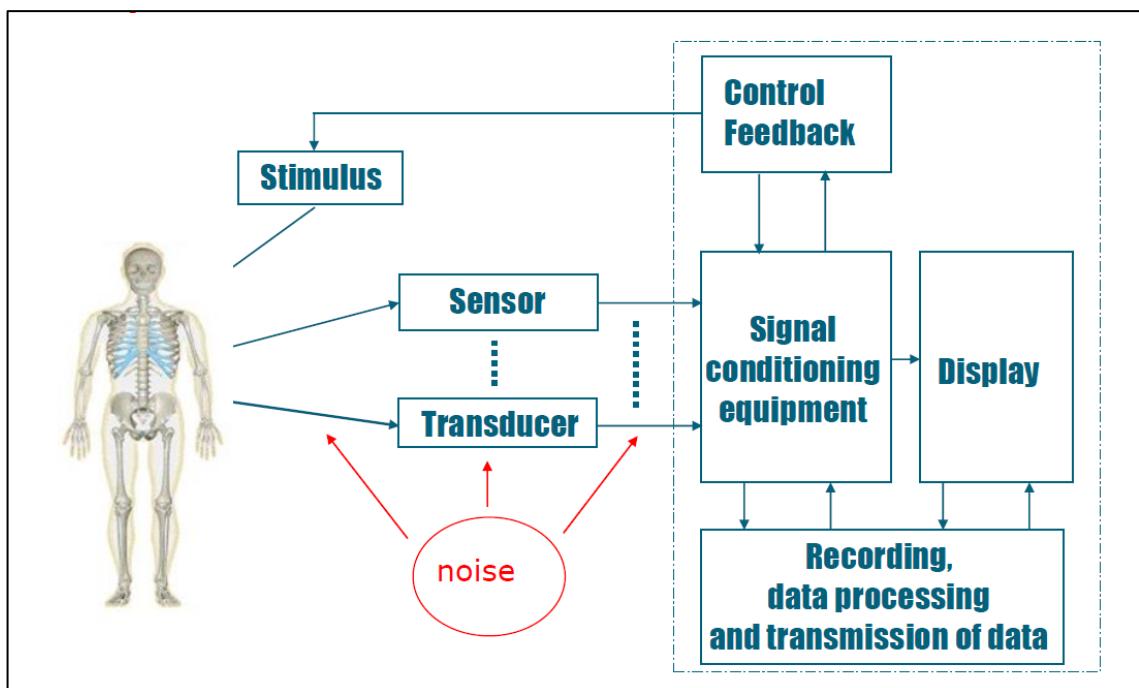


1. Draw the generalized medical instrumentation system block diagram and explain in detail

ANS:



Components of man-instrument system:

- (1) Subject-Human body is the subject on which measurement is performed.
- (2) Stimulus-External stimulus is required i.e. auditory tone ,flash of light. Stimulus may be visual or direct electrical stimulation of some part of the nervous systems.
- (3) The transducers-A transducer converts a physical measured quantity to an electric output. A transducer converts one form of energy to another.
- (4) Signal conditioning equipment-After the conversion, the electrical signal can be amplified, filtered, manipulated and displayed using analog circuitries.
- (5) Recording, data processing and transmission equipment-The conditioned signal can be then recorded ,transmitted.

2. What are the factors considered to decide the performance of medical instrumentation system?

ANS:

❖ Range

The range of input amplitude and frequency over which the device is expected to operate.

❖ Sensitivity

Instrument determines how small variation of variable or parameters can be reliably measured, which determines the resolution of the device. High sensitivity results in nonlinearities or instability. It is measured in cm/mm of Hg.

❖ Linearity

It is defined as ratio of change in output to change in input.

Variations in the output of n instrument follow input variables.

❖ Hysteresis

It is a characteristic of some instruments where a given value of the measured variable results in a different reading when reached in an ascending and descending direction.

❖ Frequency response

Frequency response of an instrument is its variation in sensitivity over which the frequency range of the measurement. System should be able to respond rapidly enough to reproduce all frequency components of the waveform with equal sensitivity.

❖ Accuracy

Accuracy is a measure of systematic error. Errors come due to tolerances of electric components , mechanical errors , component errors due to drift , errors due to poor frequency response , errors due to change in atmospheric pressure or temperature , reading errors due to parallax.

❖ Signal to noise ratio

It should be as high as possible.Noise comes due to power line frequency noise,interference due to electromagnetic,electrostatic or diathermy equipment and due to poor grounding.

❖ Stability

It is the ability of the system to resume a steady state condition following a disturbance at the input.

❖ Isolation

Instrument should not produce a direct electrical connection between subject and ground.

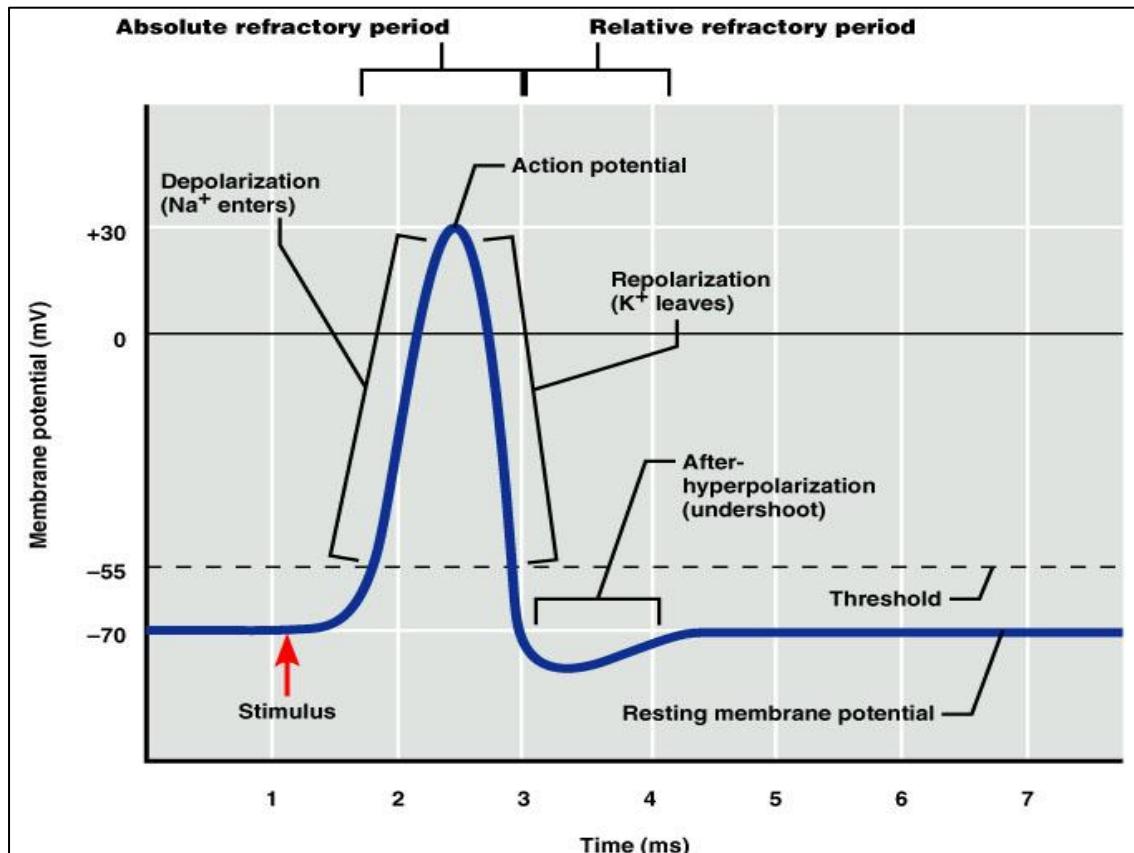
❖ Simplicity

The design of the biomedical instrumentation system should be simple, easy to debug for errors and for measurement.

3. Draw the bio potential waveform and define following terms

- a) Absolute and relative refractory period b) Resting and Action state of bio cell

ANS:



- Absolute Refractory Period:** Absolute refractory period (ARP) is the time just after the firing of an action potential. Generally, just after the firing of an action potential, sodium channels undergo inactivation spontaneously and rapidly at the peak of the action potential. However, when the sodium channels are inactivated, they are unable to reactivate immediately. This recovery from inactivation is a time and voltage-dependent process. Moreover, the full recovery of the reactivation usually takes about 4-5 msec. However, the initial time period after the peak of the action potential is the absolute refractory period.
- Relative Refractory Period:** Relative refractory period (RRP) is the time when the firing of a second action potential is possible. Generally, during the relative refractory period, sodium channels begin to recover from their inactivation. Therefore, if the stimulus is strong enough, the excitable membrane can fire a second action potential. Here, the stimulus has to be stronger than the stimulus, which can fire an action potential when the excitable membrane is at rest.

Moreover, the full recovery of sodium channels occurs at the end of the relative refractory period. However, a continuous flow of potassium ions from inside to the outside of the cell is there. Therefore, there is a tendency to oppose any depolarization. That is why it requires a stronger stimulus to fire an action potential during the relative refractory period.

3. Resting State: The membrane potential caused by the different concentration of ions is called the resting potential of the cell. Resting potential is defined as the electrical potential of an excitable cell relative to its surroundings when not stimulated or involved in passage of an impulse. It ranges from -60mV to -100mV. The nerve and muscle cells permit the entry of potassium and chloride ions but blocks the entry of sodium ions. The permeability of sodium ions is about 2×10^{-8} cm/s and for potassium and chloride ions is 4×10^{-6} cm/s.
When the cell is in resting state, then it is said to be polarized.
4. Action State: Action potential is defined as the change in electrical potential associated with the passage of an impulse along the membrane of a cell. An action potential is a rapid rise and subsequent fall in voltage or membrane potential across a cellular membrane with a characteristic pattern. Sufficient current is required to initiate a voltage response in a cell membrane; if the current is insufficient to depolarize the membrane to the threshold level, an action potential will not fire. Examples of cells that signal via action potentials are neurons and muscle cells.

4. Define the following terms

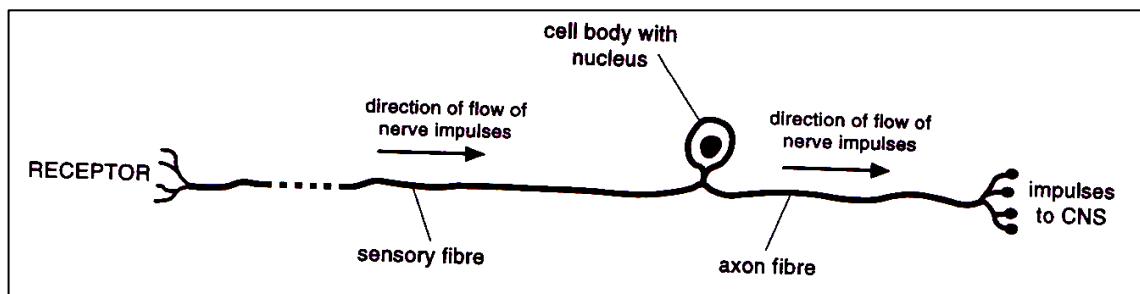
- a) ECG: A line graph that shows changes in the electrical activity of the heart over time. It is made by an instrument called an electrocardiograph. The graph can show that there are abnormal conditions, such as blocked arteries, changes in electrolytes (particles with electrical charges), and changes in the way electrical currents pass through the heart tissue. Also called EKG and electrocardiogram.
- b) EEG: Electroencephalogram (EEG) is a record of the electric signal generated by the cooperative action of brain cells, or more precisely, the time course of an extracellular field potentials generated by their synchronous action. During an EEG, a technician places small metal disks (electrodes) on your scalp. The electrodes attach to a machine that gives your healthcare provider information about your brain's activity.
- c) EMG: Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by skeletal muscles. EMG is performed using an instrument called an electromyograph to produce a record called an electromyogram. An electromyograph detects the electric potential generated by muscle cells when these cells are electrically or neurologically activated.
- d) PCG: The phonocardiogram (PCG) detects and records heart sounds, the sounds made by the various cardiac structures pulsing and moving blood. The sound is caused by the acceleration and deceleration of blood and turbulence developed during rapid blood flow.
- e) VCG: Vectorcardiogram (VCG) signals monitor both spatial and temporal cardiac electrical activities along three orthogonal planes of the body.

5. What are the types of nerve cells and explain Nervous system

ANS:

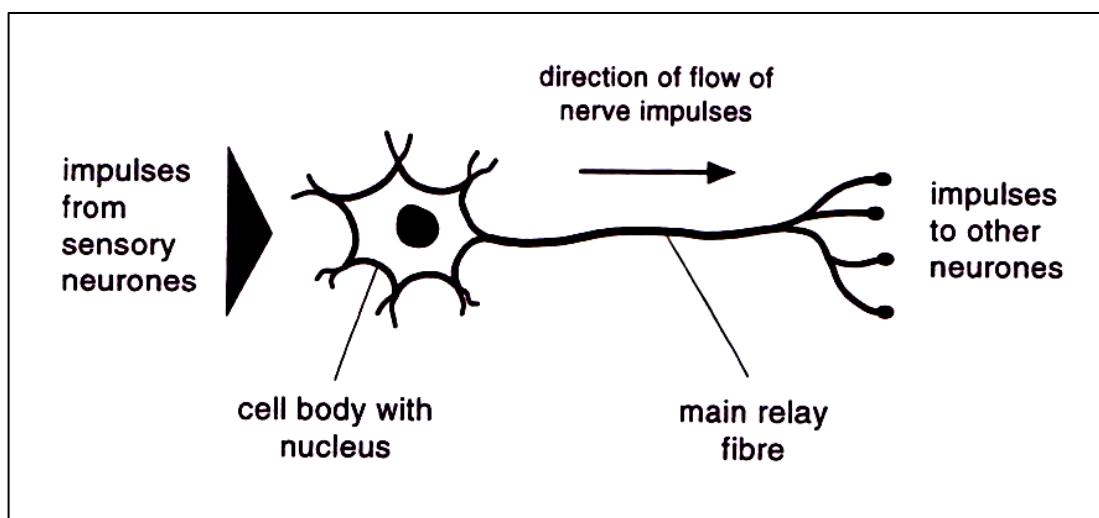
A) TYPES OF NERVE CELLS:

1. Sensory neurons:



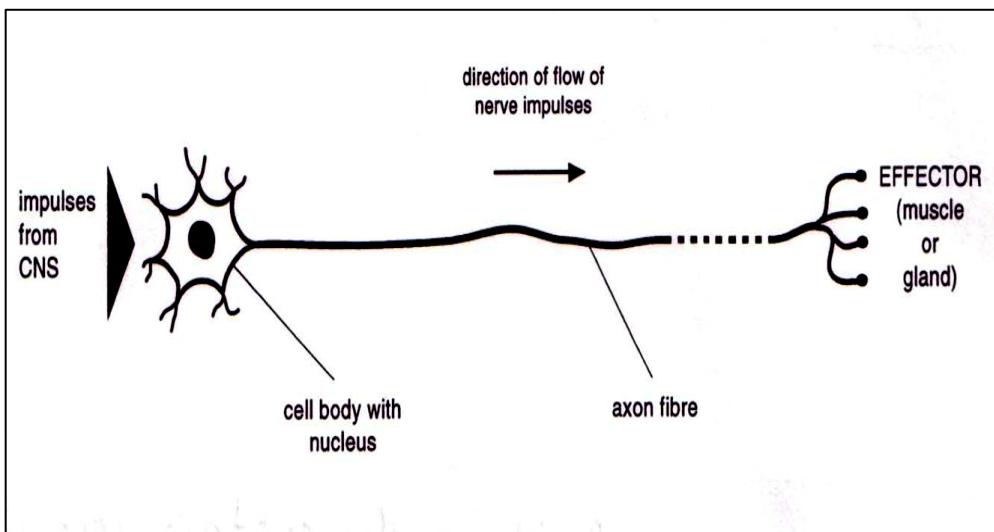
Carries impulses from receptors e.g pain receptors in skin to the CNS(brain or spinal cord)

2. Relay neuron:



Carries impulses from sensory nerves to motor nerves.

3. Motor neuron:



Carries impulses from CNS to effector e.g. muscle to bring about movement or gland to bring about secretion of hormone e.g ADH

B) NERVOUS SYSTEM: The nervous system is a highly complex part of an animal that coordinates its actions and sensory information by transmitting signals to and from different parts of its body.

- **Nervous System**
 - Brain
 - Spinal Cord
 - Nerves
- **Functions of Nervous System**
 - Regulates and coordinates all body activities
 - Center of all mental activity, including thought, learning, and memory

Nervous System Divisions:

- Central Nervous System (CNS)
 - Brain
 - Spinal Cord
 - Processes and stores sensory and motor information
 - Controls consciousness
- Peripheral Nervous System (PNS)
 - 12 Pairs of Cranial Nerves
 - 31 Pairs of Spinal Nerves
 - Transmits sensory and motor impulses back and forth between CNS and rest of body

6. What are types of bio sensors? Which sensors are used for the measurement of heart rate and explain any one method.

ANS:

Immunosensors were established on the fact that antibodies have high affinity towards their respective antigens, i.e. the antibodies specifically bind to pathogens or toxins, or interact with components of the host's immune system.

The DNA biosensors were devised on the property that single-strand nucleic acid molecule is able to recognize and bind to its complementary strand in a sample. The interaction is due to the formation of stable hydrogen bonds between the two nucleic acid strands.¹⁰

Magnetic biosensors: miniaturized biosensors detecting magnetic micro- and nanoparticles in microfluidic channels using the magnetoresistance effect have great potential in terms of sensitivity and size.¹¹

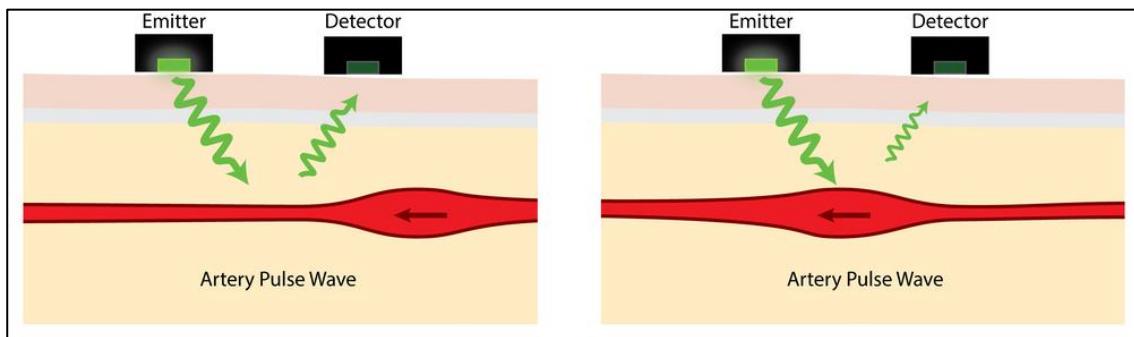
Piezoelectric biosensors are of two types: the quartz crystal microbalance and the surface acoustic wave device. They are based on the measurement of changes in resonance frequency of a piezoelectric crystal due to mass changes on the crystal structure.

Optical biosensors consist of a light source, as well as numerous optical components to generate a light beam with specific characteristics and to beeline this light to a modulating agent, a modified sensing head along with a photodetector.

The electrochemical biosensor is one of the typical sensing devices based on transducing the biochemical events to electrical signals. In this type of sensor, an electrode is a key component that is employed as a solid support for immobilization of biomolecules and electron movement.

Thermometric-biosensor is used to measure or estimate serum cholesterol. As cholesterol obtains oxidized through the enzyme cholesterol oxidase, then the heat will be produced which can be calculated. Similarly, assessments of glucose, urea, uric acid, and penicillin G can be done with these biosensors.

SENSORS ARE USED FOR THE MEASUREMENT OF HEART RATE:



An **optical heart rate sensor** measures pulse waves, which are changes in the volume of a blood vessel that occur when the heart pumps blood. Pulse waves are detected by measuring the change in volume using an optical sensor and green LED.

METHOD:

Photoplethysmography (PPG) is a simple optical technique used to detect volumetric changes in blood in peripheral circulation. It is a low cost and non-invasive method that makes measurements at the surface of the skin.

The technique provides valuable information related to our cardiovascular system. Recent advances in technology has revived interest in this technique, which is widely used in clinical physiological measurement and monitoring.

Walchand college of engineering, Sangli.

(An Autonomous Institute)

U.G. Program in Electronics Engineering

**Course
Biomedical Engineering**

**Course Teacher
Dr. B. G. Patil**

•Teaching Scheme

Lectures 3 per week

Tutorials 1 per week in 4 batches

•Evaluation Scheme

- | | | |
|----|-------------|-----------|
| 1. | <i>ISE1</i> | <i>10</i> |
| 2. | <i>MSE</i> | <i>30</i> |
| 3. | <i>ISE2</i> | <i>10</i> |
| 4. | <i>ESE</i> | <i>50</i> |

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<i>2.Classification of Biomedical Equipment</i>	2
<i>3.Bioelectric signals and their recording</i>	14
<i>4.Patient Monitoring System</i>	6
<i>5.Medical instrumentation</i>	6
<i>6.Assisting and therapeutic equipments</i>	5

Recommended Books

- 1. Medical Instrumentation by John. G. Webster –John Wiley*
- 2. Principles of Applied Biomedical Instrumentation by Goddes & Baker-John Wiley*
- 3. Biomedical Instrumentation & Measurement by Carr & Brown – Pearson*
- 4. Biomedical Instrument by Cromwell –Prentice Hall of India, New Delhi.*
- 5. Handbook of Medical instruments by R.S.Khandpur –TMH, New Delhi.*
- 6. Medical Electronics and Instrumentation by Sanjay Guha – University Publication*
- 7. Introduction to Biomedical electronics by Edwand J. Bukstein – Sane and Co.Inc.*

Syllabus

Chapter 1 Physiology and transducers

Cell and its structure-Action and resting-potential propagation of action potential-Sodium pump-Nervous system-CNS-PNS-Nerve cell-Synapse-Cardio pulmonary system-Physiology of heart and lungs Circulation and respiration-Transducers-Different types-Piezo-electric,ultrasonic,resistive,capacitive,inductive transducers-Selection criteria

Chapter 2 Classification of Biomedical Equipment

Diagnostic,therapeutic and clinical laboratory equipment

Chapter 3 Bioelectric signals and their recording

Bioelectric signals (ECG,EMG,ECG,EOG & ERG) and their characteristics,Bioelectrodes,electrodes tissue interface, contact impedance, effects of high contact impedance, types of electrodes, electrodes for ECG,EEG and EMG, Physiological pre-amplifier and specialized amplifiers, ECG lead systems, details of ECG,EMG and EEG machines

Syllabus

Chapter 4 Patient Monitoring System

Heart rate measurement, pulse rate measurement, respiration, rate measurement, blood pressure measurement, microprocessor applications in patient monitoring.

Chapter 5 Medical instrumentation

X-ray machine-Radio graphic and fluoroscopic techniques-computer tomography-MRI-Ultrasonography - Endoscopy- Thermography -different types of biotelemetry systems and patient monitoring-Electrical safety.

Chapter 6 Assisting and therapeutic equipments

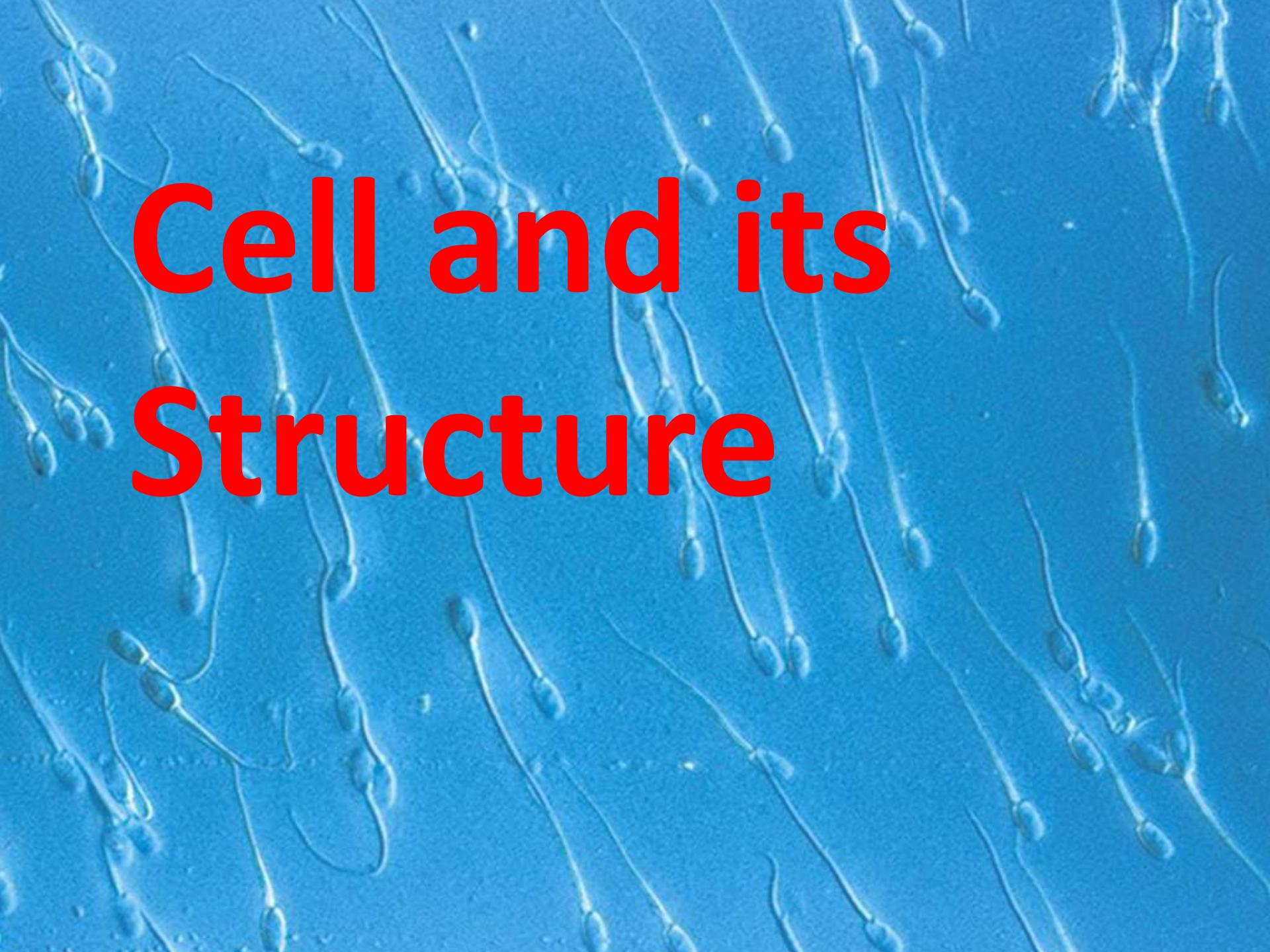
Pace makers- Defibrillators-Ventilators-Nerve and muscle stimulators-Diathermy-Heart-Lung machine-Audio meters-Dializers

Chapter 1

Physiology

and

transducers

A microscopic image showing numerous sperm cells swimming across a light blue background. The sperm are oriented vertically, with their heads at the top and tails pointing downwards. They appear as small, dark, oval-shaped heads connected by thin, wavy lines to long, thin tails.

**Cell and its
Structure**

Cells

- Smallest living unit
- Most are microscopic



Cell

- Smallest living unit of an organism
- Grow, reproduce, use energy, adapt, respond to their environment
- Many cannot be seen with the naked eye
- A cell may be an entire organism or it may be one of billions of cells that make up the organism

Discovery of Cells

- Robert Hooke (mid-1600s)
 - Observed sliver of cork
 - Saw “row of empty boxes”
 - Coined the term cell



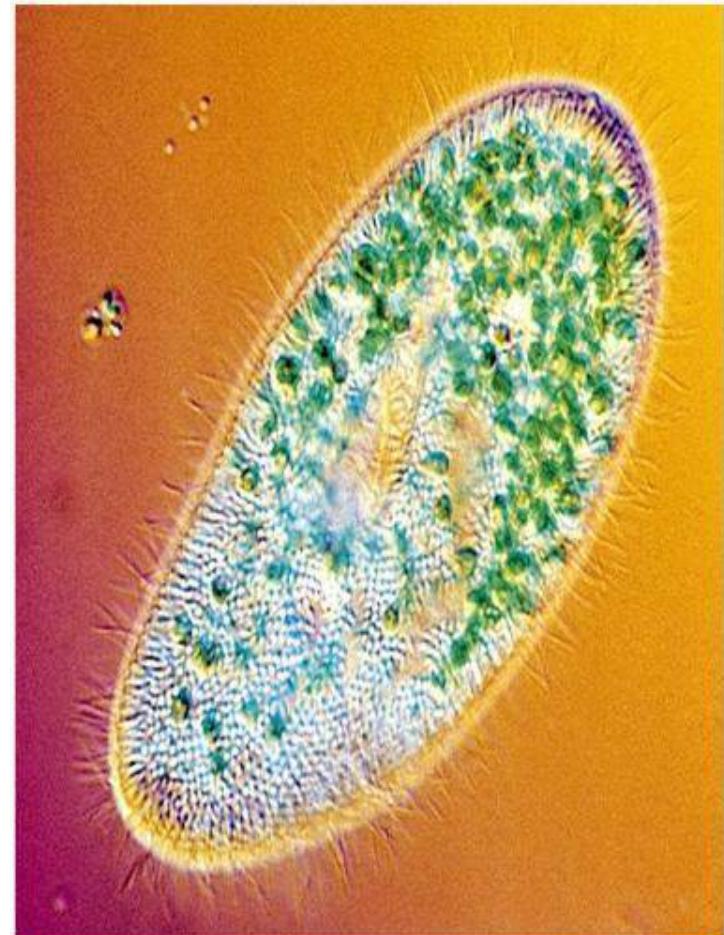
Cell theory

- (1839) Theodor Schwann & Matthias Schleiden

“ all living things are made of cells”

- (50 yrs. later) Rudolf Virchow

“all cells come from cells”



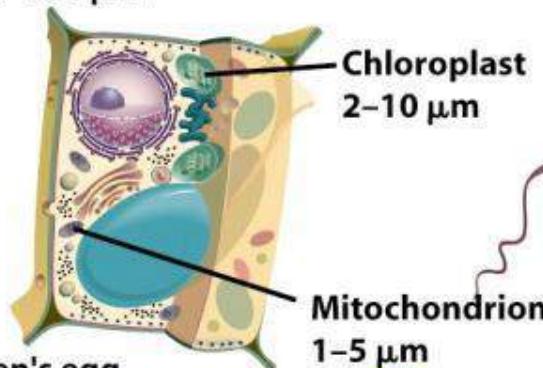
Principles of Cell Theory

- All living things are made of cells
- Smallest living unit of structure and function of all organisms is the cell
- All cells arise from preexisting cells
(this principle discarded the idea of spontaneous generation)

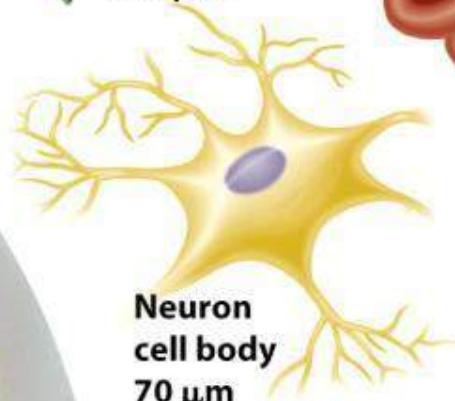
Cell Size

Typical plant cell

10–100 μm



Hen's egg
65 mm



Neuron
cell body
70 μm

Unaided vision

Light microscopes (down to 200 nm)

1 mm

100 μm

10 μm

1 μm

100 nm

10 nm

1 nm

0.5 nm

Trypanosoma (protozoan)
25 μm long



Human red
blood cell
7–8 μm diameter



Escherichia coli
(bacterium)
1–5 μm long



HIV (AIDS virus)
100 nm



Poliovirus
30 nm



DNA molecule
2 nm diameter



T4 bacteriophage
225 nm long



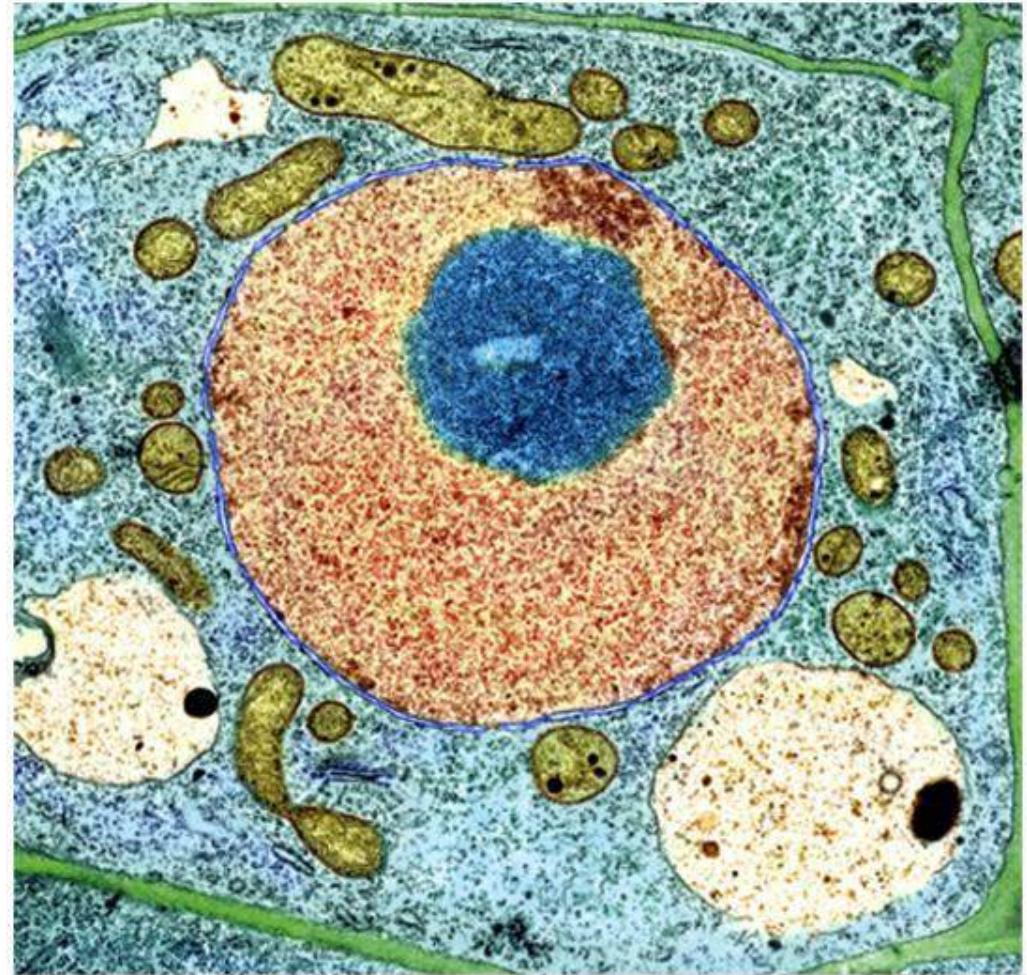
Tobacco mosaic virus
300 nm long



Electron microscopes (down to 0.5 nm)

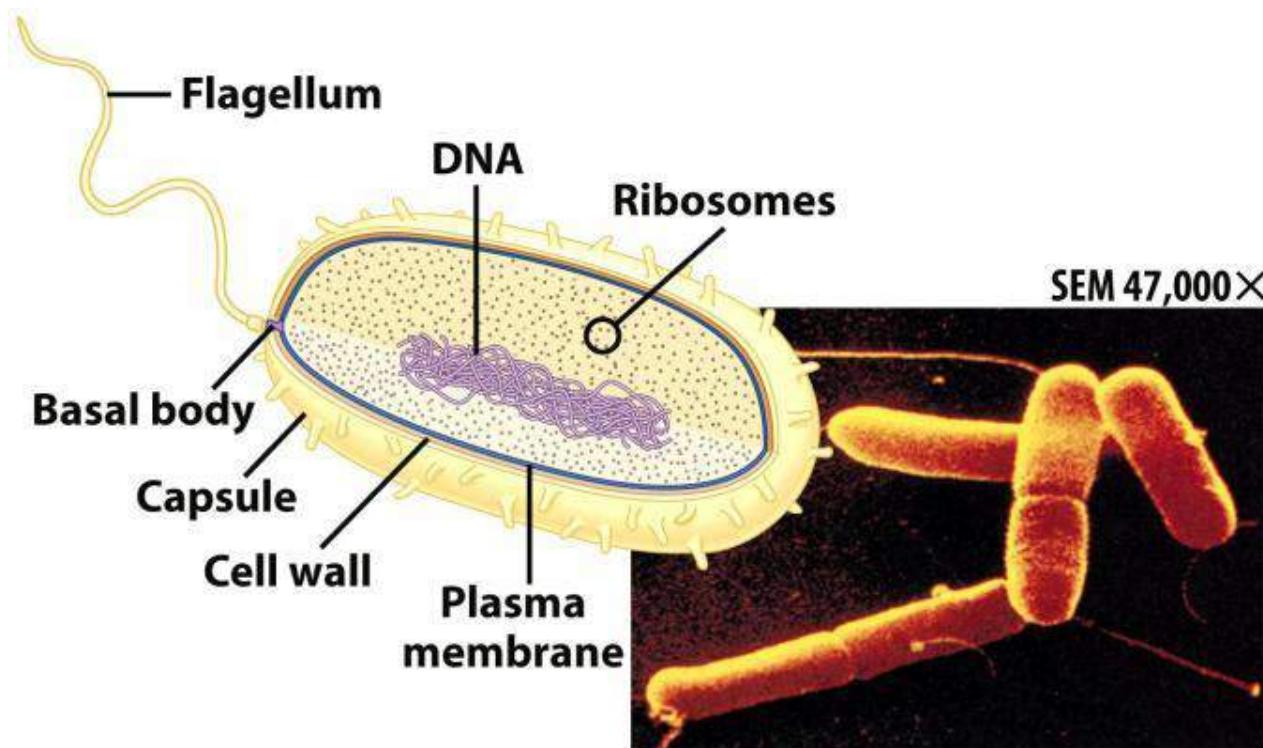
Cell Types

- Prokaryotic
- Eukaryotic



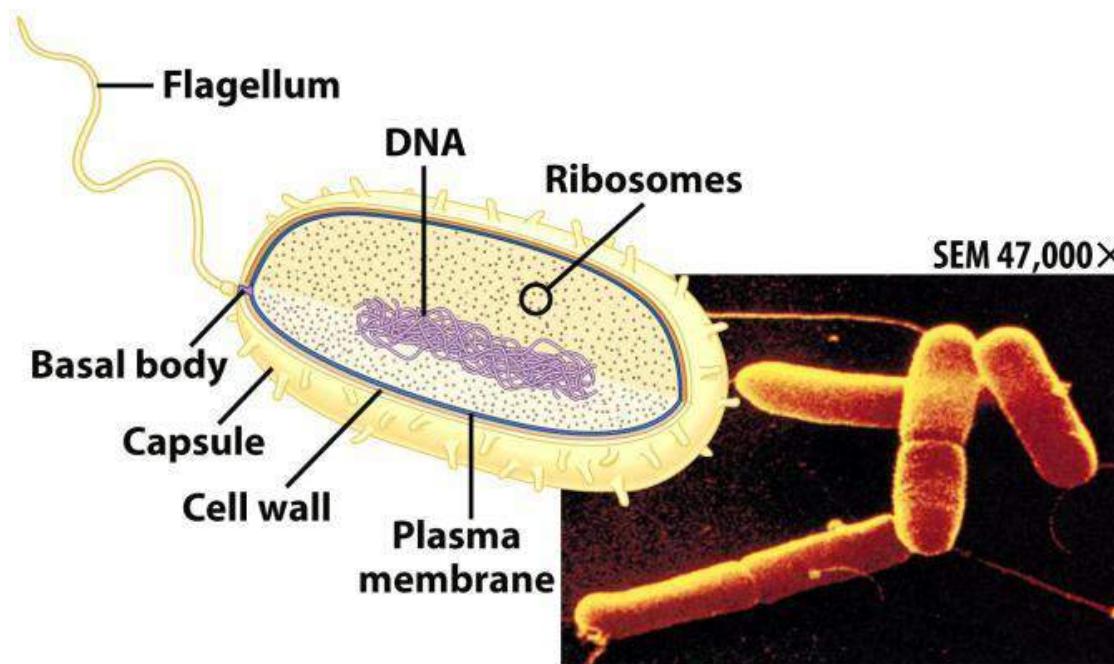
Prokaryotic Cells

- First cell type on earth
- Cell type of Bacteria and Archaea



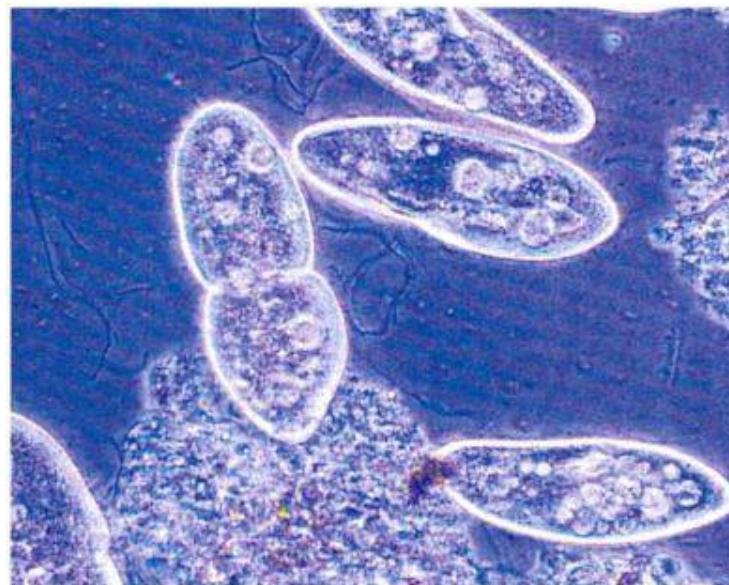
Prokaryotic Cells

- No membrane bound nucleus
- Nucleoid = region of DNA concentration
- Organelles not bound by membranes



Eukaryotic Cells

- Nucleus bound by membrane
- Include fungi, protists, plant, and animal cells
- Possess many organelles



Protozoan

Definition

- **Bioinstrumentation** is traditionally defined as a field that “applies the fundamentals of measurement science to biomedical instrumentation emphasizing common principles and unique problems associated with making measurements in living systems” [1]

[1] J.G. Webster, Bioinstrumentation, John Wiley & Sons, Inc. (2004)

Biomedical engineer

The person working in research or development in the interface area of medicine and engineering is known as Biomedical engineer.

Clinical engineer

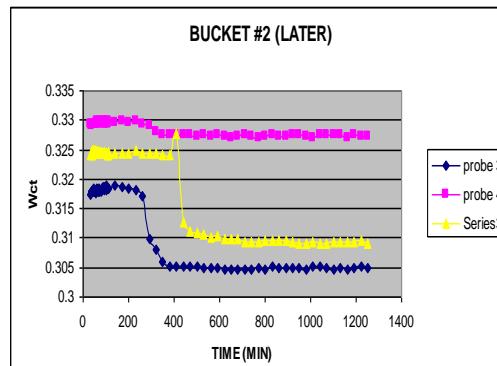
The practitioner working with physician and patients is called a clinical engineer.

Examples of Biomedical project designs

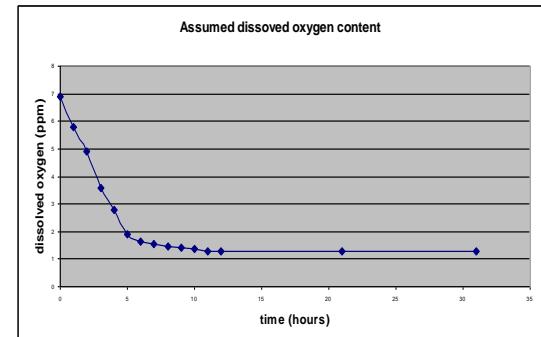
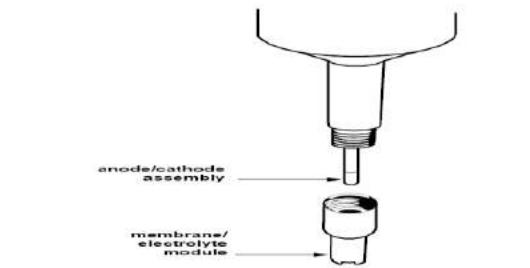
Project #1: SPR sensors



Project #2: TDR (Time Domain Reflectometry)



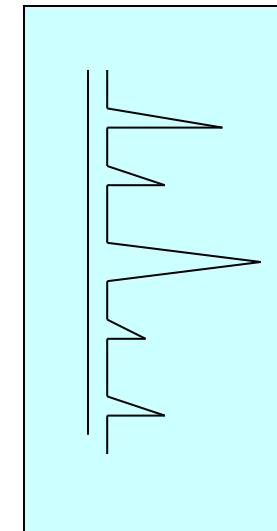
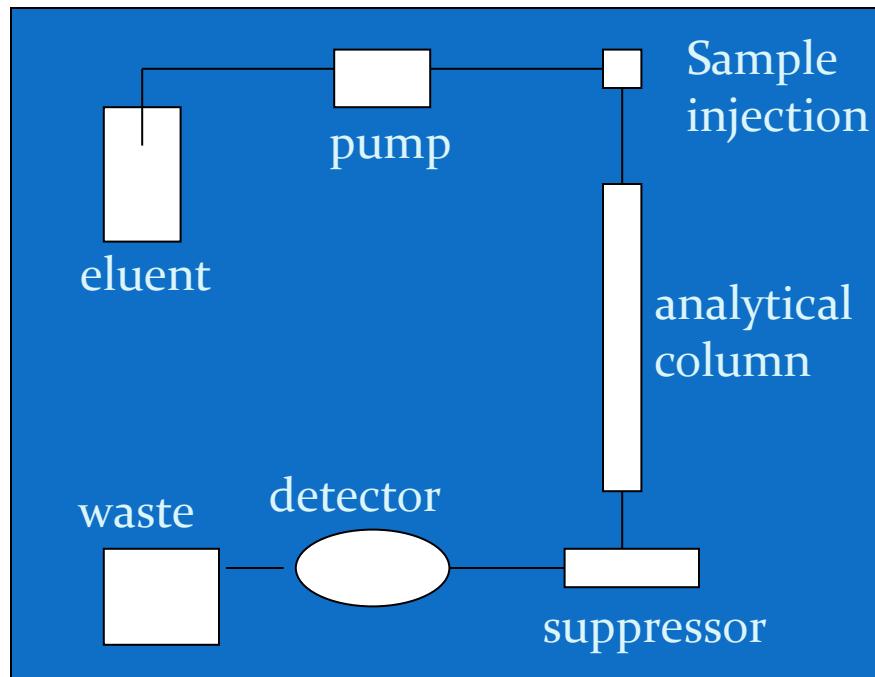
Project #3: dO₂ Probe for Bioreactor



Project 1: Wireless sensor network



Project 2: Ion Chromatography - volatile fatty acids detection with application to Bio processing and Environmental Engineering



Factors of Biomedical instrumentation Systems(1)

❖ Range

The range of input amplitude and frequency over which the device is expected to operate.

❖ Sensitivity

Instrument determines how small variation of variable or parameters can be reliably measured, which determines the resolution of the device. High sensitivity results I nonlinearities or instability. It measured in cm/mm of Hg.

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Factors of Biomedical instrumentation Systems(2)

❖ Hysteresis

It is a characteristics of some instruments where a given value of the measured variable results in a different reading when reached in an ascending and descending direction.

❖ Frequency response

Frequency response of an instrument is its variation in sensitivity over which the frequency range of the measurement. System should be able to respond rapidly enough to reproduce all frequency components of the waveform with equal sensitivity.

Factors of Biomedical instrumentation Systems(3)

❖ Accuracy

Accuracy is a measure of systemic error. Errors came due to tolerances of electric components , mechanical errors , component errors due to drift , errors due to poor frequency response , errors due to change in atmospheric pressure or temperature , reading errors due to parallax.

❖ Signal to noise ratio

It should be as high as possible.Noise came due to power line frequency noise,interference due to electromanetic,electrostatic or diathermy equipment and due to poor grounding.

Factors of Biomedical instrumentation Systems(4)

❖ Stability

It is the ability of the system to resume a steady state condition following a disturbance at the input.

❖ Isolation

Instrument should not produce a direct electrical connection between subject and ground.

❖ Simplicity

The design of the biomedical instrumentation system should be simple, easy to debug for errors and for measurement.

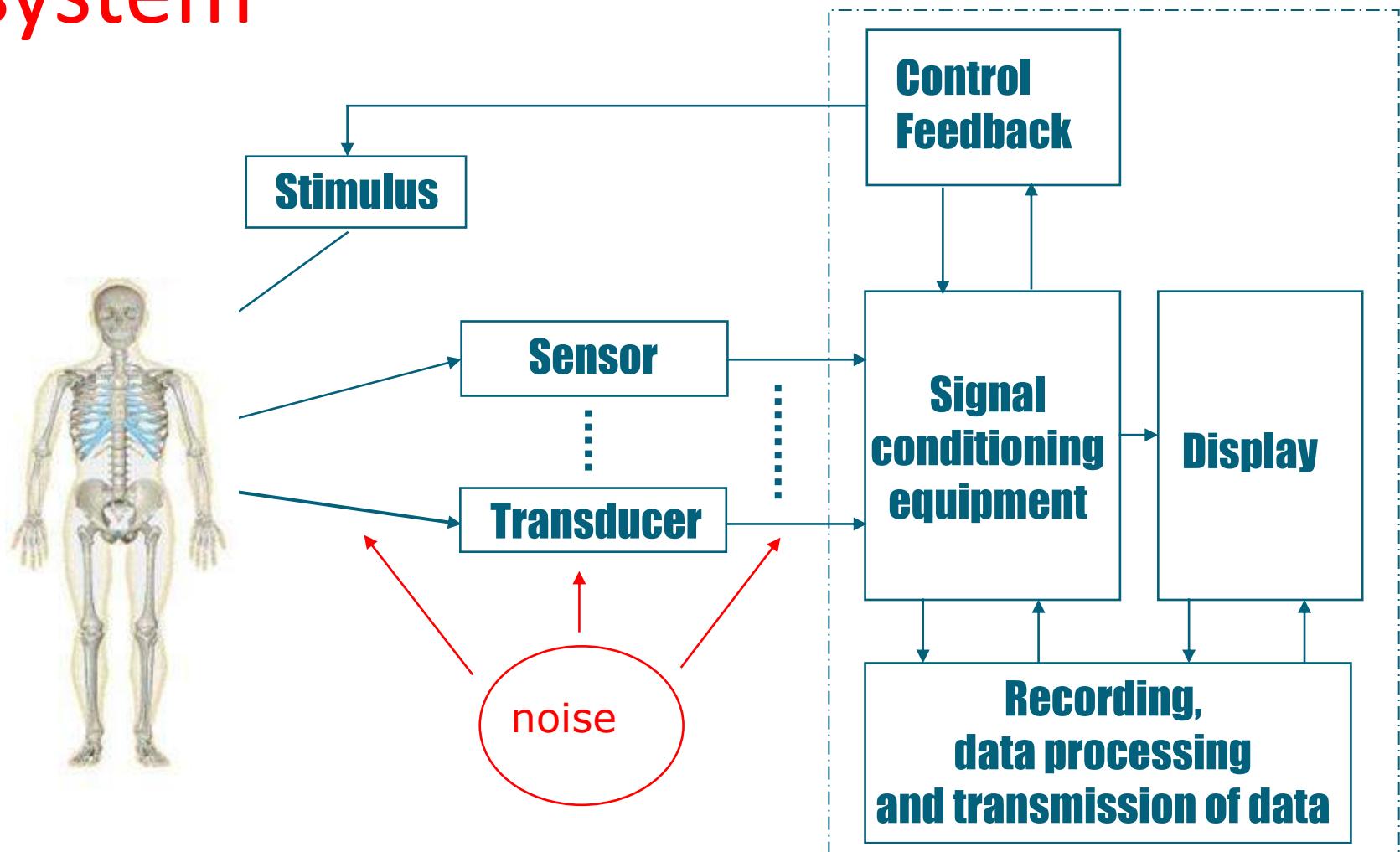
Introduction to man instrument systems

Human organism and instrumentation required for measurement of the human is called the man-instrument systems.

Objectives of the instrumentation

- Information gathering
- Diagnosis
- Evaluation
- Monitoring
- Control

Block diagram of man-instrument system

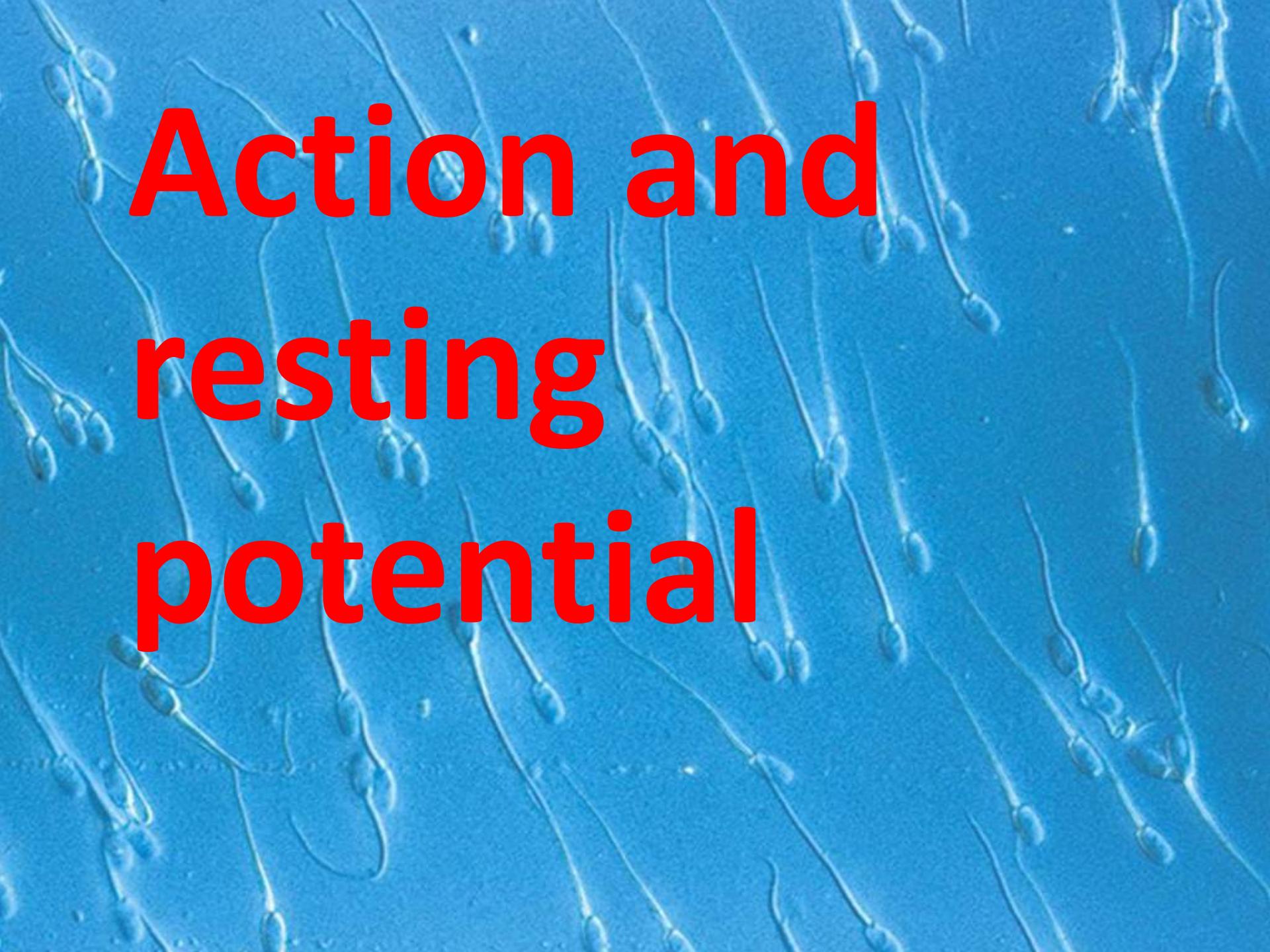


Components of man-instrument system

- (1) Subject-** Human body is the subject on which measurement is performed.
- (2)Stimulus-**External stimulus is required i.e. auditory tone ,flash of light. Stimulus may be visual or direct electrical stimulation of some part of the nervous systems.
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- (4)Signal conditioning equipment-**After the conversion, the electrical signal can be amplified, filtered, manipulated and displayed using analog circuitries.
- (5) Recording, data processing and transmission equipment-**The conditioned signal can be then recorded ,transmitted.

Problems encountered In measuring a living system

- In accessibility of variables to be measured.
- Variability of data.
- Lack of knowledge about interrelationships.
- Interaction among physiological systems.
- Effect of the transducer on the measurement.
- Artifacts.
- Energy limitations.
- Safety considerations.

A microscopic image showing numerous ciliates, likely Paramecium, swimming in a blue liquid. The ciliates are elongated with distinct cilia covering their surfaces.

Action and
resting
potential

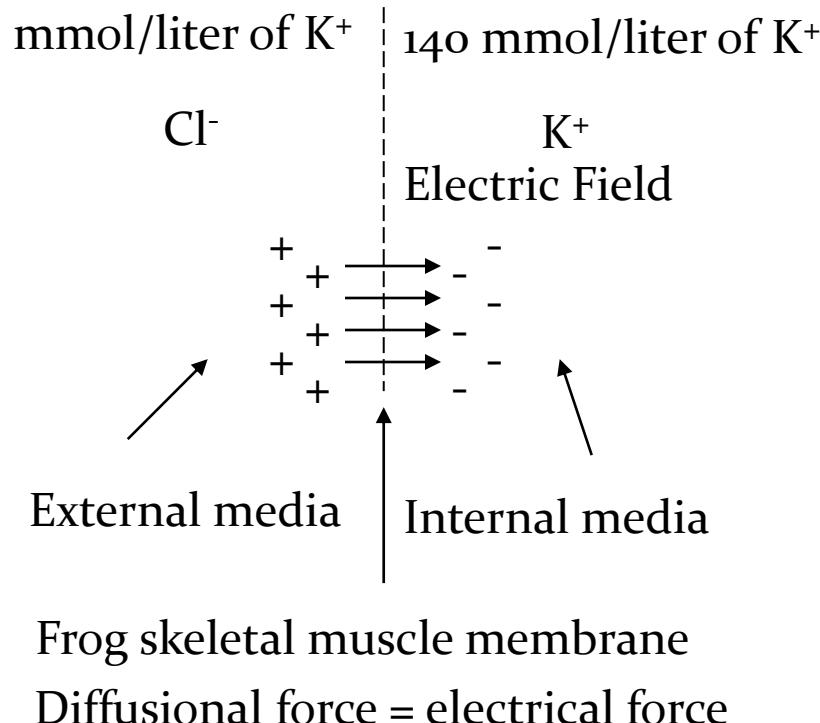
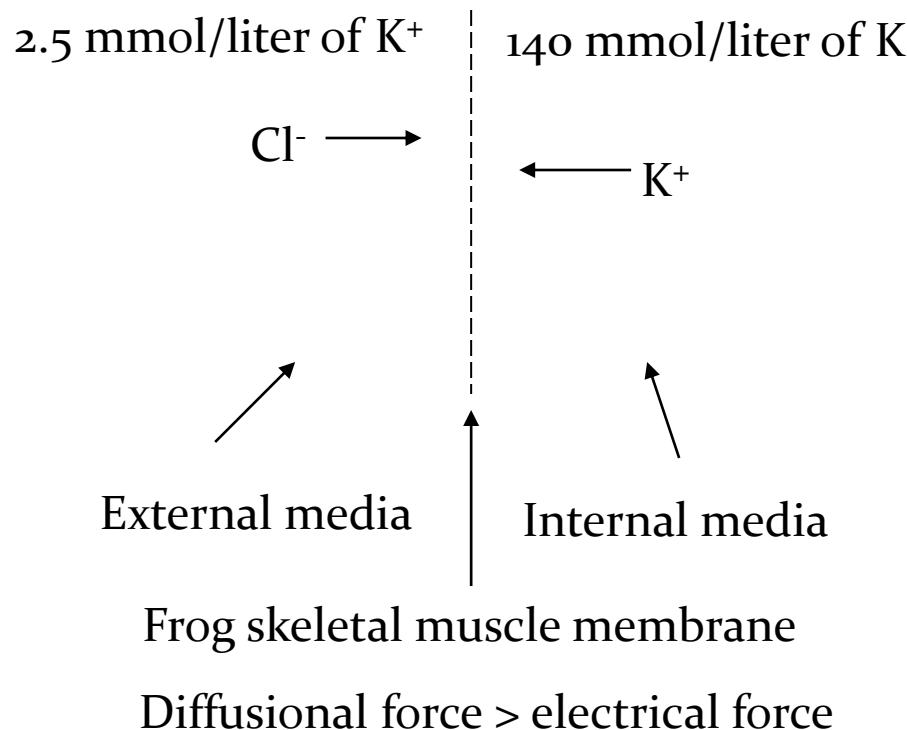
Cells and membrane potentials

- All animal cells generate a small voltage across their membranes
- This is because there is a large amount of small organic molecules in the cytoplasm
- To balance this, animal cell pump Na^+ out of the cells
- This regulates osmosis but it leaves a large number of organic molecules
- These are overall negatively charged (anions) in the cytoplasm
- Thus the cell has a potential difference (voltage) across its membrane

The Resting State

Membrane at resting state is

- slightly permeable to Na^+ and freely permeable to K^+ and Cl^-
- permeability of potassium P_K is 50 to 100 times larger than the permeability to sodium ion P_{Na} .



The Active State

Membrane at resting state is polarized (more negative inside the cell)

Depolarization : lessening the magnitude of cell polarization by making inside the cell less negative.

Hyperpolarization : increasing the magnitude of cell polarization by making inside the cell more negative.

A stimulus that depolarize the cell to a potential higher than the threshold potential causes the cell to generate an action potential.

Action Potential:

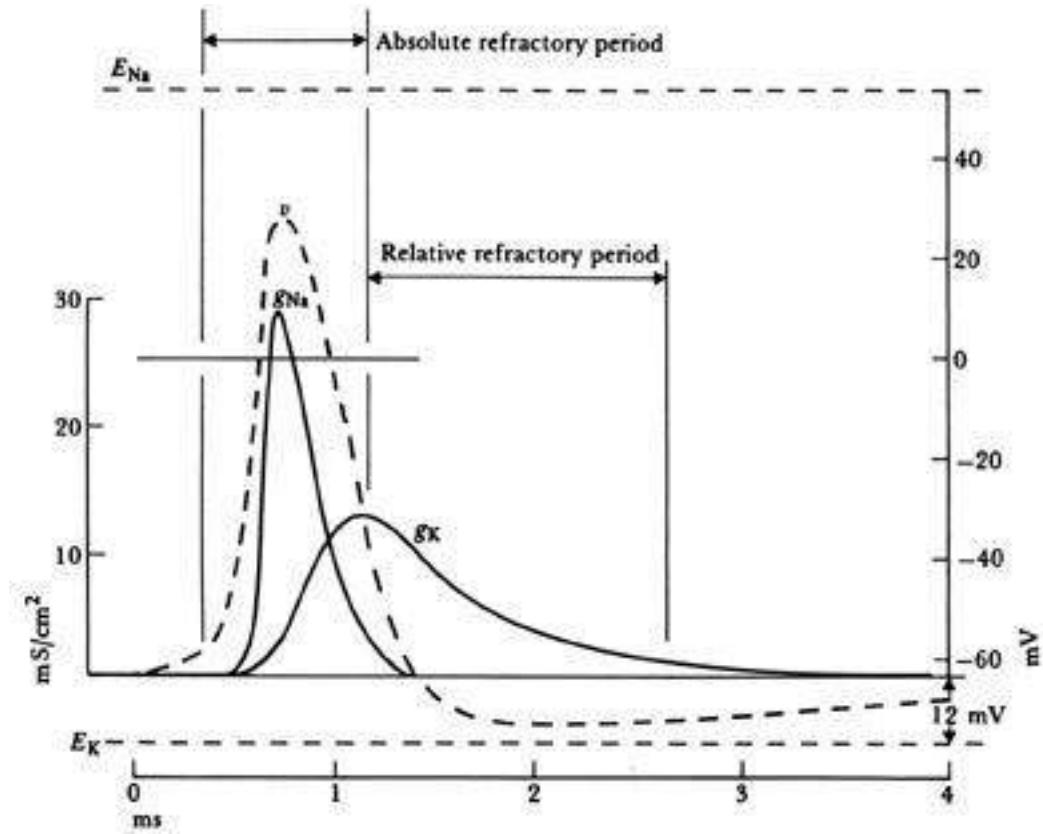
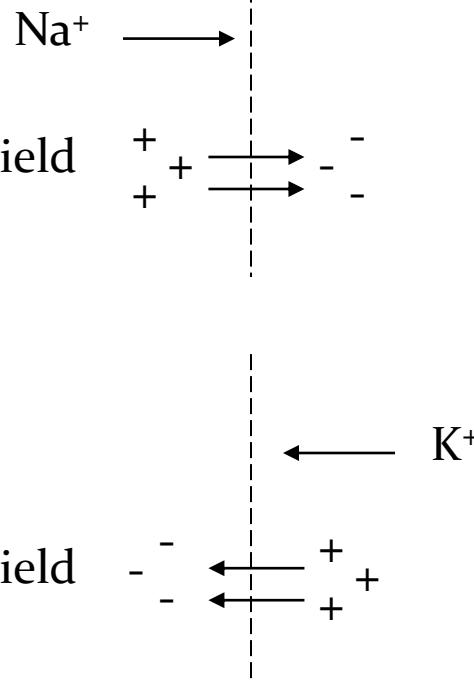
- Rate: 1000 action potential per second for nerve
- All-or-none
- $\Delta V = 120 \text{ mV}$ for nerve

Action Potential

If stimulus depolarize the cell such that $V_{\text{cell}} > V_{\text{threshold}}$ an action potential is generated.

External media Internal media

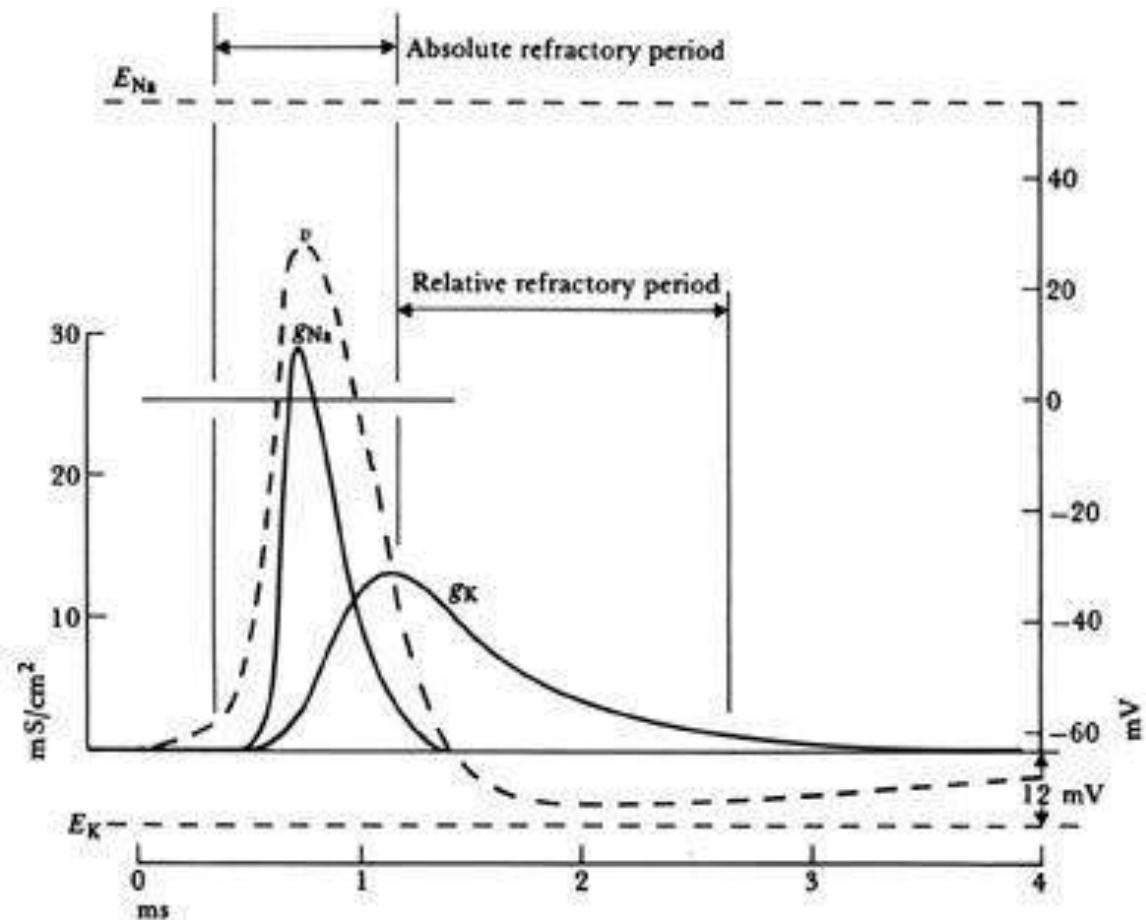
2.5 mmol/liter of K^+ 140 mmol/liter of K^+



Action Potential

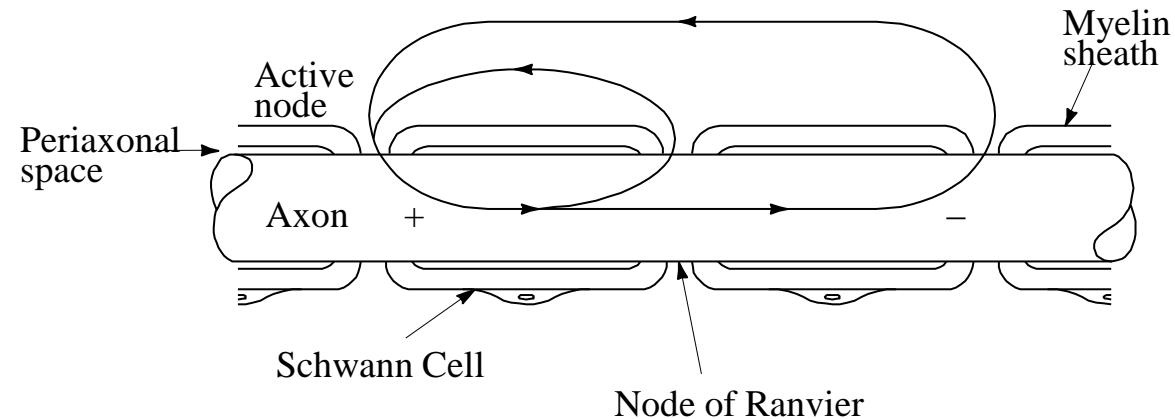
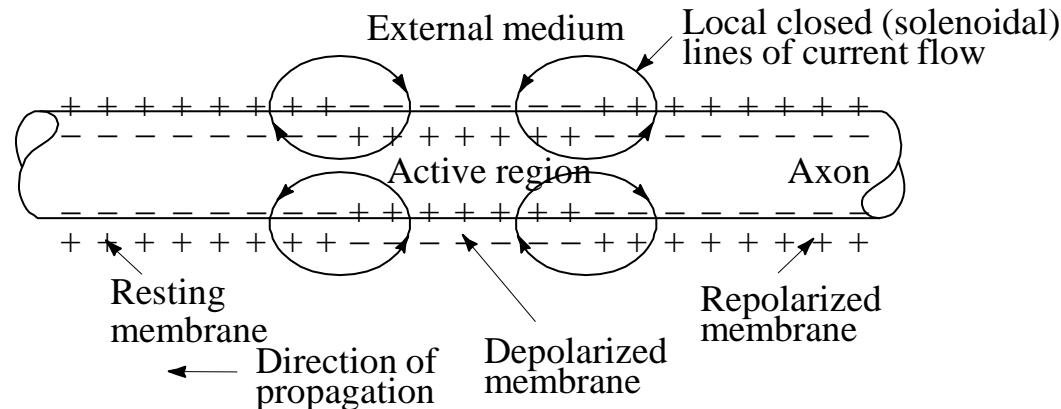
Absolute refractory period: membrane can not respond to any stimulus.

Relative refractory period: membrane can respond to intense stimulus.



Action Potential

Action potential travel at one direction.



Myelination reduces leakage currents and improve transmission rate by a factor of approximately 20.

Events preceding an Action Potential: the decision between below-threshold events and spikes

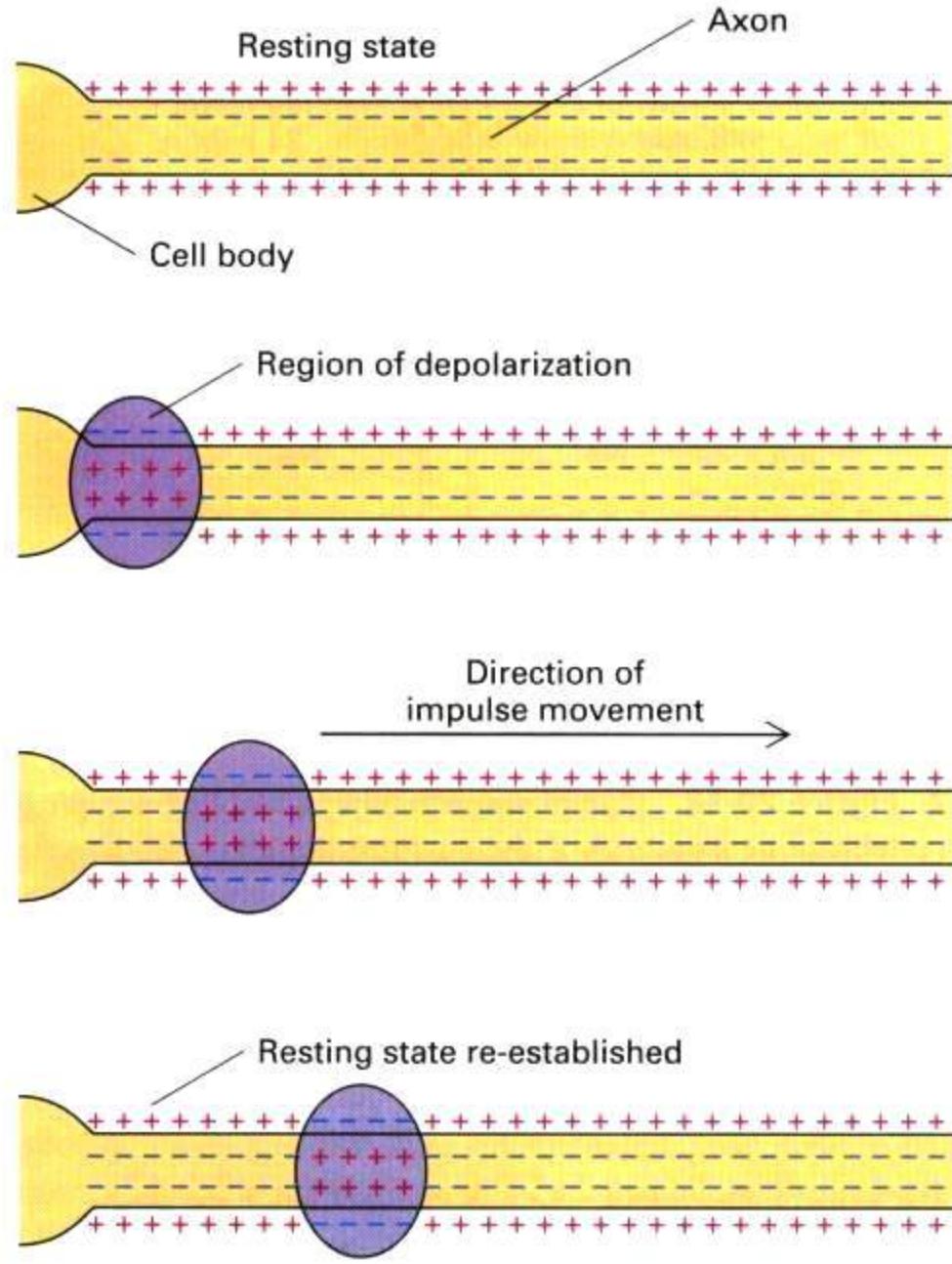
When the resting membrane potential is changed in a depolarizing direction, there are always two forces working to oppose the change and one that supports it:

- 1) Oppose: K^+ will experience a greater driving force and move out through its resting permeability channels, carrying + charge.
- 2) Oppose: Cl^- will no longer be at equilibrium, and will move inside, carrying - charge.
- 3) Support: Some of the voltage-sensitive channels may open, allowing more Na^+ to come in.

