Biomedical Instruments Design

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Medical Instrumentation

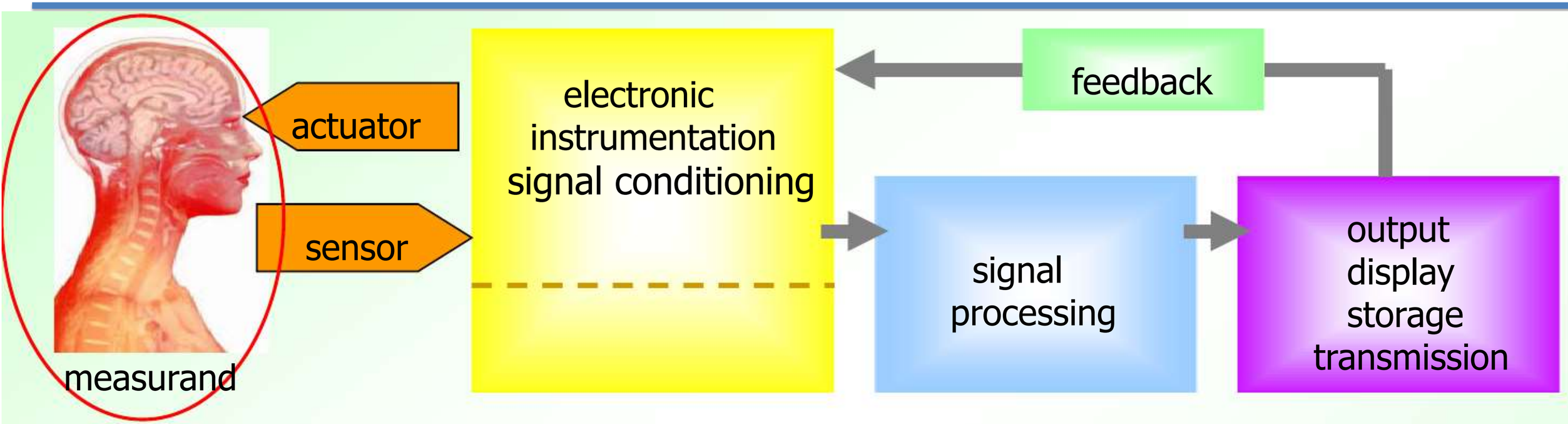
- Design of instrument must match
  - Measurement needs (environmental conditions, safety, reliability, etc)
  - Instrument performance (speed, power, resolution, range, etc)

- A medical device is
  - "any item promoted for a medical purpose that does not rely on chemical action to achieve its intended effect"
    - [Medical Device Amendments (Public law 94-295)]
    - i.e., any electrical or mechanical device for medical applications
      - this class will focus on electrical devices

- Difference from any conventional instrument
  - source of signals is living tissue
  - energy is applied to the living tissue

- Biomedical instrumentation (BI) design requirements?
  - Reliability and Safety

