Module-1: Fundamentals of Sensors

By

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Fundamentals of Sensors

Sensing and Sensor Fundamentals:

- Sensing Modalities
- Mechanical Sensors
- MEMS Sensors
- Optical Sensors
- Semiconductor Sensors
- Electrochemical Sensors
- Biosensors

Sensors Role

- Sensors play an integral role in numerous modern industrial applications such as
    - Food processing
    - Monitoring of activities such as
        - transport,
        - air quality,
        - medical therapeutics,
        - and many more.
- Modern sensors with integrated information and communications technology (ICT) capabilities—**smart sensors**.
- Advanced sensors has computational capabilities, storage, energy management, and a variety of form factors, connectivity options, and software development environments.
- Biosensors that are now found in a variety of consumer products, such as tests for diabetes, pregnancy, cholesterol, allergies, and fertility.

Sensors Role

- The development and rapid commercialization of low-cost microelectromechanical systems (MEMS) sensors, such as 3D accelerometers, has led to their integration into a diverse range of devices extending from cars to smartphones.
- Microelectromechanical system (MEMS), mechanical parts and electronic circuits combined to form miniature devices, typically on a semiconductor chip. Common applications for MEMS include sensors, actuators, and process-control units.
- Uses of the diverse range of low-cost sensors has increased the numbers of smart system applications.

Sensors

- Data from pervasive sensors promises to support new proactive healthcare paradigms with early detection of potential issues, for example, heart disease risk (elevated cholesterols levels), liver disease (elevated bilirubin levels in urine), anemia (ferritin levels in blood) and so forth.
  - Smartphone technology | Measuring Parkinson’s disease symptoms using sensors
  - https://www.youtube.com/watch?v=qAu9SyfQsQY&feature=emb_logo
- Sensors are increasingly used to monitor daily activities, such as exercise with instant access to our performance through smartphones. The relationship between our well-being and our ambient environment is undergoing significant change.
  - The wearable “smart headband” or “smart wristband” is made of flexible sensors and microprocessors that stick to the skin. It analyses chemicals in sweat, including levels of sodium, glucose, potassium, lactate, as well as skin temperature -- indicators of muscle fatigue, dehydration or dangerously high body temperature.
  - The data is relayed in real-time to a smartphone app.
  - https://www.youtube.com/watch?v=OzZBVOF8u-0&feature=emb_logo

Sensors Technology

- Sensor technologies now empower ordinary citizens with information about air and water quality and other environmental issues, such as noise pollution.
  - Portable Sensor that Tests Water Quality | The Henry Ford's Innovation Nation
  - https://www.youtube.com/watch?v=TBfBDPrnQ9U

- Sharing and socializing this data online supports the evolving concepts of citizen-led sensing. As people contribute their data online, crowdsourced maps of parameters such air quality over large geographical areas can be generated and shared.
  - How Google maps' traffic works? Can Google track you through GPS?
  - https://www.youtube.com/watch?v=CGb-Hro3nmQ

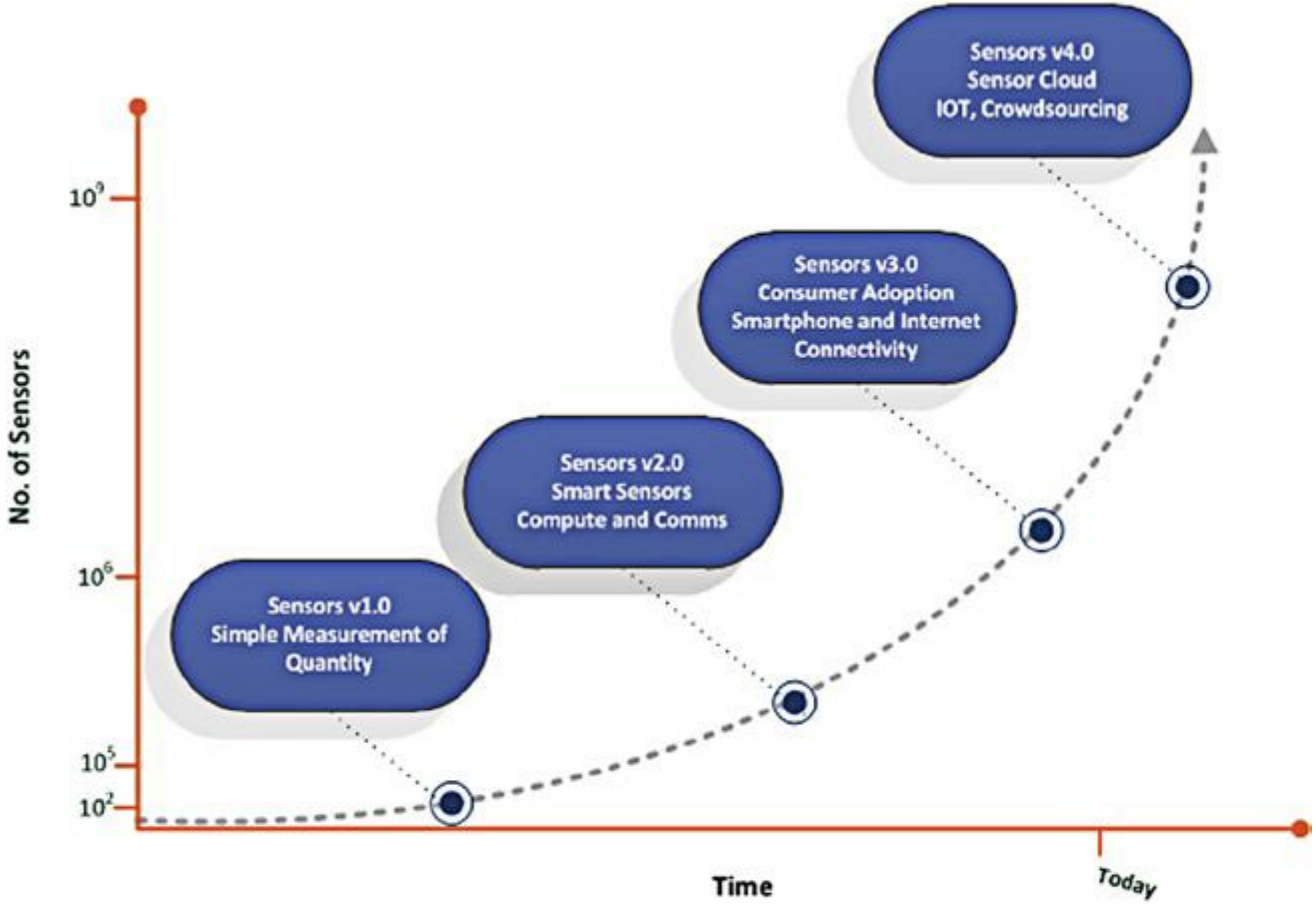
Sensor Technology

- Careful matching of the sensor and its operational characteristics to the use case of interest is critical.
- The data must be of the required accuracy with appropriate stability for the lifetime of the required application.
- Highly sensitive and accurate sensors are generally more expensive, however, and therefore the cost of the sensor should be weighed carefully against an application’s data quality requirement.
- Sensor technologies, particularly wireless sensor networks (WSNs) offer a wide variety of capabilities.

