BIOMEDICAL SENSORS

EE 370 – 2015

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Measurement Basics

- Measuring is the experimental determination of a measured value by quantitative comparison of the measurand with a comparison value in a direct or indirect manner
- Measured value obtained by this procedure is given as a product of a numeric value and a dimensional unit
- It can be recorded continuously as a temporal variation of a physical value or discontinuously at particular moments
- Deviation of measured value from the measurand is the measurement error
  - Depends on measurement procedure, measurement device, and environmental effects
  - Systematic and random errors are distinguished

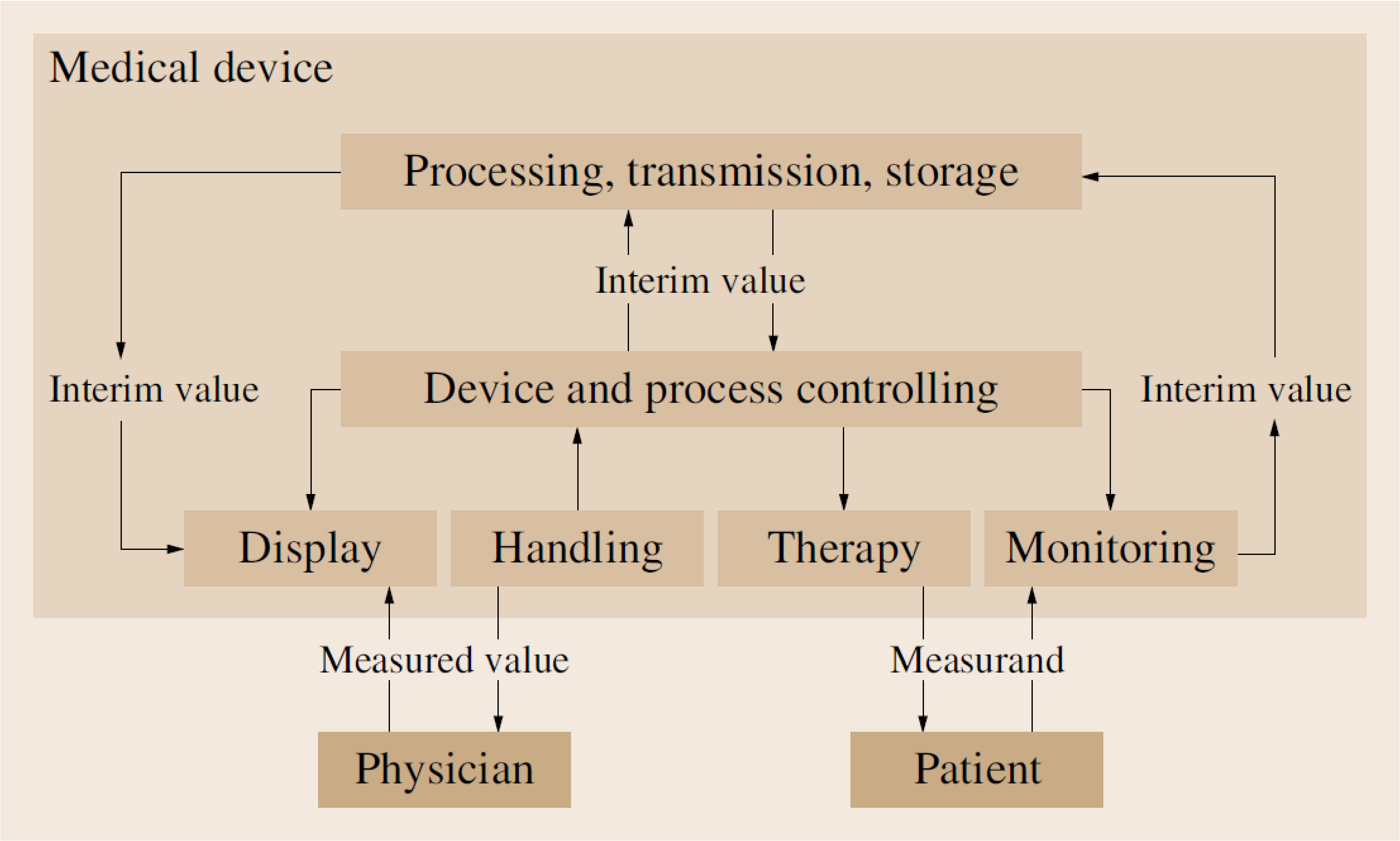
Measuring in Medicine

- Aim of measuring in medicine is objective description of state of patient who might possibly not be able to cooperate
- Goal is to help the physician to define the respective therapy and to evaluate the therapy process and assess the prognosis
- Long-term monitoring of physiological parameters is combined with an alarm function if preset limiting values are exceeded
- New developments include closed-loop systems which directly intervene in patient's state after analysis of measured values
- Unique in having inter-individual and intra-individual deviations for biological measurements, owing to biological variability
  - Measured values vary from patient to patient and within same patient

Measuring in Medicine: Objectives

- Metrological acquisition, conversion, processing and transmission of biological signals
- Measuring the reaction or the behavior of the biological object to an external stimulus
- Measurements during application of extra- or intracorporeal assist systems to support organ functions or as organ compensation, as well as manipulators for therapeutic means
- Application of substances, irradiation or waves and measurement of reflection, absorption, scattering, distribution or fluorescence to display structures and functions in the organism
- Extraction of body fluids, substances and tissues, as well as tests and analysis in clinical and chemical laboratories

Measuring in Medicine: Model



Measuring in Medicine: Unique Aspects

- Extent of inconvenience for patient and measurement procedure directly influences the reliability of measured values
- Biological sources of interference (biological artifacts with physiological origin) superimposing the measurand
- Measurement duration and the reproducibility of an examination are limited for most methods
- Wide variability of examined persons
  - Ranging from fetus, infants and trained athletes to aged people
- Include subjective methods requiring cooperation of patient
  - e.g., audiometry, vibration tests and temperature sensation

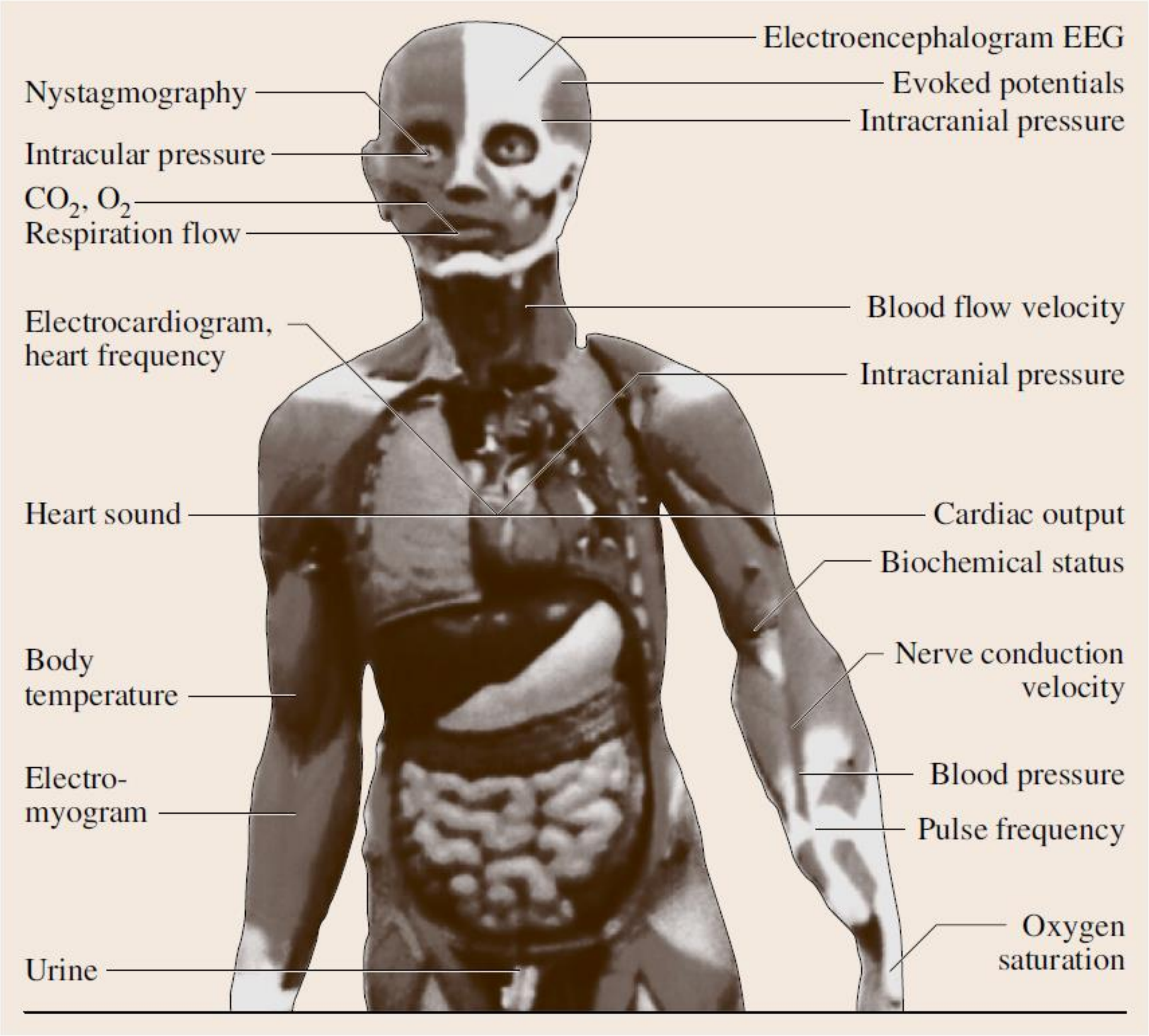
Biosignals

- Biosignals can be defined as phenomena to describe functional states and their variations in a living organism
  - Actual measurand that should be metrologically determined for diagnostic purposes
- Provide information about metabolic, morphological and functional changes, describe physiological and pathophysiological states as well as process dynamics
- To analyze them, generation locus and thus spatial and temporal correlation is significant
- Biosignals are acquired from living organisms, organs and organ parts down to single cells

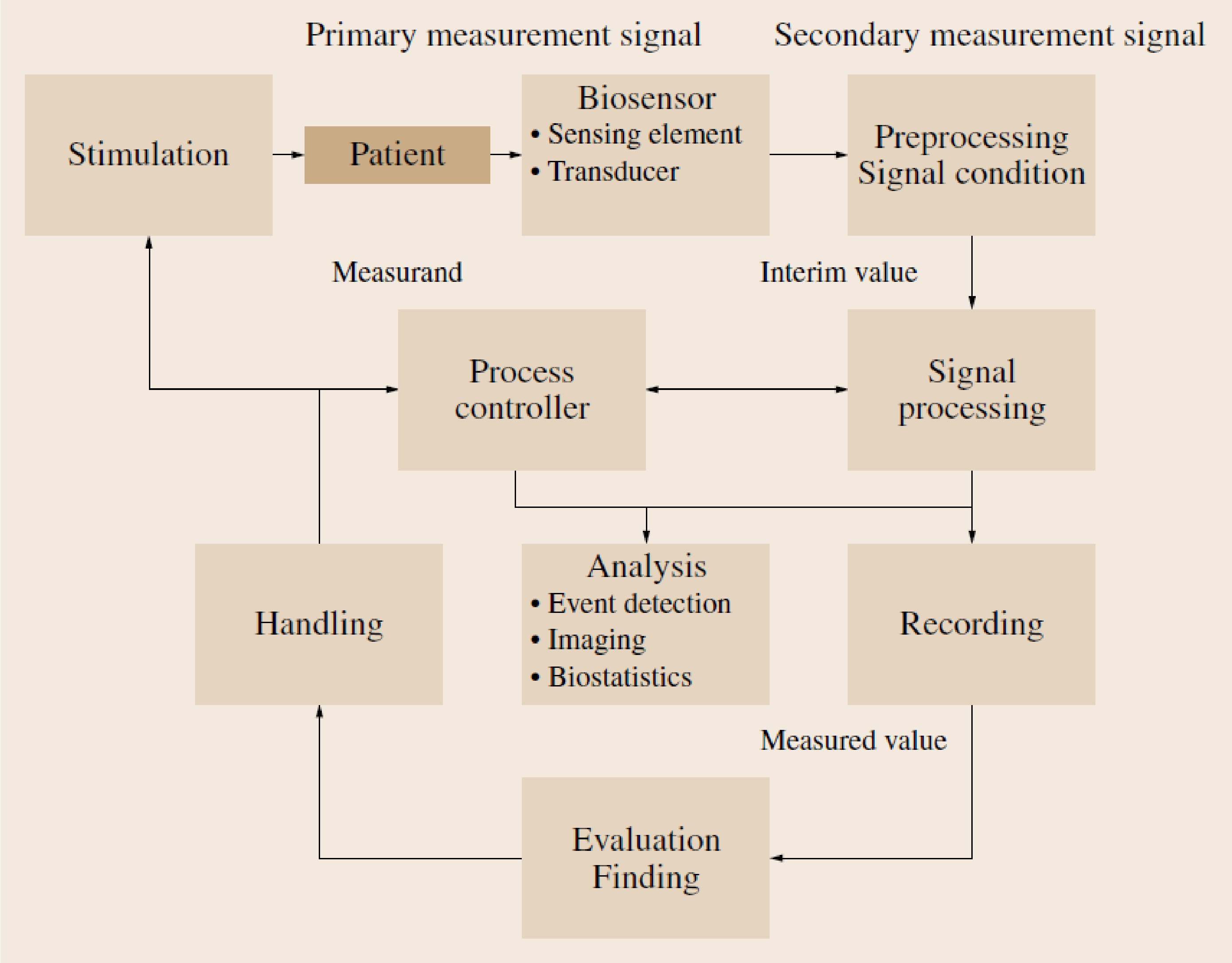
Biosignal Types

- Bioacoustic signals (heart sound, lung sounds, speech)
- Biochemical signals (substance compositions, concentrations)
- Bioelectric and biomagnetic signals (electric potentials, ion currents)
- Biomechanical signals (size, shape, movements, acceleration, flow)
- Biooptical signals (color, luminescence)
- Biothermal signals (body temperature)

