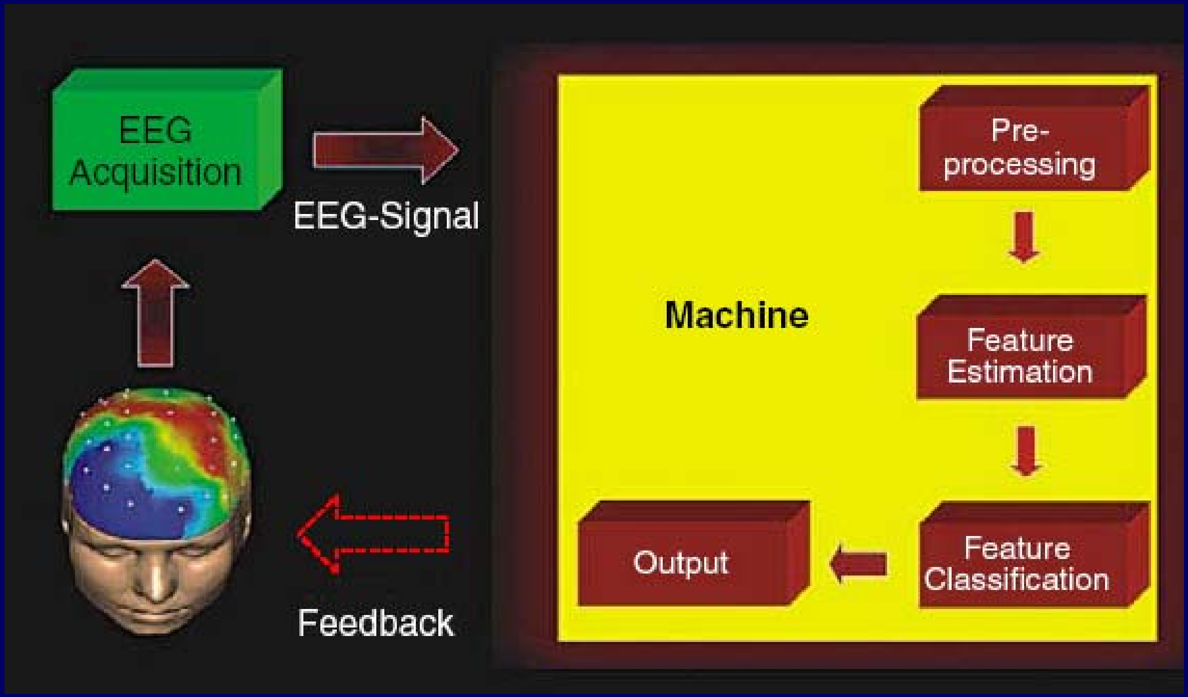
DSP概論:
Biomedical Signal Processing

台大電機系李百祺

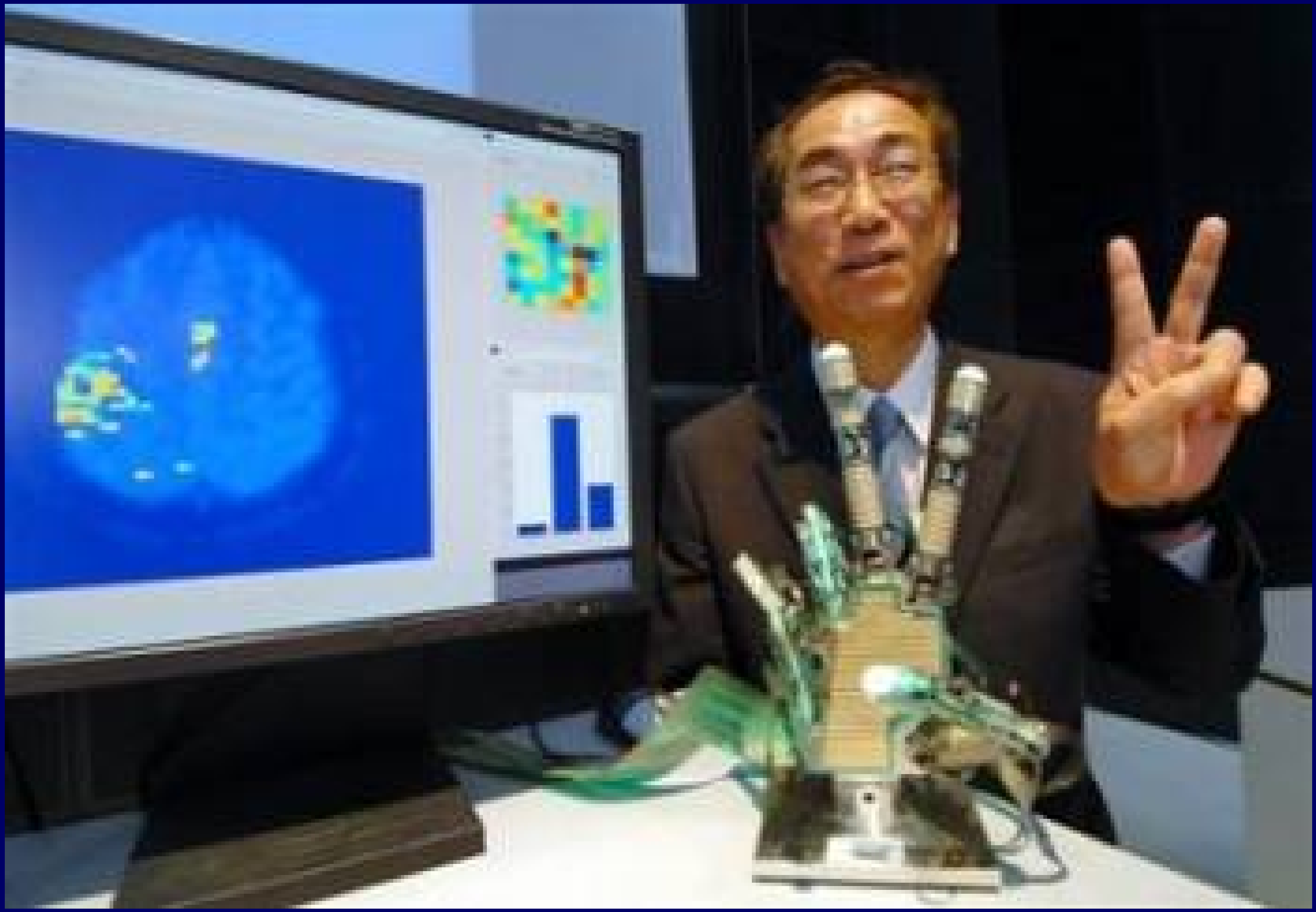
Brain-Machine Interface

Brain-Machine Interface

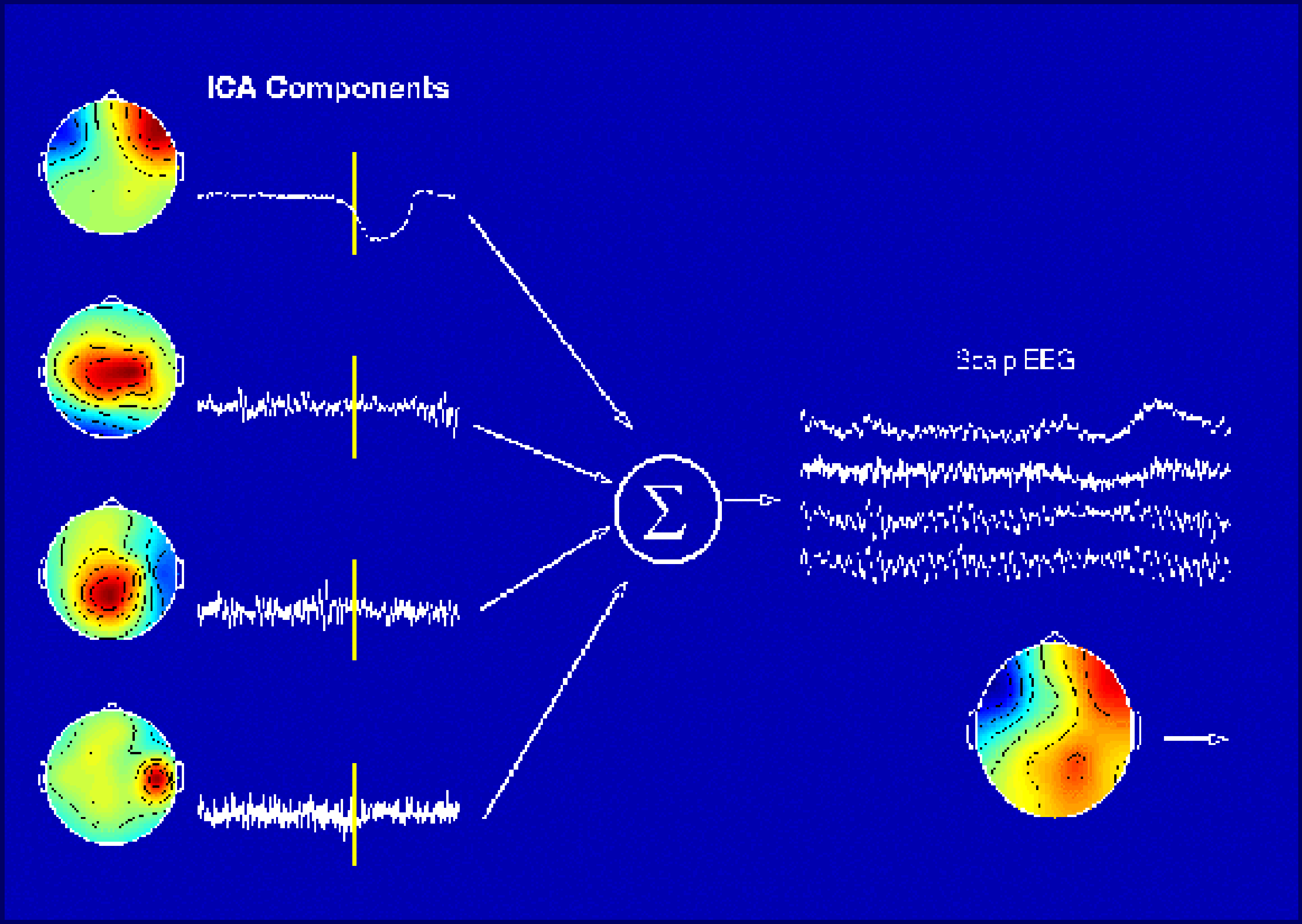


Brain-Machine Interface

(By ATR-Honda)



The Need for Biomedical Signal Processing

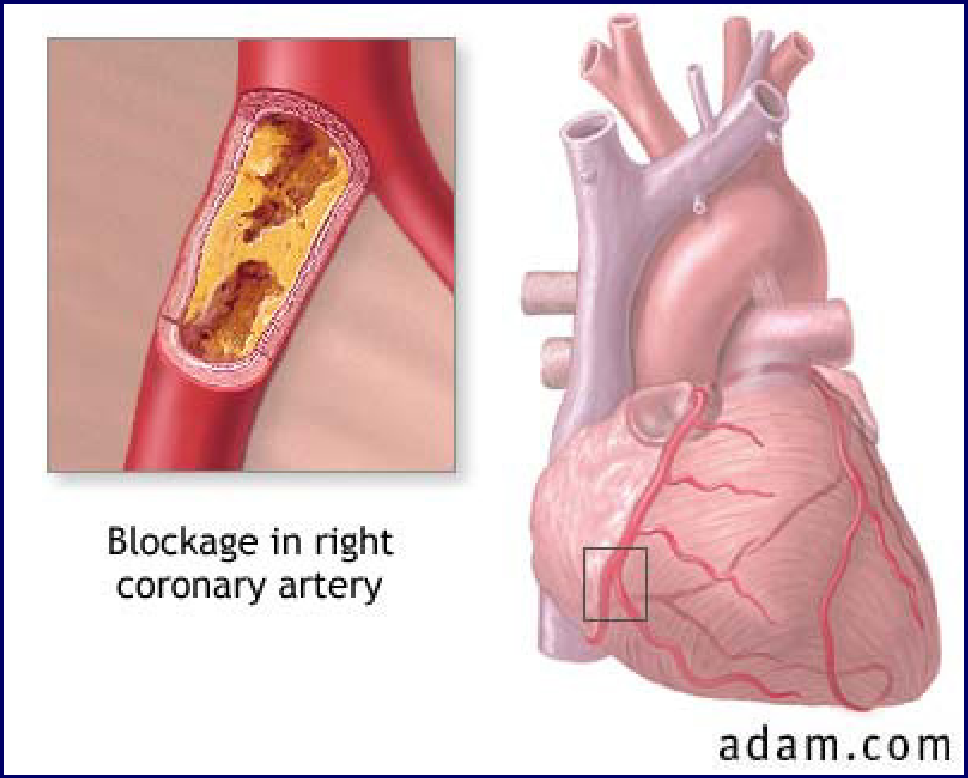


What is it?

- Biomedical Signal Processing: Application of *signal processing methods*, such as filtering, Fourier transform, spectral estimation and wavelet transform, to *biomedical problems*, such as the analysis of cardiac signals, the breathing cycle,…etc.
- A broader aspect: Biomedical imaging, genomic signal processing,…etc.

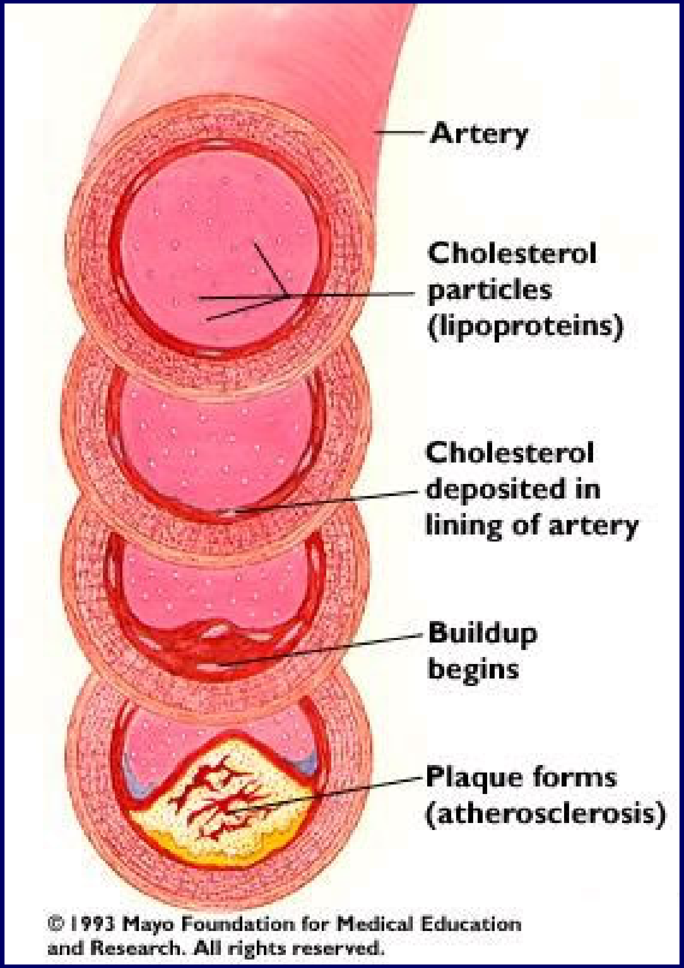
Medical Diagnosis:
Heart Attack as another Example

- Heart attack: Coronary artery disease, blockage of blood supply to the myocardium.



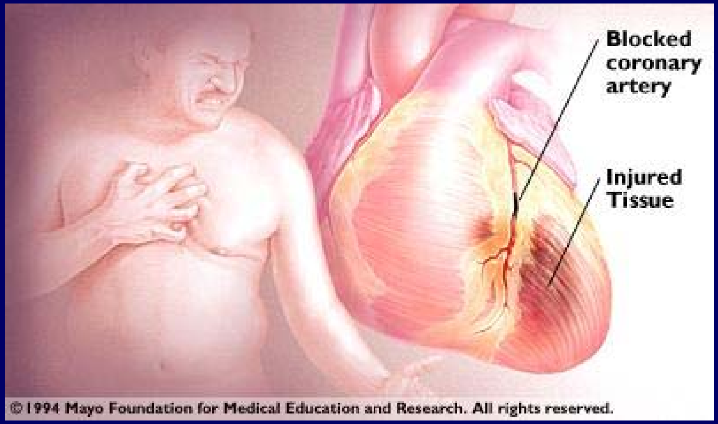
Medical Diagnosis: Heart Attack as an Example

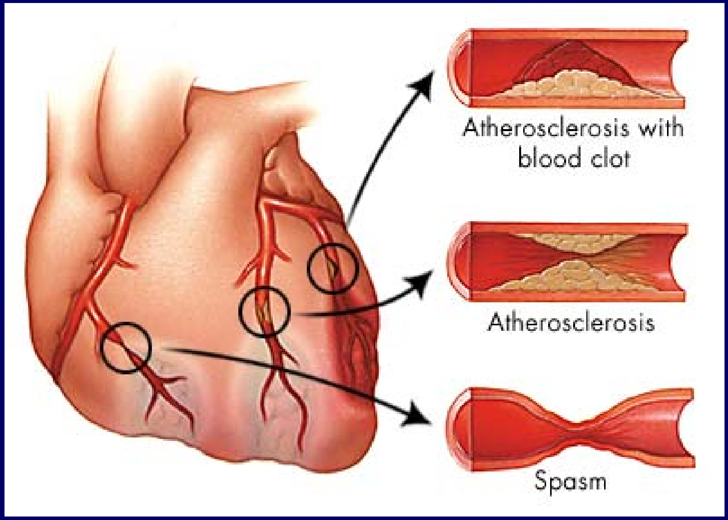
- Plaque: A gradual build-up of fat (cholesterol) within the artery wall.



Medical Diagnosis:
Heart Attack as an Example

- Symptoms:
  - Chest pressure with stress, heart burn, nausea, vomiting, shortness of breath, heavy sweating.
  - Chest pain, heart attack, arrhythmias.

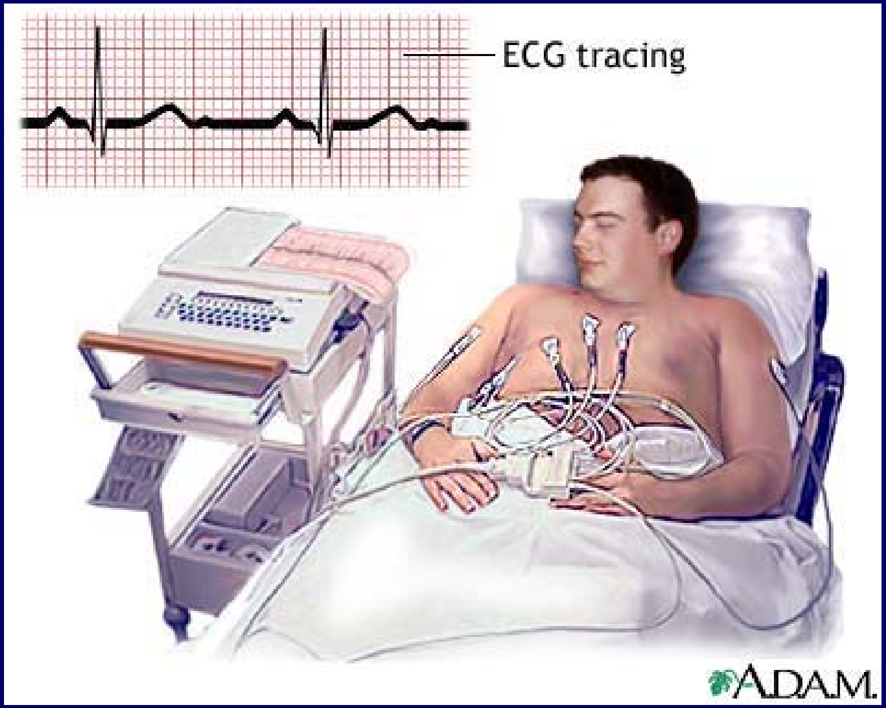


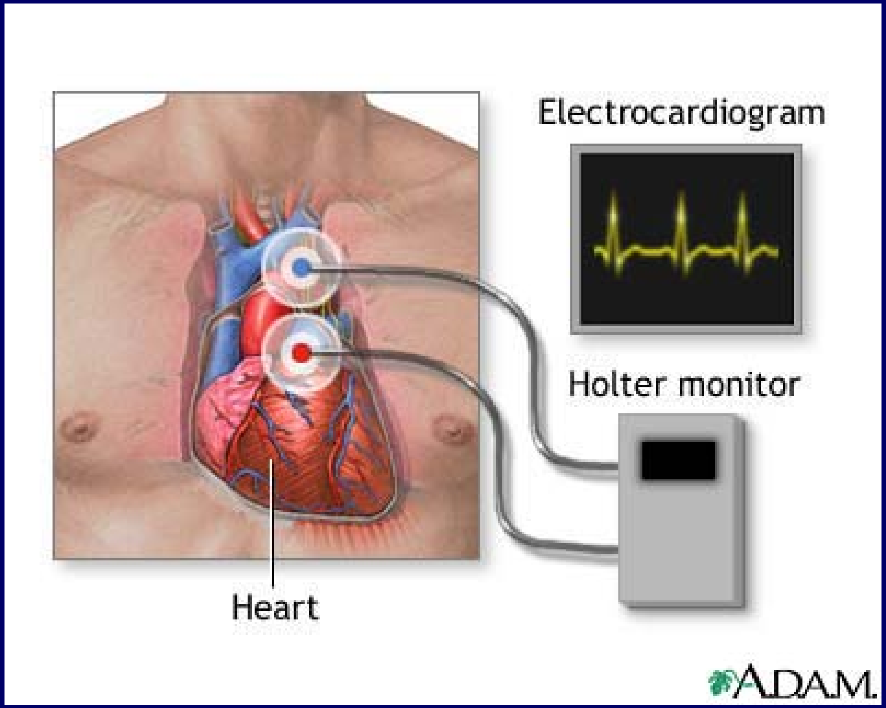


Medical Diagnosis: Heart Attack as an Example

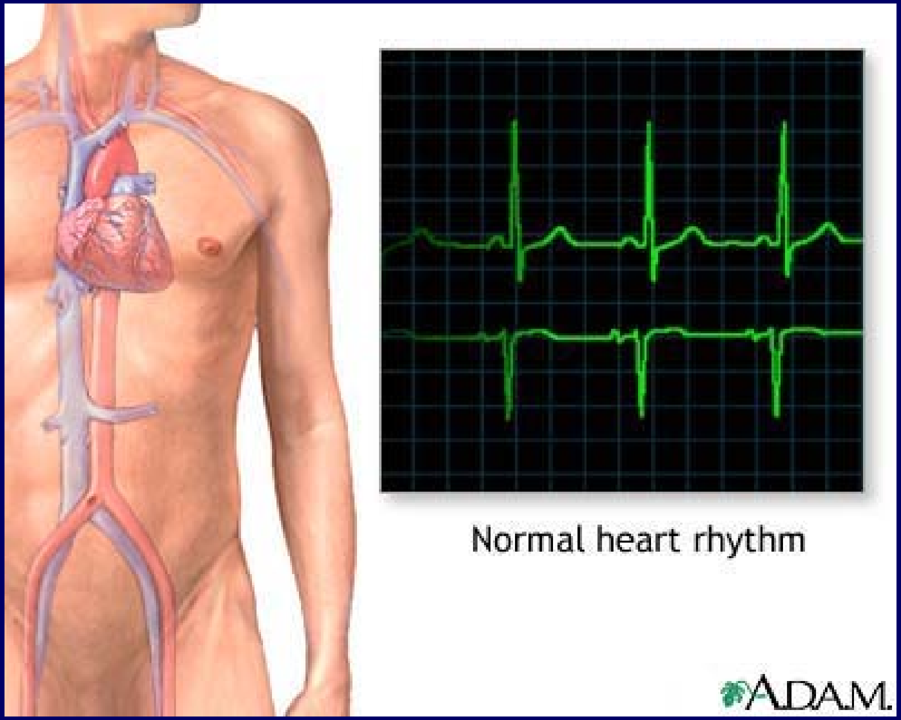
- Diagnosis:
  - – Prehospital electrocardiography (ECG).
  - – Continuous/serial ECG.
  - – Exercise stress ECG.
  - – Biochemical tests and biomarkers.
  - – Sestamibi myocardial perfusion imaging.
  - – Echocardiography.
  - – Computer-based decision aids.

