$

Shot noise

- Manifestation of the granular nature of the charges when they cross a junction between two materials.
  - The motion of electrons in a homogeneous conductor is deterministic : each electron undergoes a force –qE, then the motion of electrons is correlated.
  - In junctions the relevant phenomenon is the barrier crossing, in this case each electron has an individual probability to cross the barrier, and individual events are uncorrelated. This is analog to the emission of photons from a light source. These kinds of events are described by the Poisson distribution function.
- Shot noise is an excess noise, namely it is observed only as superimposed to a biasing current.

$$I_n = \sqrt{2 \cdot q \cdot I \cdot B} = 5.66 \cdot 10^{-10} \sqrt{I \cdot B}$$
$$I_n[pA] = 0.566\sqrt{I \cdot B}. \quad with\ I[\mu A]$$

Flicker noise or 1/f noise

- Excess noise found in many different phenomena.
- In semiconductors it has been explained as the global effect of an ensemble of traps each with a different lifetime (Van der Ziel, 1976). It is important in MOSFETs where the current flows at the oxide-semiconductor interface in a region characterized by a large density of traps.
- It grows as the frequency decreases

$$S = \frac{K}{f^{\alpha}} \quad con\,\alpha \approx 1$$

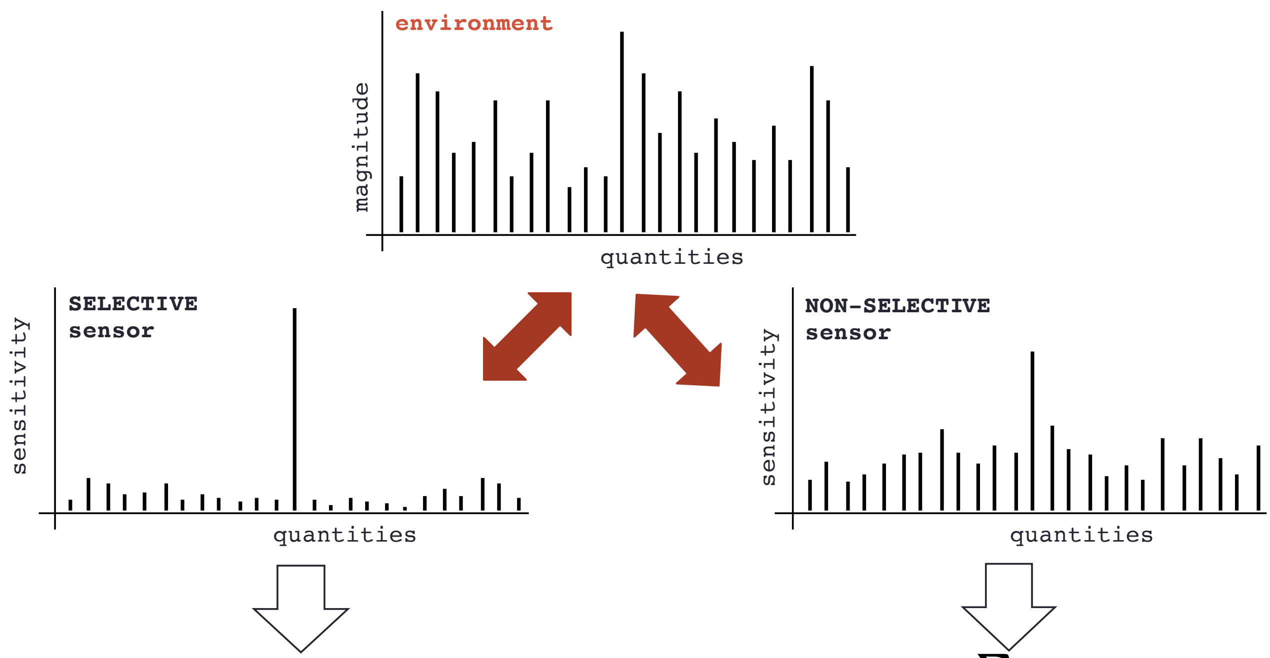
$$V_n = K\sqrt{\int_{f_1}^{f_2} \frac{1}{f} df} = K\sqrt{\log\frac{f_2}{f_1}}$$

