Sensors and Instrumentation (EEL208)

by

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What is this course?

Course focus

To introduce the students to the fundamental of sensors and the relevant instrumentation and their applications to real-world

What will you learn?

- Fundamentals of sensors and transducers
- Errors in the measurement
- Various types of sensors, transducers, and their working principles
- Signal conditioning circuit

Prerequisite

- Basics of electrical and electronics

Syllabus

Introduction:
Sensors and Transducers – Basic Block Diagrams – Sensor Parameters (Range, Accuracy, Precision, Nonlinearity, Sensitivity) – Statistical Components – Errors – Noise and Signals

Thermal Sensors:
RTD – Thermistor – Thermocouple – PTC Semiconductor sensors – Resistance Bridges

Motion Sensors:
LVDT – Induction Bridges – Level Sensors – Accelerometer – Hall Effect Sensors;

Force Sensors:
Strain Gauge – Cantilever and Load Cell – Piezoelectric – Charge Amplifier – Bourdon Gauge

Syllabus

Flow Sensors:
Pitot Tube – Orifice Plate – Permanent Pressure loss – Venturimeter – Ultrasonic Flowmeter – Optical Flowmeter – Vortex Flowmeter – Turbine Flowmeter

Chemical Sensors:
Moisture Sensors – Gas Chromatography – Voltammetry – Dopamin Sensor – pH Sensor

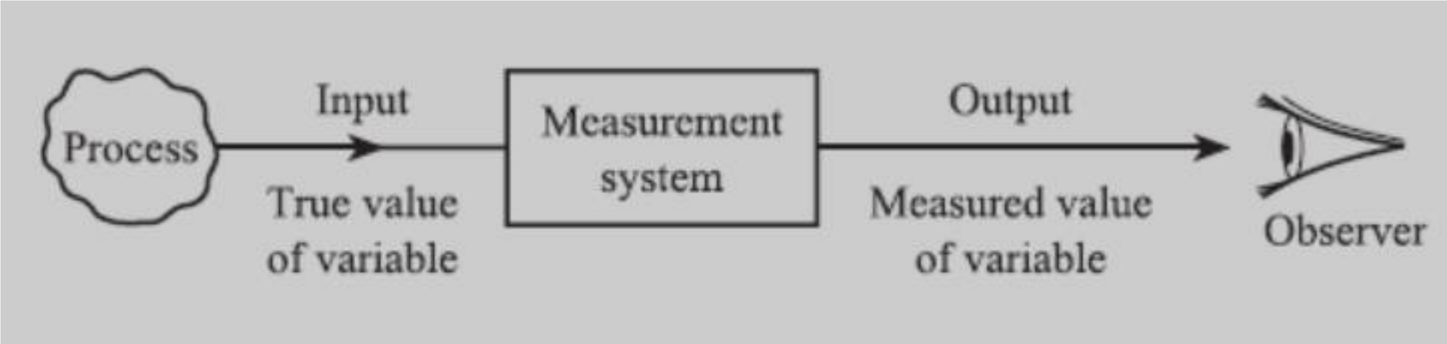
Signal Conditioning Circuit:
Filters and Instrumentation Amplifiers – CMRR – ADC – Resolution of a meter

Data Analysis:
Regression Model – Calibration and Standards – Inverse Function – Python Programming – LCD Display – Online Data Transmission

Text and reference books

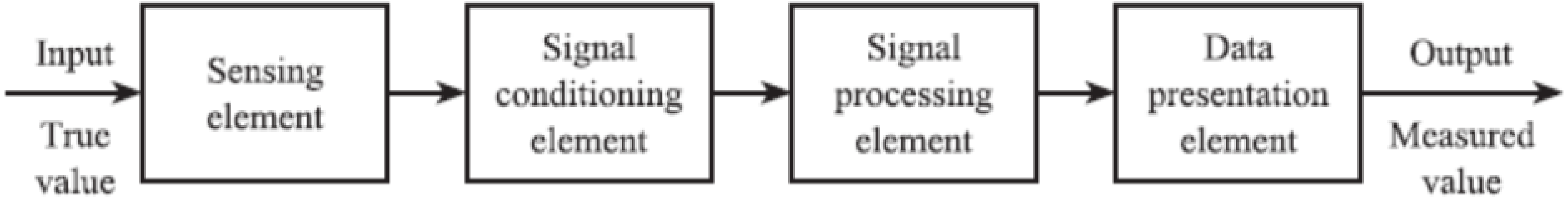
- Measurement Systems: Application and Design, Ernest O. Doebelin, Paperback
- Sensor & transducers, D. Patranabis, 2nd edition, PHI
- Instrument transducers, H.K.P. Neubert, Oxford University press
- Measurement systems: application & design, E.A.Doebelin, Mc Graw Hill.
- Electrical and Electronics Measurement, A. K. Sawhney, *Dhanpat Rai & Co* (2005)

Introduction to Systems



$$E = \text{measured value} - \text{true value}$$

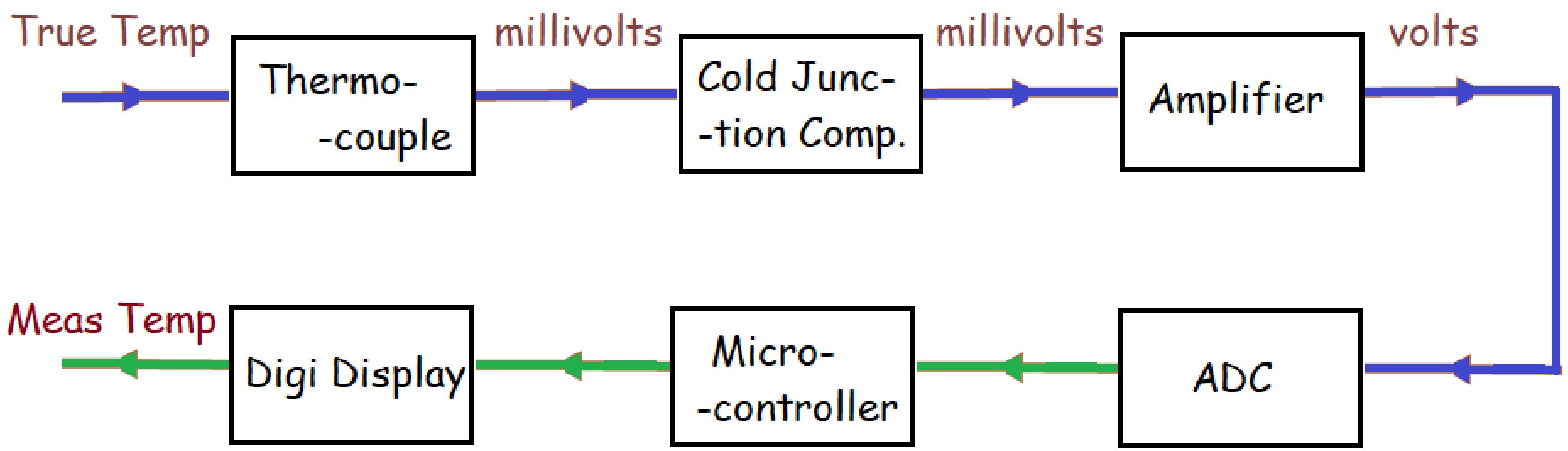
$$E = \text{system output} - \text{system input}$$