History of Sensors

- Thermostat in 1883 is considered by some to be the first modern sensor.
- Early sensors were simple devices, measuring a quantity of interest and producing some form of mechanical, electrical, or optical output signal.
- In just the last decade or so, computing, pervasive communications, connectivity to the Web, mobile smart devices, and cloud integration have added immensely to the capabilities of sensors, as shown in below figure.

History of Sensors



Sensors

- Sensing in the healthcare domain has been, until recently, restricted primarily to use in hospitals, with limited adoption outside this environment.
- Developments in both technology and care models(Bio sensing) are supporting adoption by patients, in-home care providers, public authorities, and individuals who want to proactively manage their health and wellness.
- The concept of biosensing was first proposed by Clarke and Lyons in 1962.
- Biosensors have rapidly evolved in the intervening years to the point where they are a multi-billion dollar industry.

Sensors

- The development of MEMS-based sensors led to the availability of small, accurate sensors at a price point that made it feasible to integrate them into a wide variety of devices ranging from sports watches to consumer electronics to cars.
- MEMS-based Accelerometer (ADXL50) was sold commercially by Analog Devices in 1992. This was followed in 1998 with MEMS-based gyroscopes from Bosch for commercial applications in the automotive sector.

Sensors

- Evolution of sensors has been strongly influenced by ICT technologies, with integration of microcontrollers, wireless communications modules, and permanent data storage.
- Continuous miniaturization of sensors and low-cost systems on chips (SOCs) will continue to fuel future development of the Internet of Things (IOT).
- Sensor technologies allow people to be better informed by empowering them with information about the quality of the environment and its influence on them.

Drivers for Sensor Applications

Health and Fitness

- Our diets have also changed significantly over the last century. With each passing decade, the consumption of processed foods and fast foods continues to rise globally, resulting in an increased intake of fat, salt, sweeteners, and simple sugars.
- A more significant driver for sensor technology utilization is the growing trend in fitness. People are becoming more aware of how lifestyle can affect their health, thanks especially to high visibility public health campaigns.
- Individuals are motivated by a desire to manage their weight and maintain a sufficient level of fitness for a healthy lifestyle.
- Insurance companies are also playing a role by offering premium discounts to individuals who adopt and maintain healthier lifestyles.

Drivers for Sensor Applications

Aging Demographics

- The UN estimates that, globally, life expectancy will increase from 68 years in 2005–2010 to 81 in 2095–2100
- Many countries, particularly Western ones, are suffering from an aging population.
- This demographic transition results in rising demands for health services and higher expenditures because older people are normally more vulnerable to health issues, including chronic diseases. This increased expenditure on public healthcare services is a growing concern for many governments.
- Sensors can monitor the key health indicators of a person directly or indirectly through ambient monitoring of daily patterns. In many respects, at-home healthcare is becoming part of the IOT.
- The near future will see small, wearable sensors that can monitor a person’s vital signs 24/7.

Drivers for Sensor Applications

Personalized Healthcare

- Economic health care focus on *proactive health care* rather than *reactive health care*.
- This model encompasses *prediction*, *diagnosing*, and *monitoring* using various data sources. A cornerstone of this shift is the development of personalized medicine.
- Next generation of drug therapies emerge that *target specific disease* pathways, it is important to know the *genetic profile* of a patient to see whether he or she will respond to a particular drug therapy.
- *Biosensors* are used to monitor particular protein cell that cause the decease.

Drivers for Sensor Applications

Public Health

- Healthcare spending is regularly near the top of the *political agenda* in most countries
- Public health policies are shifting away from *reactive models* of healthcare to *preventative* ones with a focus on wellness.
- Authorities see smarter healthcare as a means of maintaining quality while reducing *delivery costs*.
- Systems are supporting the delivery of in-home exercise programs to improve strength and balance in older adults as a *preventative measure* against health concerns such as falls.
- Companies are considering public health opportunities by strengthening their brand value and repositioning their products. Opportunities include activity monitoring, calorie-intake tracking, fitness evaluation through *vital-signs monitoring*, and so on.
- Shortage of nurse practitioners and physician assistants to deliver standardized protocols through the use of technology. *Sensors* will play a key role in such *clinical tools*, with intelligent software applications providing a layer of interpretation to support these practitioners.

Drivers for Sensor Applications

Technology Nexus

- Smart sensors capabilities have allowed sensors to participate in the larger technology ecosystem.
- We have now reached a technology nexus that is driving the rapid adoption of sensors technologies, this can be witnessed by smart phone users.
- Cloud-based technologies are providing ever-increasing data storage, processing, aggregation, visualization, and sharing capabilities.
- Social media gives us a mechanism to crowdsource (sensor) data, to share this data, and to derive information from the data among Internet communities.
- Clinicians now have access to tools that will allow them to move toward a model of patient care based on predictive, preventive, and personalized medicine.
- Sensing, social networking, smartphones, and connectivity will have a profound effect on medicine.

Drivers for Sensor Applications

Technology Nexus

- Rapid advancements made in sensor technologies over the last thirty years which are resulted in biosensors and MEMS-based sensors.
- Biosensors have been a key cornerstone in the development of the consumer sensor market, driven by their relative low cost and reasonable accuracy.
- As the cost of MEMs-based sensors continues to fall, they can be found with ever-greater frequency in consumer electronics.
- This has led to the rapid growth of health- and wellness-related applications based around these sensing capabilities.

Drivers for Sensor Applications

National Security

- The threat of terrorism remains a constant source of concern for government and security agencies
- Threats from terrorism have now evolved to include potential attacks from chemical, biological, radiological, and nuclear (CBRN) sources.
- Chemical threats involve the potential use of highly toxic industrial chemicals (for example, methyl isocyanate) or poisonous nerve agents (such as Sarin).
- Biological threats include the airborne release or introduction into water supplies of weaponized biological agents such as anthrax.
- Nuclear and radiological attacks pose a significant threat, particularly in urban areas. Large numbers of people could be exposed to radioactive contamination from so-called dirty bombs—non-fissile explosions of radioactive material released into the atmosphere.

Drivers for Sensor Applications

National Security

- Constant monitoring and vigilance is done by Laboratory agents but has geographical constrains which causes delay.
- Sensing capabilities that are available any time, any place to support the detection, identification, and quantification of CBRN hazards are a key requirement.
- Sensors are necessary to detect threats in air and water, and on land, personnel, equipment, or facilities. They are also required to detect these threats in their various physical states, whether solid, liquid, or gas.
- Sensing technologies has to improve the sensitivity and flexibility of detection in chemical and biological domains.

Drivers for Sensor Applications

The Internet of Things

- Pervasive connectivity and advances in ICT technologies have made possible the connection of more and more devices to the Internet.
- IoT applications that have the potential to dramatically improve the way people live, learn, work, and entertain themselves.
- Sensors play a key role in connecting the physical world (temperature, $C0_2$, light, noise, moisture) with the digital world of IoT.
- Sensors are likely to play a central role in providing the data streams upon which these applications can be built. For example, mobile and home-based environmental monitors allow people to track ambient air quality.

Drivers for Sensor Applications

Water and Food

- Terms such as water scarcity, water stress, water shortage, water deficits, and water crisis have now entered public consciousness in many parts of the world.
- Increased population changes will further increase pressure on dwindling water resources in many areas.
- Water management is extremely poor in most parts of the world. The development of smart water grids with integrated sensing capabilities is gaining prominence among utilities and government organizations.
- Sensors will provide detection of leakages, as well as the identification of water quality issues such as treatment problems or pollution.
- Sensors have the potential to help improve the sustainability of water resources through better management and protection.