Biosignal Examples

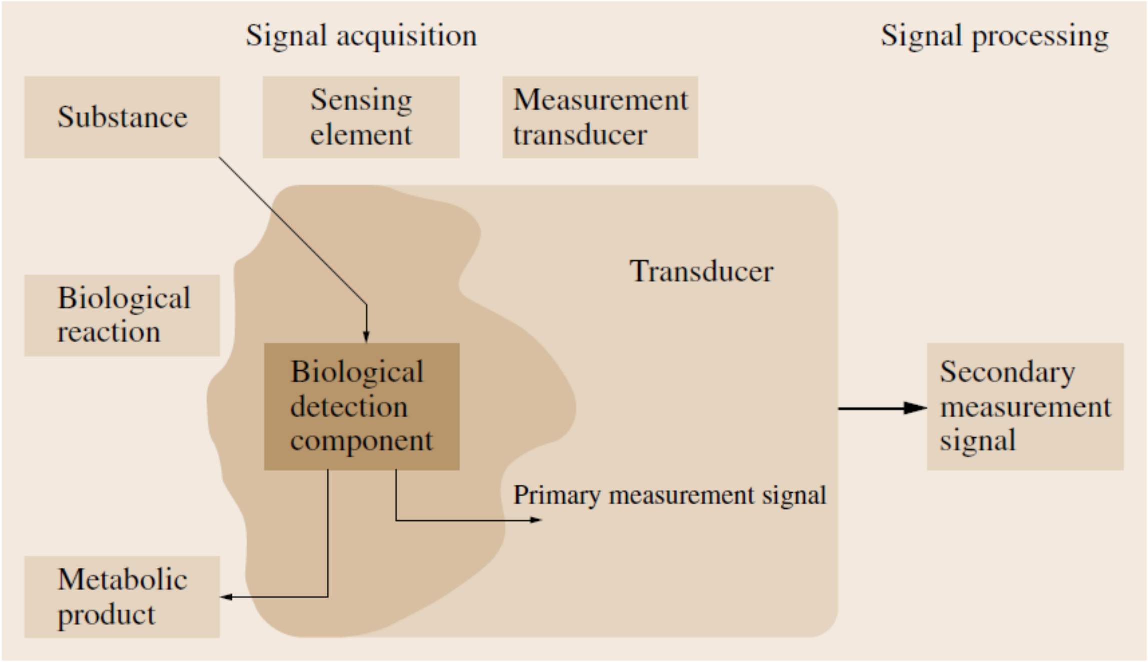


Biological Measuring Chain



Biosensor

- Biosensor is a probe to register biological events and morphological structures
- Often, it is directly connected to a transducer, or it transduces the primary measurement signal into a secondary signal itself



Biosensor Requirements

- Feedback-free registration of the signals
- Provide reproducible measurement results
- Transmission behavior has to remain constant for a long time
- Narrow production tolerances
- High biocompatibility
- Low stress to patient
- Small mass and small volume
- Application should be simple and manageable
- Allow cleaning, disinfection and possibly sterilization

Sensor Classification

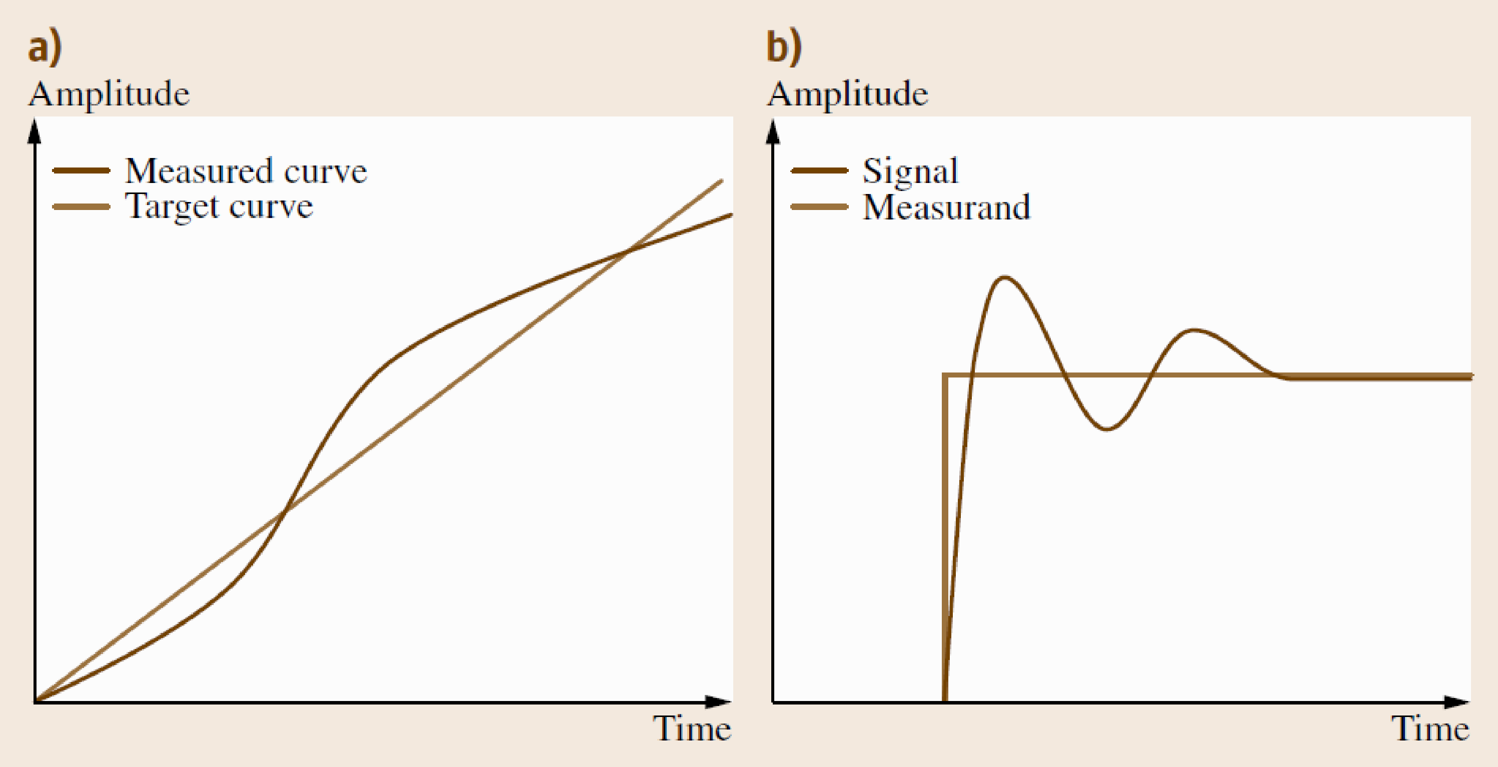
- Active or passive
- Passive sensor does not need any additional energy source
  - Directly generates electric signal in response to external stimulus
  - Examples: thermocouple, photodiode, piezoelectric transducer
- Active sensors require external power for their operation, called excitation signal.
  - Excitation signal is modified by sensor to produce the output signal
  - Examples: thermistor and resistive strain gauge

Sensor Classification

- Absolute or relative
- Absolute sensor detects a stimulus in reference to an absolute physical scale that is independent of the measurement conditions
  - Example: thermistor – electrical resistance directly related to absolute temperature scale of Kelvin
- Relative sensor produces a signal that relates to some special case
  - Example: thermocouple – produces electric voltage that is function of temperature gradient across the thermocouple wires

Dynamic Properties of Biosensors

- Ideal transmission behavior of a measuring chain is linear
  - In reality, relation is not linear, delayed and sometimes oscillating
- Signal processing is to correct for such problems

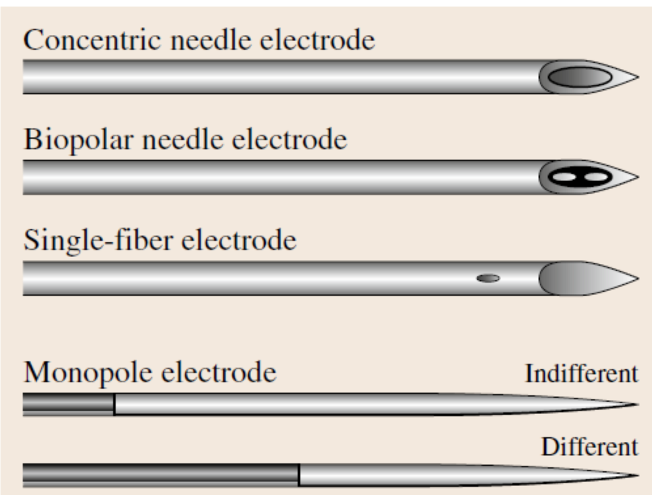


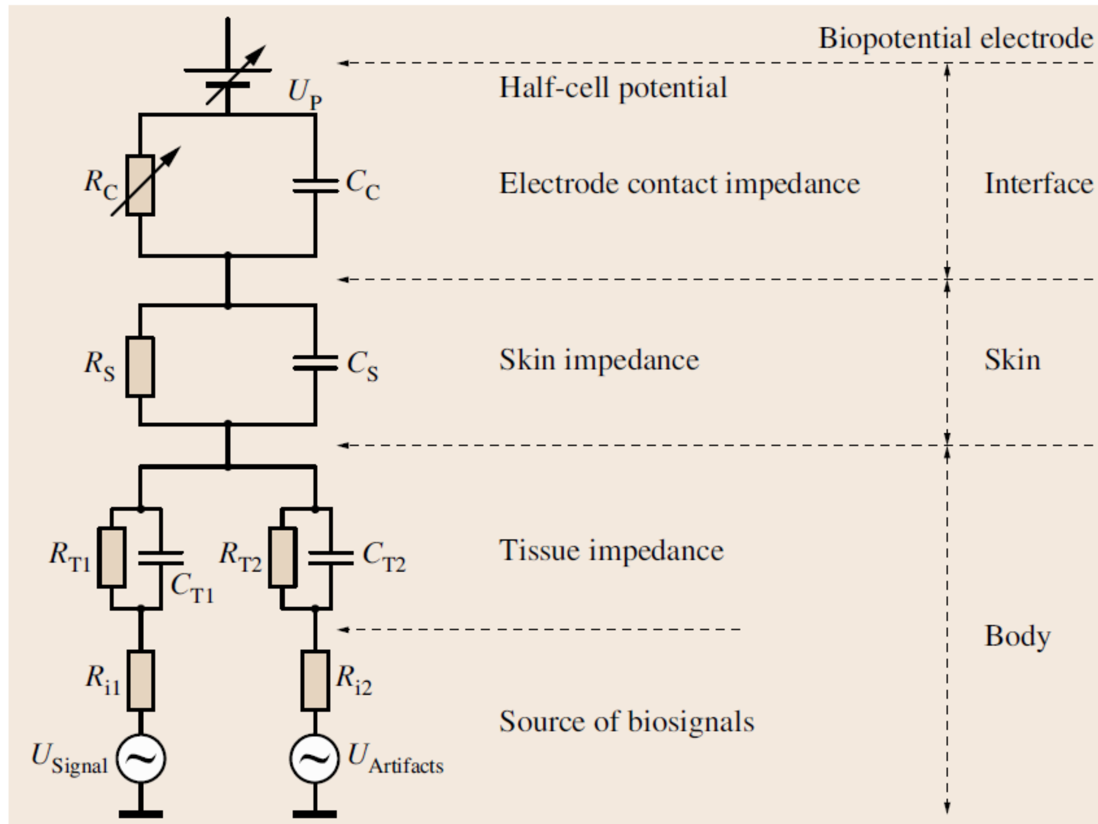
Sensing Effects

- Two basic elements in the operation of sensors
- Sensing effect
  - Physical or chemical interaction between the environment and the sensing material altering the material properties
- Transduction mechanism
  - Conversion of this material property change into a useful signal