Threshold : when your chances are 50/50

- If the restoring forces win, then the membrane potential will not initiate an action potential and the charge on the membrane charge will return to resting level.
- If the depolarizing change drives the membrane excitatory elements faster than the forces of recovery can oppose it, then for each open voltage-sensitive Na^+ channel, many Na^+ ions will enter and depolarize the interior more, directly driving the opening of more voltage-gated channels in adjacent regions of membrane. This produces the all-or nothing action potential.

How the positive internal potential changes the permeability, first opening voltage-sensitive Na^+ channels, and then opening voltage-sensitive K^+ channels, restoring the region behind the action potential so it is ready to carry another action potential.

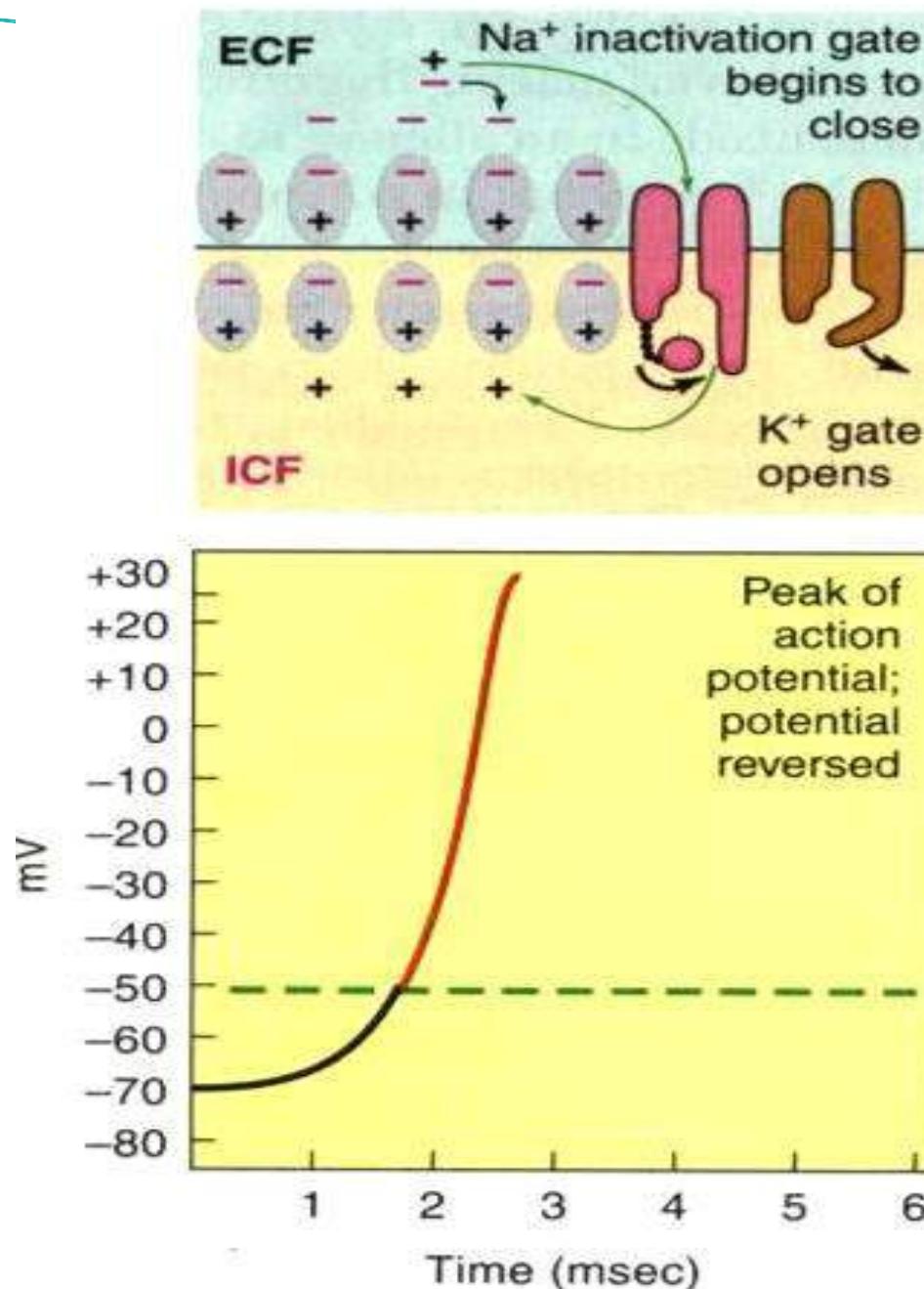


Events in the upswing of the action potential

- Many channels that allow Na^+ to pass through are open, Na^+ rushes into the cell, making the inside positively charged.

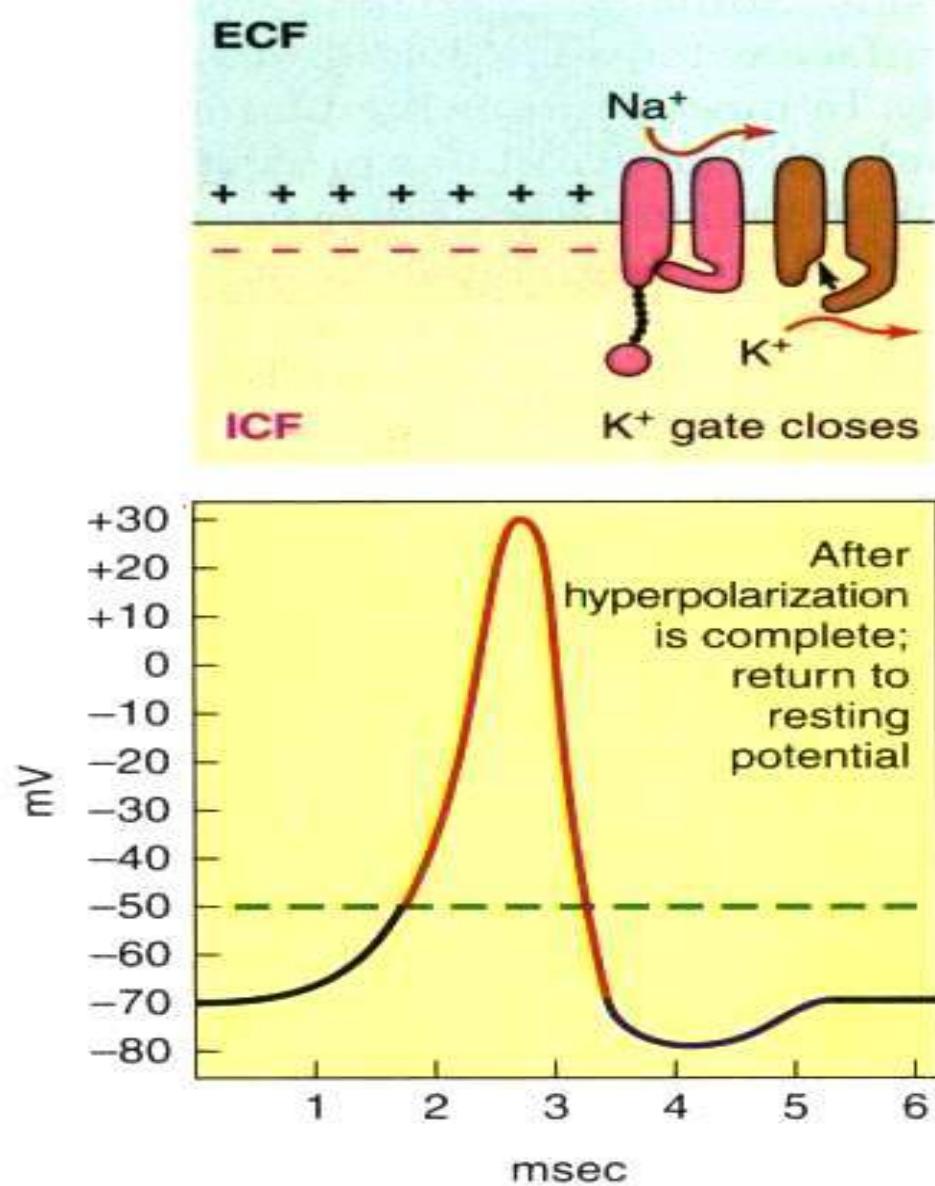
- Two factors prevent the cell from reaching the Na^+ equilibrium potential:

1. The driving force for Na^+ diminishes as the inside of the cell becomes +, because this repels Na^+ .
2. The slower-opening voltage-gated K^+ channels are opening, allowing K^+ to carry + charge out of the cell.



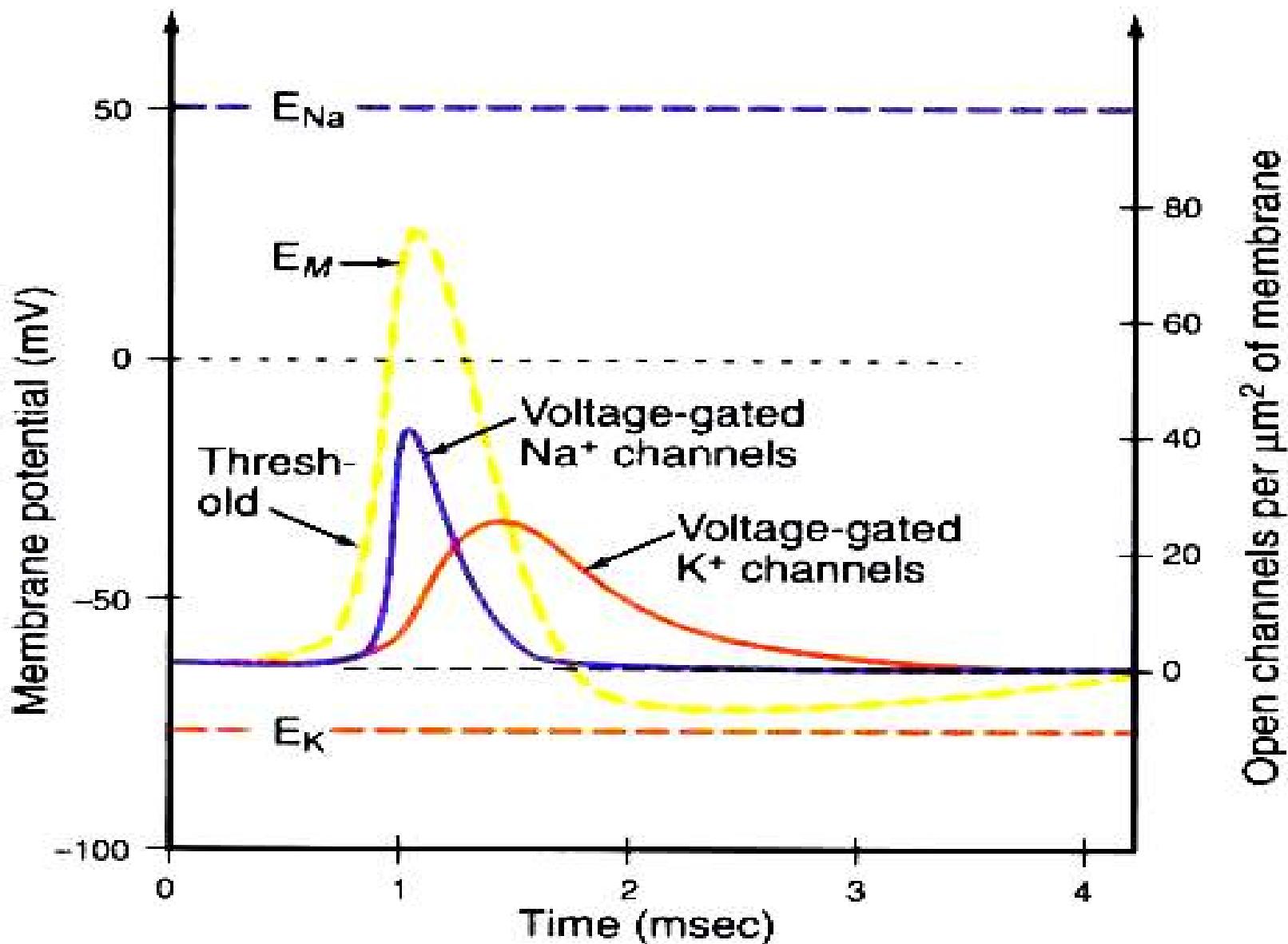
Events in the conclusion of an Action Potential

1. The voltage-gated Na^+ channels are becoming inactivated (closing and unable to reopen, even though the membrane is still depolarized) and
2. The slower voltage-gated K^+ channels are opening, with K^+ repelled by the positive interior potential flooding out.
3. the membrane potential moves back toward the resting state and then becomes even more negative, until the extra K^+ gates close.)



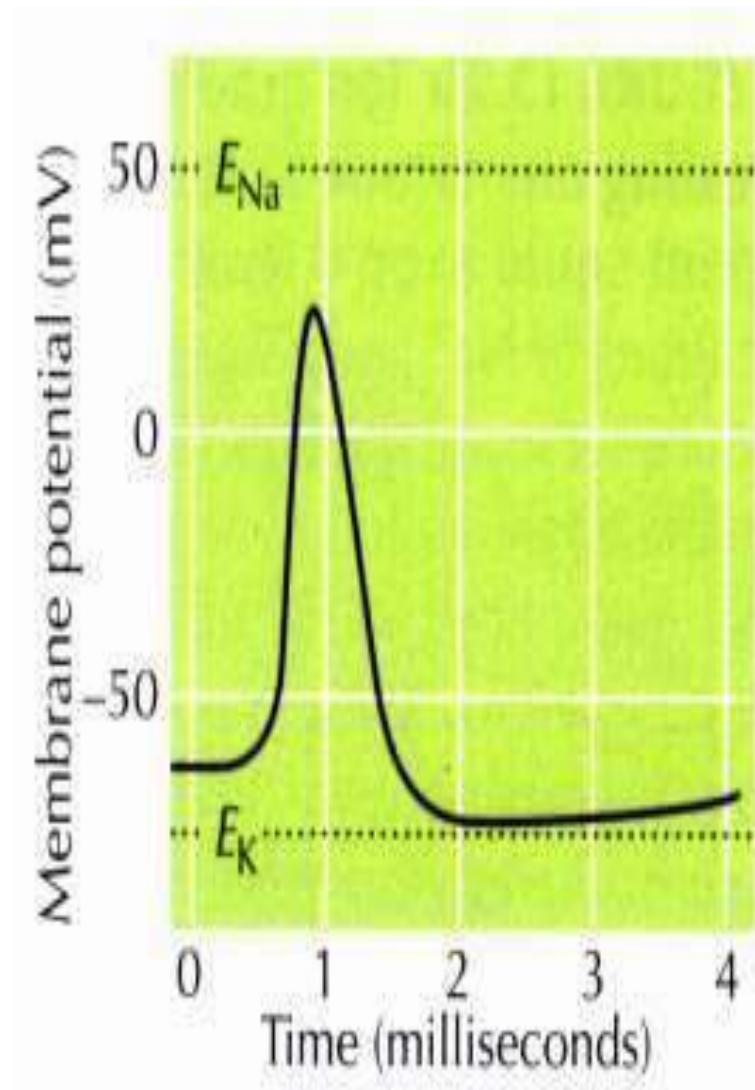
Then the K^+ gates close, and the membrane returns to resting potential.

A very important picture to understand:

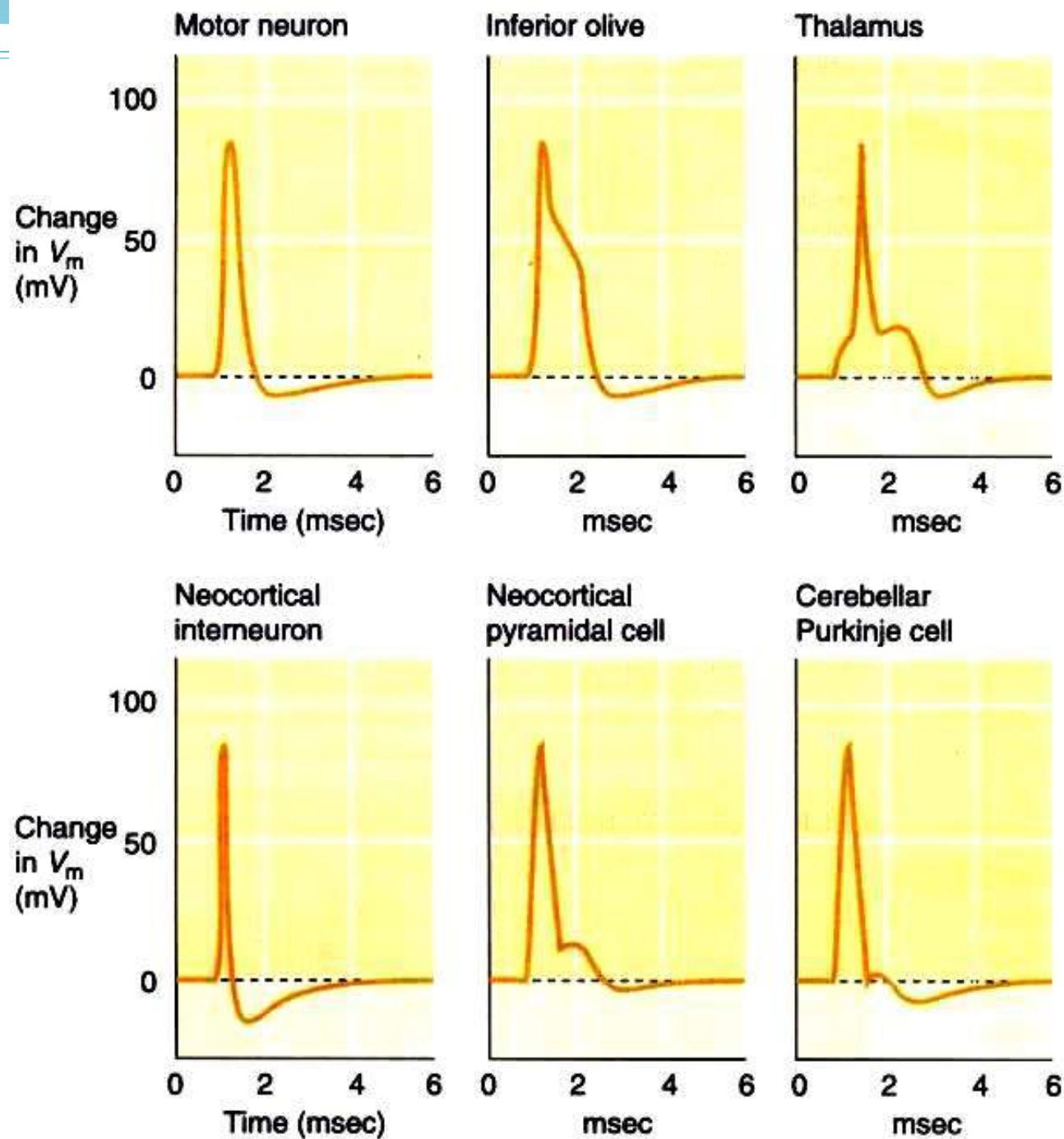


Definitions

- The resting membrane is **polarized**, internally negative.
- A change that makes the charge on the membrane more negative is a **hyperpolarizing** change.
- A change that makes the resting membrane potential less negative is **depolarizing**.
- When the influx of Na^+ makes the membrane potential cross zero and become internally positive, that is still viewed as “depolarizing”.



In the real world, neurons have a variety of additional channels that shape their action potentials



Channel performance details...

Na⁺ channels are relatively quick to respond to depolarization

Voltage-gated Na⁺ channels have 3 states:

1. Closed but responsive to voltage changes
2. Open
3. Closed and inactivated

(In this state, they are non-functional until hyperpolarization of the membrane potential resets their molecular structure so that they can again respond to depolarization by opening)

Voltage-gated K⁺ channels open more slowly in response to depolarization and are less synchronized in their response.

Voltage-gated K⁺ channels have only open and closed states

How is the Na^+ inactivation removed?

The normal events of the action potential, with its after-hyperpolarization, during which the extra open K^+ channels are allowing the membrane potential to more closely approach the K^+ equilibrium potential, is the perfect situation for getting the voltage-sensitive Na^+ channels back into a responsive state. The additional internally negative potential “pulls” on the molecule to return the channels to a closed but not inactivated state.

No big or small action potentials!

- The action potential is a stereotyped event in which the timing of the opening of voltage-gated channels allows the membrane to approach, but not reach the Na^+ equilibrium potential. By the time the membrane potential has risen above zero, the opposing force of K^+ moving outward through the open voltage-gated K^+ channels is allowing exit of $+$ to oppose entry of Na^+ . Soon, the combined effect of Na^+ channel inactivation and $+$ charge carried out by K^+ ions takes the membrane potential back in a negative direction, and it becomes hyperpolarized before it gradually returns to resting level. Each action potential goes through the same approach to the Na^+ equilibrium potential before it turns around and restores the resting state.

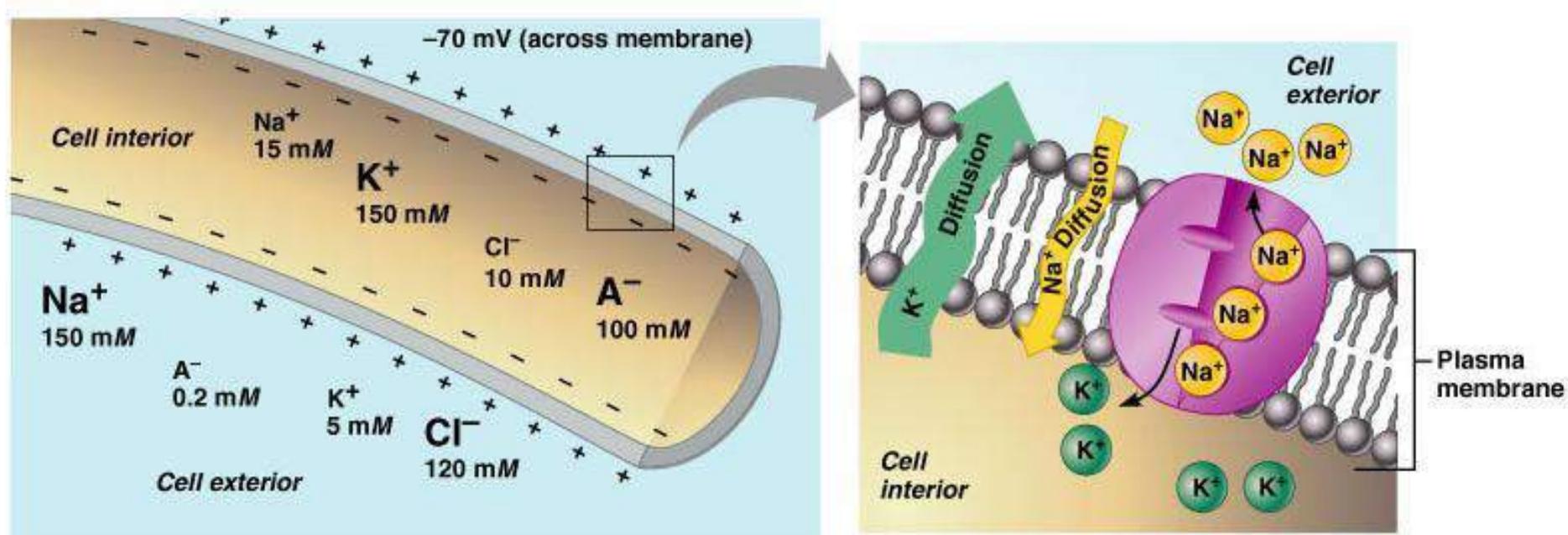
Resting Membrane Potential (V_r) -

- The potential difference (-70 mV) across the membrane of a resting neuron
- It is generated by different concentrations of Na^+ , K^+ , Cl^- , and protein anions (A^-)
- Ionic differences are the consequence of:
 - Differential permeability of the membrane to Na^+ and K^+
 - Operation of the sodium-potassium pump

The resting potential

- K^+ ions slowly leak through K^+ pore channels
- The membrane has a poor permeability to Na^+ ions so they cannot get in to the neurone
- This brings about the membrane potential of neurones
- As the K^+ leaks out the inside of the resting cell becomes more negatively charged

Resting Membrane Potential (V_r)



Passive movement of ions across a cell membrane

- The **concentration gradient**: causing the ions to diffuse down their concentration gradient
- The **electrical potential**: causing ions to be attracted to the opposite charge to the one they carry

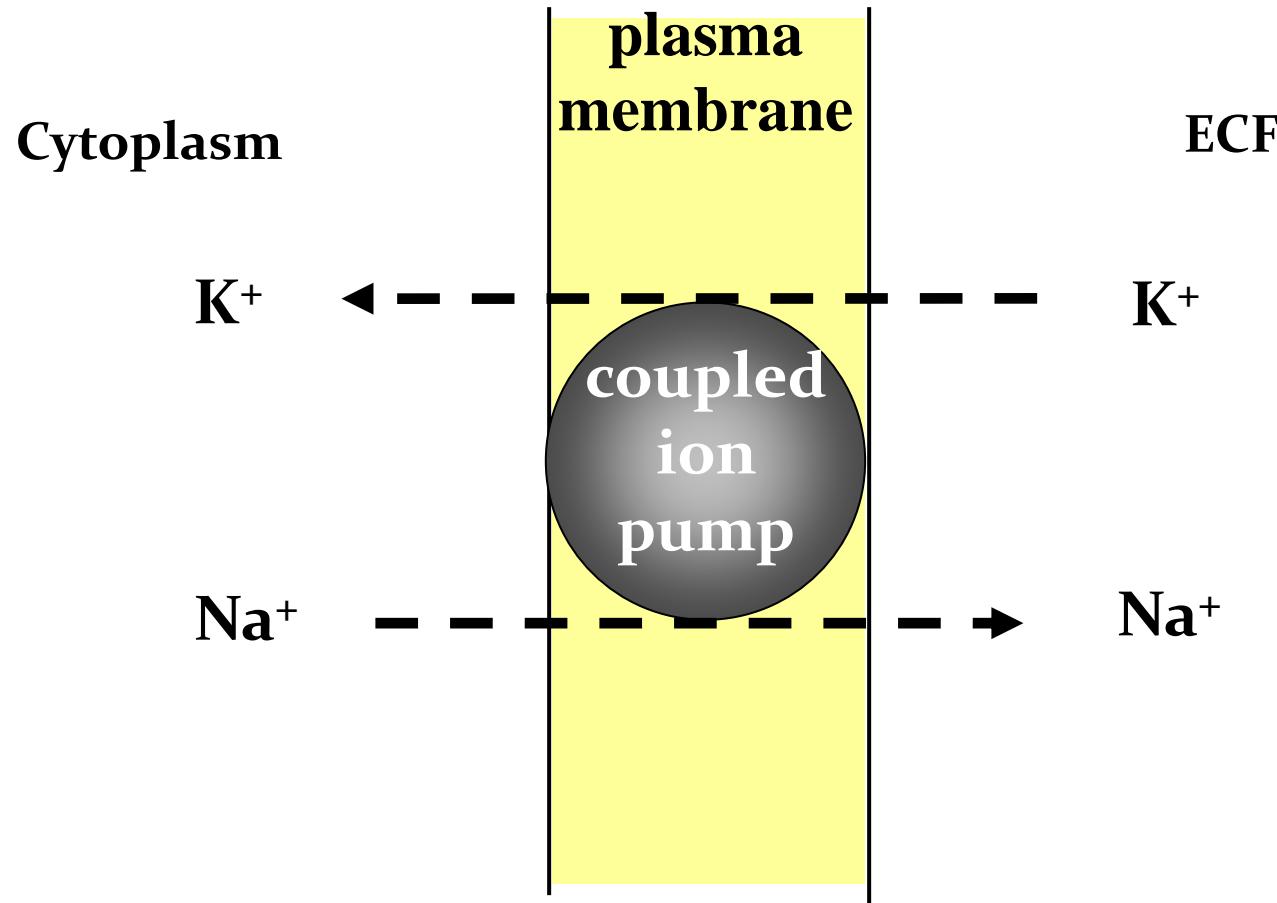
Potassium & Sodium Ions

- The two important ions in a nerve cell (neurone or neuron) are K^+ and Na^+
- Both are cations (positively charged ions)
- Na^+ ions move more slowly across the membrane than K^+ or Cl^- ions
- This is because although the Na^+ ion is smaller than the K^+ ion
 Na^+ has a larger coating of water molecules giving it a bigger diameter
- This makes the plasma membrane 25 times more permeable to K^+ than Na^+

Potassium & Sodium Ions

- In addition to this K^+ ions leak out of **K^+ ion pores** when the nerve cell is at rest
- So to maintain the high concentration of K^+ inside the cell, it has to be actively pumped inwards a bit when the cell is at rest
- The result is that the resting potential of the neurone is almost at the equilibrium for K^+ ions
- **K^+ leak out a bit and need pumping in**
- **Na^+ ions, however, are actively pumped out and kept out**

A coupled Na⁺-K⁺ pump



Getting excited!

- As the neurone's membrane at rest is more negative inside than outside, it is said to be **polarised**
- Neurones are **excitable cells**
- The cells are excited when their membranes become **depolarised**

Depolarisation

Depolarising membranes may be achieved by:

- a stimulus arriving at a receptor cell
(e.g. vibration of a hair cell in the ear)
- a chemical fitting into a receptor site
(e.g. a neurotransmitter)
- a nerve impulse travelling down a neurone

Nerve impulses

- Nerve impulses are self-propagating like a trail of gunpowder
- Localised currents in the ions occur just ahead of the impulse causing localised depolarisation
- Nerve impulses are not like electrical signals travelling down a wire

The action potential

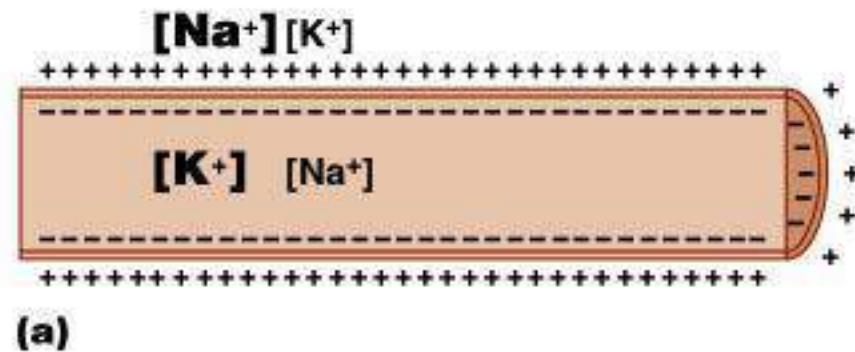
- The action potential is the state of the neurone membrane when a nerve impulse passes byA small change in the membrane voltage will depolarise the membrane enough to flip open Na^+ channels
- These are called **voltage-gated Na^+ channels**
- As Na^+ moves into the cell more and more Na^+ channels open
- A small change in the membrane permeability to Na^+ results in a **big change** in membrane potential
- This is because the volume of the axon is minute compared to the volume of the extracellular fluid

Action Potential

- A transient depolarization event that includes polarity reversal of a sarcolemma (or nerve cell membrane) and the propagation of an action potential along the membrane

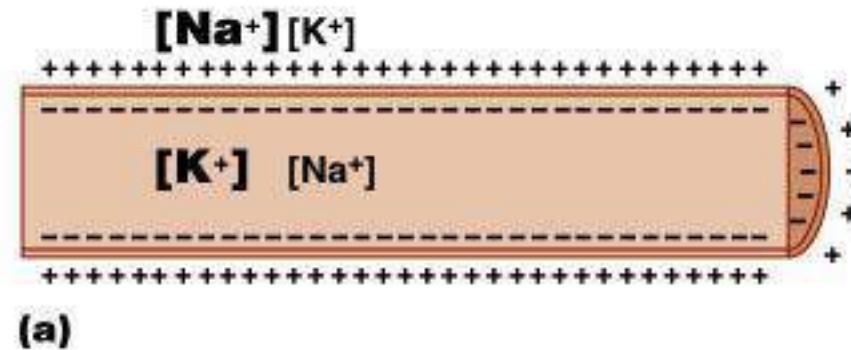
Action Potential: Electrical Conditions of a Polarized Cell

- The outside (extracellular) face is positive, while the inside face is negative
- This difference in charge is the resting membrane potential



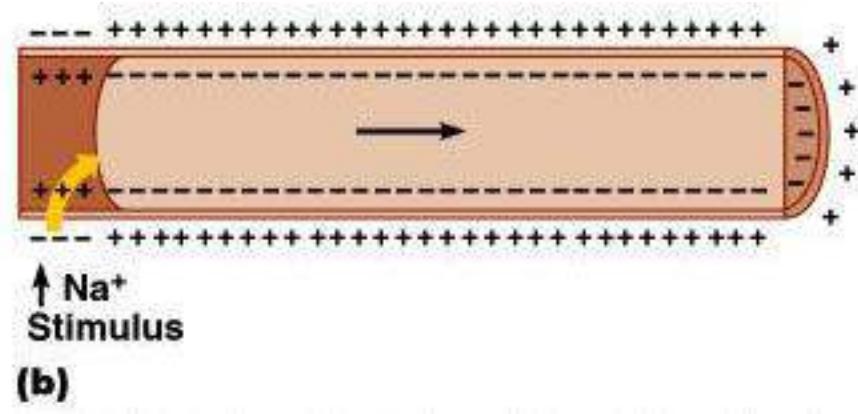
Action Potential: Electrical Conditions of a Polarized Cell

- The predominant extracellular ion is Na^+
- The predominant intracellular ion is K^+
- The sarcolemma is relatively impermeable to both ions



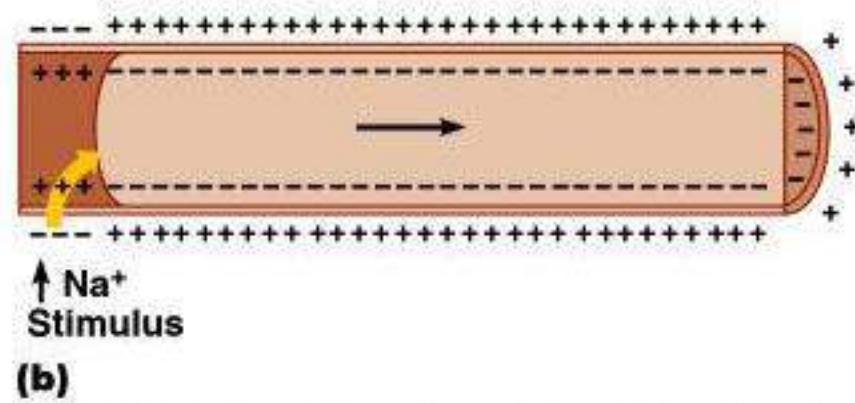
Action Potential: Depolarization and Generation of the Action Potential

- An axonal terminal of a motor neuron releases ACh and causes a patch of the sarcolemma to become permeable to Na^+ (sodium channels open)



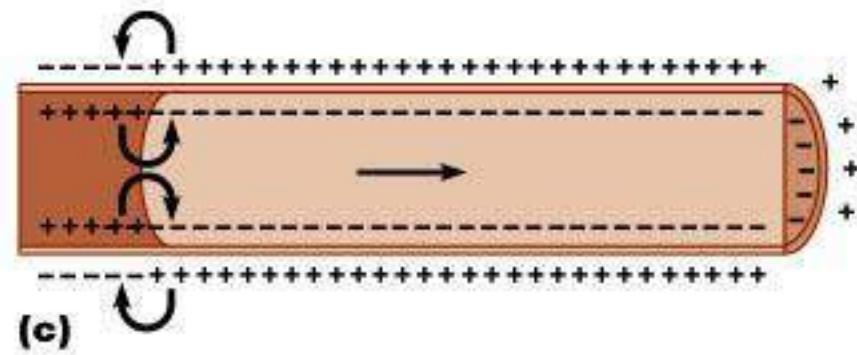
Action Potential: Depolarization and Generation of the Action Potential

- Na^+ enters the cell, and the resting potential is decreased (depolarization occurs)
- If the stimulus is strong enough, an action potential is initiated



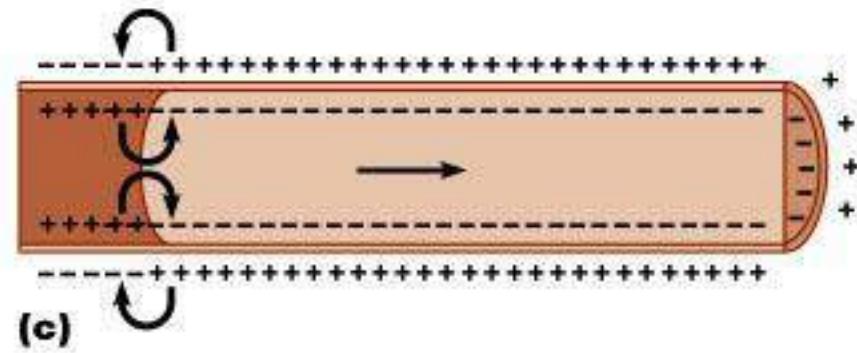
Action Potential: Propagation of the Action Potential

- Polarity reversal of the initial patch of Cell changes the permeability of the adjacent patch
- Voltage-regulated Na^+ channels now open in the adjacent patch causing it to depolarize



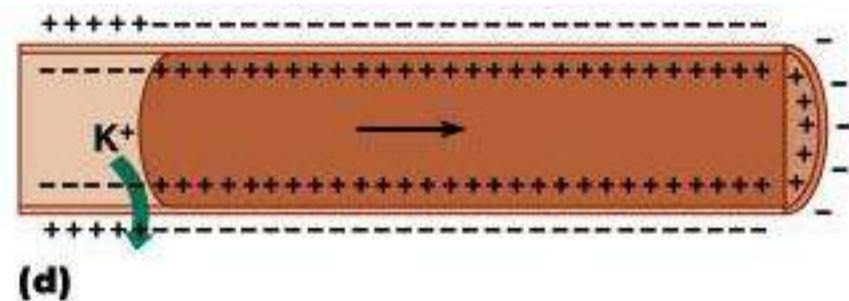
Action Potential: Propagation of the Action Potential

- Thus, the action potential travels rapidly along the cell
- Once initiated, the action potential is unstoppable, and ultimately results in the contraction of a muscle



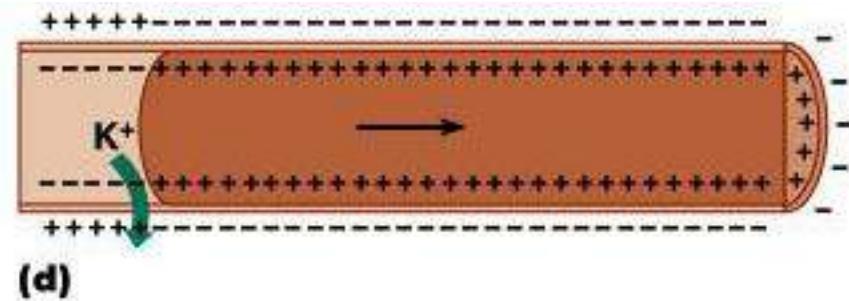
Action Potential: Repolarization

- Immediately after the depolarization wave passes, the cell permeability changes
- Na^+ channels close and K^+ channels open
- K^+ diffuses from the cell, restoring the electrical polarity of the cell



Action Potential: Repolarization

- Repolarization occurs in the same direction as depolarization, and must occur before the muscle can be stimulated again (refractory period)
- The ionic concentration of the resting state is restored by the $\text{Na}^+ \text{-} \text{K}^+$ pump



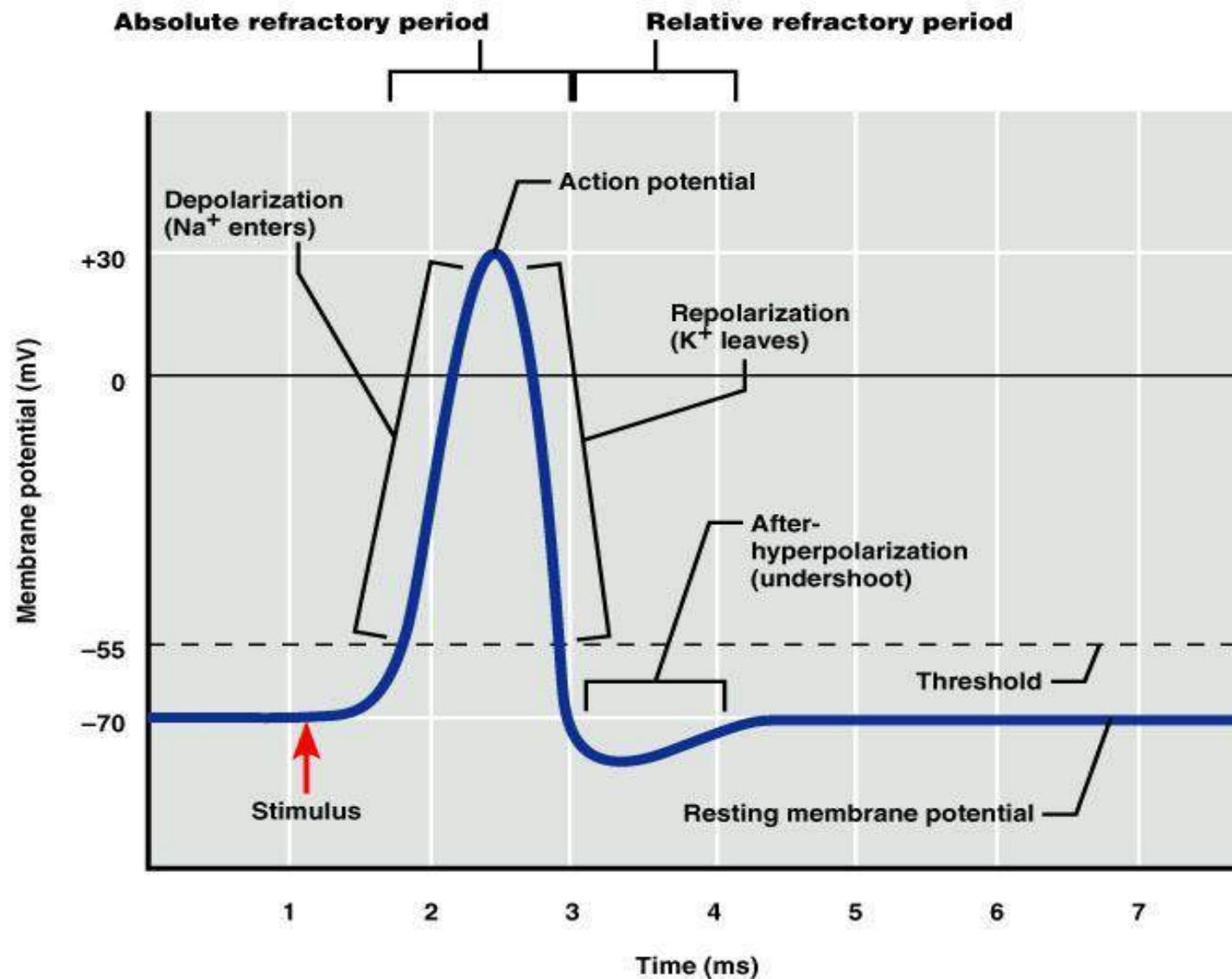
Absolute Refractory Period

- Time from the opening of the Na^+ activation gates until the closing of inactivation gates
- The absolute refractory period:
 - Prevents the neuron from generating an action potential
 - Ensures that each action potential is separate
 - Enforces one-way transmission of nerve impulses

Relative Refractory Period

- The interval following the absolute refractory period when:
 - Sodium gates are closed
 - Potassium gates are open
 - Repolarization is occurring
- The threshold level is elevated, allowing strong stimuli to increase the frequency of action potential events

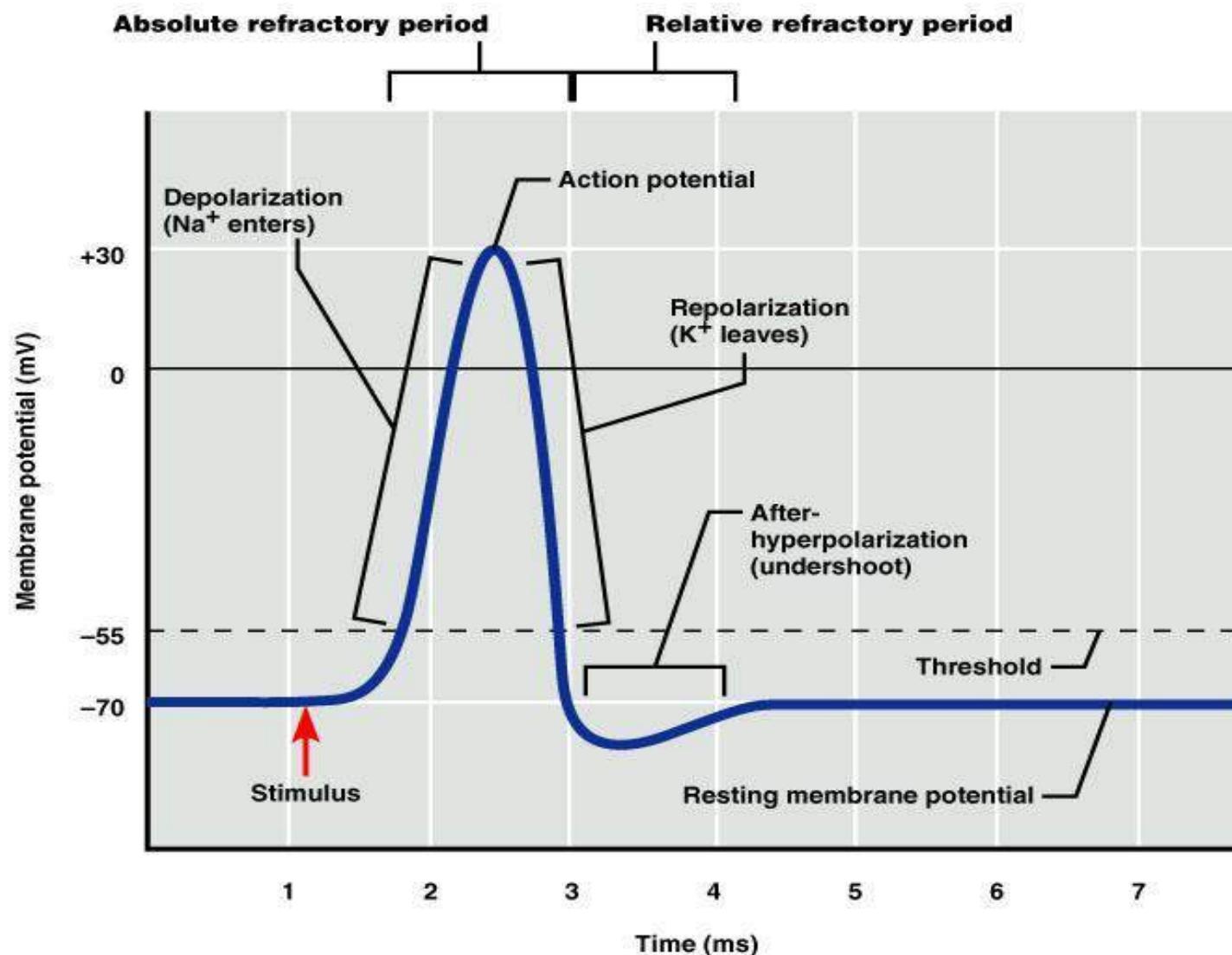
Absolute Refractory Period



Hyperpolarization

- Occurs when membrane potential increases
- Inside of membrane becomes more negative

Absolute Refractory Period



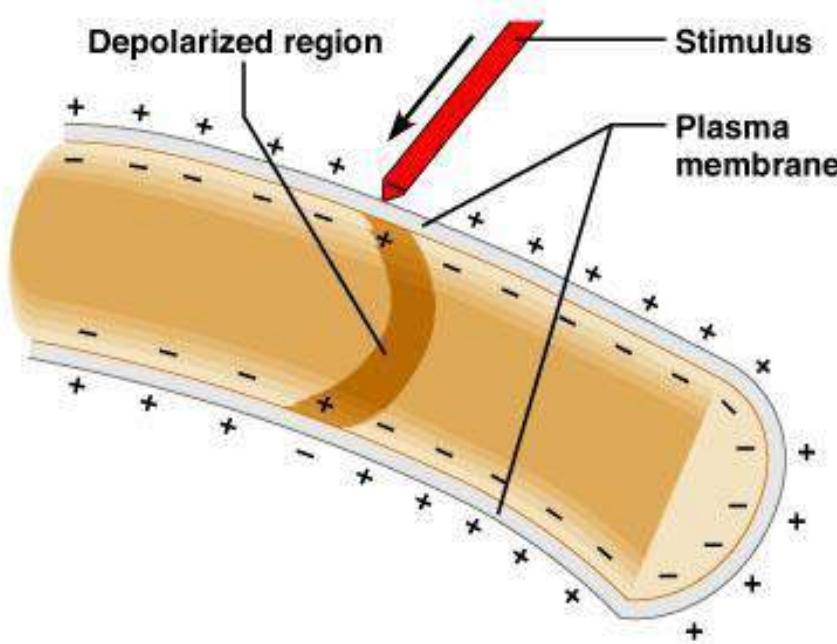
Membrane Potentials: Signals

- Used to integrate, send, and receive information
- Membrane potential changes are produced by:
 - Changes in membrane permeability to ions
 - Alterations of ion concentrations across the membrane
- Types of signals – graded potentials and action potentials

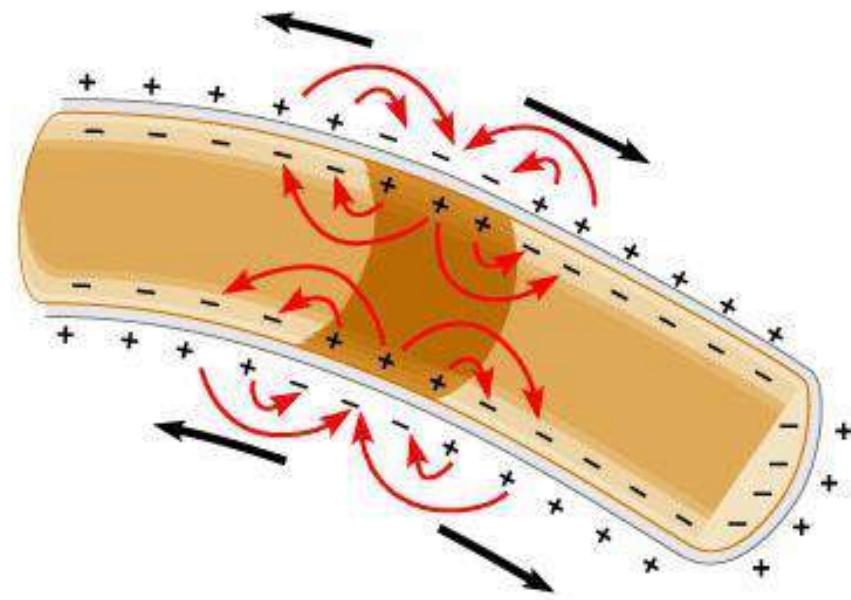
Graded Potentials

- Short-lived, local changes in membrane potential
- Decrease in intensity with distance
- Their magnitude varies directly with the strength of the stimulus
- Sufficiently strong graded potentials can initiate action potentials

Graded Potentials



(a) Depolarization



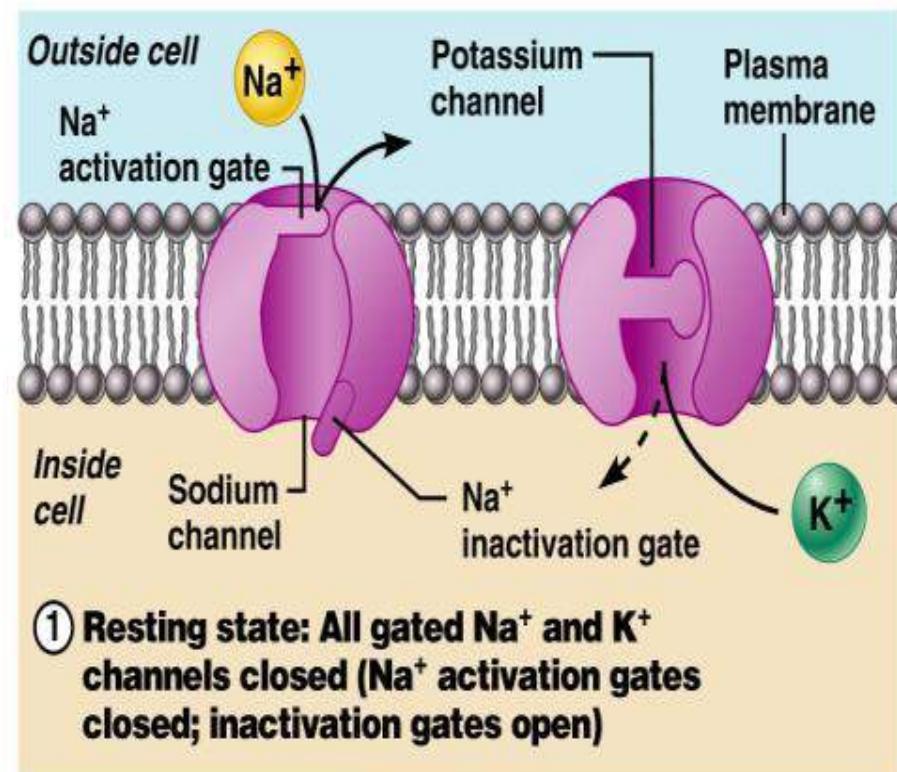
(b) Spread of depolarization

Action Potentials (APs)

- A brief reversal of membrane potential with a total amplitude of 100 mV
- Action potentials are only generated by muscle cells and neurons
- They do not decrease in strength over distance
- They are the principal means of neural communication
- An action potential in the axon of a neuron is a nerve impulse

Action Potential: Resting State

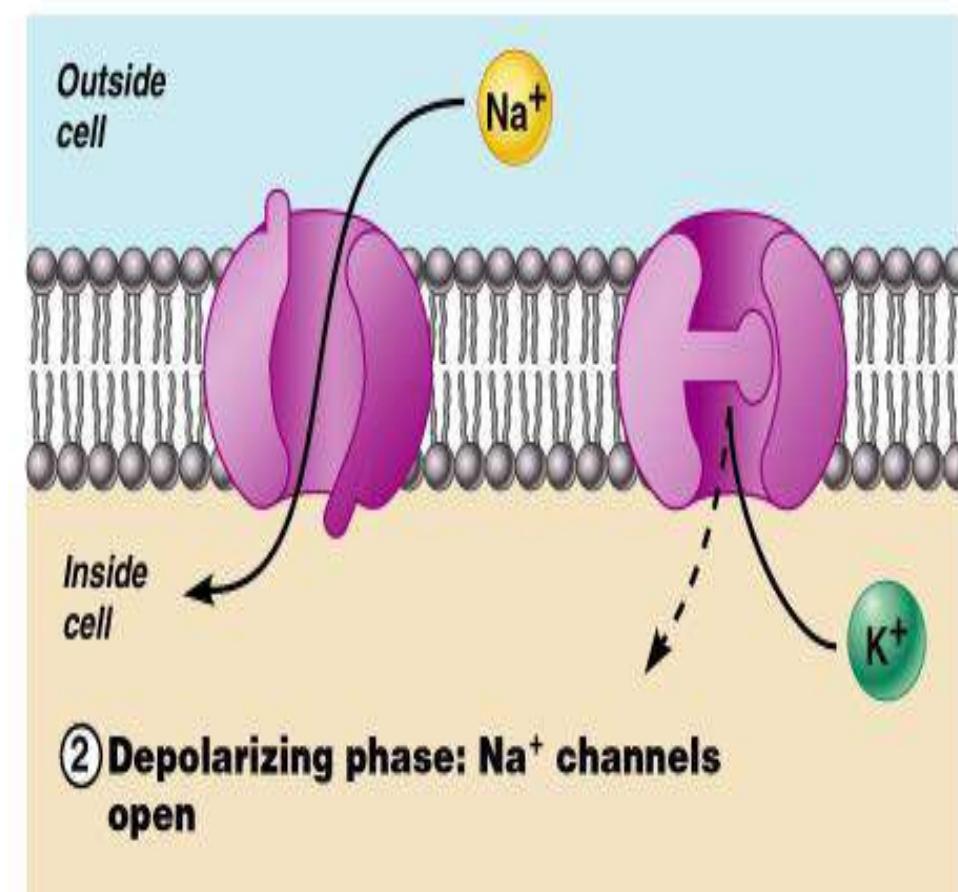
- Na^+ and K^+ channels are closed
- Leakage accounts for small movements of Na^+ and K^+
- Each Na^+ channel has two voltage-regulated gates
 - Activation gates – closed in the resting state
 - Inactivation gates – open in the resting state



Action Potential: Depolarization

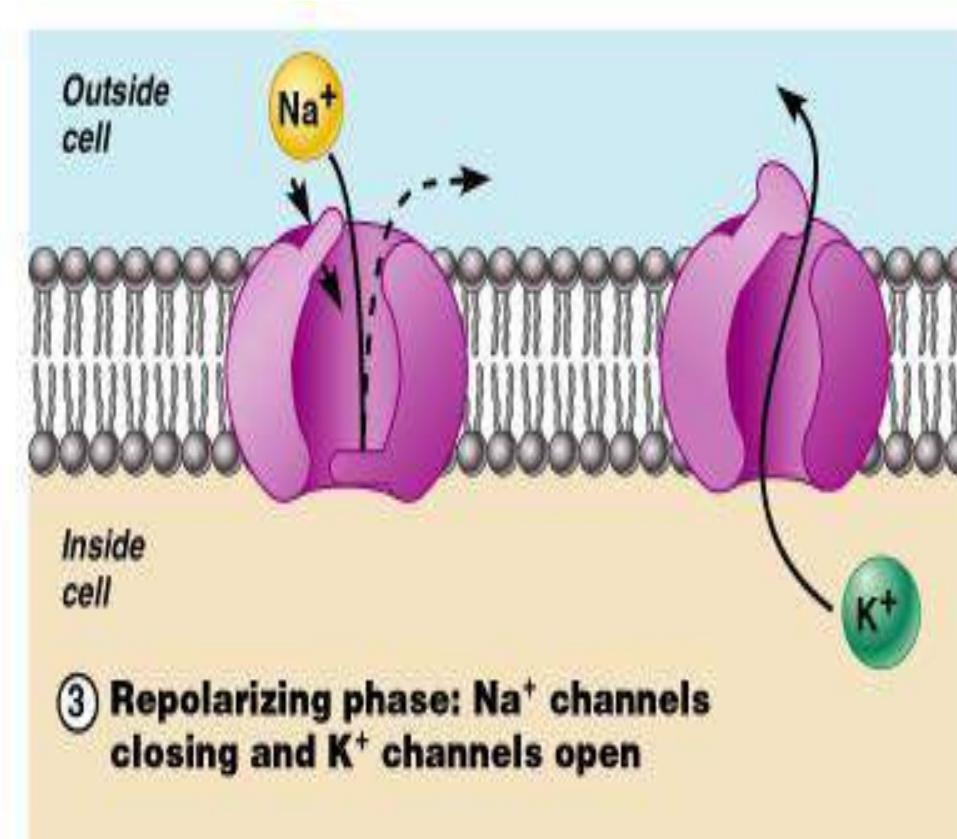
Phase

- Na^+ permeability increases; membrane potential reverses
- Na^+ gates are opened; K^+ gates are closed
- Threshold – a critical level of depolarization (-55 to -50 mV)
- At threshold, depolarization becomes self-generating



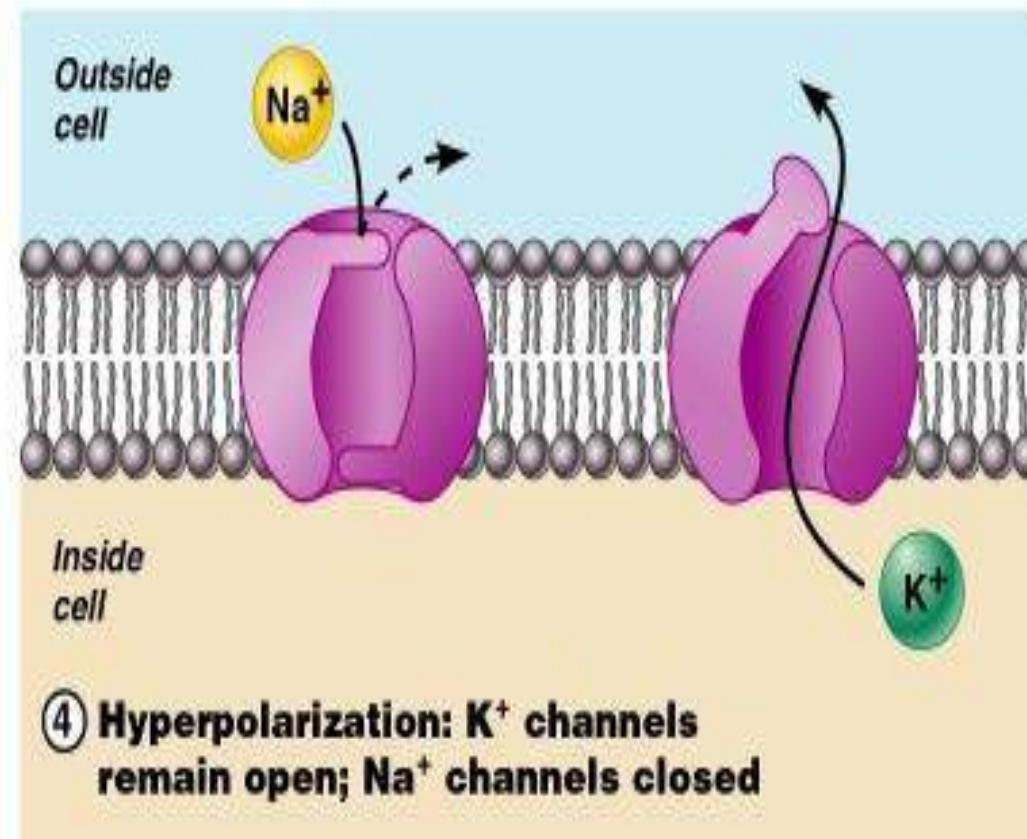
Action Potential: Repolarization Phase

- Sodium inactivation gates close
- Membrane permeability to Na^+ declines to resting levels
- As sodium gates close, voltage-sensitive K^+ gates open
- K^+ exits the cell and internal negativity of the resting neuron is restored



Action Potential: Hyperpolarization

- Potassium gates remain open, causing an excessive efflux of K^+
- This efflux causes hyperpolarization of the membrane (undershoot)
- The neuron is insensitive to stimulus and depolarization during this time



Action Potential:

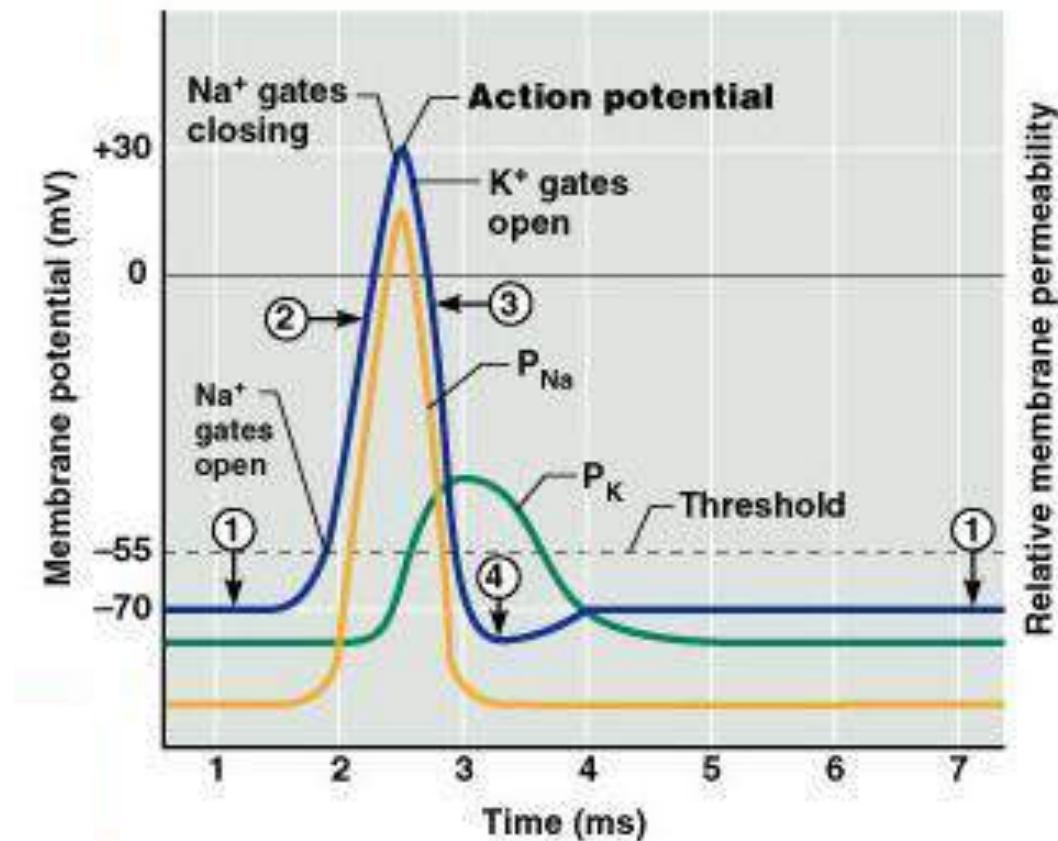
Role of the Sodium-Potassium Pump

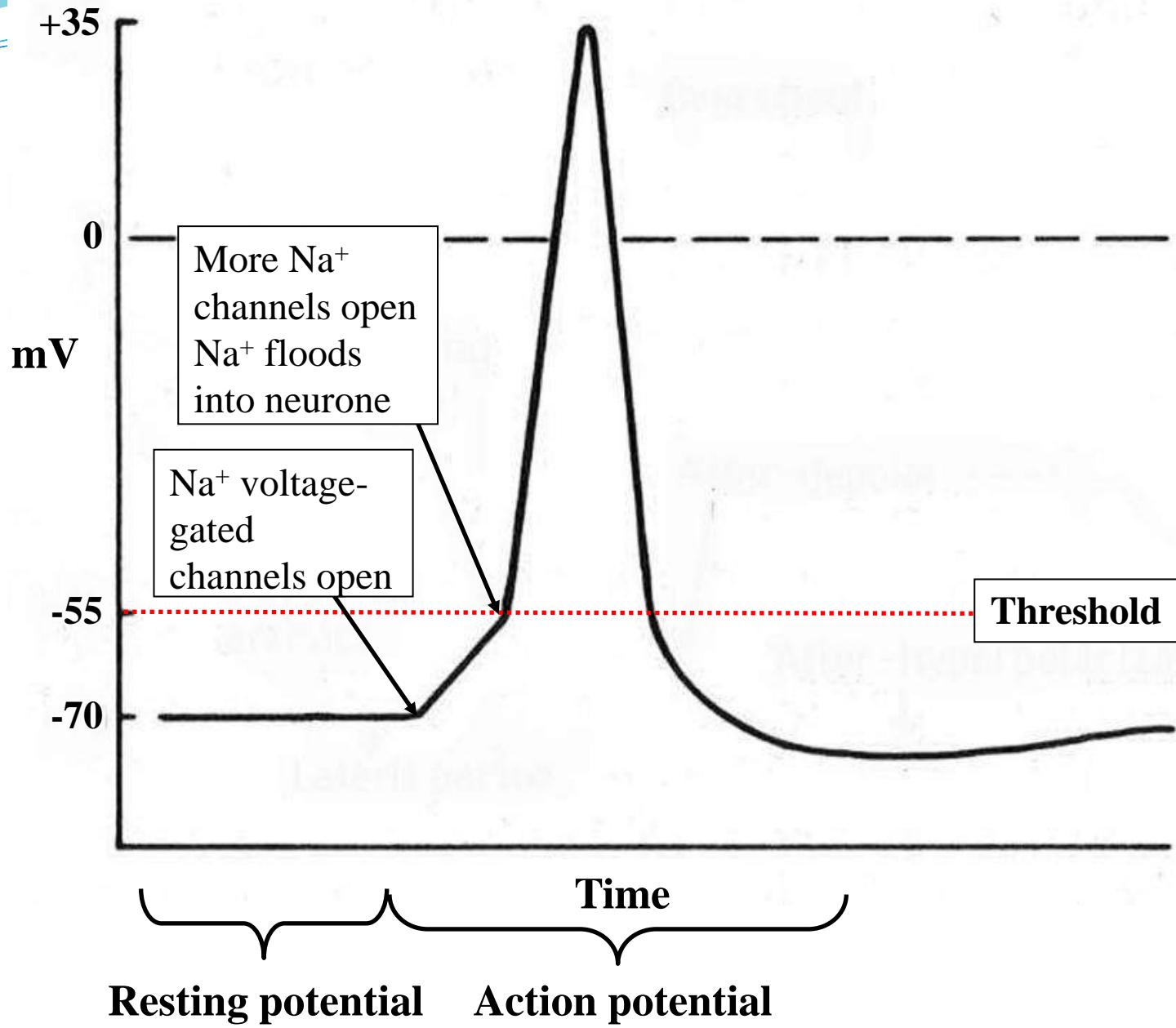
Pump

- Repolarization
 - Restores the resting electrical conditions of the neuron
 - Does not restore the resting ionic conditions
- Ionic redistribution back to resting conditions is restored by the sodium-potassium pump

Phases of the Action Potential

- 1 – resting state
- 2 – depolarization phase
- 3 – repolarization phase
- 4 – hyperpolarization



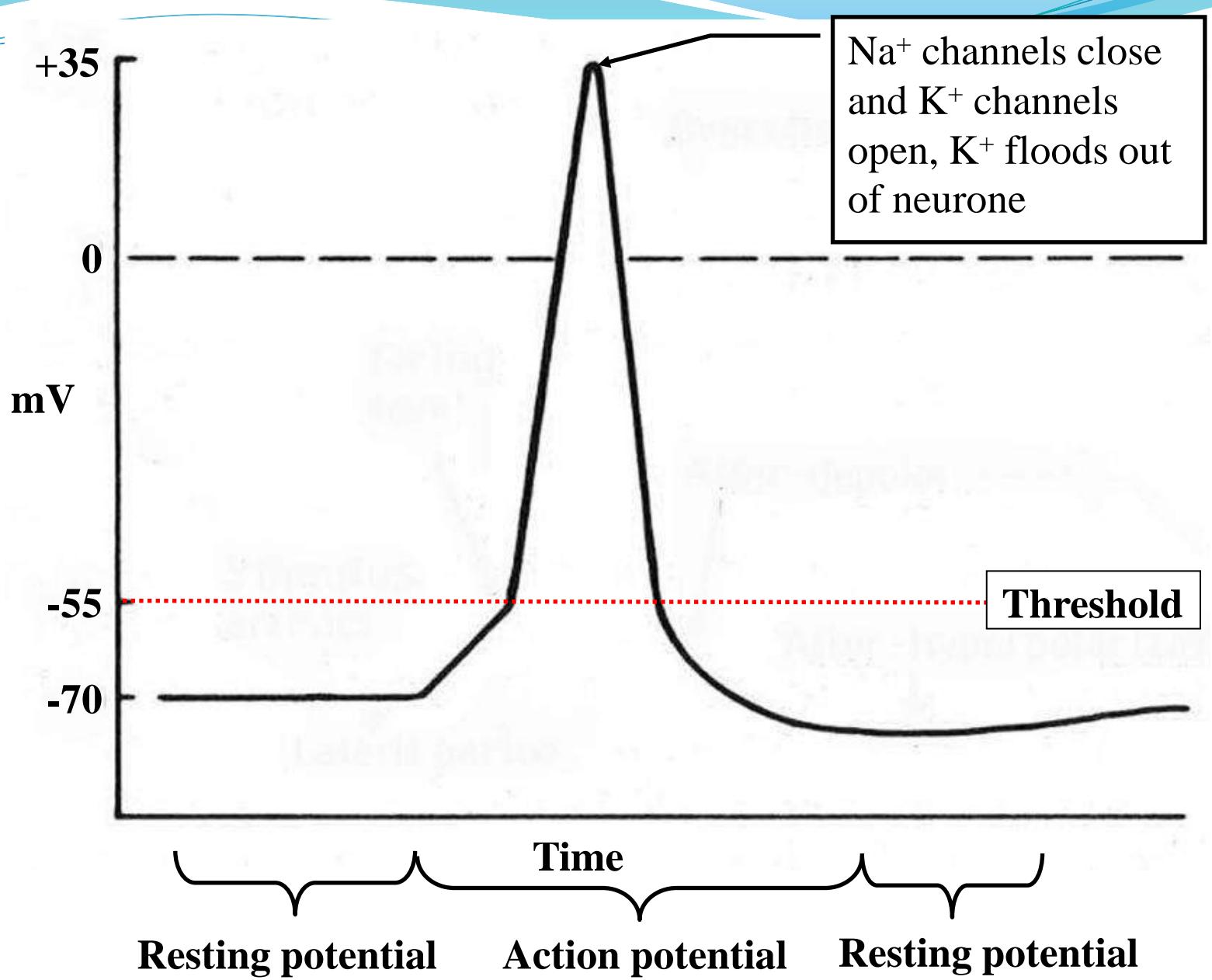


All-or-nothing

- As Na^+ moves in the cell will become more positive with respect to the outside
- The ion pumps resist the change in the membrane potential but it only has to rise by 15mV and the pumps cannot restore the equilibrium
- Na^+ floods in
- **Nerve impulses all look the same**, there are not big ones and little ones
- This is the **all-or-nothing law**

The threshold

- -55mV represents the **threshold potential**
- Beyond this we get a full action potential
- The membrane potential rises to $+35\text{mV}$ this is the peak of the action potential
- The cells are almost at the equilibrium for Na^+ ions