Drivers for Sensor Applications

Water and Food

- In the agricultural domain, water use is enormously inefficient, particularly with respect to irrigation practices
- The use of sensors to provide soil moisture measurements, combined with ambient environmental monitoring and crop-specific parameter monitoring, will enable intelligent crop irrigation. This will help to reduce water consumption while maintaining or improving crop yields.
- Sensor technologies to test the quality of their drinking water and food will become a growing trend. People are becoming more aware of the types and sources of their food.
- https://www.youtube.com/watch?v=MLsHrBNvdqs

Drivers for Sensor Applications

Environmental Challenges

- The effects of poor water and air quality, pathogens in the food supply, and noise and light pollution will continue to have significant health impacts.
- Increased urbanization, growing use of motor vehicles and other forms of transport, increased waste production (human, animal, and industrial), and other factors will increase pressure on our natural environment.
- Smog clouds, common in many large cities, can have a dramatic effect on people suffering from respiratory issues, such as chronic obstructive pulmonary disease (COPD) and asthma.
- People are now turning to sensor technologies to better understand the relationship between parameters such as air quality and their health.

Drivers for Sensor Applications

Environmental Challenges

- Institutional environmental monitoring, particularly of air quality, does provide us with insight into the quality of the environment.
- Commercial sensor technologies now starting to emerge that empower people to track the air quality of their home environments and other areas they frequent.
- Other sensor-based applications are emerging that can be used to identify and track areas of high pollen and dust that affect people suffering from asthma and other respiratory conditions.
- Sensors for Air Quality Measurements
- https://www.youtube.com/watch?v=yx5JS1cVh6g&feature=emb_logo

Challenges for Sensor Applications

- It is important to disaggregate sensors into their respective architectures: standalone, body-worn wireless networks and more general wireless sensor networks. Sensor data quality is a universal requirement.
- With standalone sensors, ensuring the measurement of a representative sample can be challenging.
- Inexpensive sensors can increase affordability and access to data, this may come at the cost of data quality.
- The deployment of WSNs at scale (thousands of nodes) is a challenge that has not yet been addressed properly.

Example

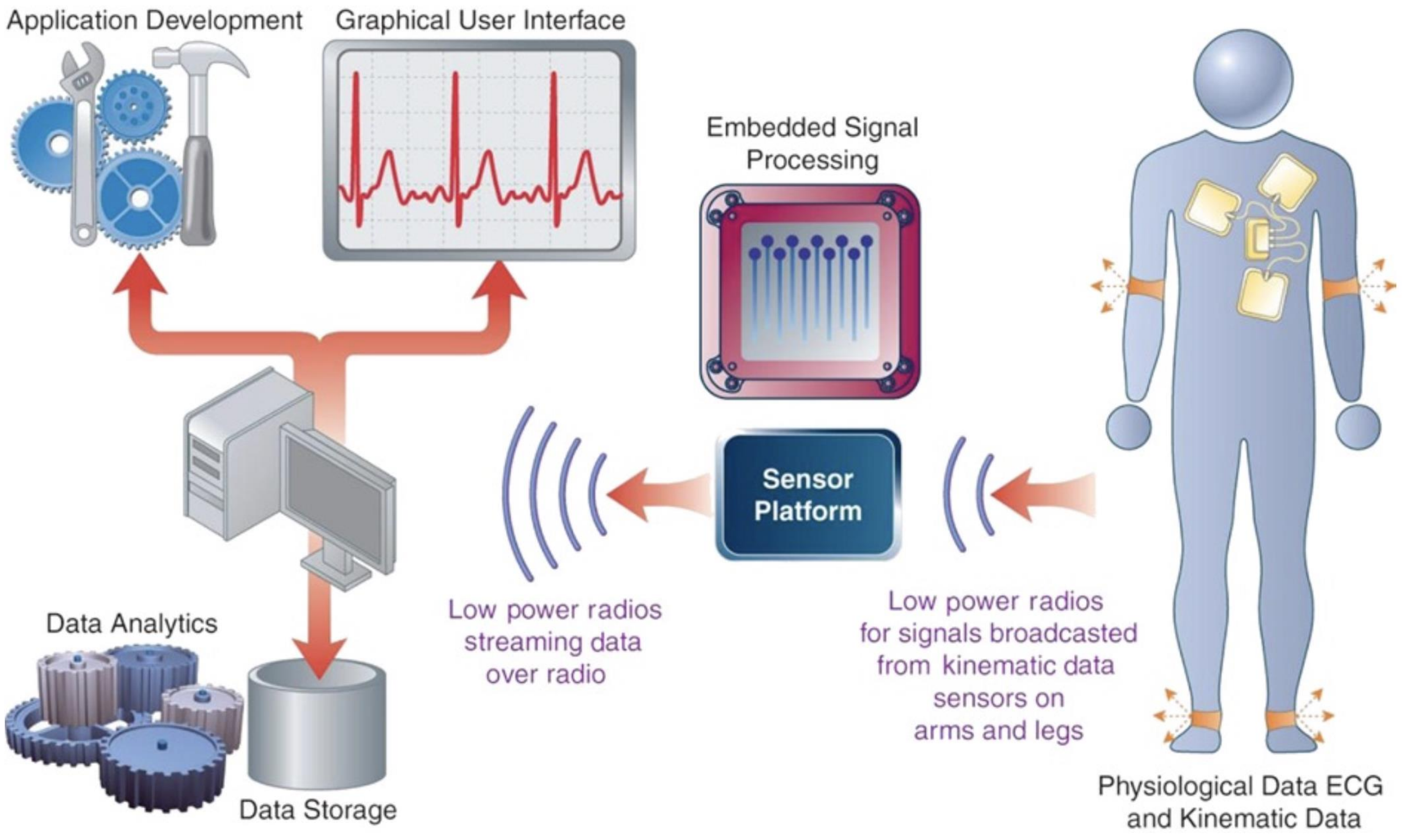


Figure 1-2. *A smart health scenario using body-worn sensors*

Sensor Definition

What Is a Sensor and What Is Sensing?

There are no uniform descriptions of sensors or the process of sensing. In many cases, the definitions available are driven by application perspectives. Taking a general perspective, a sensor can be defined as:

> *A device that receives a stimulus and responds with an electrical signal.*
>
> (Fraden, 2010)

Sensor definitions from a scientific or biomedical engineering perspective broaden the potential types of output signals to include, for example, an optical signal:

> *A device that responds to a physical input of interest with a recordable, functionally related output that is usually electrical or optical.*
>
> (Jones, 2010)

Another common variation, which takes into account the observational element of the measurement, describes a sensor as follows:

> *A sensor generally refers to a device that converts a physical measure into a signal that is read by an observer or by an instrument.*
>
> (Chen, et al., 2012)

Sensor

- Sensors can be used to measure or detect a vast variety of physical, chemical, and biological quantities, including proteins, bacteria, chemicals, gases, light intensity, motion, position, sound and many others.