Electric and Magnetic Transducers

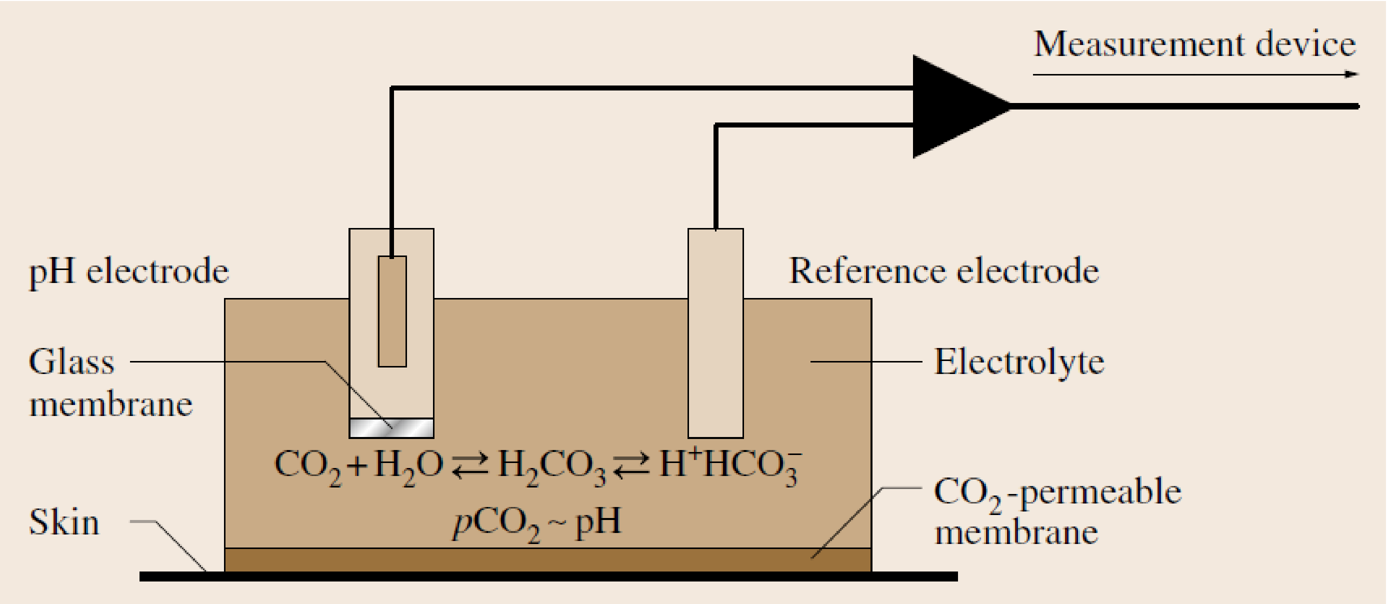
- Transduce electric signal (ion current) into electric signal (electron current)
- Two groups: microelectrodes (metal microelectrodes) and macroelectrodes (surface electrodes)





Chemoelectric Transducers

- Used for the measurement of individual chemical components in the blood, in body tissues, in the exhaled air or on the skin
  - Potentiometric sensors, based on the measurement of cell potential
  - Amperometric sensors, based on cell current
  - Conductometric sensors, based on admittance



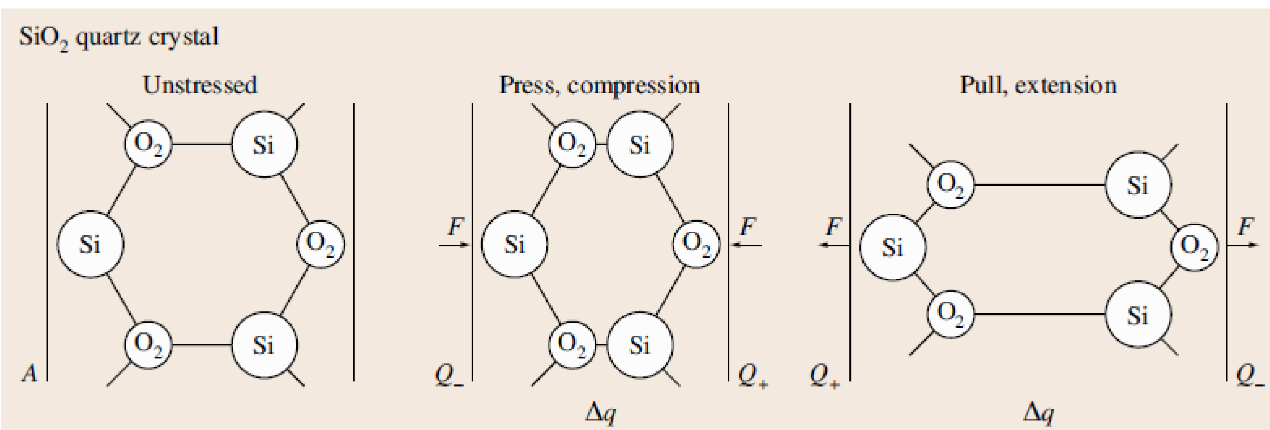
Mechanoelectric Transducers

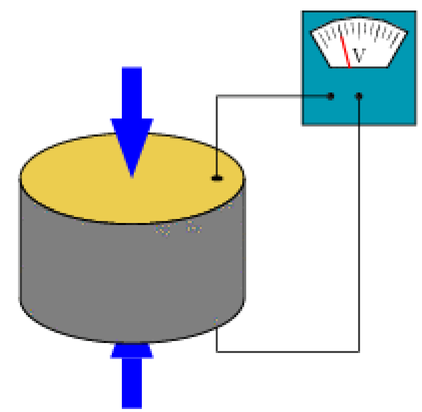
- Measure length changes, strains, pressure changes in tissue, body fluids and organs as well as for the measurement of sounds, microvibrations and blood flow
- Strain Gauge: $R=\rho L/A$ allows detecting changes in L
- Piezoresistive elements as strain gauge in a Wheatstone bridge
  - Changes in resistivity can be observed that are up to 100 times larger than the geometric effect yielding a more sensitive strain gauge
- Capacitive transducer: force applied to capacitor yielding a change in the distance between its two plates changes C

$$C_X = \varepsilon_0 \varepsilon_\gamma \frac{A}{x}$$

Piezoelectric Effect

- Production of electricity by pressure
  - Practically measured as generated voltage between two electrodes
- Piezoelectricity occurs only in insulating materials and is manifested by the appearance of charges on the surfaces of a piece of material that is being mechanically deformed

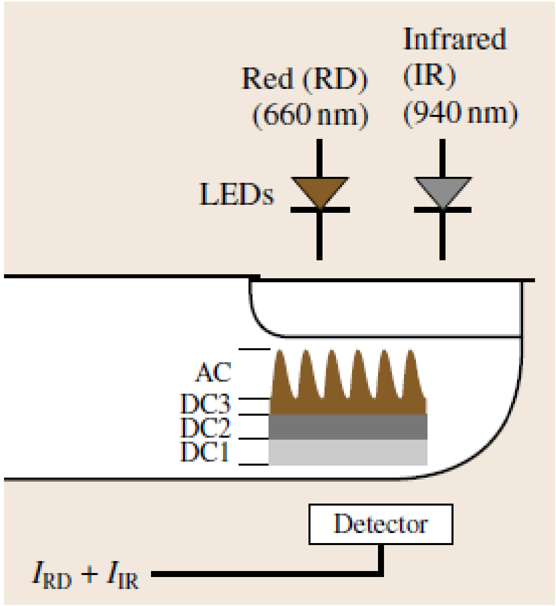




$$\Delta q = k \Delta F$$

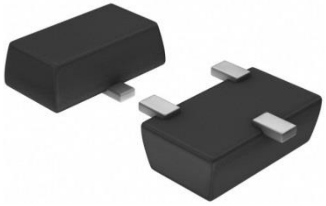
Photoelectric Effect

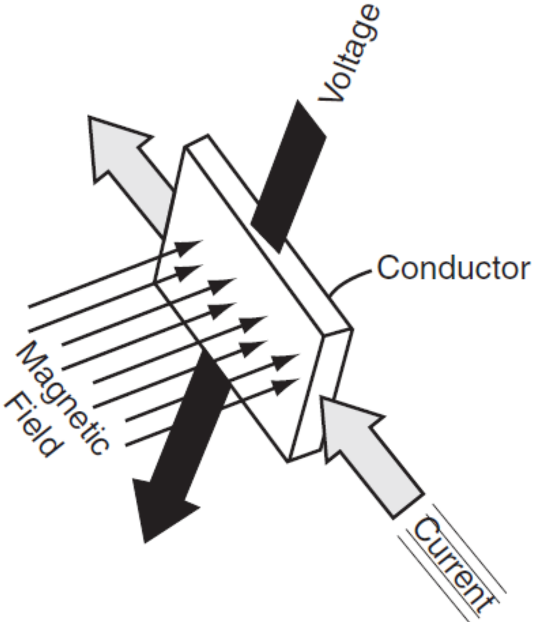
- Depending on the incident light intensity, current flowing through the sensor changes
  - Examples: photoresistors, photodiodes, and phototransistors

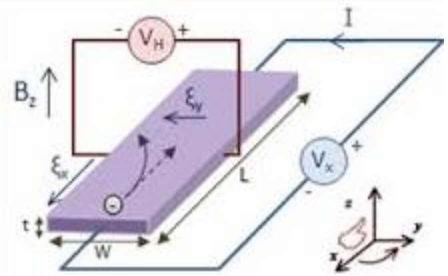


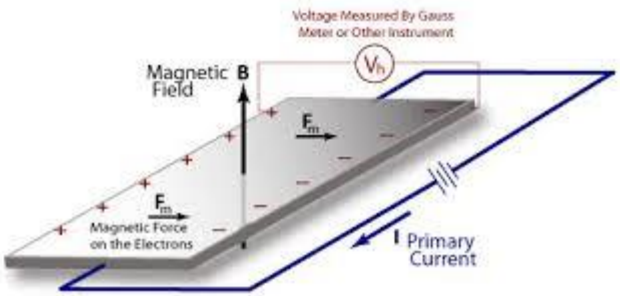
Hall Effect

- Electric current flows through material in pretty much a straight line
- When magnetic field is present, Lorentz force makes them deviate from their straight path
- With more electrons on one side of the material, there would be a difference in Hall potential (or Hall voltage) between two sides
  - Voltage proportional to electric current and strength of magnetic field







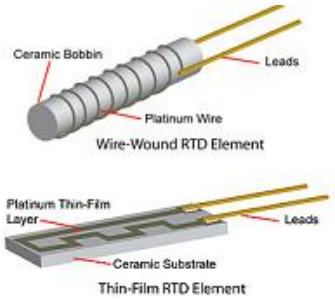


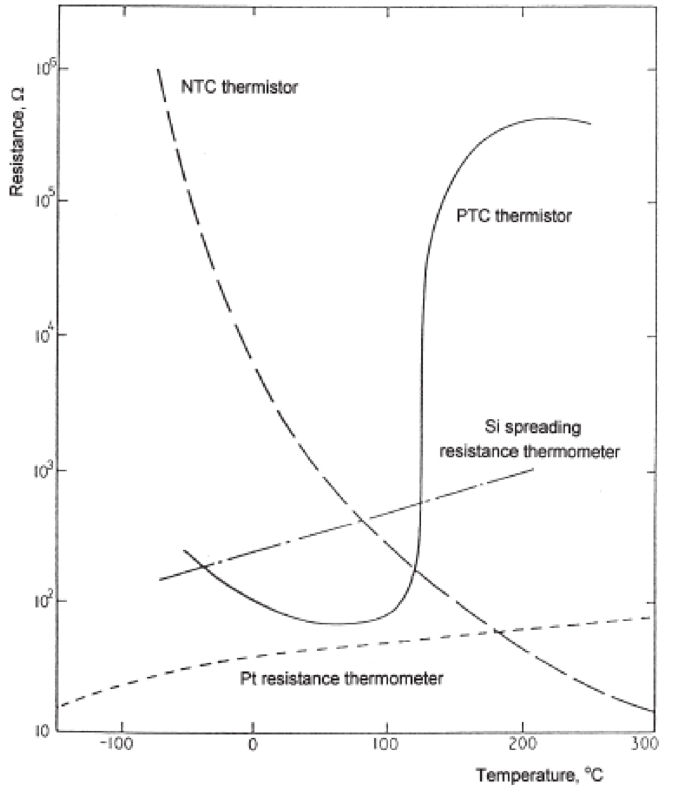
Thermoresistive Effect

- Temperature variations change electrical resistivity of conductor and semiconductor materials
- Examples: *Resistance temperature detector (RTD), Thermistor*

