ESE 3400: Medical Devices Lab

Lec 2: September 13, 2023

Sensing Principle

Lab 1 Sensors

- Hall Sensor
  - Measures magnetic field present
  - Used for position measurements in medical devices
    - Eg. proper location of needles in medical syringes, track position of components in blood analysis machines, applications where a position, gap, alignment, orientation need to be measured without contact
- Temperature Sensor
  - Measures temperature
  - Used for monitoring vital signs also maintaining temperature in devices
    - Eg. Electronic thermometers, drug storage

Lab 1 Sensors (con't)

- Photo Resistor
  - Measures intensity of light present
  - Used for sensing reflected or transverse light
    - Eg. Measure blood oxygenation by sensing light pass through finger or ear lobe, heart rate by measuring reflected/passed light
- Accelerometer
  - Measure lateral and rotational acceleration (ie. Movement)
  - Used for sensing motion and direction
    - Eg. Fitness trackers, sleep monitors, tremor monitoring, gait analysis and balance
- Other sensors: pressure, blood glucose, etc.

Lecture Outline

- System Examples
- Sensing Principle
- Vital signs
- Physical Sensor Types
  - Surface electrodes
  - Pressure sensors
  - Thermistors
  - Photodiodes
- Biosensors
- Lab 2 discussion (if time)

Definitions

- Medical instrument
  - Medical device that makes measurements
- Measurand
  - The physiologic quantity, property or condition that the system measures
- Transducer
  - Converts the energy or information from a measurand to another form
- Sensor
  - Device that transform biologic, chemical, electrical, magnetic, mechanical, optical or other stimuli input into an electrical signal output

Medical Instrument Systems

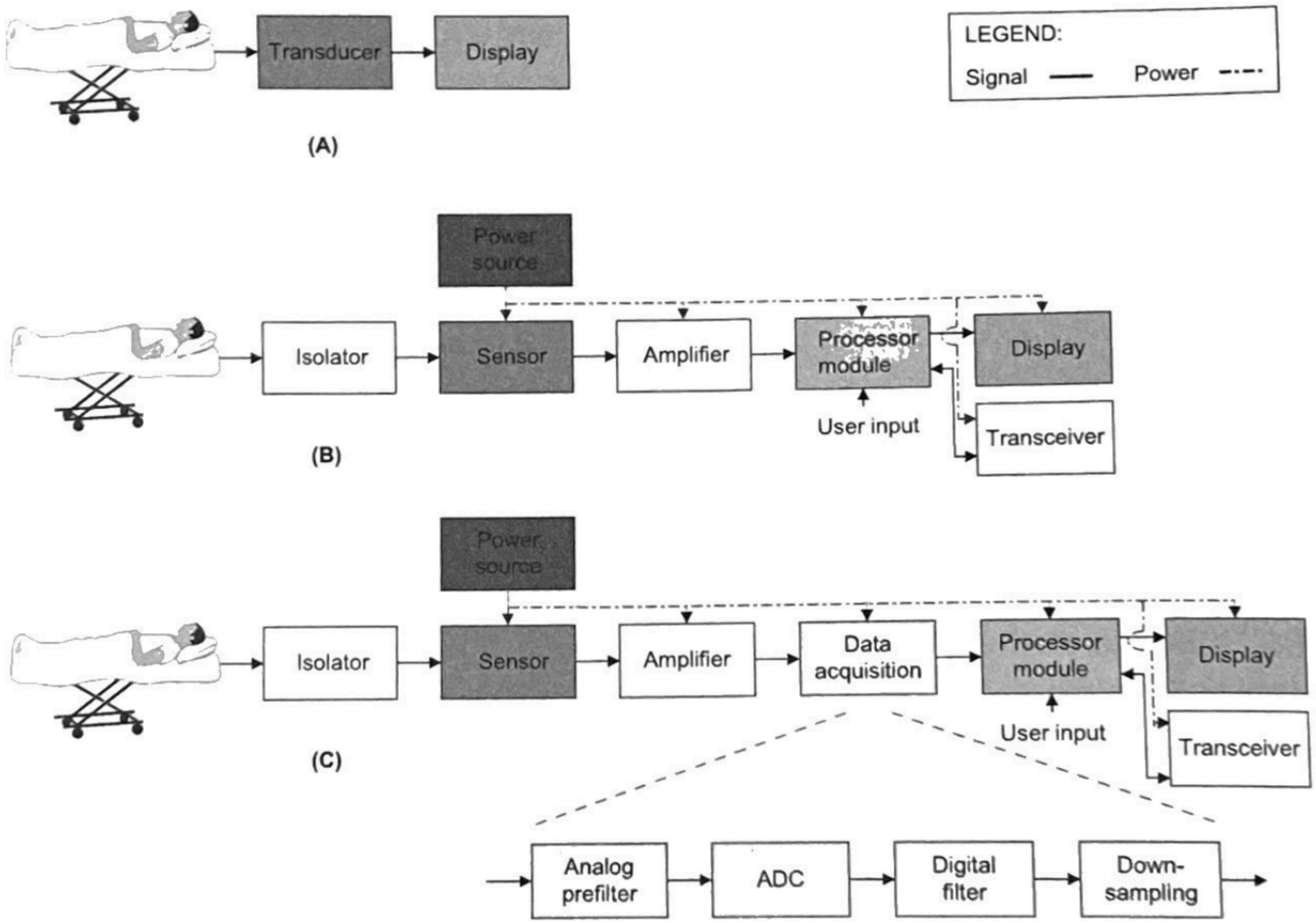


FIGURE 1.1

Three types of medical instruments. (A) Simple. (B) Analog. (C) Digital.

Pulse Oximeter System Digram

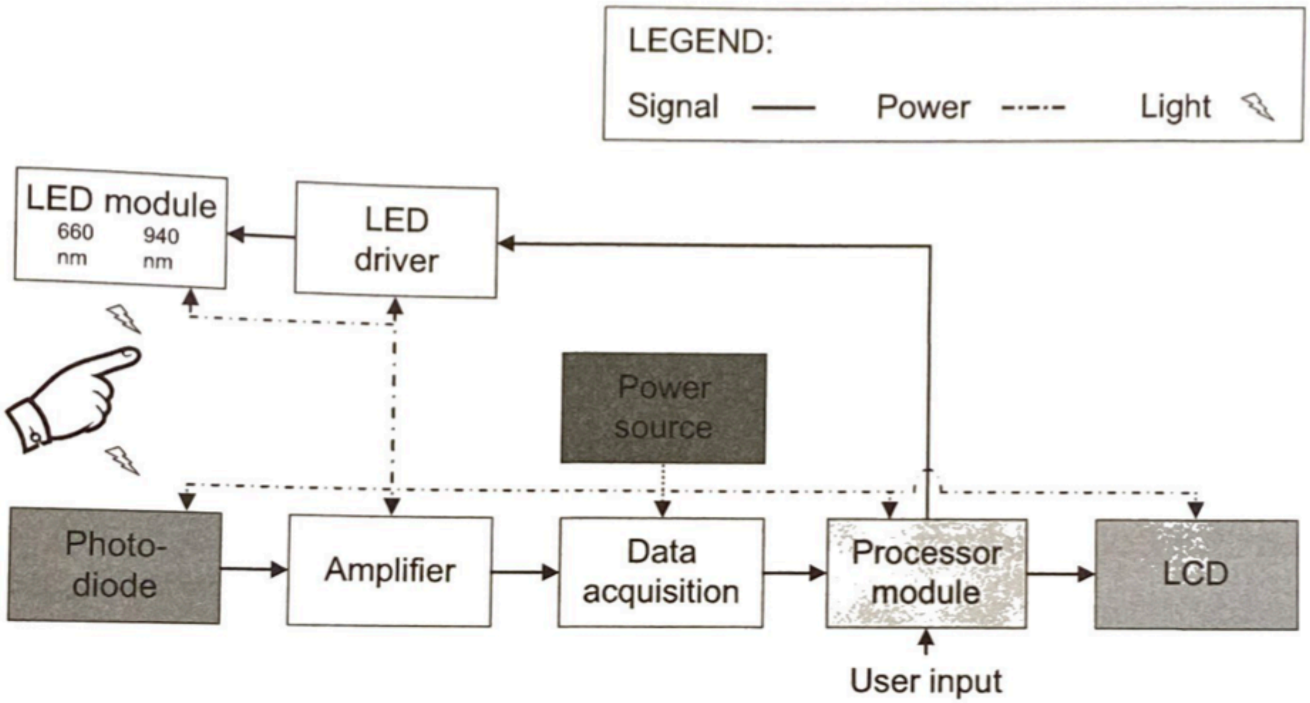
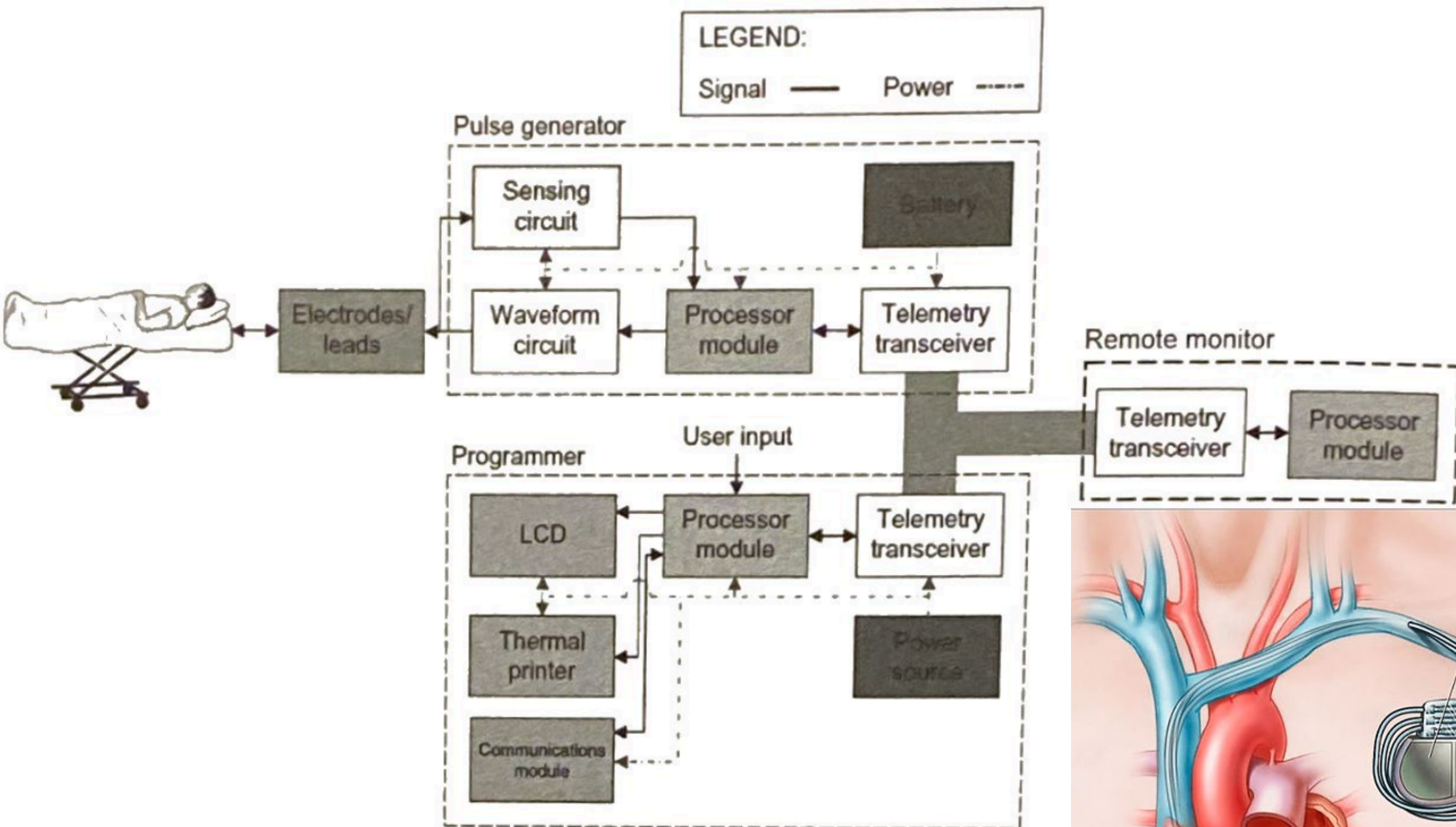
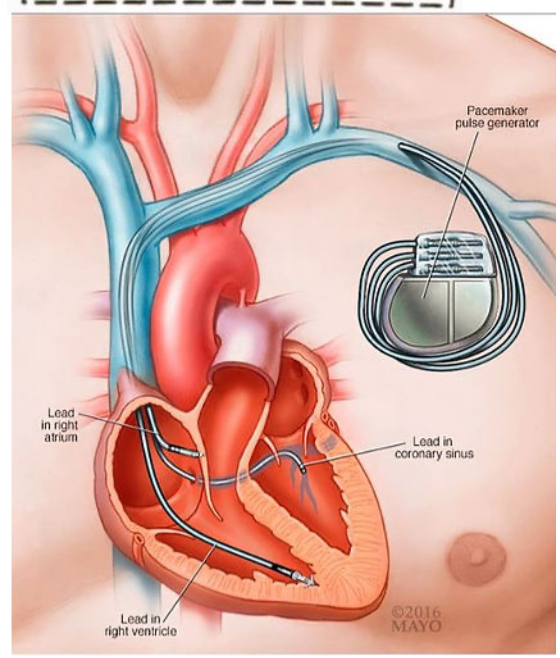


FIGURE 11.13

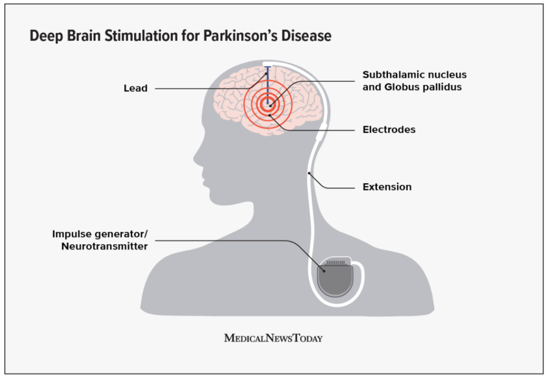
Pulse oximeter system diagram.

