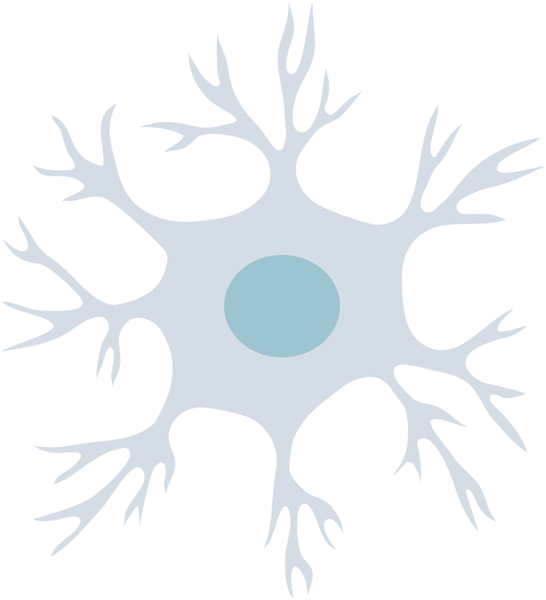

Electrical Properties of Body

Pouya Taghipour

Dr. Malikeh Nabaei

Spring 2024

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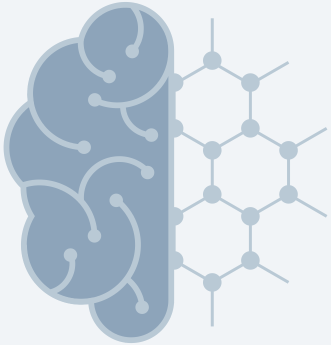
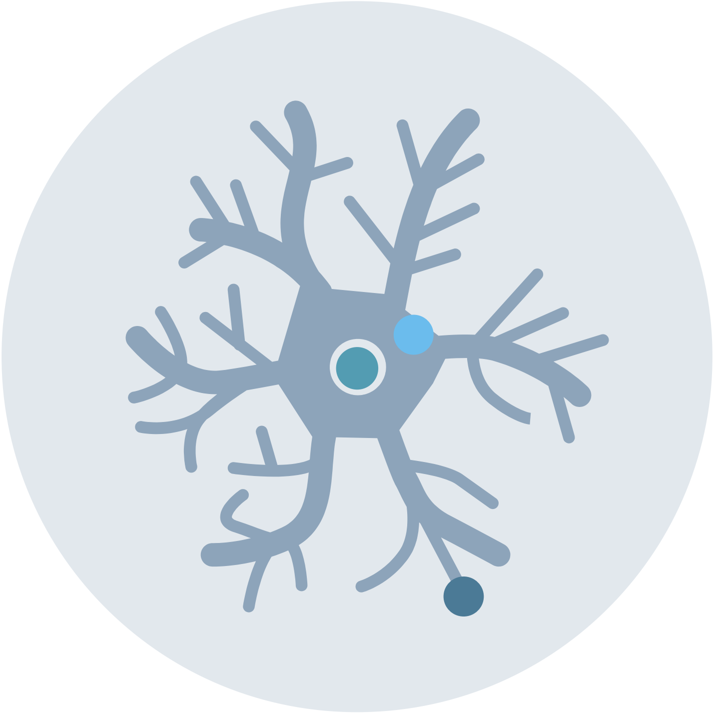
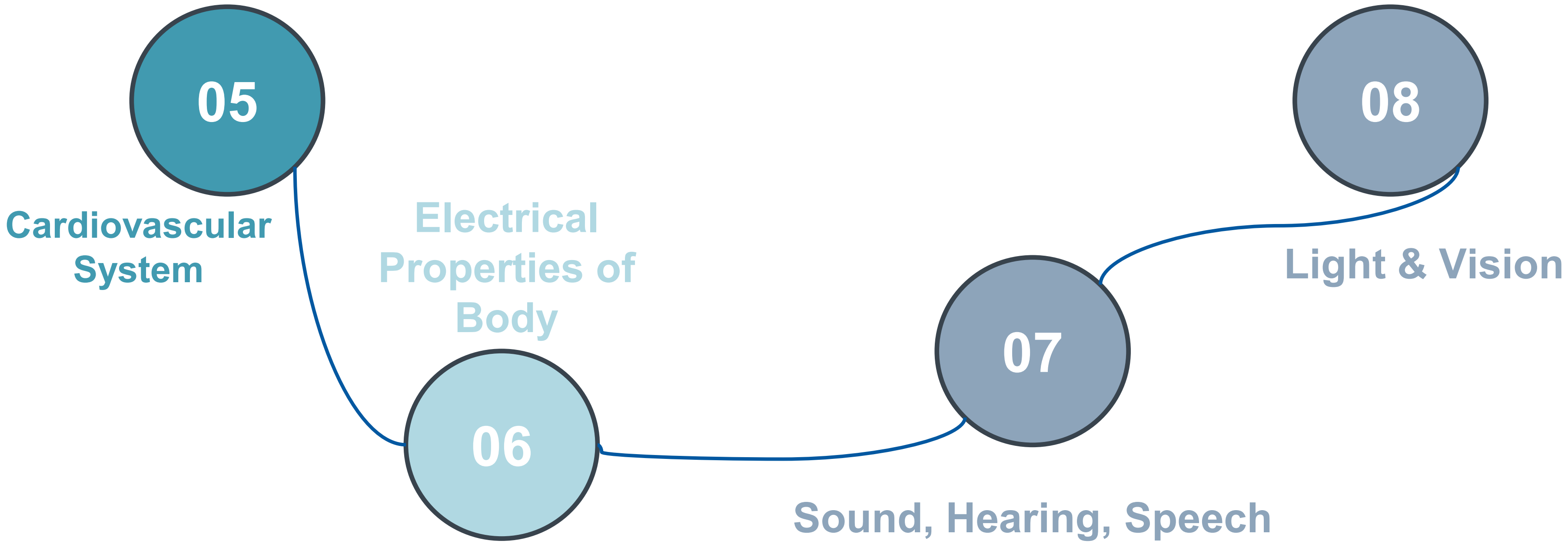


