University of Padova
Department of Information Engineering

Biomedical Wearable Technologies
for Healthcare and Wellbeing

Wearable sensors – Part 1

A.Y. 2023-2024

Giacomo Cappon

Agenda

- Definition of sensors and wearable devices
- Different types of sensors used in wearable devices based on the sensing technique:
  - Mechanical sensors
  - Electrical sensors
  - Optical sensors
  - Chemical sensors
- Sensor characteristics
  - Systematic characteristics
  - Statistical characteristics
  - Dynamic characteristics
- Embedded processing unit
  - Signal processing
  - Communication systems

Part 1

Part 2

Agenda

- Definition of sensors and wearable devices
- Different types of sensors used in wearable devices based on the sensing technique:
  - Mechanical sensors
  - Electrical sensors
  - Optical sensors
  - Chemical sensors
- Sensor characteristics
  - Systematic characteristics
  - Statistical characteristics
  - Dynamic characteristics
- Embedded processing unit
  - Signal processing
  - Communication systems

$\Bigg\}$ **Part 1**

$\Bigg\}$ **Part 2**

Wearable devices

- A wearable device is a device that can be used for sensing physiological parameters or signals which generally include two components:
  - A **sensor** that measures the physical quantity of interest (measurand)
  - An **embedded processing unit** that does some initial processing of the measurements and either stores them in a memory or sends them to another device

Sensor

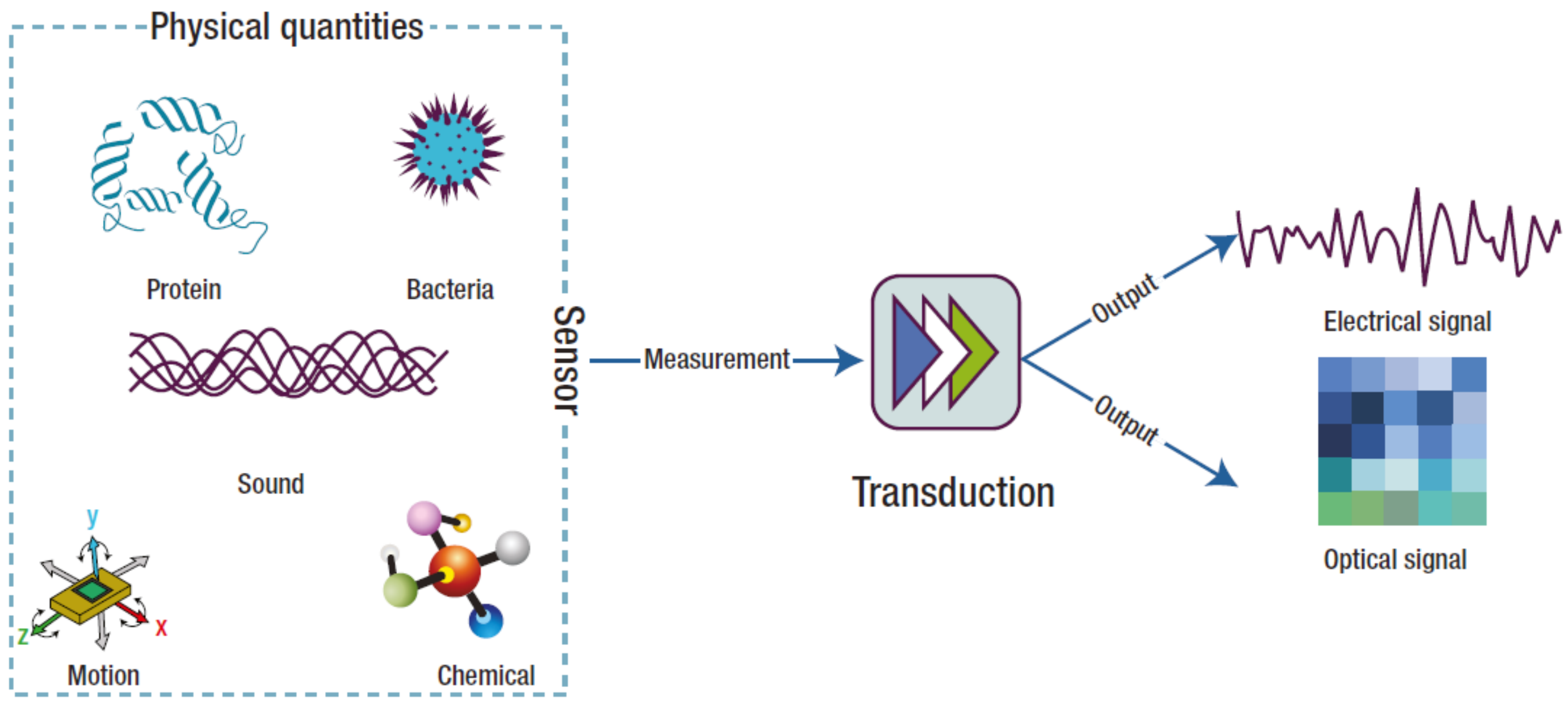
Receiver device / Gateway device (for IoT devices)

Embedded processing unit

Definitions of sensor

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

Measurand

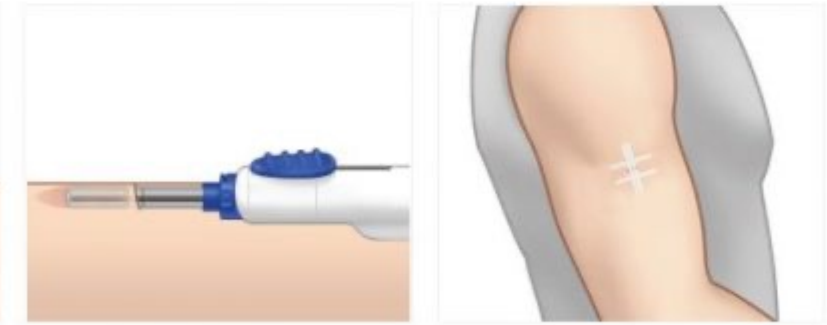


Classification of sensors based on their interaction with the measurand

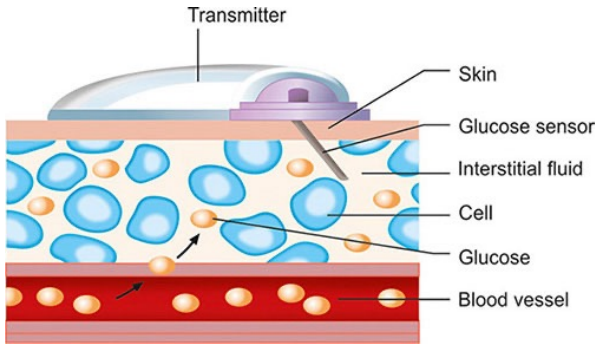
Contact sensor: sensors requiring physical contact with the measurand.

- Their deployment obviously perturbs the state of the subject to some degree.
  - Comfort and biocompatibility are important considerations
  - Response time determined by the speed at which the measurand is transported to the measurement site.
  - Poor contact can result in signal noise and the introduction of signal artifacts.

Invasive: sensors inserted into human body



Minimally-invasive: patch-type devices on the skin that monitor interstitial fluids



Non-invasive: sensors that simply have contact with the skin without effect

Classification of sensors based on their interaction with the measurand

Non-contact sensors: do not require direct contact with the measurand.

