Introduction to Biosignal Detection

Wenxi Chen
Biomedical Information Engineering Lab.
The University of Aizu

Biosignal Detection?

- **Biosignal**
  – Chemical or physical quantities that characterize the property or state of human biological condition
  – A wide spectrum in time and frequency domains
- **Detection**
  – Apply various science and engineering principles and modalities to determine or measure these quantities
- **Biosignal detection**
  – A procedure by which we can determine or measure these quantities

Synopsis

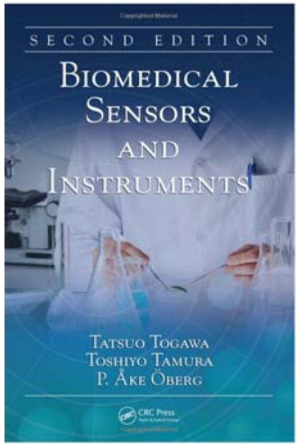
- Introductory knowledge on various physiological information in human body
- Fundamental science and engineering principles, such as physical and chemical, electrical and electronic, in measurement of various biosignals, and basic concepts of biomedical instrumentation
- Special aspects of sensing and detecting in biological system that are different from the industrial application

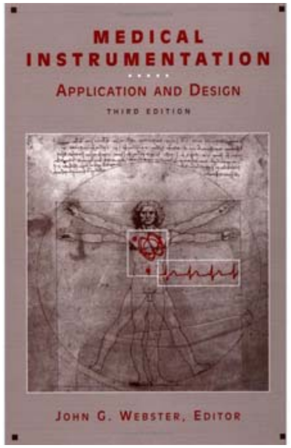
Contents

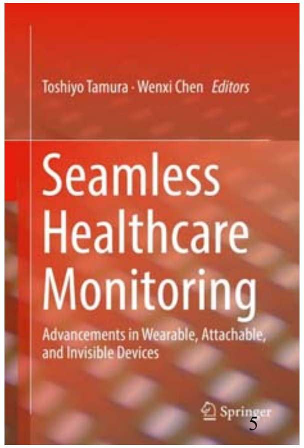
- Introduction
- Motion and Force
- Direct Pressure
- Indirect Pressure
- Direct Blood Flow
- Indirect Blood Flow
- Respiration
- Temperature
- Bioelectricity
- Biomagnetism
- Biochemistry-1
- Biochemistry-2
- Biochemistry-3
- Seamless Monitoring

Handouts and Books

- http://i-health.u-aizu.ac.jp/IBSD







1. Introduction

- Various biosignals
- Measurement methods
- Particularities
- Static and dynamic characteristics
- Signal and noise
- Types of noise
- Absolute quantity
- Types of error

Various Biosignals

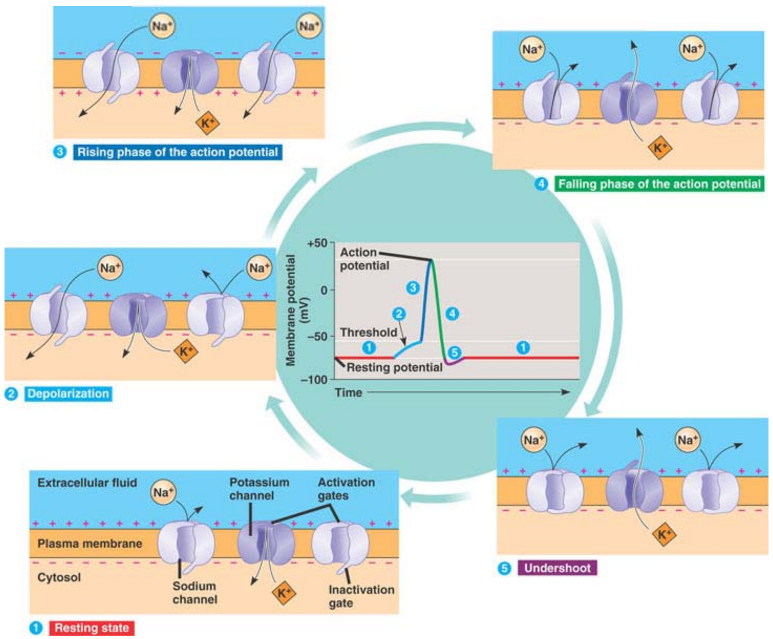
Biosignal		Range	Freq., Hz	Sensor
Ballistocardiogram (BCG)		0-7 mg	0-40	Accelerometer, strain gage
		0-100 μm	0-40	Displacement (LVDT, Linear Variable Differential Transformer)
Bladder pressure		1-100 cm H_2O	0-10	Strain gage manometer
Blood flow		1-300 ml/s	0-20	Flowmeter (electromagnetic or ultrasonic)
Blood pressure, arterial	Direct	10-400 mm Hg	0-50	Strain gage manometer
	Indirect	25-400 mm Hg	0-60	Cuff, auscultation
Blood pressure, venous		0-50 mm Hg	0-50	Strain gage

Biosignal		Range	Freq., Hz	Sensor
Blood gases	PO_2	30-100 mm Hg	0-2	Specific electrode, volumetric or manometric
	PCO_2	40-100 mm Hg	0-2	
	PN_2	1-3 mm Hg	0-2	
	PCO	0.1-0.4mm Hg	0-2	
Blood pH		6.8-7.8 pH units	0-2	Specific electrode
Cardiac output		4-25 liter/min	0-20	Dye dilution, Fick
Electrocardiogram (ECG)		0.5-4 mV	0.01-250	Skin electrodes
Electroencephalogram (EEG)		5-300 μV	0-150	Scalp electrodes

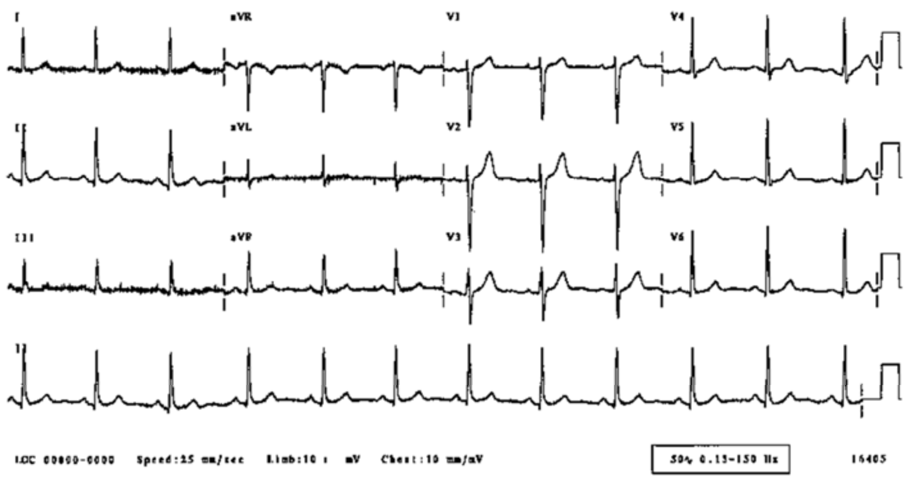
Biosignal	Range	Freq., Hz	Sensor
Electrocorticogram	10-5000 µV	0-150	Brain-surface or depth electrodes
Electromyogram (EMG)	0.1-5 mV	0-10,000	Needle electrodes, skin electrodes
Electrooculogram (EOG)	50-3500 µV	0-50	Contact electrodes
Electroretinogram (ERG)	0-900 µV	0-50	Contact electrodes
Galvanic skin response (GSR)	1-500 kΩ	0.01-1	Skin electrodes
Electrogastrogram (EGG)	10-1000 µV	0-1	Skin surface electrodes
	0.5-80 mV	0-1	Stomach surface electrodes
Gastrointestinal pressure	0-100 cm H_2O	0-10	Strain gage
Gastrointestinal forces	1-50 g	0-1	Displacement system, LVDT
Gastric pH	3 - 13 pH units	0-1	pH electrode, antimony electrode