01

Overview

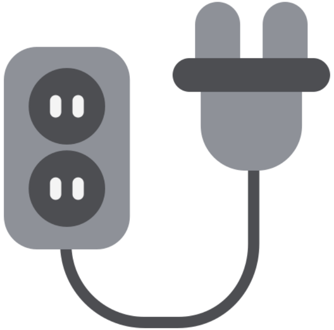


Final Exam


05
Cardiovascular System
06
Electrical Properties of Body
07
Sound, Hearing, Speech
08
Light & Vision

Introduction

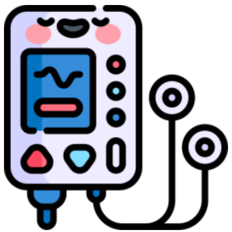
Chapter 12



Charge movement, electric fields, and voltages play essential roles in the body. The driving forces that induce such charge motion are complicated chemical and biological processes that are only partially understood. The interplay of the resulting charges and fields is physical in nature and is well understood. We have addressed the importance of electricity in the body only briefly in previous chapters. In Chap. 3 we examined the electromyograms (EMGs) of muscle activity, in Chap. 5 we saw that muscles are activated by electrical stimuli and the release of Ca2+ ions, and in Chap. 8 we learned that the polarization and depolarization of cell membranes in the heart provide the signals for electrocardiograms (EKGs, ECGs). We now discuss such electrical interactions in more depth as we focus on the electrical properties of the body, the propagation of electrical signals in the axons of nerves, and electrical potentials in the body.