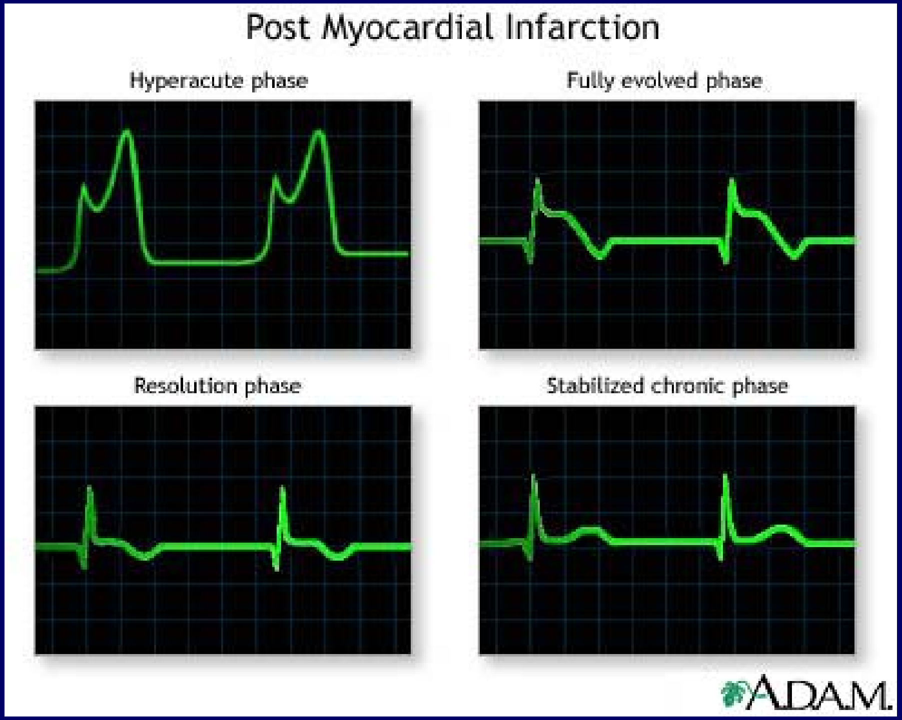
Medical Diagnosis: ECG



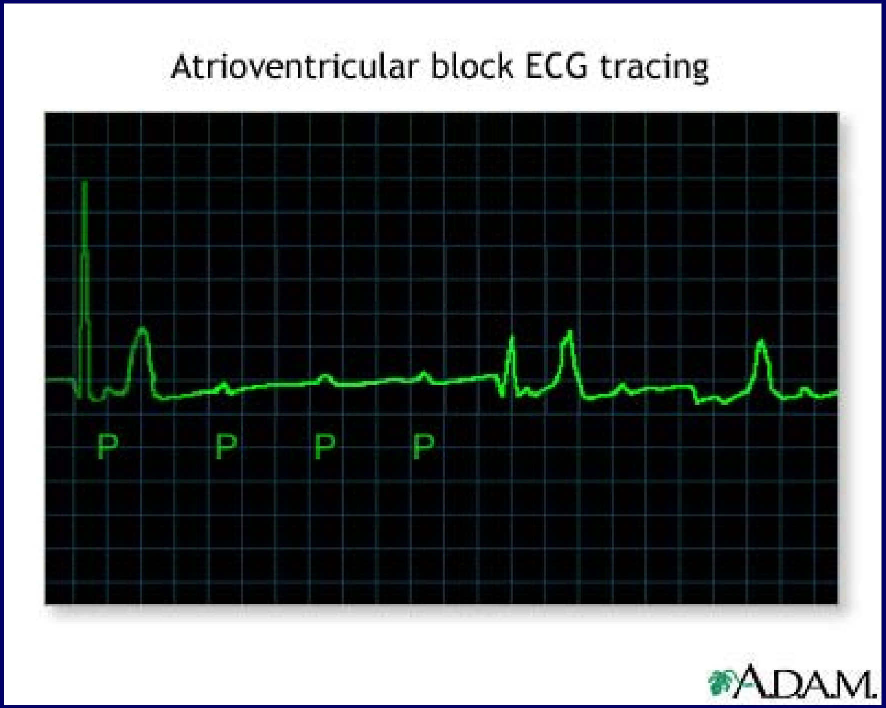


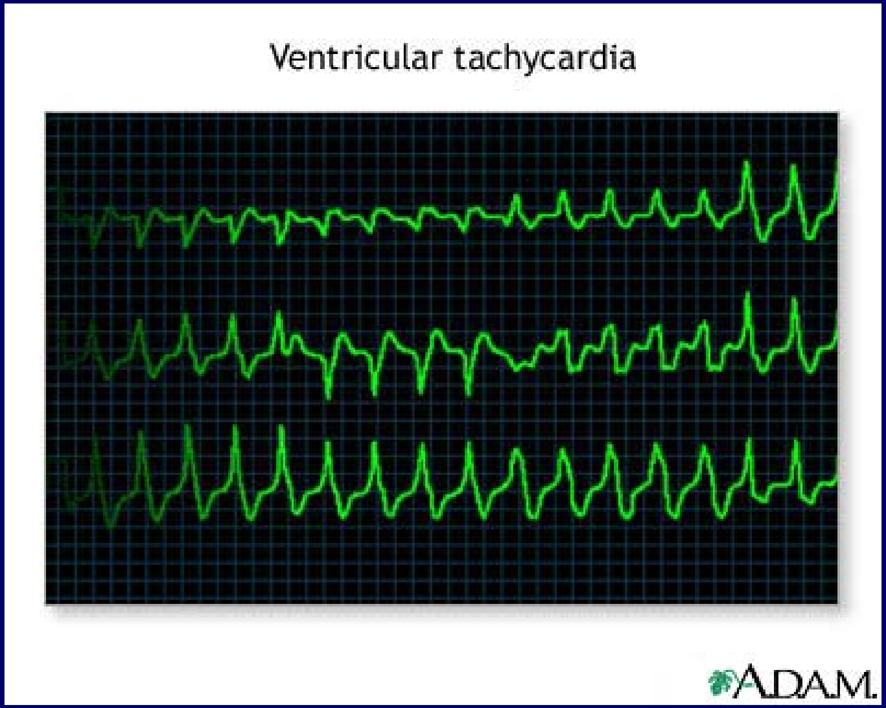
Medical Diagnosis: ECG





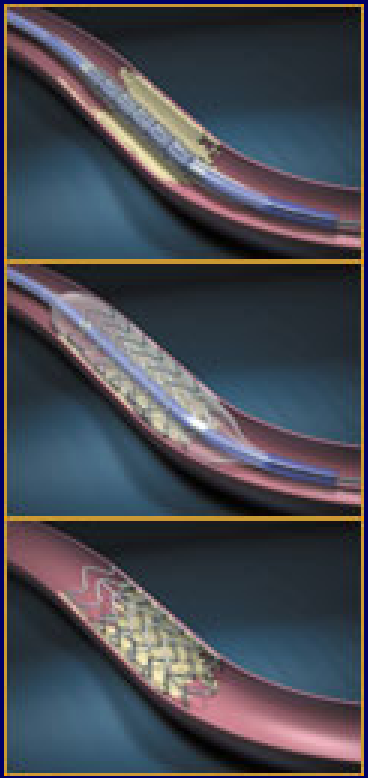
Medical Diagnosis: ECG

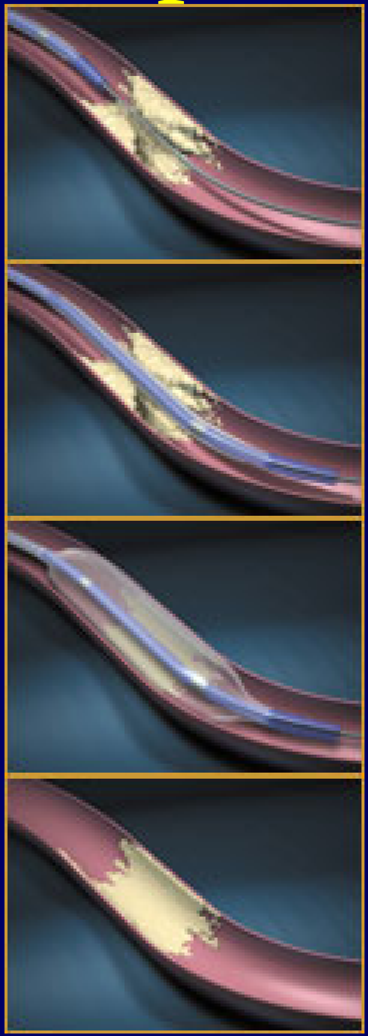


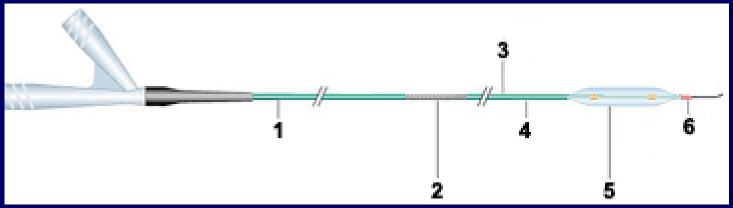


Medical Diagnosis:
Heart Attack as an Example

- Treatment:
  - Angioplasty.
  - Stent implantation.
  - Atherectomy.
  - Coronary bypass surgery.
  - Intravascular radiotherapy.
  - Excimer laser.

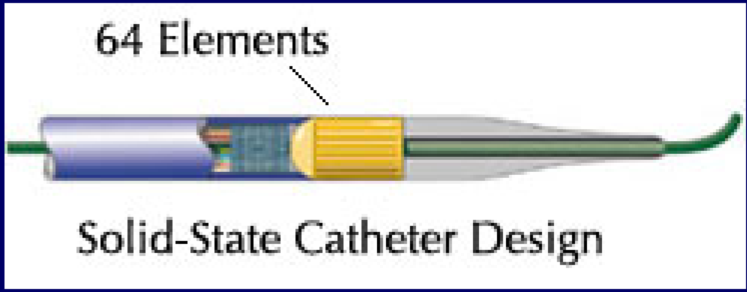


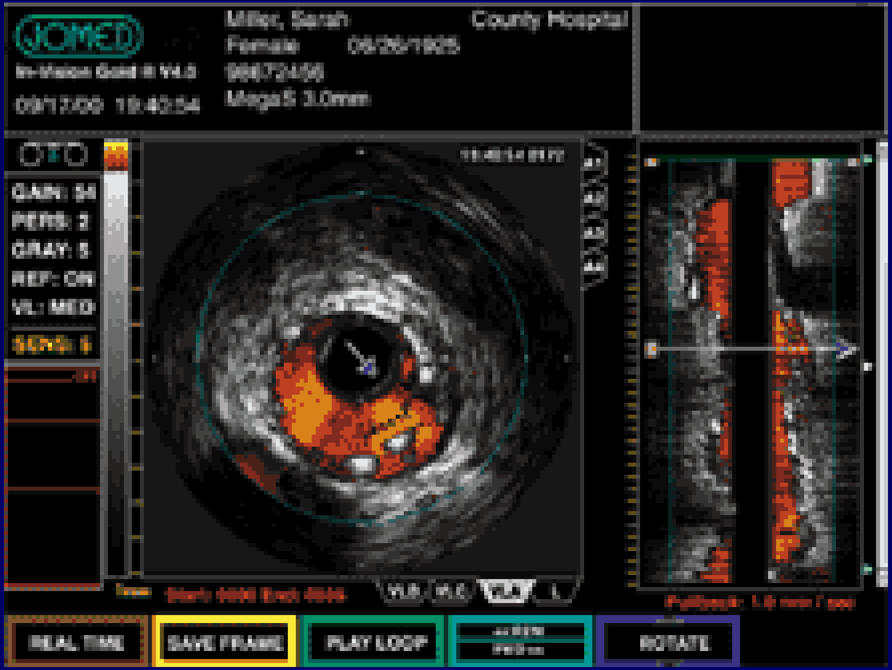




Medical Diagnosis: Heart Attack as an Example

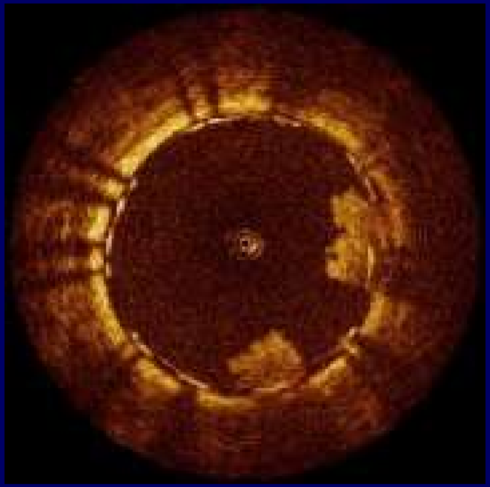
- Imaging:
  - Ultrasound.

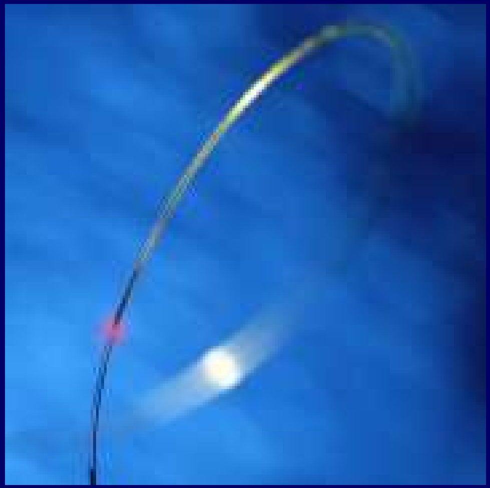
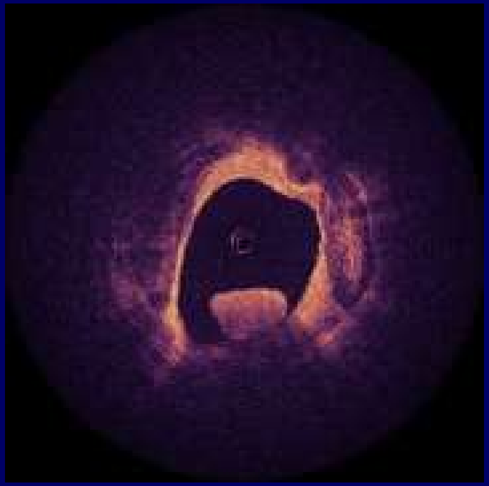




Medical Diagnosis: Heart Attack as an Example

- Imaging:
  - Optics.



Biomedical Signals: Broader Definition

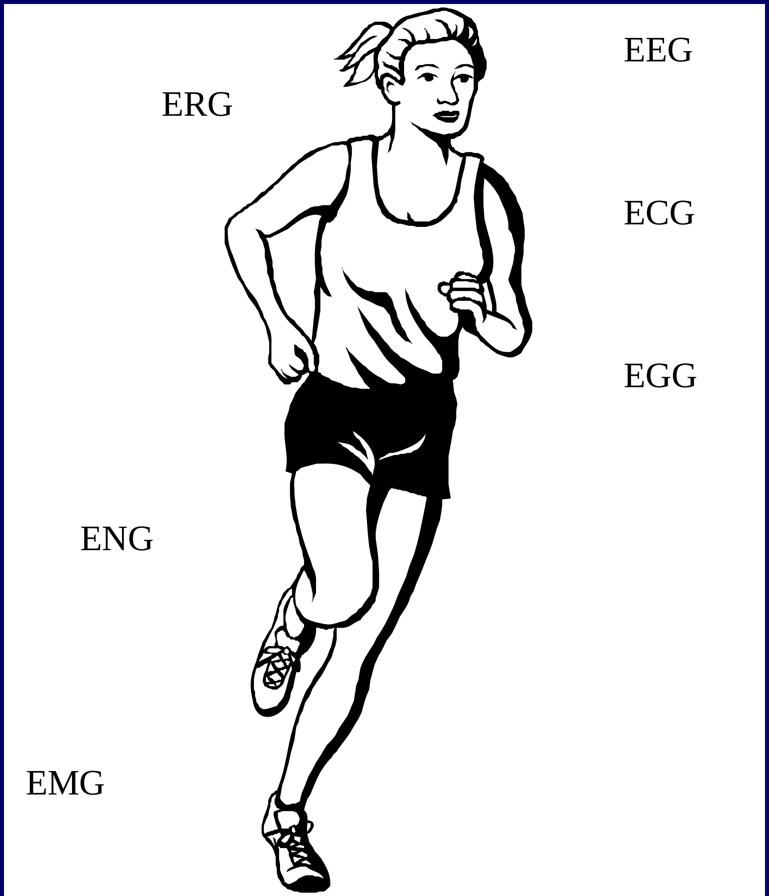
- Signals as a result of physiological activities in the body:
  - Electrical and Non-electrical
- Invasive/Non-invasive interrogation of an external field with the body
- Diagnosis and therapy

➔ *Will focus mostly on bioelectric signal.*

Outline

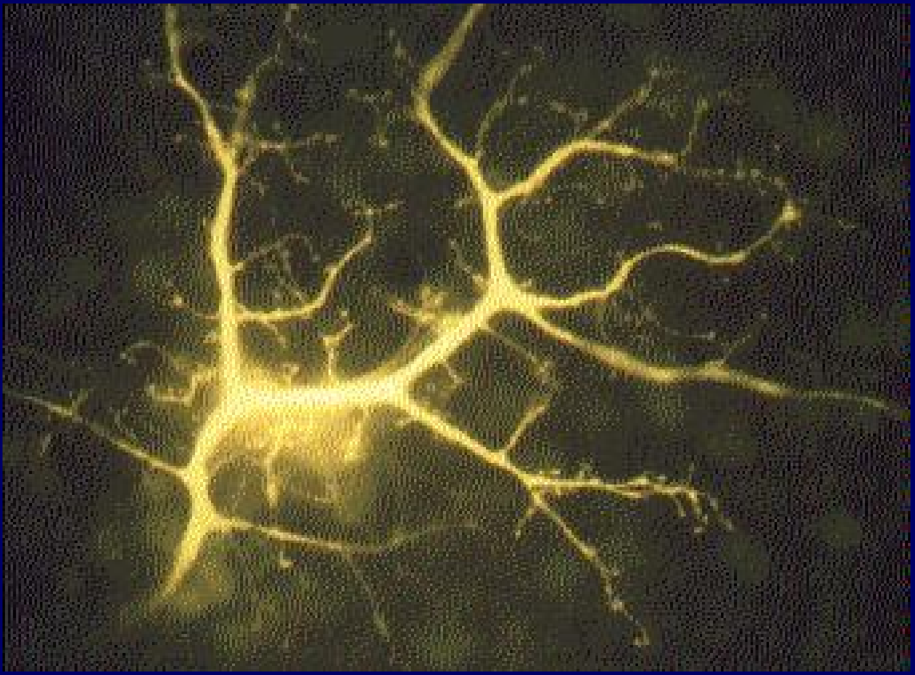
- Bioelectrical signals:
  - Excitable cells
  - Resting/action potential
- ECG, EEG,…etc
- Applications of signal processing techniques
  - Sampling, filtering, data compression,…etc
- Non-stationary nature of biomedical signals

Bioelectrical Signals

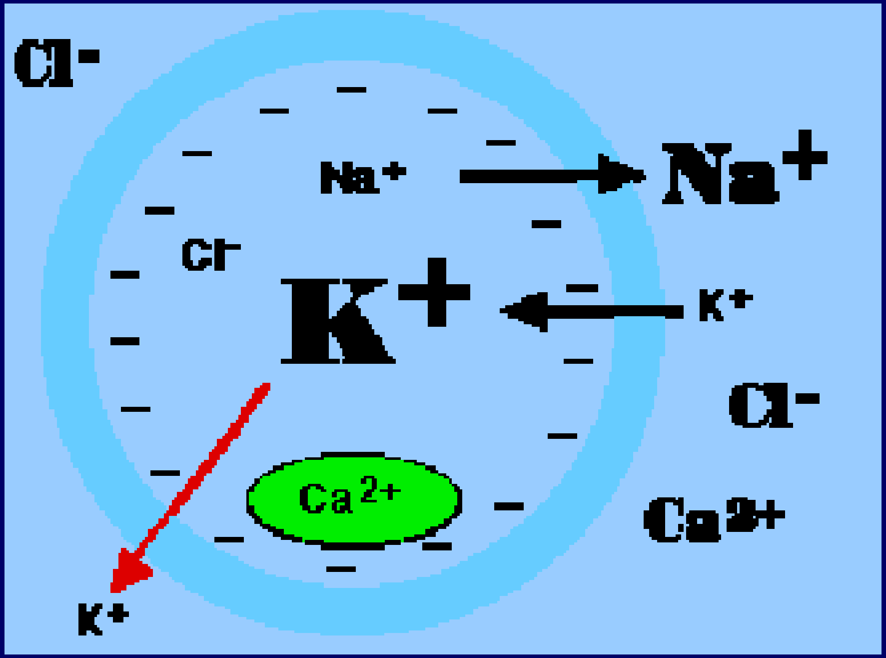


- The bioelectric signals represent many physiological activities.

Excitable Cells

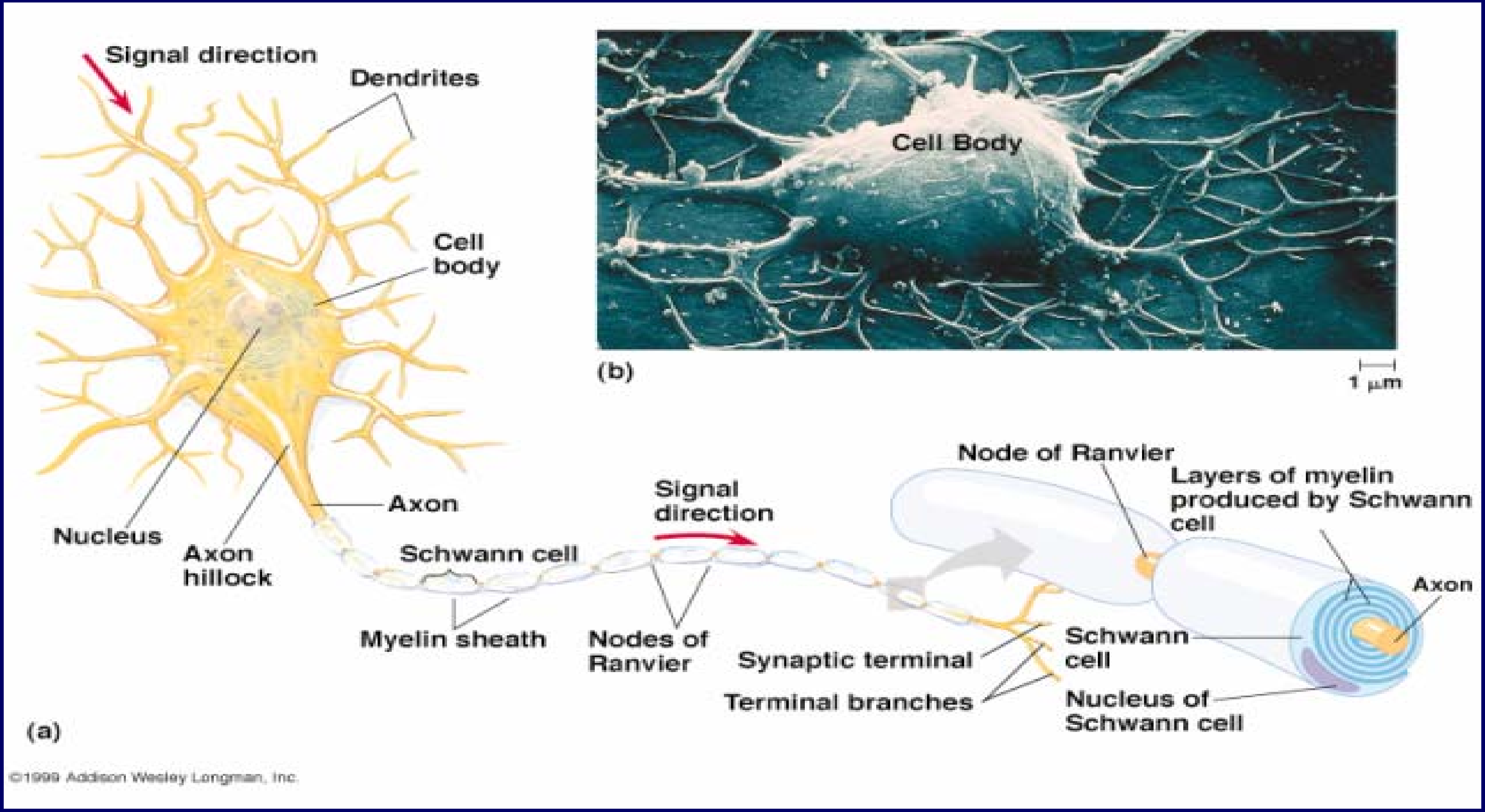


Neuron (Rabbit Retina)