- Minimum perturbation of the subject
- Generally used in ambient sensing applications
- Example: infrared thermometer

Sample based sensors: require an invasive collection of a sample of the person to be monitored by a human or automated sampling system.

- The collected samples are analyzed using sensors or laboratory-based analytical instrumentation
- Common approach in healthcare (e.g. monitoring cholesterol)

Wearable devices

- Wearable devices are equipped by sensors (generally non-invasive or minimally-invasive contact sensors) that can be worn by an individual
- Important requirement: a comfortable form factor

Classification of sensors based on their sensing technique

- Mechanical sensors
- Electrical sensors
- Optical sensors
- Chemical sensors

Mechanical sensors

- **Mechanical sensors** detect some form of mechanical deformation of a material, in response to the measurand (input), and translate it to an electrical, optical, magnetic or thermal signal (output).

- **Electromechanical sensors**:

  Measurand $\longrightarrow$ Mechanical deformation $\longrightarrow$ Electrical signal

- Types of electromechanical sensing techniques:
  - Piezoresistive sensors
  - Capacitive sensors
  - Iontronic sensors
  - Piezoelectric sensors

Electromechanical sensors - Piezoresistive sensors

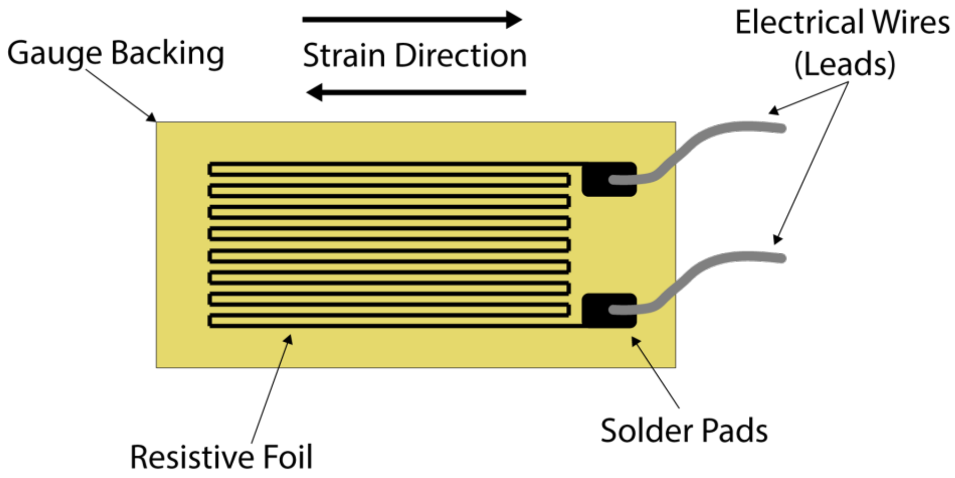
- **Piezoresistive effect**: when conductive materials are subjected to mechanical deformation, their electrical resistance changes (discovered in 1856 by Kelvin).
- The resistance R of a conductive material will change according to:

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

  - ρ: the nominal resistivity
  - L: the length
  - A: the cross-sectional area of the conductor.

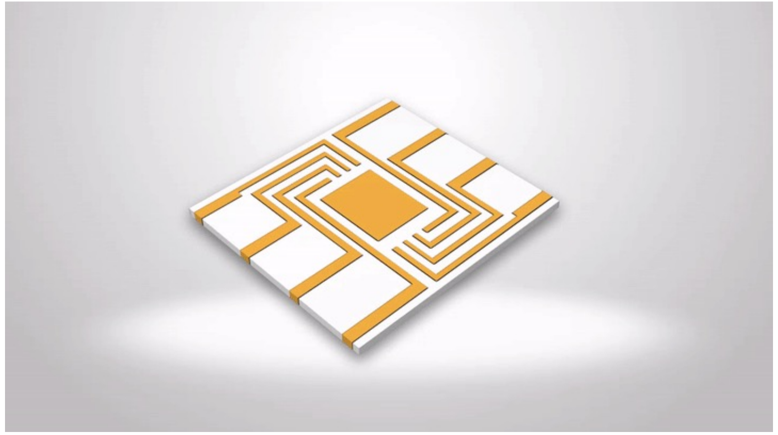
Electromechanical sensors - Piezoresistive sensors

- **Strain gauges:** contact sensors that exploit the piezoresistive effect to measure mechanically-induced deformation.
- They can be put on the human body to detect and quantify motion, such as the bending of a finger or knee, or to measure pression.
- The sensor sensitivity is characterized by the **Gauge Factor**:



$$\boxed{GF = \frac{\frac{\Delta R}{R_0}}{\varepsilon}}$$

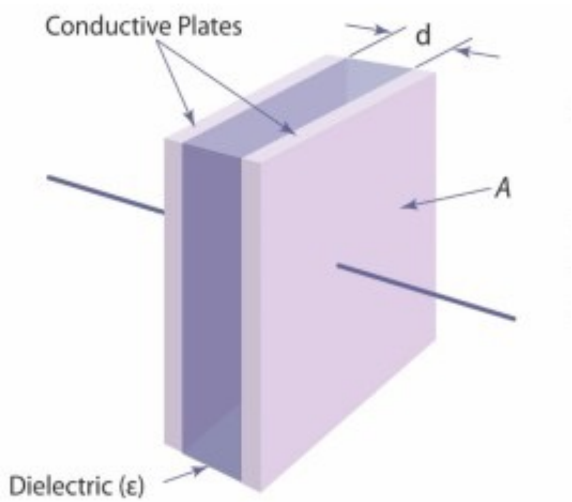
- ΔR: change in resistance
- R_0: unstrained resistance
- ε: applied strain $= \frac{L}{L_0}$
- L: new length
- L_0: length at rest



Electromechanical sensors - Capacitive sensors

- Capacitive sensors: they measure variations of capacitance of a material in response to mechanical stimuli.
- Parallel-plate configuration (most common):

Capacitor:



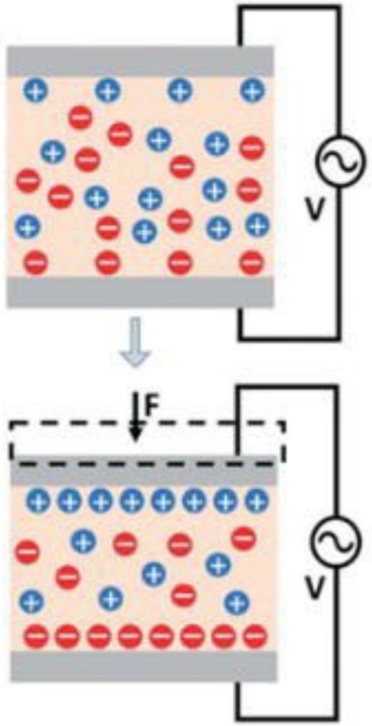
$$C = \varepsilon \cdot \frac{A}{d}$$

- C = capacitance (farads, F)
- ε = permittivity of the dielectric (F/m)
- A = area of overlap between the plates (m2)
- d = distance between the plates (m)

- Changes in A or d due to mechanical stimuli → changes of C detected by the sensor.
- Capacitive sensors are used to detect pressure and strain.
- They are also commonly used in touchscreen.

