Chapter 1

Characteristics of a measurement system

Chapter 1. Characteristics of a measurement system

- Introduction
- Basic definitions
- Types of measurements
- Different possible errors

Chapter 1. Characteristics of a measurement system

Introduction

Metrology is the set of techniques and expertise that enable measurements to be taken and sufficient confidence to be placed in their results.

Measurement is necessary for all knowledge, decision-making and action.

The logic behind any activity is:

- observe/measure,
- understand,
- predict/act,
- measure/verify.

- **Measurand**: The specific physical quantity being measured.
-Direct method: the value of the measurand is obtained directly by reading a device.

- Indirect method: the value of the measurand is a function of other measurements
- **Measurement (x):** The evaluation of a physical quantity by comparison with another quantity of the same nature taken as a unit.
- **Measurement:** all operations used to measure a physical quantity (measurand).

- **Uncertainty (dx)**: The result of the measurement x of a quantity X is not completely defined by a single number. It must be characterised by at least a pair (x, dx) and a unit of measurement. Thus, we have: $x-dx < X < x+dx$

Example: 3 cm ±10%, or 5 cm ± 1 cm.

Unit:

- In a set of quantities, it is a particular quantity chosen as a reference to which all others are compared.

- Lengths are measured by comparing them to the metre. Each unit is named and assigned a symbol.

Numerical value or measurement of a quantity

The numerical value of a quantity only has meaning when accompanied by the unit to which it has been compared to obtain that value:

MEASUREMENT = VALUE * Unit

$l = 5.5$ m $F = 10.1$ N

The unit must always be placed on the right: 18.5°

A limited number of base units

❖ In an effort to standardise, most duplicate units have been eliminated.

❖ After years of patient work, most of the units in use have been reduced to 7 basic units.

These 7 base units are independent of each other.

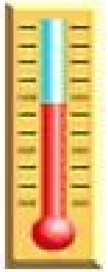
The other SI units are called "derived units".

mètre

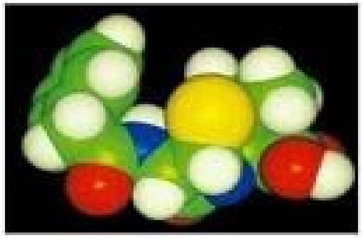
kilogramme

seconde

ampère



kelvin



mole

candela

Different possible errors:

Measurement errors are related to the nature and probabilistic and frequency distribution of possible measurement disturbances.

• **Systematic error:** discrepancy between the true value and the measured value.

•Constant or slowly varying deviation

•very low frequency error (ageing, temperature drift).

• **Random error:** set of disturbances whose sign and amplitude are random

•dispersion of successive measurements of the same quantity

Systematic error

- always occurs in the same way, originating from:

– the operator,

→ mastery of measurement, rigour and care

– the device (incorrect calibration) → calibration

– the method (measurement principle)

→ easy to take into account = easy to correct

systematic errors can be corrected

Random error

- There are many causes of these errors:

– Reading error (position of the needle on a device, etc.) → division between two successive neighbouring graduations

– Instrument error, experimental conditions (variation over time, wear and tear)

→ Calibrate

– Assembly error (wire too long, incorrect mass, etc.)

→ take care when assembling

– Measurement condition error (temperature, pressure, humidity, etc.)

→ take influencing factors into account

Random errors can only be estimated

Sensor - measurement chain

1. General

- Element sensitive to variations in a physical quantity which, based on these variations, delivers a signal.

- Amplifier of the signal delivered by the sensor to bring it to a level compatible with the display and usage unit

- Unit that allows the value of the quantity to be read and/or used in the case of a control system.

1. Role of the measurement chain

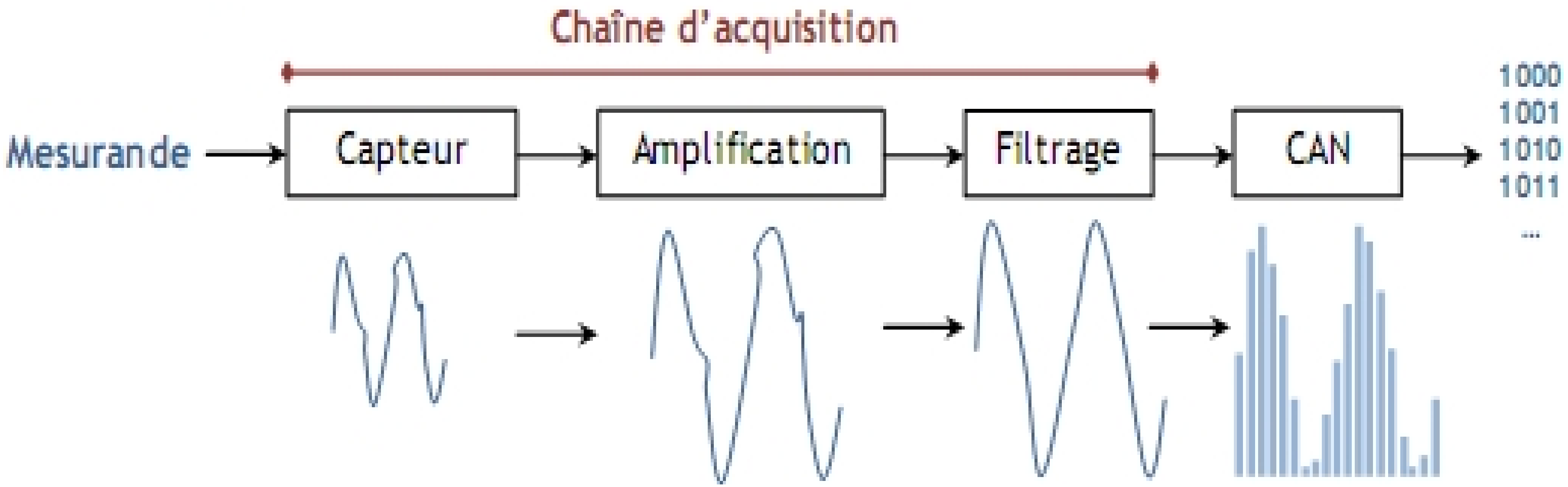
1 - A measurement chain collects the information necessary for understand the state of a system.

2 - The state of a system is characterised by physical or chemical quantities called: measurand.

3 - The chain delivers this information in a form suitable for use.

4 - The purpose of the measurement chain is to assign a value to a measurand.

Chain constitution



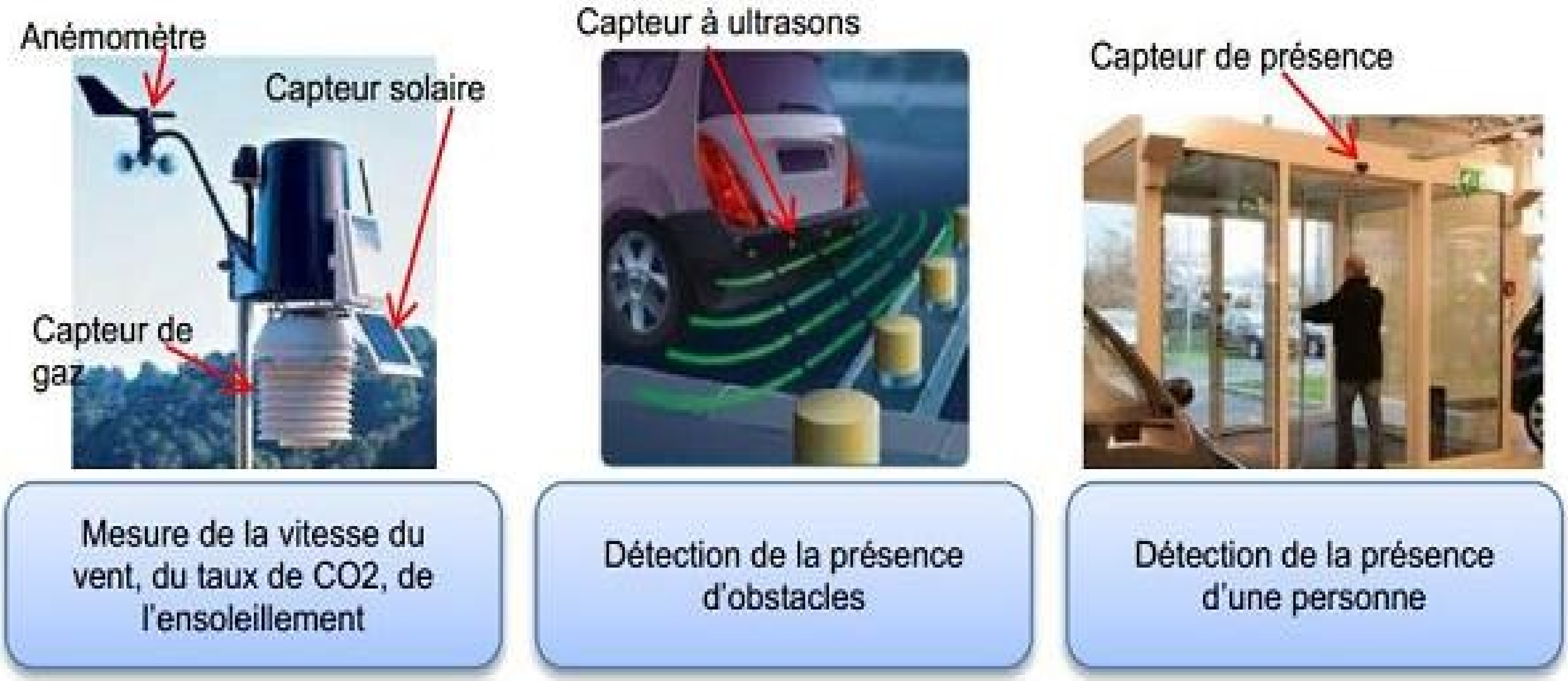
Principle of operation of a measurement chain

Generally, it consists of three parts:

- data acquisition (analogue)

sensors, conditioners, amplifiers, multiplexing.

- CAN data transformation
- data processing (computer)



Examples of measurement systems

What is a sensor?

A sensor is a device that converts a physical input quantity, called the measurand [m], into an electrical quantity (charge, voltage, current or impedance) called the response [s].

The ideal sensor is one for which:

- there is a known linear relationship between the quantity to be measured and the sensor output signal $S = f(m)$
- the conditions of use are such that no influencing quantity disturbs its operation
- no parasitic noise is superimposed on the useful signal

Interference

Physical quantity whose variations affect the operation of the sensor or the quality of the measurement: temperature, vibrations, humidity, power supply, electromagnetic interference, etc.

❖ The sensor design must seek to minimise the undesirable influence of these factors or provide a compensation device.

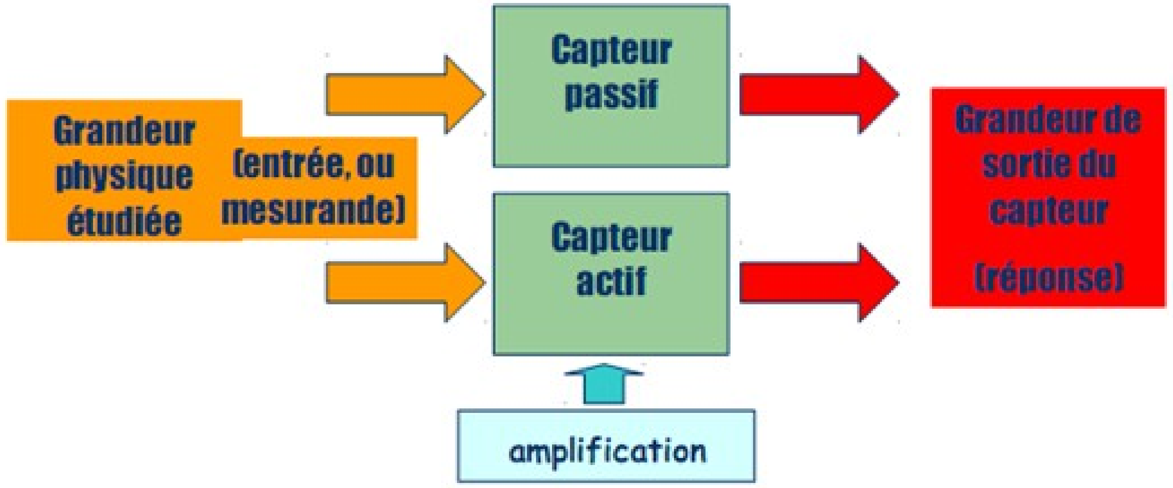
Areas of sensor use:

All fields of activity require the use of sensors
Examples:
- automotive: main field, production control, agriculture, medical (micro sensor field)
- household appliances

Classification of sensors

Classification according to:

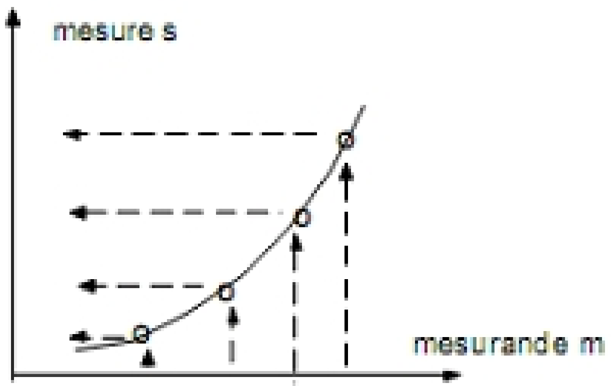
• the measurand they translate (temperature sensor, pressure sensor, etc.)
• the signal they provide
- analogue sensors (largest category), logic sensors *(key sensors)*
- digital sensors
• their operating principle (active sensor, passive sensor)

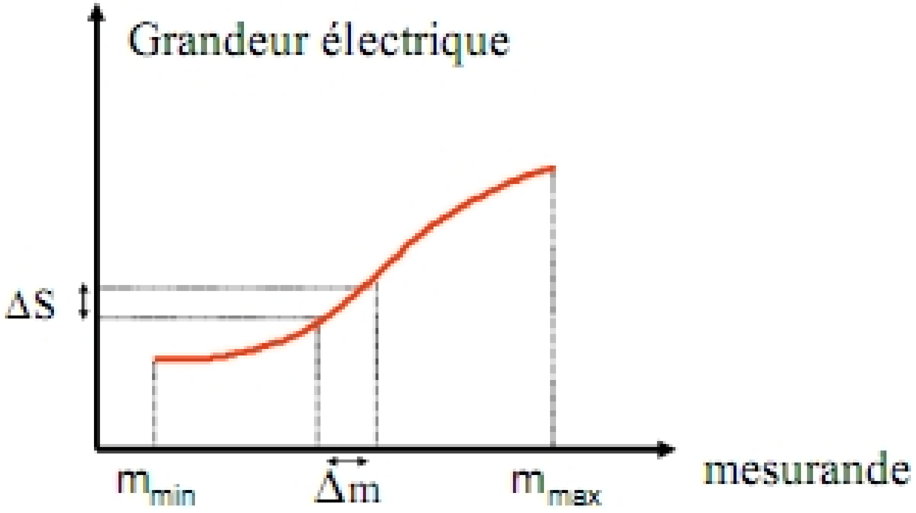


Metrological characteristics

1. Sensitivity

The sensitivity S(m) of a sensor, for a given value of the measurand, is equal to the ratio of the variation in the electrical signal to the variation in the physical signal.





$$S(m) = \left(\frac{\Delta s}{\Delta m}\right)_m$$

$$\text{Unité typique} = \frac{\text{Unité Grandeur Electrique}}{\text{Unité Mesurande}}$$

For a linear sensor, sensitivity S is a constant

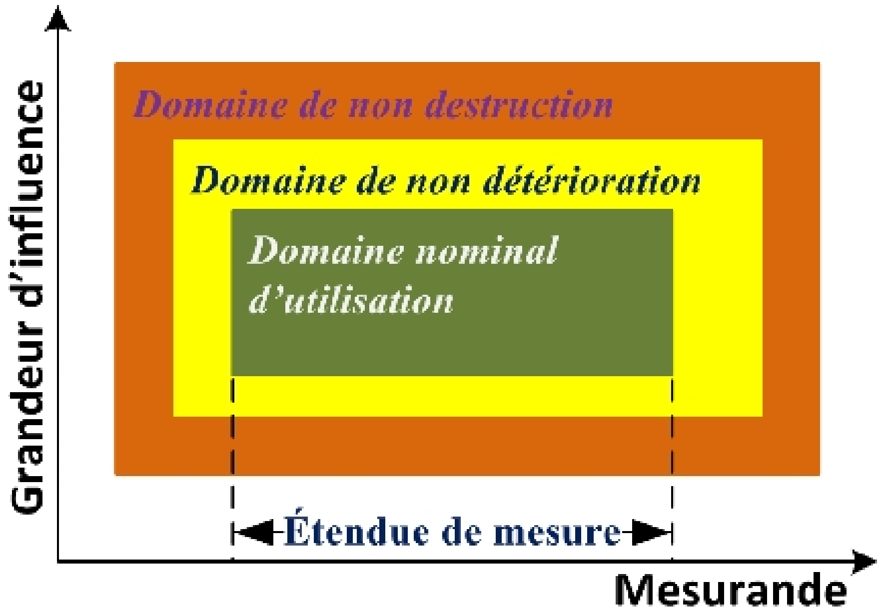
$$S_{lin} = \frac{ax_j + b - (ax_i + b)}{x_j - x_i} = a$$

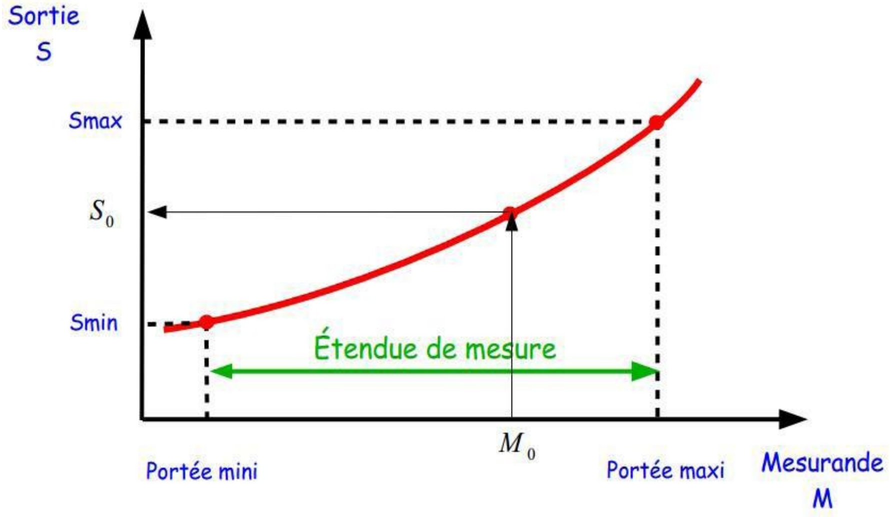
Slope of the straight line that characterises the linearity of the sensor

Example: A sensor has the following function: U=1.55 T-20 S =?

