Biomedical Instrumentation

Prof. Dr. Nizamettin AYDIN

naydin@yildiz.edu.tr

naydin@ieee.org

http://www.yildiz.edu.tr/~naydin

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Biomedical Instrumentation

Lecture 3

Measurement Systems

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Biomedical Instrumentation

- Diagnosis and therapy depend heavily on the use of medical instrumentation.
- Medical procedures:
  Medicine can be defined as a multistep procedure on an individual by a physician, group of physician, or an institute, repeated until the symptoms disappear

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The Importance of Biomedical Instrumentation

- **Medical procedure**
  1 Collection of data - qualitative and/or quantitative
  2 Analysis of data
  3 Decision making
  4 Treatment planning based on the decision

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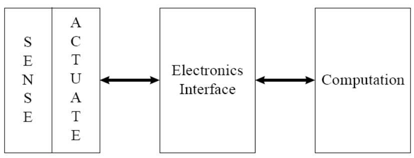
Biomedical Instrumentation System



- All biomedical instruments must interface with biological materials. That interface can by direct contact or by indirect contact

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Components of BM Instrumentation System…

- A sensor
  - Detects biochemical, bioelectrical, or biophysical parameters
  - Provides a safe interface with biological materials
- An actuator
  - Delivers external agents via direct or indirect contact
  - Controls biochemical, bioelectrical, or biophysical parameters
  - Provides a safe interface with biologic materials

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…Components of BM Instrumentation System…

- The electronics interface
  - Matches electrical characteristics of the sensor/actuator with computation unit
  - Preserves signal to noise ratio of sensor
  - Preserves efficiency of actuator
  - Preserves bandwidth (i.e., time response) of sensor/actuator
  - Provides a safe interface with the sensor/actuator
  - Provides a safe interface with the computation unit
  - Provides secondary signal processing functions for the system

…Components of BM Instrumentation System

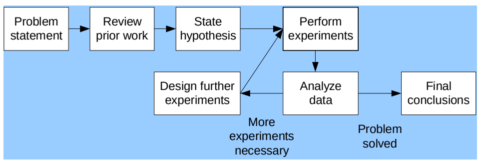
- The computation unit
  - provides primary user interface
  - provides primary control for the overall system
  - provides data storage for the system
  - provides primary signal processing functions for the system
  - maintains safe operation of the overall system

Problems Encountered in Measuring a Living System

- Many crucial variables in living systems are inaccessible.
- Variables measured are seldom deterministic.
- Nearly all biomedical measurements depend on the energy.
- Operation of instruments in the medical environment imposes important additional constraints.

The scientific method…

- In the scientific method, a hypothesis is tested by experiment to determine its validity.

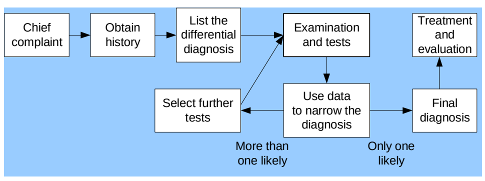


…The scientific method

- In the scientific method, a hypothesis is tested by experiment to determine its validity.
  - For example, we might hypothesize that exercise reduces high blood pressure yet experimentation and analysis are needed to support or refute the hypothesis.
    - Experiments are normally performed multiple times. Then the results can be analyzed statistically to determine the probability that the results might have been produced by chance.
    - Results are reported in scientific journals with enough detail so that others can replicate the experiment to confirm them.

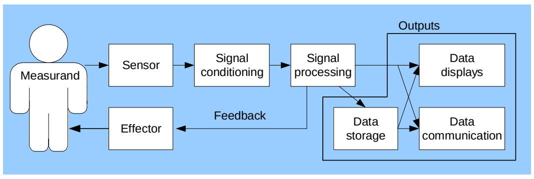
Clinical diagnoses

- Physicians often need instrumentation to obtain data as part of the scientific method.
  - For example, a physician obtaining the history of a patient with a complaint of poor vision would list diabetes as one possibility on a differential diagnosis.