Special capacitive sensors – Iontronic sensors

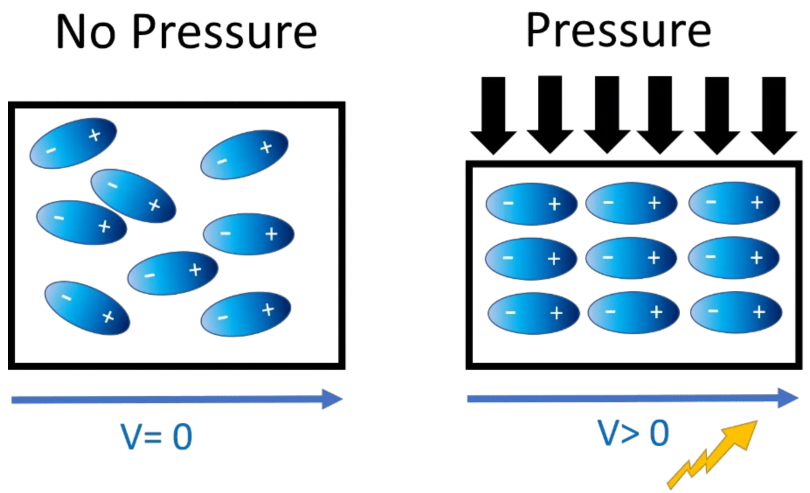
- A capacitive sensor that uses ionic liquid or gel (electrolyte) as dielectric.
- The electrons on the electrode and the counter ions from electrolyte attract to each other at a nanoscopic distance, leading to an ultrahigh unit-area capacitance.
- Capacitance at least 1000 times larger than traditional parallel plate capacitive sensors.
- This excellent property is suitable for wearable electromechanical sensors: iontronic sensor are less sensitive to environmental or body capacitive noises.



Iontronic

Electromechanical sensors - Piezoelectric sensors

- **Piezoelectric effect:** when a mechanical stress (e.g., pressure or strain) is applied to a piezo-electric material, there is a change in electrical polarization inside the material (e.g., re-orientation of molecular dipole moments). This results in a change in surface charge (voltage) at the surface of the piezoelectric material.



- Applications: skin-mounted sensors for tactile sensation, finger bending motion detection, measuring arterial pulse pressure waveform, detecting body movements, etc.

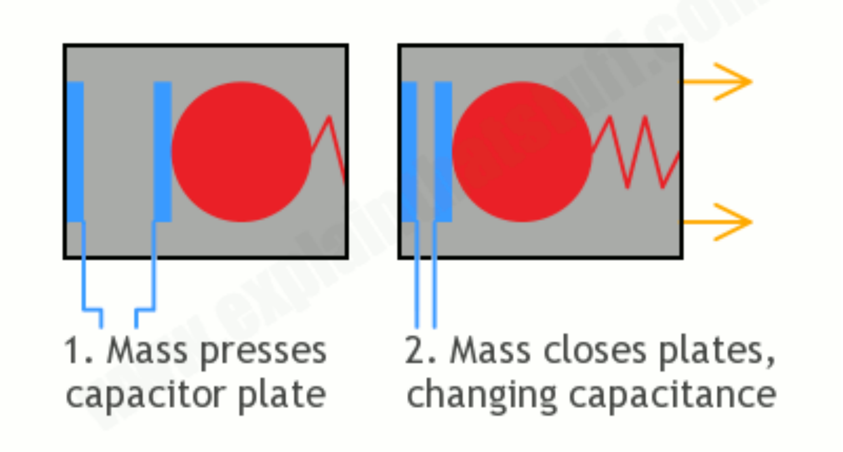
MEMS

- Micro Electro-Mechanical Systems (MEMS): miniaturized chip including mechanical and electrical structures, e.g., micro-electromechanical sensors
- Dimension: from several millimeters to less than 1 micrometer
- Two MEMS widely used in wearables as **inertial sensors** for motion sensing:
  - Accelerometer
  - Gyroscope

MEMS – Accelerometer

- **Accelerometer:** it measures proper acceleration, i.e., the rate of change of velocity of an object in its own instantaneous rest frame.
- The accelerometer measures how much a mass is pressed on an elastic element by an external force.
- Conceptually, an accelerometer is a box with a damped mass on a spring.
- When there is acceleration, the mass moves compared to the resting position.
- A movement sensor (e.g., piezoelectric or capacitive) detects the movement of the mass which is proportional to the acceleration.

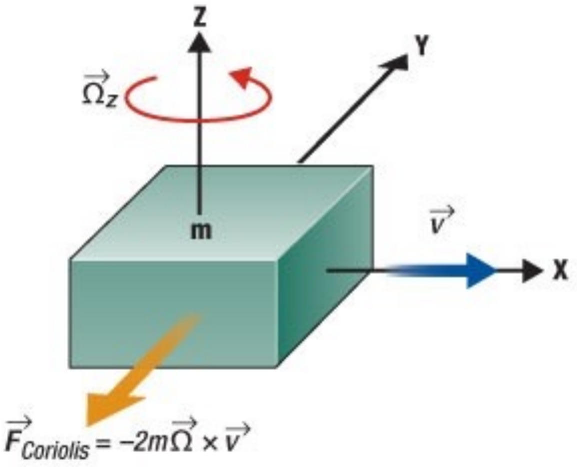
Capacitive accelerometer

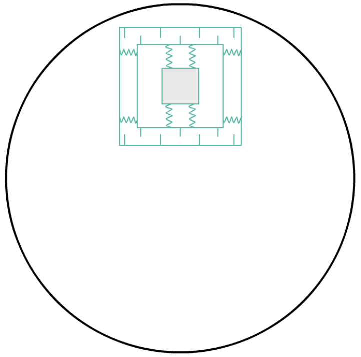


MEMS – Gyroscope

- **Gyroscope**: it measures the angular rate of rotation around one or more axes.
- Most of MEMS gyroscopes exploit the **Coriolis effect**: when a mass m is moving in linear direction with velocity v (x axis) and undergoes angular rotation with velocity Ω (around the z axis), the mass experiences an apparent force F in a direction perpendicular to z and x (y axis).

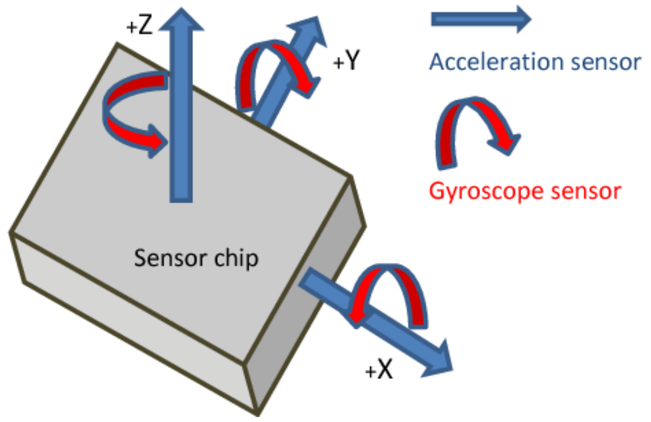
Coriolis effect





MEMS - Inertial Measurement Unit (IMU)

- An individual inertial sensor (accelerometer or gyroscope) can only sense a measurement along or about a single axis.
- **Inertial Measurement Unit:** an electronic device that measures and reports a body's specific acceleration and angular rate using a combination of accelerometers and gyroscopes.
- **3-axis IMU**: three inertial sensors mounted together into an orthogonal cluster known as a **triad**.
  - 3-axis accelerometer measures acceleration along 3 orthogonal axes
  - 3-axis gyroscope measures angular velocity around 3 orthogonal axes
- **6-axis IMU**: 3-axis accelerometer and a 3-axis gyroscope
- Sometimes IMU also includes **magnetometers**, i.e., sensors that measure the strength and direction of a magnetic field, used to determine the orientation of the body with respect to the magnetic north.
- **9-axis IMU**: inertial system consisting of a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer



Classification of sensors based on their sensing technique

- Mechanical sensors
- Electrical sensors
- Optical sensors
- Chemical sensors

Electrical sensors

- **Electrical sensors**: on-skin electrodes that measure a change in electrical resistance or the electrical charge of the skin.
- Good electrical contact with skin is required.
- **Wet electrodes:** solid conductive pad interfaced to the skin via an electrolyte gel that minimizes the impedance of skin by hydrating it and forming a conformal electrical contact with its textured surface.