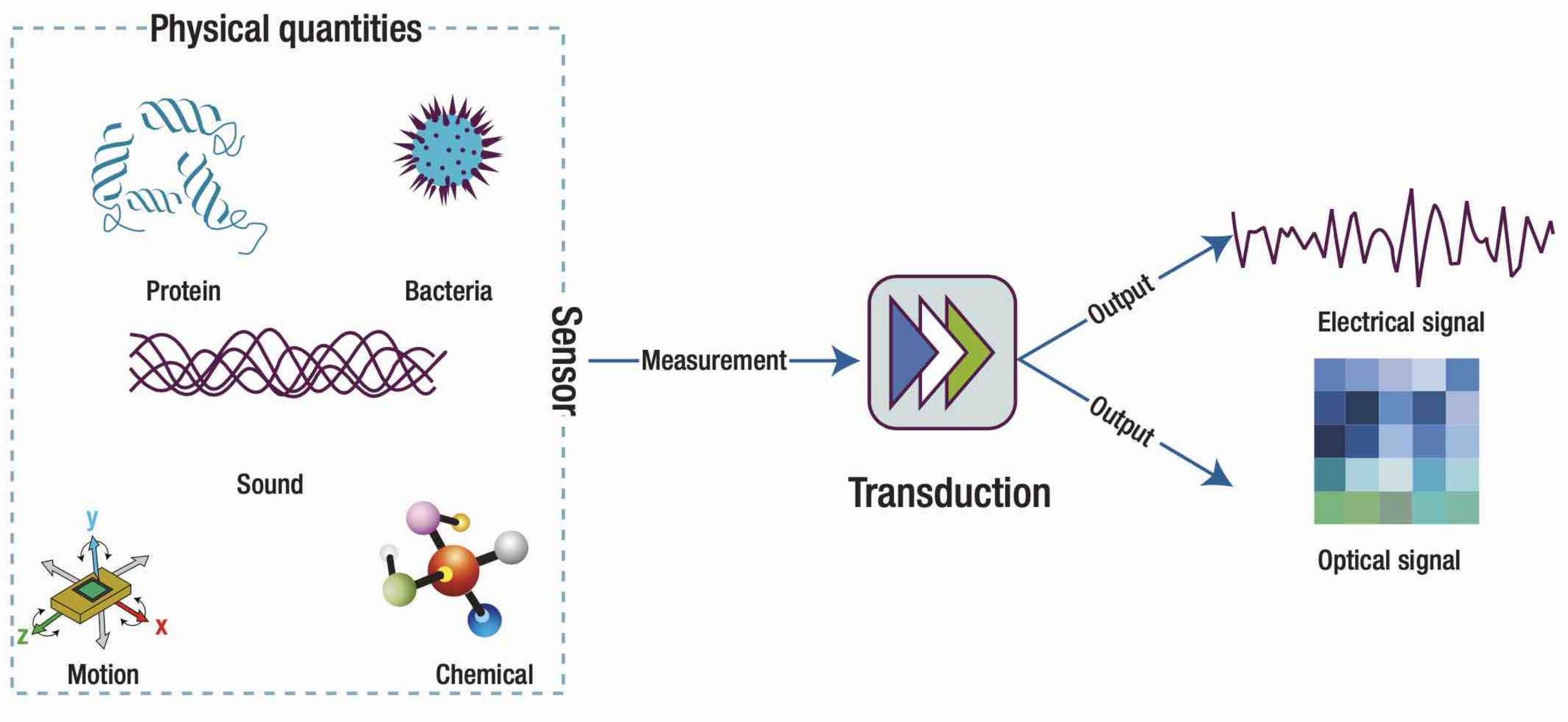


Figure 2-1. The sensing process

Three ways of sensor measurement

- Sensors can be used to measure quantities of interest in three ways:
  - Contact: This approach requires physical contact with the quantity of interest. Ex: ECG,EMG,EEG
  - Noncontact: This form of sensing does not require direct contact with the quantity of interest. Ex: Infrared
  - Sample removal: This approach involves an invasive collection of a representative sample by a human or automated sampling system. Ex: laboratory-based analytical instrumentation.

Types of sensors

- Mechanical
- Optical
- Semiconductor
- Electrochemical Sensors
- Biosensors

Mechanical Sensor

- Mechanical sensors are based on the principle of measuring changes in a device or material as the result of an input that causes the mechanical deformation of that device or material (Fink, 2012).
- Inputs, such as such motion, velocity, acceleration, and displacement that result in mechanical deformation that can be measured.
- When this input is converted directly into an electrical output, the sensor is described as being electromechanical.

Mechanical Sensor

Table 2-1. Common Mechanical and Electromechanical Sensors

Sensor	Type	Sensor	Type
Strain Gauge	Metallic Thin film Thick film Foil Bulk Resistance	Displacement	Resistive Capacitive Inductive
Pressure	Piezoelectric Strain gauge Potentiometric Inductive Capacitive	Force	Hydraulic load cell Pneumatic load cell Magneto-elastic Piezoelectric Plastic deformation
Accelerometer	Piezoelectric Piezoresistive Capacitive MEMS Quantum tunneling Hall effect	Acoustic Wave	Bulk Surface
Gyroscope	Vibrating structure Dynamically tuned MEMS London moment	Ultrasonic	Piezoelectric Magnetostrictive
Potentiometer	String Linear taper Linear slider Logarithmic Membrane	Flow	Gas Fluid Controller

Mechanical Sensor

- Strain gauge is key sensing elements in pressure sensors, load cells, torque sensors, and position sensors.
- Working of strain gauge sensor https://www.youtube.com/watch?v=FWRiSIqF3f8
- A key problem with strain measurements is that of thermal effects. Changes in temperature cause expansion or contraction of the sensing element, resulting in thermally induced strain. Temperature compensation is required to address the problem and this can be built into the Wheatstone bridge.

Mechanical Sensor

Accelerometers

- There are five modes of motion sensing: acceleration, vibration (periodic acceleration), shock (instantaneous acceleration), tilt (static acceleration), and rotation. All of these, except rotation, can be measured using accelerometers.
- It is unsurprising, therefore, that accelerometers have a wide range of applications, from triggering a hard disk protection system as a device is falling, to gesture recognition for gaming.
- Capacitive accelerometers are composed of fixed plates attached to a substrate and moveable plates attached to the frame. Displacement of the frame, due to acceleration, changes the differential capacitance, which is measured by the on-board circuitry. Capacitive accelerometers offer high sensitivities and are utilized for low-amplitude, low-frequency devices.
- Working of Capacitive accelerometers https://www.youtube.com/watch?v=T_iXLNkkjFo
- Working of Piezoresistive accelerometers https://www.youtube.com/watch?v=GNQJaB7YZB8

Mechanical Sensor

Gyroscopes

- MEMS gyroscopes measure the angular rate of rotation of one or more axes.
- Working of gyroscope https://www.youtube.com/watch?v=ti4HEgd4Fgo

Optical Sensors

- Optical sensors work by detecting waves or photons of light, including light in the visible, infrared, and ultraviolet (UV) spectral regions.
- They operate by measuring a change in light intensity related to light emission or absorption by a quantity of interest. They can also measure phase changes occurring in light beams due to interaction or interference effects.
- Measuring the absence or interruption of a light source is another common approach. Ex: automated doors and gates, measuring liquids and material levels in tanks.