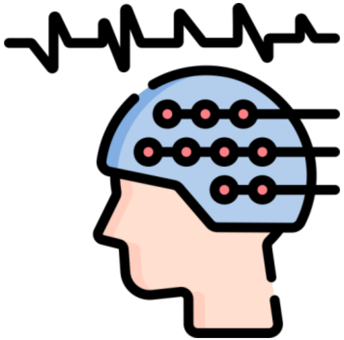
The most important signals in human body

EMG



ECG

EEG

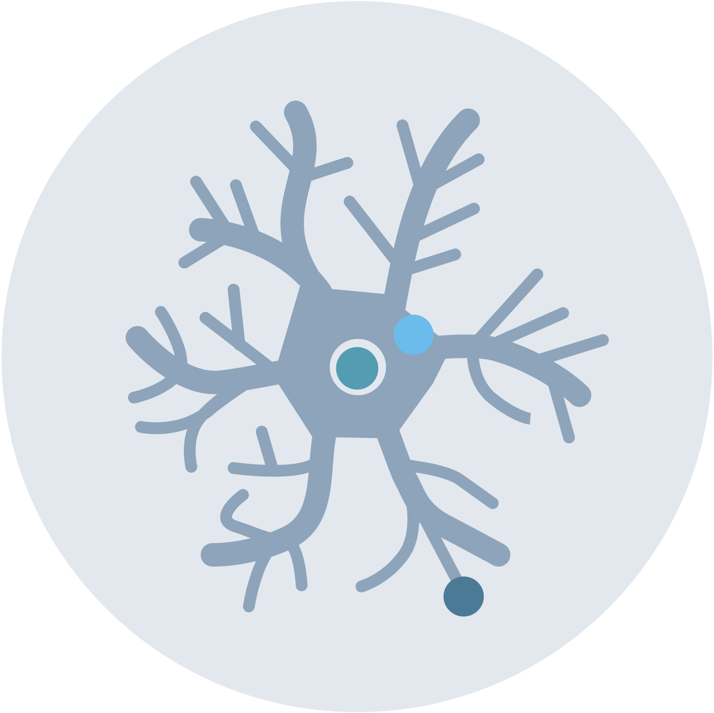


“Let the future tell the truth and evaluate each one according to his work and accomplishments. The present is theirs; the future, for which I have really worked, is mine.”

_Nikola Tesla

02

Generals



General rules and laws

Coulomb Law:

$$E = \frac{kq}{r^2}\hat{r}$$

The potential of that charge is:

$$V = \frac{kq}{r}$$

The potential difference between two points caused by a field is:

$$\Delta V = V_b - V_a = -\int_{r_a}^{r_b} E.dr$$

We can conclude:

$$E = -\nabla V \ or\ in\ one\ dimention\ E = -\frac{dV}{dx}$$

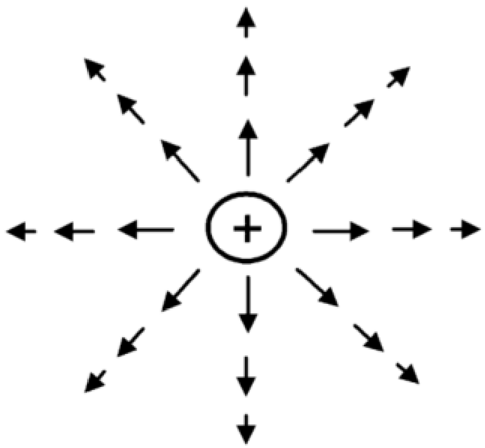
If there are two charges q and −q in vacuum in distance d:

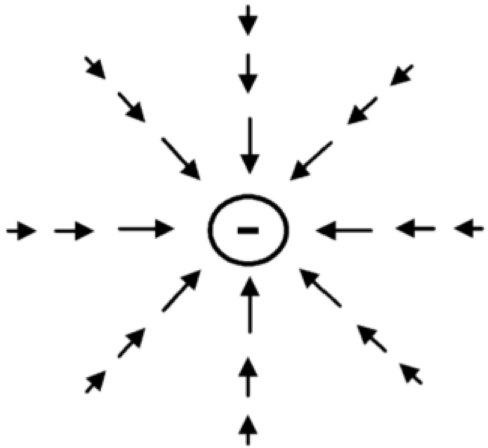
$$V = \frac{kP.r}{r^3}$$

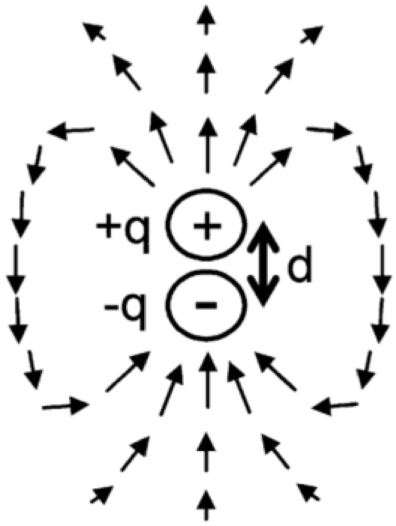
Considering the angle between P and distance vector r is θ:

$$V = \frac{kPcos\theta}{r^2}$$

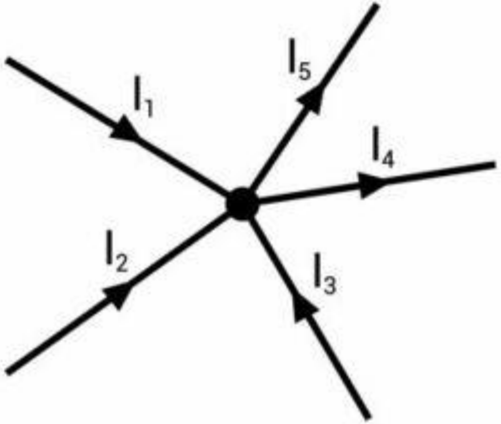
Electric Field





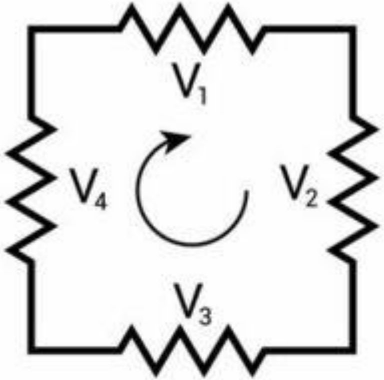


kirchhoff's current law



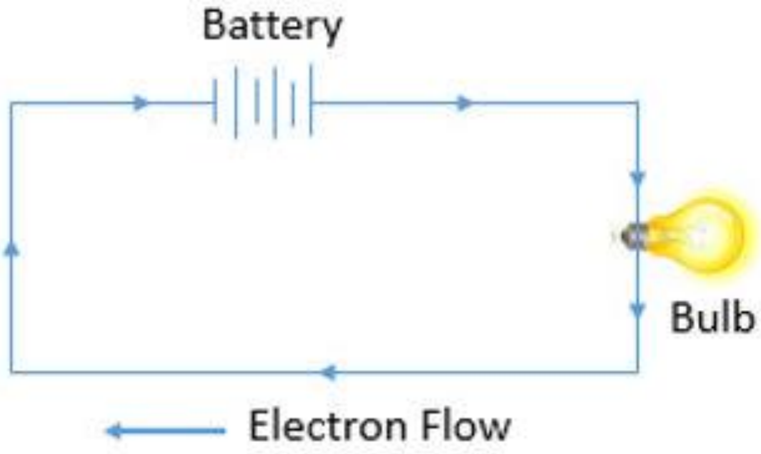
$$I_1 + I_2 + I_3 = I_4 + I_5$$

kirchhoff's voltage law



$$V_1 + V_2 + V_3 + V_4 = 0$$

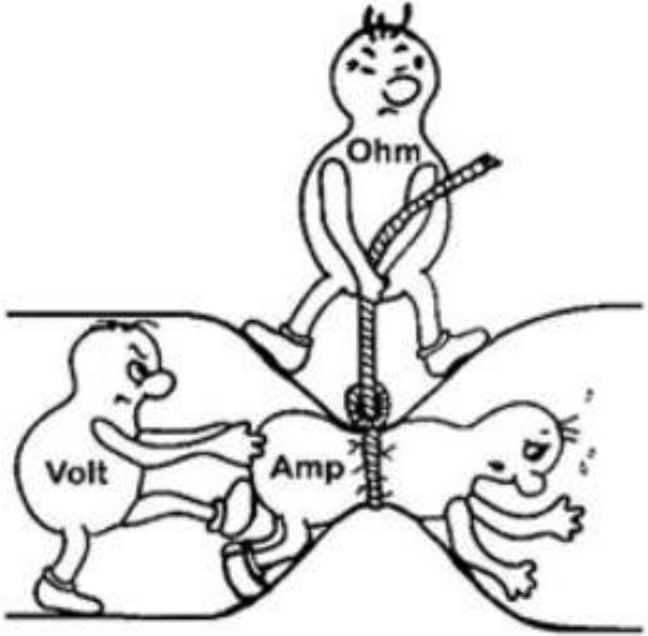
Ohm's Law

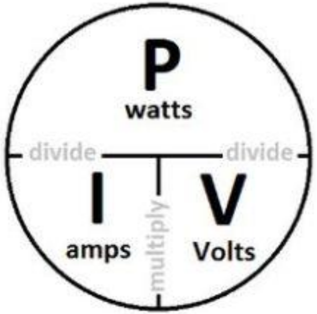


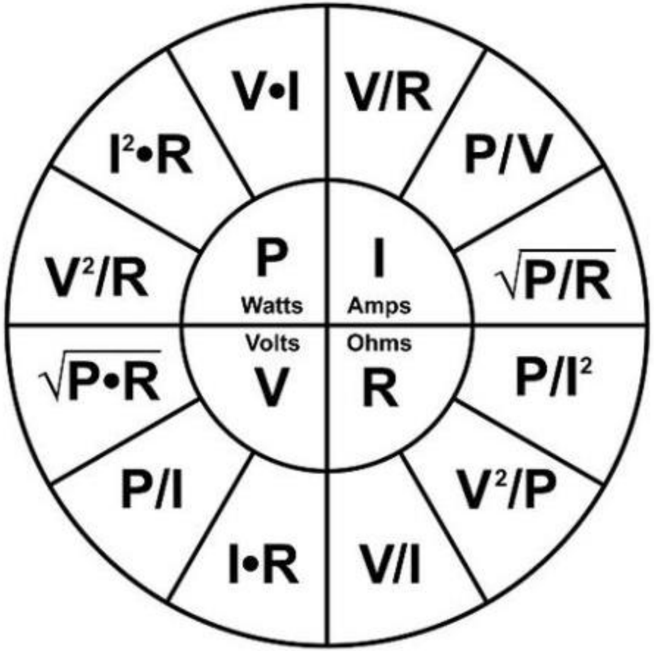
Resistance (R) = Bulb

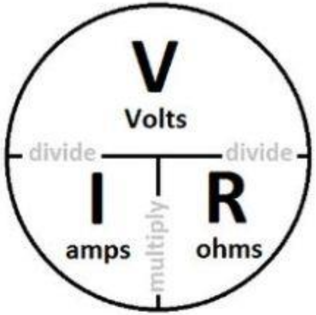
Current (I) = Flow of Electron

Voltage (V) = Battery




P
watts
divide
divide
I
amps
multiply
V
Volts


V•I
V/R
I²•R
P/V
V²/R
√P/R
P
Watts
I
Amps
Volts
V
Ohms
R
√P•R
P/I²
P/I
V²/P
I•R
V/I