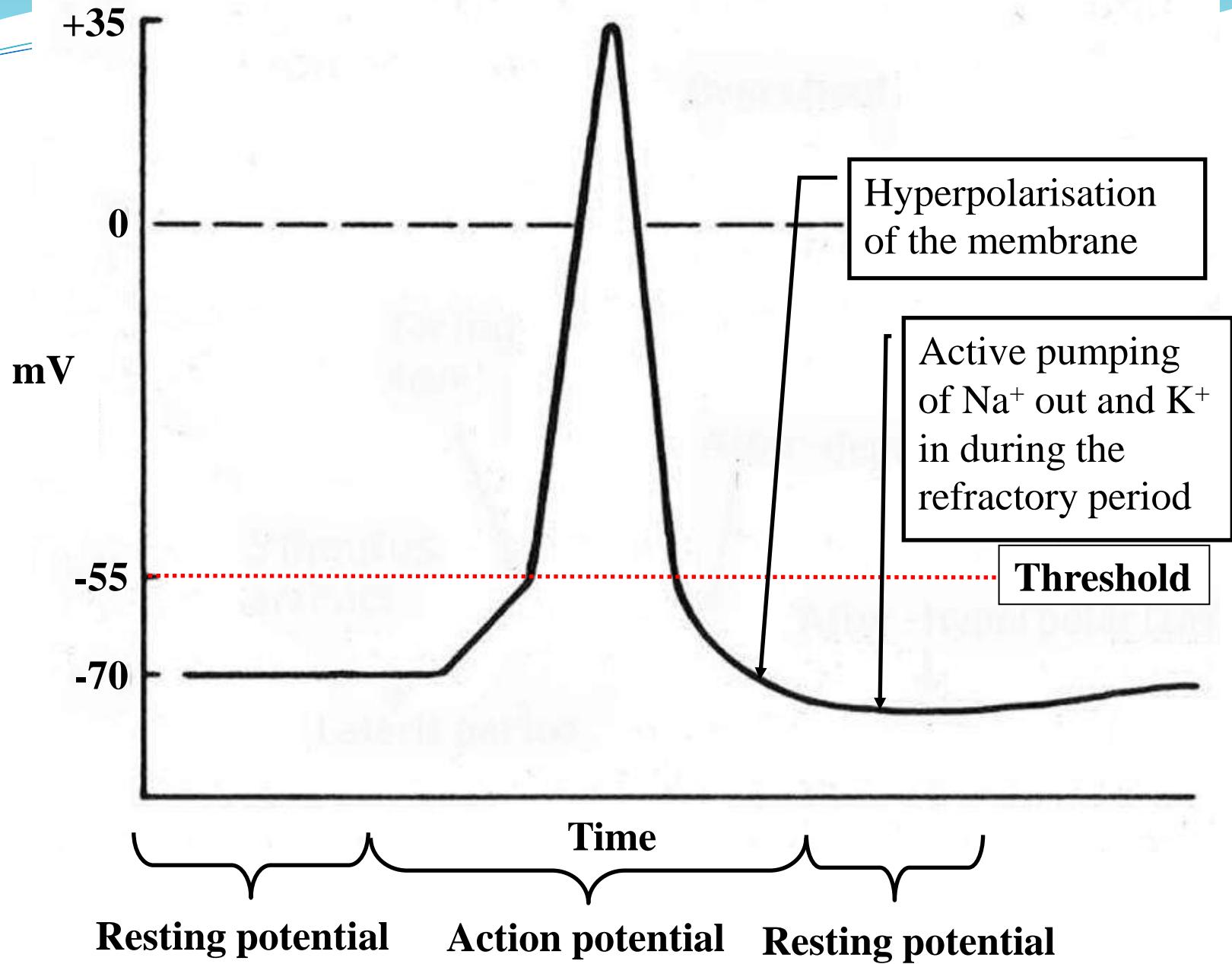


Potassium takes over

- After Na^+ moves in passively until the Na^+ channels start to close
- At the same time K^+ permeability increases as **voltage-gated K^+ channels** open – they are a bit slower to respond to the depolarisation than the Na^+ channels
- The K^+ ions move out
- This makes the cell negative inside with respect to outside again
- The membrane potential falls

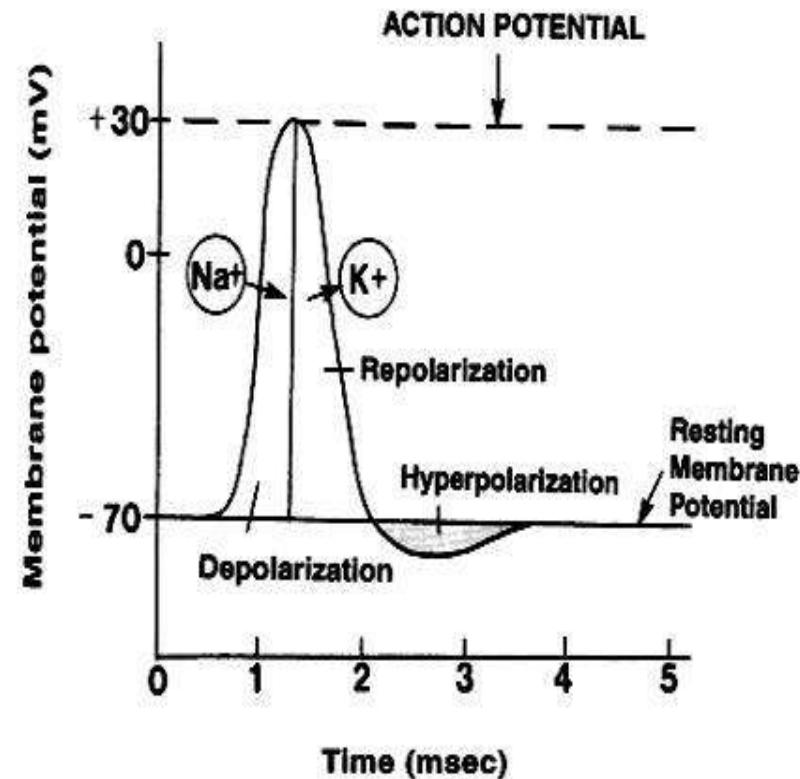
Hyperpolarisation

- The membrane potential falls below the resting potential of -70mV
- It is said to be **hyperpolarised**
- Gradually active pumping of the ions (K^+ in and Na^+ out) restores the resting potential
- During this period no impulses can pass along that part of the membrane
- This is called **the refractory period**

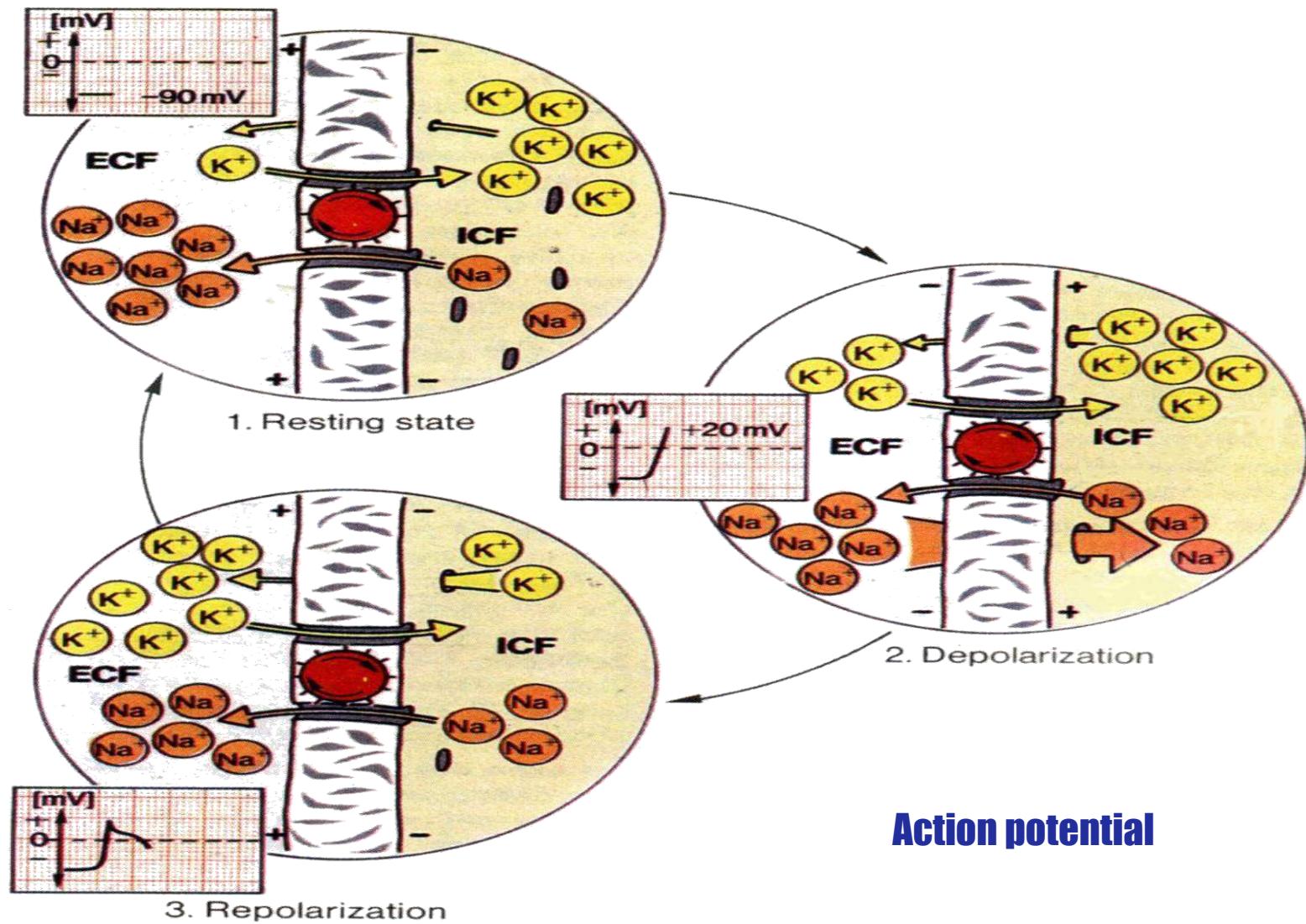


Depolarization

- Initially, this is a local electrical potential
- Later, it ignites an action potential
- directions across the sarcolemma
- Threshold – critical level of

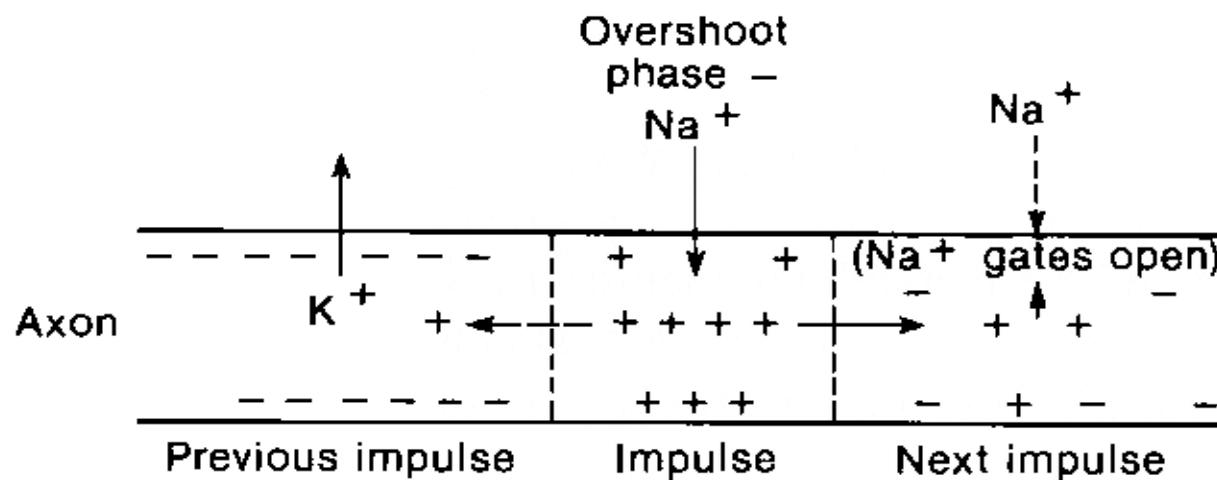
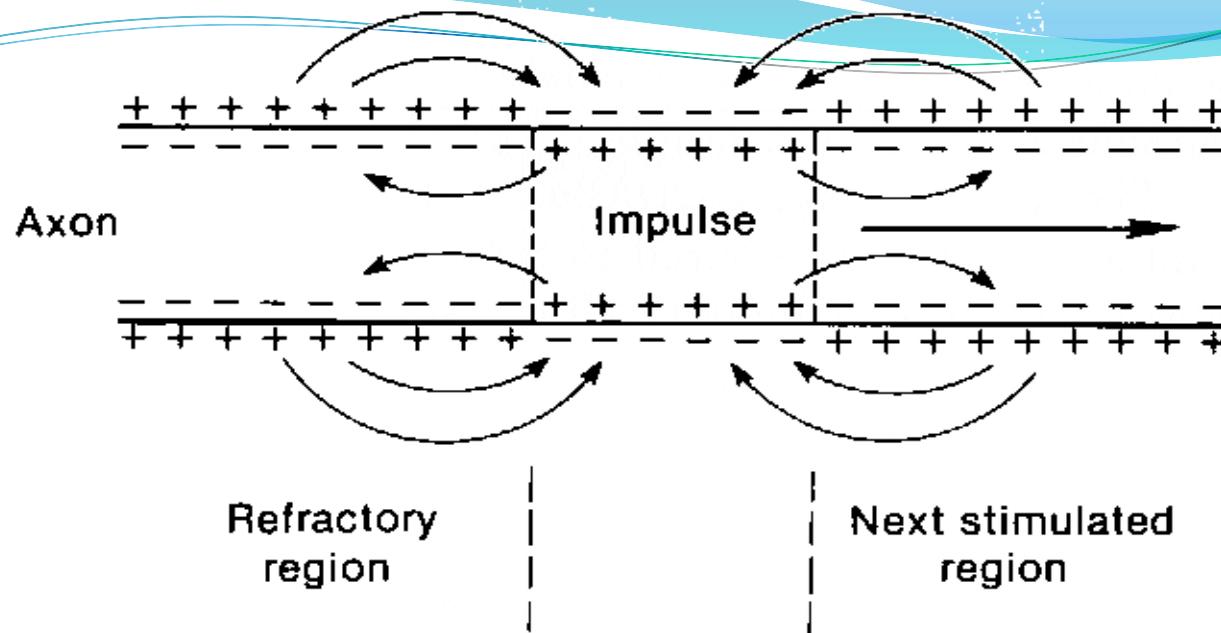


Bioelectric Phenomena



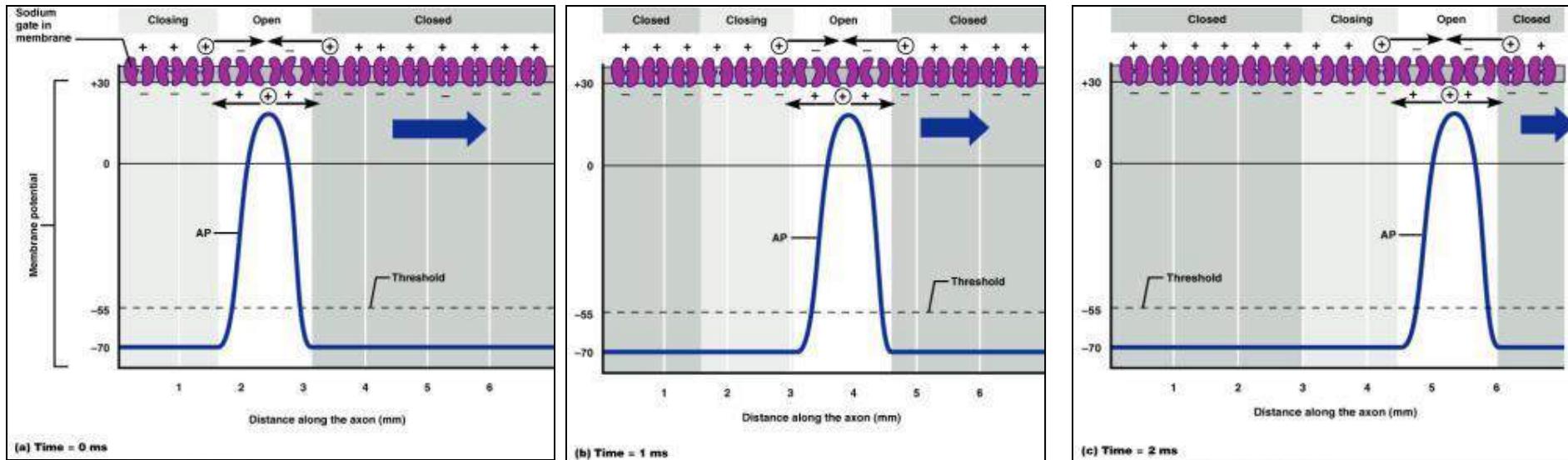
Action potential

*Propagation
of the action
potential*



Propagation of action potential

Propagation of an Action Potential



The action potential is self-propagating and moves away from the stimulus (point of origin)

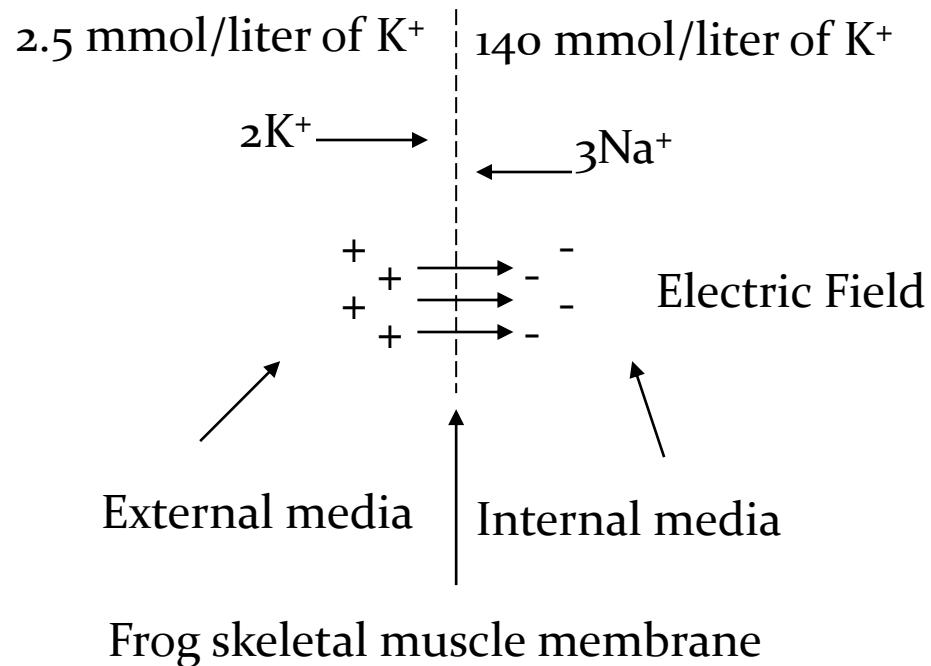
Sodium pump

Sodium-Potassium Pump

Keeping the cell at resting state requires active transport of ionic species against their normal electrochemical gradients.

Sodium-potassium pump is an active transport that transports Na^+ out of the cell and K^+ into the cell in ration $3\text{Na}^+ : 2\text{K}^+$

Energy for the pump is provided by a cellular energy adenosine triphosphate (ATP)



Equilibrium Potential- Nernst Equation

$$E_k = \frac{RT}{nF} \ln \frac{[K]_o}{[K]_i} = 0.0615 \log_{10} \frac{[K]_o}{[K]_i} \quad \text{At } 37^\circ\text{C}$$

Where n is the valence of K^+ .

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

E: Equilibrium transmembrane resting potential, net current is zero

P_M : permeability coefficient of the membrane for ionic species M

$[M]_i$ and $[M]_o$: the intracellular and extracellular concentrations of M in moles/ liter

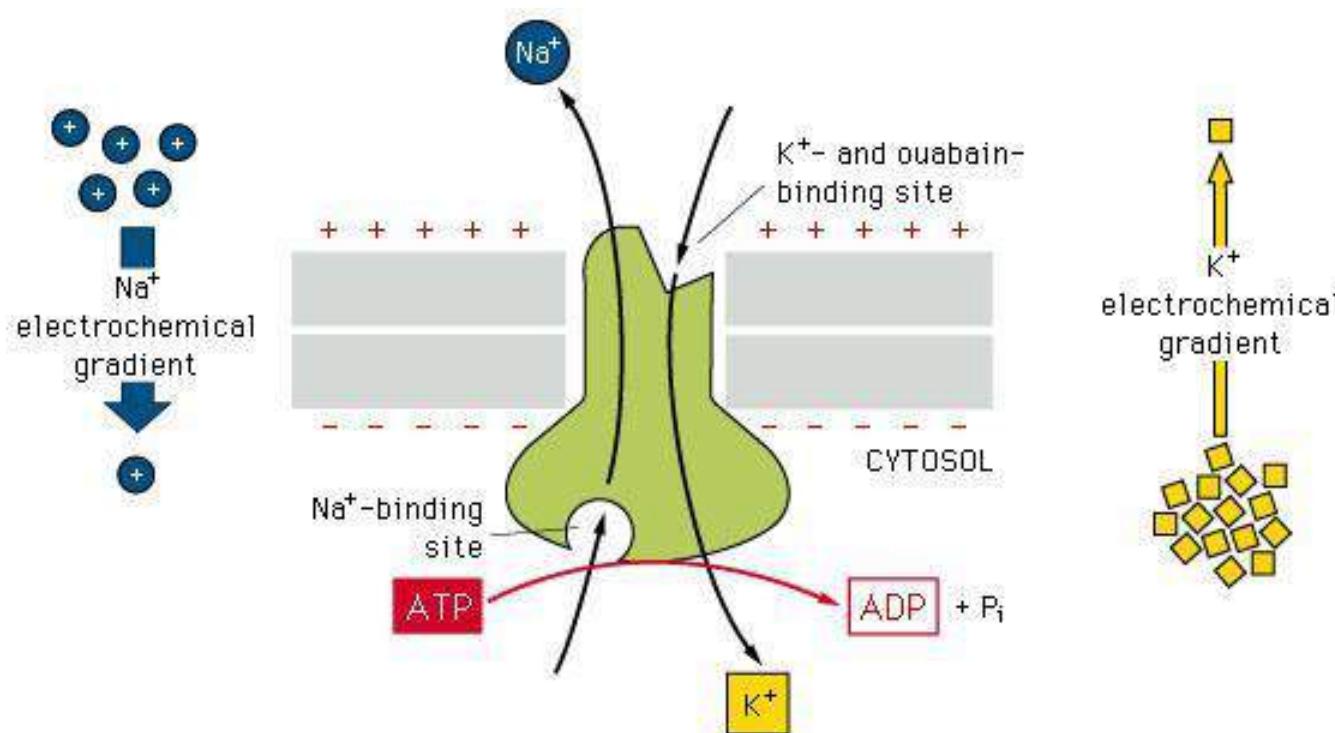
R: Universal gas constant (8.31 j/mol.k)

T: Absolute temperature in K

F: Faraday constant (96500 c/equivalent)

Na⁺-K⁺ Pump

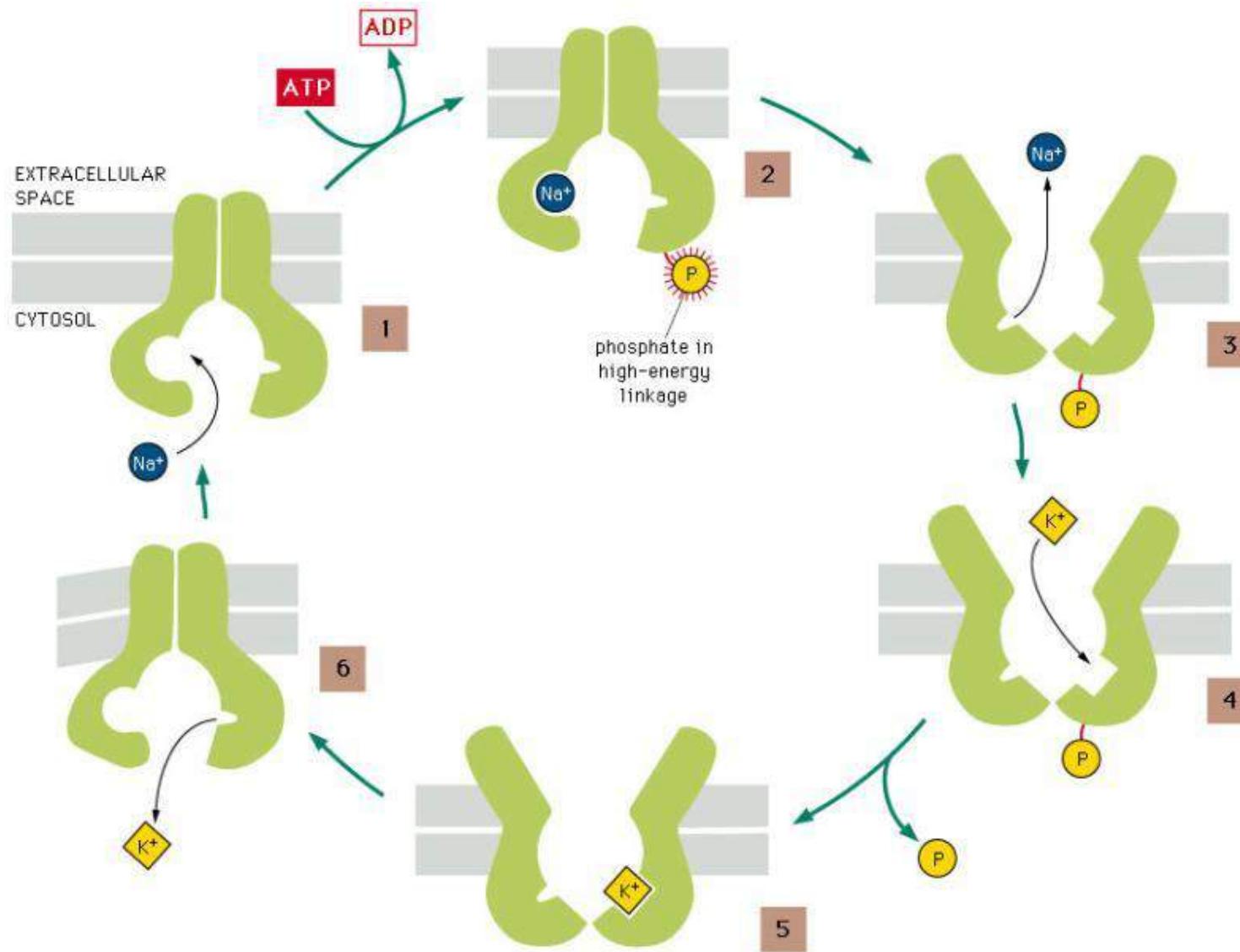
- Moves K⁺ while moving Na⁺
- Works constantly to maintain [Na⁺] inside the cell – Na⁺ comes in thru other channels or carriers



Na^+ and K^+ Concentrations

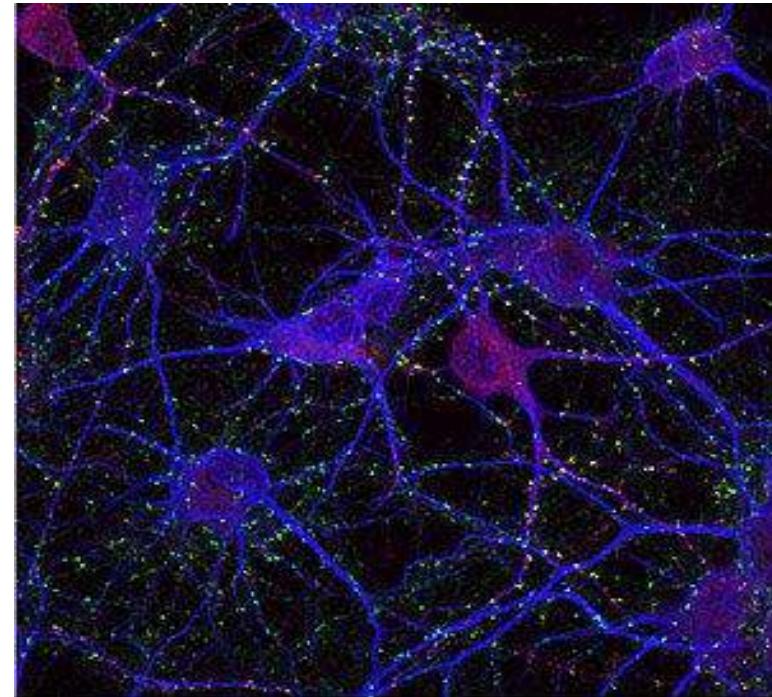
- The $[\text{Na}^+]$ outside the cell stores a large amount of energy, like water behind a dam
 - Even if the Na^+-K^+ pump is halted, there is enough stored energy to conduct other Na^+ downhill reactions
- The $[\text{K}^+]$ inside the cell does not have the same potential energy
 - Electric force pulling K^+ into the cell is almost the same as that pushing it out of the cell

Na^+-K^+ Pump is a Cycle



THE SYNAPSE

Where nerve impulses
convert to
neurotransmitters



- The synapse is where the nerve impulse passes from one cell to the next
- The electrical signal (the action potential) stops and a chemical signal takes over to cross the gap between the cells
- The chemical messenger is called a **neurotransmitter**
- The neurotransmitter crosses the gap by diffusion, which creates a small delay

Threshold and Action Potentials

Threshold Voltage— membrane is depolarized by 15 to 20 mV

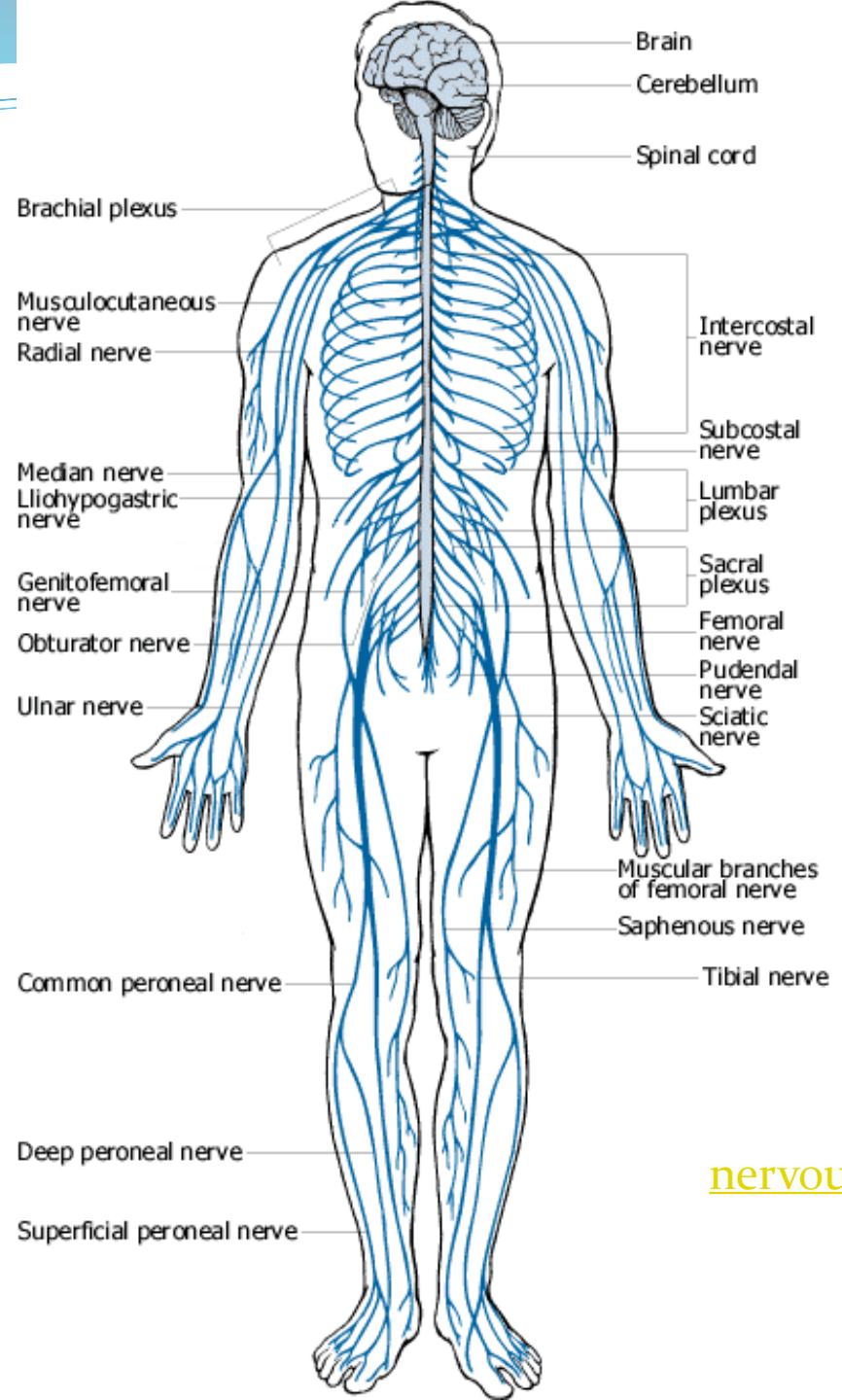
Subthreshold stimuli produce subthreshold depolarizations and are not translated into APs

Stronger threshold stimuli produce depolarizing currents that are translated into action potentials

All-or-None phenomenon – action potentials either happen completely, or not at all

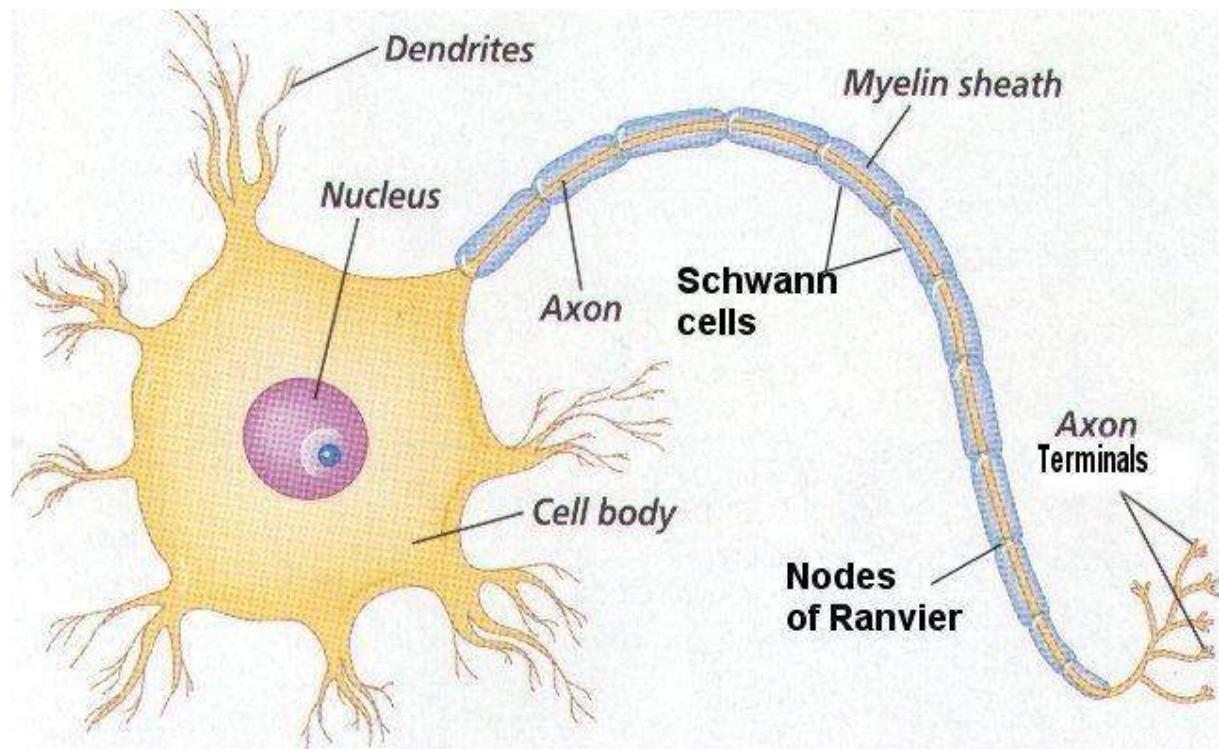


*Nervous
system*

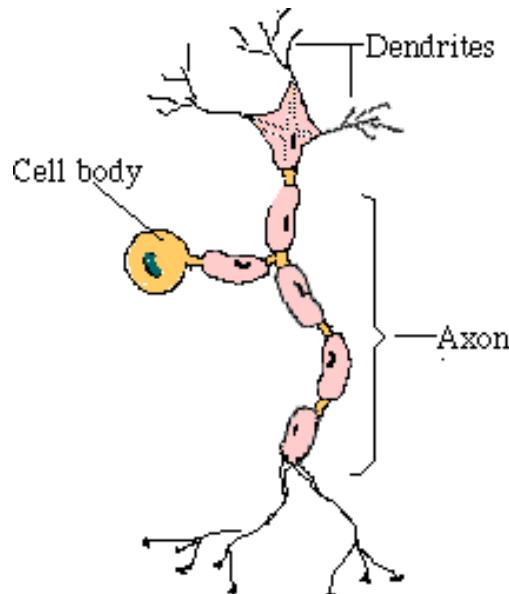


nervous system

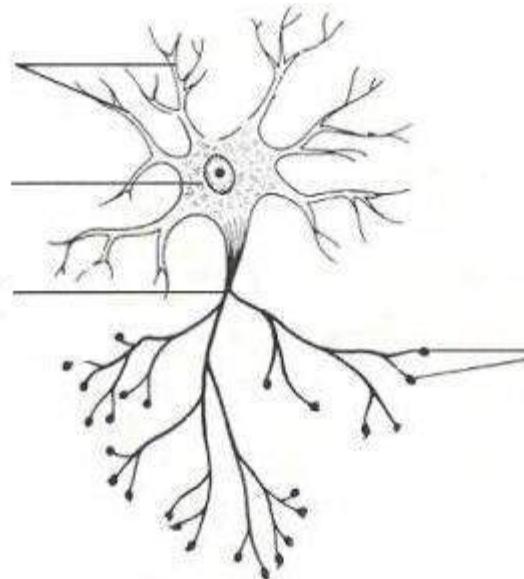
Basic nerve cell structure



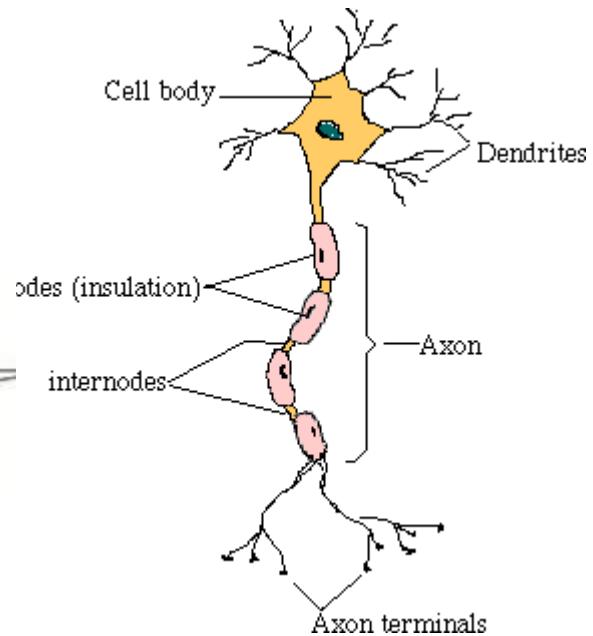
3 main types of nerve cells



sensory
neurone

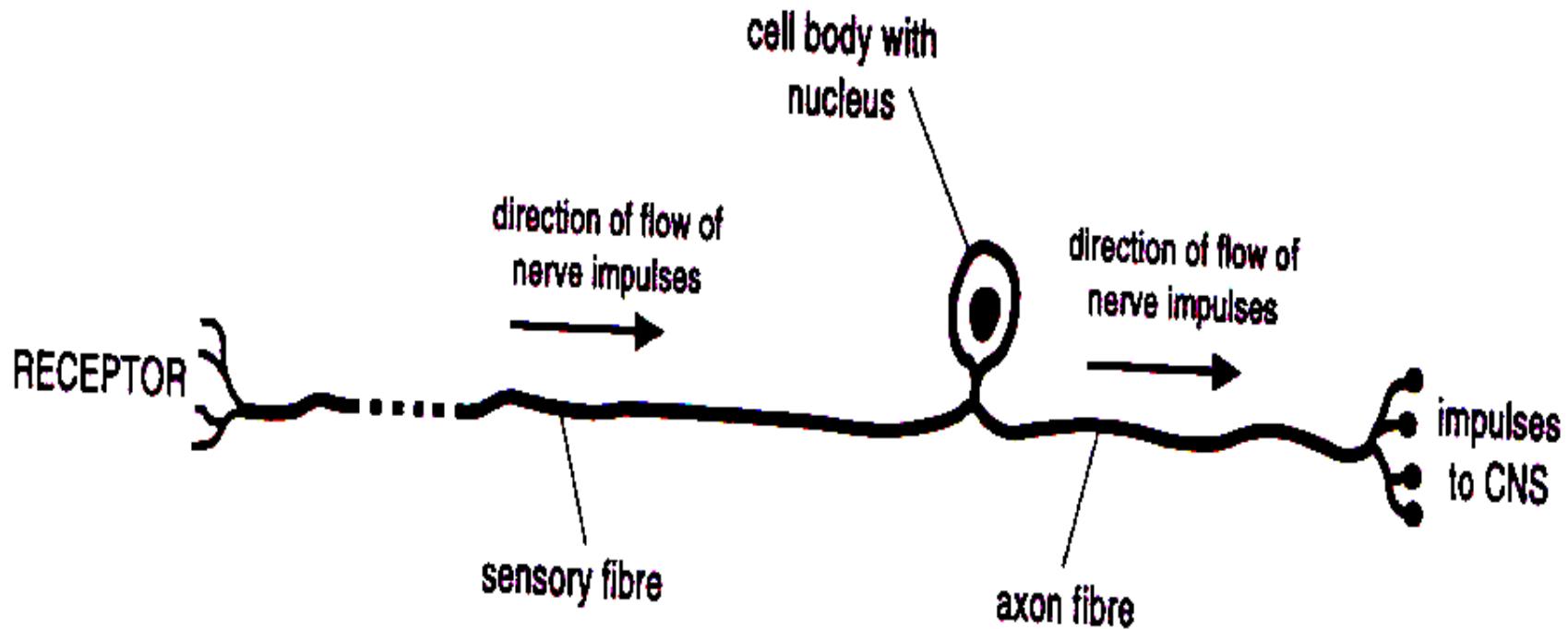


relay
neurone



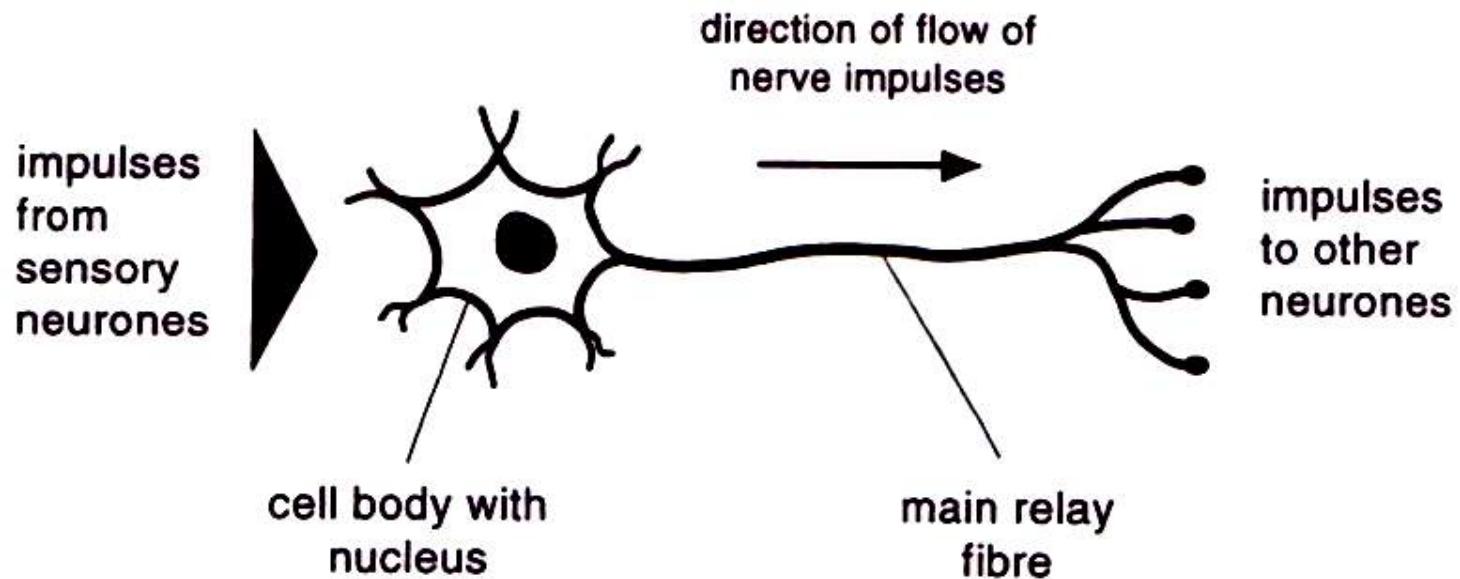
motor
neurone

Sensory neurons



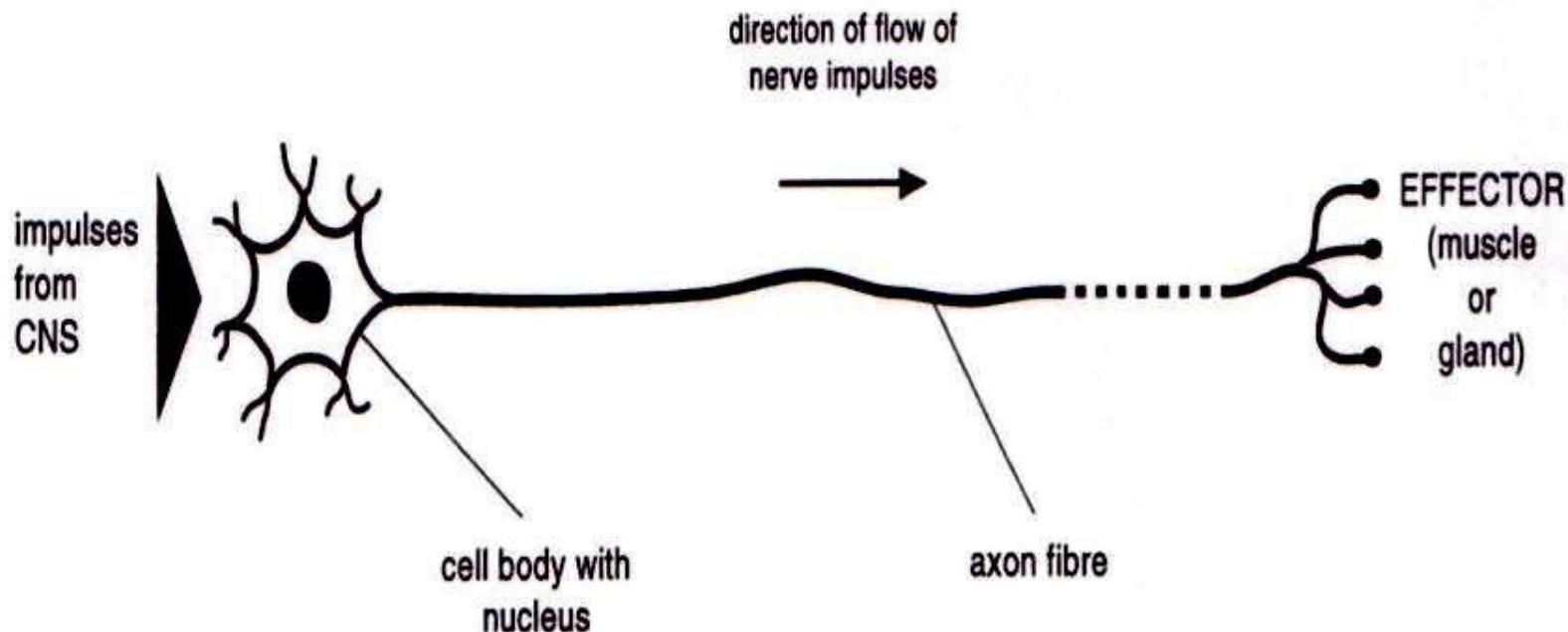
Carries impulses from receptors e.g pain receptors in skin to the CNS(brain or spinal cord)

Relay neuron



Carries impulses from sensory nerves to motor nerves.

Motor neuron



Carries impulses from CNS to effector e.g. muscle to bring about movement or gland to bring about secretion of hormone e.g ADH

Nervous System Overview

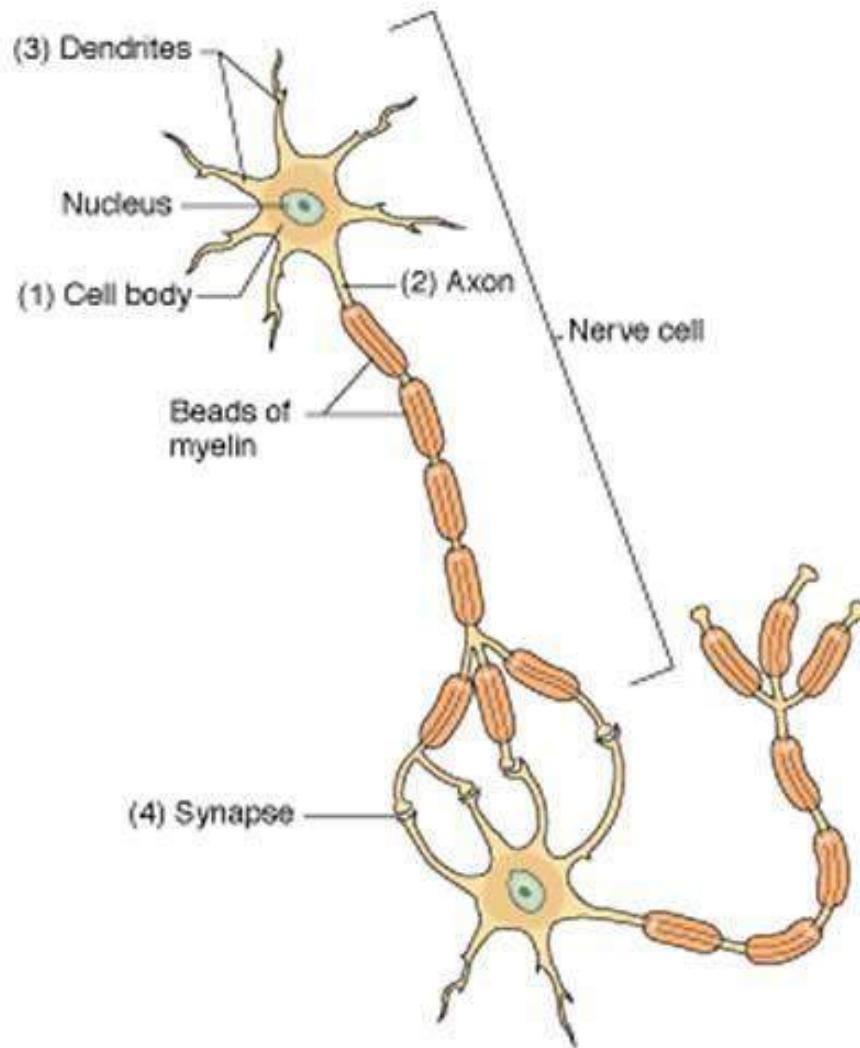
- Nervous System
 - Brain
 - Spinal Cord
 - Nerves
- Functions of Nervous System
 - Regulates and coordinates all body activities
 - Center of all mental activity, including thought, learning, and memory

Cells of the Nervous System

- **Neuron**

- Cell body
 - Contains the nucleus and cytoplasm
- Axon
 - Conducts impulses away from the cell body
 - Some axons are covered with a myelin sheath
- Dendrite
 - Conducts impulses toward the cell body
- Synapse
 - Space between two nerves which the impulse must cross

Cells of the Nervous System (contin)



Cells of the Nervous System (continued)

- Neuroglia
 - Connective tissue – support system for neurons
 - Do not conduct impulses
 - Protect nervous system through phagocytosis
- Types of Neuroglia Cells
 - Astrocytes
 - Microglia
 - Oligodendrocytes

Nervous System Divisions

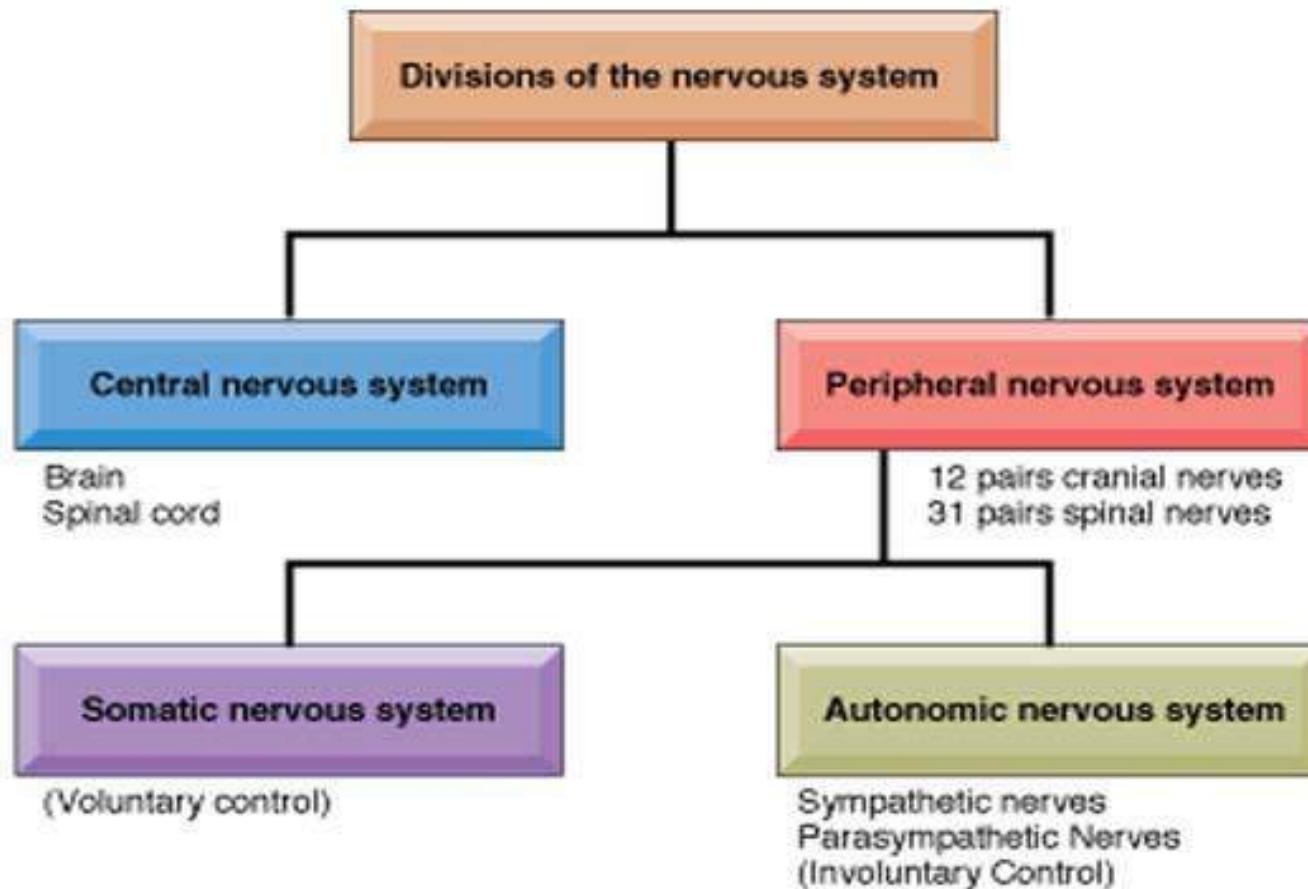
- Central Nervous System (CNS)

- Brain
- Spinal Cord
 - Processes and stores sensory and motor information
 - Controls consciousness

- Peripheral Nervous System (PNS)

- 12 Pairs of Cranial Nerves
- 31 Pairs of Spinal Nerves
 - Transmits sensory and motor impulses back and forth between CNS and rest of body

Nervous System Divisions (continued)

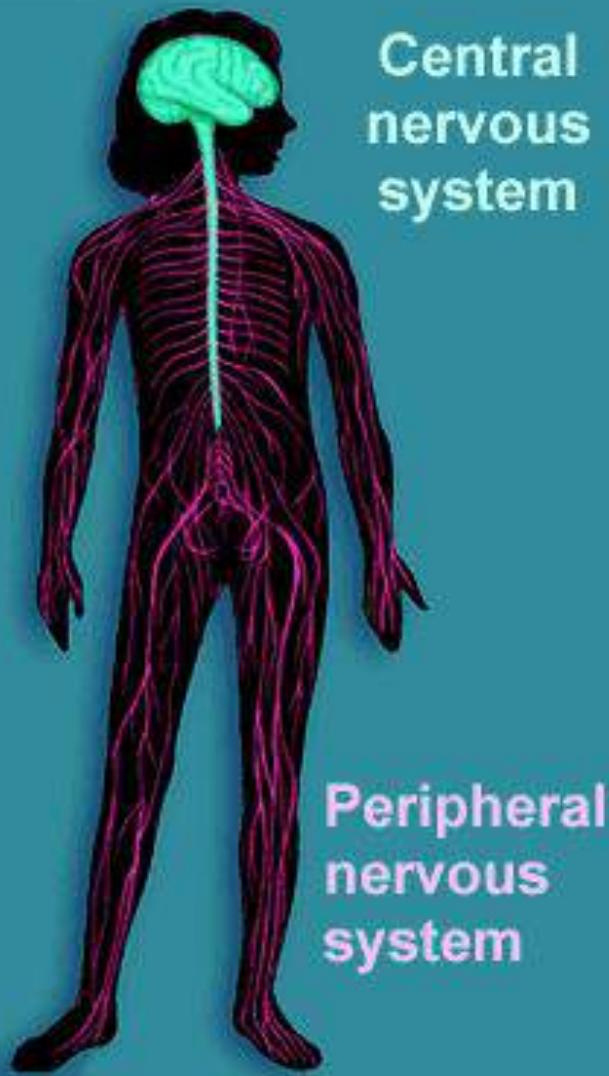




Central
nervous
system

Peripheral
nervous
system

• The Nervous System



Central Nervous System (CNS)

- comprised of the brain and spinal cord
- encased within the skull and spinal column

Peripheral Nervous System (PNS)

- comprised of nerve tissue located outside of the brain and spinal cord.

Central Nervous System

- Brain
- Surrounded by bone for protection
- Enclosed in the cranium

- Spinal Cord
- Surrounded by the vertebrae for protection
- Surrounded by the meninges and cerebrospinal fluid

Structures of the Brain

- Cerebrum
 - Largest and uppermost portion of the brain
 - Controls consciousness, memory, sensations, emotions, voluntary movements
 - Cortex = outer surface
 - Gyri = elevations
 - Sulci = grooves
 - Longitudinal fissure divides cerebrum into two hemispheres

Structures of the Brain (continued)

- Cerebellum
 - Attached to the brain stem
 - Maintains muscle tone
 - Coordinates normal movement and balance
- Diencephalon
 - Located between cerebrum and midbrain
 - Consists of thalamus, hypothalamus, and pineal gland

Structures of the Brain (continued)

- Brain Stem
 - Region between diencephalon and spinal cord
 - Consists of the midbrain, pons, and medulla oblongata
 - Serves as pathway for impulses between brain and spinal cord
 - Controls respiration, blood pressure, and heart rate

Peripheral Nervous System

- Afferent (Sensory) Nerves
 - Carry impulses from the body to the central nervous system
- Efferent (motor) Nerves
 - Carry impulses from the central nervous system to the muscles and glands
 - Cause the target organs to do something in response to the commands

Peripheral Nervous System (continued)

- Somatic Nervous System (SNS)
 - Provides voluntary control over skeletal muscle contractions
- Autonomic Nervous System (ANS)
 - Provides involuntary control over smooth muscle, cardiac muscle, and glandular activity and secretions in response to the commands of the central nervous system

Spinal Cord

- Pathway for impulses traveling to and from brain
- Carries 31 pairs of spinal nerves
 - Affects limbs and lower part of body

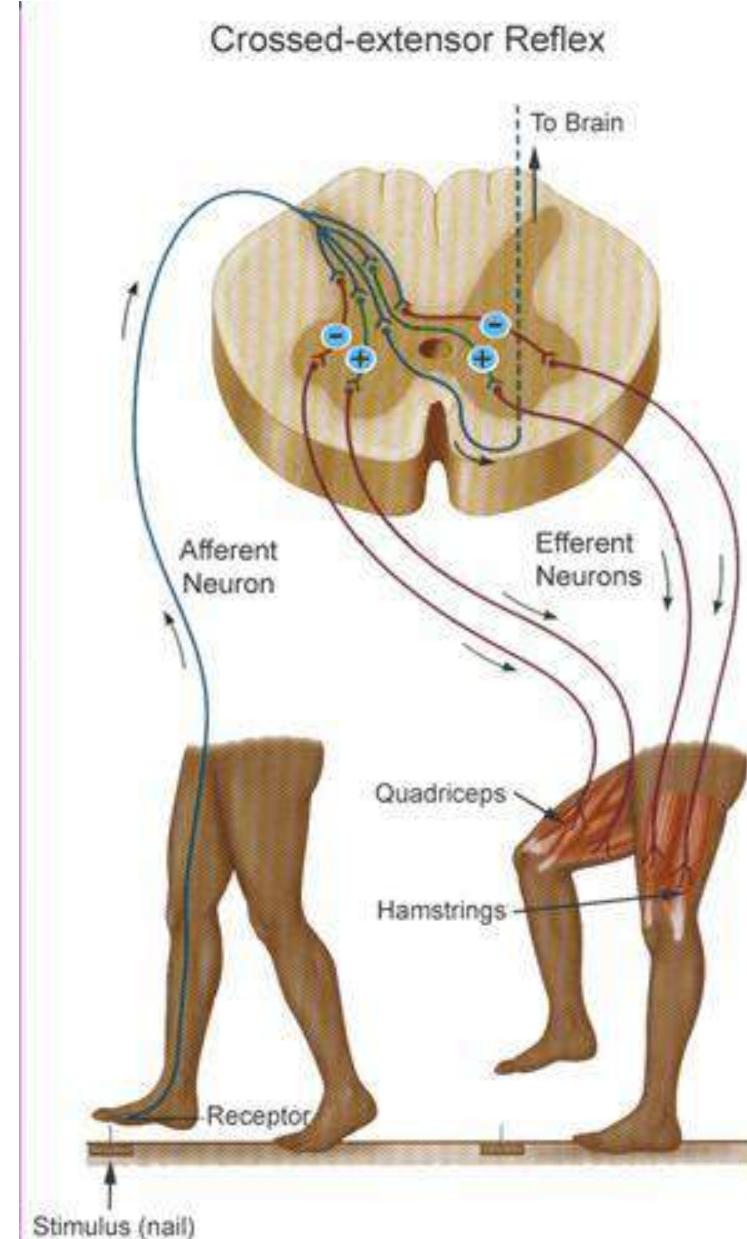
Peripheral Nervous System

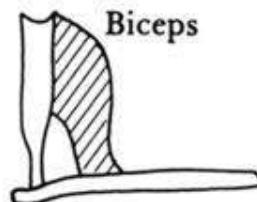
Spinal nervous system is functionally organized on the basis of what is called the reflex arc:

1. A sense organ: (ear-sound, eye-light, skin-temperature)
2. A sensory nerve: (transmit information to the CNS)
3. The CNS: serves as a central integrating station
4. Motor nerve: communication link between CNS and peripheral muscle
5. Effector organ: skeletal muscle fibers

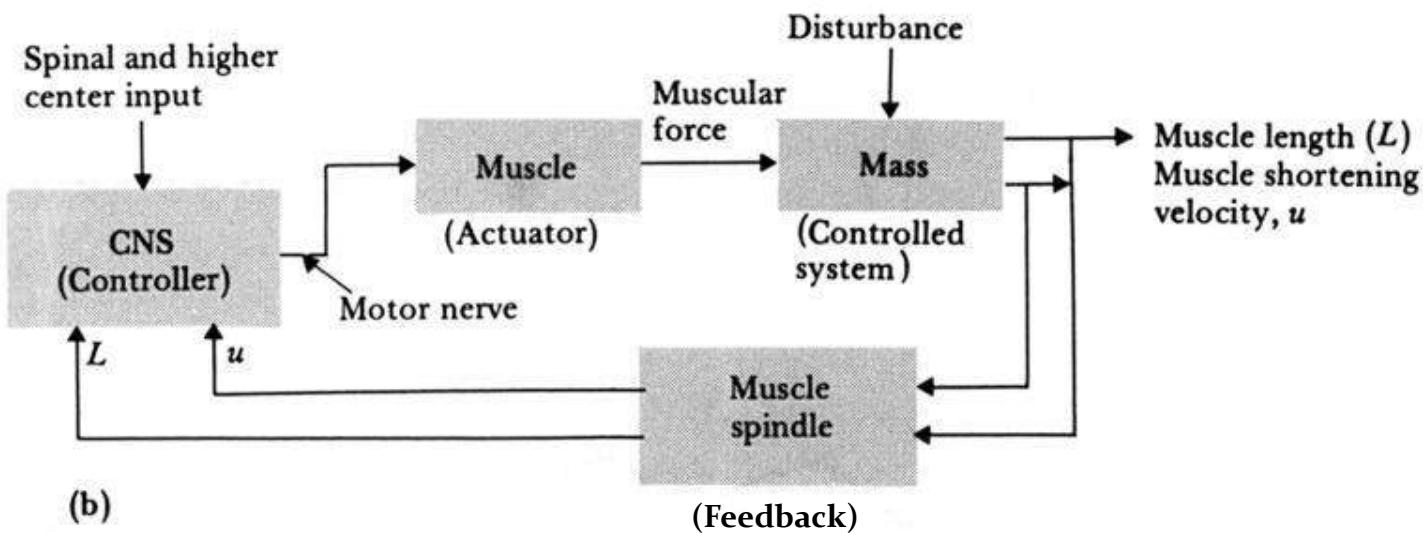
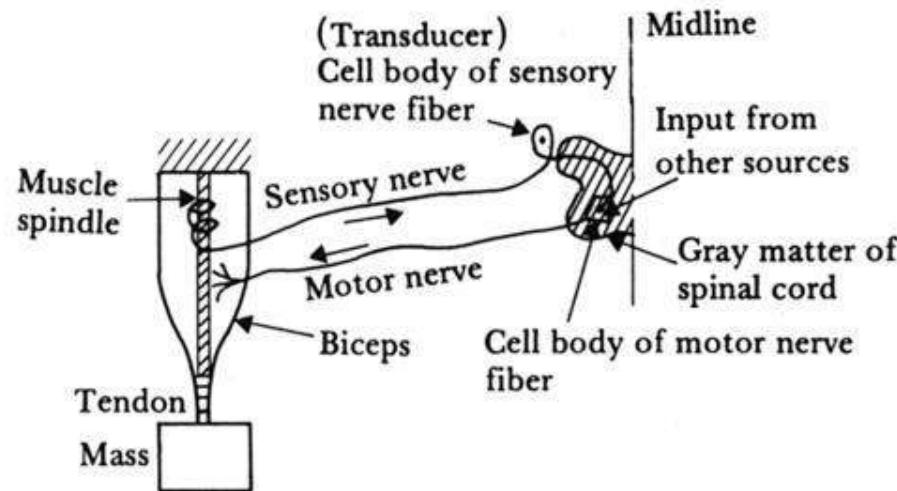
Example of reflex arc

Example of reflex arc



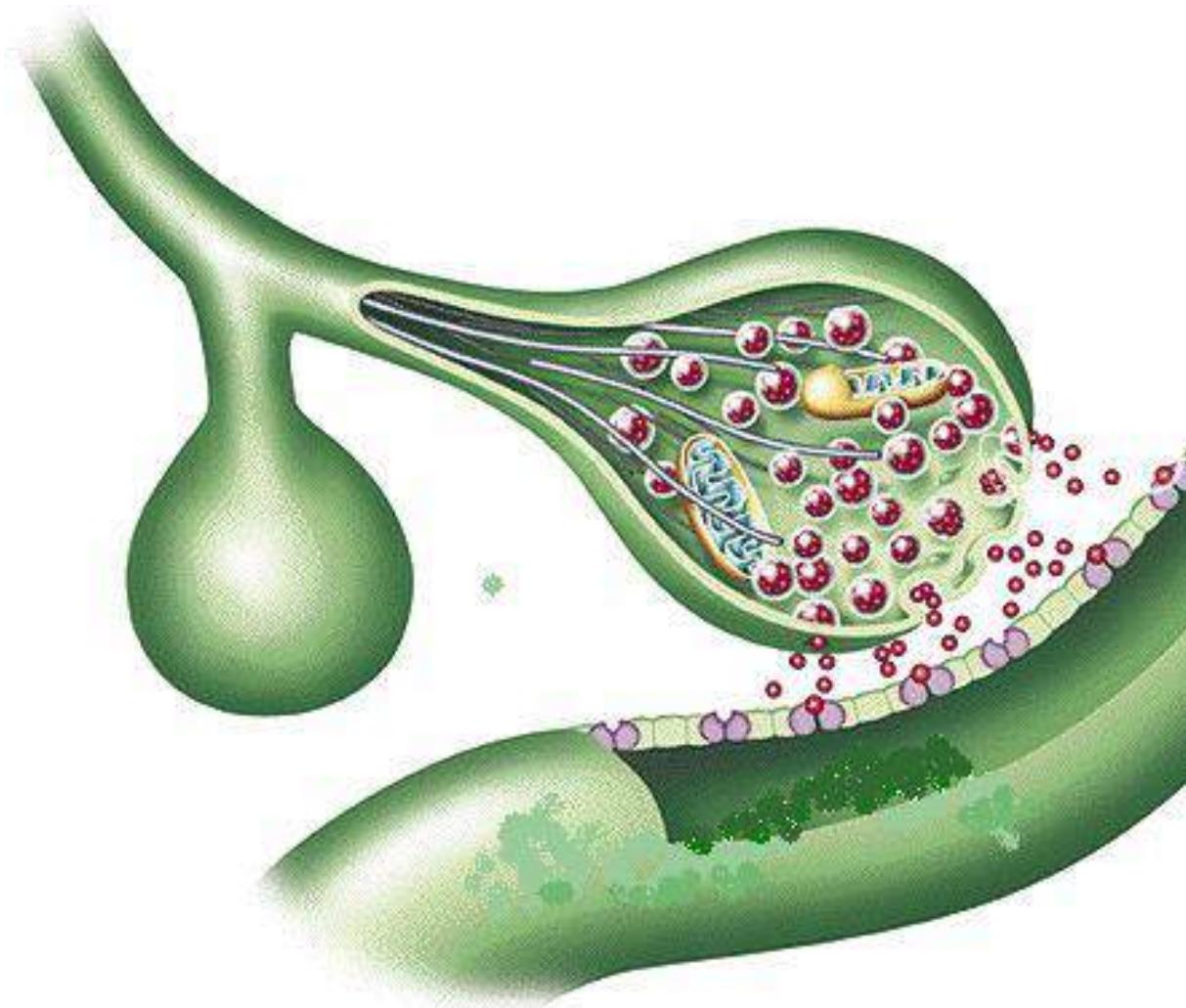


(a)



Schematic diagram of a muscle-length control system for a peripheral muscle (biceps) (a) Anatomical diagram of limb system, showing interconnections. (b) Block diagram of control system.

The Synapse



The Concept of the Synapse

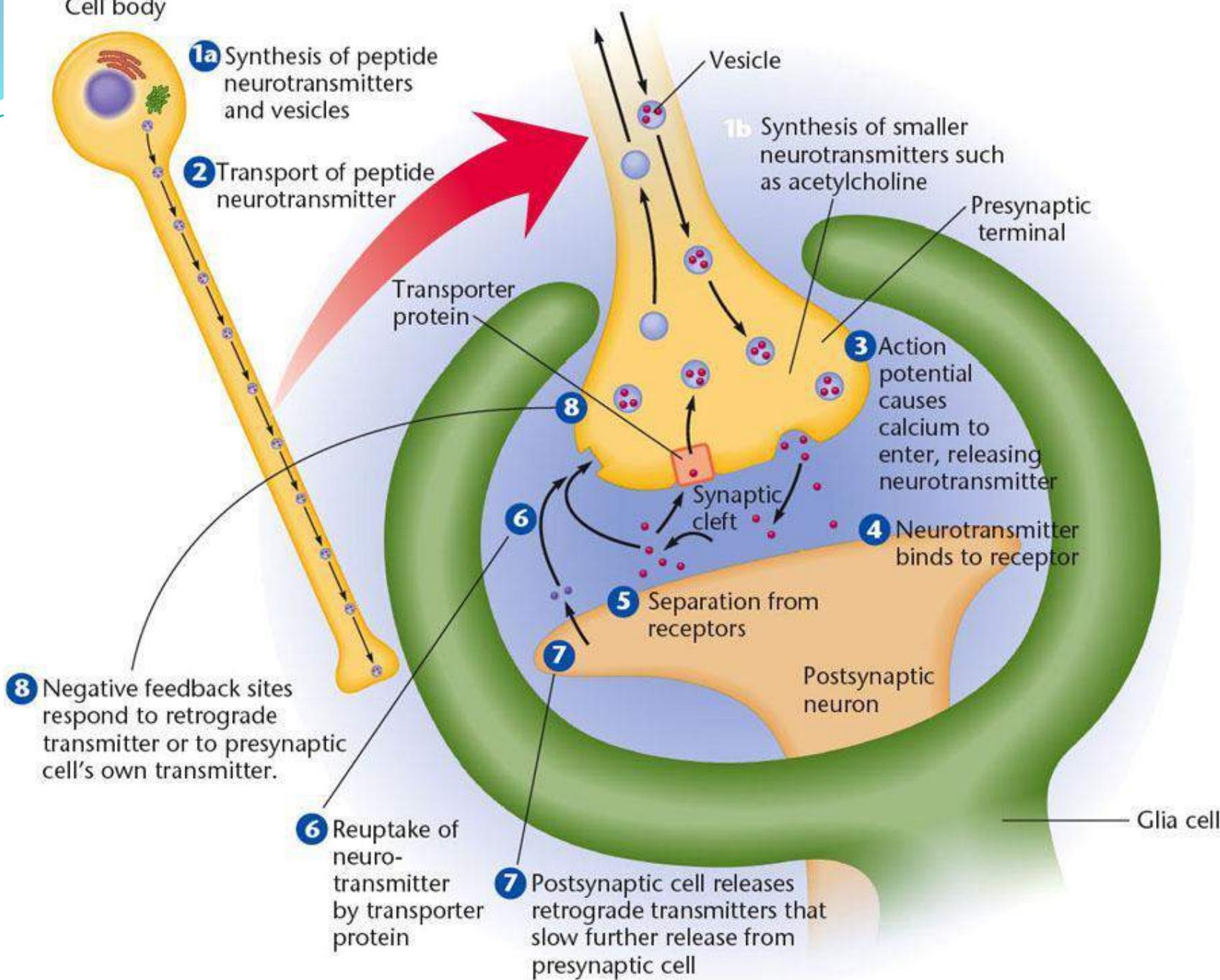
- Neurons communicate by transmitting chemicals at junctions called “synapses”
- In 1906, Charles Scott Sherrington coined the term **synapse** to describe the specialized gap that existed between neurons.

The Concept of the Synapse

- Sherrington observed that repeated stimuli over a short period of time produced a stronger response.
- Led to the idea of **temporal summation** or that repeated stimuli can have a cumulative effect and can produce a nerve impulse when a single stimulus is too weak.

The Concept of the Synapse

- Sherrington also noticed that several small stimuli on a similar location produced a reflex when a single stimuli did not.
- This led to the idea of **spatial summation** or that synaptic input from several locations can have a cumulative effect and trigger a nerve impulse.

