UCONN
UNIVERSITY OF CONNECTICUT

Introduction to Biopotentials Part I

ENGR 1166 Biomedical Engineering

An intuition of “biopotentials”

Source: *http://www.youtube.com/watch?v=8lFoUWb8kLQ&playnext=1&list=PL6D9E1BD5963BBF0C&feature=results_main*

Biopotentials

- An electric **voltage** that is measured between points in a living cell, tissue, or organism, and which accompanies all biochemical processes

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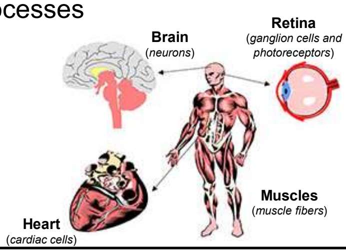
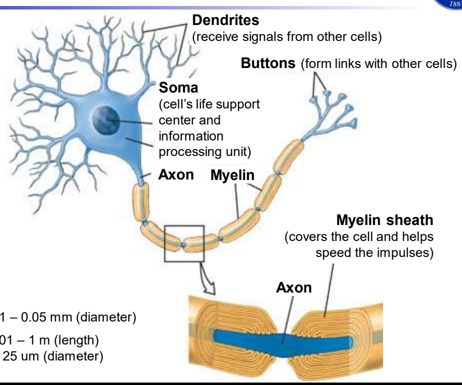
- An electric **voltage** that is measured between points in a living cell, tissue, or organism, and which accompanies all biochemical processes
- Biopotentials allows organs and muscles to communicate with each other



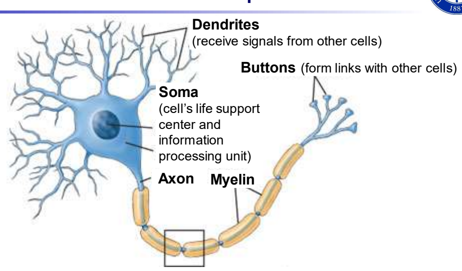
Mechanisms behind biopotentials



Soma: 0.01 – 0.05 mm (diameter)

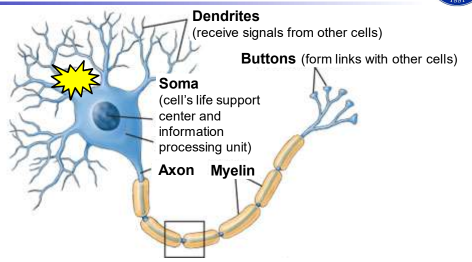
Axon: 0.001 – 1 m (length)
1 – 25 um (diameter)

Mechanisms behind biopotentials



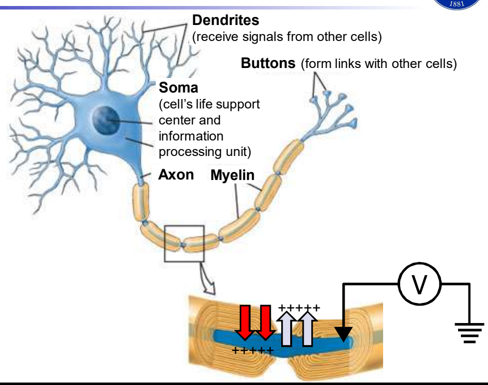
Biopotentials are due to the occurrence of one or more electrical impulses (**action potentials**) at the level of single cells

Mechanisms behind biopotentials

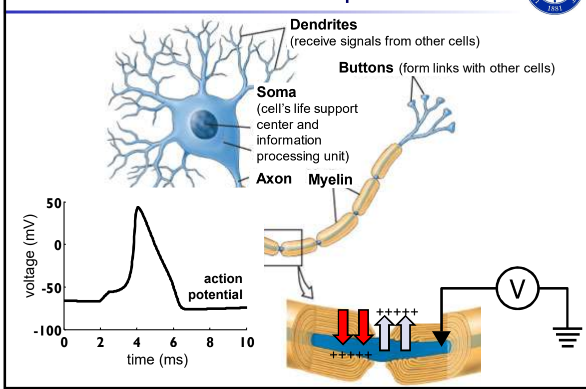


An **action potential** stems from ions moving across the membrane and travels down from the soma to the axon and buttons