- **Dry electrodes:** direct contact with the skin, less robust to movement artifacts.
- Skin electrodes allow to collect high-fidelity measurements of a broad range of physiologically relevant biopotentials:
  - electrocardiogram (ECG)
  - electroencephalogram (EEG)
  - electromyogram (EMG)
  - electrooculogram (EOG)
  - electroretinogram (ERG)
  - galvanic skin response (GSR), also known as skin impedance or electrodermal activity (EDA)

Classification of sensors based on their sensing technique

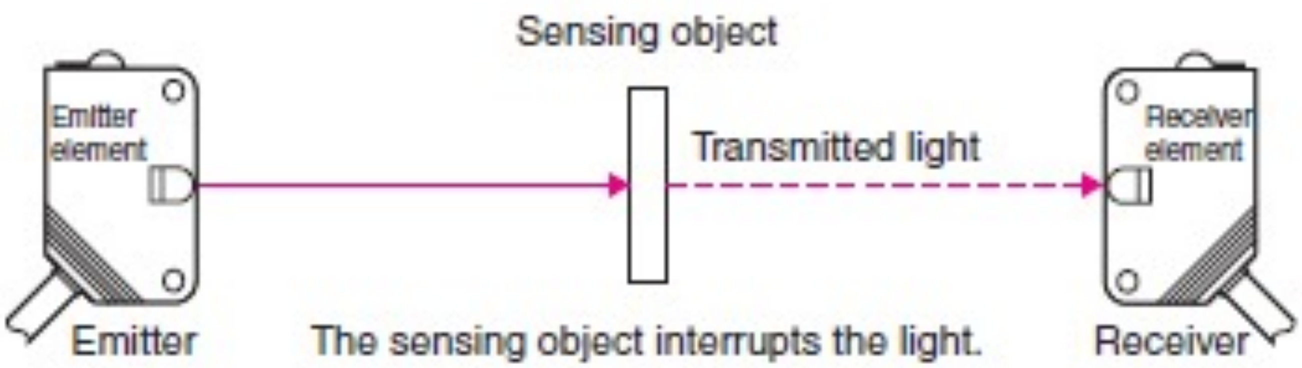
- Mechanical sensors
- Electrical sensors
- Optical sensors
- Chemical sensors

Optical sensors

- **Electro-optical sensors** detect light and convert it to an electrical signal
  - *Photoconductive* devices convert a change of incident light into a change of resistance.
  - *Photovoltaics* (solar cells) convert an amount of incident light into an output voltage.
  - *Photodiodes* and *phototransistor* convert an amount of incident light into an output current.
- <u>Operating principle of wearable optical sensors</u>: a light source introduces light into the body and based on how much the light is absorbed or reflected, measurements related to the body tissue are derived.
- The wavelength of light sources can range from UV to deep infrared, depending on needed penetration depth and the absorption peak for the relevant sensing application.
- Commonly used for monitoring of heart rate and blood oxygenation.

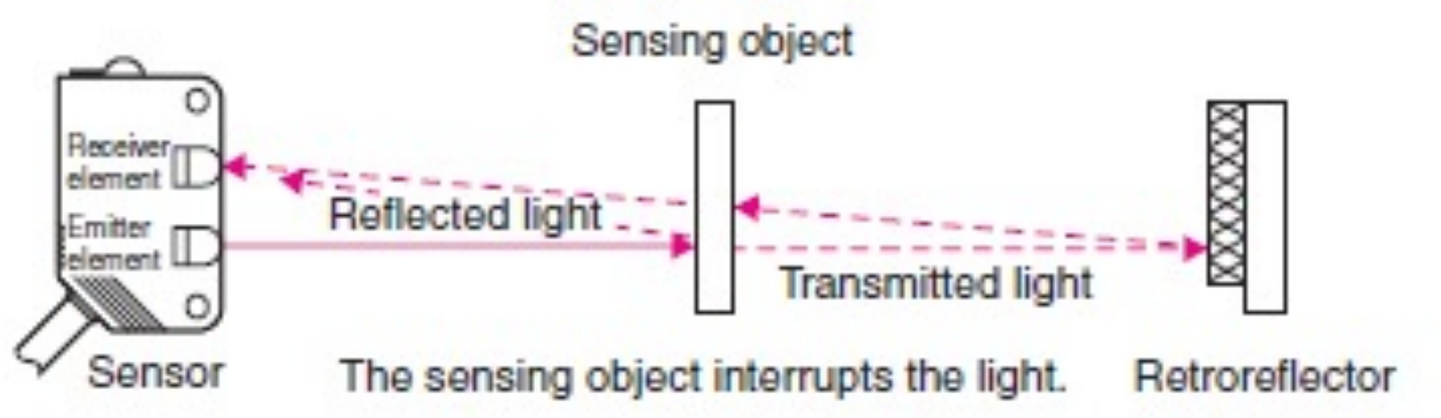
Types of optical sensors (1/3)

- **Through-beam sensors**: two separate components, a light source and a light detector mounted opposite to each other. The light source emits a light beam in the direction of the detector. The object of the measurement is interposed between the light source and the detector and based on its light absorption the measurements are derived.



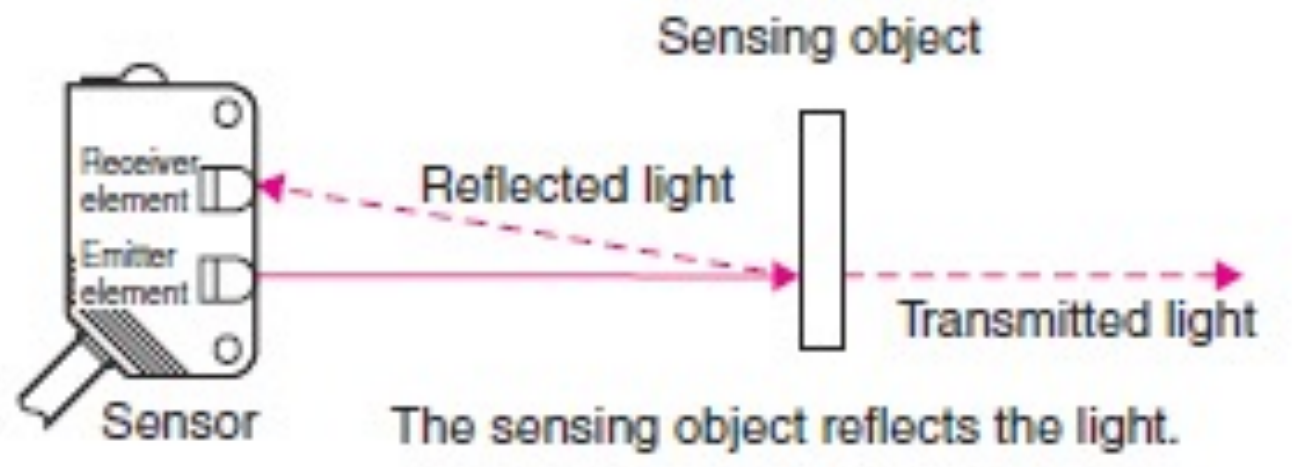
Types of optical sensors (2/3)

- **Retroreflector sensors**: Two separate components, a sensor including the emitter and the detector, and a retroreflector mounted on opposite to each other. The light beam emitted by the sensor passes across the sensing object, reaches the retroreflector which reflects it back to the sensor.



