PHYSICAL SENSORS FOR ENVIRONMENTAL SIGNALS

Irene Nutini

Master Degree in Artificial Intelligence for Science and Technology (AI4ST)

A.y. 2024-2025

OUTLINE OF THE COURSE

Second part of the ‘Physical sensors for environmental signals’ course for Master Degree in Artificial Intelligence for Science and Technology (AI4ST)

- 4 Theoretical Lectures @ Polo Cravino, Pavia
- 4 Lab sessions on Friday 9.00 am -1.00 pm @ Laboratorio B3, Polo Cravino, Pavia

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OUTLINE OF THE COURSE

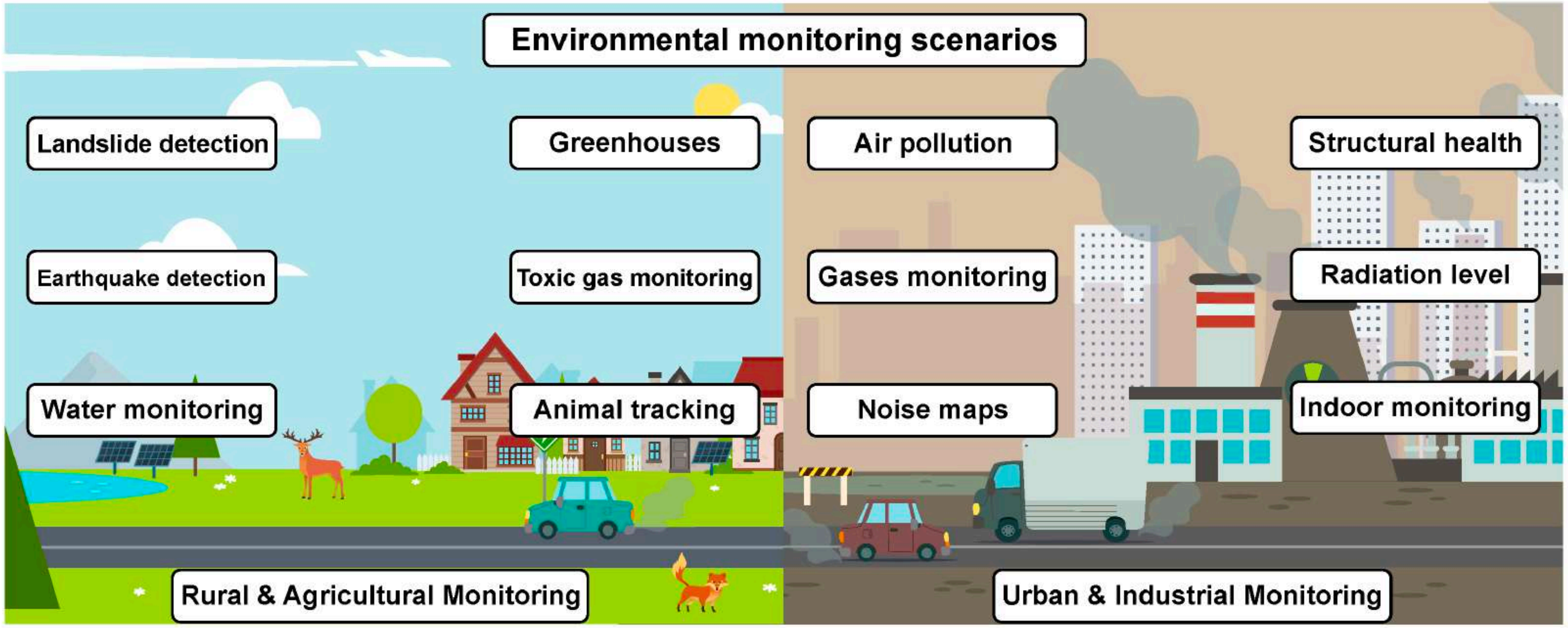
- Lecture 1: Introduction to environmental signals and physical sensors
- Lab 1: Introduction to digital signal processing and instruments for measurements
- Lecture 2: Vibrations: sources and detection
- Lab 2: Characterisation of an acoustic system
- Lecture 3: Distance, position and speed measurement
- Lab 3: Measuring distance with ultrasounds and speed with an accelerometer
- Lecture 4: Electromagnetic radiation: sources and detection
- Lab 4: Detecting and generating light

SENSING THE ENVIRONMENT

SENSING THE ENVIRONMENT

The main purpose of environmental monitoring is to provide data on environmental quality and changing trends to ensure the good quality and safety of public life and property.

The scope of environmental monitoring involves air, temperature, humidity, soil and other types. Environmental sensors are one of the key tools for pursuing these studies.



SENSING THE ENVIRONMENT

Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

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Lecture 1 today

SENSING THE ENVIRONMENT

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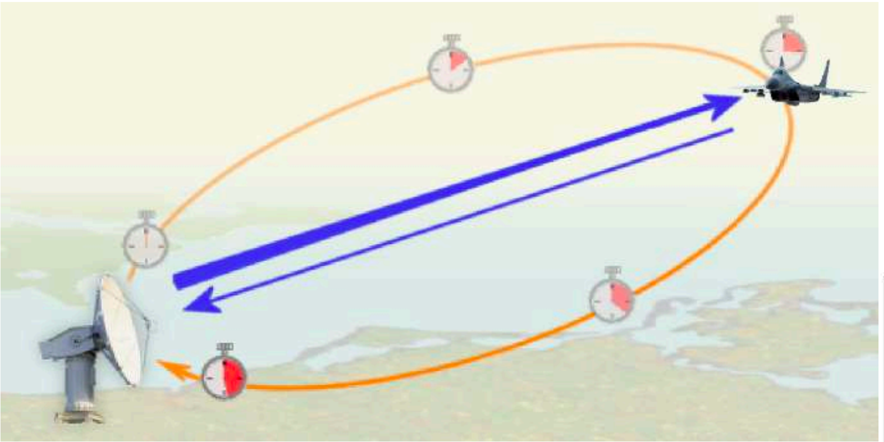

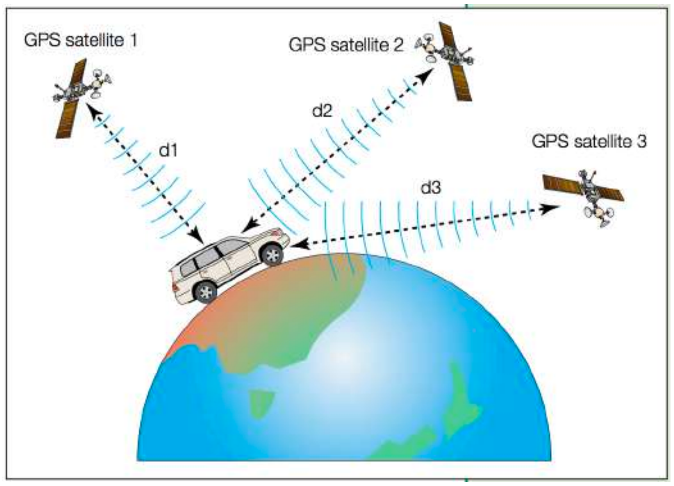

See Lecture 3

SENSING THE ENVIRONMENT

Sources

- Temperature
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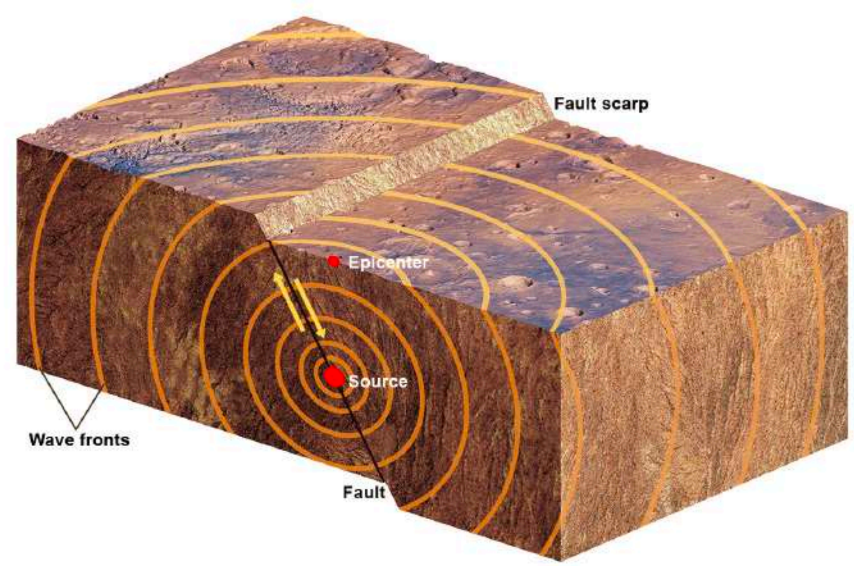
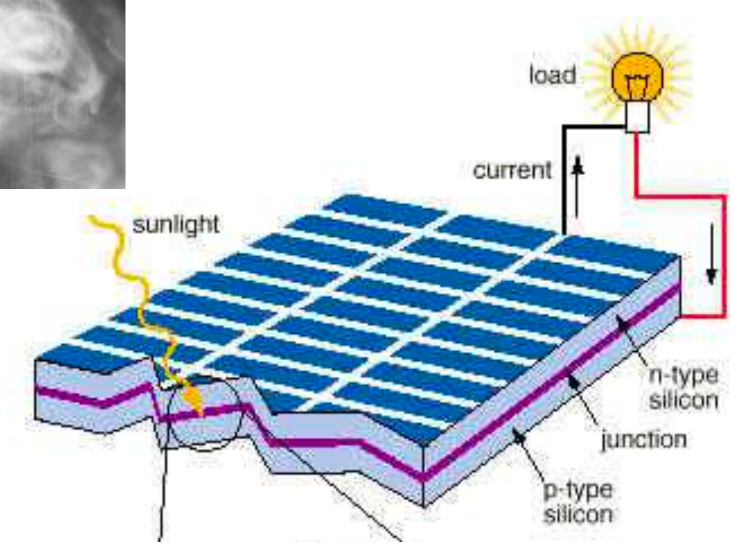


See Lecture 2

SENSING THE ENVIRONMENT

Sources

- ➤ Temperature
- ➤ Pressure
- ➤ Distance and position
- ➤ Speed
- ➤ Vibrations
- ➤ Acoustic
- ➤ Radiations: particles & light
- ➤ Chemical pollutants



See Lecture 4

SENSING THE ENVIRONMENT

Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

→ ***Lecture 1 today***

SENSING THE ENVIRONMENT

Sources

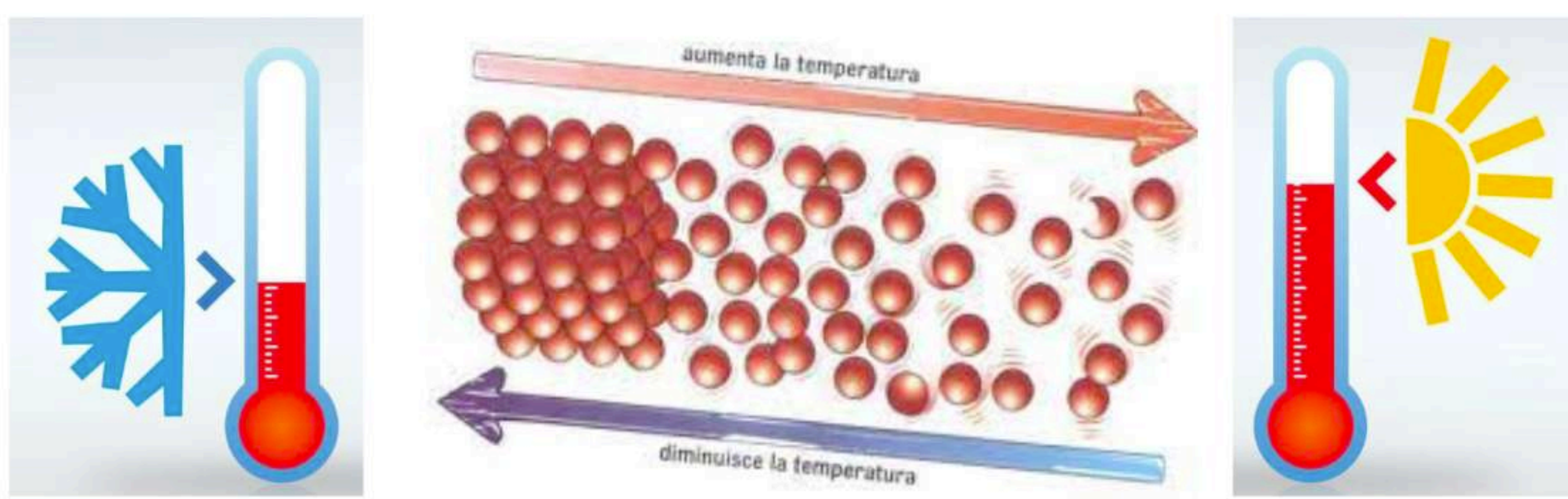
- Temperature
- Pressure

TEMPERATURE

Temperature: definition

Temperature is a measure of the average kinetic energy of the particles in a substance. In simpler terms, it indicates how hot or cold something is. Temperature is related to the movement of atoms and molecules in a substance—higher temperatures correspond to faster average particle motion.

Temperature plays a crucial role in various scientific, industrial, and everyday contexts, influencing physical and chemical processes.

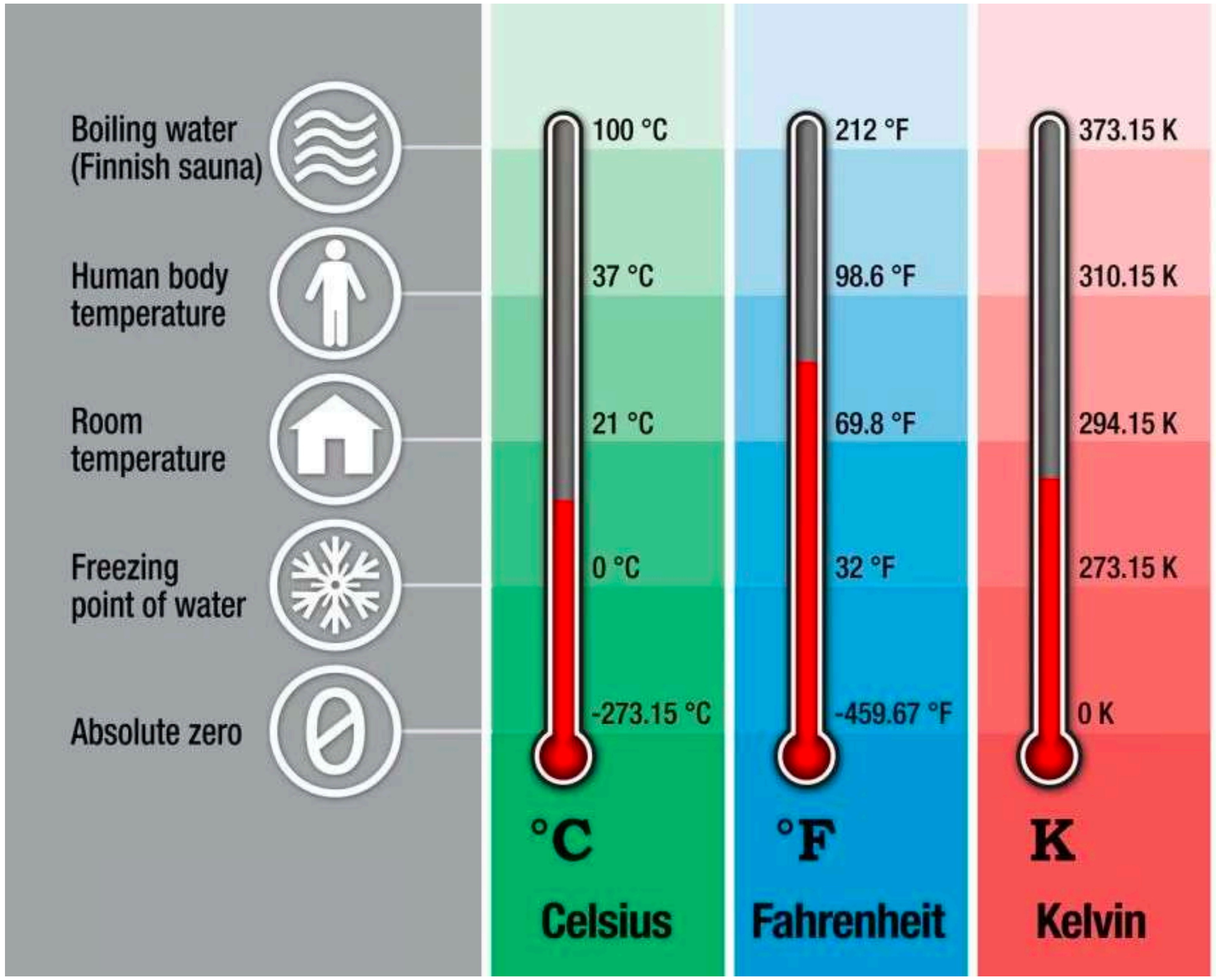


TEMPERATURE

Temperature: units and scales

The three common temperature scales are Celsius (°C), Fahrenheit (°F), and Kelvin (K).