Generalized Medical Instrumentation System

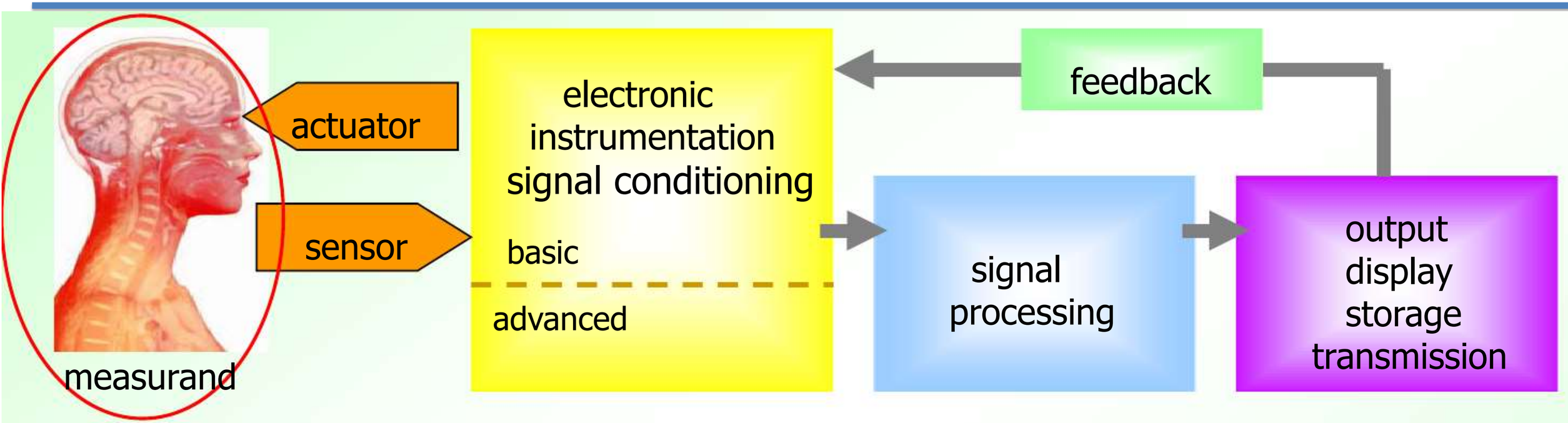


- **Measurand:** Physical quantity, property or condition that the system measures
- Types of biomedical measurands
  - Internal – Blood pressure
  - Body surface – ECG or EEG potentials
  - Peripheral – Infrared radiation
  - Offline – Extract tissue sample, blood analysis, or biopsy
- Typical biomedical measurand quantities
  - Biopotential, pressure, flow, dimensions (imaging), displacement (velocity, acceleration and force), impedance, temperature and chemical concentration

Medical and Physiological Parameters

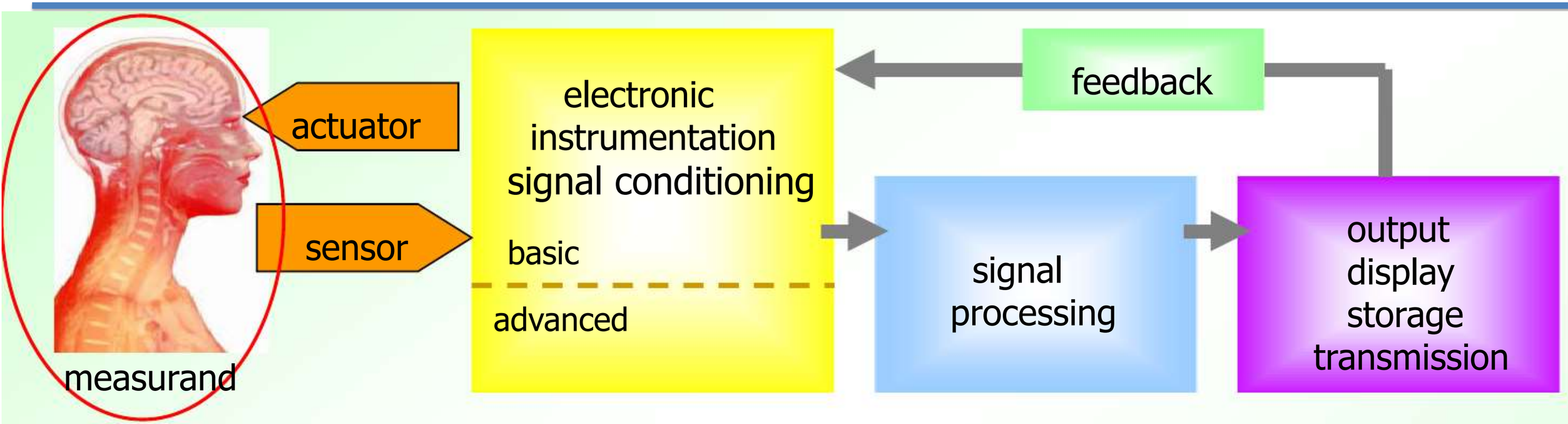
Parameter	Range	Frequency	Sensor
Blood flow	1-300 ml/s	dc – 20 Hz	Flowmeter (ultrasonic)
Arterial blood pressure	25-400mm Hg	dc – 50 Hz	strain-gage
ECG	0.5 – 4 mV	0.01 – 250 Hz	Skin electrodes
EEG	5 – 300 microV	dc – 150 Hz	Scalp electrodes
EMG	0.1 – 5 mV	dc – 10,000 Hz	Needle electrodes
Respiratory rate	2 – 50 breaths/min	0.1 – 10 Hz	Strain-gage, nasal thermistor