V
Volts
divide
divide
I
amps
multiply
R
ohms

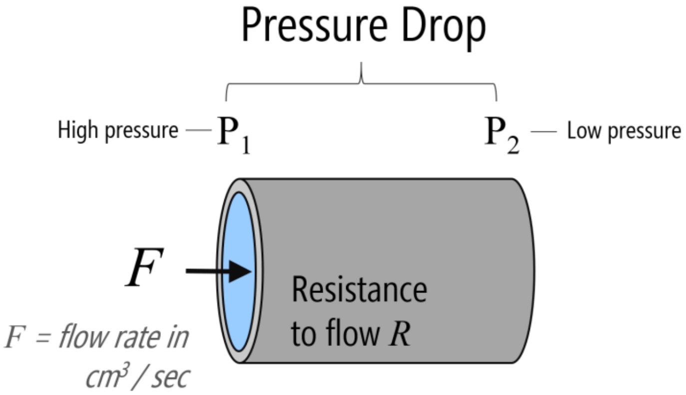
POISEUILLE'S LAW AND OHM'S LAW

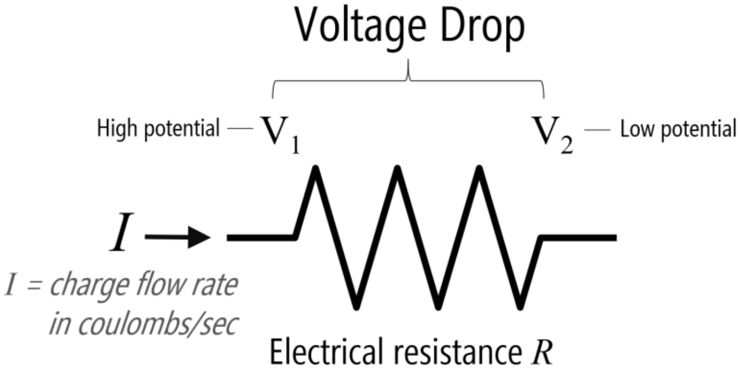
Poiseuille's Law for smooth flow (laminar flow) of fluids

circa ~1838

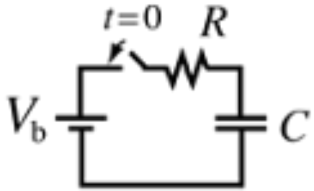
Ohm's Law for electric circuits

circa ~1825





$$Flow\ F = \frac{P_1 - P_2}{R} \quad \Leftrightarrow \quad Current\ I = \frac{V_1 - V_2}{R}$$



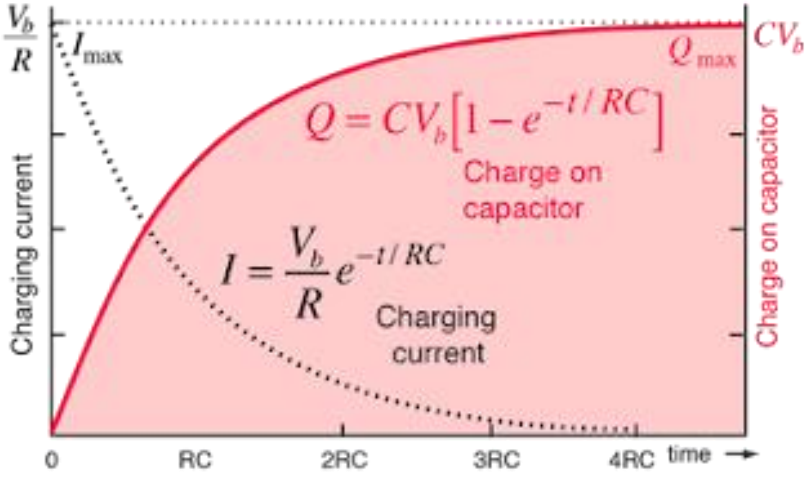
$$V_b = V_R + V_C$$

$$V_b = IR + \frac{Q}{C}$$

As charging progresses,

$$V_b = IR + \frac{Q}{C}$$

current decreases and charge increases.