- The amount of noise depends on the ratio f_2/f_1.
  - The noise observed in different decades is the same.
    - V_n[1 KHz – 10 KHz]=V_n[0.01 KHz – 0.001 KHz]
    - If the noise in the decade (0.1 Hz -1 Hz) is 1 μV, then the noise in 9 decades (10^{-9} Hz – 1 Hz) is:

$$\sqrt{9} \cdot 1\mu V = 3\mu V$$

    - 10^{-9} Hz = 30 years!

Sensors parameters selectivity and cross-sensitivity

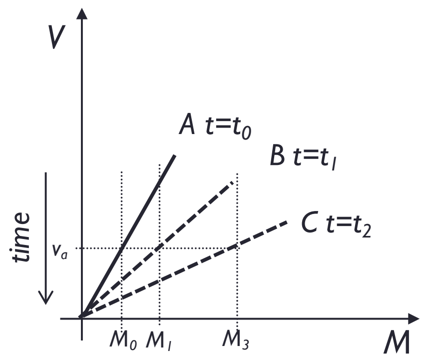


$$V = S_j \cdot M_j + err$$

$$V = \sum_k S_k \cdot M_k$$

Sensors parameters: drift

- Progressive deterioration of the sensitivity
- Sensitivity changes with the time, then drift is an additional systematic error that affects the estimation of the measurand
- Drift affects the calibration lifetime.

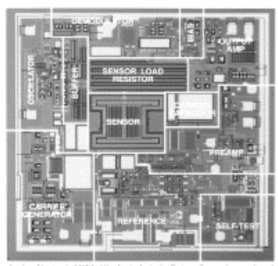


- A is the response curve calibrated at $t=t_0$.
- B, and C are the actual, but unknown, curves at $t=t_1$ and $t=t_2$. respectively.
- The signal corresponding to a constant stimulus M_A becomes progressively smaller.
- The obsolete response curve results in a measurand underestimation.

$$M_0 = \frac{v_a}{k_{(t_0)}} < M_1 = \frac{v_a}{k_{(t_1)}} < M_2 = \frac{v_a}{k_{(t_2)}}$$

Examples of parameters of a real sensor:
accelerometer ADXL50A

the practical unit for acceleration is the gravitational acceleration 1 g = 9.8 m/s²



Analog Devices' ADXL-50, the industry's first surface micromachined accelerometer, includes signal conditioning on chip.

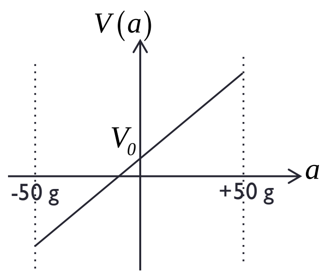
- response curve

$$V(a) = V_0 + a \cdot K \quad V_0 = 1.8\,V\,;\ K = 0.019\,\frac{V}{g}$$

$$\Rightarrow \boxed{a = \frac{V - 1.8}{0.019}\,g}$$

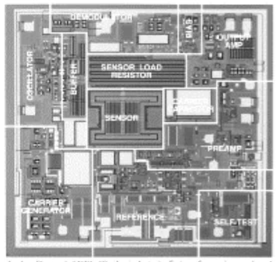
- Sensitivity

$$S = \frac{dV}{da} = K \quad S = 19\,\frac{mV}{g}$$



- Dynamic range=±50 g
  - The sensitivity is constant throughout the dynamic range

Parameters of a real sensor:
accelerometer ADXL50A



Analog Devices' ADXL-50, the industry's first surface micromachined accelerometer, includes signal conditioning on chip.