Pacemaker System Diagram





Deep Brain Stimulation System Diagram



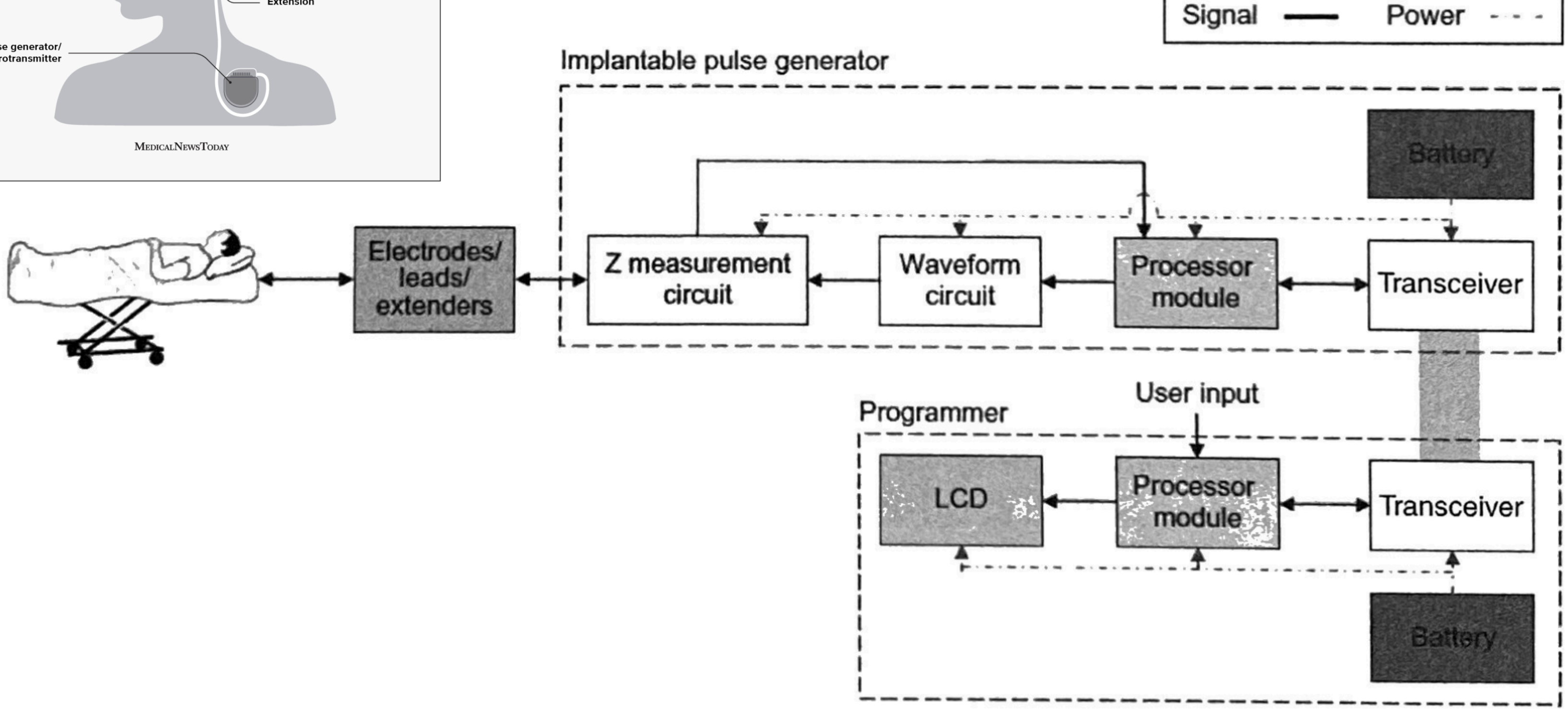


FIGURE 14.9

Deep brain stimulator system diagram.

Cochlear Implant System Diagram

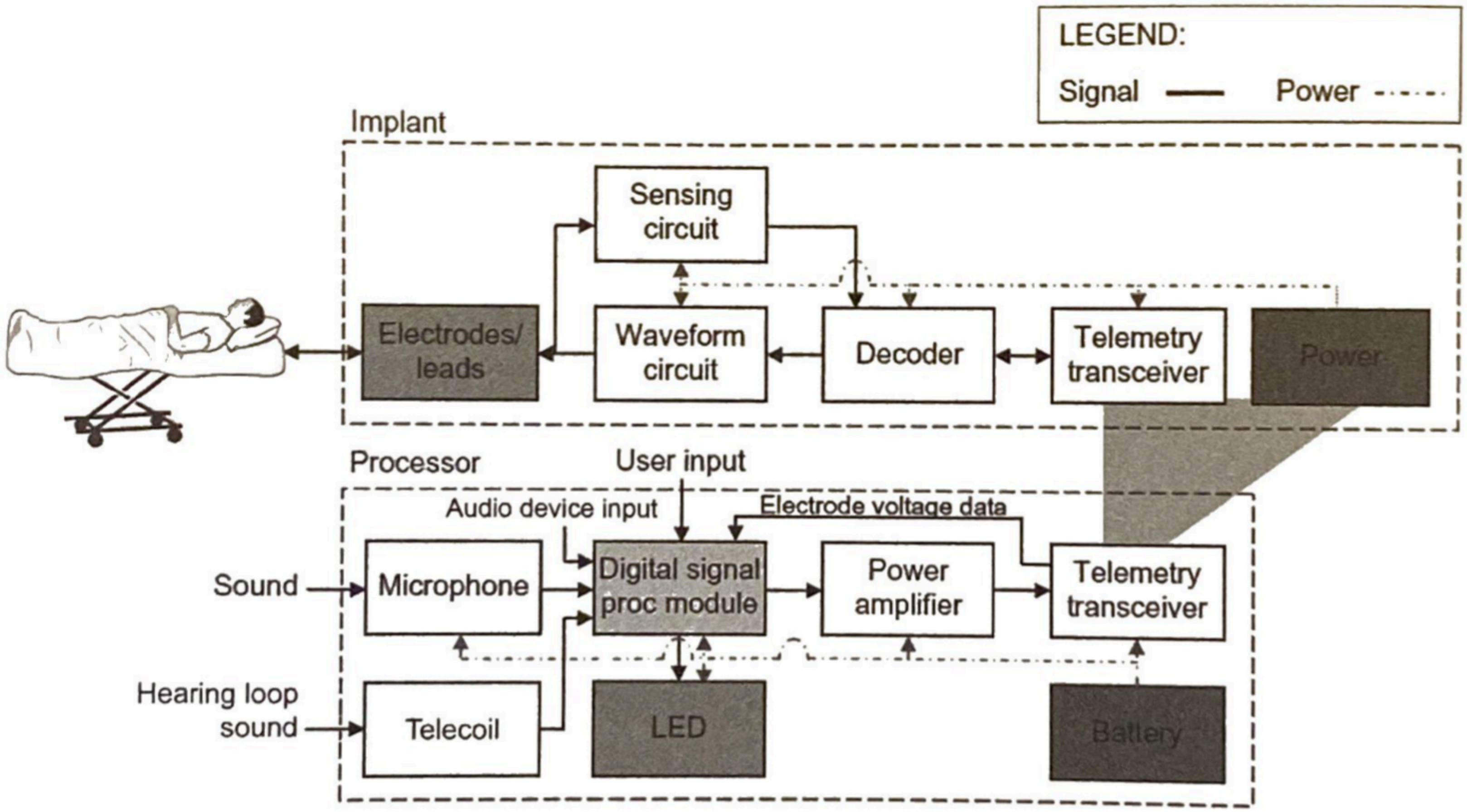


FIGURE 15.15

Cochlear implant system diagram.

Sensing Principle

- Sensor is a device that can detect changes or events in its environment as an electrical signal

Accuracy, Bias and Precision

- Accuracy "usually denotes in some sense the closeness of the measurand values to the true value, taking into consideration both precision and bias. Bias, defined as the limiting mean and the true value, is a constant, and does not behave in the same way as the index of precision, the standard deviation" (Ku, 1988)

Accuracy, Bias and Precision

- In practice:
  - Accuracy is usually defined as the percentage difference between the measured and true values, based on a full scale reading.
  - Eg. The Welch Allyn SureTemp Plus digital thermometer is ±0.2ºF, for the patient temperature range of 80-110ºF.

Accuracy, Bias and Precision

- Bland-Altman analysis:

$$\text{bias} = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n}$$

$$\text{precision} = 2\times\sqrt{\frac{\sum_{i=1}^{n}(m_i - \text{bias})^2}{n-1}}$$

- Where m_i is the measured standard and s_i is the reference standard for n samples