Types of optical sensors (3/3)

- **Diffuse-reflective sensors**: A single component integrating the light emitter and the light detector. The light source emits a light beam through the sensing object, which partially reflect light back to the detector.

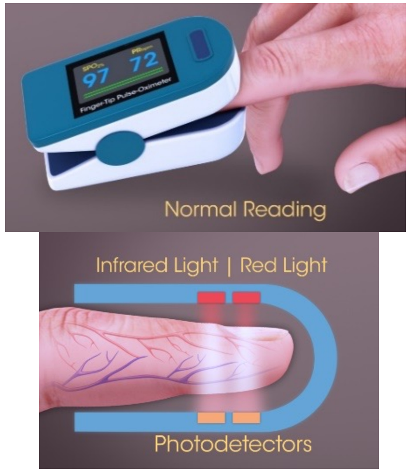


Through-beam vs. diffuse-reflective

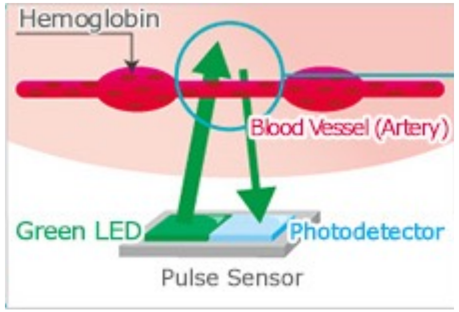
Through-beam sensors:

- Advantage: the detected light interacts through a sufficiently long optical path with the target tissue → strong signal attenuation for measurement extraction.
- Disadvantage: it can be applied easily only to some anatomical regions, e.g., finger or ear lobe; not straightforward to miniaturize.

Portable pulseoximeter (through-beam)



Wearable HR monitor (diffuse-reflective)

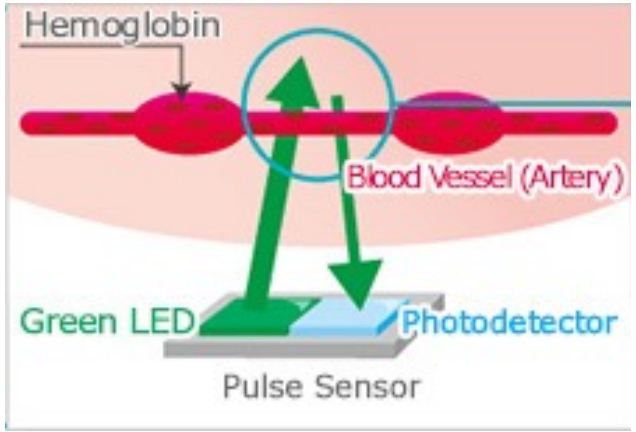


Diffuse-reflective sensors :

- Advantage: they can be used in nearly any region of the body; simple to miniaturize and to make wireless.
- Disadvantage: they are susceptible to motion artifacts; slight changes in the relative position of the optical components create noise → Filtering algorithms and systematic compensating approaches that exploit accelerometers as motion sensors are used to mitigate motion artifacts.

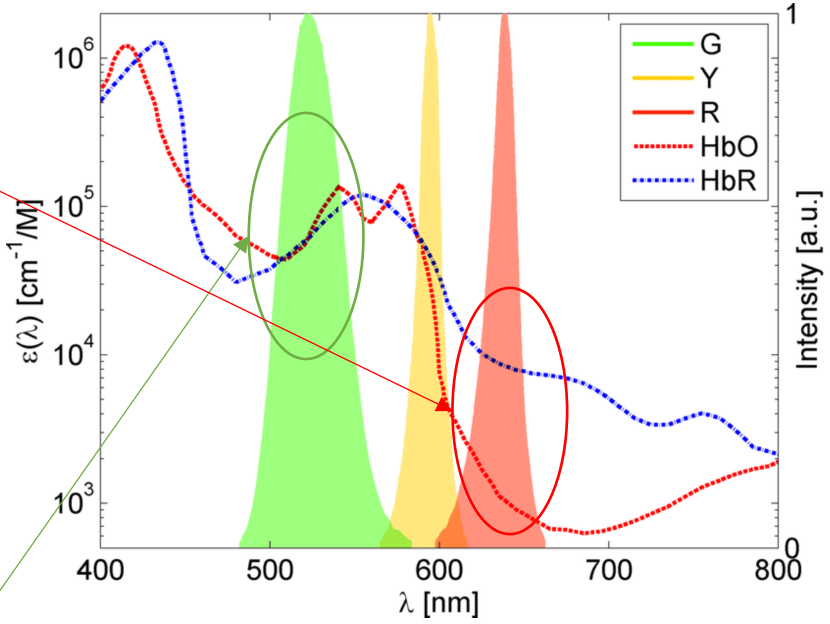
Optical HR sensor: Photoplethysmography

- Optical HR sensors integrated in commercial wearable devices (e.g., smartwatches) are diffuse-reflective sensors that use the photoplethysmography technique.
- **Photoplethysmography (PPG)** utilizes a light source and a photodetector to measure the properties of blood circulation.
- The light source emits light to a tissue and the photodetector measures the intensity of reflected light from the tissue.
- The **hemoglobin** contained in red blood cells absorbs light.