Sensor



- A **sensor** converts physical measurand to an electrical output
- Sensor requirements
  - Selective – should respond to a specific form of energy in the measurand
  - Minimally invasive (invasive = requiring entry into a part of the body)
    - sensor should not affect the response of the living tissue
- Most common types of sensors in biomedical systems
  - displacement
  - pressure

Signal Conditioning



- **Signal Conditioning:** Amplification and filtering of the signal acquired from the sensor to make it suitable for display
- General categories
  - Analog, digital or mixed-signal signal conditioning
  - Calibration (adjustment of output to match parameter measured)
  - Compensation (remove of undesirable secondary sensitivities)

Units of Measurement

- Fundamental SI units
  - SI = Systemes Internationales d'Unites

Quantity	*Standard unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Luminous intensity	candela	cd
Matter	mole	mol

- Derived SI units

Quantity	*Standard unit*	*Symbol*	*Derivation formula*
Area	square metre	m^2	
Volume	cubic metre	m^3	
Velocity	metre per second	m/s	
Acceleration	metre per second squared	m/s^2	
Angular velocity	radian per second	rad/s	
Angular acceleration	radian per second squared	rad/s^2	
Density	kilogram per cubic metre	kg/m^3	
Specific volume	cubic metre per kilogram	m^3/kg	
Mass flow rate	kilogram per second	kg/s	
Volume flow rate	cubic metre per second	m^3/s	
Force	newton	N	kg m/s²
Pressure	newton per square metre	N/m^2	
Torque	newton metre	N m	
Momentum	kilogram metre per second	kg m/s	
Moment of inertia	kilogram metre squared	$kg\ m^2$	
Kinematic viscosity	square metre per second	m^2/s	
Dynamic viscosity	newton second per square metre	$N\ s/m^2$	
Work, energy, heat	joule	J	Nm
Specific energy	joule per cubic metre	J/m^3	
Power	watt	W	J/s
Thermal conductivity	watt per metre kelvin	W/m K	

Quantity	*Standard unit*	*Symbol*	*Derivation formula*
Electric charge	coulomb	C	A s
Voltage, e.m.f., pot. diff.	volt	V	W/A
Electric field strength	volt per metre	V/m	
Electric resistance	ohm	Ω	V/A
Electric capacitance	farad	F	A s/V
Electric inductance	henry	H	V s/A
Electric conductance	siemen	S	A/V
Resistivity	ohm metre	Ωm	
Permittivity	farad per metre	F/m	
Permeability	henry per metre	H/m	
Current density	ampere per square metre	A/m^2	
Magnetic flux	weber	Wb	V s
Magnetic flux density	tesla	T	Wb/m^2
Magnetic field strength	ampere per metre	A/m	
Frequency	hertz	Hz	s^{-1}
Luminous flux	lumen	lm	cd sr
Luminance	candela per square metre	cd/m^2	
Illumination	lux	lx	lm/m^2
Molar volume	cubic metre per mole	m^3/mol	
Molarity	mole per kilogram	mol/kg	
Molar energy	joule per mole	J/mol	

source: A. Morris, Principles of Instrumentation and Measurement, 3rd Ed., Butterworth-Heinemann, 2001.