Accuracy, Bias and Precision

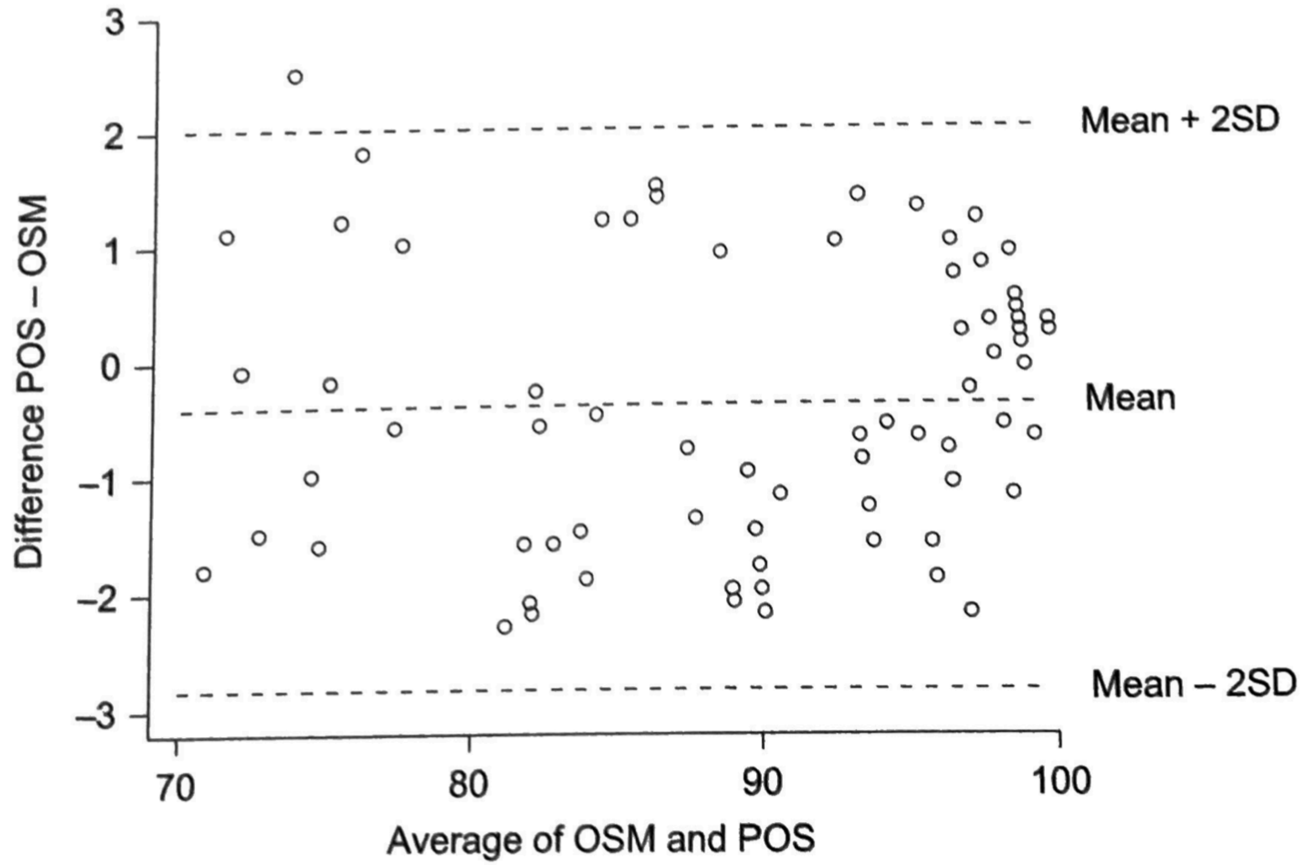
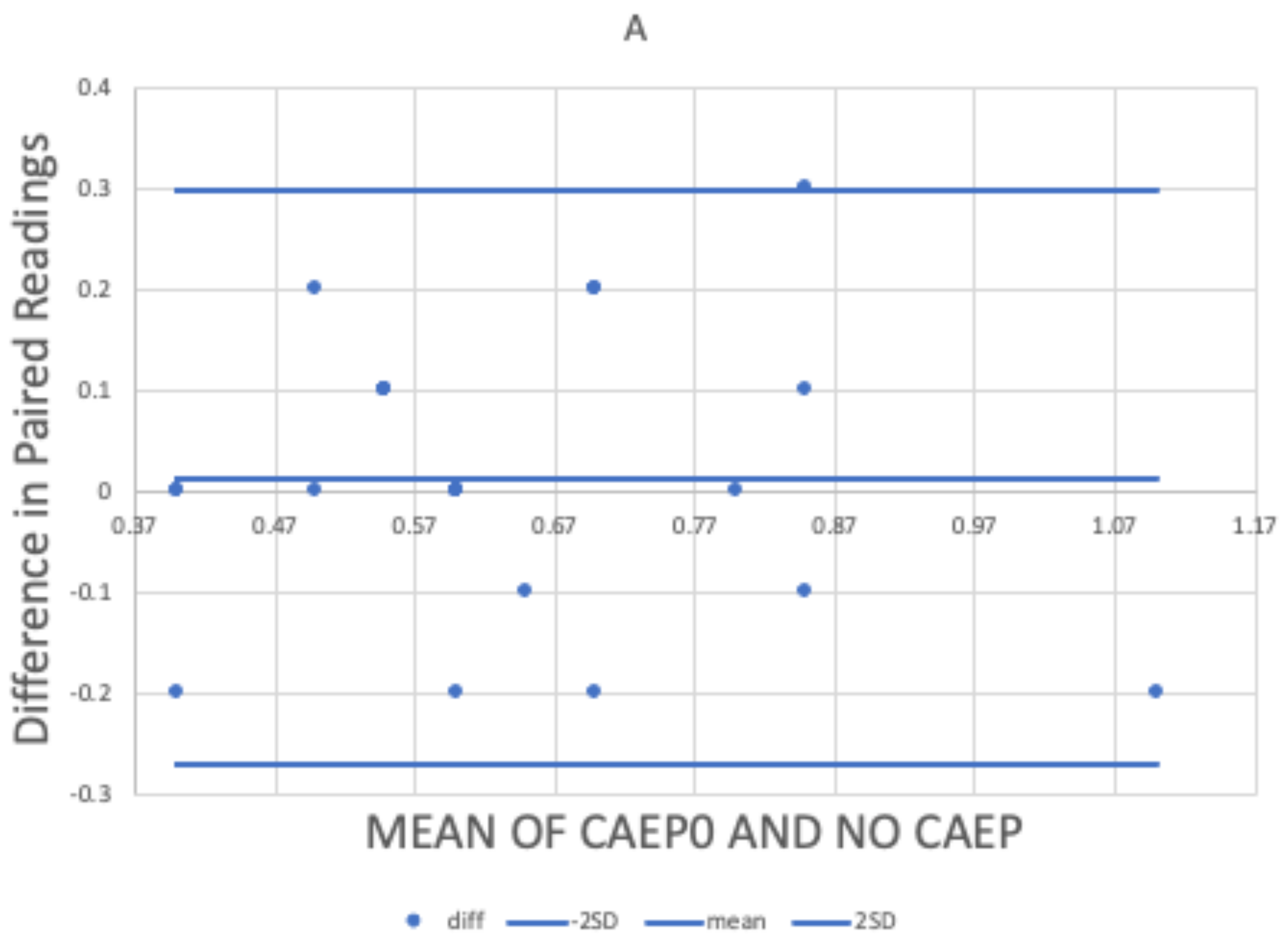


FIGURE 1.6

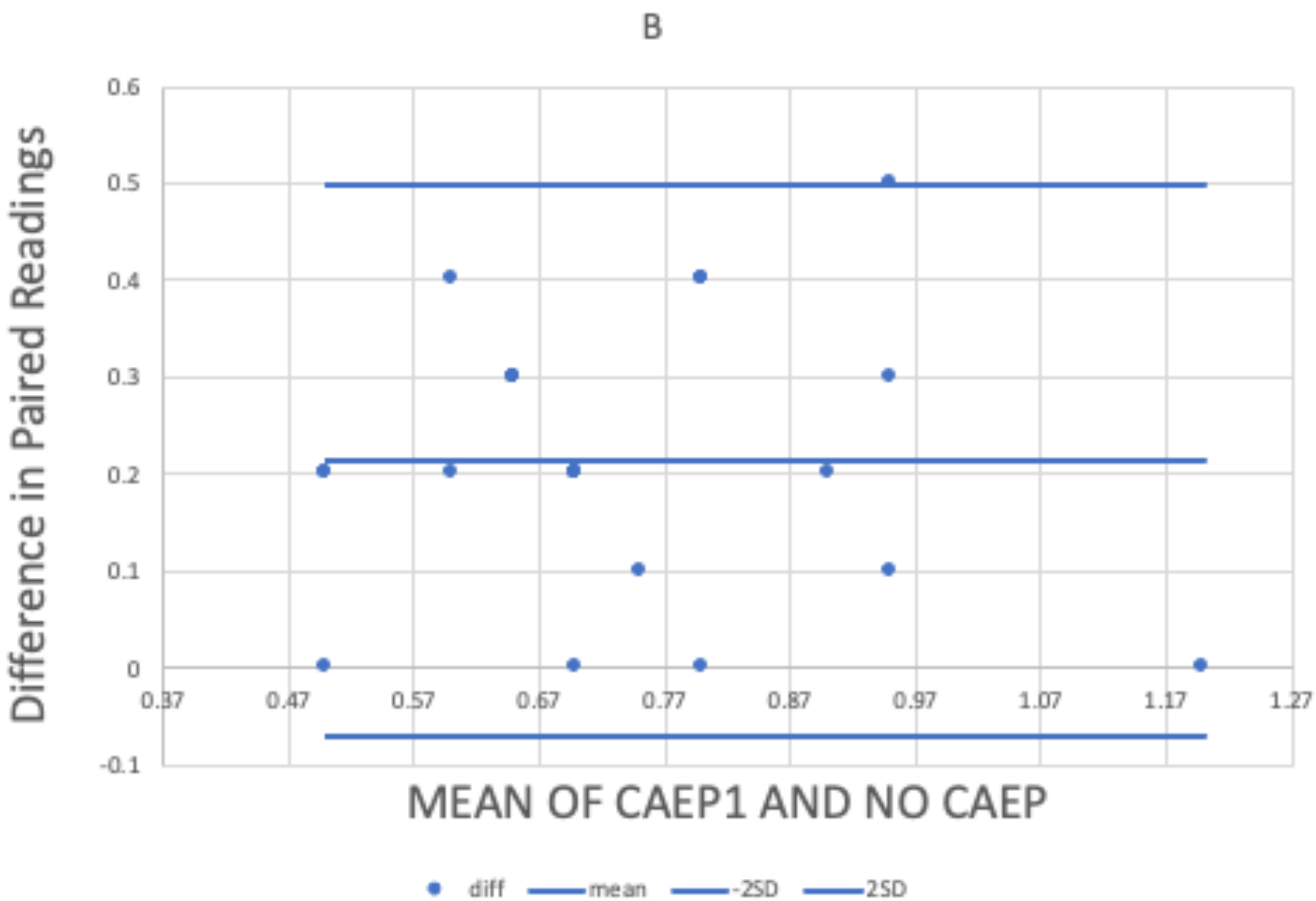
Bland-Altman plot of oxygen saturation measured by oxygen saturation monitor (OSM) and pulsed oxygen oximeter (POS). After publication of this graph, a pulsed oxygen oximeter became commonly known as a pulse oximeter.

a)



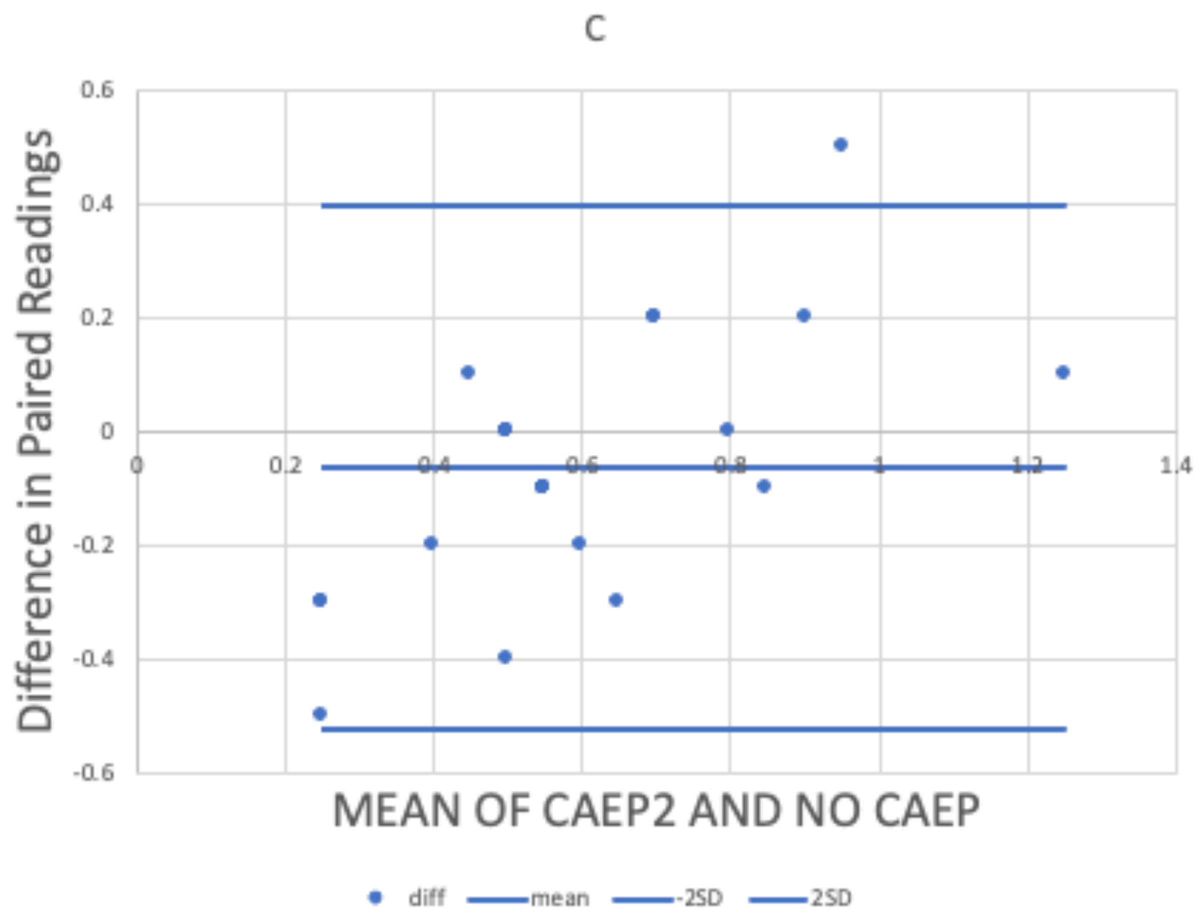
A
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.37
0.47
0.57
0.67
0.77
0.87
0.97
1.07
1.17
Difference in Paired Readings
MEAN OF CAEP0 AND NO CAEP
diff
-2SD
mean
2SD

b)



