EE 795
Lecture 7

Measurement of Biopotentials

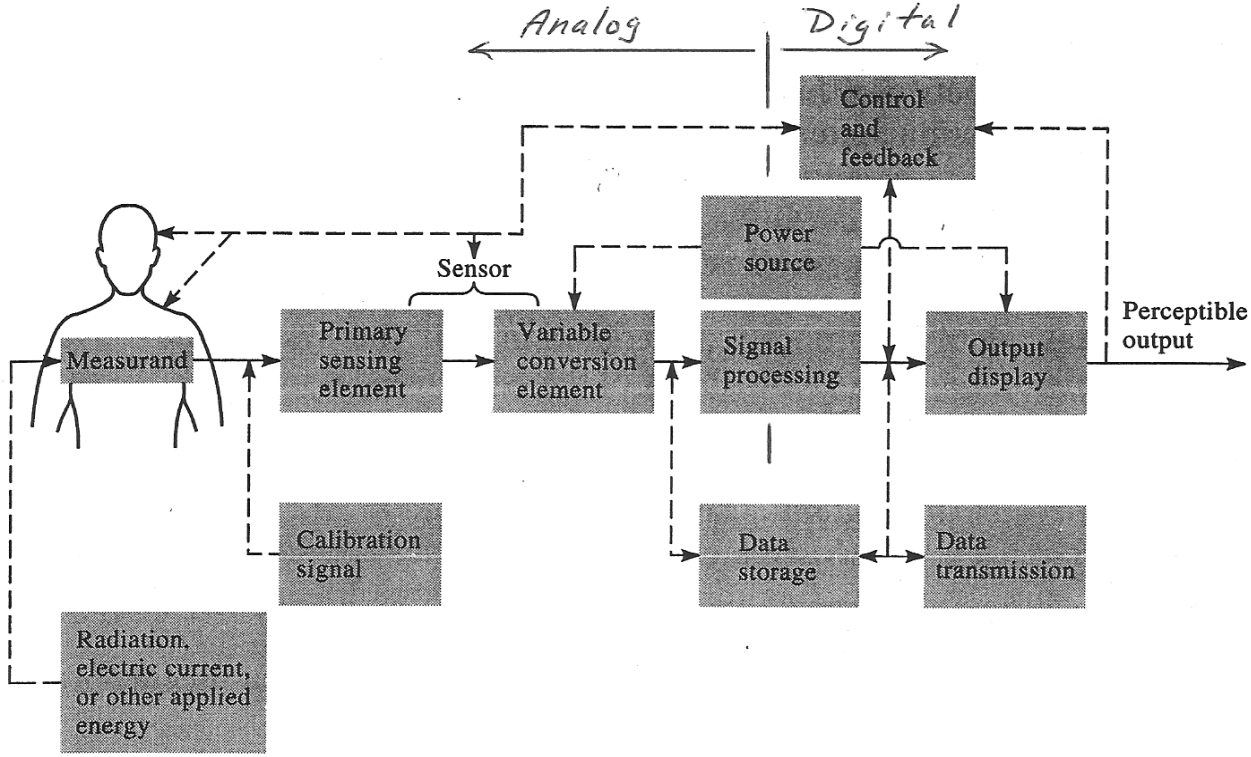


Figure 1.1 Generalized instrumentation system The sensor converts energy or information from the measurand to another form (usually electric). This signal is then processed and displayed so that humans can perceive the information. Elements and connections shown by dashed lines are optional for some applications.

Measurand : Biopotentials
Central Nervous System (Brain) EEG
Spinal and Peripheral Neurons } EMG
Muscle Fibres
Others: EOG

Sensor (Transducer): Electrodes
Convert ionic flows and concentrations to electronic

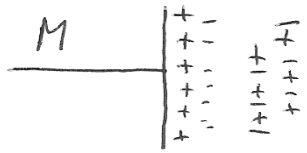
Aspects of Measurement

- General Instrumentation
- Transducers (Electrodes)
- General Recording Situation
- Sources of Noise and Solutions
- Effects of electrode size, spacing and orientation
- Digitization of Signals

Characteristics of Biopotential Signals

- Determined by size of bioelectric generator
- Determined by distance and orientation of bioelectric generator to recording electrode(s)
- Determined by size and properties of electrode(s)

Electrodes



$$M \rightleftharpoons M^{+z} + ze^-$$

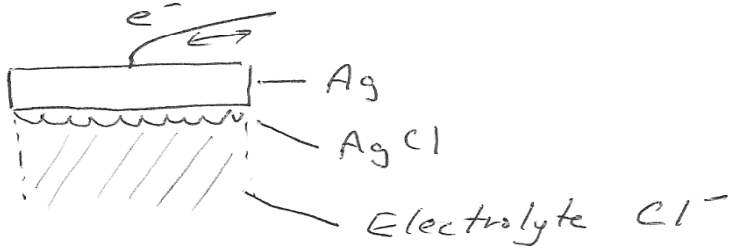
equilibrium

- thermodynamic equilibrium results in charge redistribution in vicinity of metal-solution interface
- gives rise to half-cell potential

e.g.

$$Ag \rightleftharpoons Ag^+ + e^- \qquad .7991\,V$$

Silver - Silver Chloride Electrode



$$AgCl \rightleftharpoons Ag^+ + Cl^-$$

$+e^- \downarrow \uparrow -e^-$

Ag

$.2225\,V$

Space Charge Region

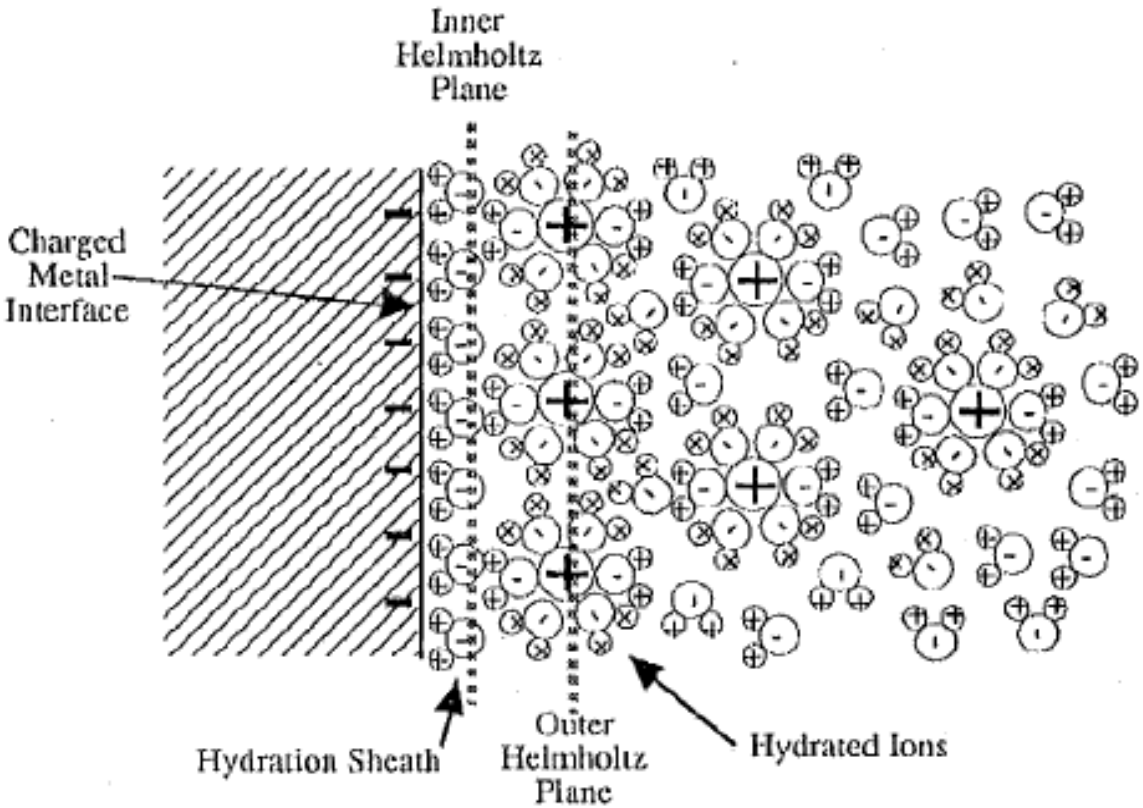


Figure 2. Space Charge Layer. Kovacs. [2]

Electrode Polarization

Half-cell potential result of equilibrium.

If current flowing in/through electrode

half cell potential changes (polarization)

$$V_p = V_r + V_c + V_a$$

V_p = total overvoltage

V_r = ohmic overvoltage (resistance of electrode)

V_c = concentration overvoltage
(changes in distribution of ions in electrolyte in vicinity of electrode/electrolyte interface)

V_a = activation overvoltage
(energy required for oxidation-reduction of metal atoms are different in general. Current flowing oxidation or reduction predominates.

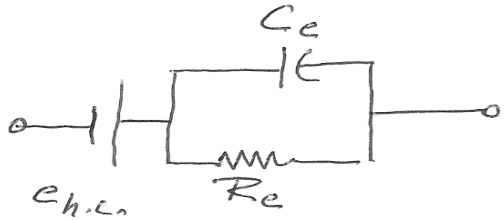
Perfectly Polarizable ⟶ Perfectly non-polarizable

