SMART SENSOR SYSTEMS

18NTO308T

Definitions of Sensors and Smart Sensors / Integrated Smart Sensors and Applications

Sensors classifications / Detection means used in sensors and conversion phenomena

Measurements / Units of Measurements

Sensor Characteristics: Transfer Function, Calibration, Static Characteristics, Accuracy,

Calibration Error, Hysteresis,Nonlinearity, Resolution, Dynamic Characteristics

Physical principles of sensing: Electric charges, Electric fields, and potentials

Capacitance, dielectric constant, Magnetic Principle

Induction Principle, Electrical Resistance

Piezoelectric effect, Pyroelectric effect

Hall effect Principle, Seebeck and Peltier effects

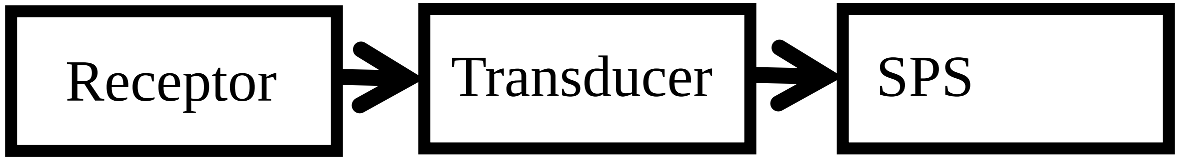
Sensors and smart sensors (definitions)

Sensors are sophisticated devices that are used to detect and respond to events or changes in its environment

A **Sensor** converts physical parameters such as temperature, pressure, humidity, speed, etc. into a signal which can be measured electrically.

3 main components

1. Receptor
2. Transducer
3. SPS (signal processing system)



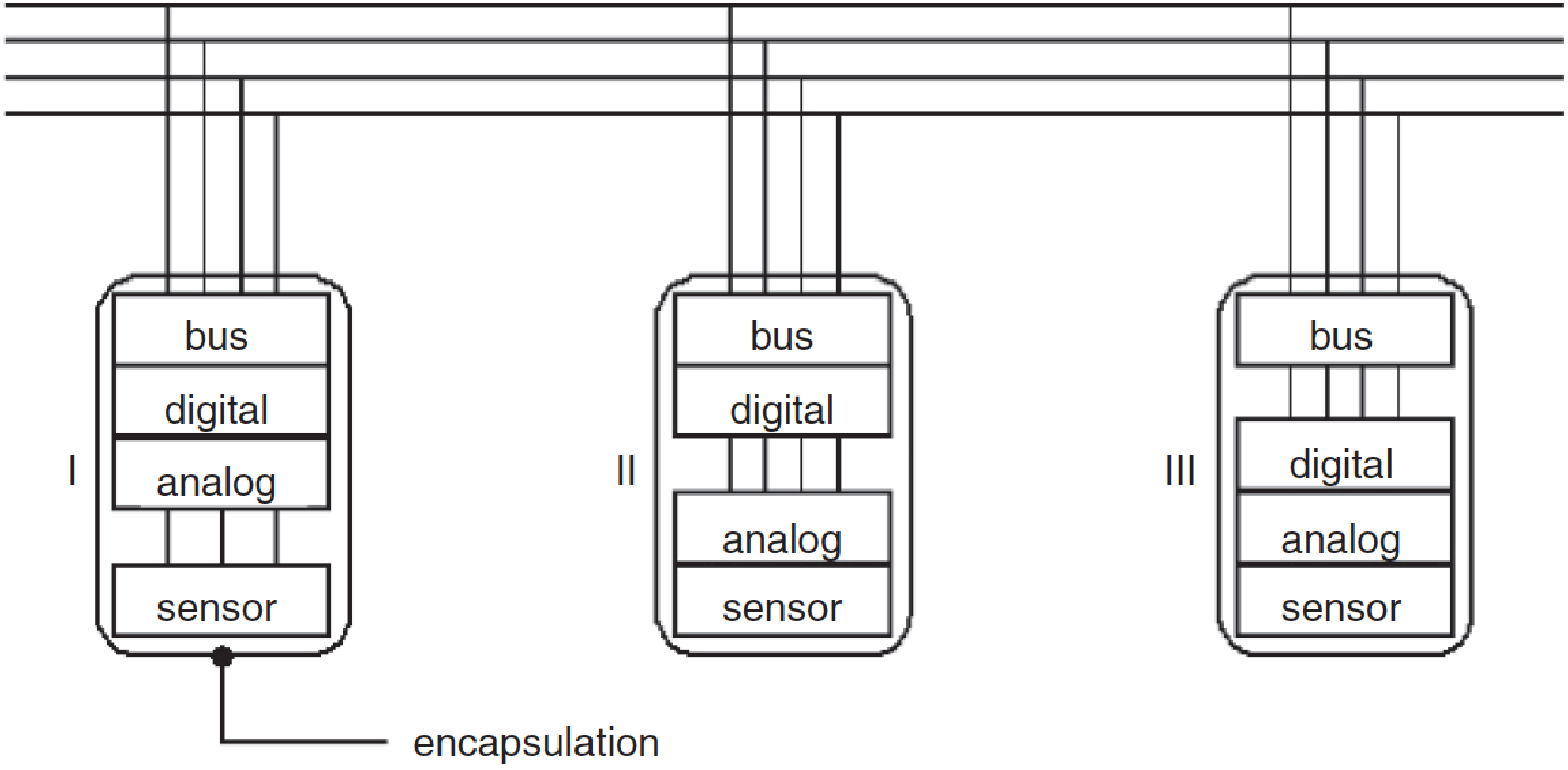
Receptor reacts with the target analyte or responds to the changing physical or chemical parameters

Transducer changes the signal of the receptor to a measurable signal preferably electrical signal

Signal processing system measures and shows the signal in a meaningful way for you.

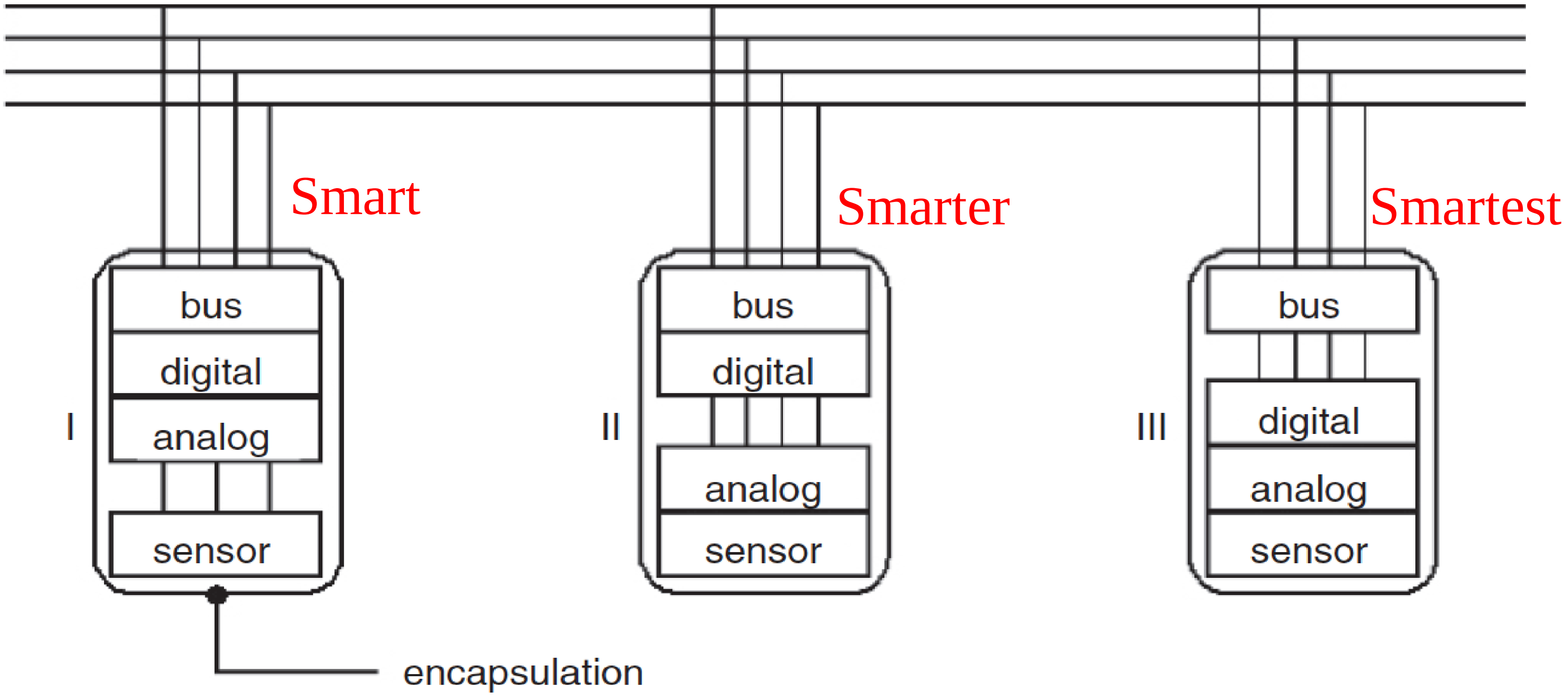
Smart sensors (definitions)

These are devices in which a sensor is combined with an analog interface circuit, an analog to digital converter (ADC) and a bus interface in one housing.



A **smart sensor** is a device that takes input from the physical environment and uses built-in computer resources to perform predefined functions upon detection of specific input and then process data before passing it on

Smart sensors (definitions)



In the first hybrid smart sensor, a universal sensor interface (USI) can be used to connect the sensor with the digital bus.

In the second one, the sensor and signal conditioner have been integrated. However, the ADC and bus interface are still outside.

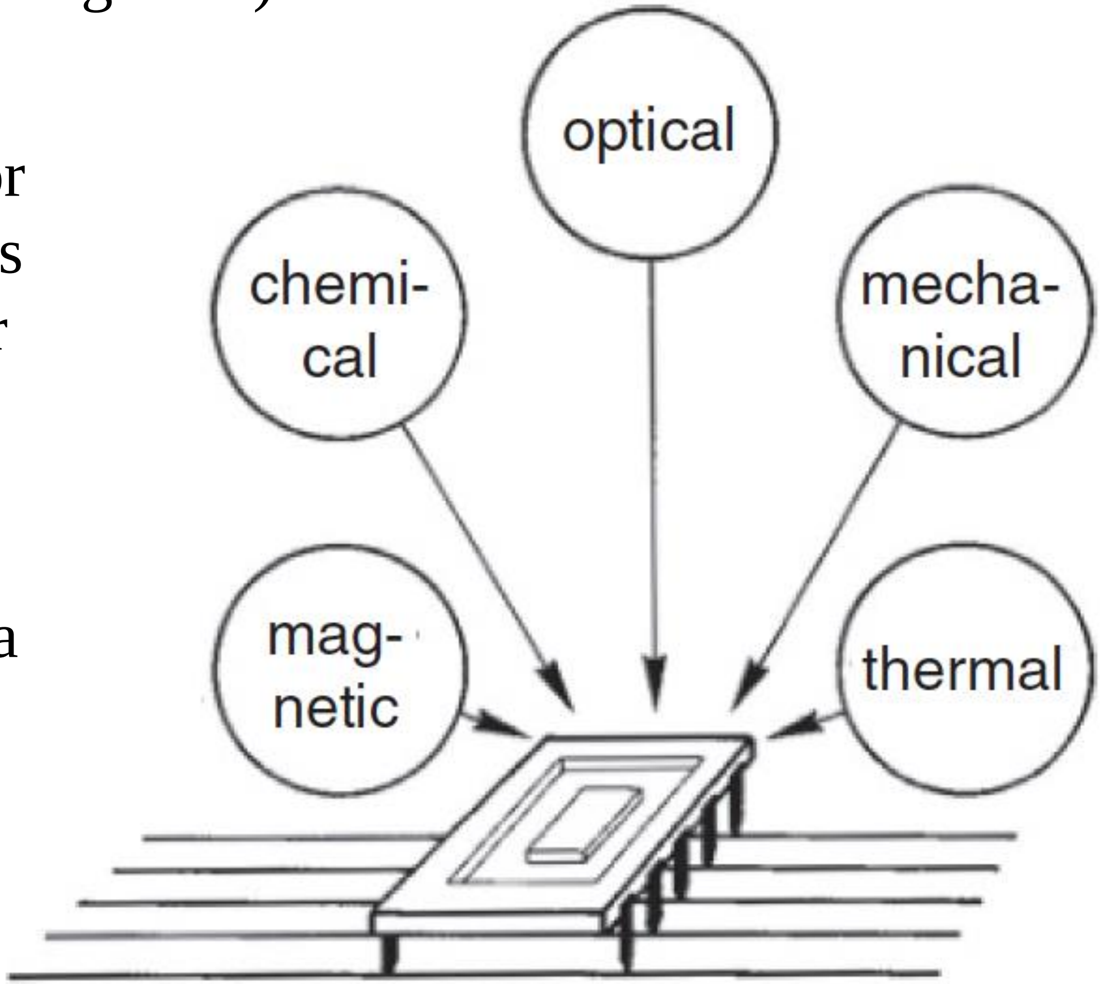
In the third hybrid, the sensor is already combined with an interface circuit on one chip that provides a duty cycle or bit stream. Just the bus interface is still needed separately.

Integrated smart sensors

These are devices in which all functions from sensor to bus interface at=re integrated in single chip

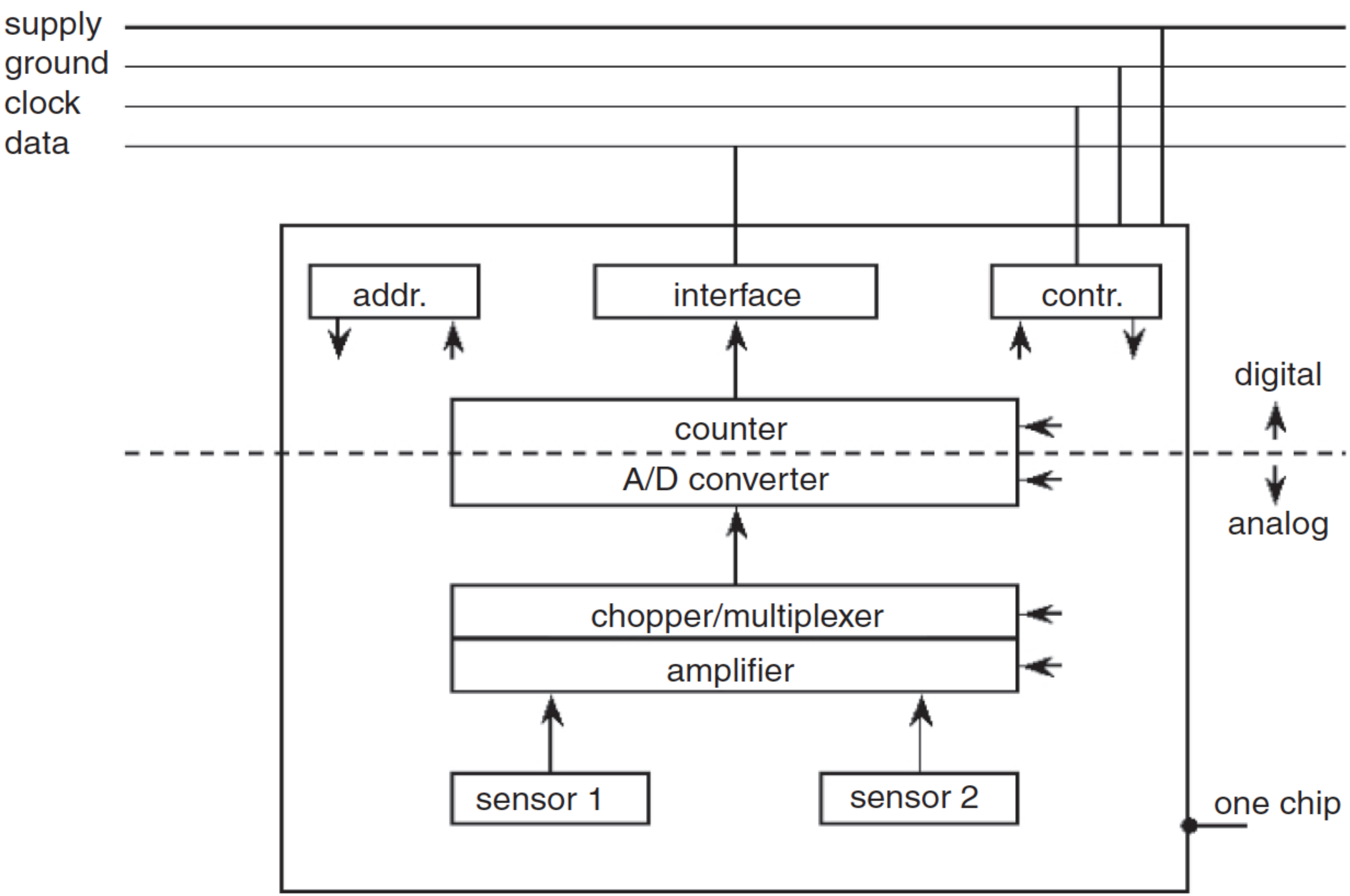
All in one package (sensor elements + driving electronics + signal processing units)

An integrated smart sensor should contain all elements necessary per node: one or more
sensors, amplifiers, a chopper and multiplexers, an AD converter, buffers, a bus interface, addresses, and control and power management.