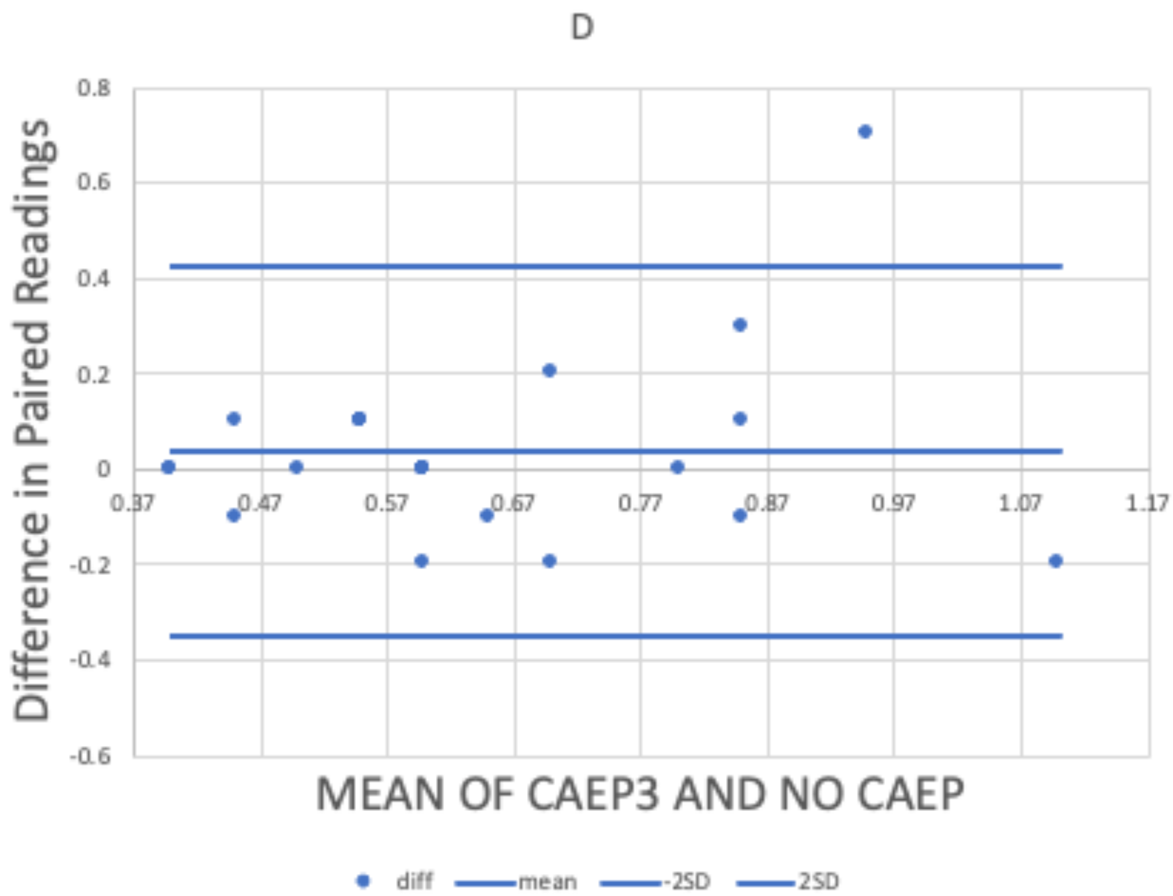
B
Difference in Paired Readings
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0.37
0.47
0.57
0.67
0.77
0.87
0.97
1.07
1.17
1.27
MEAN OF CAEP1 AND NO CAEP
diff
mean
-2SD
2SD

c)

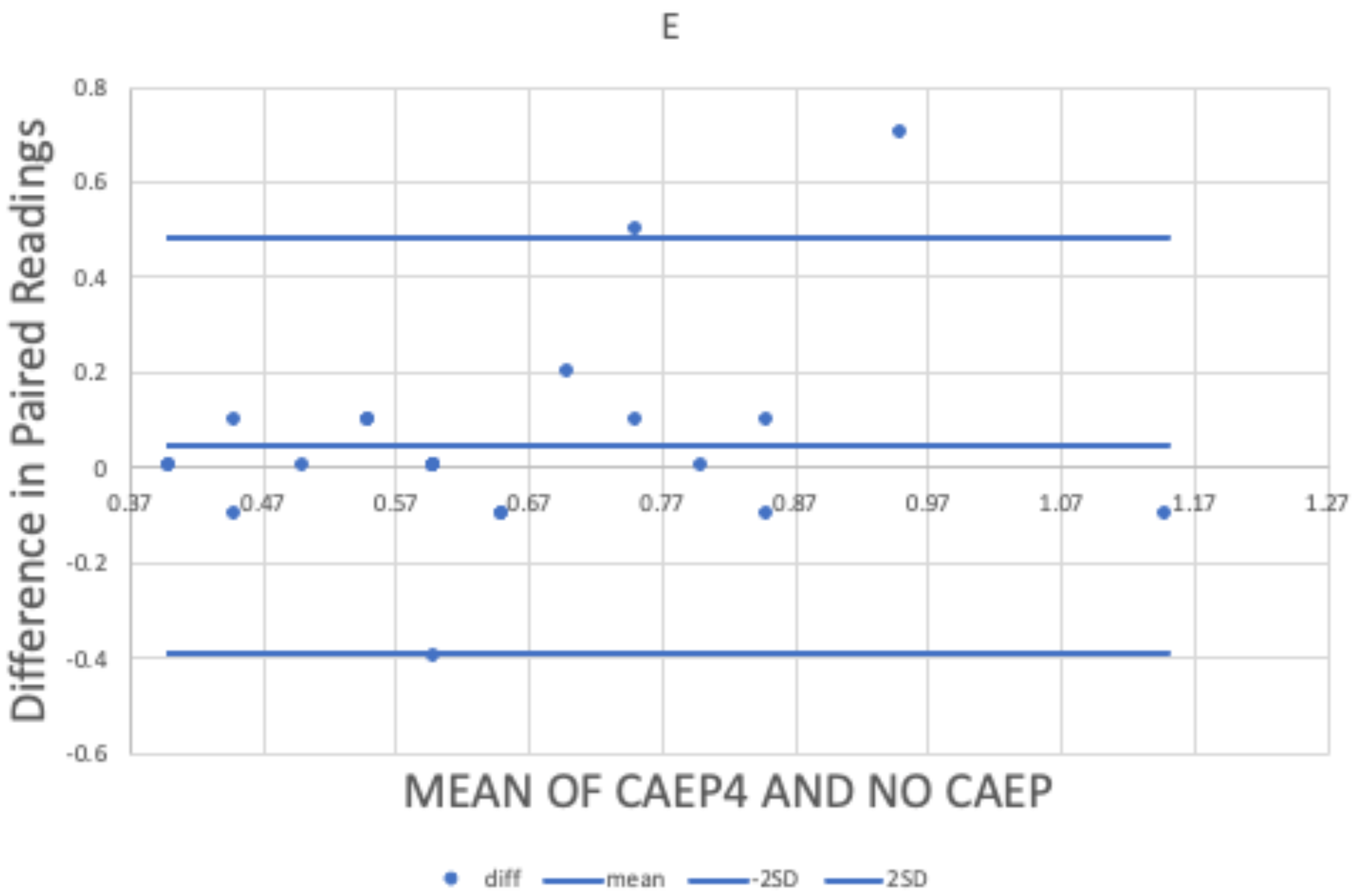


C
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Difference in Paired Readings
MEAN OF CAEP2 AND NO CAEP
diff
mean
-2SD
2SD

d)


D
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.37
0.47
0.57
0.67
0.77
0.87
0.97
1.07
1.17
Difference in Paired Readings
MEAN OF CAEP3 AND NO CAEP
diff
mean
-2SD
2SD

e)


E
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.37
0.47
0.57
0.67
0.77
0.87
0.97
1.07
1.17
1.27
Difference in Paired Readings
MEAN OF CAEP4 AND NO CAEP
diff
mean
-2SD
2SD

Summary

- **a.** A B-A plot for No CAEP paired with CAEP0. The points center about difference=0, provide a reasonable confidence interval, and remain in the same general pattern for all horizontal axis values. There is no remarkable data behavior.
- **b.** A B-A plot for No CAEP paired with CAEP1. In this type, the cluster of points may lie above or below the mean, indicating an offset, a bias, a systematic error. It might be wise to test means. In Fig. 27.1b, we can see that the mean of the data lies considerably above 0, indicating that the CAEP wearers' degrees of sway (imbalance) are consistently greater than with no CAEP.
- **c.** A B-A plot for No CAEP paired with CAEP2. The cluster of points go from below the mean on the left to above as you move to the right, showing a trend or error proportional to size of measure.
- **d.** A B-A plot for No CAEP paired with CAEP3. The cluster of points surround the mean tightly on the left and spread out to greater variability upon moving right, sort of cone-shaped, showing variability dependent on the magnitude of the measure. This effect appearing in Fig. d is not very strong.
- **e.** A B-A plot for No CAEP paired with CAEP4. Only about 5% of the data should lie outside the plus-minus CI and these points should not be dramatically far outside the confidence interval. If too many points lie outside, then the data are erratically variable. This effect needs a larger sample size (>100 data points) to see dependably if 5% of the data lie outside the 95% confidence interval. In Fig. e, 3 of the 22 points, nearly 14%, lie outside the confidence interval, a suspicious proportion.

Dynamic Range and Frequency Response

- Input dynamic range requirement specifies the mean signal level (if not 0), the range of differential signal, and the fastest acceptable amplitude rate of change (aka slew rate)
- Frequency response requirement typically specifies the frequency bandwidth in terms of the cutoff frequency at which the magnitude of the harmonics has fallen to a significant fraction of the fundamental frequency magnitude
  - The specific fraction is a medical device design choice

Noise Sources

- System noise refers to any artifact we would like to minimize
  - Older monitors have 60-Hz noise from power lines
  - EM interference from surgical cautery equipment
  - Patient motion
  - Respiration and blood pressure
- Can model system noise:

$$\boldsymbol{y}(k) = \boldsymbol{u}(k) + \boldsymbol{n}(k)$$

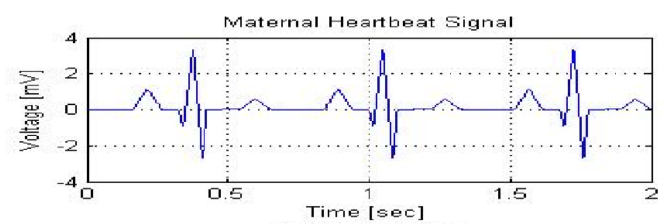


Fig. 2 Maternal heartbeat signal

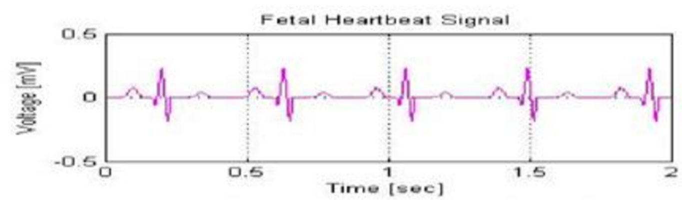
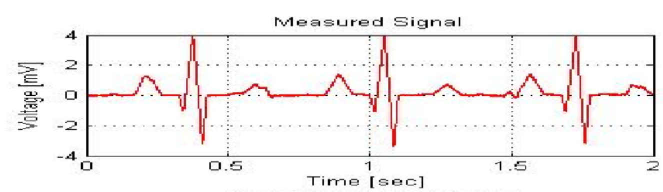
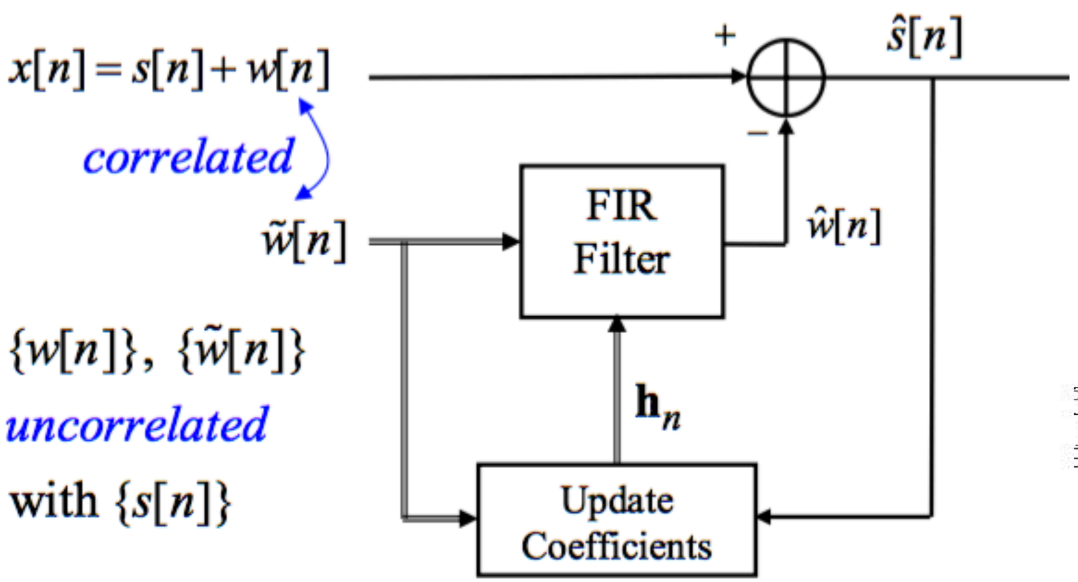