Noble metals
platinum, gold,

Ag - AgCl

Capacitive Electrodes

Warburg Model



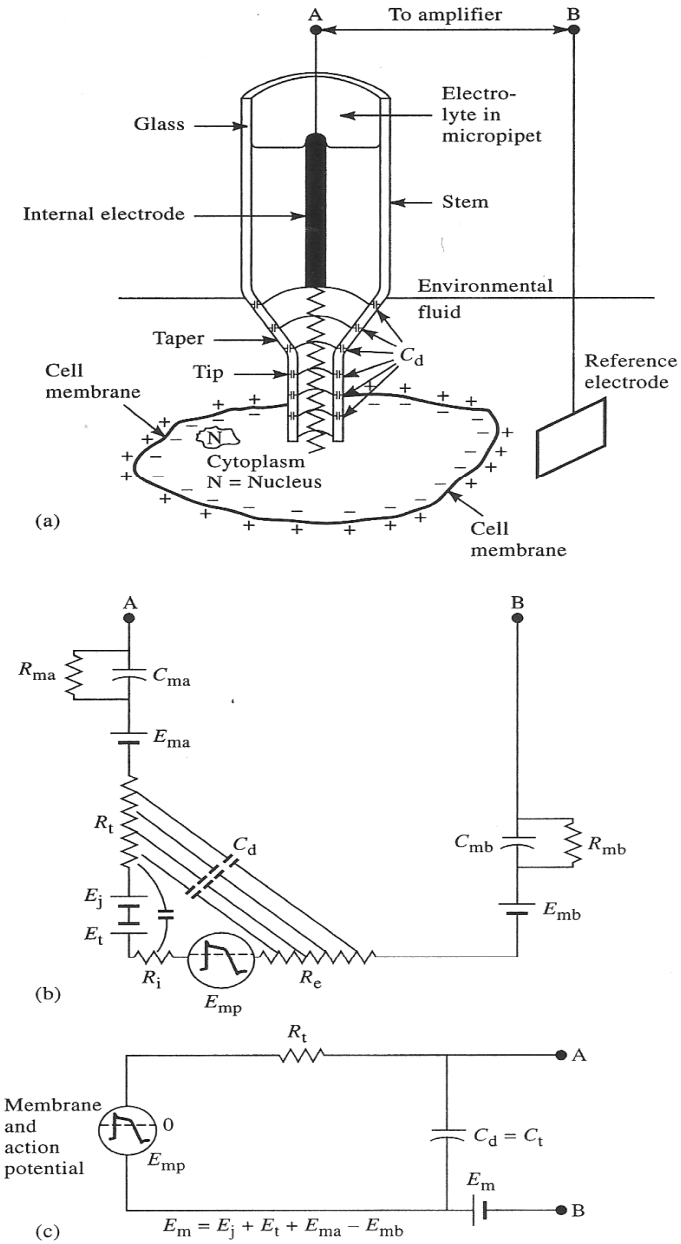


Figure 5.22 Equivalent circuit of glass micropipet microelectrode (a) Electrode with its tip placed within a cell, showing the origin of distributed capacitance. (b) Equivalent circuit for the situation in (a). (c) Simplified equivalent circuit. (From L. A. Geddes, *Electrodes and the Measurement of Bioelectric Events,* Wiley-Interscience, 1972. Used with permission of John Wiley and Sons, New York.)

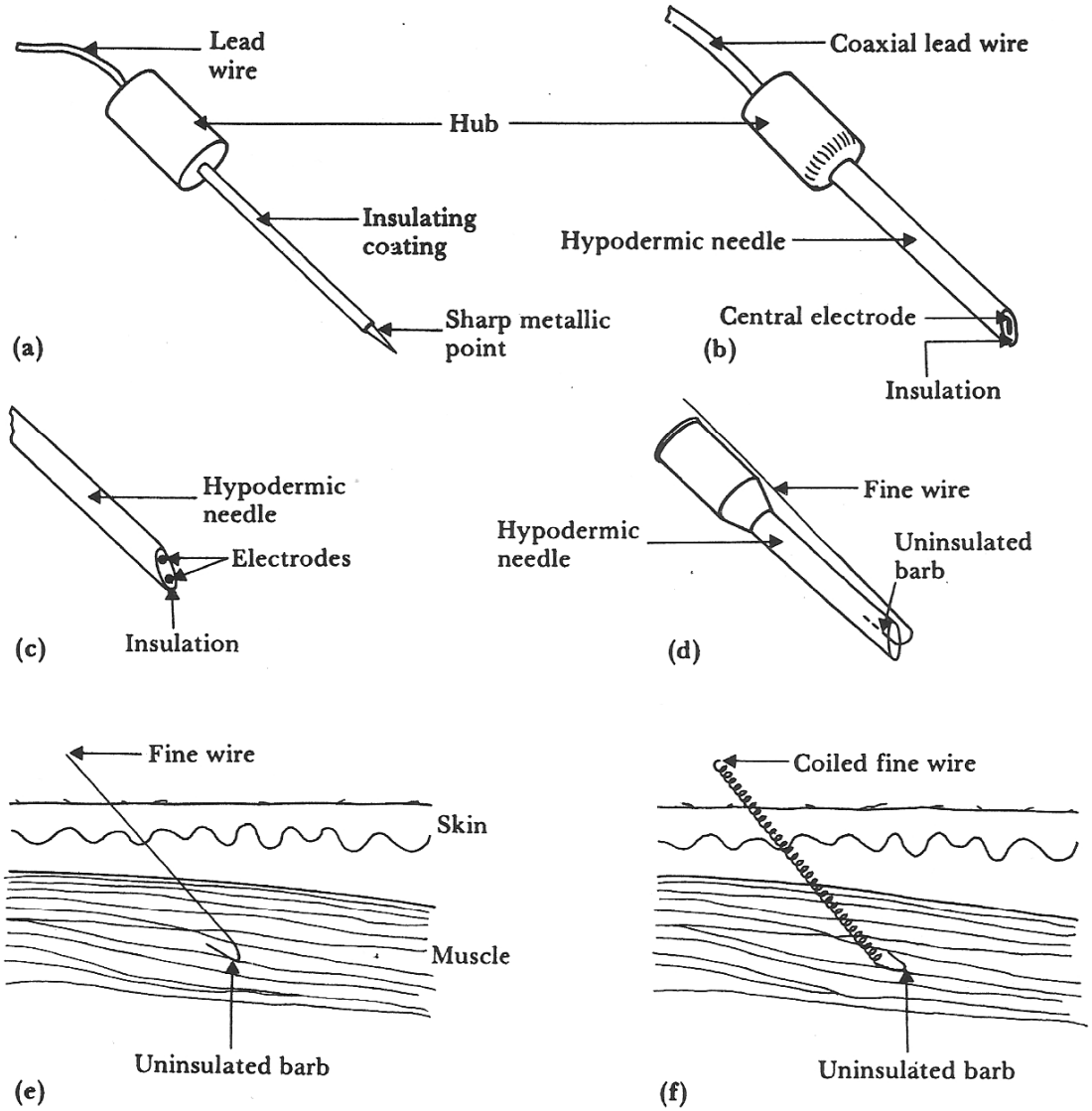


Figure 5.13 Needle and wire electrodes for percutaneous measurement of bio-potentials (a) Insulated needle electrode. (b) Coaxial needle electrode. (c) Bipolar coaxial electrode. (d) Fine-wire electrode connected to hypodermic needle, before being inserted. (e) Cross-sectional view of skin and muscle, showing fine-wire electrode in place. (f) Cross-sectional view of skin and muscle, showing coiled fine-wire electrode in place.

Needle Electrode Connections

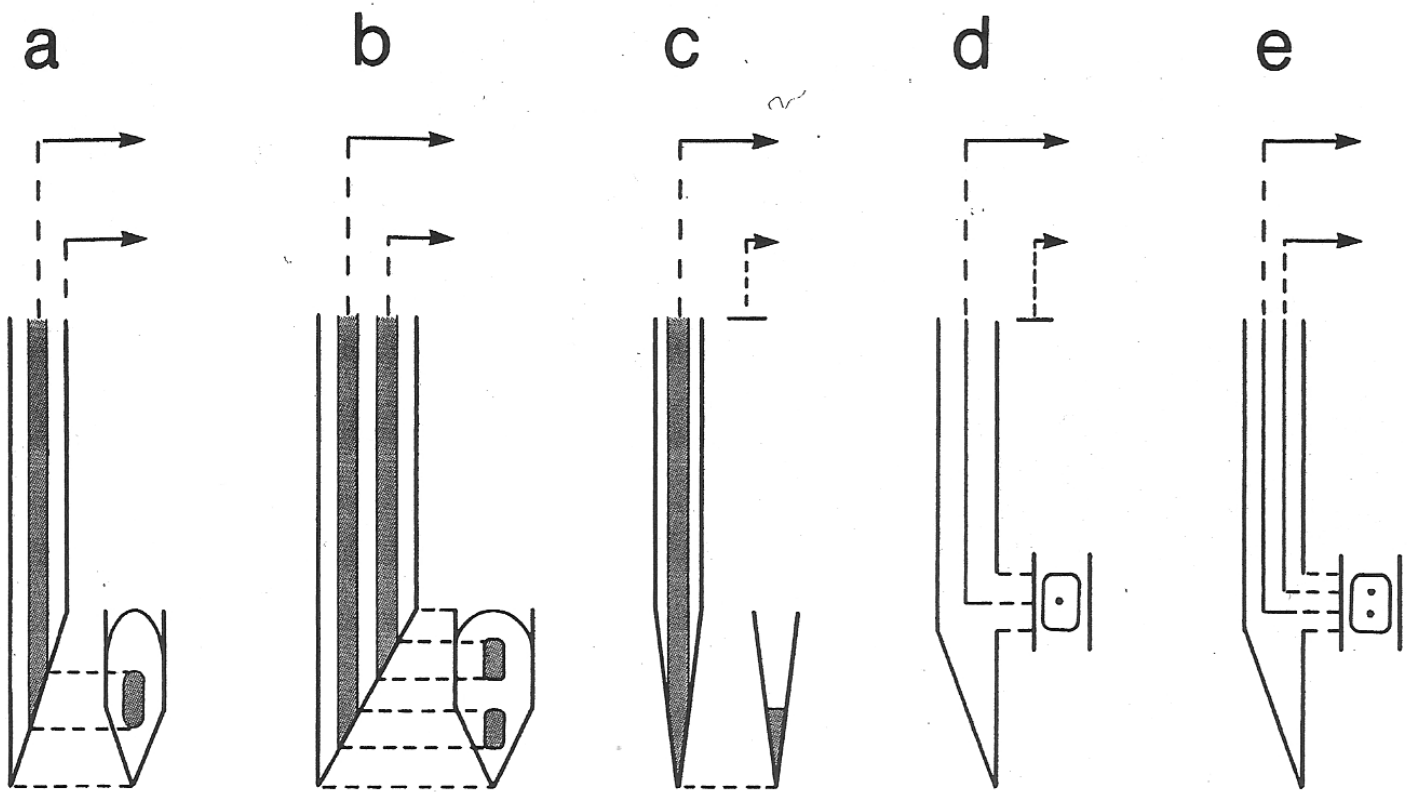


Figure 3-1

Schematic illustration of standard concentric (a), bipolar concentric (b), monopolar (c), and single fiber needles (d, e). Dimensions vary but the diameters of the outside cannulas shown are similar to 26-gauge hypodermic needles (460 μm) for (a), (d), and (e), 23-gauge needle (640 μm) for (b), and 28-gauge needle (360 μm) for (c). The exposed tip areas are about 150 μm $\times$ 600 μm for (a), 150 μm $\times$ 300 μm with spacing between wires of 200 μm center to center for (b), 0.14 mm^2 for (c), and 25 μm in diameter for (d) and (e). A separate reference electrode is necessary with monopolar needles (c) and (d) to complete the circuit. (Modified from Stålberg and Trontelj.[23])