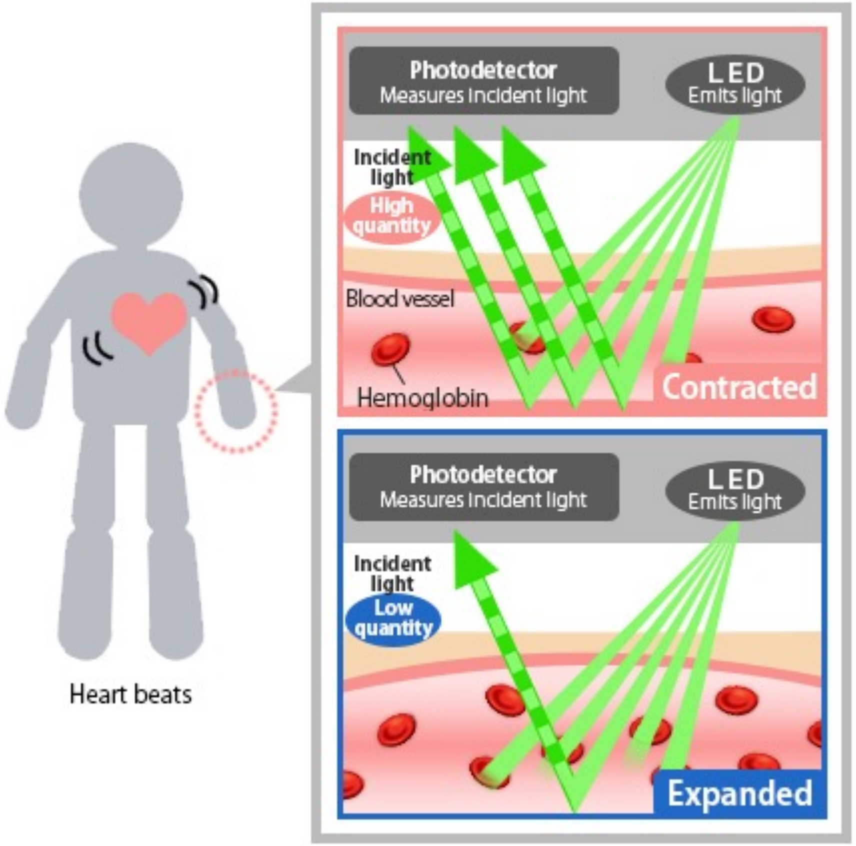
Optical HR sensor: Photoplethysmography

- The intensity of absorbed light depends on the light wavelength and the oxygenation of hemoglobin.
- **At red wavelength**: deoxygenated hemoglobin (HbR) absorbs more light that oxygenated hemoglobin (HbO) → red and infra-red lights are used in pulseoxymeters that exploit the difference in light absorption of oxygenated and deoxygenated hemoglobin to measure **peripheral oxygen saturation**.
- Most common optical HR sensors use a green light emitting diode (LED) as light source.
- **At the wavelength of green light**: the intensity of light absorbed by oxygenated and deoxygenated hemoglobin is roughly the same.



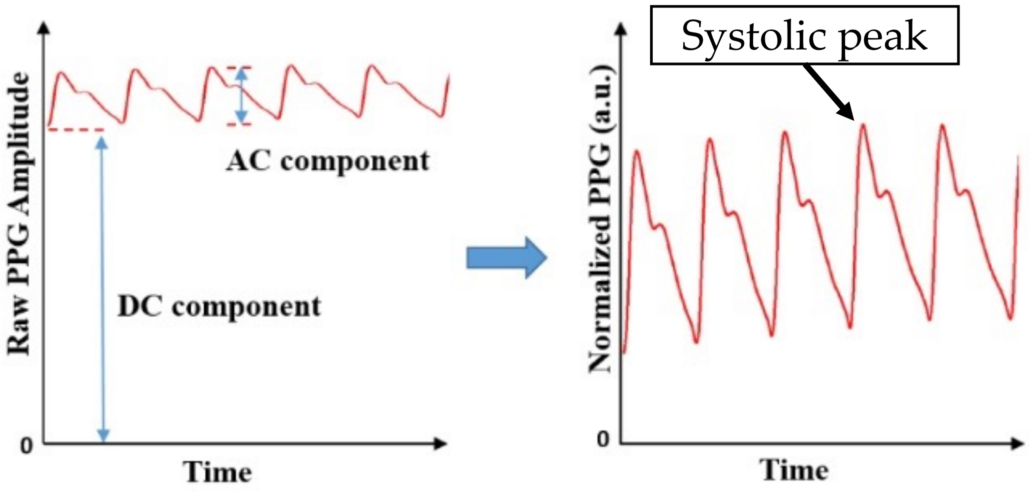
The PPG signal

- The **intensity of reflected light** directly depends from the amount of hemoglobin present in blood vessels, which can be linked to **blood volume**.
  - Large blood volume → more absorbed light → small reflected light
- The PPG signal, measured by the photodetector, represents light absorption.
- Variations in the intensity of light absorbed (or reflected) correspond to variations in blood volume.



The PPG signal

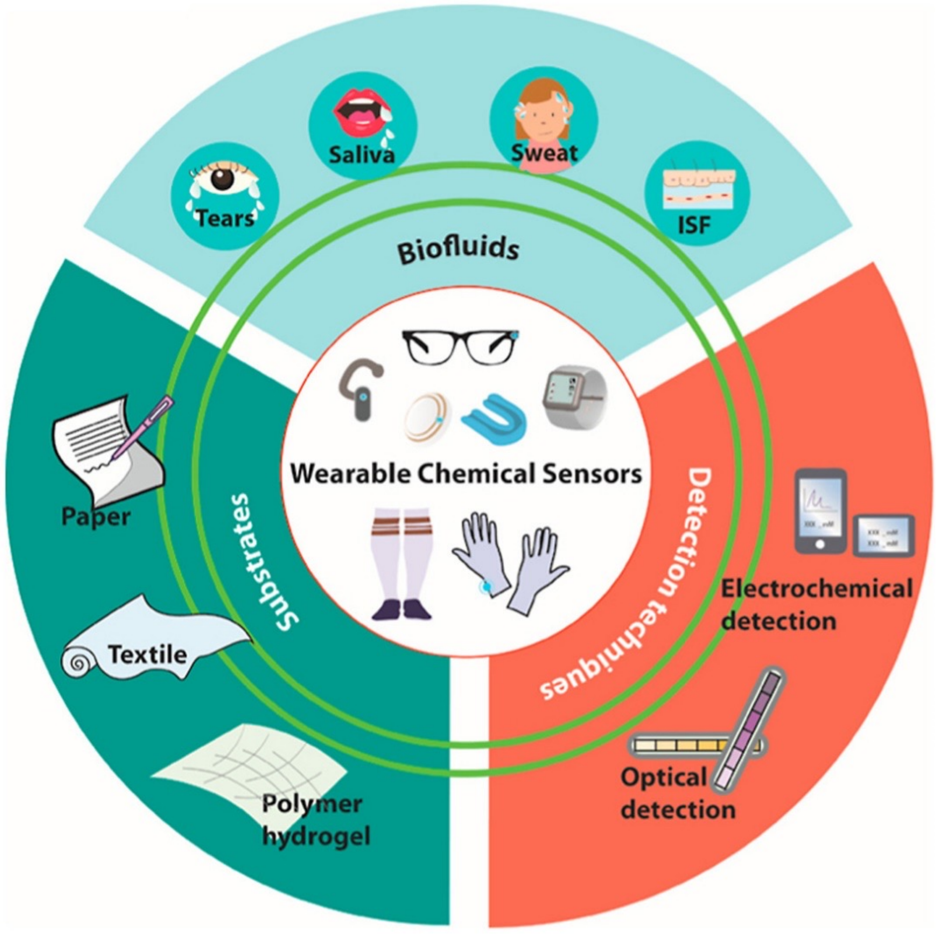
- The PPG signal has **two components**:
  - a **pulsatile** (‘**AC**’) waveform attributed to changes in the blood volume synchronous with heart beat.
  - a **slowly varying** (‘**DC**’) baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation.
- The AC can be extracted with suitable electronic filtering and amplification.
- HR is determined by calculating the frequency of PPG systolic peaks in AC.