Fig. 3 Fetal electrocardiogram signal



Adaptive Interference Cancellation



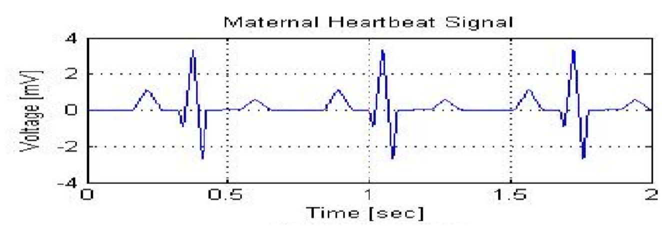


Fig. 2 Maternal heartbeat signal

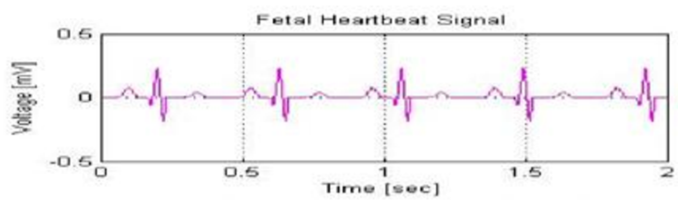
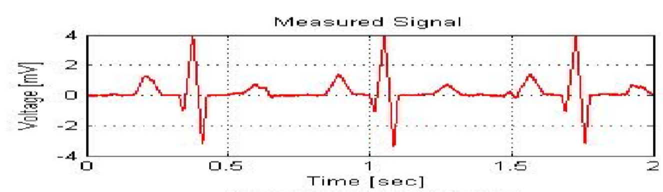


Fig. 3 Fetal electrocardiogram signal



Vital Signs

- Body Temperature
  - Thermistors
- Heart Rate and Heart Rate Variability
  - Surface electrodes
- Respiration Rate
  - Photodiodes
- Blood Pressure
  - Pressure sensors
- Height/Weight
  - Scale and ruler

Physical Sensors

- Surface electrodes
- Pressure sensors
- Thermistors
- Photodiodes

Surface Electrodes

- Monitor biopotential voltages
  - Reflects the electrical stimulation that precedes muscle contraction
  - EEG – electroencephalogram reflects brain activity
  - EMG – muscle activity
  - ECG – electrocardiogram specific to heart muscles

Surface Electrodes

- Monitor biopotential voltages

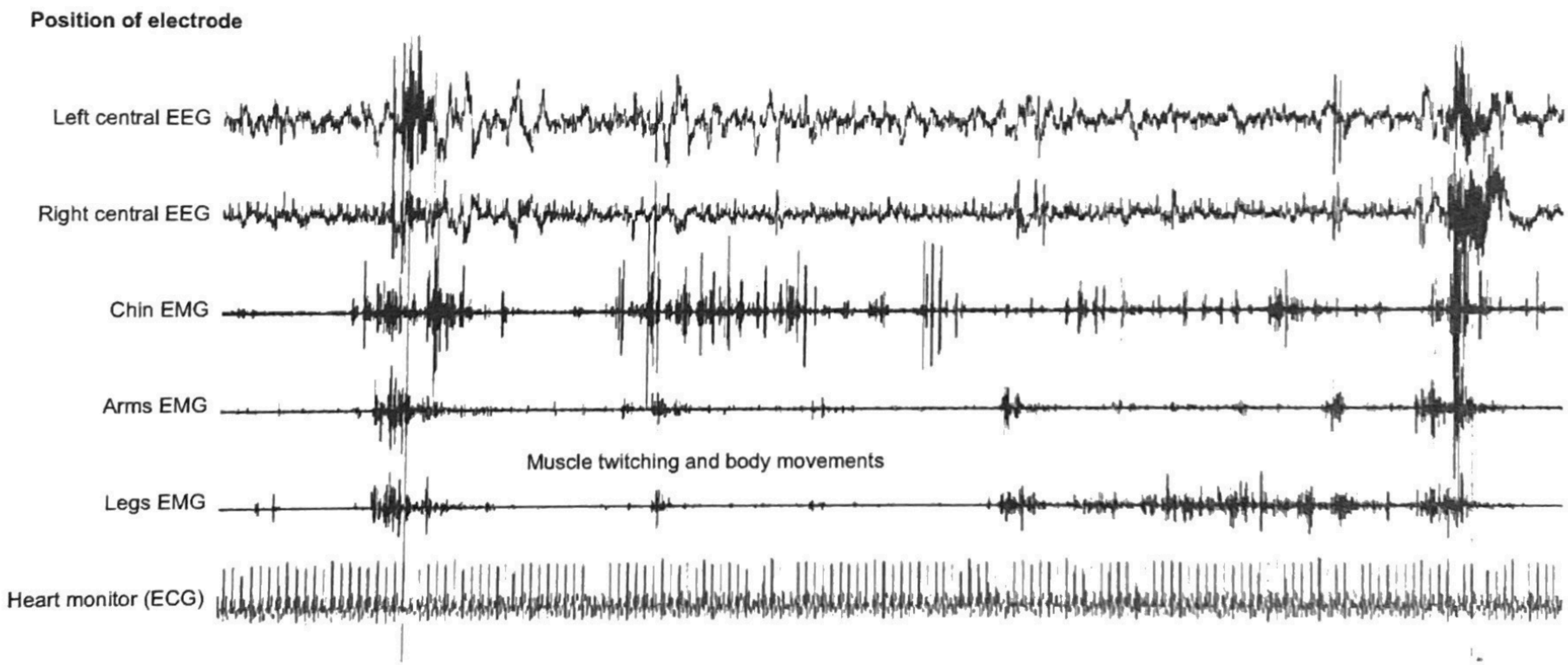


FIGURE 1.7

Examples of biopotentials in a patient with a sleep disorder.

Surface Electrodes

- Converts ionic current to electric current

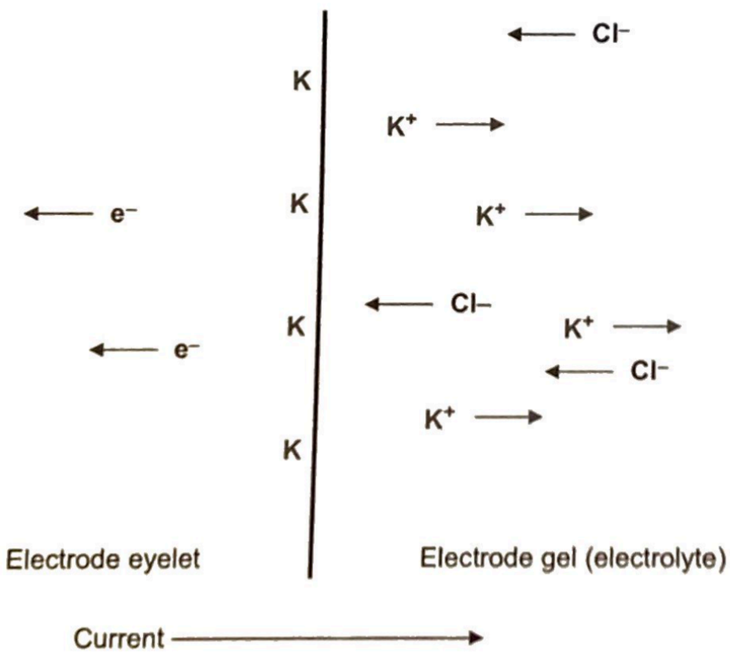


FIGURE 1.8

Electrode–electrolyte interface for KCl.

Surface Electrodes

- Modern electrodes
  - Cloth, vinyl or foam basepad
  - Polystyrene label
  - Nickel-plated brass stud
  - Carbon eyelet coated with Ag/AgCl
  - Wet or solid gel

Pressure Sensors

- Measures mechanical action changes as pressure
  - P in units of millimeters of mercury (mm Hg)
  - 760 mm Hg = 101,325 Pascals = 1 atm
- In lungs pressure is a measure of kinetic energy of the gas molecules

$$P = NRT$$

  - N = number of moles per unit volume, R = gas constant, T = absolute temperature
- For a liquid, such as blood at rest,

$$P = \frac{dF}{dA}$$

Pressure Sensors

- A pressure sensor contains three components
  - Diaphragm or plate of known area, A
  - Detector that responds to applied force
  - Interface circuit that ouptuts voltage

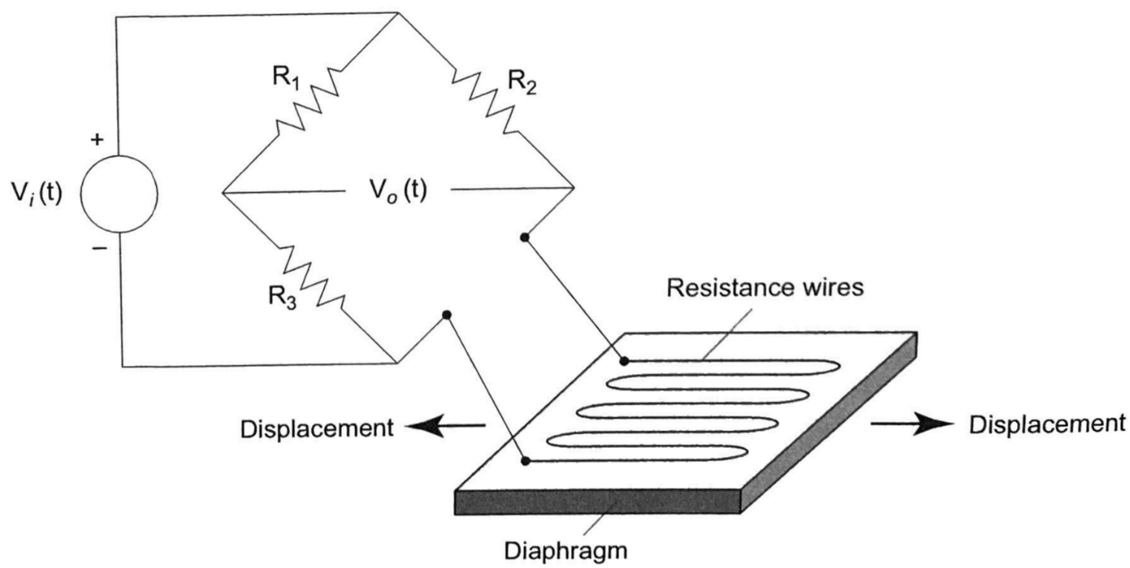


FIGURE 1.11

Pressure sensor components: a diaphragm, strain gauge, and Wheatstone bridge.

Pressure Sensors

- Intraarterial blood pressure (IAP) sensor

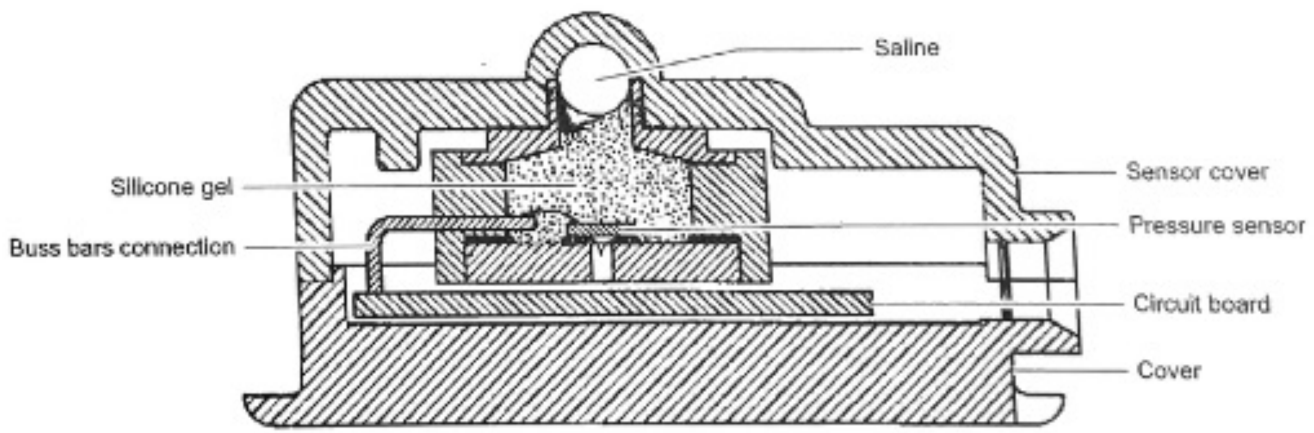


FIGURE 1.13

Deseret Medical pressure sensor cross section.