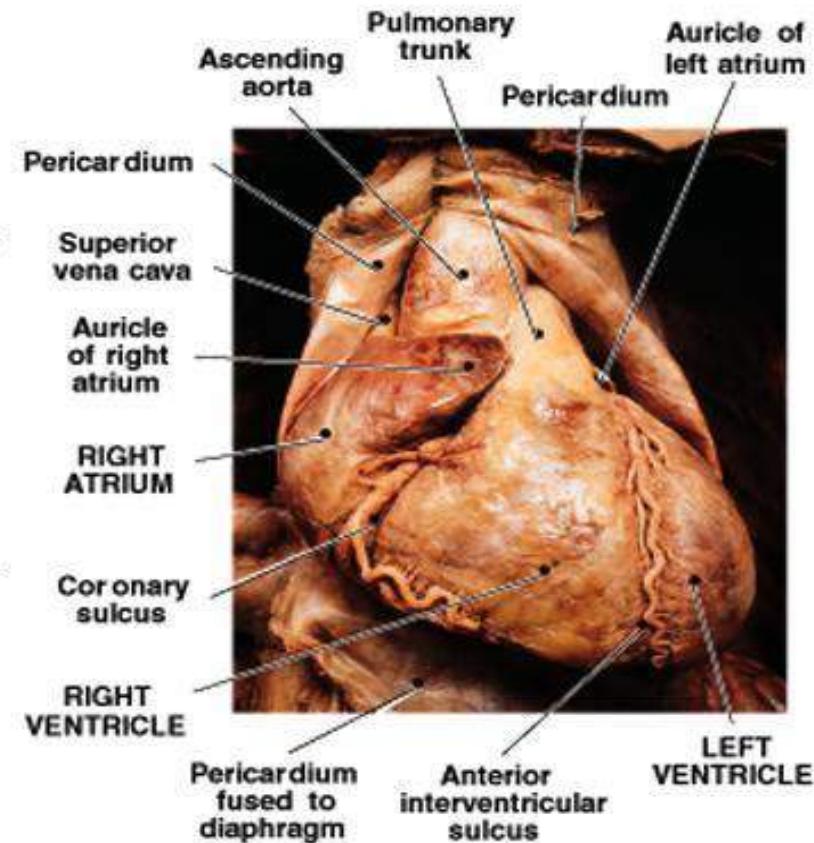
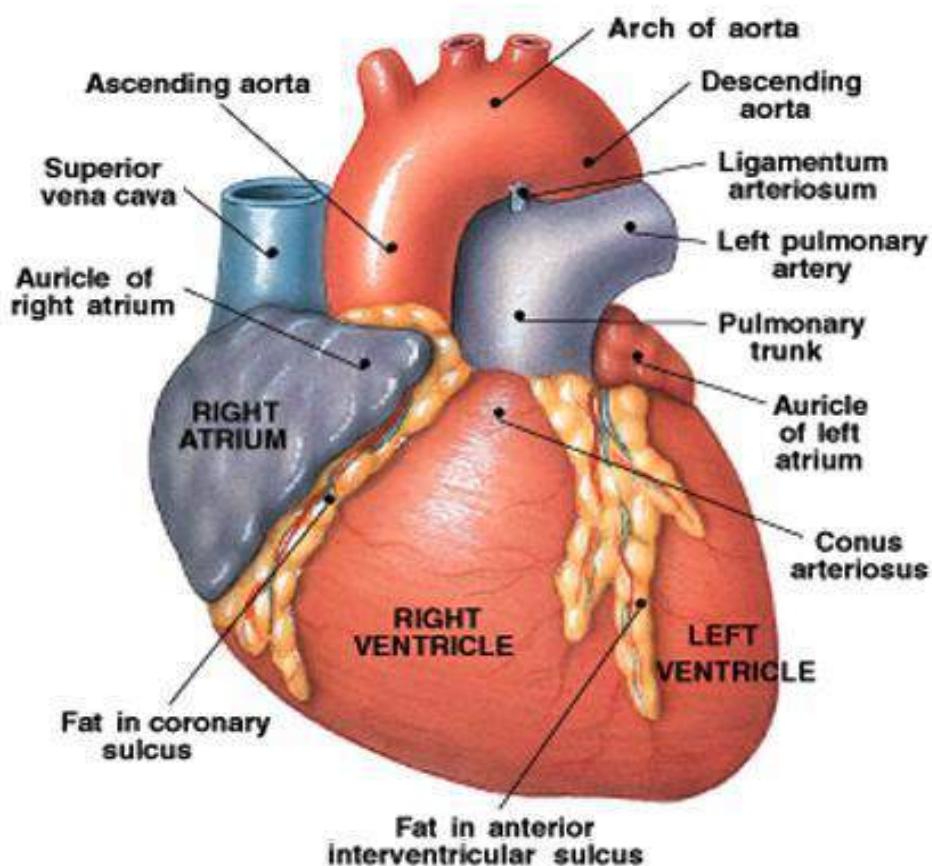


*Cardio
pulmonary
system*

Heart Anatomy

- Approximately the size of your fist Location
 - Superior surface of diaphragm
 - Left of the midline
 - Anterior to the vertebral column, posterior to the sternum

HEART

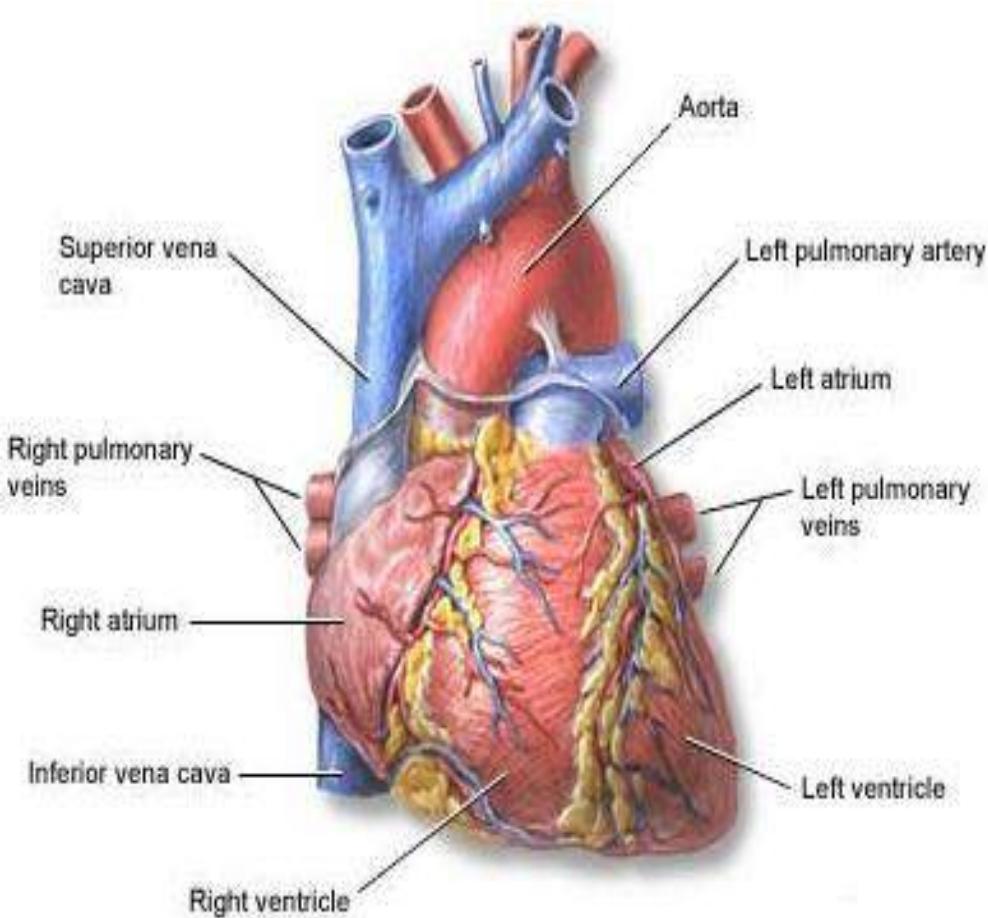


Anterior surface

HEART

- Hollow, muscular organ
- 300 grams (size of a fist)
- 4 chambers
- found in chest between lungs
- surrounded by membrane called Pericardium
- Pericardial space is fluid-filled to nourish and protect the heart.

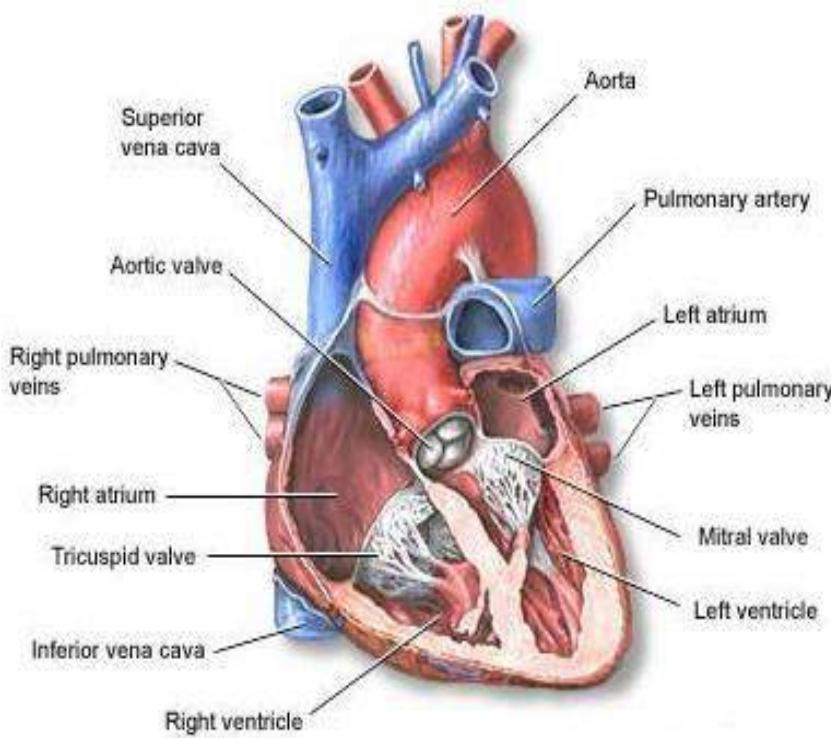
HEART ANATOMY



- The heart is a complex muscular pump that maintains blood pressure and flow through the lungs and the rest of the body.
- The heart pumps about 100,000 times and moves 7200 liters (1900 gallons) of blood every day.

HEART ANATOMY

- The heart has four chambers.
- Two atria act as collecting reservoirs.
- Two ventricles act as pumps.
- The heart has four valves for:
 - Pumping action of the heart.
 - Maintaining unidirectional blood flow.



Functions of the Heart

- Generates **blood** pressure
- Routes **blood**
 - Heart separates pulmonary and systemic circulation
- Ensures one-way **blood** flow
 - Heart valves ensure one-way flow

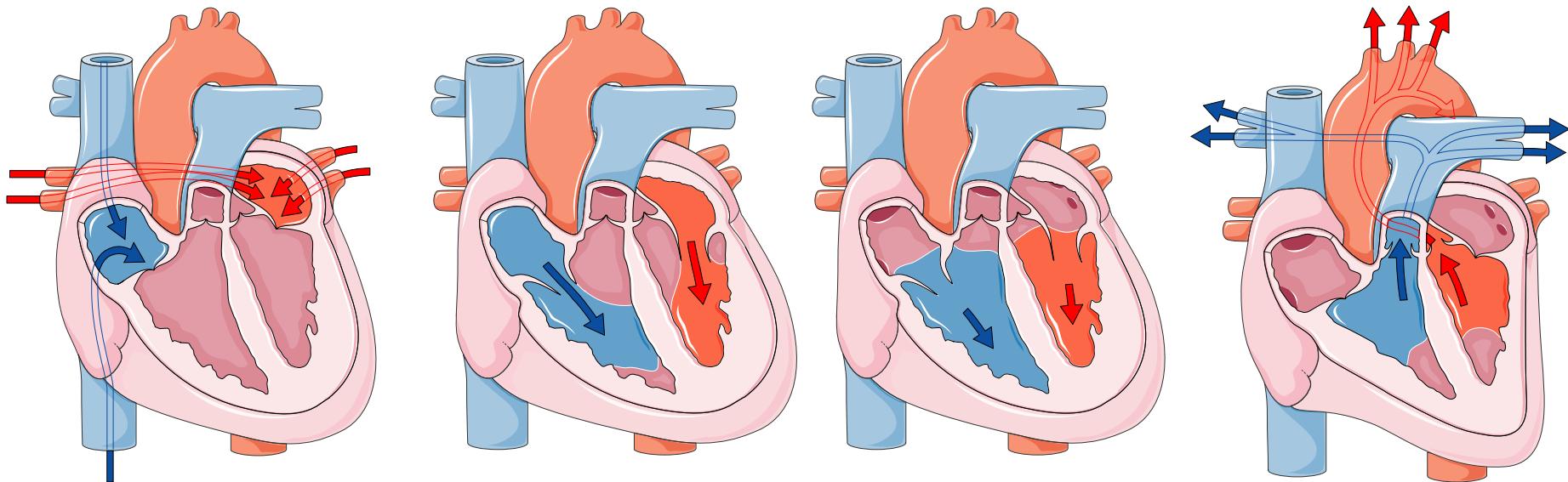
Functions of the Heart

- Regulates **blood** supply
 - Changes in contraction rate and force match blood delivery to changing metabolic needs
 - Most healthy people can increase cardiac output by 300–500%
- Heart failure is the inability of the heart to provide enough blood flow to maintain normal metabolism

Cardiac Cycle

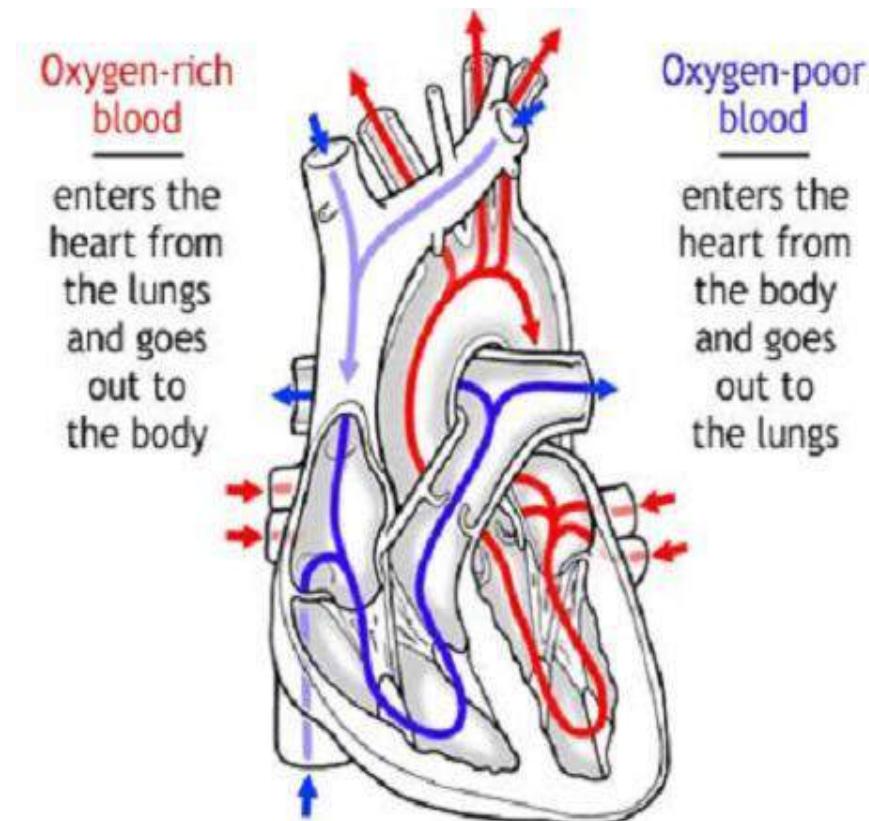
- The heart is two pumps that work together, right (**pulmonary**) and left (**systemic**) half
- Repetitive, sequential contraction (**systole**) and relaxation (**diastole**) of heart chambers
- Blood moves through circulatory system from areas of higher to lower pressure.
 - Contraction of heart produces the pressure

Cardiac Cycle



HEART

- Deoxygenated blood returns to the heart via the superior and inferior vena cava, enters the right atrium, passes into the right ventricle, and from here it is ejected to the pulmonary artery.
- Oxygenated blood returning from the lungs enters the left atrium via the pulmonary veins, passes into the left ventricle, and is then ejected to the aorta.



Blood Vessels

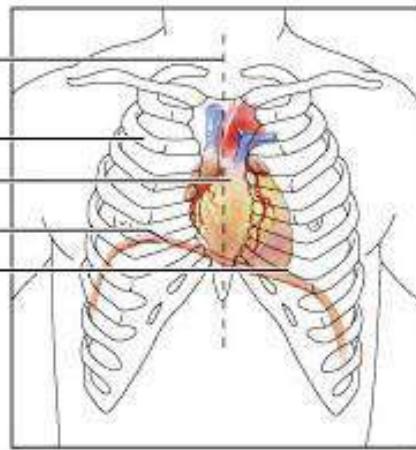
- Blood vessels are divided into a pulmonary circuit and systemic circuit.
- Artery - vessel that carries blood away from the heart. Usually oxygenated
- Vein - vessel that carries blood towards the heart. Usually deoxygenated.
- Capillary - a small blood vessel that allow diffusion of gases, nutrients and wastes between plasma and interstitial fluid.

Blood Vessels

- Systemic vessels
 - Transport blood through the body part from left ventricle and back to right atrium
- Pulmonary vessels
 - Transport blood from right ventricle through lungs and back to left atrium
- Blood vessels and heart are regulated to ensure blood pressure is high enough for blood flow to meet metabolic needs of tissues

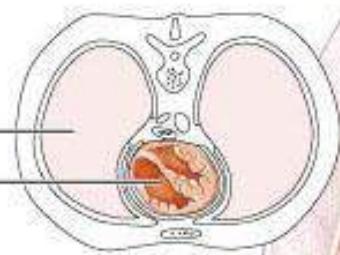
Physiology of heart and lungs

Midsternal
line
2nd rib
Sternum
Diaphragm
Point of
maximal
intensity
(PMI)



(a)

Right lung
Heart



(b)

(c)

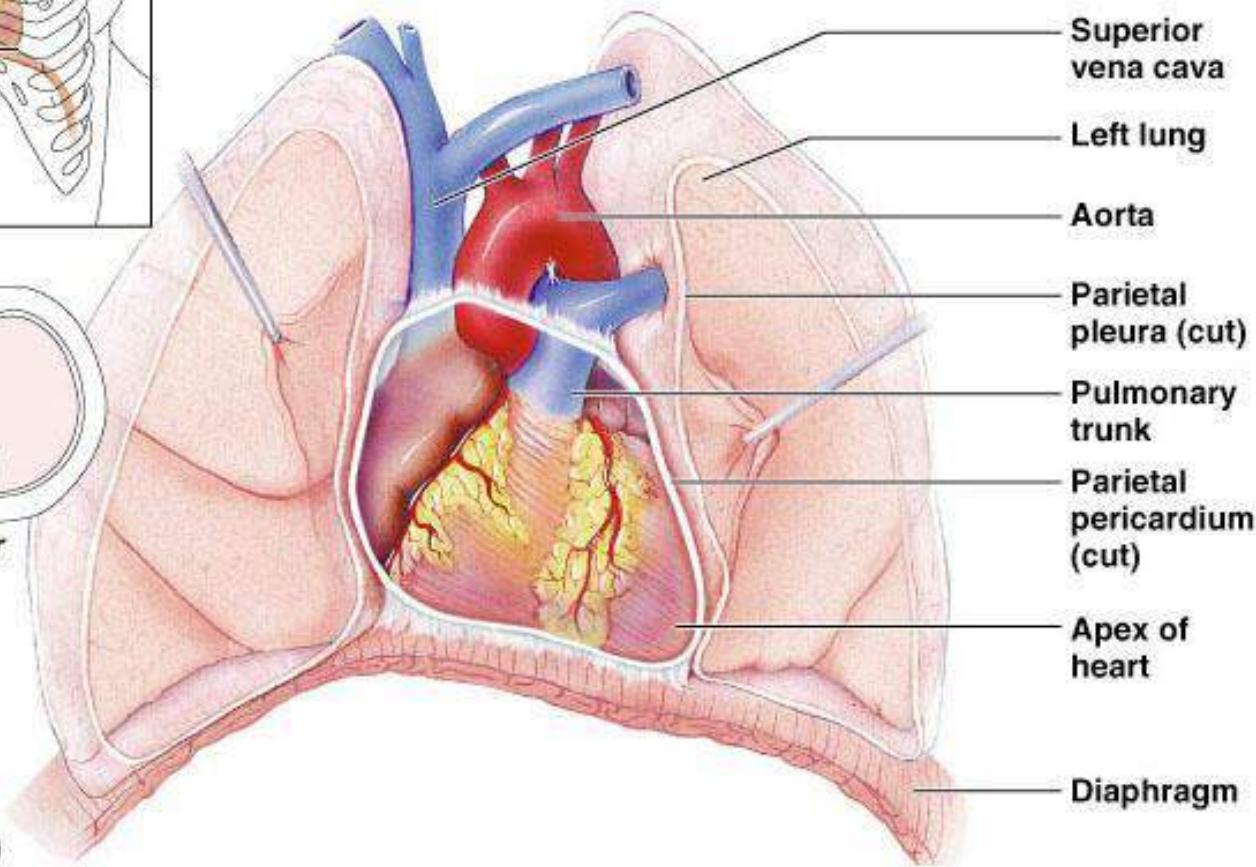


Figure 18.1

Coverings of the Heart: Physiology

- The **Function** of the Pericardium:
 - Protects and anchors the heart
 - Prevents overfilling of the heart with blood
 - Allows for the heart to work in a relatively **friction-free environment**

Pericardial Layers of the Heart

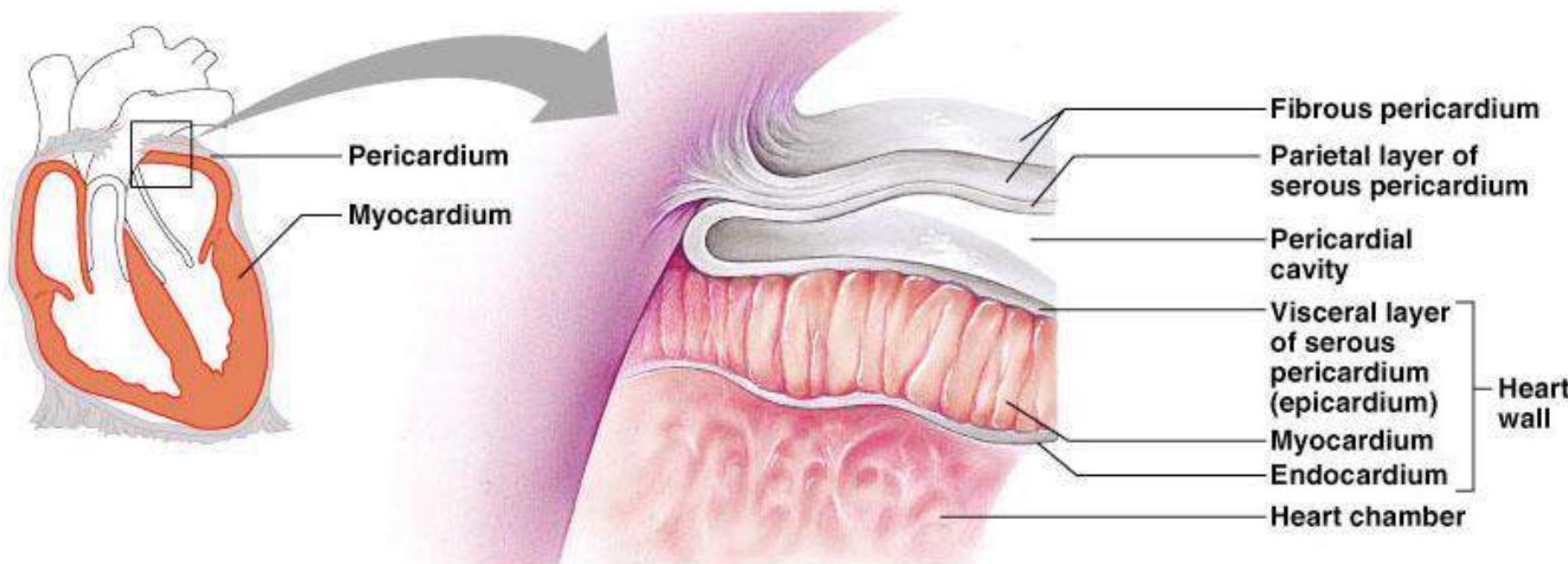


Figure 18.2

Heart Wall

- **Epicardium** – visceral layer of the **serous pericardium**
- **Myocardium** – cardiac muscle layer forming the bulk of the heart
- **Fibrous skeleton** of the heart – crisscrossing, interlacing layer of **connective tissue**
- **Endocardium** – endothelial layer of the inner myocardial surface

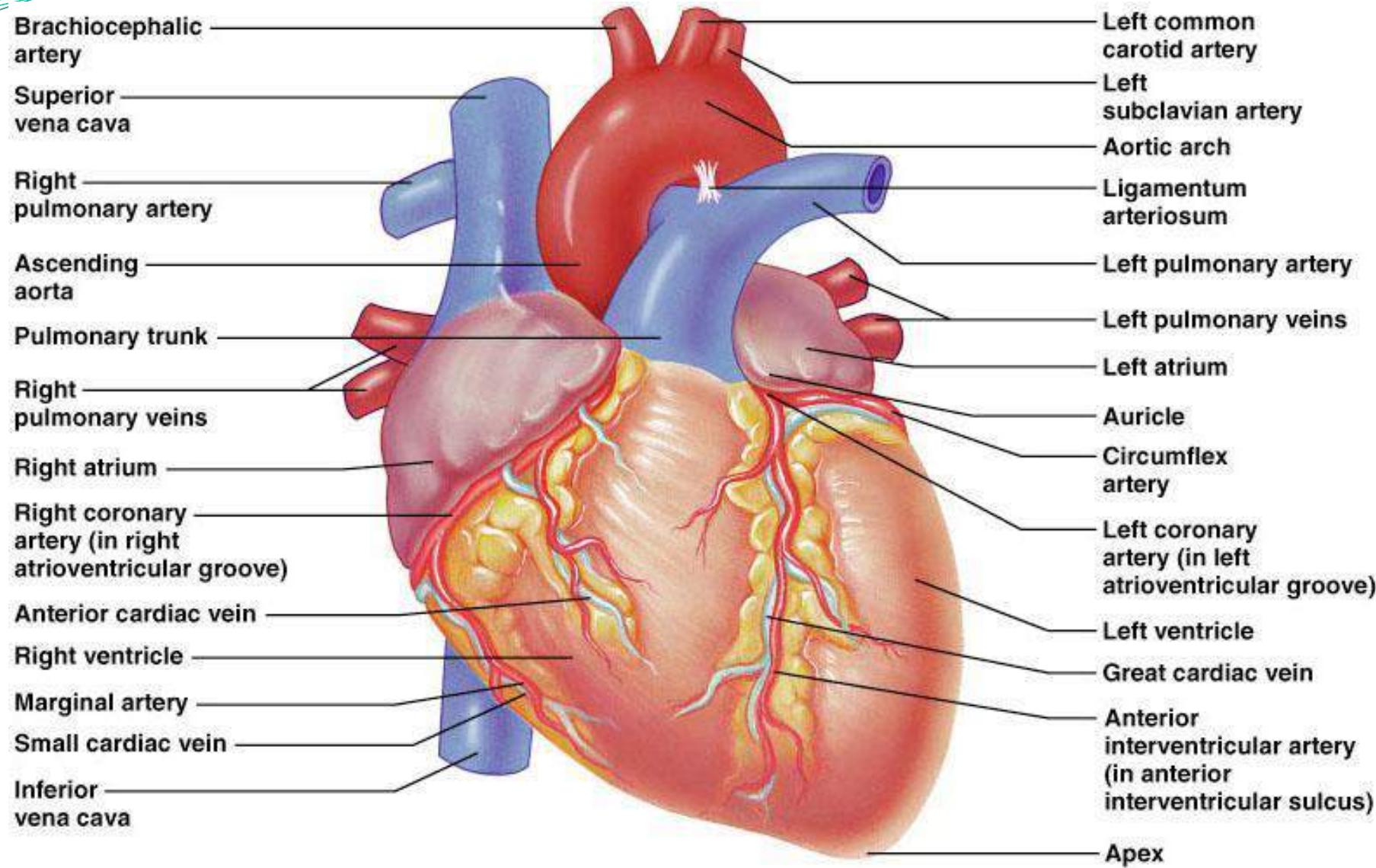


Figure 18.4b

Structure of the Heart

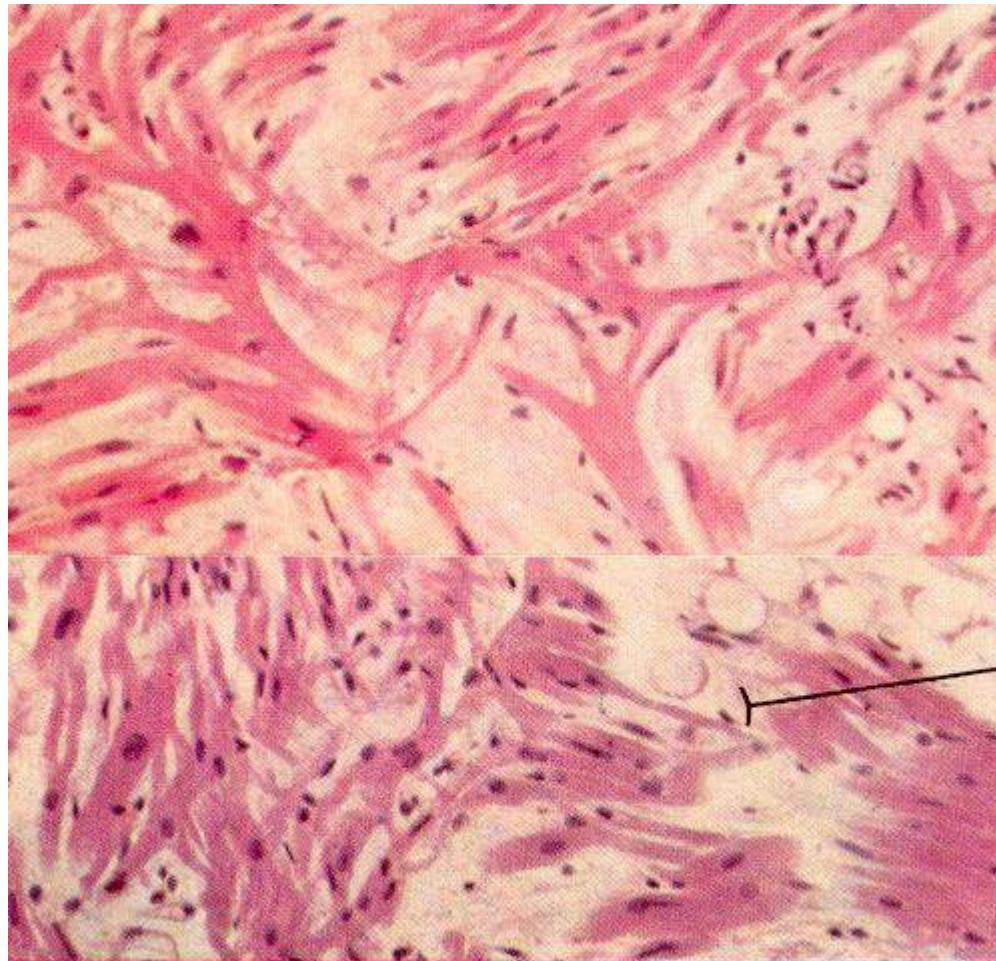
- adult human heart = 300-350 g
- built upon a “collagenous skeleton” located at atrioventricular junction (fibrotendinous ring)
- the ring isolates the atria electrically from the ventricles, except at the bundle of His

Conduction System

Conductive Fibers

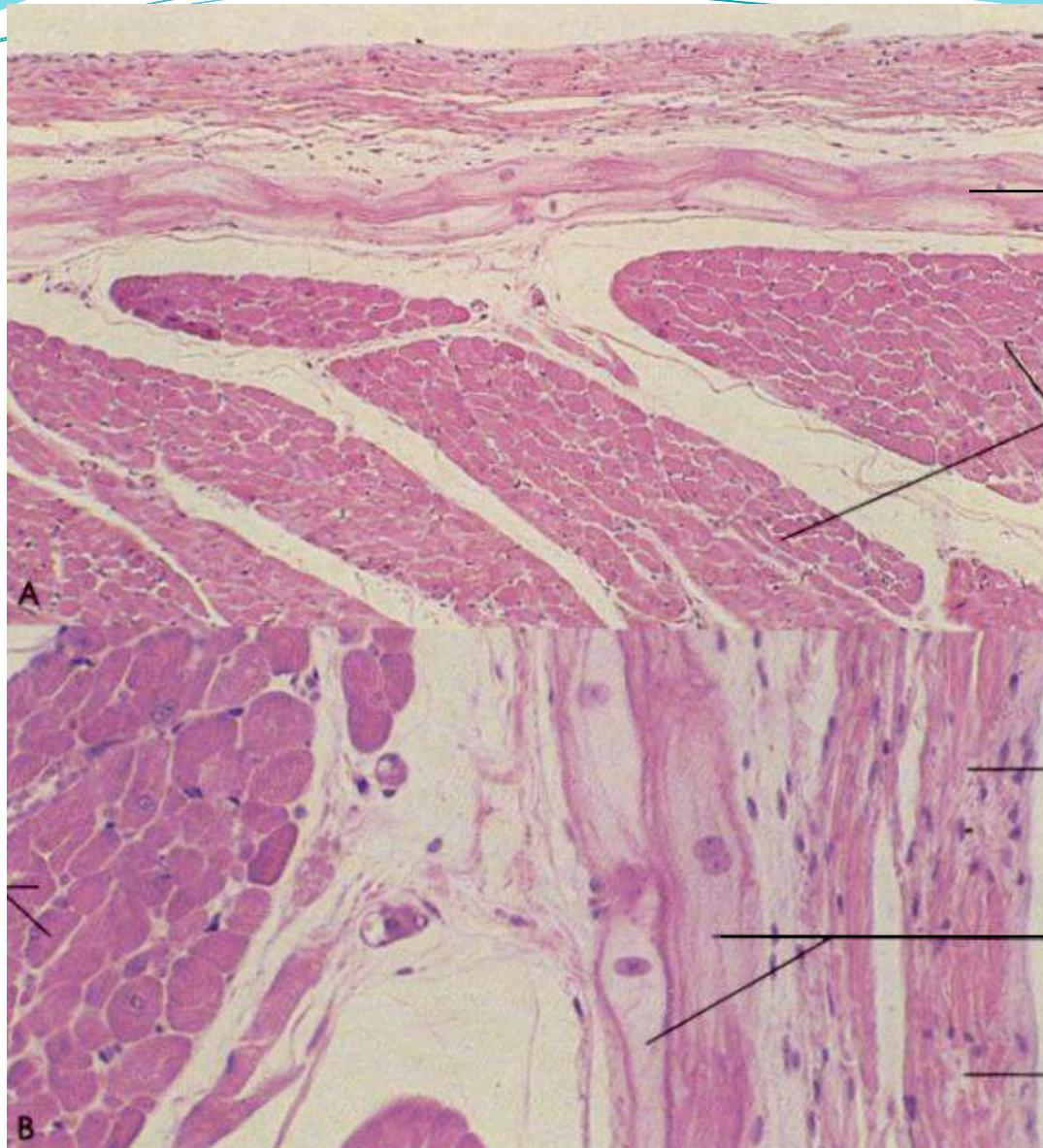
- Sinoatrial (SA) node 100-110/min
- Atrioventricular (AV) node 40-60/min
- AV bundle (Bundle of His) 20-40/min
- Left and right bundle branch
- Purkinje fibers (*rapid conduction*) 20-40/min

Specialised cardiac muscle cells



**AV node
(node of Tawara)
irregularly arranged
branching fibers**

**Bundle of His
unbranched fibers**



endothelium
endocardium
Purkinje fibers

Ventricular
myocardium

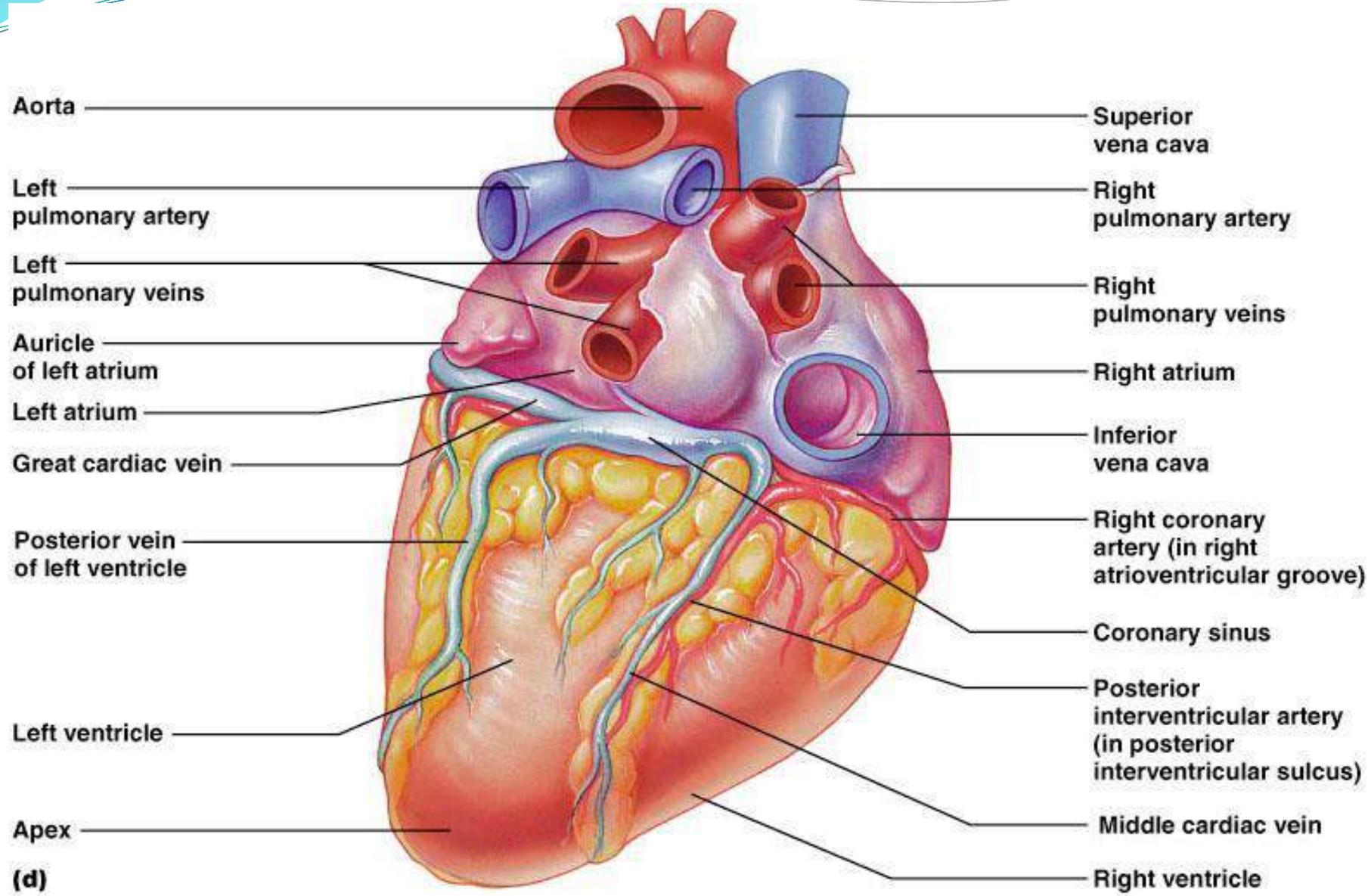
Purkinje fibers

Nodal Cells

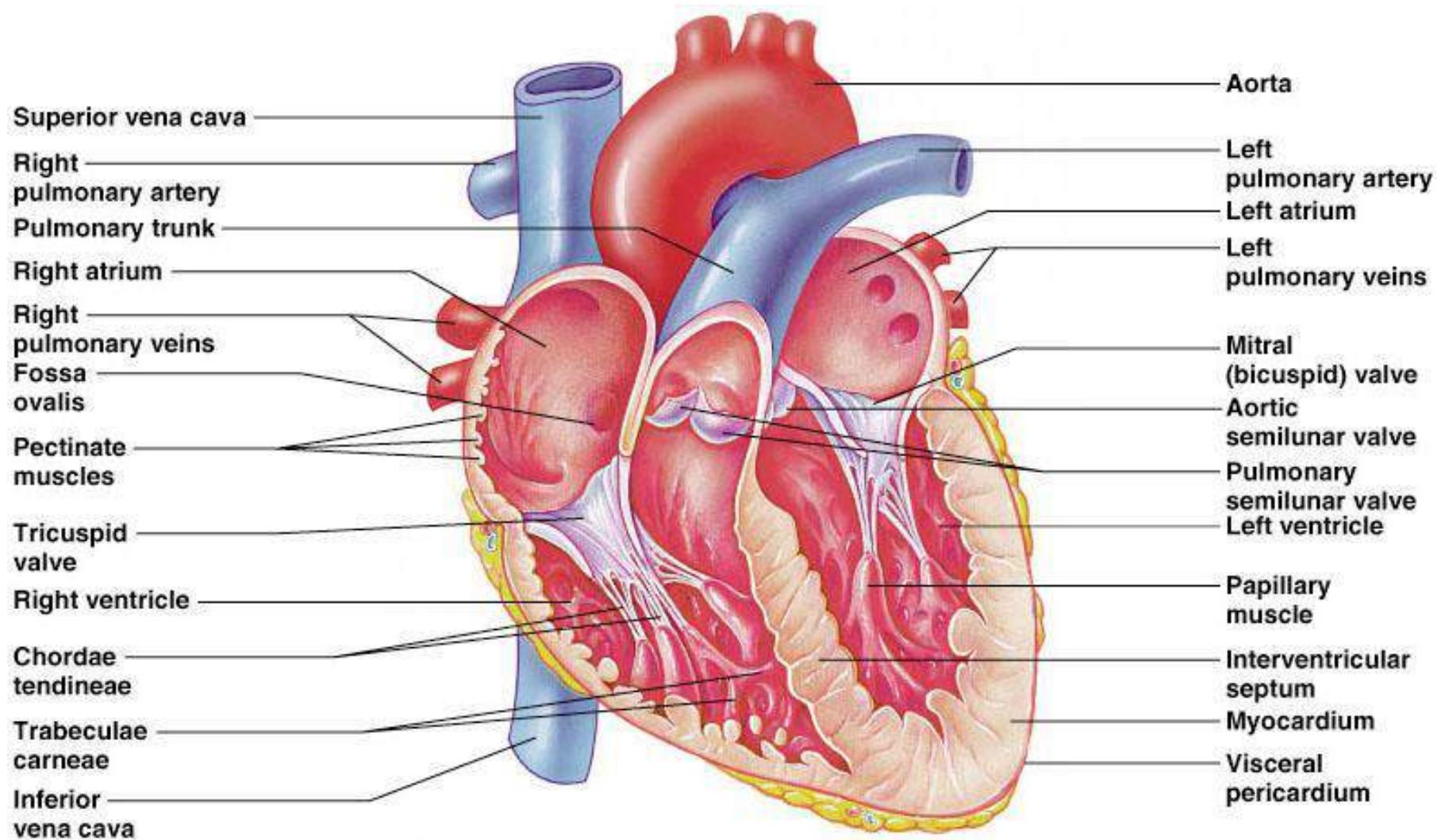
- Smaller than contractile cells or Purkinje cells
- Low propagation velocity (0.05m/sec)
- Reduced density of gap junctions
- Lack fast Na channels

Purkinje Cells

- larger than ordinary cardiac fibers and bundle fibers
- Conduct action potentials four times faster than a ventricular myocyte (4m/sec)
- may be binucleate
- few myofibrils
- vacuous cytoplasm (filled with glycogen)
- subendocardial location
- linked to cardiac fibers and bundle fibers by gap junctions and desmosomes



Gross Anatomy of Heart: Frontal Section



Atria of the Heart

- Atria are the **receiving chambers** of the heart
- Each atrium has a protruding auricle
- **Pectinate muscles** mark atrial walls
- Blood enters right atria from superior and inferior **venae cavae and coronary sinus**
- Blood enters left atria **from pulmonary veins**

Pathway of Blood Through the Heart and Lungs

- Right atrium → tricuspid valve → right ventricle
- Right ventricle → pulmonary semilunar valve → pulmonary arteries → lungs
- Lungs → pulmonary veins → left atrium
- Left atrium → bicuspid valve → left ventricle
- Left ventricle → aortic semilunar valve → aorta
- Aorta → systemic circulation

Pathway of Blood Through the Heart and Lungs

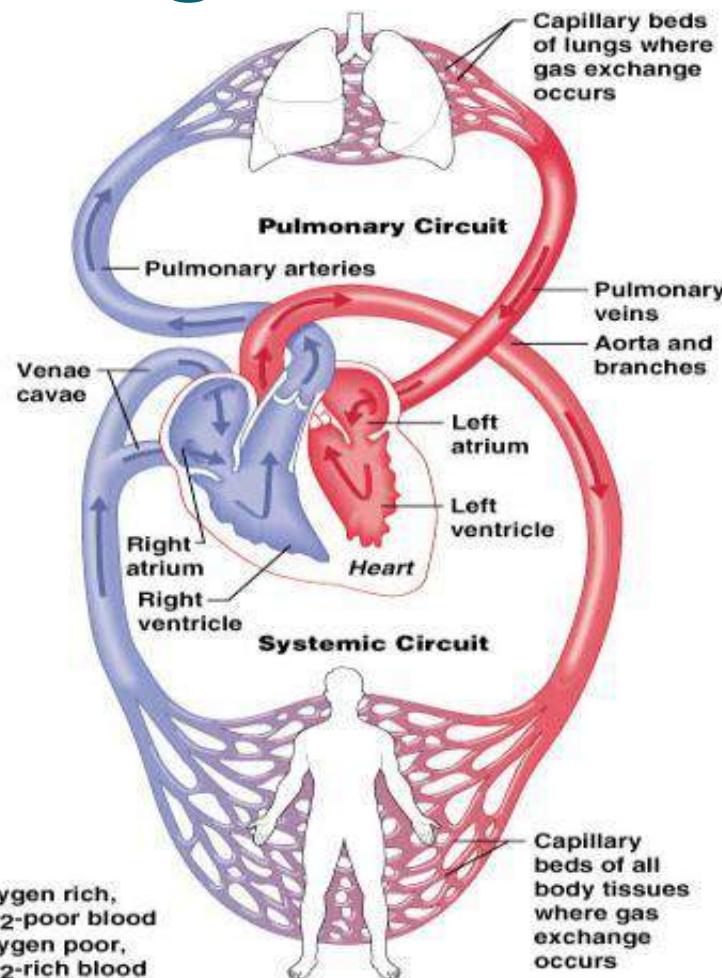
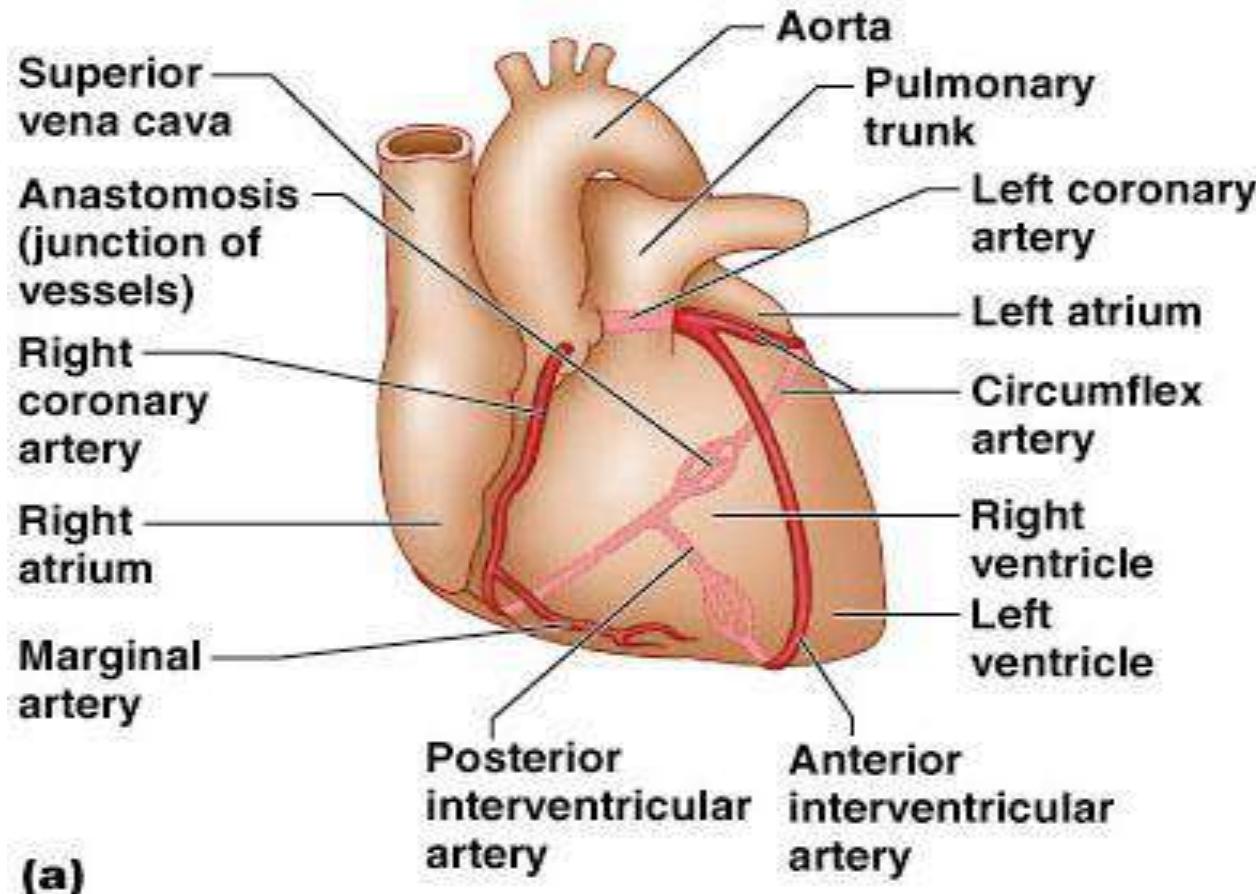


Figure 18.5

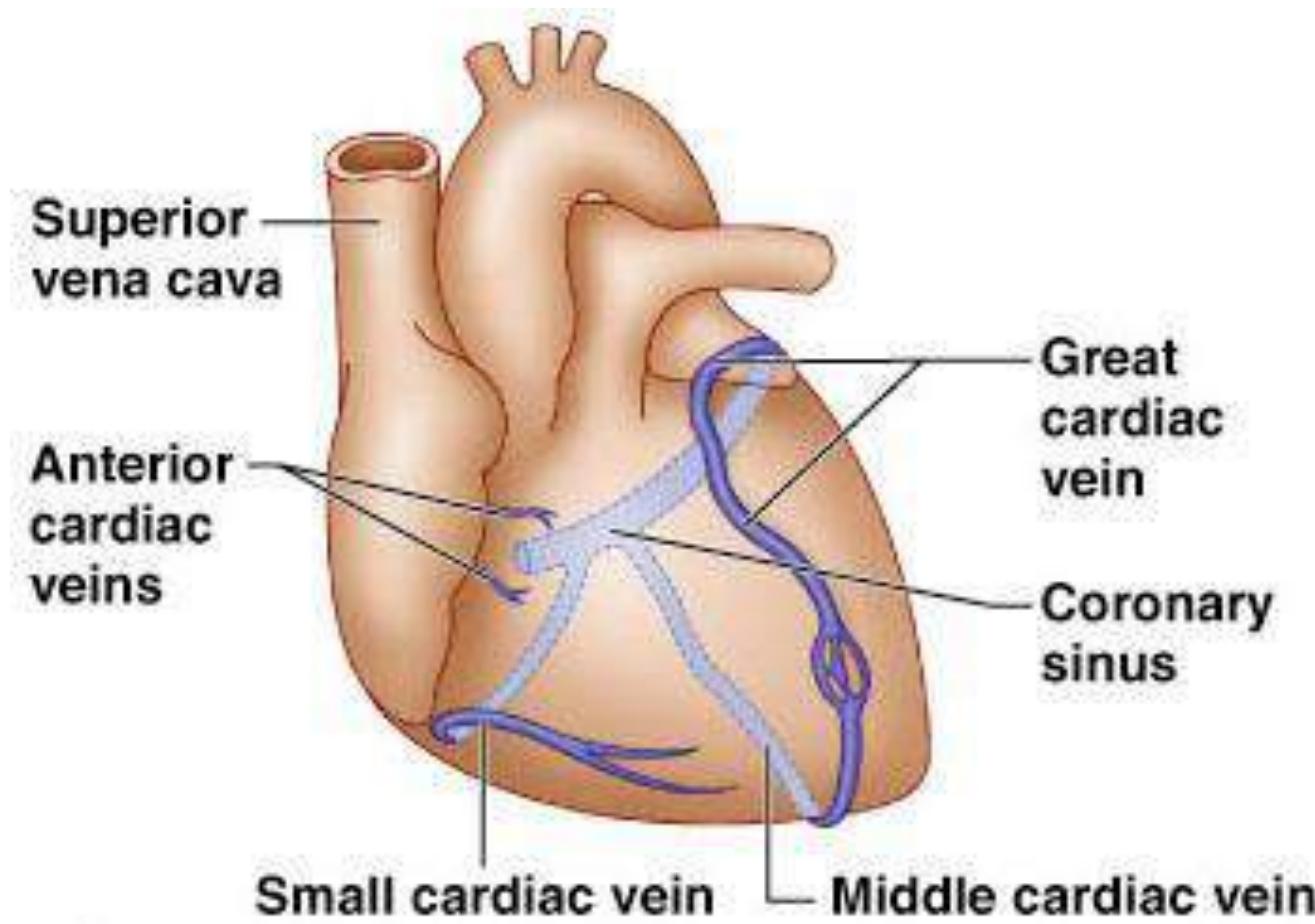
Coronary Circulation

- **Coronary circulation** is the functional blood supply to the heart muscle itself
- **Collateral routes** ensure blood delivery to heart even if major vessels are occluded

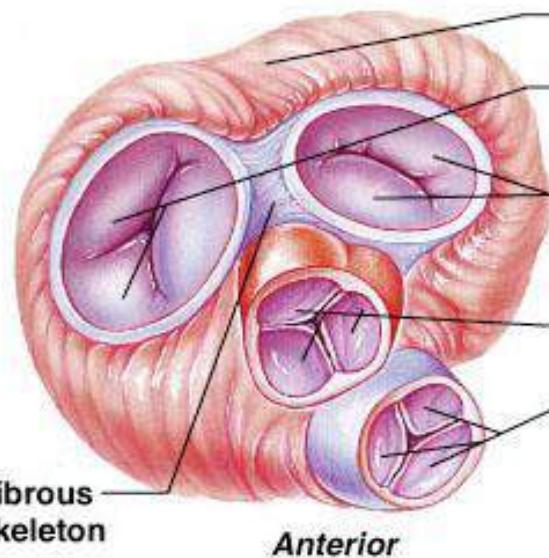
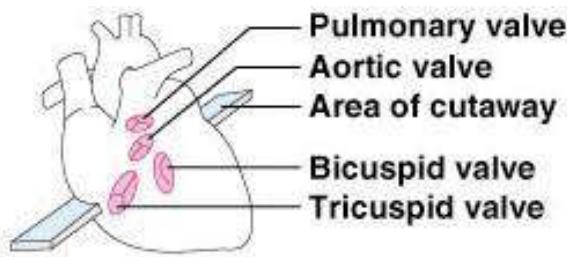
Coronary Circulation: Arterial Supply



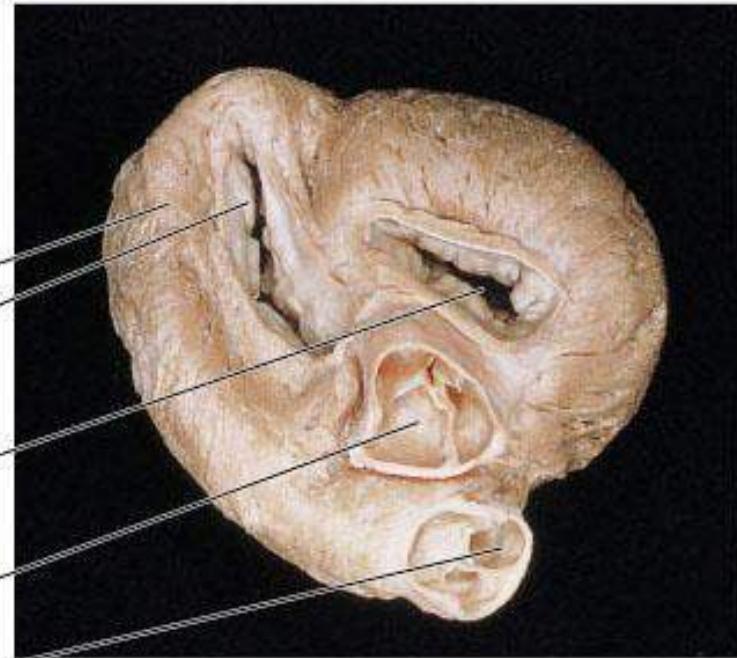
Coronary Circulation: Venous Supply



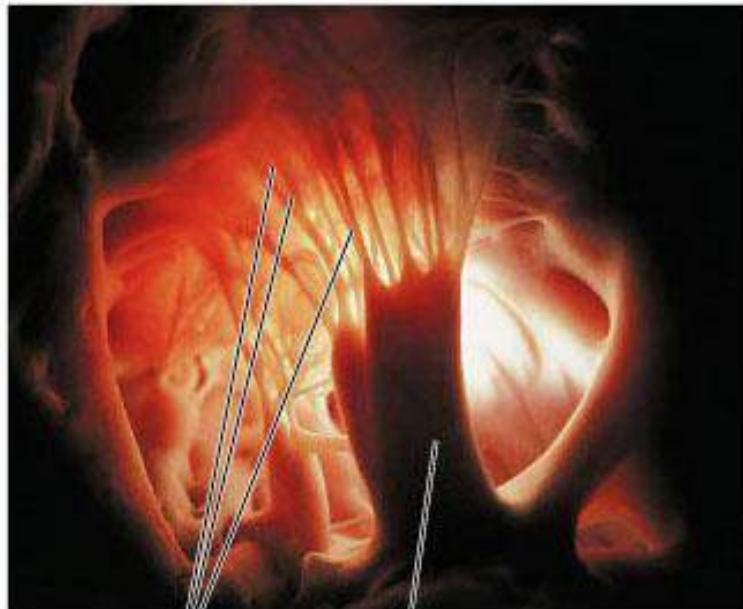
Heart Valves



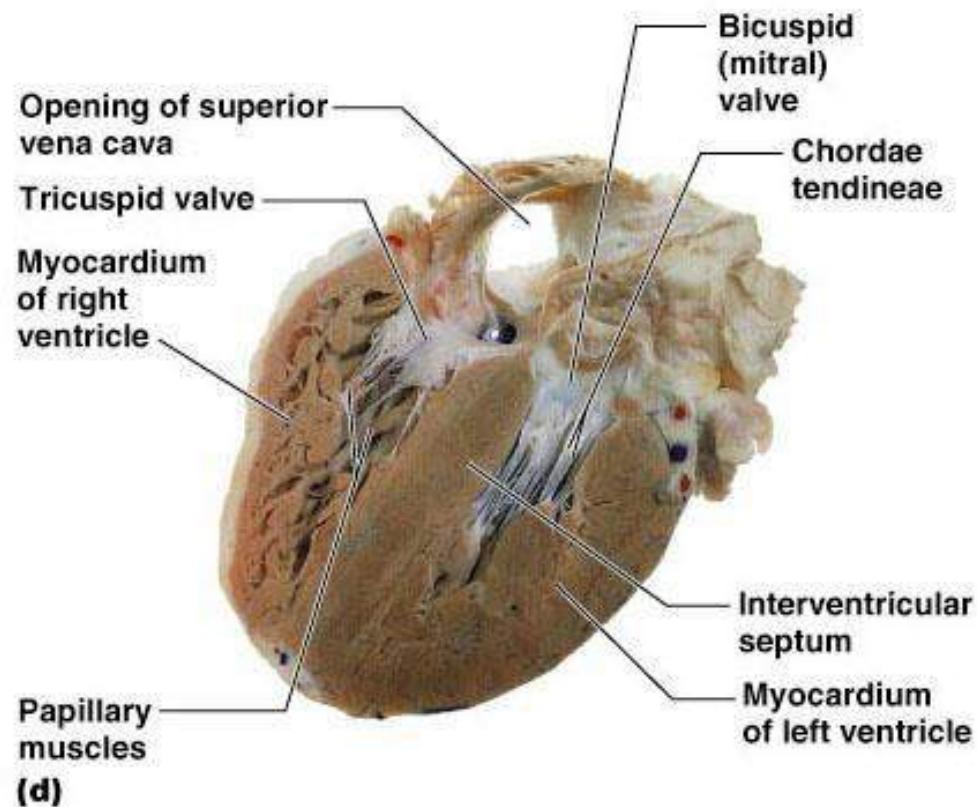
(a)



Heart Valves

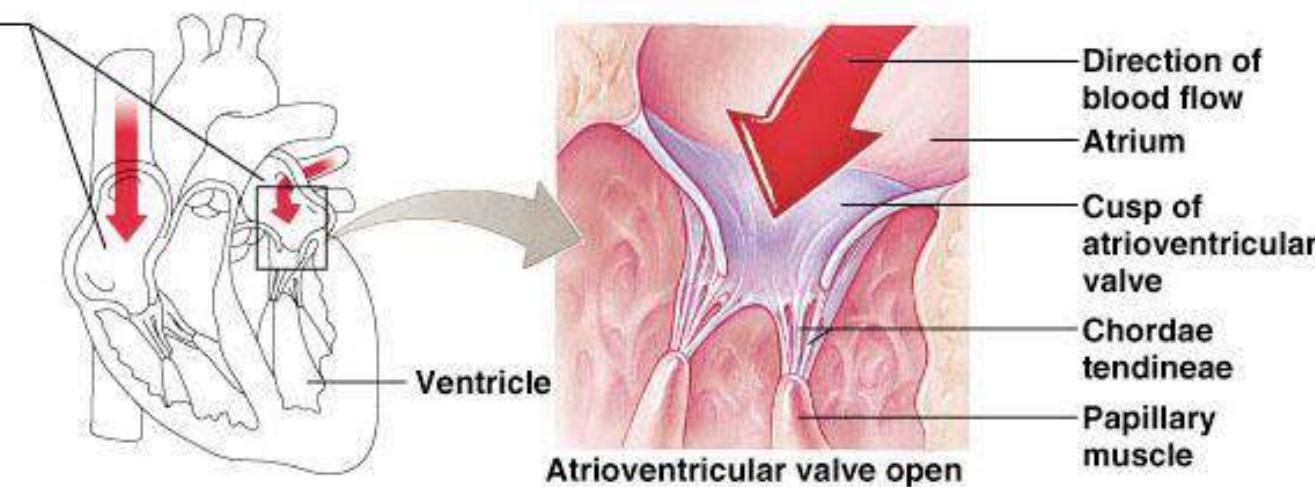


Chordae
tendineae
attached to
tricuspid
valve flap
(c)

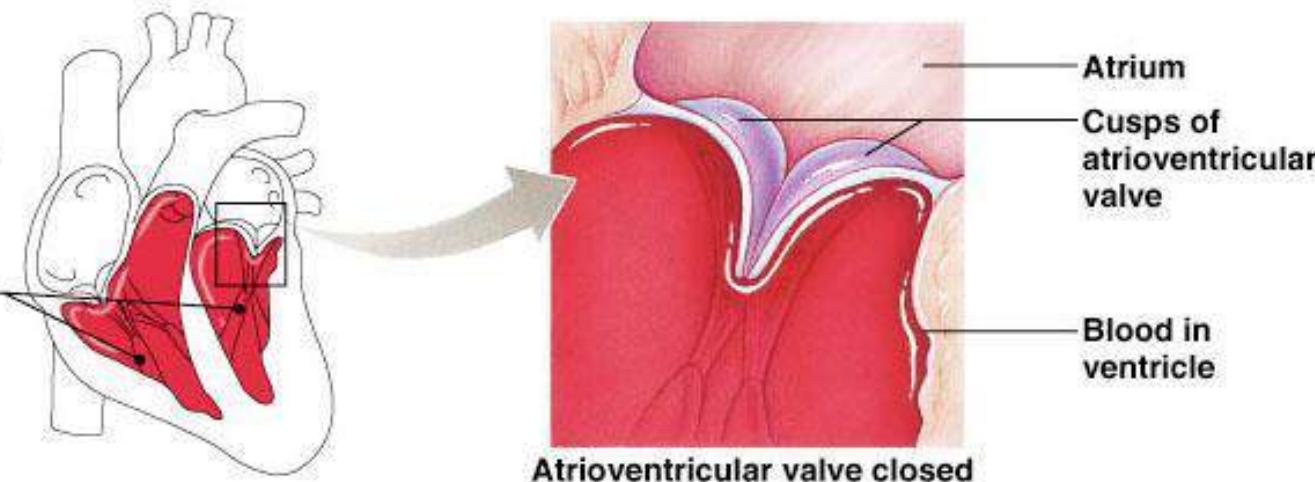


- ① Blood returning to the heart fills atria, putting pressure against atrioventricular valves; atrioventricular valves forced open
- ② As ventricles fill, atrioventricular valve flaps hang limply into ventricles
- ③ Atria contract, forcing additional blood into ventricles

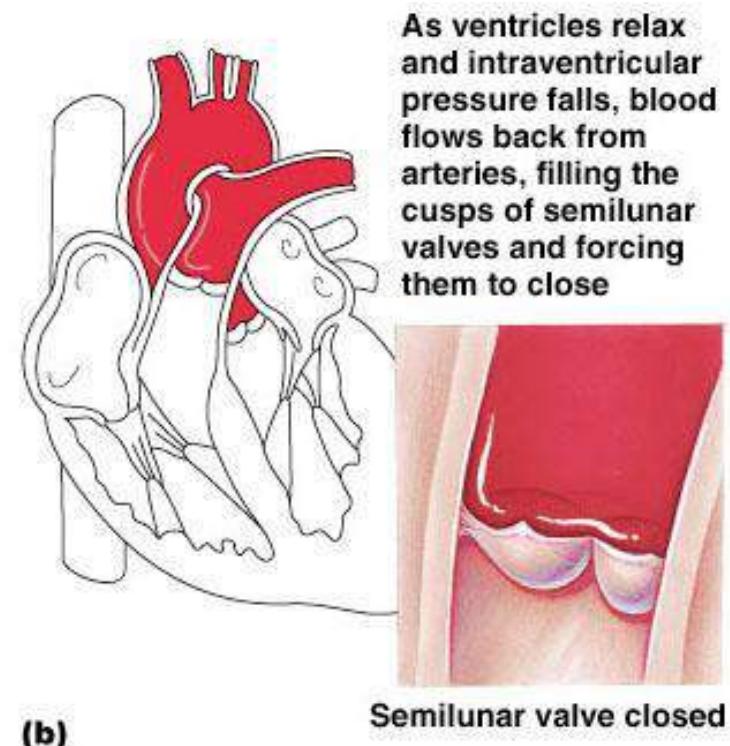
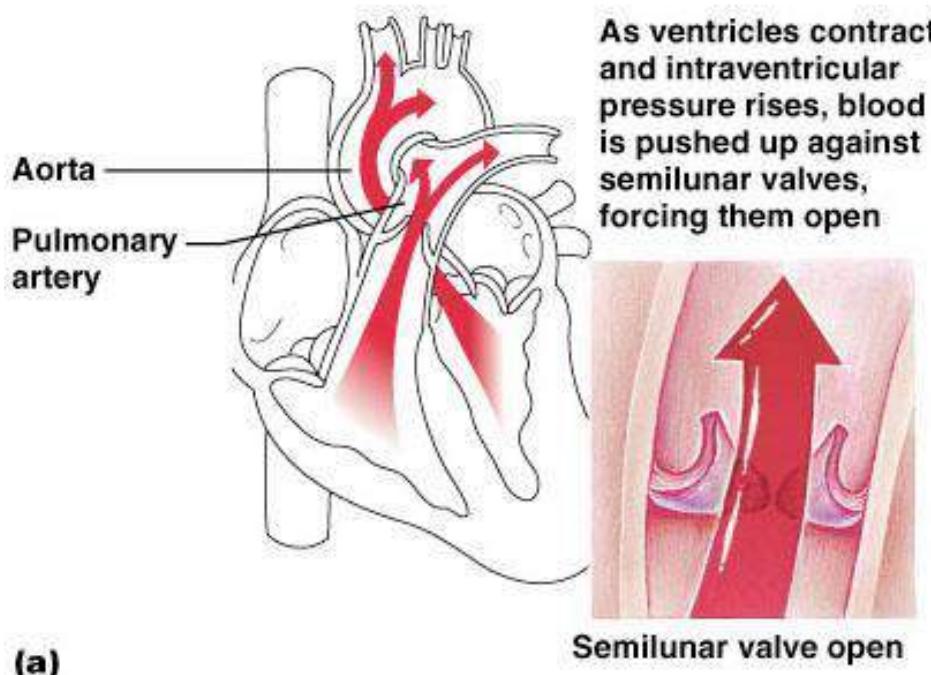
(a)



- ① Ventricles contract, forcing blood against atrioventricular valve cusps
- ② Atrioventricular valves close
- ③ Papillary muscles contract and chordae tendineae tighten, preventing valve flaps from evertting into atria



Semilunar Valve Function



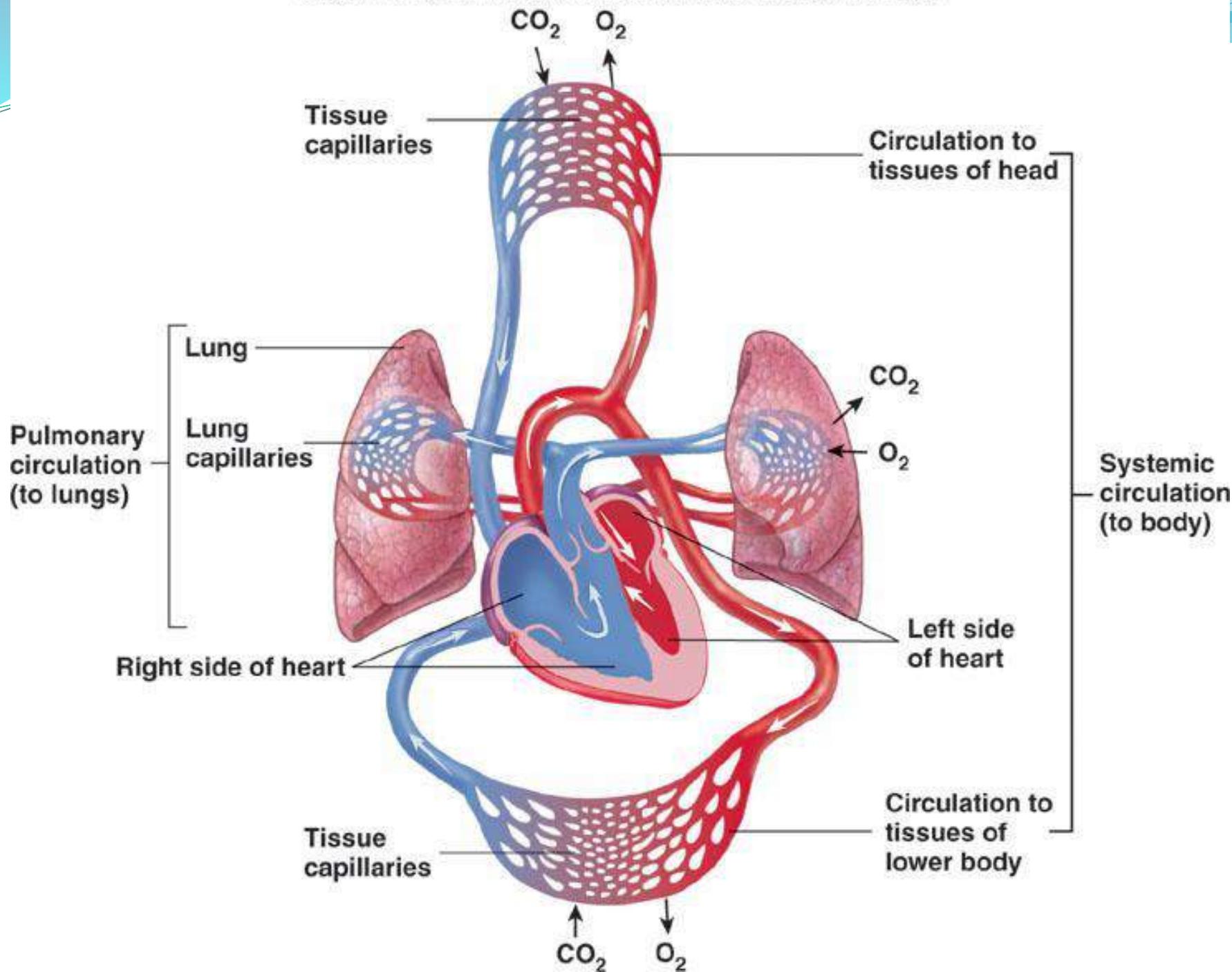
Physiology of the Heart

Functions of the Heart

- Generating blood pressure
- Routing blood: separates pulmonary and systemic circulations
- Ensuring one-way blood flow: valves
- Regulating blood supply
 - Changes in contraction rate and force match blood delivery to changing metabolic needs

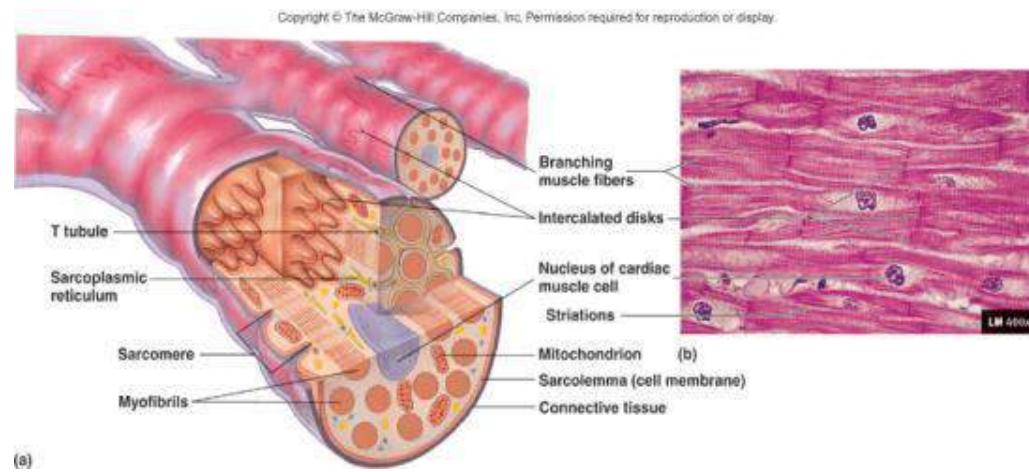
The cardiovascular system is divided into two circuits

- Pulmonary circuit
 - blood to and from the lungs
- Systemic circuit
 - blood to and from the rest of the body
- Vessels carry the blood through the circuits
 - Arteries carry blood away from the heart
 - Veins carry blood to the heart
 - Capillaries permit exchange



- Elongated, branching cells containing 1-2 centrally located nuclei
- Contains actin and myosin myofilaments
- **Intercalated disks:** specialized cell-cell contacts.
 - Cell membranes interdigitate
 - Desmosomes hold cells together
 - Gap junctions allow action potentials to move from one cell to the next.
- Electrically, cardiac muscle of the atria and of the ventricles behaves as single unit
- Mitochondria comprise 30% of volume of the cell vs. 2% in skeletal

Cardiac Muscle



Heart chambers and valves

- Structural Differences in heart chambers
 - The left side of the heart is more muscular than the right side
- Functions of valves
 - AV valves prevent backflow of blood from the ventricles to the atria
 - Semilunar valves prevent backflow into the ventricles from the pulmonary trunk and aorta