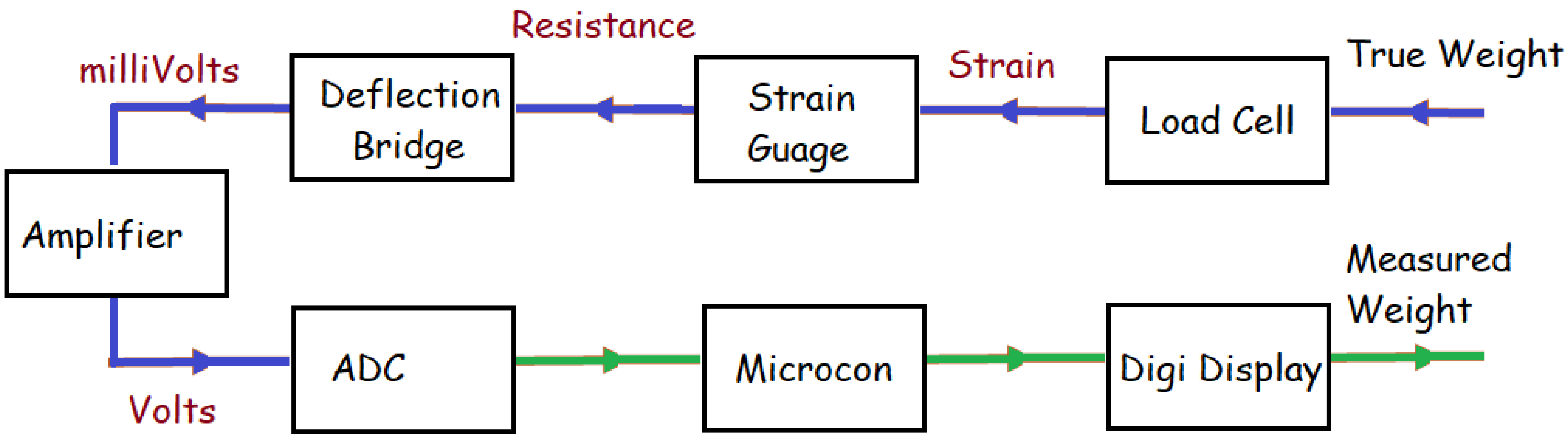
Fundamental Blocks of an Instruments

Measurement Systems

A temperature measurement system for blast furnace



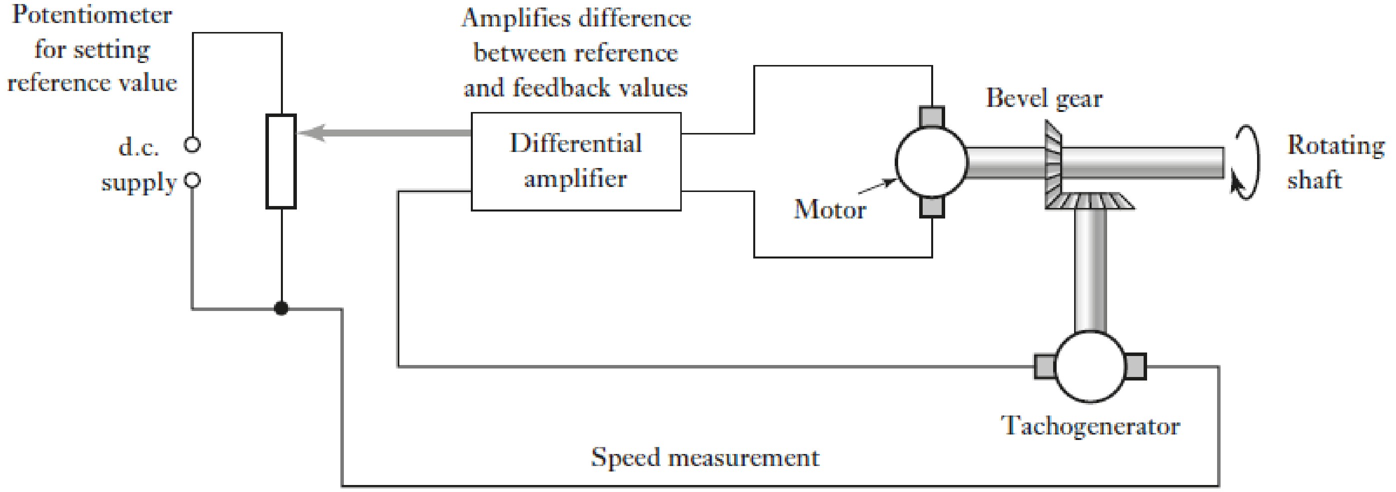
Typical weight measurement system

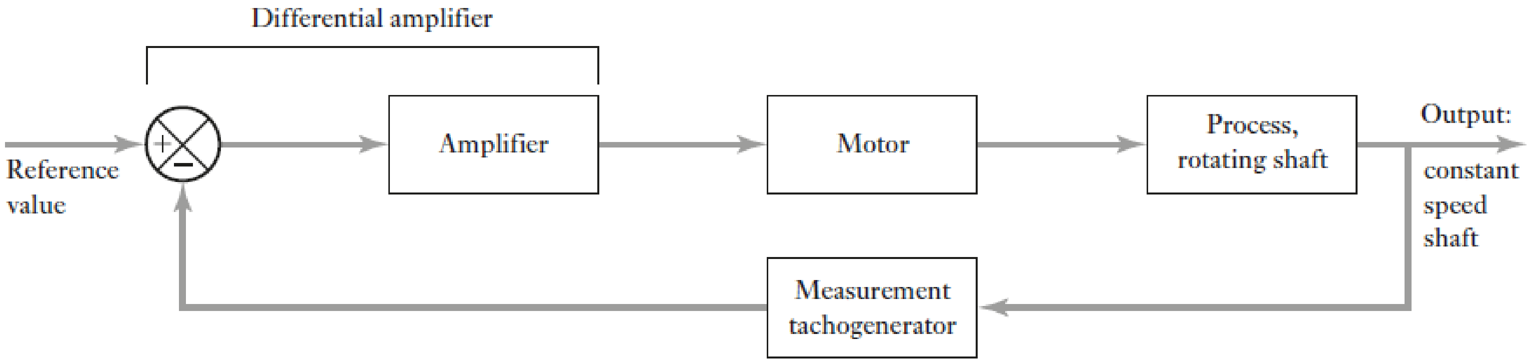


Feedback control system

Shaft speed control

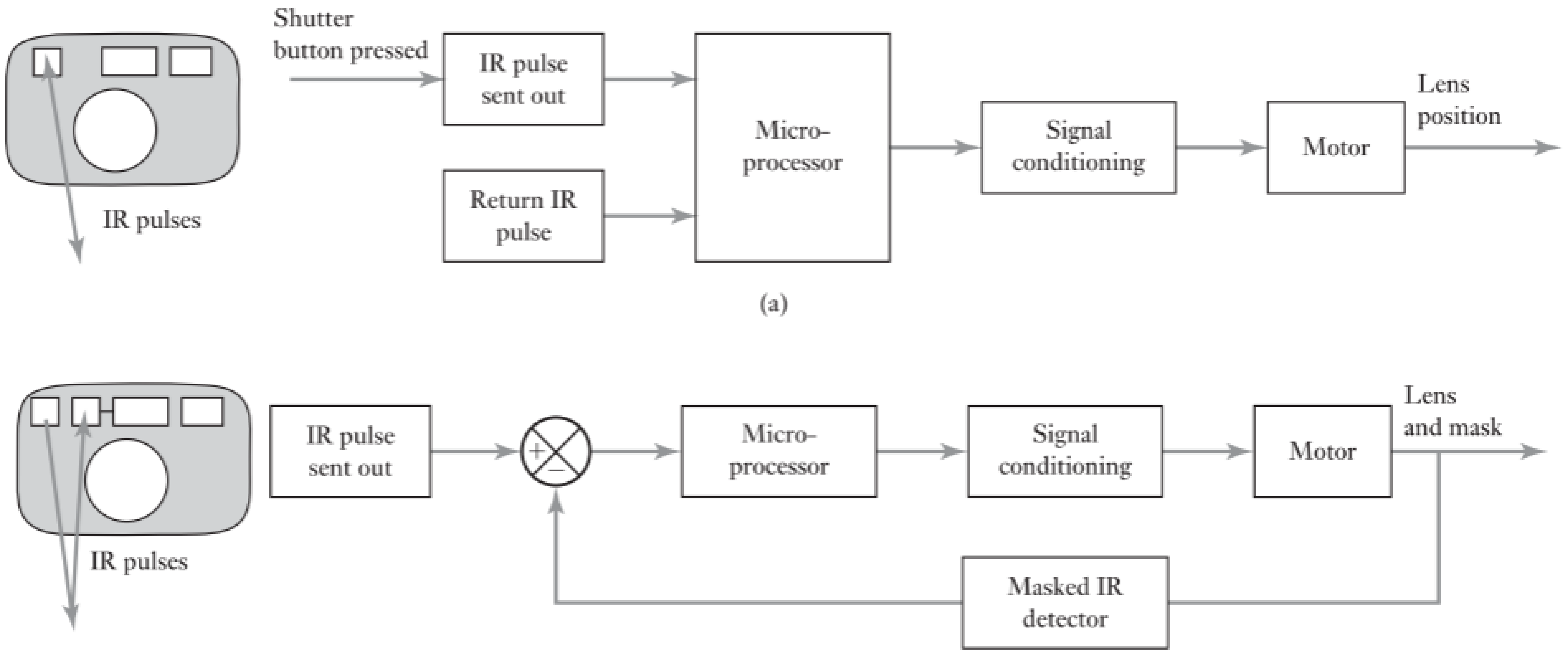
- *Controlled variable:* speed of rotation of shaft
- *Reference value:* setting of slider on potentiometer
- *Comparison element:* differential amplifier
- *Error signal:* the difference between the output from the potentiometer and that from the tachogenerator system
- *Control unit:* the differential amplifier
- *Correction unit:* the motor
- *Process:* the rotating shaft
- *Measuring device:* tachogenerator