Biosignal		Range	Freq., Hz	Sensor
Nerve potentials		0.01- 3 mV	0-10,000	Surface or needle electrodes
Phonocardiogram (PCG)		Dynamic range 80 dB, threshold about 100 µPa	5-2000	Microphone
Plethysmogram (volume change)		Varies with organ	0-30	Displacement chamber or impedance change
Respiratory functions	Flow rate	0-600 liter/min	0-40	Pneumotachograph head and differential pressure
	Respiratory rate	2-50 breaths/min	0.1-10	Strain gage on chest, impedance, nasal thermistor
	Tidal volume	50-1000 ml/breath	0.1-10	Above methods
Body temperature		32-40 °C 90-104 °F	0-0.1	Thermistor, thermocouple

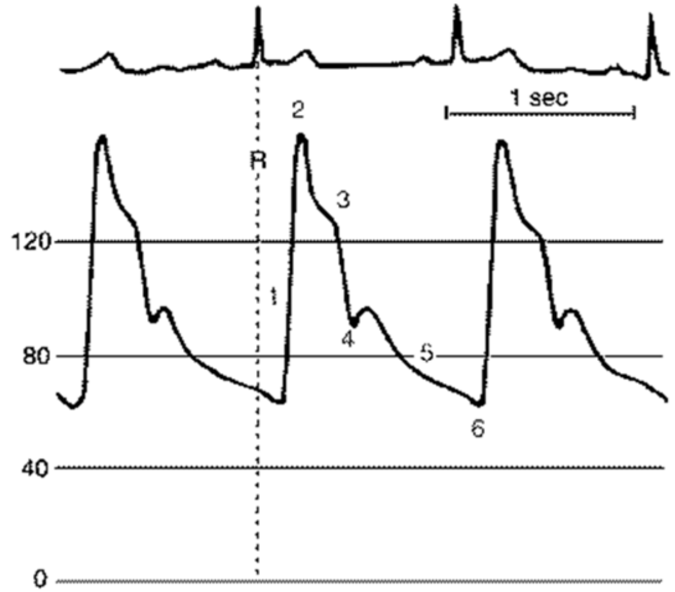
Action Potential



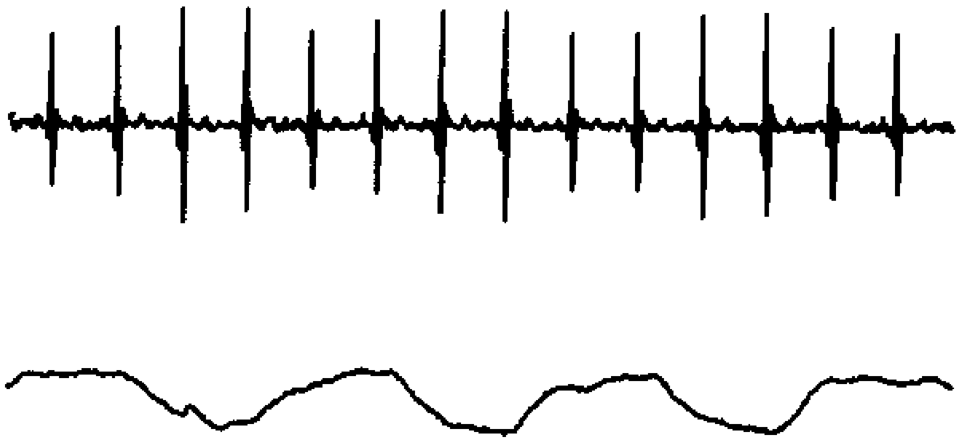
12-Lead ECG



ECG and ABP



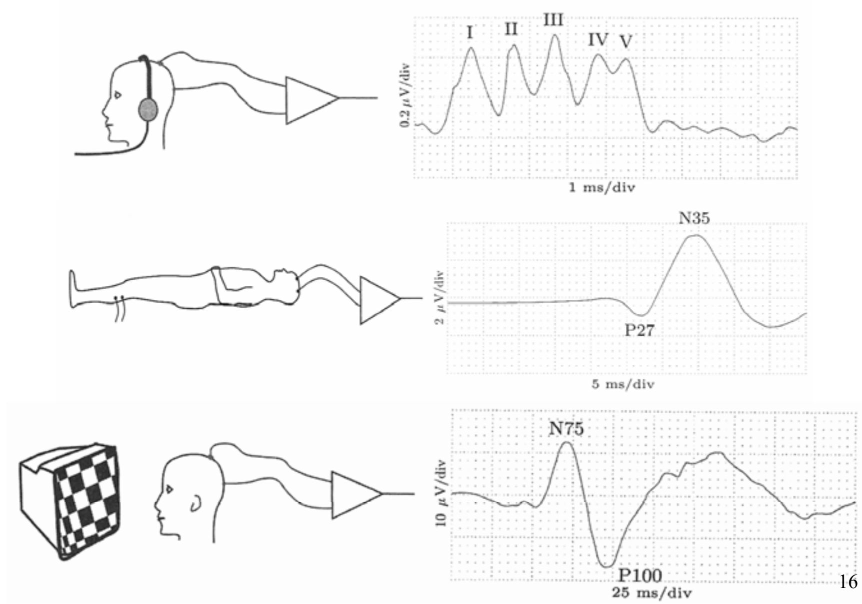