Feedback in measurement systems…

- Figure shows that the measurand is measured by a sensor converting the variable to an electrical signal, which can undergo signal processing. Sometimes the measurement system provides feedback through an effector to the subject.



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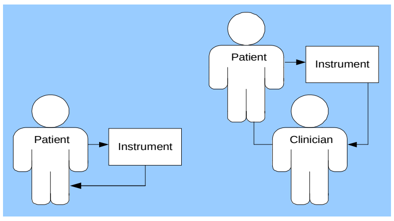
…Feedback in measurement systems

- Figure (a) shows that a patient reading an instrument usually lacks sufficient knowledge to achieve the correct diagnosis.
- Figure (b) shows that by adding the clinician to form an effective feedback system, the correct diagnosis and treatment result.



(a) (b)

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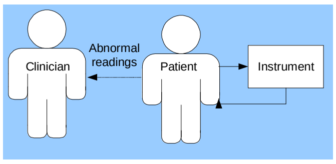
…Feedback in measurement systems

- In certain circumstances, proper training of the patient and a well-designed instrument can lead to self-monitoring and self-control (one of the goals of bioinstrumentation).
  - An example of such a situation is the day-to-day monitoring of glucose by people suffering from diabetes. Such an individual will contact a clinician if there is an alert from the monitoring instrument.



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Classifications of Biomedical Instruments

- The sensed quantity
- The principle of transduction
- The organ system for measurement
- The clinical medicine specialties
- Based on the activities involved in the medical care, medical instrumentation may be divided into three categories:
  - Diagnostic devices
  - Therapeutic devices
  - Monitoring devices

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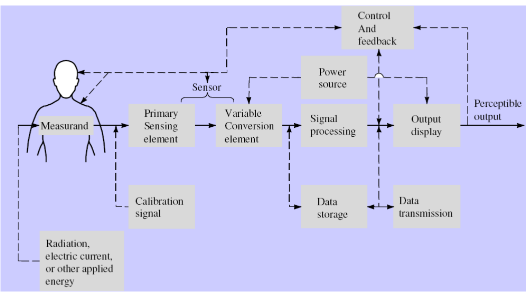
Generalized Medical Instrumentation System…



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…Generalized Medical Instrumentation System…

- Measurand
  - Physical quantity, property, or condition that the system measures
    - Biopotential
    - Pressure
    - Flow
    - Dimension (imaging)
    - Displacement (velocity, acceleration, and force)
    - Impedance
    - Temperature
    - Chemical concentrations

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…Generalized Medical Instrumentation System…

Measurement	Range	Frequency, Hz	Method
Blood flow	1 to 300 mL/s	0 to 20	Electromagnetic or ultrasonic
Blood pressure	0 to 400 mmHg	0 to 50	Cuff or strain gage
Cardiac output	4 to 25 L/min	0 to 20	Fick, dye dilution
Electrocardiography	0.5 to 4 mV	0.05 to 150	Skin electrodes
Electroencephalography	5 to 300 μ V	0.5 to 150	Scalp electrodes
Electromyography	0.1 to 5 mV	0 to 10000	Needle electrodes
Electroretinography	0 to 900 μ V	0 to 50	Contact lens electrodes
pH	3 to 13 pH units	0 to 1	pH electrode
pCO_2	40 to 100 mmHg	0 to 2	pCO_2 electrode
pO_2	30 to 100 mmHg	0 to 2	pO_2 electrode
Pneumotachography	0 to 600 L/min	0 to 40	Pneumotachometer
Respiratory rate	2 to 50 breaths/min	0.1 to 10	Impedance
Temperature	32 to 40 ℃	0 to 0.1	Thermistor

…Generalized Medical Instrumentation System…

- Sensor
  - Converts a physical measurand to an electrical output
    - Should respond only to the form of energy present in the measurand
    - Should be minimally invasive (ideally noninvasive)
- Signal conditioning
  - Amplify, filter, match the impedance of the sensor to the display
  - Convert analog signal to digital
  - Process the signal