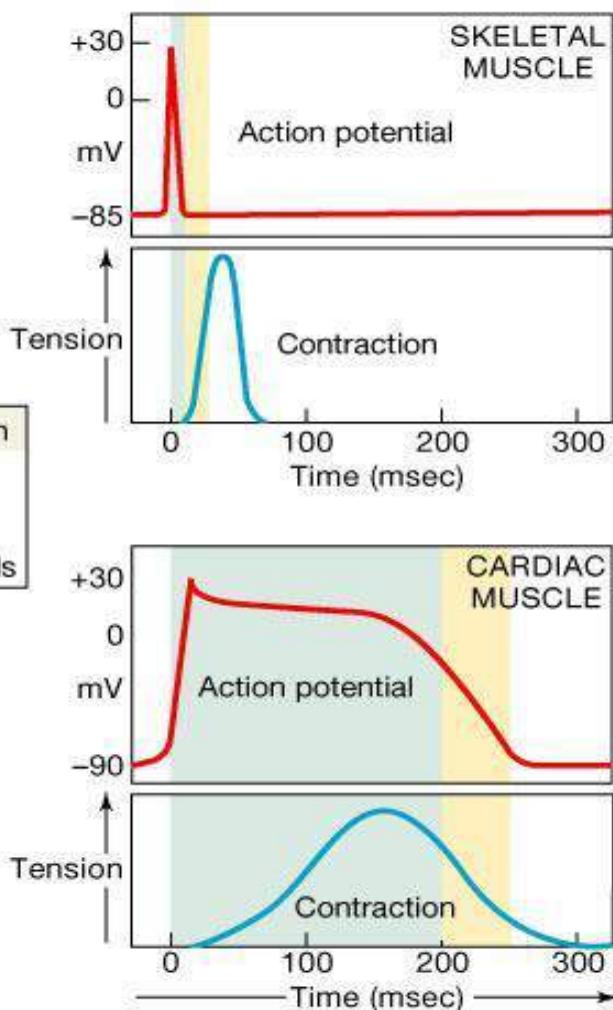
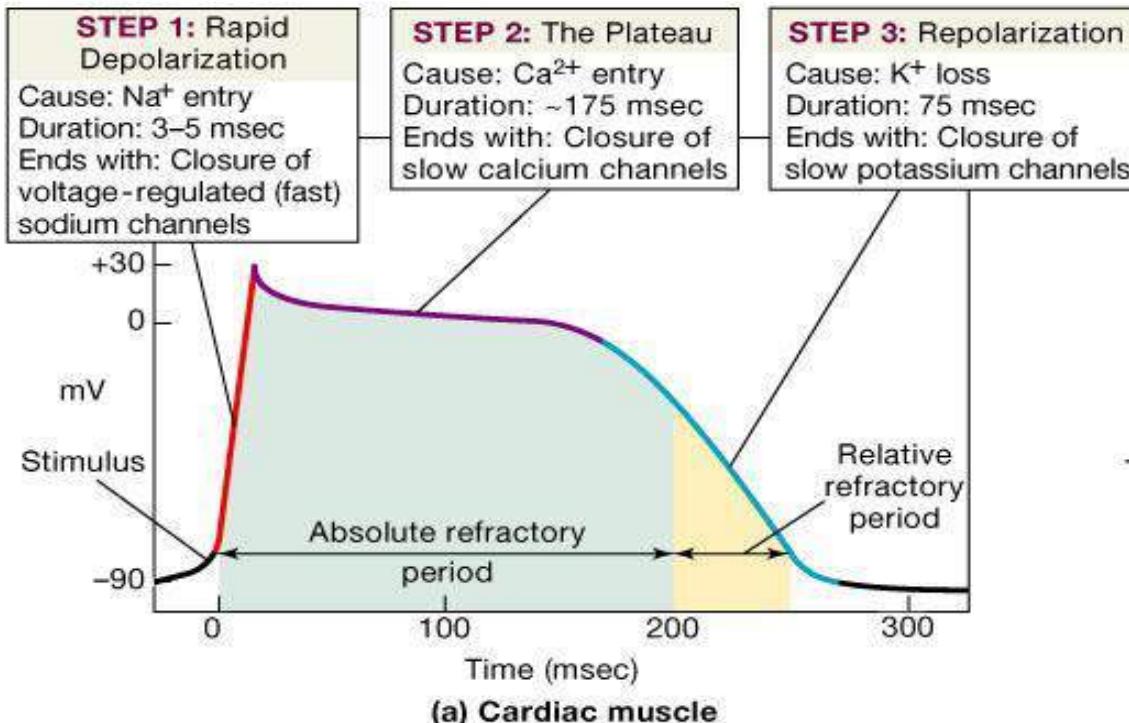
Cardiac Muscle Contraction

- Heart muscle:
 - Is stimulated by nerves and is self-excitatory (automaticity)
 - Contracts as a unit; no *motor units*
 - Has a long (250 ms) absolute refractory period
- Cardiac muscle contraction is similar to skeletal muscle contraction, i.e., sliding-filaments

Differences Between Skeletal and Cardiac Muscle Physiology

- Action Potential
 - Cardiac: Action potentials conducted from cell to cell.
 - Skeletal, action potential conducted along length of single fiber
- Rate of Action Potential Propagation
 - Slow in cardiac muscle because of gap junctions and small diameter of fibers.
 - Faster in skeletal muscle due to larger diameter fibers.
- Calcium release
 - Calcium-induced calcium release (CICR) in cardiac
 - Movement of extracellular Ca^{2+} through plasma membrane and T tubules into sarcoplasm stimulates release of Ca^{2+} from sarcoplasmic reticulum
 - Action potential in T-tubule stimulates Ca^{++} release from sarcoplasmic reticulum

The Action Potential in Skeletal and Cardiac Muscle



Electrical Properties of Myocardial Fibers

1. Rising phase of action potential

- Due to opening of fast Na^+ channels

2. Plateau phase

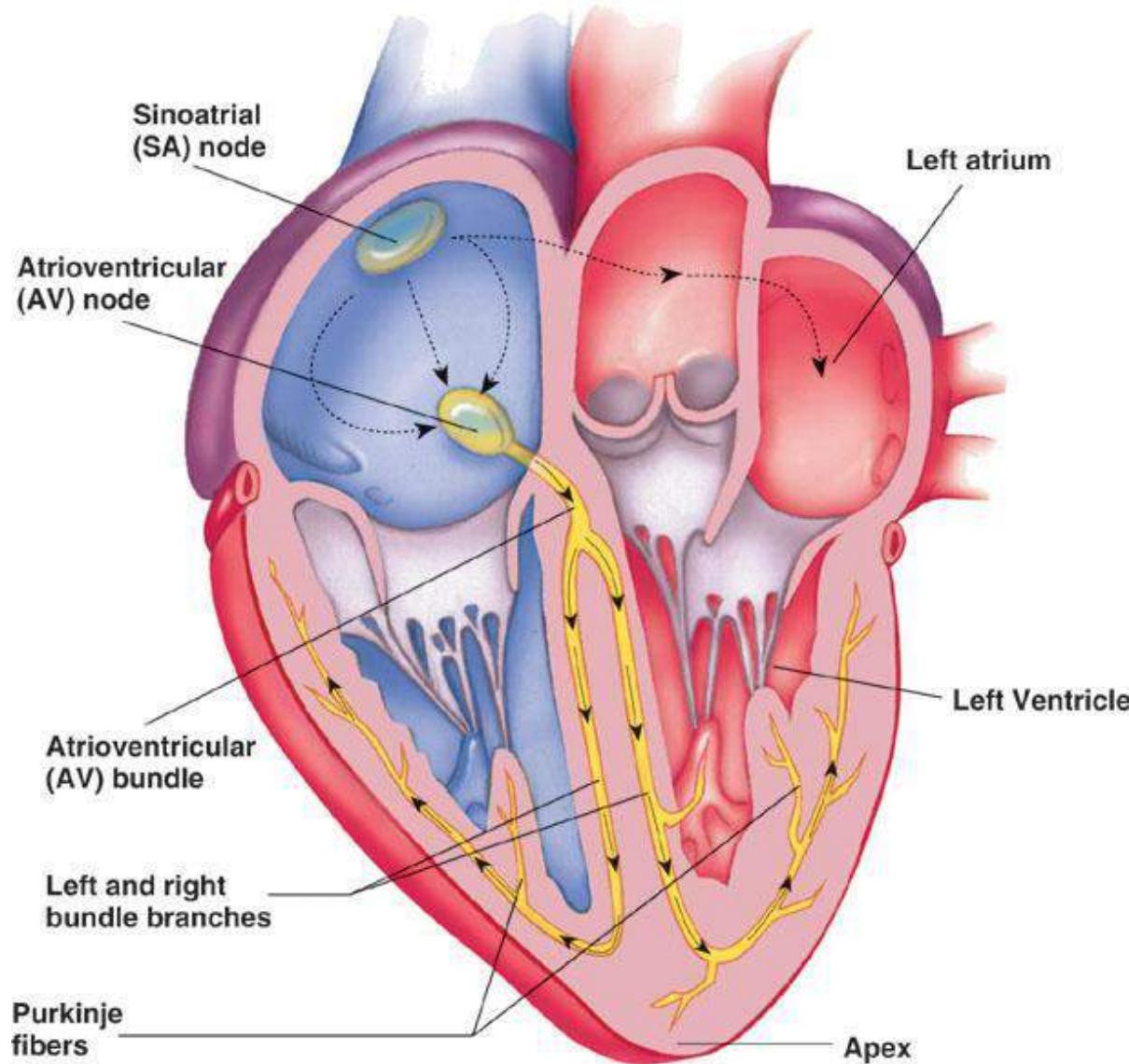
- Closure of sodium channels
- Opening of calcium channels
- Slight increase in K^+ permeability
- Prevents summation and thus tetanus of cardiac muscle

3. Repolarization phase

- Calcium channels closed
- Increased K^+ permeability

Conducting System of Heart

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Conduction System of the Heart

- **SA node:** sinoatrial node. The pacemaker.
 - Specialized cardiac muscle cells.
 - Generate spontaneous action potentials (*autorhythmic tissue*).
 - Action potentials pass to atrial muscle cells and to the AV node
- **AV node:** atrioventricular node.
 - Action potentials conducted more slowly here than in any other part of system.
 - Ensures ventricles receive signal to contract after atria have contracted
- **AV bundle:** passes through hole in cardiac skeleton to reach interventricular septum
- **Right and left bundle branches:** extend beneath endocardium to apices of right and left ventricles
- **Purkinje fibers:**
 - Large diameter cardiac muscle cells with few myofibrils.
 - Many gap junctions.
 - Conduct action potential to ventricular muscle cells (myocardium)

Heart Physiology: Intrinsic Conduction System

- Autorhythmic cells:
 - Initiate action potentials
 - Have unstable resting potentials called pacemaker potentials
 - Use calcium influx (rather than sodium) for rising phase of the action potential

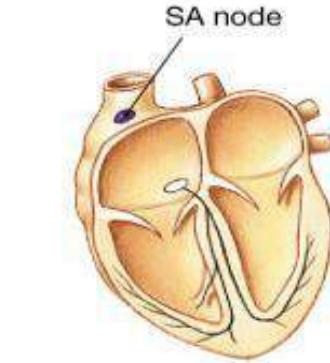
Depolarization of SA Node

- SA node - no stable resting membrane potential
- Pacemaker potential
 - gradual depolarization *from -60 mV*, slow influx of Na^+
- Action potential
 - occurs at threshold of *-40 mV*
 - depolarizing phase *to 0 mV*
 - fast Ca^{2+} channels open, (Ca^{2+} in)
 - repolarizing phase
 - K^+ channels open, (K^+ out)
 - *at -60 mV* K^+ channels close, pacemaker potential starts over
- Each depolarization creates one heartbeat
 - SA node at rest fires at 0.8 sec, about 75 bpm

Heart Physiology: Sequence of Excitation

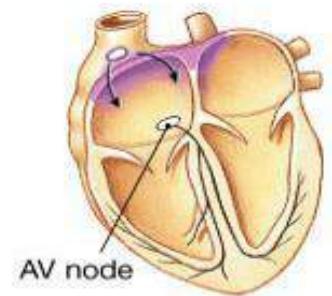
- Sinoatrial (SA) node generates impulses about 75 times/minute
- Atrioventricular (AV) node delays the impulse approximately 0.1 second
- Impulse passes from atria to ventricles via the atrioventricular bundle (bundle of His) to the Purkinje fibers and finally to the myocardial fibers

Impulse Conduction through the Heart



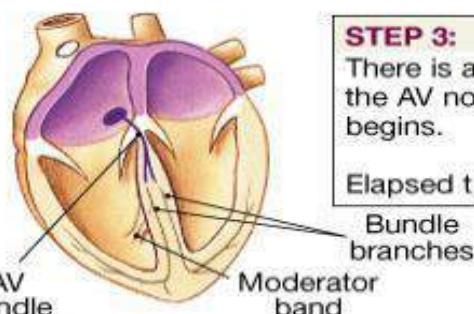
STEP 1:
SA node activity and atrial activation begin.

Time = 0



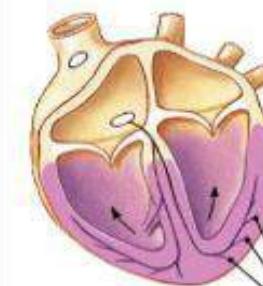
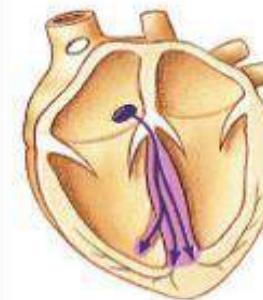
STEP 2:
Stimulus spreads across the atrial surfaces and reaches the AV node.

Elapsed time = 50 msec



STEP 3:
There is a 100-msec delay at the AV node. Atrial contraction begins.

Elapsed time = 150 msec



STEP 4:
The impulse travels along the interventricular septum within the AV bundle and the bundle branches to the Purkinje fibers and, via the moderator band, to the papillary muscles of the right ventricle.

Elapsed time = 175 msec

STEP 5:
The impulse is distributed by Purkinje fibers and relayed throughout the ventricular myocardium. Atrial contraction is completed, and ventricular contraction begins.

Elapsed time = 225 msec

Purkinje fibers

The Cardiac Cycle

- Cardiac cycle refers to all events associated with blood flow through the heart from the start of one heartbeat to the beginning of the next
- During a cardiac cycle
 - Each heart chamber goes through systole and diastole
 - Correct pressure relationships are dependent on careful timing of contractions

Phases of the Cardiac Cycle

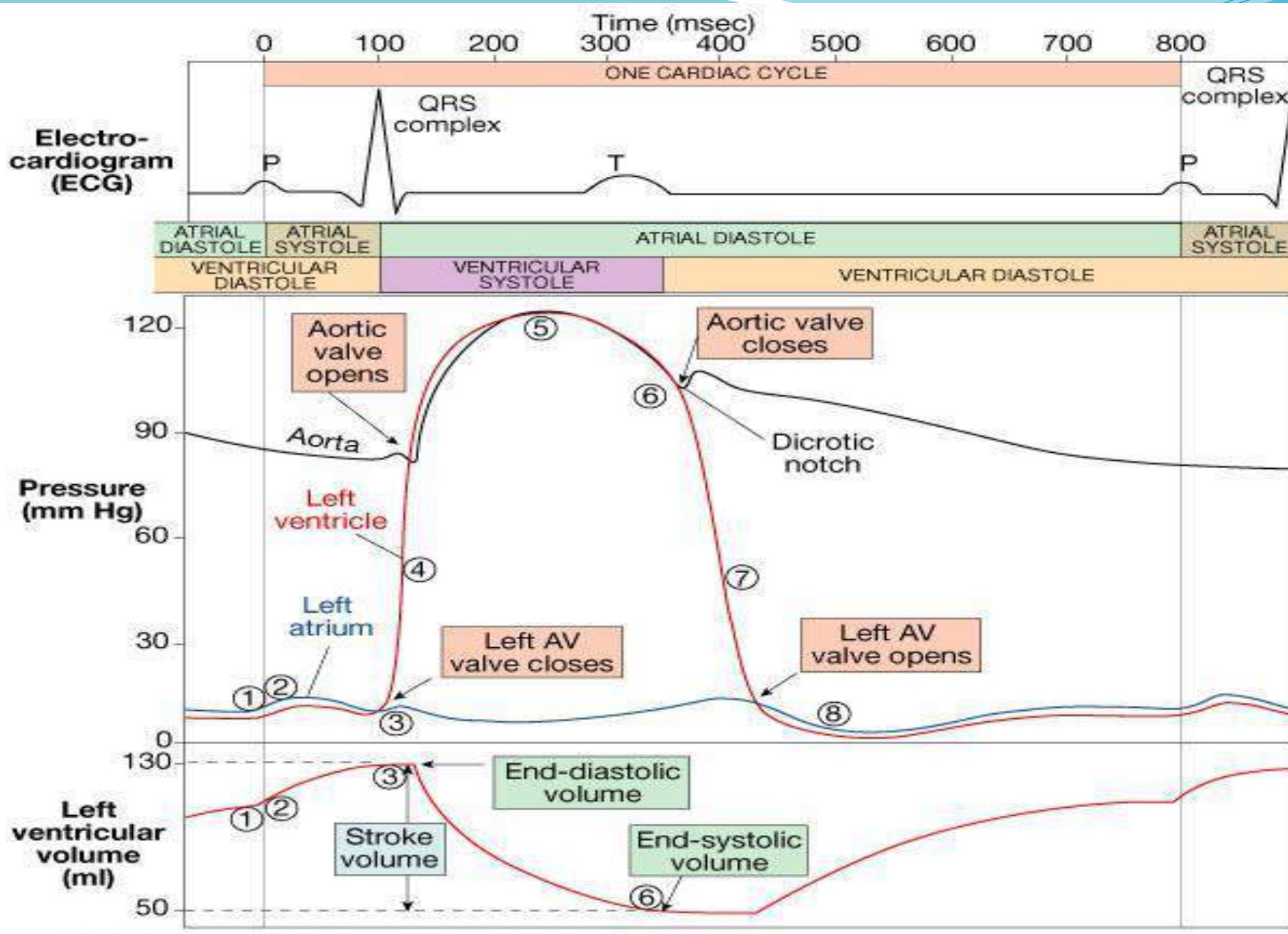
- Atrial diastole and systole -
 - Blood flows into and passively out of atria (80% of total)
 - AV valves open
 - Atrial systole pumps only about 20% of blood into ventricles
- Ventricular filling: mid-to-late diastole
 - Heart blood pressure is low as blood enters atria and flows into ventricles
 - 80% of blood enters ventricles *passively*
 - AV valves are open, then atrial systole occurs
 - Atrial systole pumps remaining 20% of blood into ventricles

Phases of the Cardiac Cycle

- Ventricular systole
 - Atria relax
 - Rising ventricular pressure results in closing of AV valves (1st heart sound - 'lubb')
 - Isovolumetric contraction phase
 - Ventricles are contracting but no blood is leaving
 - Ventricular pressure not great enough to open semilunar valves
 - *Ventricular ejection phase* opens semilunar valves
 - Ventricular pressure now greater than pressure in arteries (aorta and pulmonary trunk)

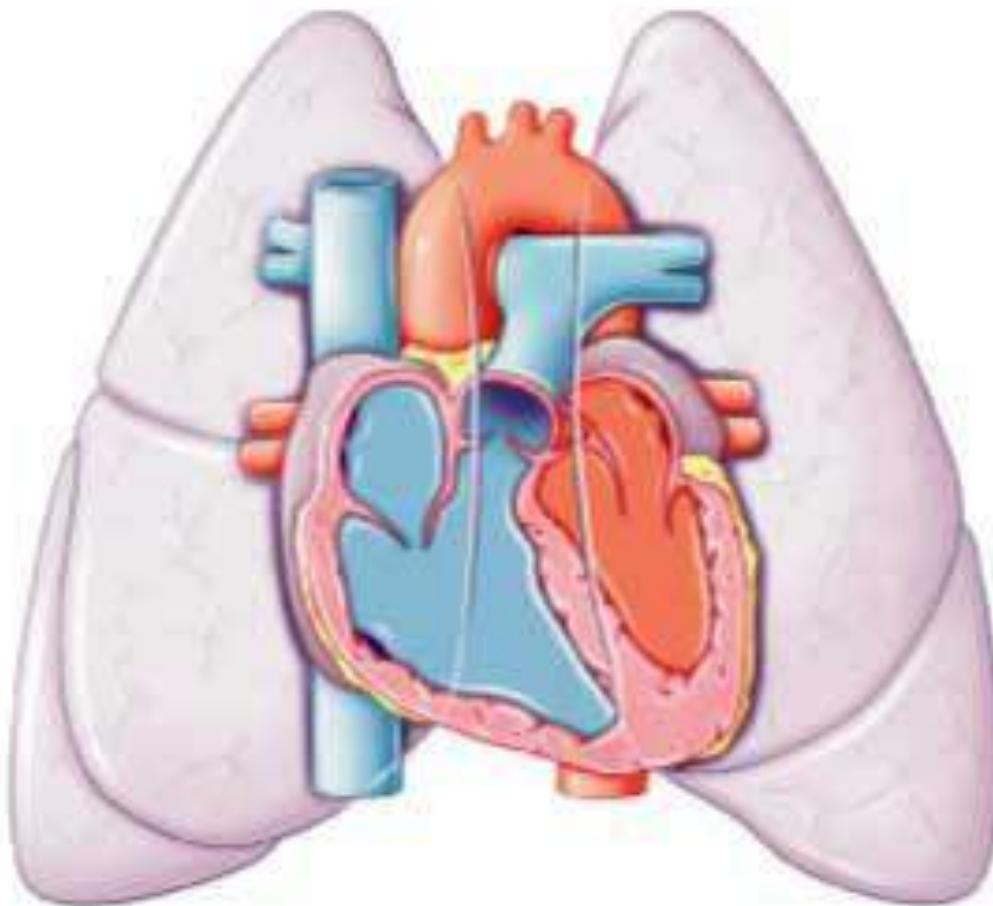
Phases of the Cardiac Cycle

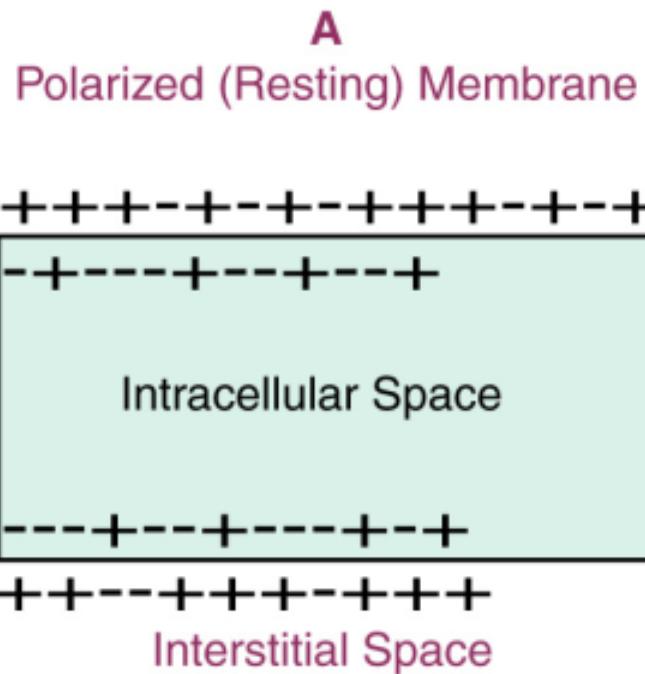
- Ventricular diastole
 - Ventricles relax
 - Backflow of blood in aorta and pulmonary trunk closes semilunar valves (2nd heart sound - “dubb
 - Dicrotic notch – brief rise in aortic pressure caused by backflow of blood rebounding off semilunar valves
 - Blood once again flowing into relaxed atria and passively into ventricles



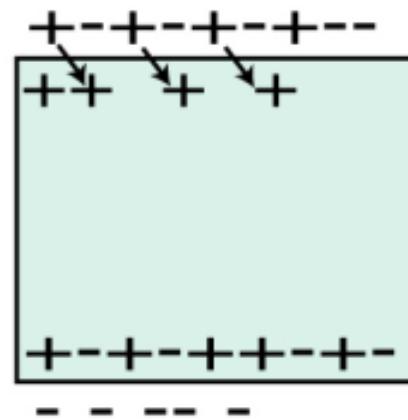
Pressure and Volume Relationships in the Cardiac Cycle

The heart and lung block

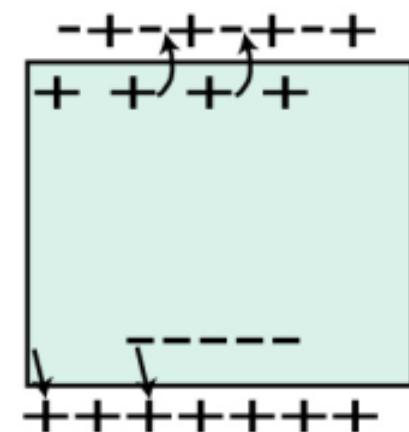




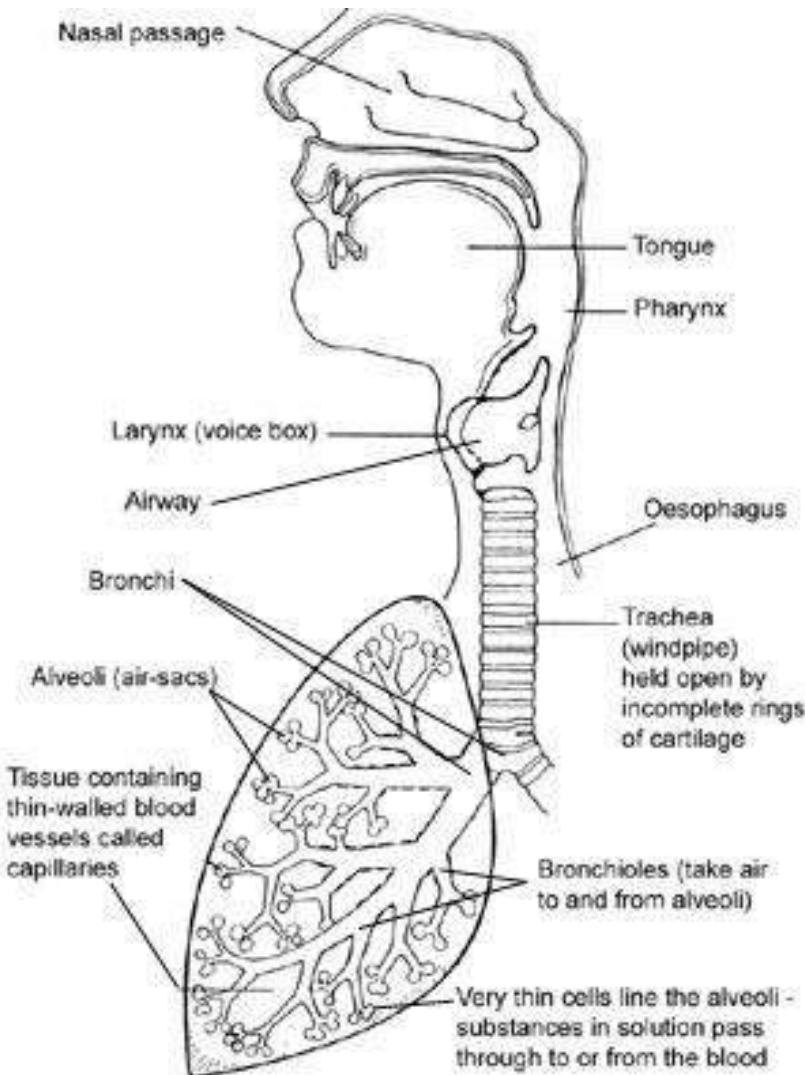
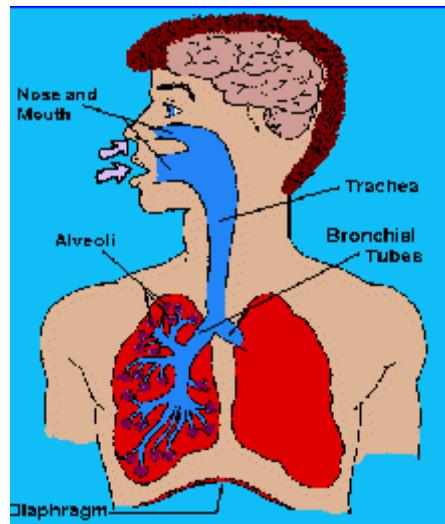
B
Depolarizing



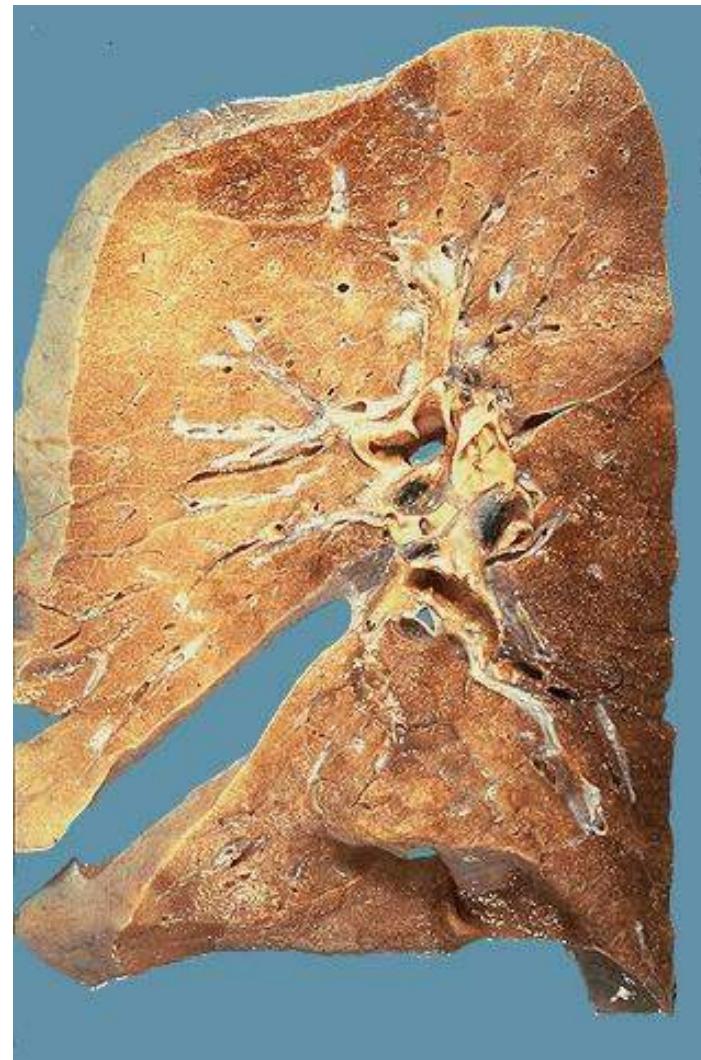
C
Repol polarizing



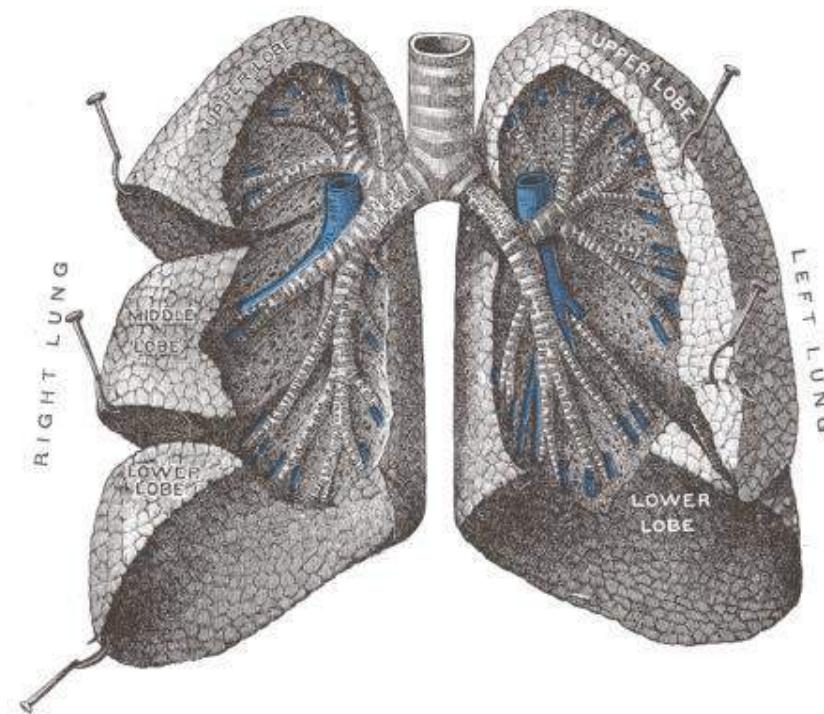
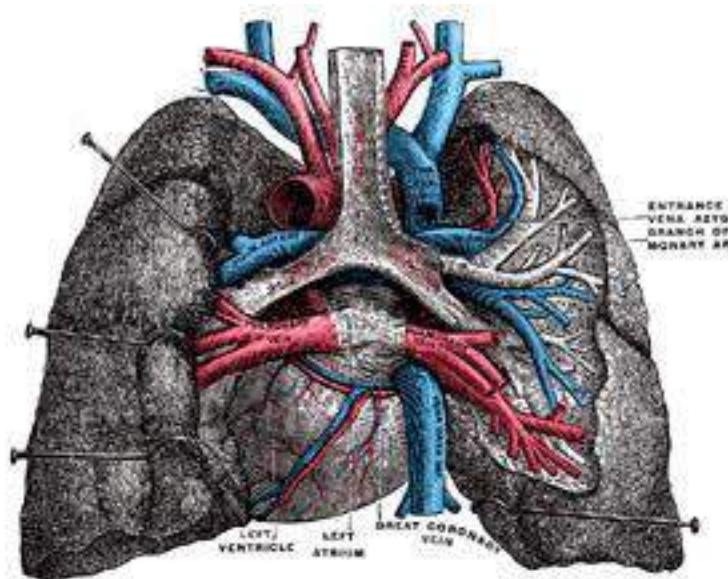
Airway Anatomy



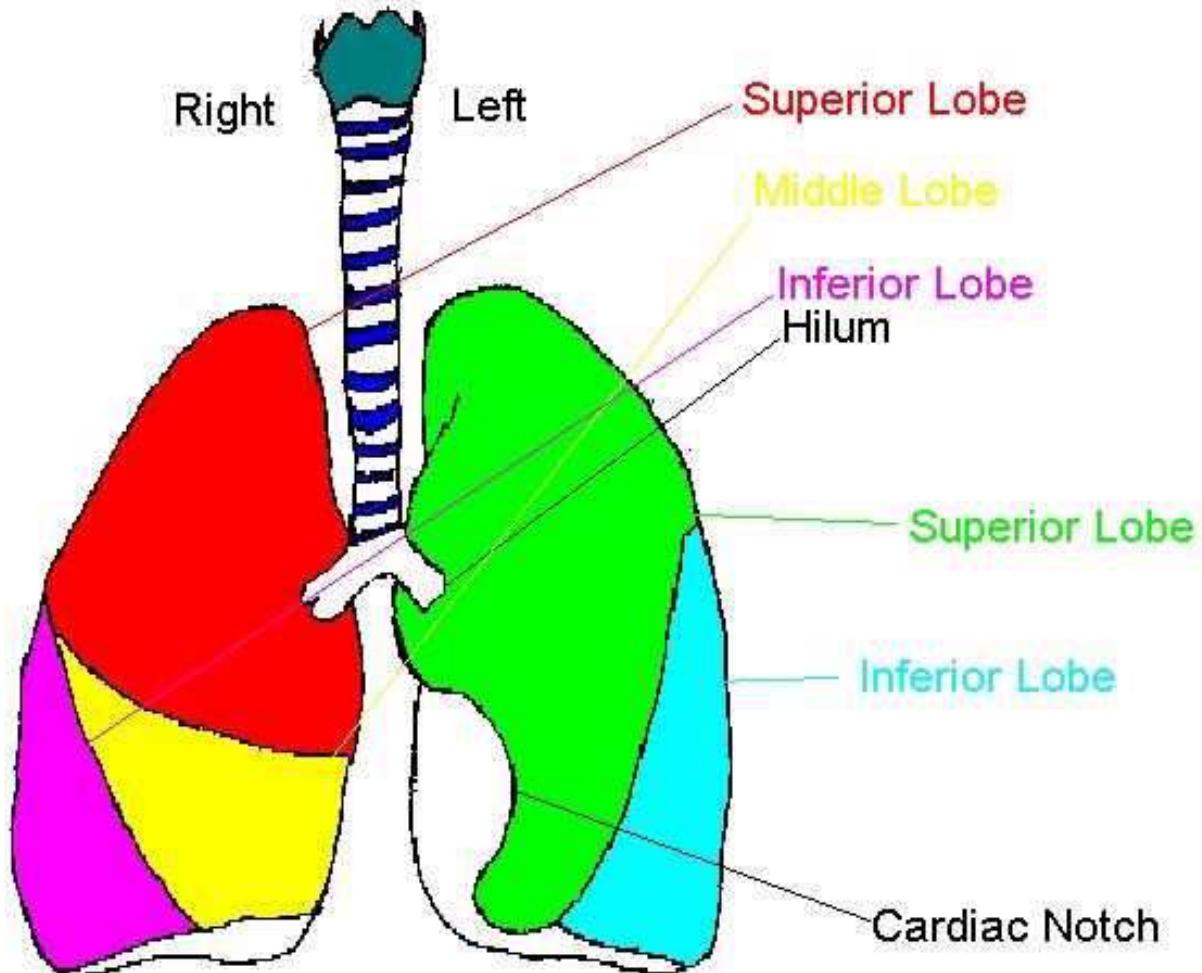
Human Lung



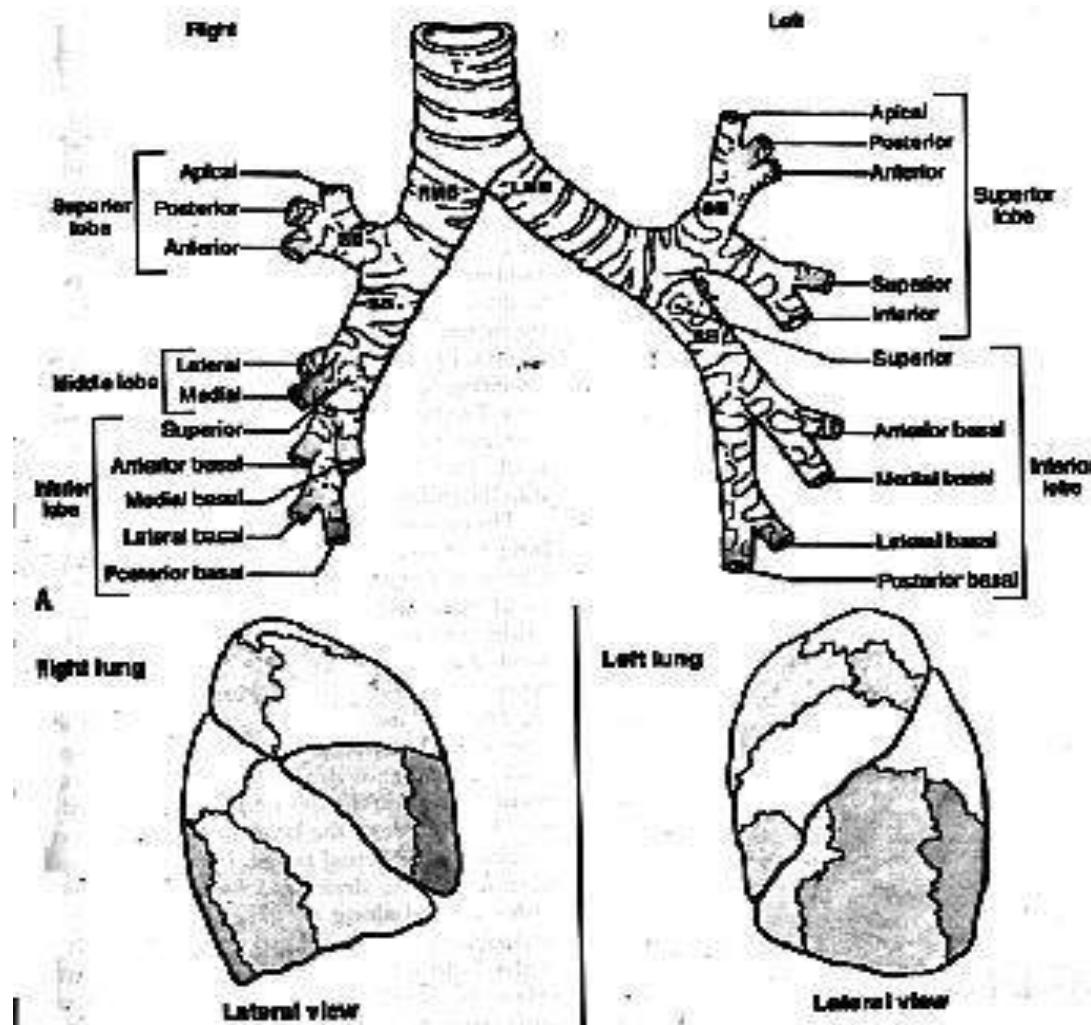
Anatomy



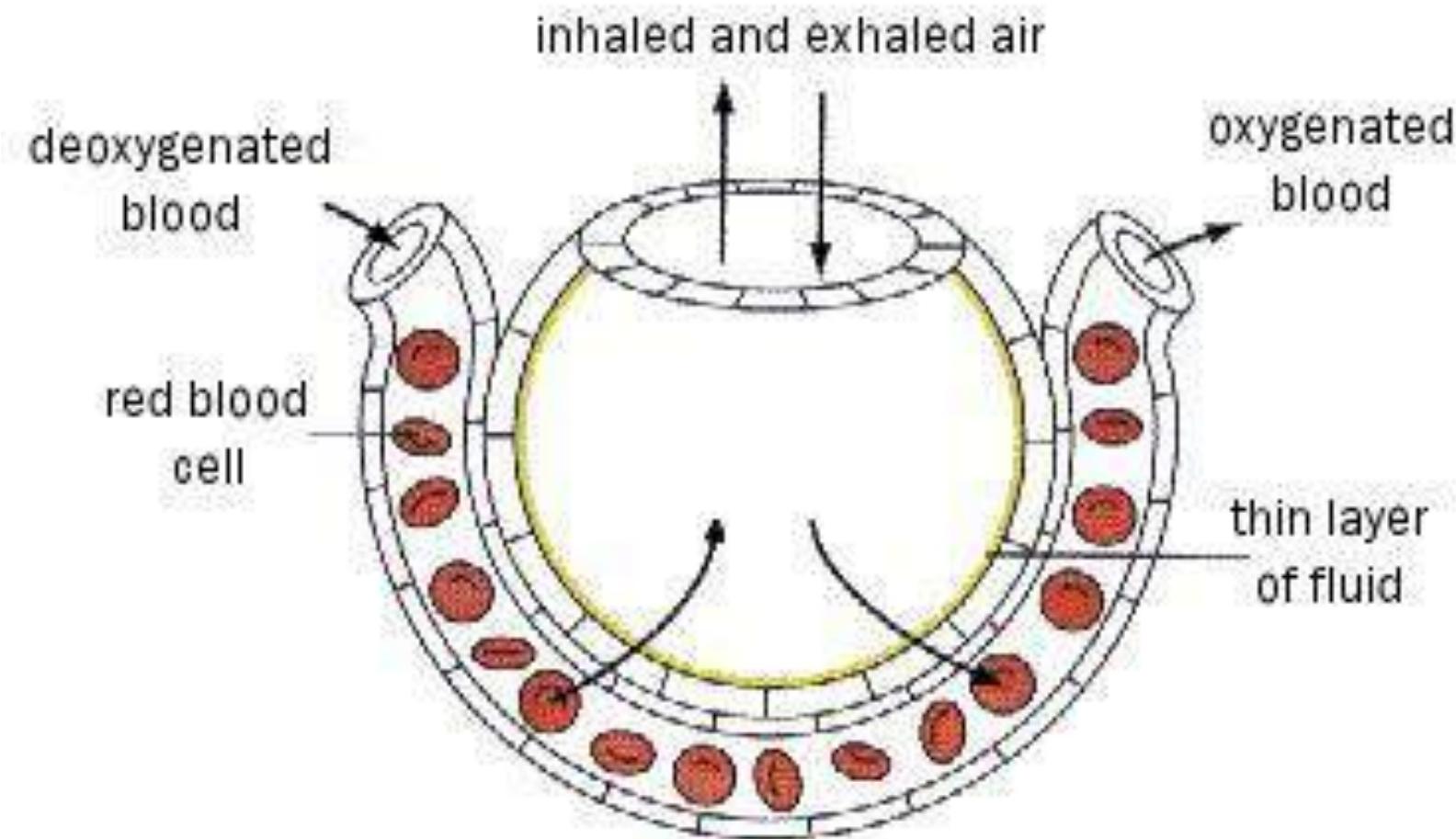
Lobes



Bronchi pulmonary Segments

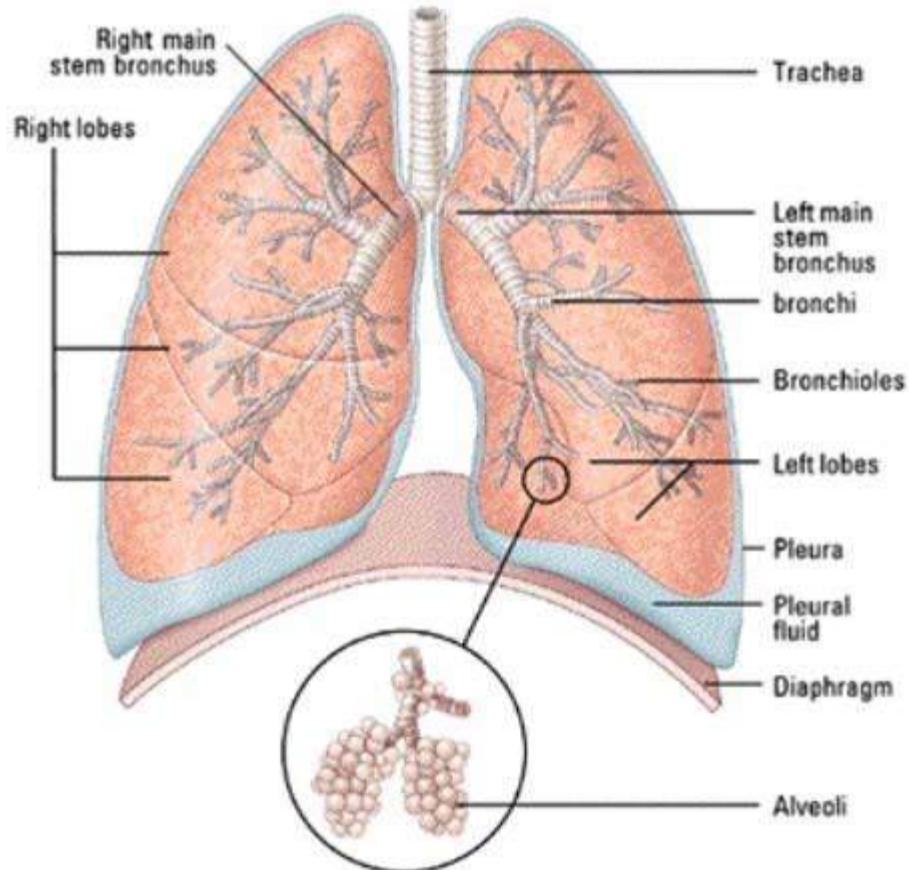


Alveolus



LUNGS

- Lungs comprised of
 - Airways
 - Alveoli



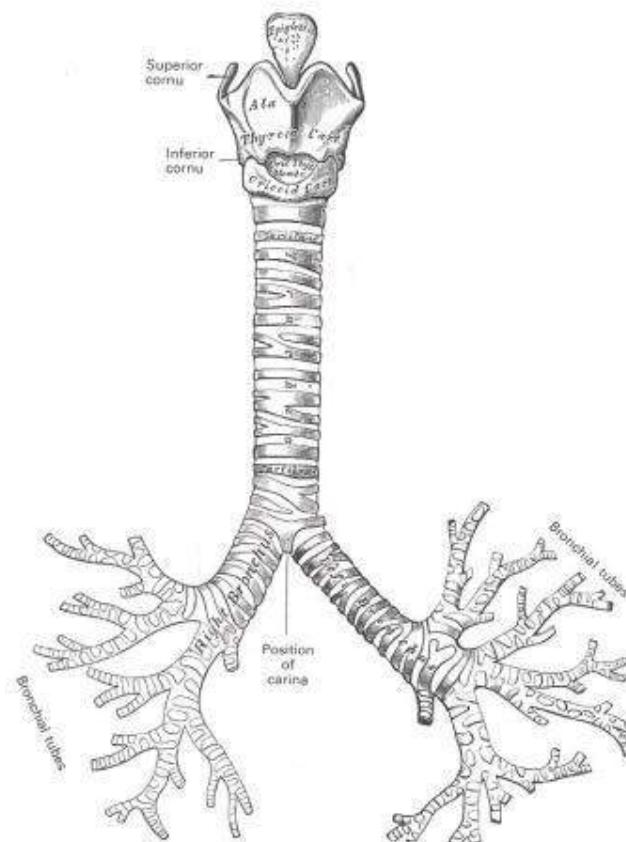
What do the lungs do?

- Primary function is gas exchange
- Let oxygen move in
- Let carbon dioxide move out

How do the lungs do this?

- First, air has to move to the region where gas exchange occurs.
- For this, you need a normal ribcage and respiratory muscles that work properly (among other things).

Conducting Airways

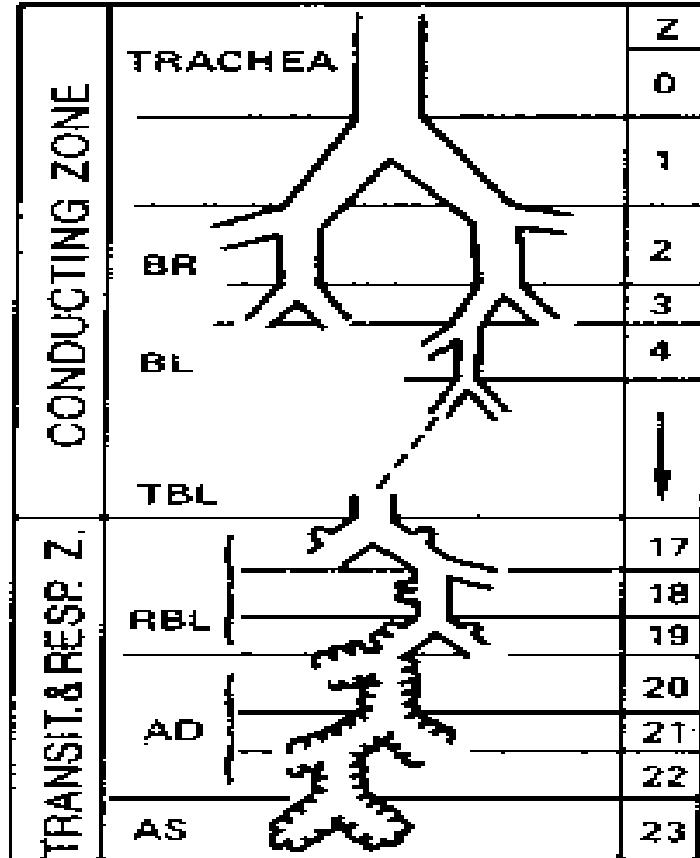


- Air travels via laminar flow through the conducting airways comprised of the following: trachea, lobar bronchi, segmental bronchi, subsegmental bronchi, small bronchi, bronchioles, and terminal bronchioles.

How do the lungs do this?

- The airways then branch further to become transitional/respiratory bronchioles.
- The transitional/respiratory zones are made up of respiratory bronchioles, alveolar ducts, and alveoli.

The Airways



- Conducting zone: no gas exchange occurs
 - Anatomic dead space
- Transitional zone: alveoli appear, but are not great in number
- Respiratory zone:
contain the alveolar sacs
- Over 8 million branches

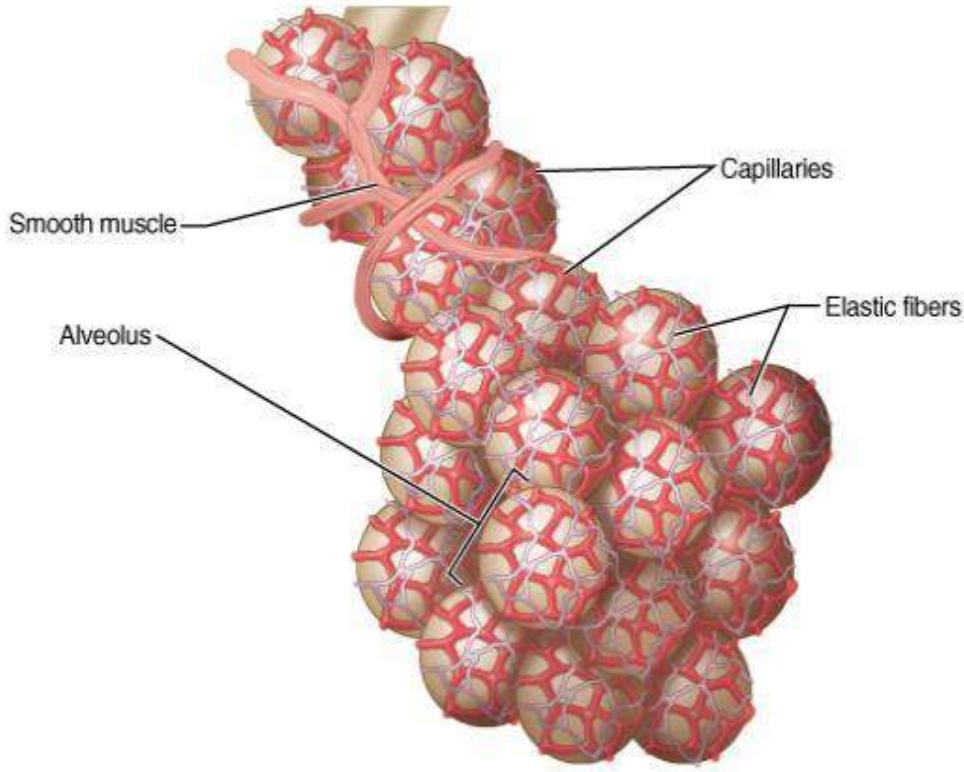
How does gas exchange occur?

- Numerous capillaries are wrapped around alveoli.
- Gas diffuses across this alveolar-capillary barrier.
- This barrier is as thin as $0.3\text{ }\mu\text{m}$ in some places and has a surface area of 50-100 square meters!

Gas Exchange

- Diffusion Barrier crossed by O₂ moving from air to blood and CO₂ from blood to air is made up of:
 - 1. an aqueous surface film
 - 2. epithelial cells of alveolus
 - 3. interstitial layer
 - 4. endothelial cells of capillaries
 - 5. blood plasma
 - 6. membrane of RBCs

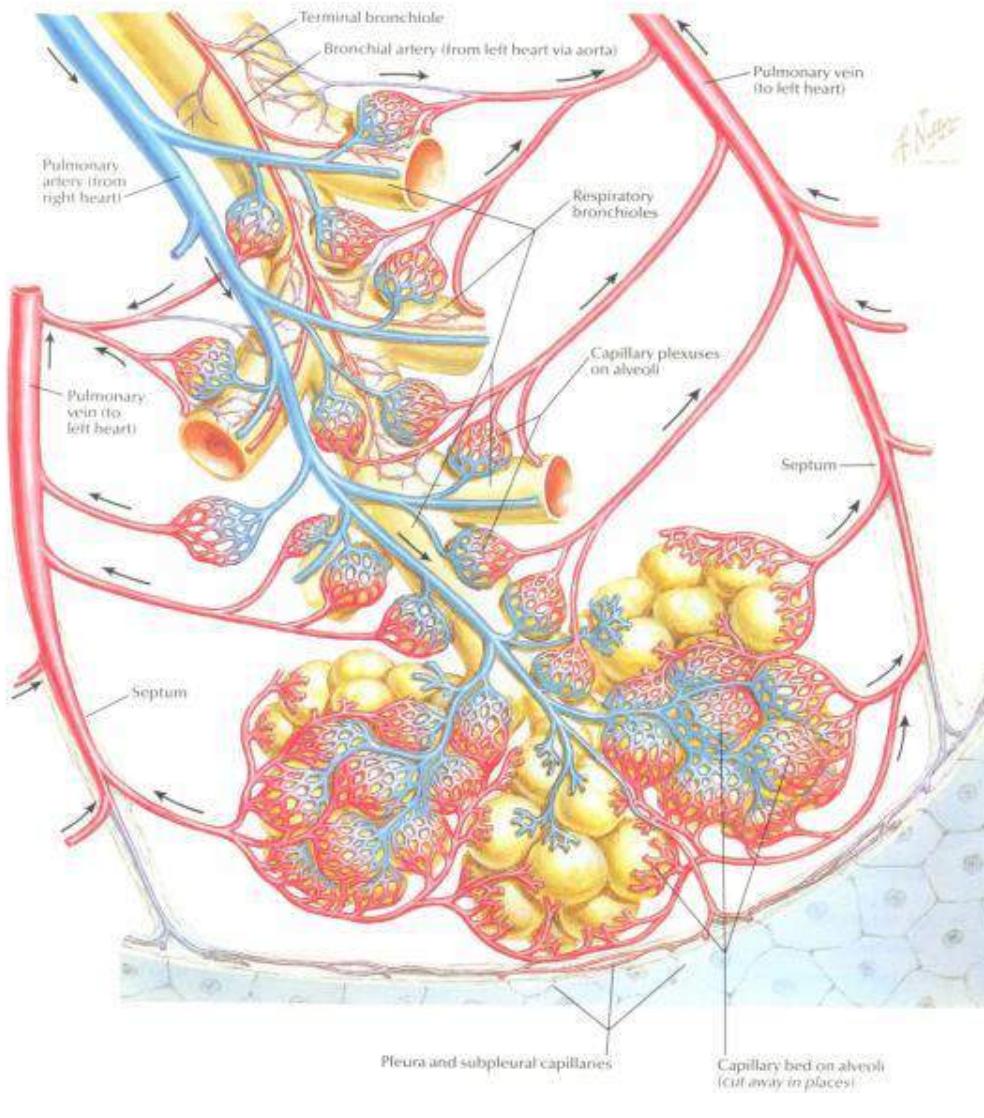
Alveoli



Copyright © 2001 Benjamin Cummings, an imprint of Addison Wesley Longman, Inc.

- Approximately 300 million alveoli
- 1/3 mm diameter
- Total surface area about 85 sq. meters (size of a tennis court)

Gas Exchange

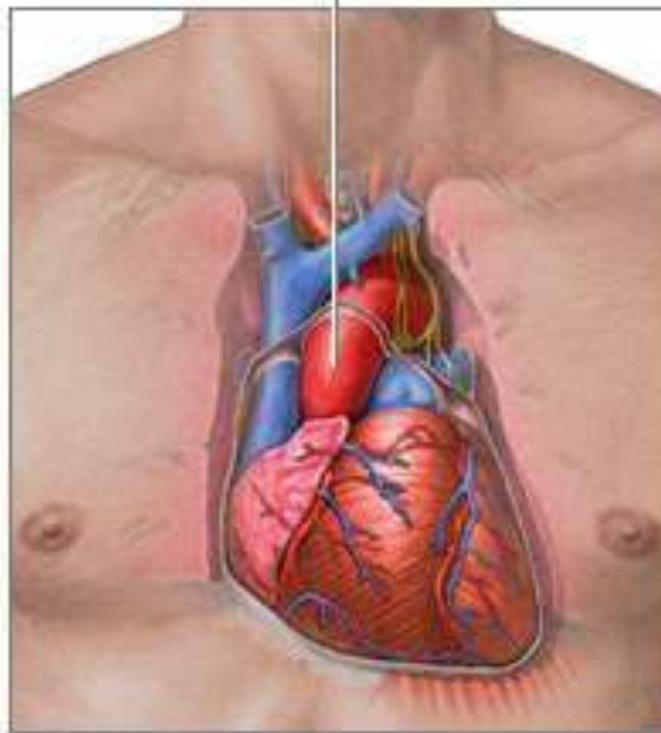


From
Netter
Atlas of
Human
Anatomy,
1989



The Circulatory System

Heart



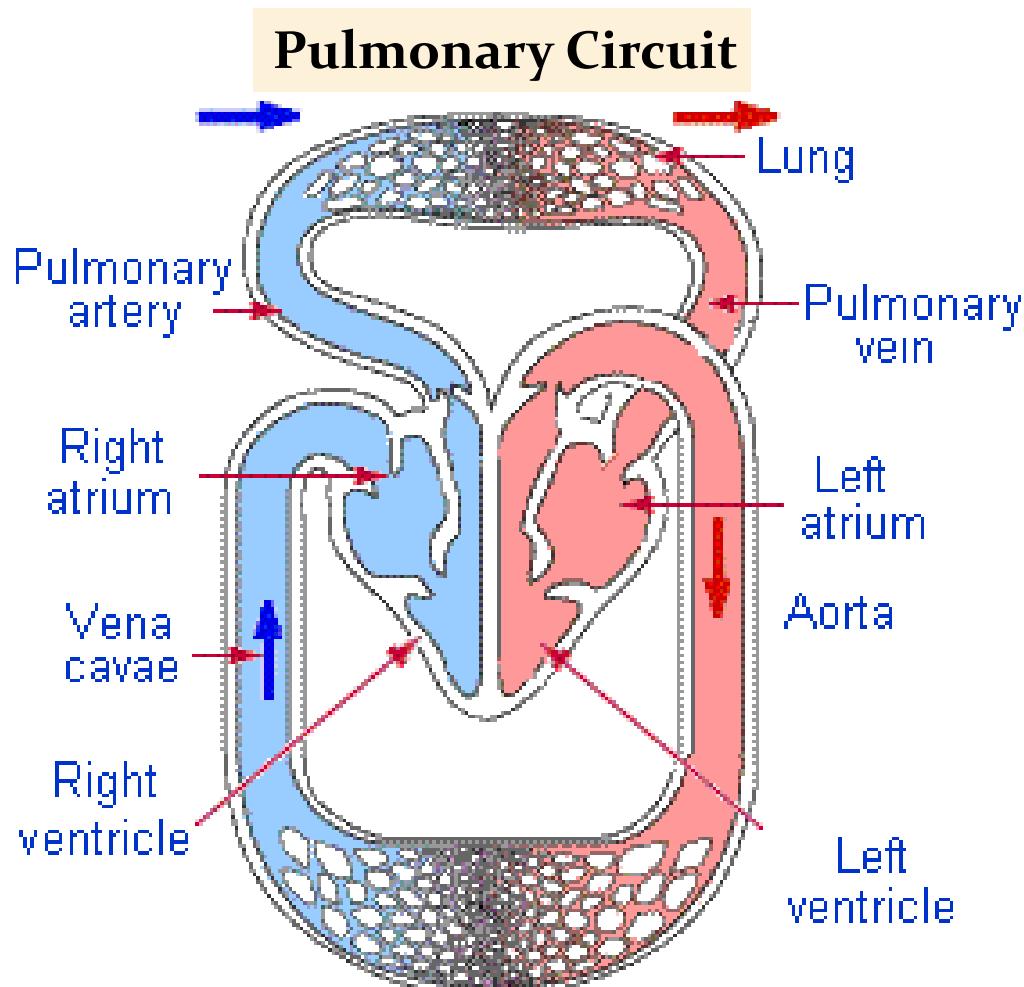
Electrocardiogram



Functions of the Circulatory System

- Transport oxygen to cells
- Transport nutrients from the digestive system to body cells
- Transport hormones to body cells
- Transport waste from body cells to excretory organs
- Distribute body heat

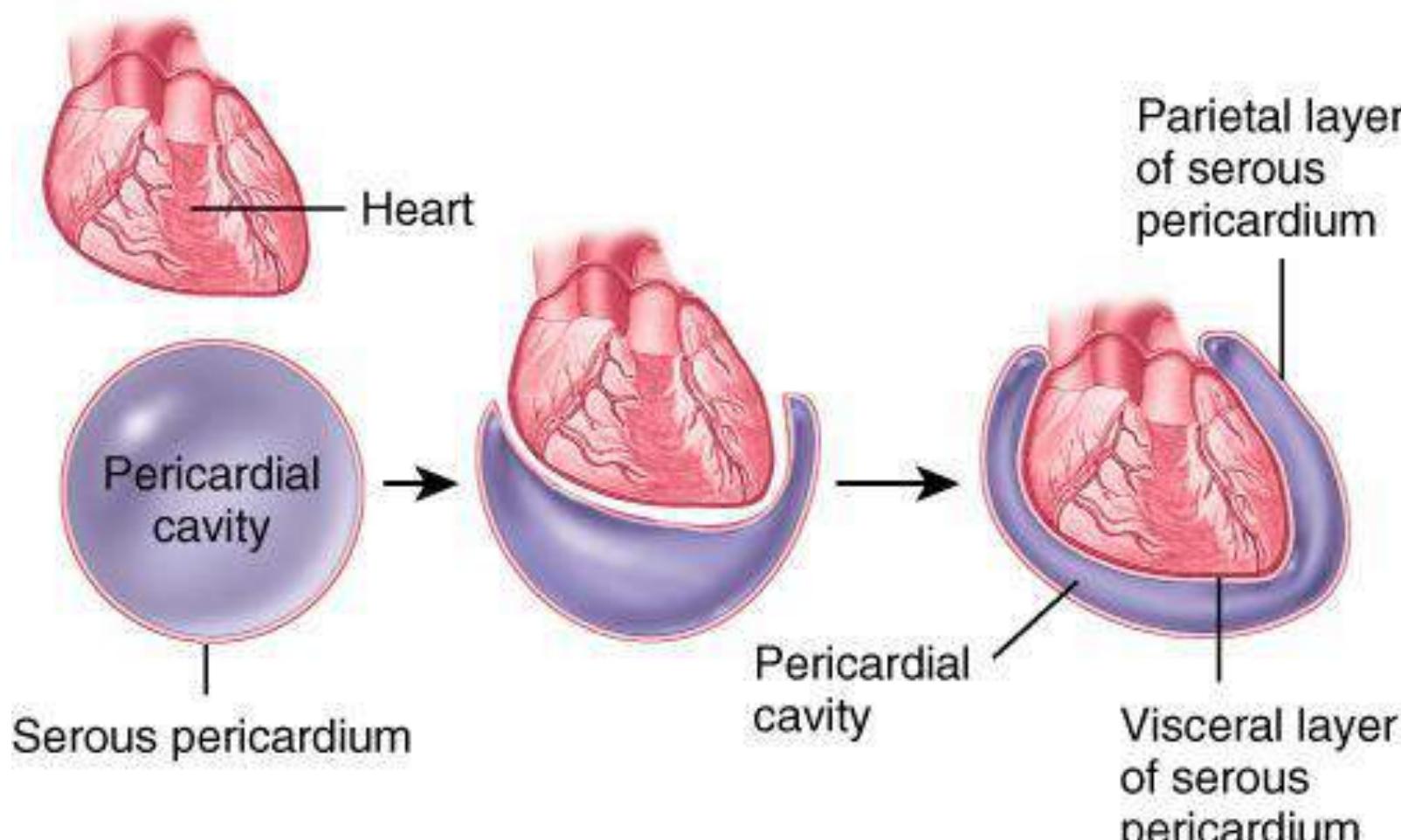
Circulation



Systemic Circuit

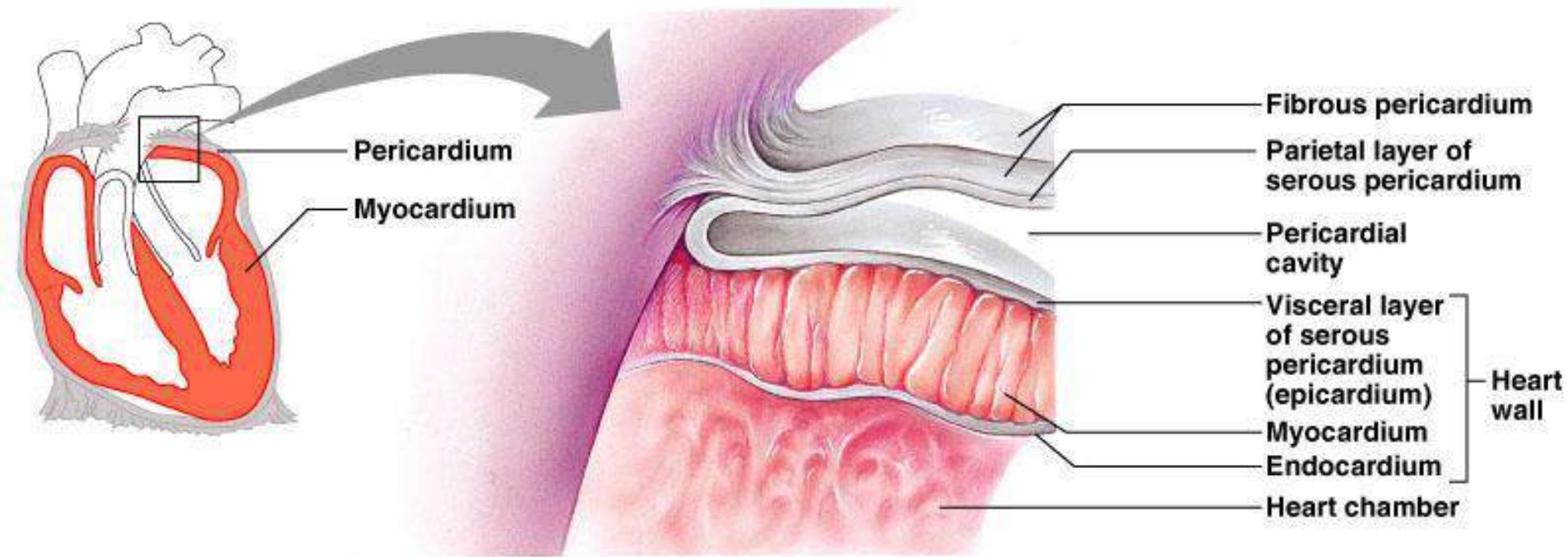
oxygen-poor blood
 oxygen-rich blood

Pericardial Cavity



(b) Simplified relationship of the serous pericardium to the heart

Layers of Cardiac Tissue



Visceral pericardium

- Outer protective layer composed of a serous membrane
- Includes blood capillaries, lymph capillaries, and nerve fibers.

Myocardium

- Relatively thick.
- Consists largely of cardiac muscle tissue responsible for forcing blood out of the heart chambers.
- Muscle fibers are arranged in planes, separated by connective tissues that are richly supplied with blood capillaries, and nerve fibers.

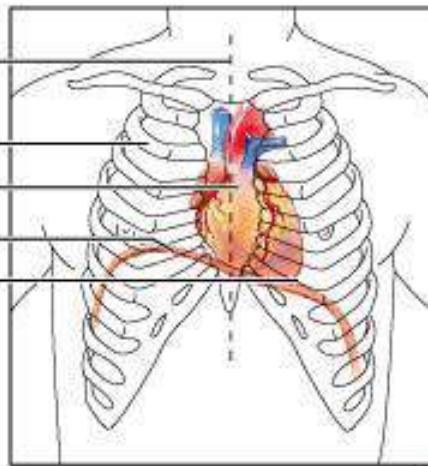
Endocardium

- Consists of epithelial and connective tissue that contains many elastic and collagenous fibers.
- Connective tissue also contains blood vessels and some specialized cardiac muscle fibers called **Purkinje fibers**.
- Lines all of the heart chambers and covers heart valves.