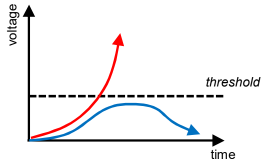
Mechanisms behind biopotentials



Mechanisms behind biopotentials

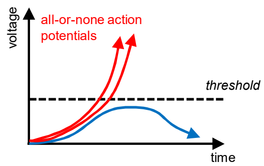


Features of an action potential



- **Threshold**
  The net excitation that a excitable cell receives must exceed a minimum intensity to generate an action potential

Features of an action potential



- **Threshold**
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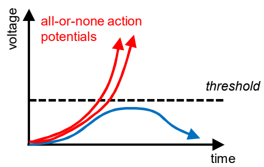
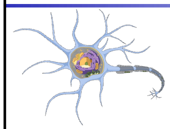
- **All-or-none response**
  An excitable cell responds to stimuli of increasing intensity by spiking more, but strength and speed of action potentials remain the same

Features of an action potential



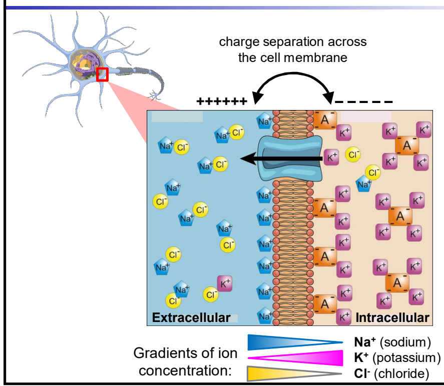
- **Threshold**
  The net excitation that a excitable cell receives must exceed a minimum intensity to generate an action potential
- **All-or-none response**
  An excitable cell responds to stimuli of increasing intensity by spiking more, but strength and speed of action potentials remain the same
- **Intensity**
  The shape of an action potential does not change along the cell's axon

Ionic concentrations and channels



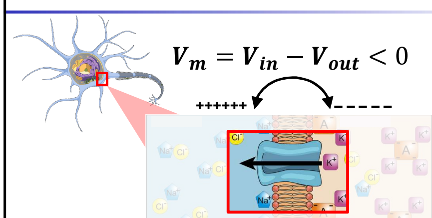
To understand the mechanisms of an action potential let us first look at what happens across the cell's membrane

Ionic concentrations and channels

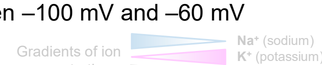


Ionic concentrations and channels

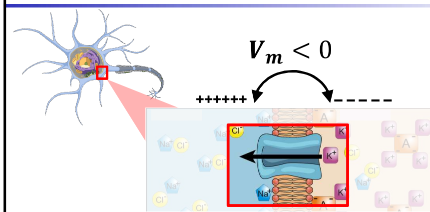
$$V_m = V_{in} - V_{out} < 0$$



- ❑ The inside of a cell is always more negative than the outside
- ❑ The transmembrane voltage V_m at rest is typically between –100 mV and –60 mV



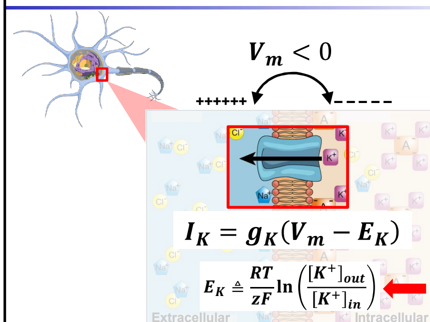
Ionic concentrations and channels



- ❑ Potassium (K^+) ion concentration is 30-50 times higher inside as compared to outside
- ❑ Across the membrane there are channels that let pass potassium ions only (**ion-specific channels**)

Gradients of ion concentration: Na^+ (sodium), K^+ (potassium), Cl^- (chloride)

Ionic concentrations and channels



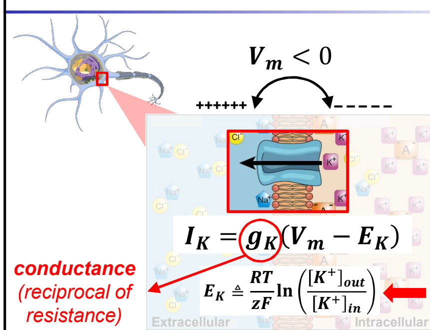
$$I_K = g_K(V_m - E_K)$$

$$E_K \triangleq \frac{RT}{zF}\ln\left(\frac{[K^+]_{out}}{[K^+]_{in}}\right)$$

Nernst equilibrium (channels are ion-specific)