S = slope = a = 1.55 V/degree Celsius

2. Areas of application





Measuring range:

The measuring range is the nominal area of use, within which the sensor's characteristics correspond to normal operating specifications; it is bounded by the lower and upper limits (ranges).

3. Accuracy

Accuracy error = accuracy error + fidelity error.

Average value $$\bar{m} = \frac{1}{n}\sum_{i=1}^{n} m_i$$

Standard deviation → $$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(m_i - \bar{m}\right)^2}$$

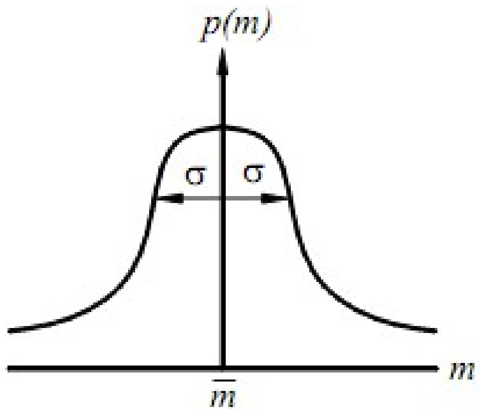
The dispersion of a series of measurements around their mean value

Repeatability

It characterises a sensor's ability to give consistent measurements for the same measured value.

Accuracy is often characterised by the standard deviation

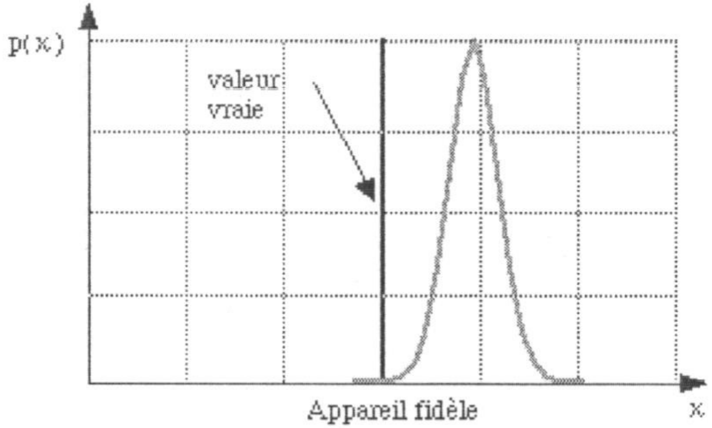
The results of repeated measurements of the same measured value remain grouped around a mean value.



$P(\bar{m} \pm \sigma)$ -------> 68.3 %

$P(\bar{m} \pm 2\sigma)$ -----> 95.5 %

$P(\bar{m} \pm 3\sigma)$ -----> 99.7 %

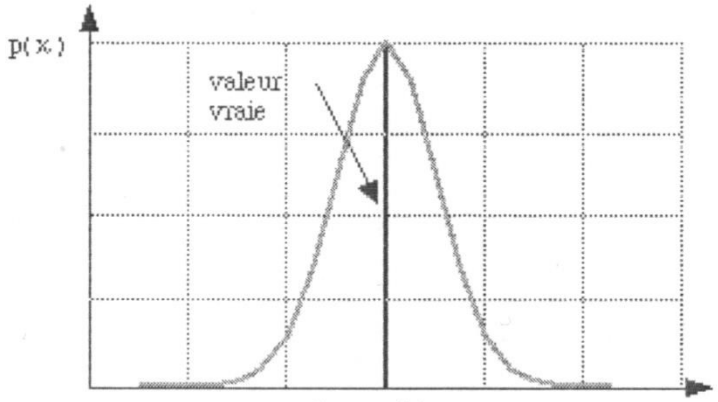


Accuracy

This characterises a sensor's ability to provide measurements close to the true value of the measured quantity, without taking accuracy errors into account.

The most probable value of the measurand is very close to the true value

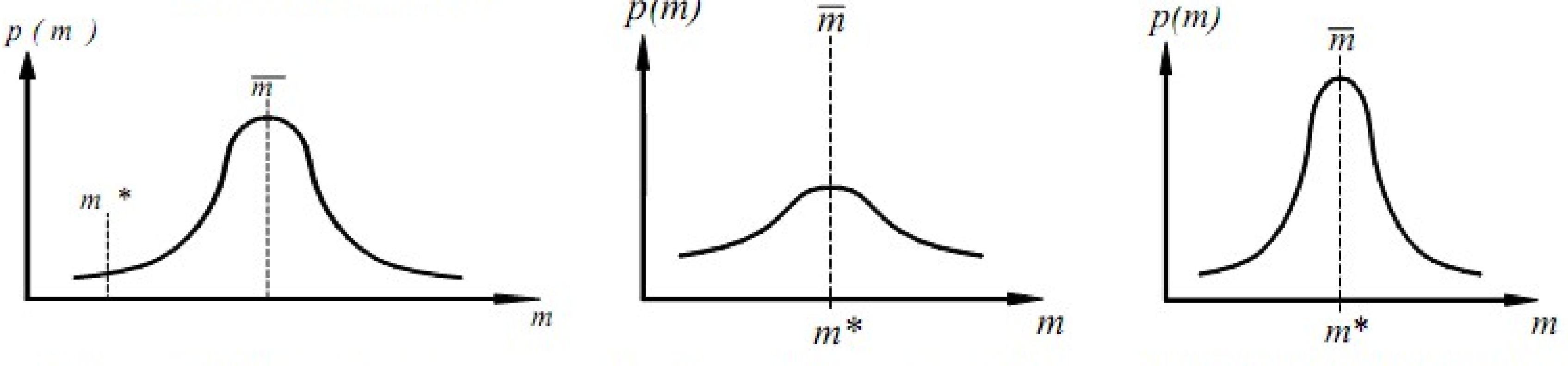
valeur moyenne ≈ valeur vraie



Appareil juste

❖ An accurate sensor will have both good fidelity and good accuracy.

(m* est la valeur vraie)



Ex. d'appareil fidèle mais pas juste — Ex. d'appareil juste mais pas fidèle — Ex. d'appareil fidèle et juste, donc précis

Lu jx-A>ion is spAifi#e jteı- l'eıu-ew de jtı-dc ioiı qiii d#ûnlite @l inteıa»+Ile aıitmıı- de le valeur mesurée. # 1'intdıienʻfiuquel un eit nıc>wd de OʻnNxzıʻ le xulew xueie du ııle»ııeılrle. fiAte emeu de jzAczion jxut “Are ıepıAsent4e de tıoz feçoıl3 :

* P< l'eılew t+lxnİue c, qiiiexprime l'eıaeW de ju#czioıl deme l%ıitd de nleiWe du nlesWeııfie:

* Ft+ı- l'ea-en- ıeletive et- qlliexprime l'eıa-eiıi- rle ju-#c ioıl eil j<wcentage jxu- ı-appmt a le s+tleiıi nleiırıAe .1/

$$e_r = \frac{e_a}{M} \times 100\%;$$

Peı- ll+clesc-e 8e ju-#czion fip. git extıı-time l'ea-en-8e jıificısion en pmıicentege prsı- ı-appmt 4 l' #tendue 8e ıneiWe *E.II.*

$$C_p = \frac{e_a}{E.\backslash l} \quad 100\%$$

4. Sensitivity

This describes the impact of the measuring instrument on the phenomenon being measured. It is the quality of a sensor that does not alter the quantity being measured by its presence. This makes it possible to evaluate the influence of the sensor on the measurement.

The less a sensor influences its environment, the better its accuracy.

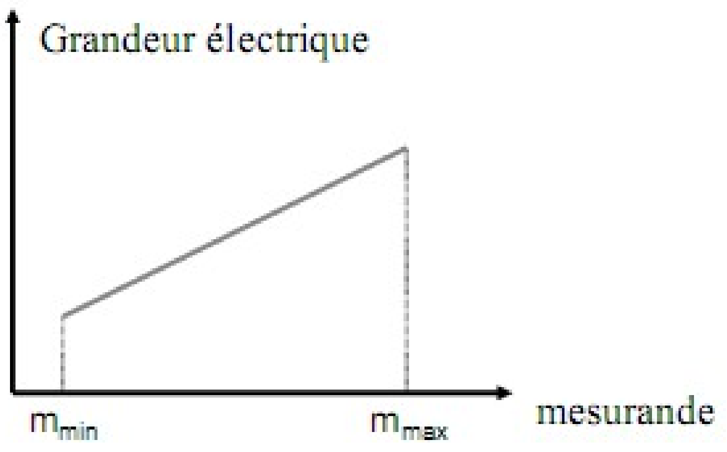
For example, a resistor can be used to measure temperature. However, in order to measure the value of the resistor, an electric current must flow through it.

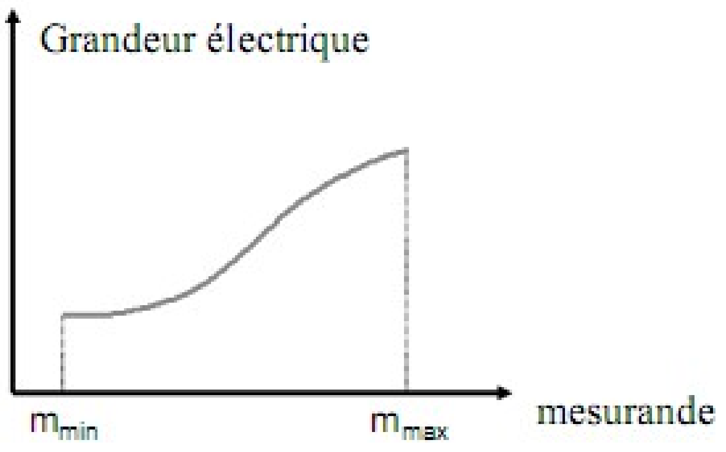
5. Calibration curve

Used to define a functional relationship between the input measurand and the electrical quantity at the sensor output.

It is defined either by a graph or by a formal relationship (linear, exponential, logarithmic, etc.).

Exemples





6. Resolution

$$\text{Résolution} = \frac{\text{Etendue de mesure}}{\text{nombre de points de mesure } N}$$

Analogue/digital conversion ⟶ Errors caused

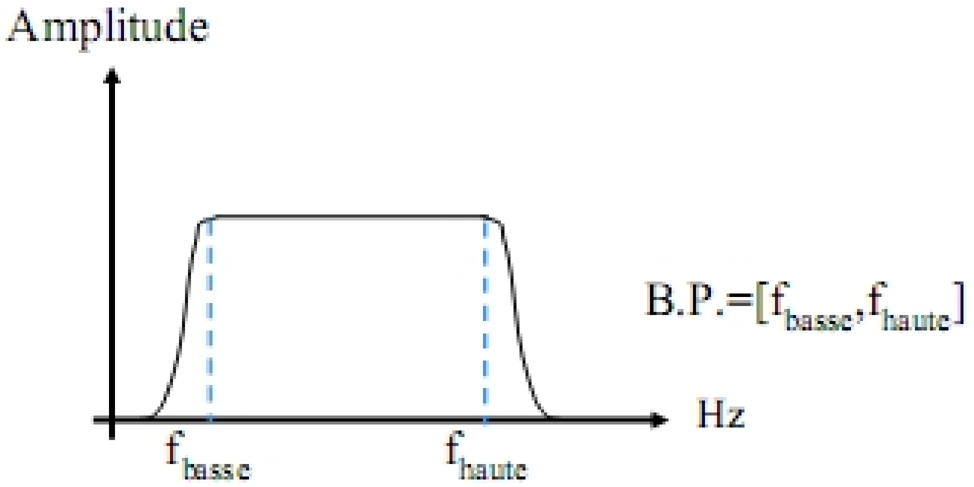
which allows the resolution error er to be defined. It depends on two parameters:
1) the number of bits in the conversion: for n bits, there are 2n different values.
2) the measurement range EM. We then have:

$$Q = \frac{EM}{2^n} \Longrightarrow e_r = \frac{Q}{2}$$

7. Bandwidth

This is defined as the frequency range of variation of the measurand where the sensor characteristics specified by the manufacturer are met.

If the frequency of the measurand is between f (low) and F (high), the amplitude of the output signal will comply with the manufacturer's specifications.



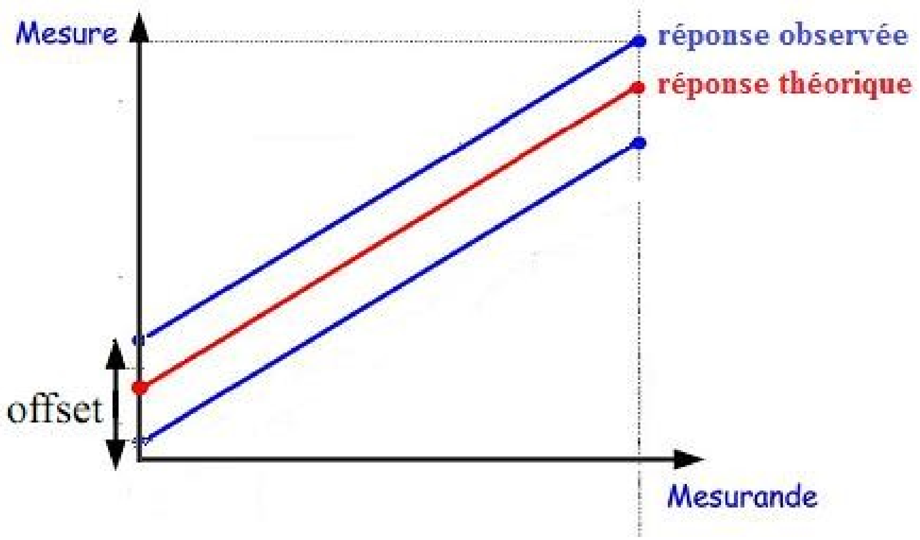
8. Drift

This is the slow variation in the output quantity independent of the value of the input quantity.

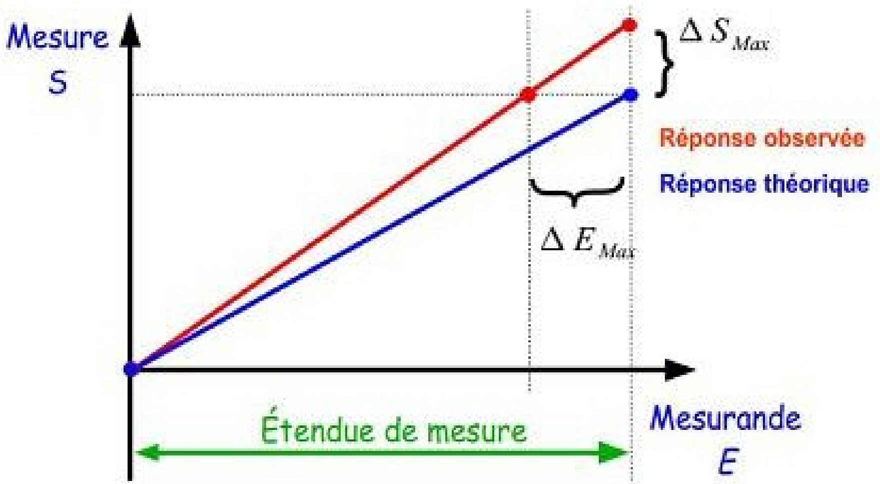
Example: consider a linear sensor characterised by its output function: $y_i = ax_i + b.$

Let the slope **a** represent the sensitivity → the **sensitivity** drift.

Let **b** be the ordinate at the origin → the **zero** drift **(offset).**



Zero drift.



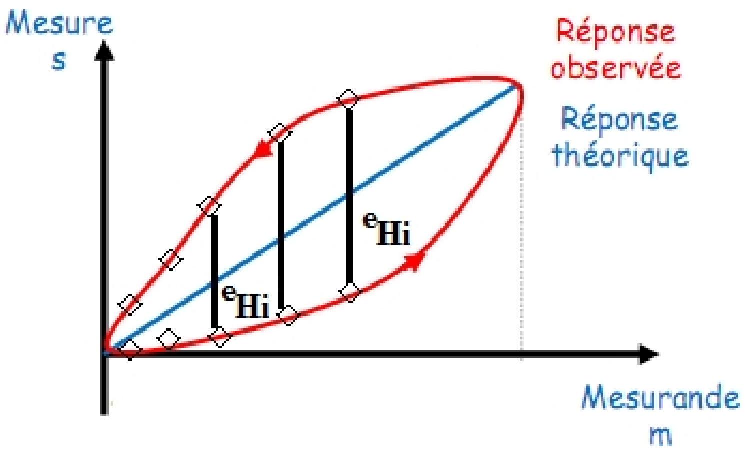
Sensitivity drift.

8. Hysteresis

Some sensors do not return the same output value for the same value of the measurand, depending on how this value is obtained (increasing or decreasing cycle).

We can see that there are two series of measurements:
* one series obtained when the value of the measurand is increasing.
* the other obtained when the value of the measurand is decreasing.