ECG and Respiration



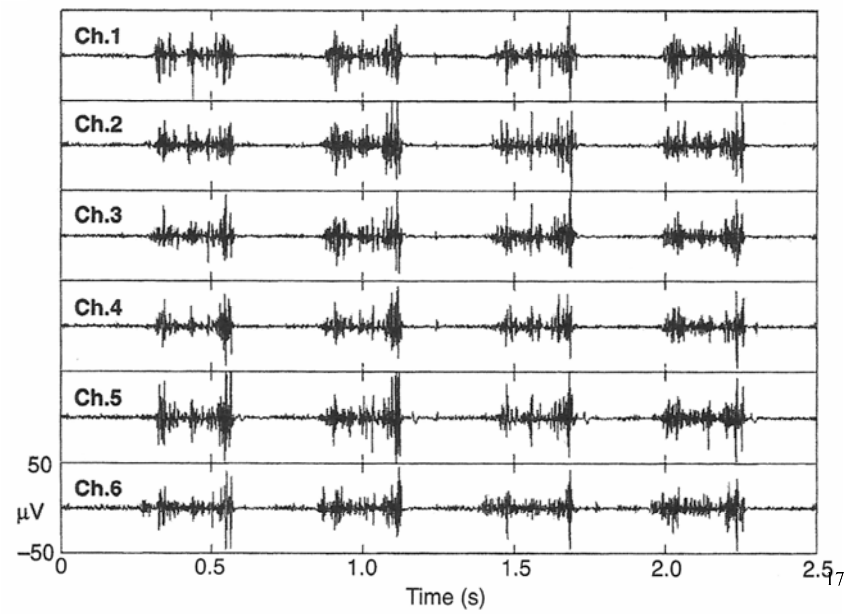
Spontaneous EEG

Position of electrode

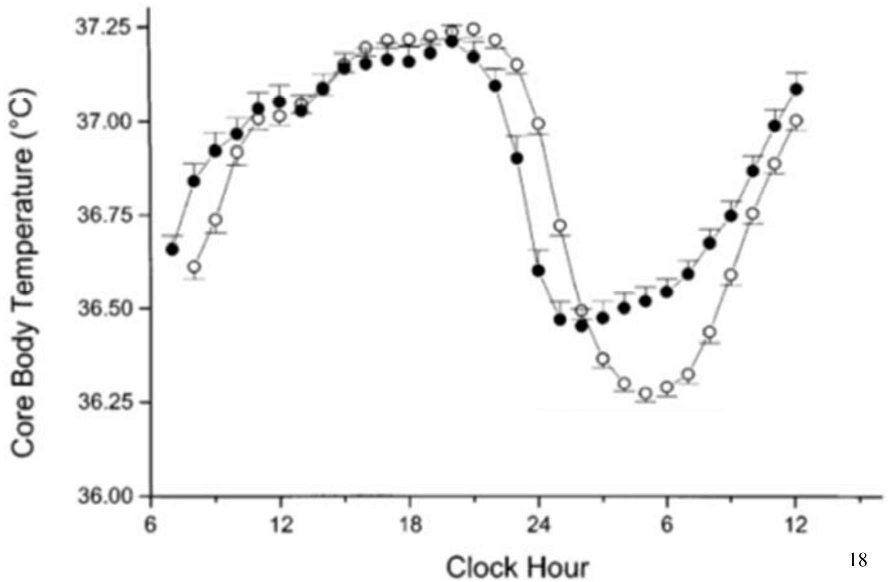
Evoked EEG



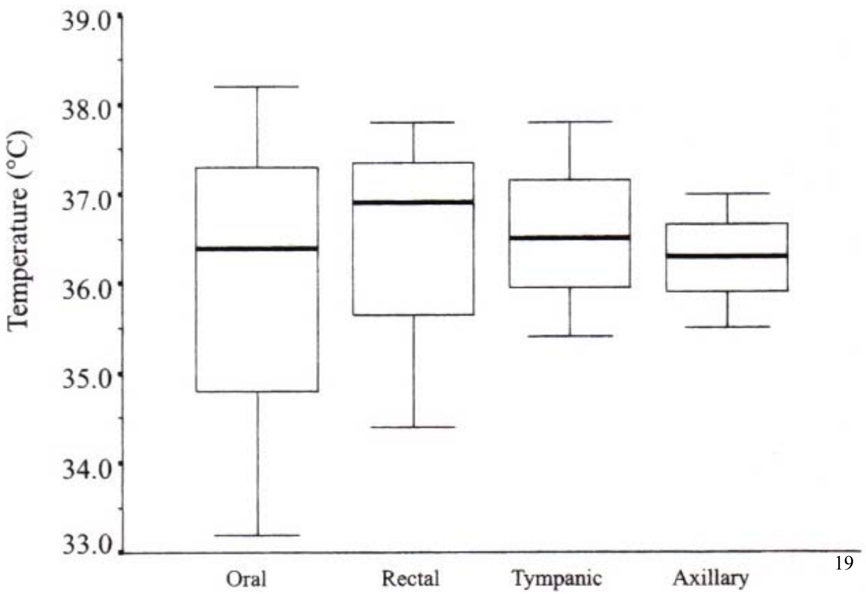
EMG



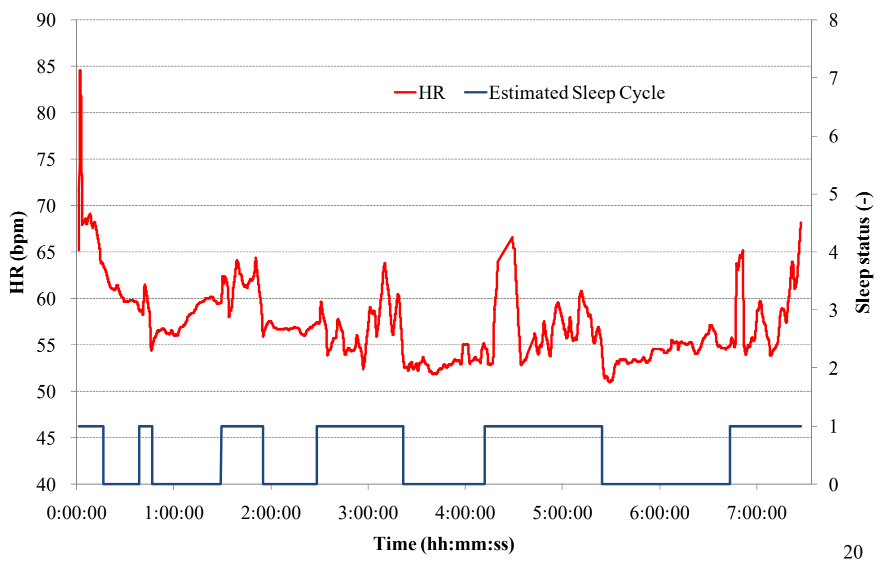
Body Temperature with Time



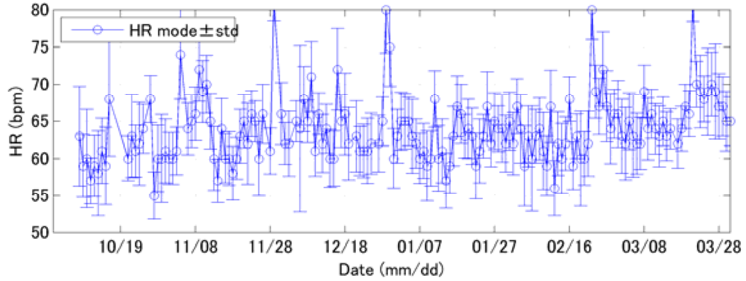
Body Temperature with Place

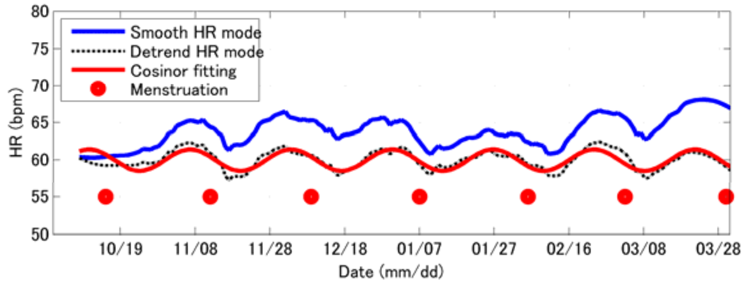


Daily HR and Sleep Cycle

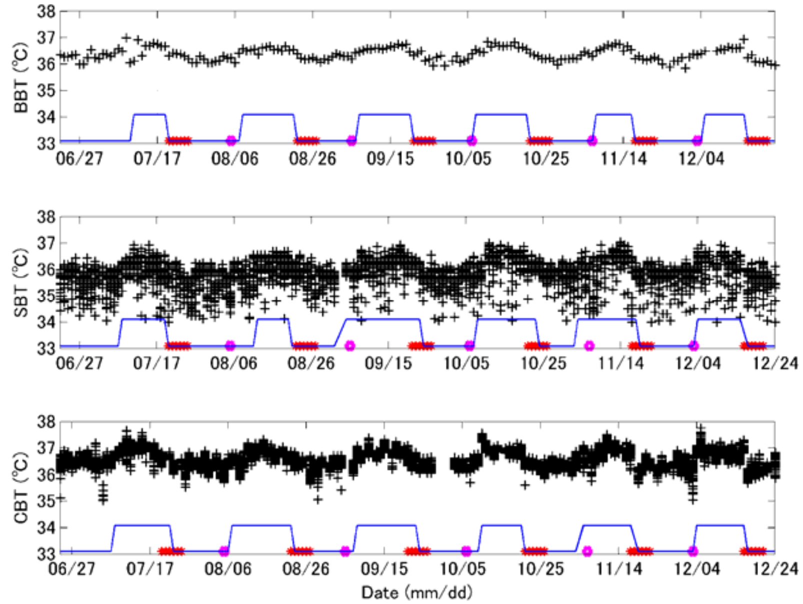


Daily HR and Menstrual Cycle

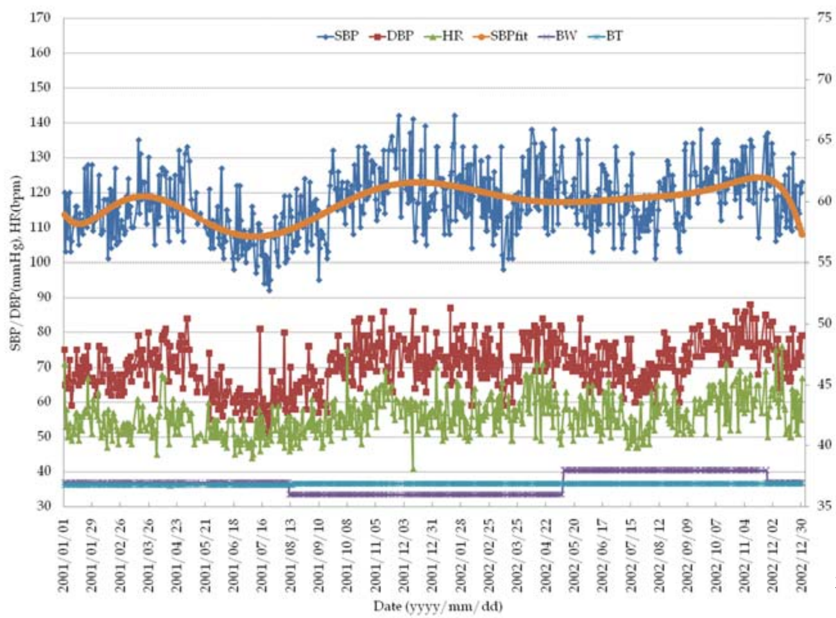




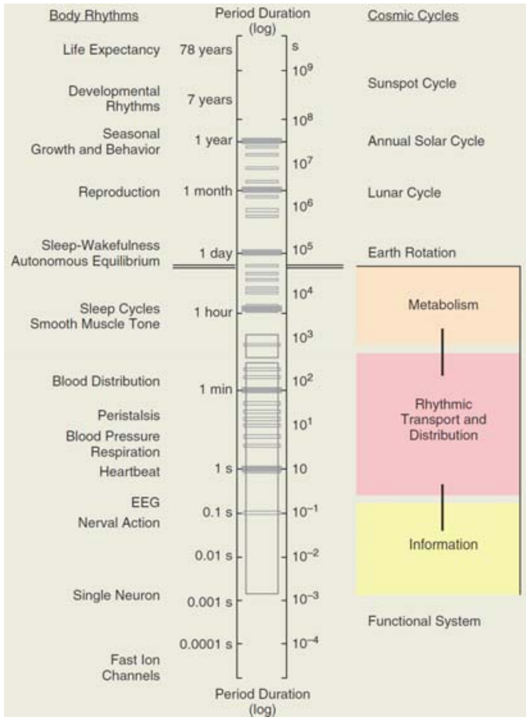
Daily BTs and Menstrual Cycle

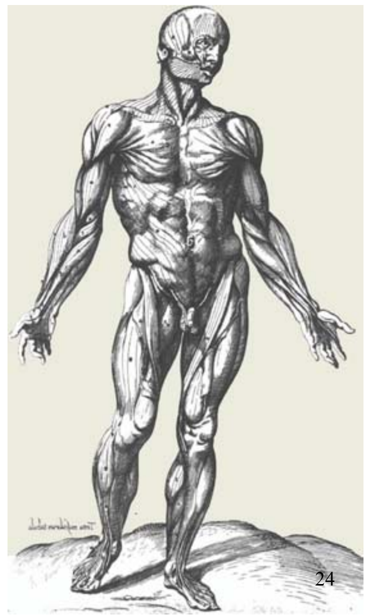


Daily BP, HR and Biorhythm



Wide spectrum of various physiological information in time and frequency domains