Units of Measurement

- Unit Definitions

Physical quantity	*Standard unit*	*Definition*
Length	metre	The length of path travelled by light in an interval of 1/299 792 458 seconds
Mass	kilogram	The mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sèvres, Paris
Time	second	9.192631770×10^9 cycles of radiation from vaporized caesium-133 (an accuracy of 1 in 10^{12} or 1 second in 36 000 years)
Temperature	kelvin	The temperature difference between absolute zero and the triple point of water is defined as 273.16 kelvin
Current	ampere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross-section placed 1 metre apart in a vacuum and producing a force of 2×10^{-7} newtons per metre length of conductor
Luminous intensity	candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz ($Hz \times 10^{12}$) and with a radiant density in that direction of 1.4641 mW/steradian. (1 steradian is the solid angle which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	mole	The number of atoms in a 0.012 kg mass of carbon-12

source: A. Morris, Principles of Instrumentation and Measurement, 3rd Ed., Butterworth-Heinemann, 2001.

BI = biomedical instrumentation

BI Operational Modes

- Direct vs. Indirect
  - Direct mode: measure desired measurand directly
    - if the sensor is invasive, direct contact with the measurand is possible but risky and least acceptable
  - Indirect mode: measure a quantity that is accessible and related to the desired measurand
    - assumption: the relationship between the measurands is already known
    - often chosen when the measurand requires invasive procedures to measure directly

- Example indirect mode
  - Cardiac output (volume of blood pumped per minute by the heart)
    - can be determined from measurement of respiration, blood gas concentration
  - Organ morphology
    - can be determined from x-ray shadows

BI Operational Modes

- Sampling vs. Continuous mode
  - Sampling: for slow varying measurands that are sensed infrequently
    - like body temperature & ion concentrations
  - Continuous: for critical measurements requiring constant monitoring
    - like electro-cardiogram and respiratory gas flow

- Generating vs. Modulating
  - Generating: also known as self-powered mode
    - derive their operational energy from the measurand itself
    - Example: piezoelectric sensors, solar cells
  - Modulating: measurand modulates the electrical signal which is supplied externally
    - modulation affects output of the sensor
    - Example: IR sensor

BI Operational Modes

- Analog vs. digital modes
  - most sensors are inherently analog
    - (some optical sensors are exceptions)
  - require analog-to-digital converters before any DSP techniques could be applied for filtering

- Real-time vs. Delayed-time mode
  - Real-time
    - Example: ECG signals need to measured in real-time to determine an cardiac arrest
  - Delayed-time
    - Example: cell cultures which requires several days before any output is acquired

Measurement Constraints

- The signal to be measured imposes constraints on how it should be acquired and processed

- Signal/frequency ranges
  - Most medical measurands parameters are typically much lower than conventional sensing parameters (microvolts, mm Hg, low frequency)

- Interference and cross-talk
  - Noise from environment, instruments, etc.
  - Other measurands affect measurement (and can't be isolated)
    - e.g., Cannot measure EEG without interference from EMG
  - Require filtering and/or compensation

- Placement of sensor(s) in/on/near the body plays a key role in any bio-instrumentation design

Measurement Constraints

- Measurement variability is inherent at molecular, organ and body level
  - Primary cause
    - interaction between different physiological systems
    - existence of numerous feedback loops whose properties are poorly understood
- Therefore evaluation of biomedical devices rely on probabilistic/statistical methods (biostatistics)

- SAFETY
  - Due to interaction of sensor with living tissue, safety is a primary consideration in all phases of the design & testing process
    - the damage caused could be irreversible
  - In many cases, safe levels of energy is difficult to establish
  - Safety of medical personnel also must be considered

- Operator constraints
  - Reliable, easy to operate and durable

Classification of biomedical instruments

- Quantity being sensed
  - pressure, flow or temperature
  - makes comparison of different technologies easy

- Principle of transduction
  - resistive, inductive, capacitive, ultrasonic or electrochemical
  - makes development of new applications easy

- Organ systems
  - cardiovascular, pulmonary, nervous, endocrine
  - isolates all important measurements for specialists who need to know about a specific area

- Clinical specialties
  - pediatrics, obstetrics, cardiology or radiology
  - easy for medical personnel interested in specialized equipment.