The hysteresis error can be estimated as follows: $e_H = \underset{i=1}{\overset{n}{Max}} e_{Hi}$

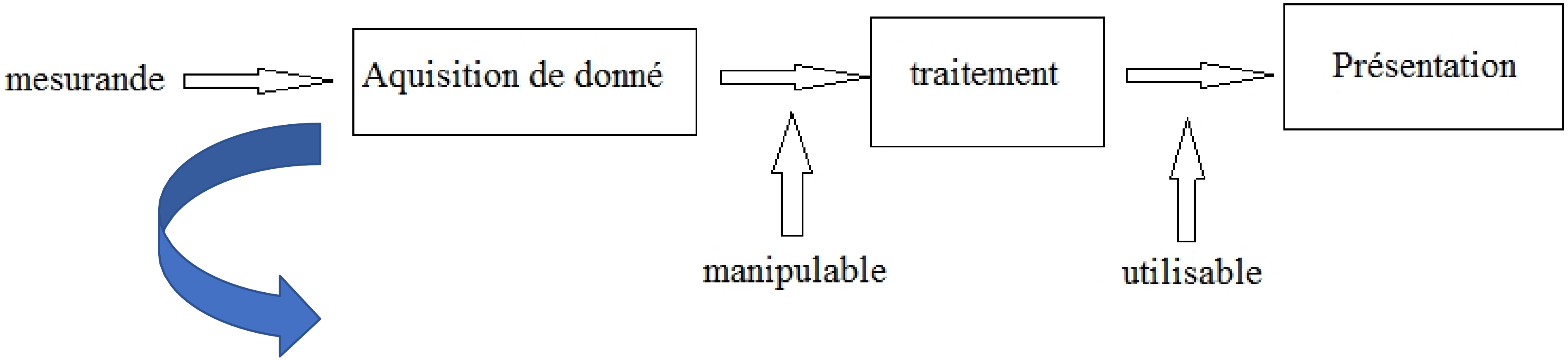


hysteresis cycle.

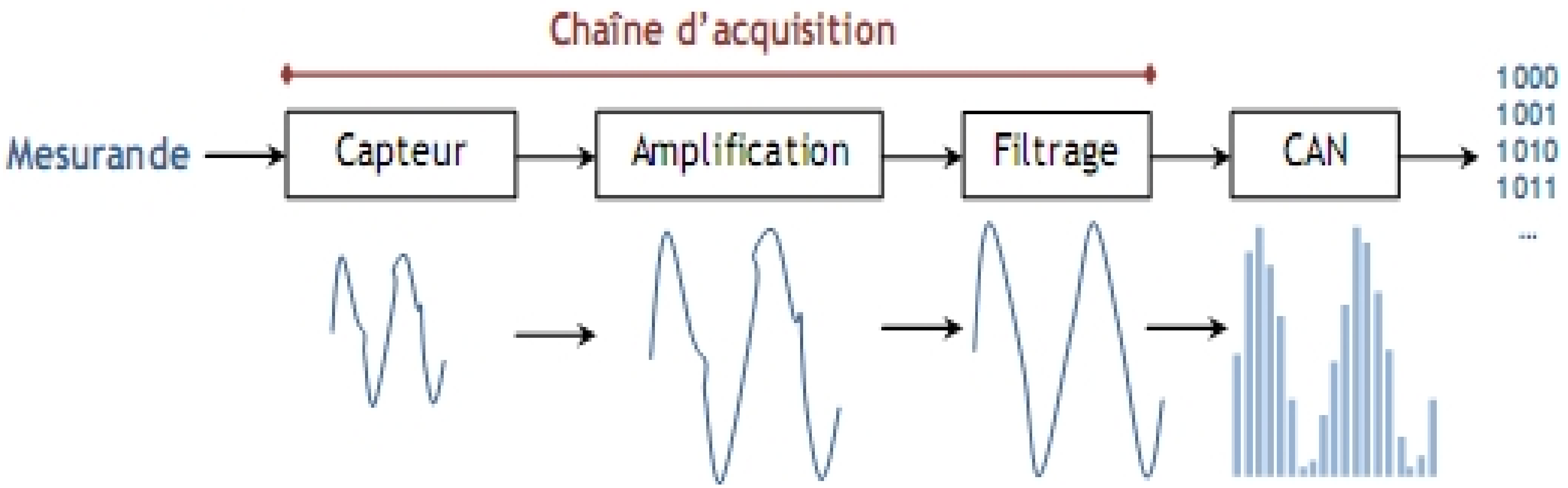
Chapter 2

Classification of sensors

Measurement chain

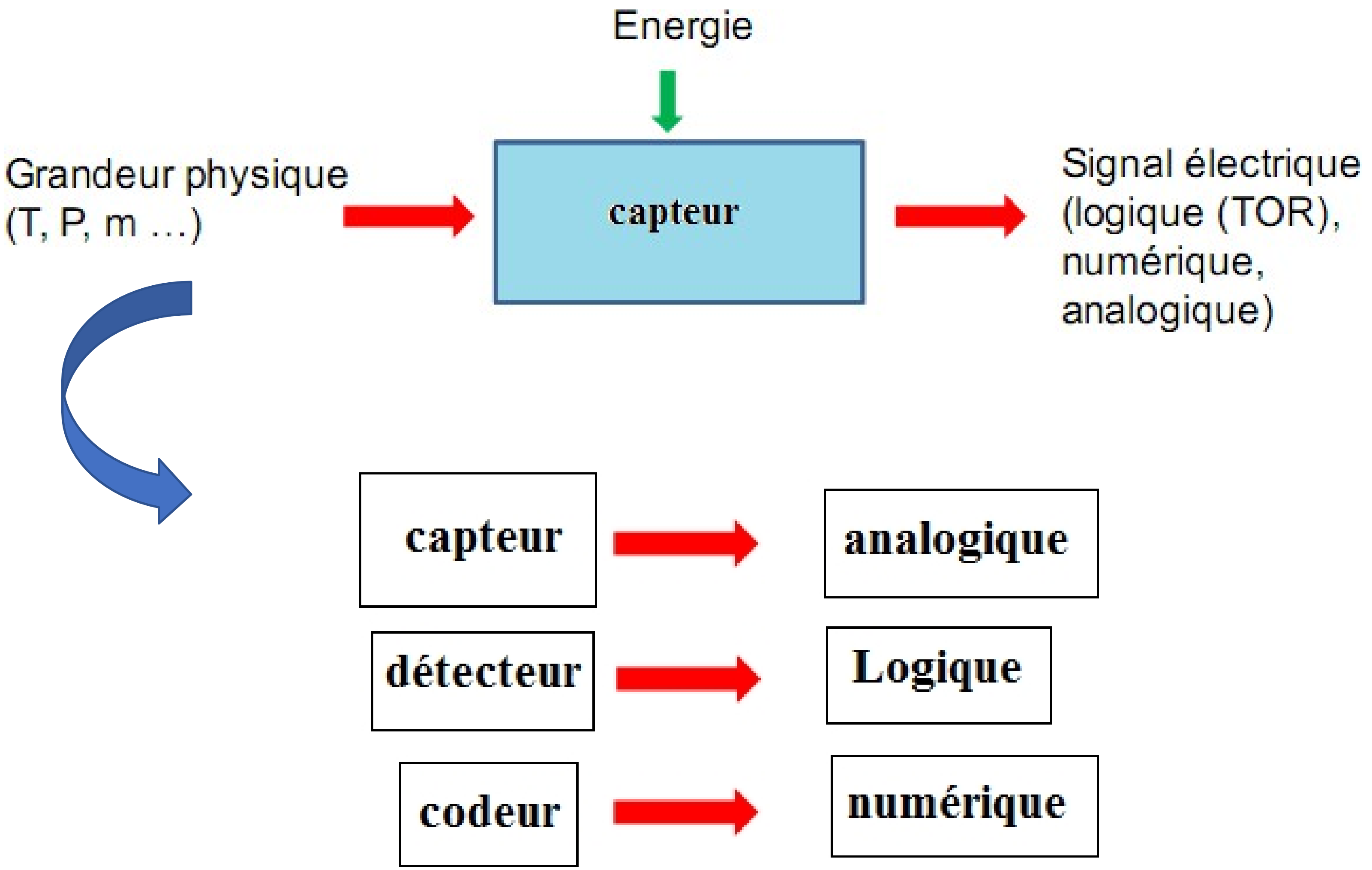


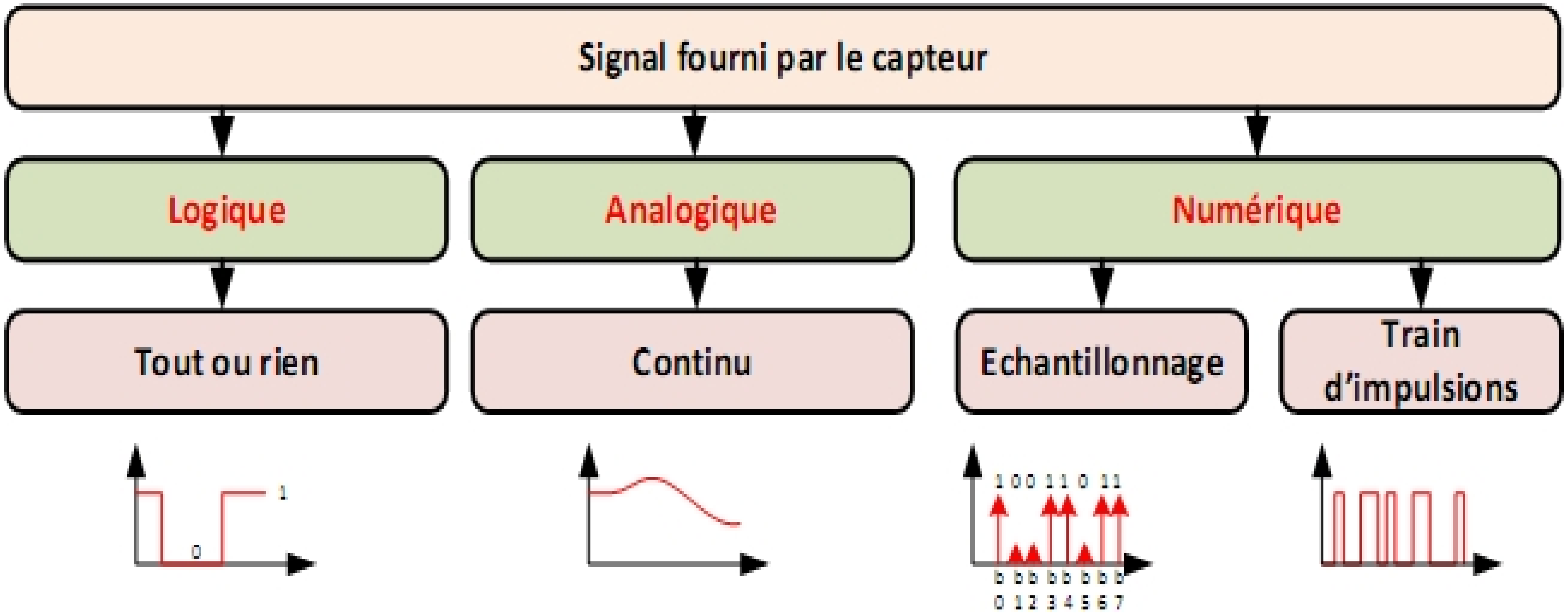
A **sensor** is a metrology device that translates variations in a physical or chemical process into a usable quantity.


Chaîne d'acquisition
Mesurande
Capteur
Amplification
Filtrage
CAN
1000
1001
1010
1011
...

2.1 Definition

A sensor is a device that converts a physical input quantity, called the measurand [**m**], into an electrical quantity (charge, voltage, current or impedance) called the response [**s**].





Types of signals.

Classification of sensors

Sensors can be classified in several ways:

•By the measurand they translate (position sensor, temperature sensor, etc.)

•According to the nature of the information delivered: these are referred to as logic sensors, also known as on/off sensors, analogue sensors or digital sensors.

•By their operating principle:

capteurs passifs

Directly convert the measurand into electrical signal

S is a resistor, an inductor or a capacitor

capteurs actifs

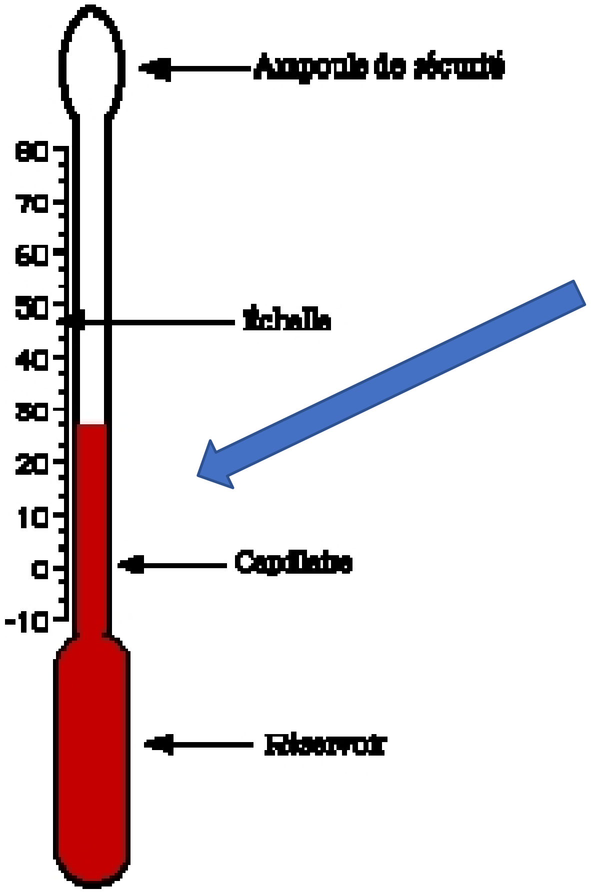
Energy is needed to determine the value of the sensor's output quantity.

Require a power supply

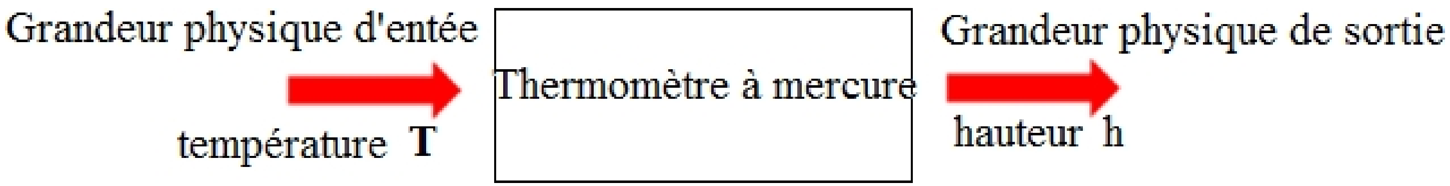
S is a load, a voltage or a current

Example of active sensor

Mercury thermometer



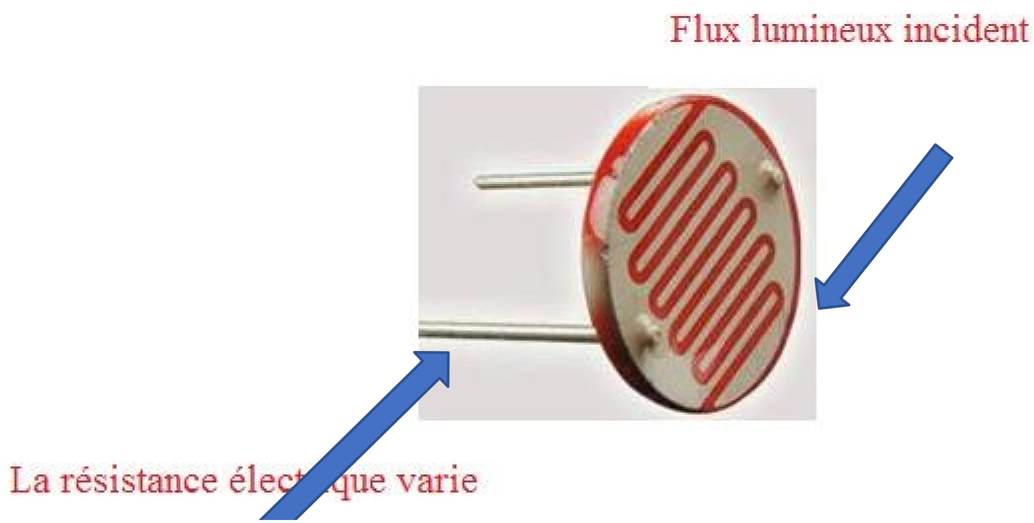
La hauteur monte ou descend



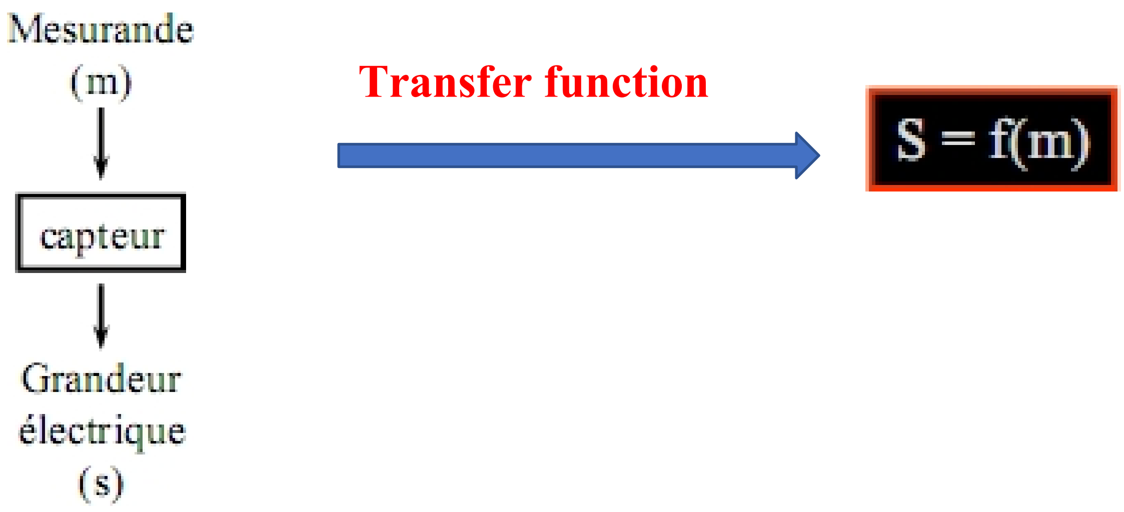
Passive sensor example

All sensors whose physical output is electrical resistance are passive sensors.
Example: ***photoresistor***

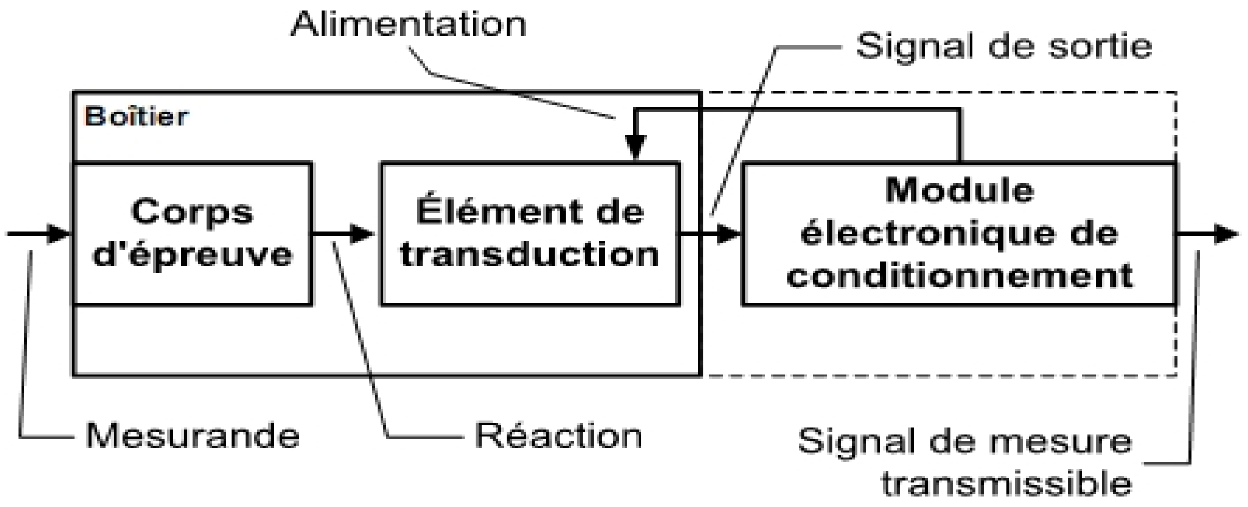
- A photoresistor is a semiconductor-based electronic component whose resistivity varies according to the amount of incident light: the more light it receives, the lower its resistivity.