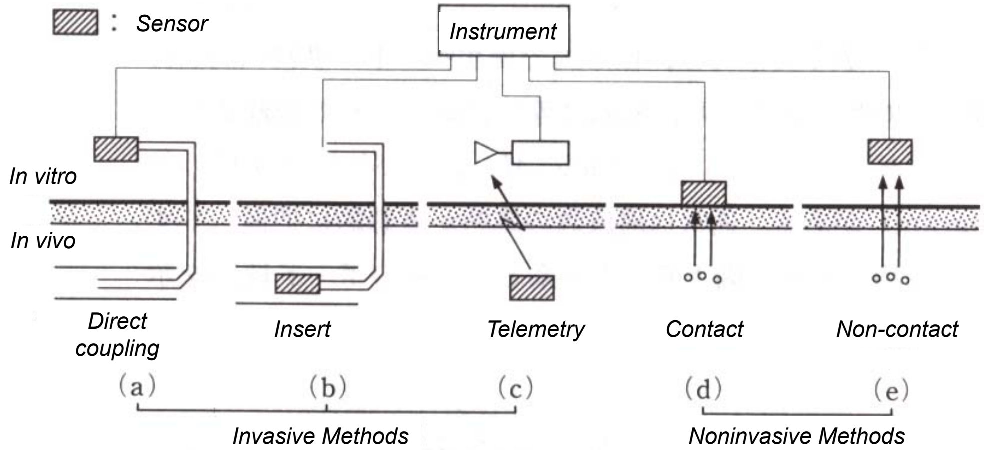




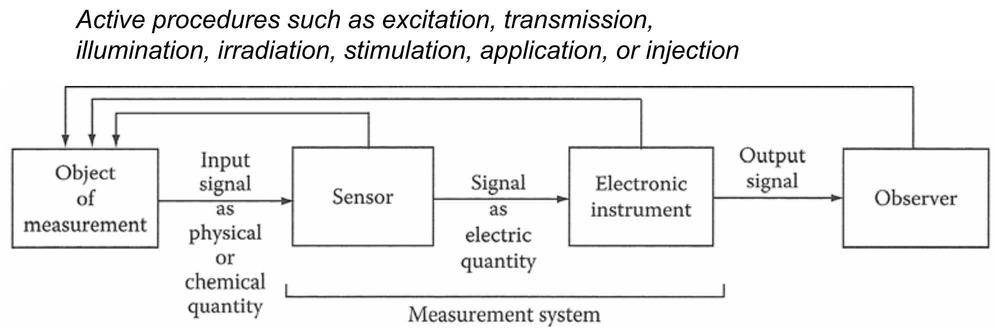
Biosignal Detection

- Biosignal
  - Physical, chemical, mechanical, thermal, electrical and magnetic quantities that contain information of health condition in physiology and psychophysiology
- Detection
  - **Transduction** - a procedure by which the quantity that characterizes the property or state of an object was sensed or transduced
  - **Conditioning** - an analogical or digital procedure of obtaining wanted information or signal components from the above object quantity

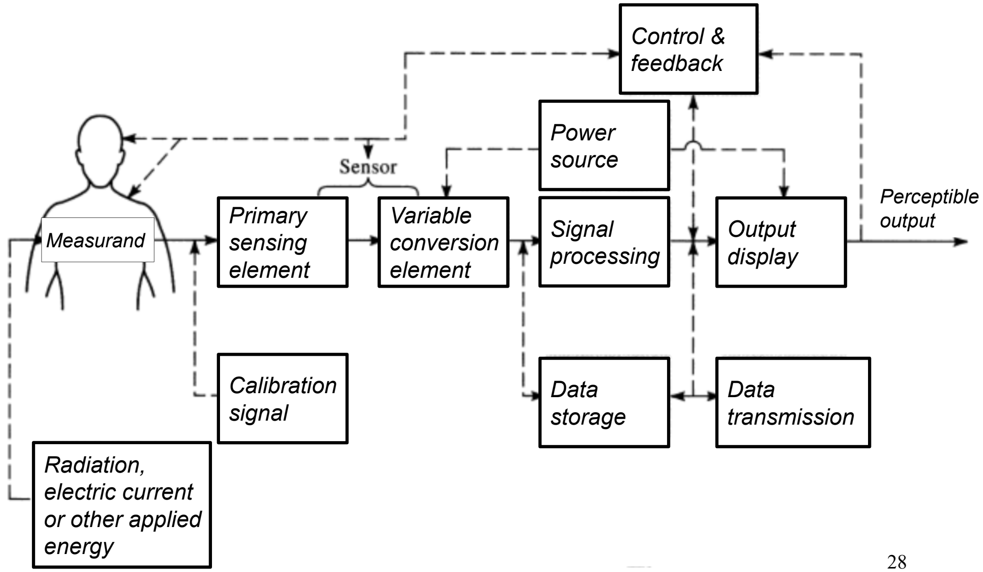
Invasive and Noninvasive



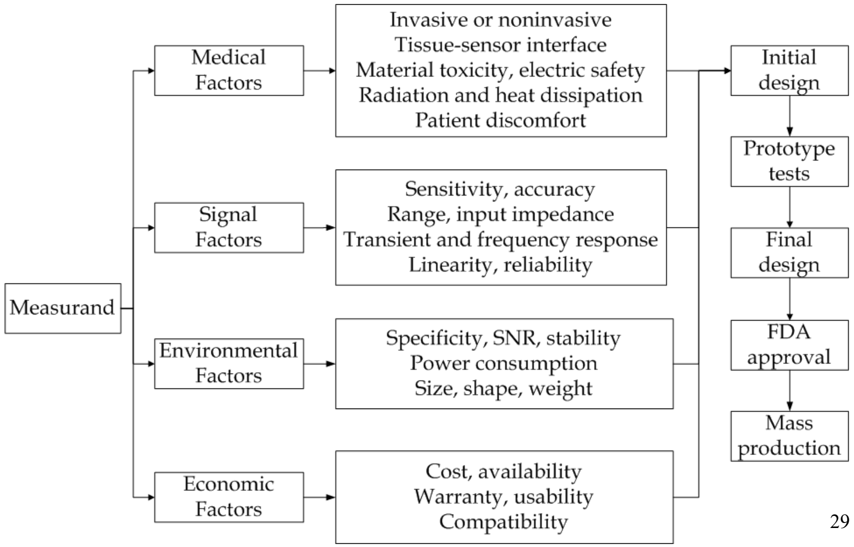
Measurement Process



System Diagram



R&D Process



Particularities

- Safety in electromagnetism, heat, radiation, vibration
- Minimum disturbance to the organs, tissues and physiological conditions
- Minimum constrained, pain and uncomfortable
- High stability in biophysical and biochemical aspects
- High biological affinity
- Inherent variability among individuals
- Wide response in frequency domain

General Performance

- Static characteristics
  - The performance of instruments for DC or very low frequency inputs.
  - Some sensors, such as piezoelectric devices, respond only to time-varying inputs and have no static characteristics.
- Dynamic characteristics
  - The performance of instruments for a transient or higher frequency inputs.
  - Differential and/or integral equations are used.