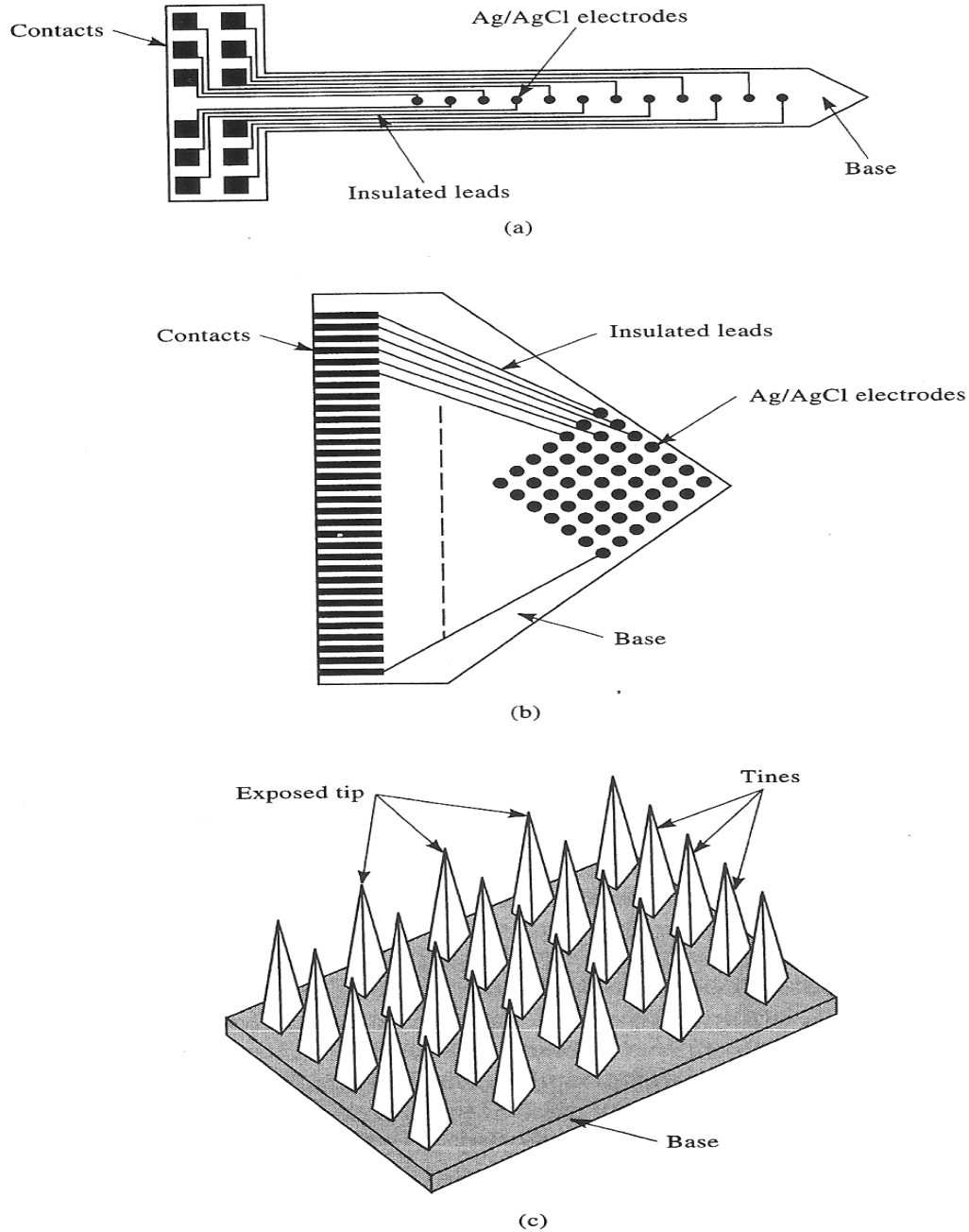


Figure 5.16 Examples of microfabricated electrode arrays. (a) One-dimensional plunge electrode array (after Mastrototaro *et al.*, 1992), (b) Two-dimensional array, and (c) Three-dimensional array (after Campbell *et al.*, 1991).

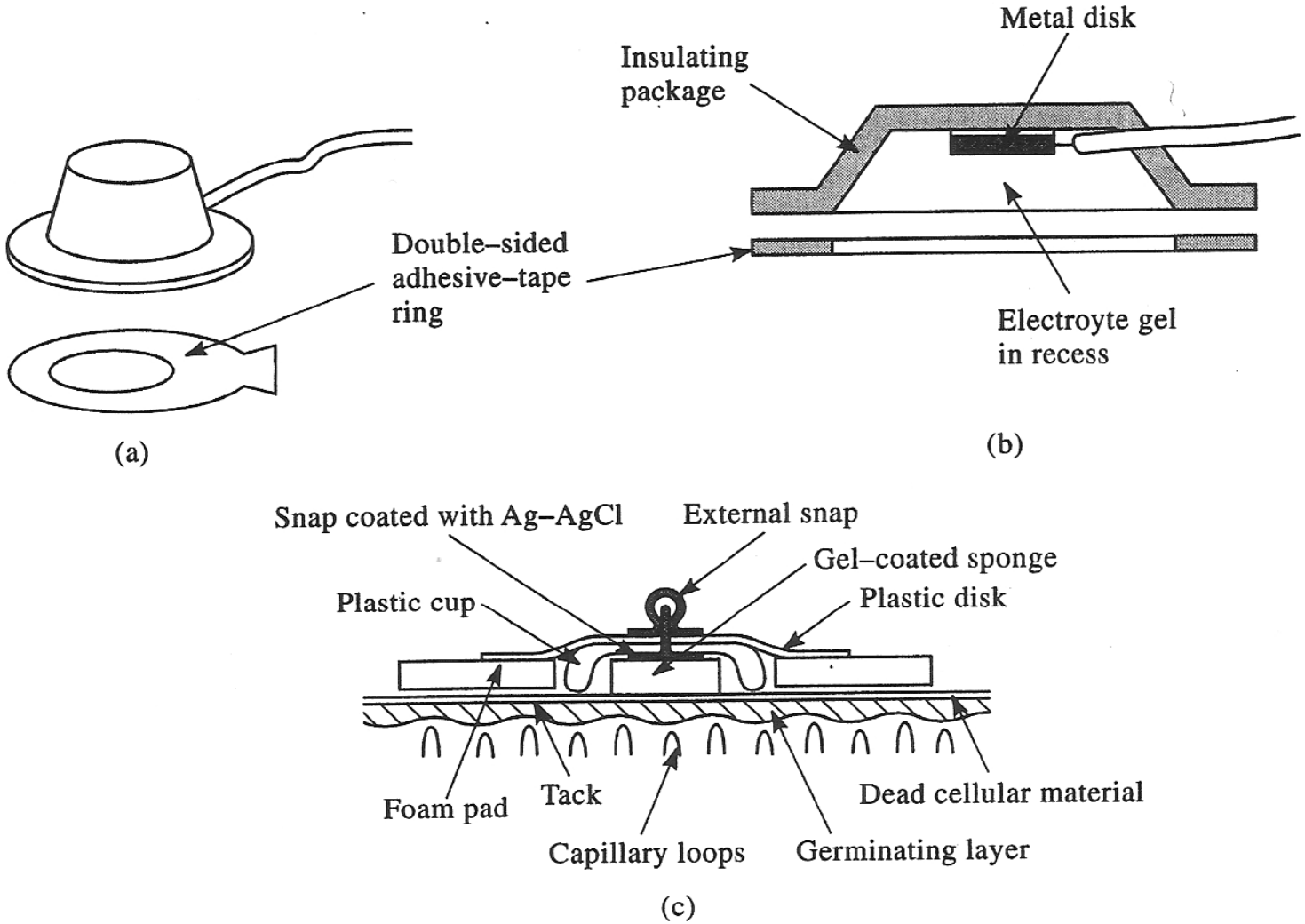


Figure 5.11 Examples of floating metal body-surface electrodes (a) Recessed electrode with top-hat structure. (b) Cross-sectional view of the electrode in (a). (c) Cross-sectional view of a disposable recessed electrode of the same general structure shown in Figure 5.9(c). The recess in this electrode is formed from an open foam disk, saturated with electrolyte gel and placed over the metal electrode.