In summary, for all sensors, we have:



Sensor structure (what does it contain inside?)



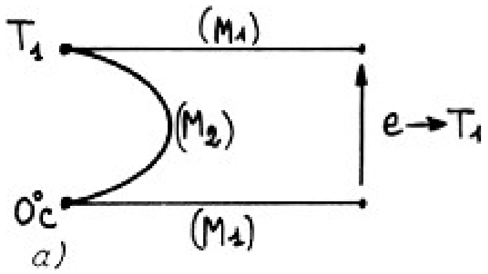
• **Test body**
Reacts selectively to the quantity to be measured by providing a measurable quantity.

• **Transducer element** (transducer)
Converts the response of the test body into a compatible signal.

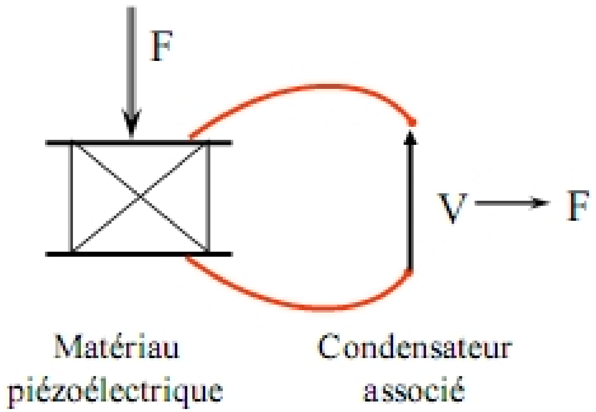
• **Conditioning module**
- When necessary, supplies power to the transducing element (passive element)
- Ensures appropriate shaping of the output signal
- Transmits the measurement signal

The physical effects of a sensor

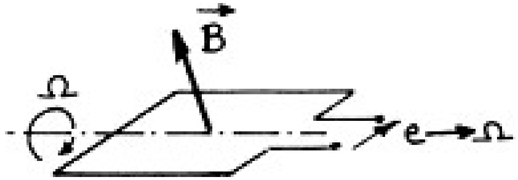
Thermoelectric effect: Two conductors of different chemical composition with junctions at different temperatures create an electromotive force.



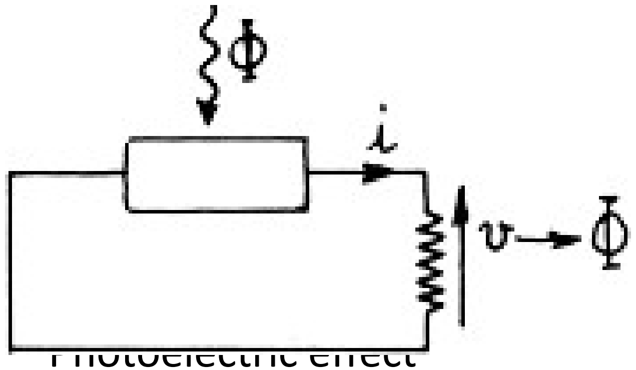
Piezoelectric effect: The application of mechanical stress to both sides of a piezoelectric material (e.g. quartz) causes deformation, which generates equal and opposite electrical charges.



Electromagnetic induction effect: Electromotive force created when a conductor moves in a fixed induction field and proportional to the speed of movement.



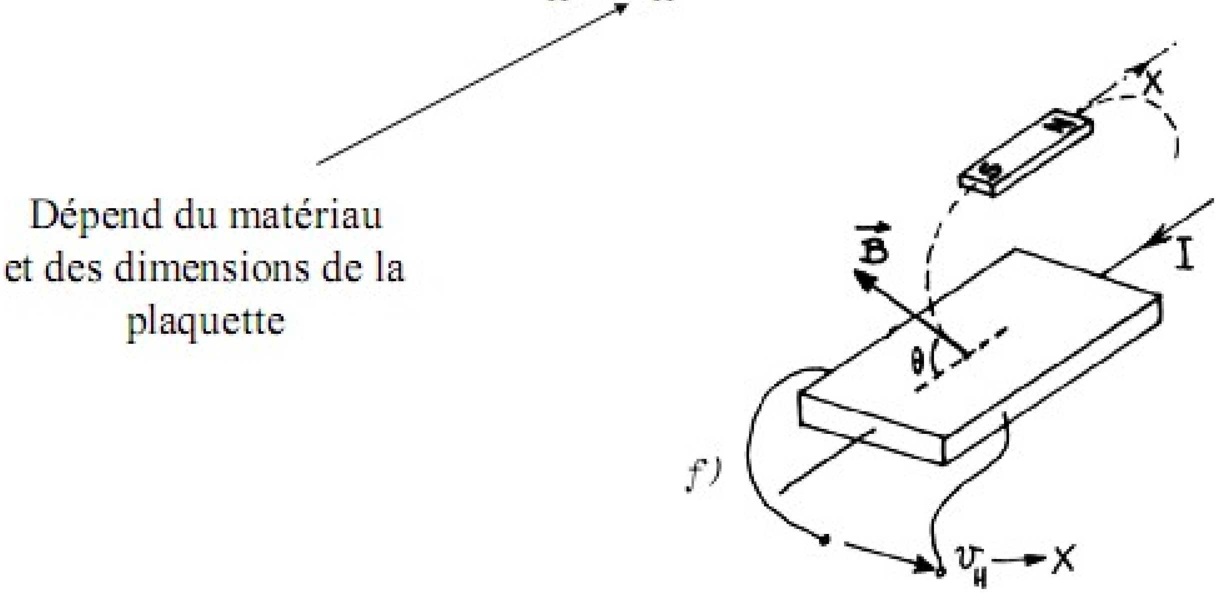
Photoelectric effect: There are several types, which differ in their manifestations but which have a common origin in the release of electrical charges in matter under the influence of light or, more generally, electromagnetic radiation with a wavelength below a threshold value characteristic of the material.



Photoelectric effect

Hall effect: A material (semiconductor wafer) through which a current I flows and which is subjected to an induction B at an angle Q to the current produces a voltage vH perpendicular to I and B:

$$v_H = K_H \,.\, I \,.\, B \,.\, \text{Sin}\, \Theta$$



Hall effect

Characteristics:

- Impedance, one of whose parameters is sensitive to the measurand.
- These variations can only be measured by integrating the sensor into an electrical circuit (to be powered).

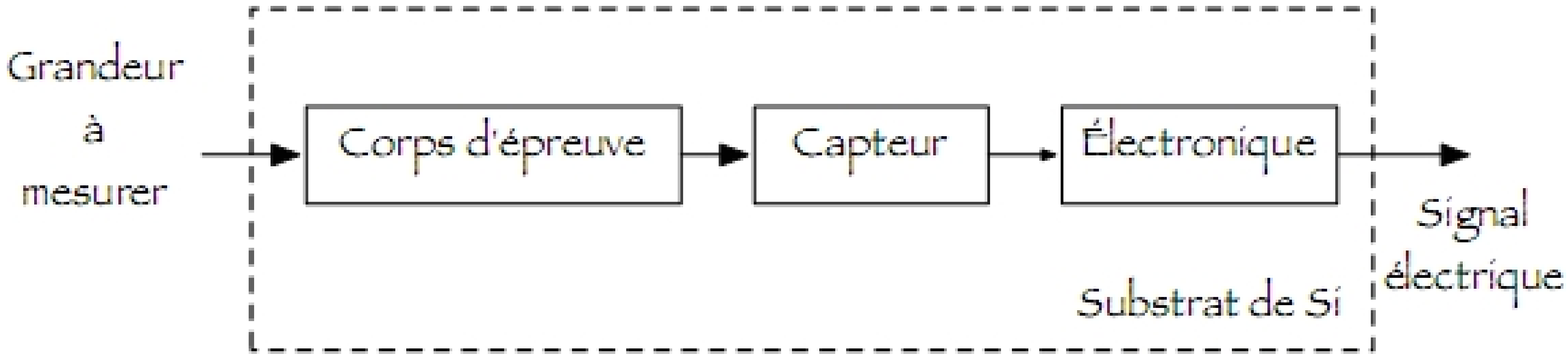
Impédance : Z = f(géométrie,dimensions, propriétés électriques des matériaux)

([ρ]résistivité; [μ] perméabilité magnétique ; [ε] cte diélectrique))

Grandeur mesurée	Caractéristique électrique sensible	Types de matériaux utilisés
Température	Résistivité électrique	Platine, Nickel, cuivre ...
Rayonnement optique	Résistivité électrique	Semi-conducteur
Déformation	Résistivité électrique	Alliage de Ni, Si dopé
	Perméabilité magnétique	Alliage ferromagnétique
Position	Résistivité électrique	Matériaux magnétorésistants (Bismuth, antimoine d'indium)
Humidité	Résistivité électrique	Chlorure de lithium

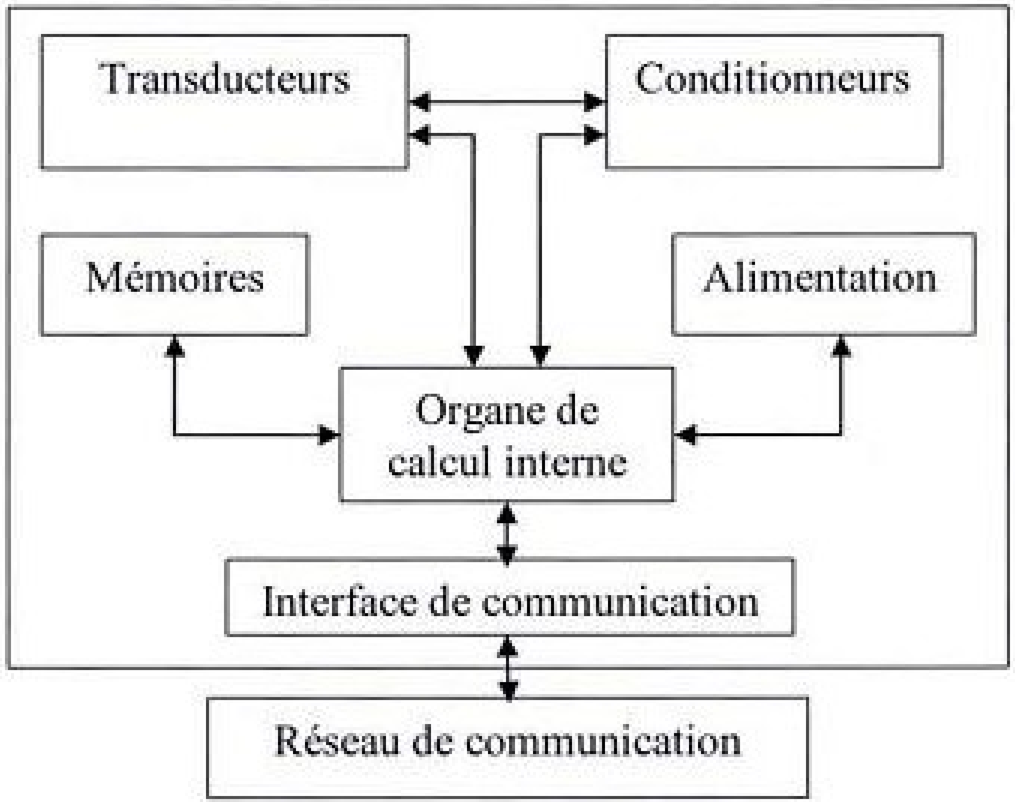
Passive sensors: physical principles and materials

Integrated sensor



Integration offers multiple advantages:
miniaturisation, reduced costs through mass production, increased reliability by eliminating numerous soldered connections, better protection against interference, as the signal is conditioned at its source.
However, the use of silicon imposes a limitation on the operating range of approximately -50°C to 150°C.

A smart sensor mainly consists of an internal computing device (microprocessor, microcontroller), a signal conditioning system (programmable or controlled) and a communication interface integrated into the sensor body.



Associated conditioner

Signal conditioning involves making the measurement from the sensor usable. The sensor-conditioner combination determines the electrical signal and its characteristics.

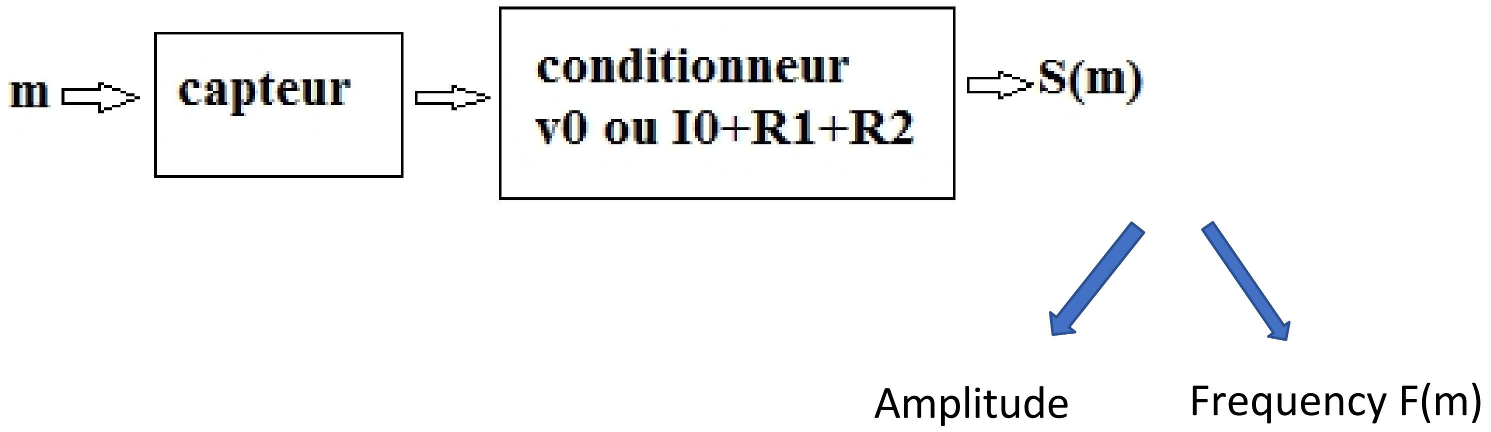
Conditionnement du signal

L’étage de conditionnement du signal des capteurs à un rôle très important :

- Il converti en tension la grandeur de sortie du capteur,
- adapte l’impédance pour le capteur
- limite l’amplification en mode commun,
- élimine les bruits électromagnétiques.

Passive sensors

This sensor provides an image of the measurand via impedance. An external voltage or current source is therefore always associated with the sensor.



Two main conditioning principles can be used: **Potentiometric and bridge circuits**: a voltage proportional to the measurand is obtained.

Oscillating circuit: the frequency of the output signal is modulated by the measurand.

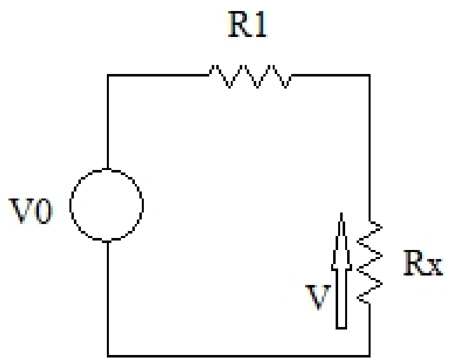
Potentiometric circuit (divider bridges)

Resistance measurement with a voltage source

In its simplest form, the conditioner consists of a simple divider bridge powered by a DC voltage source V0. Another impedance R1. The passive sensor is modelled by the resistance Rx, which depends on the measurand.