Location of Heart

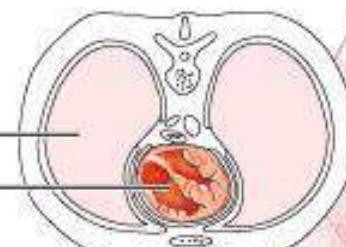
Midsternal line
2nd rib
Sternum
Diaphragm
Point of maximal intensity (PMI)

(a)

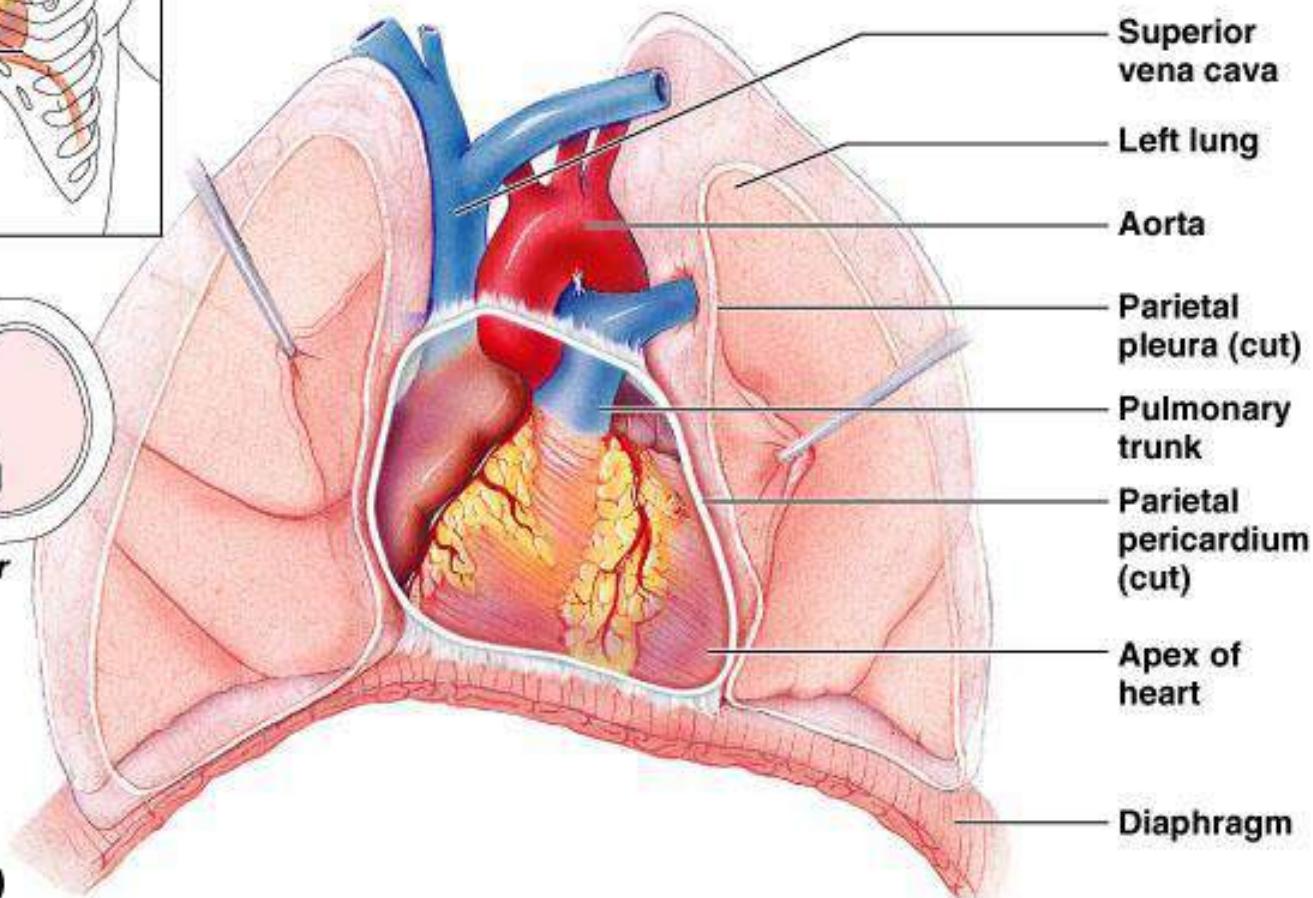


Right lung
Heart

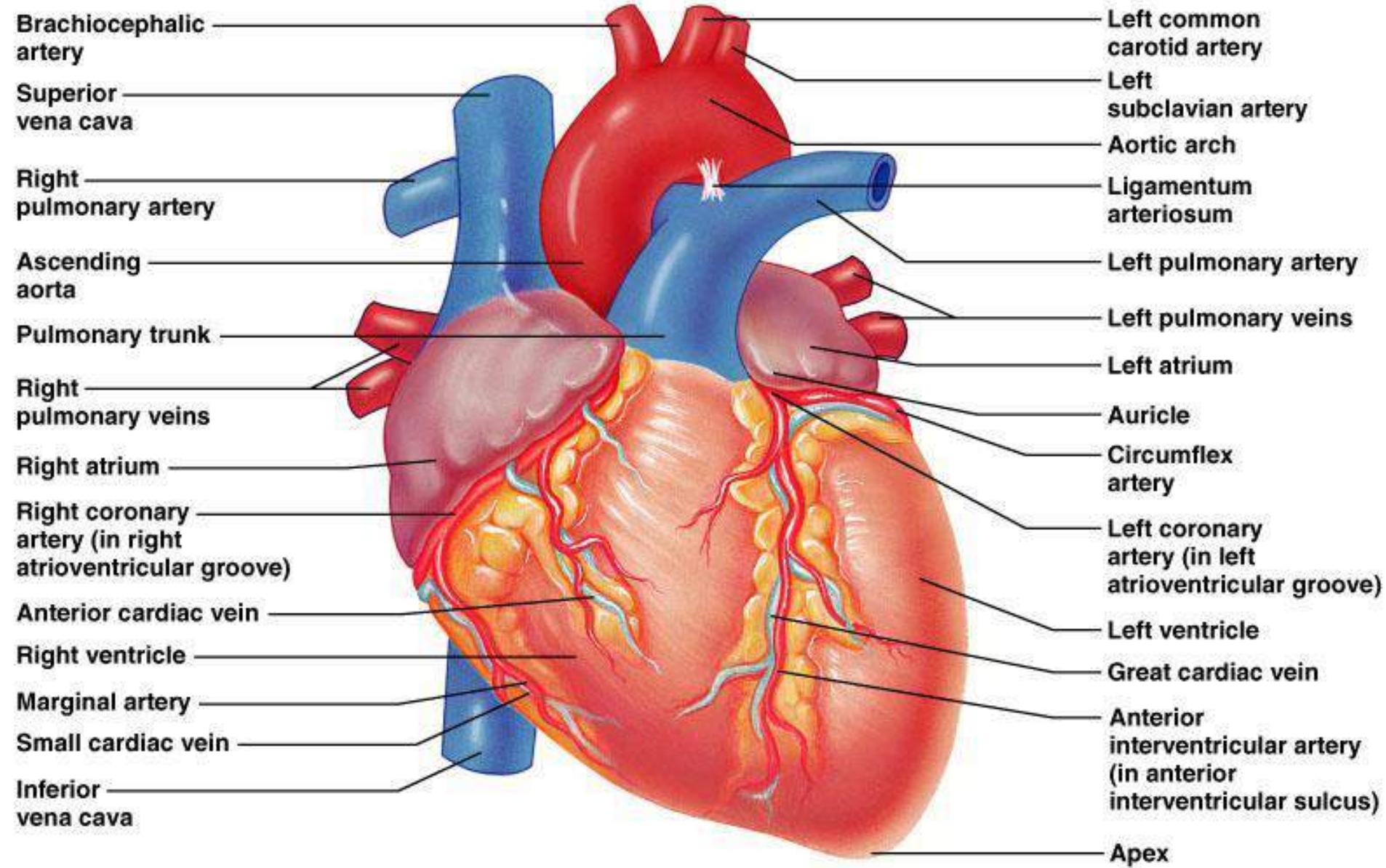
(b)



(c)

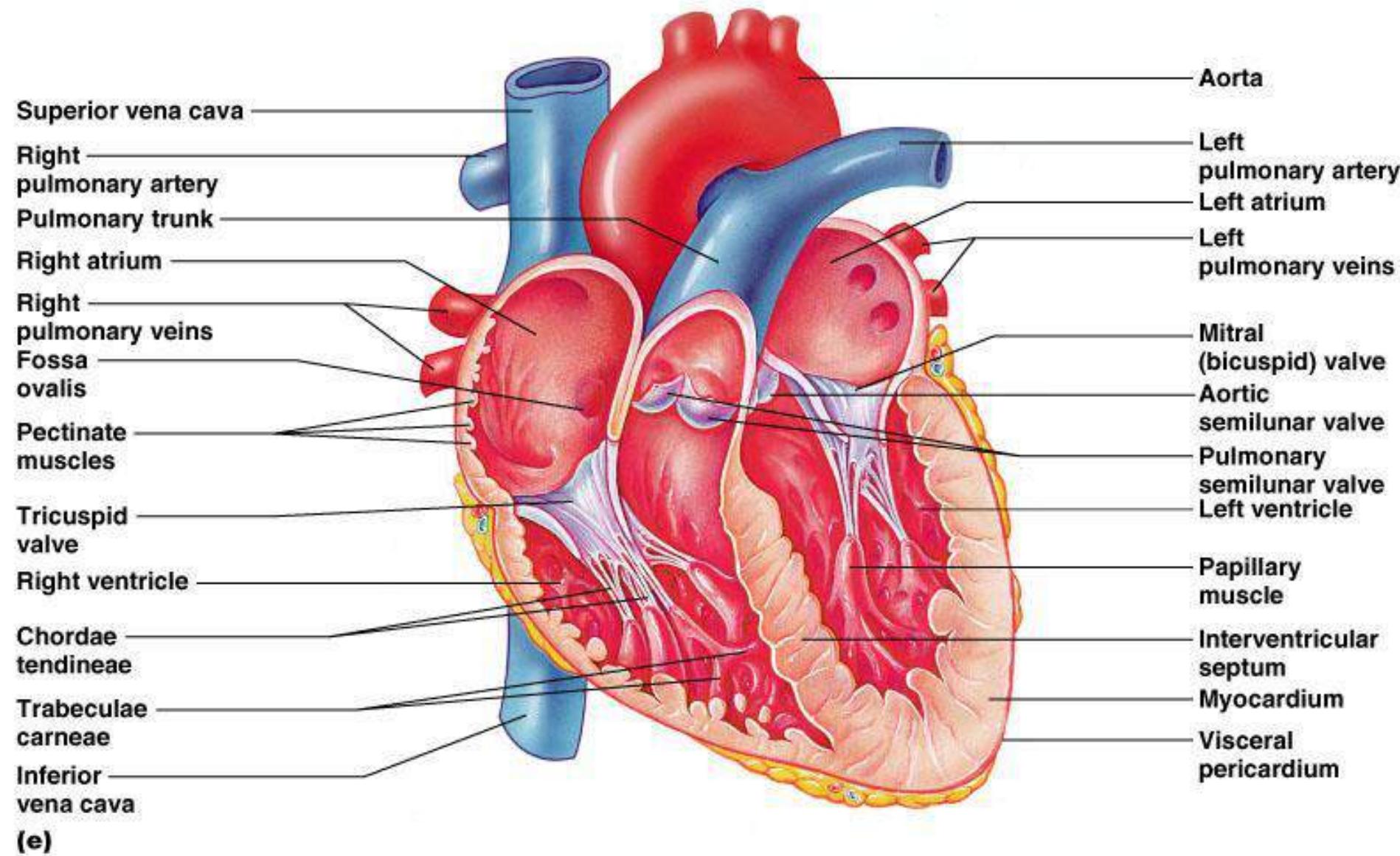


Heart Anatomy

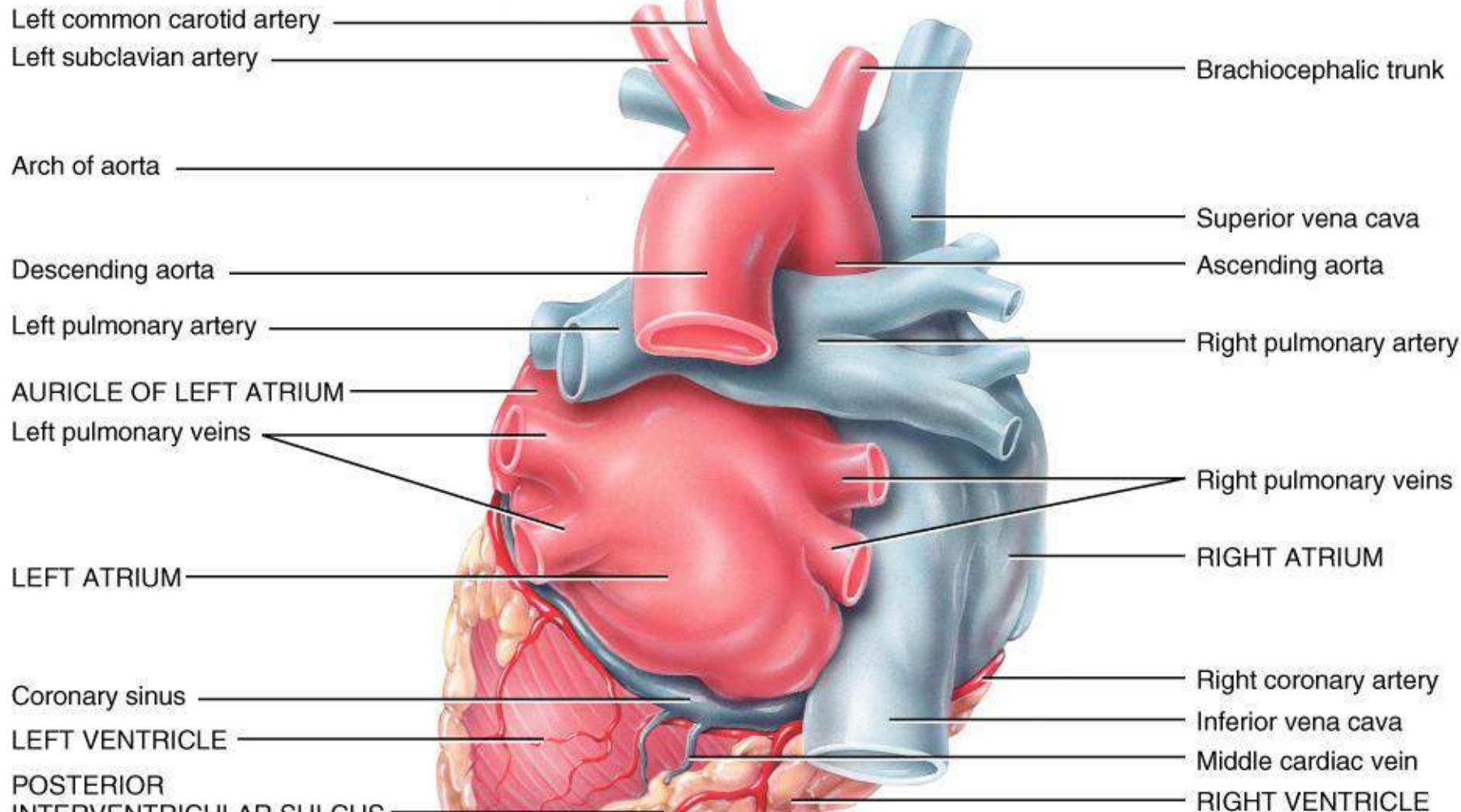


(b)

Heart Anatomy

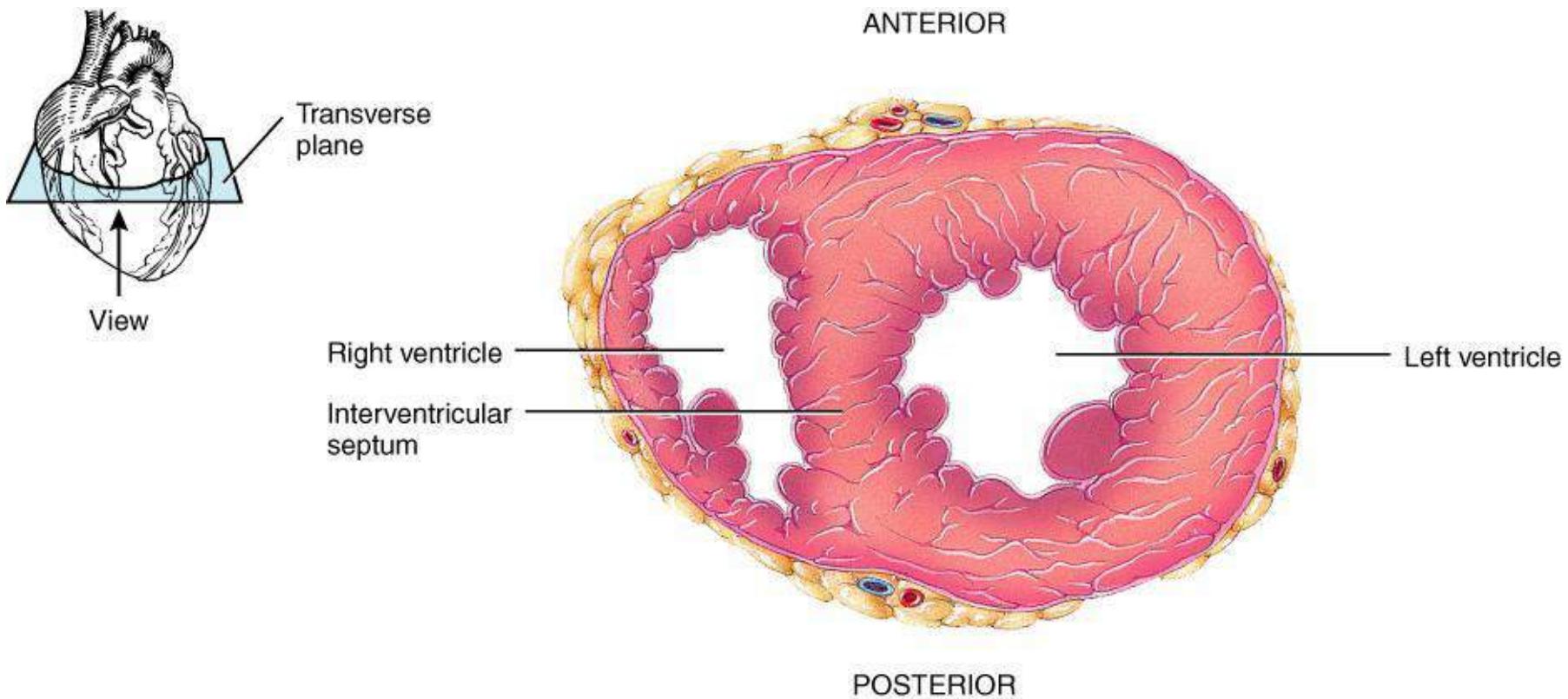


Heart Anatomy



(c) Posterior external view showing surface features

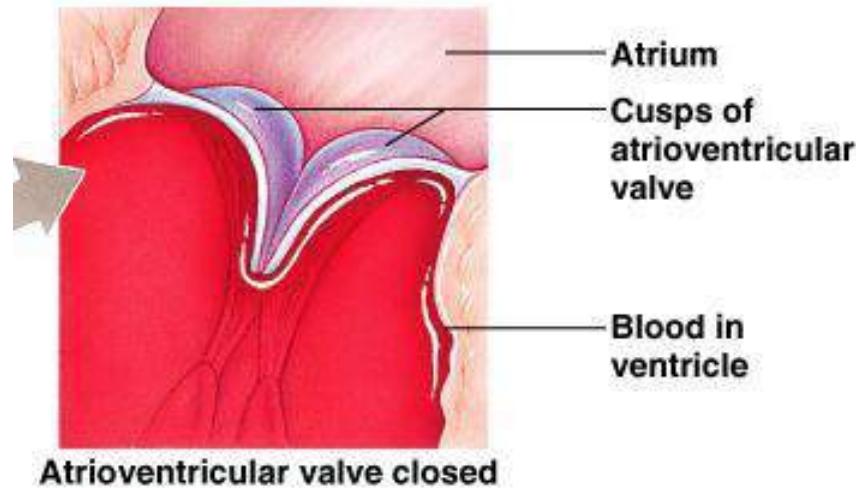
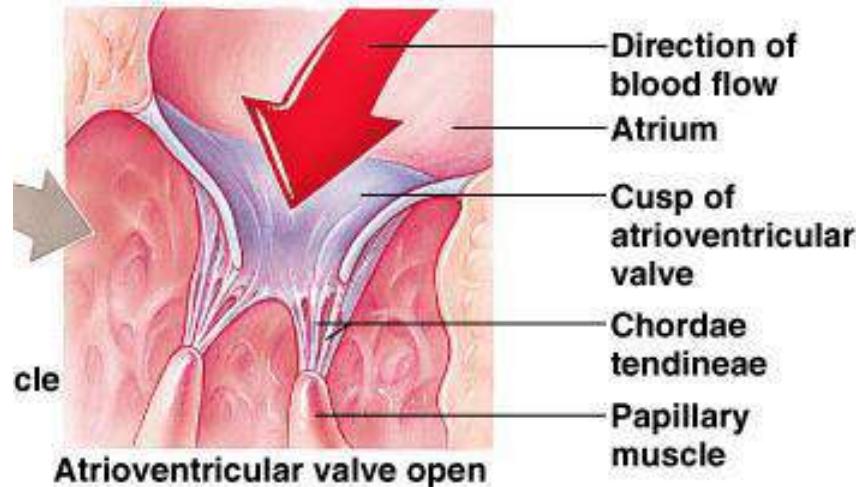
Heart Anatomy

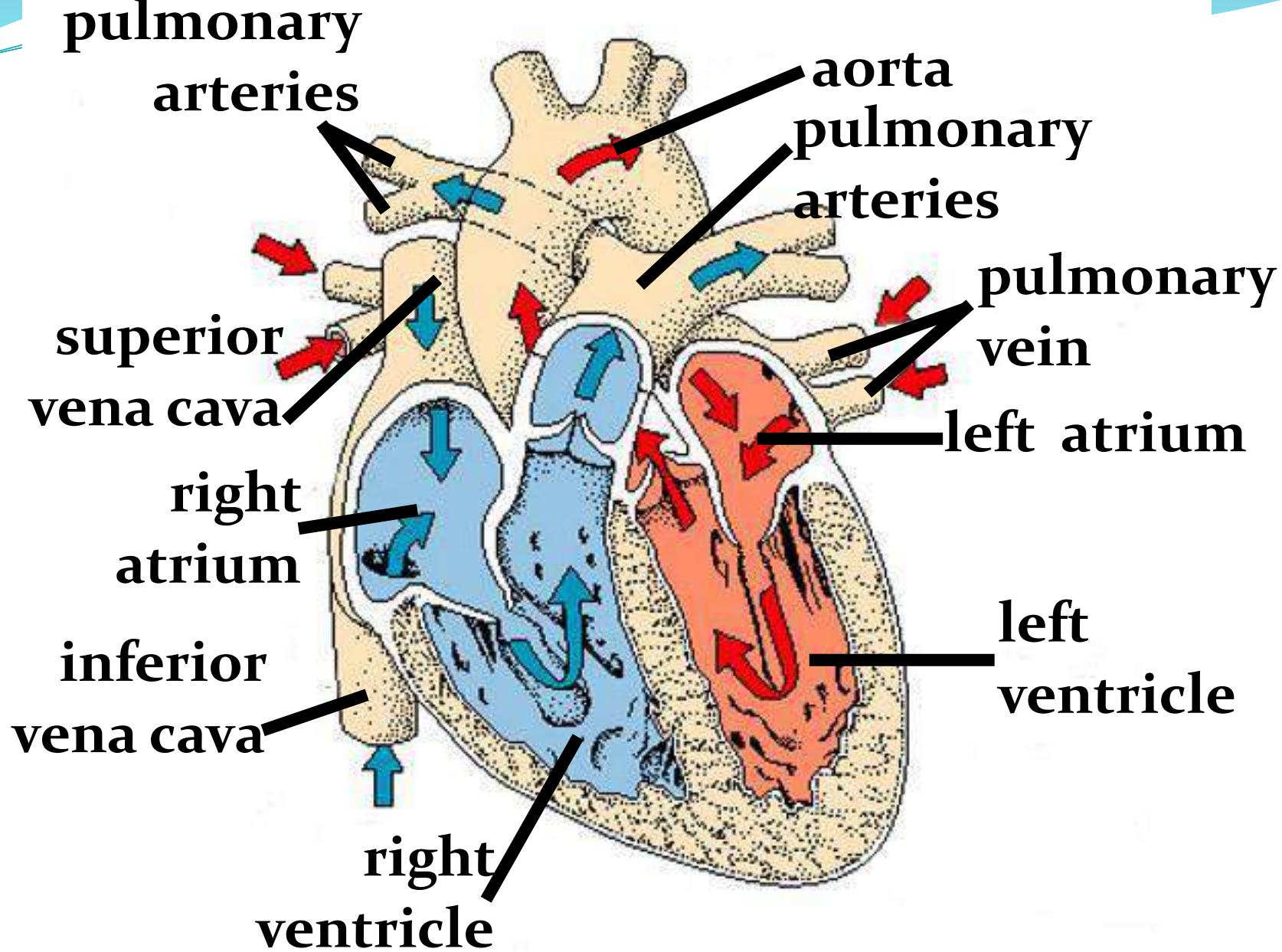


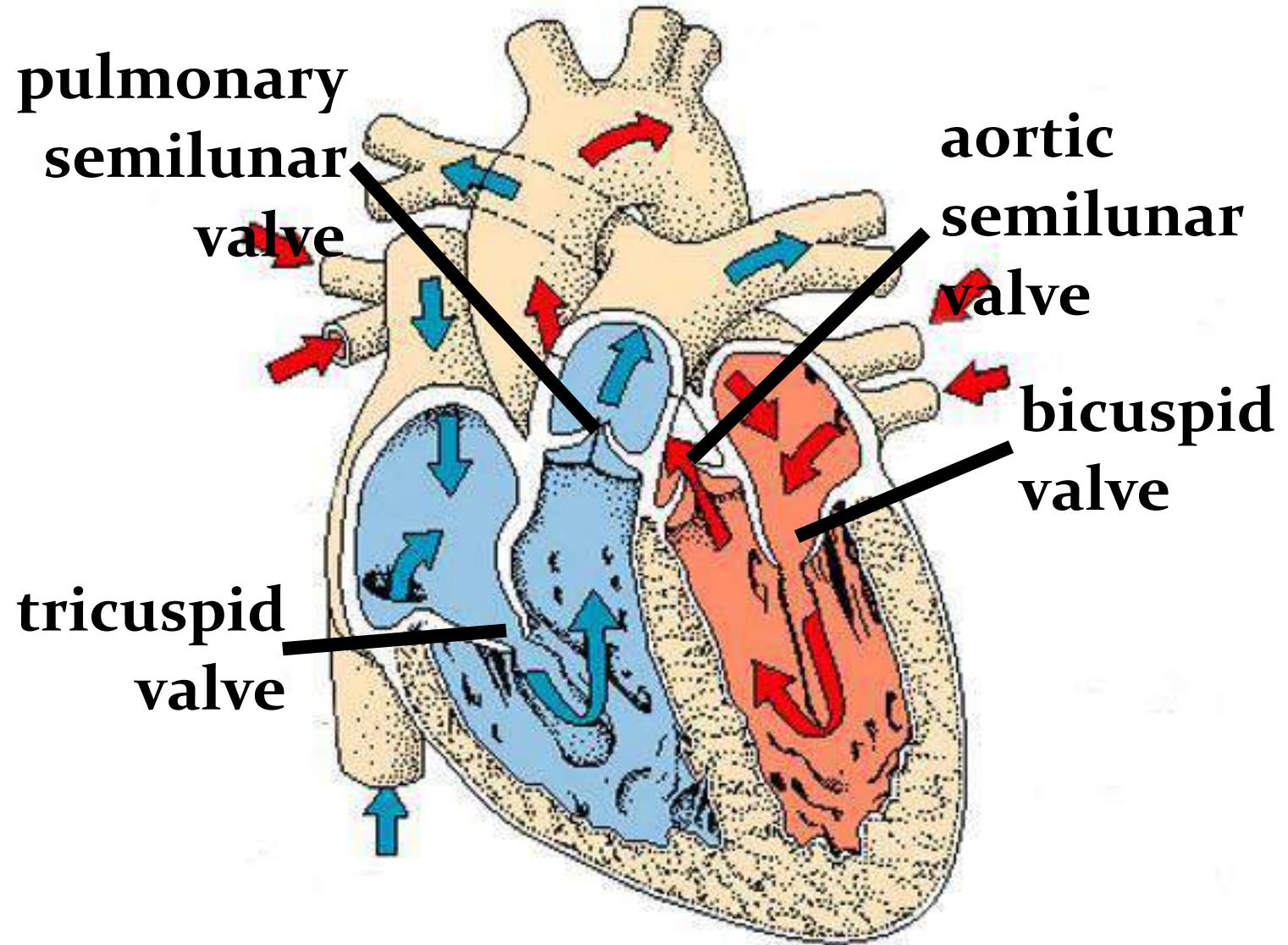
(c) Inferior view of transverse section showing differences in thickness of ventricular walls

20.04c

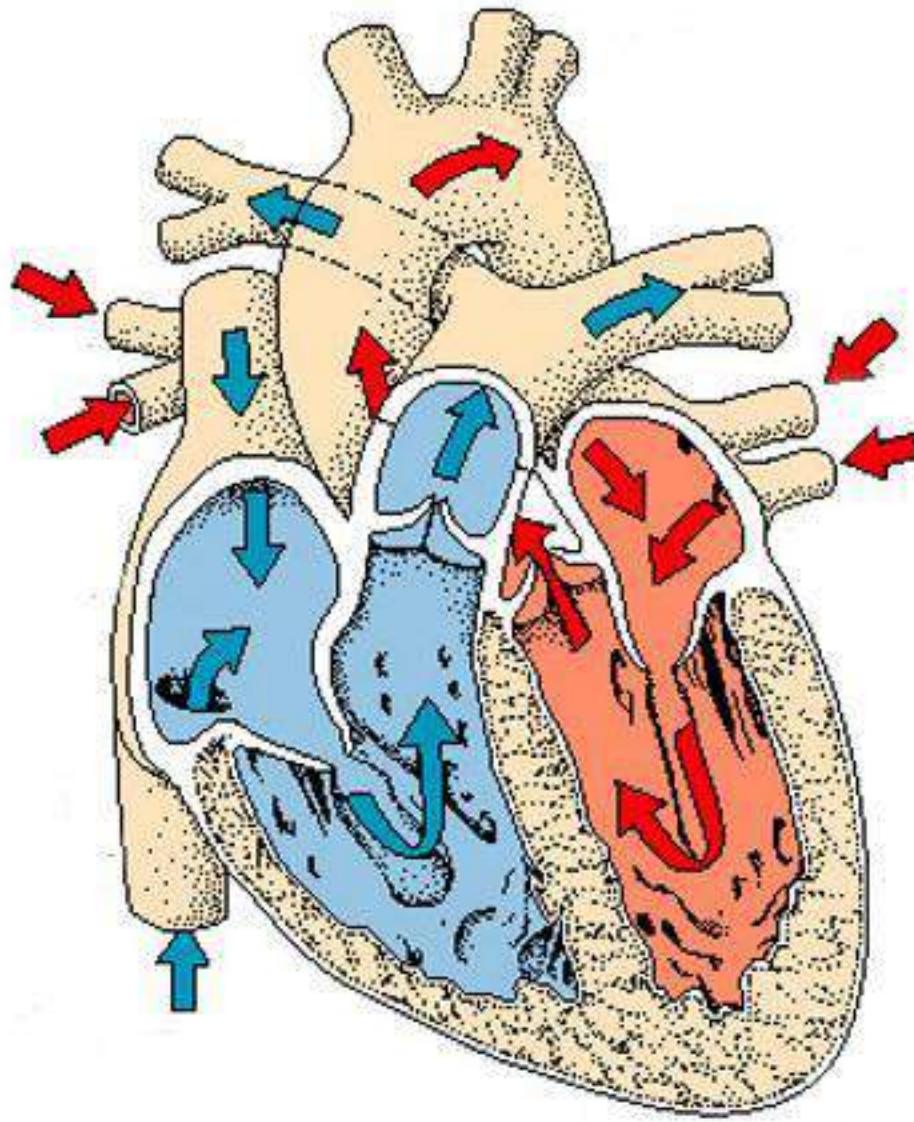
VALVES



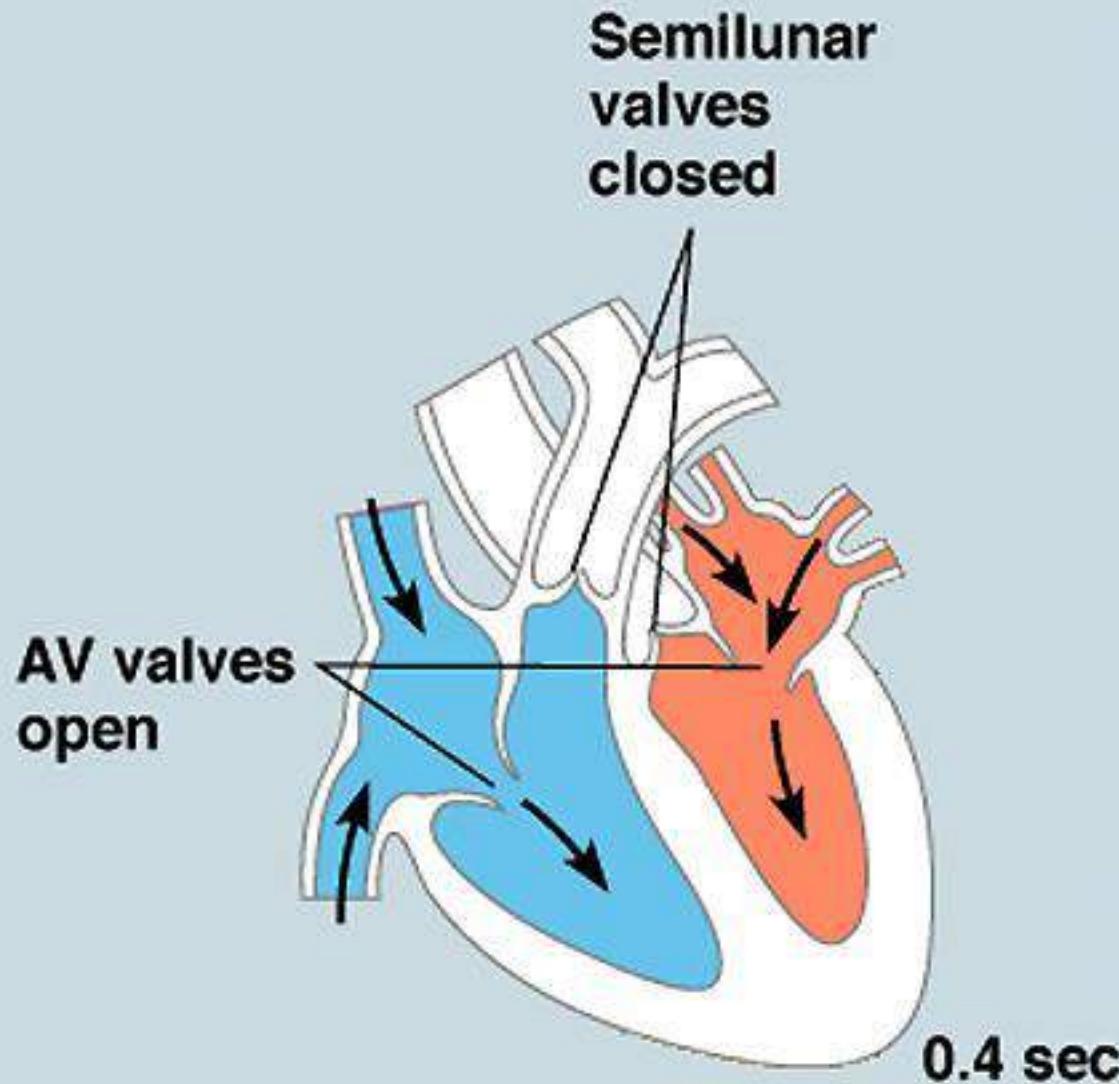




Heart Valves

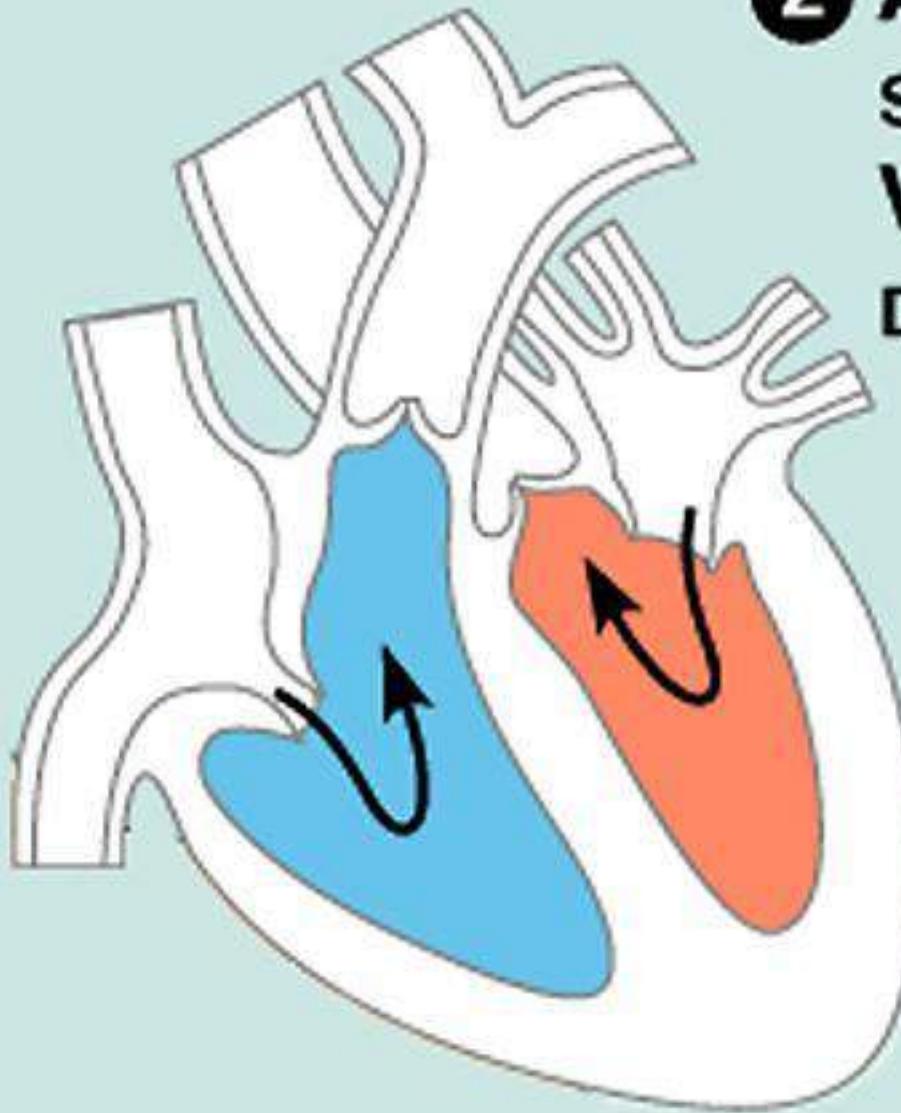


Contraction Cycle of the Heart



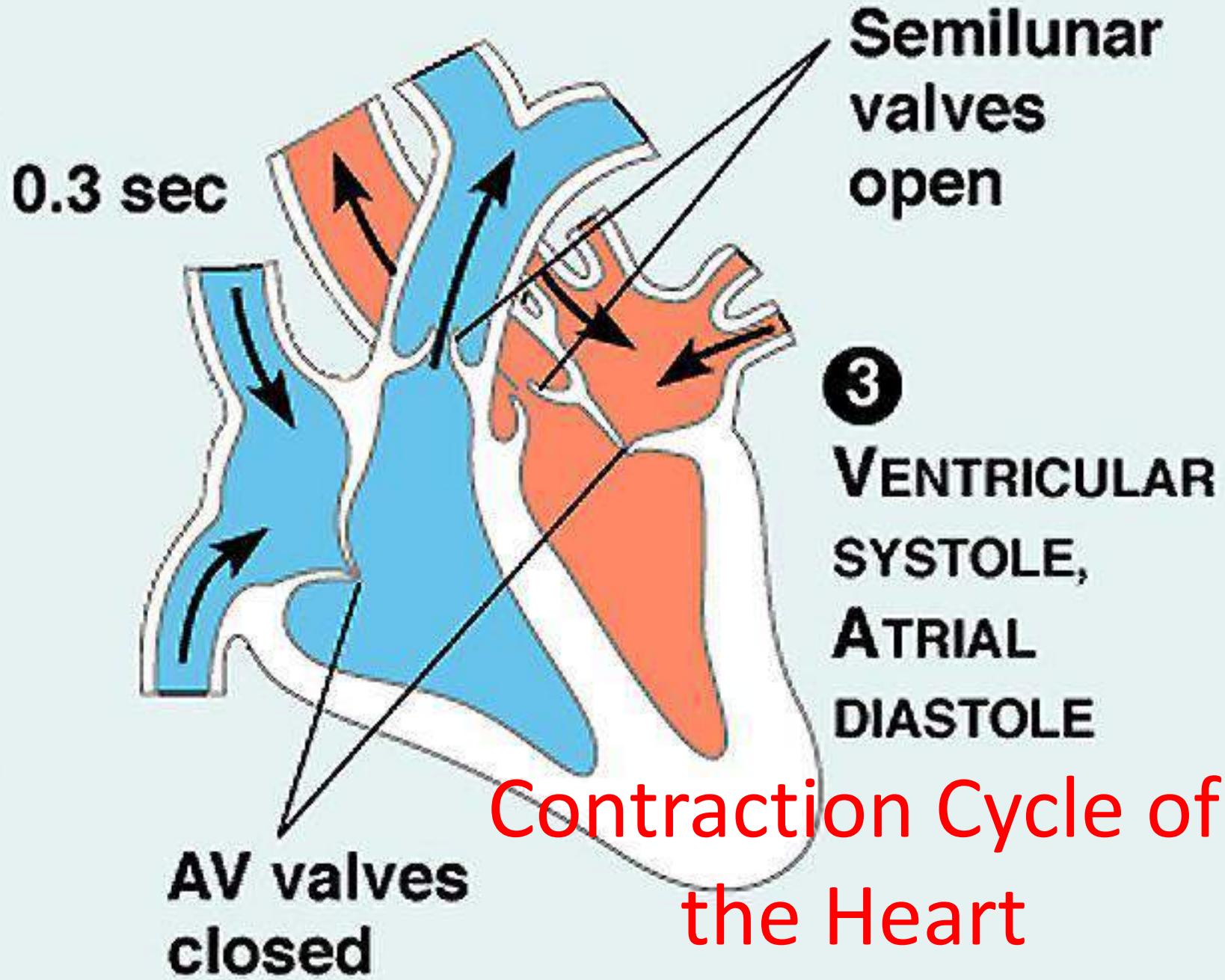
① ATRIAL AND
VENTRICULAR
DIASTOLE

**② ATRIAL
SYSTOLE,
VENTRICULAR
DIASTOLE**



0.1 sec

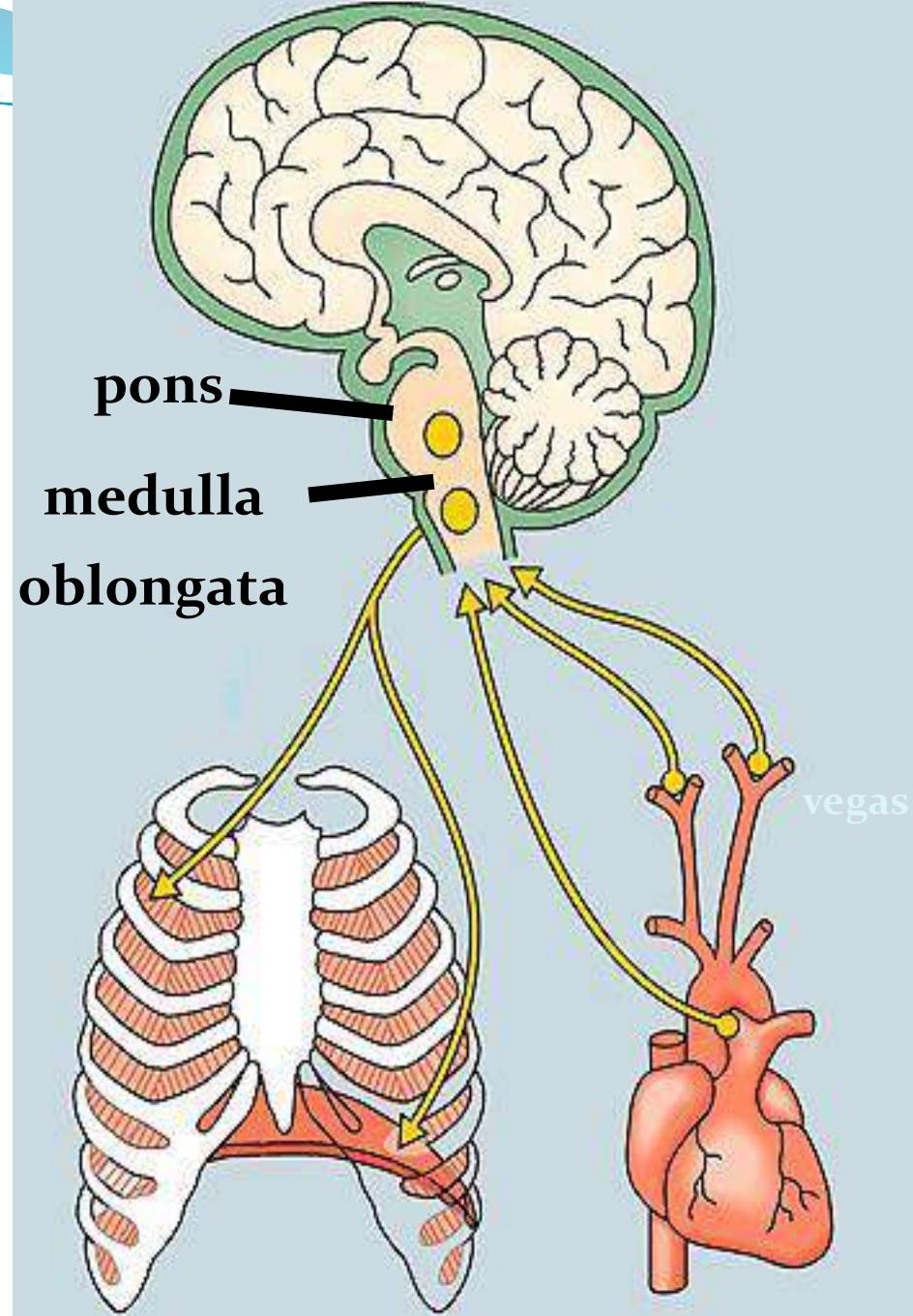
**Contraction
Cycle of the
Heart**



Nerve Innervation:

Vegas nerve from medulla
(parasympathetic division)
→ acetylcholine (slows heart)

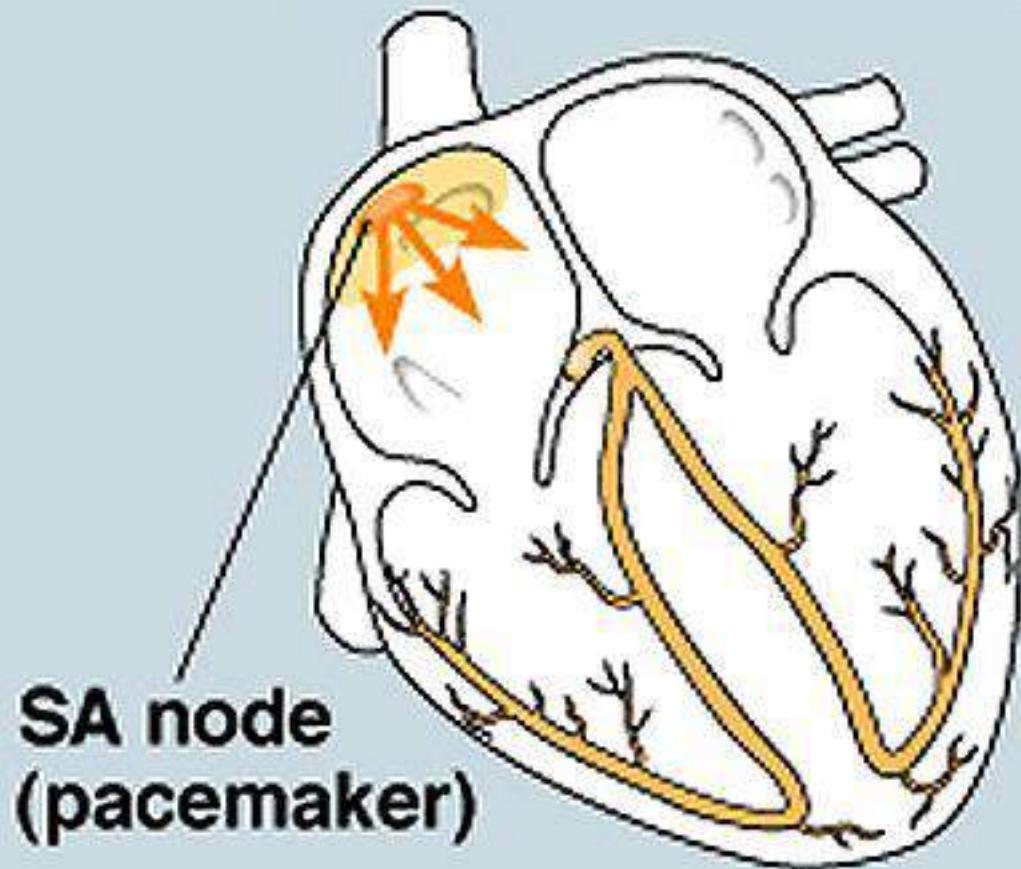
Cardioacceleratory center in medulla
(sympathetic) →
adrenaline from adrenal glands (speeds up heart)



Excitation of the Heart

Depolarization
of the atria

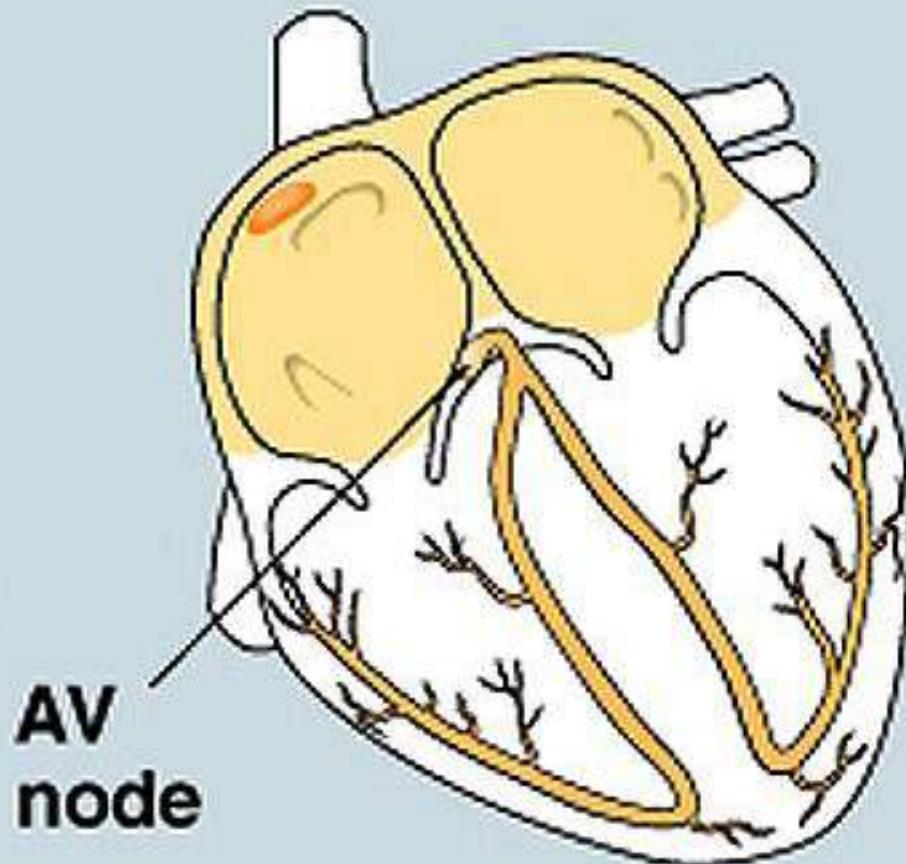
- ① Pacemaker generates wave of signals to contract



Excitation of the Heart

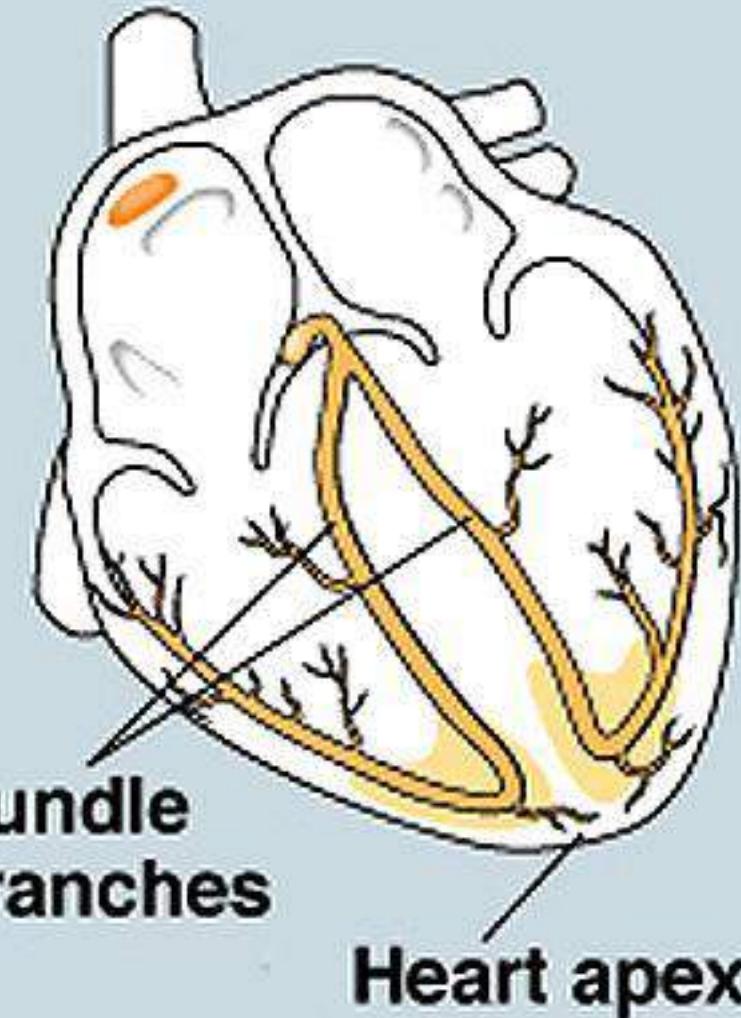
Depolarization
of the
ventricles

② Signals delayed
at AV node



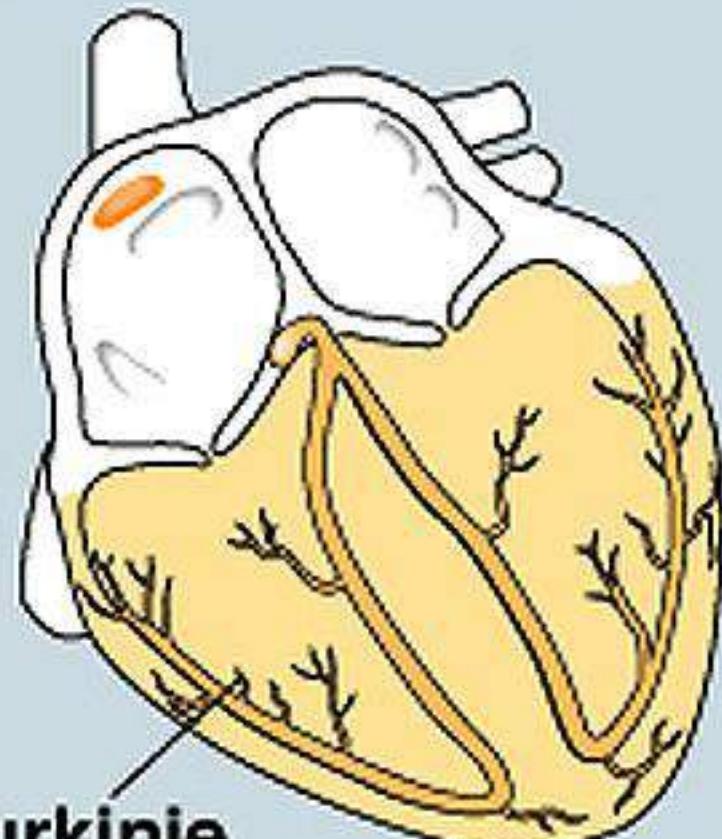
Excitation of the Heart

③ Signals pass to heart apex



Excitation of the Heart

- 4 Signals spread throughout ventricles



**Purkinje
fibers**

Transducers

Definitions - Sensors

- Also called: transducer, probe, gauge, detector, pick-up etc.
- Start with the dictionary:
- A device that responds to a physical stimulus and transmits a resulting impulse. (New Collegiate Dictionary)
- A device, such as a photoelectric cell, that receives and responds to a signal or stimulus. (American Heritage Dictionary, 3rd ed., 1996)
- A device that responds to a physical stimulus (as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control) . (Webster, 3rd ed., 1999)

Definitions - Transducer

- A device that is actuated by power from one system and supplies power usually in another form to a second system. (New Collegiate Dictionary)
- A substance or device, such as a piezoelectric crystal, that converts input energy of one form into output energy of another. (from: Transducere – to transfer, to lead) (American Heritage Dictionary, 3rd ed., 1996)
- A device that is actuated by power from one system and supplies power usually in another form to a second system (a loudspeaker is a transducer that transforms electrical signals to sound energy) . (Webster, 3rd ed., 1999)

Our definitions:

Sensor

- A device that responds to a physical stimulus.

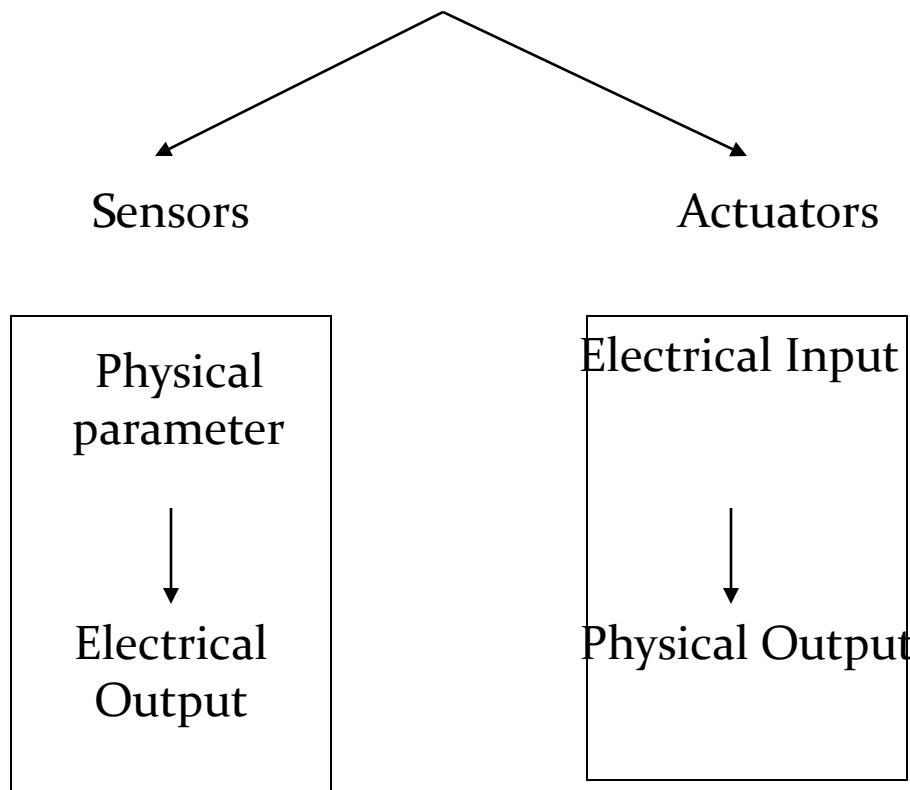
Transducer

- A device that converts energy of one form into energy of another form.

Sensor is a Transducer:

What is a transducer ?

A device which converts one form of energy to another



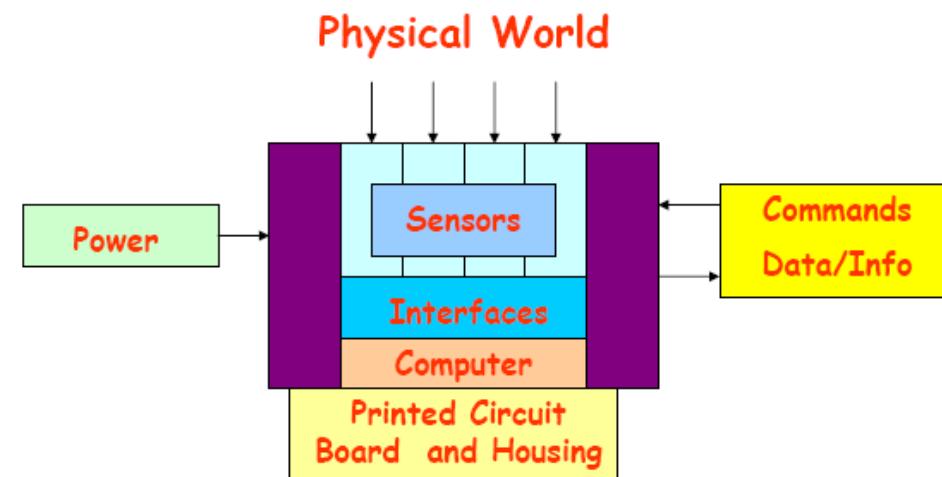
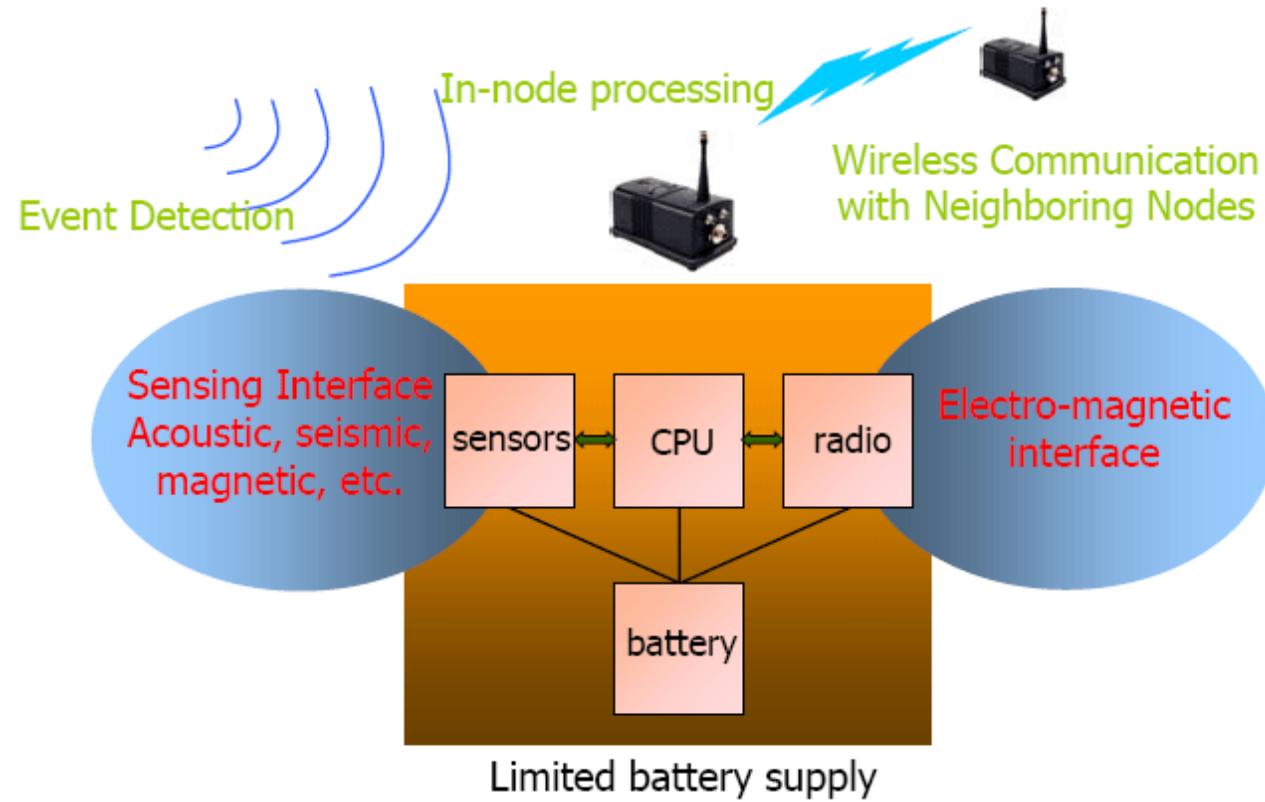
e.g. Piezoelectric:

Force -> voltage

Voltage-> Force

=> Ultrasound!

Sensors



Basic Transducer Principles

Physiological process of the body-

- Body temperature
- Electrical activity of the heart
- Arterial blood pressure
- Respiratory airflow
- Mechanical movement
- Chemical reactions

Energy form	Transducer form	Device or effect	Reversible
Mechanical	Electrical	Magnetic induction Electrical induction	Yes
Pressure	Electrical	Piezo-electric	Yes
Thermal	Electrical	Thermoelectric See-back	Yes No
Electrical	Thermal	Peltier	No
Light radiation	Electrical	Photoelectric	No
Electrical	Light	LED, Injection laser	No
Chemical	Electrical	Volta	No
Sound	Electrical	Microphone	Yes
Electrical	Sound	Loudspeaker	Yes

Physical Sensors

Physical Variables and Sensors

Physical Quantity	Sensor	Variable	
Fluidic	Pressure transducer	Pressure	• Blood flow/blood pressure
	Flow meter	Flow	
Force-Torque	Load cell	Applied force or torque	• Impact, acceleration • Surgical forceps to measure force applied
	Strain Gauge	Strain	
	LVDT	Displacement	
Geometric	Ultrasonic transit time	Displacement	• Airbag
	Velocimeter	Velocity	
	Accelerometer	Acceleration	
Thermal	Thermometer	Temperature	• Body temperature
	Thermal flux sensor	Heat flux	

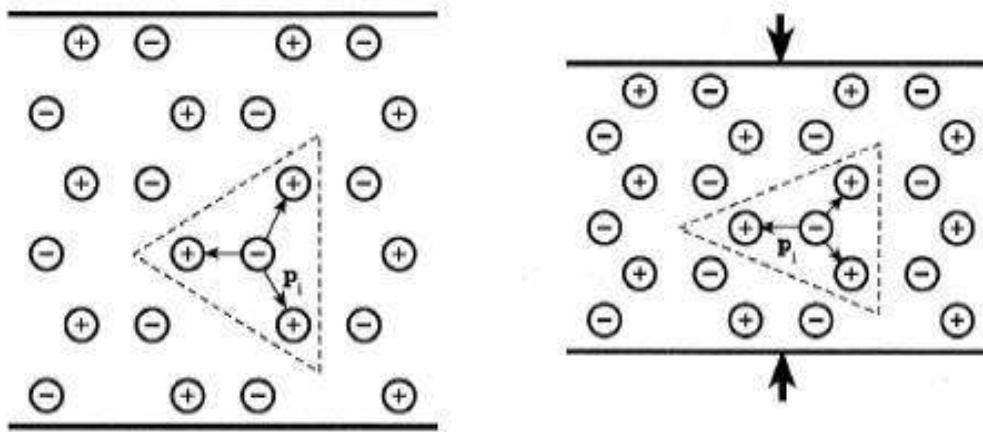
Biomedical Physical Sensors

Sensor	Application	Signal Range
Liquid metal strain guage	Breathing movement	0-0.05
Magnetic displacement sensor	Breathing movement	0-10 mm
LVDT	Muscle contraction	0-20 mm
	Uterine contraction sensor	0-5 mm
Load cell	Electronic scale	0-200 kg
Accelerometer	Subject activity	0-20 m/s ²
Miniature silicon pressure sensor	Intra-arterial blood pressure	0-350 mm Hg
	Urinary bladder pressure	0-70 mm Hg
	Intrauterine pressure	0-100 mm Hg
Electromagnetic flow sensor	Cardiac o/p (with integrator)	0-500 ml/min
	Organ blood flow	0-100 ml/min

- Pacemaker
- Airbag

Piezoelectric Sensors

What is piezoelectricity?



Different transducer applications:

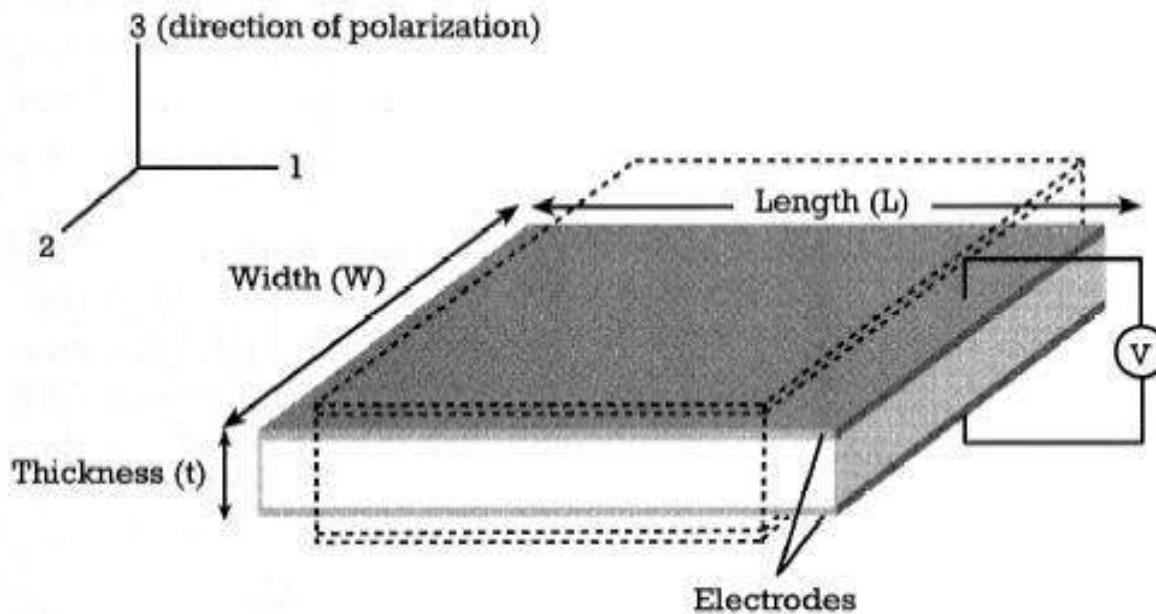
⇒ Accelerometer

⇒ Microphone

Strain causes a redistribution of charges and results in a net electric dipole (a dipole is kind of a battery!)

A piezoelectric material produces voltage by distributing charge (under mechanical strain/stress)

Piezoelectric Sensors



3_1 denotes
the crystal
axis

$$V_m = d_{31} \frac{F}{\epsilon L}$$

$$V_m = d_{31} \frac{F}{\epsilon W}$$

$$V_m = d_{33} F \frac{t}{\epsilon L W}$$

Above equations are valid when force is applied in the L,W or t directions respectively.

Piezoelectric Sensors - Circuitry

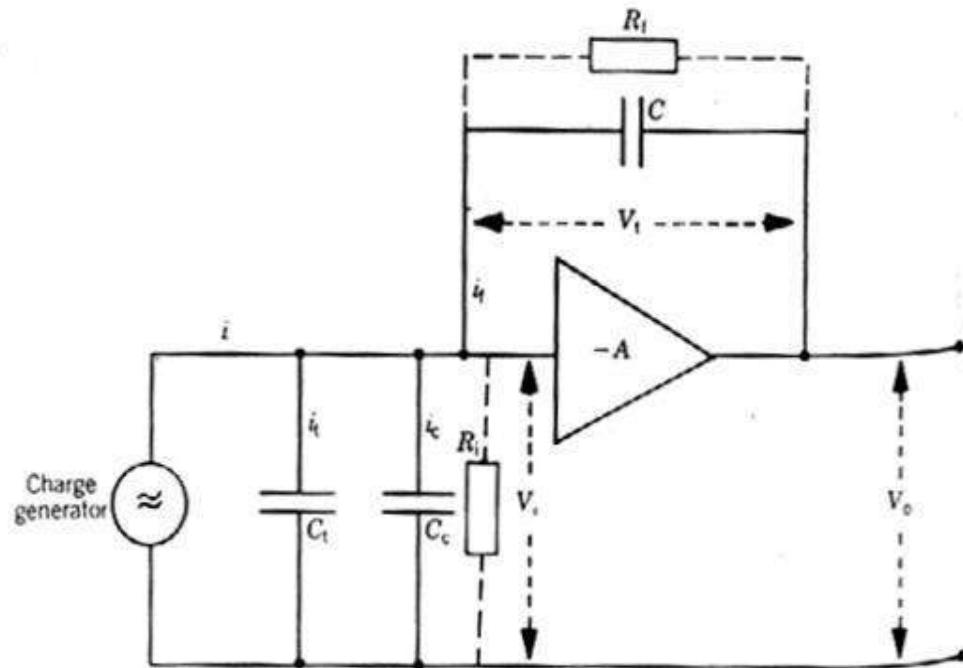
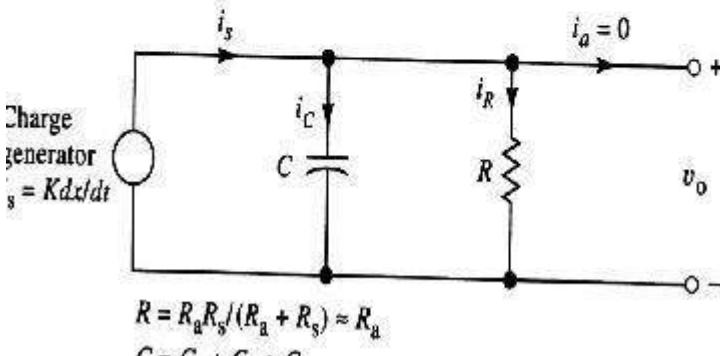
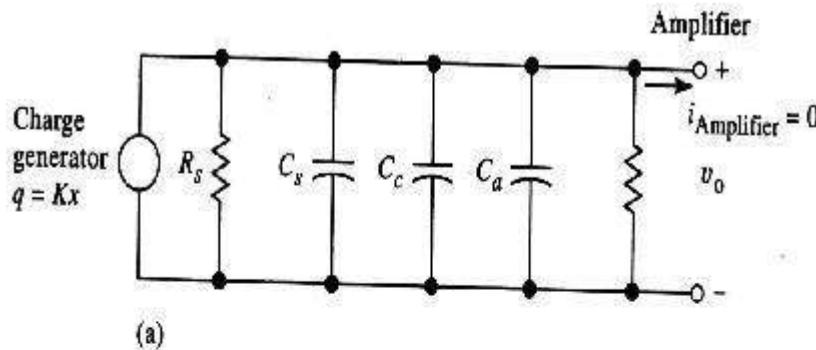


Figure 4. Schematic diagram of a charge amplifier.

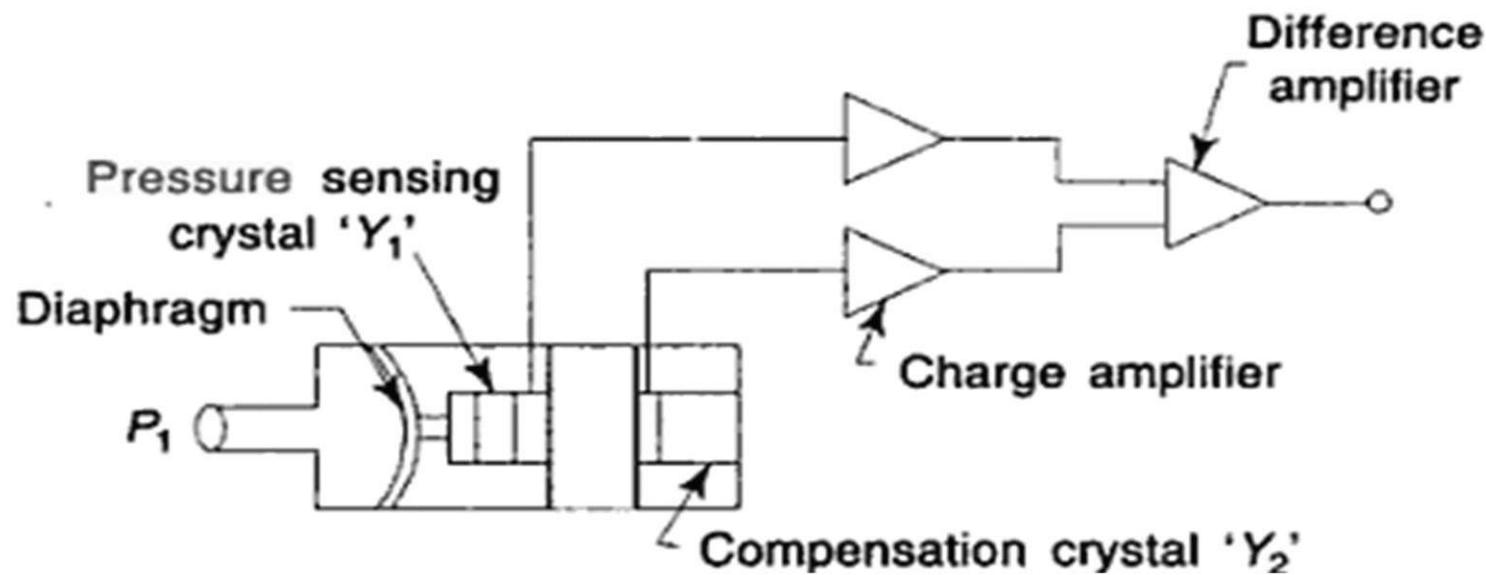
The Equivalent Circuit

Taken from Webster, "Medical Instrumentation"

Piezoelectric Pressure Transducers

These devices utilizes the piezoelectric characteristics of certain crystalline and ceramic materials (such as quartz) to generate an electrical signals.

Signals generated by crystals decays rapidly so unsuitable for static force or pressure measurements



Piezoelectric Pressure Transducers

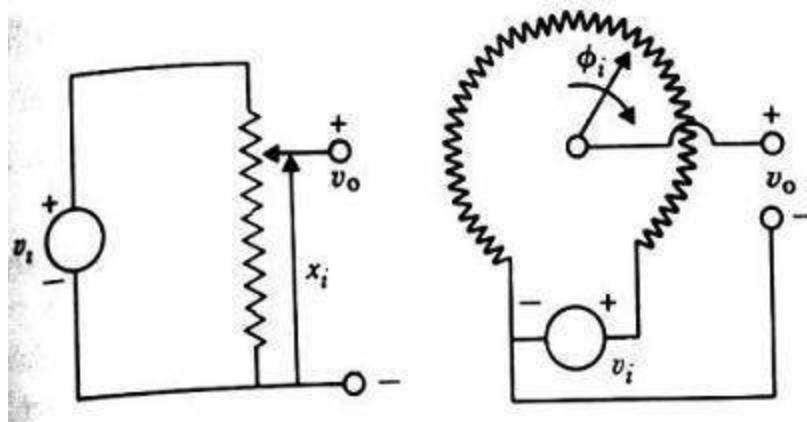
Advantages

- The transducers no needs external power
- It has a good frequency response

Disadvantages

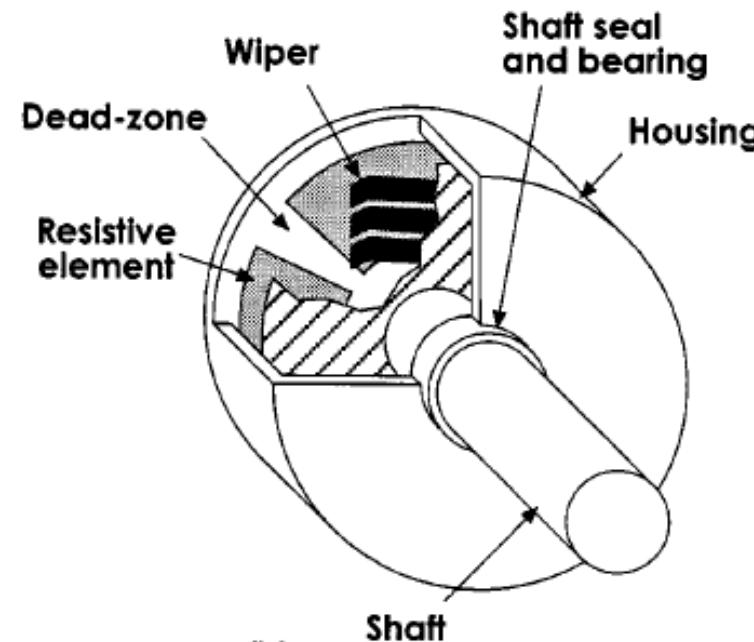
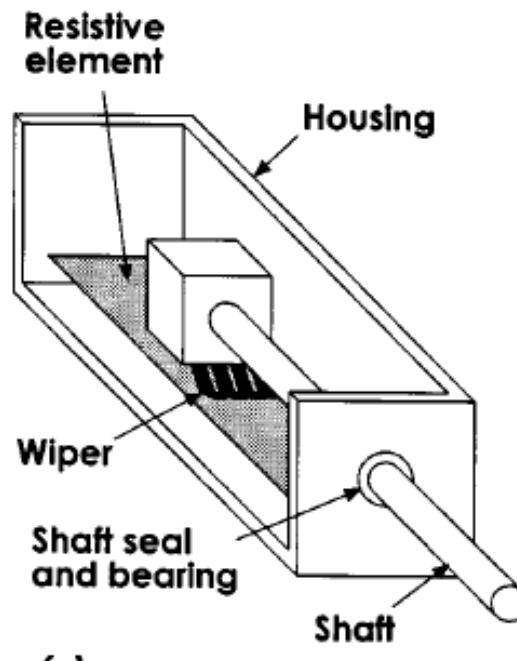
- This type of transducers cannot measure static pressure
- Output of the transducers is affected by changes in temperature

Resistive Sensors - Potentiometers



Translational and Rotational Potentiometers

Translational or angular displacement is proportional to resistance.