$z \triangleq$ ion valence
$F \triangleq$ Faraday's constant
$R \triangleq$ universal gas constant
$T \triangleq$ temperature (in ºK)

Ionic concentrations and channels



$$I_K = g_K(V_m - E_K)$$

conductance *(reciprocal of resistance)*

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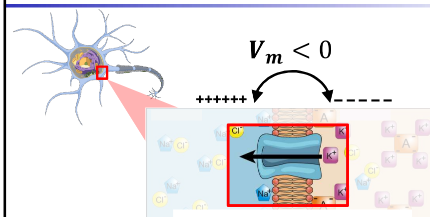
Ionic concentrations and channels

$V_m < 0$



$$I_K = g_K(V_m - E_K)$$

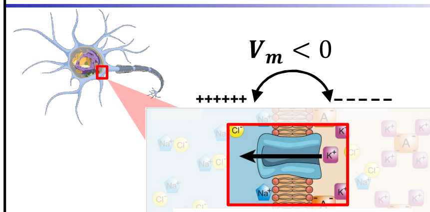
$$E_K \triangleq \frac{RT}{zF}\ln\left(\frac{[K^+]_{out}}{[K^+]_{in}}\right)$$

Nernst equilibrium
(channels are ion-specific)

$z = 1$ $F = 9.65\times104$ C mol^{-1} $R = 8.31$ J K^{-1} mol^{-1} $T = 37$ ºC $\cong 310$ ºK $[K^+]_{out} = 5$ mM $[K^+]_{in} = 155$ mM

Ionic concentrations and channels

$V_m < 0$



$$I_K = g_K(V_m - E_K)$$

$$E_K \cong -91.7\ \mathrm{mV}$$

Nernst equilibrium
(channels are ion-specific)

$z = 1$ $F = 9.65\times104$ C mol^{-1} $R = 8.31$ J K^{-1} mol^{-1} $T = 37$ ºC $\cong 310$ ºK $[K^+]_{out} = 5$ mM $[K^+]_{in} = 155$ mM

Ionic concentrations and channels

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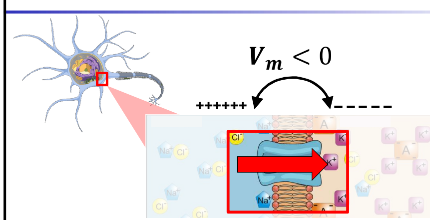
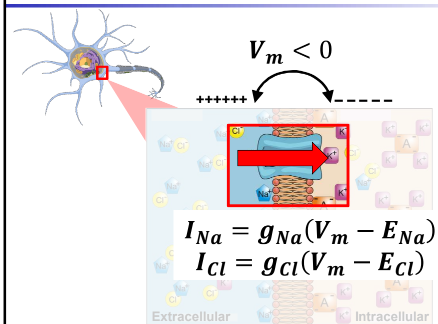


- There are other channels across the membrane that let pass only sodium (Na^+) or chloride (Cl^-) ions
- Because of the concentration gradient, the flow of Na^+ and Cl^- ions is opposite to the flow of K^+ ions

concentration: Cl^- (chloride)

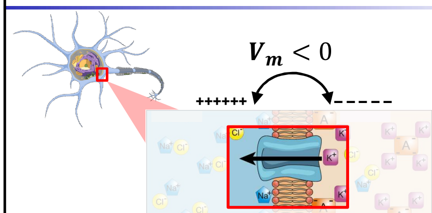
Ionic concentrations and channels



$$I_{Na} = g_{Na}(V_m - E_{Na})$$
$$I_{Cl} = g_{Cl}(V_m - E_{Cl})$$

$$E_{Na} = \frac{RT}{zF}\ln\left(\frac{[Na^+]_{out}}{[Na^+]_{in}}\right) \cong +69 \text{ mV} \qquad E_{Cl} = \frac{RT}{zF}\ln\left(\frac{[Cl^-]_{out}}{[Cl^-]_{in}}\right) \cong -91 \text{ mV}$$