From Hanlon et al. (1987).

Thermistors

- Measures temperature

- Negative thermal coefficient (NTC) bead thermometer
  - Decreasing resistance with increasing temperature

Thermistors

- Bead thermometer
  - Best for measuring body temperature because it is stable (resistance does not change with age) and has fast response time

- Based on empirical data

$$R_T(T) = \exp\left(A_o + \frac{A_1}{T} + \frac{A_2}{T^2} + \frac{A_3}{T^3}\right)$$

- T = temperature, A_i are specified by the manufacturer

Thermistors

- Typical resistance curve

$$R_T(T) \approx \mathrm{R_c} \exp\left(\beta_m\left(\frac{1}{T}-\frac{1}{T_c}\right)\right)$$

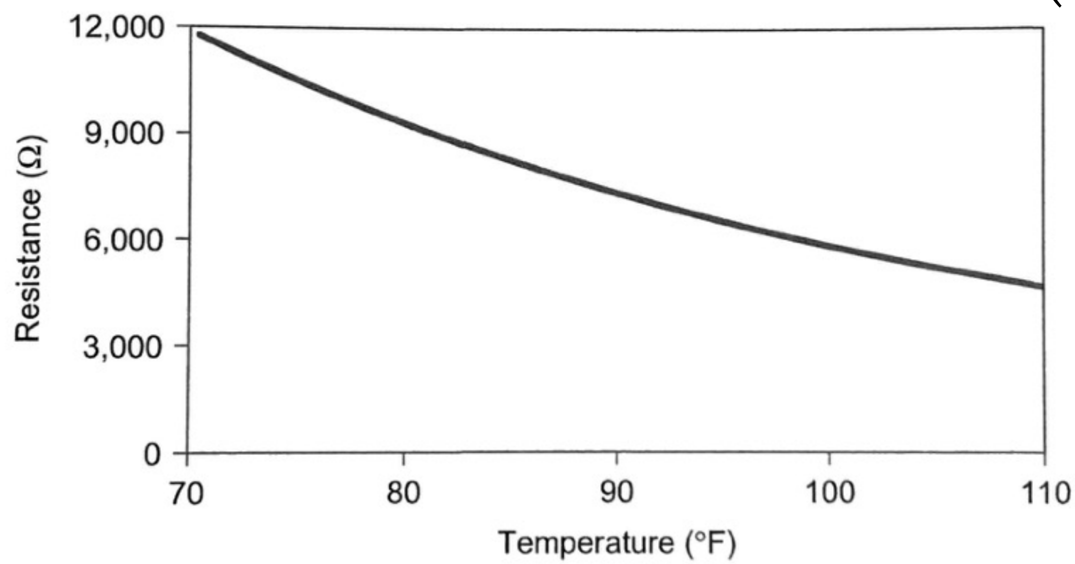


FIGURE 1.15

Resistance as a function of temperature.

- Interface circuitry is used so that output voltage is proportional to temperature

Photodiodes

- Measures changes in light interacting with the body
  - Typically light source is LED
    - Eg. Pulse oximetry uses red and infrared LEDs
  - LEDs emit range of wavelengths
    - Speed of light is the product of wavelength and optical frequency, $c = \lambda v$
    - Energy of a photon, $\mathrm{E} = hv$

Photodiodes

- Measures changes in light interacting with the body
  - Photon with energy, ***hv*** strikes reverse biased photodiode surface

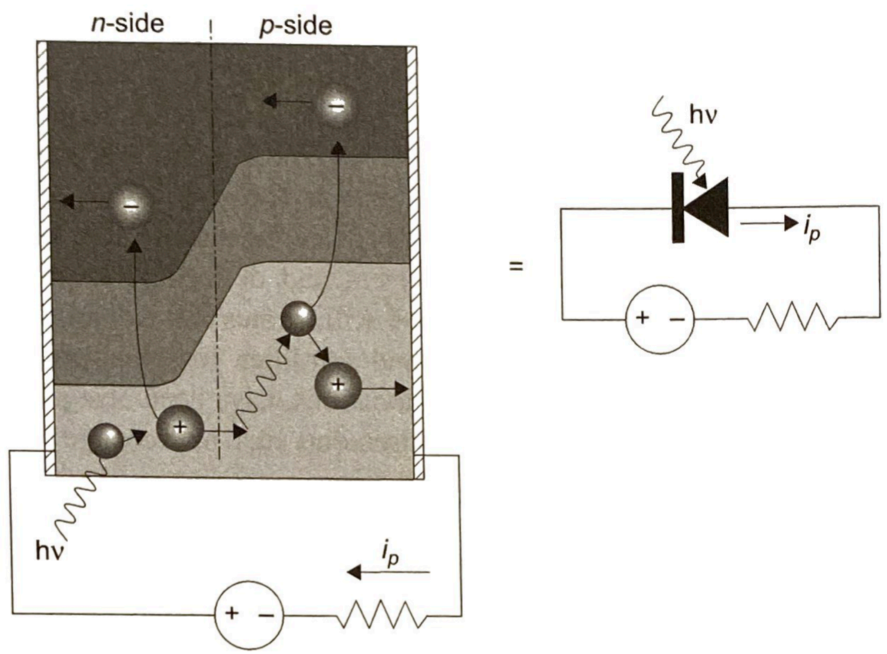


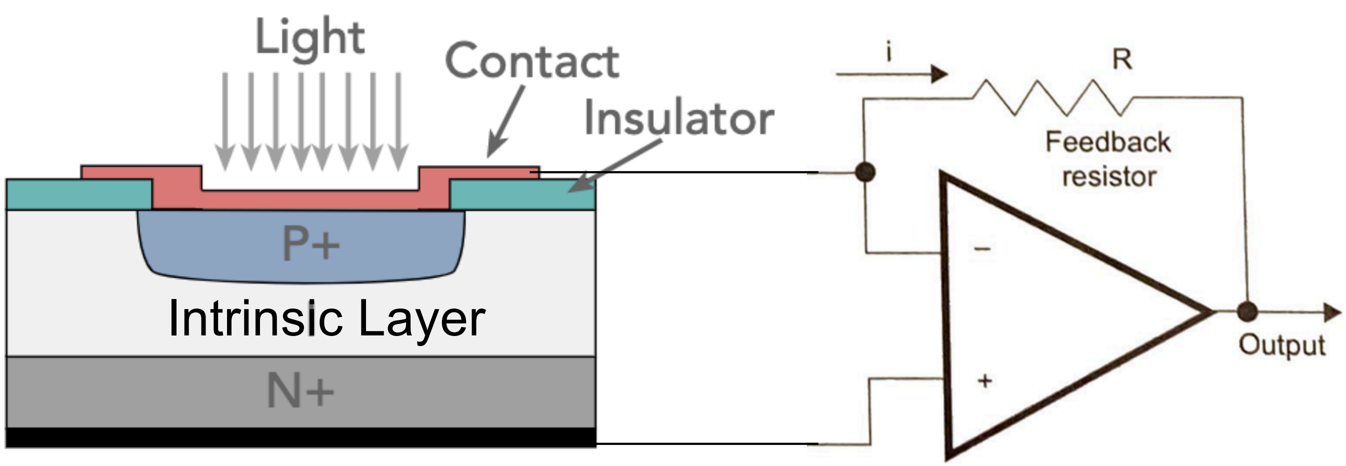
FIGURE 1.16

Photodiode structure and equivalent circuit.

Reproduced by permission from Fraden (2004).

Photodiodes

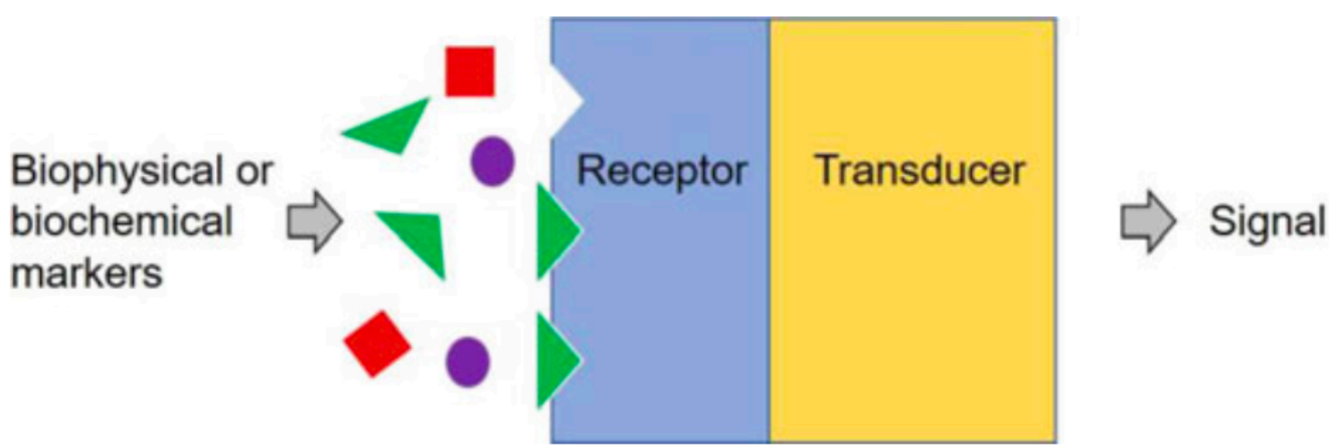
- Measures changes in light interacting with the body
  - Photon with energy, ***hv*** strikes reverse biased photodiode surface



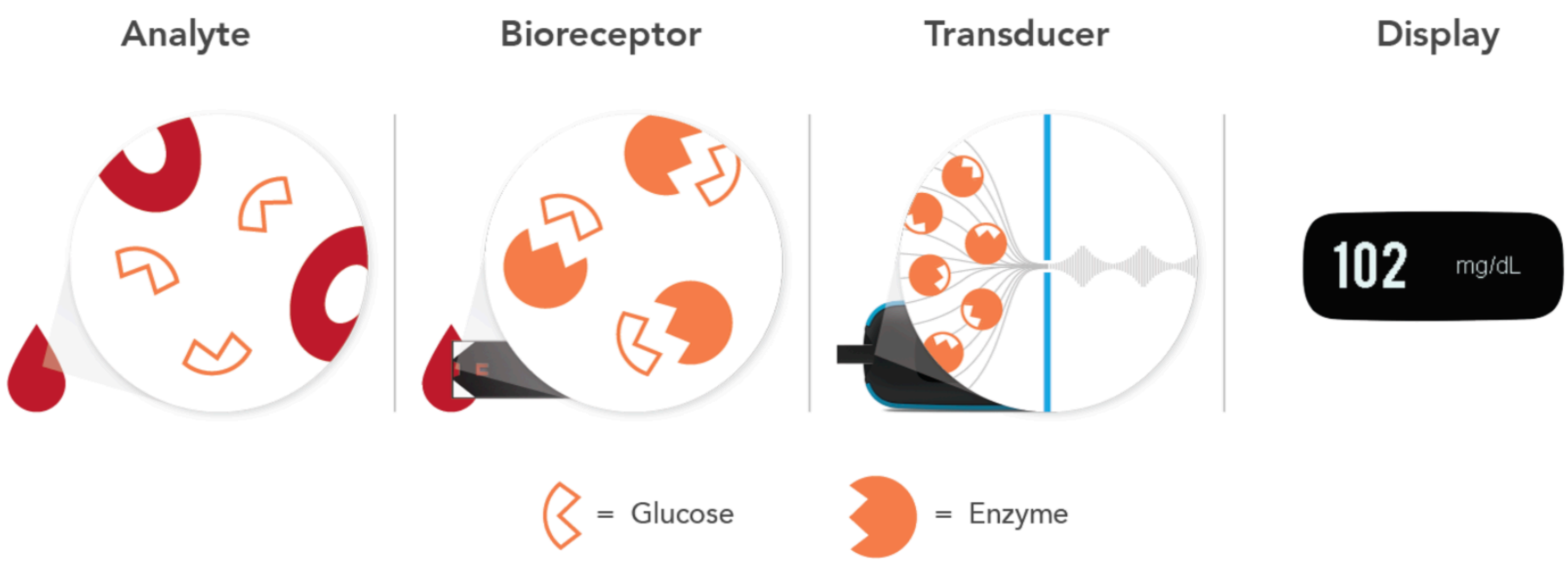
PIN photodiode structure

Biosenser

- The basic units of a biosensor are receptor and transducer. The receptor comes in close contact with the analyte and the chemical/physical interactions between the two are translated into a measurable signal by the transducer (Fig. 2.1).