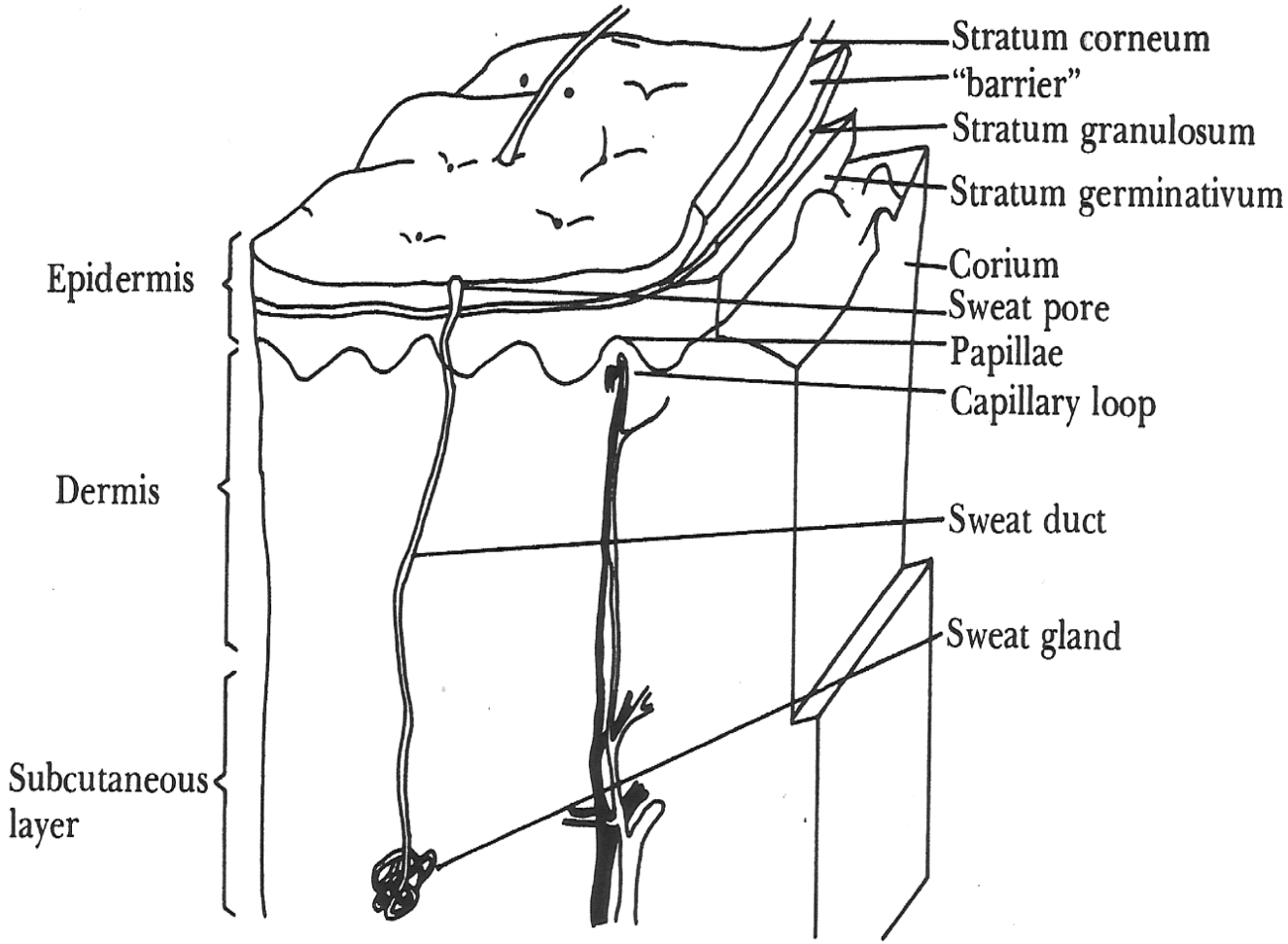


Figure 5.7 Magnified section of skin, showing the various layers (Copyright © 1977 by The Institute of Electrical and Electronics Engineers. Reprinted, with permission, from *IEEE Trans. Biomed. Eng.*, March 1977, vol. BME-24, no. 2, pp. 134–139.)

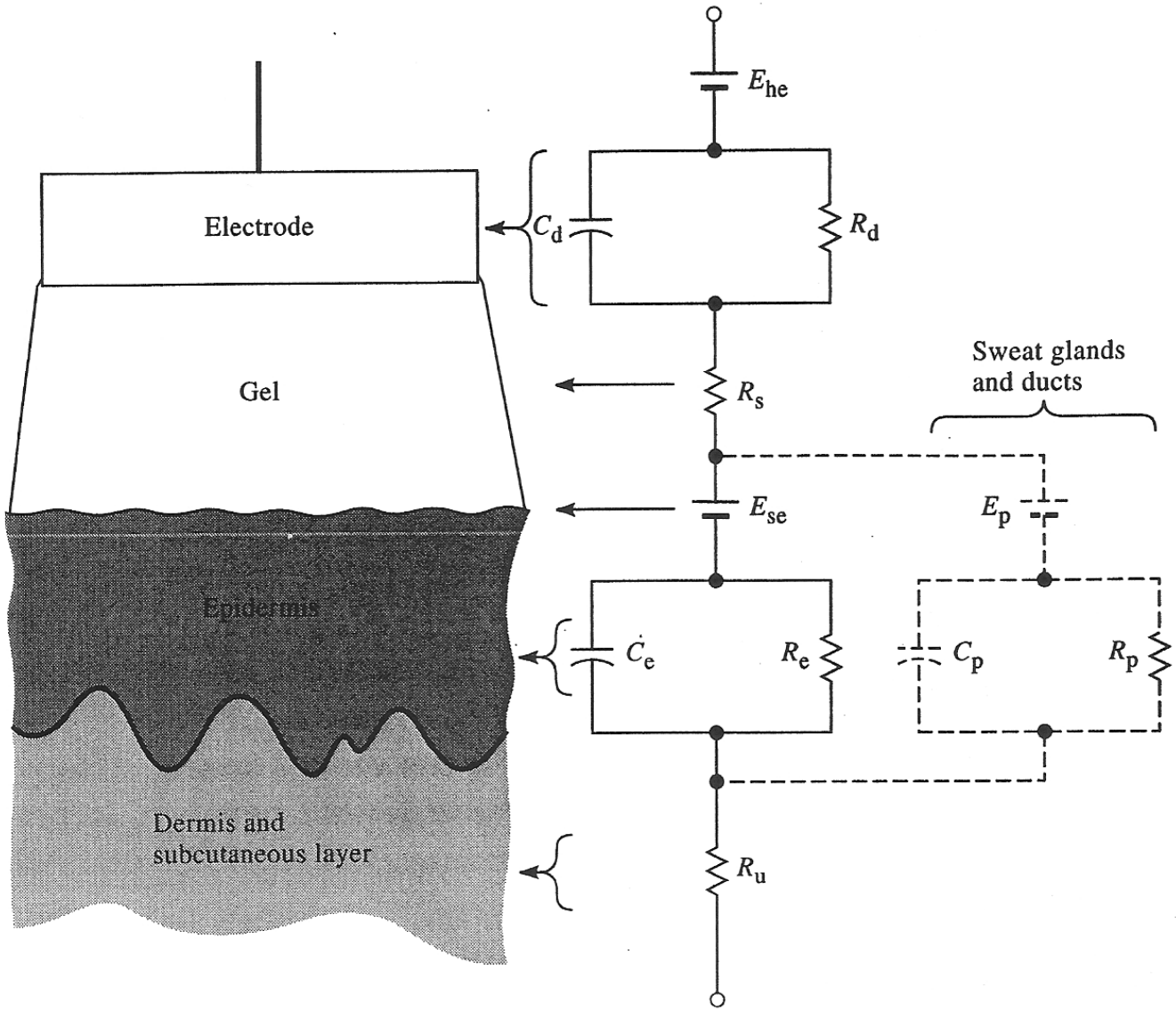


Figure 5.8 A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

Conditions of Measurement

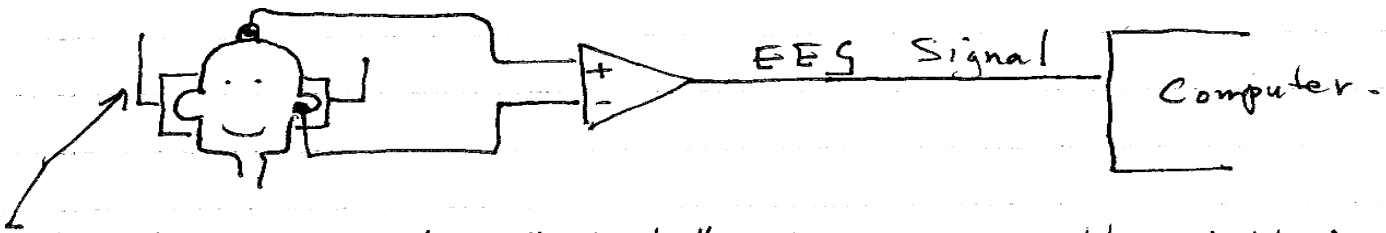
- Biopotential signals are low amplitude (<1μv – 25 mv)
- Biopotential signals are low bandwidth (d.c. – 15 kHz)
- Body is volume conductor (specificity of signal source)
- Noise is high in bandwidth of biopotential signal (60 Hz: 30 mV on skin)

Biomedical Engineering

- Understanding anatomy and physiology to select measurand
- biology/machine interface ⟶ transducer
- information to be extracted

Instrumentation Example

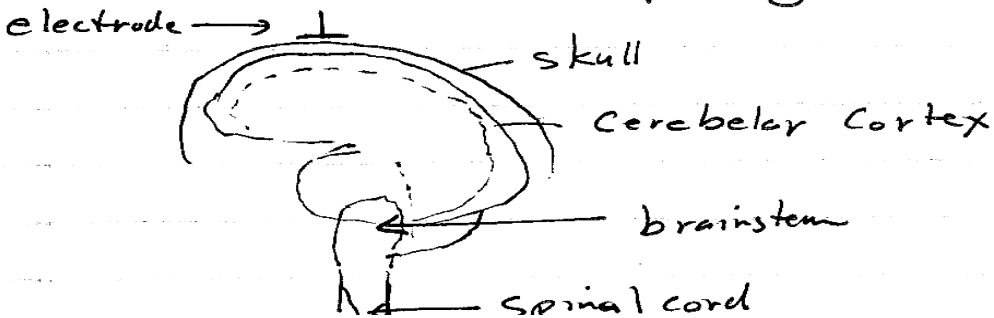
Brain Stem Auditory Evoked Potential (BSAEP)

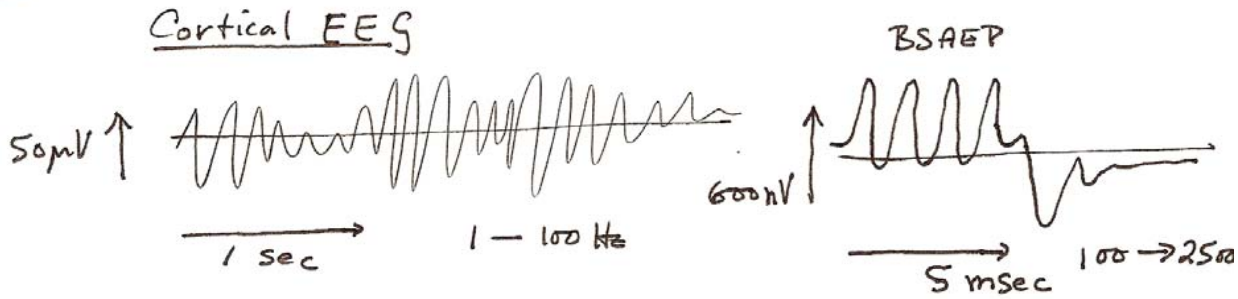


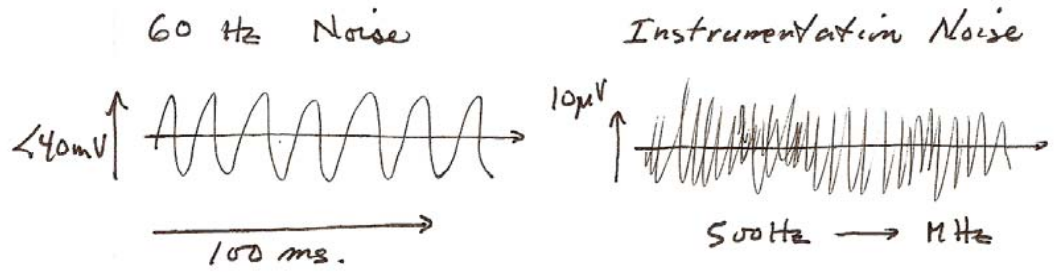
Auditory Stimulus "Click" at supra-threshold level