Absolute zero (0 K = -273.25 °C), the lowest possible temperature, is the point at which particles have minimal motion.



TEMPERATURE

Temperature: thermal energy transfer

Conduction, convection, and radiation are three fundamental modes of heat transfer from one object or substance to another.

1. Conduction:

Definition: Conduction is the process of heat transfer through direct contact between particles within a substance. It occurs in solids, liquids, and gases, but it is most effective in solids.

Mechanism: In a material, hotter particles transfer energy to adjacent cooler particles through molecular collisions. This process continues, gradually transferring heat throughout the material.

Example: When one end of a metal rod is heated, the heat is conducted along the rod, gradually raising the temperature of the entire rod.

TEMPERATURE

Temperature: thermal energy transfer

Conduction, convection, and radiation are three fundamental modes of heat transfer from one object or substance to another.

2. Convection:

Definition: Convection is the heat transfer process that occurs through the movement of fluids (liquids or gases) caused by density differences. It is more effective in fluids than in solids.

Mechanism: In a fluid, heated particles become less dense and rise, creating a flow of the fluid. Cooler, denser fluid then replaces the rising warm fluid, creating a continuous circulation pattern.

Example: Boiling water in a pot involves convection. The hot water near the heat source rises, and cooler water moves down to replace it, creating a convective current.

TEMPERATURE

Temperature: thermal energy transfer

Conduction, convection, and radiation are three fundamental modes of heat transfer from one object or substance to another.

3. Radiation:

Definition: Radiation is the transfer of heat through electromagnetic waves that can travel through a vacuum. It does not require a material medium and can occur in a vacuum or through transparent media.

Mechanism: Electromagnetic waves, such as infrared radiation, are emitted by a hotter object and absorbed by a cooler one. This process does not involve direct contact or a material medium.

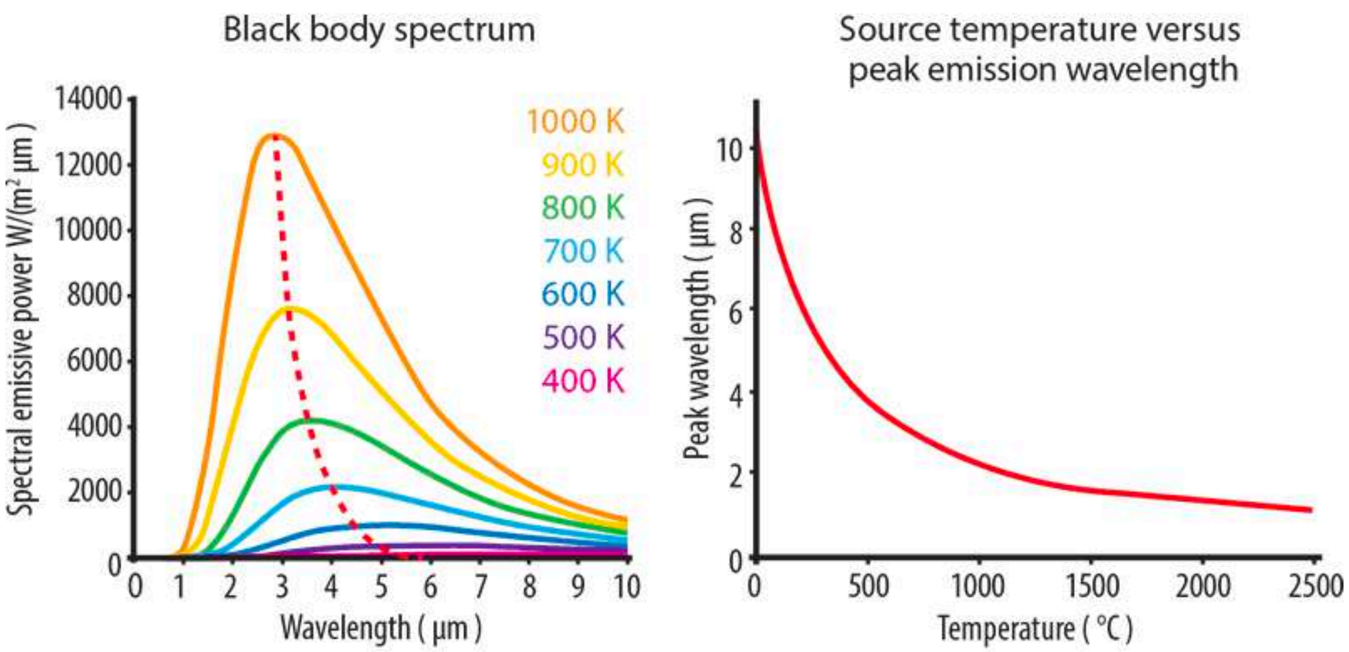
Example: The Sun's energy reaches Earth through radiation. Objects, such as a heated metal rod, also emit radiation in the form of infrared rays.

TEMPERATURE

Temperature: black body radiation

Black body radiation refers to the electromagnetic radiation emitted by a perfect absorber and emitter of energy, known as a *black body*, which absorbs all incident radiation regardless of wavelength and emits radiation according to its temperature.

While real objects may not perfectly exhibit the characteristics of an idealised black body, they emit radiation across a spectrum, and the intensity and distribution of this radiation are determined by the object's temperature.



https://www.ceramicx.com/information/support/why-infrared-laws-of-infrared-heating/

1100 °C: steel glows bright yellow
1300°C: steel will glow white hot and starts to melt

https://blacksmithu.com/how-blacksmiths-measure-temperature/

TEMPERATURE

Temperature measurement: thermometry

Measuring the temperature:

- of an environment
- of a thing
- of a body

TEMPERATURE

Temperature measurement: thermometry

Measuring the temperature:

- of an environment
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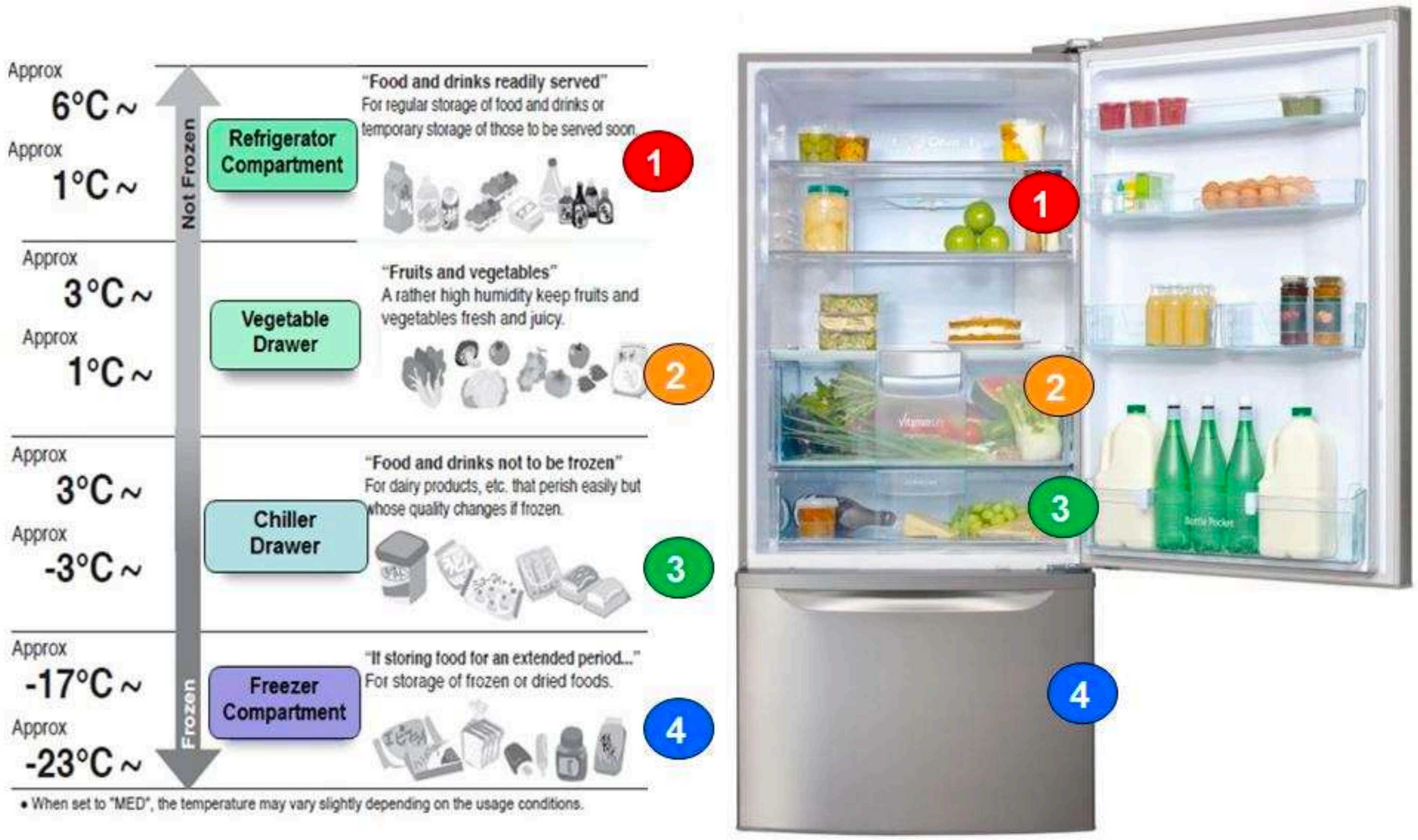


TEMPERATURE

Temperature measurement: thermometry

Measuring the temperature:

- of an environment
- of a thing
- of a body

TEMPERATURE

Temperature measurement: thermometry

Thermometry is the scientific field that deals with the measurement of temperature. It involves the use of instruments called thermometers to quantify the intensity of heat or cold in a substance or environment. The concept of thermometry is based on the fact that various physical properties of materials change in a predictable way with temperature.

The key principles behind thermometry include:

1. **Expansion and Contraction**: Many materials expand or contract with changes in temperature. Thermometers exploit this property to provide a measurable indication of temperature.

2. **Temperature Scales**: The Celsius (°C), Fahrenheit (°F), and Kelvin (K) scales provide a standardized way of communicating temperature values in scientific and industrial applications.

3. **Calibration**: Thermometers need to be calibrated to ensure accuracy. Calibration involves comparing the readings of a thermometer to those of a known reference standard at different temperature points.

4. **Thermal Equilibrium**: The measurement of temperature assumes that the thermometer and the substance being measured are in thermal equilibrium, meaning they have reached the same temperature. This ensures that the temperature reading accurately reflects the state of the substance.

TEMPERATURE

Temperature measurement: thermometry

Thermometry has applications in various fields, including meteorology, physics, chemistry, medicine, and industry. Different types of thermometers are used depending on the temperature range, accuracy requirements, and the nature of the materials being measured. The goal of thermometry is to provide reliable and standardized methods for assessing temperature in diverse settings.

TEMPERATURE

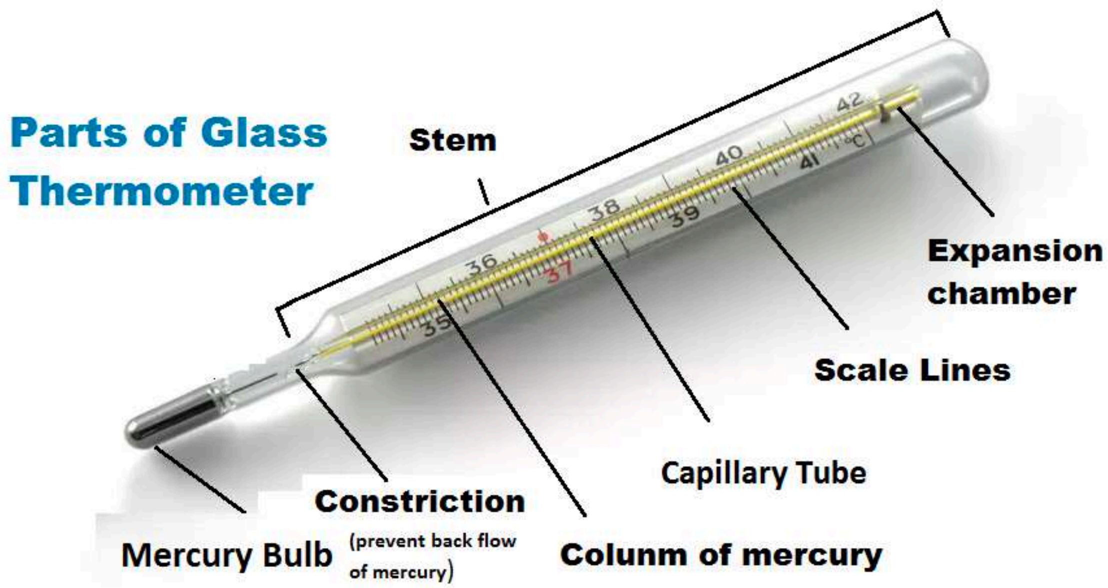
Temperature sensors: thermometers.

The most common types of thermometers include:

1. **Mercury Thermometers**:

   - Traditional thermometers that use the expansion and contraction of mercury inside a glass tube to indicate temperature changes.