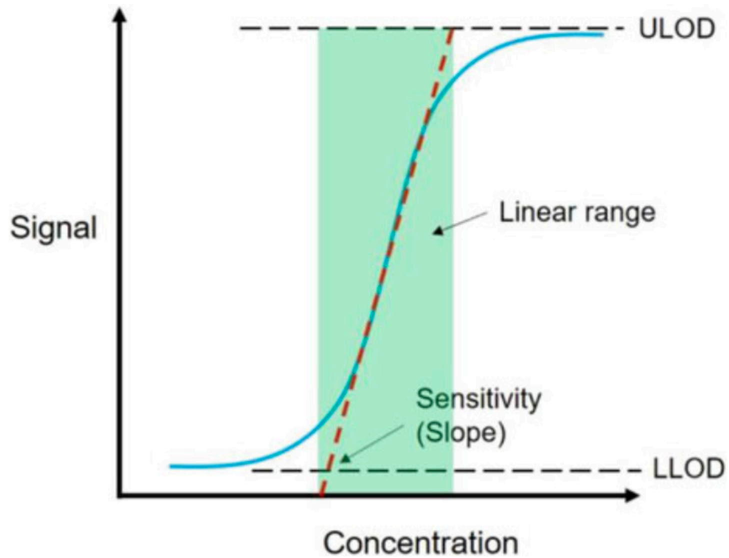


Glucose Sensor



Characteristics of Biosensors

- Limit of Detection (LOD)
  - minimum amount or concentration of the analyte that can be detected
- Detection Range
  - reflection of how much change caused by the external stimuli can be measured



Characteristics of Biosensors

- Sensitivity
  - ratio between the output signal and the input measured property
- Selectivity
  - indicates the sensor's ability to differentiate one analyte from another

Characteristics of Biosensors

- Reproducability
  - ability of the sensor to generate identical results when it is measuring the same level of external stimuli
- Stability
  - ability to maintain the same level of output signal under various environmental disturbances
- Biocompatibility
  - level of compatibility of the material/device with living tissue
    - Toxicity of materials, ractivity with living tissue, mechanical compatibility, biodegradability

Biosensors

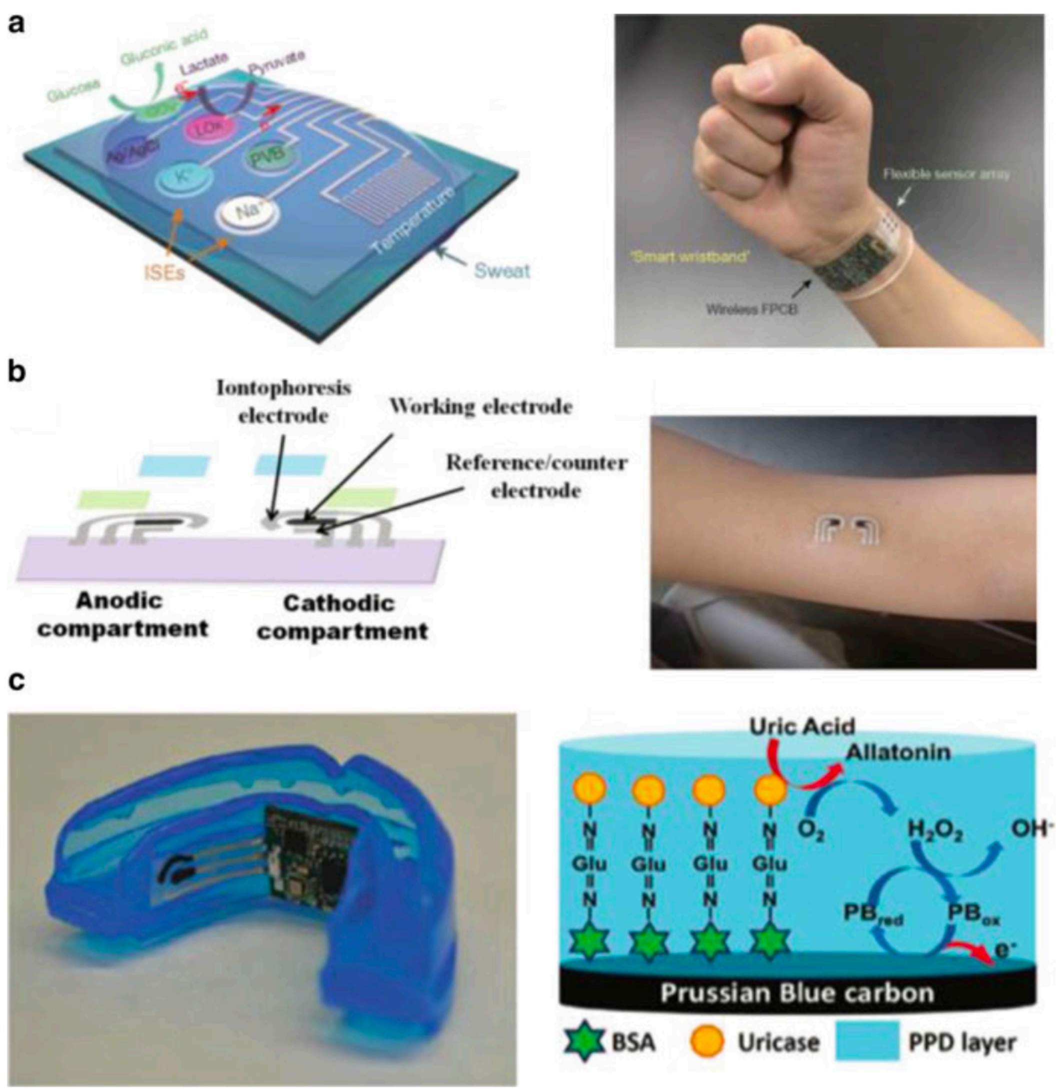
- Rely on chemical reactions or receptor–ligand binding to detect the presence of target analytes.
  - biochemical markers are cells including protein, cytokines, DNA, RNA, ions, metabolites, dissolved gases, and circulating tumor cells.
  - They are found in body fluids which are either enclosed inside body such as blood and interstitial fluid or secreted by body such as sweat and urine.

Biosensors

Table 2.1 Summary of major types of body fluids for sensing application

Body fluids	Disease-related biomarkers	Invasiveness of sampling
Blood	Contains the most comprehensive panel of biomarkers Some biomarkers are serum-bound	Invasive
Sweat	Strong correlation with blood concentration of small molecules	Non-invasive
Interstitial fluid	Contains most of the blood biomarkers but in less concentration	Minimally Invasive
Urine	Concentration of biomarkers vary from person to person High ionic strength may confound detection	Noninvasive
Saliva	Significantly lower concentration of biomarkers Some biomarkers are in free form not serum-bound (e.g., cortisol)	Noninvasive
Breath	Volatile organic compounds Correlation between breath markers and few select diseases has been strong	Noninvasive

Biosensors



a) W. Gao, S. Emaminejad, H.Y.Y. Nyein, S. Challa, K. Chen, A. Peck, et al., Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. Nature **529**, 509–514 (2016)

b) Tattoo-based platform for noninvasive glucose sensing

c) J. Kim, S. Imani, W.R. de Araujo, J. Warchall, G. Valdes-Ramirez, T.R. Paixao, et al., Wearable salivary uric acid mouthguard biosensor with integrated wireless electronics. Biosens. Bioelectron. **74**, 1061–1068 (2015)

Big Ideas

- Sensors convert measurand into electrical signal
  - Bland-Altman analysis for Accuracy, bias and precision
  - Dynamic range, frequency response, and noise
- Six* main vital signs for health monitoring
- Four physical sensor types
  - Electrodes
  - Pressure sensors
  - Thermistors
  - Photodiodes
- Biosensors
  - Use fluids for sensing biomarkers

Admin

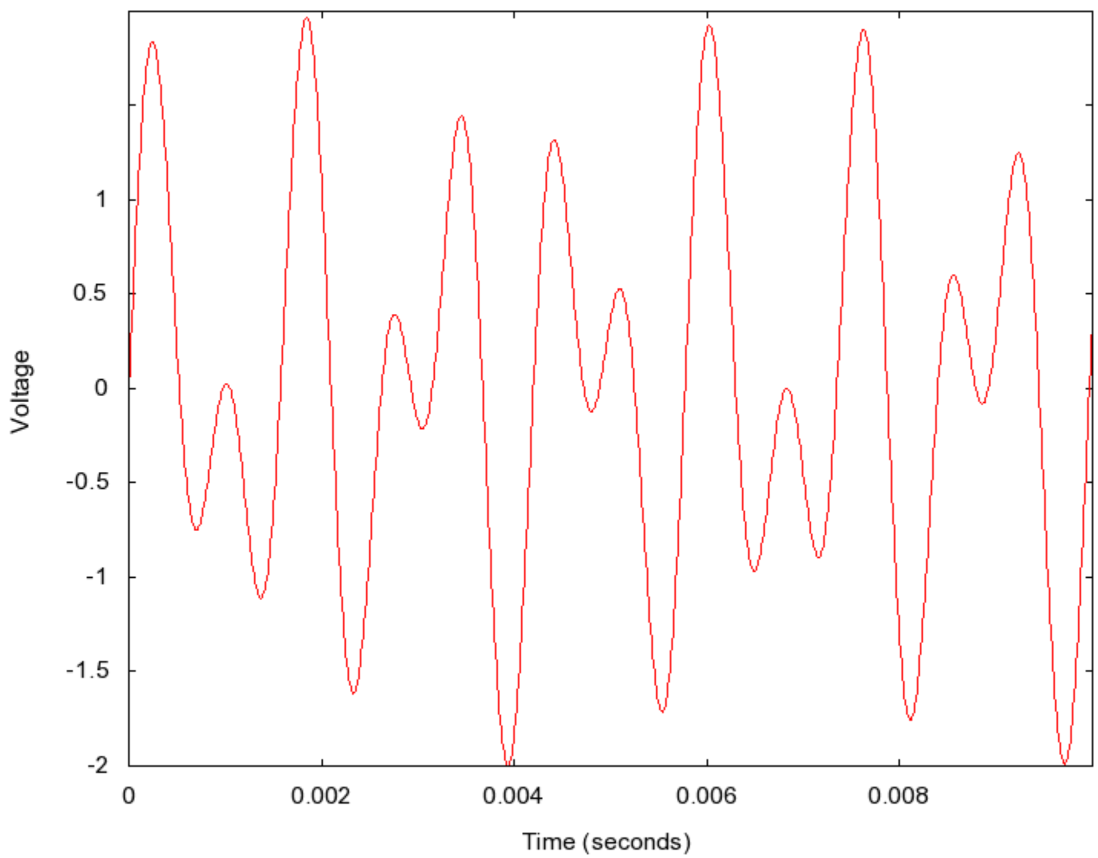
- Submit Lab 1 deliverables in Canvas by next lab day at midnight
- Filters lab on Monday