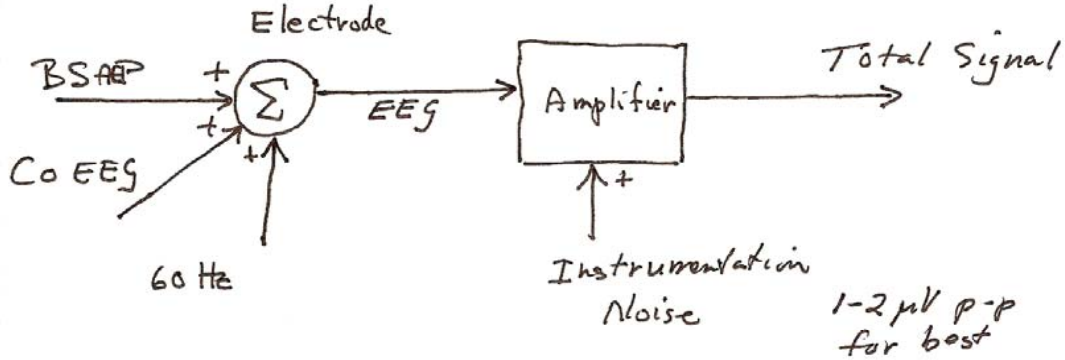
Purpose: to determine whether auditory pathway and associated neural structures are OK.

Measurand - Electroencephalogram (EEG)

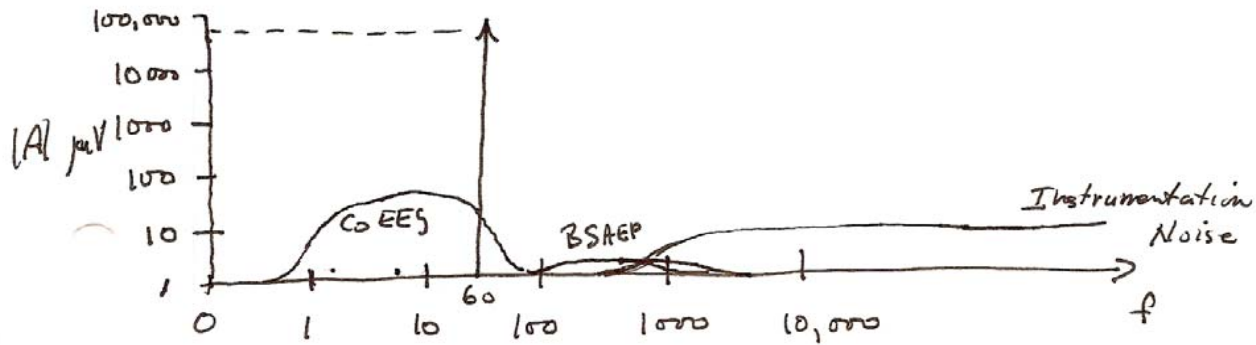








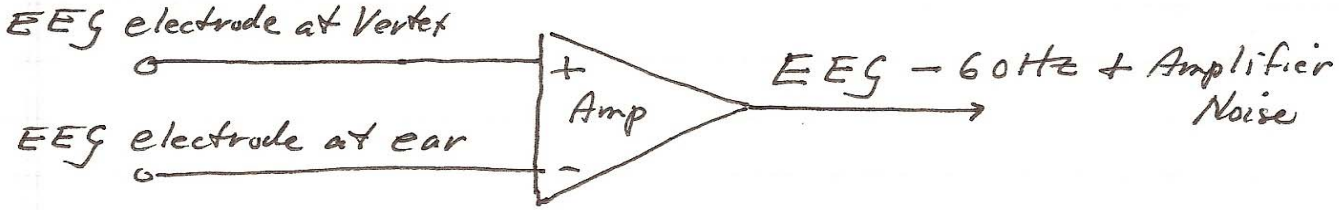
Frequency Spectrum of Total Signal (EEG)



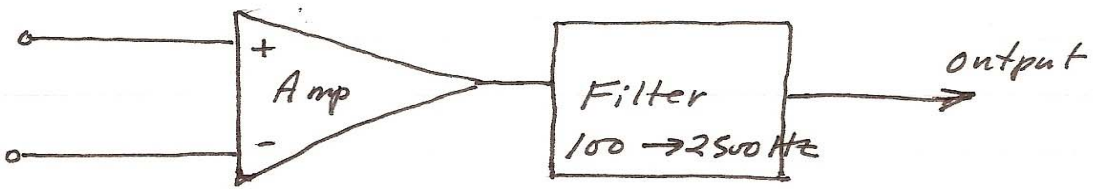
How do we Maximize SNR?

i.e. $\frac{\text{BSAEP Power}}{\Sigma \text{ All other powers.}}$

60 Hz Noise Reduction



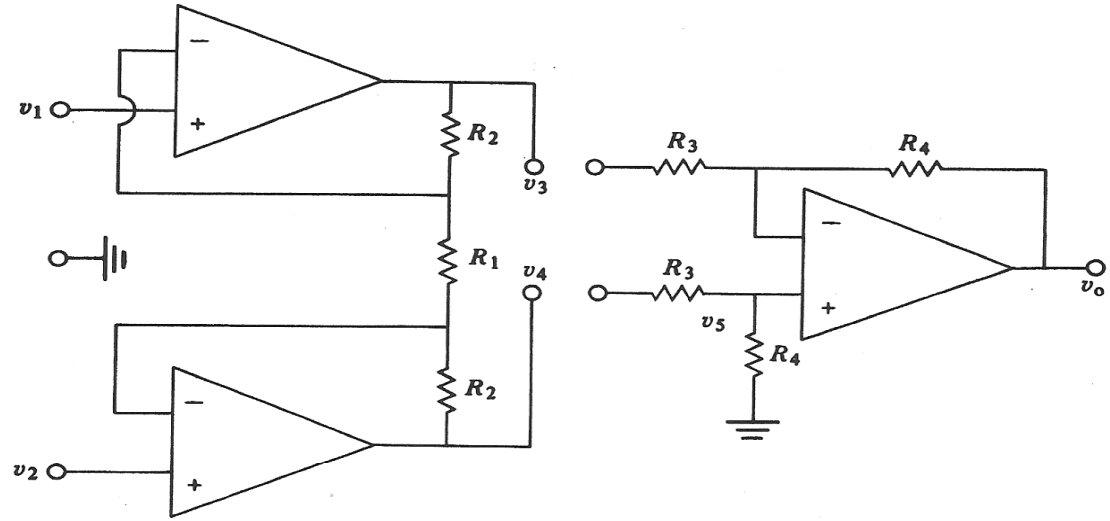
Co EEG & Instrumentation Noise Reduction



Output includes BSAEP, some Co EEG, Instr. Noise

This exhausts our possibilities in the analog domain

∴ Need to digitize and use other processing techniques



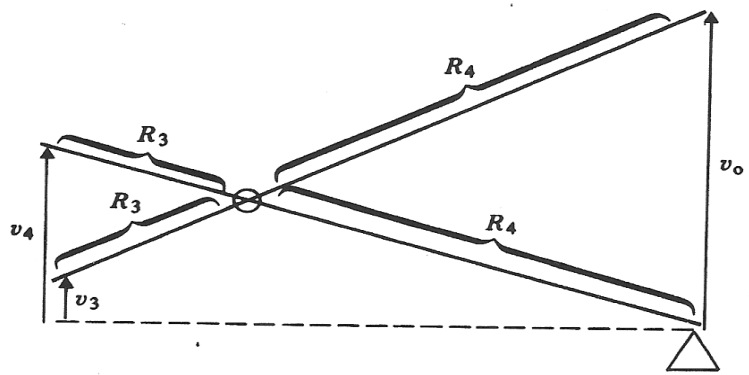
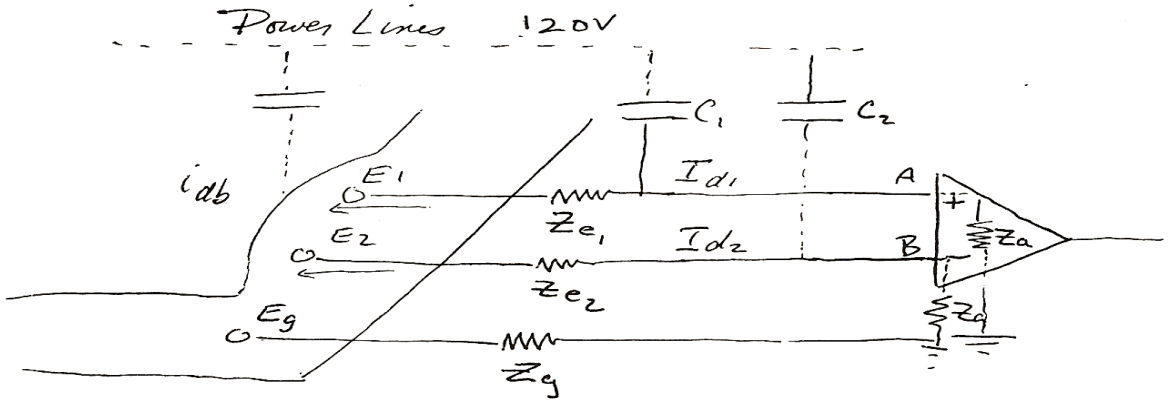


Figure 3.5 (a) The right side shows a one-op-amp differential amplifier, but it has low input impedance. The left side shows how two additional op amps can provide high input impedance and gain. (b) For the one-op-amp differential amplifier, two levers with arm lengths proportional to resistance values make possible an easy visualization of input–output characteristics.

$$V_o = \underbrace{\frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)}(V_2 - V_1)$$

$$CMRR = \frac{G_d}{G_c}$$

Sources of 60 Hz



Total body resistance = 500 Ω can usually be ignored because of the other impedances

$V_A - V_B = I_{d1} Z_{e1} - I_{d2} Z_{e2}$

If two leads are close

$I_{d1} = I_{d2}$

$\therefore V_A - V_B = I_{d1} (Z_{e1} - Z_{e2})$

For 2 meter cable $I_{d1} \approx 2$ na

If $Z_{e1} - Z_{e2} = 20$ KΩ

$V_A - V_B = 2 \times 10^{-9} \times 20 \times 10^3 = 40\,\mu V$ of ~~60~~ 60 Hz

This assumes that the CMRR of the amplifier is ∞.