Feedback control system

Digital camera and autofocus



A few definitions

Transducer: a device that converts one form of energy into a corresponding signal

- **Primary Energy Forms:** mechanical, thermal, electromagnetic, optical, chemical, etc.
- Take the form of a **sensor** or an **actuator**.

A few definitions

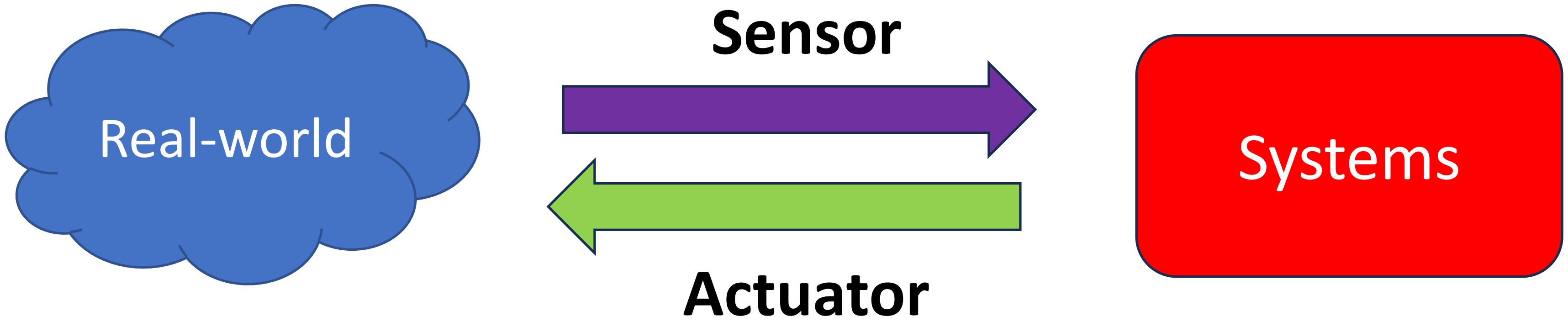
Sensor: a device that converts a physical parameter to an electrical output.

- **Example:** Thermometer
- A device that detects/measures a signal or stimulus.
- Acquires information from the “real world”.

A few definitions

Actuator: a device that converts an electrical signal to a physical output.

- **Example:** Heater
- A device that generates a signal or stimulus.