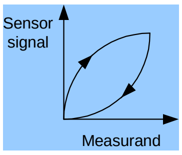
…Generalized Medical Instrumentation System…

- The specifications for a typical blood pressure sensor.
  - Sensor specifications for blood pressure sensors are determined by a committee composed of individuals from academia, industry, hospitals, and government

Specification	Value
Pressure range	–30 to +300 mmHg
Overpressure without damage	–400 to +4000 mmHg
Maximum unbalance	±75 mmHg
Linearity and hysteresis	± 2% of reading or ± 1 mmHg
Risk current at 120 V	10 μA
Defibrillator withstand	360 J into 50 Ω

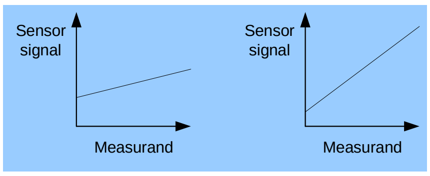
…Generalized Medical Instrumentation System…

- A hysteresis loop.
  - The output curve obtained when increasing the measurand is different from the output obtained when decreasing the measurand.



…Generalized Medical Instrumentation System…

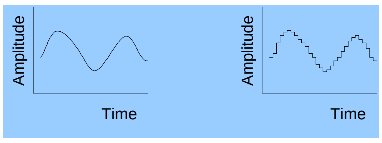
- (a) A low-sensitivity sensor has low gain. (b) A high sensitivity sensor has high gain.



(a) (b)

…Generalized Medical Instrumentation System…

- Most sensors are analog and provide a continuous range of amplitude values for output (a).
- Other sensors yield the digital output (b).
  - Digital output has poorer resolution, but does not require conversion before being input to digital computers and is more immune to interference



(a) (b)

…Generalized Medical Instrumentation System…

- Bioinstrumentation should be designed with a specific signal in mind.
  - Table shows a few specifications for an electrocardiograph
  - The values of the specifications, which have been agreed upon by a committee, are drawn from research, hospitals, industry, and government.

Specification	Value
Input signal dynamic range	±5 mV
Dc offset voltage	±300 mV
Slew rate	320 mV/s
Frequency response	0.05 to 150 Hz
Input impedance at 10 Hz	2.5 MΩ
Dc lead current	0.1 μA
Return time after lead switch	1 s
Overload voltage without damage	5000 V
Risk current at 120 V	10 μA

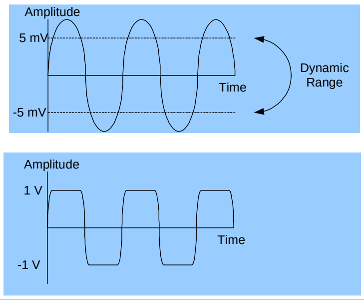
…Generalized Medical Instrumentation System…

(a) An input signal which exceeds the dynamic range.

(b) The resulting amplified signal is saturated at ±1 V.

(a)

(b)

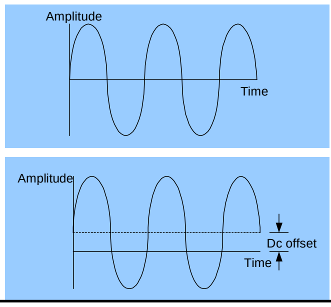


…Generalized Medical Instrumentation System…

- DC offset voltage is the amount a signal may be moved from its baseline and still be amplified properly by the system. Figure shows an input signal without (a) and with (b) offset.

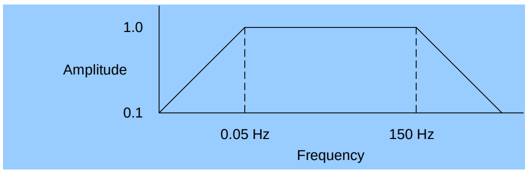
(a)

(b)



…Generalized Medical Instrumentation System…

- The frequency response of a device is the range of frequencies of a measurand that it can handle.
- Frequency response is usually plotted as gain versus frequency.
- Figure shows Frequency response of the electrocardiograph.