Avoid this by shielding the cables and grounding the shield at the amplifier end.

Effects of Electrode Impedance Mismatch

For common mode signals

V_{cm} = common mode signal in the body

$= i_{db} Z_g$

$= .2 \times 10^{-6}$ amps $\times$ 50 KΩ for a typical environment

$= 10\,mV$

In this case Z_g is higher than usually found in a good recording environment.

For high electrical environments such as the OR and ICU.

$i_{db} > 1\,\mu A$

$V_{cm} > 50\,mV$

Considering the voltages presented at the amplifier inputs

$$V_A - V_B = \left(\frac{Z_a}{Z_a + Z_{e_1}} - \frac{Z_a}{Z_a + Z_{e_2}} \right) V_{cm}$$

Z_{e_1} & $Z_{e_2} \ll Z_a$

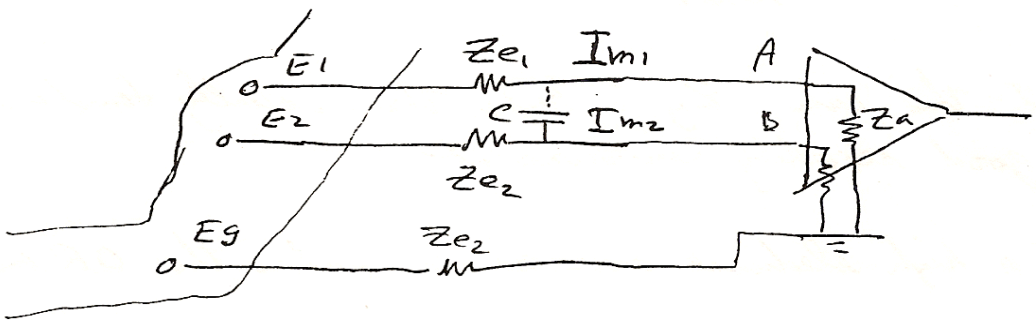
$$V_A - V_B = \frac{Z_{e_2} - Z_{e_1}}{Z_{in}} V_{cm}$$

Mismatch Cont'd and Motion Artifact

if mismatch in Z_e of 20 KΩ

$$= \frac{20\,K\Omega}{5M\Omega} \times 50\,mV = 40\,\mu V$$

Motion Artifact

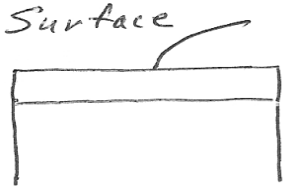


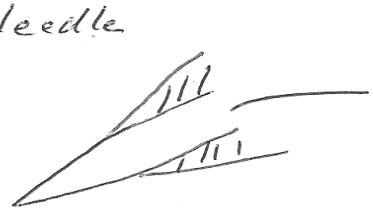
If cables connecting E_1 & E_2 to amplifier are flexed and their relative distances changed, then coaxial capacitance of cable changes - causing currents I_{m_1} & I_{m_2} to flow. These will flow to ground through electrodes.

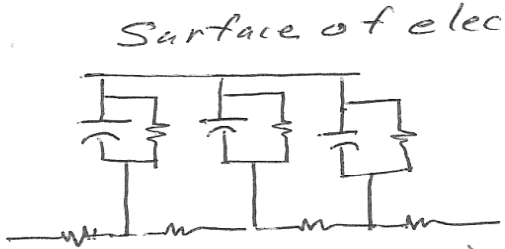
$$V_A - V_B = I_{m_1} Z_{e_1} - I_{m_2} Z_{e_2}$$

This results in a low frequency additive signal.

Effects of Electrode Size







i.e. as electrode size increases signal from a larger volume of tissue on skin surface is averaged.

i.e. Electrode is integrator (Decreases signal bandwidth).

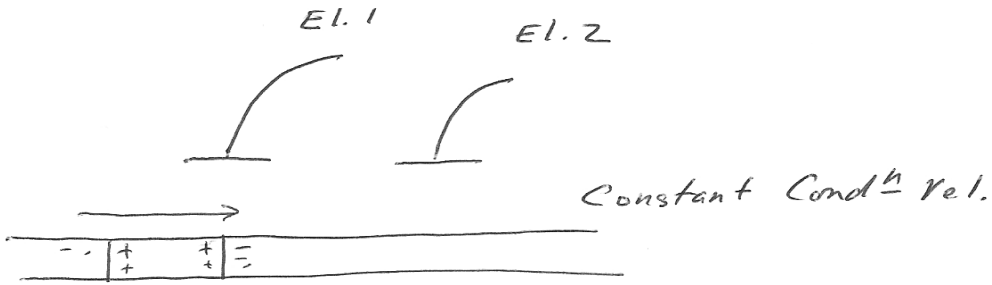
∴ Electrode Size is determined by size of bioelectric generator one is interested in.

Selectivity ⟷ single fibre?

Motor unit?

Whole muscle?

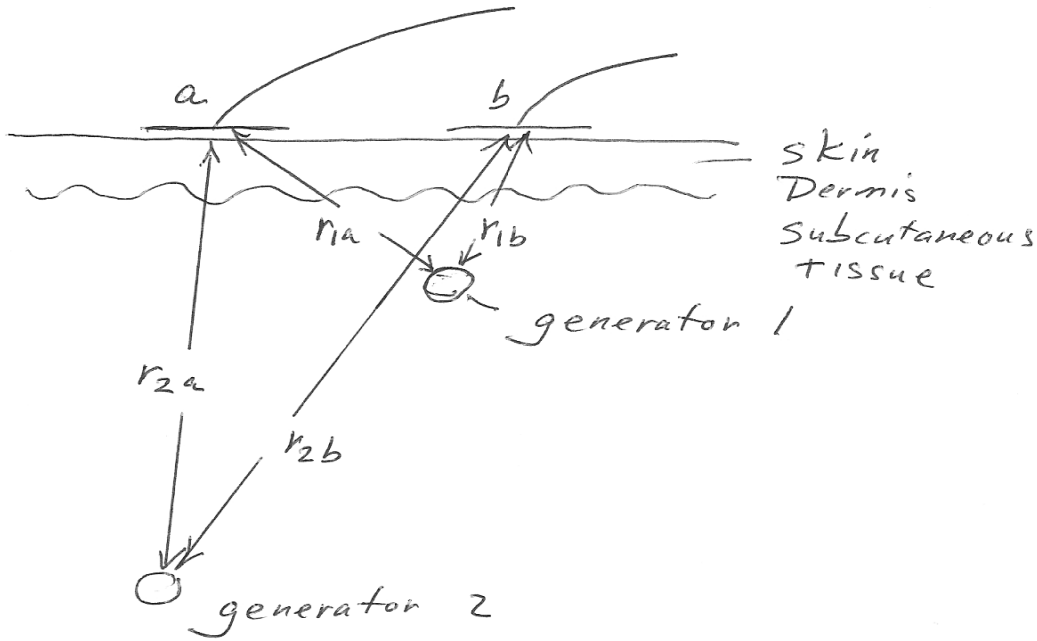
Effects of Electrode Spacing



As electrode spacing ↓ bandwidth ↑
amplitude ↓

provided both electrodes are over ~~average~~ active region.

Common Mode Electrophysiological Signals

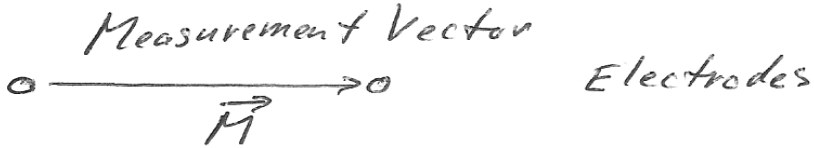


Common Mode Electrophysio;logical Signals (cont'd)

$$A_s \frac{|r_a - r_b|}{\frac{r_a + r_b}{2}}$$

decreases the generator starts to resemble a common mode source

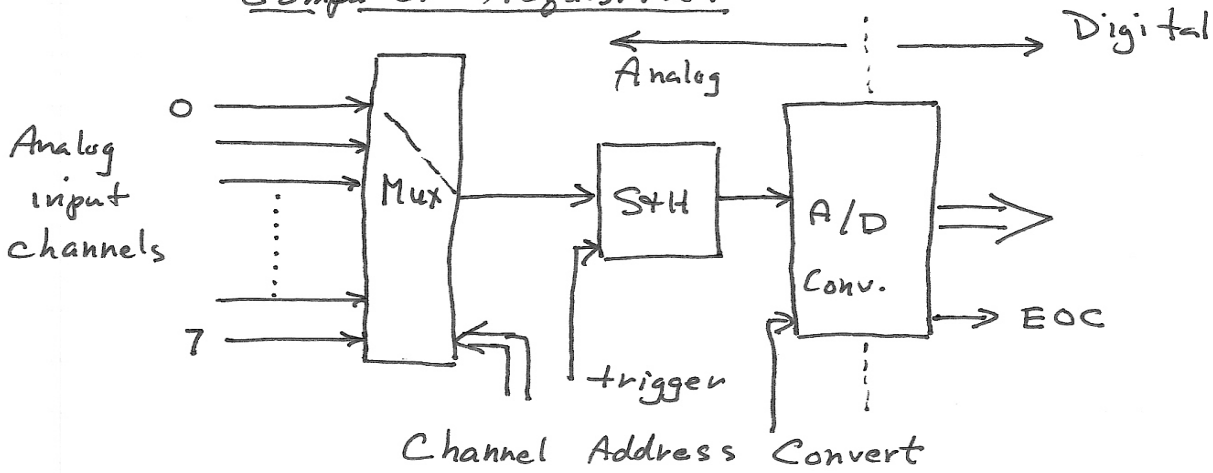
Effect of Electrode Orientation to Generator



Measured signal $= \vec{M} \cdot \vec{D}$

$= f(D \cos\theta)$

Computer Acquisition



This could be on a board in the computer, or in an external device which presents digital info to a standard computer port (eg. USB).