Optical Sensors: Photodetectors

- Photodetector sensors are based on the principle of photoconductivity, where the target material changes its conductivity in the presence or absence of light.
- Active pixel sensors, Charged-coupled devices (CCD), Light-dependent resistors (LDRs), Photodiodes, Phototransistors, Photomultipliers are found in smartphone cameras, digital cameras, street lighting systems, room lighting-level control systems, healthcare equipment like flow cytometers (blood flow analysis) respectively.
- Infrared (IR) comes in two form

  i) active sensor

  ii)Passive sensor

Optical Sensors: Infrared (IR)

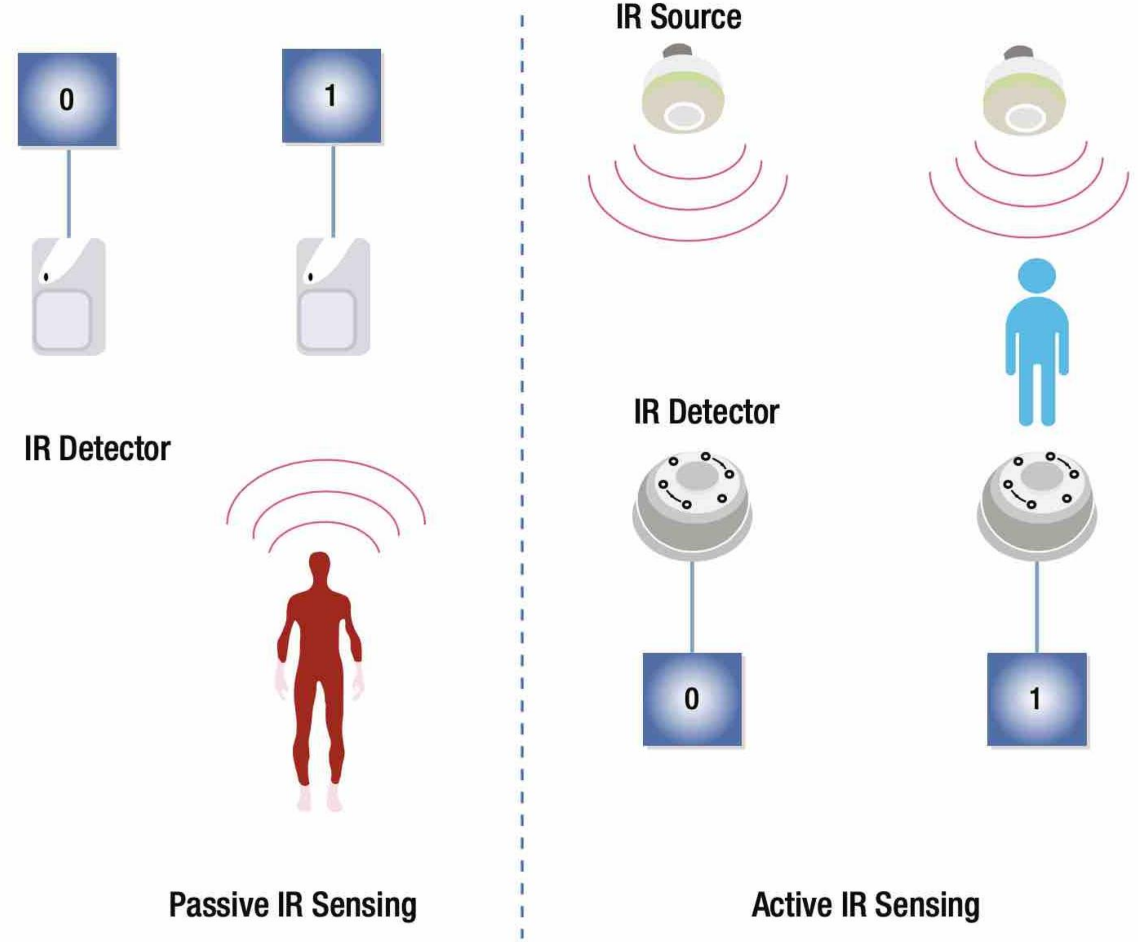


Figure 2-4. *Passive and active infrared sensing modes*

Optical Sensors: Fiber Optic

- Optical sensor uses an optical glass fiber as the sensing element. Optical fibers can be coated with materials that respond to changes in strain, temperature, or humidity.
  i. **Strain sensing:** Mechanical strain in the fiber changes the geometric properties of the fiber, which changes the refraction of the light passing through it. These changes can be correlated to the applied strain.
  ii. **Temperature sensing:** Strain in the fiber is caused by thermal expansion or contraction of the fiber. A strain measurement can be correlated directly with changes in temperature.
  iii. **Pressure sensing:** Fiber-optic pressure sensors can be of two types—intensity and interferometric. In intensity-sensing fiber-optic sensors, the magnitude of light intensity reflected from a thin diaphragm changes with applied pressure. Interferometric pressure sensors work on the principle that pressure changes introduce perturbations into the sensor, which generate path-length changes in a fiber. This in turn causes the light/dark bands of an interference pattern to shift. By measuring the shift of the wavelength spectrum, the pressure applied on it can be quantitatively obtained (Lee, et al., 2012).

Optical Sensors: Fiber Optic

iv) Humidity sensing: A broad range of principles have been applied to optical fiber-based humidity sensors, including (i) luminescent systems with fluorescent dyes that are humidity-sensitive (ii) refractive index changes due to absorption in a hygroscopic (moisture absorbing) fiber coating such as polyimide; and (iii) reflective thin film-coated fibers made from tin dioxide (SiO_2) and titanium dioxide (TiO_2), which change the refractive index, resulting in a shift in resonance frequency (Morendo-Bondi, et al., 2004).

https://www.youtube.com/watch?v=ZKsInPJ7ilk

https://www.youtube.com/watch?v=gi1KDEvs8c4

Optical Sensors: Interferometers

- An interferometer is a device used to measure changes in a propagating light beam, such as path length or wavelength along the path of propagation. Generally, the sensor uses a light source such as a laser LED and two single fibers.
- The light is split and coupled into both of the fibers. The quantity being measured modulates the phase of the optical signal, which can be detected by comparison with a reference optical signal.
- Different interferometric configuration can measure physical quantities, such as temperature, velocity, vibration, pressure, and displacement.

Advantages and disadvantages of optical sensors

***Table 2-2.** Advantages and Disadvantages of Optical Sensors*

Advantages	Disadvantages
High sensitivity	Susceptible to interference from environmental effects
Chemically inert	Can be costly
Small and lightweight	Susceptible to physical damage
Suitable for remote sensing	
Immunity to electromagnetic interference	
Wide dynamic range	
Capable of monitoring a wide range of chemical and physical parameters	
Reliable operation	

Semiconductor Sensors

- Semiconductor sensors have grown in popularity due to their low cost, reliability, low power consumption, long operational lifespan, and small form factor. They can be found in a wide range applications including:
  - Gas monitoring
  - Pollution monitoring, for example CO, NO2, SO2, and O3
  - Breath analyzers, for breath-alcohol content (BAC) measurements
  - Domestic gas monitoring, such as propane
  - Temperature, as in integrated electronic equipment
  - Magnetism, for example, magnetometers for six degrees of freedom applications
  - Optical sensing, such as in charge-coupled device detectors in cameras

Semiconductor Sensors : Gas sensors

- Semiconductor sensors are commonly used to detect hydrogen, oxygen (O2), alcohol, and harmful gases, such as carbon monoxide (CO).
- Working of MOS gas sensors
- https://www.youtube.com/watch?v=usEe3spV5vI
- Despite many advantages, including low cost, relatively low maintenance, and long operational lifespan, semiconductor gas sensors can lack specificity in mixed gas environments.
- Thus, gases that are not of interest contribute to the overall signal response, resulting in an inaccurate elevated reading or false positives.
- To increase the selectivity of the gas sensors, chemical filters can be placed before the sensing material to remove the interfering components in the sample.
- https://www.youtube.com/watch?v=yjQyJjiatl0

Semiconductor sensor: Temperature

- Semiconductor temperature sensors are based on the change of voltage across a p-n junction, which exhibits strong thermal dependence.
- https://www.youtube.com/watch?v=w3Hfj2kMrGo
- For accurate readings, the sensor needs to be calibrated properly.