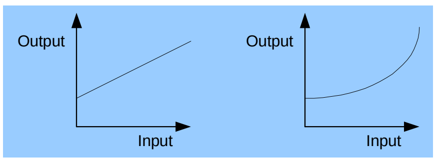


…Generalized Medical Instrumentation System…

- Linearity is highly desirable for simplifying signal processing

(a) A linear system fits the equation $y = mx + b$. Note that all variables are italic.

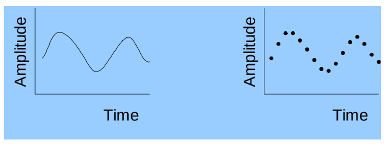
(b) A nonlinear system does not fit a straight line.



(a) (b)

…Generalized Medical Instrumentation System…

- All bioinstrumentation observes the measurand either continuously or periodically. However, computer-based systems require periodic measurements since by their nature, computers can only accept discrete numbers at discrete intervals of time.
  - (a) Continuous signals have values at every instant of time.
  - (b) Discrete-time signals are sampled periodically and do not provide values between these sampling times.



(a) (b)

…Generalized Medical Instrumentation System…

- Signal conditioning
  - Amplify, filter, match the impedance of the sensor to the display
  - Convert analog signal to digital
  - Process the signal

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…Generalized Medical Instrumentation System…

- Output display
  - Results must be displayed in a form that the human operator can perceive
    - Numerical, Graphical, Discrete or continuous, Permanent or temporary, Visual or acoustical
- Auxiliary elements
  - Data storage
  - Data transmission
  - Control and feedback
  - Calibration signal

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…Generalized Medical Instrumentation System…

- Panels and series
- Certain groups of measurements are often ordered together because they are very commonly used or because they are related.
- This may occur even if the measurements are based on different principles or are taken with different sensors.
- Table in next slide is an example of one of these groups of measurements, which are called panels or series.

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…Generalized Medical Instrumentation System…

- Complete blood count for a male subject.

Laboratory test	Typical value
Hemoglobin	13.5 to 18 g/dL
Hematocrit	40 to 54%
Erythrocyte count	4.6 to 6.2 × 10^6/ µL
Leukocyte count	4500 to 11000/ µL
Differential count	Neutrophil 35 to 71% Band 0 to 6% Lymphocyte 1 to 10% Monocyte 1 to 10% Eosinophil 0 to 4% Basophil 0 to 2%

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…Generalized Medical Instrumentation System

- Hemoglobin is the protein which caries oxygen in the bloodstream.
- Hematocrit is the percent of solid material in a given volume of blood after it has been centrifuged.
- An erythrocyte is a red blood cell.
- A leukocyte is a white blood cell.
  - The differential count tells how many of each type of white blood cell there are in one microliter of blood.
  - Unusual values for different leukocytes can be indicative of the immune system fighting off foreign bodies.

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Errors in measurements…

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- When we measure a variable, we seek to determine the true value, as shown in Figure (next slide) .
- This true value may be corrupted by a variety of errors. For example
  - Movement of electrodes on the skin may cause an undesired added voltage called an artifact.
  - Electric and magnetic fields from the power lines may couple into the wires and cause an undesired added voltage called interference
  - Thermal voltages in the amplifier semiconductor junctions may cause an undesired added random voltage called noise. Temperature changes in the amplifier electronic components may cause undesired slow changes in voltage called drift.
- We must evaluate each of these error sources to determine their size and what we can do to minimize them.

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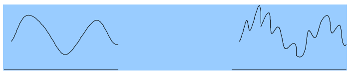
…Errors in measurements…

(a) Signals without noise are uncorrupted.

(b) Interference superimposed on signals causes error.

Frequency filters can be used to reduce noise and interference.



(a) (b)

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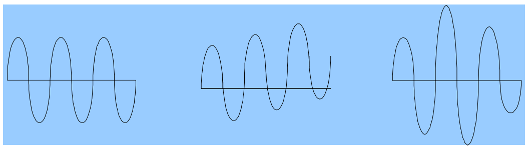
…Errors in measurements…

(a) Original waveform.