At $t = 0$

$Q = 0$

$V_C = 0$

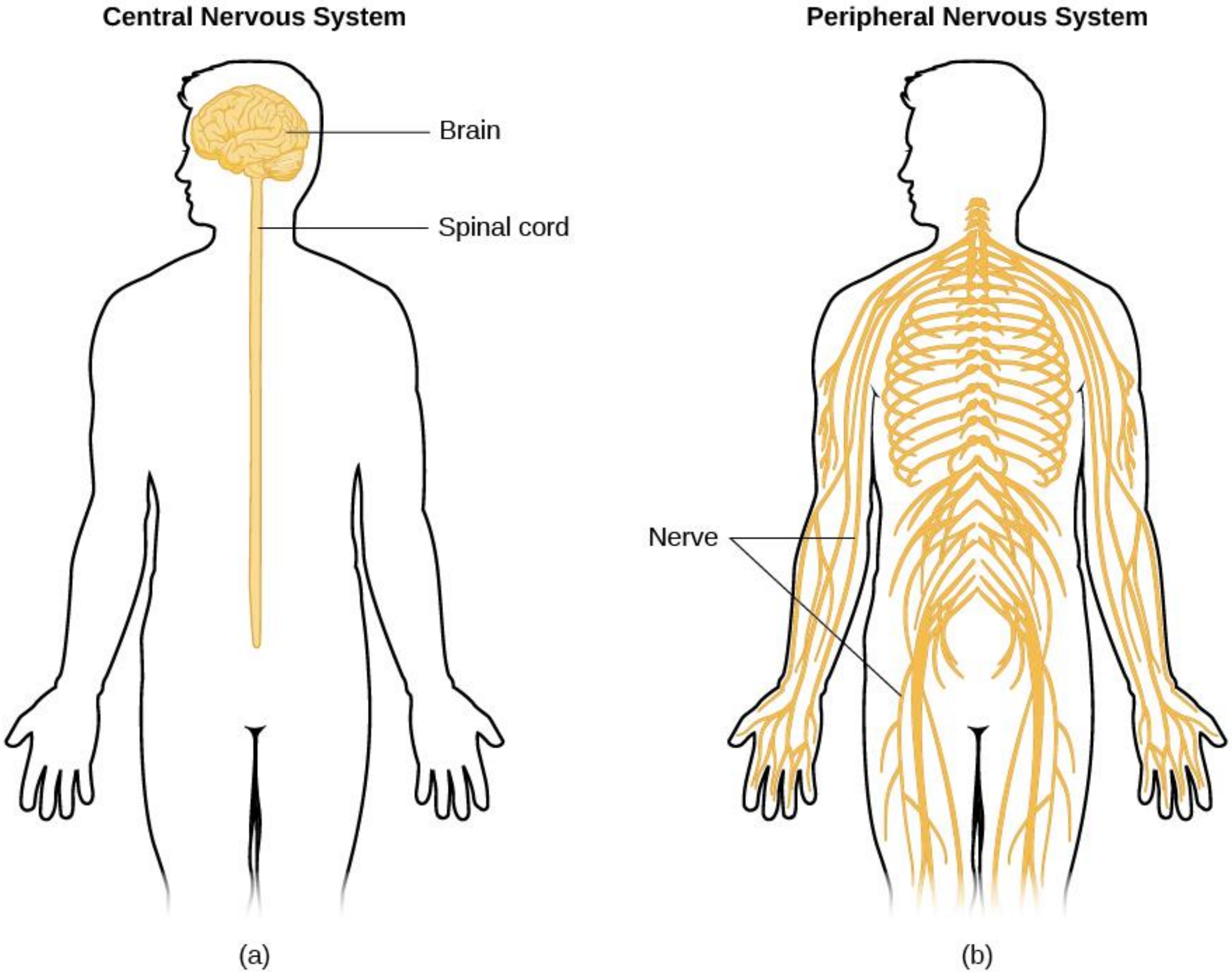
$I = \frac{V_b}{R}$