Integrated smart sensors

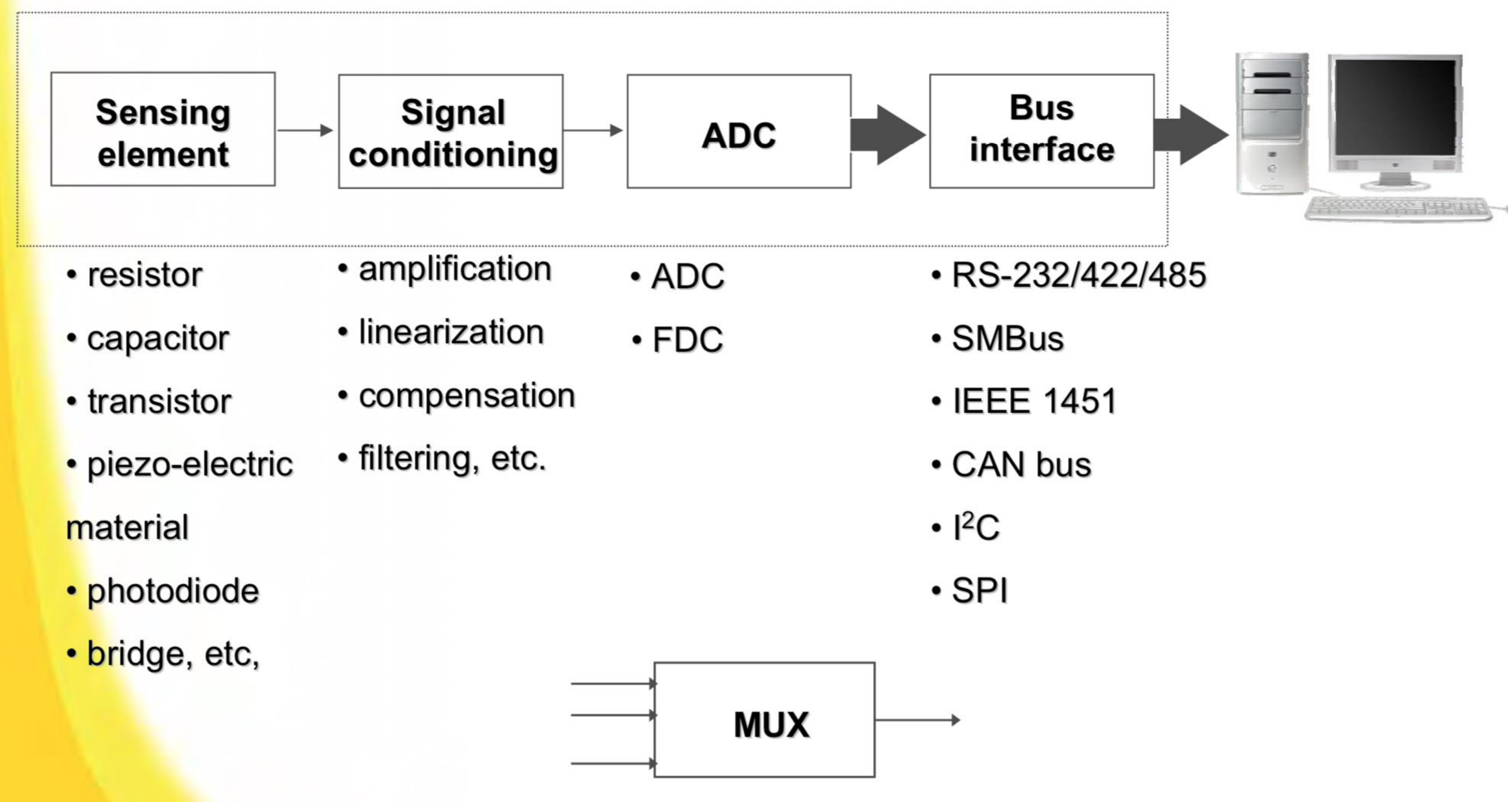
Functions of an integrated smart sensor



Integrated smart sensor systems

Smart sensors with integrated power supply and wireless communication interfaces

Several sensors (gas, temperature, pressure, humidity, etc.) are integrated together to perform a common task such as environment monitoring, food testing etc.



Integrated smart sensors and applications

Integrated smart sensors will be applied in all areas of daily life: in smart homes and appliances, in smart cars, and in smart production machines.

Industries
(bio)chemical industry
Metal industry
Car industry
Textile industry
Food industry
Building industry
Agriculture industry

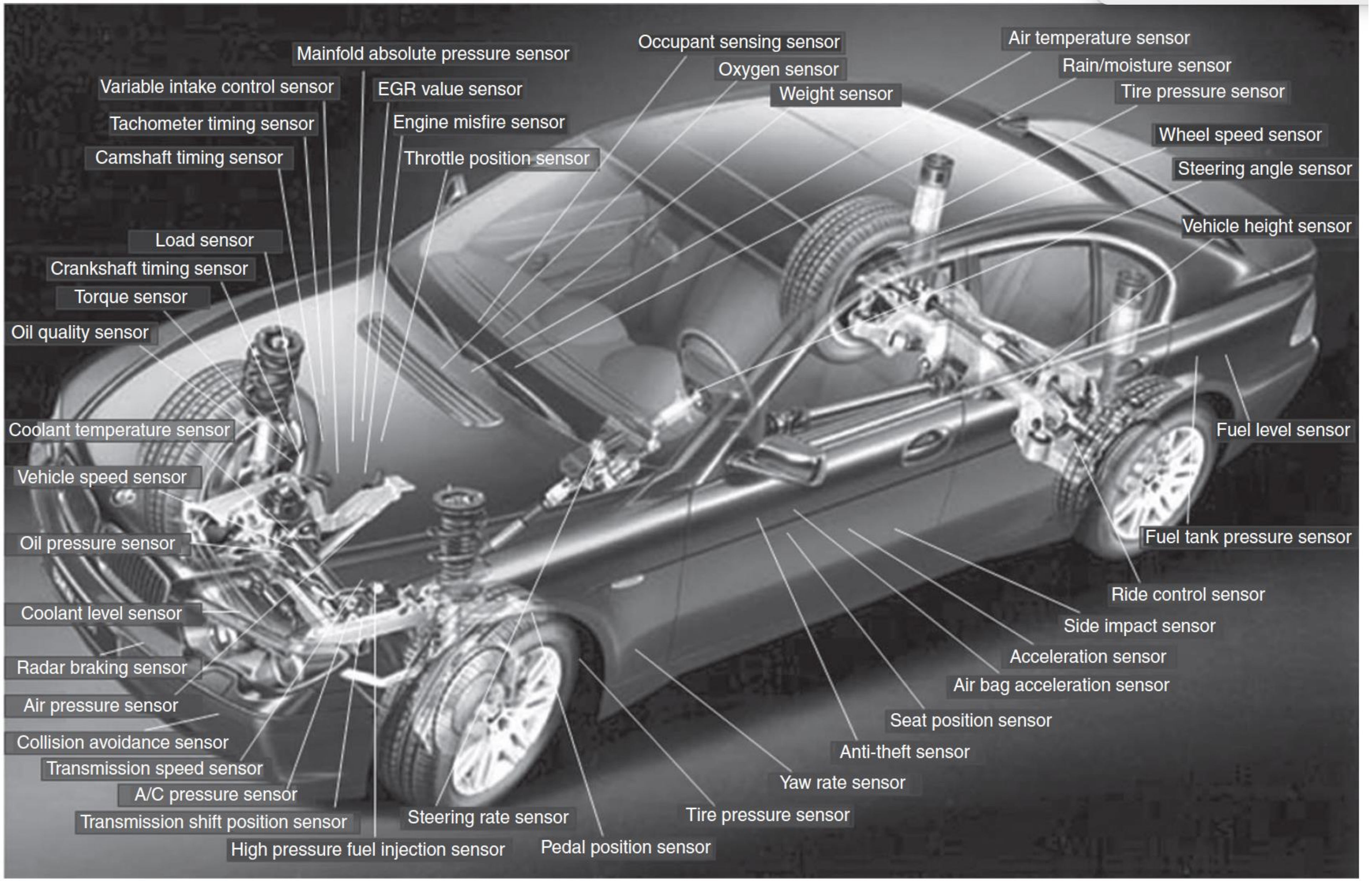
Professional monitoring
Traffic control
Environmental monitoring
Health care
Health monitoring
Security
Office automation
Food quality monitoring

Automated consumer products
Smart cars
Smart homes
Smart domestic appliances
Smart toys

Smart Cars

Modern cars incorporated more than 40 sensors. It will only be possible to accommodate more sensors if a distributed sensor bus is used instead of a star-connected sensor system. only smart sensors make this economically viable. Otherwise the car breaks down under the load of wires

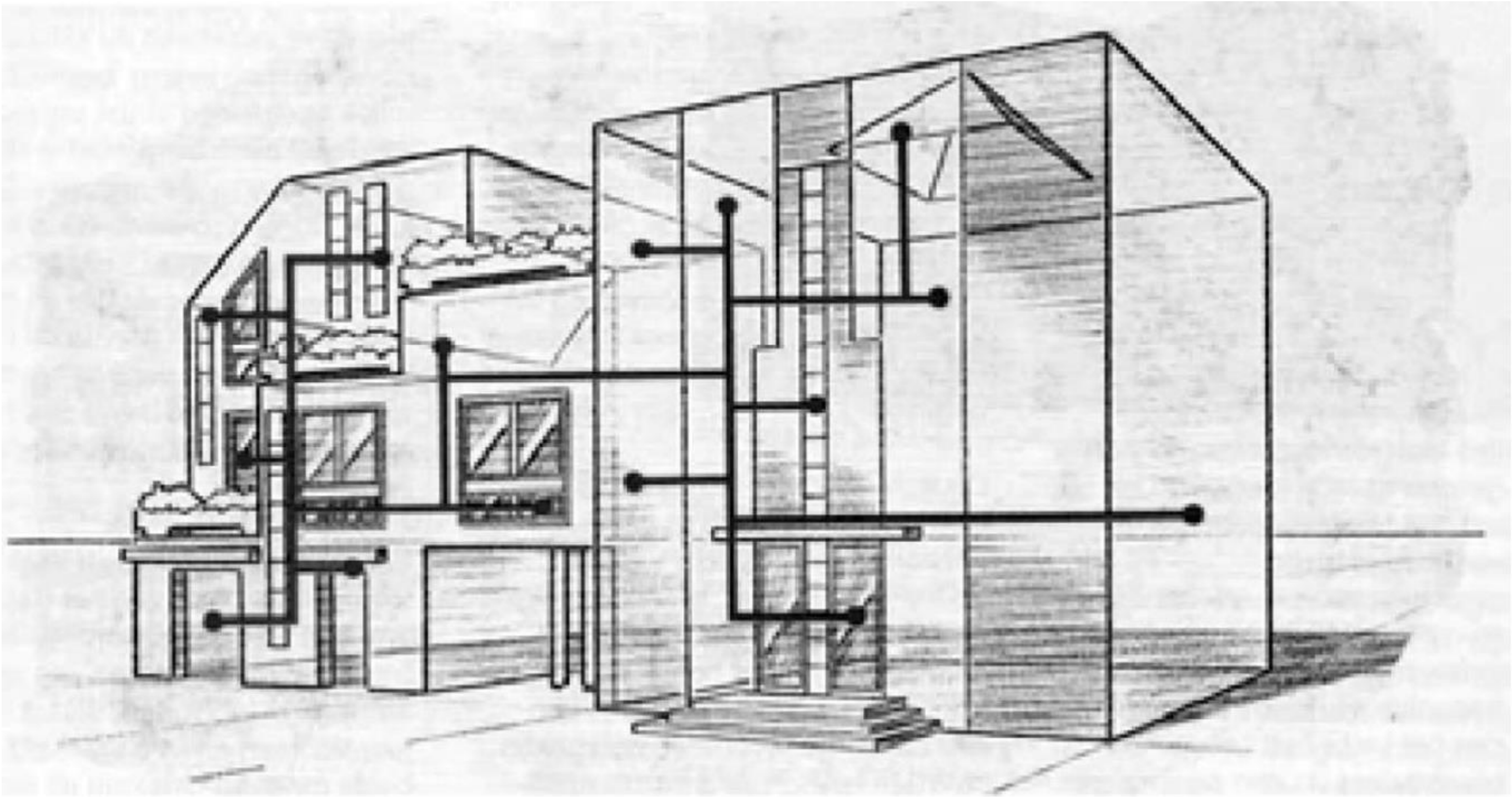
Integrated smart sensors and applications



Integrated smart sensors and applications

Smart Homes

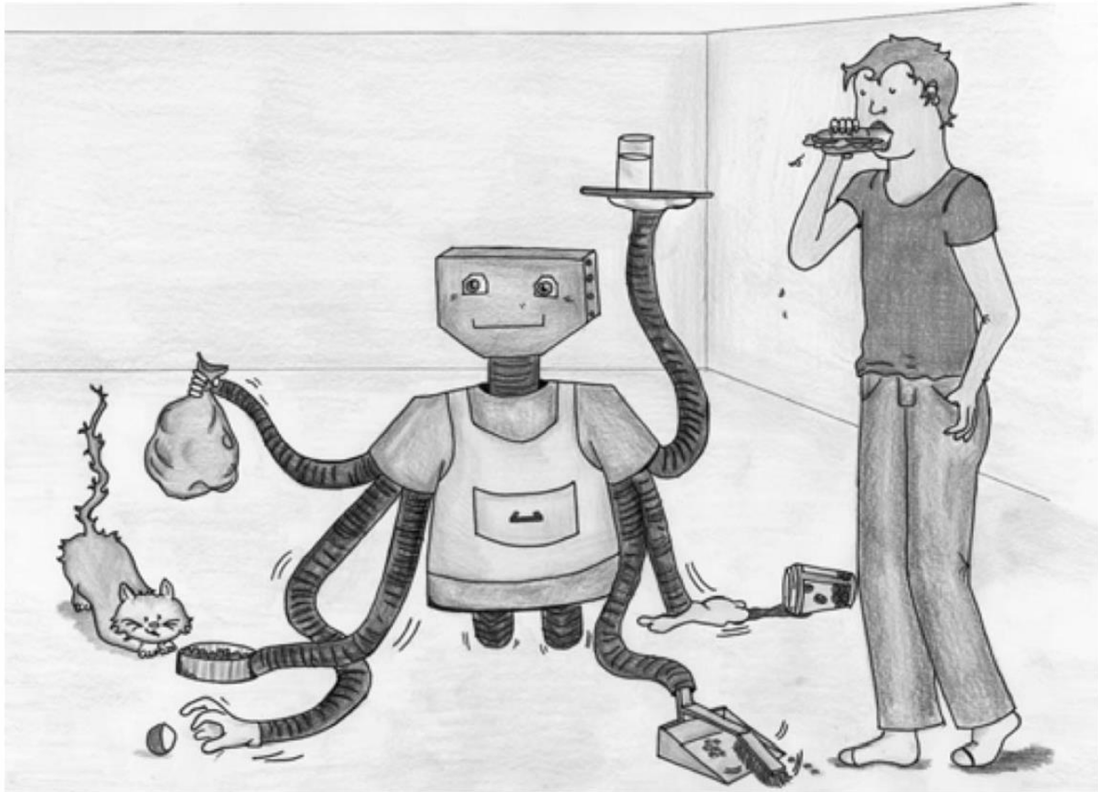
Like cars, houses can only accommodate many sensors if a distributed bus system is used instead of a point-to-point network



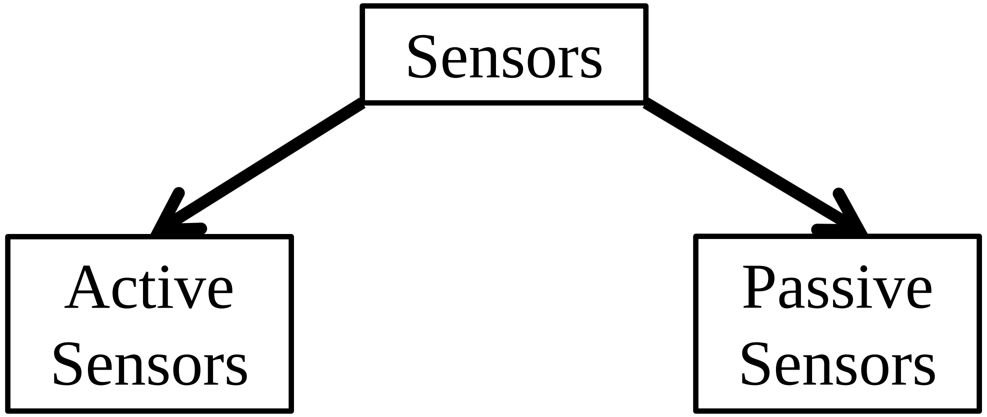
Integrated smart sensors and applications

Smart domestic appliances

Automated vacuum cleaner that automatically moves from its socket once a week and vacuum the rooms, without running over a cat or knocking over a vase, refrigerators that detects when the supply of certain items is running low and will communicate this, so that it can be refurnished, washing machines that determines how much detergent is needed to clean the laundry and use no more than that, a robotic butler, supplying the needs of the family members



Sensors classifications



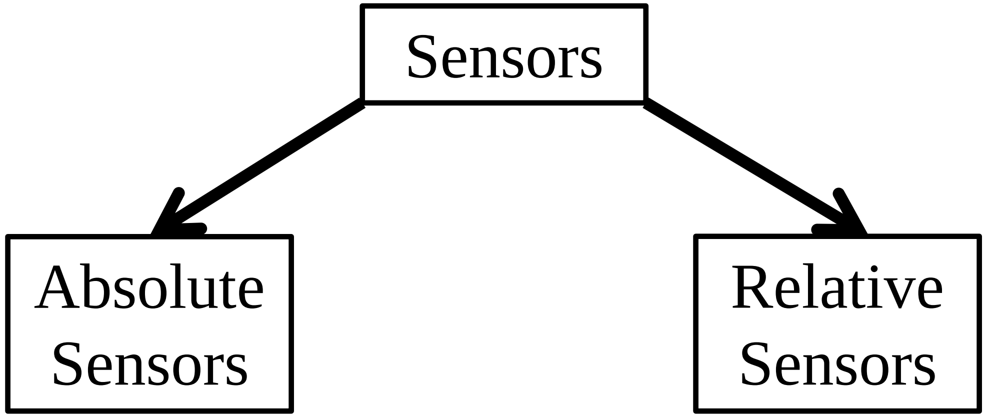
A passive sensor does not need any additional energy source and directly generates an electric signal in response to an external stimulus; that is, the input stimulus energy is converted by the sensor into the output signal.