Multiplexor – analog switch connects output channel to one of input channels

Sample and Hold – holds input value until triggered to hold next value

Analog-to-Digital Convertor – Output is parallel digital word containing binary equivalent of analog value. Minimum is usually 12 bits but 16-bit are very common now. Speed of conversion is important with 5 μsec typical inexpensive (i.e. 200 KHz sample rate).

Amplitude Resolution

- Determines number of bits required

- Amplitude range of input signals usually setable
  $0 \rightarrow 10V$. $0 \rightarrow 5V$.
  $\pm 10V$ $\pm 5V$.

Assume $\pm 5V$. input range with 12-bit convertor

Amplitude Resolution $= (2^{12})^{-1} * 10V$

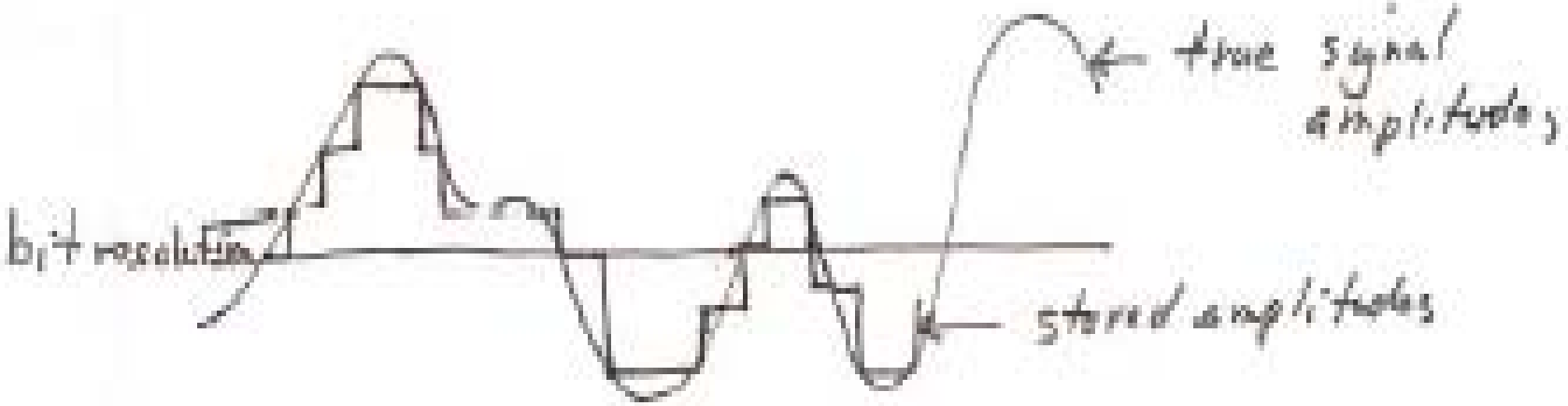
$$= \frac{10{,}000\ mV}{4096} \approx 2.5\ mV/bit$$

Implications - Most physiological signals are in millivolt range or less
∴ need amplification first.

NB Need to amplify and filter all signals before sending them to the computer.

If need higher resolution for same amplitude range increase # of bits in A/D.

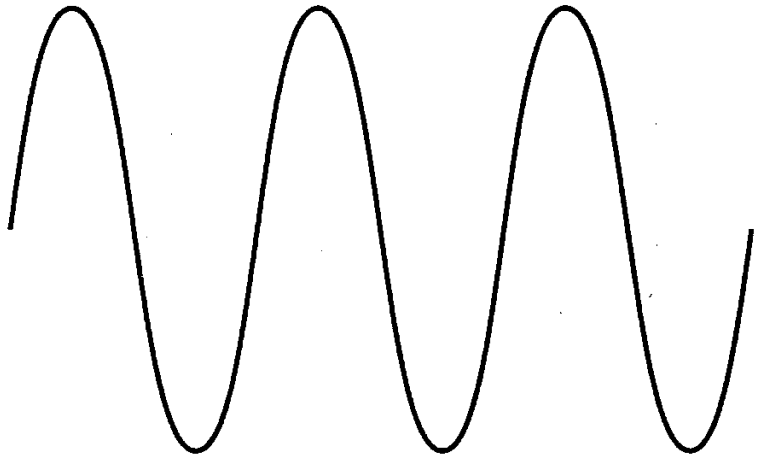
If front-end amplifier gain is G then resolution
$= (2^{\text{No of bits}})^{-1} * G^{-1} *$ Amplitude Range



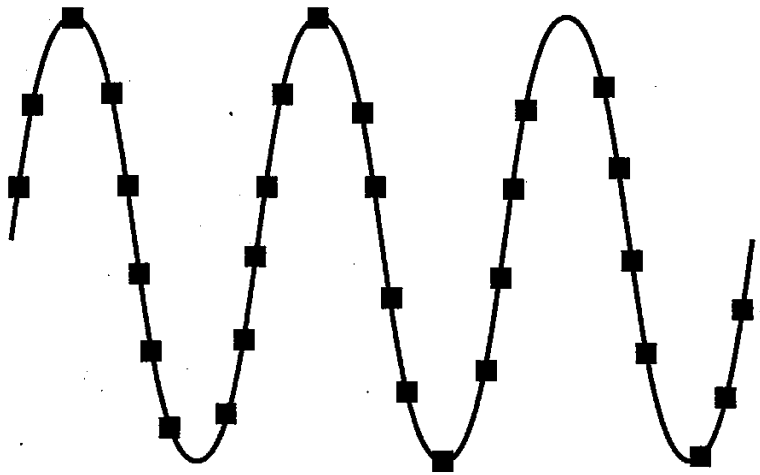
This staircase effect can be avoided by increased gain of the signal prior to A/D conversion

In the example, by increasing gain to 80,000 bit resolution becomes .125 μvolts and our signal can now be represented by 80 discrete levels, more closely approximating the true amplitudes.

Analog to Digital (Sampling)



Actual Signal



Sampled Signal

Signal Sampling

Sampling Theorem

If $x(t)$ is a bandlimited signal with its Fourier transform $X(\omega) = 0$ for $|\omega| > \omega_B$, $x(t)$ is uniquely determined by its sample values $x(kT)$, $k = 0, \pm 1, \pm 2, \ldots$, if

$$\omega_s > 2\omega_B \tag{7.1}$$

where $\omega_s = 2\pi/T$, t is time, ω, ω_B, and ω_s are frequencies in rad/s. Here, T is the sampling time and $2\omega_B$, which is the minimal sampling rate, is referred to as the Nyquist rate. ■

$$p(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT)$$

Signal Sampling (cont'd)

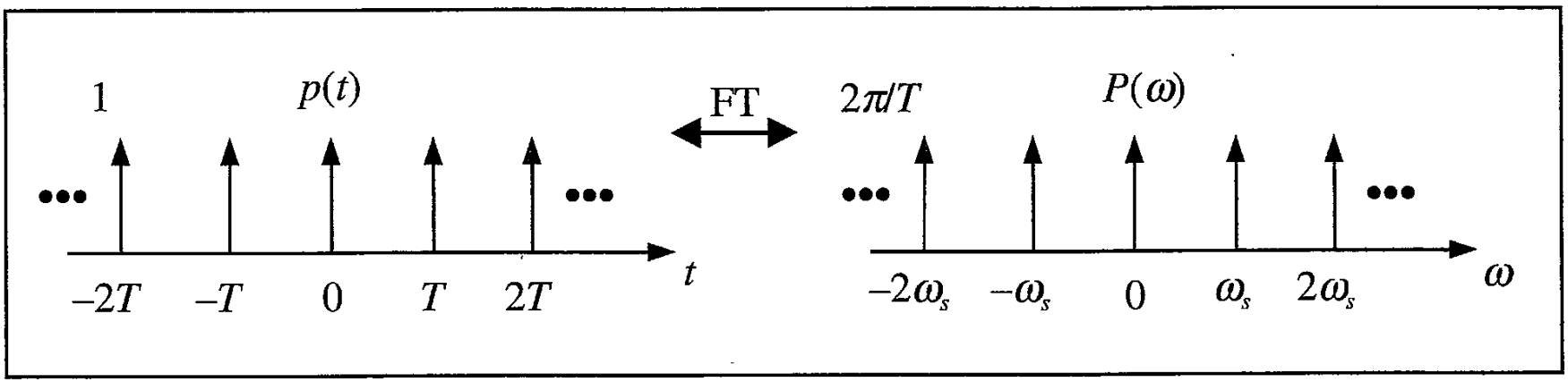


Figure 7.1
Fourier transform of an impulse train.

$$P(\omega) = \frac{2\pi}{T} \sum_{k=-\infty}^{\infty} \delta\left(\omega - k\frac{2\pi}{T}\right) \tag{7.3}$$

Signal Sampling (cont'd)

You can write a sampled signal $x_p(t)$ as

$$x_p(t) = x(t)p(t)$$

If you take the Fourier transform of $x_p(t)$,

$$X_p(\omega) = \frac{1}{2\pi} X(\omega) * P(\omega)$$

where $*$ indicates convolution. Substituting (7.3) in (7.5),

Signal Sampling (cont'd)

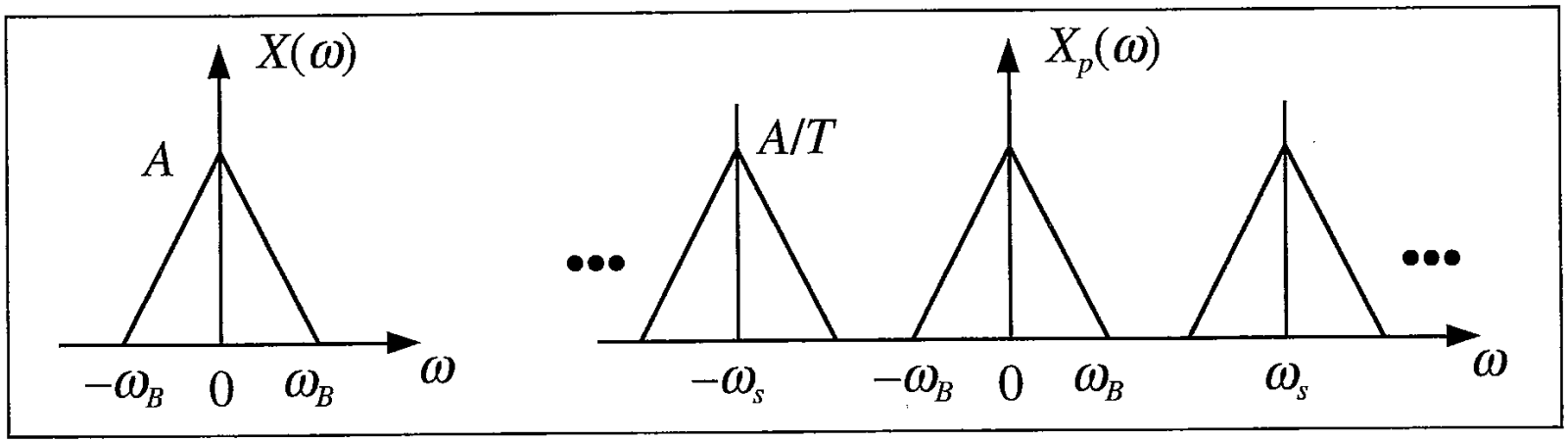


Figure 7.2
Original signal $X(\omega)$ and the spectrum of the sampled signal $X_p(\omega)$.