Goldman-Hodgkin-Katz equilibrium



If nothing perturbs the cell, the sum of the ionic currents will eventually reaches zero (**equilibrium**). This happens when V_m reaches the value

$$V_m = E \stackrel{\text{def}}{=} \frac{RT}{F}\ln\left(\frac{p_K[K^+]_{out} + p_{Na}[Na^+]_{out} + p_{Cl}[Cl^-]_{in}}{p_K[K^+]_{in} + p_{Na}[Na^+]_{in} + p_{Cl}[Cl^-]_{out}}\right)$$

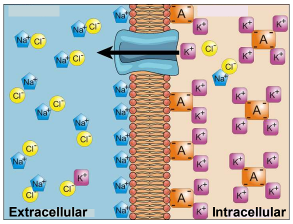
Goldman-Hodgkin-Katz equilibrium

$$V_m = E \stackrel{\text{def}}{=} \frac{RT}{F}\ln\left(\frac{p_K[K^+]_{out} + p_{Na}[Na^+]_{out} + p_{Cl}[Cl^-]_{in}}{p_K[K^+]_{in} + p_{Na}[Na^+]_{in} + p_{Cl}[Cl^-]_{out}}\right)$$

- ❑ E is called Goldman-Hodgkin-Katz (GHK) equilibrium. It is approximately –85 mV
- ❑ p_k, p_{Na}, and p_{Cl} are **permeability coefficients** and account for the ability of the cell's membrane to be crossed by potassium, sodium, and chloride ions, respectively

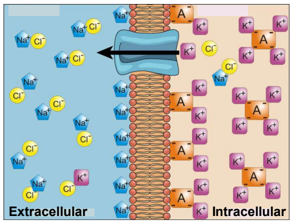
K-Na active pump

The fact that $I_{Na} + I_K + I_{Cl} = 0$ at GHK equilibrium does not mean that each ionic current is zero



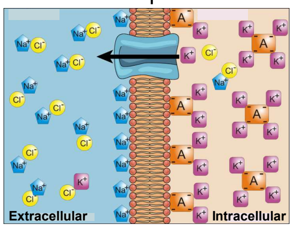
K-Na active pump

There is still a flow of Na^+, K^+, and Cl^- ions across the membrane due to concentration gradient



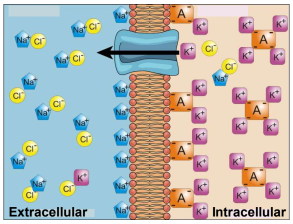
K-Na active pump

Because the amount of ions inside a cell is finite, this flow would change the concentrations and hence the GHK equilibrium



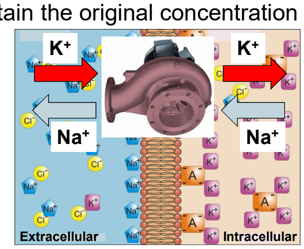
K-Na active pump

The GHK equilibrium remains stable, instead, because there are **active pumps** across membrane



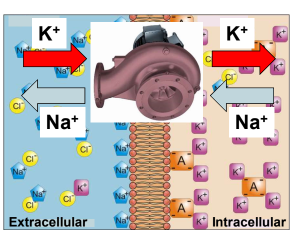
K-Na active pump

A pump is a channel that actively pushes K^+ ions inside the cell and Na^+ ions outside the cell to maintain the original concentration gradient



K-Na active pump

A pump pushes 2 K^+ ions inside the cell for every 3 Na^+ ions removed from the cell



K-Na active pump

A pump pushes 2 K^+ ions inside the cell for every 3 Na^+ ions removed from the cell

- Pumps change the electric balance between inside and outside until the concentrations of Na^+ and K^+ reach the original value again
- Pumps consume metabolic energy to perform this task

Note this…

$$I_{Na} = g_{Na}(V_m - E_{Na})$$
$$I_K = g_K(V_m - E_K)$$
$$I_{Cl} = g_{Cl}(V_m - E_{Cl})$$

$$V_m = I_{Na}/g_{Na} + E_{Na}$$
$$V_m = I_K/g_K + E_K$$
$$V_m = I_{Cl}/g_{Cl} + E_{Cl}$$

Note this…

$$I_{Na} = g_{Na}(V_m - E_{Na})$$
$$I_K = g_K(V_m - E_K)$$
$$I_{Cl} = g_{Cl}(V_m - E_{Cl})$$

$$V_m = R_{Na}I_{Na} + E_{Na}$$
$$V_m = R_K I_K + E_K$$
$$V_m = R_{Cl}I_{Cl} + E_{Cl}$$