- Thermocouple
- Photodiode
- Piezoelectric sensor.

The active sensors require external power for their operation, which is called an excitation signal . That signal is modified by the sensor to produce the output signal. The active sensors sometimes are called parametric because their own properties change in response to an external effect and these properties can be subsequently converted into electric signals.

- Resistive strain gauge
- Thermistor
- Accelerometer/gyroscope

Sensors classifications



Depending on the selected reference, sensors can be classified into absolute and relative .

An absolute sensor detects a stimulus in reference to an absolute physical scale that is independent on the measurement conditions

Thermistor is an example for absolute sensors. Its electrical resistance directly relates to the absolute temperature scale of Kelvin

A relative sensor produces a signal that relates to some special cases dependent on the measurement conditions

Thermocouple is an example for relative sensor. It produces an electric voltage that is function of a temperature gradient across the thermocouple wires. Thus a thermocouple output signal cannot be related to any particular temperature without referencing to a known baseline.

Detection means used in sensors

Biological
Chemical
Electric, magnetic, or electromagnetic wave
Heat, temperature
Mechanical displacement or wave
Radioactivity, radiation

Conversion phenomena used in sensors

Physical	Chemical
Thermoelectric	Chemical transformation
Photoelectric	Physical transformation
Photomagnetic	Electrochemical process
Magnetoelectric	Spectroscopy
Electromagnetic	Other
Thermoelastic	**Biological**
Electroelastic	Biochemical transformation
Thermomagnetic	Physical transformation
Thermooptic	Effect on test organism
Photoelastic	Spectroscopy

Measurements and units of measurements

- Acoustic
  - Wave amplitude, phase, polarization
  - Spectrum
  - Wave velocity
  - Other
- Biological
  - Biomass (types, concentration, states)
  - Other
- Chemical
  - Components (identities, concentration, states)
  - Other
- Electric
  - Charge, current
  - Potential, voltage
  - Electric field (amplitude, phase, polarization, spectrum)
  - Conductivity
  - Permitivity
  - Other
- Magnetic
  - Magnetic field (amplitude, phase, polarization, spectrum)
  - Magnetic flux
  - Permeability
  - Other
- Optical
  - Wave amplitude, phase, polarization, spectrum
  - Wave velocity
  - Refractive index
  - Emissivity
  - reflectivity, absorption
  - Other
- Mechanical
  - Position (linear, angular)
  - Acceleration
  - Force
  - Stress, pressure
  - Strain
  - Mass, density
  - Moment, torque
  - Speed of flow,rate of mass transport
  - Shape, roughness, orientation
  - Stiffness, compliance
- Viscosity
  - Crystallinity, structural integrity
  - Other
- Radiation
  - Type
  - Energy
  - Intensity
  - Other
- Thermal
  - Temperature
  - Flux
  - Specific heat
  - Thermal conductivity
  - Other

Measurements and units of measurements

Quantity	Name	Symbol	Defined by (Year Established)
Length	Meter	m	The length of the path traveled by light in vacuum in 1/299,792,458 of a second. (1983)
Mass	Kilogram	kg	After a platinum–iridium prototype (1889)
Time	Second	s	The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom (1967)
Electric current	Ampere	A	Force equal to 2×10^{-7} Nm of length exerted on two parallel conductors in vacuum when they carry the current (1946)
Thermodynamic temperature	Kelvin	K	The fraction 1/273.16 of the thermodynamic temperature of the triple point of water length(1967)
Amount of substance	Mole	mol	The amount of substance which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12 (1971)
Luminous intensity	Candela	cd	Intensity in the perpendicular direction of a surface of 1/600,000 m^2 of a blackbody at temperature of freezing Pt under pressure of 101,325 Nm^2 (1967)
Plane angle	Radian	rad	(Supplemental unit)
Solid angle	Steradian	sr	(Supplemental unit)

Sensor Characteristics

Static characteristics

1. Transfer function
2. Calibration
3. Accuracy
4. Calibration error
5. Hysteresis
6. Nonlinearity
7. Resolution

Sensor Characteristics

1. Transfer function

A mathematical function which relates the output of the sensor to the stimulus

i.e. Output = transfer function × stimulus (input)

If S is the electrical signal produced by a sensor and the stimulus is s, then a unidimensional (o/p versus one i/p stimulus) linear relationship is given by the equation,

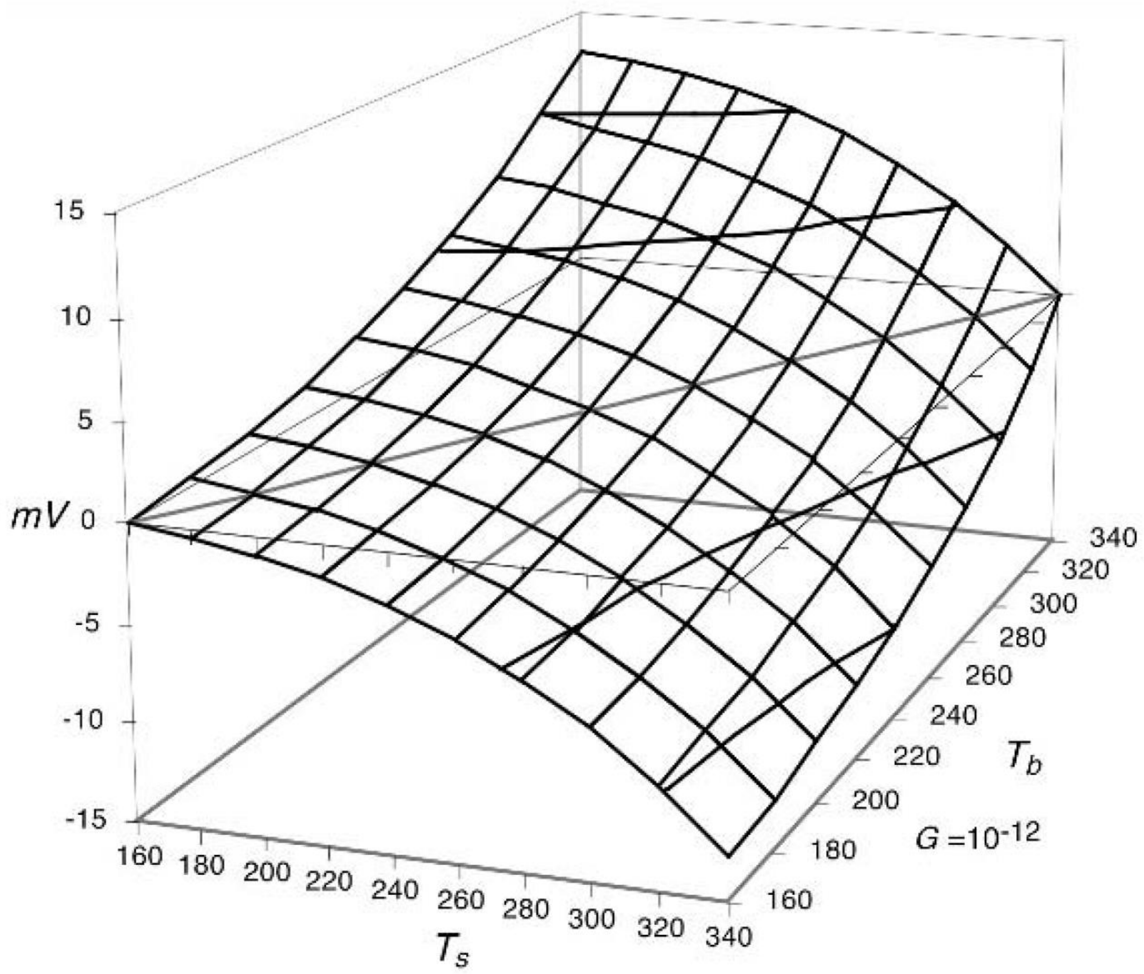
$$S = a + bs$$

a – intercept (o/p signal at zero i/p)

b – slope of the curve which is the sensitivity of the sensor

S is one of the characteristics of the output electric signal used by the data acquisition devices as the sensor’s output. It may be amplitude, frequency, or phase, depending on the sensor properties

Two-dimensional transfer function of a thermal radiation sensor. determined from two input temperatures



Sensor Characteristics

2. Calibration

It is the process of determining the specific variables that describe the overall transfer function, which means the transfer function of the entire circuit, including the sensor, the interface circuit, and the A/D converter

If the sensor's manufacturer's tolerances and tolerances of the interface (signal conditioning) circuit are broader than the required system accuracy, a calibration is required.

For example, if one uses a forward-biased semiconductor p-n junction for temperature measurement, with a high degree of accuracy its transfer function (temperature is the input and voltage is the output) can be considered linear

$$v = a + bt$$

To determine constants a and b , such a sensor should be subjected to two temperatures (t1 and t2) and two corresponding output voltages (v1 and v2) will be registered. Then, after substituting these values into the above equation, we arrive at

$$v_1 = a + bt_1$$

and

$$v_2 = a + bt_2$$

Sensor Characteristics

2. Calibration

and the constants are computed as

$$b = \frac{v_1 - v_2}{t_1 - t_2} \quad \text{and} \quad a = v_1 - bt_1.$$

To compute the temperature from the output voltage, a measured voltage is inserted into an inversed equation

$$t = \frac{v - a}{b}.$$

To calibrate sensors, it is essential to have and properly maintain precision and accurate physical standards of the appropriate stimuli. For example, to calibrate contact temperature sensors, either a temperature-controlled water bath or a “dry-well” cavity is required. To calibrate the infrared sensors, a blackbody cavity would be needed. To calibrate a hygrometer, a series of saturated salt solutions are required to sustain a constant relative humidity in a closed container

Sensor Characteristics

3. Accuracy

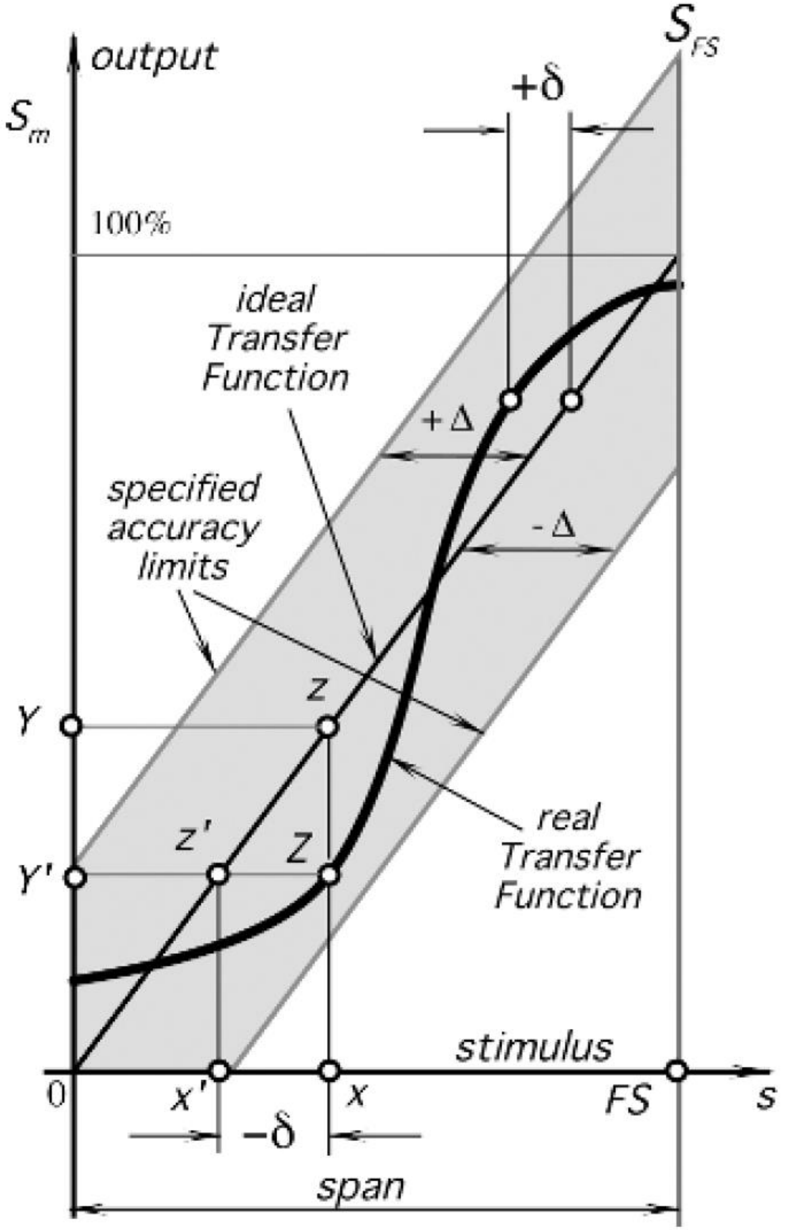
A very important characteristic of a sensor is accuracy which is a measure of inaccuracy .
Inaccuracy is measured as a highest deviation of a value represented by the sensor from the ideal or true value at its input.

The deviation can be described as a difference between the value which is computed from the output voltage and the actual input value. For example, a linear displacement sensor ideally should generate 1 mV per 1-mm displacement; that is, its transfer function is linear with a slope (sensitivity) b= 1 mV/mm. However, in the experiment, a displacement of s = 10 mm produced an output of S = 10. 5mV. Converting this number into the displacement value by using the inversed transfer function (1/b= 1 mm/mV), we would calculate that the displacement was sx =S/b= 10. 5 mm; that is sx −s = 0. 5 mm more than the actual. This extra 0.5 mm is an erroneous deviation in the measurement, or error. Therefore, in a 10-mm range, the sensor's absolute inaccuracy is 0.5 mm, or in the relative terms, inaccuracy is (0. 5mm/ 10mm)Å~ 100%= 5%. If we repeat this experiment over and over again without any random error and every time we observe an error of 0.5 mm, we may say that the sensor has a systematic inaccuracy of 0.5 mm over a 10-mm span. Naturally, a random component is always present, so the systematic error may be represented as an average or mean value of multiple errors.