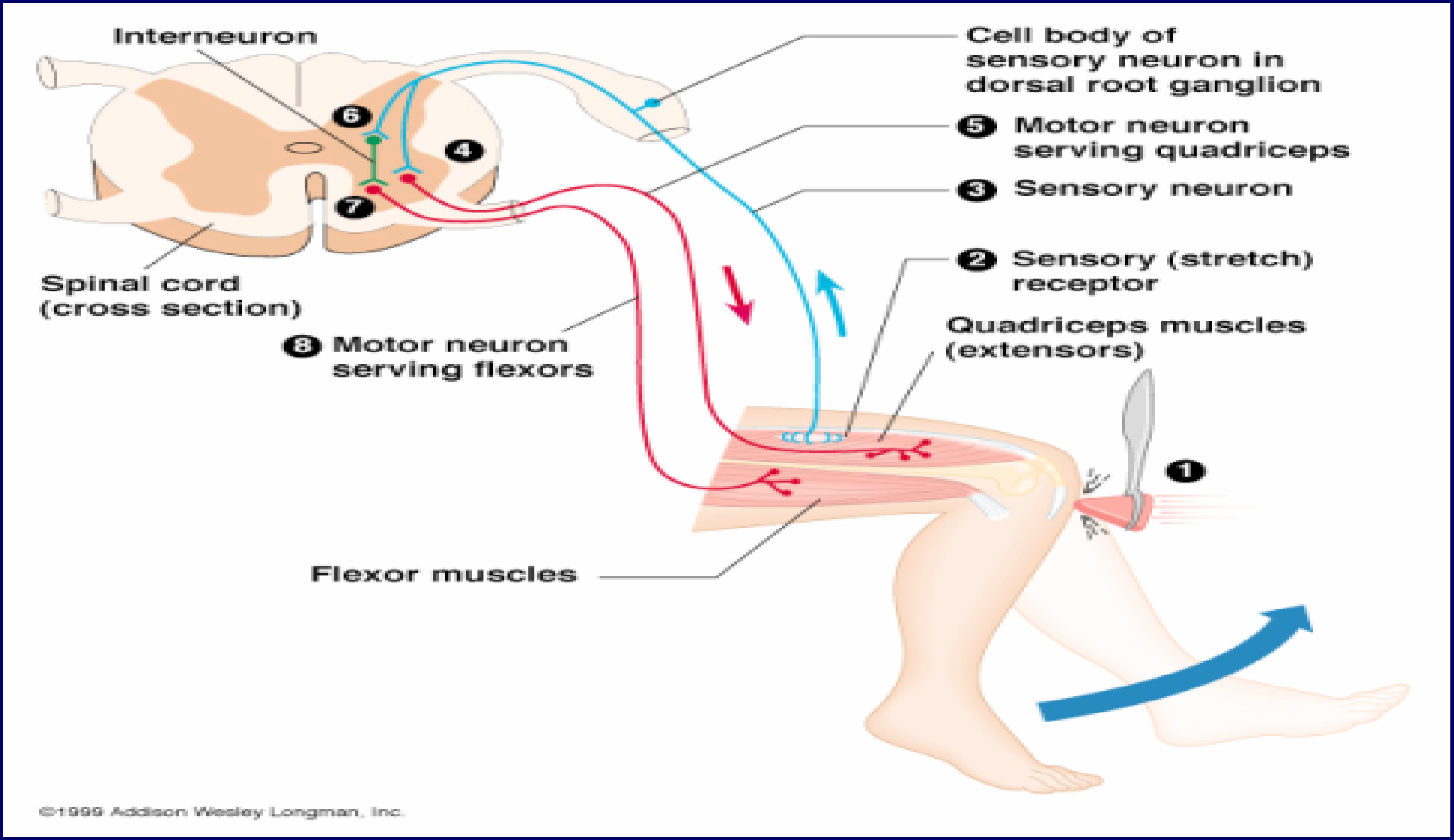


Ionic Relations in the Cell

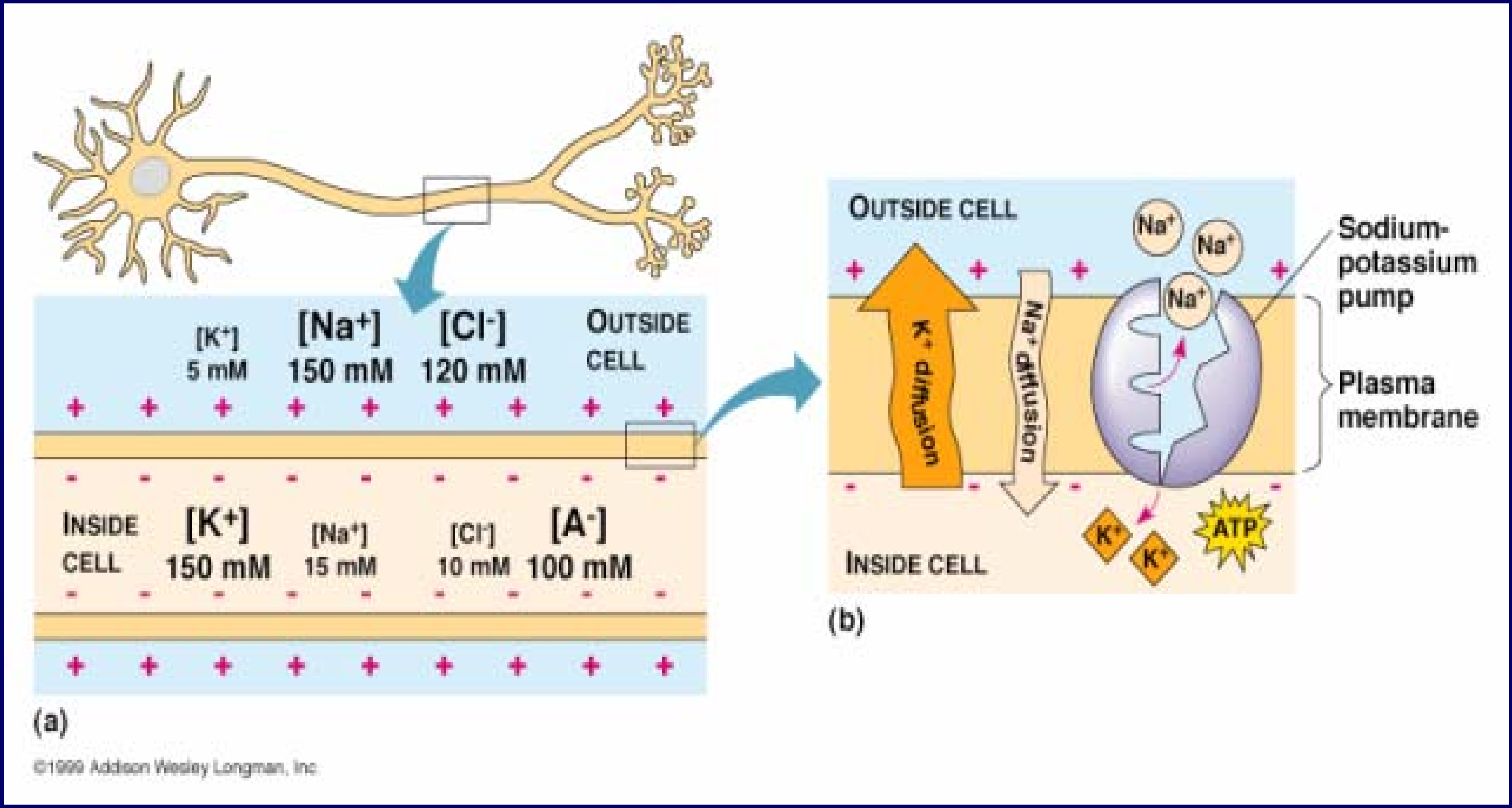
Structural unit



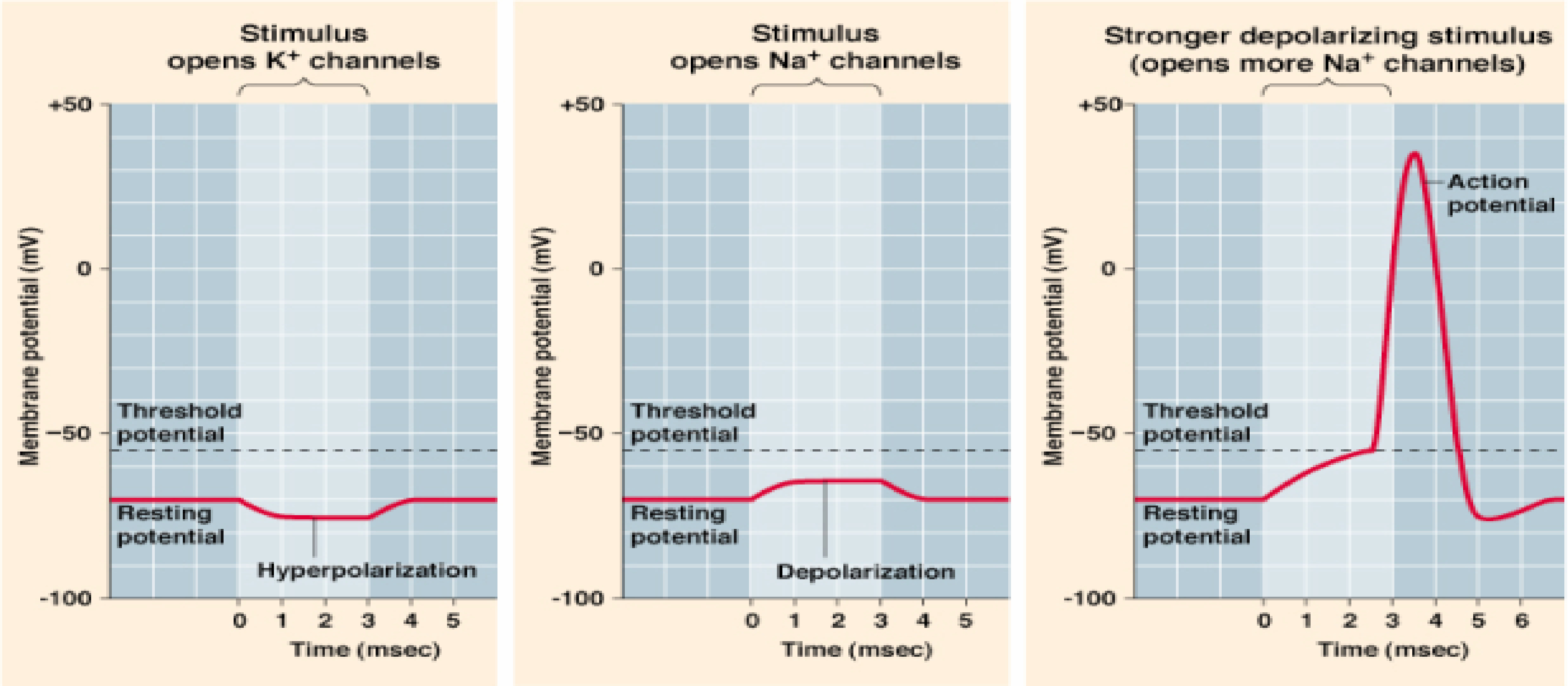
Functional unit



Neural signaling (I)



Neural signaling (II)

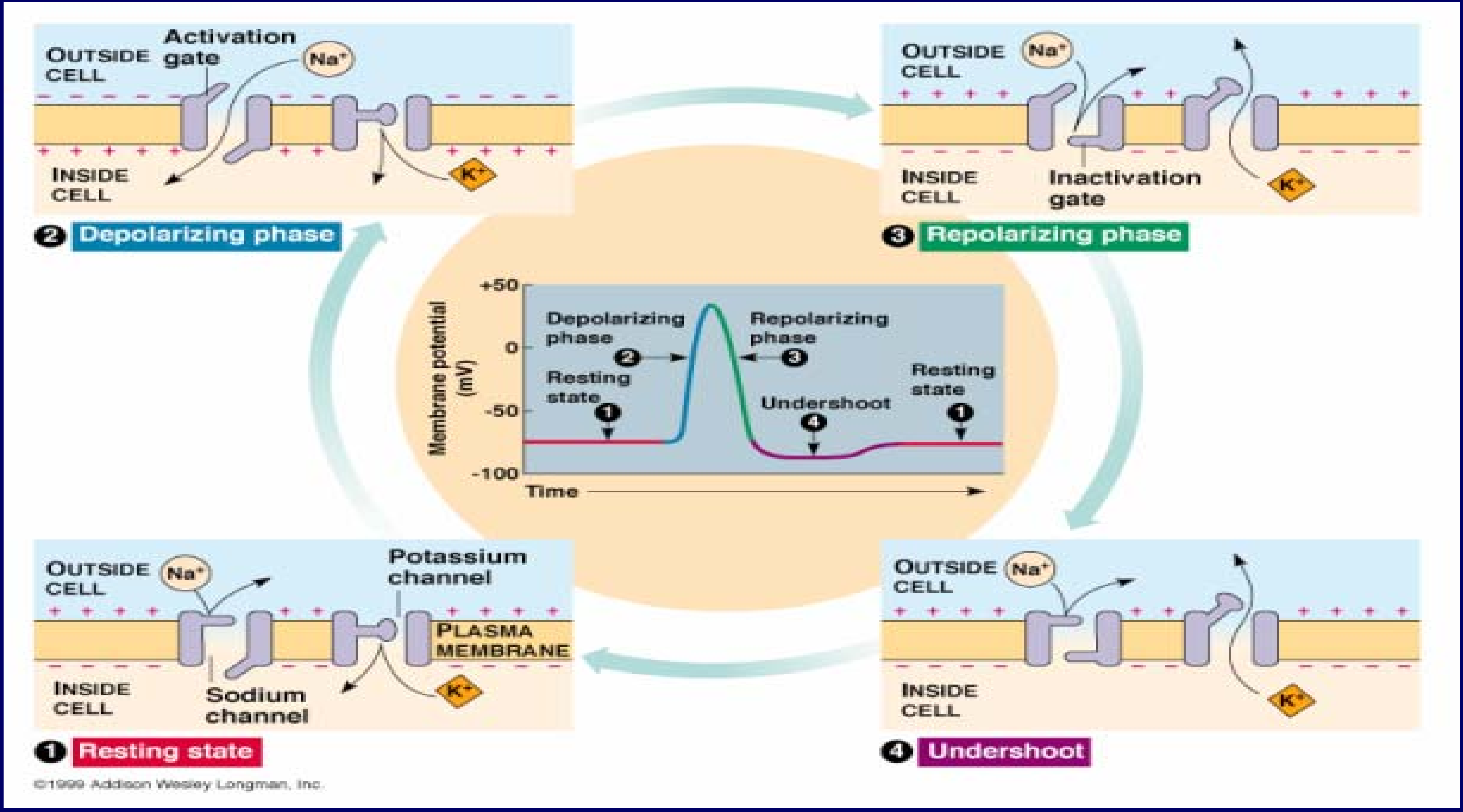


(a) Graded potential: hyperpolarization

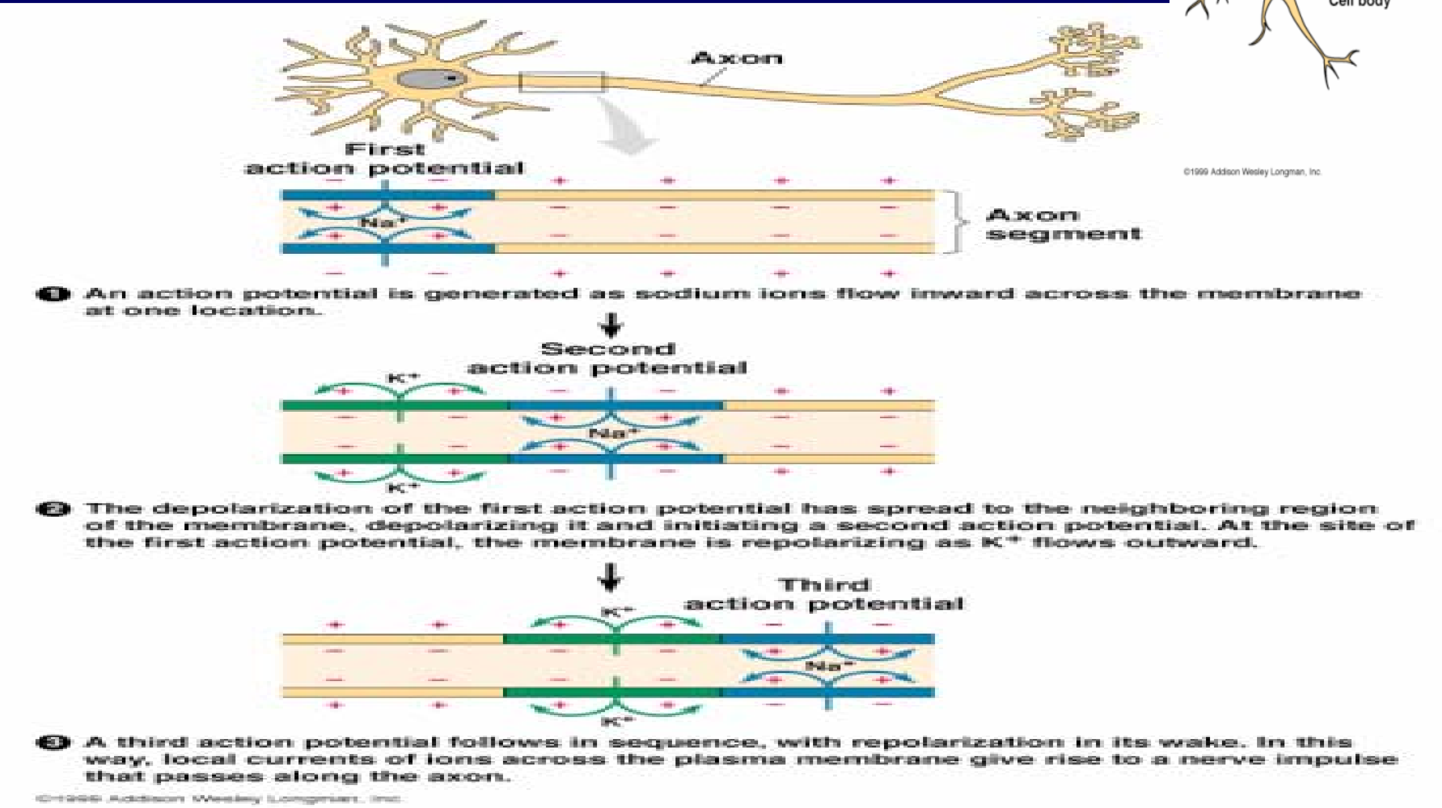
(b) Graded potential: depolarization

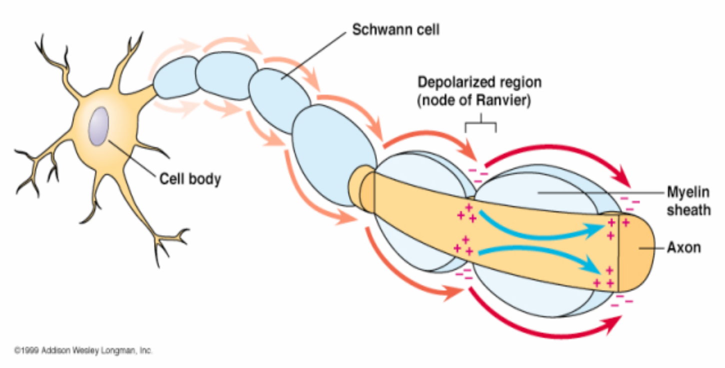
(c) Action potential

Neural signaling (III)



Neural signaling (IV)

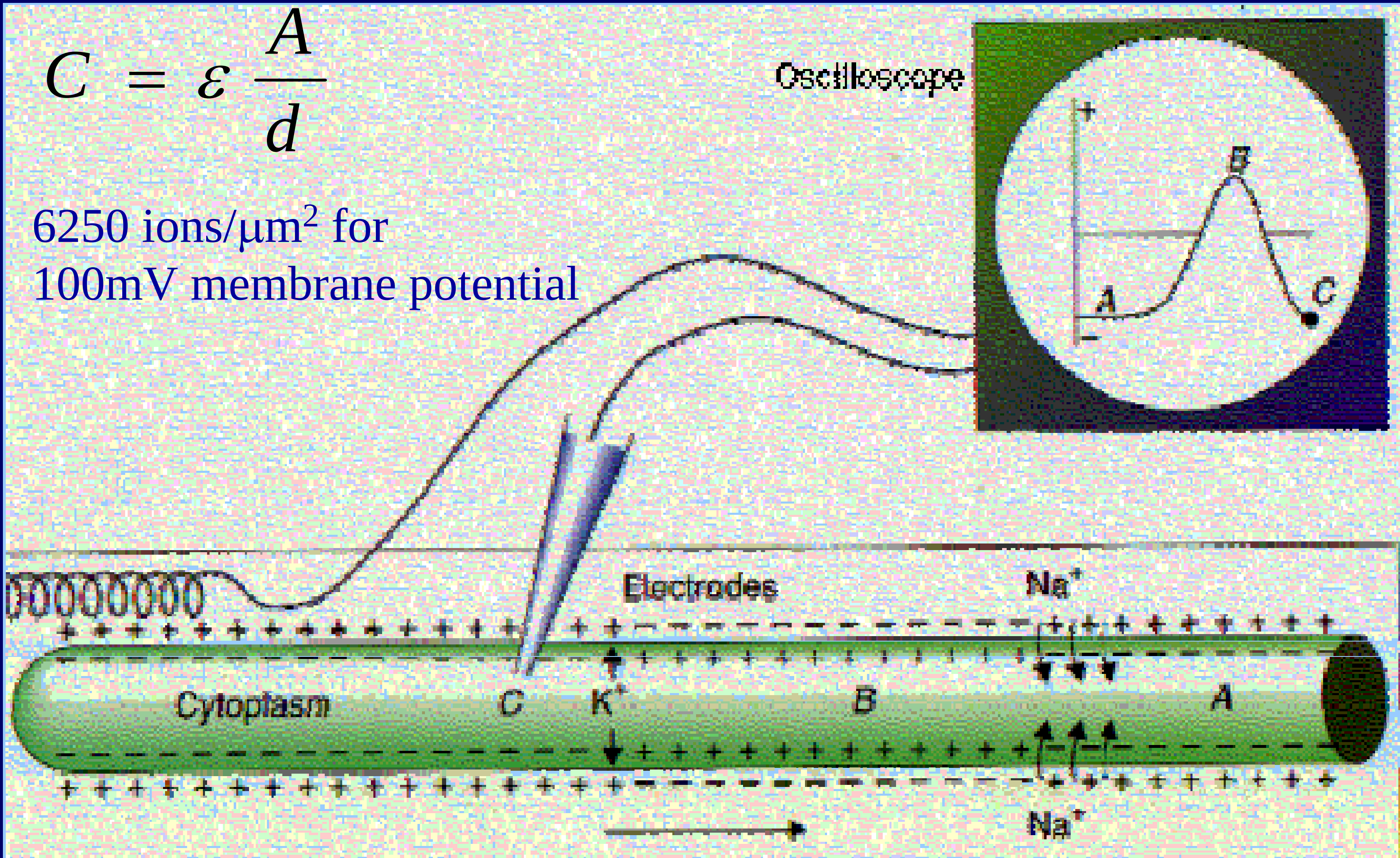




Measurements of Action Potential

$$C = \varepsilon \frac{A}{d}$$

6250 ions/μm^2 for
100mV membrane potential



Goldman Equation

$$E = \frac{RT}{F} \ln \left\{ \frac{P_K [K]_o + P_{Na} [Na]_o + P_{Cl} [Cl]_i}{P_K [K]_i + P_{Na} [Na]_i + P_{Cl} [Cl]_o} \right\}$$

- *E*: Equilibrium resting potential
- *R*: Universal Gas Constant (8.31 J/(mol*K))
- *T*: Absolute temperature in K
- *F*: Faraday constant (96500 C/equivalent)
- P_{M}: Permeability coefficient of ionic species M.

Example: Ion Concentration

Species	Intracellular (millimoles/L)	Extracellular (millimoles/L)
Na^+	12	145
K^+	155	4
Cl^-	4	120

(For frog skeletal muscle)

Example: Equilibrium Resting Potential for frog skeletal muscle

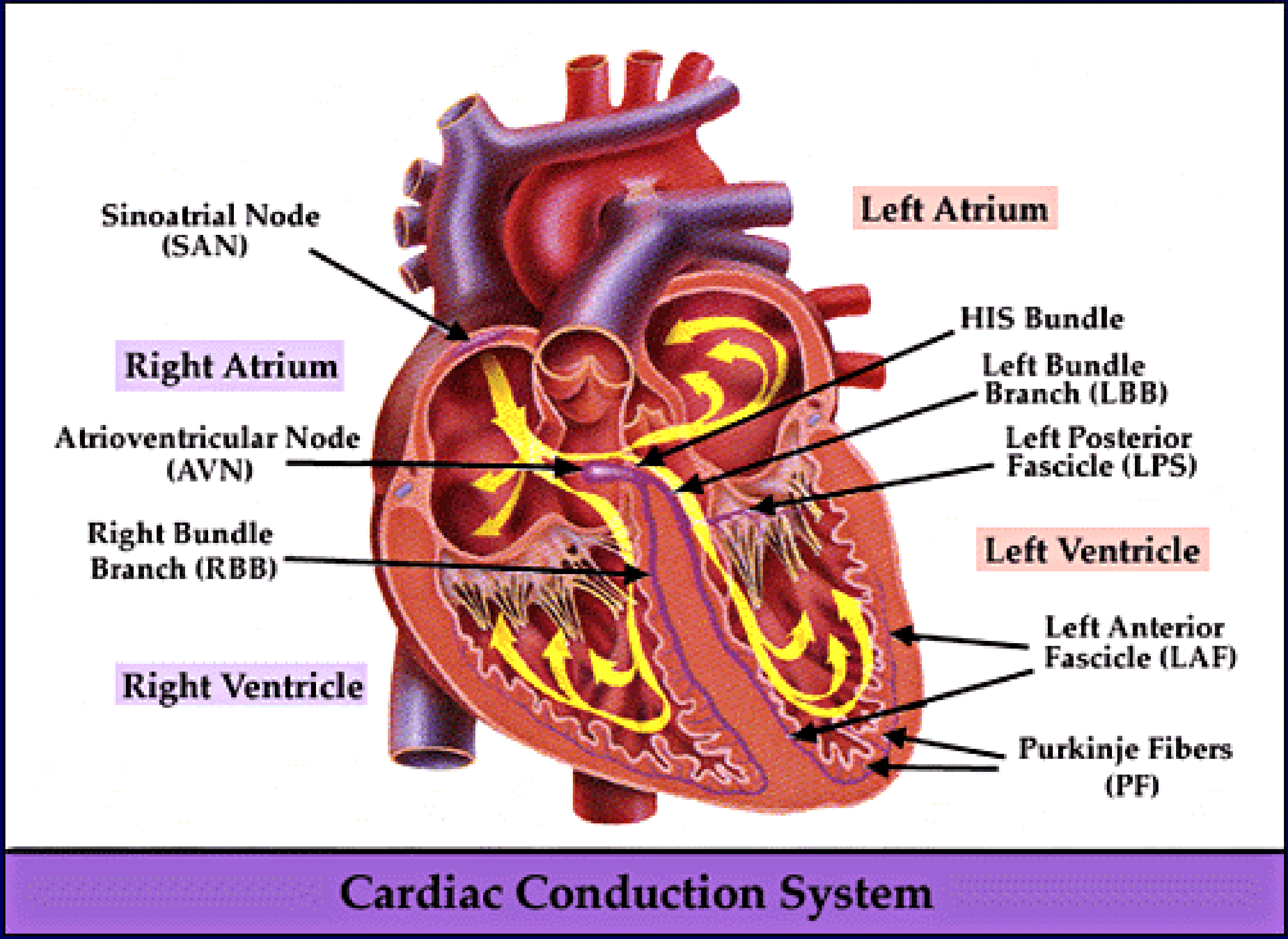
- P_{Na}: 2 X 10^{-8} cm/s
- P_K : 2 X 10^{-6} cm/s
- P_{Cl} : 4 X 10^{-6} cm/s
- E=-85.3 mV

Electrocardiogram (ECG)

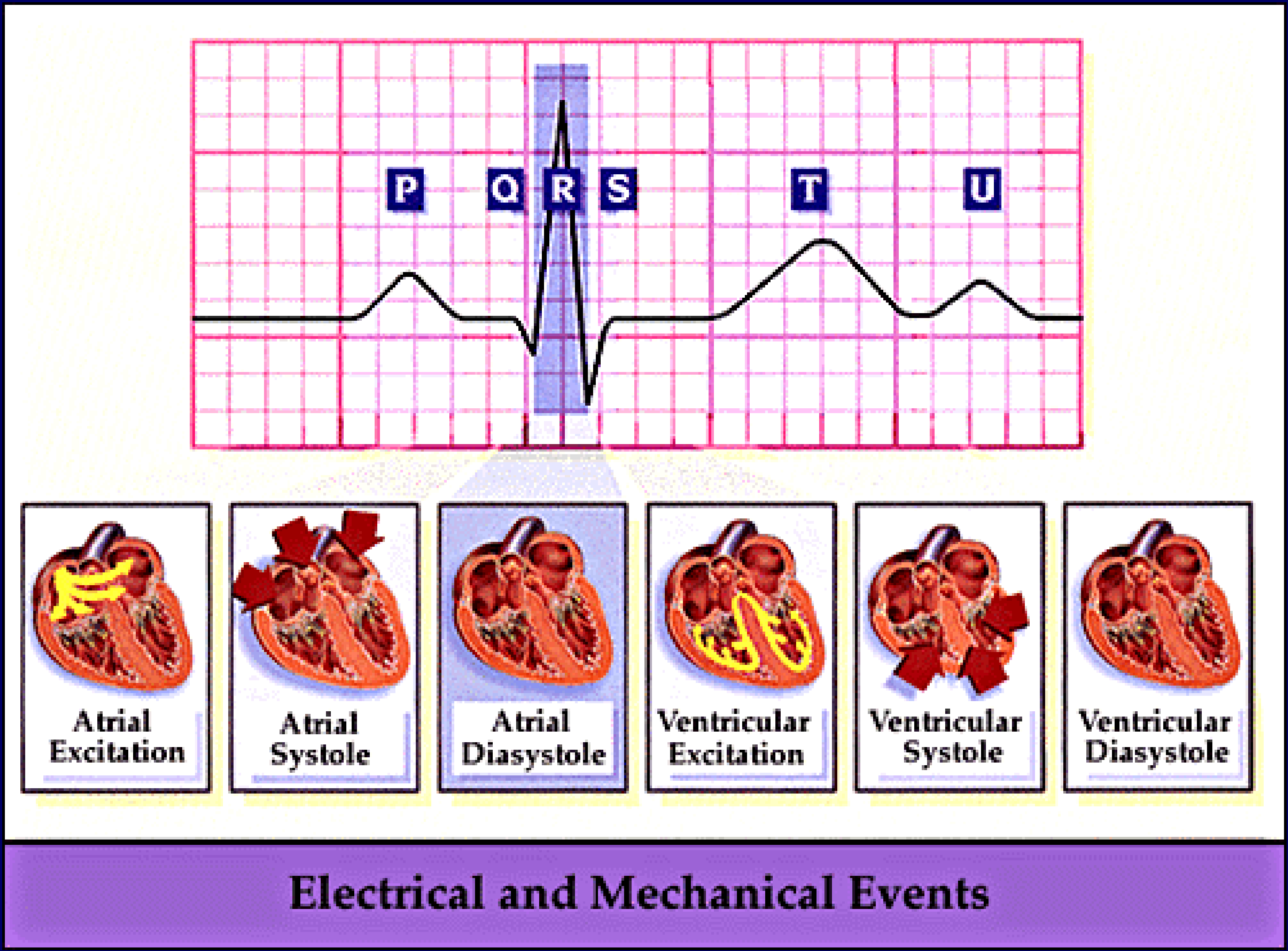
ECG

- One of the main methods for assessing heart functions.
- Many cardiac parameters, such as heart rate, myocardial infarction, and enlargement can be determined.
- Five special groups of cell:
  - SA, AV, common bundle, RBB and LBB.