  - *Linear (RTD)*

$$\rho(T) = \rho_o(1 + \alpha\Delta T)$$





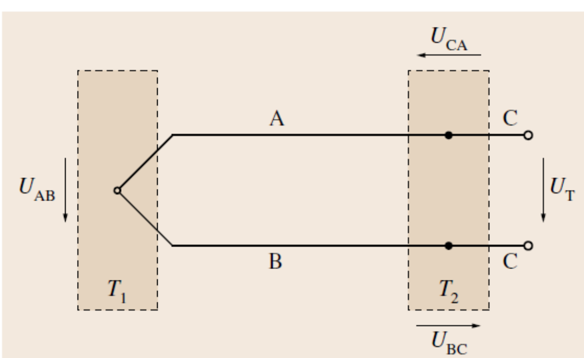
  - *Nonlinear (NTC Thermistor)*

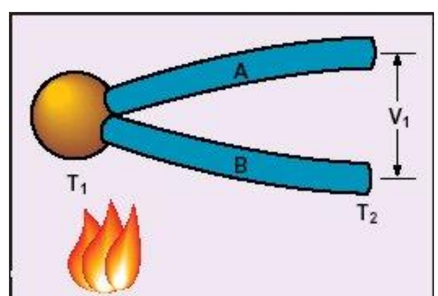
$$\rho(T) = \rho_o\exp(B/T)$$

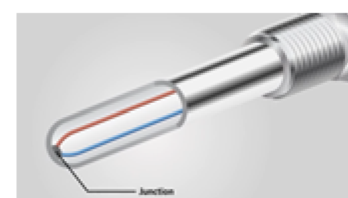
Thermoelectric Effect

- Generation of electric voltage proportional to temperature difference
- Thermoelement (thermocouple) is a junction of two conducting (metal or semiconductor) materials, A and B, electrically connected at a "hot" point of temperature, T1, while the nonconnected ends of both legs are kept at another temperature T2 ("cold" point)
  - Seebeck EMF

$$U_{\mathrm{T}} = \alpha_{\mathrm{T}} \cdot (T_2 - T_1)$$

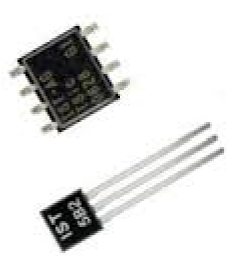


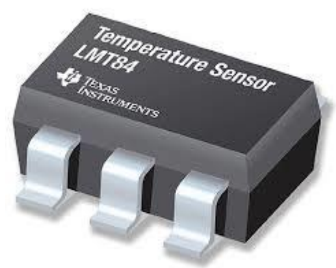




Semiconductor Temperature Dependence

- Semiconductor diodes have temperature-sensitive voltage vs. current characteristics
  - When two identical transistors are operated at a constant ratio of collector current densities, the difference in base-emitter voltages is directly proportional to the absolute temperature
- Use of IC temperature sensors is limited to applications where the temperature is within –55° to 150°C range
  - Advantages: small, accurate, and inexpensive
- Output in analog form (voltage or current proportional to temperature) or digital (communicate digital temperature value)





Comparison of Temperature Sensors

Characteristic	**Platinum RTD**	**Thermistor**	**Thermocouple**	**Temperature IC**
Active Material	Platinum Wire	Metal Oxide Ceramic	Two Dissimilar Metals	Silicon Transistors
Changing Parameter	Resistance	Resistance	Voltage	Voltage or Current
Temperature Range	-200°C to 500°C	-40°C to 260°C	-270°C to 1750°C	-55°C to 150°C
Sensitivity	2 mv/°C	40 mV/°C	0.05 mV/°C	~1 mv/°C or ~1 uA/°C
Accuracy	-45 to 100°C: ±0.5°C; 100 to 500°C: ±1.5°C; 500 to 1200°C: ±3°C	-45 to 100°C: ±0.5°C; degrades rapidly over 100°C	0 to 275°C: ±1.5 °C to ±4°C; 275 to 1260°C: ±0.5 to ±0.75%	±2 °C
Linearity	Excellent	Logarithmic, Poor	Moderate	Excellent
Response Time	2-5 s	1-2 s	2-5 s	
Stability	Excellent	Moderate	Poor	Excellent
Base Value	100 Ω to 2 kΩ	1 kΩ to 1 MΩ	< 10 mV	Various
Noise Susceptibility	Low	Low	High	High
Drift	+/- 0.01% for 5 years	+/- 0.2 to 0.5°F per year	1 to 2°F per year	0.1°C per month
Special Requirements	Lead Compensation	Linearization	Reference Junction	None
Device Cost	$60 - $215	$10 - $350	$20 - $235	$5 - $50
Relative System Cost	Moderate	Low to Moderate	Moderate	Low

Bioelectric and Biomagnetic Signals

Signal	Frequency (Hz)	Amplitude (mV)
ECG (heart)	0.2–200	0.1–10
EEG (brain)	0.5–100	2–1000 μV
EMG (muscle)	10–10 000	0.05–1
EGG (stomach)	0.02–0.2	0.2–1
EUG (uterus)	0–200	0.1–8
ERG (retina)	0.2–200	0.005–10
EOG (eye)	0–100	0.01–5
FAEP (brain stem)	100–3000	0.5–10 μV
SEP (somatosensory system)	2–3000	0.5–10 μV
VEP (visual system)	1–300	1–20 μV

Biomechanical Signals

Signal	**Spezification**	**Amplitude**	**Conversion**
Pulse (rate)		$720\text{–}200\ \mathrm{min}^{-1}$	
Breathing (rate)		$5\text{–}60\ \mathrm{min}^{-1}$	
Blood pressure (arterial)	Systole	8–33 kPa	60–250 mmHg
	Diastole	5–20 kPa	40–150 mmHg
Blood pressure (venous)		0–4 kPa	0–30 mmHg
Intraocular pressure		0–7 kPa	0–50 mmHg
Blood flow		0.05–5 l/min	
Blood flow velocity		0.05–40 cm/s	
Respiratory flow velocity		20–120 cm/s	
Cardiac output		3–8 l/min	
Respiratory volume		200–2000 ml/gasp	
Muscle work		10–500 W	
Blood volume	Adults	7000 ml	
Amount of urine	Adults	1500 ml/d	
Nerve conduction velocity	Median nerve	50–60 m/s	

Bioacoustic Signals

- Includes sounds of the upper respiratory tracts (snoring, speech), lung sounds and heart sound
- Can be registered with a microphone or a stethoscope

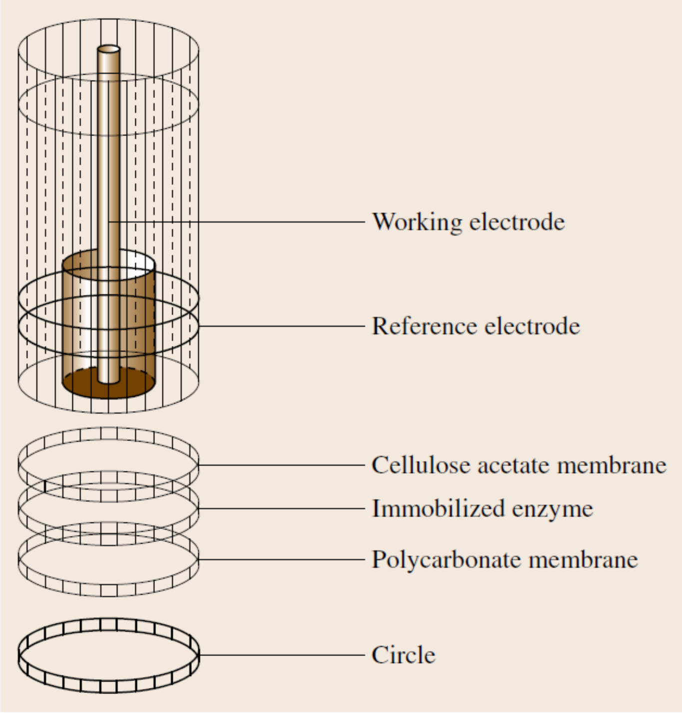
Signal	Specification	Frequency (Hz)
Heart sound	Adults	15–1000
	Fetus	15–150
Lung		0.2–10

Biochemical Signals: Glucose

- Can be determined *in vivo* or *in vitro*
- They can be registered directly or indirectly by reaction
- Example: Glucose identification
  - Amperometrically detected by the O_2 consumption or the hydrogen peroxide formation

$$\text{Glucose} + O_2 \xrightarrow{\text{GOD}} \text{Gluconolactone} + H_2O$$

$$\xrightarrow{H_2O_2} \text{Gluconic acid} + H_2O_2$$

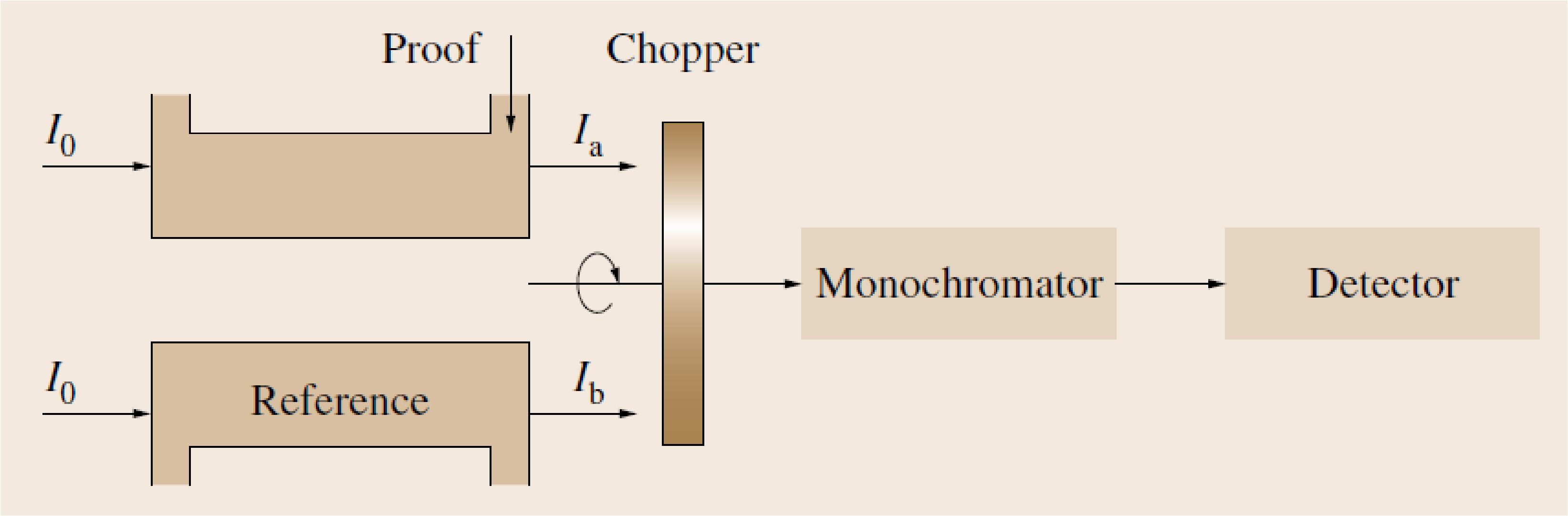


Biochemical Signals: Concentration

- Infrared spectrometers measure the intensity attenuation of infrared radiation after passing a measuring cuvette and compare it with a reference

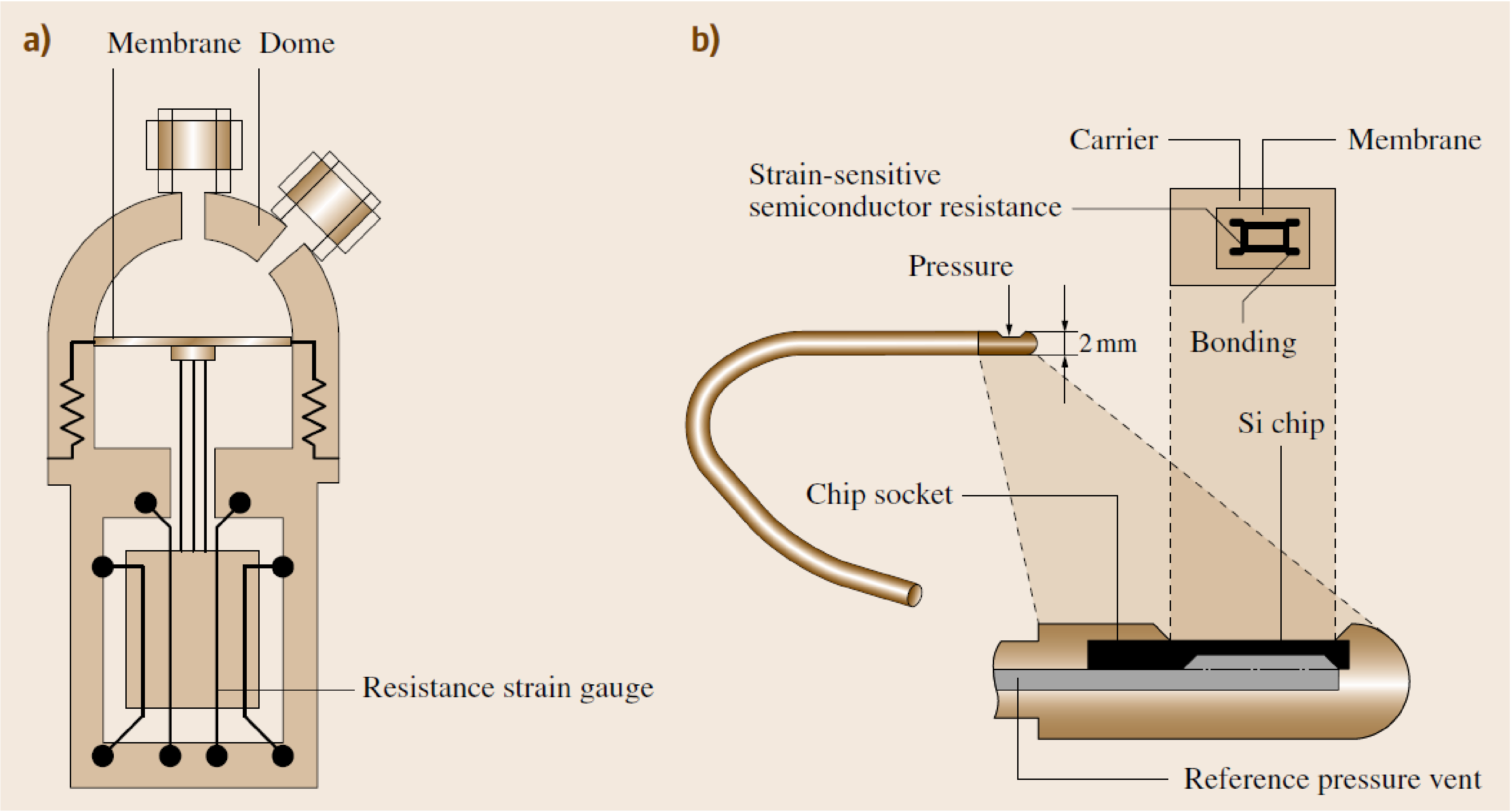
$$I_a = I_0 e^{-kcl}$$

  - I_a :output intensity, I_0 :input intensity, c :concentration, l :layer thickness, and k :constant of proportionality