Note this…

$$I_{Na} = g_{Na}(V_m - E_{Na})$$
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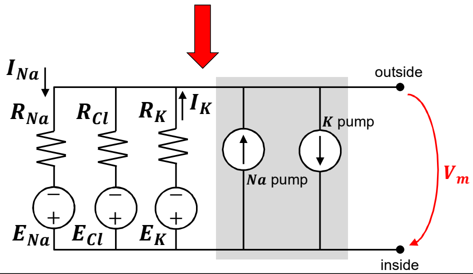
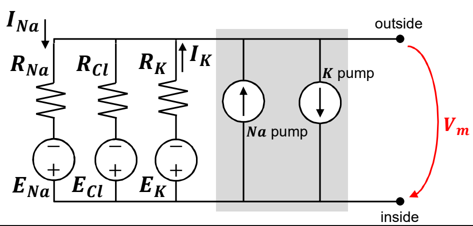


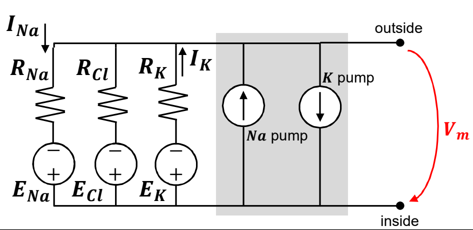
Note this…

The cell's membrane can be represented as a circuit and can be analyzed with tools we have learned!

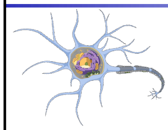


Note this…

We just need to remember that resistances R_{Na}, R_K, and R_{Cl} may vary with the voltage V_m i.e., **Ohm's law is not valid**



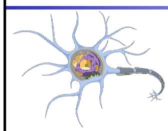
Origins of an action potential (AP)



Now we have enough tools to understand how an action potential begins.

Let us first introduce three technical words:

Origins of an action potential (AP)

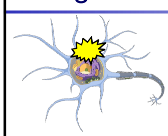


Now we have enough tools to understand how an action potential begins.

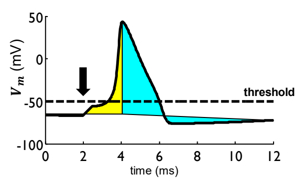
Let us first introduce three technical words:

- Because it is more negative inside the cell than outside, the cell's membrane is said **polarized**
- **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

Origins of an action potential (AP)



First, an action potential begins because chemical reactions occur at the dendrites and lead to a sudden increase of the voltage V_m across membrane



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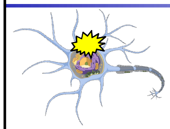
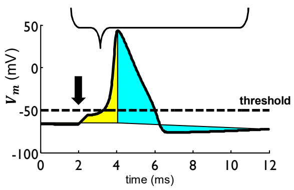


During the phase in yellow this cascade of events happens:

depolarization

decrease of R_{Na}



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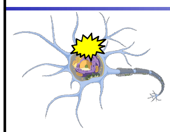
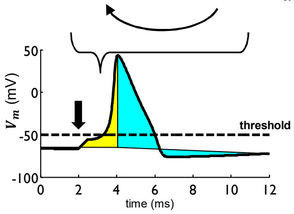


During the phase in yellow this cascade of events happens:

depolarization

Na^+ inflow

decrease of R_{Na}



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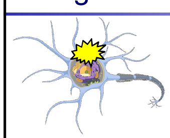

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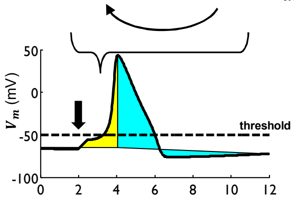
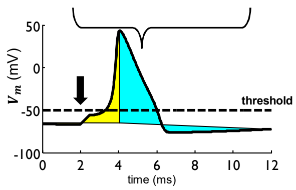


Origins of an action potential (AP)

During the phase in blue, a saturation has been reached and a new cascade of events starts:



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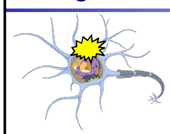
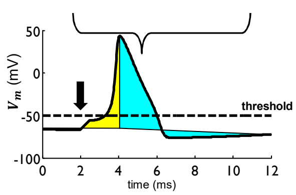