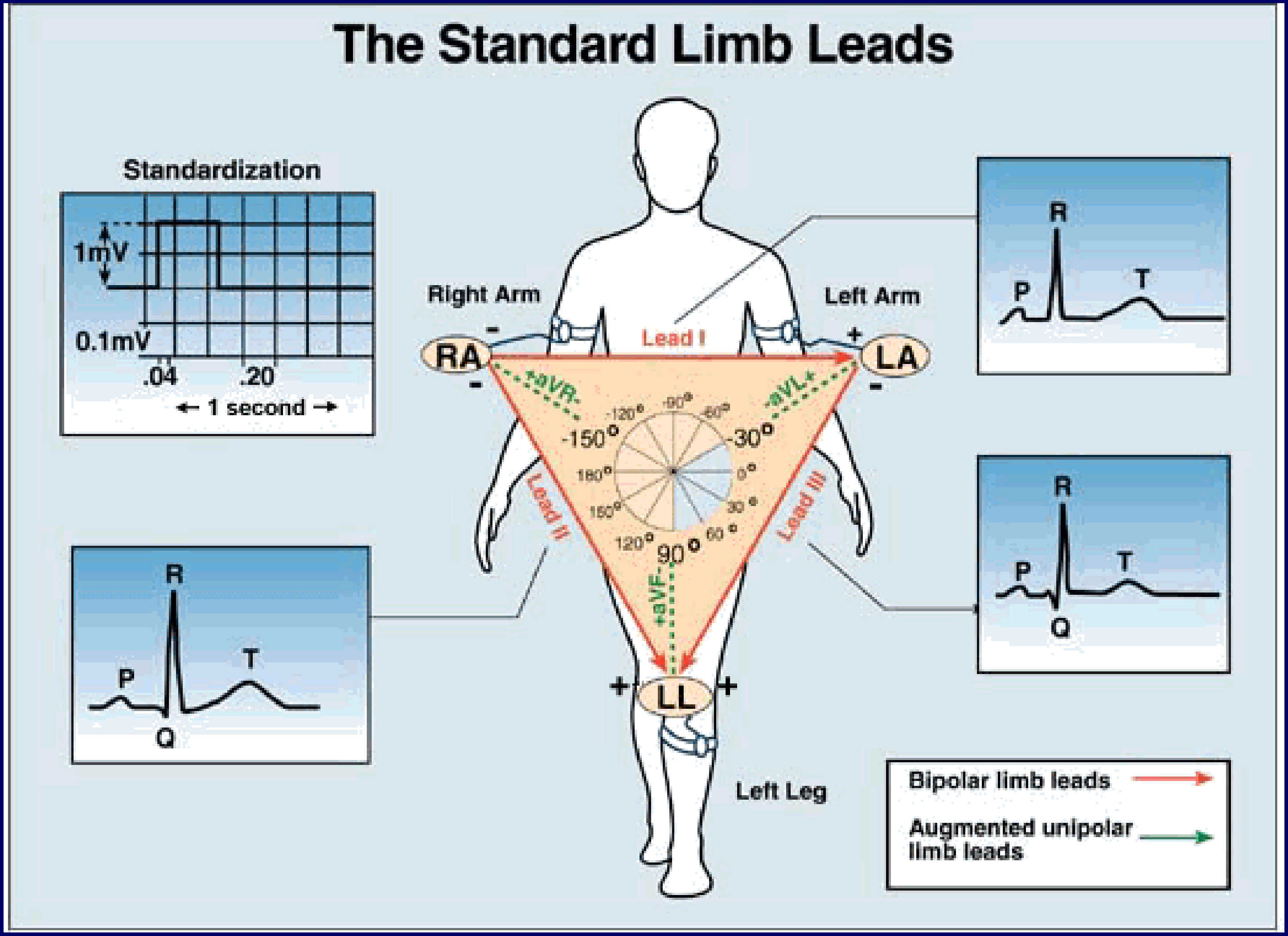
ECG


Sinoatrial Node
(SAN)
Right Atrium
Atrioventricular Node
(AVN)
Right Bundle
Branch (RBB)
Right Ventricle
Left Atrium
HIS Bundle
Left Bundle
Branch (LBB)
Left Posterior
Fascicle (LPS)
Left Ventricle
Left Anterior
Fascicle (LAF)
Purkinje Fibers
(PF)
Cardiac Conduction System

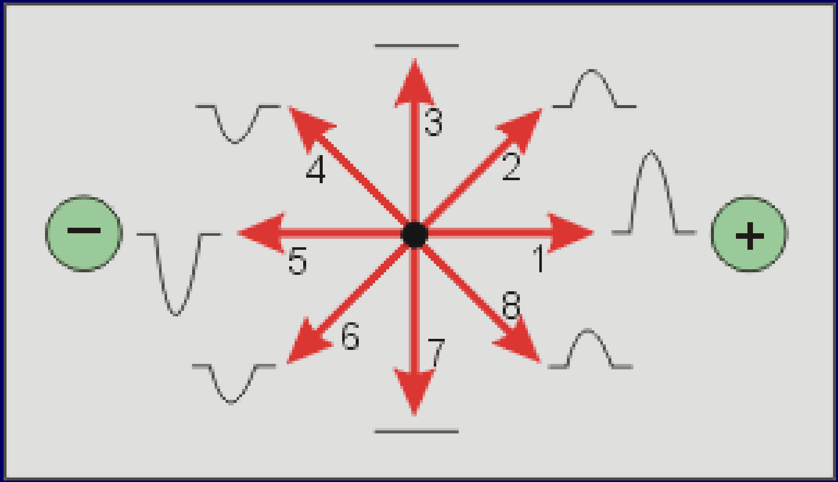
ECG


P
Q
R
S
T
U
Atrial Excitation
Atrial Systole
Atrial Diasystole
Ventricular Excitation
Ventricular Systole
Ventricular Diasystole
Electrical and Mechanical Events

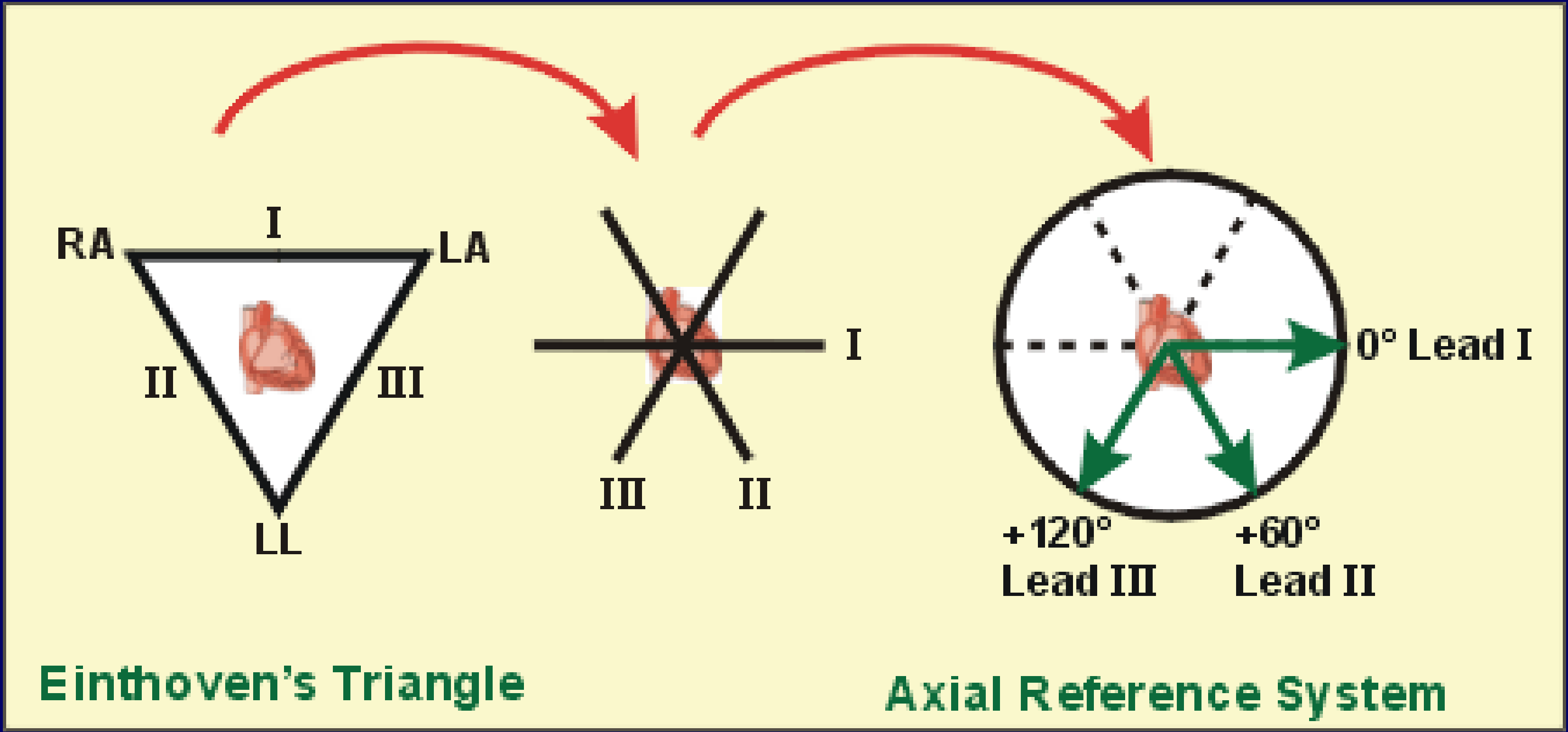
ECG Leads



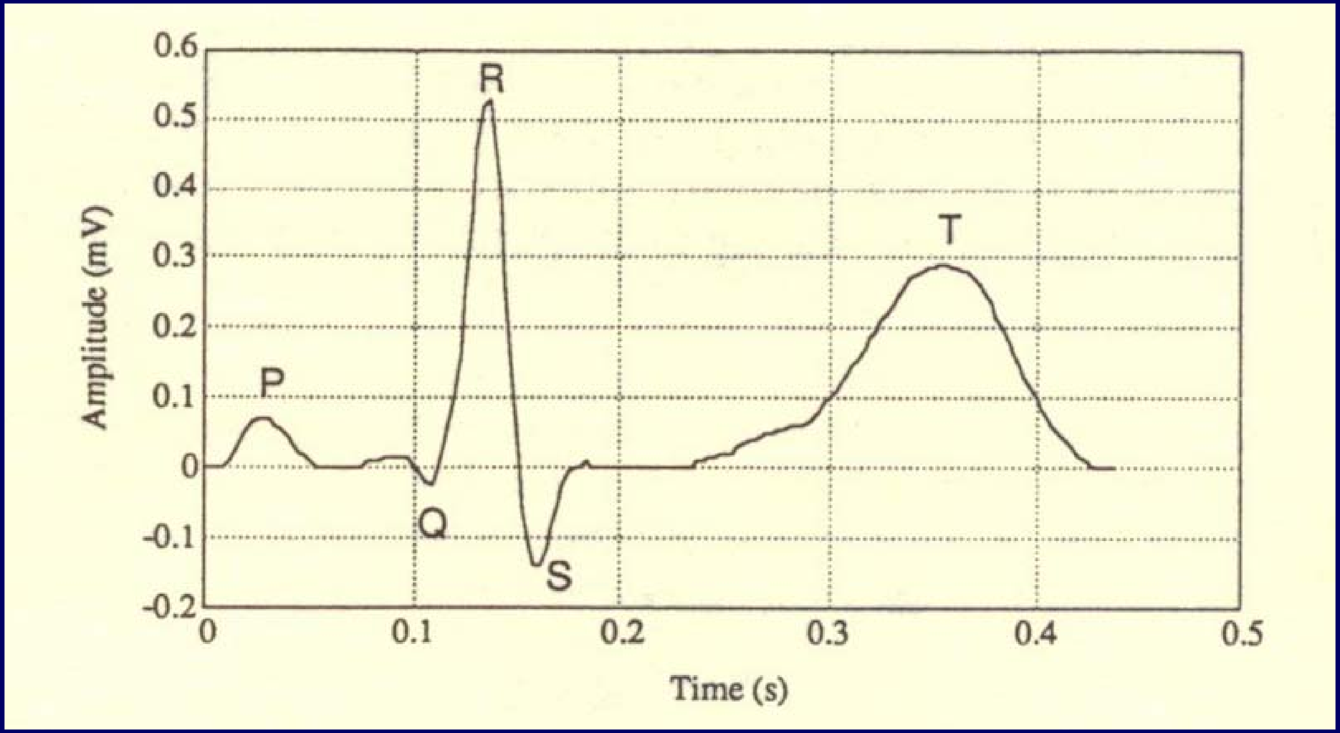
The Standard Limb Leads
Standardization
1mV
0.1mV
.04
.20
← 1 second →
Right Arm
Left Arm
Left Leg
RA
LA
LL
Lead I
Lead II
Lead III
+aVR-
-aVL+
+aVF-
-150°
-30°
90°
-120°
-90°
-60°
180°
0°
150°
30°
120°
60°
P
Q
R
T
Bipolar limb leads
Augmented unipolar limb leads



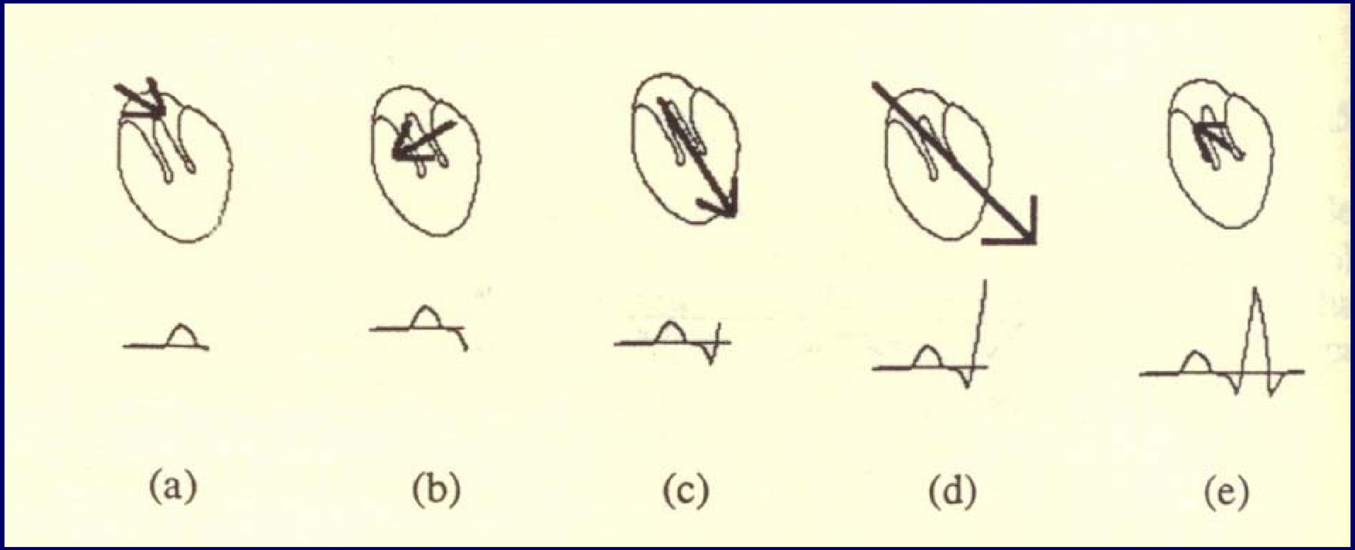
3
4
2
5
1
8
6
7



RA
I
LA
II
III
LL
I
III
II
0° Lead I
+120°
Lead III
+60°
Lead II
Einthoven's Triangle
Axial Reference System

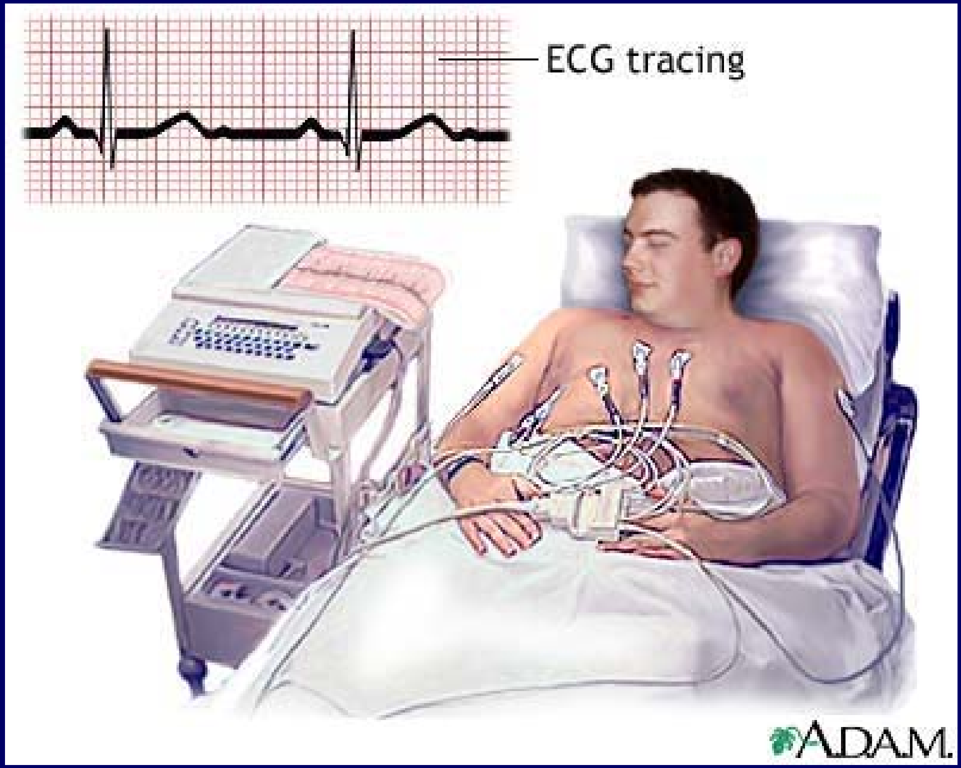


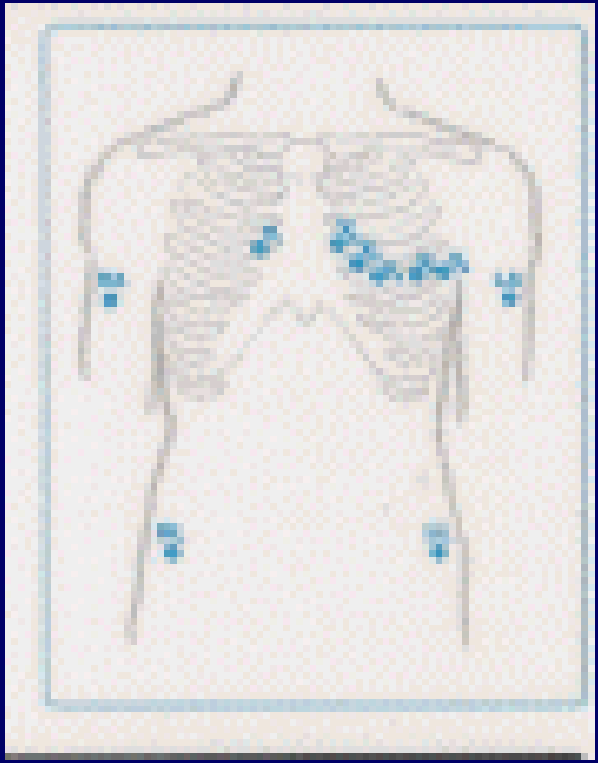
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Amplitude (mV)
P
Q
R
S
T
0
0.1
0.2
0.3
0.4
0.5
Time (s)



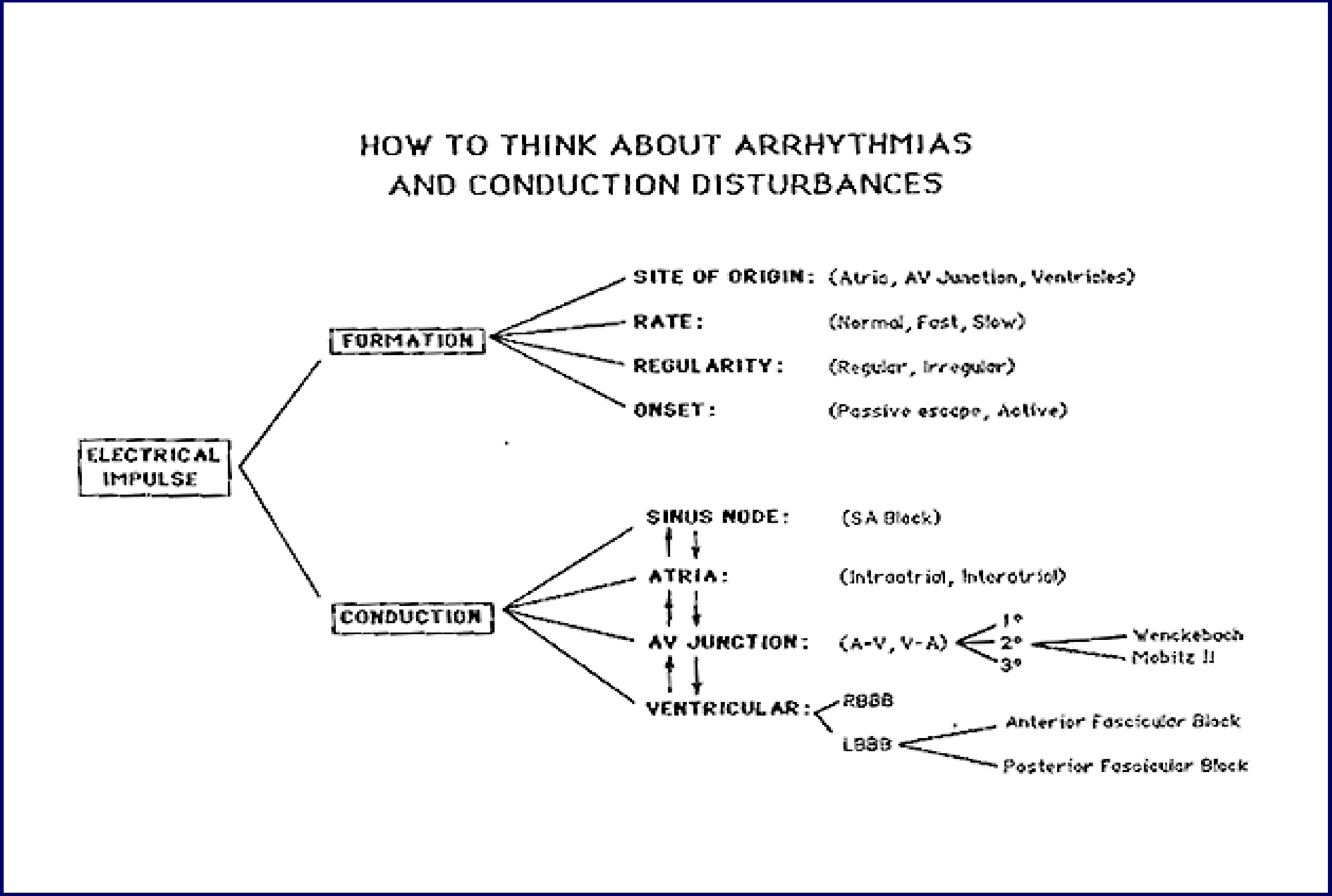
(a)
(b)
(c)
(d)
(e)