Resistive Sensors - Strain Guages

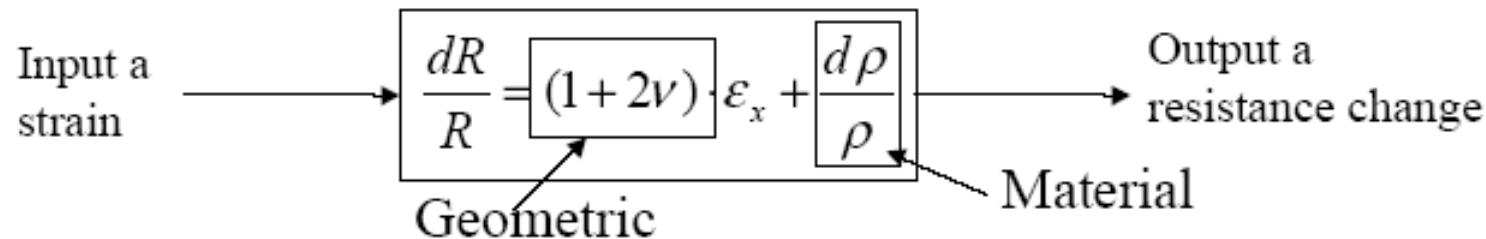
Resistance is related to length and area of cross-section of the resistor and resistivity of the material as

$$R \equiv \frac{\rho l}{A}$$

By taking logarithms and differentiating both sides, the equation becomes

$$\frac{dR}{R} = \underbrace{\frac{dl}{l} - \frac{dA}{A}}_{\text{Dimensional}} + \underbrace{\frac{d\rho}{\rho}}_{\text{piezoresistance}}$$

Strain gage component can be related by poisson's ratio as



Resistive Sensors - Strain Guages

Gage Factor of a strain gage

$$G = \frac{\text{fractional change in resistance}}{\text{fractional change in strain}}$$

$$G = \frac{1}{\varepsilon} \frac{dR}{R} = (1 + 2\nu) + \boxed{\frac{1}{\varepsilon} \frac{d\rho}{\rho}}$$

G is a measure of sensitivity

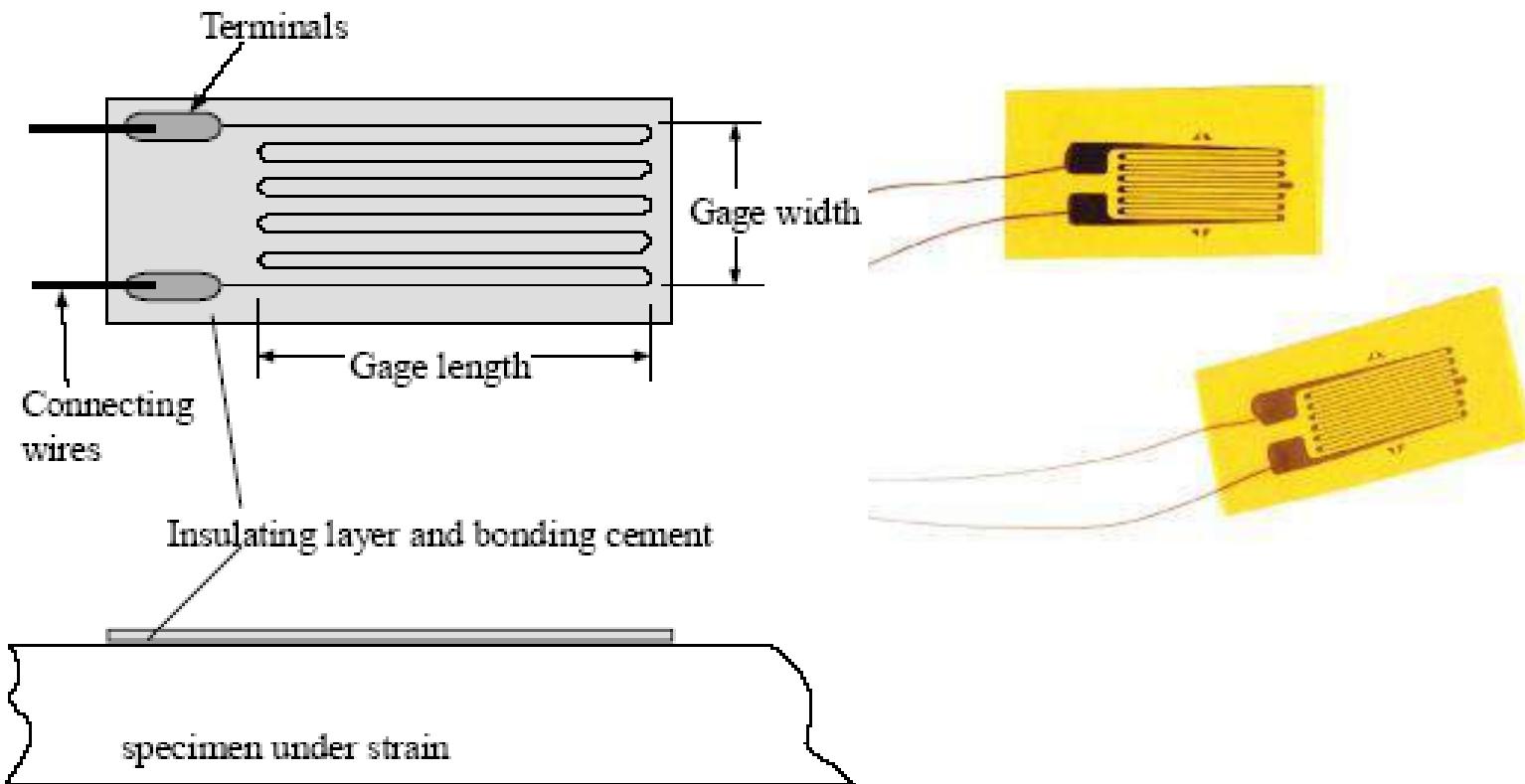
Think of this as a Transfer Function!

⇒ Input is strain

⇒ Output is dR

- ⇒ Put mercury strain gauge around an arm or chest to measure force of muscle contraction or respiration, respectively
- ⇒ Used in prosthesis or neonatal apnea detection, respectively

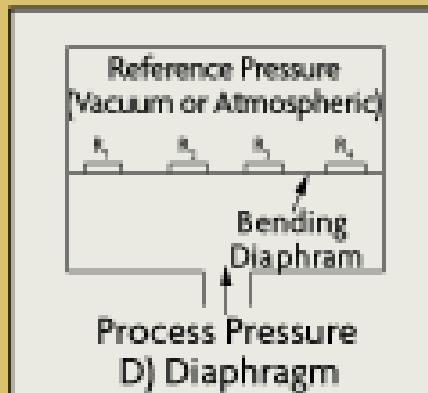
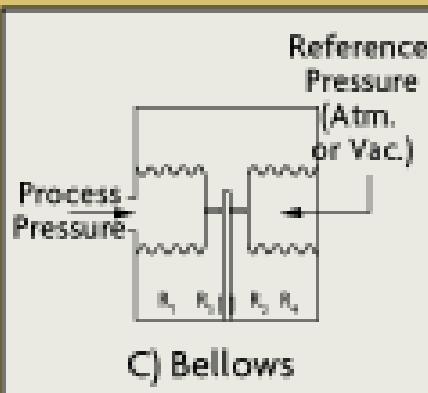
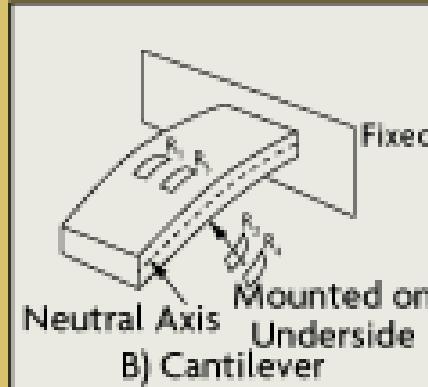
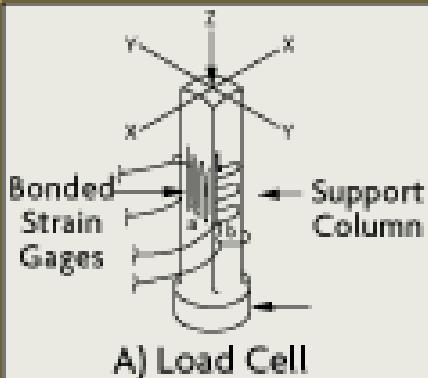
Resistive Sensors - Strain Guages



Strain gages are generally mounted on cantilevers and diaphragms and measure the deflection of these.

More than one strain gage is generally used and the readout generally employs a bridge circuit.

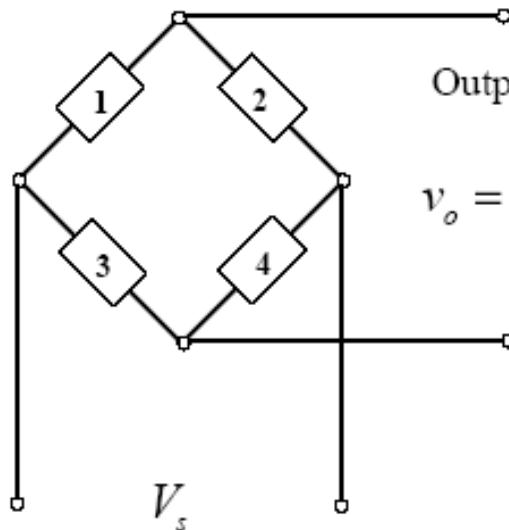
Strain Gage Mounting



Applications!

- ⇒ Surgical forceps
- ⇒ Blood pressure transducer (e.g. intracranial pressure)

Bridge Circuits



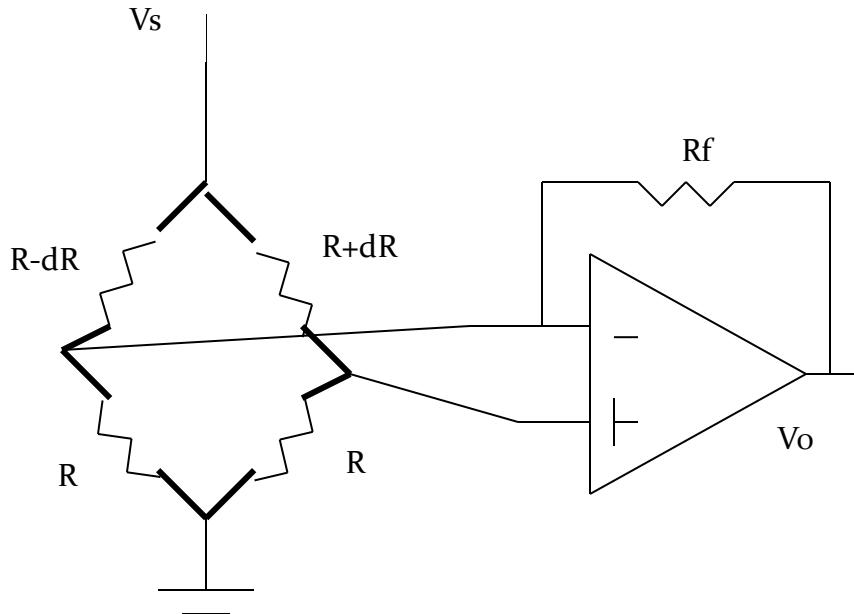
Output DC voltage

$$v_o = \left[\frac{R_1 R_4 - R_2 R_3}{(R_1 + R_2)(R_3 + R_4)} \right] \cdot V_s$$

Null condition is satisfied when: $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

Wheatstone's Bridge

Real Circuit and Sensor Interface



Capacitive Sensors

$$C(x) = \epsilon A/x = \epsilon_r \epsilon_0 A/x$$

where ϵ = the dielectric constant or permittivity

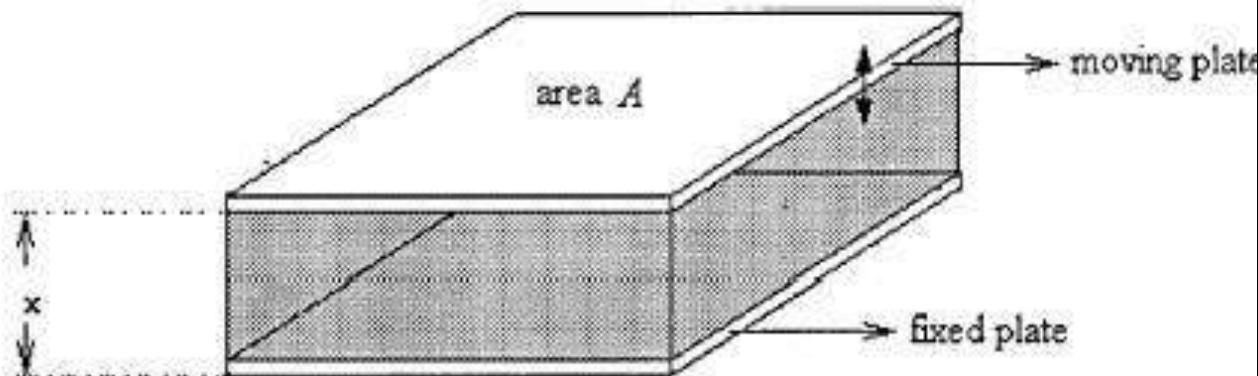
ϵ_r = the relative dielectric constant (in air and vacuum $\epsilon_r \approx 1$)

$\epsilon_0 = 8.854188 \times 10^{-12} \text{ F/m}^{-1}$, the dielectric constant of vacuum

x = the distance of the plates in m

A = the effective area of the plates in m^2

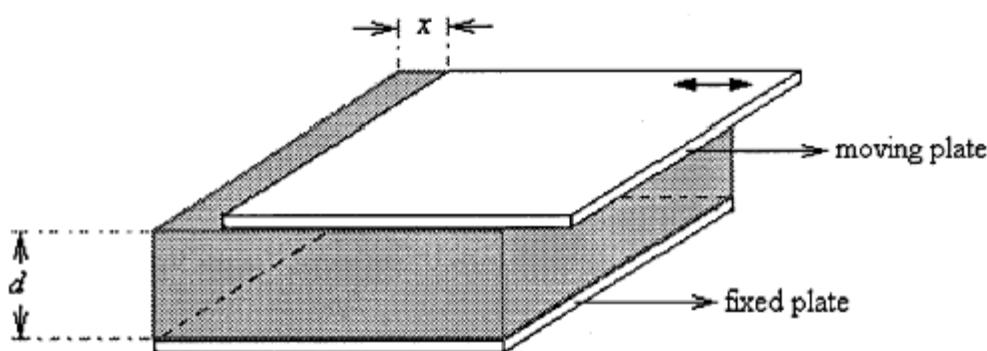
Electrolytic or ceramic capacitors are most common



e.g. An electrolytic capacitor is made of Aluminum evaporated on either side of a very thin plastic film (or electrolyte)

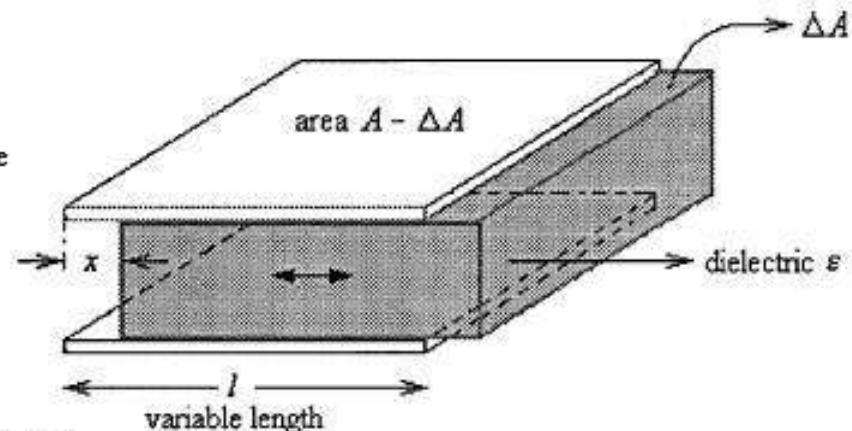
Capacitive Sensors

Other Configurations



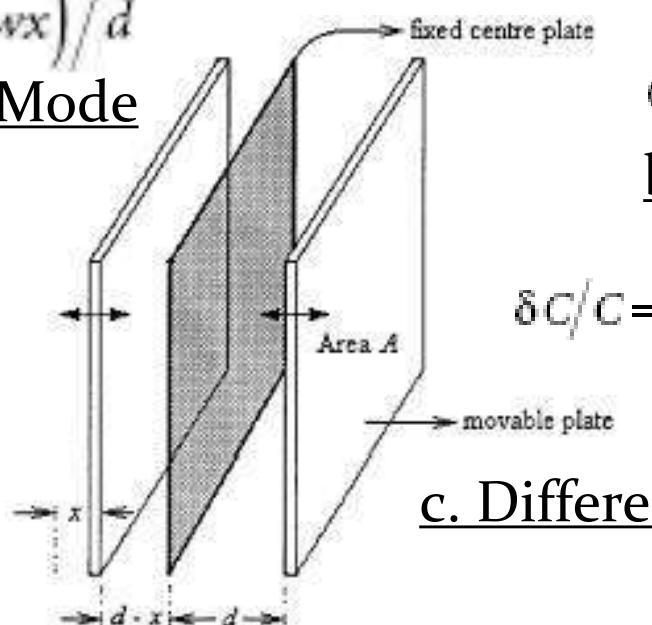
$$C = \epsilon_r \epsilon_0 (A - wx) / d$$

a. Variable Area Mode



$$C = \epsilon_0 w \left[\epsilon_2 l - (\epsilon_2 - \epsilon_1) x \right]$$

b. Variable Dielectric Mode



$$\delta C/C = \delta d/d$$

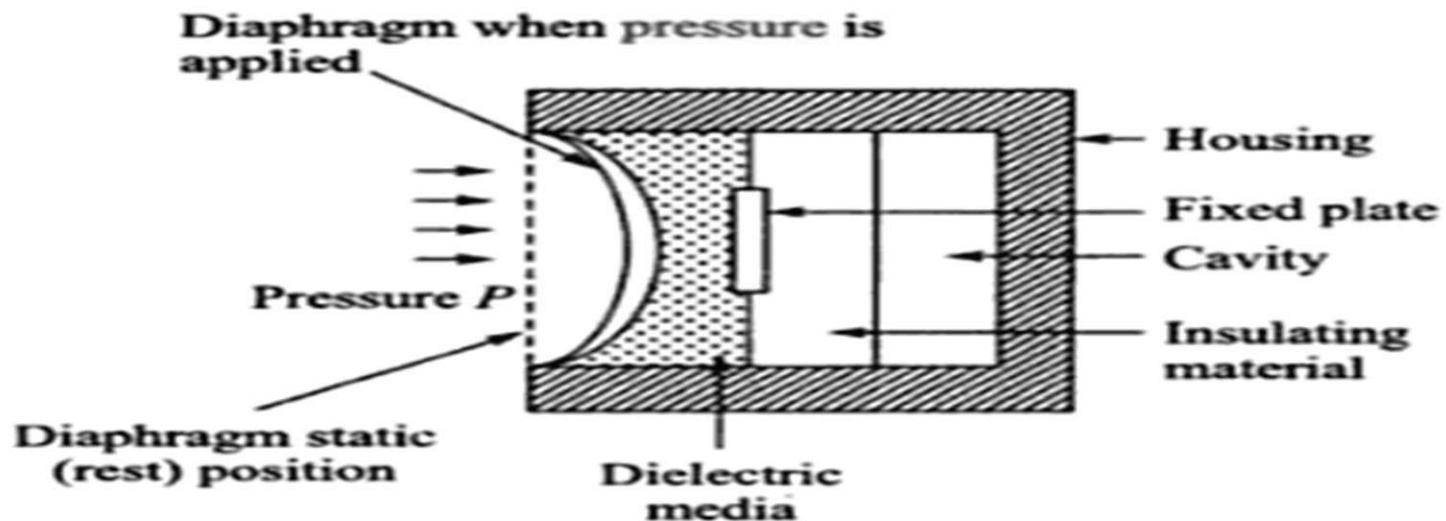
c. Differential Mode

Capacitive Pressure Transducers

The term capacitor is defined as two metal plates are separated by a distance d .

A dielectric medium is placed between the plates. When voltage or potential difference is applied to them, equal and opposite charges are getting developed on the plates.

A capacitive transducer works on the principle of capacitance of parallel plate capacitor



Capacitive Pressure Transducers

$$C = \epsilon_0 \epsilon_r A/d$$

Where,

C = the capacitance of a capacitor in farad

A = area of each plate in m²

d = distance between two plates in m

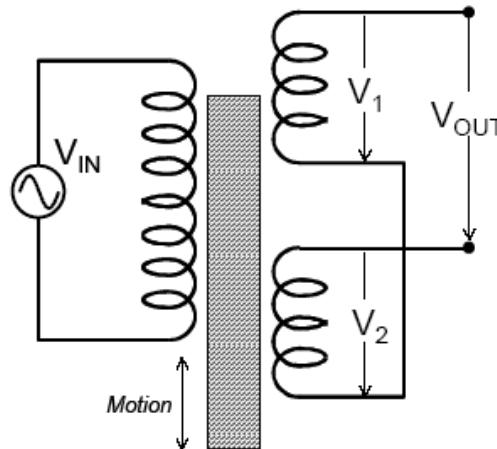
ϵ_r = dielectric constant

$\epsilon_0 = 8.854 \times 10^{-12}$ farad/m²

In capacitive transducers, pressure is utilized to vary any of the above mentioned factors which will cause change in capacitance and that is a measureable by any suitable electric bridge circuit and is proportional to the pressure.

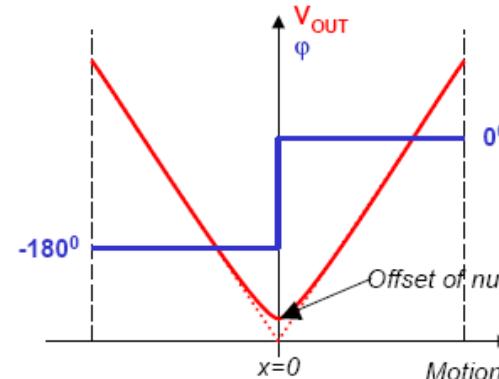
Inductive Sensors

Primary



Secondary

Displacement Sensor



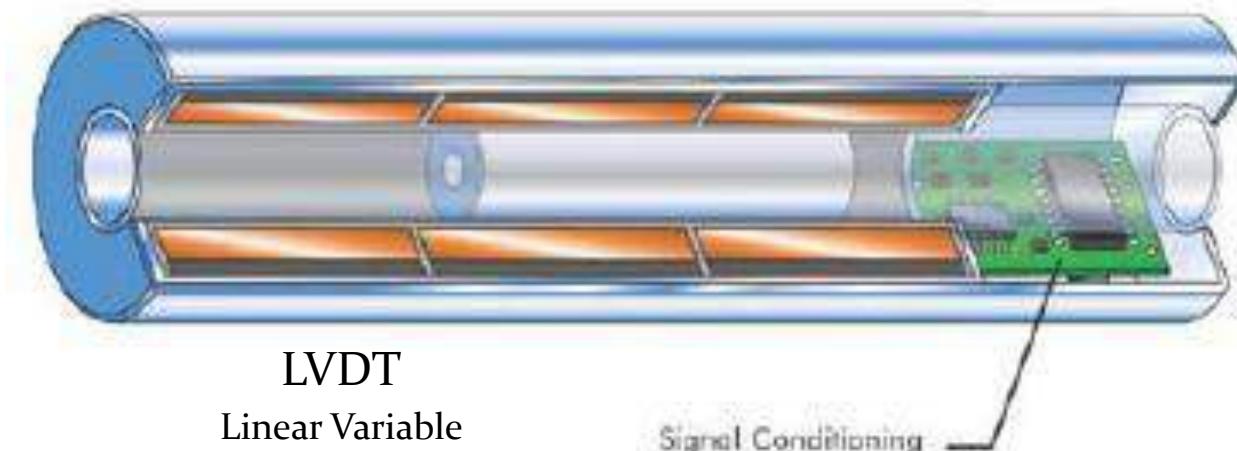
An inductor is basically a coil of wire over a “core” (usually ferrous)

It responds to electric or magnetic fields

A transformer is made of at least two coils wound over the core: one is primary and another is secondary

Inductors and transformers work only for ac signals

Inductive Sensors - LVDT



Taken from

LVDT
Linear Variable
Differential
Transformer

<http://www.pages.drexel.edu/~pyo22/mem351-2004/lecture04/ppo62-073lvdt.pdf>

An LVDT is used as a sensitive displacement sensor: for example, in a cardiac assist device or a basic research project to study displacement produced by a contracting muscle.

Temperature Sensors

1. Resistance based
 - a. Resistance Temperature Devices (RTDs)
 - b. Thermistors
2. Thermoelectric – Thermocouples
3. Radiation Thermometry
4. Fiber Optic Sensor

RTDs

RTDs are made of materials whose resistance changes in accordance with temperature

Metals such as platinum, nickel and copper are commonly used.

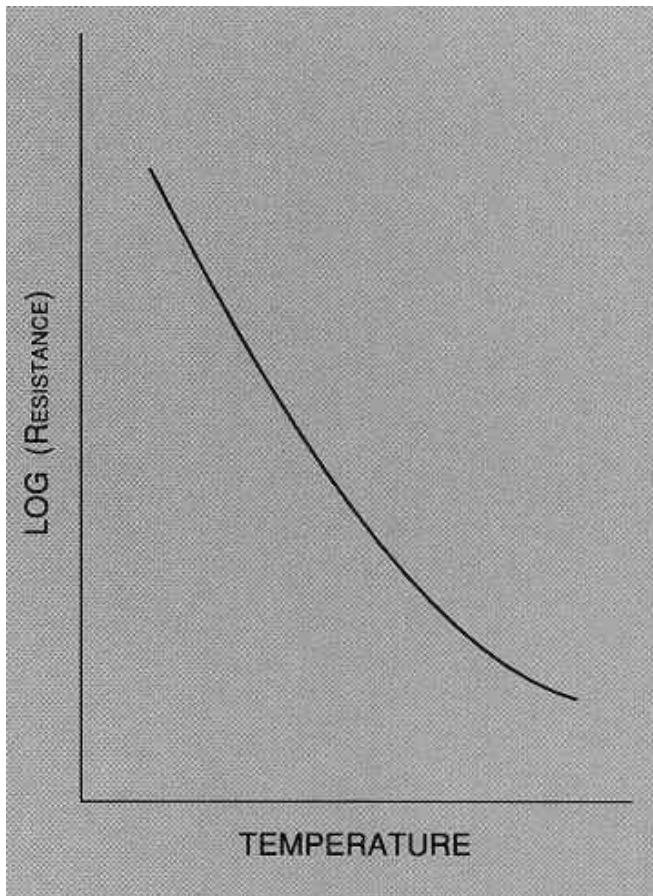
They exhibit a positive temperature coefficient.

$$R_T = R_0 [1 + \alpha_1 T + \alpha_2 T^2 + \dots + \alpha_n T^n] \approx R_0 [1 + \alpha_1 T]$$



A commercial ThermoWorks RTD probe

Thermistors



Thermistors are made from semiconductor material.

Generally, they have a negative temperature coefficient (NTC), that is NTC thermistors are most commonly used.

$$R_T = R_0 \exp \left[B \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

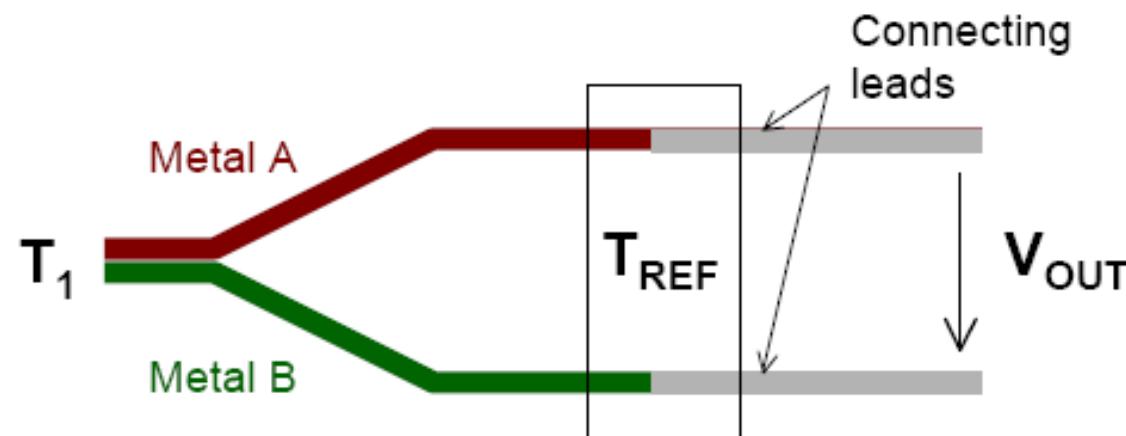
R_0 is the resistance at a reference point (in the limit, absolute 0).

Thermocouples

Seebeck Effect

When a pair of dissimilar metals are joined at one end, and there is a temperature difference between the joined ends and the open ends, thermal emf is generated, which can be measured in the open ends.

This forms the basis of thermocouples.



Thermocouples

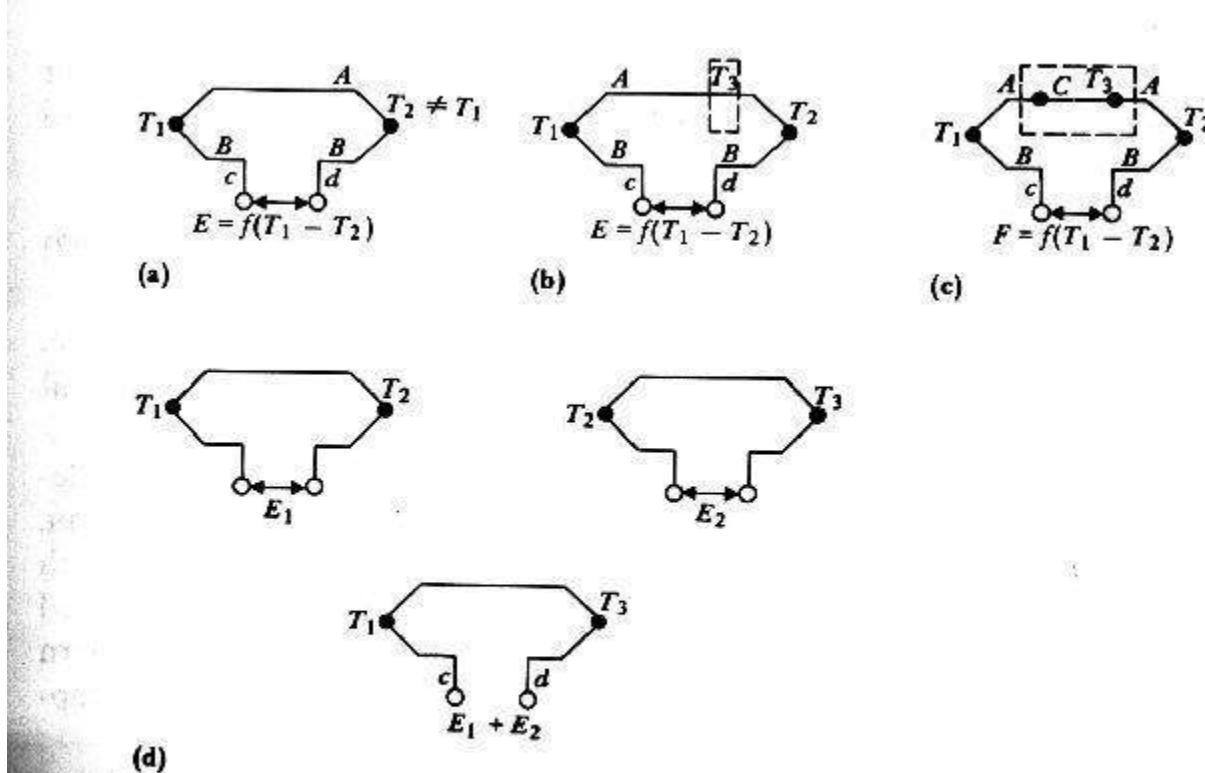


Figure 2.12 Thermocouple circuits (a) Peltier emf. (b) Law of homogeneous circuits. (c) Law of intermediate metals. (d) Law of intermediate temperatures.

Sensor Performance Characteristics

Transfer Function:

The functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics. For expensive sensors which are individually calibrated, this might take the form of the certified calibration curve.

Sensitivity:

The sensitivity is defined in terms of the relationship between input physical signal and output electrical signal. The sensitivity is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with respect to physical signal. Typical units : **Volts/Kelvin**. A Thermometer would have "high sensitivity" if a small temperature change resulted in a large voltage change.

Span or Dynamic Range:

The range of input physical signals which may be converted to electrical signals by the sensor. Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier as the range over which other performance characteristics described in the data sheets are expected to apply.

Sensor Performance Characteristics

Accuracy:

Generally defined as the largest expected error between actual and ideal output signals. Typical Units : Kelvin. Sometimes this is quoted as a fraction of the full scale output. For example, a thermometer might be guaranteed accurate to within 5% of FSO (Full Scale Output)

Hysteresis:

Some sensors do not return to the same output value when the input stimulus is cycled up or down. The width of the expected error in terms of the measured quantity is defined as the hysteresis. Typical units : Kelvin or % of FSO

Nonlinearity (often called Linearity):

The maximum deviation from a linear transfer function over the specified dynamic range. There are several measures of this error. The most common compares the actual transfer function with the 'best straight line', which lies midway between the two parallel lines which encompasses the entire transfer function over the specified dynamic range of the device. This choice of comparison method is popular because it makes most sensors look the best.

Sensor Performance Characteristics

Noise:

All sensors produce some output noise in addition to the output signal. The noise of the sensor limits the performance of the system based on the sensor. Noise is generally distributed across the frequency spectrum. Many common noise sources produce a white noise distribution, which is to say that the spectral noise density is the same at all frequencies. Since there is an inverse relationship between the bandwidth and measurement time, it can be said that the noise decreases with the square root of the measurement time.

Resolution:

The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out.

Bandwidth:

All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cutoff frequencies, respectively. The bandwidth of a sensor is the frequency range between these two frequencies.

*End of
chapter 1*

Chapter 1

Biopotential Electrodes

by
Michael R. Neuman

in
John G. Webster (Editor)
Medical Instrumentation: Application and Design
John Wiley & Sons, 1998

ISBN 0-471-15368-0

Biopotential Electrodes

Outline

- **The Electrode-Electrolyte Interface**
- **Polarization**
- **Polarizable and Nonpolarizable Electrodes**
- **Electrode Behavior & Circuit Models**
- **The Electrode-Skin Interface & Motion Artifact**
- **Body-Surface Recording Electrodes**
- **Internal Electrodes**
- **Electrode Arrays**
- **Microelectrodes**
- **Electrodes for Electric Stimulation of Tissue**
- **Practical Hints in Using Electrodes**

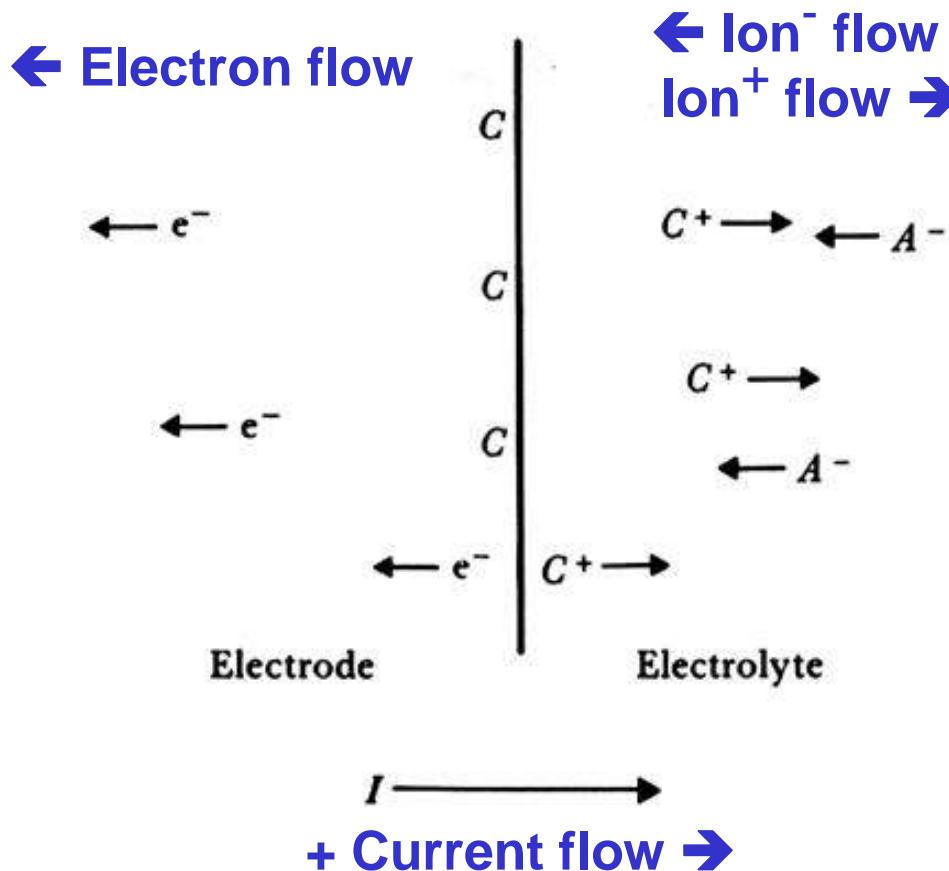
Bio-potential Electrodes

- 1. Microelectrode :Electrodes used to measure bioelectric potential near or within a single cell**
- 2. Skin Surface Electrode; Electrodes used to measure ECG,EEG, and EMG potential from the surface of the skin**
- 3. Needle Electrode: To record EEG potential from local region of the brain**

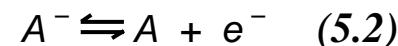
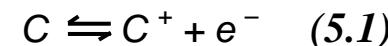
Biopotential Electrodes – The Basics

- The interface between the body and electronic measuring devices
- Conduct current across the interface
- Current is carried in the body by ions
- Current is carried in electronics by electrons
- Electrodes must change ionic current into electronic current
- This is all mediated at what is called the **Electrode-Electrolyte Interface** or the **Electrode-Tissue Interface**

Current Flow at the Electrode-Electrolyte Interface



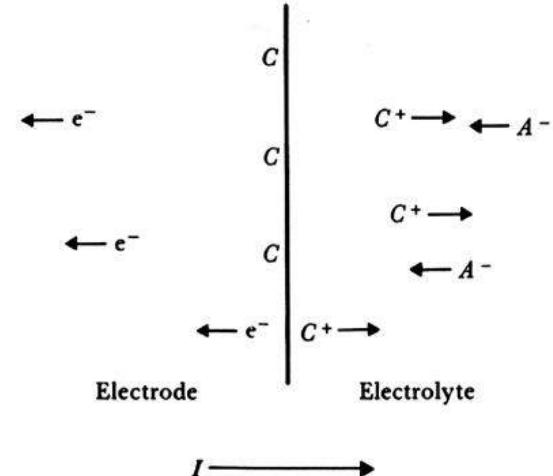
- Electrons move in opposite direction to current flow
 - Cations (C^+) move in same direction as current flow
 - Anions (A^-) move in opposite direction of current flow
 - Chemical oxidation (current flow right) - reduction (current flow left) reactions at the interface:



- **No current at equilibrium**

Figure 5.1 The current crosses it from left to right. The electrode consists of metallic atoms C. The electrolyte is an aqueous solution containing cations of the electrode metal C^+ and anions A $^-$.

Half-Cell Potential

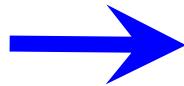


- When metal (C) contacts electrolyte, oxidation ($C \rightarrow C^+ + e^-$) or reduction ($A^- \leftarrow A + e^-$) begins immediately.
- Local concentration of cations at the surface changes.
- Charge builds up in the regions.
- Electrolyte surrounding the metal assumes a different electric potential from the rest of the solution.
- This potential difference is called the half-cell potential (E^0).
- Separation of charge at the electrode-electrolyte interface results in a electric double layer (**bilayer**).
- Measuring the half-cell potential requires the use of a second reference electrode.
- By convention, the hydrogen electrode is chosen as the reference.

Half-Cell Potentials of Common Metals at 25 °C

Metal	Potential E^0 (volts)
-------	-------------------------

Al	- 1.706
Zn	- 0.763
Cr	- 0.744
Fe	- 0.409
Cd	- 0.401
Ni	- 0.230
Pb	- 0.126
H	0.000
AgCl	+ 0.223
Hg ₂ Cl ₂	+ 0.268
Cu	+ 0.522
Ag	+ 0.799
Au	+ 1.680



By definition: Hydrogen is bubbled over a platinum electrode and the potential is defined as zero.

Electrode Polarization

- **Standard half-cell potential (E^0):**
 - Normally E^0 is an equilibrium value and assumes zero-current across the interface.
 - When current flows, the half-cell potential, E^0 , changes.
- **Overpotential (V_p):**
 - Difference between non-zero current and zero-current half-cell potentials; also called the *polarization potential* (V_p).
- **Components of the overpotential (V_p):**
 - **Ohmic** (V_r): Due to the resistance of the electrolyte (voltage drop along the path of ionic flow).
 - **Concentration** (V_c): Due to a redistribution of the ions in the vicinity of the electrode-electrolyte interface (concentration changes).
 - **Activation** (V_a): Due to metal ions going into solution (must overcome an energy barrier, the activation energy) or due to metal plating out of solution onto the electrode (a second activation energy).

$$V_p = V_r + V_c + V_a \quad (5.4)$$

Nernst Equation

- Governs the half-cell potential:

$$E = E^0 + \frac{RT}{nF} \ln(a_{C^{n+}}) \quad (5.6)$$

where

E – half-cell potential

E^0 – standard half-cell potential

(the electrode in an electrolyte with unity activity at standard temperature)

R – universal gas constant [8.31 J/(mol K)]

T – absolute temperature in K

n – valence of the electrode material

F – Faraday constant [96,500 C/(mol/valence)]

$a_{C^{n+}}$ – ionic activity of cation C^{n+}
(its availability to enter into a reaction)

Polarizability & Electrodes

- **Perfectly polarizable electrodes:**
 - No charge crosses the electrode when current is applied
 - Noble metals are closest (like platinum and gold); they are difficult to oxidize and dissolve.
 - Current does not cross, but rather changes the concentration of ions at the interface.
 - Behave like a capacitor.
- **Perfectly non-polarizable electrodes:**
 - All charge freely crosses the interface when current is applied.
 - No overpotential is generated.
 - Behave like a resistor.
 - Silver/silver-chloride is a good non-polarizable electrode.

The Classic Ag/AgCl Electrodes

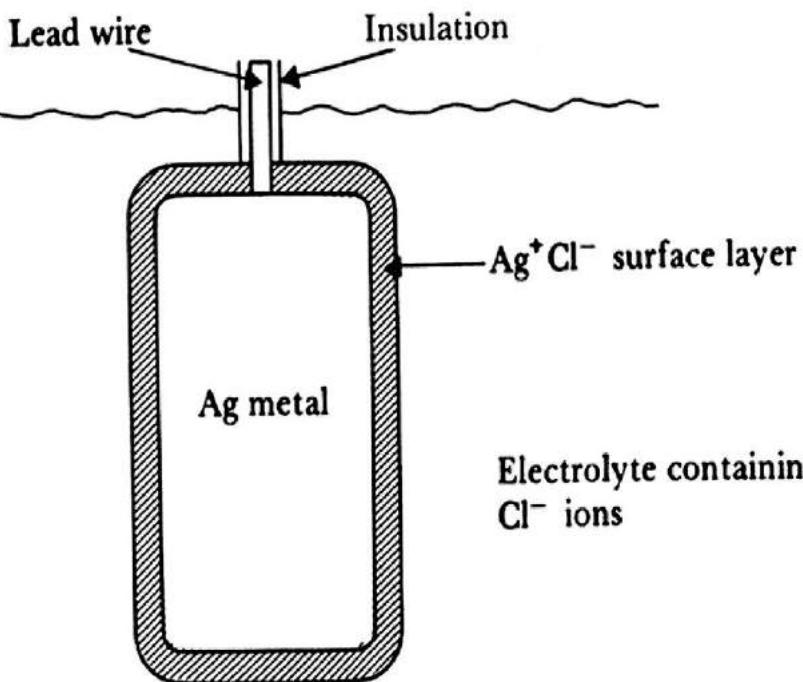


Figure 5.2 A silver/silver chloride electrode, shown in cross section.

- **Features:**

- Practical electrode, easy to fabricate.
- Metal (Ag) electrode is coated with a layer of slightly soluble ionic compound of the metal and a suitable anion (Cl).

- **Reaction 1:** silver oxidizes at the Ag/AgCl interface
$$Ag \rightleftharpoons Ag^+ + e^- \quad (5.10)$$
- **Reaction 2:** silver cations combine with chloride anions
$$Ag^+ + Cl^- \rightleftharpoons AgCl \quad (5.11)$$

AgCl is only slightly soluble in water so most precipitates onto the electrode to form a surface coating.

Ag/AgCl Electrodes

- **Solubility product (K_s):** The rate of precipitation and of returning to solution. At equilibrium:

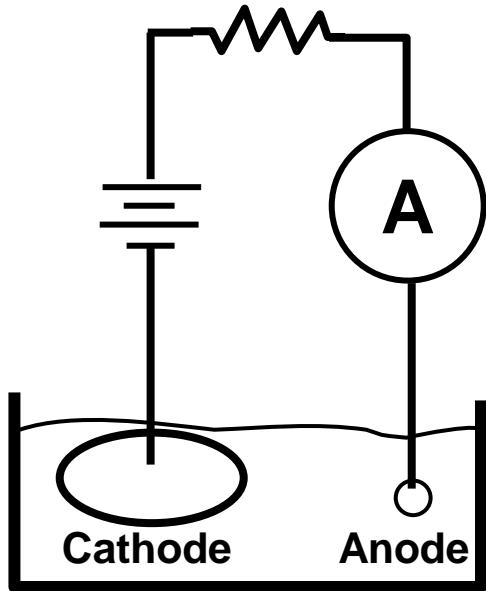
$$K_s = a_{Ag^+} \times a_{Cl^-} \quad (5.12)$$

- The equation for the half-cell potential becomes

$$E = \underbrace{E_{Ag}^0 + \frac{RT}{nF} \ln (K_s)}_{\text{constant}} - \frac{RT}{nF} \ln (a_{Cl^-}) \quad (5.15)$$

- Determined by the activity of the chloride ion. In the body, the activity of Cl^- is quite stable.

Ag/AgCl Fabrication



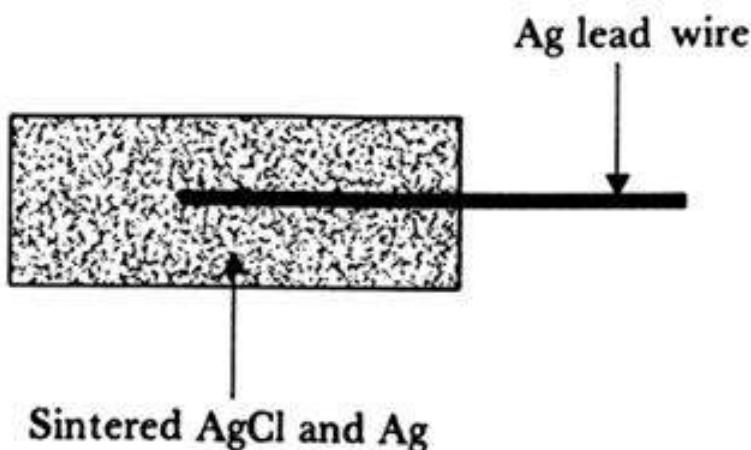
Electrochemical Cell

- Electrolytic process
- Large Ag/AgCl electrode serves as the cathode.
- Smaller Ag electrode to be chloridized serves as the anode.
- A 1.5 volt battery is the energy source.
- A resistor limits the current.
- A milliammeter measures the plating current.
- Reaction has an initial surge of current.
- When current approaches a steady state (about $10 \mu\text{A}$), the process is terminated.

Sintered Ag/Ag Electrode



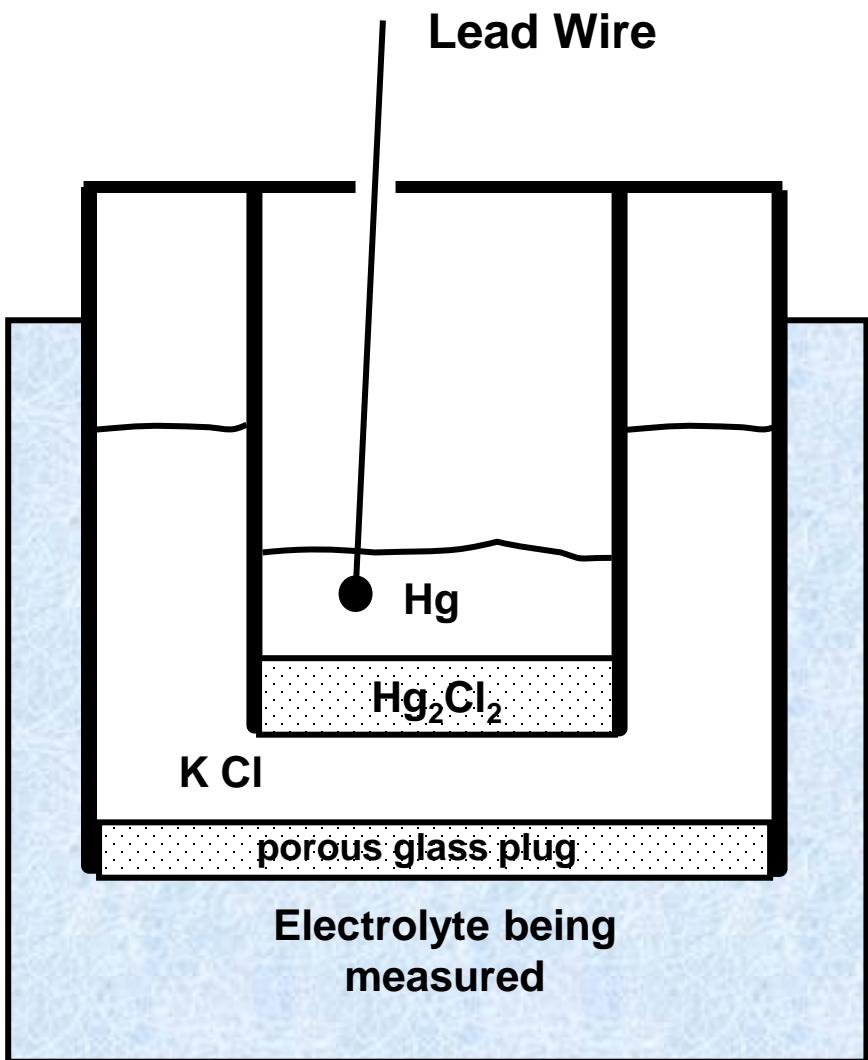
Figure 5.3



Sintering Process

- A mixture of Ag and AgCl powder is pressed into a pellet around a silver lead wire.
- Baked at 400 °C for several hours.
- Known for great endurance (surface does not flake off as in the electrolytically generated electrodes).
- Silver powder is added to increase conductivity since AgCl is not a good conductor.

Calomel Electrode



- Calomel is mercurous chloride (Hg_2Cl_2).
- Approaches perfectly non-polarizing behavior
- Used as a reference in pH measurements.
- Calomel paste is loaded into a porous glass plug at the end of a glass tube.
- Elemental Hg is placed on top with a lead wire.
- Tube is inserted into a saturated KCl solution in a second glass tube.
- A second porous glass plug forms a liquid-liquid interface with the analyte being measured.

Electrode Circuit Model

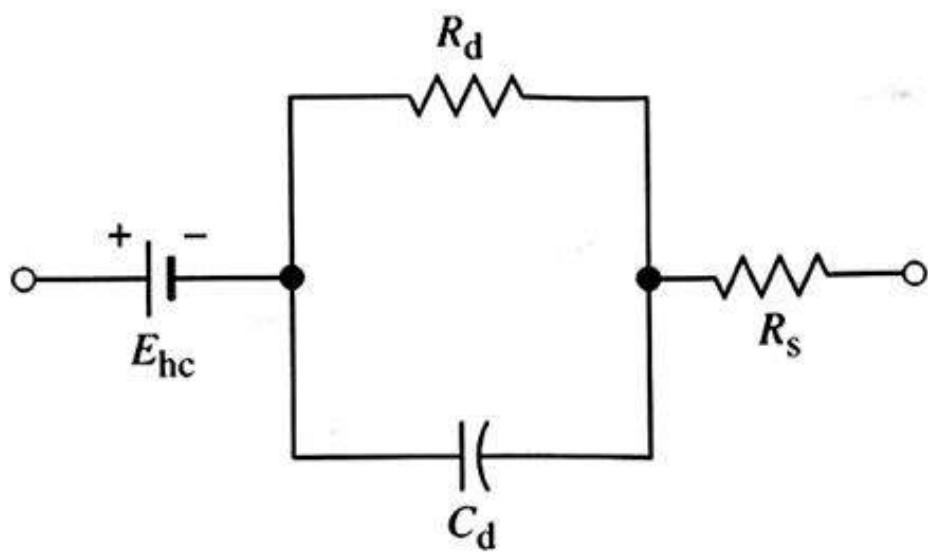


Figure 5.4

- E_{hc} is the half-cell potential
- C_d is the capacitance of the electric double layer (polarizable electrode properties).
- R_d is resistance to current flow across the electrode-electrolyte interface (non-polarizable electrode properties).
- R_s is the series resistance associated with the conductivity of the electrolyte.
- At high frequencies: R_s
- At low frequencies: $R_d + R_s$

Ag/AgCl Electrode Impedance

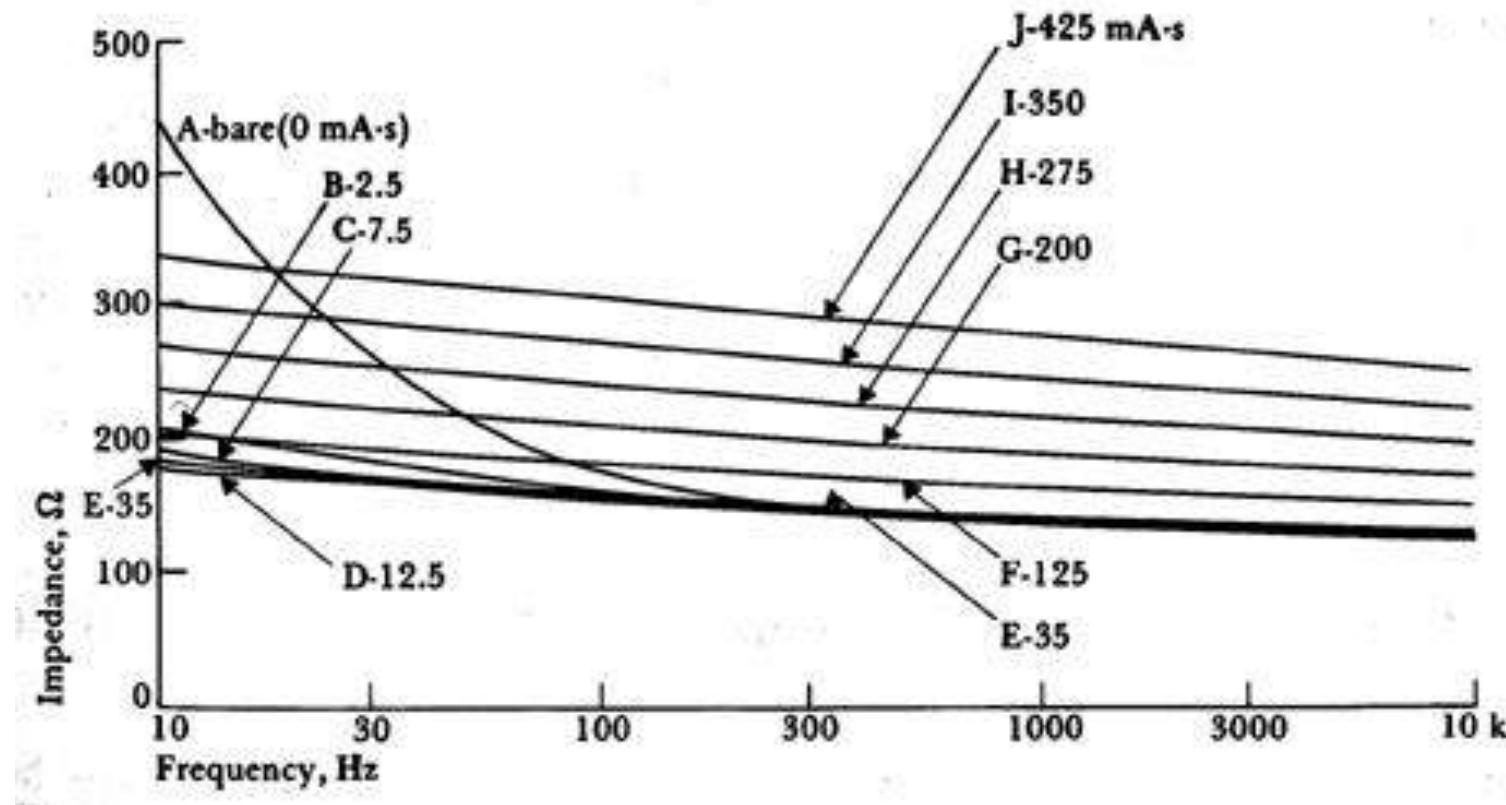


Figure 5.5 Impedance as a function of frequency for Ag electrodes coated with an electrolytically deposited AgCl layer. The electrode area is 0.25 cm^2 . Numbers attached to curves indicate the number of $\text{mA}\cdot\text{s}$ for each deposit.

Nichel- & Carbon-Loaded Silicone

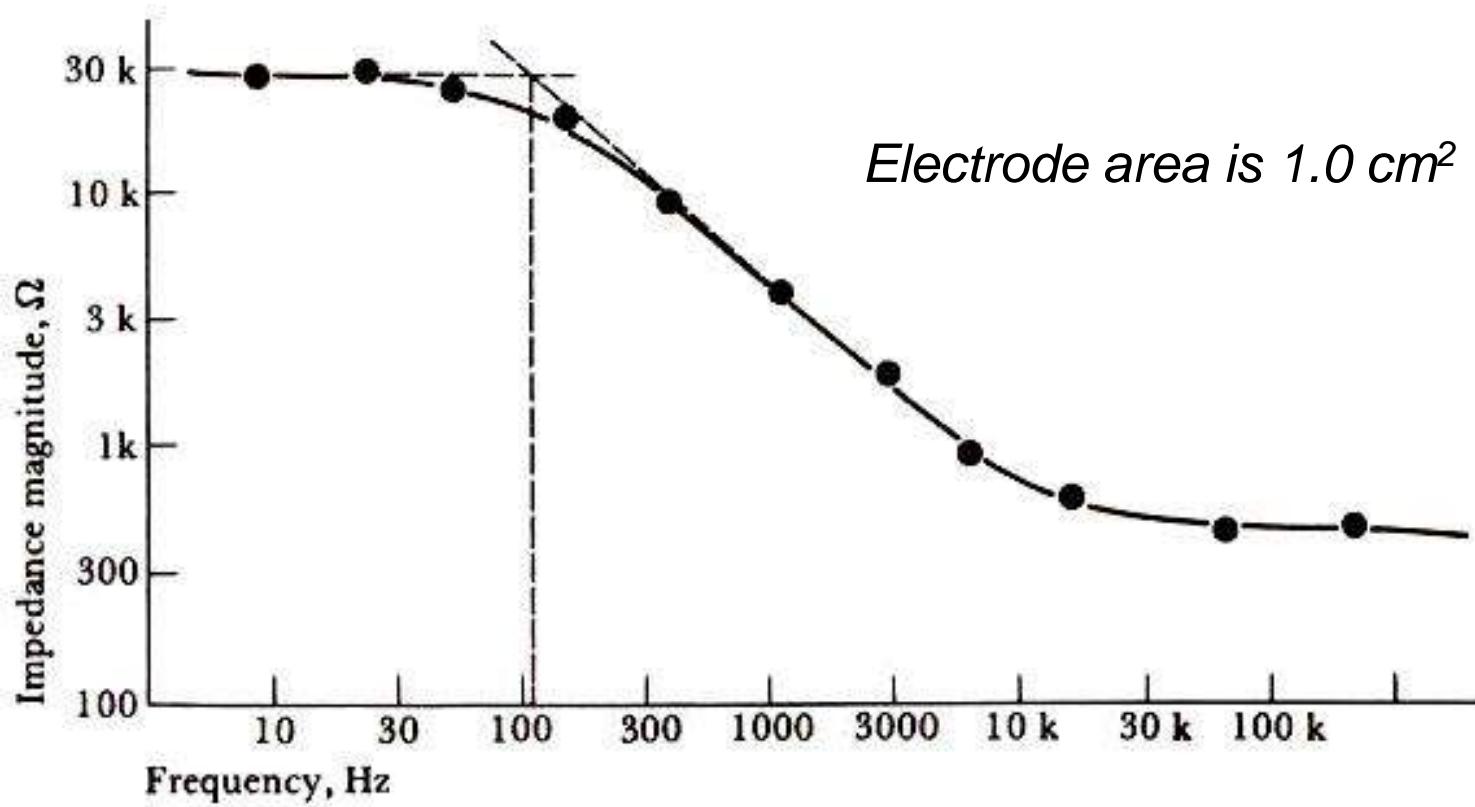


Figure 5.6

Skin Anatomy

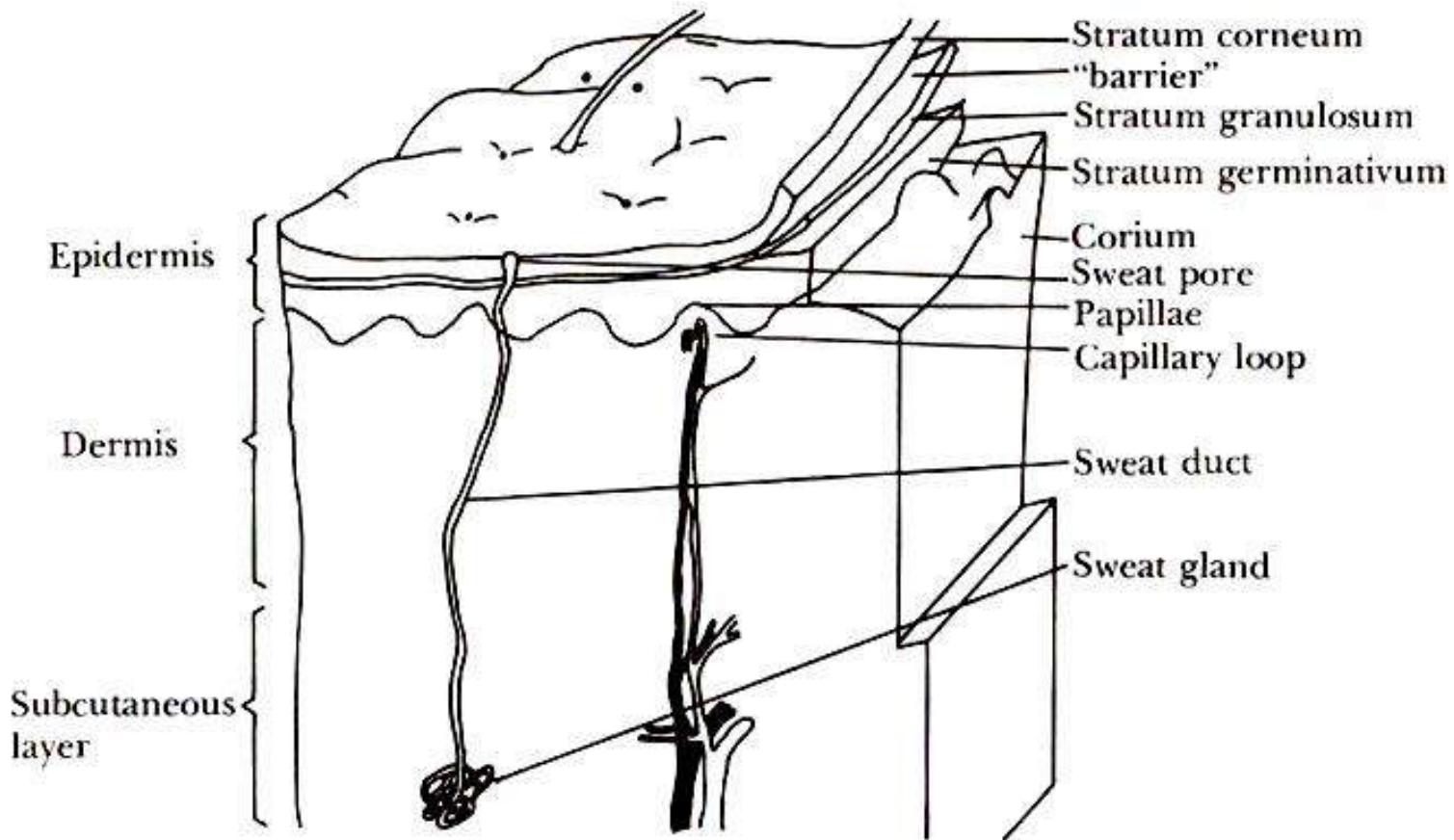


Figure 5.7

Electrode-Skin Interface Model

Motion artifact:

- Gel is disturbed, the charge distribution is perturbed changing the half-cell potentials at the electrode and skin.
- Minimized by using non-polarizable electrode and mechanical abrasion of skin.
- Skin regenerates in 24 hours.

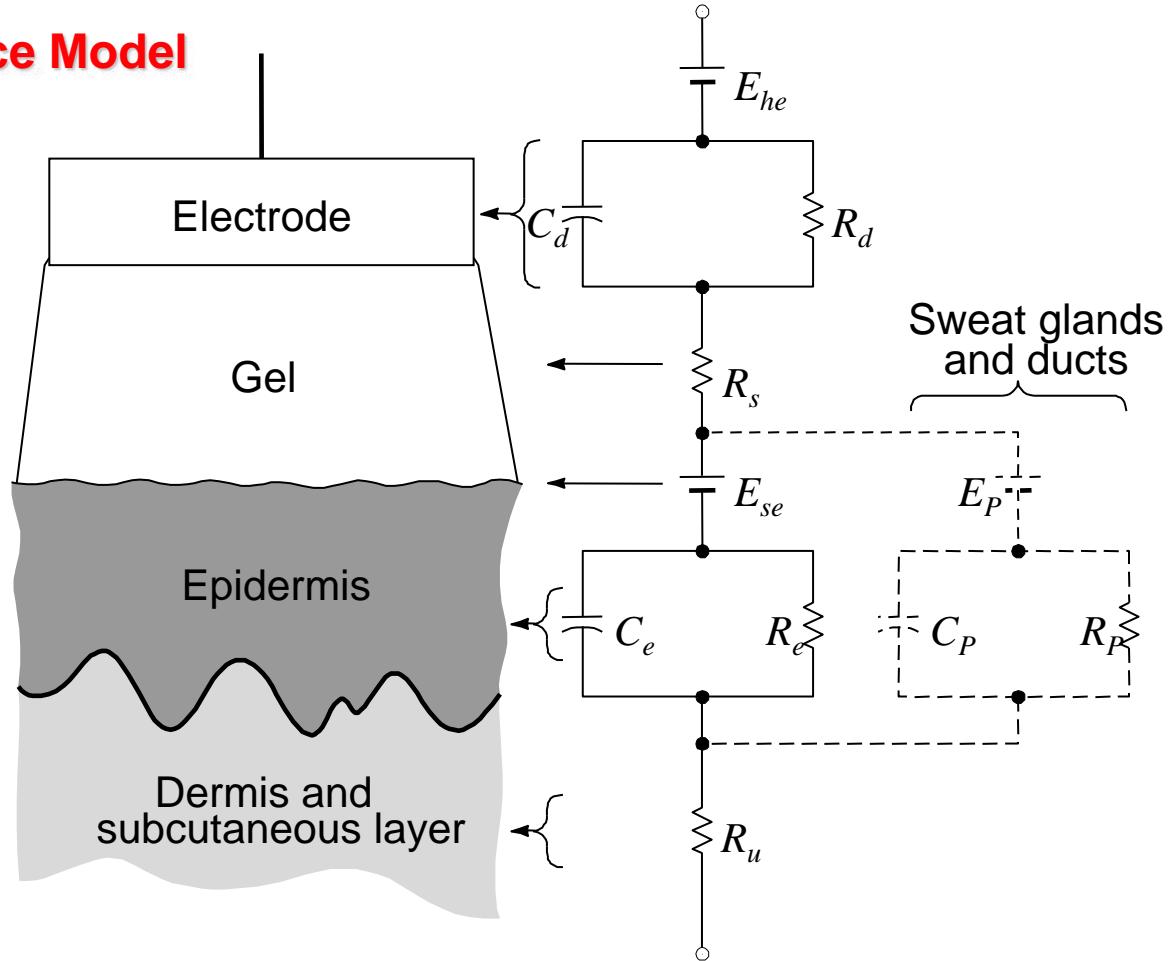


Figure 5.8 A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

Metal Electrodes

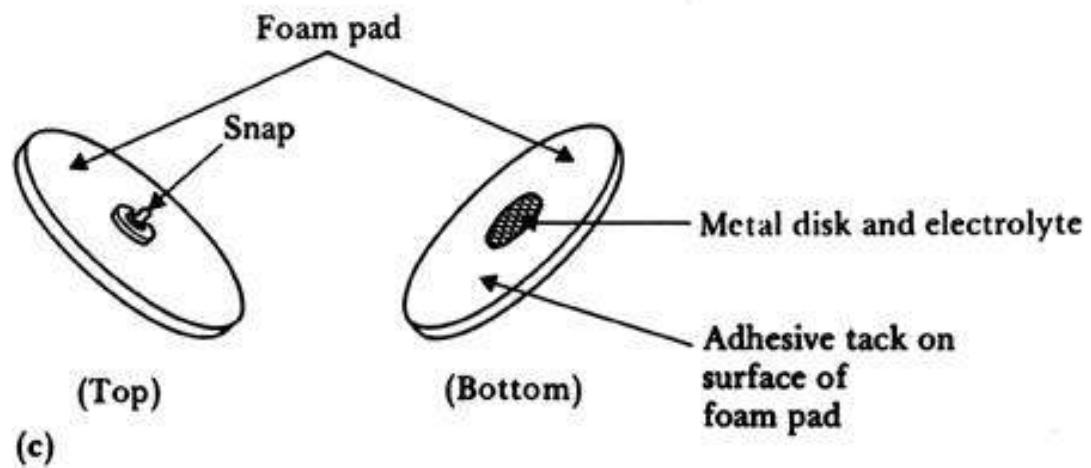
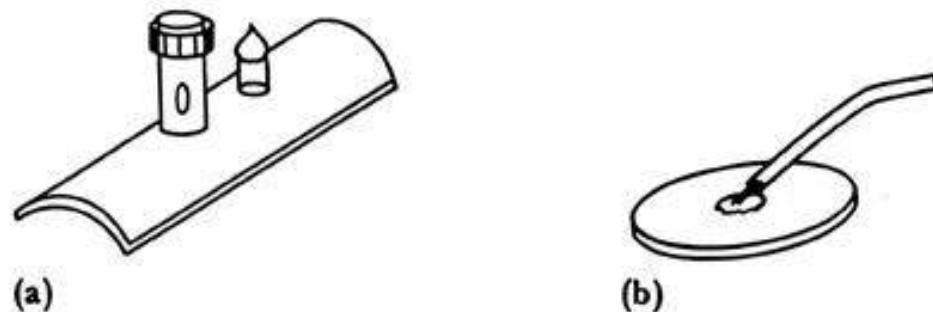


Figure 5.9 Body-surface biopotential electrodes **(a)** Metal-plate electrode used for application to limbs. **(b)** Metal-disk electrode applied with surgical tape. **(c)** Disposable foam-pad electrodes, often used with electrocardiograph monitoring apparatus.

Metal Suction Electrodes

- A paste is introduced into the cup.
- The electrodes are then suctioned into place.
- Ten of these can be used with the clinical electrocardiograph – limb and precordial (chest) electrodes

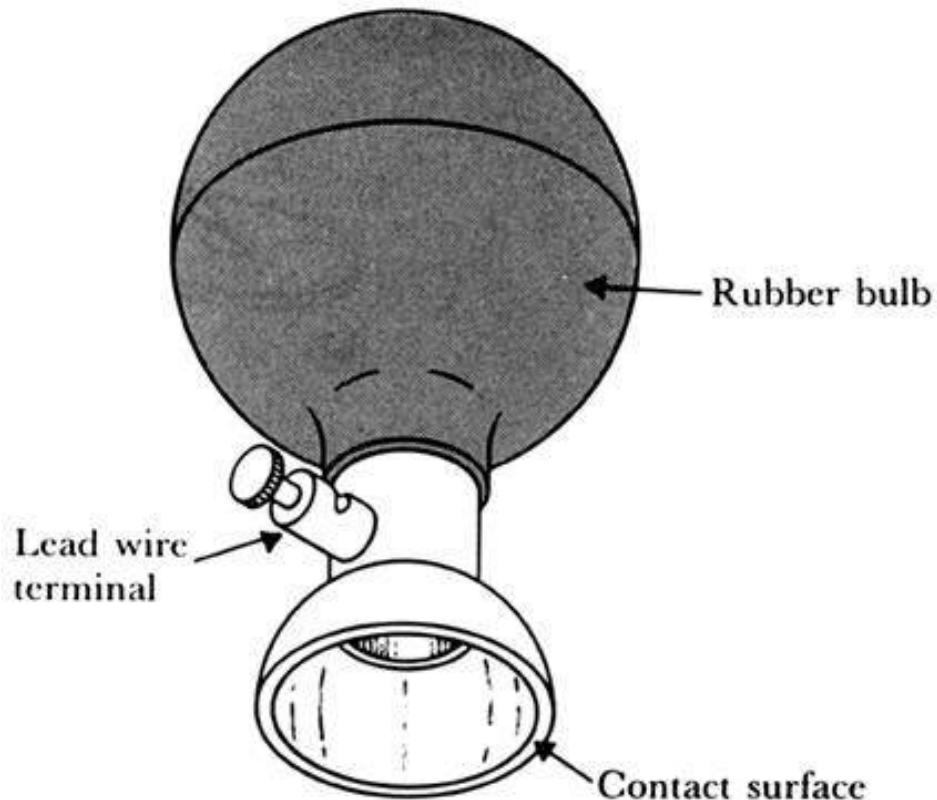


Figure 5.10

Floating Metal Electrodes

- Mechanical technique to reduce noise.
- Isolates the electrode-electrolyte interface from motion artifacts.