Sensor Characteristics

3. Accuracy

A possible real transfer function is represented by a thick line, which generally may be neither linear nor monotonic. A real function rarely coincides with the ideal. Because of material variations, workmanship, design errors, manufacturing tolerances, and other limitations, it is possible to have a large family of real transfer functions, even when sensors are tested under identical conditions. However, all runs of the real transfer functions must fall within the limits of a specified accuracy. These permissive limits differ from the ideal transfer function line by $\pm\Delta$. The real functions deviate from the ideal by $\pm\delta$, where $\delta \leq \pm\Delta$



Two point calibration is be applied to improve the accuracy of the sensor

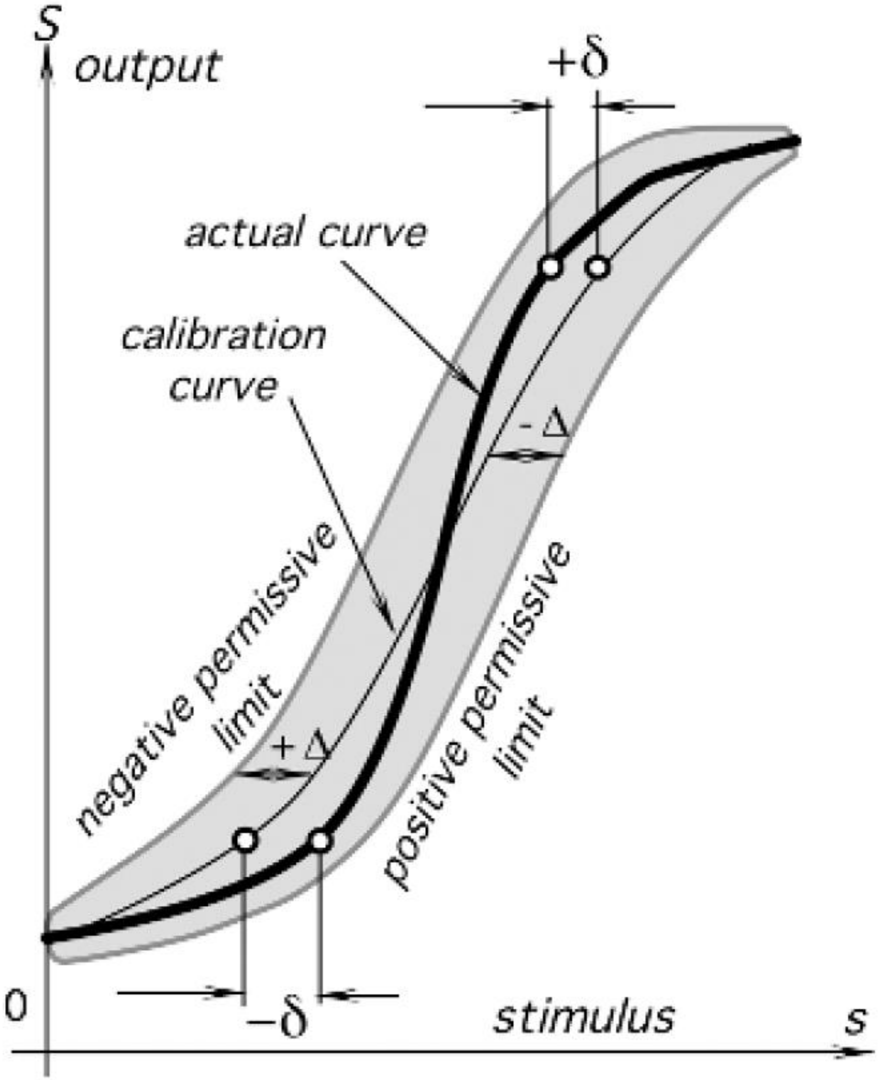
Sensor Characteristics

3. Accuracy

The accuracy rating includes a combined effect of part-to-part variations, a hysteresis, a dead band, calibration, and repeatability errors

Multiple point calibration technique can be employed to further improve the accuracy of the sensor so that the deviation $\pm\Delta$ may more closely follow the real transfer function, meaning better tolerances of the sensor's accuracy.

Multiple point calibration is be applied to improve the accuracy of the sensor



Sensor Characteristics

3. Calibration error

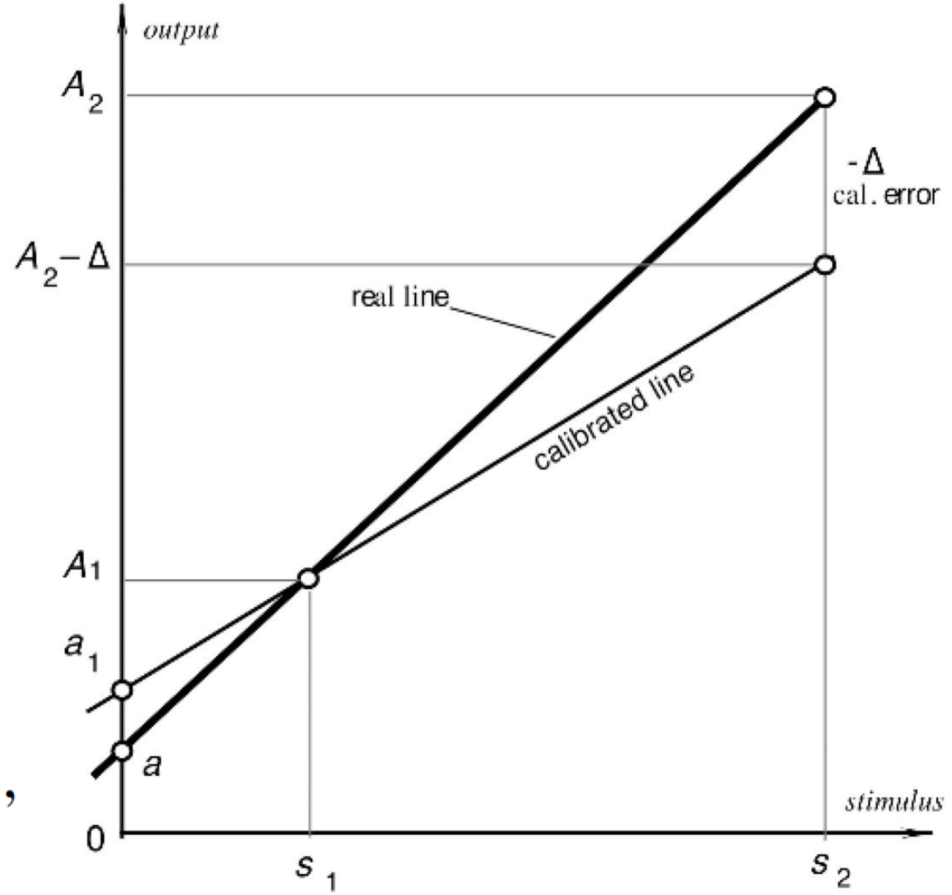
The calibration error is inaccuracy permitted by a manufacturer when a sensor is calibrated in the factory. This error is of a systematic nature, meaning that it is added to all possible real transfer functions. It shifts the accuracy of transduction for each stimulus point by a constant. This error is not necessarily uniform over the range and may change depending on the type of error in the calibration.

For example, let us consider a two-point calibration of a real linear transfer function (thick line in Fig.). To determine the slope and the intercept of the function, two stimuli, s1 and s2 , are applied to the sensor. The sensor responds with two corresponding output signals A1 and A2 . The first response was measured absolutely accurately, however, the higher signal was measured with error −Δ. This results in errors in the slope and intercept calculation. A new intercept, a1 , will differ from the real intercept, a , by

$$\delta_a = a_1 - a = \frac{\Delta}{s_2 - s_1},$$

and the slope will be calculated with error

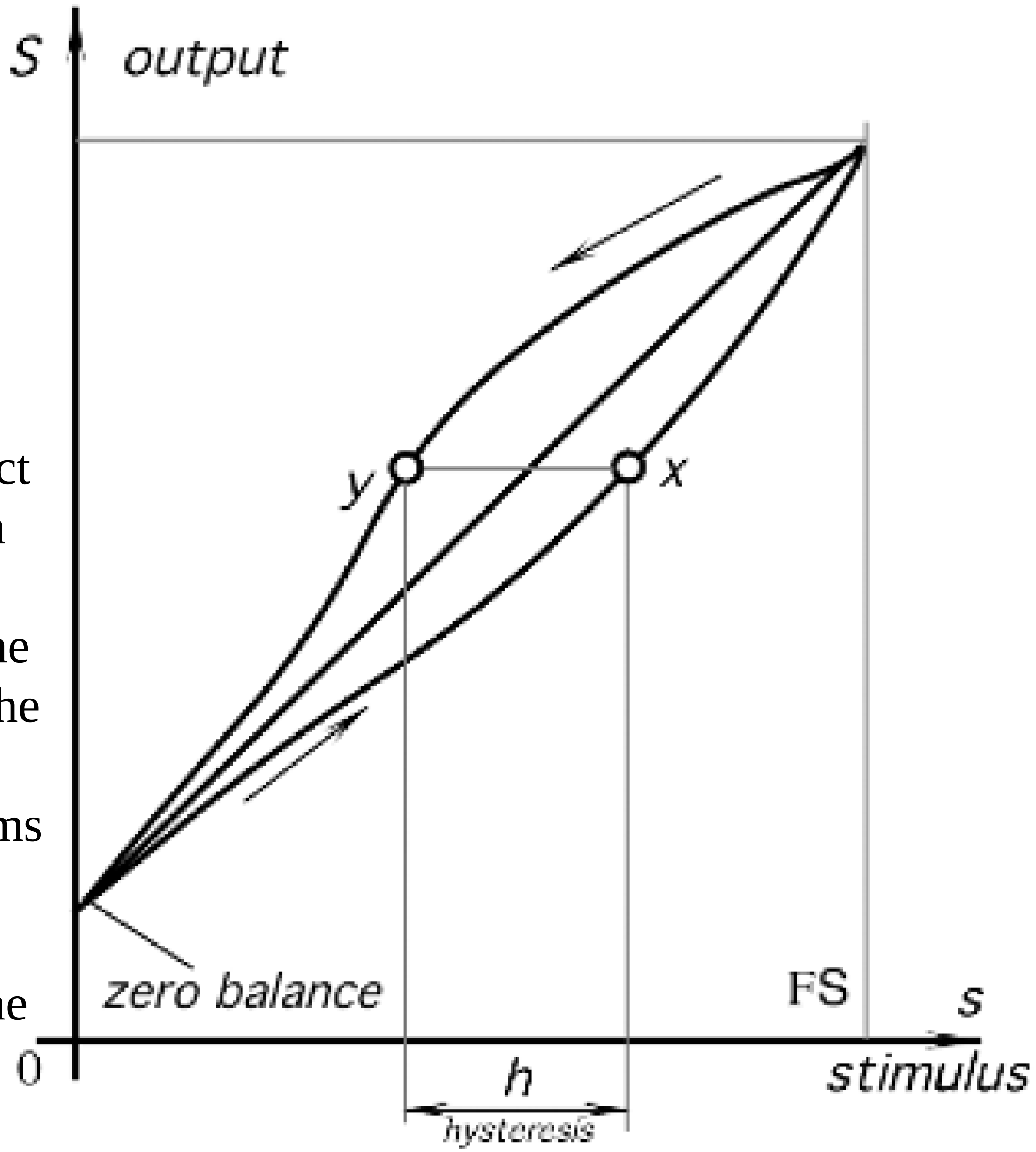
$$\delta_b = -\frac{\Delta}{s_2 - s_1},$$



Sensor Characteristics

4. Hysteresis

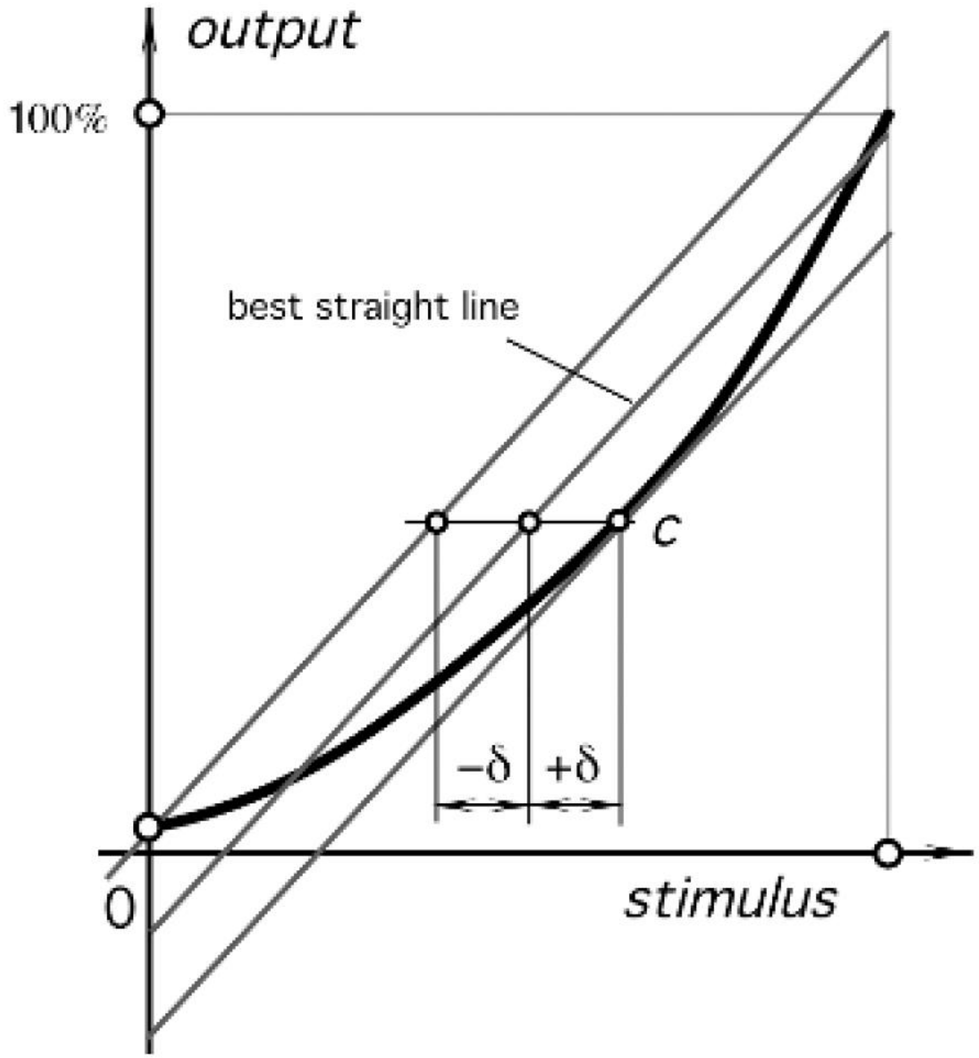
A hysteresis error is a deviation of the sensor’s output at a specified point of the input signal when it is approached from the opposite directions. For example, a displacement sensor when the object moves from left to right at a certain point produces a voltage which differs by 20 mV from that when the object moves from right to left. If the sensitivity of the sensor is 10 mV/mm, the hysteresis error in terms of displacement units is 2 mm. Typical causes for hysteresis are friction and structural changes in the materials.



Sensor Characteristics

4. Nonlinearity

Nonlinearity error is specified for sensors whose transfer function may be approximated by a straight line. Therefore nonlinearity is a measure of maximum deviation (L) of a real transfer function from the approximation straight line.



There are several ways to specify a nonlinearity, depending how the line is superimposed on the transfer function. One way is to use terminal points (Fig.); that is, to determine output values at the smallest and highest stimulus values and to draw a straight line through these two points (line 1). Here, near the terminal points, the nonlinearity error is the smallest and it is higher somewhere in between.

Sensor Characteristics

4. Resolution

Resolution describes the smallest increments of stimulus which can be sensed. When a stimulus continuously varies over the range, the output signals of some sensors will not be perfectly smooth, even under the no-noise conditions. The output may change in small steps.

This is typical for potentiometric transducers, occupancy infrared detectors with grid masks, and other sensors where the output signal change is enabled only upon a certain degree of stimulus variation. In addition, any signal converted into a digital format is broken into small steps, where a number is assigned to each step. The magnitude of the input variation which results in the output smallest step is specified as resolution under specified conditions (if any)

Dynamic Characteristic

If a sensor has time dependent response or characteristics, then the sensor is said to have dynamic characteristics

Under static conditions, a sensor is fully described by its transfer function, span, calibration, and so forth. However, when an input stimulus varies, a sensor response generally does not follow with perfect fidelity. The reason is that both the sensor and its coupling with the source of stimulus cannot always respond instantly. In other words, a sensor may be characterized with a time -dependent characteristic, which is called a dynamic characteristic .

If a sensor does not respond instantly, it may indicate values of stimuli which are somewhat different from the real; that is, the sensor responds with a dynamic error .A difference between static and dynamic errors is that the latter is always time dependent. If a sensor is a part of a control system which has its own dynamic characteristics, the combination may cause, at best, a delay in representing a true value of a stimulus or, at worst, cause oscillations.

The dynamic characteristics of a sensor is described by a constant coefficient linear differential equation. Depending on the sensor design, the differential equation can be of several orders.

A zero-order sensor is characterized by the following relationship in which the input and output are functions of time *t*

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

Dynamic Characteristic

The value a is called an offset and b is called static sensitivity. The above Equation requires that the sensor does not incorporate any energy storage device, like a capacitor or mass. A zero-order sensor responds instantaneously. In other words, such a sensor does not need any dynamic characteristics.

A first-order differential equation describes a sensor that incorporates one energy storage component. The relationship between the input *s(t)* and output *S(t)* is the differential equation

$$b_1 \frac{dS(t)}{dt} + b_0 S(t) = s(t).$$

A typical example of a first-order sensor is a temperature sensor for which the energy storage is thermal capacity.

A second-order differential equation describes a sensor that incorporates two energy storage components. The relationship between the input s(t) and output S(t) is the differential equation

$$b_2 \frac{d^2 S(t)}{dt^2} + b_1 \frac{dS(t)}{dt} + b_0 S(t) = s(t).$$

An example of a second-order sensor is an accelerometer that incorporates a mass and a spring.