ECG Leads

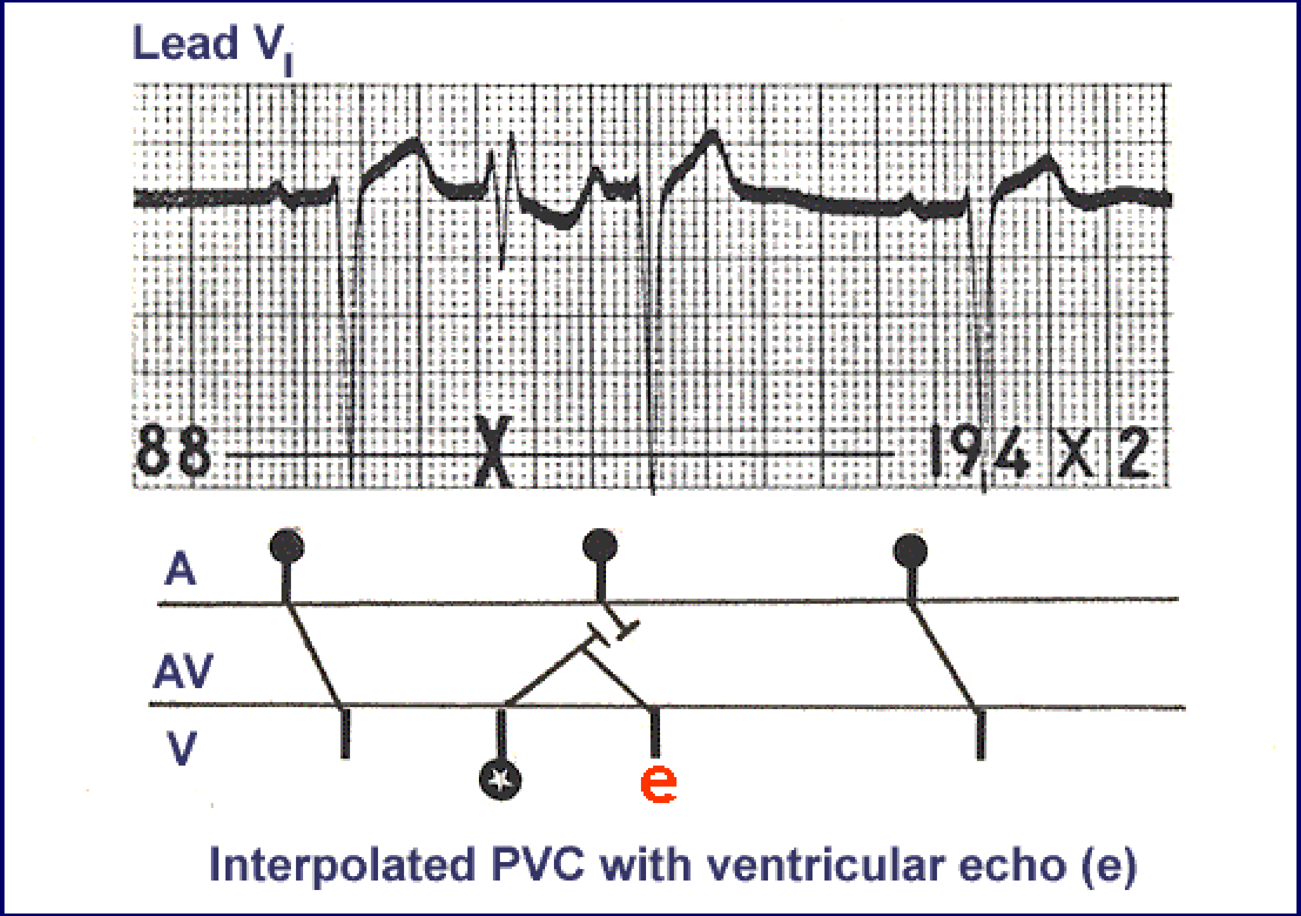




ECG Diagnosis

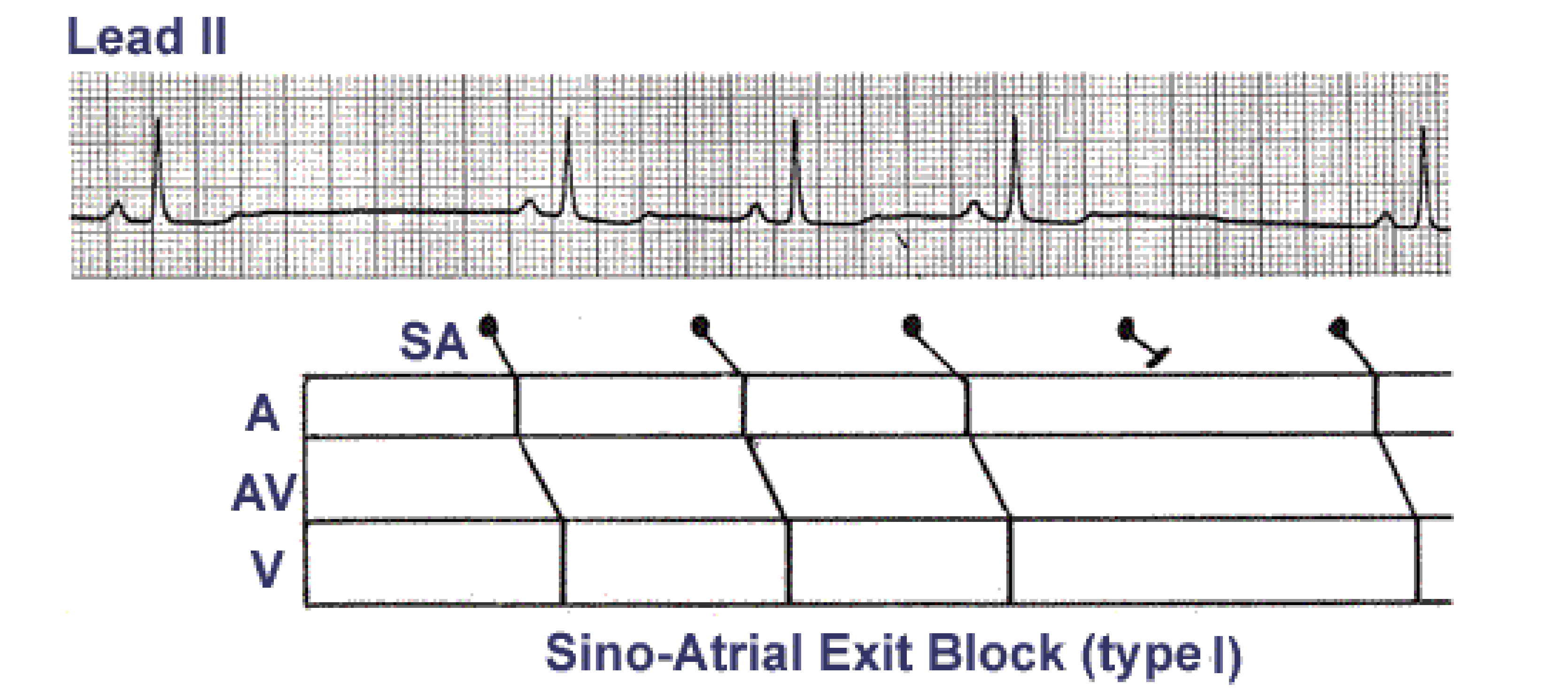


ECG Diagnosis



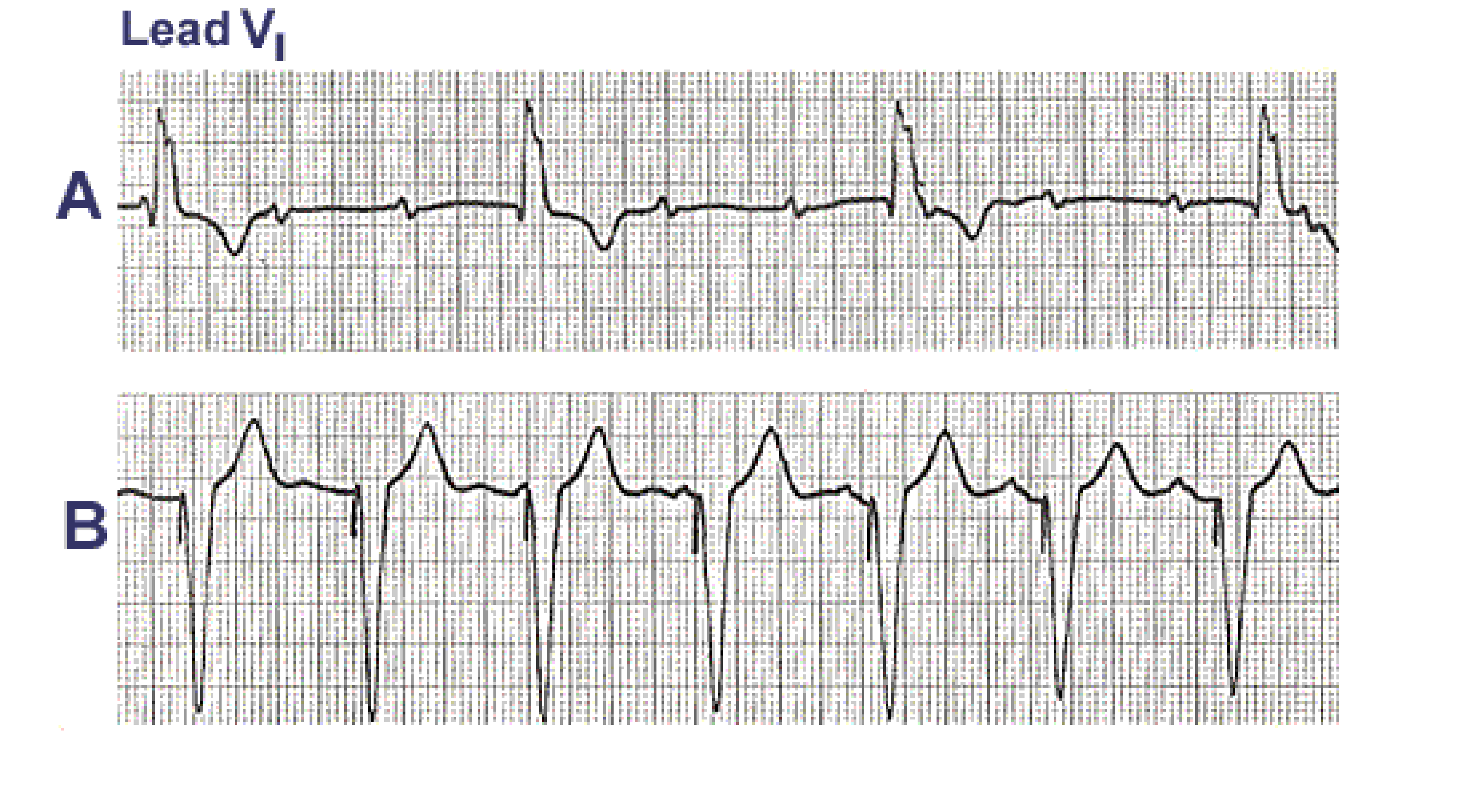
PVC with echo

ECG Diagnosis



Conduction: SA Block (Type I)

ECG Diagnosis



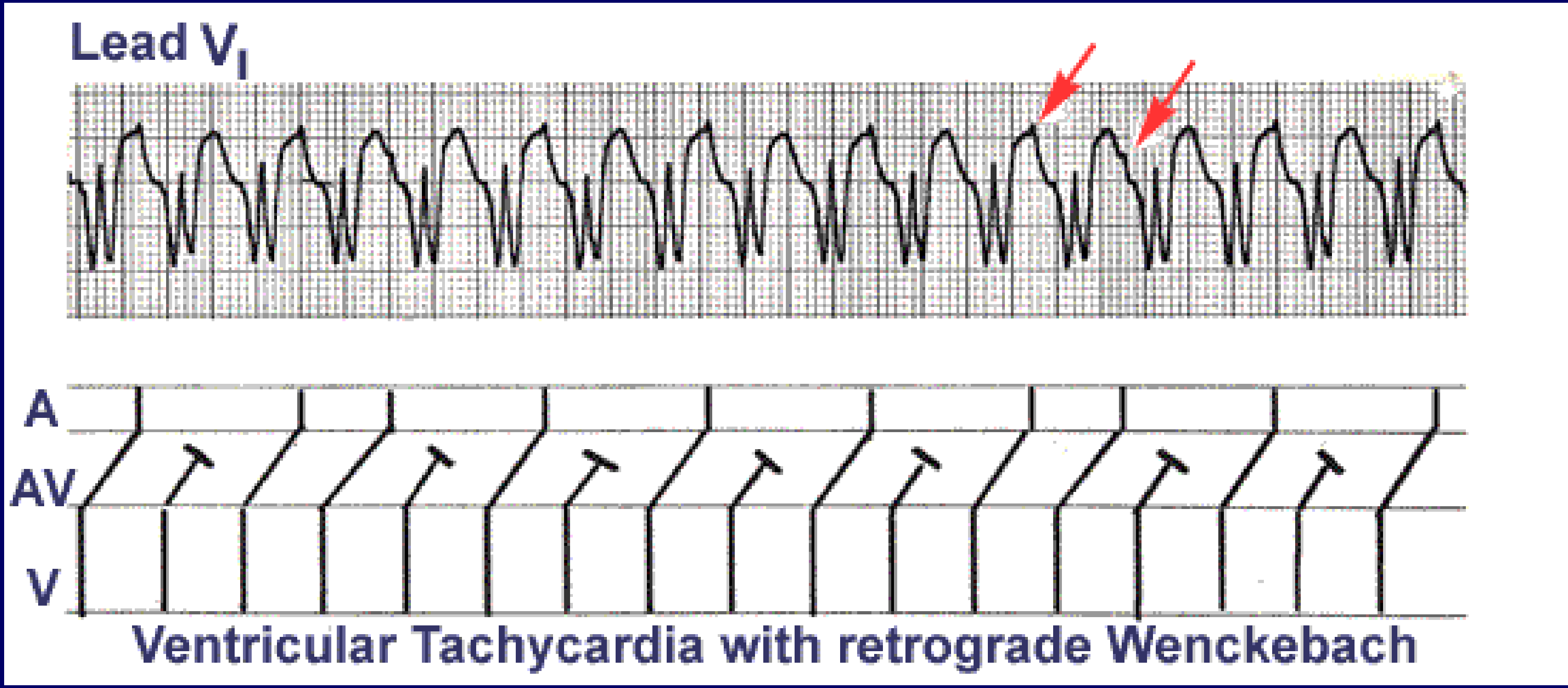
Conduction: Complete AV Block

ECG Diagnosis

Atrial tachycardia with variable AV block

Rate: Atrial Tachycardia (160 bpm)

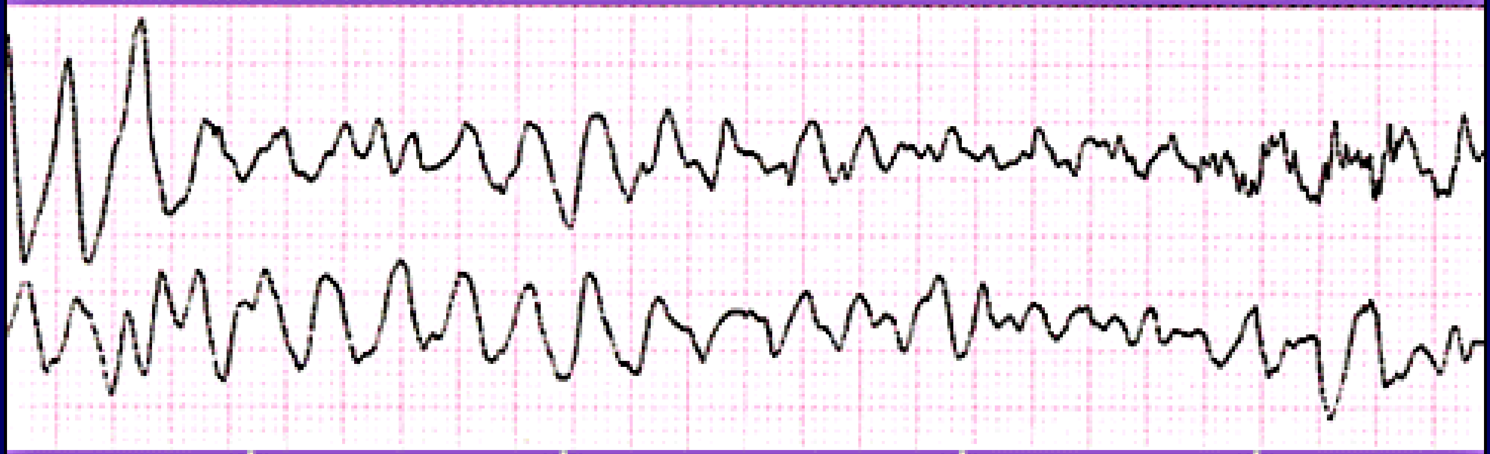
ECG Diagnosis



Rate: Ventricular Tachycardia

ECG Diagnosis

Ventricular Fibrillation

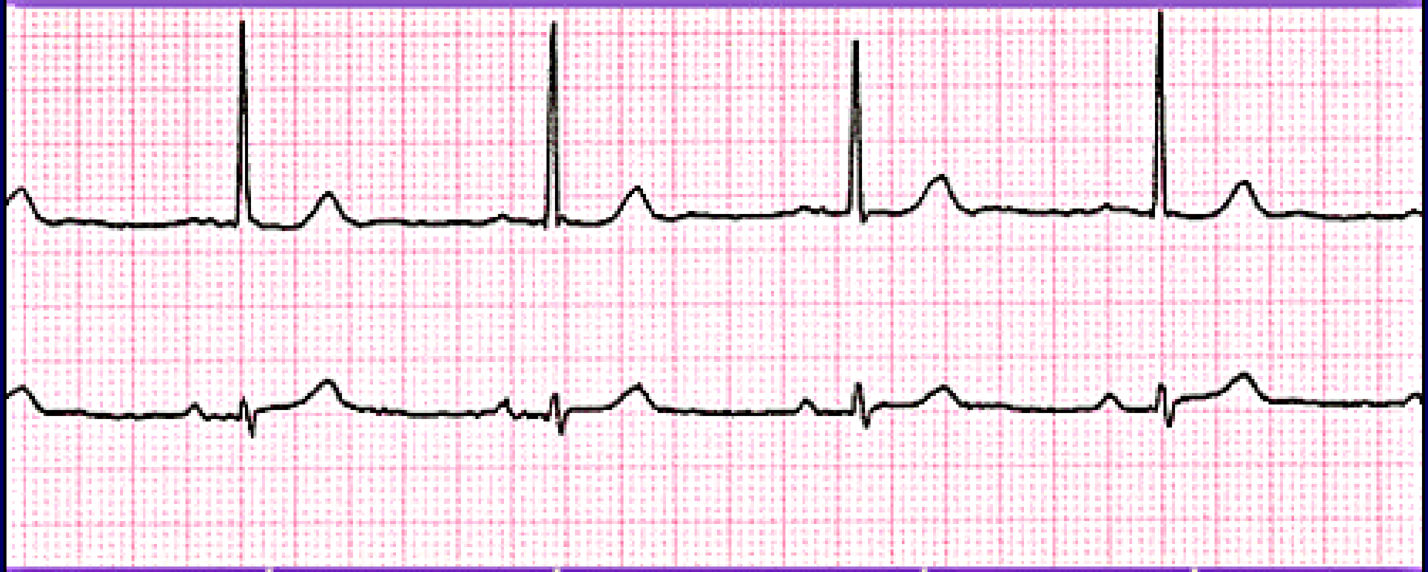


Heart Rate	Rhythm	P Wave	PR interval (in seconds)	QRS (in seconds)
300-600	Extremely irregular	Absent	N/A	Fibrillatory baseline

Rate: Ventricular Fibrillation

ECG Diagnosis

Sinus Bradycardia

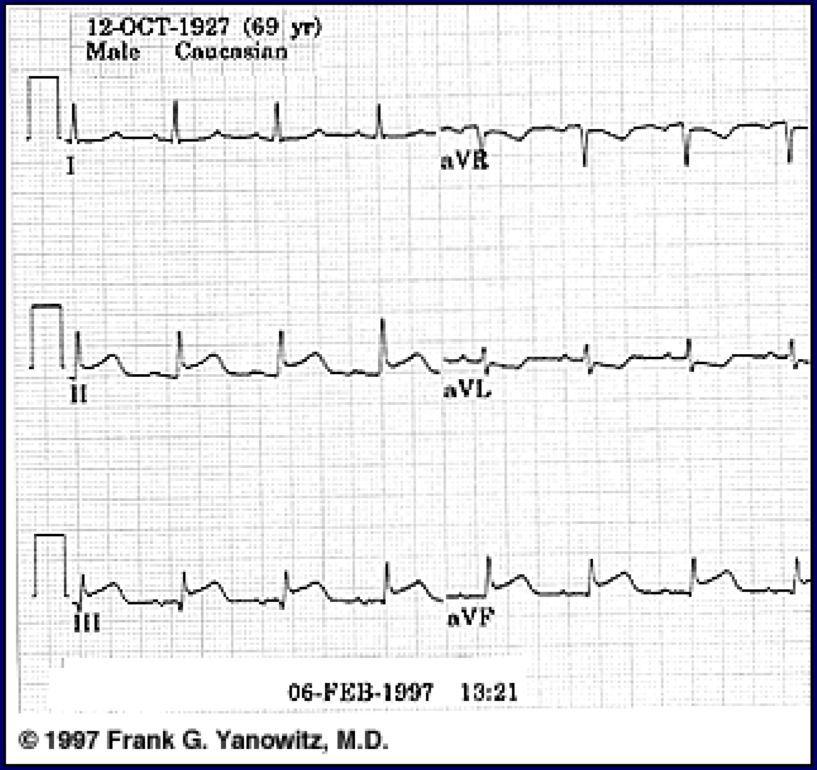


Heart Rate	Rhythm	P Wave	PR interval (in seconds)	QRS (in seconds)
<60 bpm	Regular	Before each QRS, identical	.12 to .20	<.12

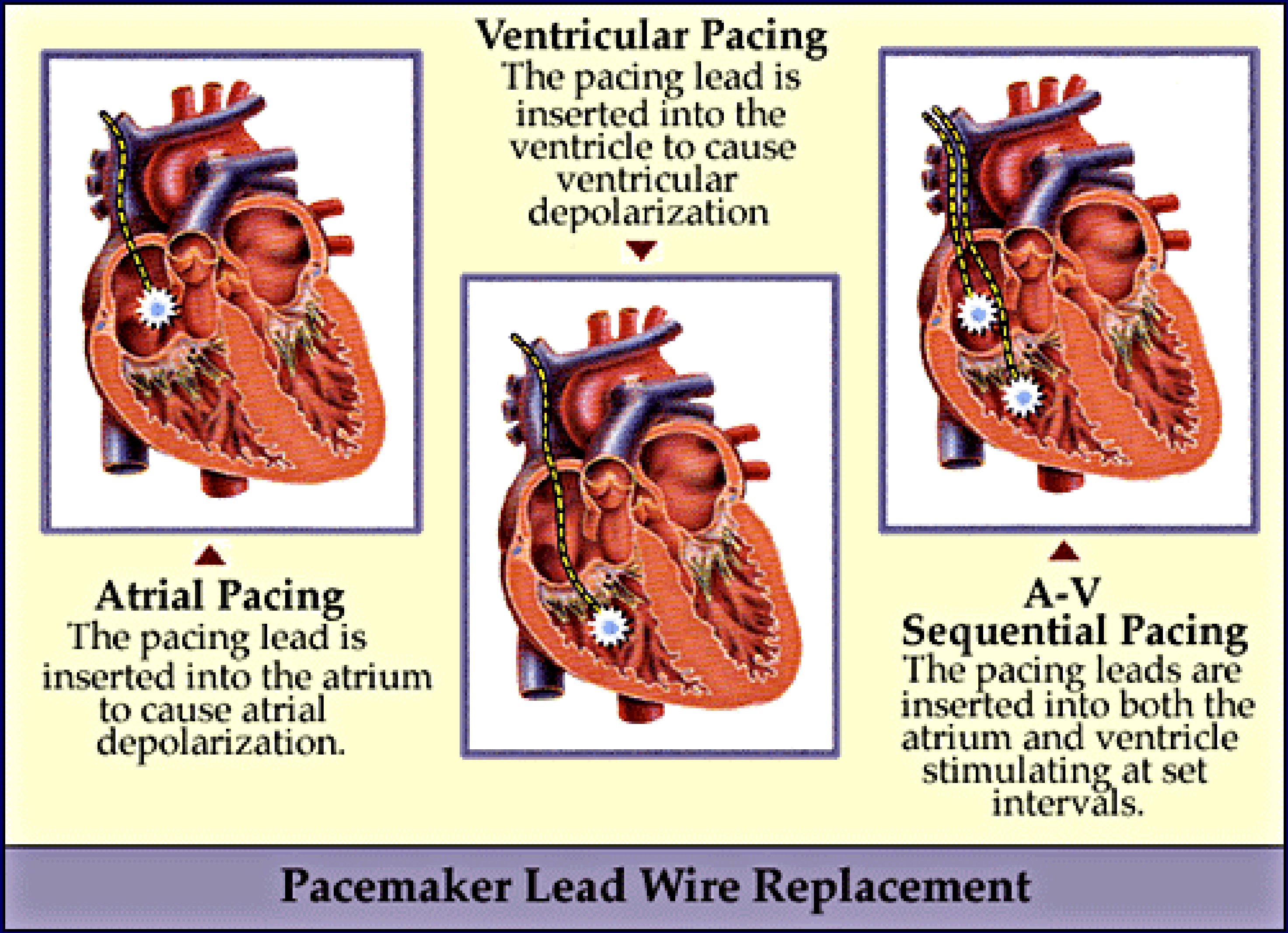
Rate: Sinus Bradycardia

ECG Diagnosis

- Other abnormalities:
  - Myocardial infarction
  - Atrial/Ventricular enlargement
  - ST segment elevation
  - ……