Classification of sensors based on their sensing technique

- Mechanical sensors
- Electrical sensors
- Optical sensors
- Chemical sensors

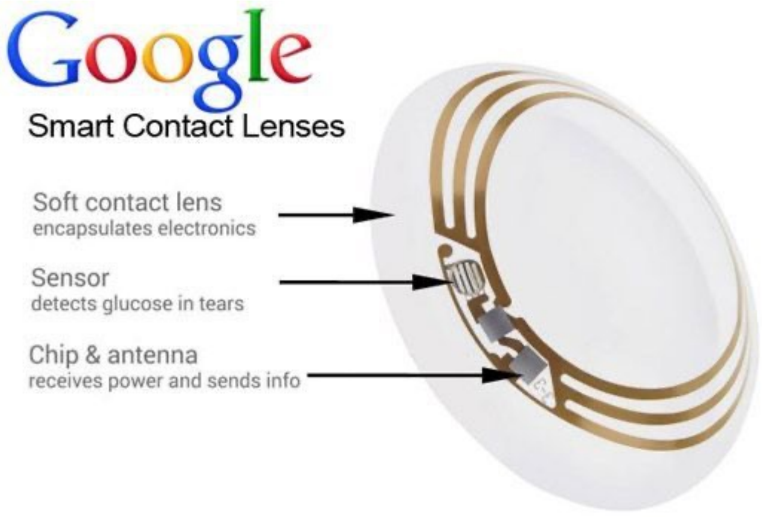
Chemical sensors



- They quantify chemical markers, or analytes, in biological fluids and convert this information in an optical (**optochemical sensor**) or electrical signal (**electrochemical sensor**).
- Require direct chemical interaction with the biomarker (contact sensors).
- Wearable chemical sensors use non-invasive or minimally-invasive techniques to measure analytes in **alternative biofluids** instead of invasive blood sampling.
  - Biofluids secreted by the body (saliva, sweat, tears)
  - Interstitial fluid reached through minimally-invasive sensors or by reverse iontophoresis
- When a new wearable chemical sensor is designed, the relationship between analyte concentration in the chosen biofluid and that in the traditional samples (e.g., blood) must be confirmed.

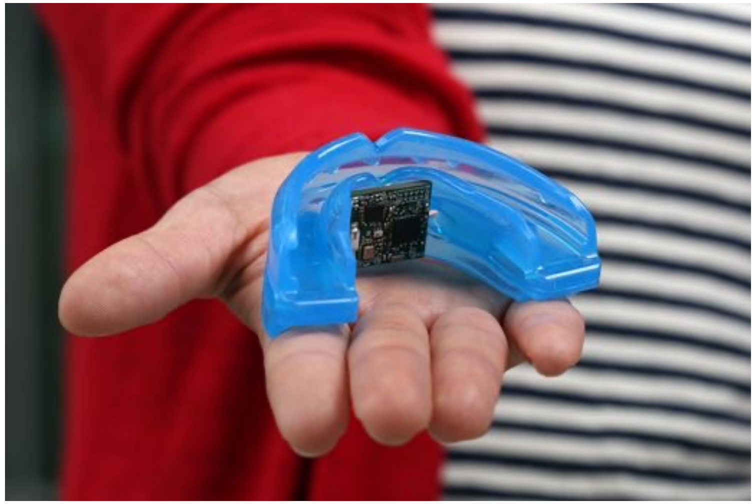
Biofluids: Tears

- **Tears** contain a variety of biomarkers: electrolytes (e.g., Na^+, K^+, and Cl^-), metabolites (e.g., glucose, lactate, and ascorbate), and proteins (e.g., lysozyme, lactoferrin, lipocalin, and albumin).
- Tear biomarkers have been used for the diagnosis of both ocular diseases and common diseases (e.g., diabetes)
- <u>Pros:</u> Tear biomarkers directly diffuse from blood → close correlation between the biomarker concentration in tears and blood.
- <u>Cons</u>: small sample volume, rapid evaporation during sample collection, eye irritation, and a lack of tear fluids of users who face with a dry eye syndrome.
- Typical form factor: smart contact lens.



Biofluids: Saliva

- **Saliva** contains small metabolites (e.g., glucose, uric acid, and creatinine), proteins (e.g., lactate dehydrogenase (LDH), a-amylase, and albumin), and hormones (e.g., cortisol, testosterone, and progesterone)
- Saliva biomarkers can be used for diagnosing oral diseases, diabetes, cancer, kidney disease and cardio-vascular disease.
- <u>Pros</u>: Large volume of saliva; easy, low-cost, non-invasive sample collection.
- <u>Cons</u>: the concentration of salivary biomarkers is usually lower than blood and other non-invasive biofluids; food particles, bacteria, and other contaminants limit the performance of saliva diagnostics.
- Typical form factor: mouthguard with embedded sensor.



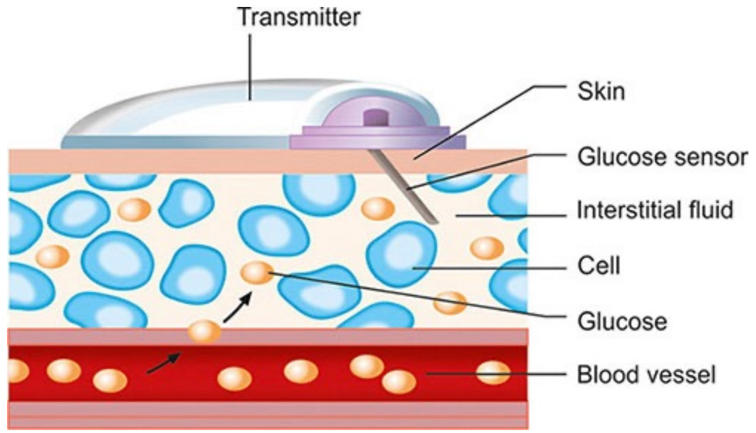
Biofluids: Sweat

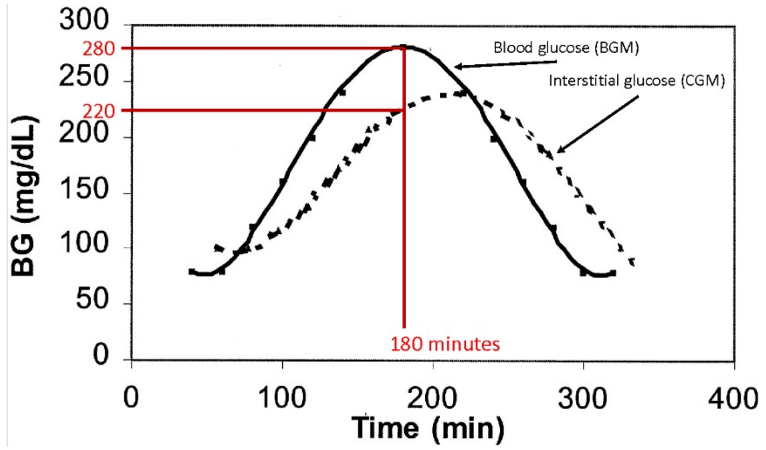
- **Sweat** contains electrolytes (e.g., Na^+, Cl^-, K^+, and $Ca2^+$), metabolites (e.g., lactate, creatinine, glucose, and uric acid), small molecules (e.g., amino acid and cortisol), and proteins (e.g., interleukin, tumor necrosis factor, and neuropeptide)
- Pros: Sweat biomarkers contain abundant health information (e.g., hydration status, physical stress, and bone mineral loss).
- Cons: variation of sweat secretion (which depends on the weather, heat, physical activity, stress, and chemical stimulus); sample evaporation; skin surface contamination.
- Typical form factor: skin tattoo biosensors.