Transduction principles

Actuator

↑

Inputs: Mechanical, Thermal, **Electrical**, Magnetic, Radiant, Chemical

Outputs: Mechanical, Thermal, **Electrical**, Magnetic, Radiant, Chemical

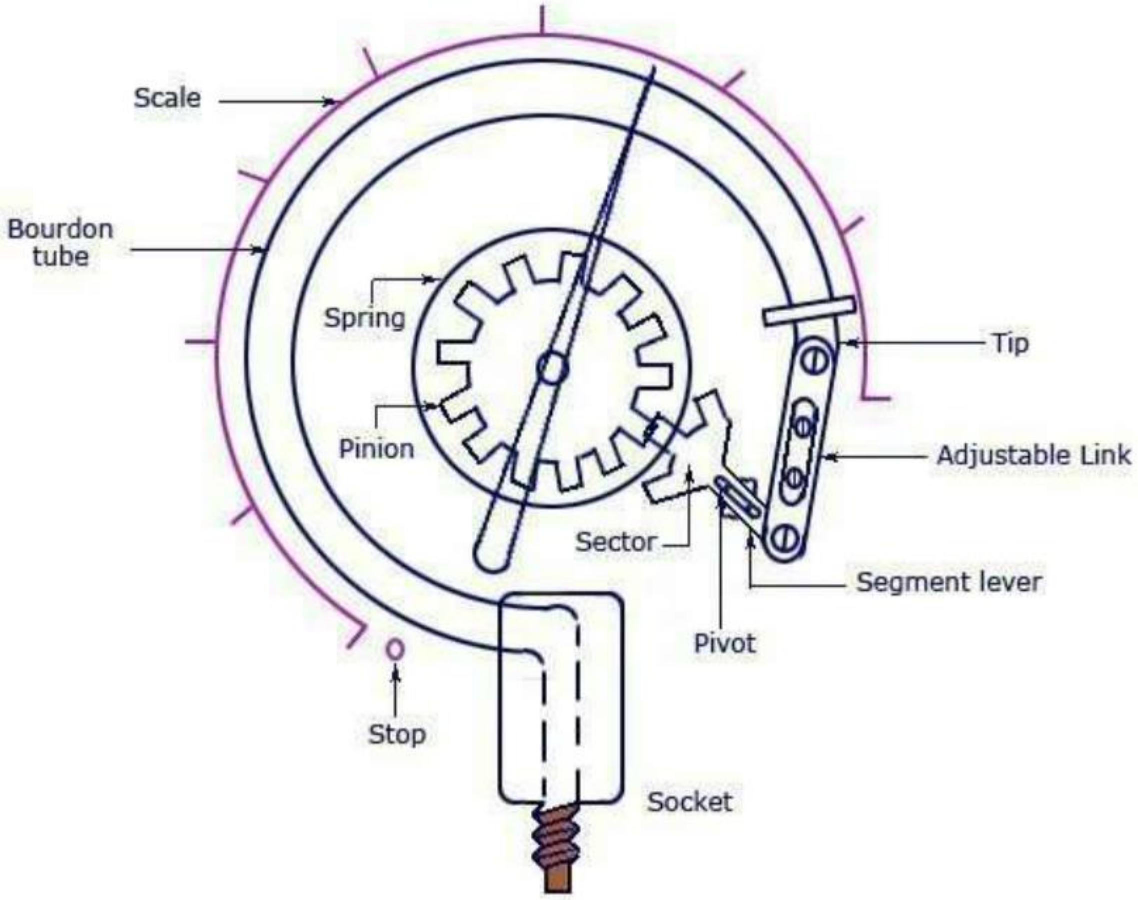
↓

Sensor

Examples of transduction principles

Mechanical-to-mechanical

Bourdon Tube Pressure Gauge

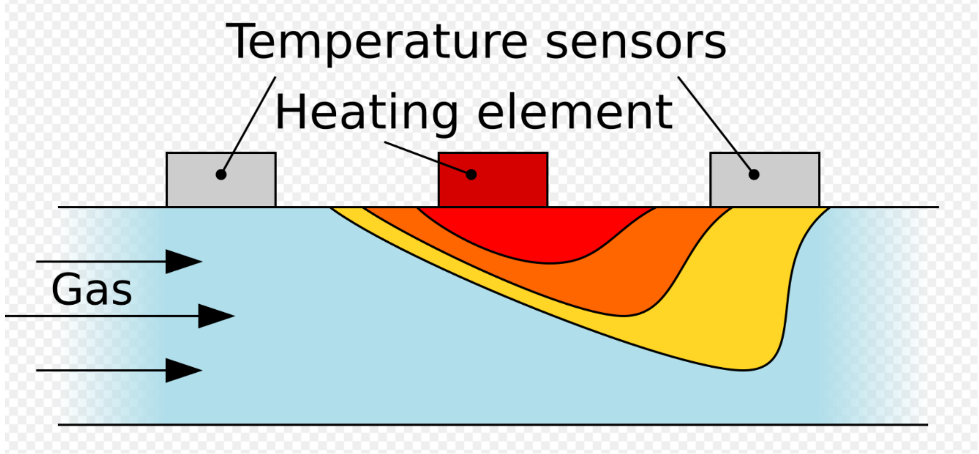


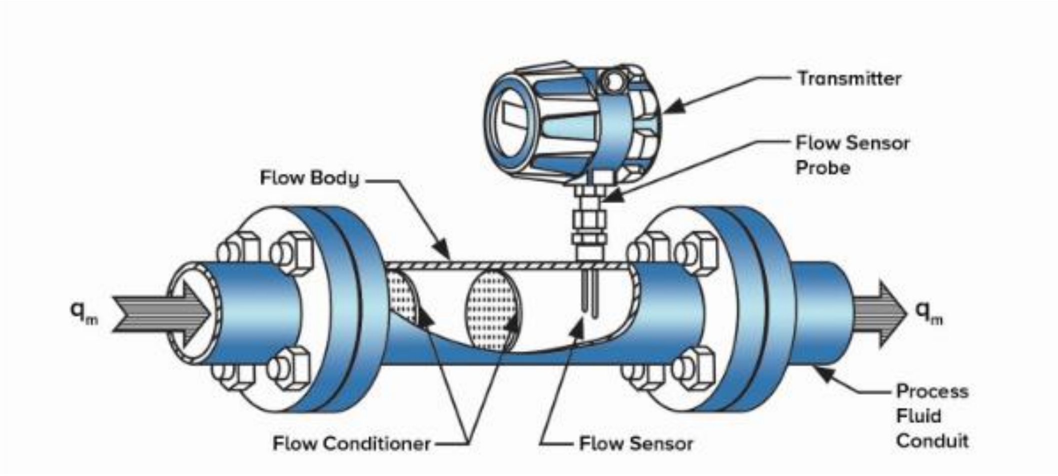
https://www.mycelectric.com/pressure-measurement/

Examples of transduction principles

Thermal-to-mechanical

Thermal flowmeter



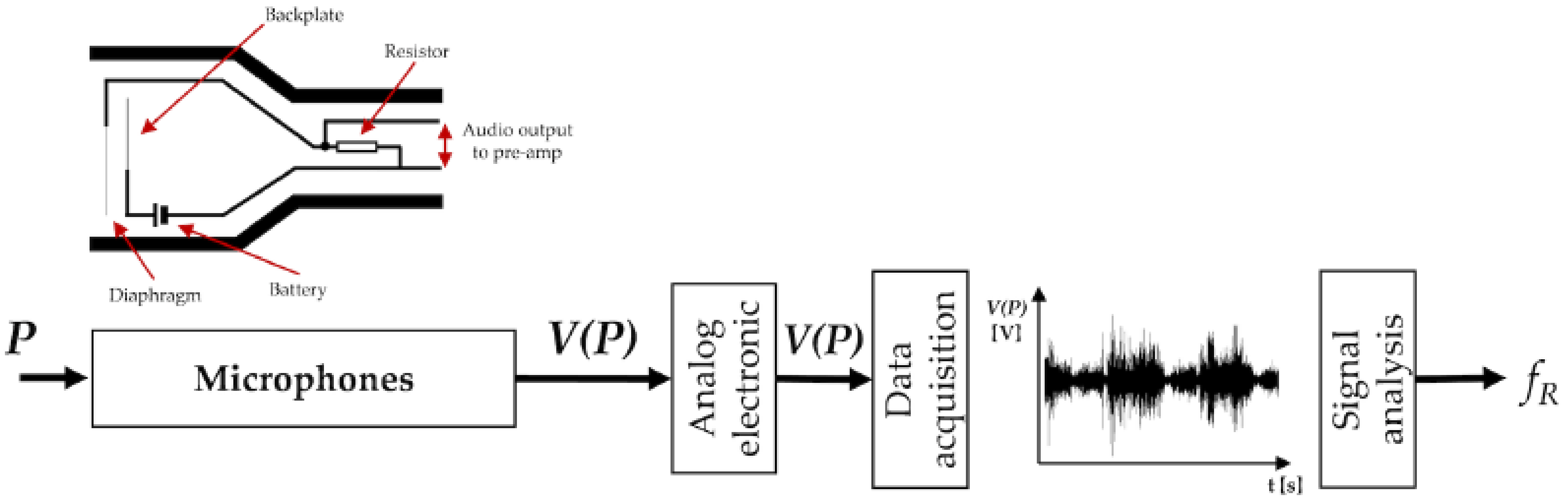


https://www.sierrainstruments.com/blog/?thermal-flowmeter-work-sierra-instruments

Examples of transduction principles

Mechanical-to-electrical

Acoustic sensor



Li, S.H.; Lin, B.S.; Tsai, C.H.; Yang, C.T.; Lin, B.S. Design of wearable breathing sound monitoring system for real-time wheeze detection. Sensors **2017**, 17, 171