(b) An interfering input may shift the baseline.

(c) A modifying input may change the gain.



(a) (b) (c)

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Accuracy and precision…

- Resolution
  - the smallest incremental quantity that can be reliably measured.
    - a voltmeter with a larger number of digits has a higher resolution than one with fewer digits.
  - However, high resolution does not imply high accuracy.
- Precision
  - the quality of obtaining the same output from repeated measurements from the same input under the same conditions.
  - High resolution implies high precision.
- Repeatability
  - the quality of obtaining the same output from repeated measurements from the same input over a period of time.

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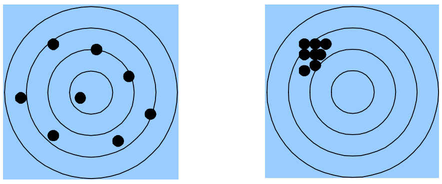
…Accuracy and precision…

- Data points with

  (a) low precision and (b) high precision.



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…Accuracy and precision…

- Accuracy
  - the difference between the true value and the measured value divided by the true value.

- **Obtaining the highest possible precision, repeatability, and accuracy is a major goal in bioinstrumentation design.**

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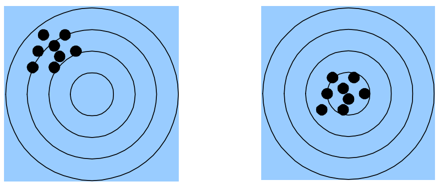
…Accuracy and precision…

- Data points with

  (a) low accuracy and (b) high accuracy



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Calibration…

- Measuring instruments should be calibrated against a standard that has an accuracy 3 to 10 times better than the desired calibration accuracy.
- The accuracy of the standard should be traceable to the institutions regulating the standards (National Institute of Standards and Technology, TSI, etc.) .

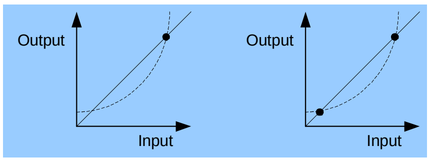
Calibration…

- If the instrument is linear,
  - its output can be set to zero for zero input. Then a one-point calibration defines the calibration curve that plots output versus input (next slide).
- If the linearity is unknown,
  - a two-point calibration should be performed and these two points plus the zero point plotted to ensure linearity (next slide).
- If the resulting curve is nonlinear,
  - many points should be measured and plotted to obtain the calibration curve.
- If the output cannot be set to zero for zero input,
  - measurements should be performed at zero and full scale for linear instruments and at more points for nonlinear instruments.
- Calibration curves should be obtained at several expected temperatures to determine temperature drift of the zero point and the gain.

…Calibration

(a) The one-point calibration may miss nonlinearity.

(b) The two-point calibration may also miss nonlinearity.



(a) (b)

Statistics

- Mean
  - If we make n measurements of x, for example of the weights of a population, we may wish to report an estimate of them in a condensed way.
  - The simplest statistic is the estimated sample mean

$$\bar{x} = \frac{\sum x_i}{n}$$

where $i = 1, 2, \ldots n$.

Statistics

- Standard Deviation
  - A measure of the spread of data about the mean is the estimated sample standard deviation

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

- Used with the mean for symmetric distributions of numerical data.

Statistics

- Standard deviation of the mean (standard error of the mean (SEM))
  - Expresses the variability to be expected among the means in future samples, whereas the standard deviation describes the variability to be expected among individuals in future samples.

$$s_{\bar{x}} = \frac{\sum s}{\sqrt{n-1}}$$

Gaussian Distribution…

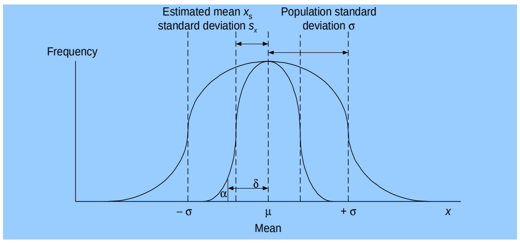
- The spread (distribution) of data may be rectangular, skewed, Gaussian, or other.
- The Gaussian distribution is given by

$$f(X) = \frac{e^{-(X-\mu)^2/(2\sigma^2)}}{\sqrt{2\pi}\sigma}$$

where μ is the true mean and σ is the true standard deviation of a very large number of measurements.