Physical principles of sensing: electric charges, electric fields, and potentials

Electric charges

Electric charge is the fundamental property of the two subatomic particles named electrons and protons

Electrons are assumed to have negative charge and protons are assumed to have positive charge. The value of one electronic charge is 1.602×10^{-19} C

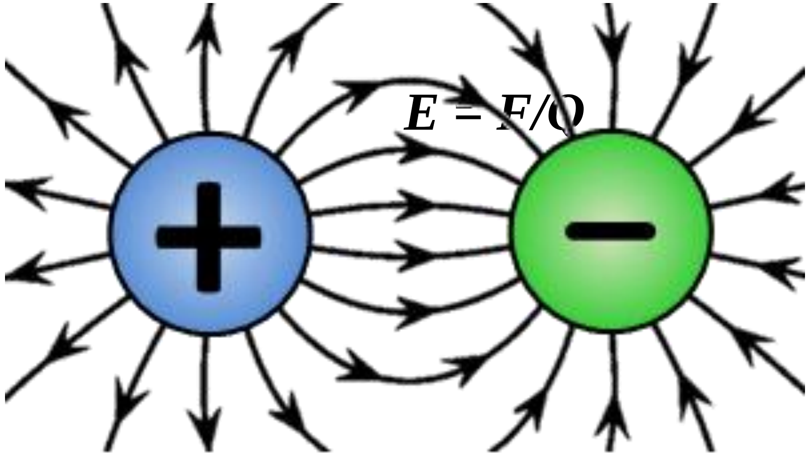
Like charges repel each other and unlike charges attract each other.

Electric fields

Electric field is the vicinity around a unit charge in which it experiences the presence of another test charge.

Technically it is the force per unit charge having the unit V/m,

$$E = F/Q$$



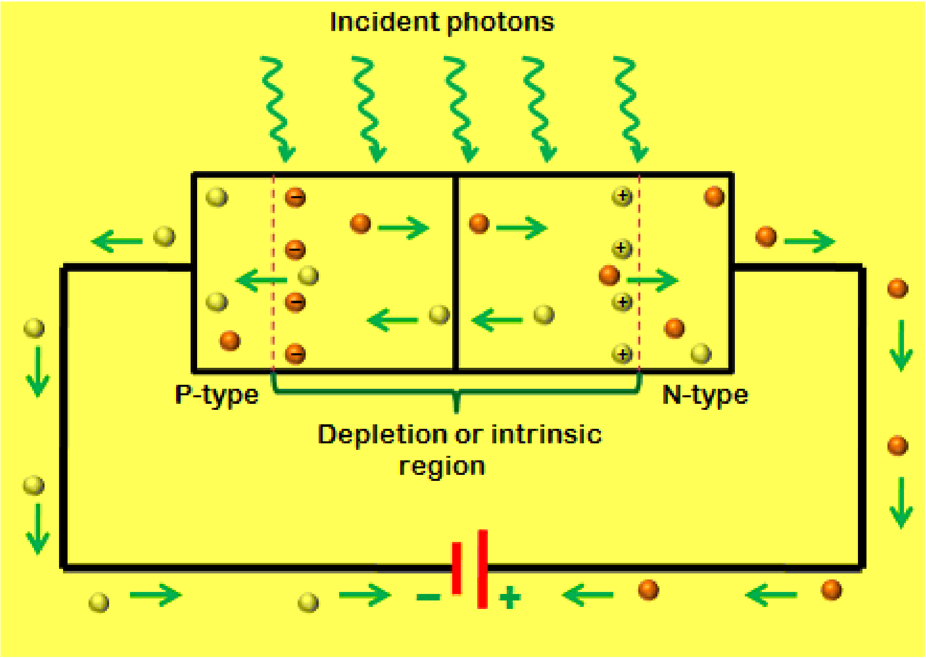
The electric field lines originates from positive charges and terminates on negative charges

Physical Principles of Sensing

- A sensor convert generally nonelectrical effects into electrical signals, one and often several transformation steps are required before the electric output signal can be generated.

- There are two types of sensor: *direct* and *complex*.

- A *direct sensor* is the one that can directly convert a nonelectrical stimulus into an electric signal.



* *Photodetectors can directly convert the photons into electrical signals*

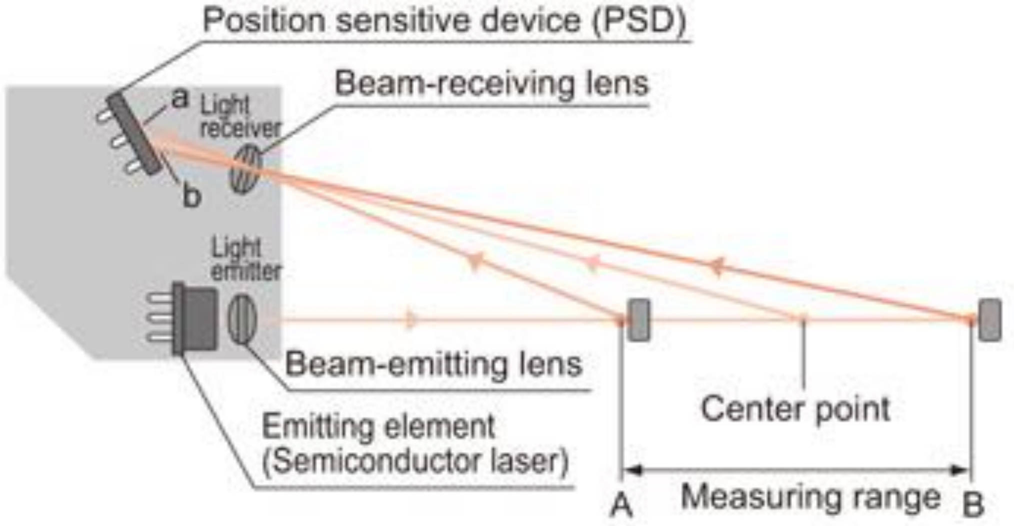
Complex sensor

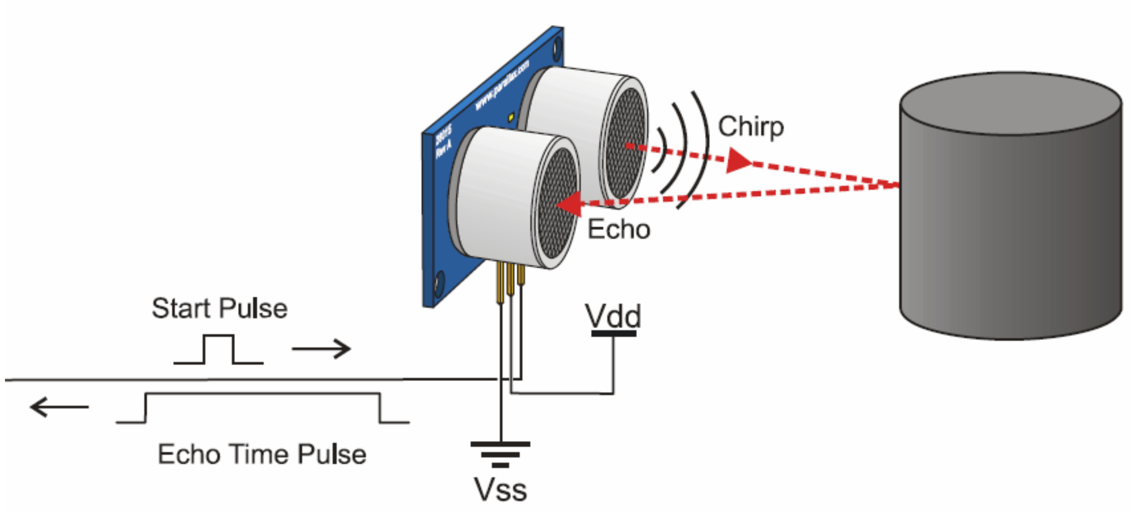
Many stimuli cannot be directly converted into electricity, thus multiple conversion steps would be required.

If, for instance, one wants to detect the displacement of an opaque object, a fiber-optic sensor can be employed.

such a sensor involves the transformation of electrical current into photons, the propagation of photons through some refractive media, reflection, and conversion back into electric current.

** Change in the position could not be directly convert into electrical signals as stated.*





Physical Principles of Sensing (cont..)

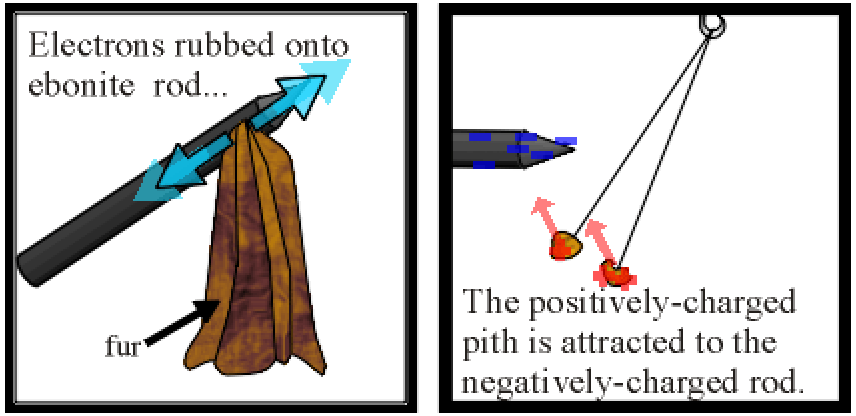
- There are several physical effects which result in the direct generation of electrical signals in response to nonelectrical influences and thus can be used in direct sensors.

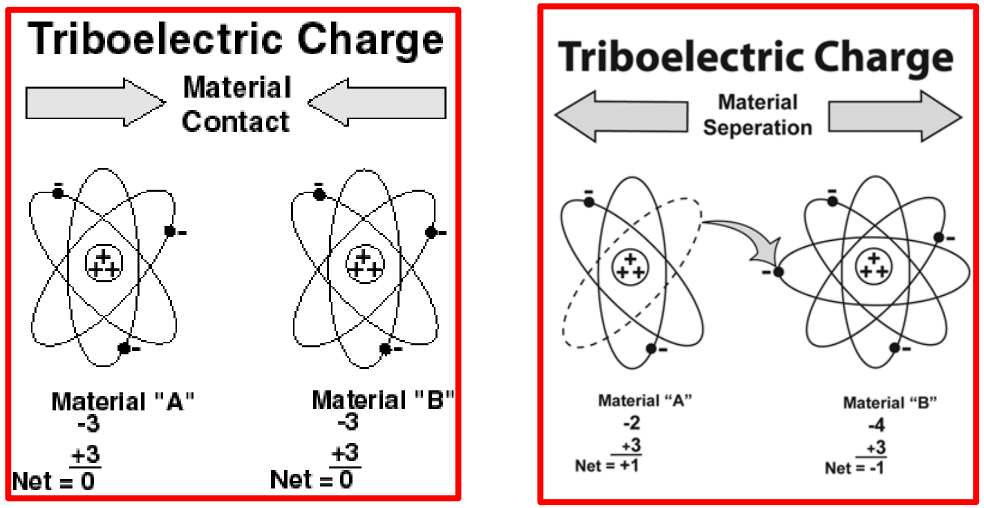
- Examples are thermoelectric (Seebeck) effect, piezoelectricity, and photoeffect.

- Various physical effects that can be converted into electrical signals are Electrical charges, fields & potentials; Capacitance; Magnetism; Induction; Resistance; Piezoelectric effect; Pyroelectric effect; Hall Effect; Seebeck & Peltier Effect; Sound Waves; Temperature and thermal effects; Heat Transfer; Ligt;

Electrical charges, fields & potentials;

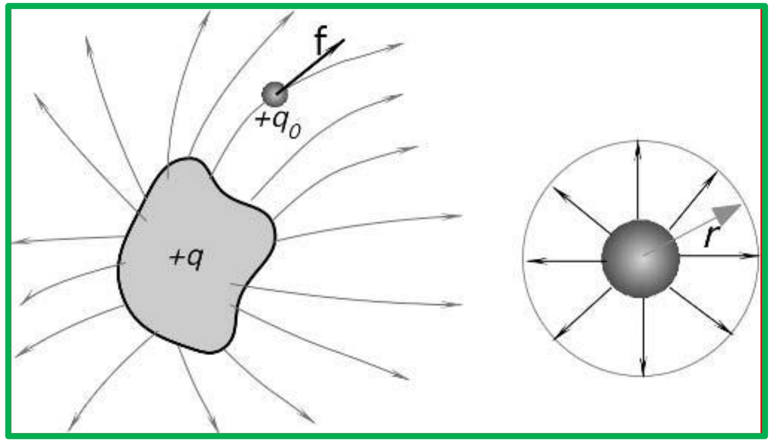
- *Triboelectric effect* is a process of an electric charge separation due to object movements, friction of clothing fibers, air turbulence, atmosphere electricity, and so forth.





A triboelectric effect is a result of a mechanical charge redistribution. For instance, rubbing a glass rod with silk strips electrons from the surface of the rod, thus leaving an abundance of positive charges (i.e., giving the rod a positive charge).

Electrical Field: An **electric** charge is a property of matter that causes two objects to attract or repel depending on their charges (positive or negative). An **electric field** is a region of space around an electrically charged particle or object in which an **electric** charge would feel force



Positive test charge in the vicinity of a charged object and the electric field of a spherical object.

Electric Field $\mathbf{E} = \mathbf{f}/q_0$

E is vector in the same direction as **f** because q_0 is scalar.

- The field is indicated in above Figure by the *field lines* which in every point of space are tangent to the vector of force.
  By definition, the field lines start on the positive plate and end on the negative.
  The density of field lines indicates the magnitude of the electric field **E** in any particular volume of space.

A vector field may be characterized by a distribution of vectors which form the so-called flux *(ϕ)*. Flux is a convenient description of many fields, such as electric, magnetic, thermal, and so forth. The word "flux" is derived from the Latin word *fluere* (to flow).

A familiar analogy of flux is a stationary, uniform field of fluid flow (water) characterized by a constant flow vector **v**, the constant velocity of the fluid at any given point.

If we replace **v** by **E** (vector representing the electric field), the field lines form flux. If we imagine a hypothetical closed surface (Gaussian surface) ***S***, a connection between the charge q and flux can be established as

$$\varepsilon_0 \, \phi_E = q$$

where $\varepsilon_0 = 8.8542 \times 10^{-12}$ C^2/N m^2 is the permitivity constant, or by integrating flux over the surface,

$$\varepsilon_0 \int_s \mathbf{E} ds = q,$$

where the integral is equal to ϕ_E. In the above equations, known as Gauss' law, the charge q is the net charge surrounded by the Gaussian surface. If a surface encloses equal and opposite charges, the net flux ϕ_E is zero.

Gauss' law can be used to make an important prediction, namely ***an exact charge on an insulated conductor is in equilibrium, entirely on its outer surface.***

Coulomb's law itself can be derived from Gauss' law. It states that the force acting on a test charge is inversely proportional to a squared distance from the charge:

$$f = (1/\ 4\pi\varepsilon_0\ )\ (q.q_0\ /\ r^2)$$

Another result of Gauss' law is that the electric field outside any spherically symmetrical distribution of charge is directed radially and has magnitude (note that magnitude is not a vector)

$$E = (1/\ 4\pi\varepsilon_0\ )\ (q/\ r^2),$$ where r is the distance from the sphere centre

Similarly, the electric field inside a uniform sphere of charge q is directed radially and has magnitude

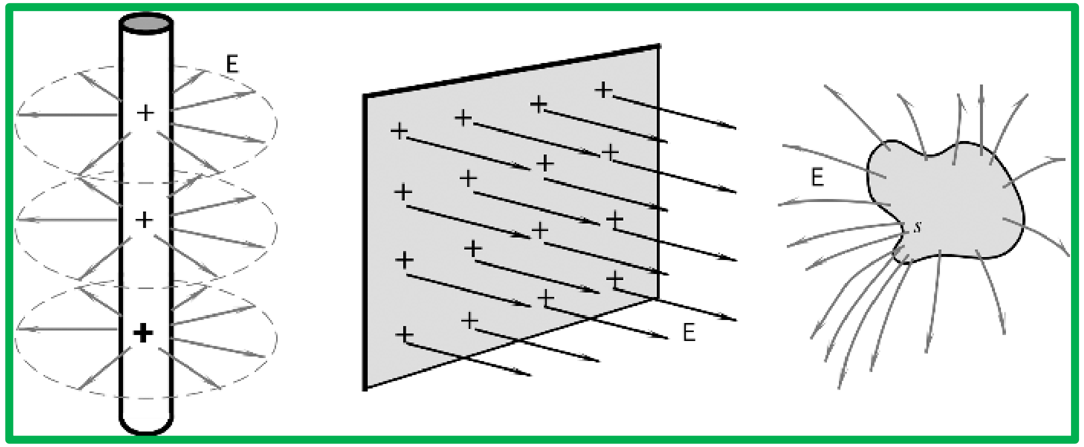
$$E = (1/\ 4\pi\varepsilon_0\ )\ (qr\ /\ R^3),$$ where r is the distance from the sphere centre & R is the Spheres radius

It should be noted that the electric field in the center of the sphere ($r = 0$) is equal to zero.