To reconstruct the original signal $x(t)$, use a lowpass filter $H(\omega)$ to extract only the spectrum in the baseband; that is,

$$\hat{X}(\omega) = X_p(\omega)H(\omega) \tag{7.7}$$

where

$$H(\omega) = \begin{cases} T, & |\omega| < \dfrac{\omega_s}{2} \\ 0, & \text{otherwise} \end{cases} \tag{7.8}$$

Signal Reconstruction

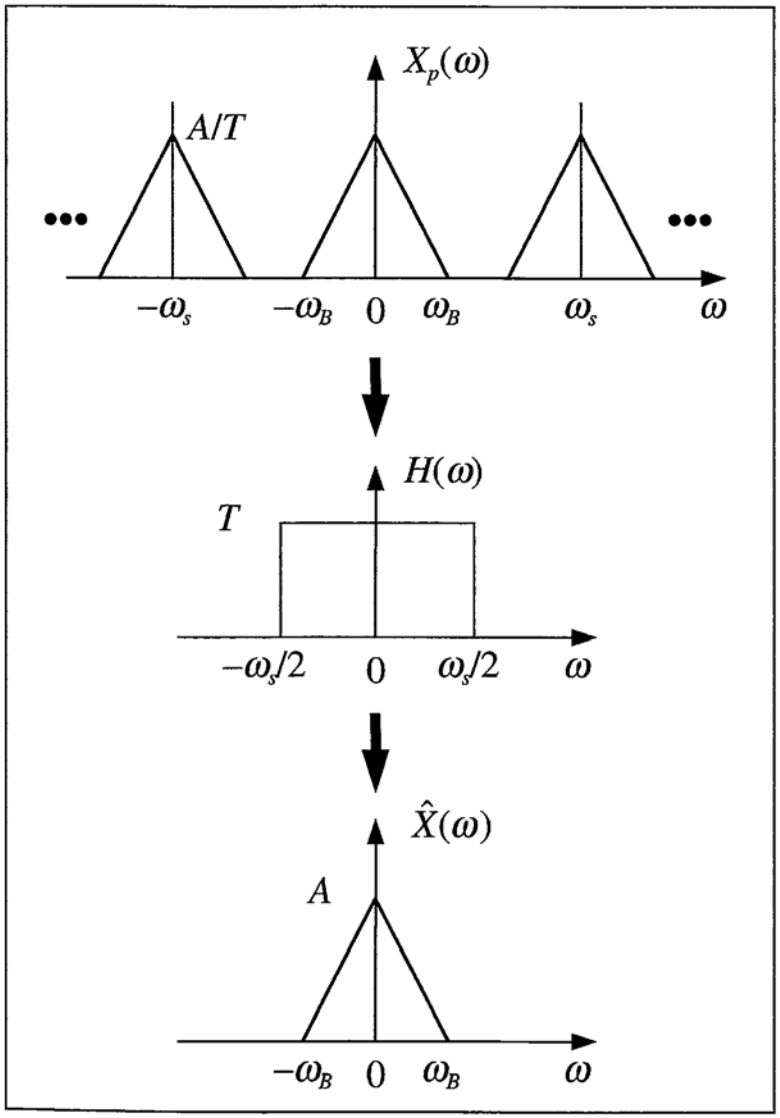
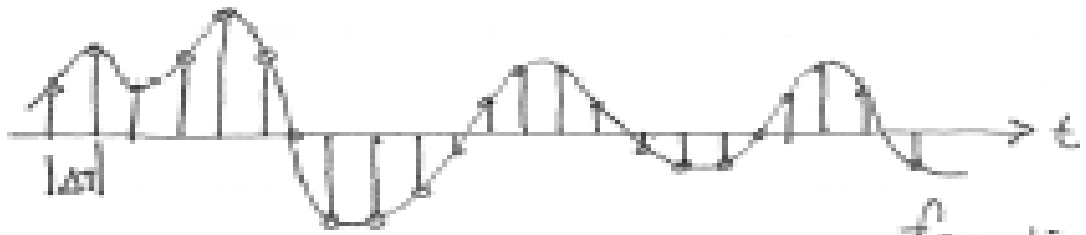


Figure 7.3 Reconstruction of the original signal from its samples.

Sampling Rate

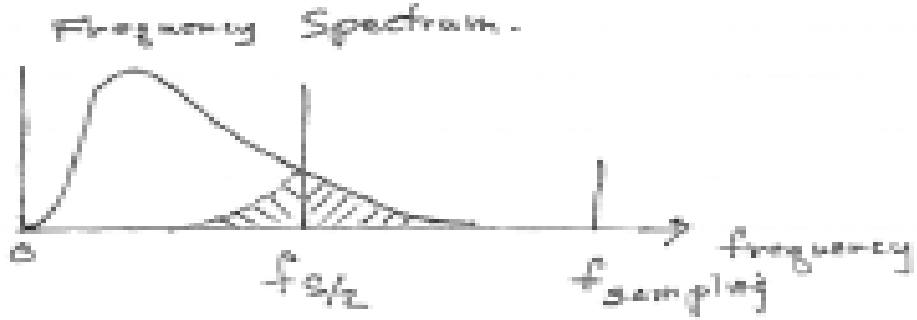


$f_{sampling} = \frac{1}{\Delta T}$

Nyquist Criterion – if f_N is the highest frequency component in the signal then $f_{sampling} \geq 2 f_N$

If $f_{sampling} < 2 f_N$, then frequency aliasing takes place

i.e.

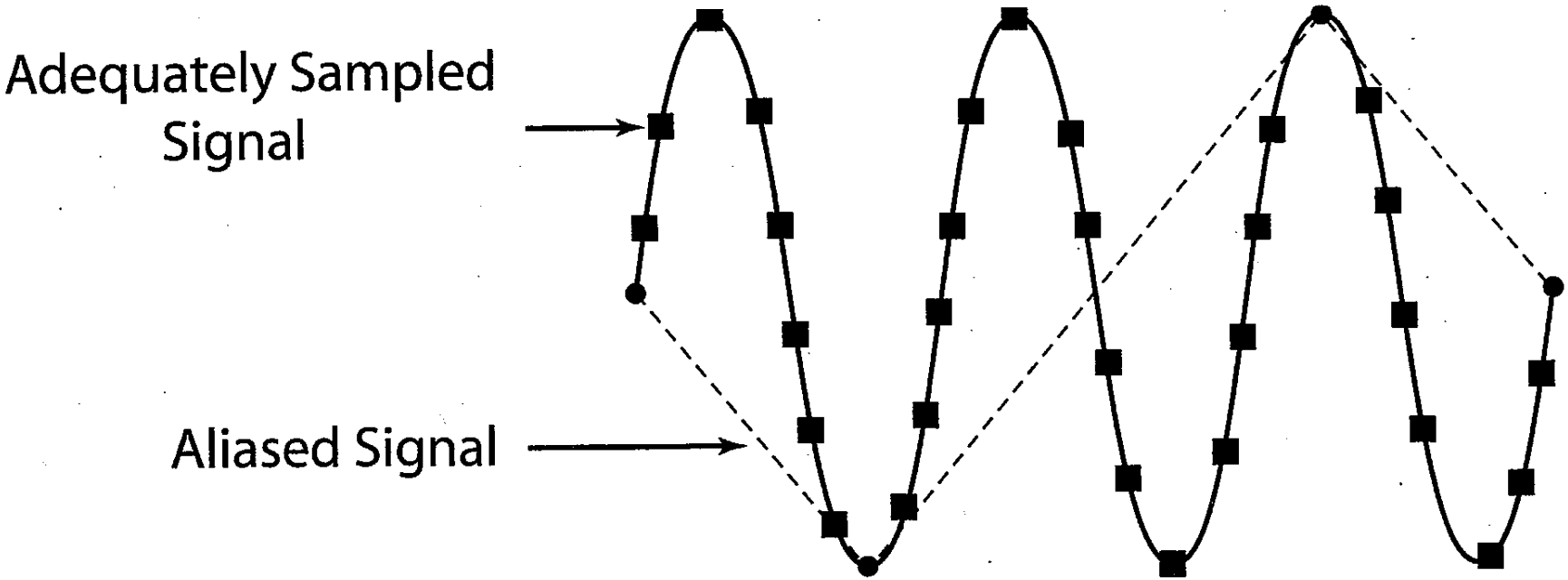


Each frequency component higher than $f_{s/2} (f_{sampling/2})$

$f = f_{s/2} + \Delta f$ is aliased to $f_{s/2} - \Delta f$

$\therefore$ $f_{sampling/2}$ is also called the <u>folding frequency</u>

Aliasing



If information in the signal is in frequency amplitudes, Nyquist criterion is adequate

NB However, if information is in time - amplitude domain (e.g. time of occurrence of or amplitude of a peak)

$$f_{sampling} \geq 10 f_H$$

∴ Must filter the signal sent to the computer by a low-pass filter with

$$f_{cutoff} < f_{sampling}/2$$

Results if signal amplitude too low compared to bit resolution of A/D converter.

i.e. bit resolution for a ±5 Volt input 12-bit A/D converter = $\frac{\pm 10 \text{ Volts}}{2^{12} \times \text{Gain}} = \frac{2.5 \text{ millivolts}}{\text{Gain}}$

Suppose signal amplitude = 10 μvolts (e.g. EEG) and gain = 2000

∴ bit resolution referred to source signal

$$\frac{2.5 \text{ millivolts}}{2 \times 10^3} = 1.25 \text{ μVolts}.$$

i.e. the digitized signal can only have 8 levels.