- Noise
  - Spectral density of thermal noise

$$125\frac{\mu V}{\sqrt{Hz}}$$

  - If the signal is filtered by a low-pass filter with a corner frequency of 10 Hz, the rms value of the noise is:

$$V_{noise,rms} = 125\frac{\mu V}{\sqrt{Hz}} \cdot \sqrt{10Hz} = 395\mu V$$

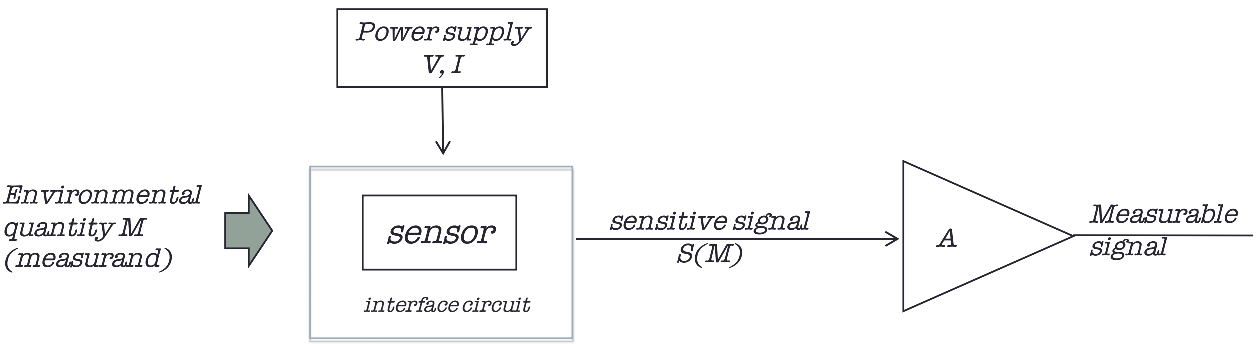
- Resolution

$$a_{res} = \frac{V_n}{S} = \frac{125\frac{\mu V}{\sqrt{Hz}}}{19\frac{mV}{g}} = 6.6\frac{mg}{\sqrt{Hz}}$$

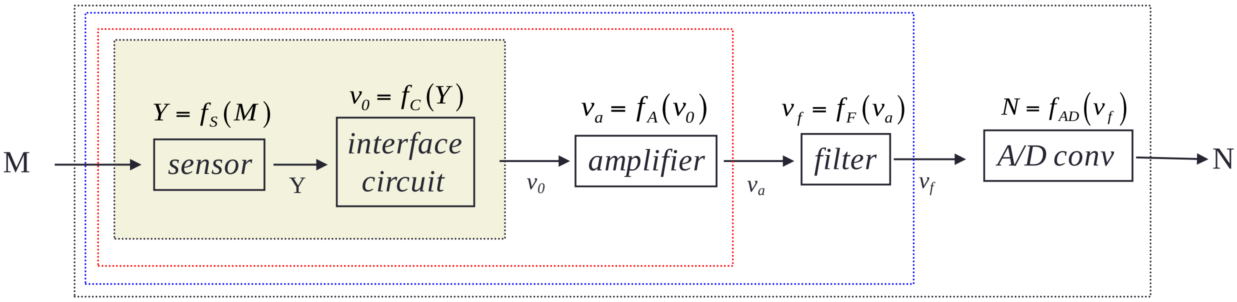
  - With a bandwidth of 10 Hz the resolution is 20 mg.
  - Airbag control needs a quick measurement of the acceleration, T=0.1 ms → B=10 KHz → a_{res}=0.6 g

Some issues about electronics for sensors

- Most sensors are passive devices able to condition the networks at which they are connected.
- Due to the sensor, the electric quantities (current and voltage) become function of outer world quantities.