If the electric charge is distributed along an infinite (or, for the practical purposes, long) line (Fig. A), the electric field is directed perpendicularly to the line and has the magnitude

$$E = (1/\ 2\pi\varepsilon_0\ )\ (\lambda\ /\ r),$$

where r is the distance from the line and λ is the linear charge density (charge per unit length).



Electric field around an infinite line (A) and near an infinite sheet (B). A pointed conductor concentrates an electric field (C).

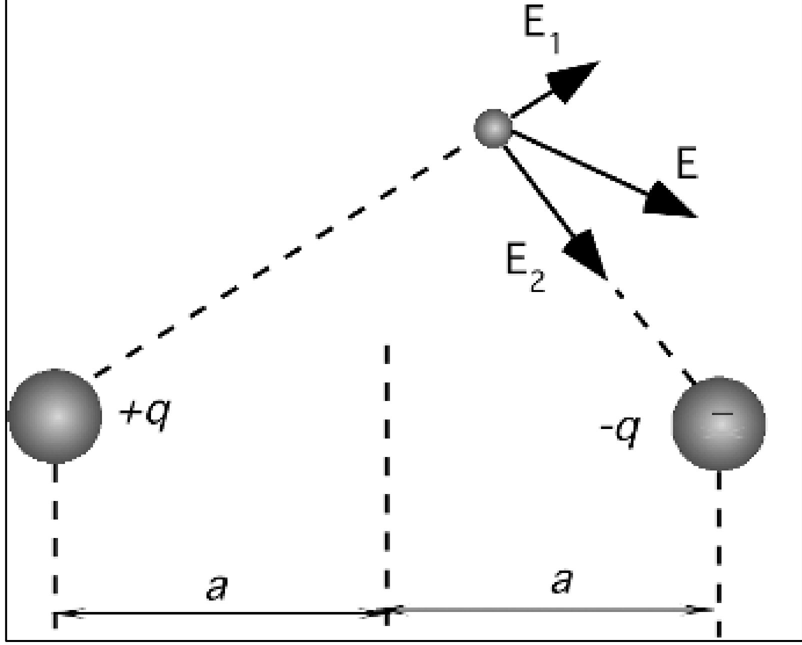
The electric field due to an infinite sheet of charge (Fig. B) is perpendicular to the plane of the sheet and has magnitude

$E = \sigma / 2\varepsilon_0$ where σ is the surface charge density (charge per unit area)

However, for an isolated conductive object, the electric field is two times stronger:

$$E = \sigma / \varepsilon_0$$

An ***electric dipole*** is a combination of two opposite charges placed at a distance $2a$ apart (Fig). Each charge will act on a test charge with force which defines electric fields $\mathbf{E}_1$ and $\mathbf{E}_2$ produced by individual charges. A combined electric field of a dipole, $\mathbf{E}$, is a vector sum of two fields. The magnitude of the field is



$$E = (1 / 4\pi\varepsilon_0) (qa / r^3)$$

where r is the distance from the center of the dipole.

The essential properties of the charge distribution are the magnitude of the charge q and the separation $2a$

The product qa is called the electric dipole moment p.

$$E = (1 / 4\pi\varepsilon_0) (p / r^3)$$

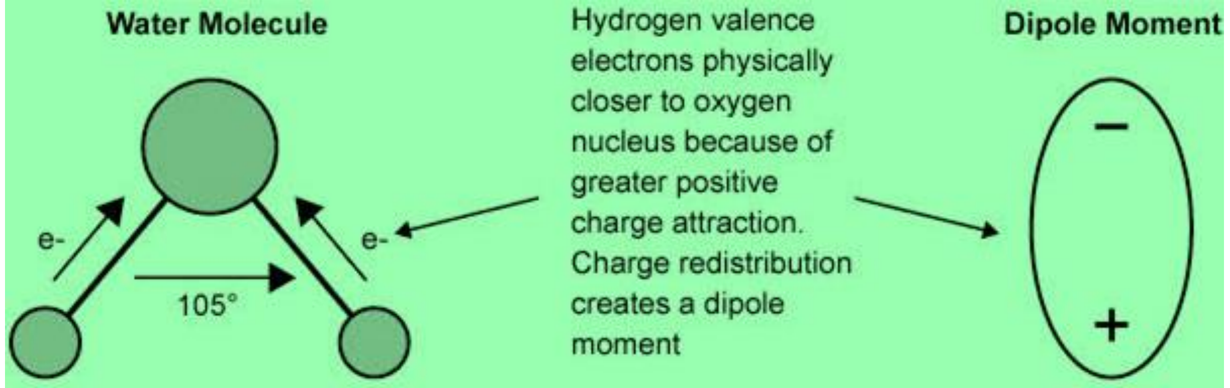
The spatial position of a dipole may be specified by its moment in vector form: $\mathbf{p}$.

All materials do not have a dipole moment

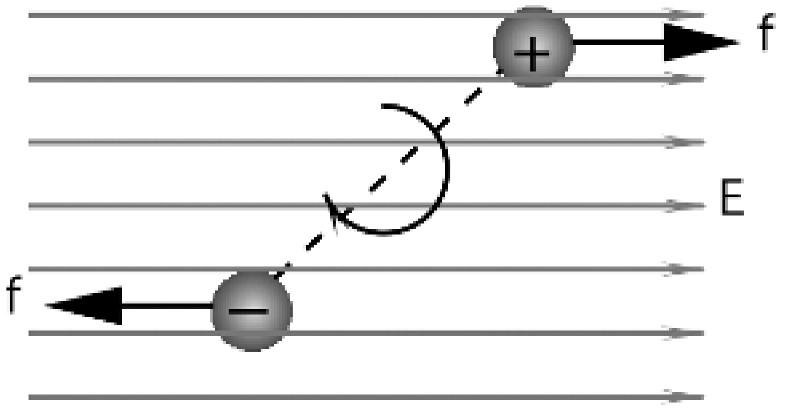
Gases such as methane, acetylene, ethylene, carbon dioxide, and many others have no dipole moment.

Water has a strong dipole moment (6.17×10^{-30}C m).

Carbon monoxide has a weak dipole moment (0.37×10^{-30}Cm)



Dipoles are found in crystalline materials and form a foundation for such sensors as piezoelectric and pyroelectric detectors. When a dipole is placed in an electric field, it becomes subjected to a rotation force



Usually, a dipole is a part of a crystal which defines its initial orientation.
An electric field, if strong enough, will align the dipole along its lines. Torque, which acts on a dipole in a vector form, is

$$\tau = \mathbf{p}\ \mathbf{E}.$$

Work must be done by an external agent to change the orientation of an electric dipole in an external electric field. This work is stored as potential energy U in the system consisting of the dipole and the arrangement used to set up the external field. In a vector form this potential energy is

$$U = -\ \mathbf{pE}.$$

A process of dipole orientation is called *poling*. The aligning electric field must be strong enough to overcome a retaining force in the crystalline stricture of the material. To ease this process, the material during the poling is heated to increase the mobility of its molecular structure. The poling is used in fabrication of piezoelectric and pyroelectric crystals

The electric field around the charged object can be described not only by the vector **E**, but by a scalar quantity, the *electric potential V* as well. Both quantities are intimately related and usually it is a matter of convenience which one to use in practice. A potential is rarely used as a description of an electric field in a specific point of space. A potential difference (voltage) between two points is the most common quantity in electrical engineering practice.
To find the voltage between two arbitrary points, we may use the same technique as above—a small positive test charge q_0. If the electric charge is positioned in point A, it stays in equilibrium, being under the influence of force $q_0\mathbf{E}$. Theoretically, it may remain there infinitely long. Now, if we try to move it to another point B, we have to work against the electric field. Work (W_{AB}) which is done against the field (that is why it has negative sign) to move the charge from A to B defines the voltage between these two points:

$$V_B - V_A = -W_{AB} / q_0$$

$$V = -W / q_0$$

If we travel through the electric field along a straight line and measure V as we go, the rate of change of V with distance l that we observe is the components of **E** in that direction

$$E_l = -dV/dl$$

The minus sign tells us that **E** points in the direction of decreasing V. Therefore, the appropriate units for electric field is volts/meter (V/m).

Capacitance

Capacitance is the ability of a body to store electrical charge.

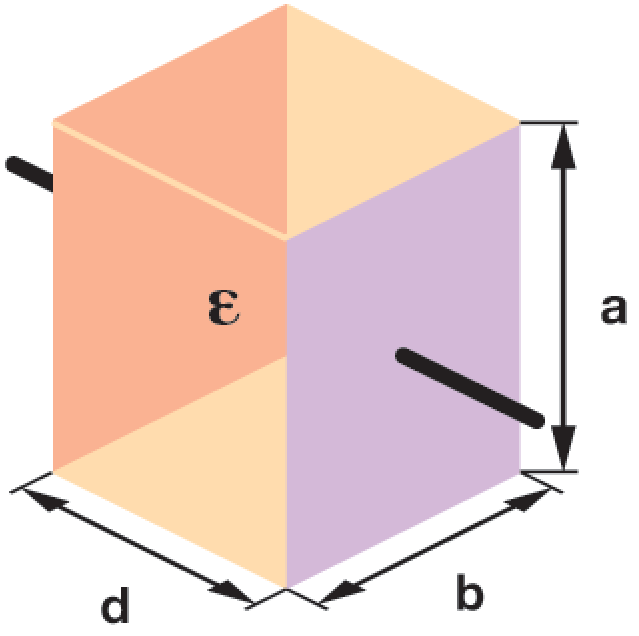
The capacitance, *C*, is given by $$C = \frac{Q}{V}$$

where *Q* is the charge on the capacitor and *V* is the voltage across the capacitor.

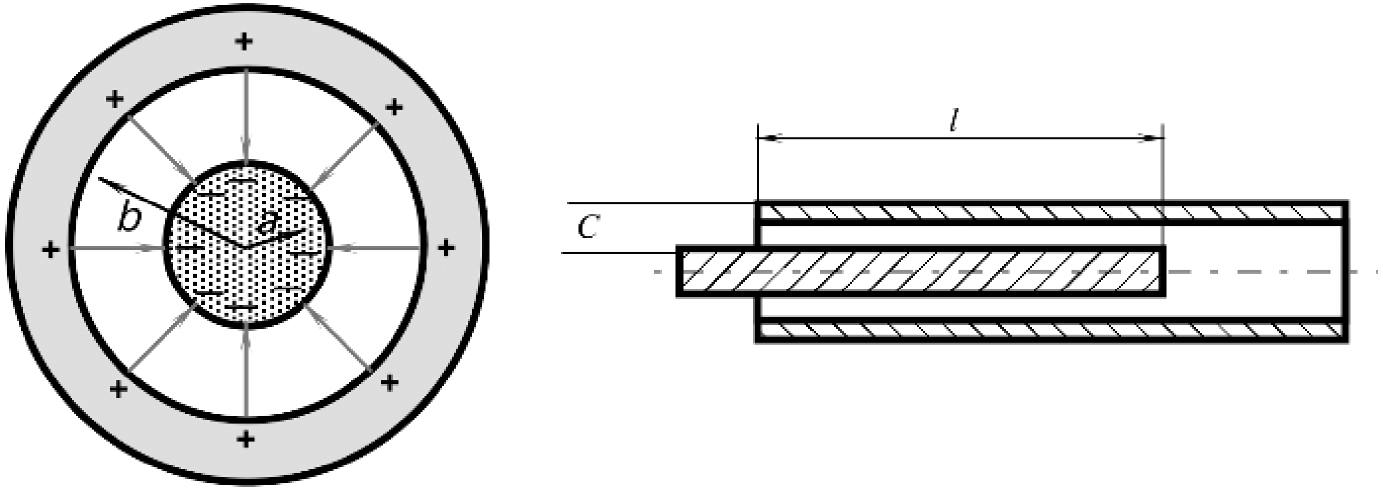
In the capacitor shown in Figure 1, two parallel metal plates with area *A* are separated by distance d.

The capacitance, *C*, is

$$C = \varepsilon_O \times \varepsilon_R \frac{A}{d}$$



where
- *C* is the capacitance in Farads
- *A* is the area of overlap of the two plates = a × b
- *d* is the distance between the two plates
- ε_R is the relative static permittivity
- ε_O is the permittivity of free space ($\varepsilon_O \approx 8.854 \times 10^{-12}$ Fm^{-1})



Cylindrical capacitor (A); capacitive displacement sensor (B).

A cylindrical capacitor, consists of two coaxial cylinders of radii *a* and *b* and length *l*. For the case when *lb*, we can ignore fringing effects and calculate capacitance from the following formula:

$C = 2\pi\varepsilon_0 l \ln(b/a)$

In this formula, *l* is the length of the overlapping conductors and $2\pi l[\ln(b/a)]^{-1}$ is called a geometry factor for a coaxial capacitor. A useful displacement sensor can be built with such a capacitor if the inner conductor can be
moved in and out of the outer conductor. According to Eqn., the capacitance of such a sensor is in a linear relationship with the displacement, *l*.

Piezoelectric Effect

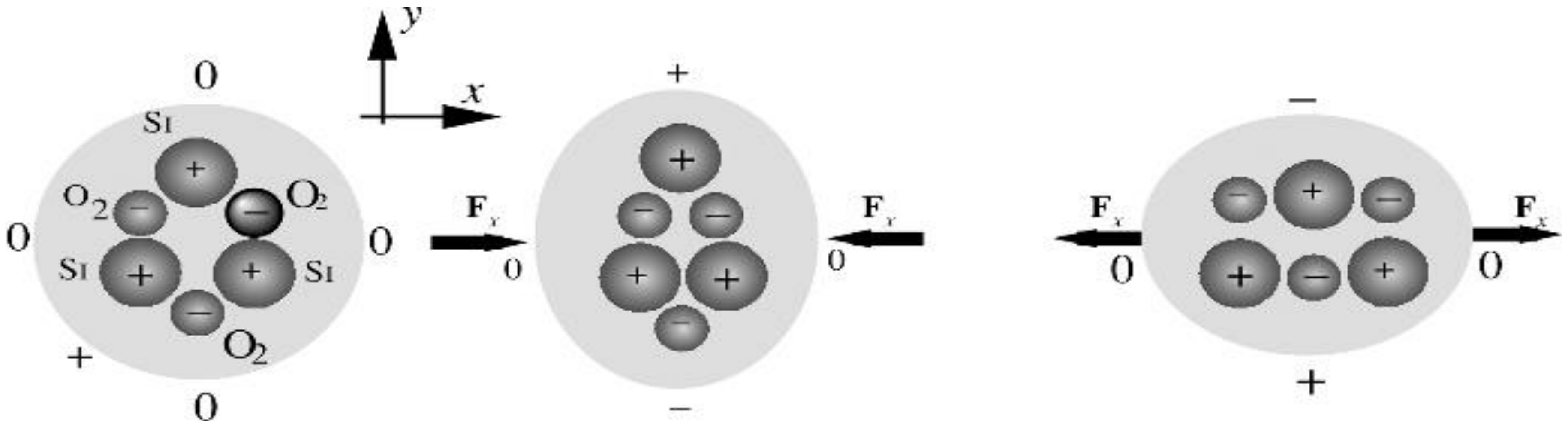
The piezoelectric effect is the generation of electric charge by a crystalline material upon subjecting it to stress

The effect exists in natural crystals, such as quartz (chemical formula SiO_2), and poled (artificially polarized) man-made ceramics and some polymers, such as polyvinylidene flouride.

The Curie brothers discovered the piezoelectric effect in quartz in 1880, but very little practical use was made until 1917, when another Frenchman, Professor P. Langevin used x-cut plates of quartz to generate and detect sound waves in water. His work led to the development of sonar.

A quartz crystal is modeled as a helix with one silicon, Si, and two oxygen, O_2, atoms alternating around the helix. In a single-crystal cell, there are three silicon atoms and six oxygen atoms. Oxygen is being lumped in pairs. Each silicon atom carries four positive charges and a pair of oxygen atoms carries four negative charges (two per atom). Therefore, a quartz cell is electrically neutral under the no-stress conditions.

When an external force, F_x, is applied in one axis, the hexagonal lattice becomes deformed. Figure shows a compressing force which shifts atoms in a crystal in such a manner that a positive charge is built up at the silicon atom side and a negative charge at the oxygen pair side. This simple model illustrates that crystalline material can develop electric charge on its surface in response to a mechanical deformation.



Piezoelectric effect in a quartz crystal

To pick up an electric charge, conductive electrodes must be applied to the crystal at the opposite sides of the cut. As a result, a piezoelectric sensor becomes a capacitor with a dielectric material which is a piezoelectric crystal.

Crystallities (crystal cells) in the material can be considered electric dipoles. In some materials, like quartz, these cells are naturally oriented along the crystal axes, thus giving the material sensitivity to stress.