   - Mercury expands when heated, causing it to rise in the narrow tube, and contracts when cooled, causing it to fall.



$$\Delta V = V_0 \alpha \Delta T$$

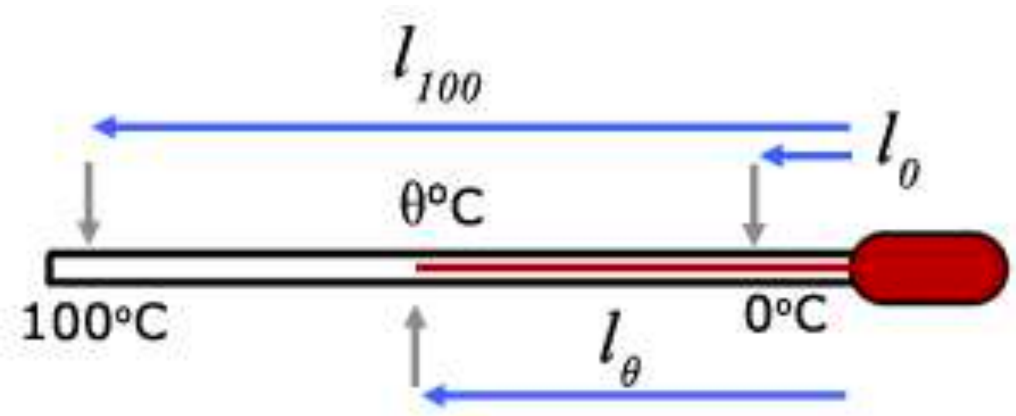
$$\Delta V = V_1 - V_0$$

$$\Delta T = T_1 - T_0$$

$$V_0 = \pi R^2 L_0$$

$$V_1 = \pi R^2 L_1$$

$$T_1 > T_0, L_1 > L_0$$



TEMPERATURE

Temperature sensors: thermometers.

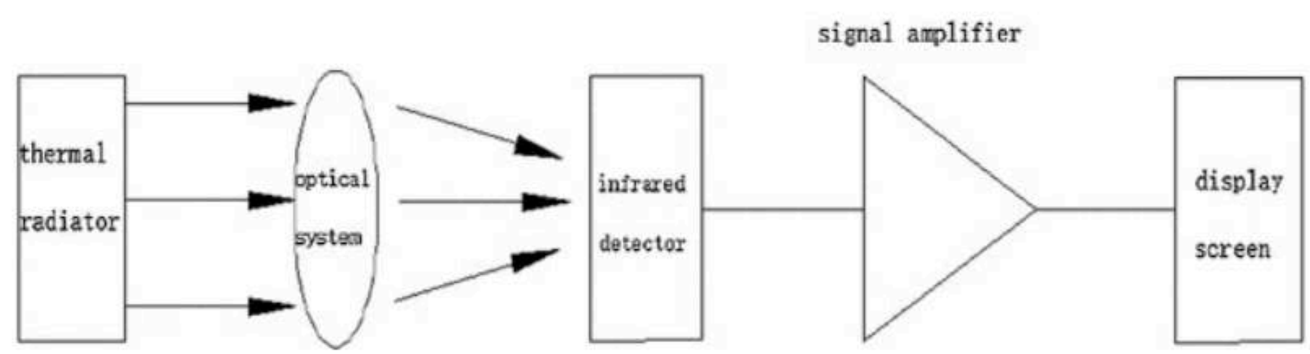
The most common types of thermometers include:

2. **Infrared Thermometers**:

- Measure temperature without direct contact with the object being measured.

- Use the infrared radiation emitted by an object to determine its temperature.

Much of a person's energy is radiated away in the form of long-wave infrared (LWIR) light



From: 10.1007/s10586-018-1828-5

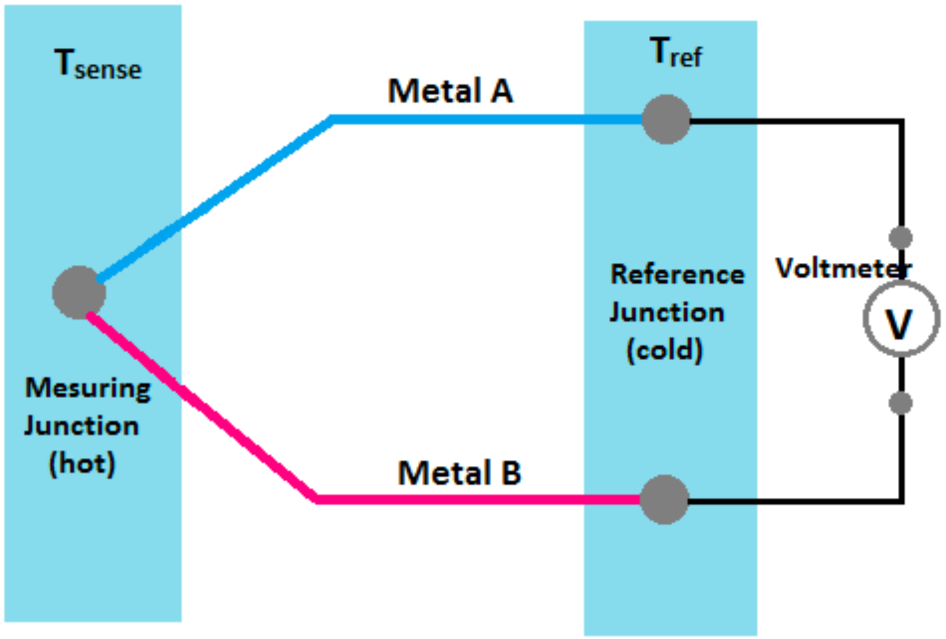
TEMPERATURE

Temperature sensors: thermometers.

3. **Thermocouples**:

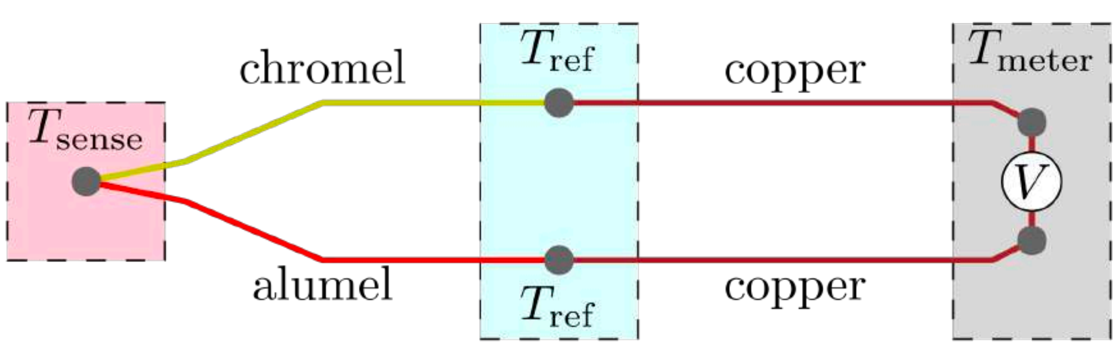
- Consist of two different metals (conductors) joined at one end (electrical junction).

- Generate a voltage that varies with temperature, allowing for temperature measurement.

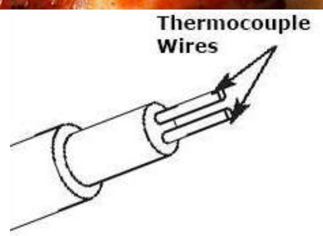


https://www.etechnog.com/2021/06/thermocouple-diagram-circuit.html

Thermoelectric/Seebeck effect:
Voltage difference that develops across two points of an electrically conducting material when there is a temperature difference between them



K-type thermocouple (chromel–alumel)



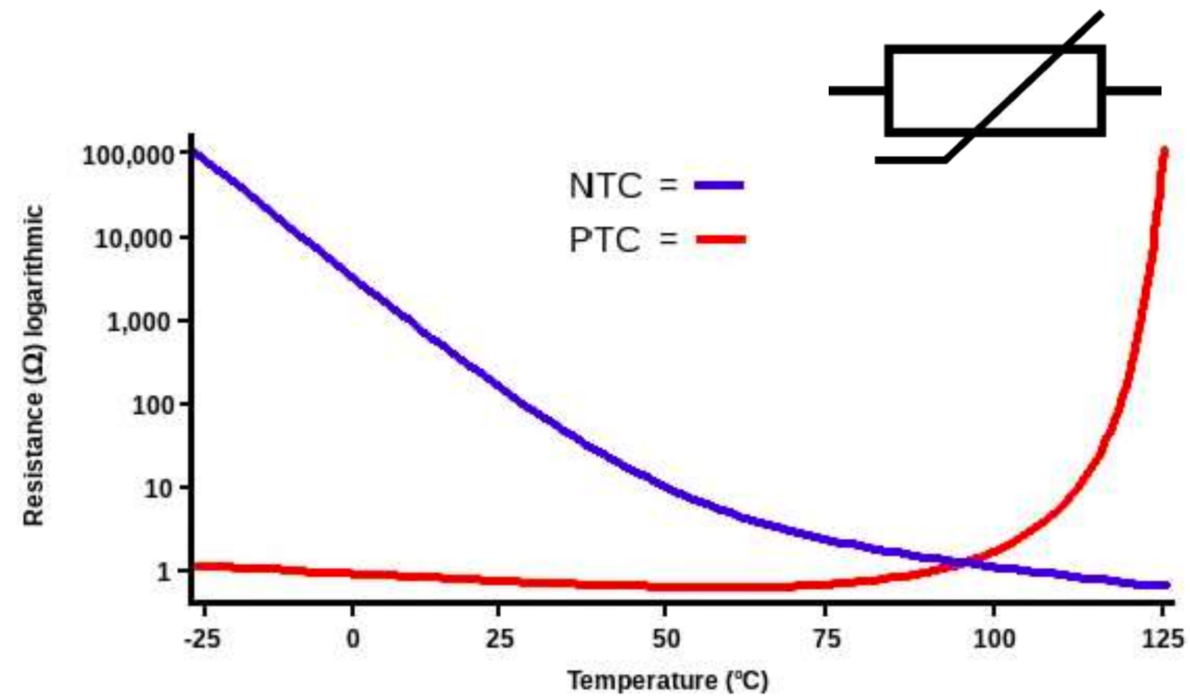
TEMPERATURE

Temperature sensors: thermometers.

4. **Thermistors**:

- Are temperature-sensitive resistors that exhibit a change in resistance with temperature

- Commonly used in electronic devices and systems for temperature measurement.

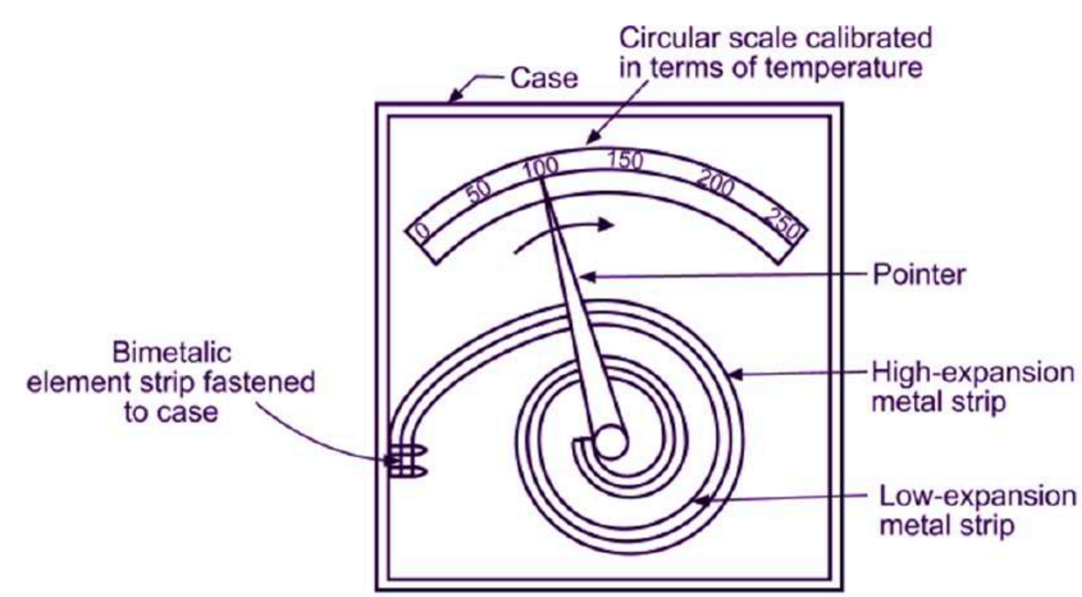


https://www.seeedstudio.com/blog/2020/10/27/thermistors-ntc-and-ptc-thermistors-explained/

5. **Bimetallic Thermometers**:

- Contain two different metals bonded together.

- The different rates of expansion of the metals cause the thermometer to bend with temperature changes, providing a visual indication.



https://electricalworkbook.com/bimetallic-thermometer/

TEMPERATURE

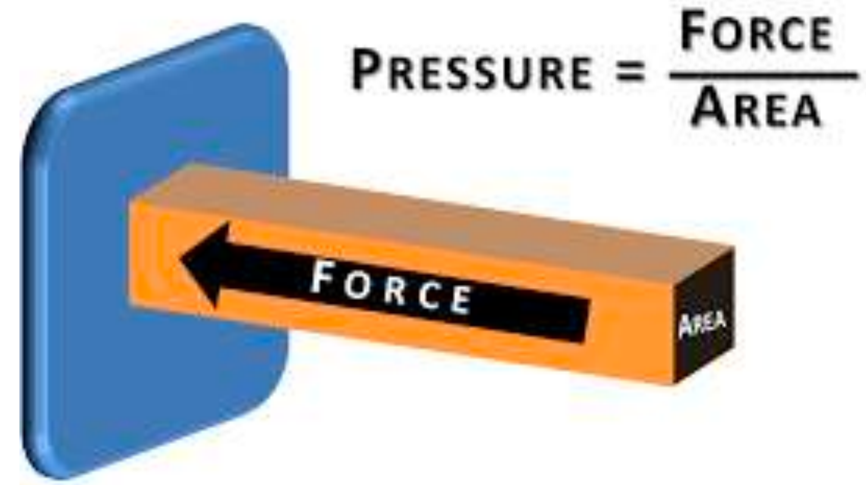
Temperature sensors: thermometers.

The choice of thermometer depends on the specific requirements of the measurement, the temperature range involved, and the application. Each type has its advantages and limitations, but they all operate based on the principle that certain physical properties change predictably with temperature.

PRESSURE

Pressure: definition

Pressure is a measure of force applied over a specific area and is defined as the force per unit area.



Pressure is directly proportional to the force applied and inversely proportional to the area over which the force is distributed. A greater force or a smaller area results in higher pressure.