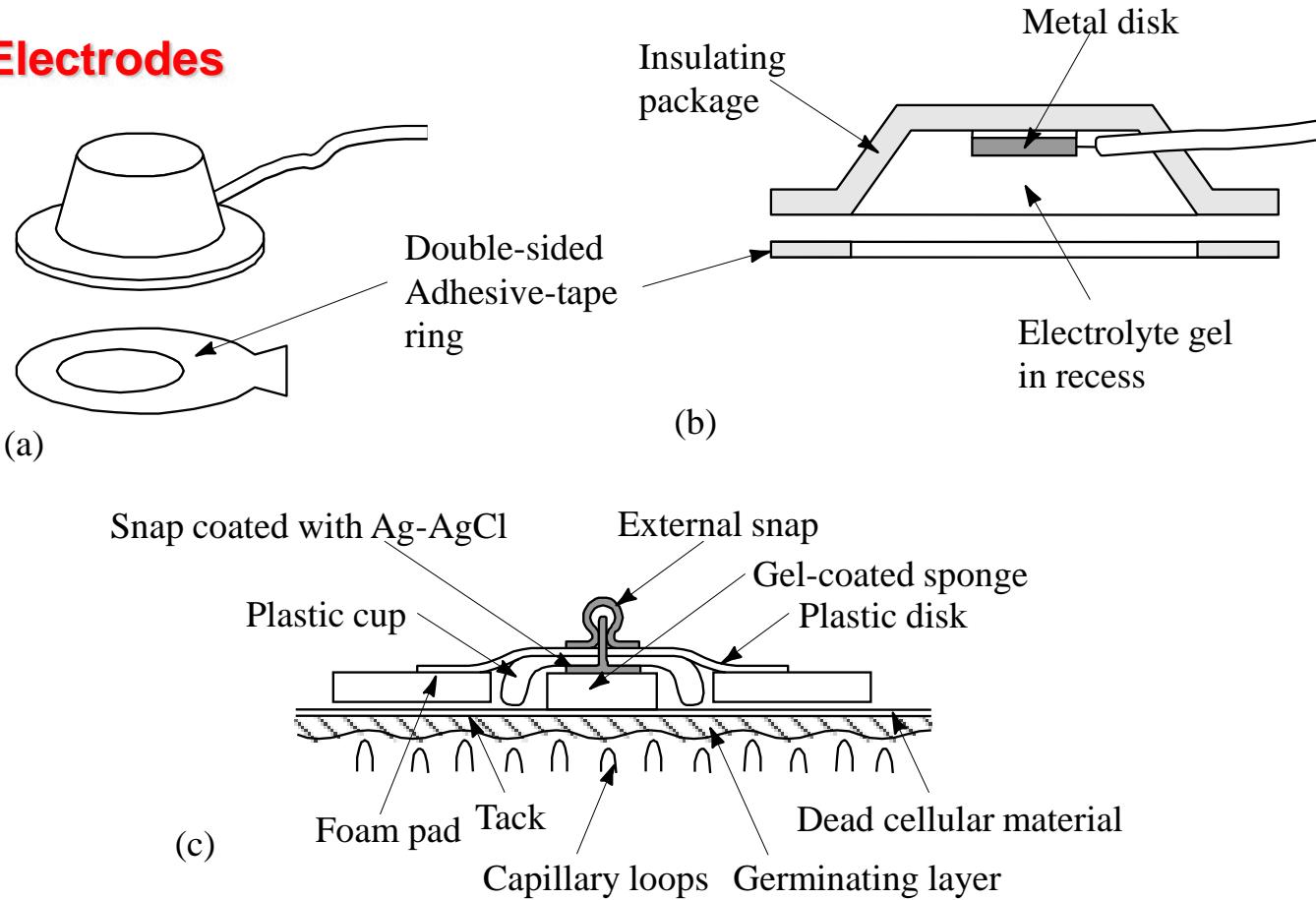
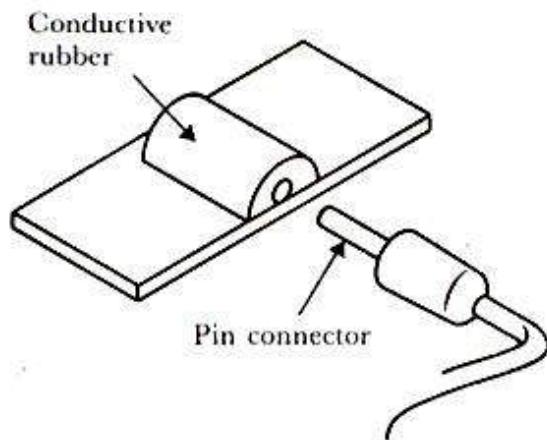
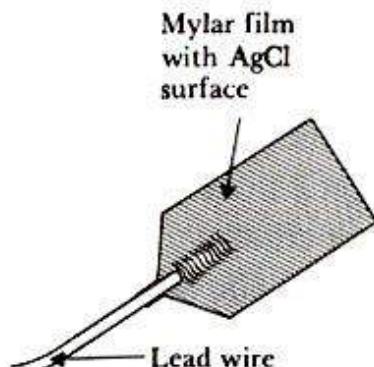


Figure 5.11 (a) Recessed electrode with top-hat structure. (b) Cross-sectional view of the electrode in (a). (c) Cross-sectional view of a disposable recessed electrode of the same general structure shown in Figure 5.9(c). The recess in this electrode is formed from an open foam disk, saturated with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

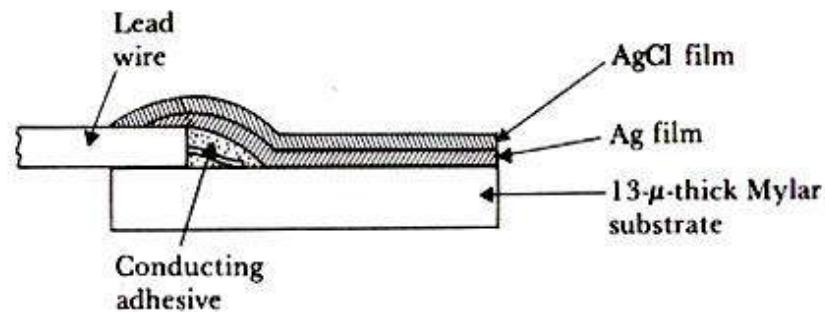
Flexible Body-Surface Electrodes



(a)



(b)



(c)

(a) Carbon-filled
silicone rubber

(b) Flexible Mylar
film with
Ag/AgCl
electrode

(c) Cross section of
the Mylar
electrode

Figure 5.12

Percutaneous Electrodes

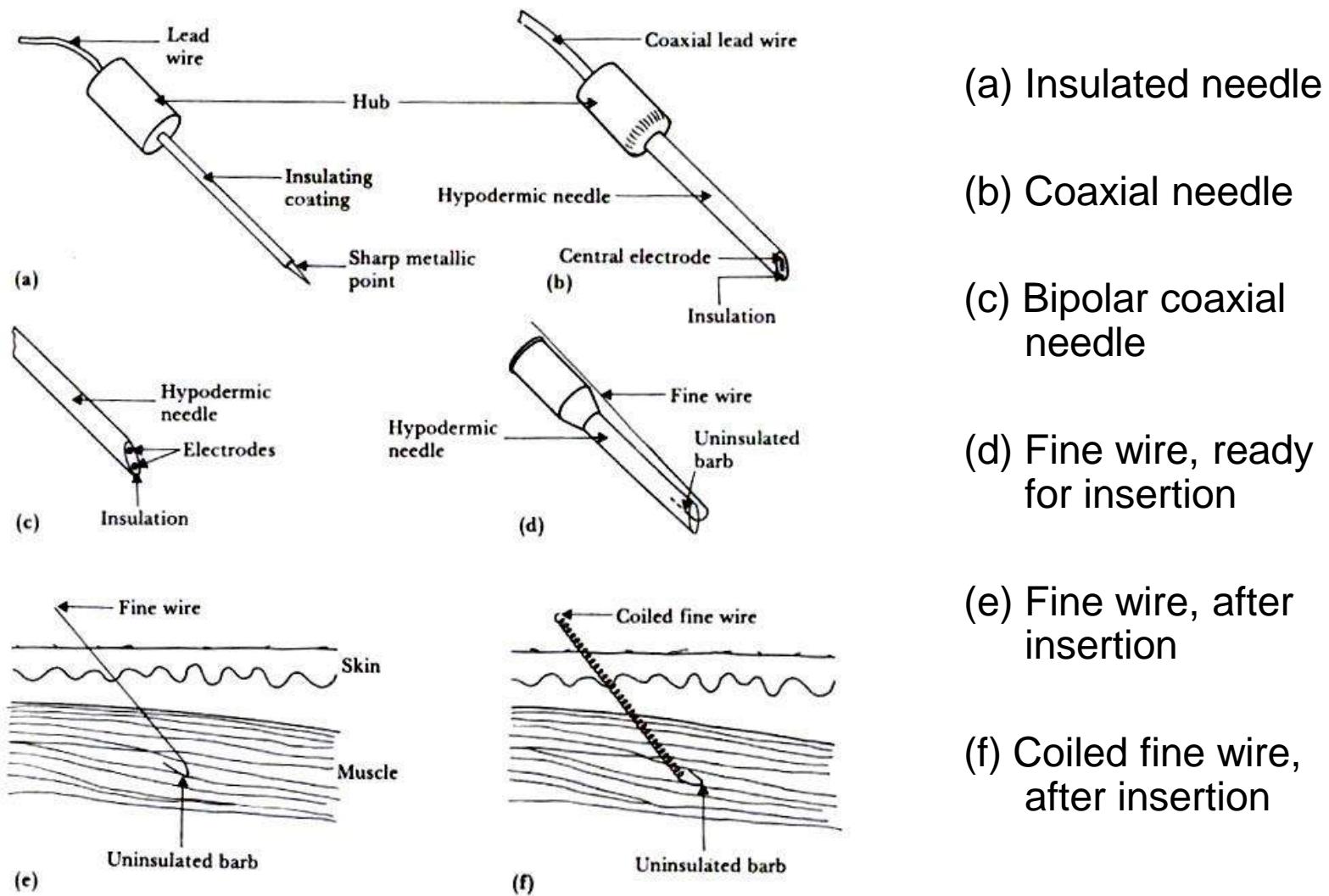
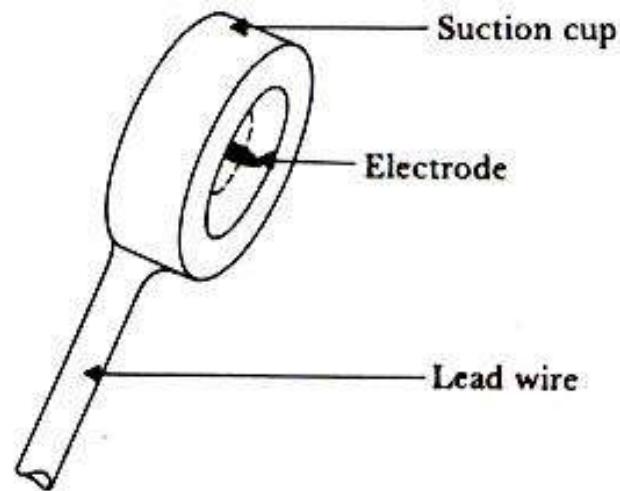
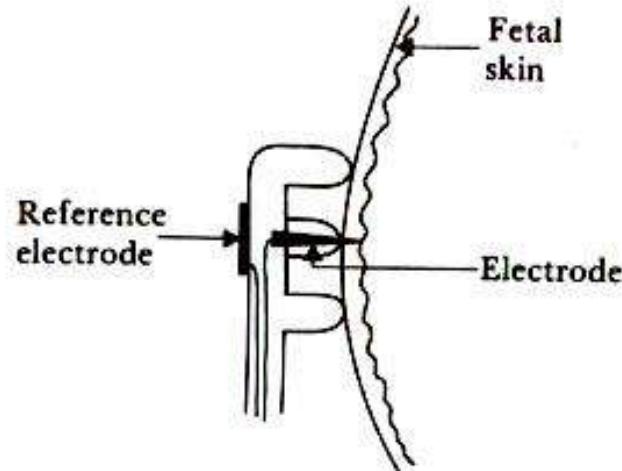


Figure 5.13

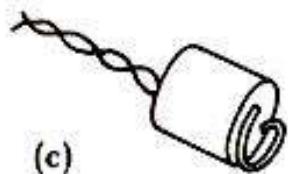
Fetal Intracutaneous Electrodes



(a) Suction needle electrode



(b) Suction electrode (in place)



(c) Helical electrode (attached by corkscrew action)

Figure 5.14

Implantable Electrodes

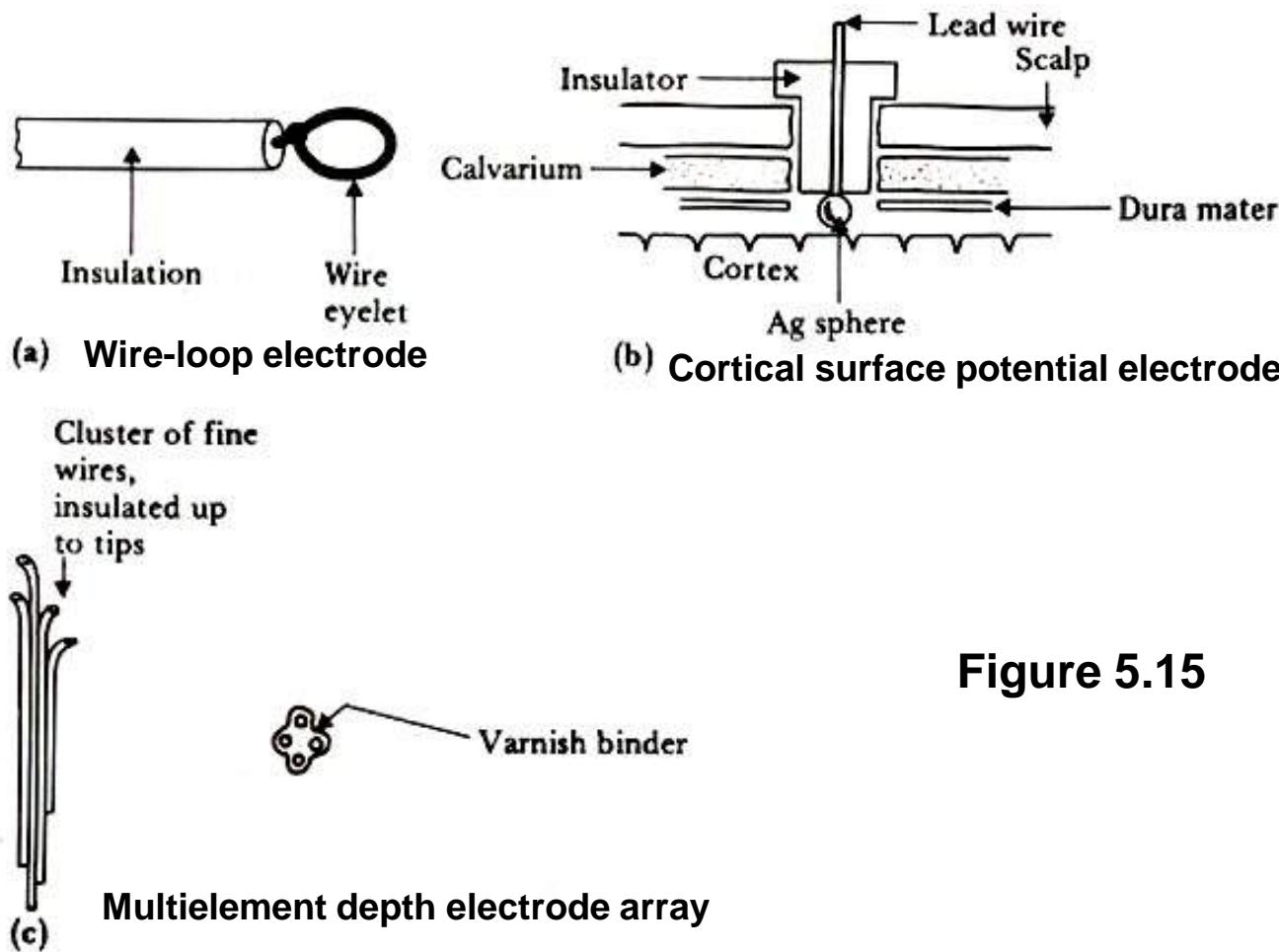


Figure 5.15

Microfabricated Electrode Arrays

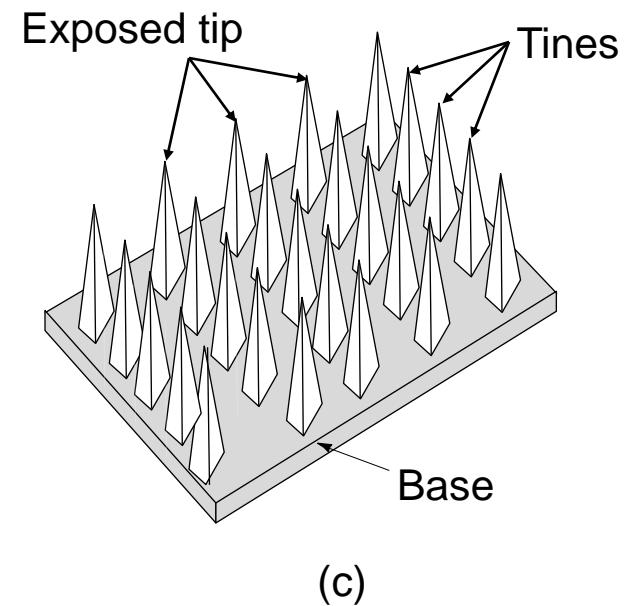
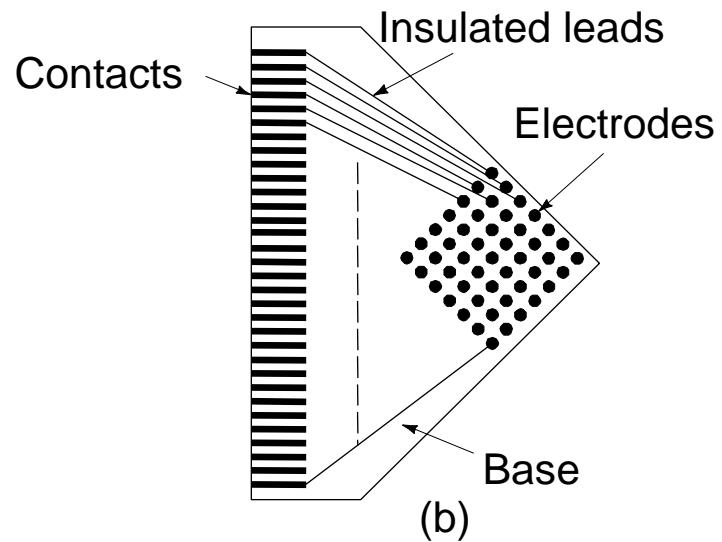
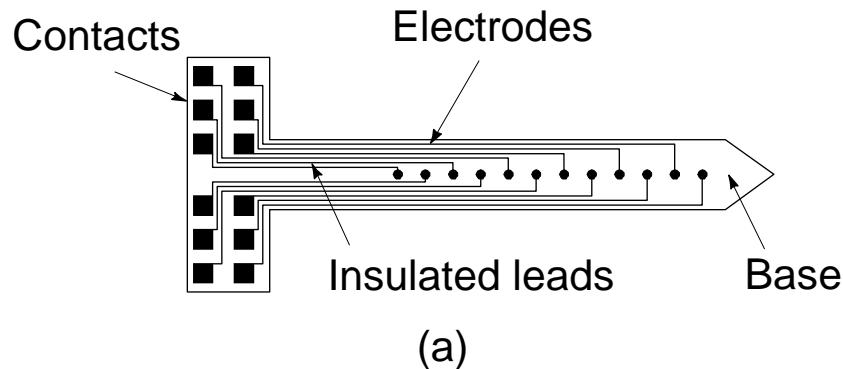


Figure 5.16

- (a) One-dimensional plunge electrode array
- (b) Two-dimensional array, and
- (c) Three-dimensional array

Intracellular Recording Electrode

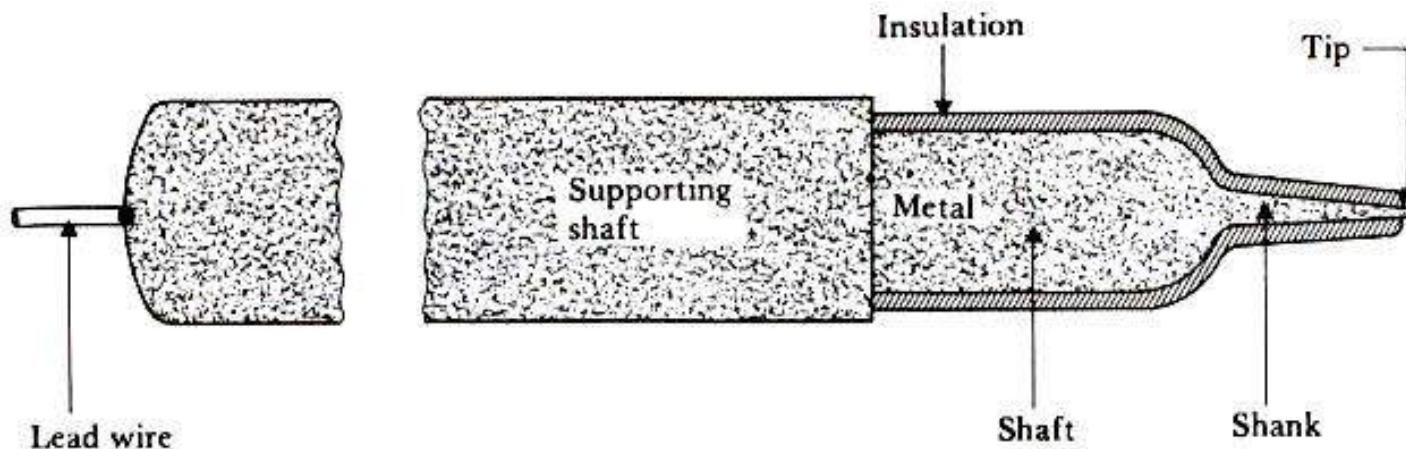


Figure 5.17

- Metal needle with a very fine tip (less than $1.0 \mu\text{m}$)
- Prepared by electrolytic etching
- Metal needle is the anode of an electrolytic cell, and is slowly drawn out of the electrolyte solution (difficult to produce)
- Metal must have great strength: stainless steel, platinum-iridium, tungsten, tungsten carbide.

Supported Metal Electrodes

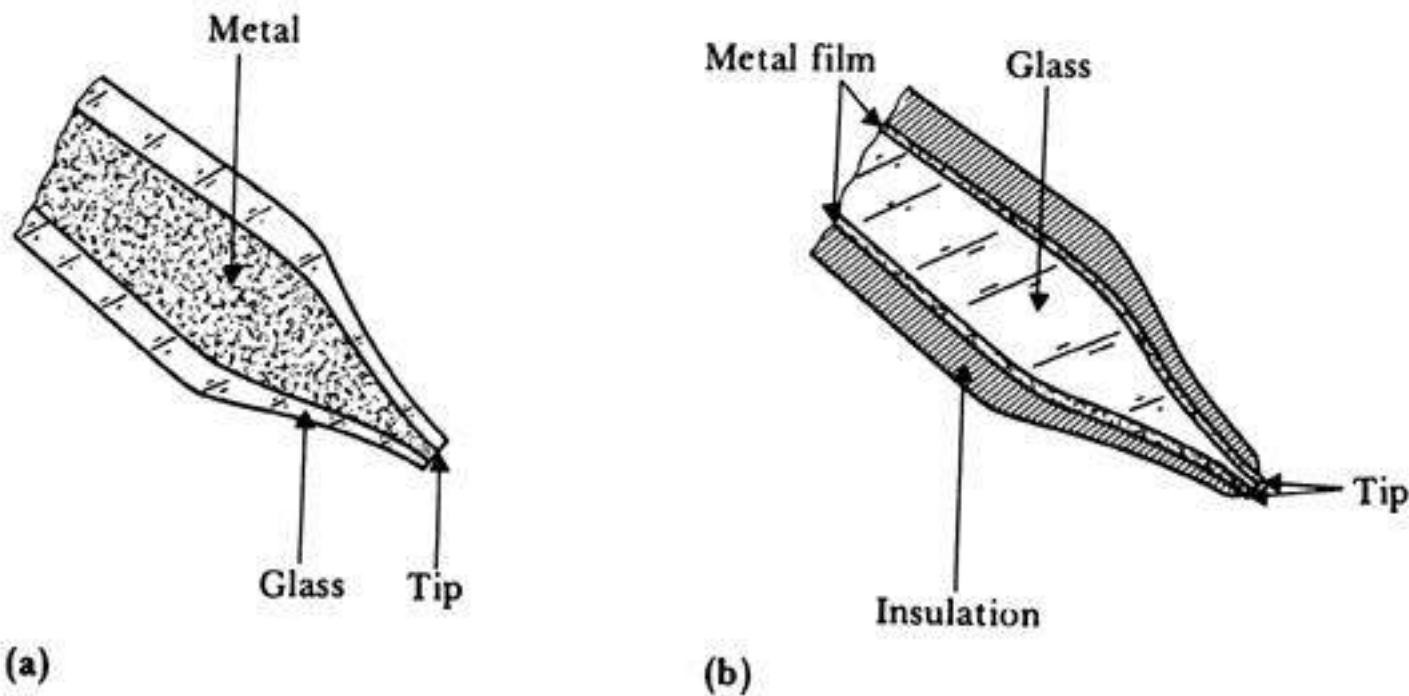


Figure 5.18

- (a) Metal-filled glass micropipet.
- (b) Glass micropipet or probe, coated with metal film.

Glass Micropipet Electrodes

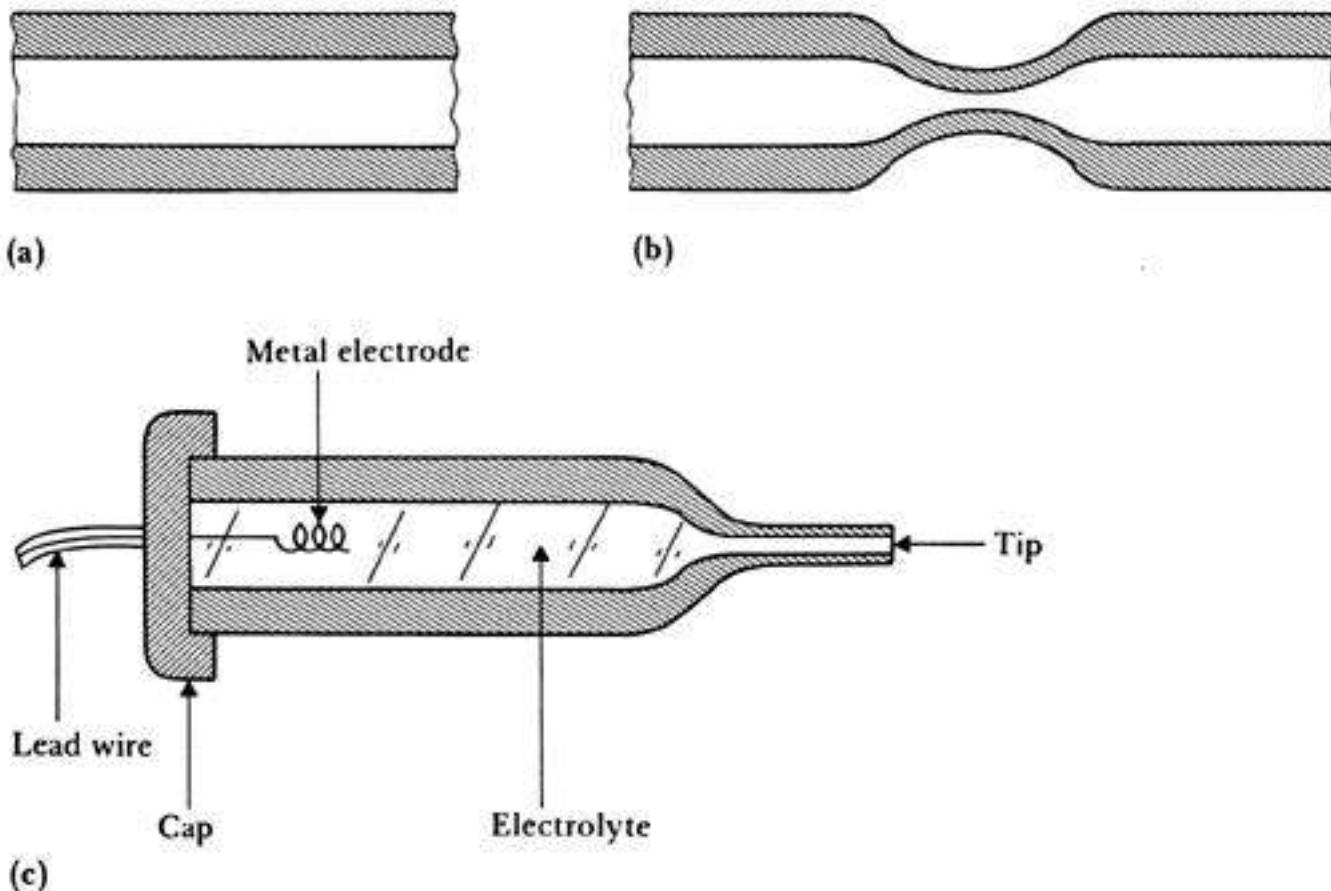
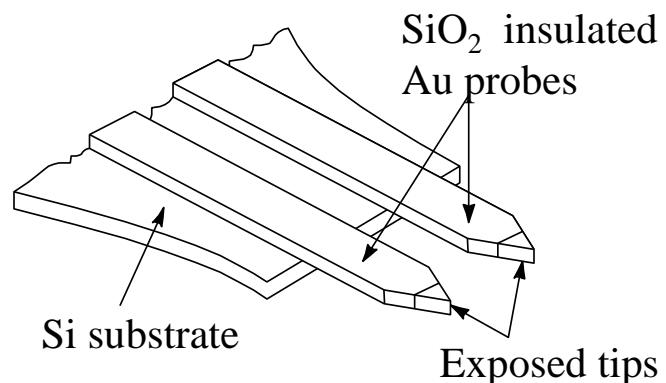
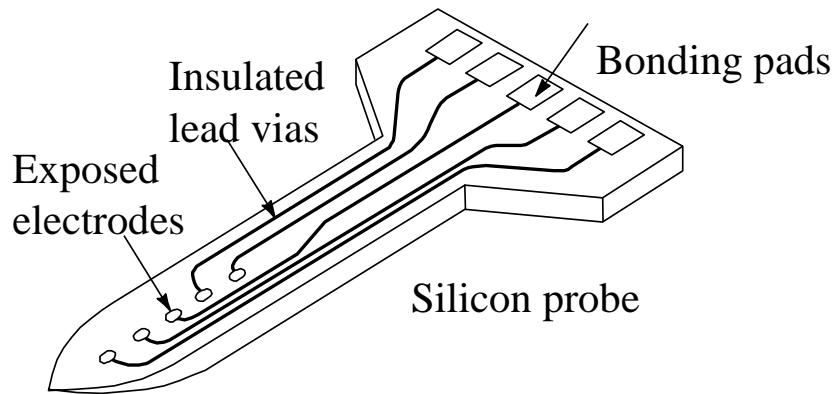


Figure 5.19 A glass micropipet electrode filled with an electrolytic solution
(a) Section of fine-bore glass capillary. **(b)** Capillary narrowed through heating and stretching. **(c)** Final structure of glass-pipet microelectrode.

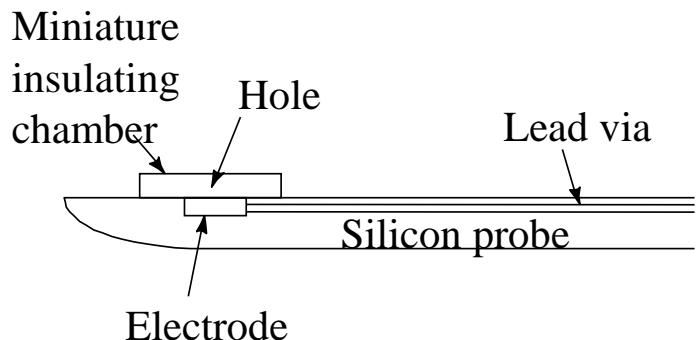
Microfabricated Microelectrodes



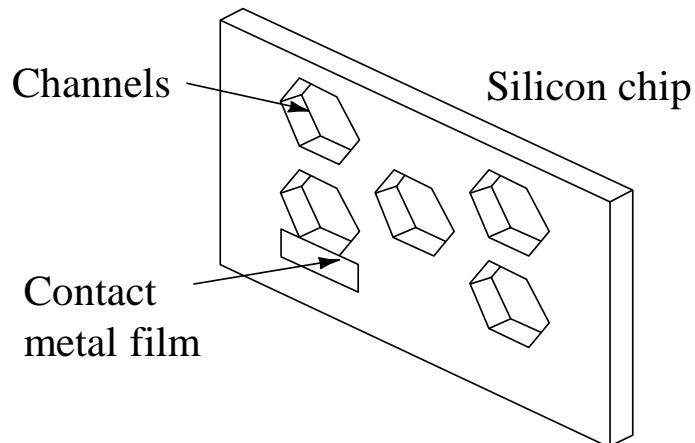
(a) Beam-lead multiple electrode



(b) Multielectrode silicon probe



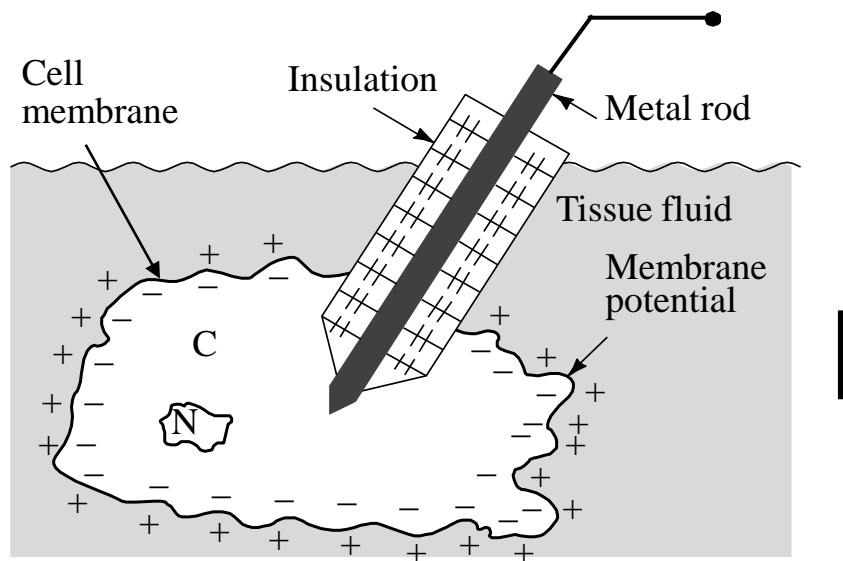
(c) Multiple-chamber electrode



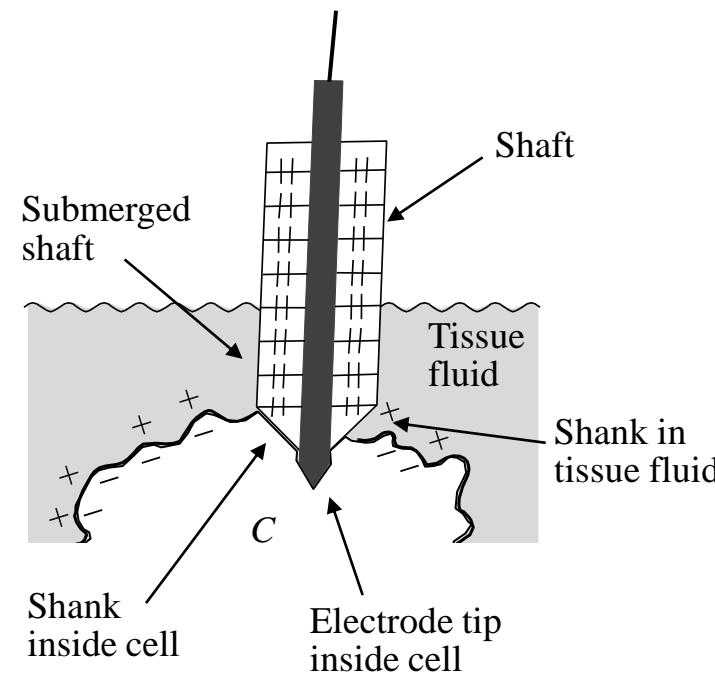
(d) Peripheral-nerve electrode

Figure 5.20

Microelectrode Electrical Model



N = Nucleus
 C = Cytoplasm



Shank Capacitance:

$$\frac{C_{d1}}{L} = \frac{2\pi\epsilon_r\epsilon_0}{\ln(D/d)} \quad (5.16)$$

Figure 5.21 (a)
 Electrode with tip placed within a cell, showing origin of distributed capacitance

Submerged Shaft Capacitance:

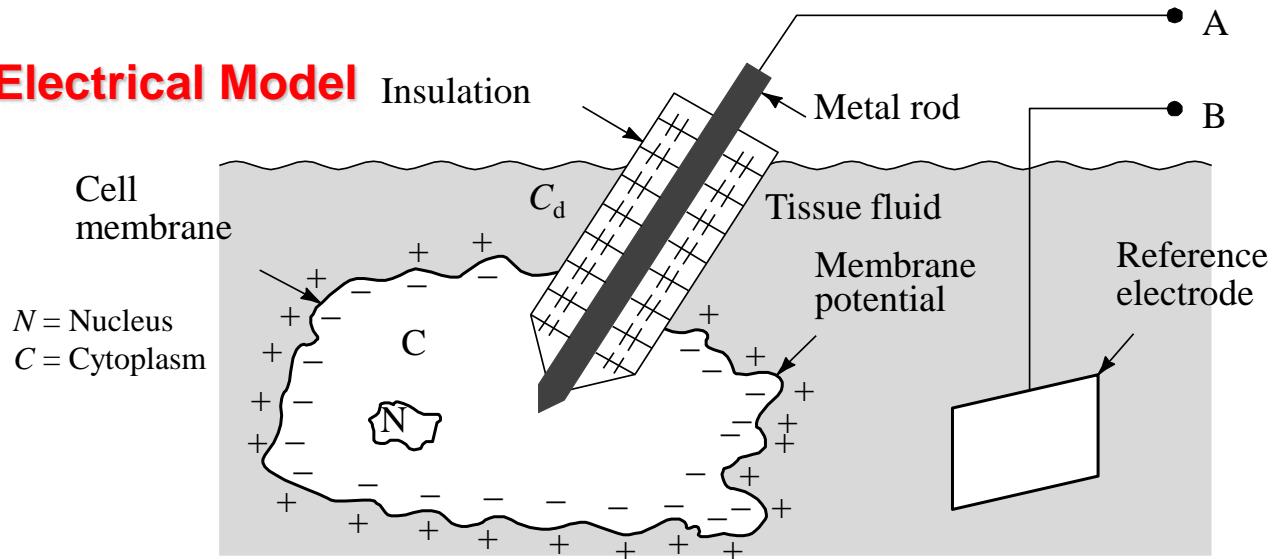
$$\frac{C_{d2}}{L} = \frac{\epsilon_r\epsilon_0\pi d}{t} \quad (5.17)$$

ϵ_r, ϵ_0 = dielectric const.
 D = avg. dia. of shank
 d = dia. of electrode
 t = thickness of insulation layer
 L = length of shank & shaft, respectively

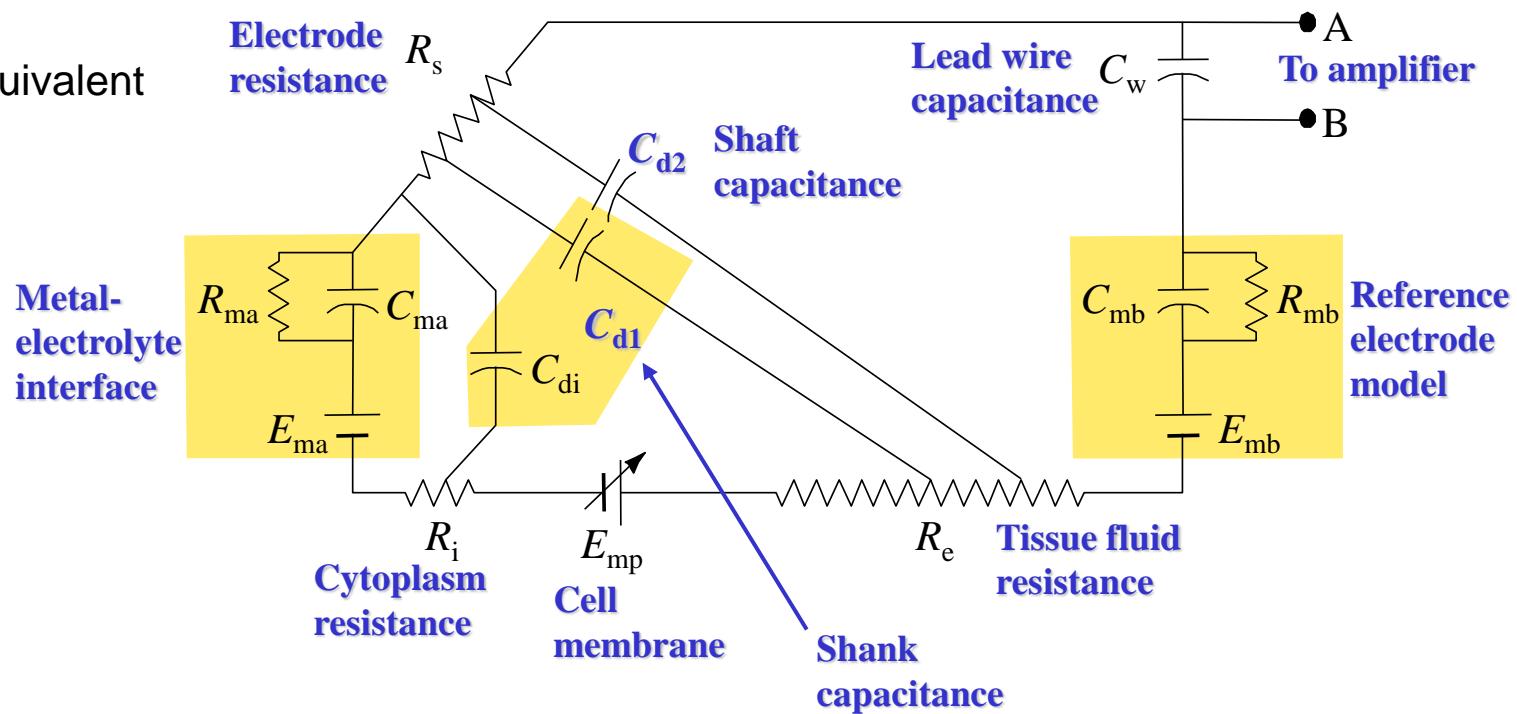
Microelectrode Electrical Model

Figure 5.21

(a) Electrode with tip placed within a cell



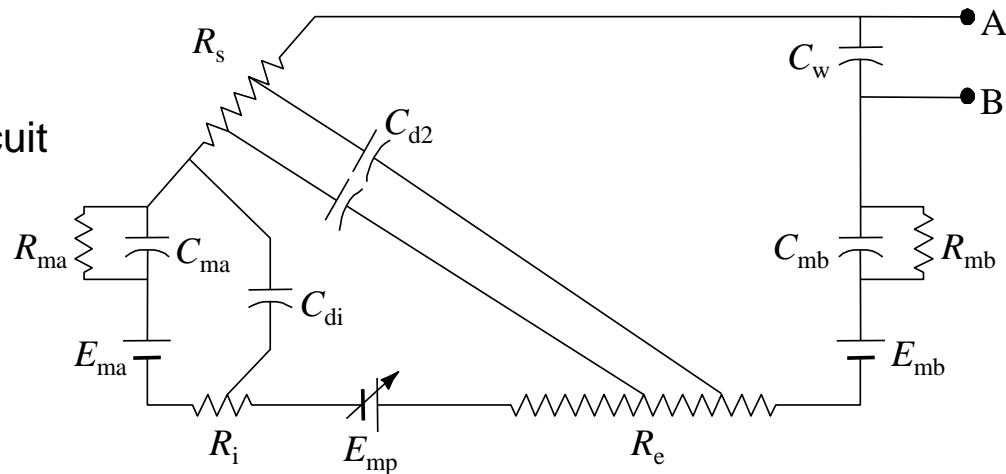
(b) Equivalent circuit



Microelectrode Electrical Model

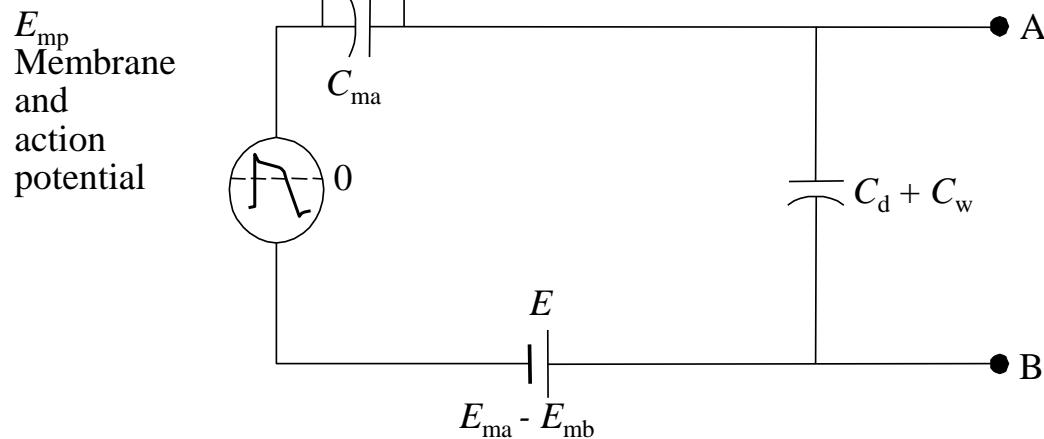
Figure 5.21

(b) Equivalent circuit



(c) Simplified equivalent circuit

R_s , R_i , R_e , and R_{mb} are very small compared to R_{ma} .



Glass Micropipet

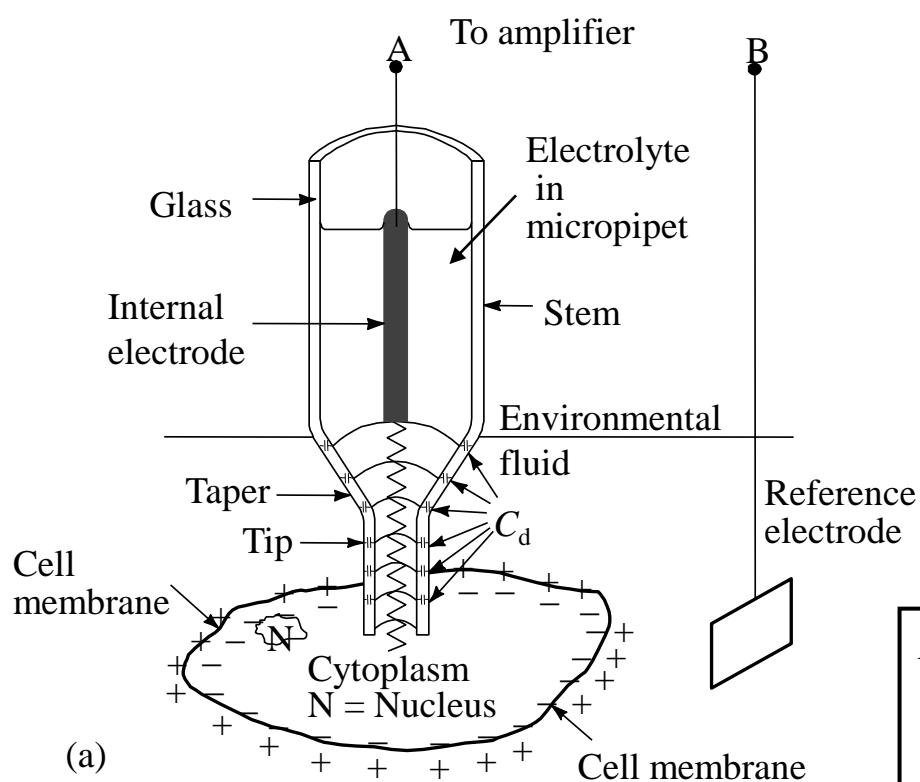
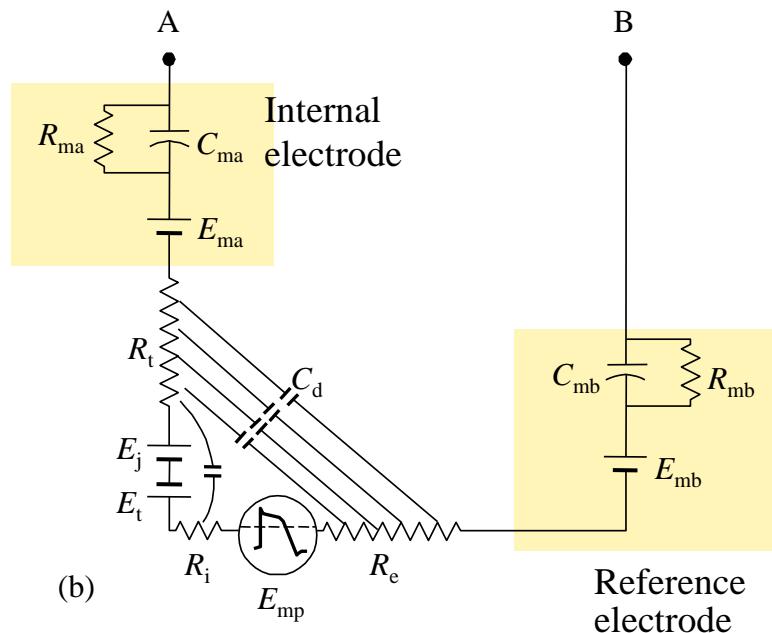


Figure 5.22
(a) Electrode with its tip placed within a cell, showing the origin of distributed capacitance.
(b) Equivalent circuit.



R_t = electrolyte resistance in shank & tip

C_d = capacitance from micropipet electrolyte to environmental fluid

E_j = liquid-liquid junction potential between micropipet electrolyte & intracellular fluid

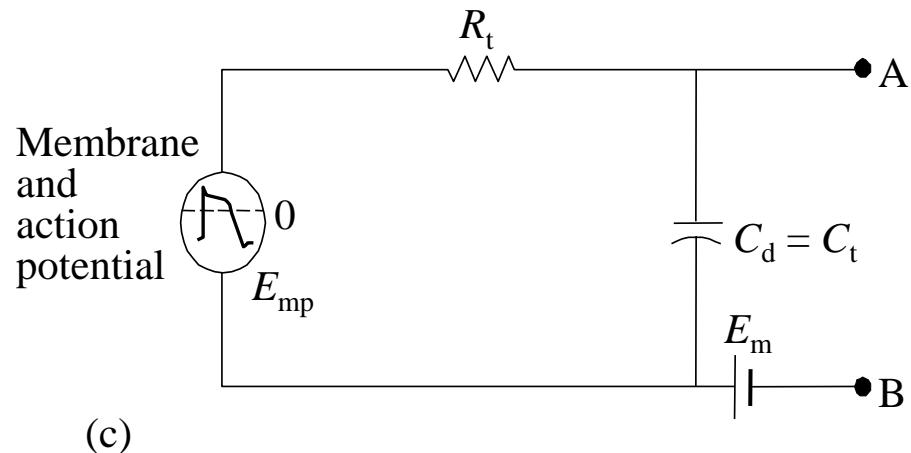
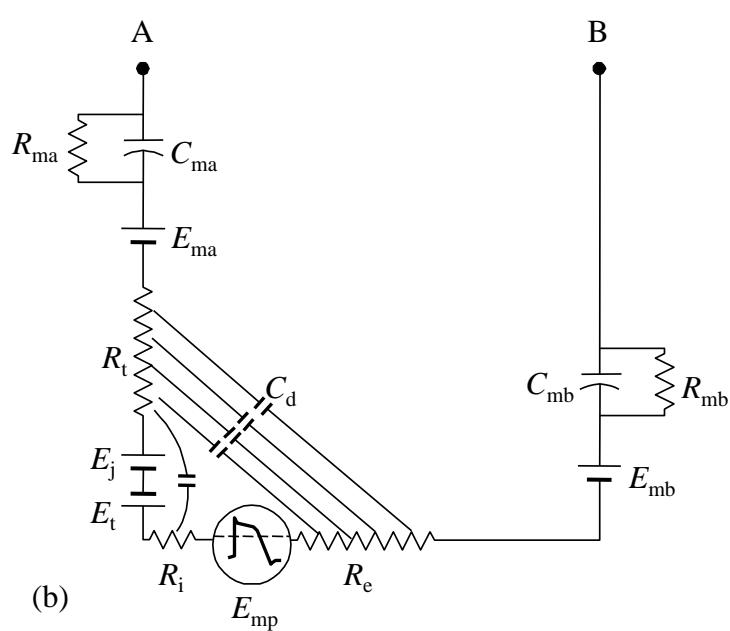
E_t = tip potential generated by the thin glass membrane at micropipet tip

R_i = intracellular fluid resistance

E_{mp} = cell membrane potential

R_e = extracellular fluid resistance

Glass Micropipet



$$E_m = E_j + E_t + E_{ma} - E_{mb}$$

R_t = all the series resistance lumped together
(ranges from 1 to 100 MΩ)

C_t = total distributed capacitance lumped
together (total is tens of pF)

E_m = all the dc potentials lumped together

Behaves like a low-pass filter.

Figure 5.22
(b) Equivalent circuit.
(c) Simplified equivalent circuit.

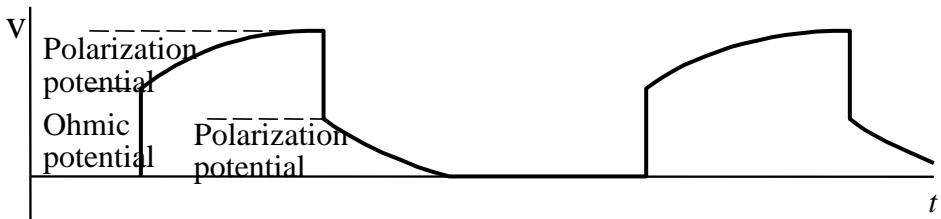
Stimulating Electrodes

Figure 5.23

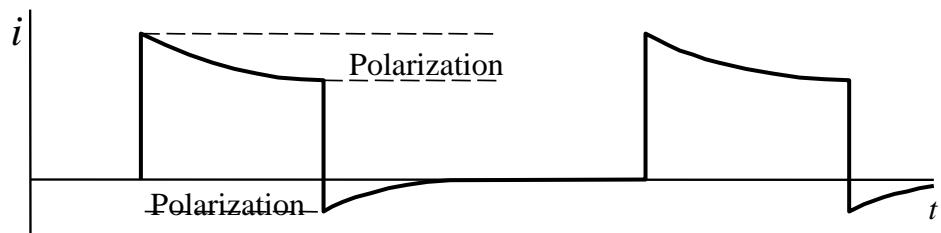
(a) Constant-current stimulation

(b) Constant-voltage stimulation

Charge transfer characteristics of the electrode are very important. Platinum black and Iridium oxide are very good stimulating electrode materials.



(a)



(b)

Practical Hints in Using Electrodes

- **Ensure that all parts of a metal electrode that will touch the electrolyte are made of the same metal.**
 - Dissimilar metals have different half-cell potentials making an electrically unstable, noisy junction.
 - If the lead wire is a different metal, be sure that it is well insulated.
 - Do not let a solder junction touch the electrolyte. If the junction must touch the electrolyte, fabricate the junction by welding or mechanical clamping or crimping.
- **For differential measurements, use the same material for each electrode.**
 - If the half-cell potentials are nearly equal, they will cancel and minimize the saturation effects of high-gain, dc coupled amplifiers.
- **Electrodes attached to the skin frequently fall off.**
 - Use very flexible lead wires arranged in a manner to minimize the force exerted on the electrode.
 - Tape the flexible wire to the skin a short distance from the electrode, making this a stress-relief point.

Practical Hints in Using Electrodes

- **A common failure point in the site at which the lead wire is attached to the electrode.**
 - Repeated flexing can break the wire inside its insulation.
 - Provide strain relief by creating a gradual mechanical transition between the wire and the electrode.
 - Use a tapered region of insulation that gradually increases in diameter from that of the wire towards that of the electrode as one gets closer and closer to the electrode.
- **Match the lead-wire insulation to the specific application.**
 - If the lead wires and their junctions to the electrode are soaked in extracellular fluid or a cleaning solution for long periods of time, water and other solvents can penetrate the polymeric coating and reduce the effective resistance, making the lead wire become part of the electrode.
 - Such an electrode captures other signals introducing unwanted noise.
- **Match your amplifier design to the signal source.**
 - Be sure that your amplifier circuit has an input impedance that is much greater than the source impedance of the electrodes.

Biomedical Instrumentation

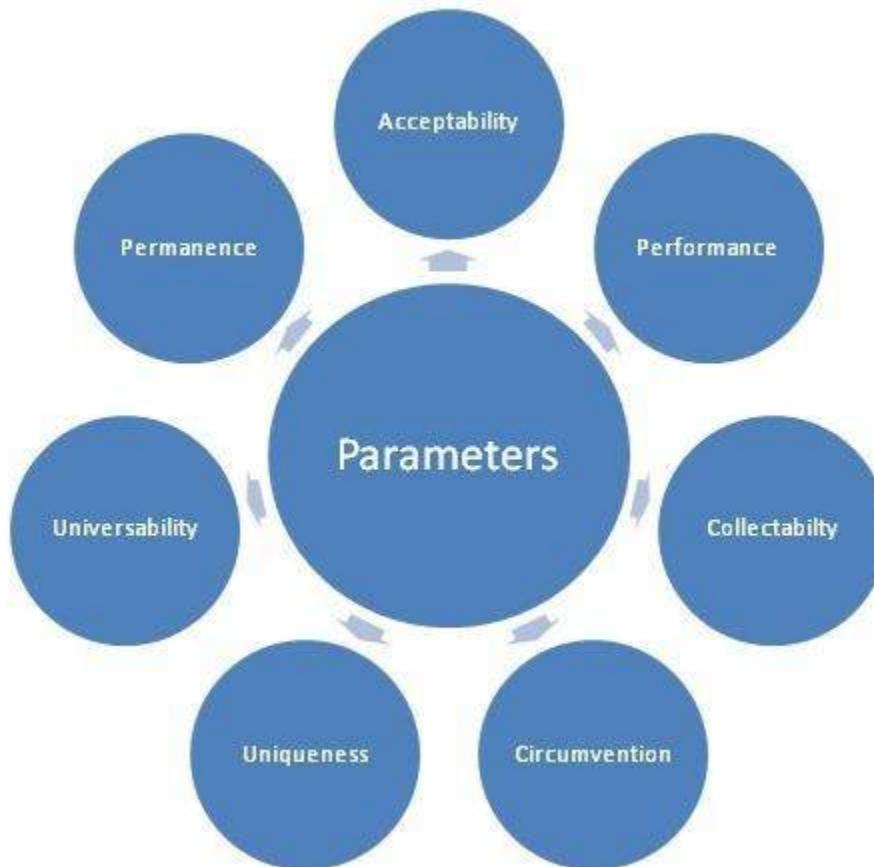
Biomedical Engineer: person working in research , Development in the interface area of medicine

Clinical Engineer: Practitioner working with physician and patient

Biomedical instrumentation: Method of measurements within the field. It provides tools by which measurement can be achieved

Biometrics: Metrics measurements, Bio- physiological variables and parameters

Basic Criteria for Biometrics Security System



Continued

- **Uniqueness:** It will indicate how differently and uniquely the biometric system will be able to recognize each user among groups of users.
- **Universality:** This parameter indicates requirements for unique characteristics of each person in the world
- **Permanence:** It needs to be constant for a certain period of time period, This parameter will mostly be affected by the age of the user.
- **Collectability:** It requires the collection of each characteristic and trait by the system in order to verify their identification
- **Performance:** The accuracy and robustness are main factors for the biometric security system. These factors will decide the performance of the biometric security system.
- **Acceptability:** It will choose fields in which biometric technologies are acceptable
- **Circumvention:** It will decide how easily each characteristic and trait provided by the user can lead to failure during the verification process.

Advantages of biometrics security system



FINGERPRINTS

- 5-9 Second Processing Time
- Commonly Used in Border Management
- Also Used in Law Enforcement



FACIAL RECOGNITION

- Non-invasive Collection
- Currently Used for Passports and National ID Documents



IRIS

- Low False Acceptance Rates
- Difficult to Replicate
- Two Second Processing Time



DNA

- Establishes Familial Relationship
- Commonly Used in Law Enforcement
- Highly Unique/ Impossible to Replicate



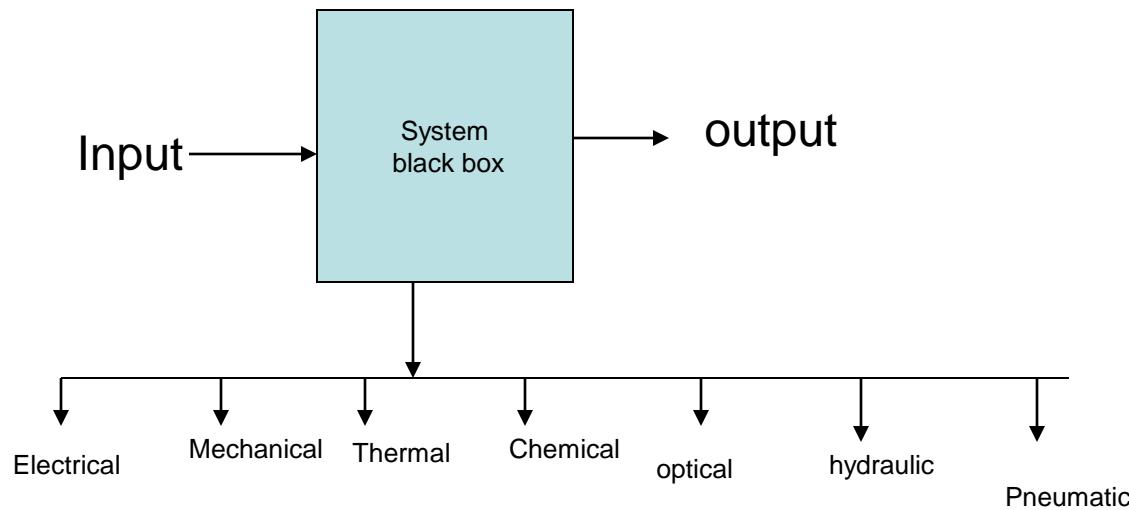
Design of biomedical Instrumentation

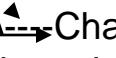
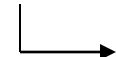
- **Range:** Input amplitude and frequency
- **Sensitivity:** Instrument determine how small variation of variable, determine resolution of the device
- **Linearity:** Ratio of change in output to input
- **Hysteresis:** Measurements ascending- [----- Difference-----] descending orders
- **Frequency response:** Variation in sensitivity over which the frequency of the measurement System should be able to respond rapidly enough to reproduce all frequency components of the waveforms with equal sensitivity.
- **Accuracy:** Measure of systemic error
 - Tolerance of electronic components
 - Mechanical error
 - Component error due to drift
 - Poor frequency response, reading error

- **Signal to noise ratio:** As high as possible ,power line frequency noise, interference due to electromagnetic, electrostatic field
- **Stability:** Ability of the system to resume a steady state condition following a disturbance at the input
- **Isolation:** Instrument dose not produce a direct electrical connection between subject and ground
- **Simplicity**

Man instrument system

- System which includes both the human organism and the instrumentation required for measurement of human is called the man instrument system



- **The biochemical system:** food, water, air incorporates an efficient waste disposal system
- **The cardiovascular system:**
 - Hydraulic system –Four chamber pumps (heart)
elastic tubing (blood vessels)
 - Part of the system– arteries
 - Reservoirs—veins  Change their volume and characteristics to satisfy certain control requirements
 - Hydraulics resistances (Vasoconstrictors, vasodilators)
 -  Continually alters the pattern of fluid flow

- **Pump-: (Atrium)** ---- collect fluid (blood) pumps in to 2nd stage (ventricles)
- **Two stage pumps (right side pumps)**--- pumps it through an oxygenation system (the lungs)
- **Left side of heart** --- Receives blood from oxygenation system and pumps it into the main hydraulic system
- **Speed of pump** ---Heart rate
- **Stroke volume**---- effeciency

The respiratory system---Pneumatic system

Air pump : Diaphragm creates +ve and –ve pressure in sealed chamber (thoracic cavity) due to that air stucked into and forced out of elastic bags(lungs) connection

Bags--- nasal cavities,

Respiratory center of the heart :

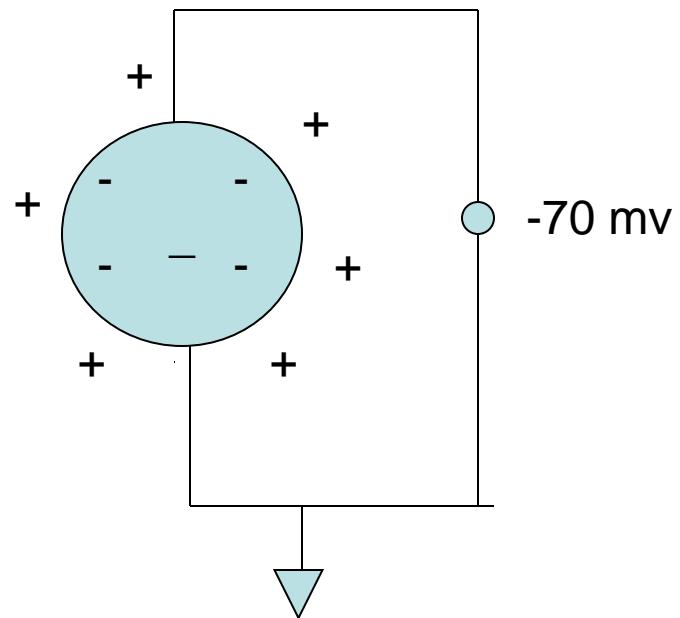
Maintain pump operation at a speed that is adequate to supply oxygen and carry off CO₂

The nervous system: Communication network system

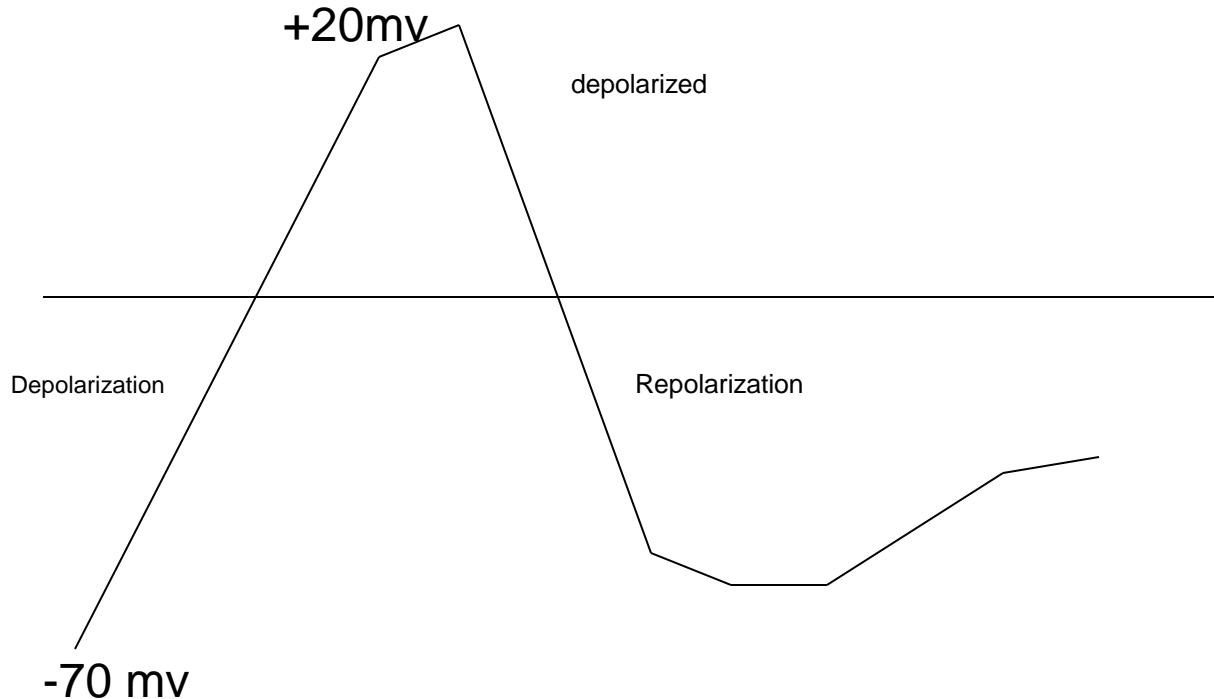
- The nervous system— Communication network system

sources of bioelectric potential —Ionic voltages produced due to electrochemical activity of certain special types of cells

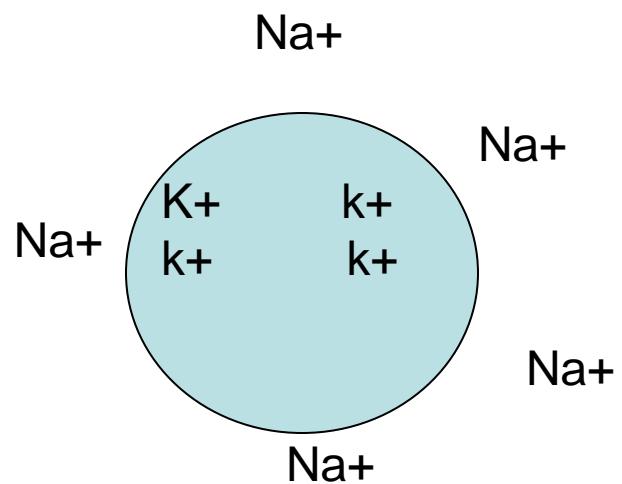
Body fluid – conductive solution contains charged atoms ka+
 Na^+ (Cl^-)



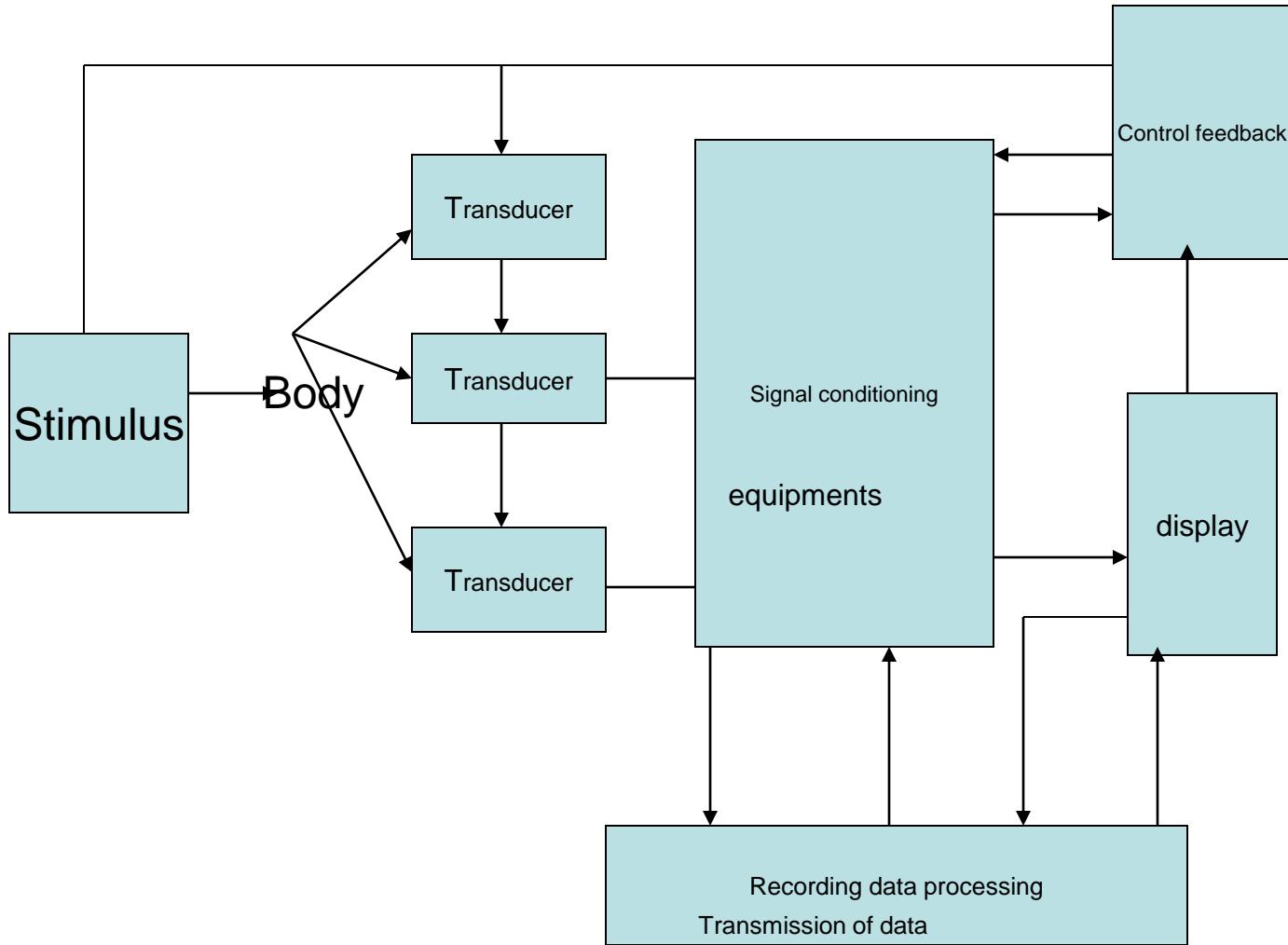
- Action potential



- Action potential +20 mv Depolarized



The man instrument system



- **Components of the man- instrument system**

Subject: Human body is the subject on which measurement is performed

Stimulus: Direct electrical stimulation of some part of the nervous system

The transducer

Signal- conditioning equipments

Display equipment

Recording, data processing and transmission equipment

Man Instrument System(Difficulties)

- Safety Consideration
- The environment of the hospital in which the measurement are performed
- The medical personnel usually involved in the measurement
- Occasionally even ethical and legal consideration

Objectives of the instrumentation

- **Information gathering**
- **Diagnosis**
- **Evaluation- proof- of – performance or quality control tests**
- **Control**

Biomedical Instrumentation:

Clinical Instrumentation-----Diagnosis purpose

Research Instrumentation-----New knowledge pertaining to the various system

Measurements:

- a. Vivo measurement: Internal measurement
- b. Vitro measurement: External measurement

Problems encountered in measuring a living system

- **In accessibility of variables to measurement**
- **Variability of the data**
- **Lack of knowledge about interrelationships**
- **Interaction among physiological system**
- **Effect of the transducer on the measurement**
- **Artifacts**
- **Energy limitation**
- **Safety consideration**