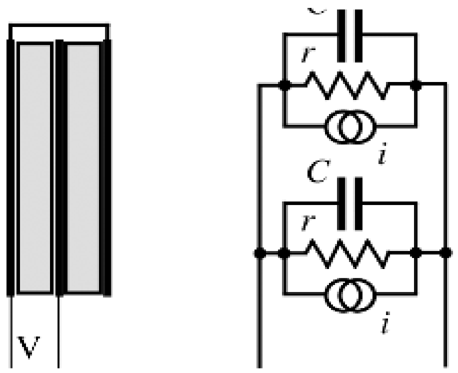
In other materials, the dipoles are randomly oriented and the materials need to be "poled" to possess piezoelectric properties. To give a crystalline material piezoelectric properties, several poling techniques can be used.

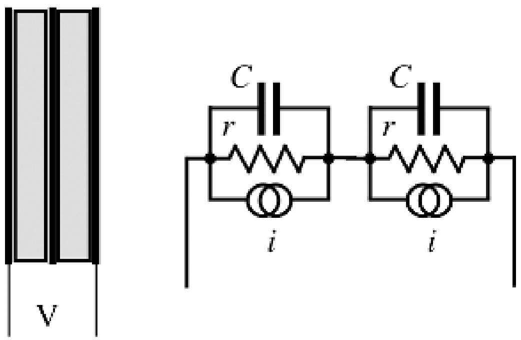
The piezoelectric elements may be used as a single crystal or in a multilayer form where several plates of the material are laminated together. This must be done with electrodes placed in between. Figure shows a two-layer force sensor.

When an external force is applied, the upper part of the sensor expands while the bottom compresses. If the layers are laminated correctly, this produces a double output signal.

Double sensors can have either a parallel connection a serial connection in Figure.
The electrical equivalent circuit of the piezoelectric sensor is a parallel connection of a stress-induced current source *(i)*, leakage resistance *(r)*, and capacitance *(C)*. Depending on the layer connection, equivalent circuits for the laminated sensors are as shown in Figure.

The leakage resistors are very large (on the order of $10^{12}-10^{14}\Omega$), which means that the sensor has an extremely high output impedance. This requires special interface circuits, such as charge and current-to-voltage converters, or voltage amplifiers with high input resistances.



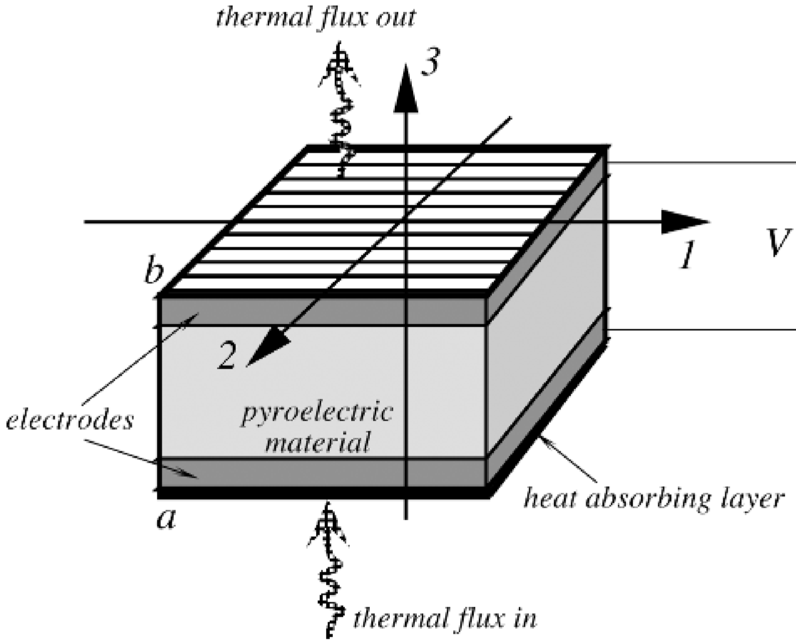


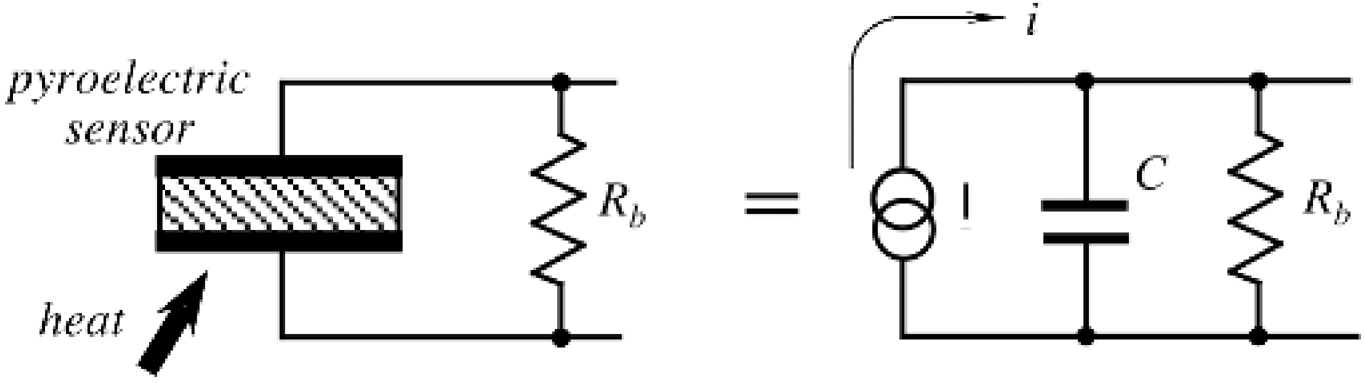
Parallel and serial laminated piezoelectric sensors and their corresponding equivalent circuits.

Pyroelectric Effect

Pyroelectric materials are crystalline substances capable of generating an electrical charge in response to heat flow. The pyroelectric effect is very closely related to the piezoelectric effect

Like piezoelectrics, the pyroelectric materials are used in the form of thin slices or films with electrodes deposited on the opposite sides to collect the thermally induced charges. The pyroelectric sensor is essentially a capacitor which can be electrically charged by an influx of heat. The detector does not require any external electrical bias (excitation signal).





Pyroelectric sensor and its equivalent circuit.

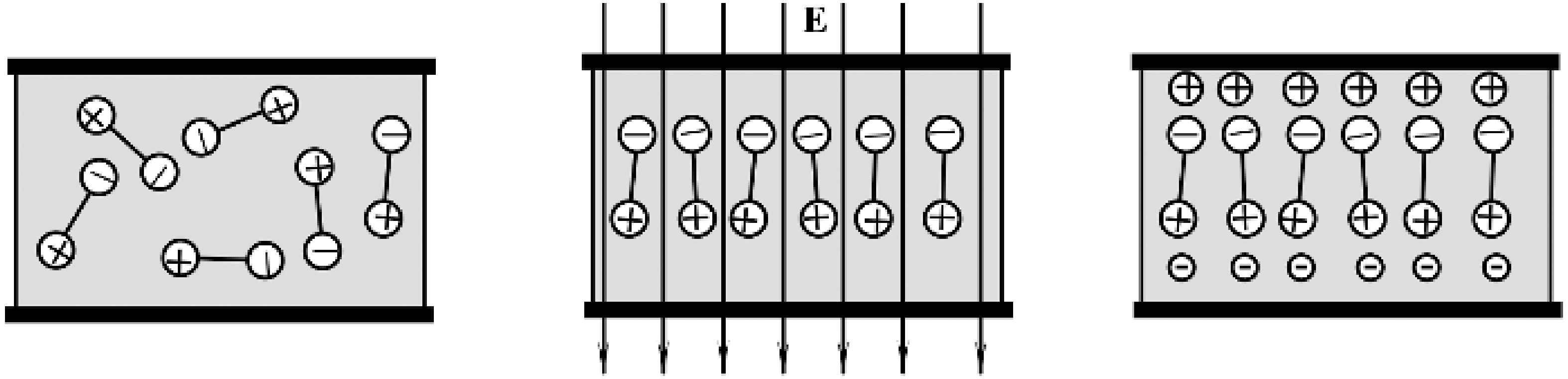
A pyroelectric material can be considered as a composition of a large number of minute crystallities, each of which behaves as a small electric dipole. All of these dipoles are randomly oriented.

Above a certain temperature, known as the *Curie point*, the crystallities have no dipole moment. Manufacturing (poling) of pyroelectric materials is analogous to that of piezoelectrics

Temperature changes may cause a shortening or elongation of individual dipoles. It may also affect the randomness of the dipole orientations due to thermal agitation. These phenomena are called ***primary* pyroelectricity.**

There is also ***secondary* pyroelectricity,** which, in a simplified way, may be described as a result of the piezoelectric effect, (i.e., a development of strain in the material due to thermal expansion).

Being electrically polarized, the dipoles are oriented (poled) in such a manner as to make one side of the material positive and the opposite side negative. However, under steady-state conditions, free-charge carriers (electrons and holes) neutralize the polarized charge and the capacitance between the electrodes appears not to be charged.



Thermal poling of a piezoelectric and pyroelectric material.

When the pyroelectric sensor is subjected to a thermal gradient, its polarization (electric charge developed across the crystal) varies with the temperature of the crystal.

The voltage pyroelectric coefficient, P_v, is a slope of the polarization curve. It increases dramatically near the Curie temperature where the polarization disappears and the material permanently loses its pyroelectric properties. The curves imply that the sensor's sensitivity increases with temperature at the expense of nonlinearity.

Two pyroelectric coefficients:

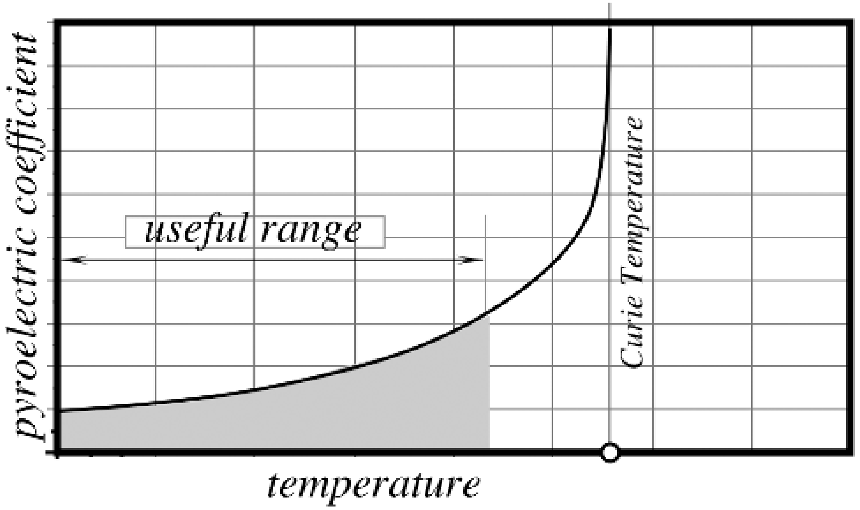
$P_Q = dP_s/d$, Pyroelectric charge coefficient, ;

$P_V = dE/dT$, Pyroelectric voltage coefficient,

Where P_s is the spontaneous polarization (which is another way to say *electric charge*), E is the electric field strength, and T is the temperature (in K). Both coefficients are related by way of the electric permitivity, ε_r, and dielectric constant, ε_0

$$P_Q / P_V = dP_s / dE = \varepsilon_r \varepsilon_0$$

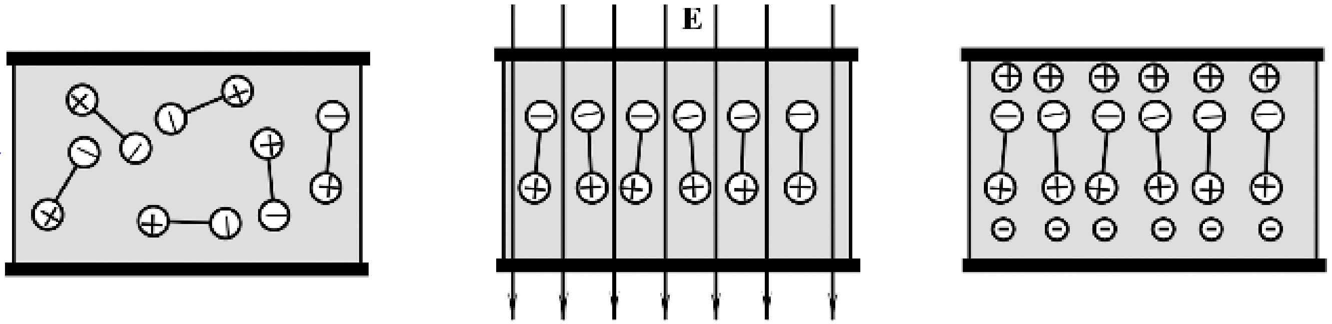
The polarization is temperature dependent and, as a result, both pyroelectric coefficients are also functions of temperature.



If a pyroelectric material is exposed to a heat source, its temperature rises by T and the corresponding charge and voltage changes can be described by the following equations:

$$Q = P_Q AT, \qquad V = P_v hT.$$

WHAT IS POLING?



The dipoles are randomly oriented and the materials need to be "poled" to possess piezoelectric properties.
To give a crystalline material piezoelectric properties, several poling techniques can be used. The most popular poling process is a thermal poling, which includes the following steps:

1. A crystalline material (ceramic or polymer film) which has randomly oriented dipoles is warmed up slightly below its Curie temperature. In some cases (for a PVDF film), the material is stressed. A high temperature results in stronger agitation of dipoles and permits us to more easily orient them in a desirable direction.

2. Material is placed in strong electric field, **E,** where dipoles align along the field lines. The alignment is not total. Many dipoles deviate from the filed direction quite strongly; however, statistically predominant orientation of the dipoles is maintained.

3. The material is cooled down while the electric field across its thickness is maintained.

4. The electric field is removed and the poling process is complete. As long as the poled material is maintained below the Curie temperature, its polarization remains permanent. The dipoles stay "frozen" in the direction which was given to them by the electric field at high temperature

Seebeck Effect (1821)

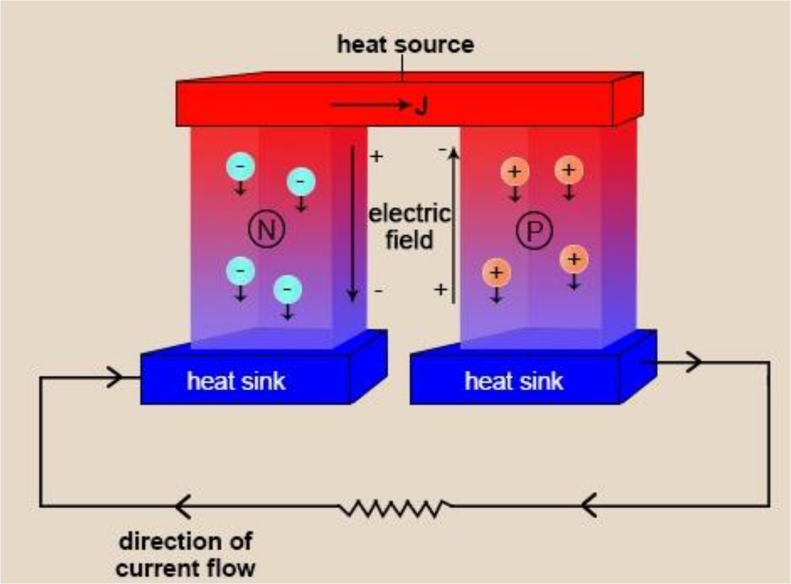
- The Seebeck Effect and the Peltier Effect can both be classified under the term **thermoelectric effect**.
- Any thermoelectric effect involves the conversion of differences in temperatures into voltage differences.
- The Seebeck and Peltier Effects are different manifestations of the same physical process. In some instances, they are linked and known as the **Seebeck-Peltier Effect**.