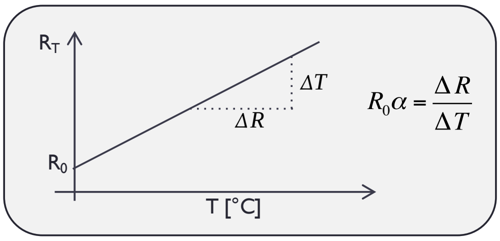
Total sensitivity



- Each block is characterized by a proper sensitivity
- The global sensitivtity is the combination combining all blocks

$$S = \frac{dN}{dM} = \frac{dN}{dv_f}\cdot\frac{dv_f}{dv_a}\cdot\frac{dv_a}{dv_0}\cdot\frac{dv_0}{dY}\cdot\frac{dY}{dM} = \frac{df_{AD}}{dv_f}\cdot\frac{df_F}{dv_a}\cdot\frac{df_A}{dv_0}\cdot\frac{df_C}{dY}\cdot\frac{df_S}{dM}$$

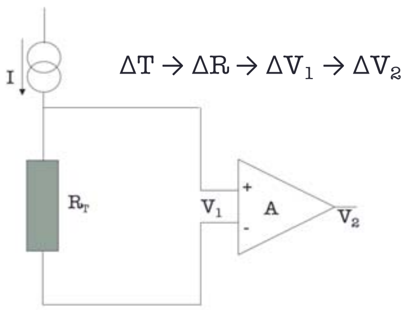
Example: temperature sensitive resistor

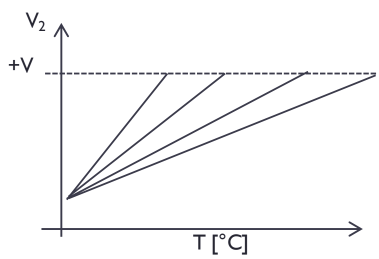


$$R_T(T) = R_0(1+\alpha T);$$
$$V_1 = R_T(T)\cdot I_0$$
$$V_2 = A\cdot V_1 = A\cdot I_0\cdot R_0(1+\alpha T)$$

$$S = \frac{\partial V_2}{\partial T} = \frac{\partial V_2}{\partial V_1}\cdot\frac{\partial V_1}{\partial R}\cdot\frac{\partial R}{\partial T}$$
$$S = A\cdot I_0\cdot\alpha\cdot R_0$$

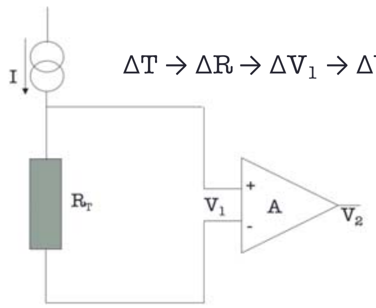
$$S = \prod_j S_j$$





- Apparently: arbitrary values of sensitivity can be obtained combining the sensor with circuit parameters.
- Signal limitations restrict the dynamic range
  - V_2 is confined in [-V +V] range

Example: resolution of a temperature sensitive resistance



$\Delta T \rightarrow \Delta R \rightarrow \Delta V_1 \rightarrow \Delta V_2$

$$S = \frac{\partial V_2}{\partial T} = \frac{\partial V_2}{\partial V_1} \cdot \frac{\partial V_i}{\partial R} \cdot \frac{\partial R}{\partial T} = S_i \cdot S_T \cdot S_A$$

$$S = A \cdot I \cdot \alpha \cdot R_o$$

$$\Delta T_{res} = \lim_{\Delta V_2 \to V_{noise}} \frac{\Delta V_2}{|S_{tot}|} = \lim_{\Delta V_2 \to V_{noise}} \frac{\Delta V_2}{A \cdot I \cdot \alpha \cdot R_o}$$

$$\Delta T_{res} = \lim_{\Delta V_2 \to V_{noise}} \frac{\Delta V_2}{\prod_j |S_j|}$$

- Arbitrary increase of sensitivity does not improve the resolution
  - The amplifier is applied to both signal and noise, then it doesn not increase the performance.
  - Noise increases with the current level and the resistance

$$V_{noise}^2 = A^2 V_{n1}^2 + V_{nA}^2 = A^2 \cdot \left(V_{johnson}^2 + R_T^2 \cdot I_n^2\right) + V_{nA}^2$$

$$V_{noise}^2 = A^2 \cdot \left(4kTR_T B + R_T^2 \cdot \underset{\propto I}{\underset{\uparrow}{I_n^2}}\right) + \underset{\propto A}{\underset{\uparrow}{V_{nA}^2}}$$