The aim is to measure the voltage V at the sensor terminal.

$$V = \frac{Rx}{R1+Rx} v0$$



The relationship between the output voltage (V0) and the image parameter of the measurand (Rx) is not linear. The sensitivity of the circuit is therefore not constant.

a. Linearisation of the measurement

To linearise the sensor response, the following solutions can be used:

*** Solution No. 1 (small signal operation):**

One way to express the resistance of the passive sensor is to consider:

$$R_x = R_0 \pm \Delta x \quad \Longrightarrow \quad V = \frac{R_0 \pm \Delta x}{R_1 + R_0 \pm \Delta x} V_0$$

In this case, we are dealing with small variations in the measurand: $\Delta x \ll (R_1 + R_0)$

Then we obtain: $V = \dfrac{R_0 \pm \Delta x}{R_1 + R_0} V_0$ $\Longrightarrow$ This is a linear relationship limited to small variations of Δx

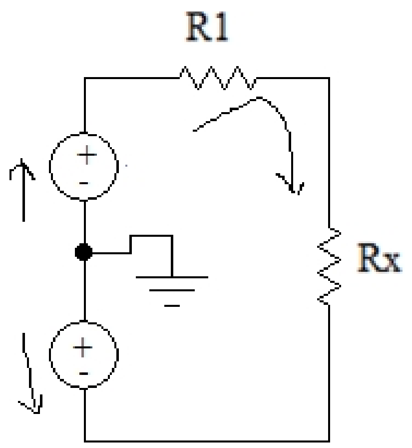
$$V = \frac{R_0}{R_1 + R_0} V_0 \qquad V = \frac{\pm \Delta x}{R_1 + R_0} V_0 \quad \Longrightarrow \quad V = V_1 \pm V_x \quad \Longrightarrow \quad V - V_1 = \pm V_x$$

Static component (for $V = \dfrac{R_0}{R_1 + R_0} V_0$)

Dynamic component (for $V = \dfrac{\pm \Delta x}{R_1 + R_0} V_0$)

What circuit allows this operation to be performed?

There are two inverse voltage sources v0/2 and –v0/2. Therefore:



$$V = V_A - V_{masse} = V_A$$

Now: $\frac{V_0}{2} = R_1 i + V$ and $i = \frac{\frac{V_0}{2} - (-\frac{V_0}{2})}{R_1 + R_x} = \frac{V_0}{R_1 + R_x}$

Therefore:

$$\frac{V_0}{2} = R_1 \frac{V_0}{R_1 + R_x} + V \quad d'ou\ V = \frac{V_0}{2} - R_1 \frac{V_0}{R_1 + R_x} = \frac{V_0(R_1 + R_x) - 2R_1 V_0}{2(R_1 + R_x)}$$

$$V = \frac{V_0}{2} \frac{R_x - R_1}{R_1 + R_x} = \frac{V_0}{2} \frac{R_0 \pm \Delta x - R_1}{R_0 \pm \Delta x + R_1}$$

if we choose R1=R0: $\Rightarrow$ $V = \frac{V_0}{2} \frac{\pm \Delta x}{R_0 \pm \Delta x}$ $\xrightarrow{\Delta x \ll 2R_0}$ $V = \frac{\pm \Delta x V_0}{4R_0}$

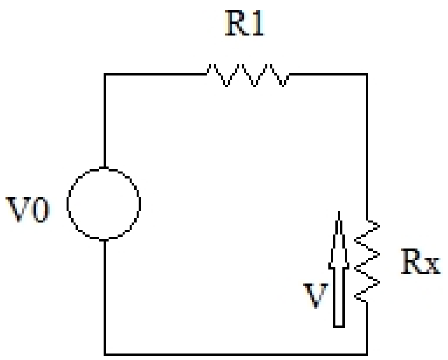
Push-pull circuit

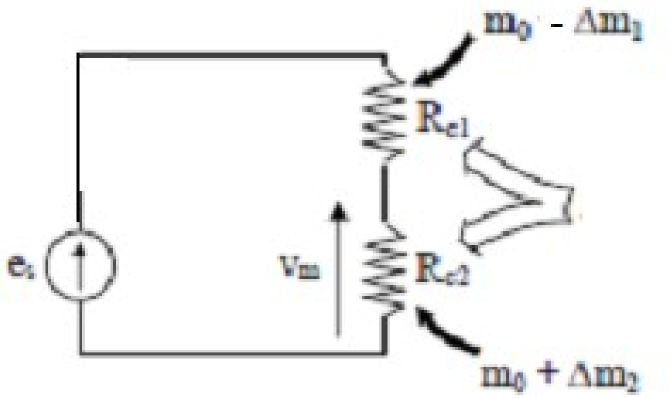
In this case, the fixed resistor R1 is replaced by a second resistive sensor, identical to the first but with variations of opposite sign.

$$R_x^- = R_0 - \Delta x$$

$$R_x^+ = R_0 + \Delta x$$

$$V = \frac{Rx}{R1+Rx} v0$$



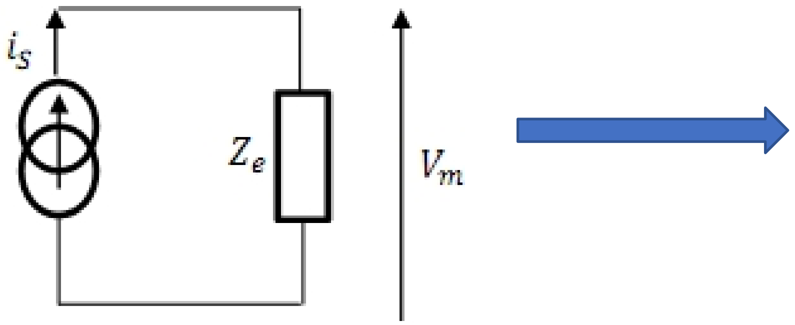


$$V = \frac{R_x^+}{R_x^+ + R_x^-} V_0 = \frac{R_0 + \Delta x}{R_0 + \Delta x + R_0 - \Delta x} V_0 = \frac{R_0 + \Delta x}{2R_0} V_0 = \frac{V_0}{2}(1 + \frac{\Delta x}{R_0}$$

Disadvantages: Use of two identical sensors that must have symmetrical responses symmetrical

Case of a current source:

The use of an IS current source makes the circuit directly linear if we neglect the internal impedance of the source, i.e.:



$$Vm = I_S . Rx$$

Capteur alimenté en courant

Conclusion :

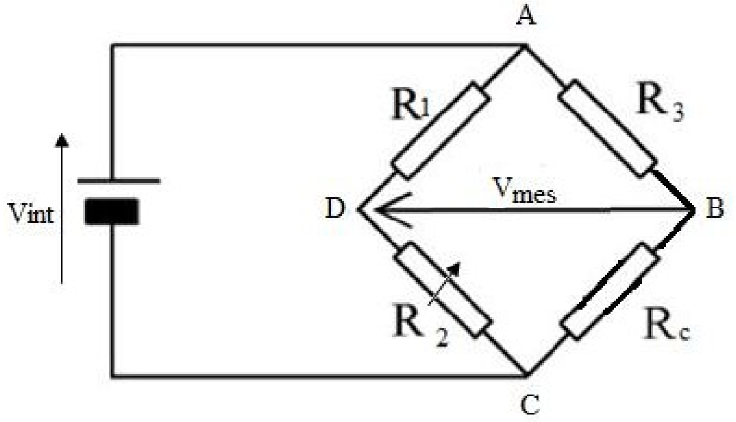
Ce montage donne une évolution linéaire de ΔVm *en fonction de ΔRc/R* mais il présente les inconvénients suivants :

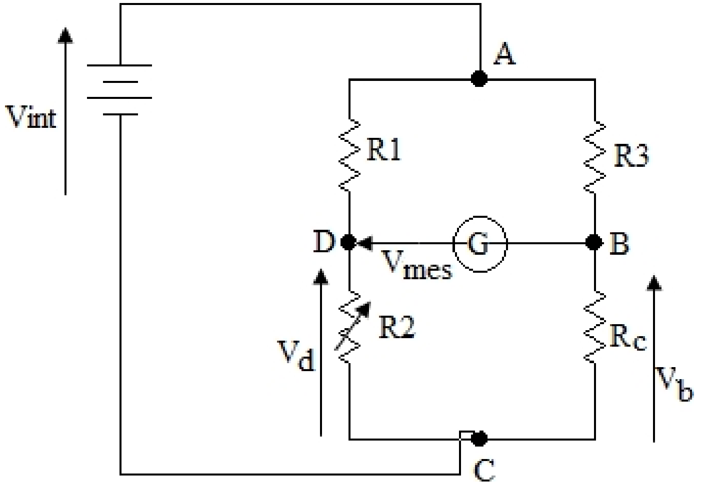
- **faible variation de la tension de sortie pour une variation Δ*Rc donnée,***
- **sensibilité de Vm par rapport à l'alimentation E.**

Bridge circuit (Wheatstone bridge)

Le pont de Wheatstone est le circuit le mieux adapté pour la mesure de petites variations de résistances électriques (maximum 10%) telles que rencontrées lors de l'utilisation de jauges de déformation

The general structure of the Wheatstone bridge is shown in the figure:





Divider bridges

$$\begin{cases} V_D = V_{in}\dfrac{R_2}{(R_1+R_2)} \\ V_B = V_{in}\dfrac{R_c}{(R_3+R_c)} \end{cases}$$

$$V_m = V_D - V_B = \frac{R_2}{R_1+R_2}V_{in} - \frac{R_c}{R_3+R_c}V_{in}$$

$$= V_{in}\frac{R_2(R_3+R_c)-R_c(R_1+R_2)}{(R_1+R_2)(R_3+R_c)}$$

$$\boxed{V_m = V_{in}\frac{R_2R_3-R_1R_c}{(R_1+R_2)(R_3+R_c)}}$$

Bridge balance condition

The bridge is said to **be balanced** when VD=VB, which implies that the current in branch DB is zero.

$$V_D = V_B \Longrightarrow \frac{R_2}{(R_1+R_2)} = \frac{R_c}{(R_3+R_c)} \Longrightarrow R_c\,(R_1+R_2) = R_2\,(R_3+R_c)$$

$$R_2R_3 = R_1 R_C \Longrightarrow \boxed{R_c = \frac{R_2R_3}{R_1}}$$

Note that the bridge balance condition depends only on the bridge resistances: it is independent of the supply voltage.

Applications

It is used as a strain gauge (for measuring stress)

Chapter 3

Some examples of sensors

1. Resistive sensors

1.1 Extensometer-based sensor

La jauge est un petit élément résistif qui est collé sur une pièce au point où on veut mesurer la déformation. Cet élément est fait d'un fil fin enroulé selon une direction préférentielle et collé à la pièce par l'entremise d'un support d'isolation. Lorsque la pièce est soumise au chargement, sa déformation est transmise à travers la colle et le support à la jauge. Un changement proportionnel de la résistance en résulte.

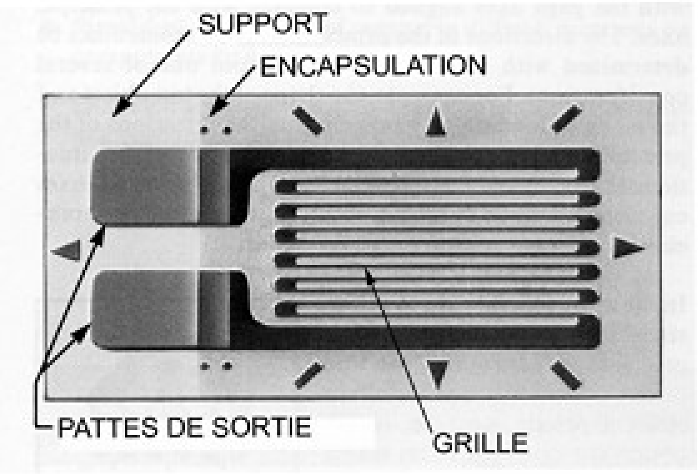


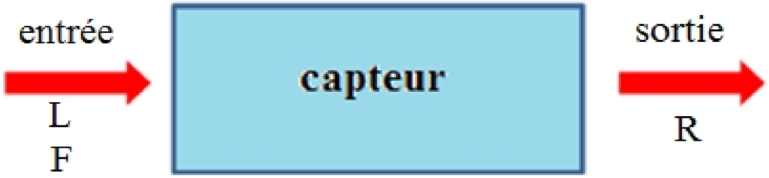
Diagramme d'une jauge

Changement de résistance provoqué par la déformation

La résistance d'un conducteur est définie comme étant:

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

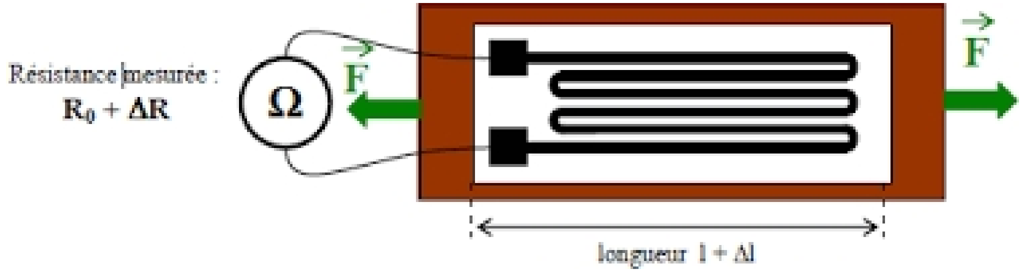
où
- ρ = résistivité (Ω.m)
- L = longueur du conducteur (m)
- A = section du conducteur (m^2)



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

By measuring the resistance, we can then calculate these physical quantities.

1. 1.1 Force sensor

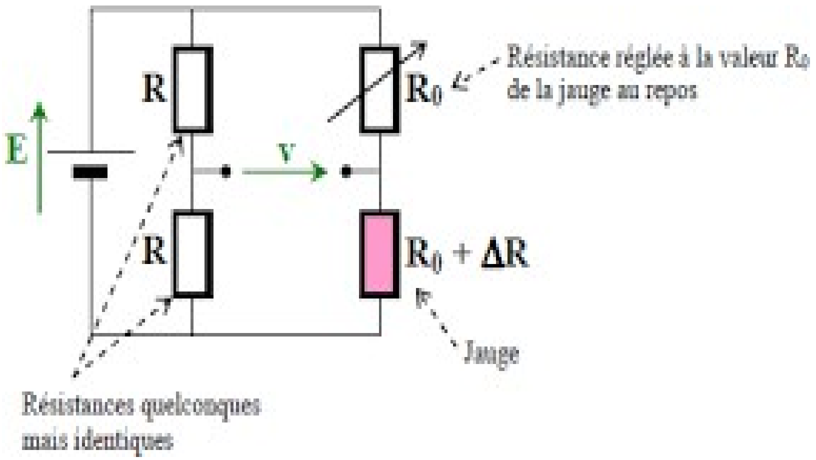


$R = \frac{\rho L}{A}$ → $R = \frac{\rho(l_0 + \Delta l)}{s}$ → $R = R_0 + \Delta R$

$R = R_0 - \Delta R$

power supply

Wheatstone bridge



$$V_d = V_{in}\frac{R_0}{2R_0} = \frac{V_{in}}{2}$$

$$V_B = V_{in}\frac{R_c}{R_0 + R_c} = V_{in}\frac{R_0 - \Delta R}{2R_0 - \Delta R}$$

$$V_{mes} = V_D - V_B = V_{in}\frac{R_0 + \Delta R}{2R_0 + \Delta R} - \frac{V_{in}}{2}$$

$$= V_{in}\left(\frac{R_0 + \Delta R}{2R_0 + \Delta R} - \frac{1}{2}\right) = V_{in}\frac{2R_0 + 2\Delta R - 2R_0 - \Delta R}{4R_0 - 2\Delta R}$$

$\Delta R \ll R_0$ →

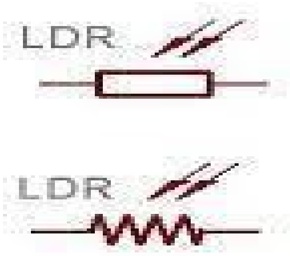
$$V_{mes} = V_{in}\frac{\Delta R}{4R_0}$$

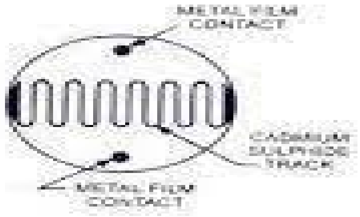
1.1.2 Light sensor (photoresistor)

• A photoresistor is a component whose resistance in ohms depends on the amount of light to which it is exposed. It is also known as an LDR (Light Dependent Resistor).

• The main use of the photoresistor is to measure light intensity (cameras, detection, counting and alarm systems, etc.).

The materials used are generally cadmium sulphide or cadmium selenide, which behave like semiconductors.





Photographic sensors (CCD) (charge-coupled devices)

❖ A photographic photographic is a electronic
electronic used to convert electromagnetic radiation (UV, visible or IR) into
an analogue electrical signal. This
signal is then amplified, digitised by an analogue-to-digital converter and finally
processed to obtain a digital image.

❖ If we were to draw an analogy with **film** cameras, the film in these cameras is replaced by **sensors**.

1 – History, field of application and general information

❖ CCDs (Charge Coupled Devices) were invented at Bell Laboratories **in 1969** by George Smith and Willard Boyle (Nobel Prize in Physics 2009).

❖ CCDs are used in many applications (commercial, scientific and military).

Digital camcorder

Digital camera

Smartphone

Image formation on the sensor

The photographic sensor works like a conventional camera

The scene to be photographed can be projected onto the sensor using a converging lens defined by its focal length f.