Biomechanical Signals: Pressure

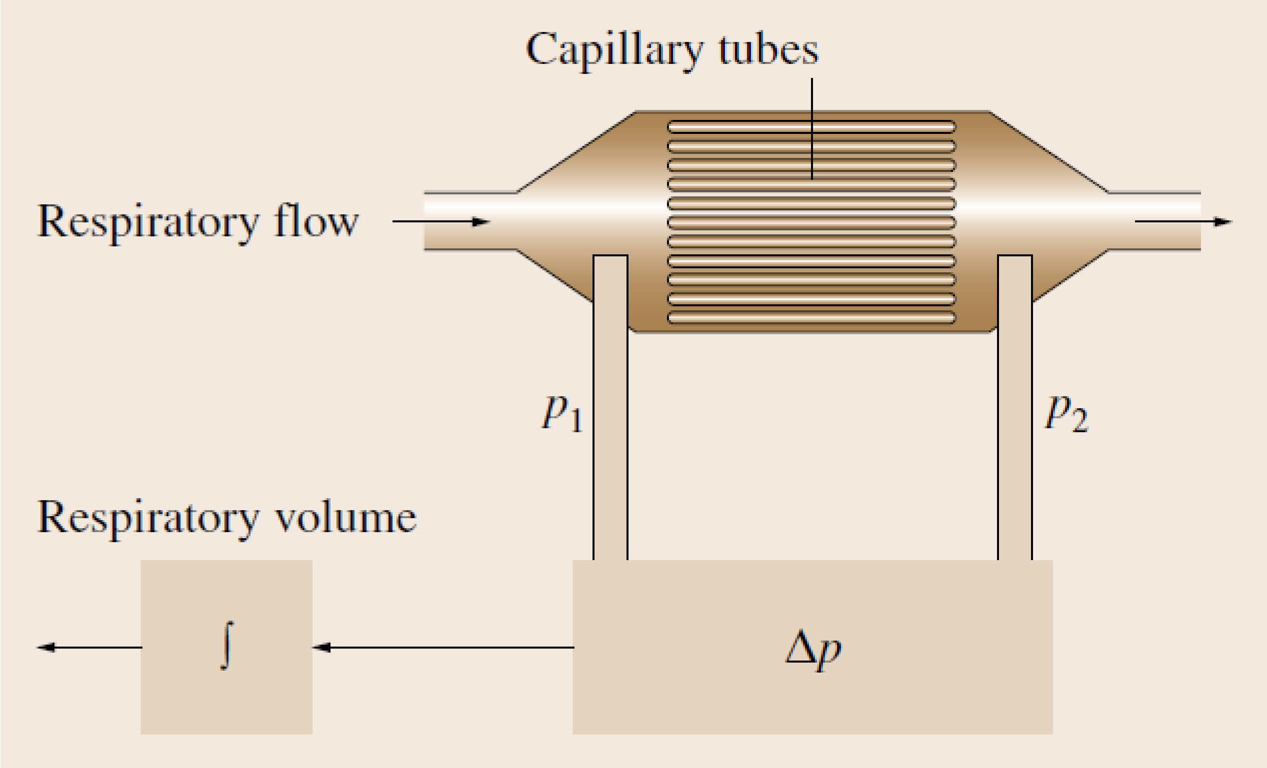
- IBP: Invasive probe



Biomechanical Signals: Volume

$$\dot{V} = \frac{\pi r^4 \Delta p}{8 l \eta}$$

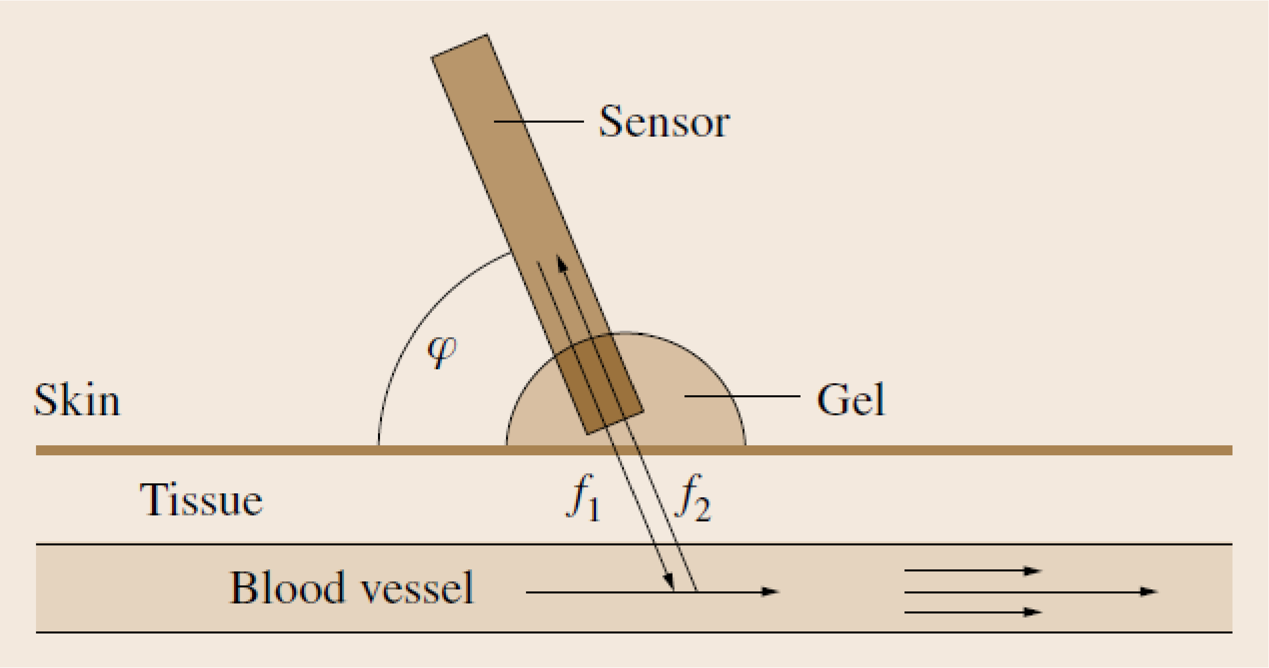
$$V = \int_0^t \dot{V}\, dt$$



Biomechanical Signals: Flow Velocity

- Doppler effect

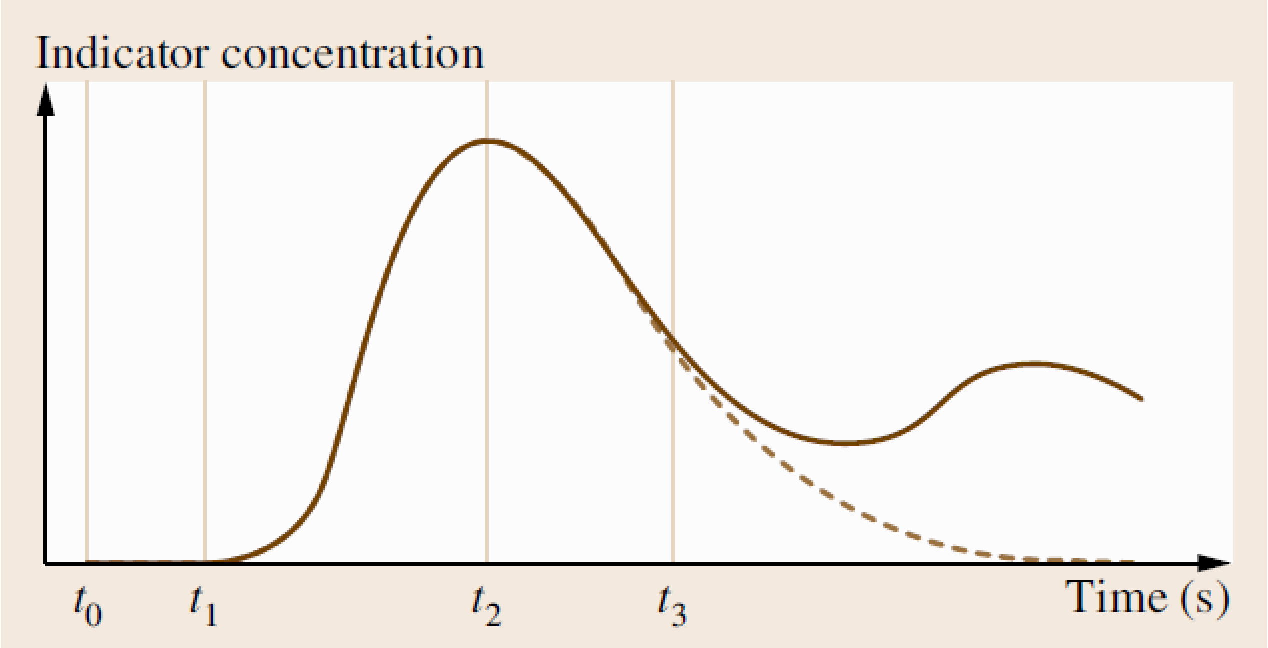
$$\Delta f = f_1 - f_2 = f_1 \frac{2v\cos\varphi}{c}$$