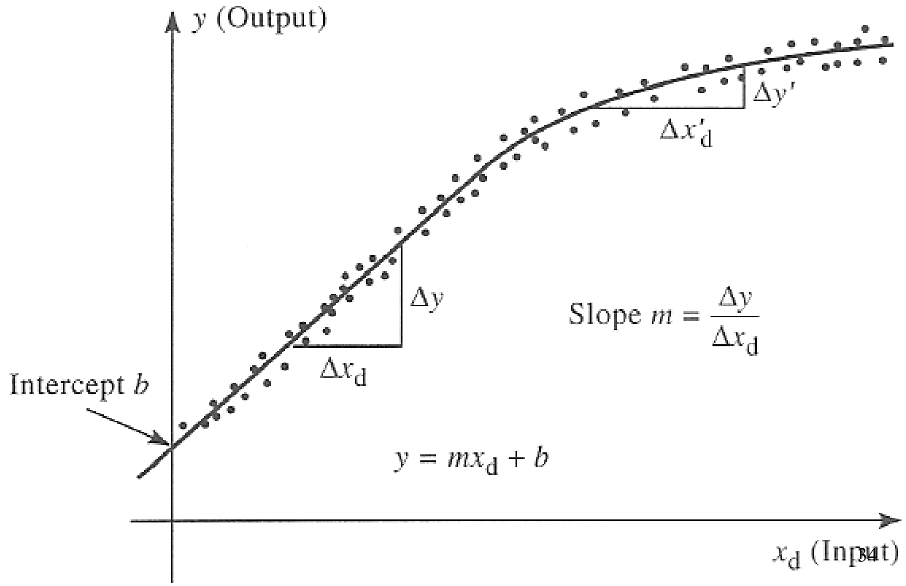
Static Characteristics - 1

- Accuracy
  - The difference between the true value and the measured value divided by the true value (reference)
- Precision
  - The number of distinguishable alternatives from which a given result is selected
- Resolution
  - The least value of the object quantity that can be distinguished at the output of the measurement system
- Reproducibility or repeatability
  - The ability to give the same output for equal inputs over time
- Sensitivity
  - The ratio of the incremental output quantity to the incremental input quantity

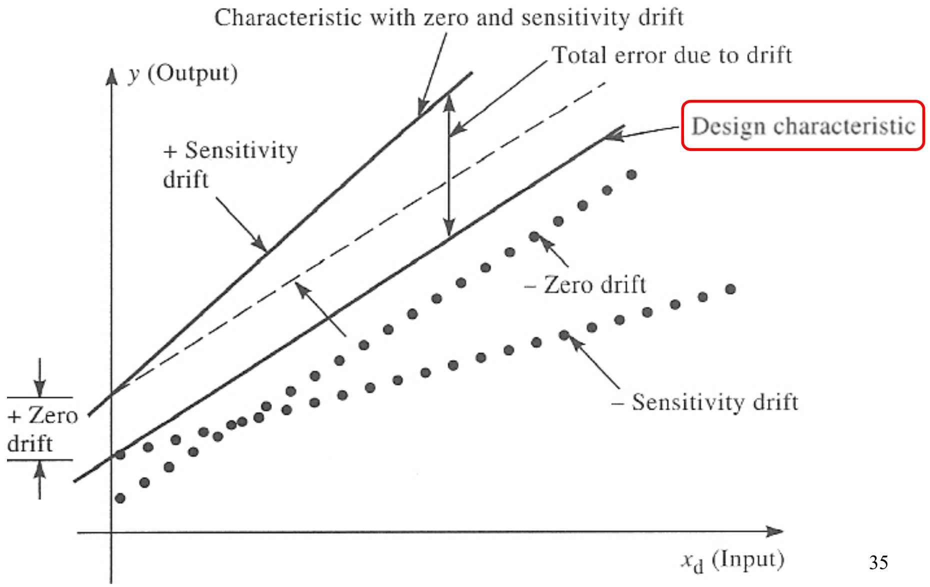
Static Characteristics - 2

- Linearity
  - Response property of outputs to addition and multiplication of inputs
- Range
  - Minimal resolvable inputs – a lower bound on the quantity to be measured
  - Measurement range – the maximal allowable change of the object quantity that give the nominal performance
- Input impedance
  - The ratio of the phasor equivalent of a steady-state sinusoidal effort input variable (voltage, force, pressure) to the phasor equivalent of a steady-state sinusoidal flow input variable (current, velocity, flow)
- Hysteresis
  - The input-output relation depends on the direction and the range of successive input values

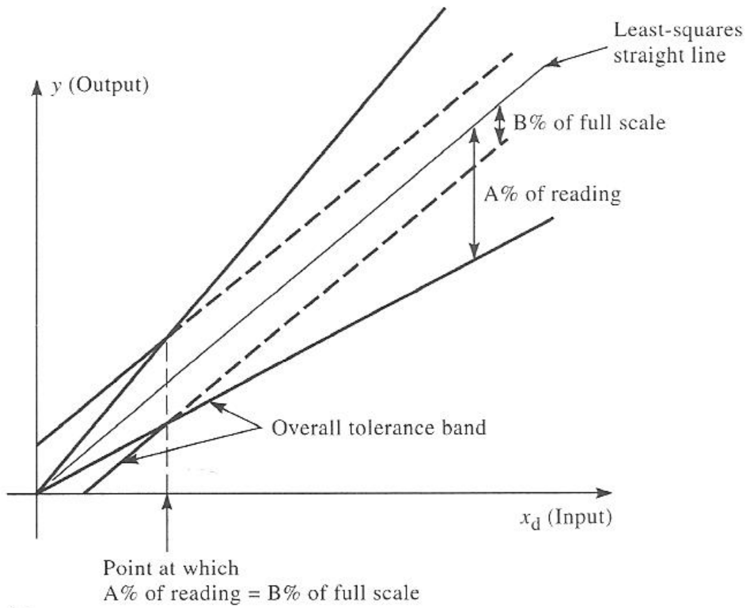
Sensitivity Change



Sensitivity Drift



Linearity



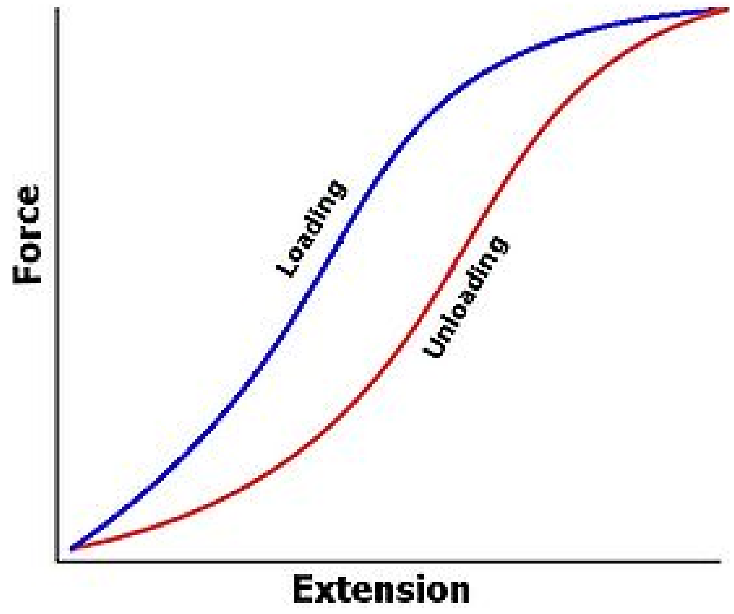
Input Impedance

- The degree to which instruments disturb the quantity being measured → smaller=better
- X_{d1} – desired input quantity we seek to measure
- X_{d2} – implicit input quantity to be required by instruments
- Generalized input impedance Z_x → larger=better

$$Z_x = \frac{X_{d1}}{X_{d2}} = \frac{effort\_variable}{flow\_variable}$$

- Power $P=X_{d1}*X_{d2}$ → smaller=better
  - instantaneous rate at which energy is transferred across the tissue-sensor interface