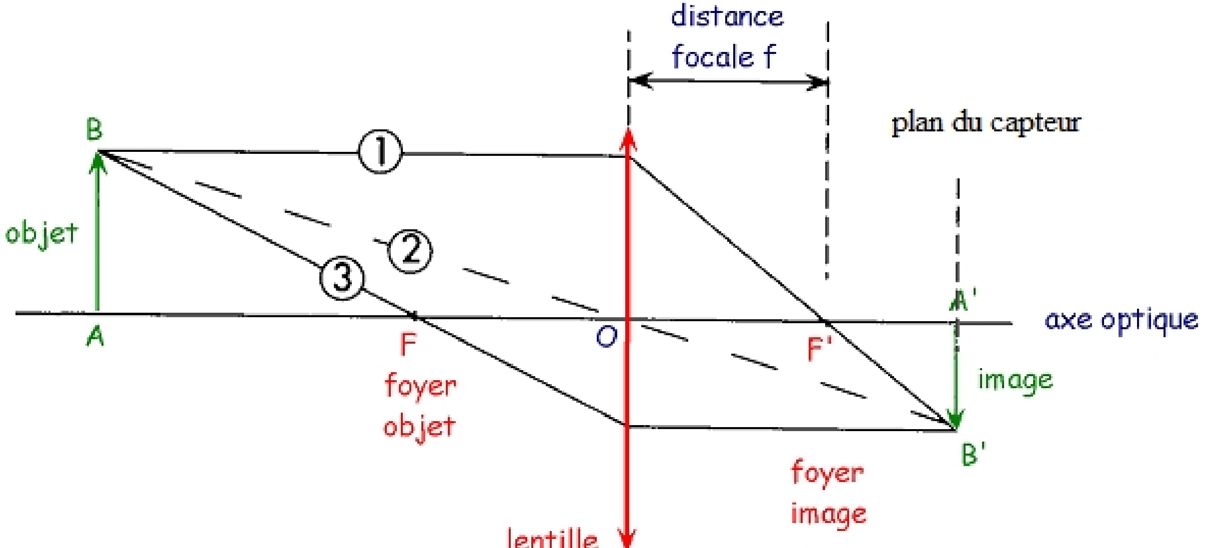
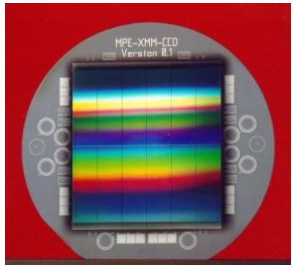


Image creation by a converging lens.



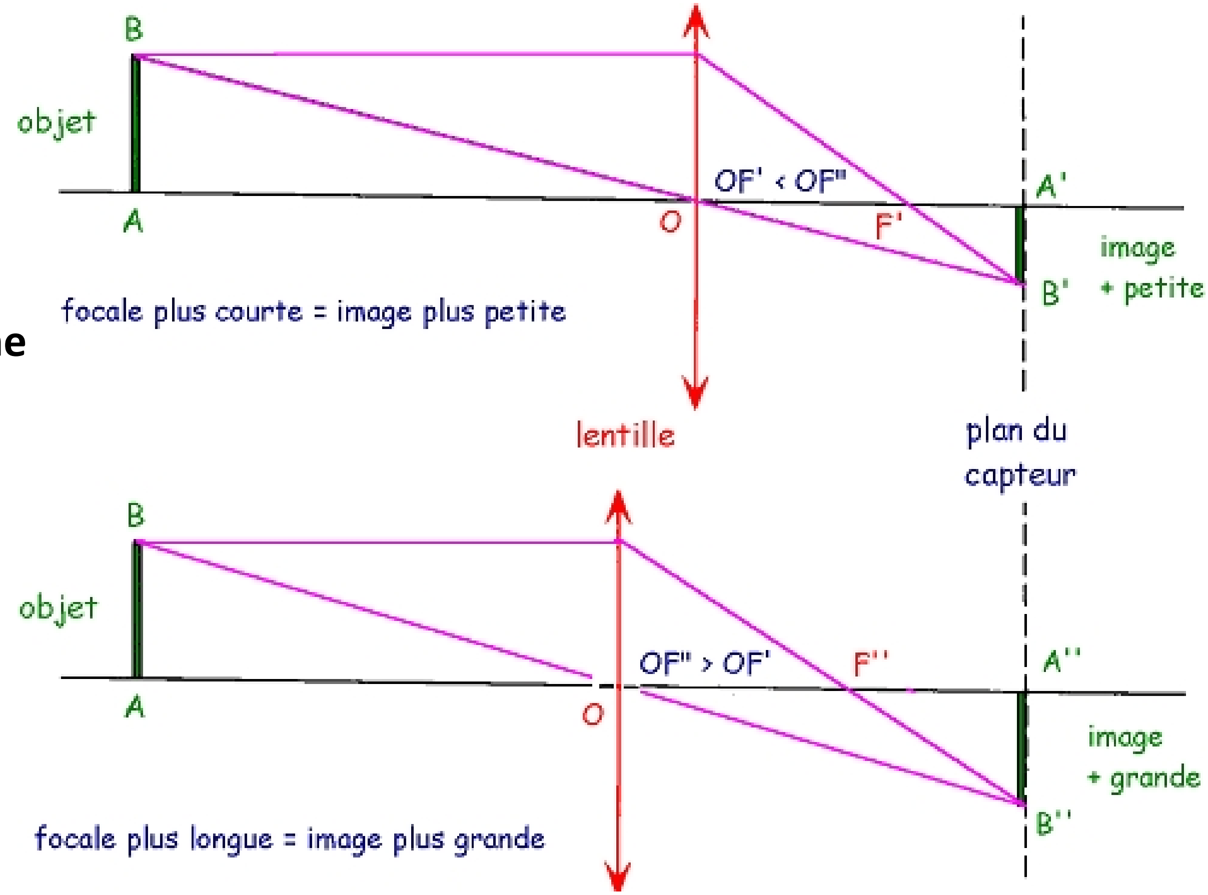
The location and size of this image is simple:

- object AB is projected as an inverted image A'B'
- the ray (1) parallel to the optical axis exits the lens through the focal point F'
- the ray (2) passing through the optical centre is not deflected
- Point B' is located at the intersection of rays (1) and (2)
- note: ray (3) passes through the other focal point F, emerges parallel to the axis and also passes through

B'

To vary the size of the image projected onto the sensor, it is necessary to be able to change the focal length of the lens.

Adjusting the size of the image by varying the focal length.



By changing the focal length and moving the lens to refocus, the image size varies, allowing the sensor surface to be used to its full potential. To do this, you can :

* change lenses and switch from a short focal length to a long focal length.
* use a variable focal length or "zoom" lens

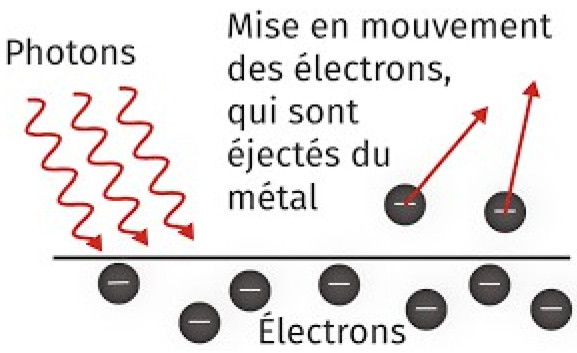
The basic principle of a sensor is based on two important concepts

capacitor

The ability to store electrical energy, where Q=CV

the photoelectric effect

In physics, the photoelectric effect primarily refers to the emission of electrons by a material subjected to the action of light.



Photoelectric effect

Electromagnetic wave

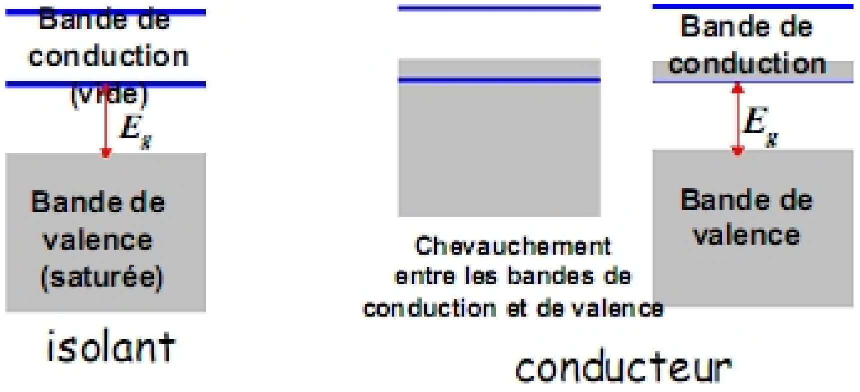
- Frequency
- Wavelength
- Speed of propagation in a vacuum

$\nu = c/\lambda$

Wave model of light → Light exhibits a particle-like behaviour.

Photons: → *E=hv*

Example: Silicon: semiconductor



Semiconductor = properties intermediate between insulator and conductor / an electron can pass into the conduction band through thermal agitation or by applying an electric field.

When an electron passes into the conduction band, a "hole" is created in the valence band. This "hole" can be likened to a virtual particle called a hole (with the opposite charge to that of the electron).

For silicon, Eg = 1.12 eV at 300 K.

Principle of operation

1. Charge generation

2. Collection and storage of charges

3. Charge transfer (reading)

4. Charge measurement (readout chain)

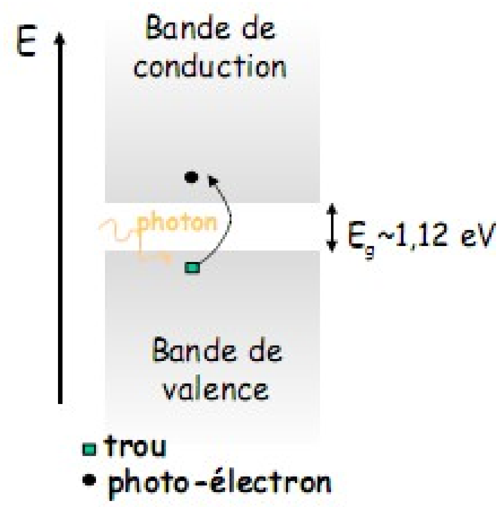
1. Charge generation

* The interactions of photons with the silicon in the CCD occur in the photoelectric domain.

* During these interactions, a photon transfers all its energy to an electron belonging to a silicon atom.

* This gives rise to one or more electron (e)/hole (h) pairs

* The number of e-/h pairs formed depends on the energy of the incident photons.



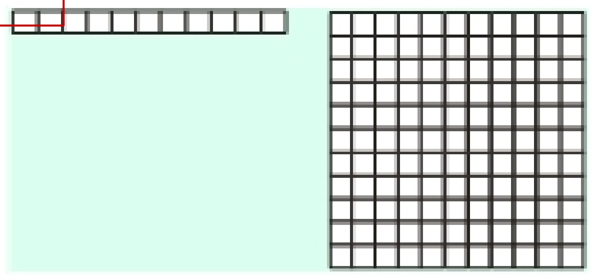
At what **energy** level is it possible to form photoelectrons?

* The energy required to produce an e-/h pair is w=1.12 eV for silicon at T = 300 K.

Movement of charges

A complete photographic sensor is an assembly of silicon sensors arranged in a regular pattern pattern.

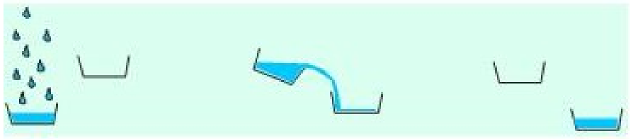
Each individual sensor corresponds to a pixel (photosite)

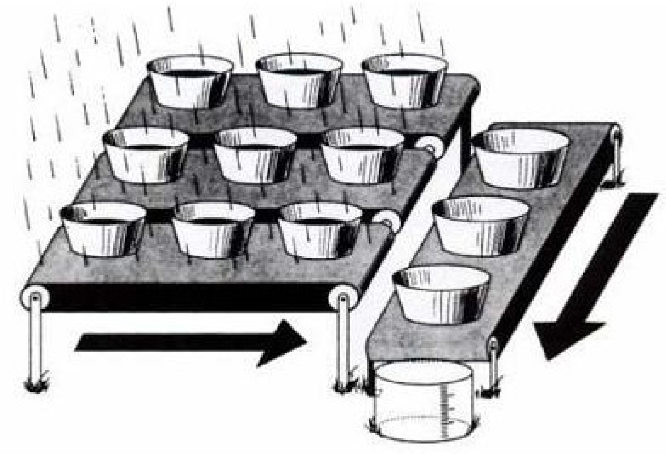


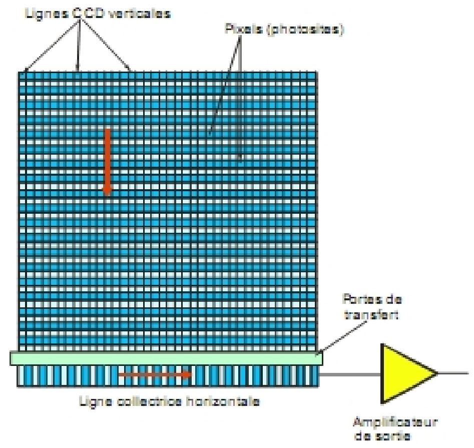
Ligne et matrice CCD

* By combining several pixels in a row, a CCD line is formed; several vertical lines can create a CCD matrix capable of capturing an image.

* The charges from each pixel, like cups filled with water, spill into each other. They are then sent to an output register.





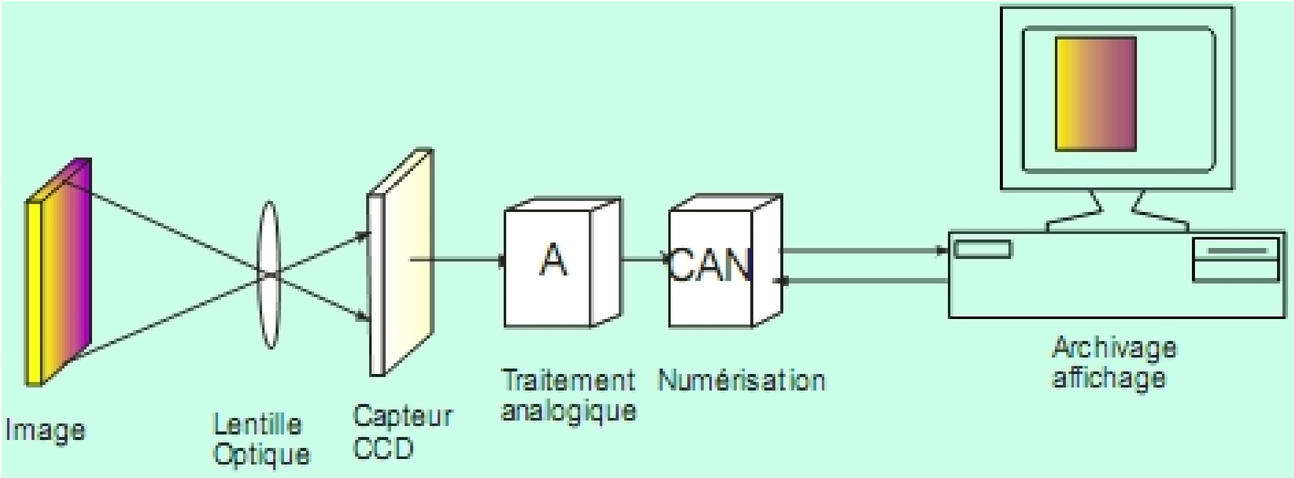


Capteur CCD FFT (Full Frame Transfert)

Finally, the charges are converted into voltage proportional to the number of electrons. This signal will be amplified and digitised outside the CCD.

Output signal; Processing.

For each pixel, the voltage obtained at the CCD output must be converted using an A/D converter in order to reconstruct the corresponding image (or line) from a computer file.



Chaine de traitement de l'information

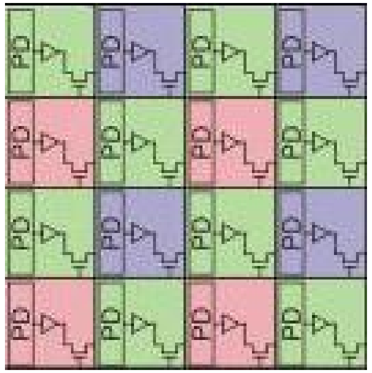
The amount of charge in each pixel is representative of the light intensity at each point in the captured image.

CMOS sensors

- CMOS (Complementary Metal Oxide Semiconductor) sensors work differently, even the basic principle remains the same.

- The photosites, as on a CCD, are sensitive to light and acquire a certain electrical charge depending on the amount of light received.

- A major difference is that each pixel contains a photodiode (which is used for photon-to-charge conversion and charge storage) and an amplifier that convert the charges into voltage in the pixel itself.



* The information from each pixel can thus be read independently without any transfer. This greatly reduces the reading time.

* Another major difference is that the photodiode can be made of a material other than silicon. This allows for a wide variety of applications at different wavelengths.

CCD sensors

Advantages:

- High image quality
- Very low noise

Noise is low with a CCD sensor because there are fewer electronic components in the sensor.

- High sensitivity

This allows these sensors to be used in low-light conditions.

Negative points:

Sensor saturation in bright light

This can create circular white spots, known as blooming, which can be compensated for using image editing software or by minimising the exposure time.

Sound sensors (microphones)

Sound

- It is molecules that, by moving closer together and then further apart, allow sound to propagate.
- On the moon, there is no air, so there is no sound. The first microphone was invented on 4 March 1877 by Emile Berliner, but it was Alexander Graham Bell who invented the first truly usable microphone.

Audio sound → Sound audible to humans → 20 Hz-20 KHz.

Acoustic waves are mechanical waves that are classified according to their frequency f - infrasound: f < 20 Hz; - audible sound: **20 Hz < f < 20 kHz**; - ultrasound: 20 kHz < f < 200 MHz; - hypersound: f > 200 MHz.

How can sound be transmitted from one person to another?

When we speak, we cause air molecules to vibrate.

↓

These vibrations are transmitted step by step to the listener's ear

Three essential elements that characterise sound

1. Amplitude
2. Pitch
3. Timbre

1. Definition

- A **microphone is** an **electroacoustic** transducer, i.e. a device capable of converting an acoustic signal into an electrical signal.

- **The conversion of acoustic pressure variations into mechanical variations**: this is the role of the open or closed membrane/cavity. → **acoustic** function of the microphone.

- These mechanical variations must then be transformed into an electrical signal. This is the **electrical** function of the microphone.