Examples of transduction principles

Thermal-to-mechanical

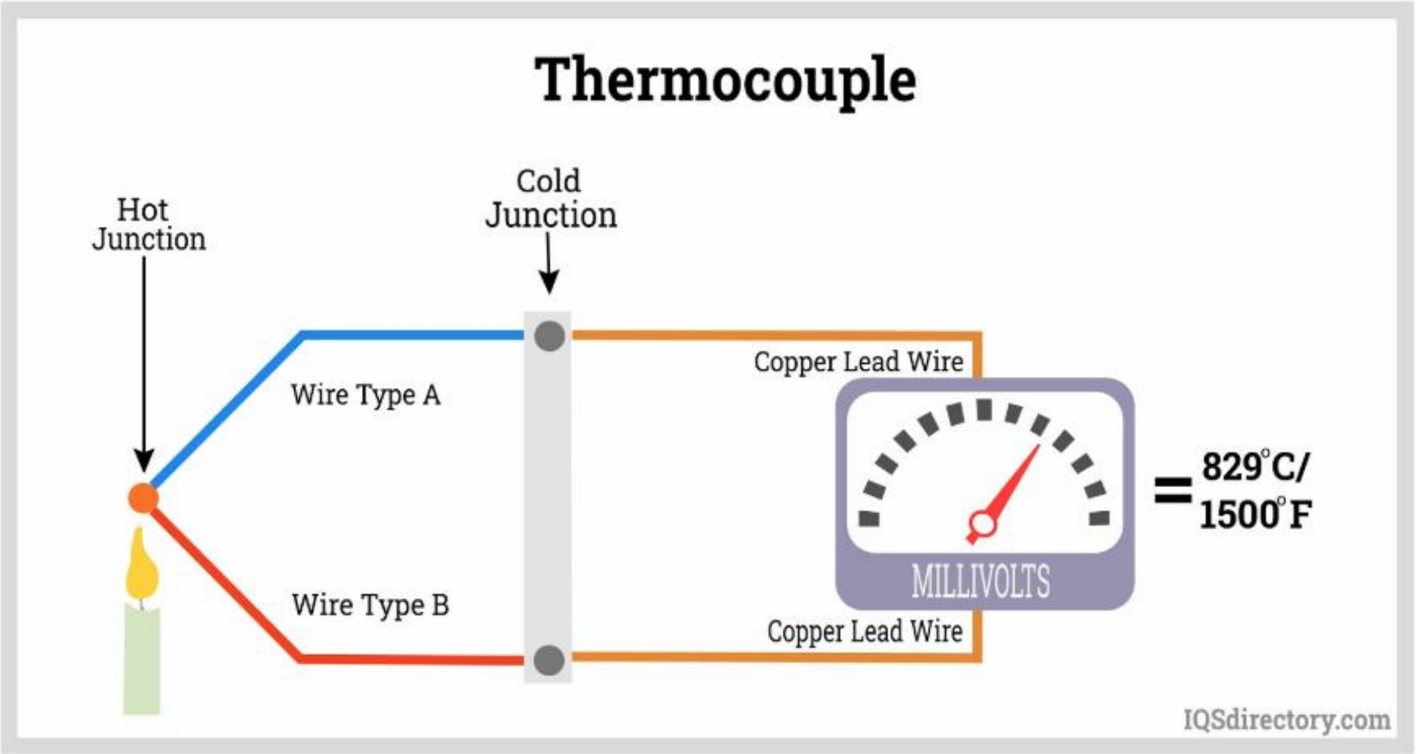
Expansion thermometer

https://www.physicsfox.org/matter/thermal-expansion/

Examples of transduction principles

Thermal-to-electrical

Thermocouple

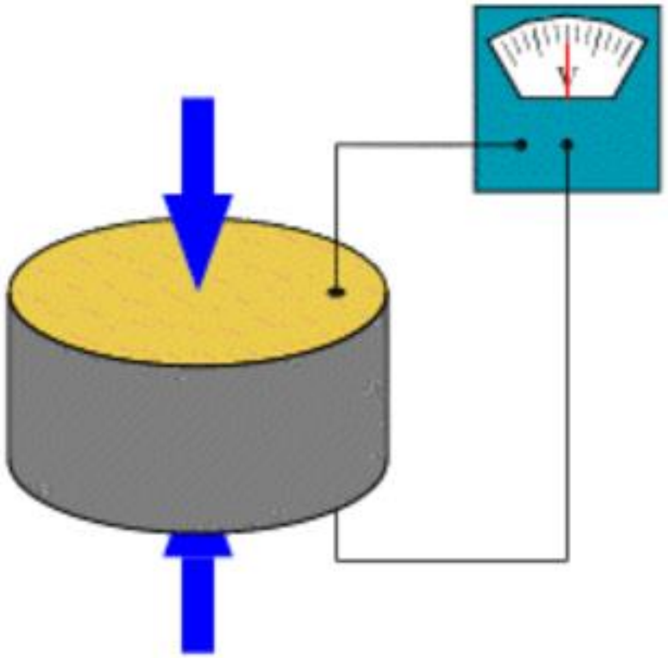


https://www.iqsdirectory.com/articles/thermocouple.html

Examples of transduction principles

Electrical-to-mechanical

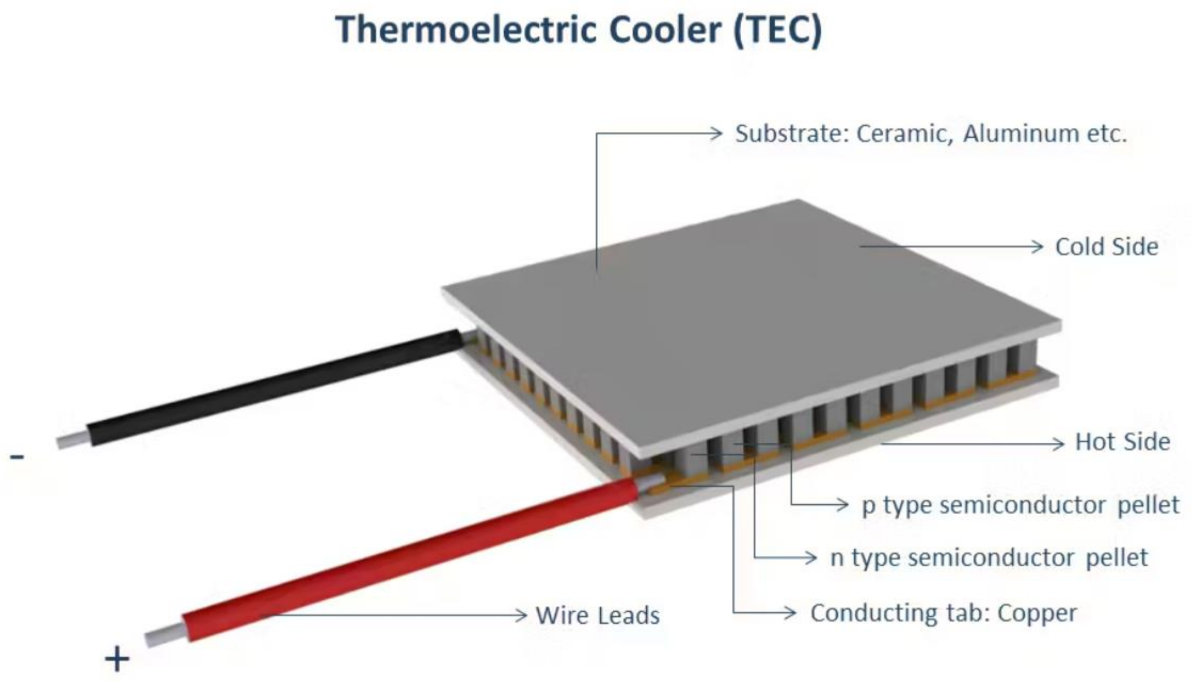
Piezoelectric sensor



Examples of transduction principles

Electrical-to-thermal

Peltier sensor

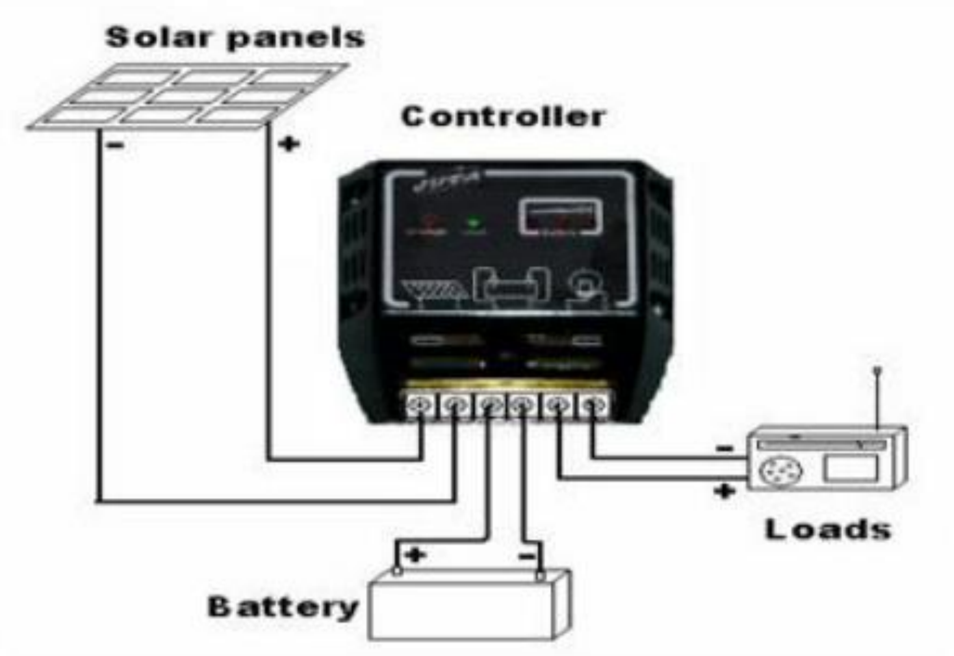


https://www.hackster.io/314404/peltier-cooler-94a048

Examples of transduction principles

Electrical-to-electrical

Charge control devices

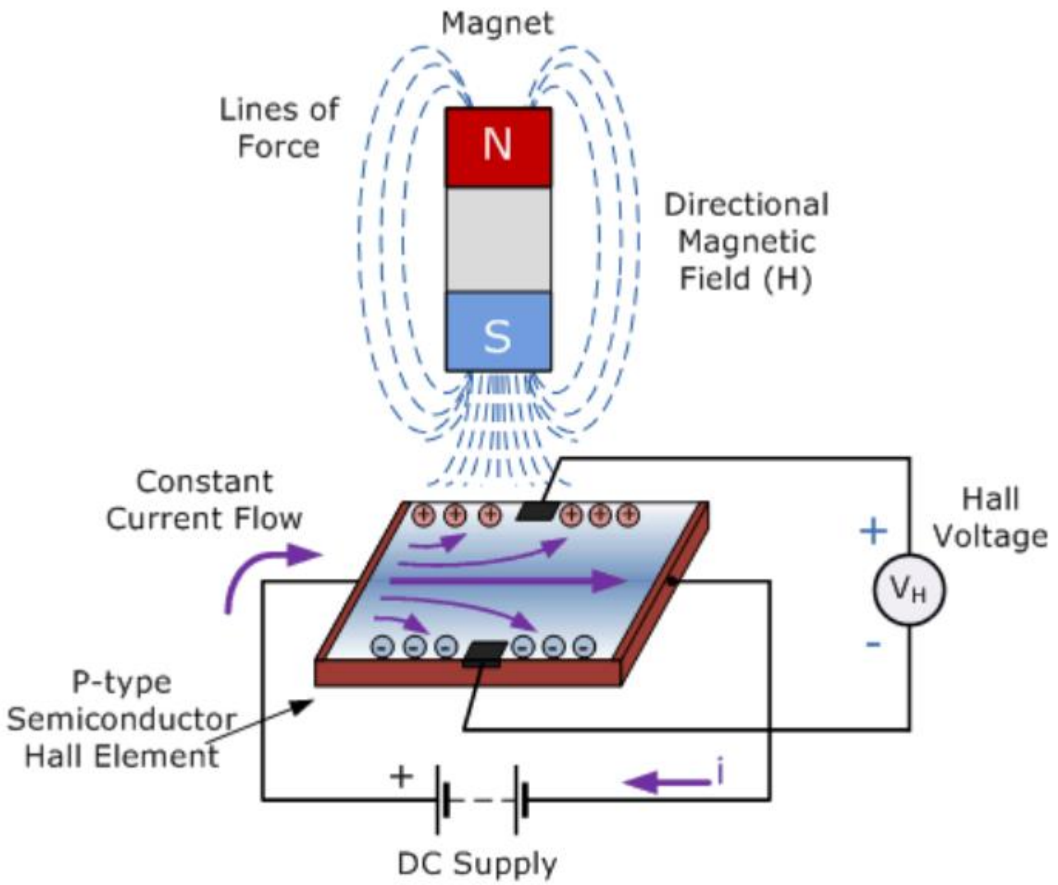


https://www.indmall.in/faq/what-is-a-charge-controller/

Examples of transduction principles

Magnetic-to-electrical

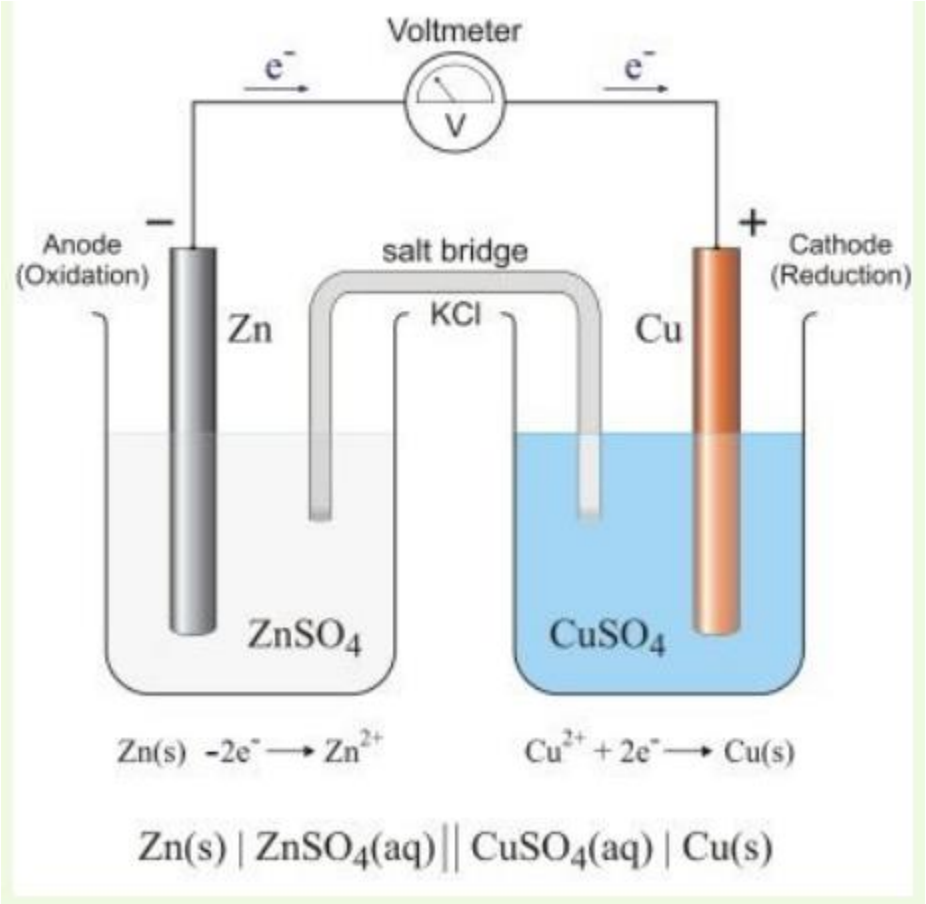
Hall effect sensor



Examples of transduction principles

Chemical-to-electrical

Galvanic cell



https://www.toppr.com/ask/question/galvanic-cell-convert-chemical-energy-into-electrical-energy/

Energy and measurands

Note: Some sensors have more than one input (e.g., Hall Sensor has magnetic as well as electrical input).
Hence, sometimes application aspect/measurand type is given more importance than input type.

Energy	Measurands
Mechanical	Length, area, volume, force, pressure, acceleration, torque, mass flow, acoustic intensity, and so on.
Thermal	Temperature, heat flow, entropy, state of matter.
Electrical	Charge, current, voltage, resistance, inductance, capacitance, dielectric constant, polarization, frequency, electric field, dipole moment, and so on.

Energy and measurands

Energy	Measurands
Magnetic	Field intensity, flux density, permeability, magnetic moment, and so forth.
Radiant	Intensity, phase, refractive index, reflectance, transmittance, absorbance, wavelength, polarization, and so on.
Chemical	Concentration, composition, oxidation/reduction potential, reaction rate, pH, and the like.

Sensor classification

It is difficult to classify the sensors under one criterion and hence, different criteria may be adopted for the classification of sensors:

1. Transduction Principle
2. Primary input quantity (i.e., measurand)
3. Material and technology
4. Applications based
5. Property based

Sensor classification: transduction

Transduction principle based upon physical, chemical or biological effects

Physical
Thermoelectric, Photoelectric, Photomagnetic, Magnetoelectric, Electromagnetic, Thermoelastic, Electroelastic, Thermomagnetic, Thermo-Optic, Photoelastic, and Other

Chemical
Chemical transformation, Physical transformation, Electrochemical process, Spectroscopy, and Other

Biological
Biochemical transformation, Physical transformation, Effect on test organism, Spectroscopy, and Other

Sensor classification: measurand

Stimulus

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, Permittivity, Other

Sensor classification: measurand

Stimulus

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

Sensor classification: measurand

Stimulus

Radiation: Radiation Type, Energy, Intensity, Other

Thermal: Temperature, Flux, Specific heat, Thermal conductivity, Other

Sensor classification: material

Sensor fabrication material-based classification

Inorganic	**Organic**
Conductor	Insulator
Semiconductor	Liquid, gas, or plasma
Biological substance	Other

Sensor classification: property

Flow
Differential pressure, positional displacement, vortex, thermal mass, electromagnetic, Coriolis, ultrasonic, anemometer, open channel.
Level
Mechanical, magnetic, differential pressure, thermal displacement, vibrating rod, magnetostrictive, ultrasonic, radio frequency, capacitance type, microwave/radar, nuclear.
Temperature
Filled-in systems, RTDs, thermistors, IC, thermocouples, inductively coupled, radiation (IR).

Sensor classification: property

Pressure
Elastic, liquid-based, manometers, inductive/LVDT, piezoelectric, electronic, fiber optic, MEMS, vacuum

Proximity and displacement
Potentiometric, inductive/LVDT, capacitive, magnetic, photoelectric, magnetostrictive, ultrasonic

Sensor classification: property

Acceleration
Accelerometers, gyroscopes

Image
CMOS.
CCDs (charge-coupled devices).
Acceleration

Gas and chemical
Chemical bead, electrochemical, thermal conductance, paramagnetic, ionization, infrared, semiconductor.