Hysteresis



Dynamic Characteristics

- Transfer functions
  - 0th order, 1st order, 2nd order
- Linear and nonlinear systems
  - Linear system – the response to simultaneous inputs is the sum of their independent inputs
  - Nonlinear system – higher harmonics appear but close to linear system in small range
- Frequency response
  - The distribution of the amplitude and the phase shift of the output to sinusoidal inputs of unit amplitude over the whole frequency range
- Time parameters
  - Time constant, response time, rise time, settling time, time delay

Transfer Function

Differential equation

$$a_n \frac{d^n y(t)}{dt^n} + \ldots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^m x(t)}{dt^m} + \ldots + b_1 \frac{dx(t)}{dt} + b_0 x(t)$$

Laplace transform

$$\frac{Y(s)}{X(s)} = \frac{b_m s^m + \ldots + b_1 s + b_0}{a_n s^n + \ldots + a_1 s + a_0}$$

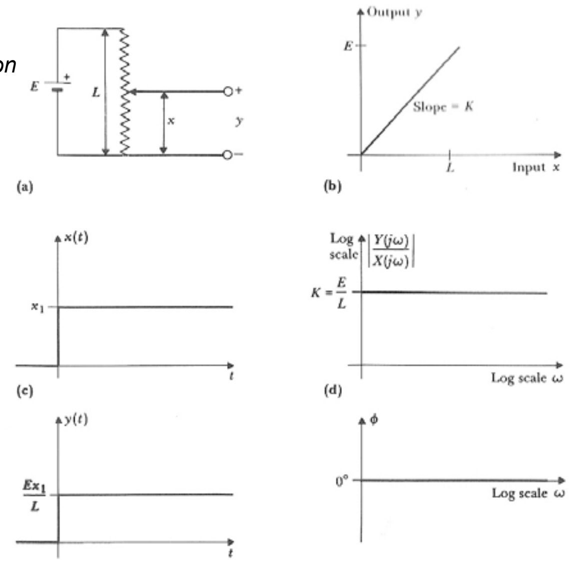
When $s = j\omega$

$$\frac{Y(j\omega)}{X(j\omega)} = \frac{b_m (j\omega)^m + \ldots + b_1 (j\omega) + b_0}{a_n (j\omega)^n + \ldots + a_1 (j\omega) + a_0}$$

Zero-order System

Differential equation

$$a_0 y(t) = x(t)$$



Static sensitivity

$$\frac{1}{a_0} = K$$

Input

Output

Constant

Zero phase shift

First-order System

Differential equation

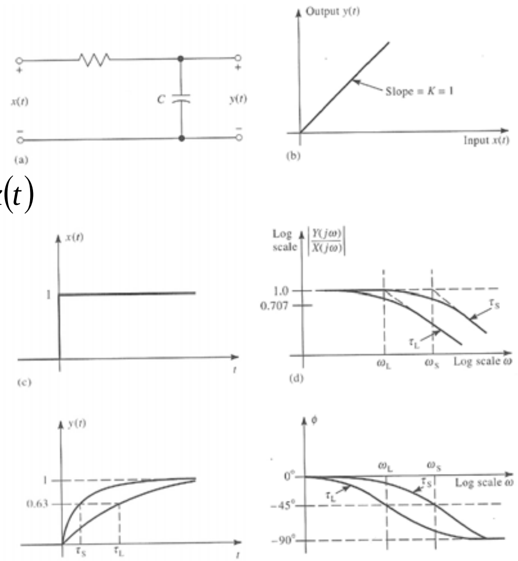
$$a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)$$

Step response

$$y(t) = K\left(1 - e^{-t/\tau}\right)$$

Time constant

$$\tau = \frac{a_1}{a_0}$$



Static sensitivity

$$\frac{1}{a_0} = K$$

Cutoff frequency

$$\omega = \frac{1}{\tau}$$

Second-order System

Differential equation

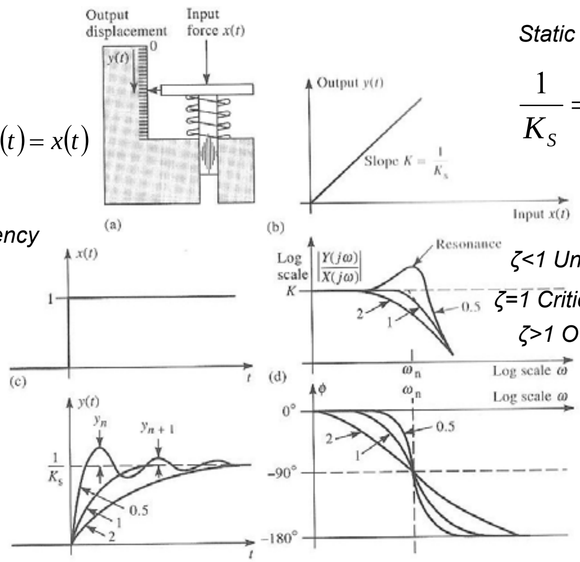
$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)$$