PRESSURE

Pressure: units and scales

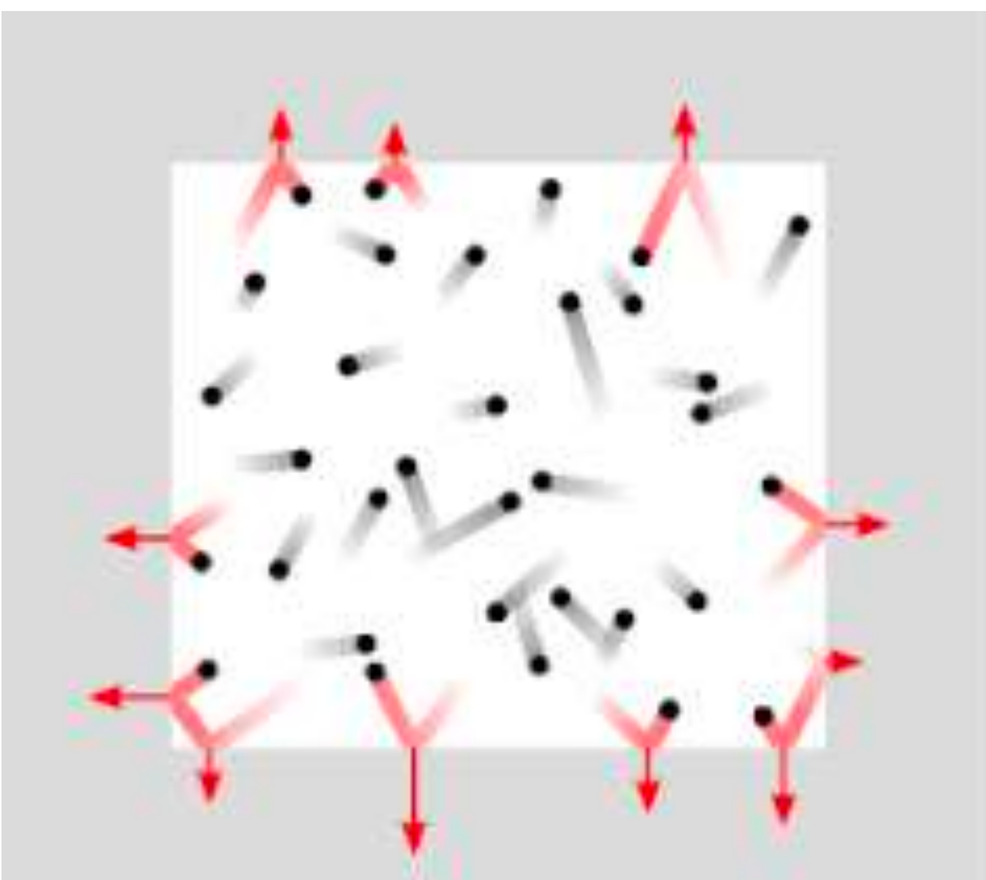
Pressure is commonly measured in units such as Pascals (Pa), atmospheres (atm), millimeters of mercury (mmHg), or pounds per square inch (psi), depending on the context.

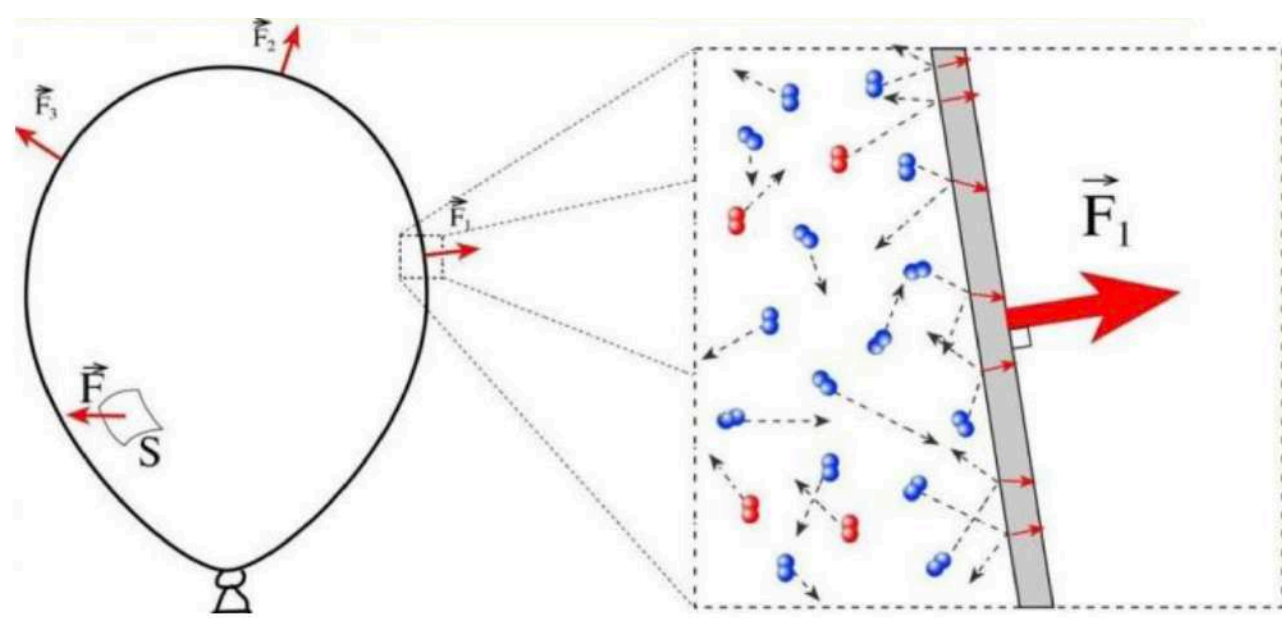
Units	Symbol	Equivalent to 1 atm
Atmosphere	atm	1 atm
Millimeter of Mercury	mmHg	760 mmHg
Torr	Torr	760 Torr
Pascal	Pa	101326 Pa
Kilopascal	kPa*	101.326 kPa
Bar	bar	1.01325 bar
Millibar	mb	1013.25 mb
Pounds per square inch	psi	14.7 psi

PRESSURE

Pressure: Fluid pressure

In fluids (liquids and gases), pressure is transmitted equally in all directions. This is known as Pascal's principle, and it underlies the functioning of hydraulic systems.

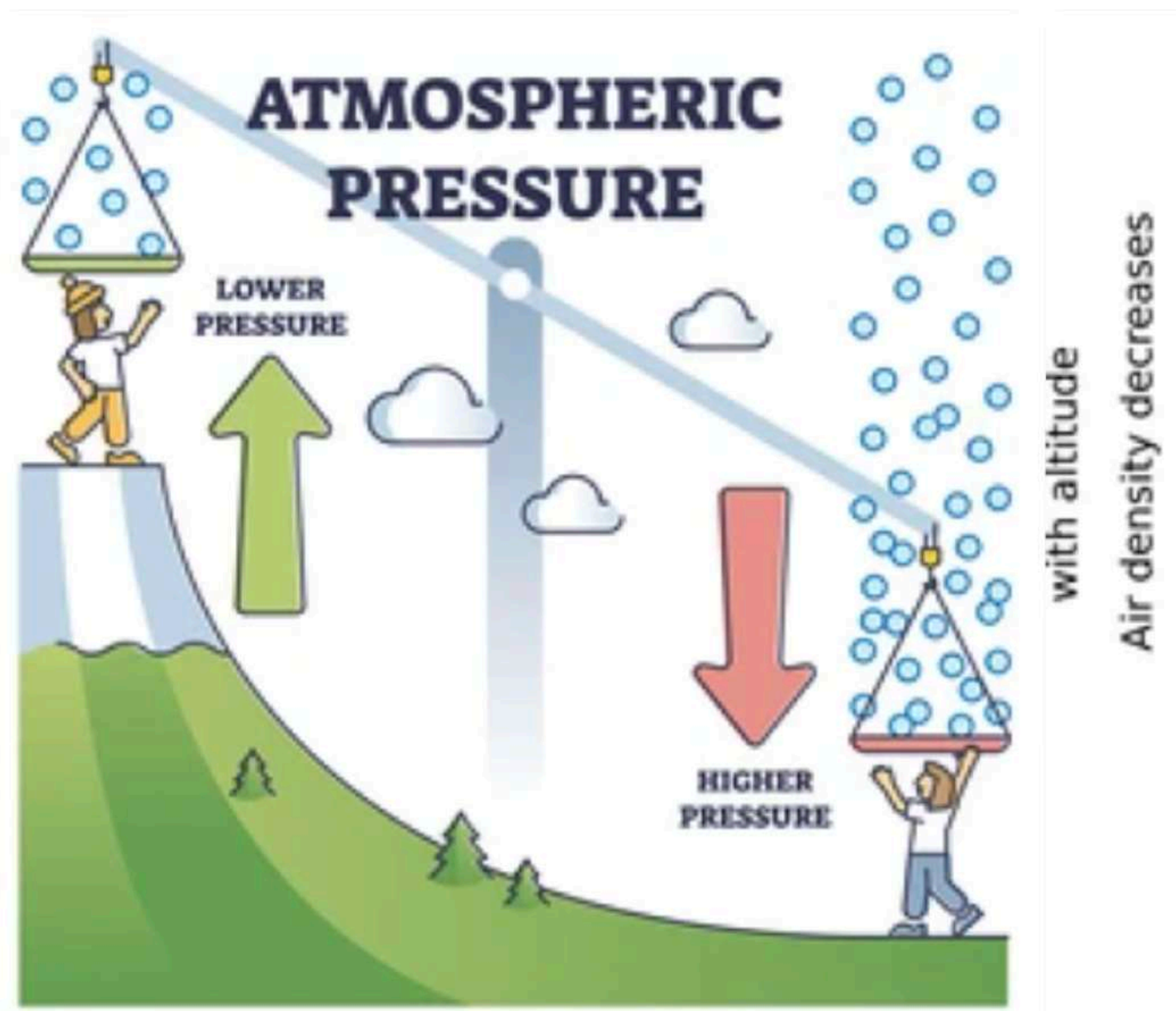




PRESSURE

Pressure: Atmospheric pressure

The pressure exerted by the Earth's atmosphere at a given point is called atmospheric pressure. It decreases with altitude, and standard atmospheric pressure at sea level is approximately 101.3 kPa.



PRESSURE

Pressure: Applications

Understanding pressure is crucial in various fields, including physics, engineering, meteorology, and medicine. It is fundamental in fluid dynamics, hydraulic systems, weather systems, and physiological processes.

Pressure plays a vital role in describing and predicting the behaviour of fluids and gases, as well as in designing systems where the distribution of force is a critical factor.

PRESSURE

Pressure measurement

The concept of pressure measurement involves quantifying the force exerted by a fluid (liquid or gas) on a surface and expressing it as force per unit area.

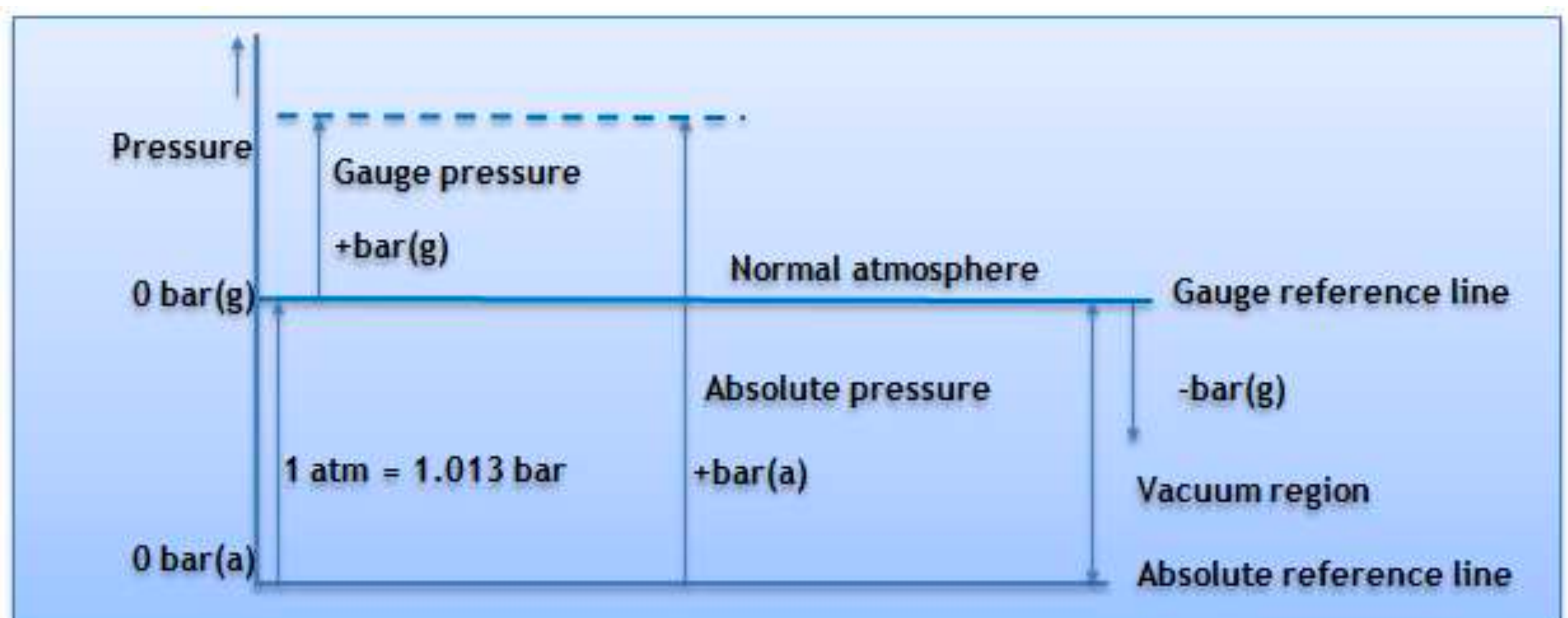
Pressure sensors and transducers are devices designed to convert the applied pressure into a readable and often electrical output.

Calibration is a crucial aspect of pressure measurement. It involves comparing the output of a pressure measurement device to a known reference standard.

Absolute Pressure vs.

Gauge Pressure:

- Absolute pressure is measured relative to a perfect vacuum, while gauge pressure is measured relative to atmospheric pressure.

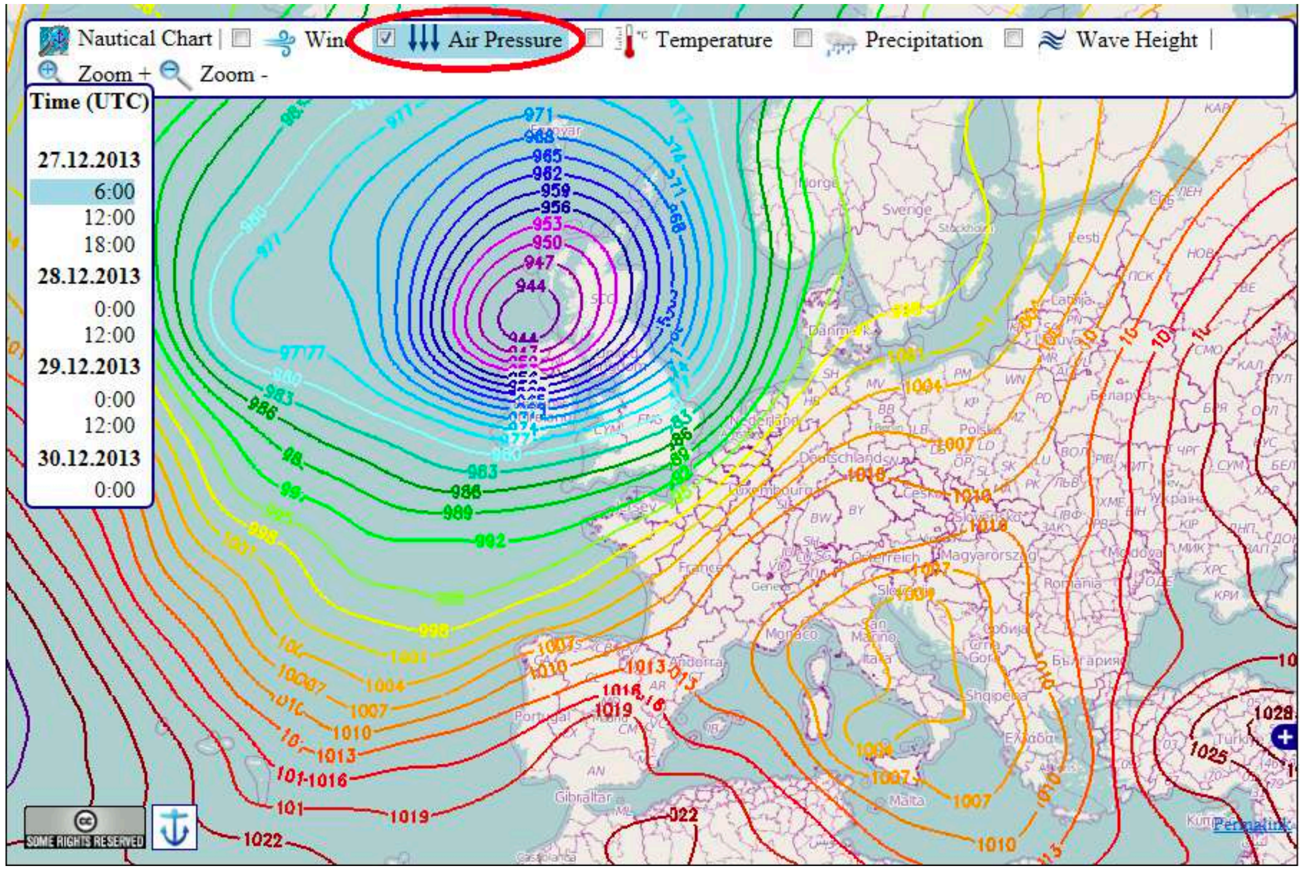


PRESSURE

Pressure measurement

Pressure measurement is essential in numerous fields, including fluid dynamics, meteorology, industrial processes, aviation, and healthcare.