Pace Makers



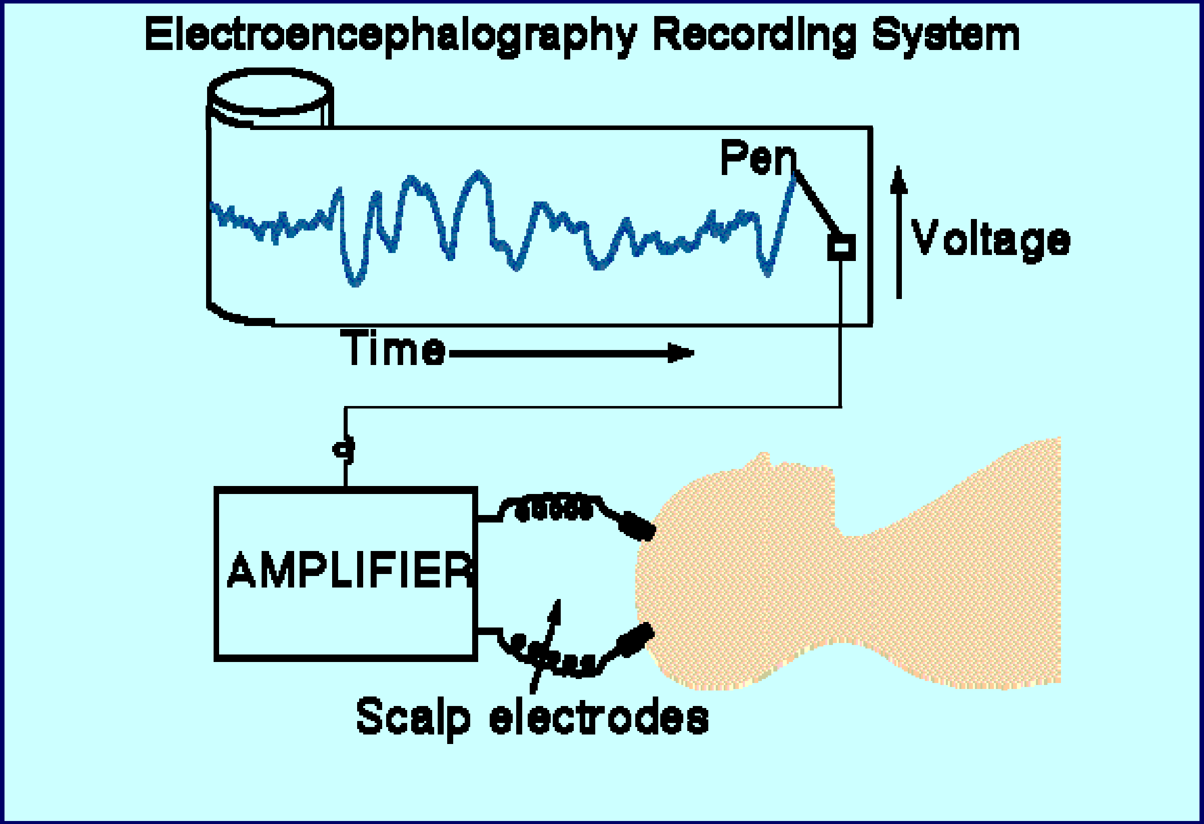
Ventricular Pacing
The pacing lead is inserted into the ventricle to cause ventricular depolarization
Atrial Pacing
The pacing lead is inserted into the atrium to cause atrial depolarization.
A-V Sequential Pacing
The pacing leads are inserted into both the atrium and ventricle stimulating at set intervals.
Pacemaker Lead Wire Replacement

Electroencephalogram (EEG)

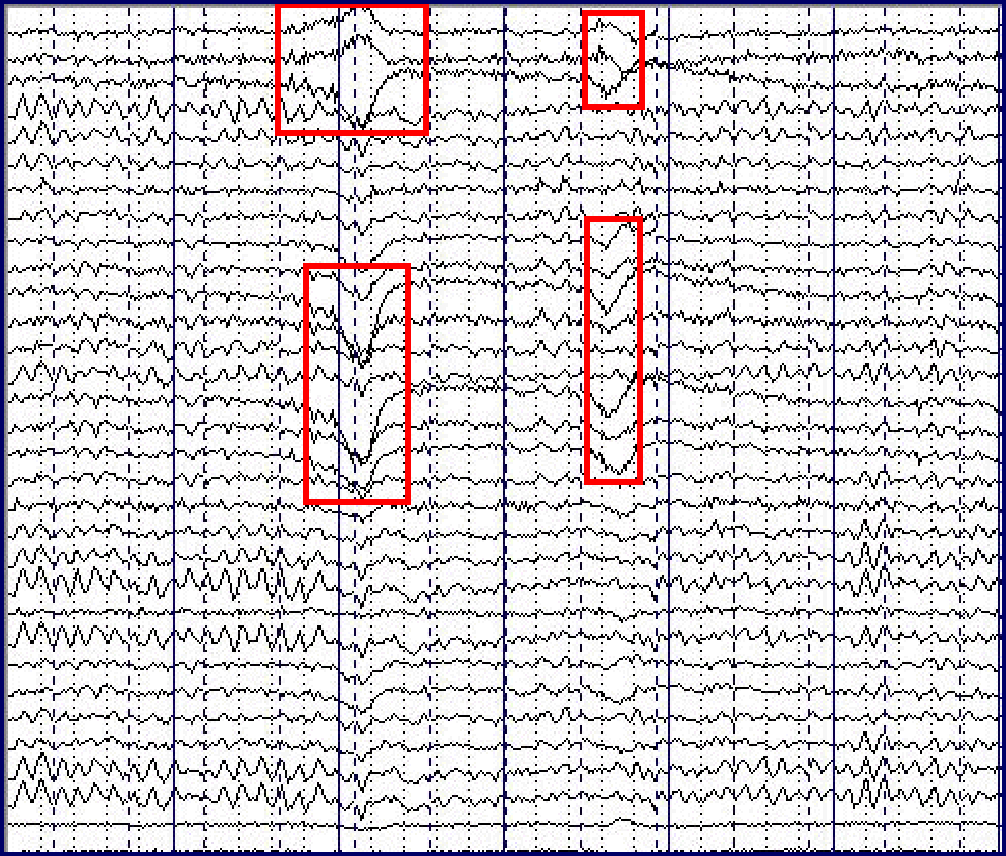
EEG

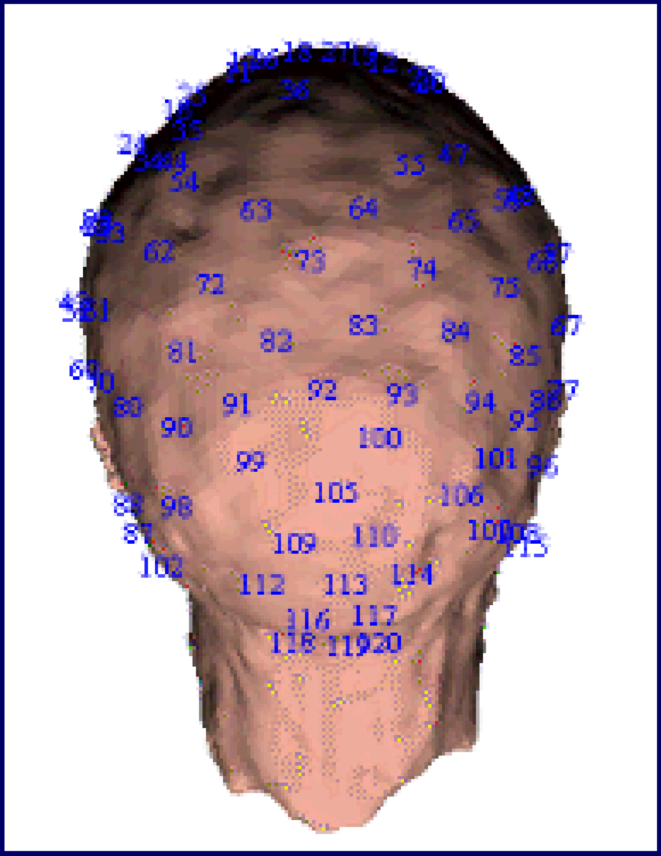
- Electrical potential fluctuations of the brain.
- Under normal circumstances, action potentials in axons are asynchronous.
- If simultaneous stimulation, projection of action potentials are detectable.
- The analysis is based more on frequency than morphology.

EEG: Instrument

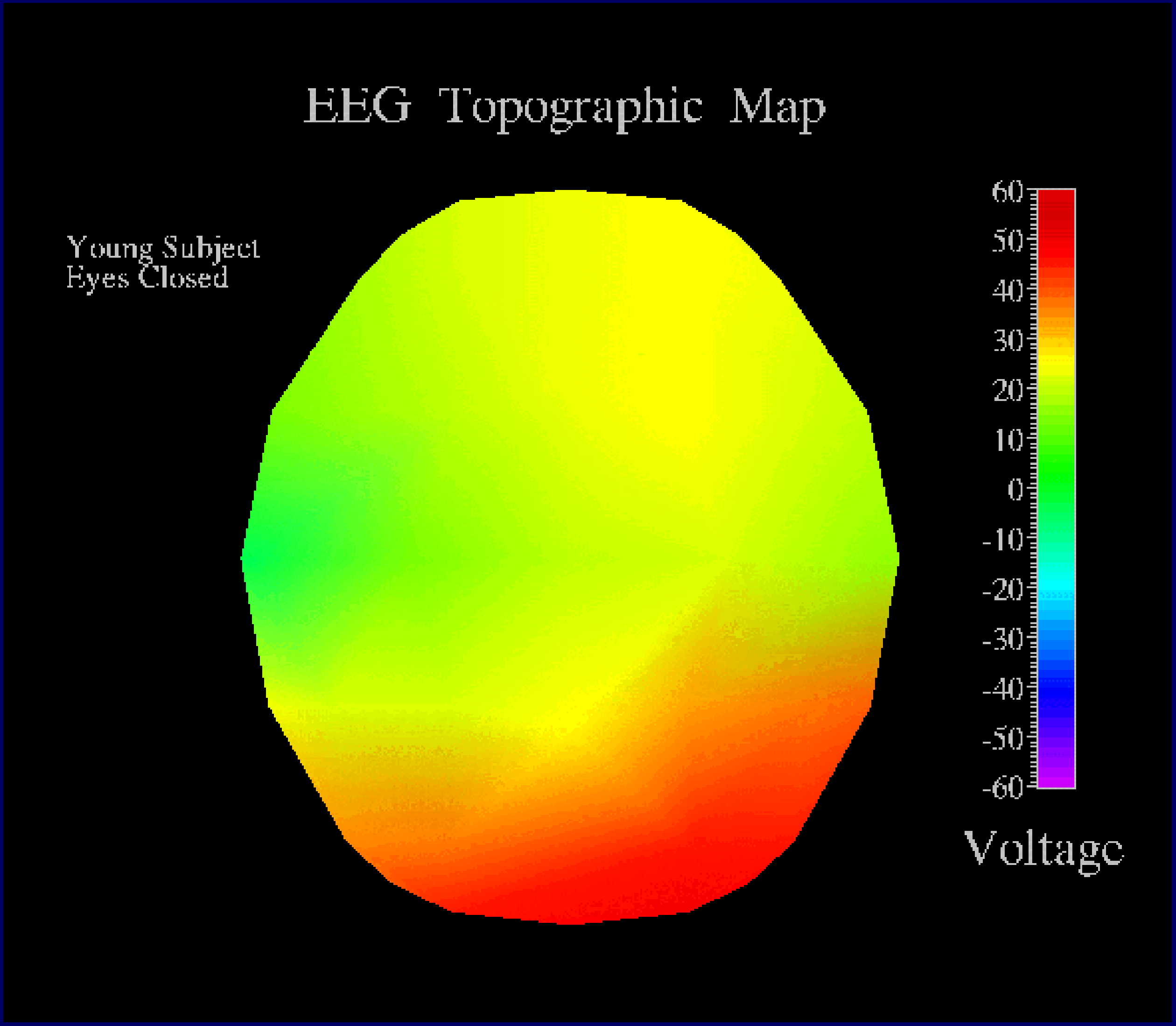


EEG: Spatial and Temporal Characteristics

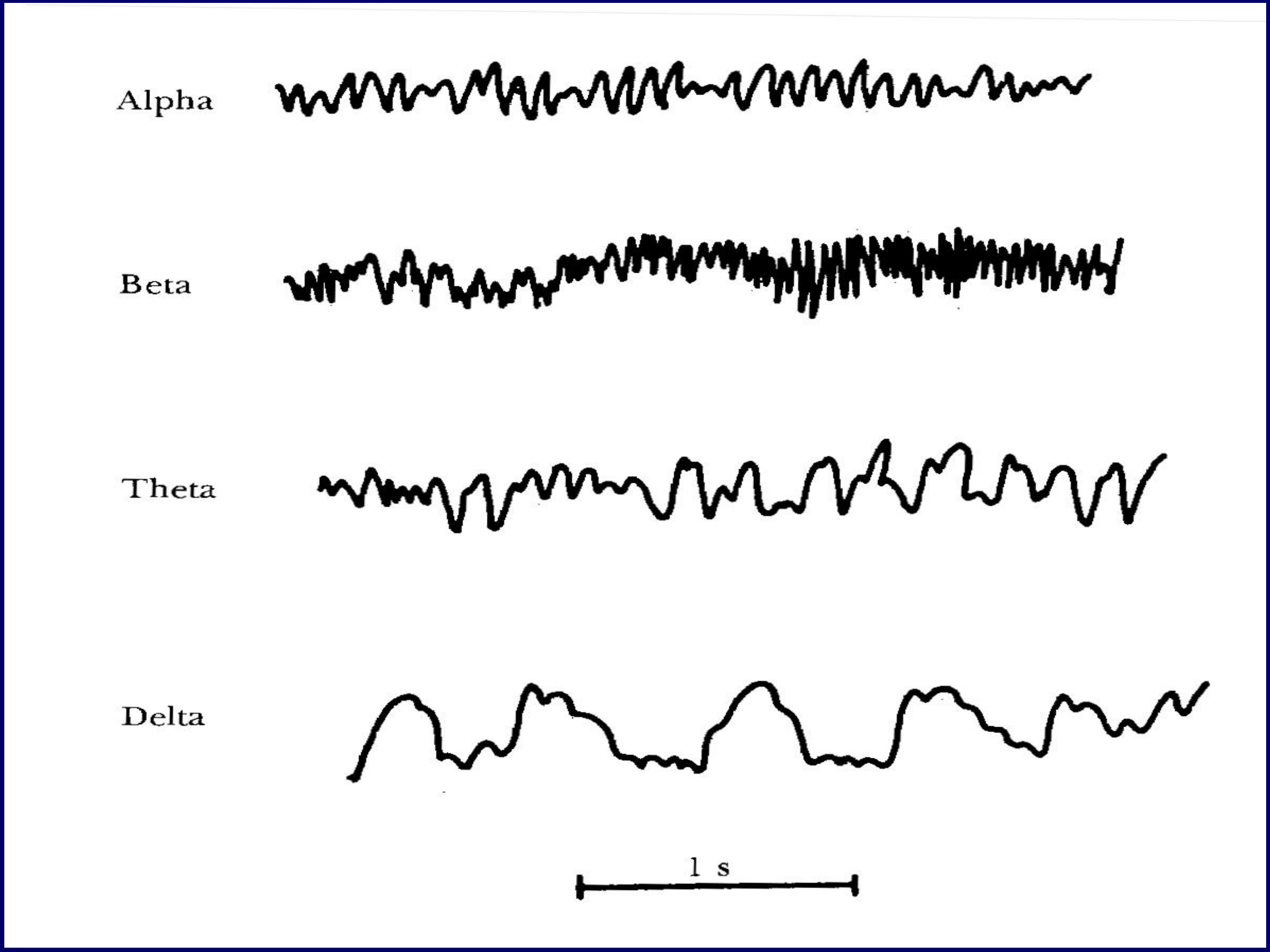




EEG: Presentation



EEG Classification



EEG Classification

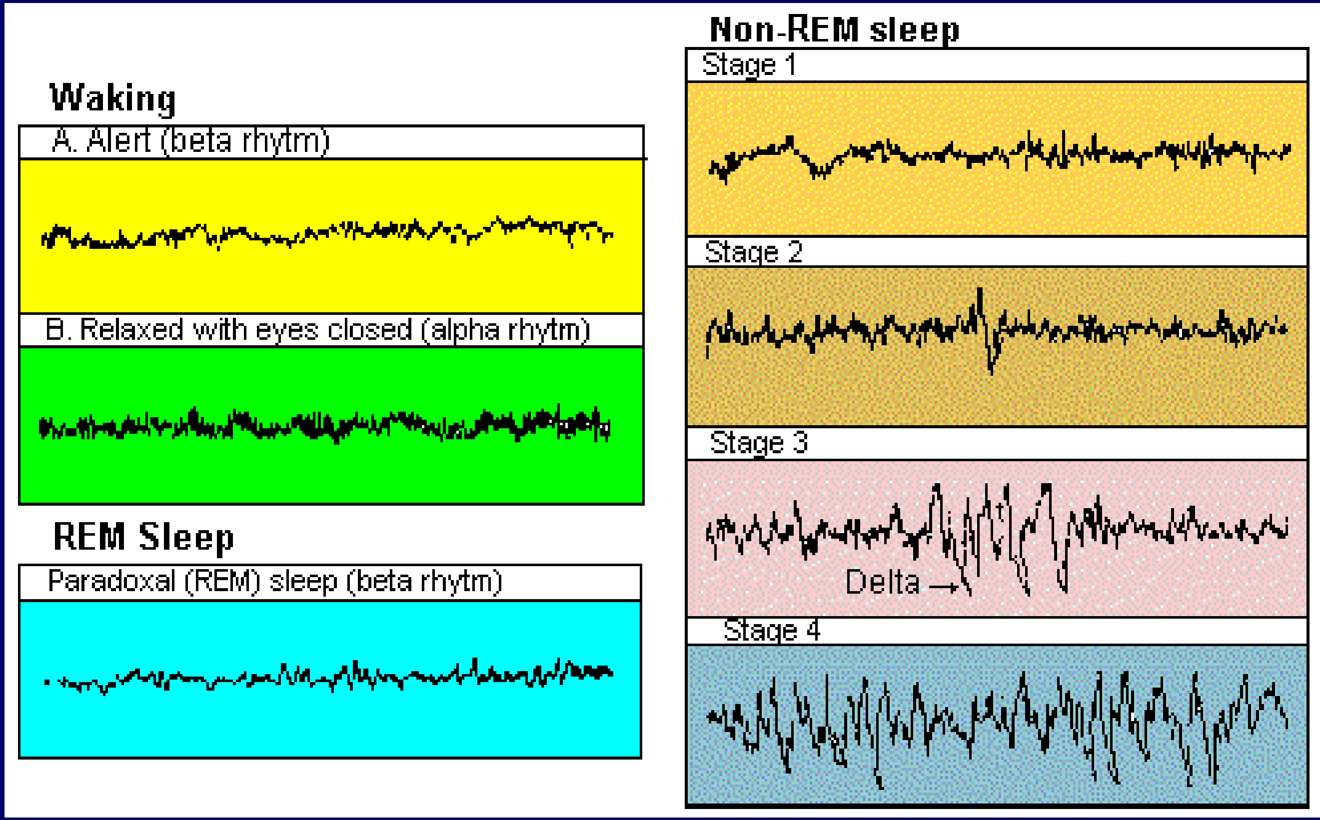
- Alpha:
  - 8 to 13Hz.
  - Normal persons are awake in a resting state.
  - Alpha waves disappear in sleep.
- Beta:
  - 14 to 30Hz.
  - May go up to 50Hz in intense mental activity.
  - Beta I waves: frequency about twice that of the alpha waves and are influenced in a similar way as the alpha waves.
  - Beta II waves appear during intense activation of the central nervous system and during tension.

EEG Classification

- Theta waves:
  - 4 to 7Hz.
  - During emotional stress.
- Delta waves
  - Below 3.5Hz.
  - Deep sleep or in serious organic brain disease.

EEG Applications

- Epilepsy.
- Dream:



Other Biomedical Signals

- Electrical:
  - Electroneurogram (ENG)
  - Electromyogram (EMG)
  - Electroretinogram (ERG)
  - Electrogastrogram (EGG).

Other Non-Electrical Biomedical Signals

- Circulatory system
  - Blood pressure
  - Heart sound
  - Blood flow velocity
  - Blood flow volume

Other Non-Electrical Biomedical Signals

- Respiratory system
  - Respiratory pressure
  - Gas-flow rate
  - Lung volume
  - Gas concentration

Applications of Signal Processing Techniques

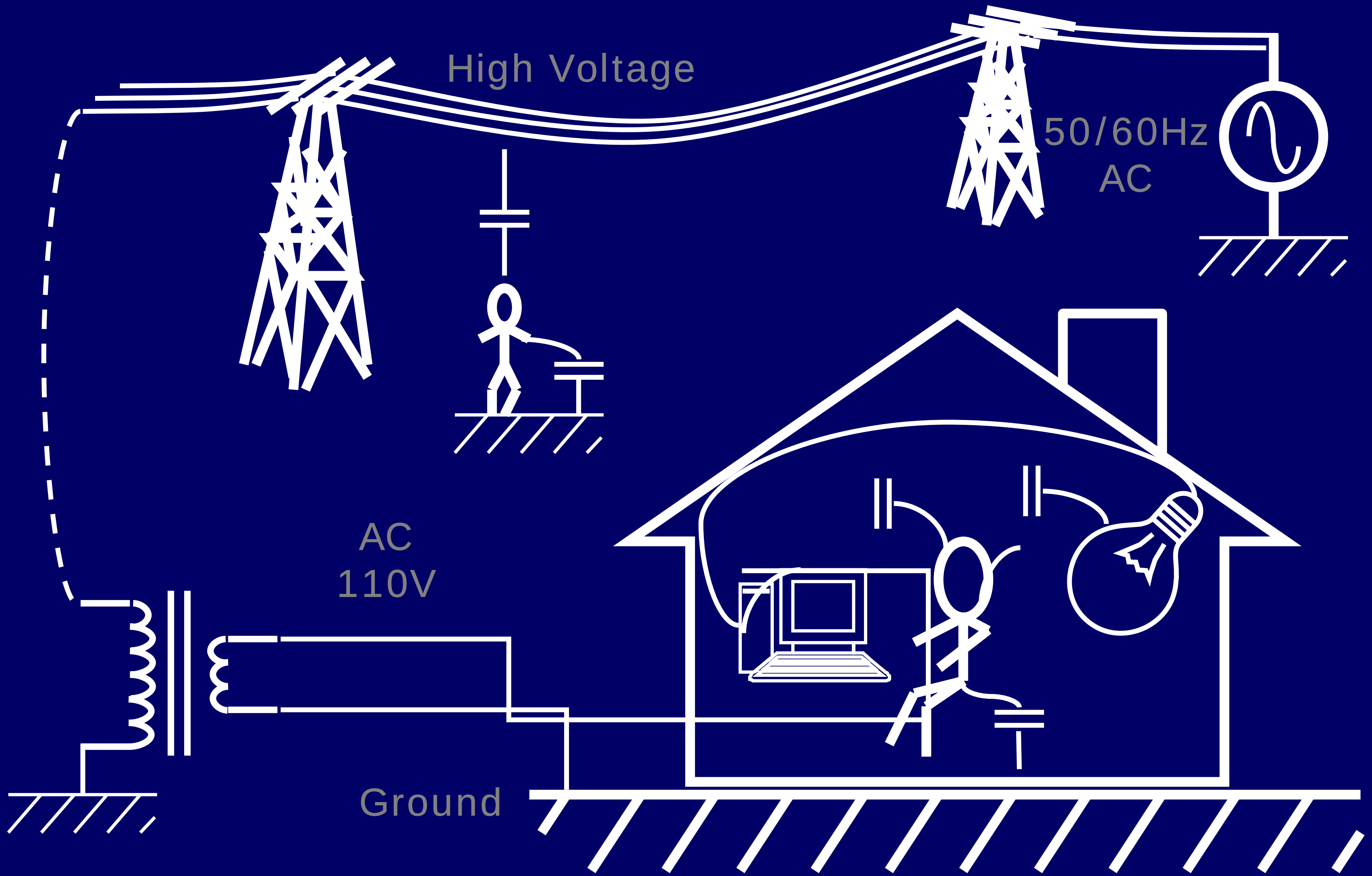
Sampling

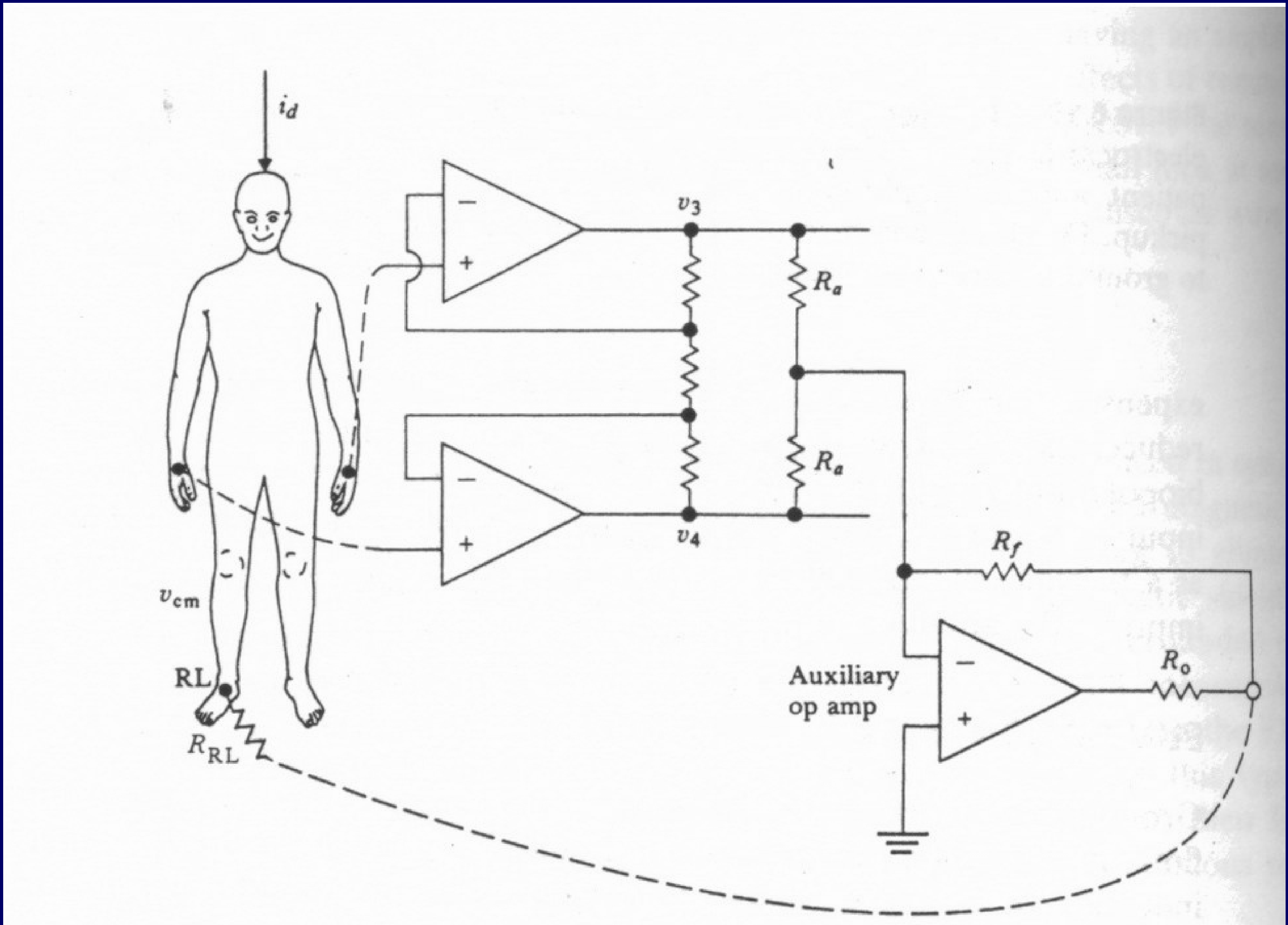
- Digital analysis and presentation of biomedical signals.
- Sampling requirements.
  - Low frequencies.
  - Frequency ranges of different physiological signals may be overlapping.
  - Electronic noise and interference from other physiological signals.
  - Very weak (maybe μV level), the pre-amp circuit is often very challenging.