Semiconductor Sensor: Magnetic Sensors

- Semiconductor magnetic sensors detect changes or disturbances in magnetic fields and convert these changes into a measurable electrical signal.
- They can produce information on properties, such as directional movement, position, rotation, angle, or electrical currents in machines or devices.
- They are used in medical devices such as ventilators , to control the extent of movement, opening and shutting of a device; and in renewable-energy scenarios, such as solar installations.
- For example, in domestic solar installations, magnetic sensors are used in power invertors that convert the electricity generated by the solar panels into usable electrical current for the home.
- https://www.youtube.com/watch?v=5HDCpyk7_IU

Semiconductor Sensor: Magnetic Sensors

- Hall-effect sensors comprise a thin layer of p-type (or n-type) semiconductor material that carries a continuous current.
- https://www.youtube.com/watch?v=Sr680_wwXlM
- Hall-effect sensors demonstrate good environmental immunity to problems such as dust, vibration, and moisture.

Magnetic Sensor : Optical Sensors

- There are a variety of optical semiconductor sensors, the most common of which is the photodiode, a type of photodetector that converts light into either current or voltage.
- Photodiodes normally have a window or optical fiber connection to allow light to reach a p-n or a PIN junction.
- Working of photodiodes https://www.youtube.com/watch?v=8k9UIlwo7W4
- Photodiodes are used in a variety of applications, including pulse oximeters, blood particle analyzers, nuclear radiation detectors, and smoke detectors.
- Another form of photodetector is the phototransistor and Light-dependent resistor (LDR).
- https://www.youtube.com/watch?v=ilN8XIK77dc

Magnetic Sensor: Ion-Sensitive Field-Effect Transistors (ISFETs)

- ISFETs are used for measuring ion concentrations in solution, such as H+ in pH measurements.
- pH sensor working https://www.youtube.com/watch?v=P1wRXTl2L3I

Electrochemical Sensors

- An electrochemical sensor is composed of a sensing or working electrode, a reference electrode, and, in many cases, a counter electrode.
- These electrodes are typically placed in contact with either a liquid or a solid electrolyte. In the low-temperature range (<140° C), electrochemical sensors are used to monitor pH, conductivity, dissolved ions, and dissolved gases.
- Electrochemical sensors present a number of advantages, including low power consumption, high sensitivity, good accuracy, and resistance to surface-poisoning effects.
- However, their sensitivity, selectivity, and stability are highly influenced by environmental conditions, particularly temperature.

Electrochemical Sensors

- Potentiometric Sensors: This type of sensor measures differences in potential (voltage) between the working electrode and a reference electrode.
- Amperometric Sensors: This form of electrochemical sensor measures changes in current. The potential of the working electrode is maintained at a fixed value (relative to a reference electrode) and the current is measured on a time basis.
- Coulometric: Coulometric sensors measure the quantity of electricity in coulombs as a result of an electrochemical reaction. This is achieved by holding a working electrode at a constant potential and measuring the current that flows through an attached circuit.
- Conductometric Sensors : This form of sensor operates on the principle that electrical conductivity can change in the presence or absence of some chemical species.

Biosensors

- Biosensors use biochemical mechanisms to identify an analyte of interest in chemical, environmental (air, soil, and water), and biological samples (blood, saliva, and urine).
- The sensor uses an immobilized biological material, which could be an enzyme, antibody, nucleic acid, or hormone, in a self-contained device.

Biosensors

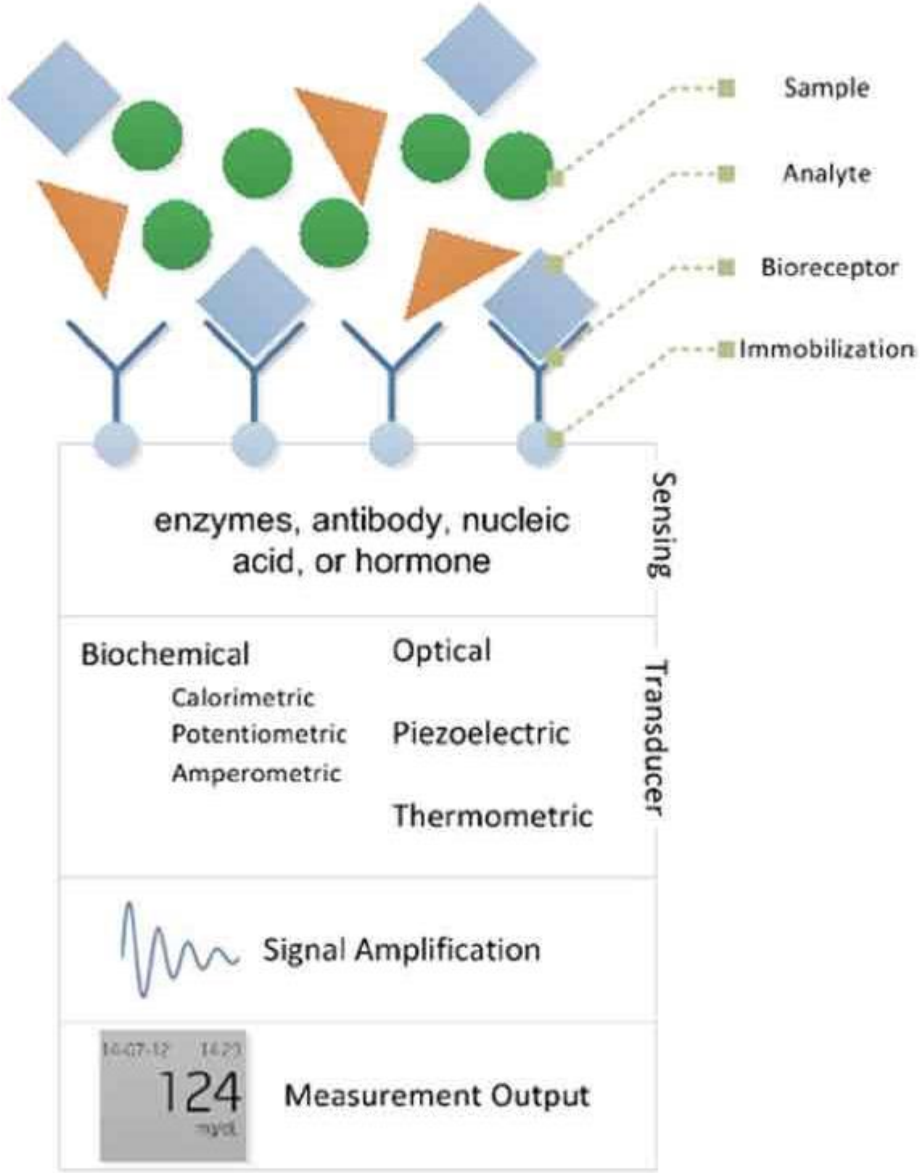


Figure 2-5. The biosensing process

Transducers for Biosensors

- The transduction process in a biosensor involves converting the biological activity that the sensor has measured via a bioreceptor into a quantifiable signal, such as current, an optical signal, or a change in measurable mass.
- The most commonly utilized transducer mechanisms are electrochemical, optical, piezoelectric, and thermometric.
- Electrochemical sensing approaches used in biosensors are Conductometric, Potentiometric, Amperometric biosensors and Coulometric biosensors.
- Optical biosensors uses Piezoelectric, thermometric and calorimetric biosensors.