Monitoring air pressure for forecast



https://hotcore.info/babki/air-pressure-map.htm

Measuring P:

- of an environment
- of a fluid inside a container
- of a body

PRESSURE

Pressure measurement

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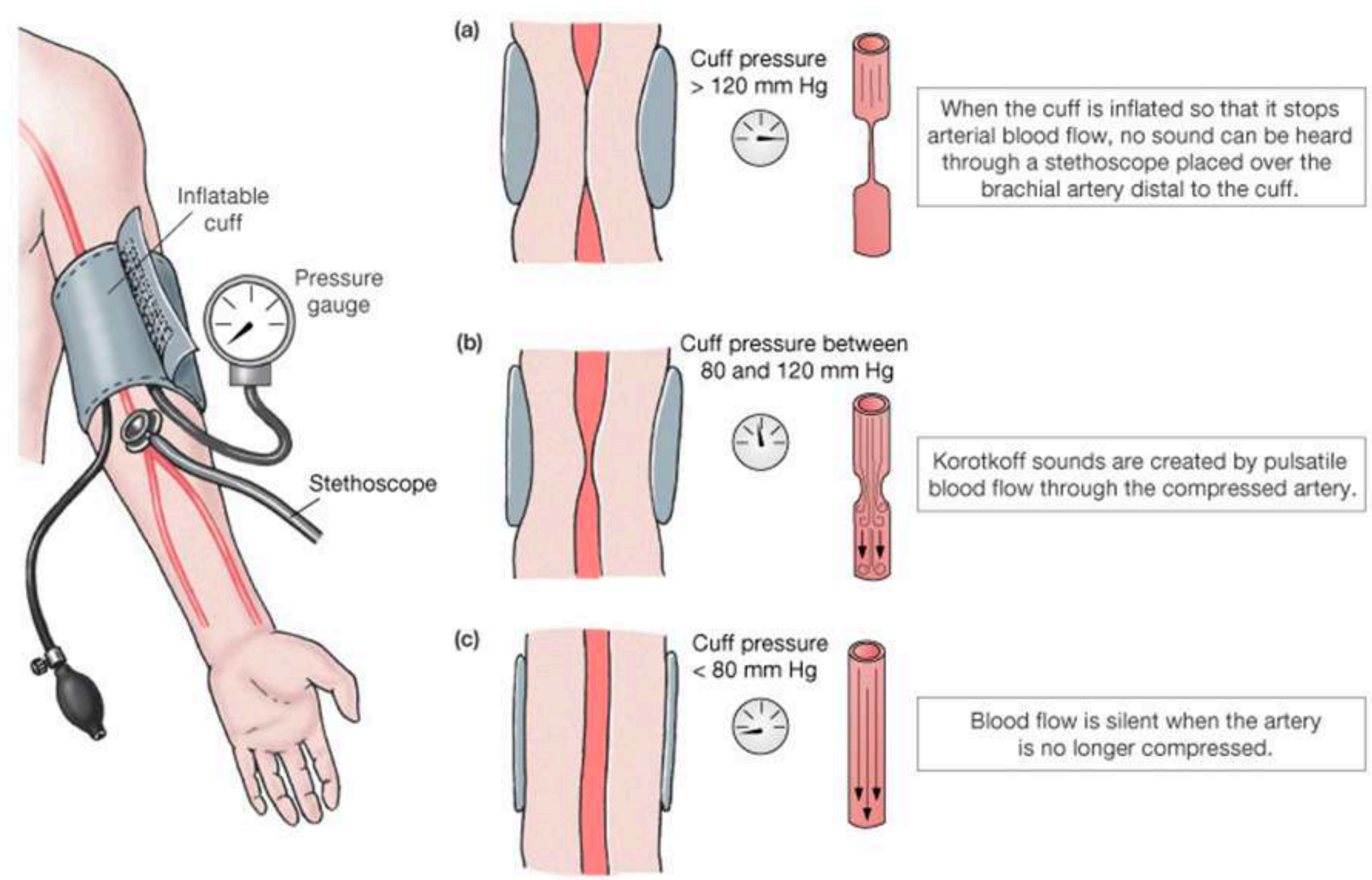


Measuring blood pressure

PRESSURE

Pressure sensors:

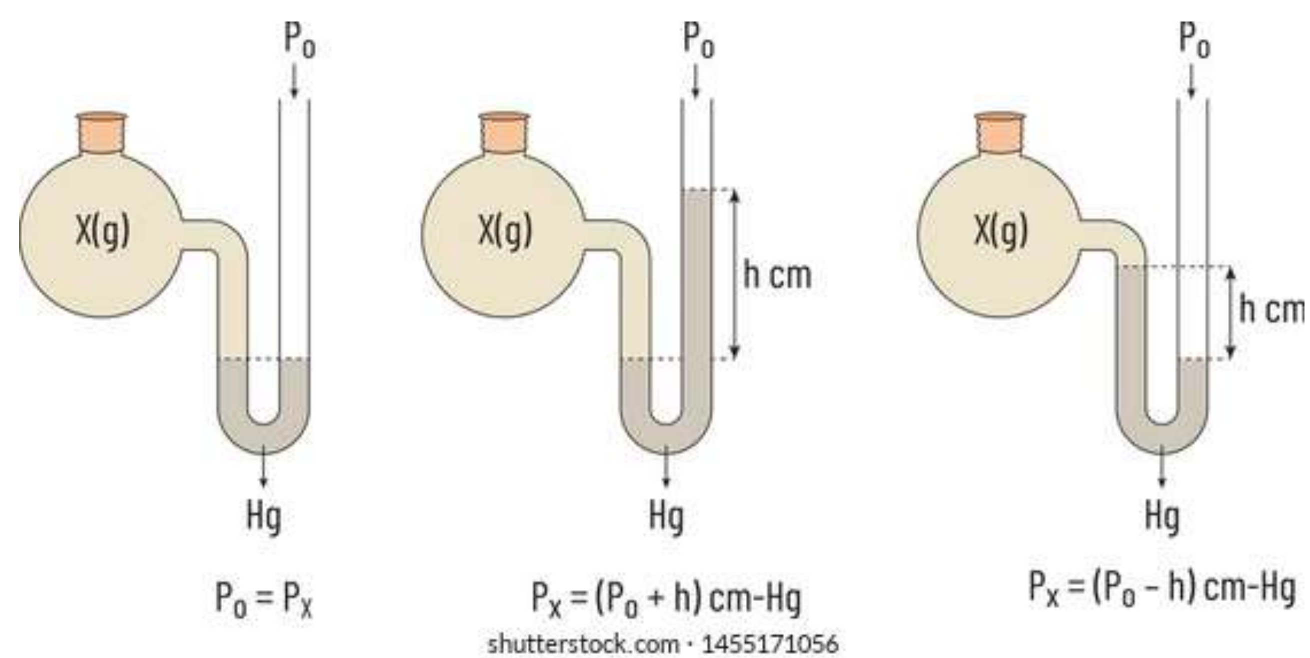
Pressure is commonly measured using devices called pressure gauges or pressure sensors. Here are some common methods for measuring pressure:

https://atlas-scientific.com/blog/types-of-pressure-sensors/

1. **Manometers**:

Manometers are simple devices that measure pressure by balancing the weight of a fluid in a vertical column against the pressure of the gas or liquid being measured.

Types of manometers include U-tube manometers, well-type manometers, and inclined-tube manometers.



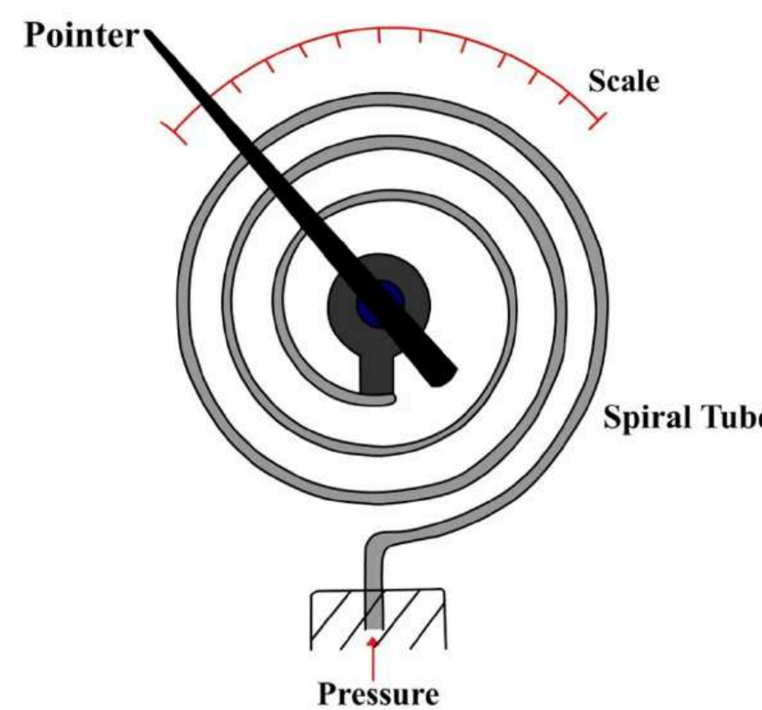
PRESSURE

Pressure sensors:

2. **Bourdon Tubes**:

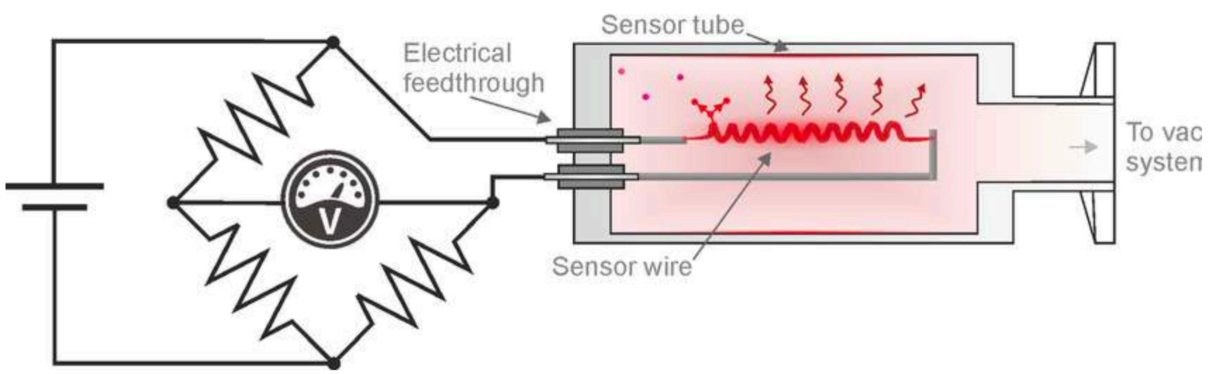
Bourdon tubes are curved tubes that straighten when pressurized. This mechanical deformation is then translated into a rotational movement, which can be used to indicate pressure on a dial.

Bourdon tube pressure gauges are widely used in various industrial applications.



3. **Vacuum sensors**:

When the pressure drops below atmospheric levels, mechanical pressure sensors that observe and measure the effects on the material are used. This is where vacuum pressure sensors come in. A Pirani sensor is the most common and well-known sensor used to measure low vacuum pressure ranges.



These types of pressure sensors measure the resistance of a heated sensor filament (thin tungsten, nickel, or platinum wire) inside the gauge chamber. As the gauge chamber becomes exposed to the surrounding vacuum pressure, gas molecules collide with the filament wire, and heat is transported from the sensor wire. The wire is connected to an electrical circuit.

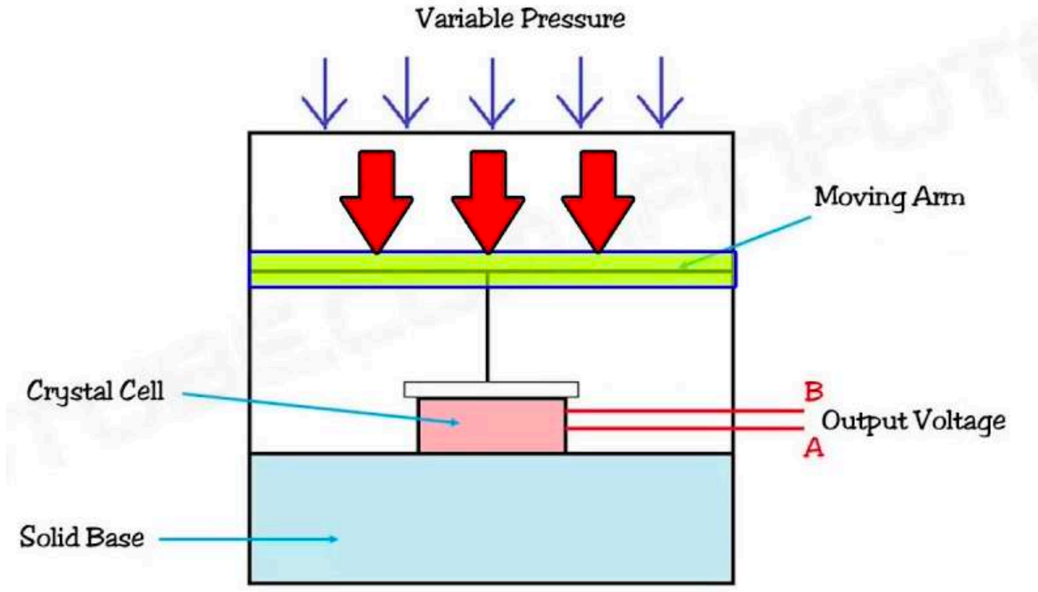
PRESSURE

Pressure sensors:

4. **Piezoelectric Sensors**:

Piezoelectric pressure sensors utilize the piezoelectric effect, where certain materials generate an electric charge in response to mechanical stress.