During the phase in blue, a saturation has been reached and a new cascade of events starts:

K^+ outflow → hyperpolarization



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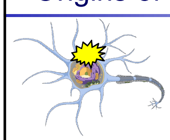
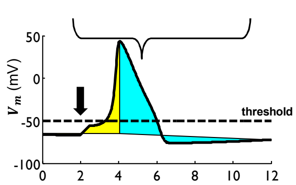


During the phase in blue, a saturation has been reached and a new cascade of events starts:

K^+ outflow → hyperpolarization → decrease of R_K



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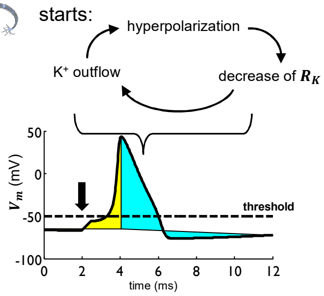
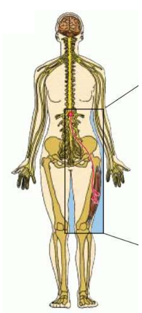


From APs to muscle contraction



- ❑ Action potentials are transmitted from one neuron to one another from the brain down the spinal cord until they activate **motoneurons**

Picture from: *Neuroscience*. 2nd edition. Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001

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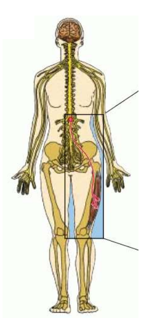
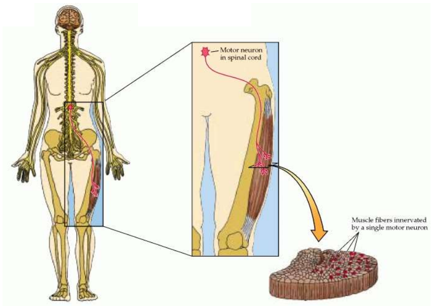


- ❑ Action potentials are transmitted from one neuron to one another from the brain down the spinal cord until they activate **motoneurons**
- ❑ A **motoneuron** is a neuron that has the soma in the spinal cord and innervates 10 to 2,000 muscle fibers

Picture from: *Neuroscience*. 2nd edition. Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001

From APs to muscle contraction



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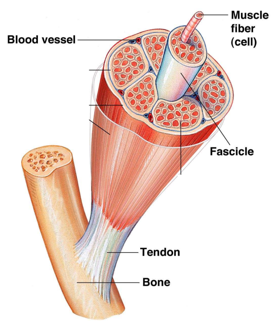

- A muscle fiber is a cell that converts an action potential in a mechanical contraction

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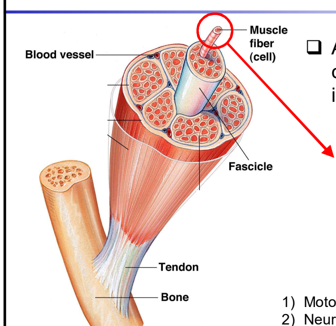

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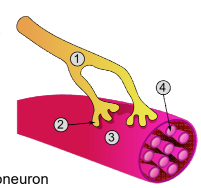
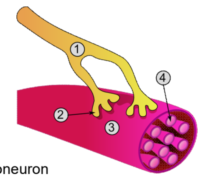


1) Motoneuron
2) Neuro-muscular junction
3) Muscle fiber
4) Tubular filaments that are contracted because of the action potential

Electromyogram (EMG)

- EMG measures the electric potential outside the muscle fibers innervated by one or more motoneurons



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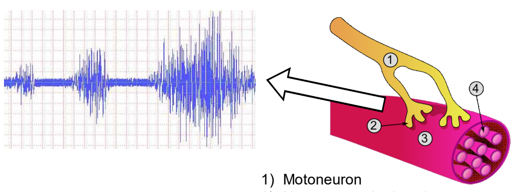

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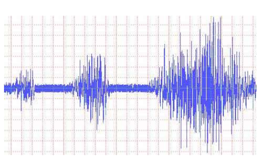

- Voltage amplitude:
  1 – 10 mV
- Frequency bandwidth:
  20 – 2000 Hz
- Electrodes are always connected close to the muscle being measured
- Applications: Muscle function; Neuromuscular disease; Prosthesis