Biomechanical Signals: Cardiac Output

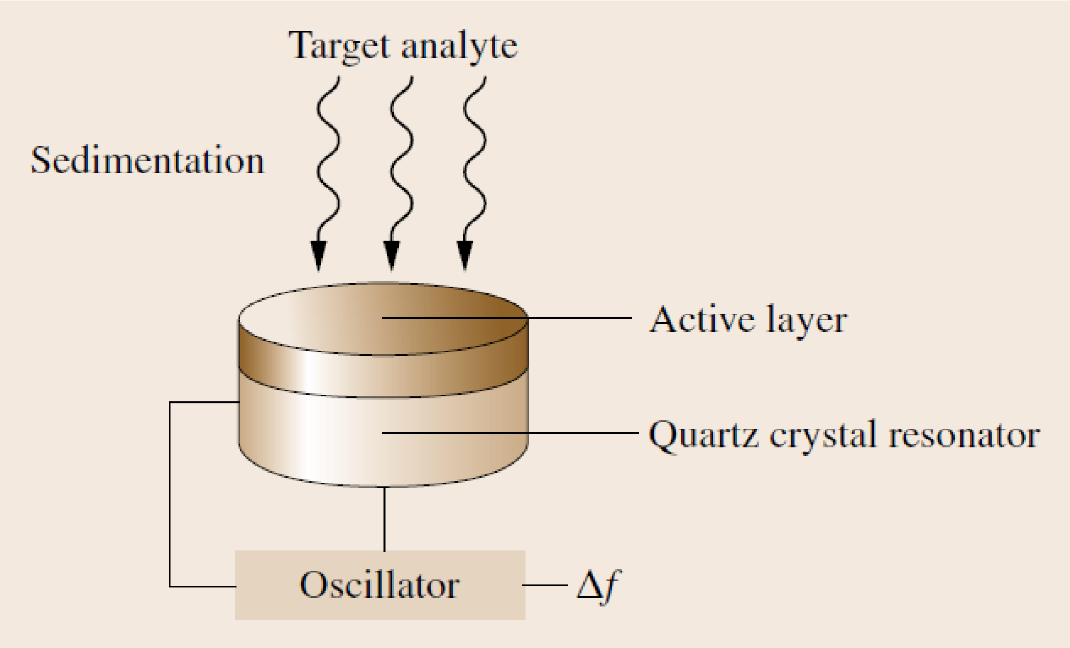
- Indicator-Dilution method

$$\text{CO} = \frac{m_0}{\int_{t_0}^{\infty} c(t)\,\mathrm{d}t}$$



Biomechanical Signals: Mass

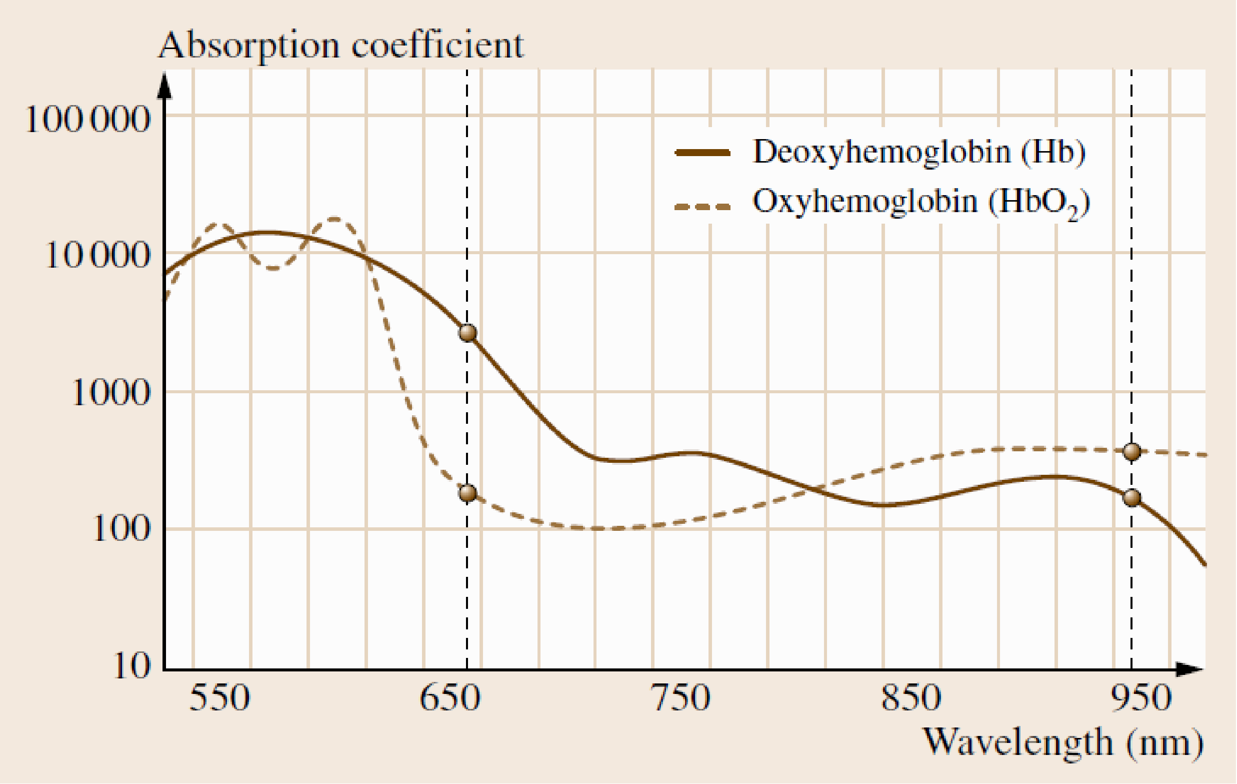
- Quartz microbalance
  - measurement is based on resonance frequency shift of an oscillating crystal due to deposition of substances on the crystal surface



$$\Delta f = \frac{2.3 \times 10^6 f_0^2 \Delta m}{A}$$

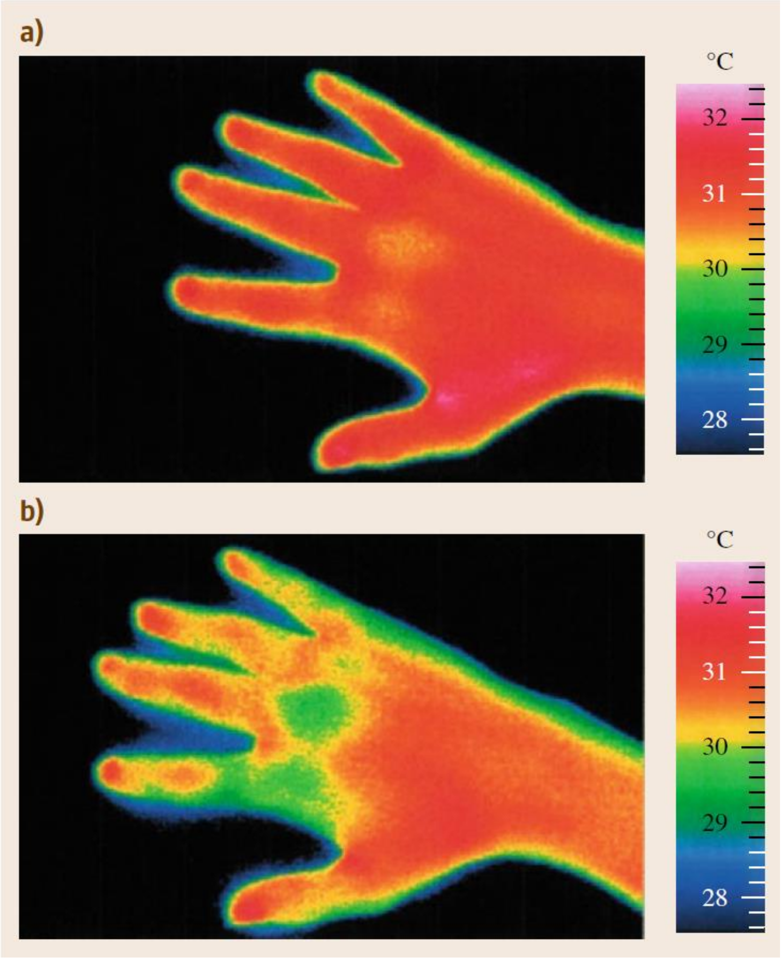
Bioptical Signals: O_2 Saturation

- Evaluation of color (skin)
- Evaluation of O_2 saturation based on the different absorption characteristics of oxygenated and deoxygenated hemoglobin



Biothermal Signals: Thermography

- The Most important biothermal signal is the body temperature
- Using thermography, temperature distribution on a skin area can be determined.
- Pathological changes can be detected from distribution relative to normal areas
  - Example: reduction of blood flow due to smoking

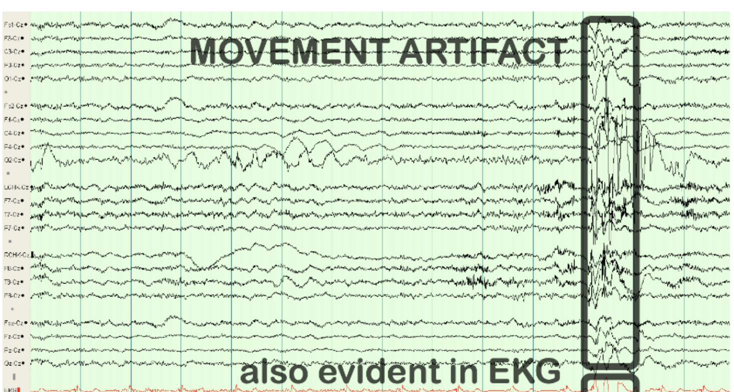


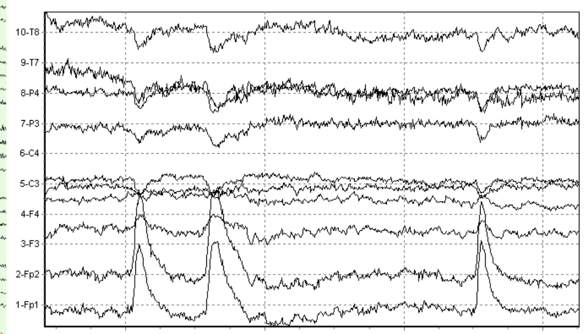
Artifacts

- Biosignals are often superimposed by interferences, called artifacts
- Those are registered together with the wanted signal and impede or preclude its evaluation
- With respect to their point of origin, artifacts can be divided into biological and technical artifacts
- They are caused by metrology, applied method and by patient

Artifacts: Examples

- Physiological artifacts are biological signals superimposed on measured signal from different
  - Example: ECG, EOG, or EMG related artifacts when measuring EEG
- Technical artifacts are errors in recording
  - Examples: cable movements, defects and absence of grounding
- Externally caused technical artifacts from coupled interferences
  - Example: noise from electromagnetic fields on measured ECG signals



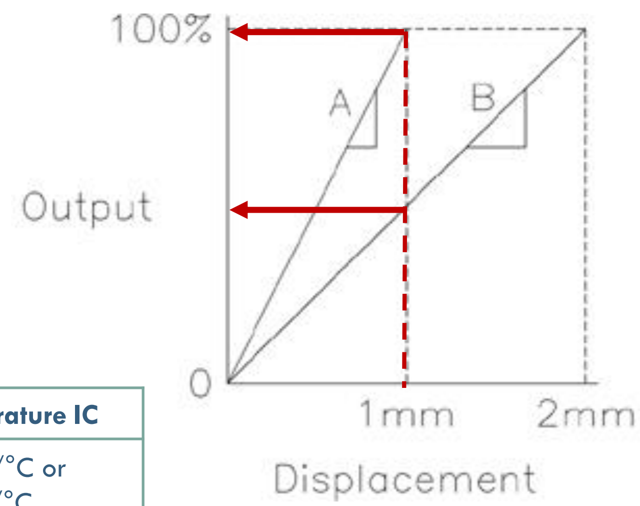


Sensor Specifications

Sensitivity	Stimulus range (span)
Stability (short and long term)	Resolution
Accuracy	Selectivity
Speed of response	Environmental conditions
Overload characteristics	Linearity
Hysteresis	Dead band
Operating life	Output format
Cost, size, weight	Other

Sensor Sensitivity

- Sensitivity is typically defined as the ratio of output change for a given change in input
  - Another definition can be given as the slope of the calibration line relating the input to the output (i.e., ΔOutput/ΔInput)
- Example: Sensor A is more sensitive than sensor B
  - Same displacement, higher output from A
- Example: Temperature sensors



Characteristic	Platinum RTD	Thermistor	Thermocouple	Temperature IC
Sensitivity	2 mv/°C	40 mV/°C	0.05 mV/°C	~1 mv/°C or ~1 uA/°C

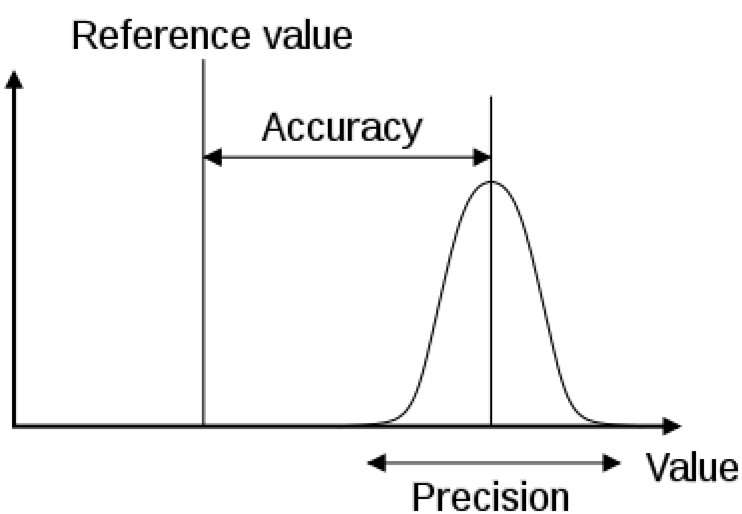
Sensor Dynamic Range

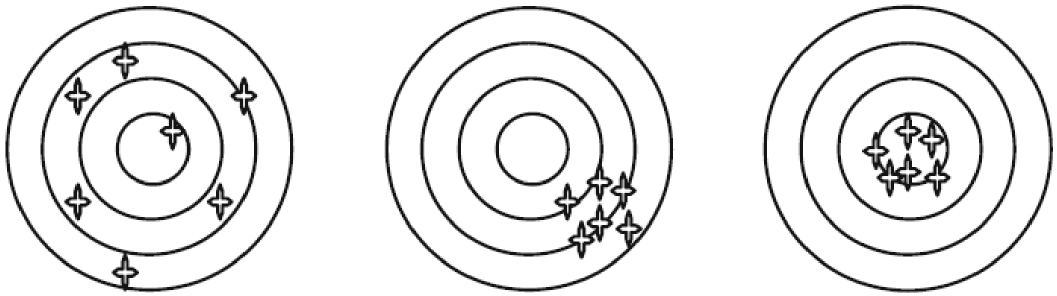
- Dynamic range of a sensor corresponds to the minimum and maximum operating limits that the sensor is expected to measure accurately
  - Also called stimulus range or span
- Example: Temperature sensors have very different ranges that suit different applications
  - From measuring human temperature to measuring temperature in steam sterilizers

Characteristic	**Platinum RTD**	**Thermistor**	**Thermocouple**	**Temperature IC**
Temperature Range	-200°C to 500°C	-40°C to 260°C	-270°C to 1750°C	-55°C to 150°C

Sensor Accuracy and Precision

- Accuracy refers to the difference between the true value and the actual value measured by the sensor
- Precision refers to degree of measurement reproducibility
  - Very reproducible readings indicate a high precision
- Precision should not be confused with accuracy
  - Measurements may be highly precise but not necessary accurate