Key Characteristics of Biosensors

- Biosensors can offer superior sensitivity and specificity over other sensor types.
  - they can have stability or time-dependent degradation of performance
  - Biosensors are normally for single use only.
  - Biosensors often have a limited operational range, in terms of factors such as temperature, pH,or humidity, in which they will operate reliably.
  - Sample preparation may increase the complexity of sensors.
  - Sensor fouling can be a significant issue, particularly with biological samples, as in the case of protein deposits
  - Some compounds can interfere with the sensor readings, particularly biochemical transducers, as in the case of paracetamol interference in glucose measurements.
  - Generally, biosensors exhibit very high sensitivity and specificity.

Key Biosensor Application Domains

Table 2-3. *Key Biosensor Application Domains*

Domain	Application
Healthcare	Chronic disease management, such as glucose monitoring in diabetes Diagnosis and screening for home pregnancy testing; stomach ulcers: Helicobacter pylori Biochemistry, for example, cholesterol testing Bacterial infection testing Acute disease evaluation, as for cancers, such as prostate
Biotechnology/fermentation	Wine fermentation Citric acid Brewing Enzyme production Biopharmaceutical production
Food quality	Chemical contaminant detection, such as contamination with antibiotics Toxin detection Pathogen detection Hormone detection, as in milk
Personal safety/law enforcement/ employment	Alcohol testing Drug testing
Environmental monitoring	Pollution, such as testing for fecal coliforms in water Agriculture Pesticides in water such as organophosphates Heavy metals Hormones
Security	Chemical and warfare agent detection

Application Domains of Biosensors

Environmental Monitoring

- Increased urbanization, intensive agricultural methods, industrialization, demands for power, and climate change have significantly impacted our ability to maintain a clean environment.
- Contaminants and pollutants from a large variety of sources can affect our air, water, soil, and ambient environment. These range from chemical pollutants, biological blooms, heavy metals, gases, and bacterial pathogens, to ambient noise sources (Ho, et al., 2005).
- Protection of human health and ecosystems is of the highest priority, requiring rapid, sensitive, robust, and scalable sensor solutions that are capable of detecting pollutants, often at very low concentrations and on a widespread basis.

Application Domains of Biosensors

Air

- Air pollutants come in many forms, including: sulfur dioxide (SO_2), CO, NO_2, and volatile organic compounds, such as benzene (C_6H_6).
- The sources of these pollutants include vehicle emissions, electric power plants, farming, and industrial manufacturing.
- Air pollution remains an issue both in the developed and developing world.
- A variety of sensor technologies are being utilized for air quality and ambient environmental applications, including:
  - Semiconductor sensors are used to monitor atmospheric gases (CO, CO_2, O_3, ammonia (NH_3), CH_4, NO_2), as well as ambient temperature, humidity and atmospheric pressure
  - Optical and optical fiber sensors are used for ambient monitoring of humidity and temperature, as well as for monitoring atmospheric gases (SO_2, NO_2, O_2 H_2, CH_4, NH_3)
  - Electrochemical sensors are used for atmospheric gases monitoring (O_3, CO, H_2S, H_2, NO, NO_2, SO_2)

Application Domains of Biosensors

Water

- The increasing need for clean water, driven by global demand for drinking water and industrial water requirements, has created a critical requirement for monitoring water quality.
- There are normally three major categories of interest: physical (turbidity, temperature, conductivity,) chemical (pH, dissolved oxygen, metals concentration, nitrates, organics), and biological (biological oxygen demand, bacterial content).
- A number of sensor technologies are being used commercially or are currently being evaluated to measure water quality parameters, including:
  - Electrochemical (pH (ISFET), ammonium, conductivity)
  - Amperometric (chlorine, biochemical oxygen demand (BOD), dissolved oxygen, nitrates)
  - Colorimetric (organics, pesticides such as methyl parathion, Cl)
  - MEMS (dissolved oxygen, NH3)
  - Optical (dissolved oxygen, turbidity, calcium (Ca), metal ions)
  - Natural biosensors (bacteria, toxins)

Application Domains of Biosensors

Sound (Noise Pollution)

- As our society becomes more urbanized and we live in closer proximity to each other, noise and noise pollution becomes more problematic.
- Noise can have significant implications for the quality of life, ranging from being a nuisance to having a substantial physiological or psychological impact.
- More recently, with the rapid adoption of smartphones, citizen-led monitoring of noise levels in urban environments has gained popularity.
- Smartphone apps use the phone's built-in microphone (MEMS) to collect noise-level data points, which are tagged with location information from the phone's GPS coordinates and uploaded to the Web over 3G or Wi-Fi.
- Citizens can then use the data to create noise maps to influence city planners to make changes that improves quality of life within the city.

Application Domains of Biosensors

Soil

- A number of handheld instruments to measure the characteristics and quality of soil are in commonly use.
- A key advantage of the technique is that it requires almost no sample preparation, such as acid digestion.
- Instruments include temperature and moisture meters and penetrometer for the measurement of soil strength.
- When using sensors to monitor or analyze soil, we are normally interested in the soil's physical, chemical, and biological content.
- Key measurements include water content : capacitance, neutron moisture gauge, time-domain transmission (TDT), and time-domain reflectometry (TDR), temperature, pH, organic matter content (optical reflectance), and nitrogen levels.
- Soil contaminants can be classified as microbiological (such as fecal coliforms), radioactive (such as tritium), inorganic (such as chromium (Cr)), synthetic organic (such as organophosphate pesticides), and volatile organic compounds (such as benzene).

Application Domains of Biosensors

Healthcare

- Sensor applications in the healthcare domain range from physiological monitoring, such as heart rate, to screening applications, such as blood biochemistry, to falls risk estimation.
  - Screening and Diagnostics: Biochemical and optical sensors are used for point-of-care monitoring and diagnostics applications, including blood and tissue analysis.
  - Motion and Kinematics: Body-worn wireless sensors, such as accelerometer and gyroscopes, can be used to identify balance and falls risk issues and to monitor the impact of clinical interventions.
  - Physiological: Sensors in this category are used to measure key physiological indicators of health, such as ECG/EKG and blood pressure
  - Musculoskeletal: Body-worn sensors, such as an EMG, are used to assess muscular issues and tissue damage
  - Imaging: Low cost CCD and ultrasound sensors are used for medical imaging. Smart pills can be used for intestinal imaging
  - https://www.youtube.com/watch?v=vwJrMDZoE8Q&feature=emb_logo

Application Domains of Biosensors

- **Monitoring Recreational Activity**
  - Devices such as body-worn heart-rate and blood-pressure monitors, integrated activity monitors, and pulse oximeters are increasingly being used in this emerging domain. Ex: Health bands
- **Personal Safety**
  - smoke detectors and CO sensors
  - Electrochemical instant detection and response (IDR) sensors are frequently used by emergency personnel, such as fire fighters, to determine almost immediately if a building contains dangerous levels of CO
- **Activity and Location Detection**
  - The availability of GPS trackers and other sensors, such as accelerometers in smartphones, has enabled new personal location-tracking capabilities.