ESE 3400 Lab 2

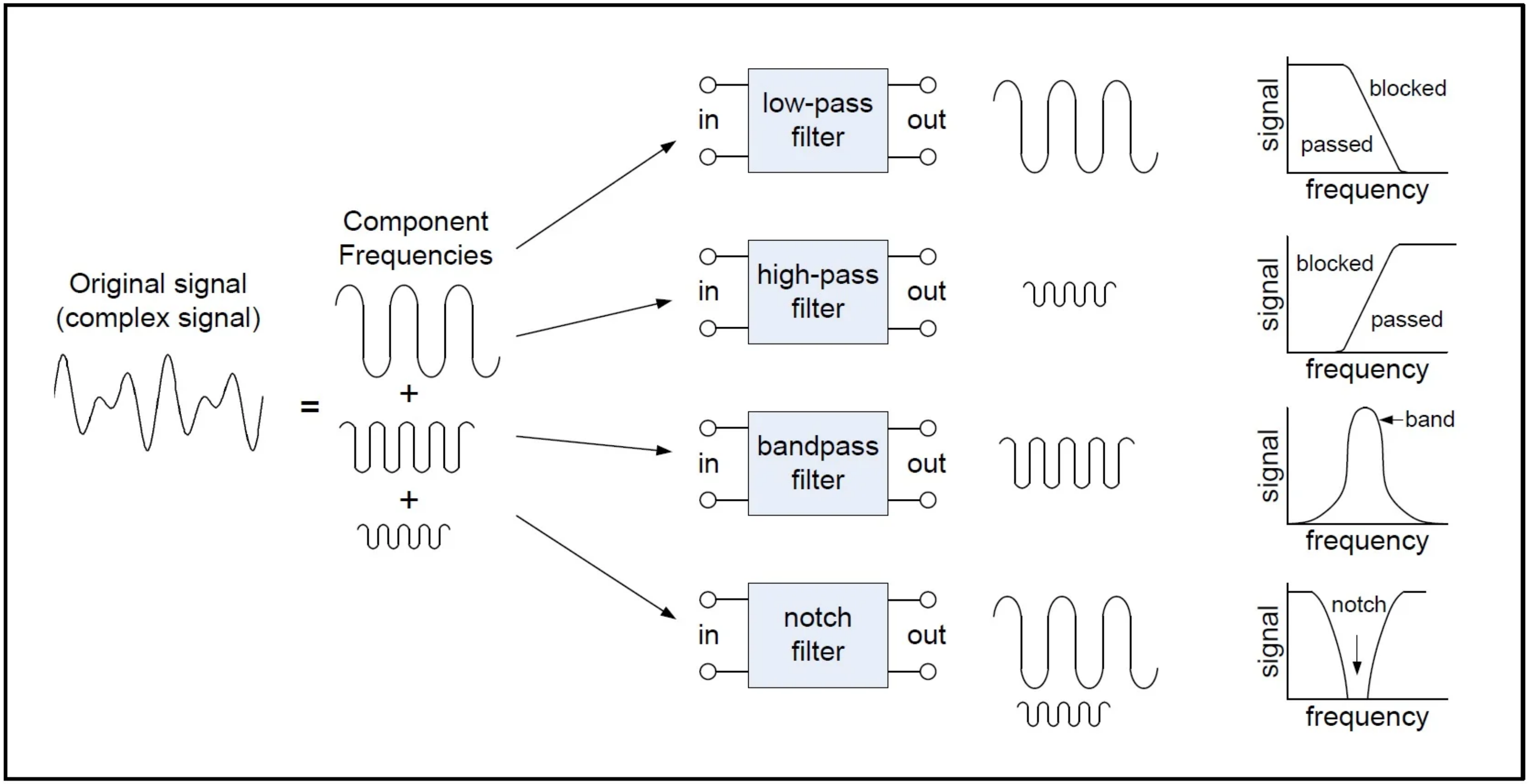
Filters

Time vs. Frequency domains

- Signals like this one are the combination of many sine waves at different frequencies
- Using the time domain is limiting for this reason

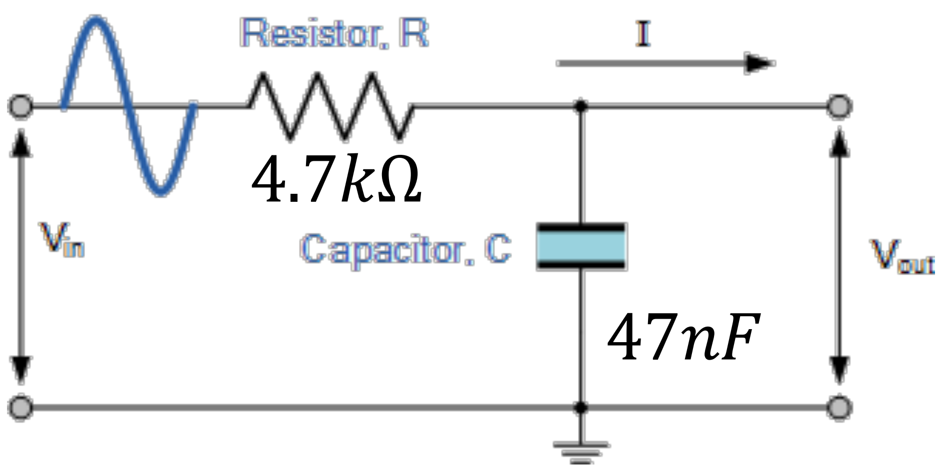


Four Basic Filters



allaboutcircuits.com

What is the frequency response of this circuit?



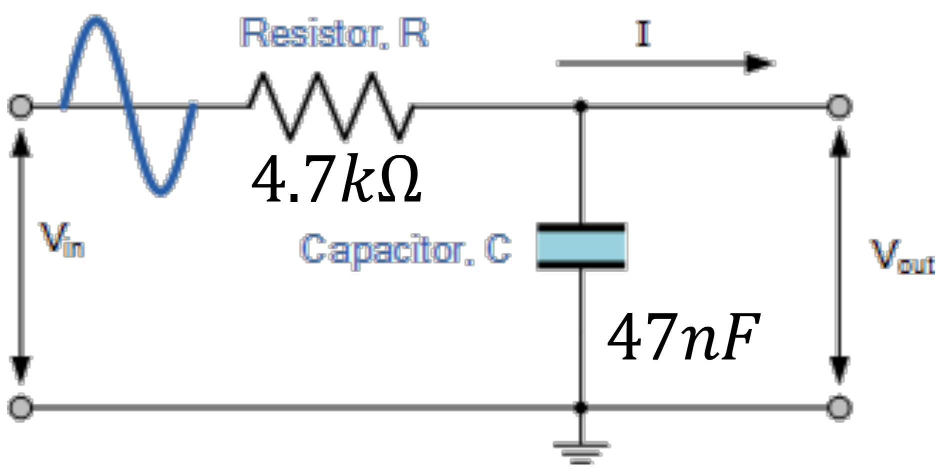
$$X_C = \frac{1}{2\pi f C}$$

$$|Z| = \sqrt{R^2 + \ X_C{}^2}$$

$$V_{out} \ = \ V_{in} \times \frac{X_C}{\sqrt{R^2 + \ X_C{}^2}} = V_{in} \ \frac{X_C}{|Z|}$$

$V_{in} \ = 10V$

What is the frequency response of this circuit?



$V_{in} = 10V \; at \; 100Hz$

$$X_C = \frac{1}{2\pi f C}$$

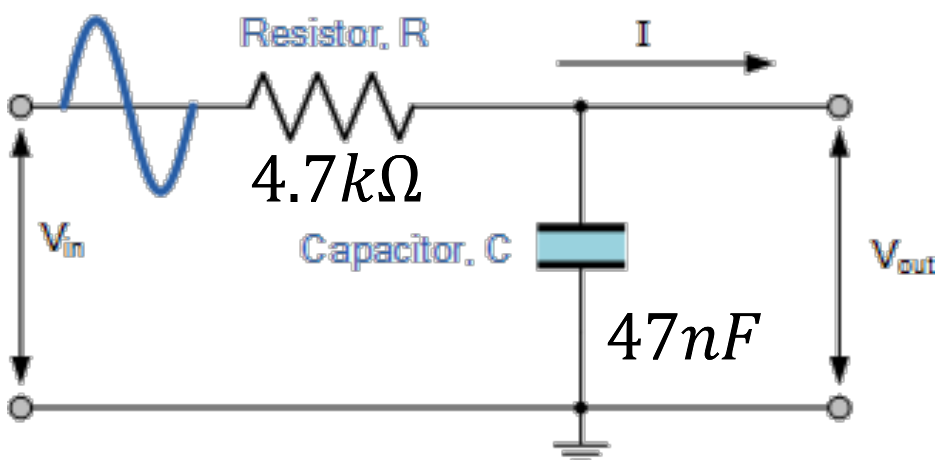
$$|Z| = \sqrt{R^2 + {X_C}^2}$$

$$V_{out} = V_{in} \times \frac{X_C}{\sqrt{R^2 + {X_C}^2}} = V_{in} \frac{X_C}{|Z|}$$

$$V_{out} = 10 \times \frac{33{,}863}{\sqrt{(4700)^2 + (33{,}863)^2}}$$

$$= 9.9V$$

What is the frequency response of this circuit?



$V_{in} = 10V \ at \ 10kHz$

$$X_C = \frac{1}{2\pi f C}$$

$$|Z| = \sqrt{R^2 + X_C{}^2}$$

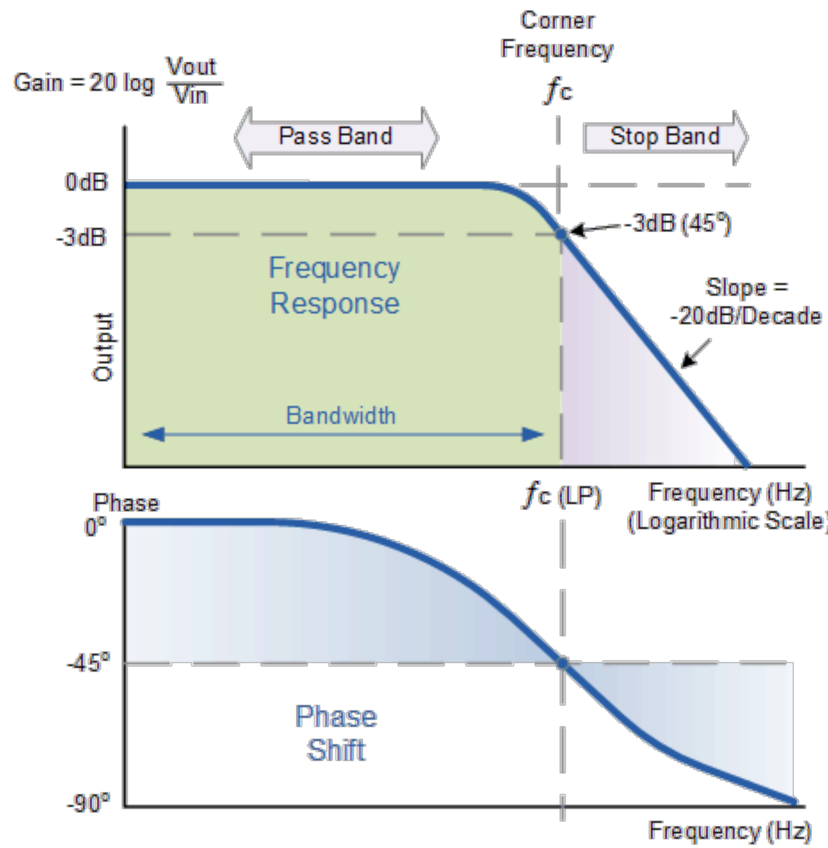
$$V_{out} = V_{in} \times \frac{X_C}{\sqrt{R^2 + X_C{}^2}} = V_{in} \frac{X_C}{|Z|}$$

$$V_{out} = 10 \times \frac{338.6}{\sqrt{(4700)^2 + (338.6)^2}}$$

$$= .72V$$

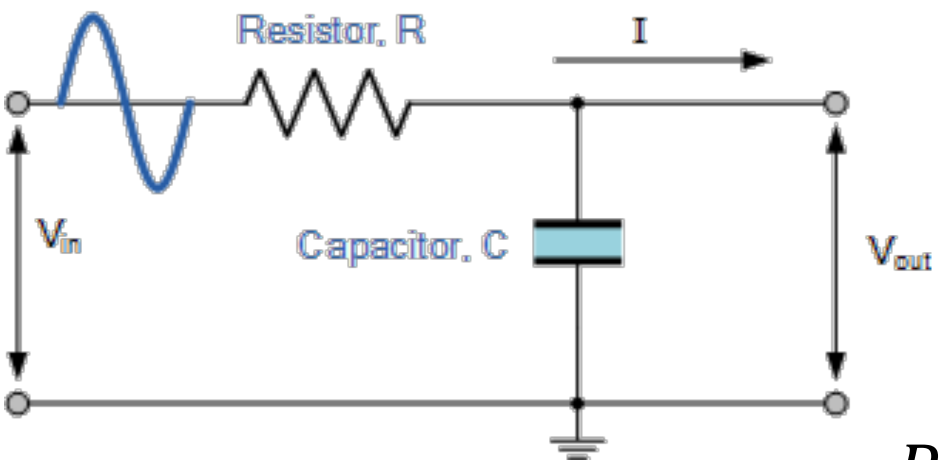
Frequency response of a low pass filter

- Gain
- Bandwidth
- Pass band vs stop band
- Corner frequency
- 3dB point
- Roll off



https://www.electronics-tutorials.ws/filter/filter_2.html

Back to the previous example



$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 4.7k\Omega \times 47nF}$$

$$f_c = 720Hz$$

$$Phase\ shift\ \varphi = -\tan^{-1}(2\pi fRC)$$

$$\varphi = -45° \ at\ 720Hz$$

At f_c, $20\log(^{V_{in}}/_{V_{out}}) = 70.7\%$ of the input