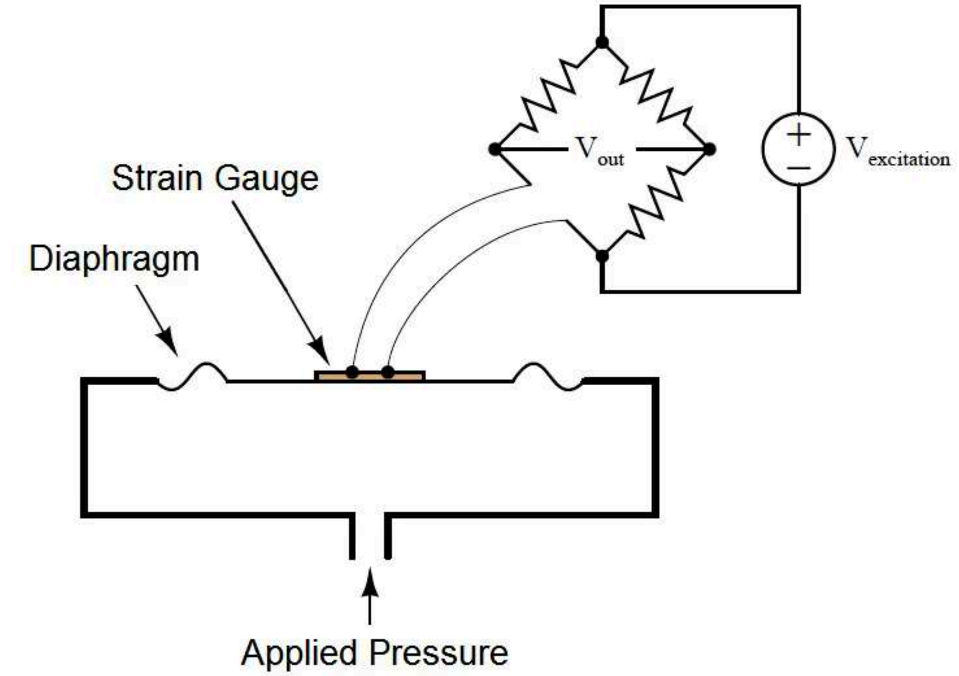
When pressure deforms the material, it generates a charge that can be measured and converted into a pressure reading.



5. **Strain Gauge Pressure Transducers**:

Strain gauges are devices that change resistance when subjected to mechanical strain. These are often attached to a flexible diaphragm. These gauges are often used for low-pressure measurements.

The change in resistance is proportional to the applied pressure, and this change is converted into an electrical signal for measurement.



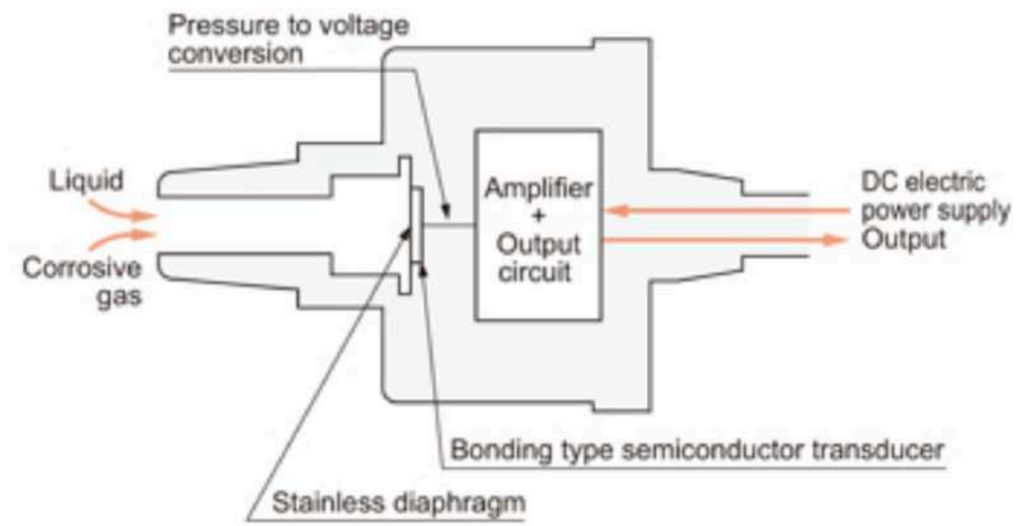
PRESSURE

Pressure sensors:

6. **Electronic Pressure Sensors**:

Modern electronic pressure sensors use various technologies, including capacitive, inductive, or resistive elements, to detect pressure changes.

These sensors provide accurate and often digital readings, making them suitable for a wide range of applications.



8. **Hydraulic Pressure Sensors**:

Hydraulic pressure sensors measure pressure by transmitting force through a liquid to a diaphragm or other sensing element.

The resulting displacement or change in pressure is then measured and converted into a pressure reading.

PRESSURE

Pressure sensors

The choice of a particular device depends on factors such as the range of pressures to be measured, the required accuracy, the environmental conditions and the application-specific requirements.

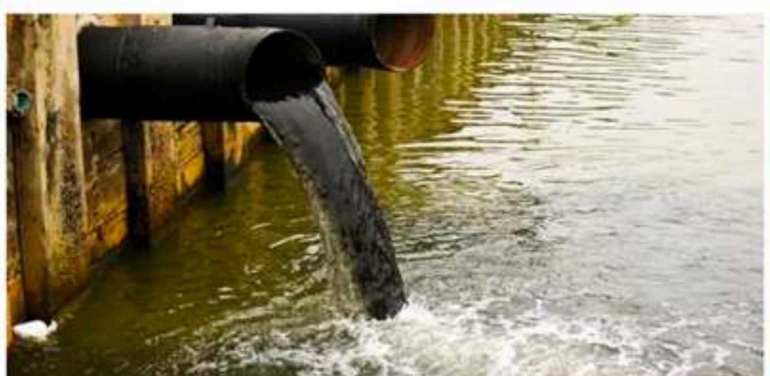
SENSING THE ENVIRONMENT

Sources

- Chemical pollutants

CHEMICAL POLLUTANTS

Chemical pollutants are substances released into the environment that can have harmful effects on ecosystems, human health, and other living organisms. These pollutants can originate from various sources, including industrial activities, agriculture, transportation, and improper waste disposal. The reasons for monitoring chemical pollutants are multifaceted and include environmental protection, public health, regulatory compliance, and scientific research.



CHEMICAL POLLUTANTS

Here are some common chemical pollutants

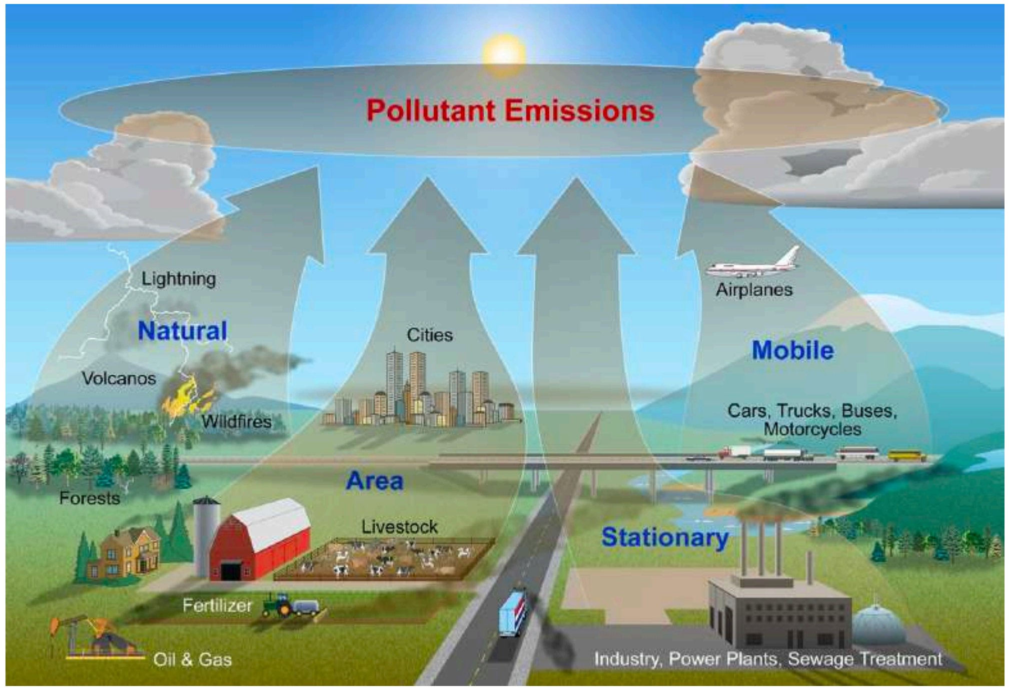
1. Air Pollutants:

   - Particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), and lead.

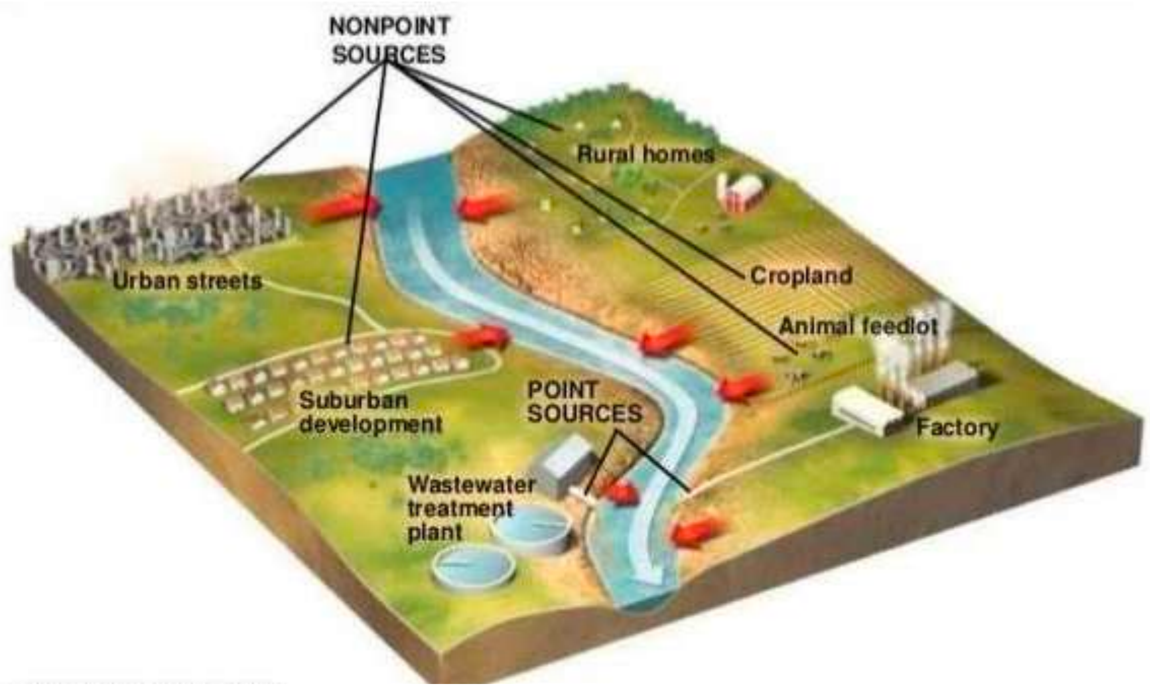
2. Water Pollutants:

   - Heavy Metals: Mercury, lead, cadmium, and arsenic are examples of heavy metals that can contaminate water.

   - Nutrients: Excessive levels of nutrients like nitrogen and phosphorus can lead to water pollution, causing issues such as algal blooms and oxygen depletion.



https://www.nps.gov/subjects/air/sources.htm



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CHEMICAL POLLUTANTS

3. Soil Pollutants:

- Pesticides and Herbicides: Agricultural chemicals can contaminate soil, affecting crop quality, harming beneficial organisms, and posing risks to human health.

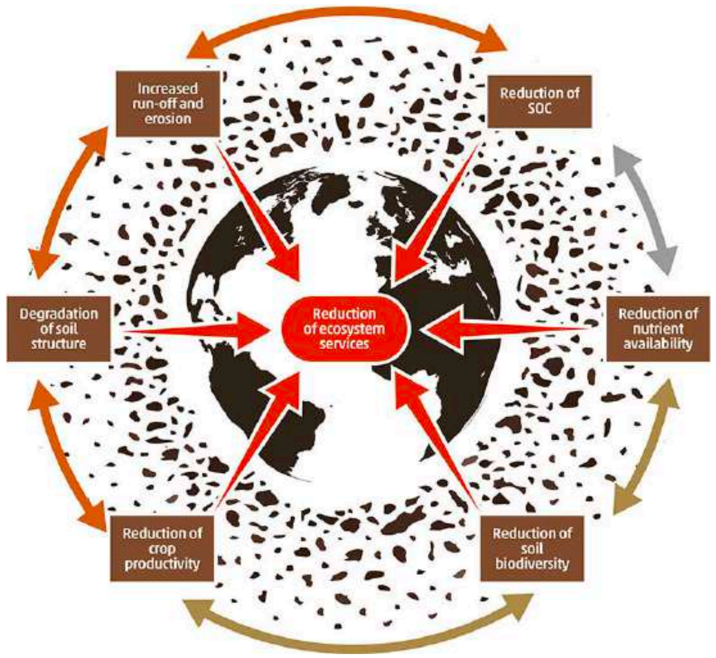
- Industrial Contaminants: Chemicals from industrial activities, such as heavy metals, solvents, and hydrocarbons, can contaminate soil.

4. Hazardous Waste:

- Persistent Organic Pollutants (POPs): Substances like polychlorinated biphenyls (PCBs), dioxins, and furans are toxic and resist degradation.

5. Indoor Air Pollutants:

- Volatile Organic Compounds (VOCs): VOCs emitted from indoor sources like paints, cleaning products, and building materials can impact indoor air quality.



https://www.fao.org/3/cb4894en/online/src/html/chapter-04-2.html

CHEMICAL POLLUTANTS

Reasons for Monitoring Chemical Pollutants:

1. **Human Health Protection**: Many chemical pollutants can have adverse effects on human health, causing respiratory problems, cancers, neurological issues, and other illnesses. Monitoring helps identify and mitigate risks to public health.

2. **Environmental Protection**: Chemical pollutants can harm ecosystems, biodiversity, and natural resources. Monitoring is essential to understand the impact on the environment, prevent ecological imbalances, and promote sustainable practices.

3. **Regulatory Compliance**: Monitoring ensures compliance with environmental regulations and standards set by governmental bodies. It helps industries and individuals adhere to limits on pollutant emissions and discharges.

4. **Early Detection and Prevention**: Monitoring allows for the early detection of pollution incidents, enabling prompt corrective actions. This helps prevent the escalation of environmental and health hazards.

5. **Scientific Research**: Monitoring chemical pollutants provides valuable data for scientific research on pollution trends, sources, and impacts. This information contributes to the development of effective environmental policies and practices.