Sensor classification: property

Biosensors

Electrochemical, light-addressable potentiometric (LAP), surface plasmon resonance (SPR), resonant mirror

Others

Mass, force, load, humidity, moisture, viscosity

Emerging sensor technology

Image sensors

Technology: CMOS-based

Traffic and security surveillance, blind-spot detection as autosensors (robots, etc.), video conferencing, consumer electronics, biometrics, PC imaging.

Motion detectors

Technology: IR, ultrasonic, microwave/radar

Obstruction detection (robots, auto), security detection (intrusion), toilet activation, kiosks, videograms and simulations, light activation.

Emerging sensor technology

Biosensors

Technology: electrochemical

Water testing, food testing (contamination detection), medical care device, biological warfare agent detection.

Accelerometers

Technology: MEMS-based

Vehicle dynamic system (auto), patient monitoring (including pacemakers, etc.).

Sensor parameters

Static Characteristics

- Range
- Span
- Nonlinearity
    - Hysteresis
    - Modifying Input
    - Interfering Input
    - Error band

- Sensitivity
- Resolution
- Precision
- Accuracy
    - Error Analysis

Dynamic Characteristics

Transient

Peak overshoot
Peak time
Settling Time / Time constant
Critical gain (Marginal stability)
Stability Analysis

Special Features

Total Harmonic Distortion (THD)
Power Spectral Density (PSD)
Loading Effect

Sensor parameters

Static characteristic

- Sensor output settles down after receiving some input (steady state)

Dynamic characteristic

- Transient response (Input changes → steady state)

Sensor parameters: static characteristics

Range and span

- Limits between which the input can vary
- Maximum value of the input minus the minimum value
- Example: 1) Cantilever beam: Input range 0 to 104 Pa; Output range = 4 to 20 mA

  2) RTD: input range 0 – 400 deg C; output range 0-10 mV

Span

$$S_{input} = I_{MAX} - I_{MIN}$$

$$S_{output} = O_{MAX} - O_{MIN}$$

Sensor parameters: static characteristics

Error

- error = measured value – true value
- Systematic error
- Random error: due to noise
- Gross error: human mistake
- Causes: Inadequate calibration, environmental factors (temperature, humidity, vibration), sensor aging, electronics/electrical noise

Sensor parameters: static characteristics

Accuracy

- Maximum expected deviation between the sensor's reading and true value
- Expressed in two ways: absolute accuracy and relative accuracy
- Influence factors: sensor calibration, environmental conditions, etc

Sensor parameters: static characteristics

Precision

- The degree to which the further measurement show the same or similar results

Sensor parameters: static characteristics

Accuracy vs Precision

Accuracy	Precision
Degree to which the measured value is close to its correct value	How close the measured values are to each other in a set of data
Single factor measurement	Multiple measurement
For measurement to be accurate it should be precise	The measurement can be precise without being accurate

Sensor parameters: static characteristics

Sensitivity

- Relationship indicating change in output per unit change in input

$$\text{Sensitivity} = \frac{\Delta\text{Output}}{\Delta\text{Input}}$$

- Example: RTD sensitivity 0.5 ohm/deg C
- High sensitivity
- Low sensitivity

Sensor parameters

Selectivity

- Ability of a system, device, or instrument to differentiate between **desired signals** or measurements and **unwanted signals, disturbances, or interferences**

- Example: gas sensor

Sensor parameters: static characteristics

Non-linearity error

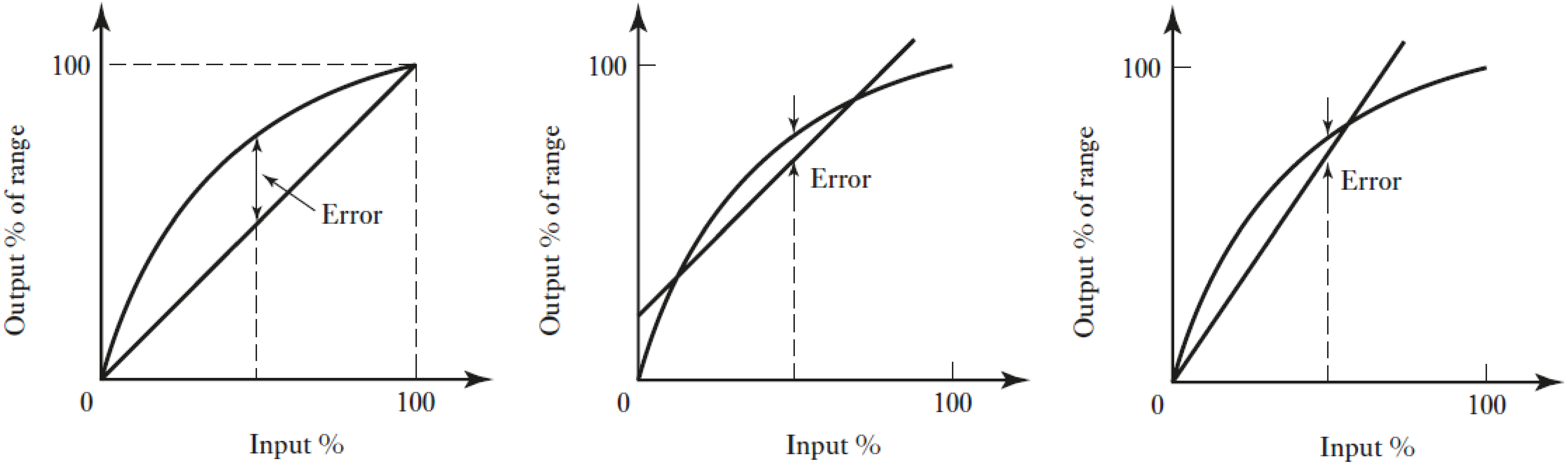
- Deviation of a sensor's actual output from an **ideal straight-line response**

$$\text{Non-linearity Error (\%)} = \frac{\text{Maximum Deviation from Linear Response}}{\text{Full-Scale Output}} \times 100$$

- Reason:
  - Material limitations
  - Non-uniformity in the transduction mechanism
  - External factors

Sensor parameters: static characteristics

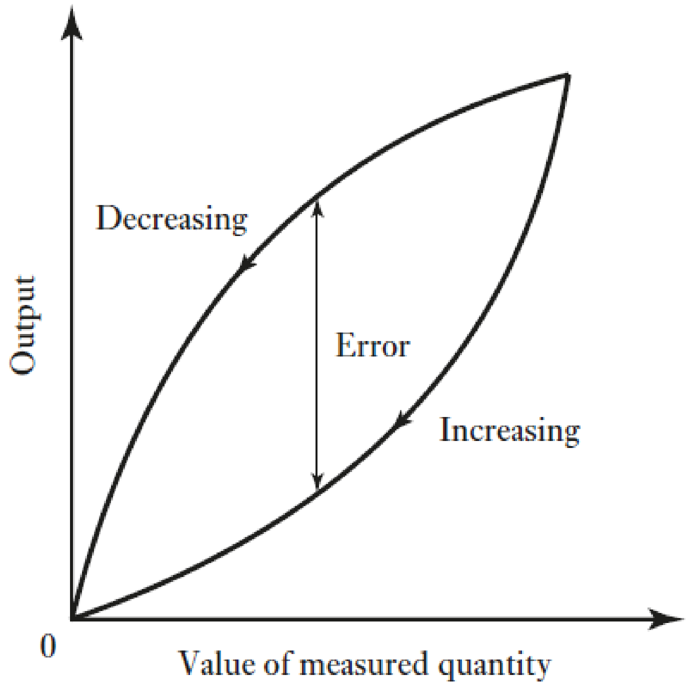
Non-linearity error



Sensor parameters: static characteristics

Hysteresis

- Dependency on input history
- Different values for same input
- Causes:
  - Material properties (e.g., magnetism, elasticity, or piezoelectric effects)
  - Mechanical friction or backlash
- Reduces measurement accuracy and repeatability.