…Gaussian Distribution

- For the normal distribution, 68% of the data lies within ±1 standard deviation. By measuring samples and averaging, we obtain the estimated mean , which has a smaller standard deviation s_x. α is the tail probability that x_s does not differ from μ by more than δ.



Poisson Probability…

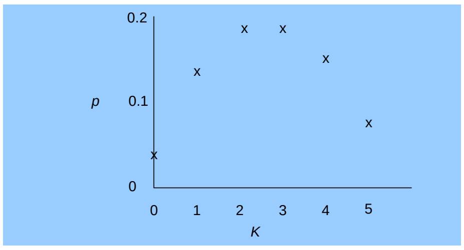
- The Poisson probability density function is another type of distribution.
  - It can describe, among other things, the probability of radioactive decay events, cells flowing through a counter, or the incidence of light photons.
- The probability that a particular number of events *K* will occur in a measurement (or during a time) having an average number of events *m* is

$$p(K,m) = \frac{e^{-m}m^K}{K!}$$

- The standard deviation of the Poisson distribution is $\sqrt{m}$

…Poisson Probability

- A typical Poisson distribution for $m = 3$.



Hypothesis testing…

- In hypothesis testing, there are two hypotheses.
  - H_0, the null hypothesis, is a hypothesis that assumes that the variable in the experiment will have no effect on the result
  - H_a is the alternative hypothesis that states that the variable will affect the results.
- For any population, one of the two hypotheses must be true.
- The goal of hypothesis testing is to find out which hypothesis is true by sampling the population.
- In reality, H_0 is either true or false and we draw a conclusion from our tests of either true or false. This leads to four possibilities (next slide)

…Hypothesis testing…

- The four outcomes of hypothesis testing.

Conclusion	Real situation	
	H_0 true	H_a true
Accept H_0	Correct decision	Type II error, $p = b$
Reject H_0	Type I error, $p = a$	Correct decision

…Hypothesis testing…

- Equivalent table of the table given in previous slide for results relating to a condition or disease.

Test result	**Has condition?**	
	No	Yes
Negative	True negative (TN)	False negative (FN)
Postitive	False positive (FP)	True positive (TP)

…Hypothesis testing…

- The terms in the Table in previous slide are useful for defining measures that describe the proportion of, for example, a disease in a population and the success of a test in identifying it.
- Incidence
  - is the number of cases of a disease during a stated period, such as *x* cases per 1000 per year.

…Hypothesis testing…

- Prevalence
  - the number of cases of a disease at a given time such as *y* cases per 1000.
- It is all diseased persons divided by all persons.

$$\text{Prevalence} = \frac{\text{TP} + \text{FN}}{\text{TN} + \text{TP} + \text{FN} + \text{FP}}$$

…Hypothesis testing…

- Sensitivity
  - the probability of a positive test result when the disease is present.
  - Among all diseased persons, it is the percent who test positive.

$$\text{Sensitivity} = \frac{\text{TP}}{\text{TP} + \text{FN}} 100\%$$

- Specificity
  - the probability of a negative diagnostic result in the absence of the disease.
  - Among all normal persons, it is the percent who test negative.

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}} 100\%$$

…Hypothesis testing…

- Considering only those who test positive, positive predictive value (PPV) is the ratio of patients who have the disease to all who test positive.

$$\text{PPV} = \frac{\text{TP}}{\text{TP} + \text{FP}} 100\%$$

- Considering only those who test negative, negative predictive value (NPV) is the ratio of nondiseased patients to all who test negative.

$$\text{NPV} = \frac{\text{TN}}{\text{TN} + \text{FN}} 100\%$$

…Hypothesis testing

- The test result threshold is set to minimize false positives and false negatives.