CHEMICAL POLLUTANTS

The measurement of chemical pollutants involves various techniques and instruments to quantify the presence and concentration of harmful substances in air, water, soil, and other environmental media. Here's a brief summary of how we measure chemical pollutants:

1. Air Quality Monitoring:

   - Gas Chromatography (GC): GC is a widely used technique for analyzing volatile organic compounds (VOCs) in the air. It separates and identifies different chemical compounds based on their interaction with a chromatographic column.

   - Mass Spectrometry (MS): MS is often coupled with GC to enhance the identification and quantification of pollutants in air samples. It measures the mass-to-charge ratio of ions, providing detailed information about the chemical composition.

2. Water Quality Monitoring:

   - High-Performance Liquid Chromatography (HPLC): HPLC is commonly employed for the analysis of water samples, particularly for non-volatile and polar compounds. It separates and detects various pollutants, including pesticides, pharmaceuticals, and heavy metals.

   - Atomic Absorption Spectroscopy (AAS): AAS is used to measure the concentration of specific heavy metals in water, such as lead, mercury, and cadmium. It works by measuring the absorption of light at characteristic wavelengths.

CHEMICAL POLLUTANTS

3. Soil and Sediment Analysis:

- X-Ray Fluorescence (XRF): XRF is utilized to analyze the elemental composition of soil and sediment samples. It measures the characteristic X-rays emitted when a sample is irradiated with X-rays, providing information about the presence of various elements.

- Inductively Coupled Plasma Mass Spectrometry (ICP-MS): ICP-MS is a powerful technique for the analysis of trace elements in soils. It ionizes the sample in an inductively coupled plasma source and then measures the mass-to-charge ratio of the ions.

4. Biosensors:

- Enzyme-Linked Immunosorbent Assay (ELISA): ELISA is a biochemical method used to detect the presence of specific pollutants, such as pesticides and toxins, in environmental samples. It relies on the binding of antibodies to target substances.

- Biosensors: Biosensors use biological components, such as enzymes or microorganisms, to detect and quantify pollutants. They can be designed for specific contaminants and offer real-time monitoring capabilities.

5. Remote Sensing:

- Satellite and Drone-Based Imaging: Remote sensing technologies, including satellite and drone-based sensors, can provide spatial and temporal data on environmental conditions. These technologies are useful for monitoring large areas and identifying pollution sources.

CHEMICAL POLLUTANTS

Measurement of chemical pollutants

The mentioned methods and technologies are just a few examples of the diverse approaches used to measure chemical pollutants. The choice of method depends on the specific pollutants of interest, the environmental matrix being analyzed, and the required level of sensitivity and precision. Environmental monitoring programs often employ a combination of these techniques to comprehensively assess the quality of air, water, and soil.

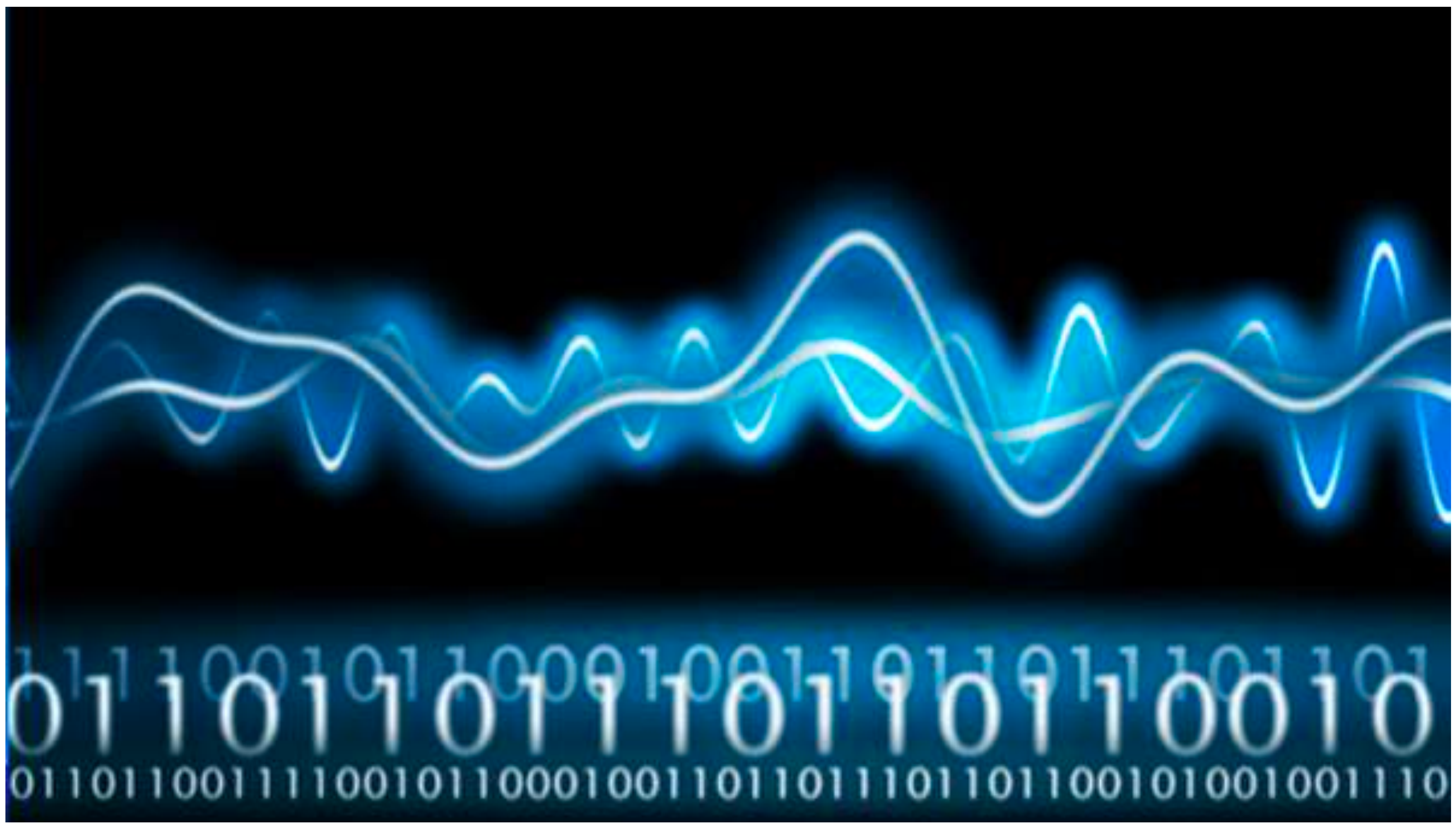
https://pubs.acs.org/doi/10.1021/acs.est.9b06379

SENSING THE ENVIRONMENT

Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

SENSORS AND SIGNAL PROCESSING



Will be covered in details in Lab.1

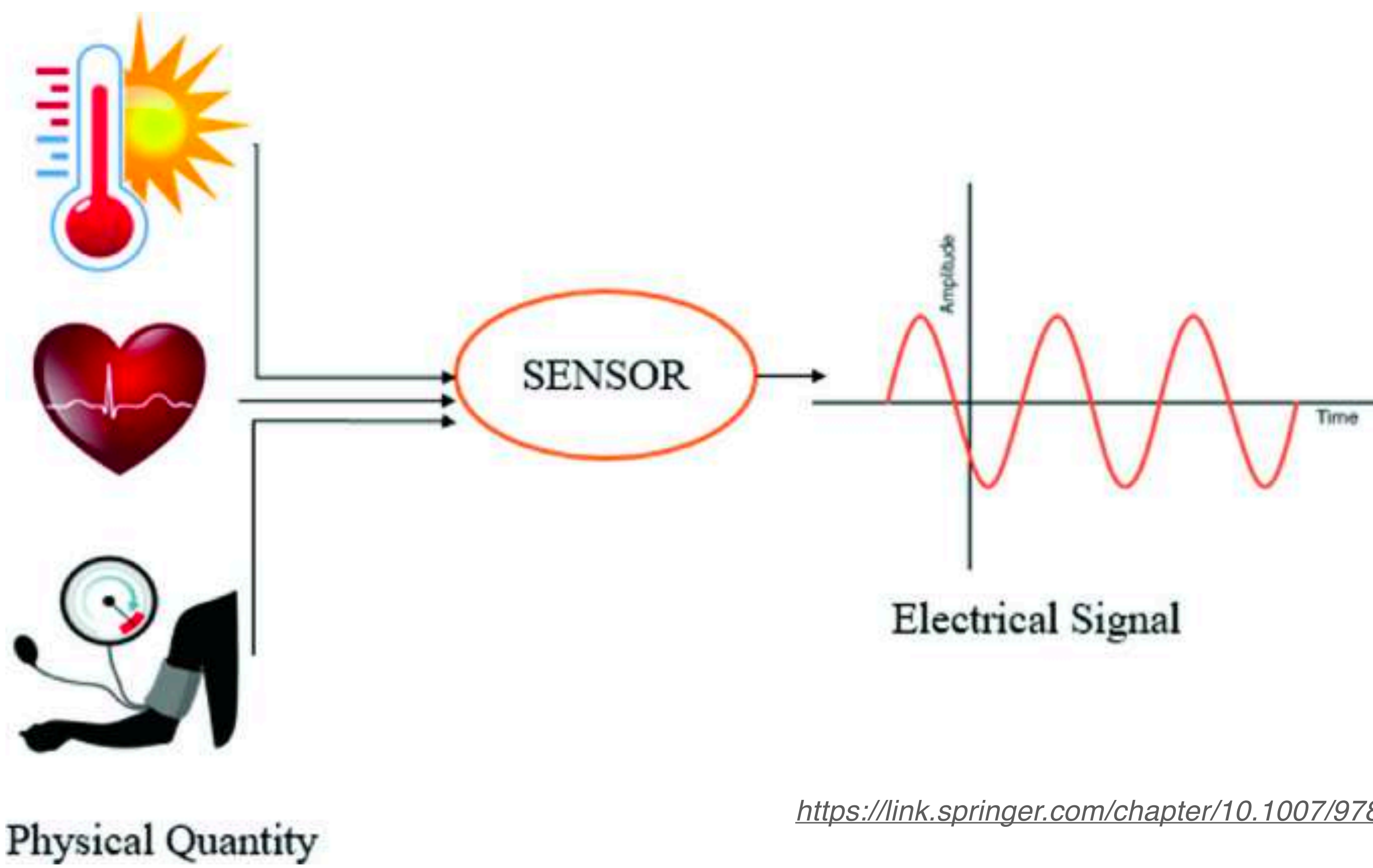
THE GENERAL PRINCIPLE OF A SENSOR

External source $\xrightarrow{\text{Probe}}$ Sensor $\rightarrow$ Output signal

Physical quantity: temperature, position, speed, pressure,…

Sensing the physics phenomena and converting that into an electrical form

Electrical (voltage/current) output

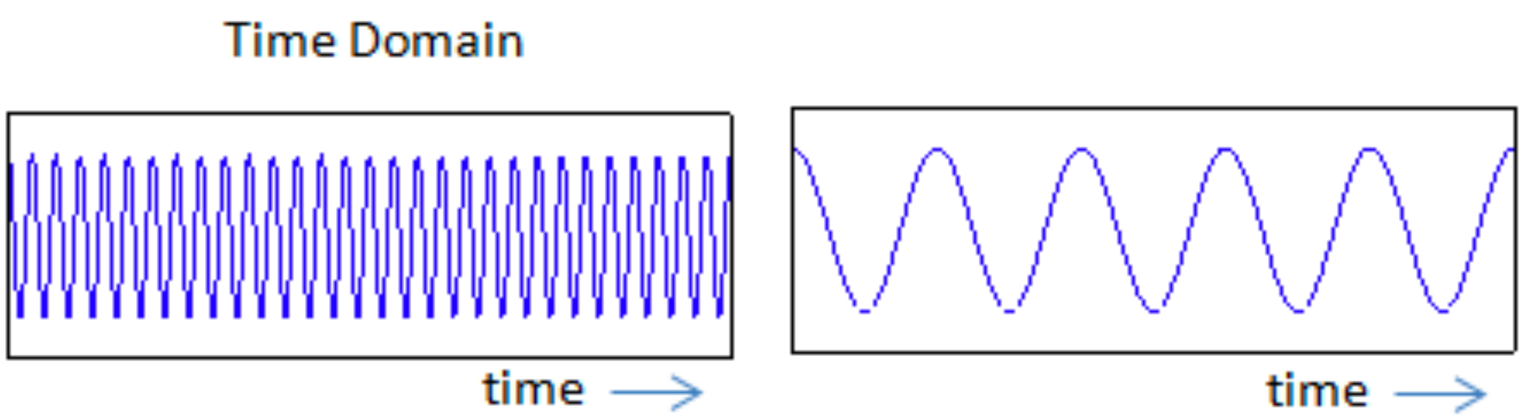


https://link.springer.com/chapter/10.1007/978-981-19-1408-9_17

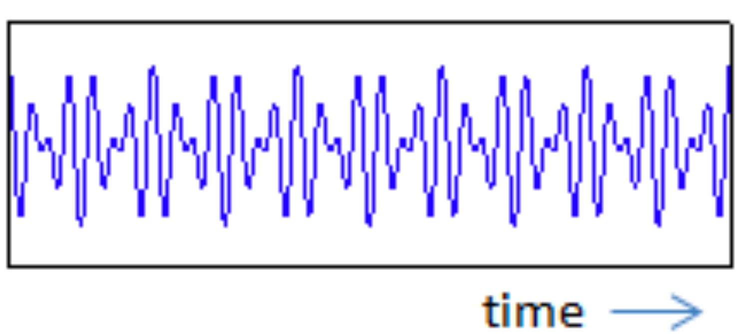
SIGNALS

Signals in the time domain

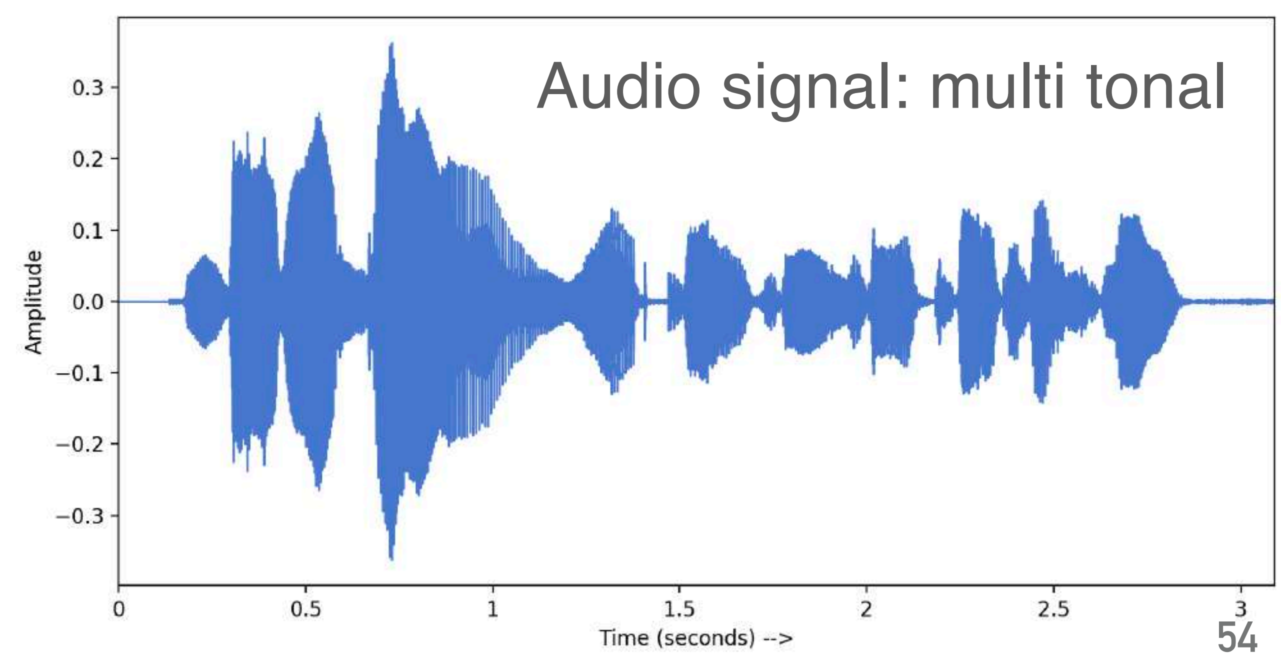
The time domain is simply the graph or plot of a signal f(t) as a function of time or other time variables. It provides information about the signal's properties and the changes it undergoes with respect to time.