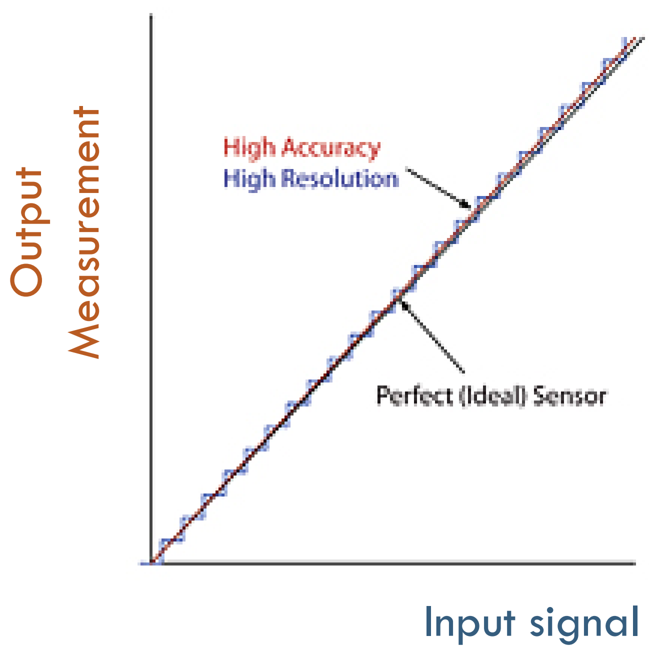
Low precision - low accuracy

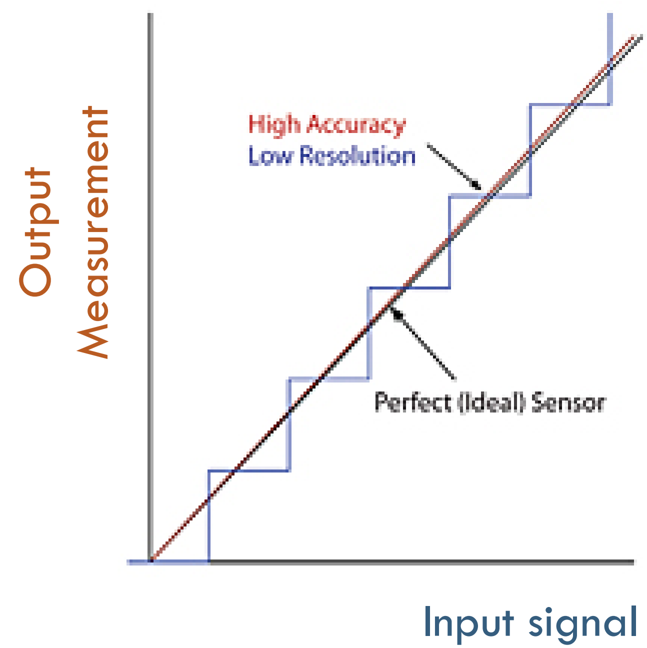
High precision - low accuracy

High precision - high accuracy

Sensor Resolution

- Resolution is defined as the smallest change of the measurand that can produce a detectable change in the output signal
- Example: sensors with digital output only change in steps of 1 bit
  - 12-bit sensors will have better resolution than 8-bit sensors



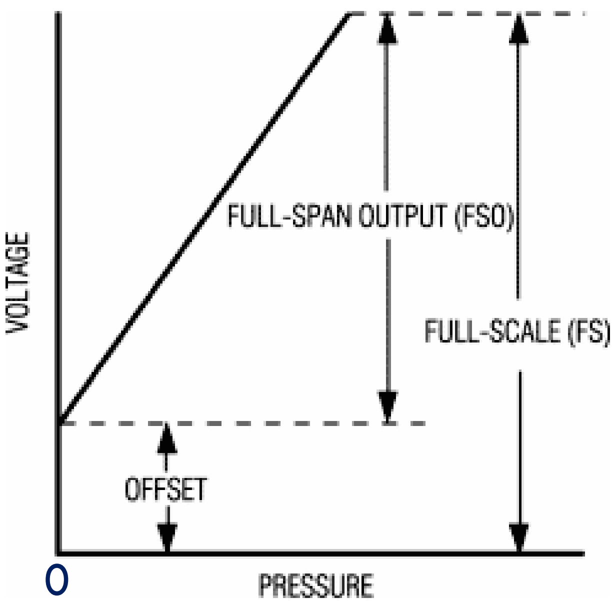


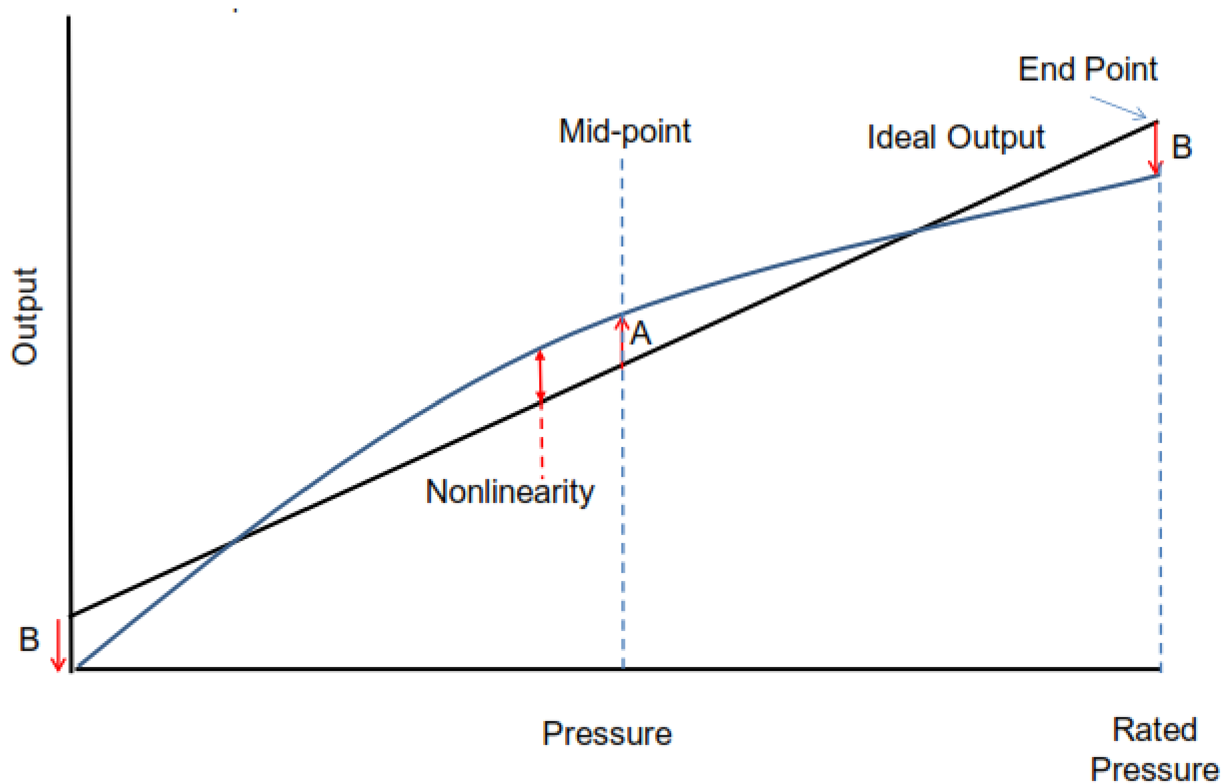
Sensor Reproducibility

- Reproducibility is the degree to which an experiment or study can be accurately reproduced, or replicated, by someone else working independently or over time
  - Sometimes called repeatability or stability (short-term and long-term)
- Reproducibility can vary depending on the measurement range
  - Readings may be highly reproducible over one range and less reproducible over a different operating range

Sensor Linearity and Offset

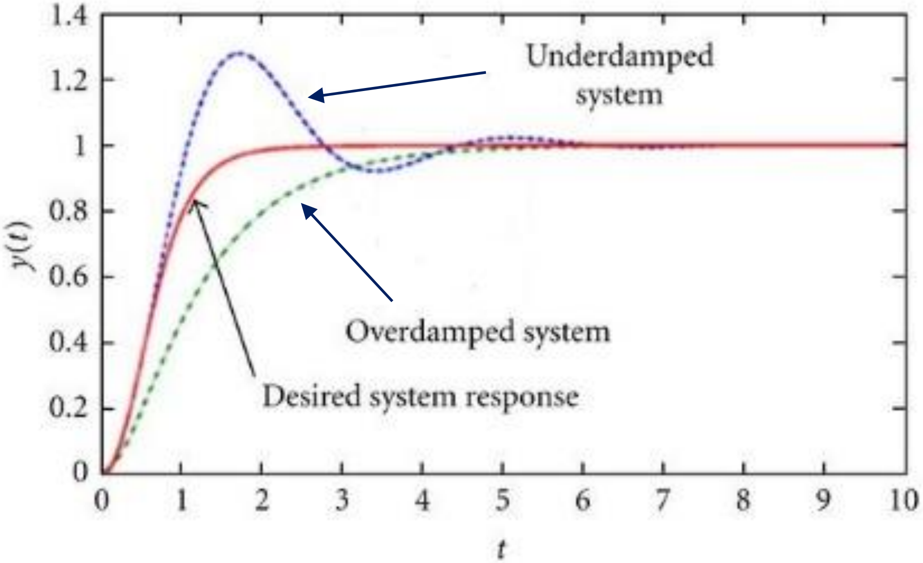
- Linearity is a measure of the maximum deviation of any reading from a straight calibration line
- Offset refers to the output value when the input is zero

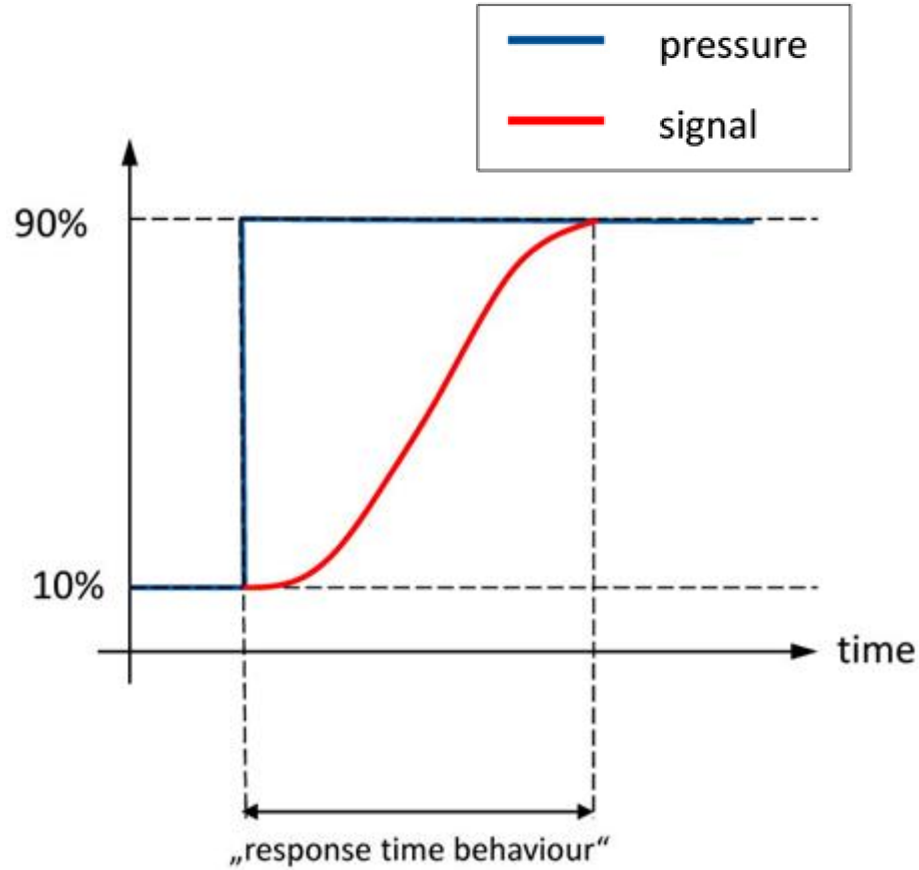




Sensor Response Time

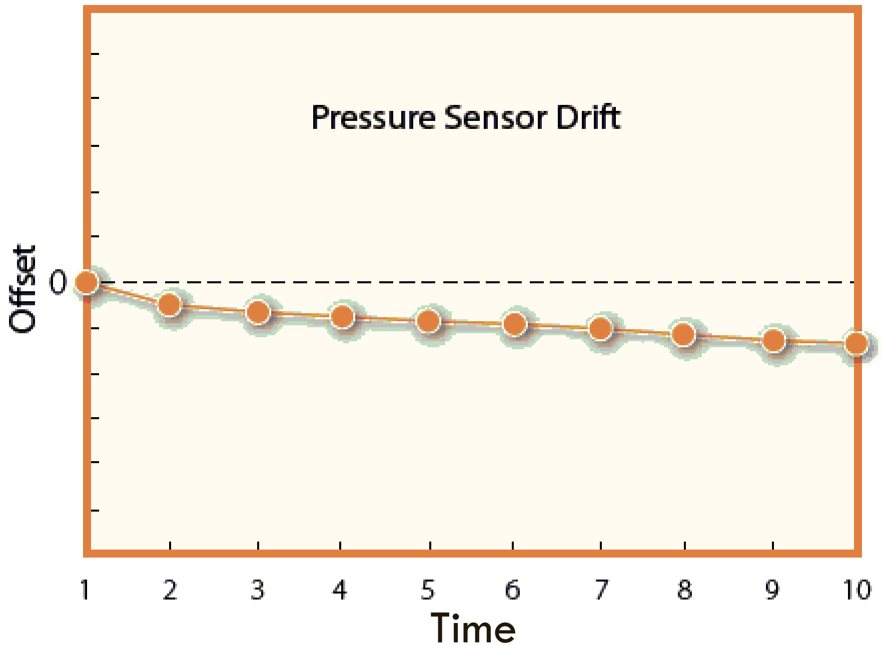
- Response time indicates the time it takes a sensor to reach a stable (steady-state) value when the input is changed
  - Same as recovery time