We can schematically represent a microphone by the three "parts" A, B and C in the figure.

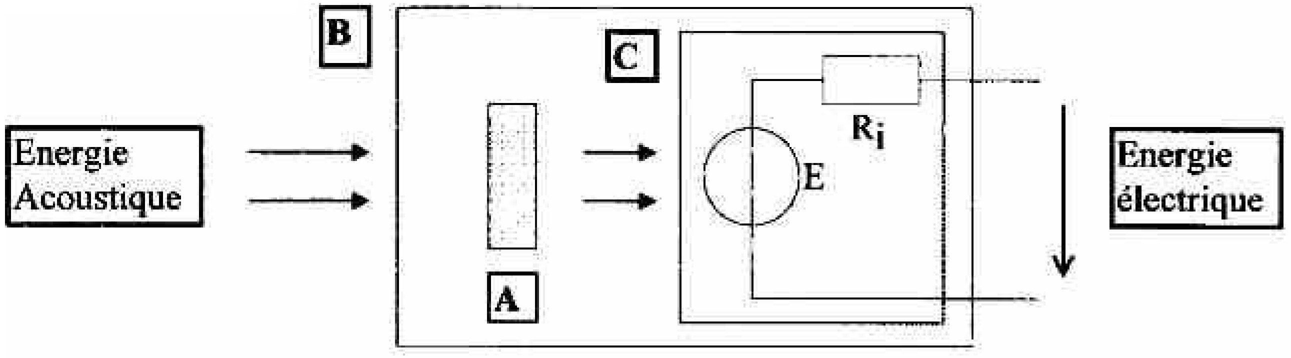


Diagram of a microphone

Classification of microphones

Microphones can be selected according to several criteria:

•**By their mode of use:**

* service microphones (telephone and hearing aids).
* Sound recording microphones (sound reinforcement, radio broadcasting, studio recording).

* **By their transducer conversion modes**: electrodynamic (coil , ribbon), electrostatic,

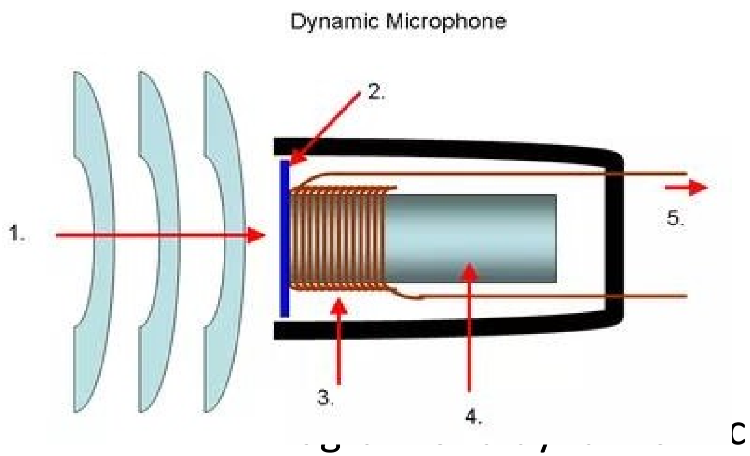
* **By their directivity modes**: omnidirectional microphones, bidirectional microphones

* **By their mode of action or diaphragm attack mode**

2. The different types of microphones

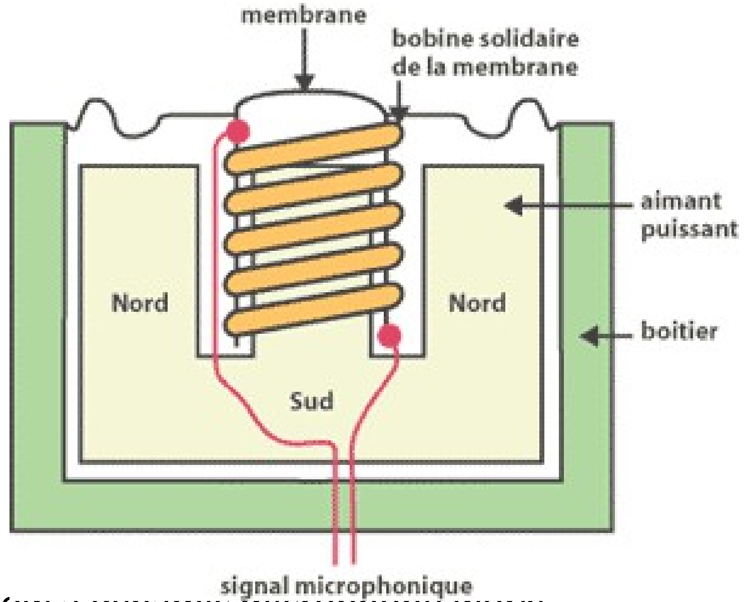
2.1 The dynamic microphone

It consists of a membrane stretched over a movable frame. Air vibrations are transmitted to the membrane, on which a coil is mounted. The coil becomes the source of an induced current as it moves relative to a fixed magnet. This electrical voltage is transmitted to the amplification or recording system to which the microphone is connected.



1 - Sound wave
2 - Diaphragm
3 - Moving coil
4 - Magnet
5 - Electrical signal

crophone



How a dynamic microphone works

This type of microphone does not require a power supply; the sound image voltage is produced directly by the coil.

Examples

The SM57 and SM58 from **Shure** are probably **the two most famous famous** and most widely used microphones in the world.

Advantages

Robust and durable

Not affected by temperature

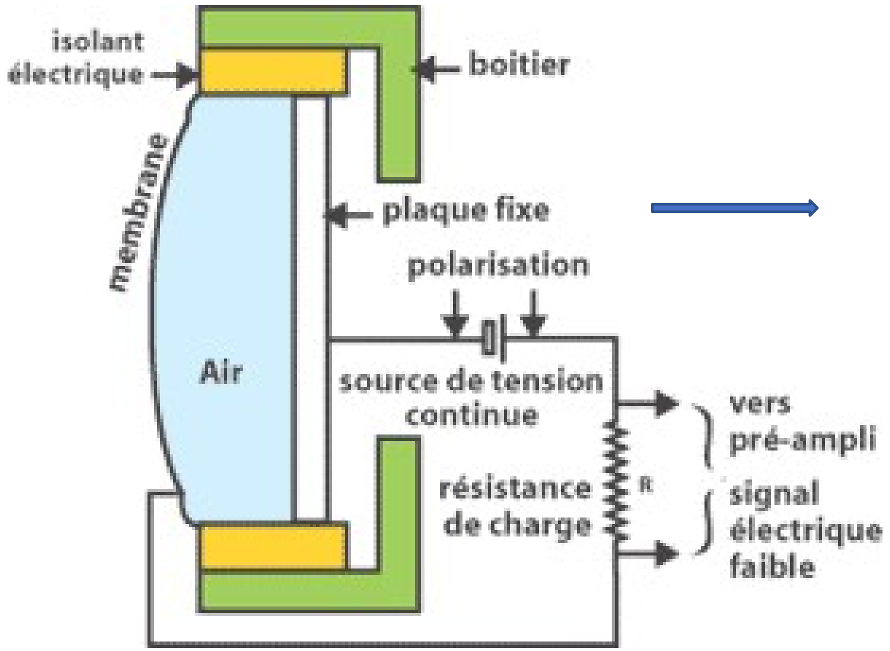
Reasonable price

Disadvantages

Limited frequency response

The Shure SM-58 SM-57

2.2 The condenser microphone (electrostatic)



This electronic system requires a power supply, often called "*phantom power*", with a voltage of 48V DC. This power supply is also used to polarise the diaphragm.

How an electrostatic microphone works

Examples

Dozens of brands have proven themselves in the production of electrostatic microphones, including Neumann, AKG, Schoeps, DPA, Blue, Coles, and Audio-Technica.

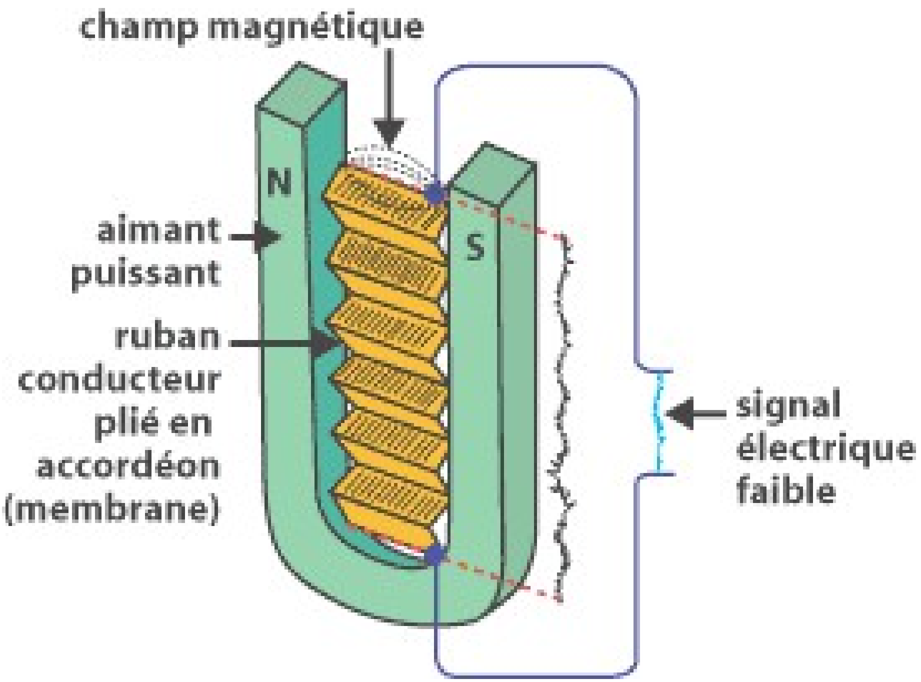
Advantages

- Highly detailed sound
- Sensitive to variations in air pressure

Disadvantages

- More expensive (from a few hundred pounds to a few thousand) and, above all, much more sensitive to shocks, wind and high sound pressure levels, which can damage them. It is therefore difficult to use them outdoors or for concert sound systems.

2.2 The ribbon microphone



How a ribbon microphone works

❖ This type of microphone offers very smooth high frequencies.

❖ It is also extremely sensitive to shocks, wind and acoustic overpressure. As a result, it is used less and less.

However, it gives very good results on certain instruments such as strings.

❖ The high-end brand Royer has made this its speciality, particularly with the R-121 and R-122.

3. MICROPHONE FEATURES

* Its manufacturing technology:

This is what we have seen above.

* Its directivity:

The directivity of a microphone characterises its sensitivity depending on the source of the sound, according to its central axis.

* Its frequency response curve:

This is the theoretical electrical level in dB as a function of frequency. This curve therefore gives an idea of the microphone's range of application.

* Its sensitivity:

This is the output level for a given pressure measured in mV/Pa. It varies greatly depending on the technology and characteristics of the microphone.

Dynamic microphone	Condenser microphone	Ribbon microphone
S ranges from 1mV/Pa to 5mV/Pa	10mV/Pa to over 50mV/Pa	Very low S, rarely exceeding 1mV/Pa.

*** Its maximum permissible sound pressure:**

Measured in **dB SPL**, which stands for Sound Pressure Level, this is the maximum level before the diaphragm saturates or even deteriorates. It also depends on the type of microphone. Examples:

* The Neumann U87 large-diaphragm condenser microphone has a maximum pressure of 117 dBSPL
* The Scheops MK4 small-diaphragm condenser microphone has a maximum pressure of 132 dBSPL
* The AKG C535 electret microphone has a maximum pressure of 130 dBSPL.

*** The size of its membrane:**

A large diaphragm is more sensitive than a small diaphragm. As a result, it can handle lower maximum pressures.

*** Noise level:**

Each microphone has its own noise level, independent of the sound pressure level it receives. This noise is generally very low and will not cause any problems during normal use.

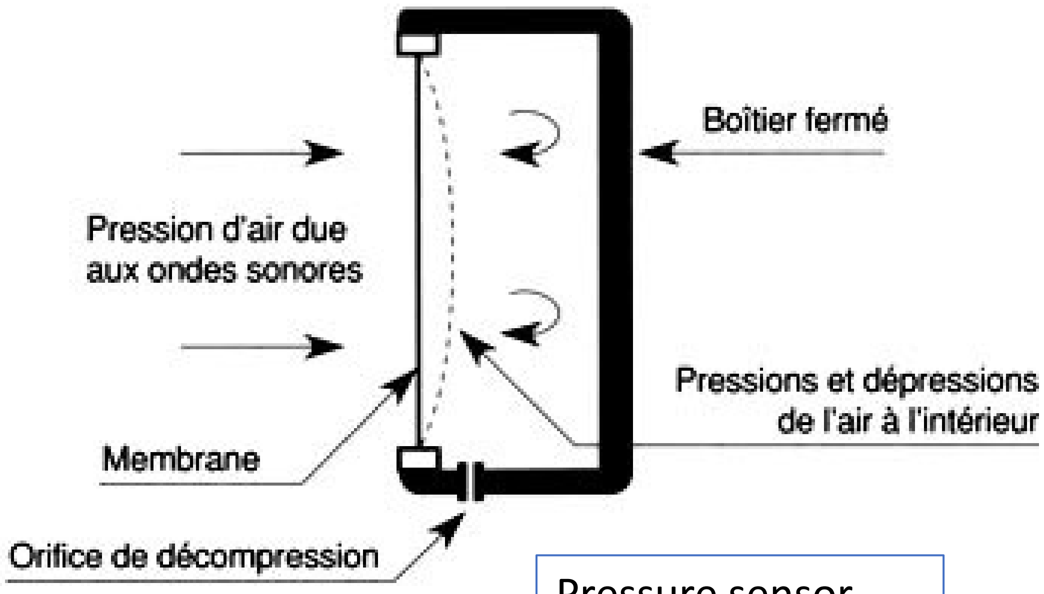
• Filtering, pop filter and attenuator:

A **pop** filter, often made of foam, can be integrated into the microphone to act as a "windscreen". This only applies to microphones for stage vocals.

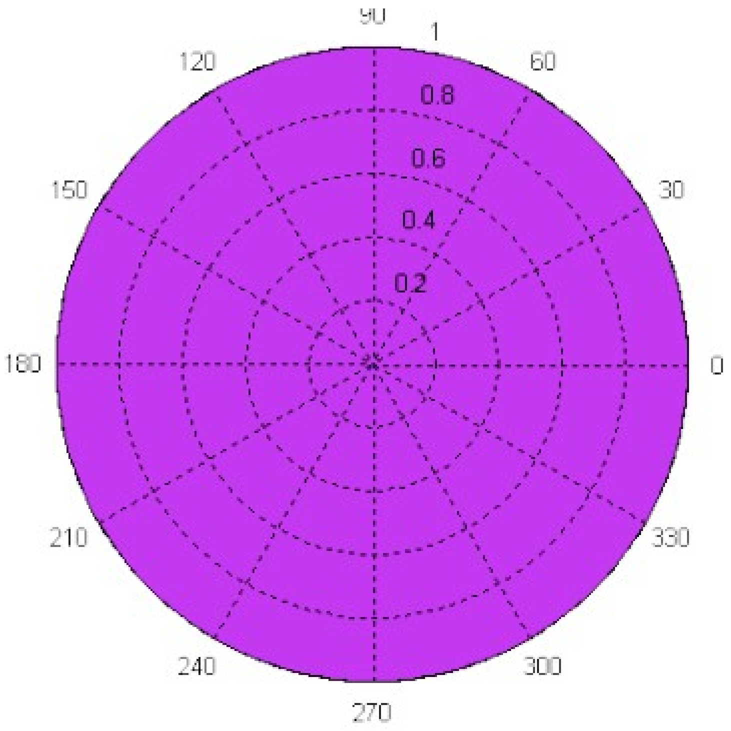
4. Sensor type and directivity

1. The pressure sensor

The pressure sensor consists of a diaphragm and a closed cavity: Only one of the sides of the diaphragm receives sound vibrations.



Pressure sensor



Directivité omnidirectionelle

In theory

The sensor is **omnidirectional**

When viewed in three-dimensional space, the pressure sensor has **spherical** directivity.

In practice

the sensitivity of a pressure sensor depends on:

* the size of the membrane
* the frequency of the incident wave and its angle of incidence.

1- When the wavelength is **large** in relation to the dimensions of the membrane low

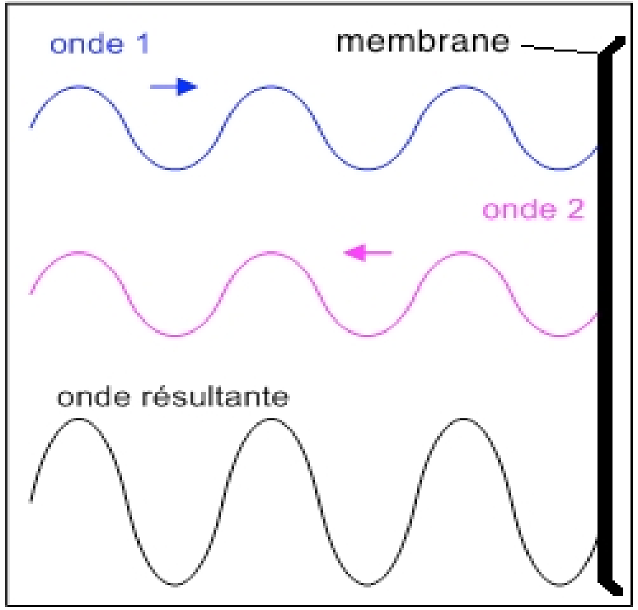
↓ frequencies

the sensor is omnidirectional. This is estimated to be the case for frequencies up to approximately **1 kHz**.