(The reason why these two effects are separated is due to their independent discoveries by two different individuals)

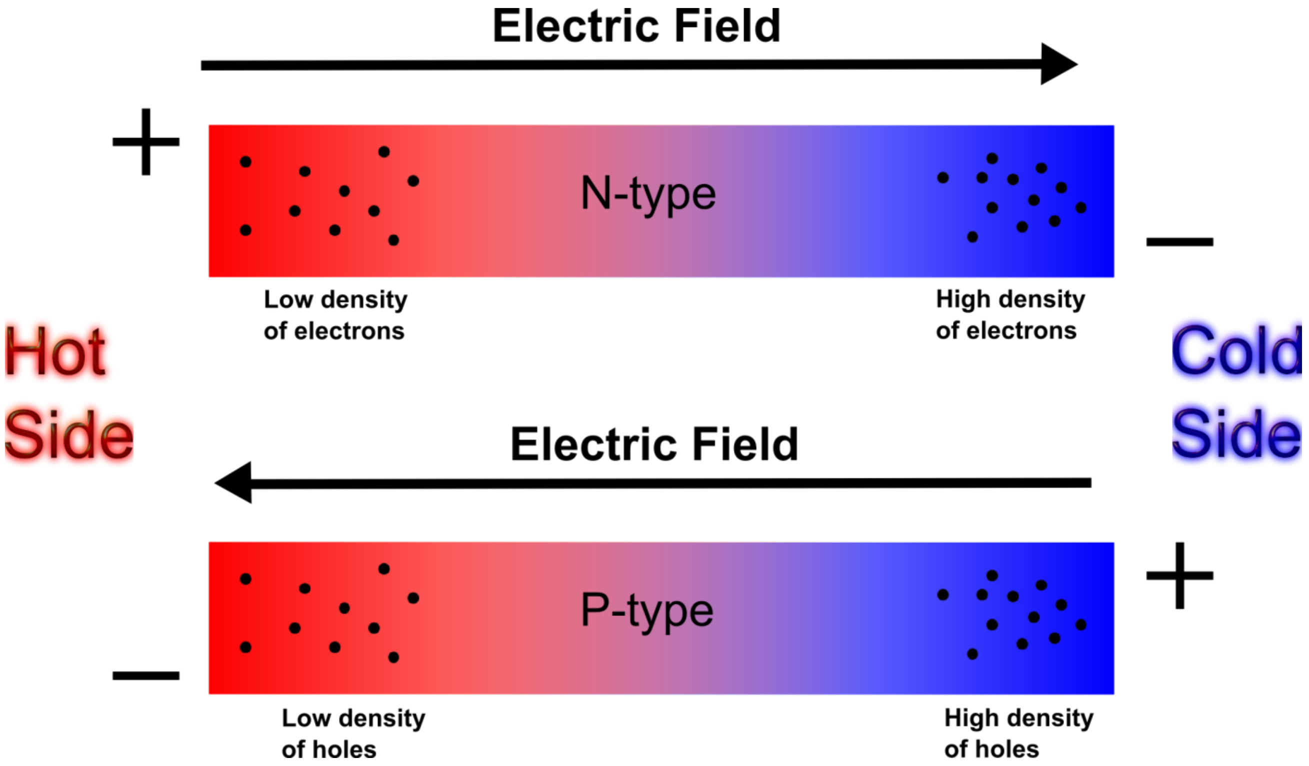
The Seebeck Effect was discovered by the Baltic German physicist Thomas Johann Seebeck.

The Seebeck Effect is a phenomenon in which a temperature difference between two dissimilar electric conductors or semiconductors produces a voltage difference between those two substances.

When heat is applied to one of the two conductors or semiconductors, the electrons become excited due to the heat. Since only one of the two sides is heated, the electrons start moving towards the cooler side of the two conductors. If both of the conductors are connected in the form of a circuit, a direct current flows through the circuit.



Seebeck Effect



The Seebeck Effect can help us calculate the electromotive field generated by a device. This can be done by using the Seebeck Coefficient. The Seebeck Coefficient of a material is the measure of the magnitude of the increased thermoelectric voltage in response to the temperature differences in a given material.

Using the Electromotive force, we can also calculate the current density of the thermoelectric material. The relevant equations for this are as follows:

$$\mathbf{E_{emf} = -S\Delta T}$$

$$\mathbf{J = \sigma(-\Delta V + E_{emf})}$$

Here, J signifies the current density and **σ** signifies the local conductivity of the conductor.

The voltages produced by the Seebeck Effect are tiny. The range of the voltage produced is usually on the order of a few microvolts (one-millionth of a volt) per Kelvin of temperature difference at the junction. If the temperature difference is significant enough, some devices can go on to produce a few millivolts (which is one-thousandth of a volt). Several such devices can be connected in parallel to increase the maximum deliverable current. Such devices have been shown to provide a small-scale level of electrical power if a large temperature difference is maintained across the junctions.

Peltier Effect (1834)

Another way of defining the seebeck coefficient is entropy transport per charge carrier divided by the charge. If an electric current is sent through the rod the charge carriers will transport heat in the direction of the electric current, resulting in heating at one end and cooling at the other end of the rod. This is called **the peltier effect** and the peltier coefficient (π) is defined as $\pi = \alpha T$.

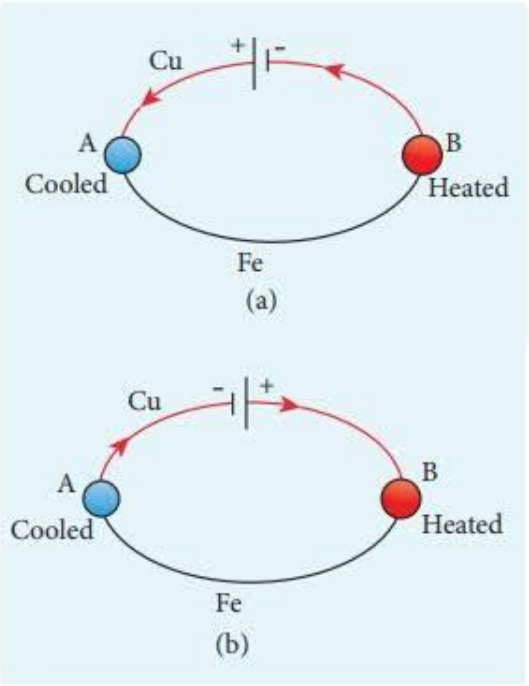
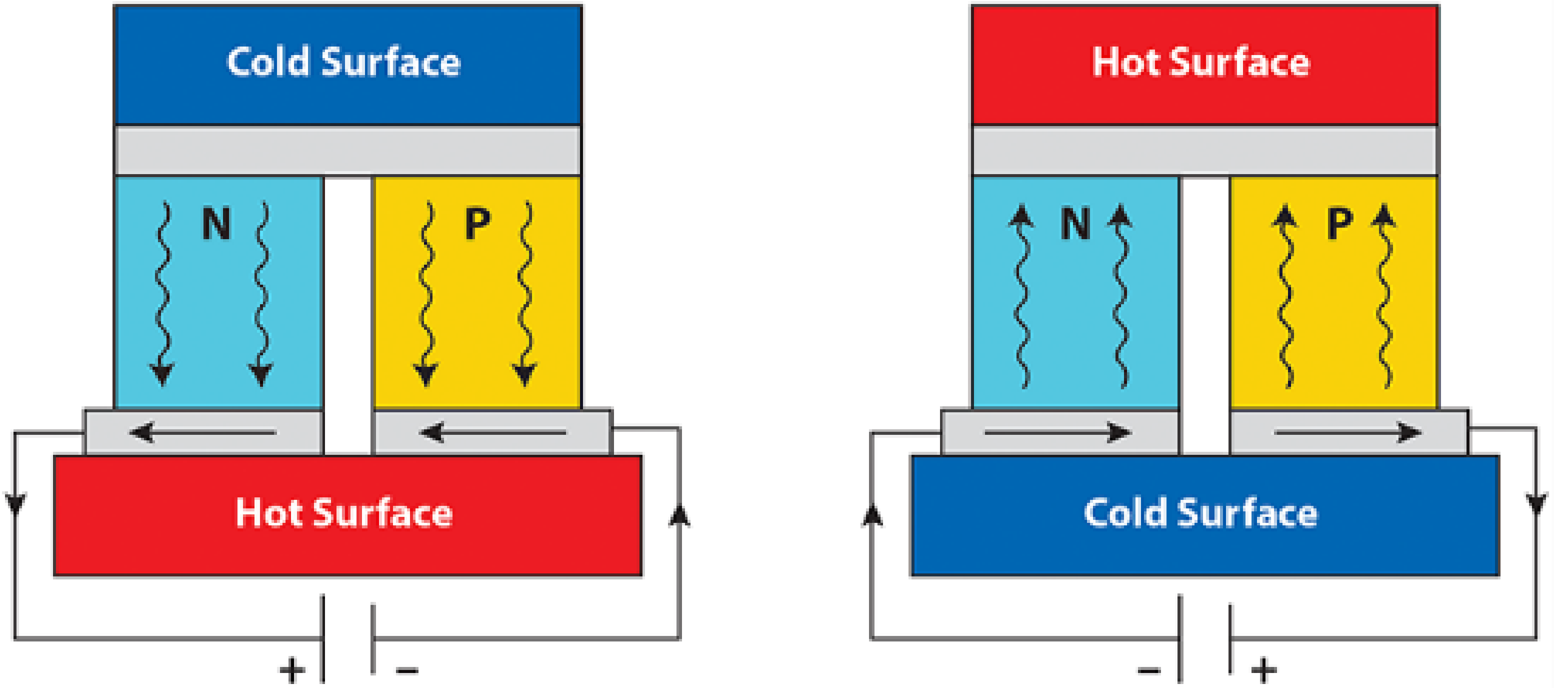


Figure 2.36 Peltier effect: Cu – Fe thermocouple

The Peltier effect is a temperature difference created by applying a voltage between two electrodes connected to a sample of semiconductor material. This phenomenon can be useful when it is necessary to transfer heat from one medium to another on a small scale.



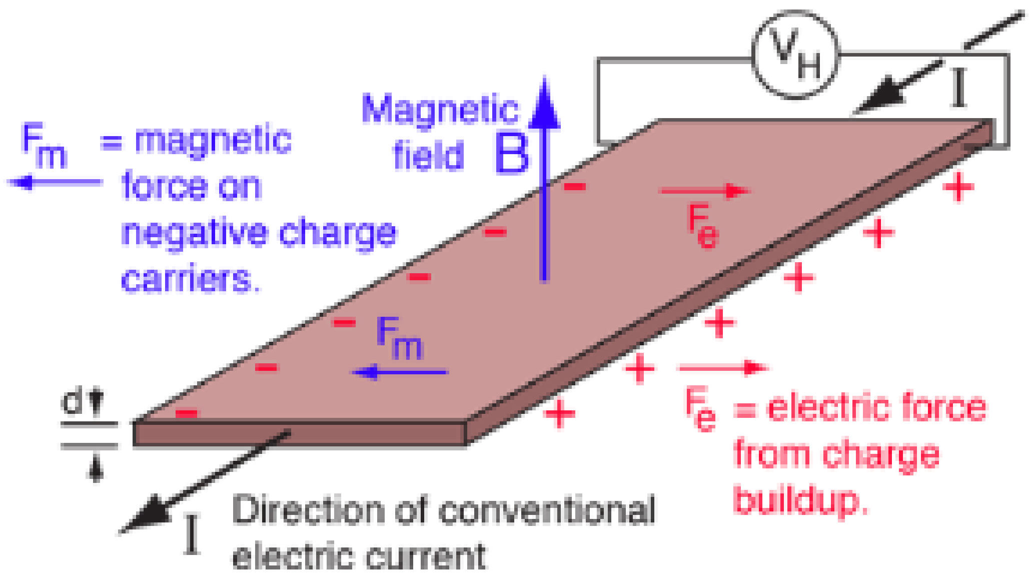
Hall Effect Sensor

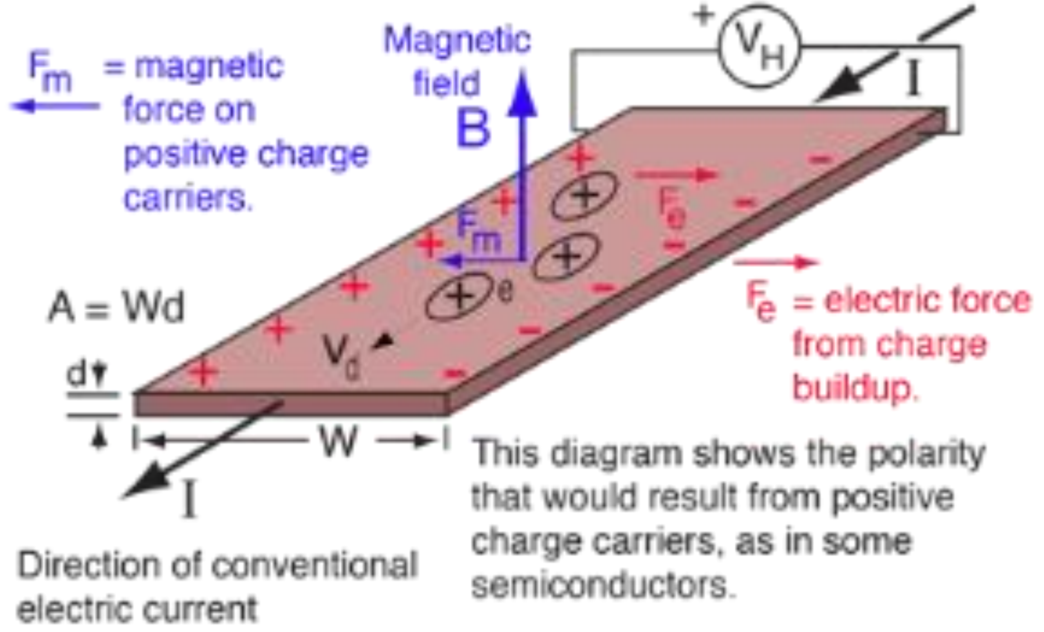
Hall Effect Principle says that when a conductor or semiconductor with current flowing in one direction is introduced perpendicular to a magnetic field a voltage could be measured at right angles to the current path.

The transverse voltage ([Hall effect]) measured in a [Hall probe] has its origin in the [magnetic force] on a moving charge carrier.

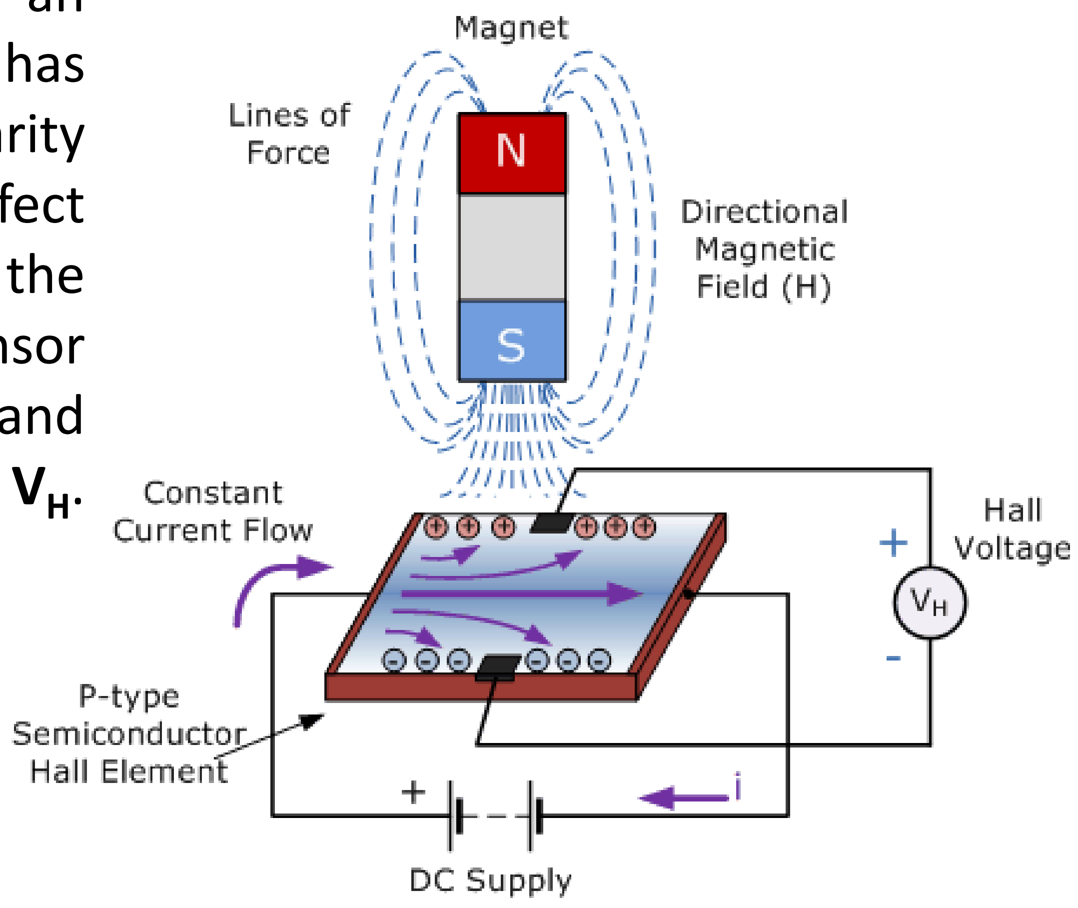
The magnetic force is $F_m = ev_dB$ where v_d is the [drift velocity] of the charge.

The current expressed in terms of the drift velocity is $I = neAvd$





Hall Effect Sensors are devices which are activated by an external magnetic field. We know that a magnetic field has two important characteristics flux density, (B) and polarity (North and South Poles). The output signal from a Hall effect sensor is the function of magnetic field density around the device. When the magnetic flux density around the sensor exceeds a certain pre-set threshold, the sensor detects it and generates an output voltage called the **Hall Voltage, V_H**. Consider the diagram below.



Hall Effect Sensors consist basically of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), indium antimonide (InSb) or indium arsenide (InAs) passing a continuous current through itself.

When the device is placed within a magnetic field, the magnetic flux lines exert a force on the semiconductor material which deflects the charge carriers, electrons and holes, to either side of the semiconductor slab. This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material

Suggested Questions

Big Questions

- List of Statistic Characteristics of a Sensor
- Explaining the Principles of electricity

Short Questions

- Definitions of Sensors & Smart Sensors
- Piezoelectric effect
- Pyro Electric Effect
- Capacitance
- Seebeck Effects
- Peltier Effects