Filtering

- Digital filters are used to keep the in-band signals and to reject out-of-band noise.
- Low-pass, band-pass, high-pass and band-reject.
- Similar to those of other applications.

Noise Sources of ECG


High Voltage
50/60Hz
AC
AC
110V
Ground

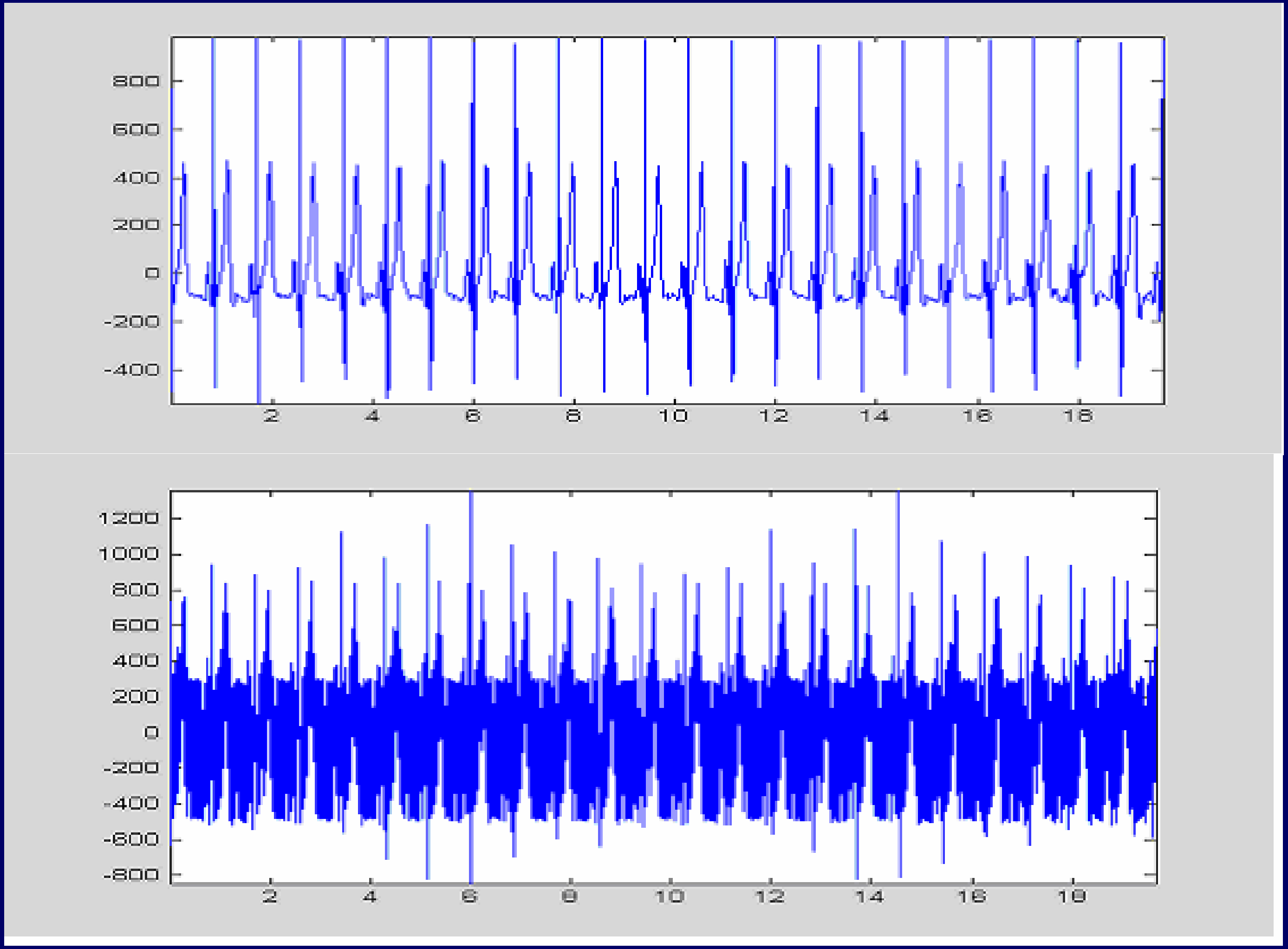


i_d
v_3
R_a
R_a
v_4
R_f
v_{cm}
RL
R_{RL}
Auxiliary
op amp
R_o

Noise Sources

- Inherent
- Instrumentation
- Environment
- From the body
- …

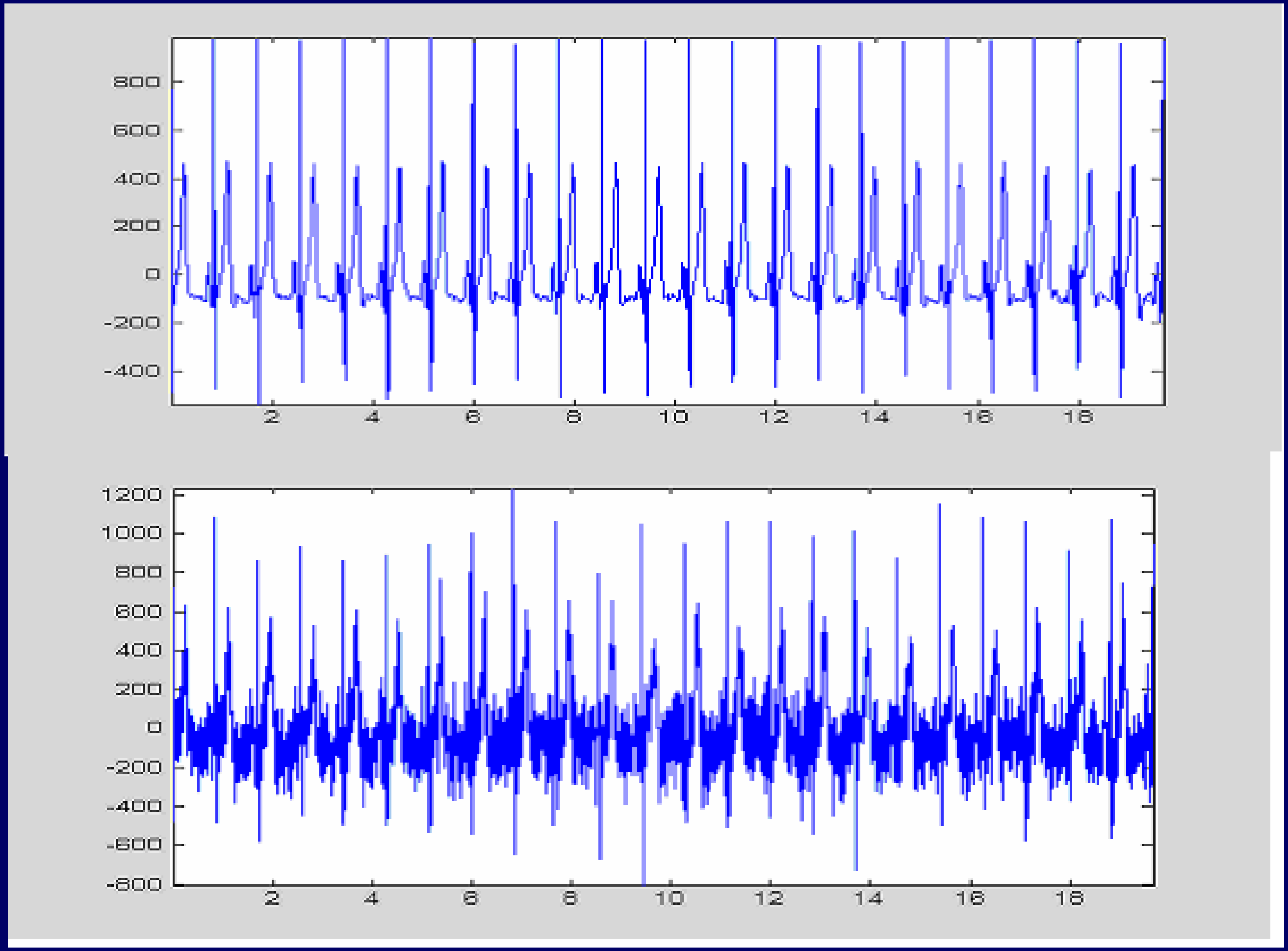
Ideal Signal Vs. Signal with Powerline Noise



Ideal Signal Vs. Signal with Powerline Noise

- Powerline interference consists of 60Hz tone with random initial phase.
- It can be modeled as sinusoids and its combinations.
- The characteristics of this noise are generally consistent for a given measurement situation and, once set, will not change during a detector evaluation. Its typical SNR is in the order of 3dB.

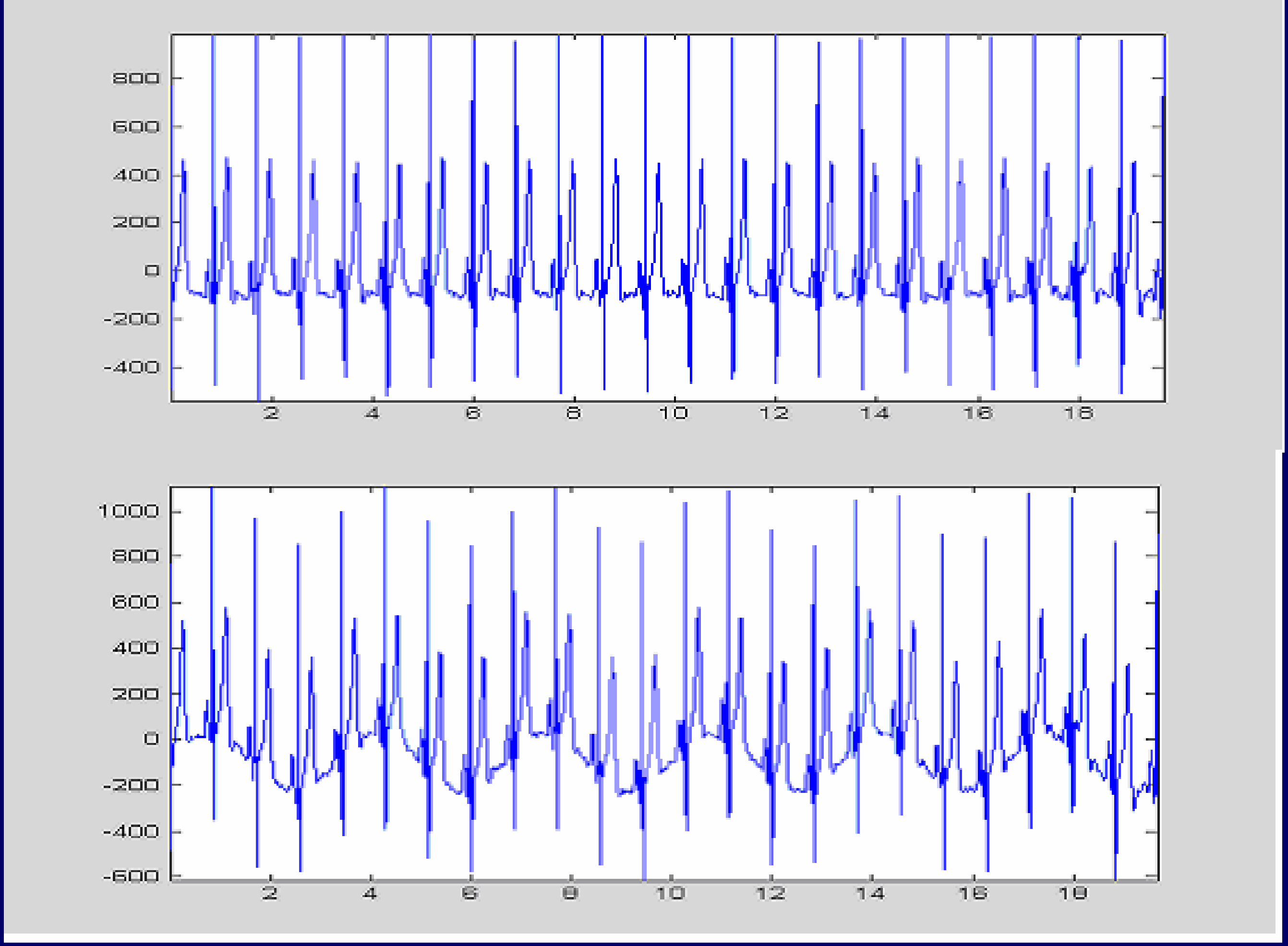
Ideal Signal Vs. Signal with Electromyographic Noise



Ideal Signal Vs. Signal with Electromyographic Noise

- EMG noise is caused by muscular contractions, which generate millivolt-level potentials.
- It is assumed to be zero mean Gaussian noise. The standard deviation determines the SNR, whose typical value is in the order of 18dB.

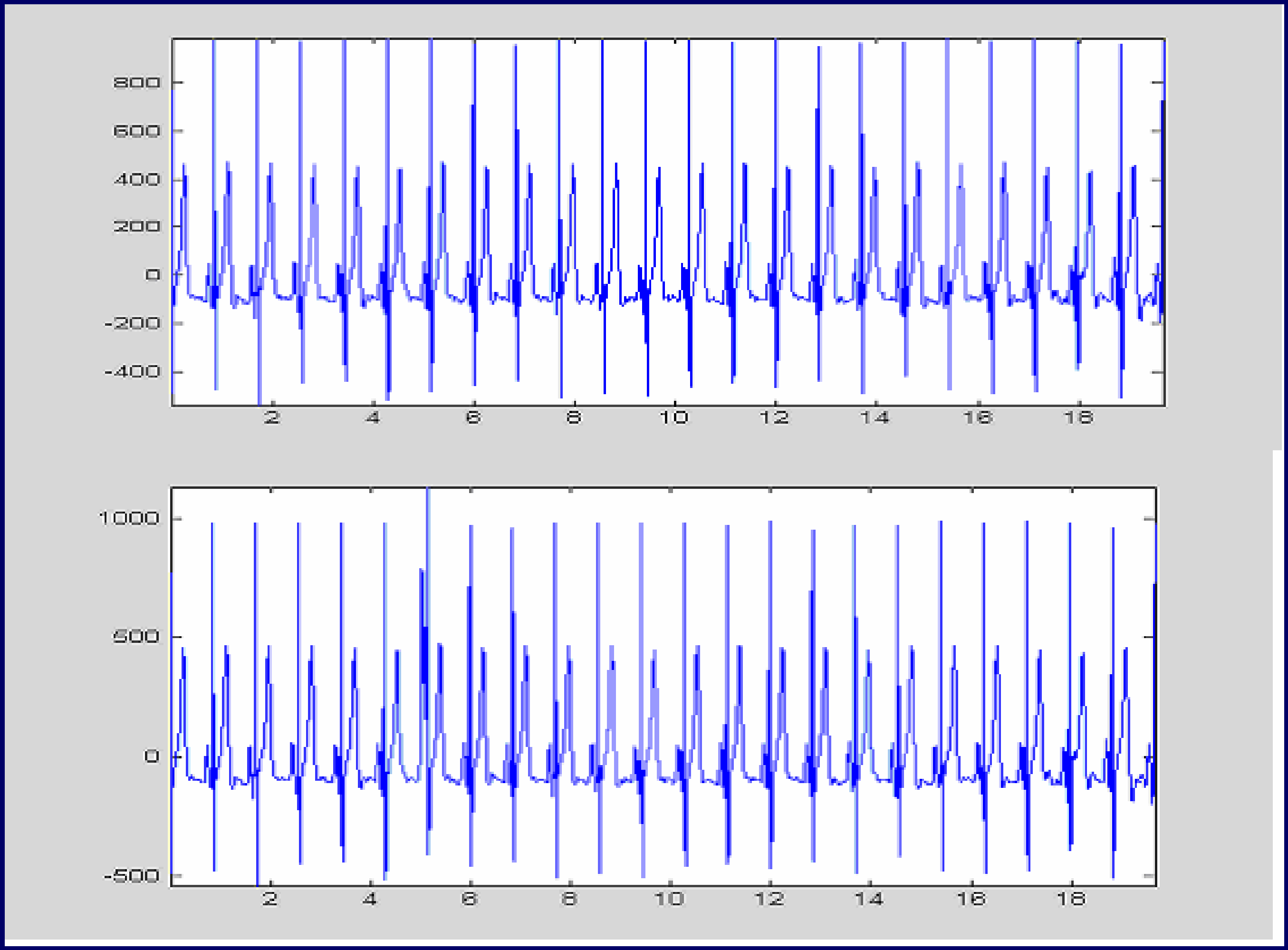
Ideal Signal Vs. Signal with Respirational Noise



Ideal Signal Vs. Signal with Respirational Noise

- Respiration noise considers both the sinusoidal drift of the baseline and the ECG sinusoidal amplitude modulation.
- The drift can be represented as a sinusoidal component at the frequency of respiration added to the ECG signal.
- The amplitude variation is about 15 percent of peak-to-peak ECG amplitude. It is simulated with a sinusoid of 0.3Hz frequency with typical SNR 32dB.
- The modulation is another choice of representing respiration noise. It can be simulated with 0.3Hz sinusoid of 12dB SNR.

Ideal Signal Vs. Signal with Motion Artifacts



Ideal Signal Vs. Signal with Motion Artifacts

- Motion artifact is caused by displacements between electrodes and skin due to patients' slow movement.
- It is simulated with an exponential function that decays with time.
- Typically the duration is 0.16 second and the amplitude is almost as large as the peak-to-peak amplitude.
- The phase is random with a uniform distribution.

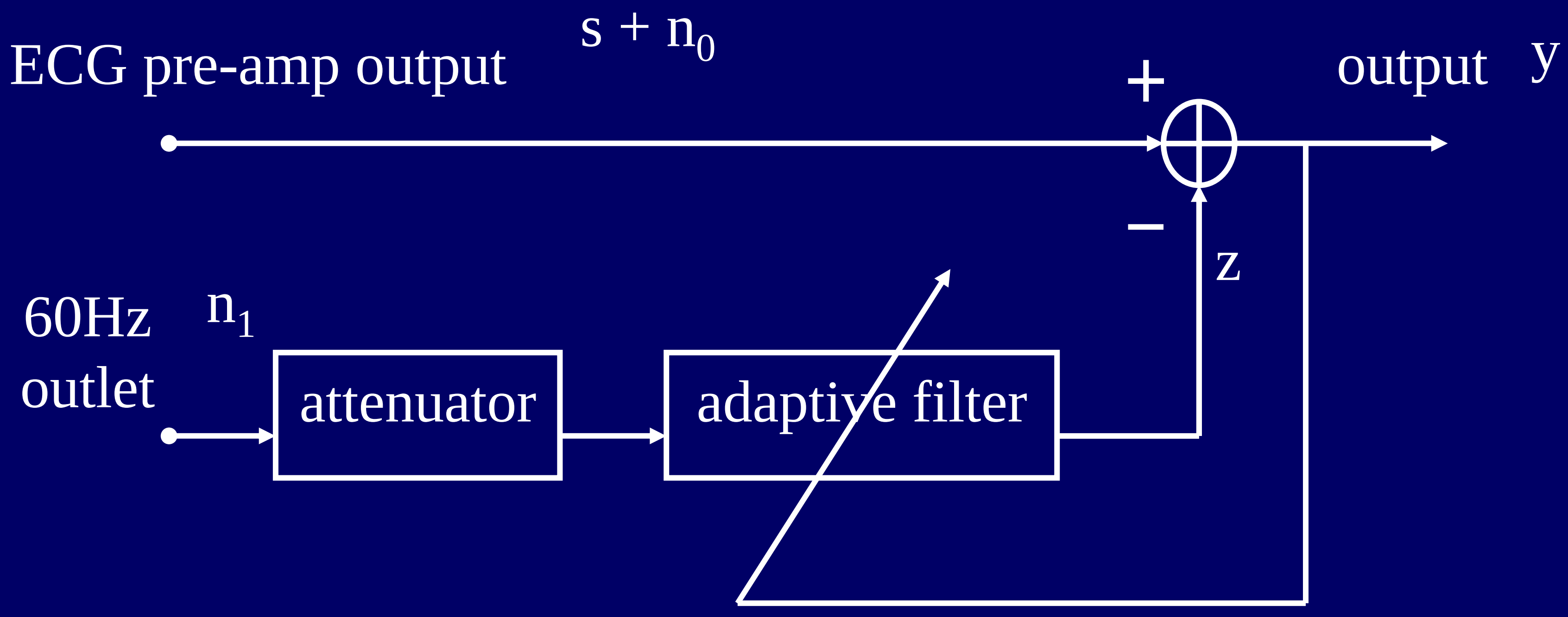
Noise Removal

- The four types of noises are mostly sinusoidal or Gaussian. The sinusoidal noises are usually removed with a notch filter. Other distortions are zeroed out using the moving average.

Adaptive Noise Cancellation

- Noise from power line (60Hz noise).
- The noise is also in the desired frequency range of several biomedical signals (e.g., ECG), notch filter is required.
- Adaptive filtering: The amplitude and exact frequency of the noise may change.

Adaptive Filter



Adaptive Filter

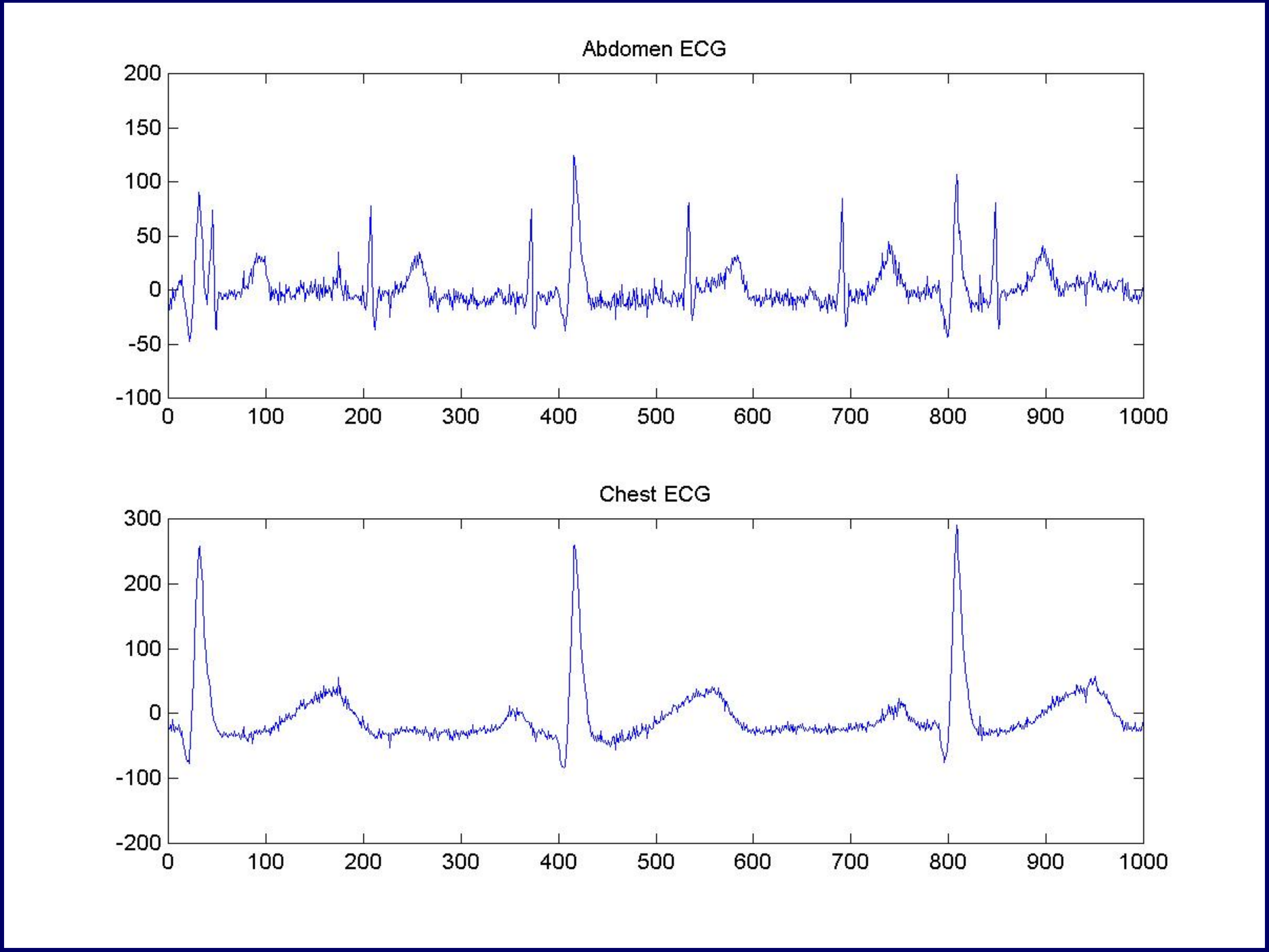
$$y(nT) = s(nT) + n_0(nT) - z(nT)$$

$$y^2 = s^2 + (n_0 - z)^2 + 2s(n_0 - z)$$

$$E[y^2] = E[s^2] + E[(n_0 - z)^2] + 2E[s(n_0 - z)] = E[s^2] + E[(n_0 - z)^2]$$

$$\min E[y^2] = E[s^2] + \min E[(n_0 - z)^2]$$

Adaptive Filtering for Fetal ECG



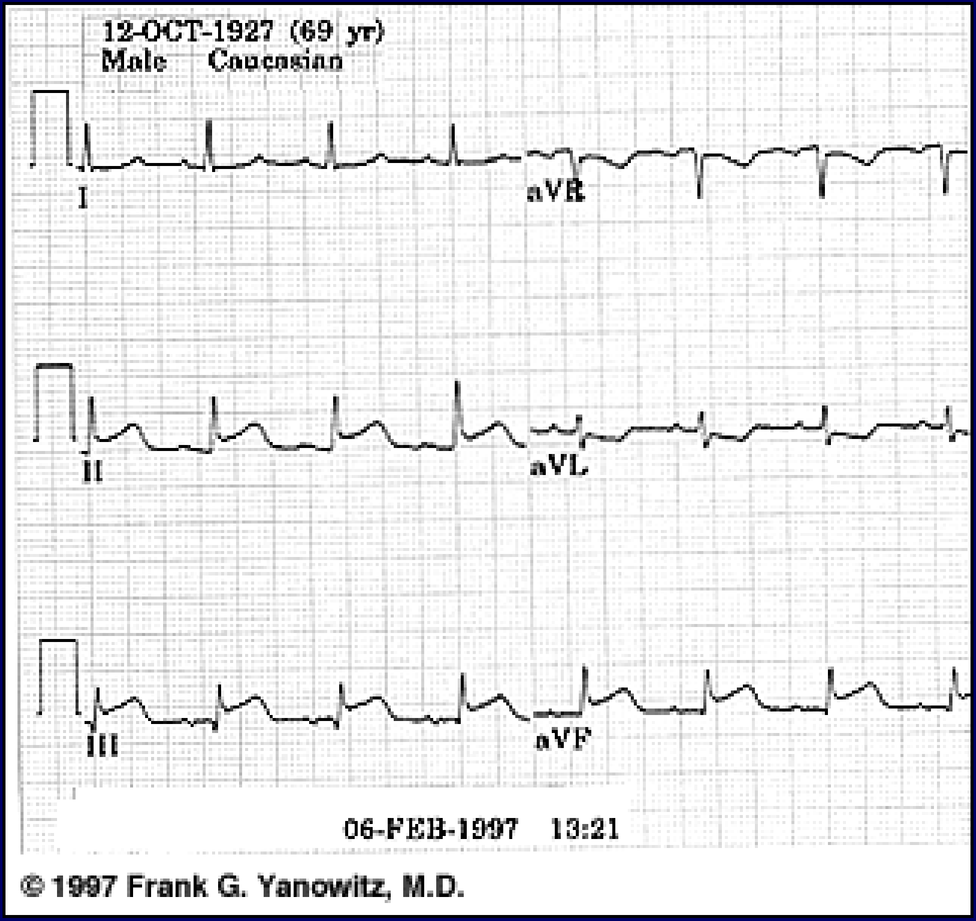
Pattern Recognition

- Abnormal physiological signals vs. the normal counterparts.
- An average of several known normal waveforms can be used as a template.
- The new waveforms are detected, segmented and compared to the template.
- Correlation coefficient can be used to quantify the similarity.

$$\rho = \frac{\sum_{i=1}^{N}(T_i - \mu_T)(X_i - \mu_X)}{\sqrt{\sum_{i=1}^{N}(T_i - \mu_T)^2}\sqrt{\sum_{i=1}^{N}(X_i - \mu_X)^2}}$$

Pattern Recognition

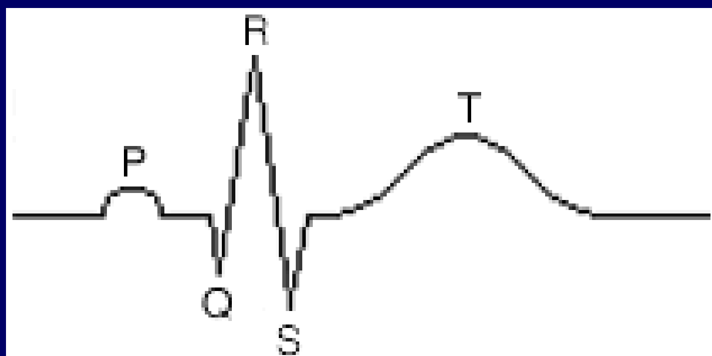
Ex. ECG



Data Compression

- For large amount of data (e.g., 24 hour ECG).
- Must not introduce distortion, which may lead to wrong diagnosis.
- Formal evaluation is necessary.