Wearable lactate sensor

Biofluids: Interstitial fluid

- **Interstitial fluid (ISF):** extracellular fluid surrounding all cells in the body. ISF contains electrolytes (e.g., Na^+, Mg^{2+}, K^+, and Ca^{2+}), metabolites (e.g., glucose, ethanol, and cortisol), and proteins that diffuse from the capillary endothelium.
- <u>Pros</u>: Most of ISF analyte concentrations are similar to blood concentrations → reliable correlation between blood and ISF biomarkers.
  - Example: in steady-state conditions glucose concentration in ISF is equal to that in blood. During dynamics, concentration of glucose in ISF is delayed and attenuated compared to that in the blood because of the time needed by glucose to diffuse from plasma to ISF.
- <u>Cons</u>: ISF analysis requires either minimally-invasive needle electrodes or additional method, such as reverse iontophoresis, to bring the ISF to the skin surface for non-invasive monitoring.
- Typical form factor: needle electrodes or reverse iontophoresis electrodes.





Detection techniques

- The signal from biomarkers can be detected, either directly (e.g., Na^+ and K^+ in sweat by ion-selective host), or indirectly from other species generated from the reaction between biomarker and recognition element (e.g., glucose measurement via H_2O_2 generated from the glucose oxidase-catalysed reaction)

- Two most popular detection techniques:
  - Optochemical detection
  - Electrochemical detection

Optochemical sensors

- They exploit materials whose optical properties are related to the analyte of interest.

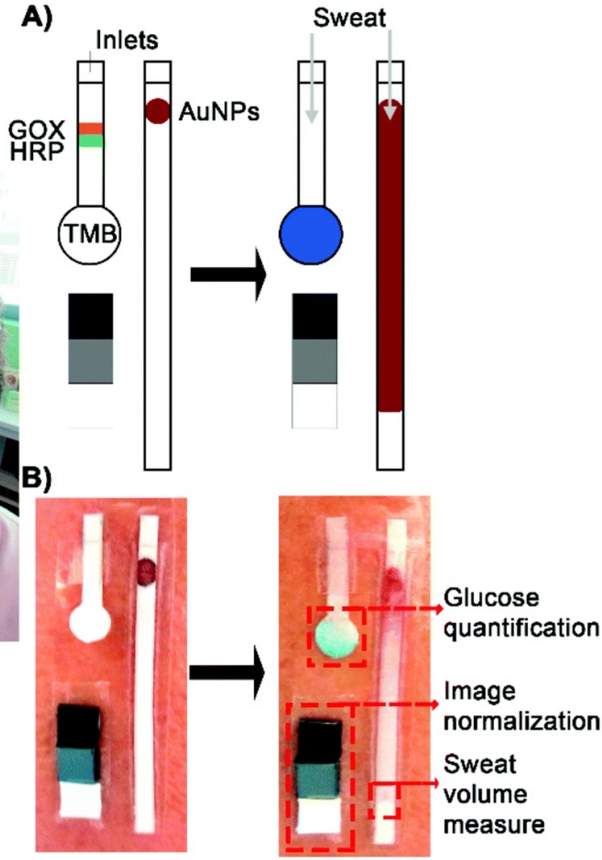
- **Colorimetric biosensors**: The sensor uses an immobilized chemical material. When an analyte comes into contact with the sensor, a chemical reaction occurs between the analyte and sensor chemical material which produces a measurable color change.

- Generally based on the naked-eye measurement.
  - Pros: it does not require any external energy source, which allows simpler instrumentation.
  - Cons: our eyes cannot differentiate small changes of color.

- The smartphone camera can be used to differentiate colors with high sensitivity. A smartphone captures the color change photo and quantifies the intensity of light in RGB scales, which is then correlated to the analyte concentration.

Optochemical sensors – Example
Wearable colorimetric sensor of glucose concentration in sweat

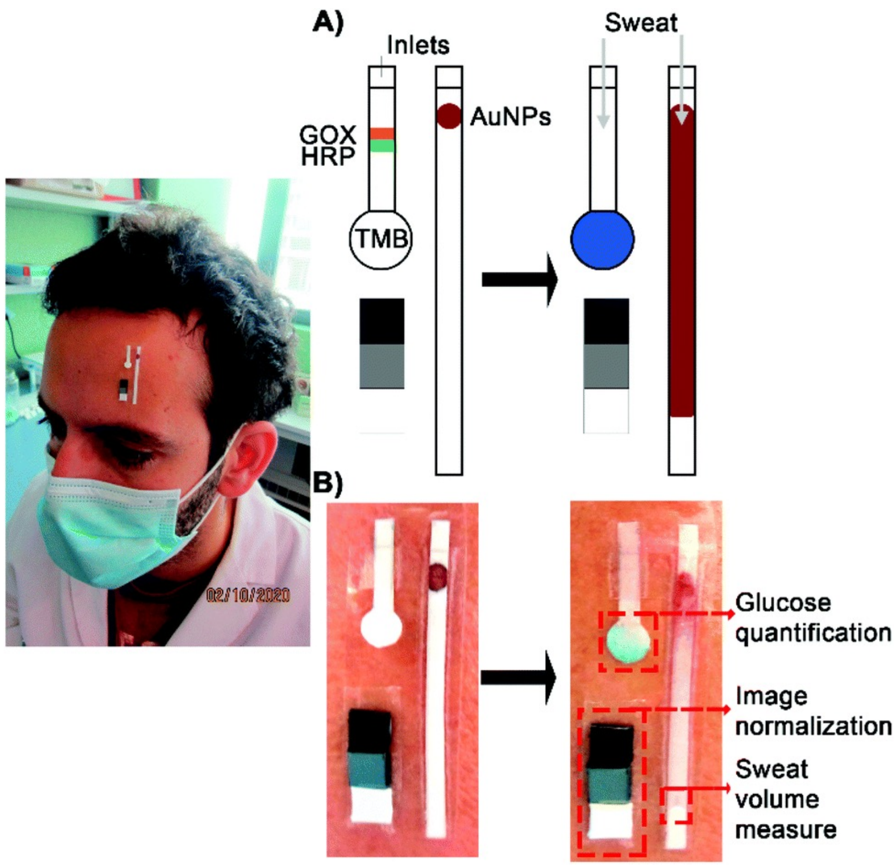
- The system includes:
  - a biosensor for measuring glucose;
  - a sensor for determining the sweat volume;
  - a color chart for signal normalization.
- The sensors are made of filter paper and are fixed on the skin with adhesive medical tape, where they absorb sweat.
- The glucose biosensor contains two enzymes: glucose oxidase (GOX) and horseradish peroxidase (HRP).
- The detection zone of the sensor contains the chromogen TMB (3,3′,5,5′-tetramethylbenzidine), a white substance that becomes blue if oxidized.



Vaquer et al., Analyst, 2021

Optochemical sensors – Example
Wearable colorimetric sensor of glucose concentration in sweat

- Sweat carries GOX and HRP to the detection zone.
- Glucose in sweat reacts with GOX and produce H_2O_2. The HRP and the H_2O_2 produced by glucose-oxidation induce the oxidation of TMB which becomes blue.
- The sweat volume sensor contains pegylated gold nanoparticles (AuNPs) that allow estimating the volume of sweat entering the platform.
- The color chart is used as a reference for normalizing the color of pictures taken with a smartphone, which enables signal quantification in different ambient light conditions.



Vaquer et al., Analyst, 2021