Undamped natural frequency

$$\omega_n = \sqrt{\frac{a_0}{a_2}}$$

Damping ratio

$$\zeta = \frac{a_1}{2\sqrt{a_0 a_2}}$$



Static sensitivity

$$\frac{1}{K_S} = \frac{1}{a_0} = K$$

ζ<1 Underdamped

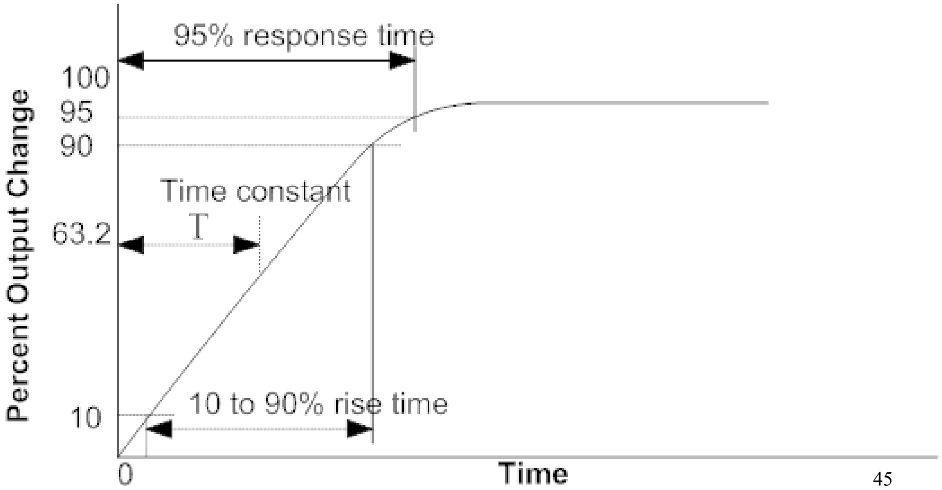
ζ=1 Critically damped

ζ>1 Overdamped

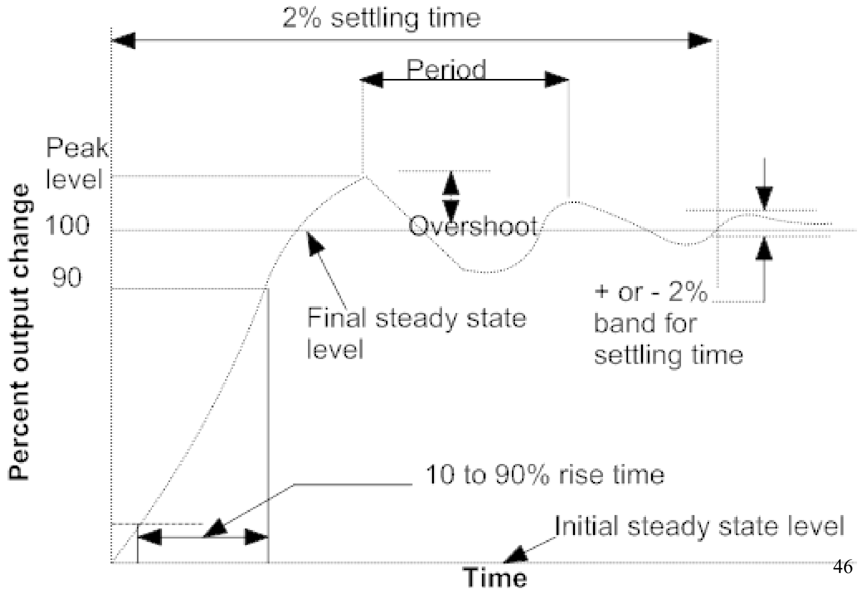
Time Parameters

- Time constant
  - 1st order system, time to 63.2% of the final value in step response
- Response time
  - time to 95% of the final value
- Rise time
  - 2nd order system, time interval from 10% to 90% of the final value
- Settling time
  - 2nd order system, time to settle within a definite range, ex. ±5%, near the final value
- Time delay
  - time to output after input is applied
  - phase angle varies with frequency – the delay is not constant in frequency domain

First-order System



Second-order System



Amplitude and Power

- Peak-to-peak value $\max(x(t)) - \min(x(t))$
  - Difference between the maximal peak and the minimal valley
- Root-Mean-Square (RMS) amplitude
  - Root of average squared signal over time $\sqrt{\overline{x(t)^2}}$
- Power
  - Average squared signal over time $\overline{x(t)^2}$

Power Spectrum

- Distribution of signal power over frequency
- Fourier series of any periodic function of time

$$x(t) = \sum_{n=1}^{\infty} \left(A_n \cos(n\omega_0 t) + B_n \sin(n\omega_0 t)\right) \quad \textit{where} \quad \omega_0 = \frac{2\pi}{T}$$

- Total power

$$\overline{x(t)^2} = \frac{1}{2} \sum_{n=1}^{\infty} \left(A_n^2 + B_n^2\right)$$

- Fourier transform of any function of time

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt$$

- Total power

$$\overline{x(t)^2} = \frac{1}{2\pi} \int_0^{\infty} \left|X(\omega)\right|^2 d\omega$$

Signal and Noise

- Signal
  - the component of a variable that contains information about the object quantity
- Noise
  - a component unrelated to the object quantity
- Signal ↔ Noise
  - not defined by physical nature but by the intention of the observer
- Signal-to-Noise Ratio (SNR)

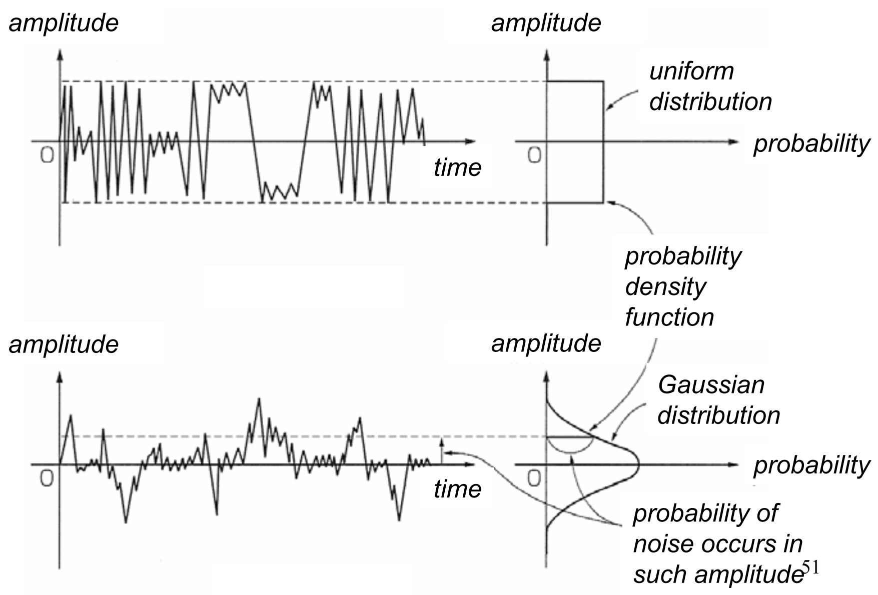
$$SNR(\mathrm{dB}) = 10\log_{10}\frac{P_S}{P_N} = 20\log_{10}\frac{A_S}{A_N}$$

  - P and A indicate power and RMS amplitude, respectively

Types of Noise

- Thermal Noise
  - Random thermal agitation relevant to temperature
  - Uniform distribution of power density
- 1/f Noise
  - Many natural phenomena
  - Power density is inversely proportional to the frequency
- Interference
  - Electromagnetic coupling - power line, fluorescent lamps
- Artifact
  - Superimposed on the object quantity and caused by external factors such as motion – skin-electrode contact

Distribution of Noise



Absolute Quantity

- Standard
  - Intrinsic standards such as mercury column and gravity of the earth for pressure, ice point of pure water and melting point of gallium for temperature
  - Reliable instruments such as crystal-resonator temperature sensors for body temperature thermometer
- Calibration
  - Nonlinear system – many points
  - Linear system – two points
  - Curve fitting in the sense of least squared errors between input and output
- Accuracy
  - How close the measured value is to the true value
- Error
  - Difference between the measured value and the true value

Types of Error

- Random error
  - Appears unpredictably in repeated measurements
  - Averaging is an effective way to reduce random errors
- Systematic error
  - The bias from the true value appearing equally in repeated measurements of the same object quantity
  - Origins – drift, improper calibration, uncorrected nonlinearity, round down in digital data
- Dynamic error
  - Occurring from imperfect dynamic characteristics when the object quantity varies so quickly that the output of the measurement system does not follow the change of the input
- Quantization error
  - The difference between the original analog value and the converted digital value during conversion of an analog value to a digital value

Quantization Error