2- When the wavelength is **of the order** of the size of the membrane, or less

↓ medium and high frequencies

A phenomenon of **reflection and diffraction will occur when** short or medium wavelength **waves** strike the membrane



3- For high frequencies

↓

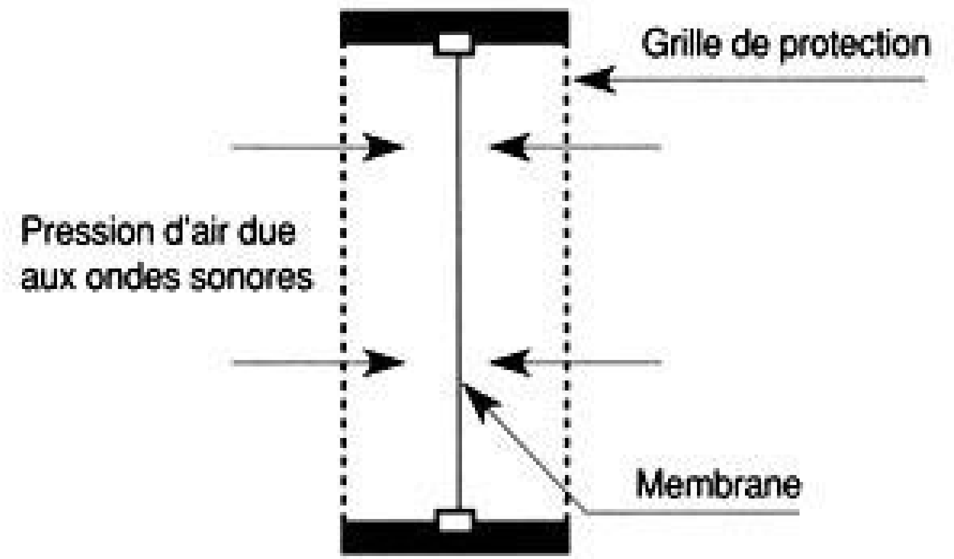
the directivity narrows, with the effect becoming more pronounced as the frequency increases and the angle of incidence becomes greater.

In summary

omnidirectional sensors are mainly effective for frequencies below approximately 1kHz. Up to 10kHz, they are **slightly more directional**, and above 10kHz, they are highly **directional**.

2. The pressure gradient sensor

In this case, the membrane is exposed to the open air (there is no longer an insulating cavity), so sound vibrations reach both sides of the membrane. The resulting signal is therefore the difference (*gradient) between the signals arriving at the same time on each side of the* membrane.



Pressure gradient sensor

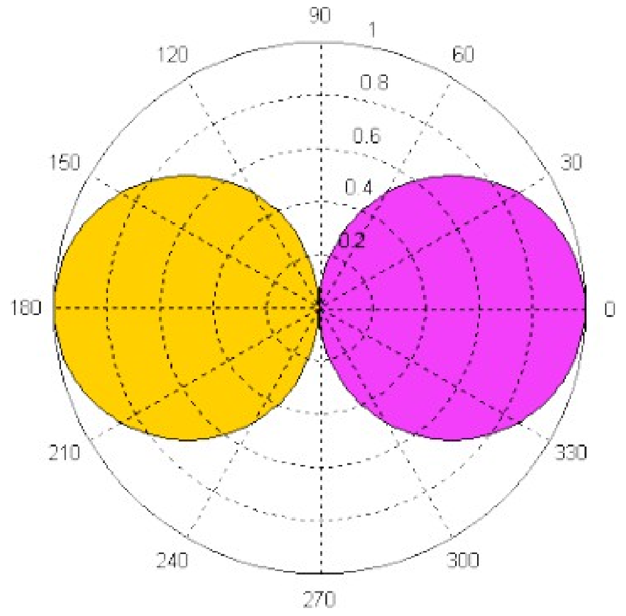
The directivity of such a system can be easily deduced when studying specific cases:

1. the signal arrives at the same time (in phase) on both sides of the membrane and therefore cancels itself out.

2. If the source is located in the axis of the microphone (at 0° or 180°), the sound wave arrives alternately on both sides of the membrane and therefore the pressure difference between the two sides of the membrane is maximum. It is therefore on this axis that the sensitivity of the microphone is strongest.

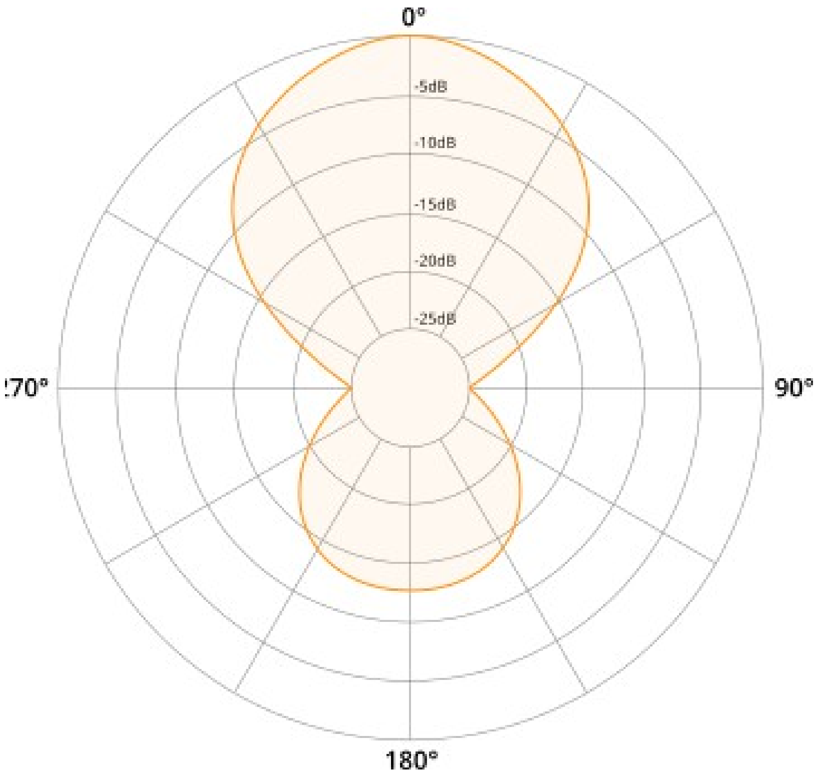
symmetrical directivity on each side of the membrane, known as **bidirectional (or figure-8) directivity.**

Bidirectional directivity



3. Representation of directivity

We use what are called **polar diagrams**, such as this one:



* Imagine the microphone being studied at the centre studying.

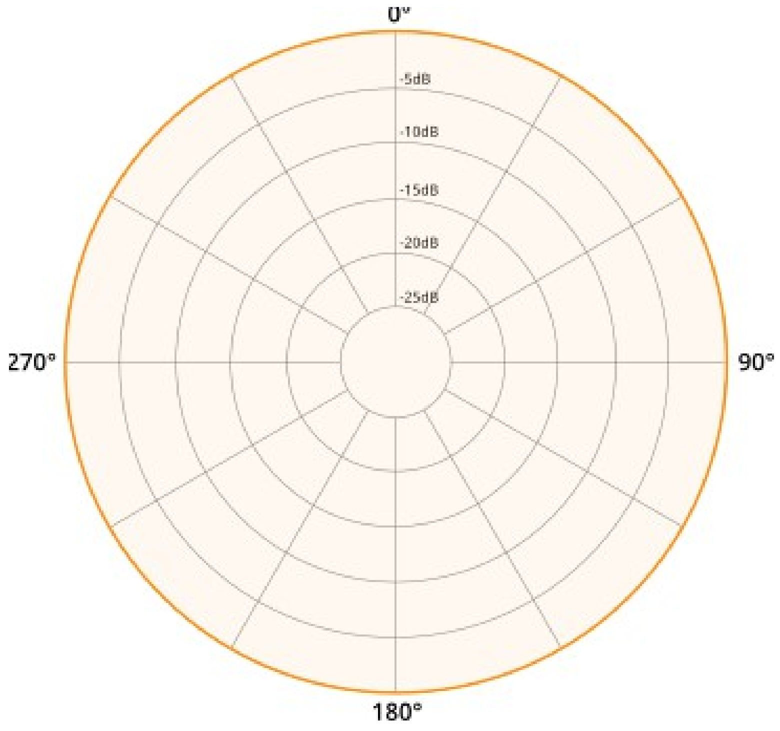
* The circles represent the acoustic space surrounding it, at 360 degrees:
0° = in front of the microphone
180° = behind the microphone

Example of the polar diagram of a hypothetical microphone

3.1 Omnidirectional microphones

These are characterised by equal sensitivity in all directions, regardless of the position of the sound source being recorded.

However, their directivity means that they are very sensitive to:
* to the ambience of the room in which they are used;
* to other surrounding sounds



Uses

•Their omnidirectional directivity allows them to capture sound identically, regardless of how they are attached to clothing.

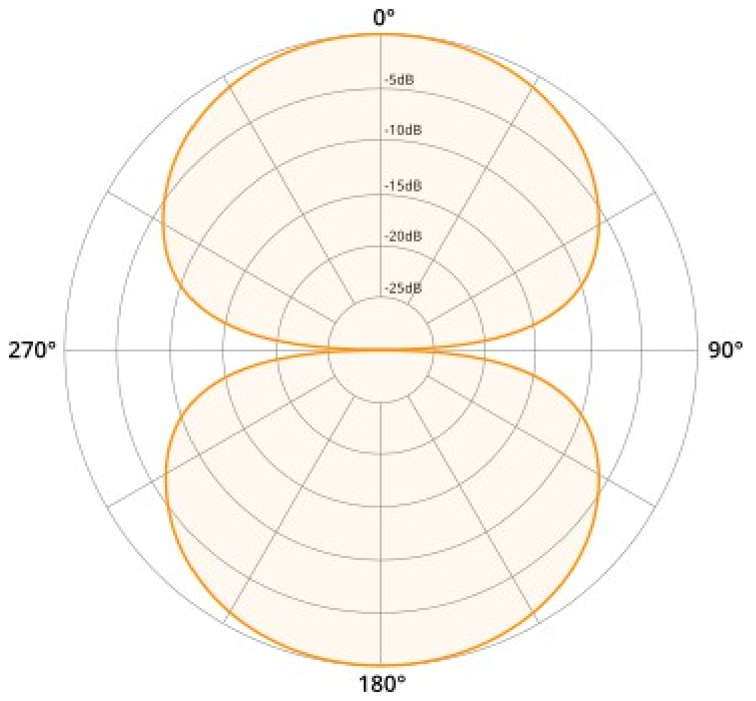
* They are not necessarily the most common choice for studio use. However, they can be used in many applications **as long as you are recording in a room with good acoustics.**

3.2 Bidirectional microphones

Unlike omnidirectional microphones, figure-8 microphones function as **pressure gradient sensors**.

Consequence

They are sensitive to sound sources in front of and behind the microphone, while **sounds coming from the sides are in a blind spot**. This can be seen in the polar diagram opposite.



Uses

•Simultaneous recording of two singers;

•Recording a singer playing the guitar;

* Mid/Side recording techniques

3.3 Cardioid microphones

Cardioid microphones have a heart-shaped polar pattern, hence their name. This is because they are only sensitive to sounds coming from the front, which greatly simplifies their use.

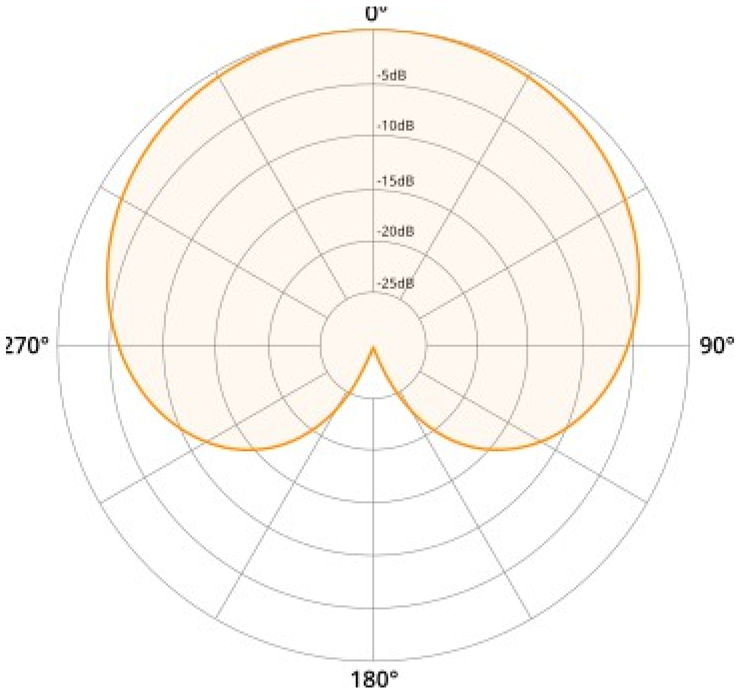
Consequence

Less prone to feedback, they can easily isolate them from sound sources that do not want to record.

Uses

•Unsurprisingly, cardioid microphones are mainly used when recording a directional sound source: singers, guitar amps, drum kit components, etc.

* For example, the Shure SM57 (cardioid) is often used to record snare drums, as it is not sensitive to sounds coming from behind.

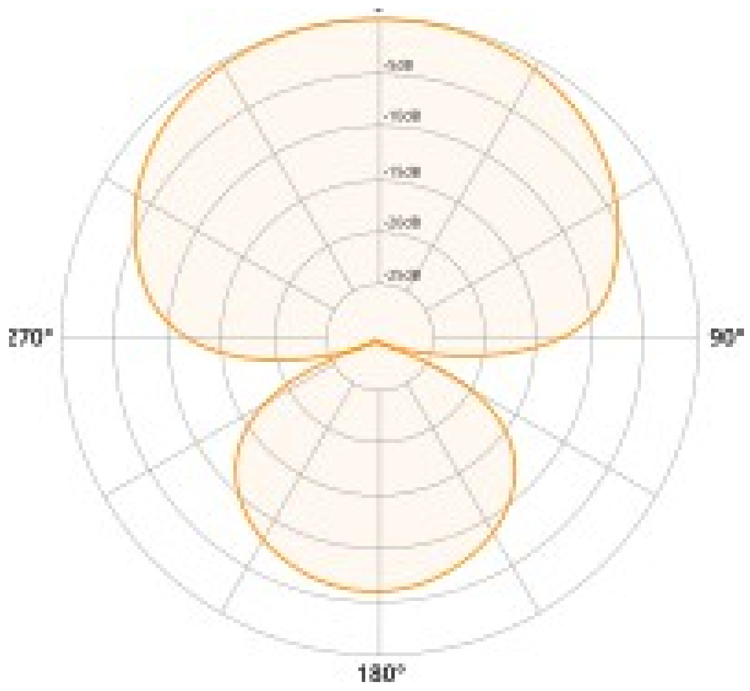


Supercardioid, Hypercardioid

* Supercardioid and hypercardioid microphones are simply variations of cardioid directivity.

* They are characterised by a more restricted forward sensitivity in terms of angle, but in return there is greater sensitivity towards the rear.

* In other words, their polar pattern could be drawn as shown opposite.



In summary, the three main directivities are as follows:

Cardioid

the most commonly used in studios and home studios, it corresponds to microphones that are only sensitive to sounds coming from the front;

Omnidirectional

these microphones are equally sensitive to sound from all angles, regardless of the position of the sound source.

Figure-8

The microphone picks up sound from the front and rear but is not sensitive to sound sources from the sides.
Of course, each directivity has a number of possible uses, although in home studios, cardioid directivity is the most common for obvious reasons related to recording conditions.

Chapter 4
MEASUREMENTS IN TELECOMMUNICATIONS

IMPORTANCE OF MEASUREMENTS

- Providing the customer with quality service in terms of equipment control and reliability for proper operation.

- This quality of service is what makes our profession so reputable.

- **Static measurements**
  - continuity testing
  - verification of connections
  - Voltage checks

- **Dynamic measurements**
  - physical tests simulating the operation of a link or bus.
  - Digital tests simulating operation

TYPES OFEQUIPMENT USED

- **for static measurements:**
  - multimeter
  - reflectometer
  - fibre optic testers

- **For dynamic measurements:**
  - link testers
  - frame analysers
  - protocol analysers

Measuring electrical continuity

Purpose:

Identify the measuring device required to measure resistance and check continuity.
continuity.

Continuity concepts:

Continuity is the presence of a complete path for the flow of current.

Example

* A circuit is complete when its switch is closed.

* The continuity test mode on a digital multimeter can be used to test switches, fuses, electrical connections, conductors and other components.

* A good fuse should show continuity.

* During a continuity test, the digital multimeter sends current through the circuit to measure its resistance.

The continuity measurement allows you to determine:

* The condition of a fuse

* The condition of the conductors

* The operating condition of the switches

* The condition of a circuit

<u>Steps for measuring continuity</u>

*Set the rotary selector to Continuity Test mode (Continuity test icon).

•First insert the black test lead into the COM socket.

* Then insert the red lead into the Tesion/hom socket.

* Connect the test leads to the component being tested (fuse). The position of these leads is arbitrary.

* The digital multimeter (DMM) will beep if a complete path (continuity) is detected.

* When the measurement is complete, switch off the multimeter to save battery power. battery.

How should test results be interpreted?

Device indication.

It is likely that the symbol on the rotary selector shares its location with one or more other functions, usually resistance.

The multimeter display may show "OL", "over" or "1" and ohms.

Example:

Two fuses (A, B)

A: OL M Ω → Bad

B: 0.1Ω → Good

Purpose:

Identify the measuring device required to locate faults in metal cables and, in the optical field, fibre optics.

The time domain reflect**ometer** or **TDR**

Reflectometry is a diagnostic method based on the principle of radar.

The purpose of reflectometry:

* To measure the length of the link or event
* To determine the attenuation
* Visualise variations and incidents along the fibre

Areas of application

•Time reflectometry was developed as a result of work on radar towards the end of the Second World War, but it only became truly usable in the early 1960s with the advent of oscilloscopes.

Today, reflectometry is used in many fields, ranging from measuring soil moisture and respiratory tracts to detecting faults in cables and optical fibres.

•A probe signal is sent into the system or medium to be diagnosed. This signal propagates according to the laws of propagation of the medium under study, and when it encounters a discontinuity, part of its energy is returned to the injection point.

* Analysis of the reflected signal provides information about the system or medium in question. Reflectometry is therefore a non-destructive testing method.