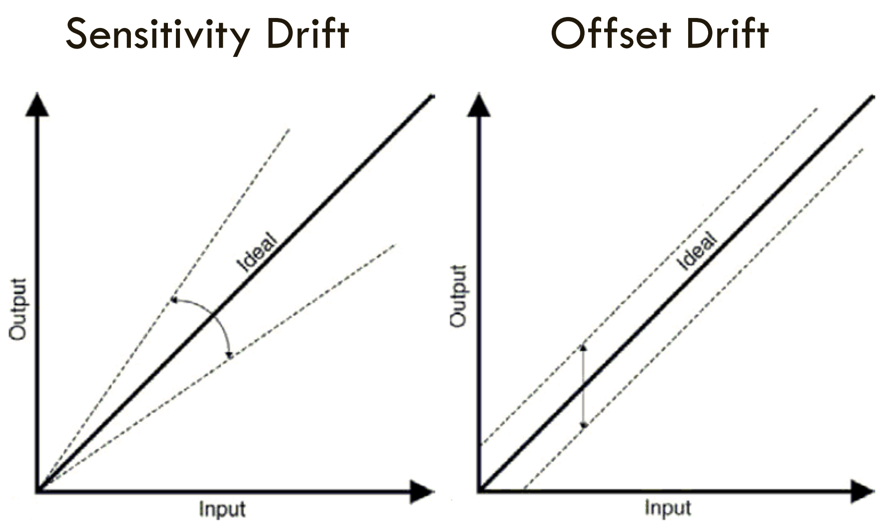




Sensor Drift

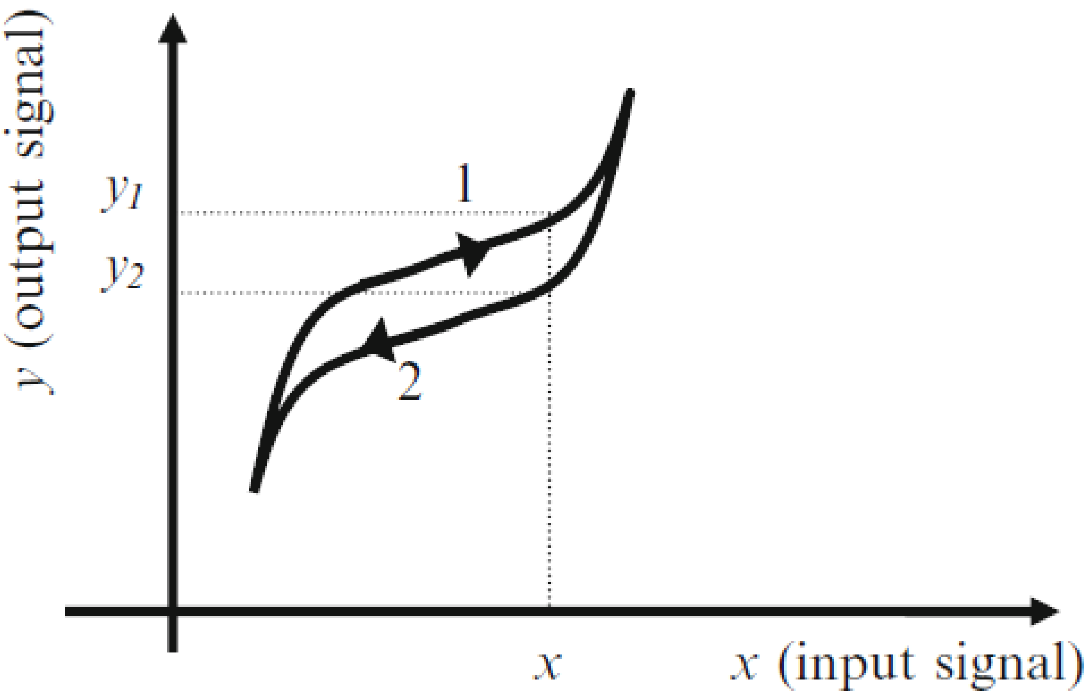
- Drift is a gradual change in the measurement output is seen while the measurand actually remains constant
  - Drift is undesired systematic error that is unrelated to the measurand
  - Drift may affect offset and/or sensitivity





Sensor Hysteresis

- Hysteresis is the difference between output readings for the same measurand, depending on the trajectory followed by the sensor
  - Depending on whether path 1 or 2 is taken, two different outputs are obtained for the same input



Practical Sensor Applications

Biomedical Application Field	Measurand	Sensor/Measurement Type	Basis of the Sensing Effect	Sensor Structure	Present Status
Body surface temperature image	temperature mapping	pyroelectric vidicon	pyroelectric	capacitor	CA*
		parabolic antenna	EM waves	microwave antenna	CA
		IR camera	photo- or pyroelectric	SSD, POSFET	CA, R&D*
Ultrasound imaging	ultrasound impulse time of flight	transmitter/receiver arrays	piezoelectric	capacitor array	CA
				POSFET array	R&D
Digital teleradiology	X-ray image	Charpak-detector	ionization	vacuum tube array	R&D, CA
		scintillation detector array	fluorescence + electron-hole generation	phosphor-CCD array or mosaic	CA
X-ray computer tomography (CT)	X-ray intensity profile(s)	scintillation or semi-conductor detector array	fluorescence + photoelectric effect	BGO/LSO/CWO + PEM/PIN/APD	CA
			photoelectric effect	Si-SSD, HPGe	R&D
Angiography	γ-intensity map	scintillation Anger camera	fluorescence + photoelectric effect	NaI + PSPEM	CA
Single photon emission CT (SPECT)	γ-intensity distribution	scintillation γ-camera array	fluorescence + photoelectric effect	div. collimator + NaI + PSPEM	CA
			photoelectric effect	Ge, CZT array	R&D
Positron emission tomography	γ-intensity distribution	scintillation γ-detector block rings	fluorescence + photoelectric effect	segmented BGO + PSPEM/PIN/APD	CA
Nuclear magnetic resonance imaging	magnetic pulses	special arrangement of coil inductors	EM induction	cooled Cu or HTS (planar) coils	CA
Biomagnetism	magnetic pulses	SQUID	superconductor quantum interference	1 or 2 Josephson junctions	CA
Ophthalmoscopy	light parameters	SLO, SLT, SLP, OCT	optical	photodiode, APD	CA
Blood vessel lumen	flow mapping	Doppler sonography	piezoelectric	capacitor array	CA
		NMRI	EM induction	EM coils	CA
		MBI	Hall effect	Hall sensor	R&D

*CA = Commercially Available; R&D = Research and Development

Practical Sensor Applications

Biomedical Application Field	Measurand	Sensor/Measurement Type	Basis of the Sensing Effect	Sensor Structure	Present Status
Body core temp.	temperature	body thermometer	thermoresistive	thermistor	CA
		ear thermometer	thermoelectric,	metal junction	CA
			pyroelectric	capacitor	CA
Blood pressure	pressure	Korotkoff	piezoelectric	capacitor	CA
		oscillometric	piezoresistive	Si resistor bridge	
Heart rate, apnea Breathing wave Fetal heart rate	pressure pulses	fingertip sensor, phonocardigraph, flexible belt	piezoelectric	capacitor	CA
Glucose in blood and tissues	glucose concentration	GOD-based biosensors	catalytic reaction and transduction with the products	electrochemical cells, optrodes, and calorimetric types	some types CA, others in R&D
		low-potential cyclic voltammetry	acidic behavior of glucose	electrochemical cell	R&D, some types CA
		optical polarimetry	optical rotation	interferometer	
		SPR	plasmon resonance	optrode	R&D
		near IR spectroscopy	attenuated total reflection	optosensors	R&D, CA
Hearing aid	acoustic pressure	microphones	electret-based	capacitor, Si-micromachined	CA
Artificial retina	optical image	planar array on VLSI signal conditioner	photoelectric	photodiode array	R&D
Artificial limbs	tactile image	tactile sensor array	piezoresistive	resistor array	R&D, some types CA
			optical	phototr. array	
			capacitive	capacitor array	
			magnetoresistive	permalloy array	
			piezoelectric	capacitor array	
			ultrasonic	transmitter array	

Practical Sensor Applications

Biomedical Application Field	Measurand	Sensor/Measurement Type	Basis of the Sensing Effect	Sensor Structure	Present Status
Hemodynamic blood pressure	pressure	invasive	piezoresistive	Si resistor bridge	CA
		catheter tip	piezoresistive	Si resistor bridge	
			optical reflectance	optrode	R&D
Blood temp.	temperature	catheter tip	thermoelectric, thermoresistive	Si-diode, thermo-couple, thermistor	CA
			phosphorescency	optrode	R&D
Blood flow	flow rate, velocity	SBF sensor	calorimetric	thermopiles	R&D
		hot-film anemometer	calorimetric	thermistor	CA
		Doppler sonography	piezoelectric	twin-capacitor	CA
		electrodynamic	Lorentz-force effect	magnet + contacts	CA
Joint angle	angular displacement	monitor gloves, etc.	piezoresistive	strain gauge	CA
Internal ocular pressure (IOP)	pressure	tonometer	piezoresistive	Si resistor bridge	R&D
Respiratory flow	air flow rate	Fleish sensor	Venturi + piezoresistive	Si resistor bridge	CA
		turbine	Hall effect	Hall sensor	CA
		vortex shedding	piezoelectric	capacitor	R&D
		catheter tip	freflectance	optical fiber	R&D
		nose clip	calorimetric	Si or film thermistor bridge	CA
in vitro nuclear diagnostics	β-intensity distribution	β-detector array	photoelectric effect	Si-APD array	R&D, CA
Electronic dosimeter	X- or γ-dosis	semiconductor detector + CMOS counter	photoelectric effect	Si-SSD	CA
Bioelectric signals	electric impulses	pickup electrodes	no transduction effect	electrode array	CA, R&D

Practical Sensor Applications

Biomedical Application Field	Measurand	Sensor/Measurement Type	Basis of the Sensing Effect	Sensor Structure	Present Status
Blood dissolved O_2	pO_2	Clark electrochemical cell	permeation through membranes	amperometric cell	CA
		transcutaneous Clark cell	permeation through skin and membranes	heat-controlled amperometric cell	CA
		optical-fiber technique	fluorescence	optrode	CA
Blood dissolved CO_2	pCO_2	Stow-Severinghaus cell	permeation through membranes	poteniometric cell, pH-ISFET	CA
		transcutaneous Stow-Severinghaus cell	permeation through membranes	heat-controlled potenciometric cell	CA
		optical-fiber technique	colorimetric effect	optrode	CA, R&D
Blood acidity	pH	electrochemical	H^+-ion-complexation in membranes	potentiometric cell, pH-ISFET	CA CA
		optical fiber	colorimetric effect fluorescence	optrode optrode	R&D
Blood oxygen saturation	SO_2	invasive oximetry	absorbance/reflectance	pure-fiber optrode	CA
		ear oximetry	spectrum variations of hemoglobin	photodiodes	CA
		pulse oximetry		photodiodes	CA
Cerebral oxygenation	Cytochrome oximetry	tissue oximetry	reflectance variations of cytochrome oxidase	photodiodes	R&D
Ionic compounds in blood	Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NH_4^+ concentrations	electrochemical	ion complexation in membranes	poteniometric cells, ISFETs	CA, R&D
Gastric acidity	pH	electrochemical	ion complexation in membranes	poteniometric cells, ISFETs	CA, R&D
		optical fiber	colorimetric	optrode	R&D
Sweat analysis	Na^+/Cl^- concentration	electrochemical	ion complexation in membranes	Na^+/Cl^- ISFETs	R&D

Practical Sensor Applications

Biomedical Application Field	Measurand	Sensor/Measurement Type	Basis of the Sensing Effect	Sensor Structure	Present Status
Tissue acidity and oxygenation	pH/pO_2 mapping	scanning electrochemical microscopy	electrochemical	microelectrodes and their arrays	R&D
Metabolites and other substrates in blood	urea, uric acid, lactate, cholesterol, ATP, etc.	enzymatic biosensors	catalytic reaction and transduction with the products	electrochemical cells, optrodes, and calorimetric types	mainly R&D
		living biosensors			
Immunoreaction reading	antigens/antibodies	immunosensors	chemical affinity and recognition + indirect/direct sensing	electrochemical, gravimetric	mainly R&D
				SPR, SPRS	CA
Macromolecules in blood and tissues	DNA	DNA sensors	chemical recognition + direct sensing	BAW, SPR	R&D
	or DNA segment recognition	DNA or genetic chips	or with labeling	fluorescent readout	CA
Pharmacological effects on bacteria	dpH/dt	microphysiometer	pH-shift due to bacterial metabolism	LAPS	R&D

Further Reading and Assignments

- Chapter *46 of Springer Handbook of Medical Technology (2011)*.
- Chapter 4 of *Sensors in Biomedical Applications* (2000).
- Chapter 2 of Sensors, An Introductory Course (2013).

- Check class web site for problem sets