$$\text{Hysteresis}(\%) = \frac{\text{Maximum Difference in Output}}{\text{Full-Scale Range}} \times 100$$

Sensor parameters: static characteristics

Repeatability/ reproducibility

- Ability to provide the same output for repeated application of the same input value

$$\text{repeatability} = \frac{\text{max.} - \text{min. values given}}{\text{full range}} \times 100$$

- Repeatability = ±0.01% of the full scale

Sensor parameters: static characteristics

Drift

- Change in output that occurs over time
- Zero drift

Dead band

- Range of input values for which there is no output
- **Example:** weight measuring machine that does not respond < 500gm

Sensor parameters

Distortion

- A consequence of non-linearity is **distortion**, which is defined as the deviation from an expected output of the sensor or transducer.
- Harmonic distortion

Sensor parameters: static characteristics

Resolution

- Smallest change in the input signal that the sensor can reliably detect and reflect in its output
- **Example:** wire wound potentiometer resolution 0.5 deg
- **Example:** digital output resolution = 1 bit; data N bit, i.e., a total of 2^N bits, resolution = $1/2^N$

Output impedance

- Output impedance is the measure of the resistance or impedance seen by the load connected to the sensor's output
- High vs. Low Output Impedance

Sensor parameters: static characteristics

Dynamic range

- Ratio of the largest measurable signal to the smallest detectable signal

Dynamic Range

DR (or DnR) $= I_{MAX} / I_{MIN}$

$= 20 \log (I_{MAX} / I_{MIN})$ dB

$= \log_2 (I_{MAX} / I_{MIN})$ bit or stops

Sensor parameters: dynamic characteristics

Dynamic range

- Example: dynamic range of human hearing = 150 dB
- Varying with frequency from the threshold of hearing (around −9 dB at 3 kHz) to the threshold of pain (from 120–140 dB)
- Example 2: Audio engineers use *dynamic range* to describe the ratio of the amplitude of the loudest possible undistorted signal to the noise floor, for of a microphone or loudspeaker

Sensor parameters: dynamic characteristics

Dynamic range of digital signal

- In digital audio system DR is limited by quantization error

- The maximum achievable DR for a digital audio system with **Q-bit uniform quantization** is calculated as the ratio of total bits/ LSB?

$$\boxed{\mathrm{DR}_{\mathrm{ADC}} = 20 \times \log_{10}\left(\frac{2^Q}{1}\right) = (6.02 \cdot Q)\ \mathrm{dB}}$$

Sensor parameters: static characteristics

Strain gauge pressure sensor specification

Ranges: 70 to 1000 kPa, 2000 to 70 000 kPa

Supply voltage: 10 V d.c. or a.c. r.m.s.

Full range output: 40 mV

Non-linearity and hysteresis: 60.5% full range output

Temperature range: 254°C to 1120°C when operating

Thermal zero shift: 0.030% full range output/°C

Sensor parameters: static characteristics

Numerical Example

There are two sets of data from measurement on Two Transducer.
Find which Transducer is more precise.

Set A: 32.56, 32.55, 32.48, 32.49, 32.48
Set B: 15.38, 15.37, 15.36, 15.33, 15.32.

Solution

Subtract the lowest data point from the highest:
Set A: $32.56 - 32.48 = 0.08$
Set B: $15.38 - 15.32 = 0.06$
Sample B has the lowest range (0.06) and so is the more precise.

Sensor parameters: static characteristics

Numerical Example

A measurement system can make measurements across a ±10 V range using a 16-bits A/D converter. Determine the Resolution of the system.

Solution

That is, $2^{16} = 65{,}5362$ or 1 part in 65,536.

20 V ÷ 65,536=305 microvolt (μV)

Sensor parameters: static characteristics

Numerical Example

The length of a rectangular box is 1.2 meters, but it was measured with tape, and the length was measured as 1.22 meters. Find the accuracy of measurement.

Solution

Given the length of the rectangular box = 1.20 meters

The measured length of the rectangular box = 1.22 meters

$$\text{Error Rate} = \frac{|\text{Measured Value} - \text{Given Value}|}{\text{Given Value}} \times 100$$

$$= \frac{(1.22 - 1.20)}{1.20} \times 100$$

$$= \frac{0.02}{1.20} \times 100$$

$$= 1.67\%$$

Hence the accuracy is = 98.33%

Sensor parameters: static characteristics

Numerical Example

A measuring tape can measure with an accuracy of 99.8%. What is the possible range of length which can be obtained by using this measuring tape, to measure a cloth of length 2 meters?

Solution

The error rate for the measurement = 100% - 99.8% = 0.2%
The new measurement using this measuring tape
$= 2\text{m} \pm 0.2\% \times 2\text{m}$
$= 2 \pm 0.004$
Maximum value of the measurement = 2.004
Minimum value of the measurement = 1.996

Sensor parameters: static characteristics

Numerical: Dynamic range

If the ceiling of a device is 5 V (rms) and the noise floor is 10 μV (rms) then what is DR?

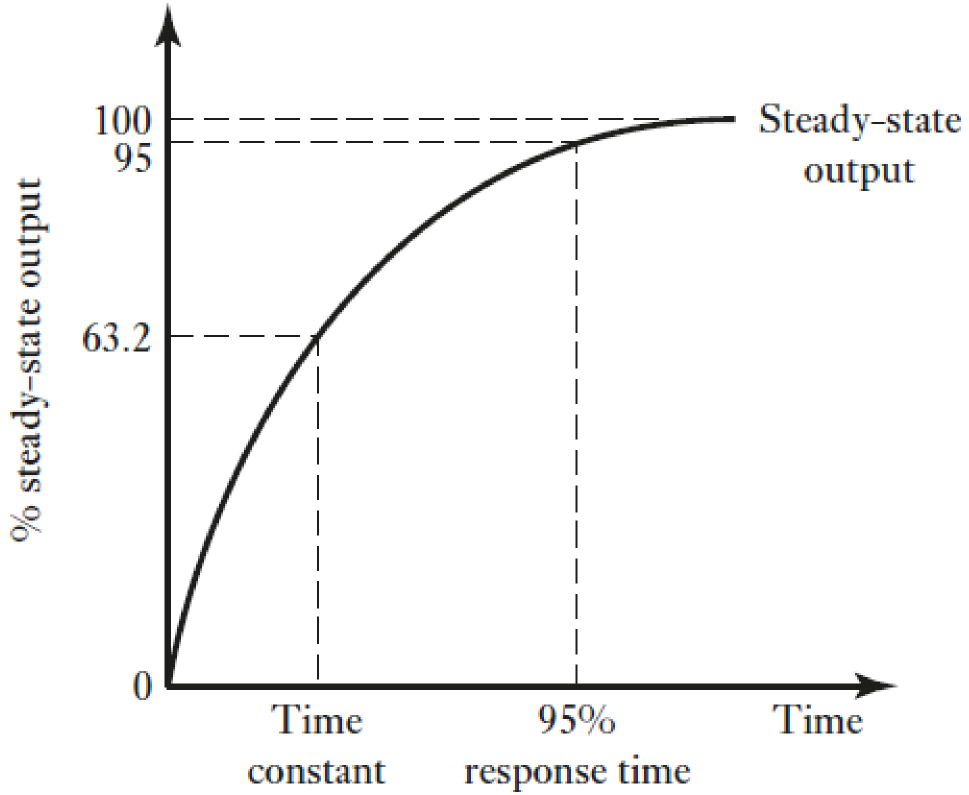
Solution:

$$20 \times \log_{10}\left(\frac{5\,\mathrm{V}}{10\,\mu\mathrm{V}}\right) = 20 \times \log_{10}(500000) = 20 \times 5.7 = 114\,\mathrm{dB}$$

Sensor parameters: dynamic characteristics

Response time

Time elapsed to reach 95% of the input value



Time constant

- 63.2% response time
- Measure of sensor inertia

Sensor parameters: dynamic characteristics

Peak time

Time it takes for the sensor's output to reach its maximum response after being exposed to a stimulus

Settling time

Output to settle to within some percentage, e.g. 2%, of the steady-state value

Thank you for your attention!