ECG Data Compression



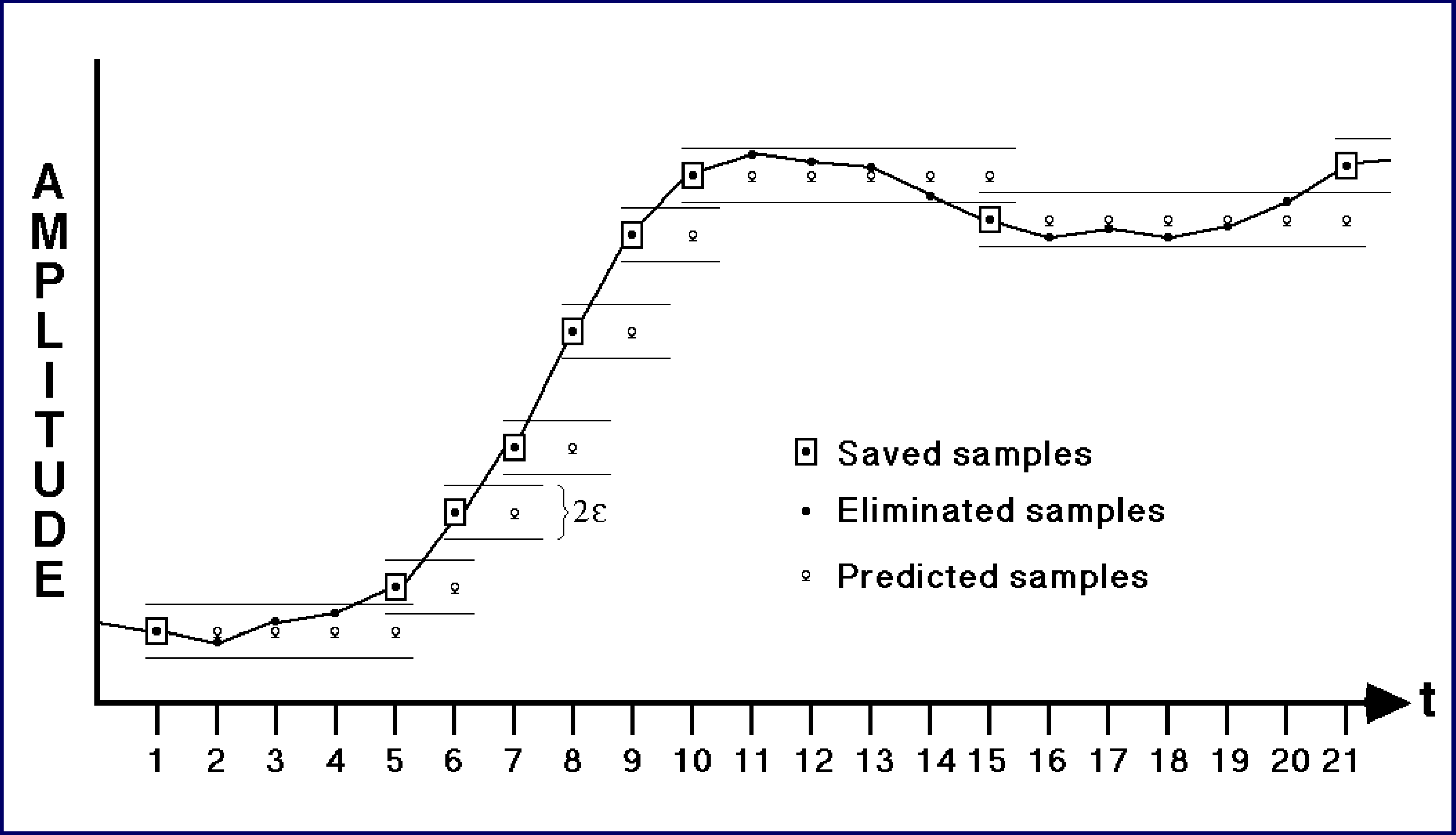
$$PRD = 100 \cdot \sqrt{\frac{\sum_{i=1}^{n}\left(ORG(i) - REC(i)\right)^2}{\sum_{i=1}^{n}(ORG(i))^2}}$$

WGAQQQQQQRBCCCCCHZY

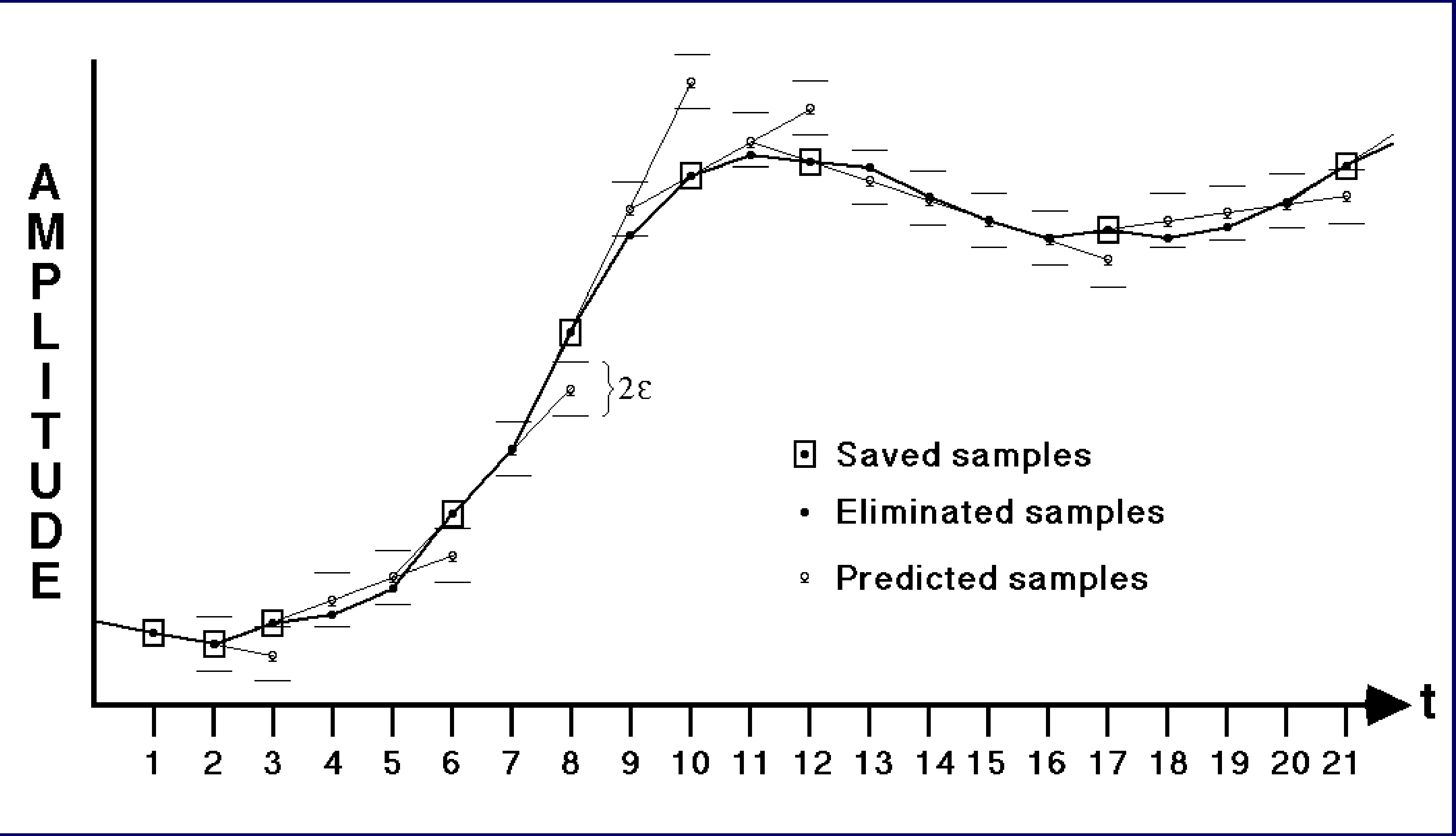
↓

WGAQ*6RBC*5HZY

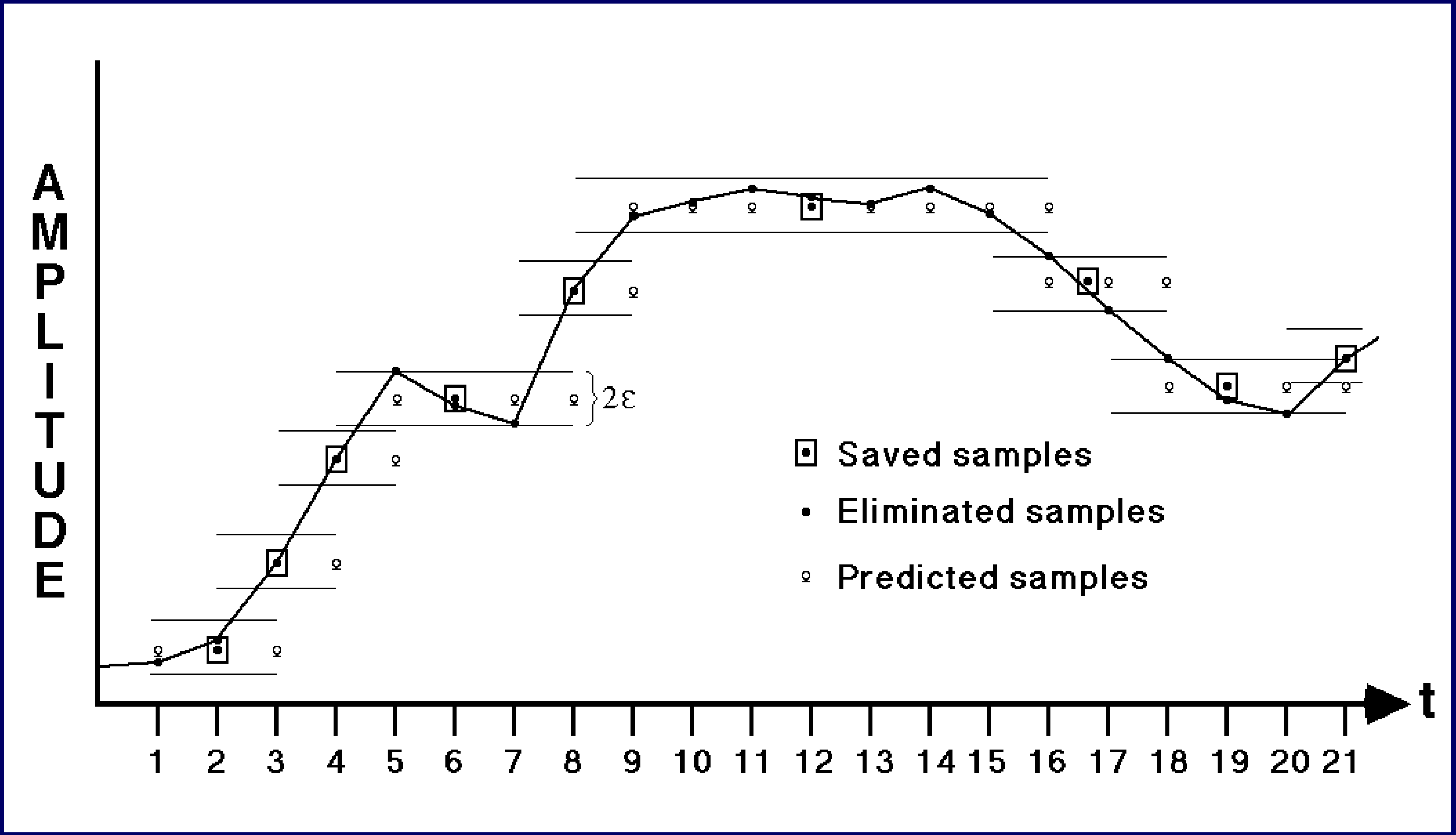
ECG Data Compression



ECG Data Compression



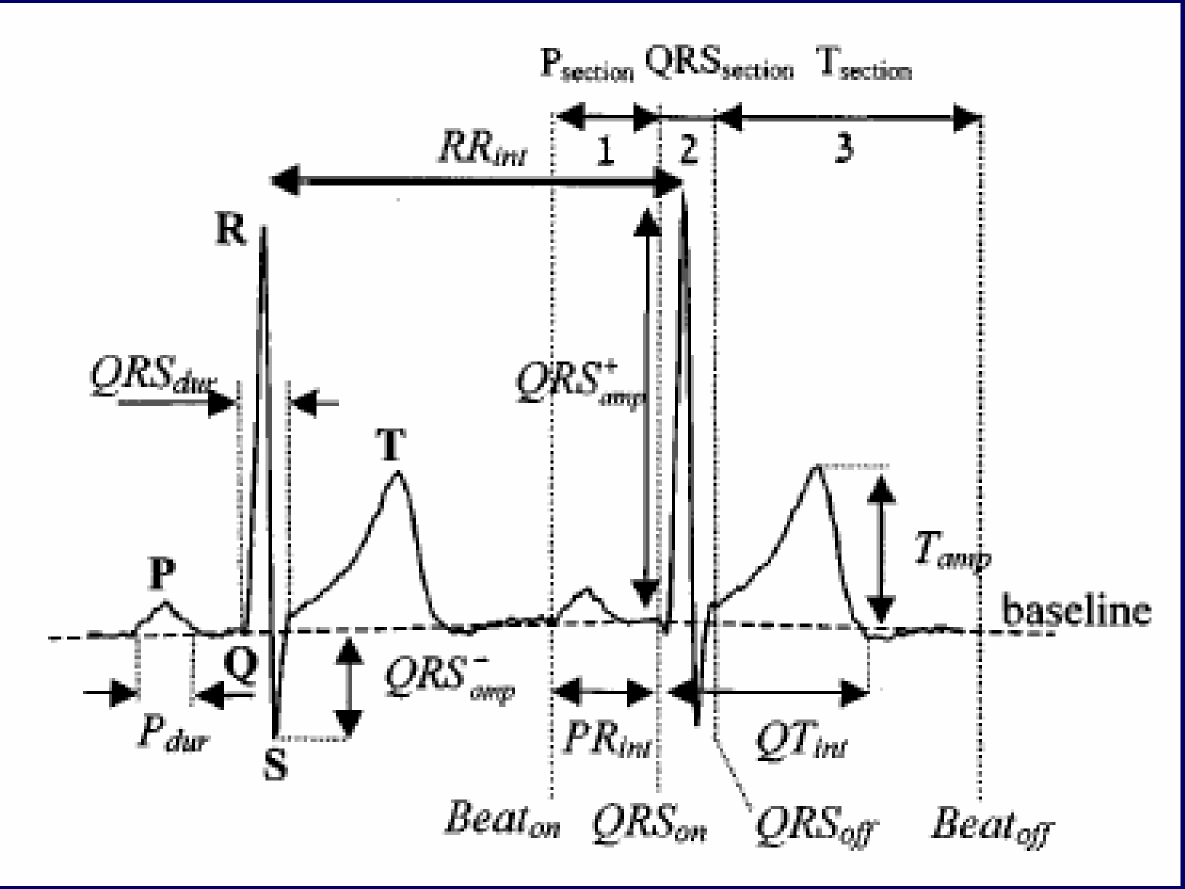
ECG Data Compression



Is *straightforward* implementation sufficient for biomedical signals?

Characteristics of Biomedical Signals (I): Weak $\neq$ Unimportant

- The information is in the details:



OK!

JPEG Compression

4302 Bytes

2245 Bytes

1714 Bytes

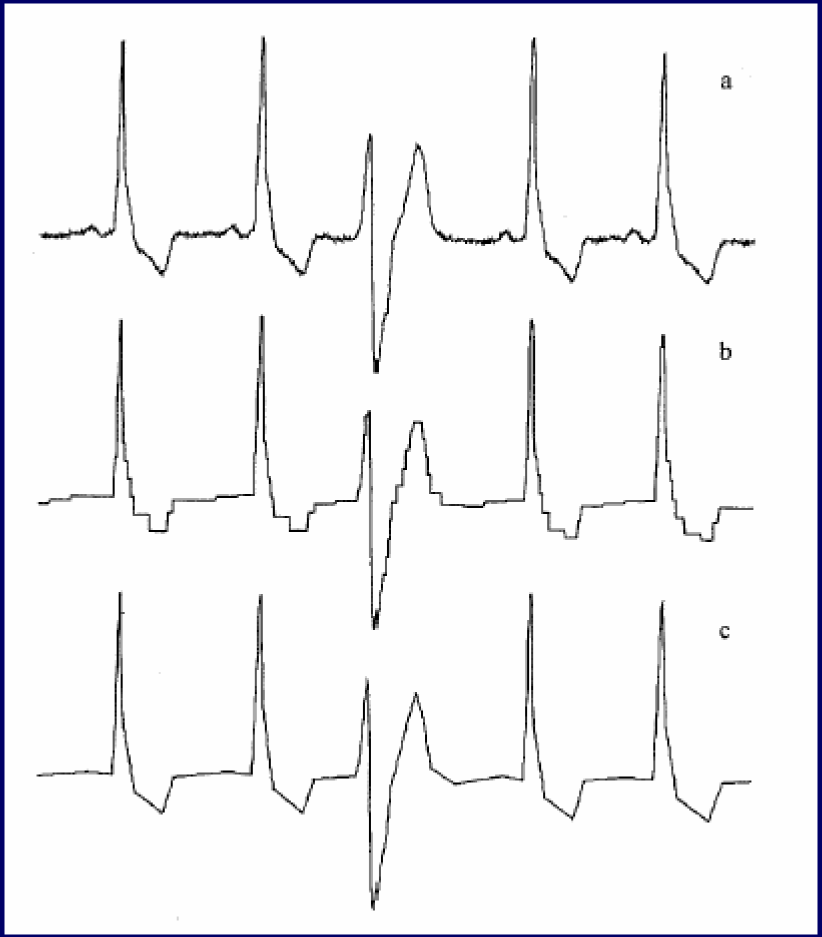
4272Bytes

2256 Bytes

1708 Bytes

Wavelet Compression

OK?

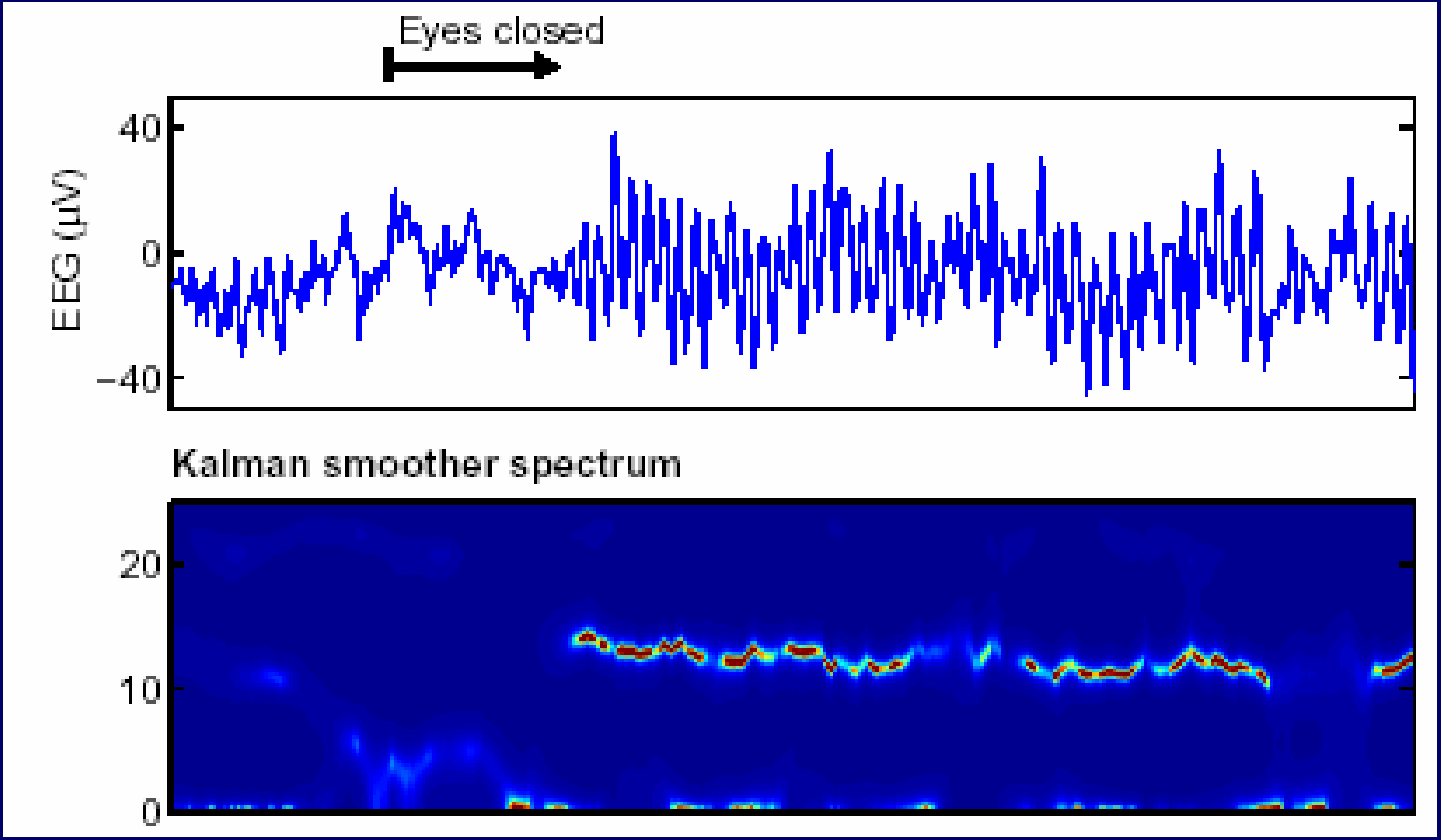


Characteristics of Biomedical Signals (II): Nonstationarity

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

- Fourier transform requires signal stationarity.
- Biomedical signals are often time-varying.
  - Short-time Fourier analysis
  - Time-frequency representation
  - Cyclo-stationarity

Nonstationarity: An EEG Example



Spectral Estimation for Nonstationary Signals

- Fourier Transform → Short Time Fourier Transform

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

$$\Downarrow$$

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

Another Example:
Signal Processing for
Blood Velocity Estimation

(Please refer to the class notes.)

Other Important Biomedical Applications

- Biomedical imaging:
  - X-ray, CT, MRI, PET, OCT, Ultrasound,…
- Genomic signal processing
- …,etc

Term Project

http://ultrasound.ee.ntu.edu.tw

課程→數位訊號處理概論