Mono tonal signals



Bi-tonal signal



Audio signal: multi tonal

SIGNALS

From time to frequency

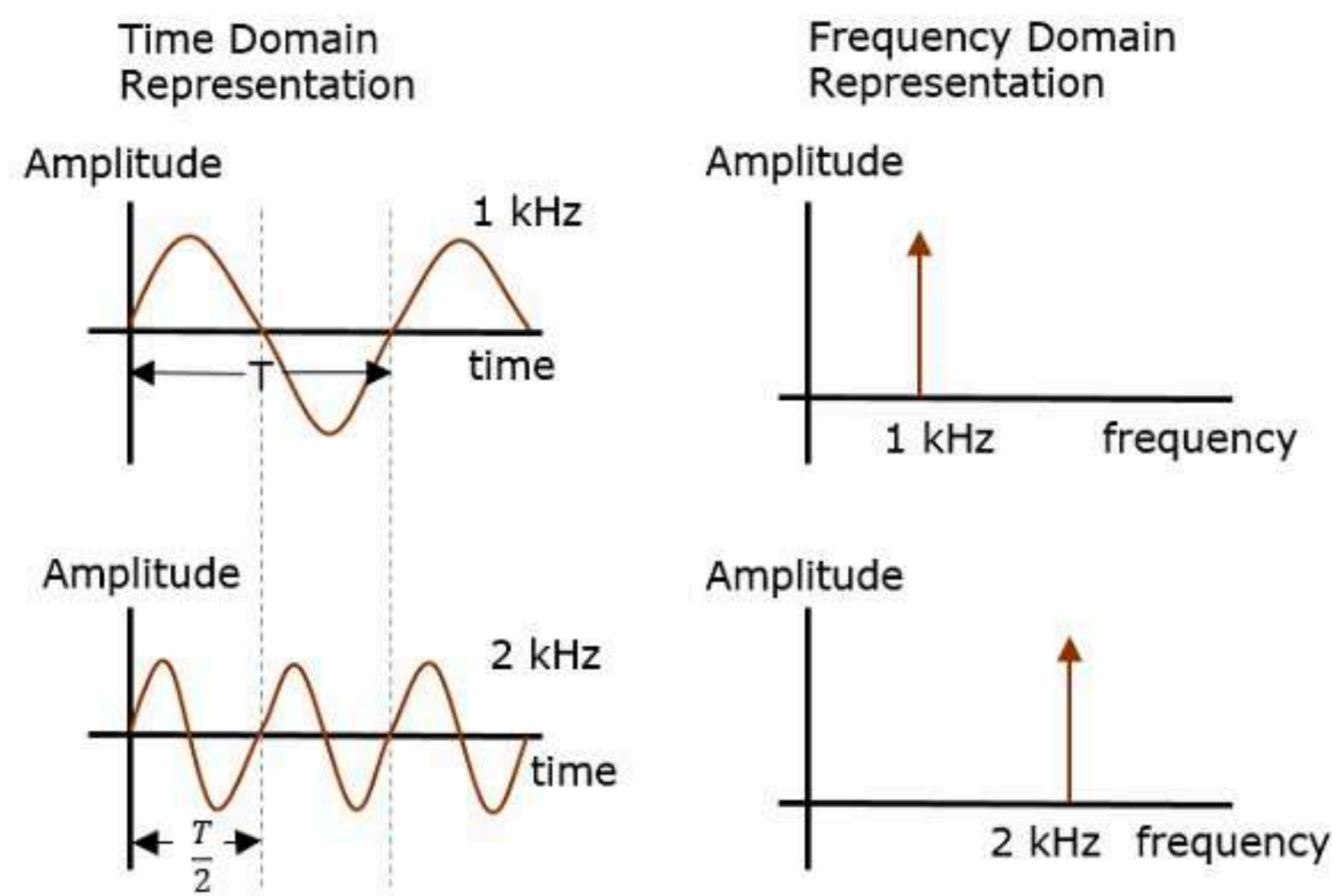
The frequency domain is a graphical representation of a signal's amplitude at different frequencies. It provides insight into the frequency content of a signal and the relative contribution of different frequency components to the overall signal.

T period

f frequency

$$f = \frac{1}{T}$$

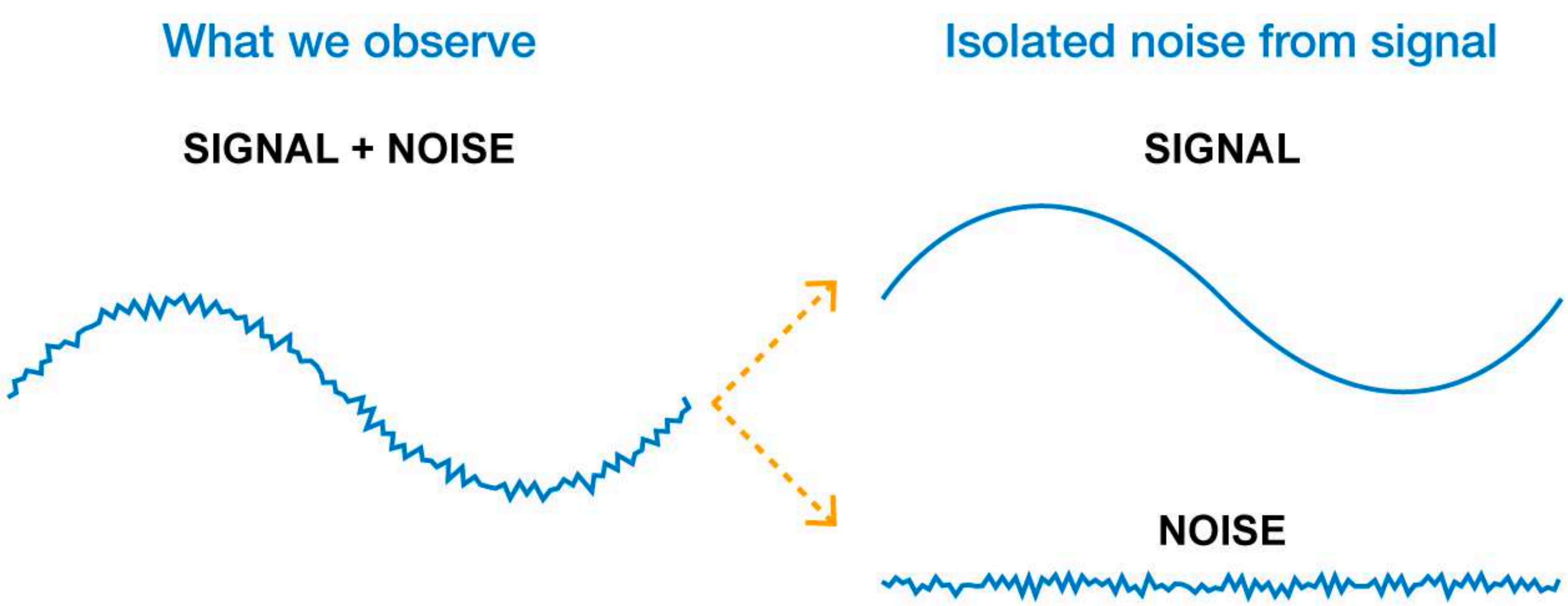
$$\omega = 2\pi f$$



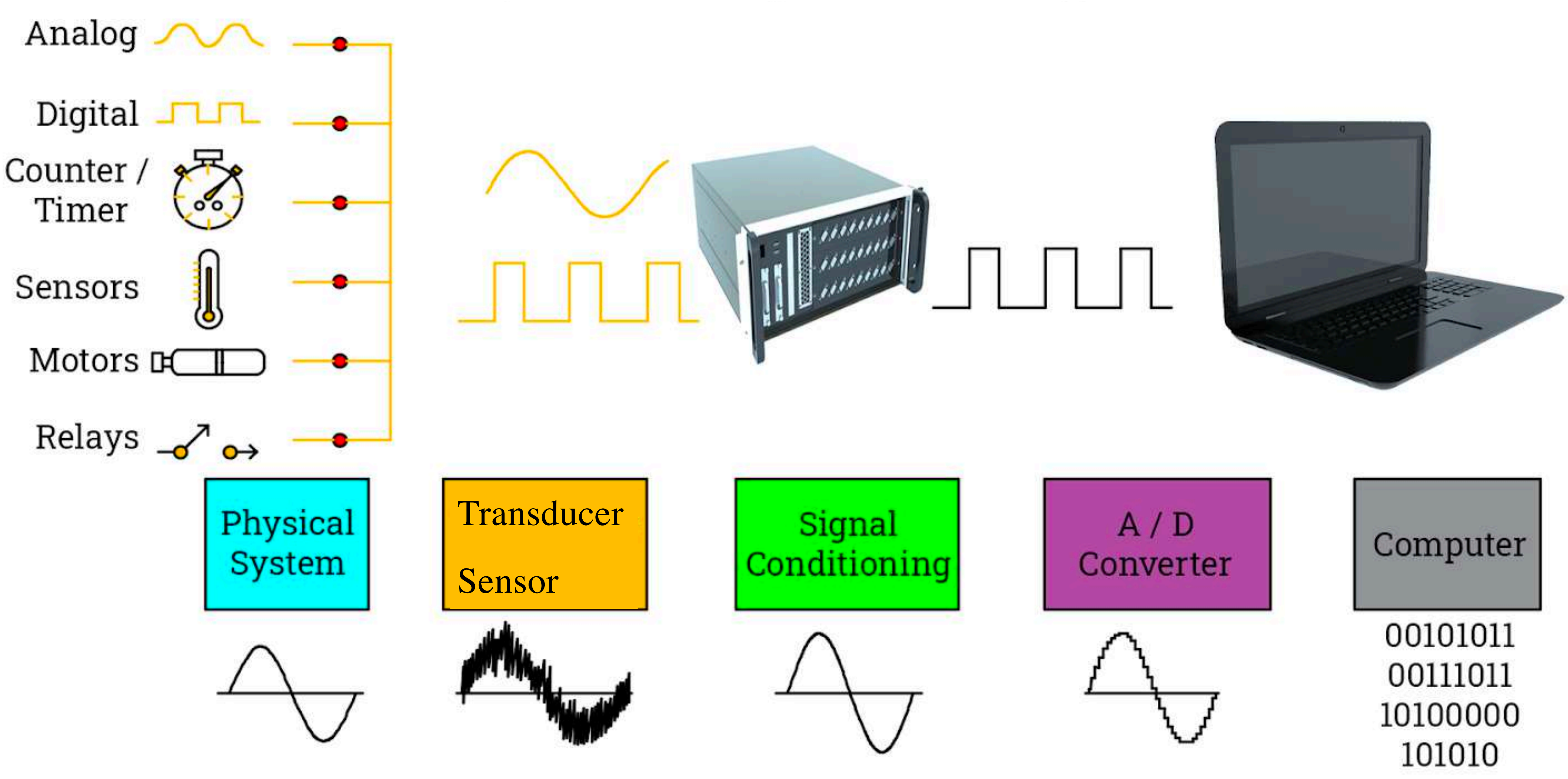
DIGITAL SIGNAL PROCESSING

A real analog signal: Spectral analysis - signal and noise

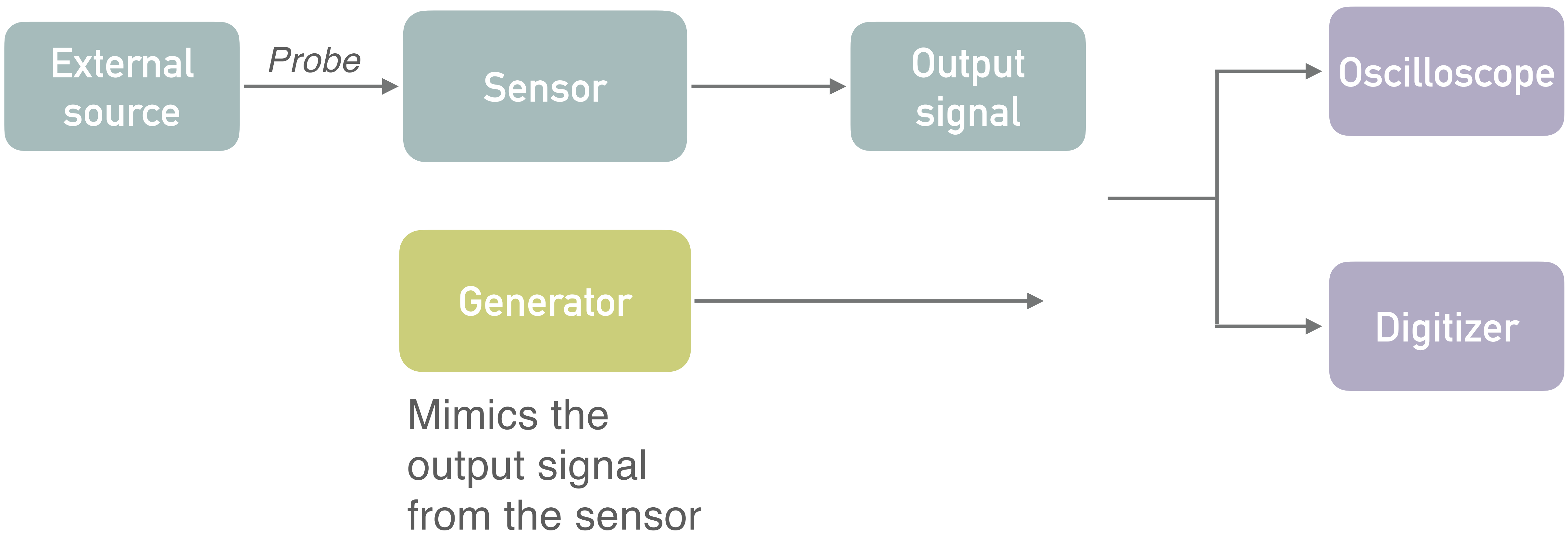
Noise in a signal refers to any unwanted or random interference or disturbance that affects the fidelity of the original signal. It can manifest as additional electrical fluctuations, disturbances, or variations in the signal that are not part of the intended information.



SENSOR DATA ACQUISITION CHAIN



EXAMPLE: A SENSOR READOUT CHAIN



- Generate a signal: the waveform generator
- Read the signal output (1): the oscilloscope
- Read the signal output (2): the digitiser

See Lab.1