Sensor Characteristics

Range:

- Range is a static characteristic and, as the name implies, it describes both the minimum and maximum values of the input or output.
- Operating voltage range describes the minimum and maximum input voltages that can be used to operate a sensor. Applying an input voltage outside of this range may permanently damage the sensor.

Transfer Function

- Sensor characteristics describe the relationship between the measurand and the electrical output signal.
- This relationship can be represented as a table of values, a graph, or a mathematical formula.
- Linear Transfer Functions(End-point method, Best-fit method)
- Non-Linear Transfer Functions (Logarithmic functions, Exponential functions, Power functions)

Sensor Characteristics

- **Environmental Effects**
  - Sensor outputs can be affected by external environmental inputs as well as the measurand itself. These inputs can change the behaviour of the sensor, thus affecting the range, sensitivity, resolution, and offset of the sensor.
- **Modifying Inputs**
  - Modifying inputs changes the linear sensitivity of a sensor.
- **Interfering Inputs**
  - Interfering inputs change the straight-line intercept of a sensor. Temperature is a common example of an interfering input, as it changes the zero-bias of the sensor
- **Hysteresis**
  - The output of a sensor may be different for a given input, depending on whether the input is increasing or decreasing. This phenomenon is known as hysteresis.

Sensor Characteristics

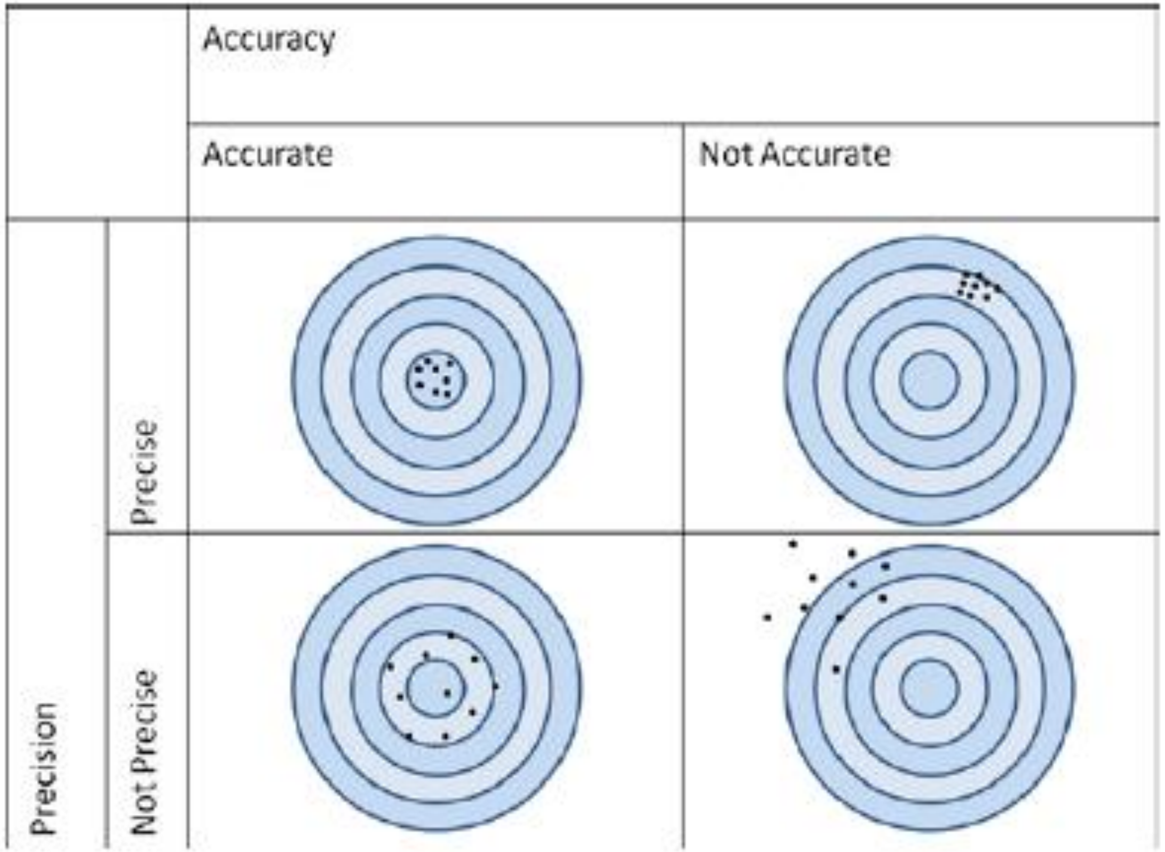
- **Resolution**
  - Resolution, also called discrimination, is the smallest increment of the measurand that causes a detectable change in output. The resolution of modern sensors varies considerably, so is important to understand the resolution required for an application before selecting a sensor.
- **Accuracy**
  - Accuracy refers to a sensor's ability to provide an output close to the true value of the measurand.

$$Percentage\ Relative\ Error = \frac{(Measured\,Value - True\,Value)}{(True\,Value)} \times 100$$

- **Precision**
  - Precision is sometimes confused with accuracy. Precision describes the ability of an output to be constantly reproduced.

Sensor Characteristics

- **Precision**



Sensor Characteristics

Error

- Error is the difference between the measured value and true value, where true value is a reference to an absolute or agreed standard. There are two forms of error: systematic error and random error.
  - **Systematic errors** are reproducible inaccuracies that can be corrected with compensation methods, such as feedback, filtering, and calibration (Wilson, 2004).
  - **Random error** (also called noise) is a signal component that carries no information. The quality of a signal is expressed quantitatively as the signal-to-noise ratio (SNR), which is the ratio of the true signal amplitude to the standard deviation of the noise. A high SNR represents high signal quality.

Sensor Characteristics

Error

- Error bands combine several sensor characteristics (including nonlinearity, hysteresis, and resolution) into a single measure and guarantee that the output will be within a $\pm$h of the ideal straight line.

- **Statistical Characteristics**
  - Repeatability is the ability of a sensor to produce the same output when the same input is applied to it. Lack of repeatability generally occurs due to random fluctuations in environmental inputs or operator error.
  - Tolerance describes the variations in the reported output among a batch of similar elements due to small random manufacturing variations. If a manufacturer reports a tolerance of $\pm$ 5 percent

Sensor Characteristics

Dynamic Characteristics

- Response Time: Sensors do not change their output immediately following a change in the input. The period of time taken for the sensor to change its output from its previous state to a value within a tolerance band of the new correct value is called response time.
- The dynamic linearity of a sensor is a measure of its ability to follow rapid changes in the input parameter. Amplitude distortion characteristics, phase distortion characteristics, and response time are important in determining dynamic linearity.