As $t \to \infty$

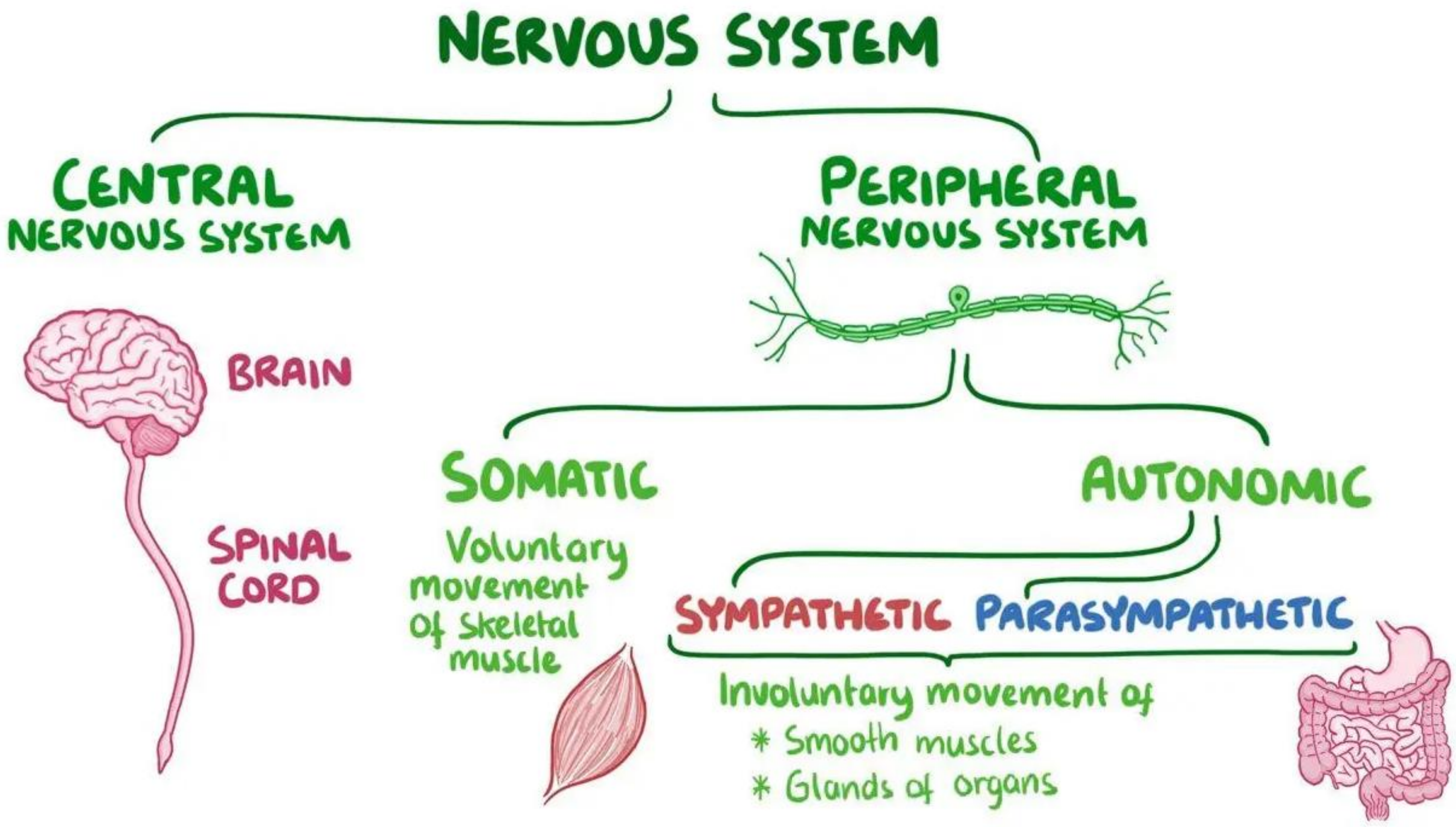
$Q \to CV_b$

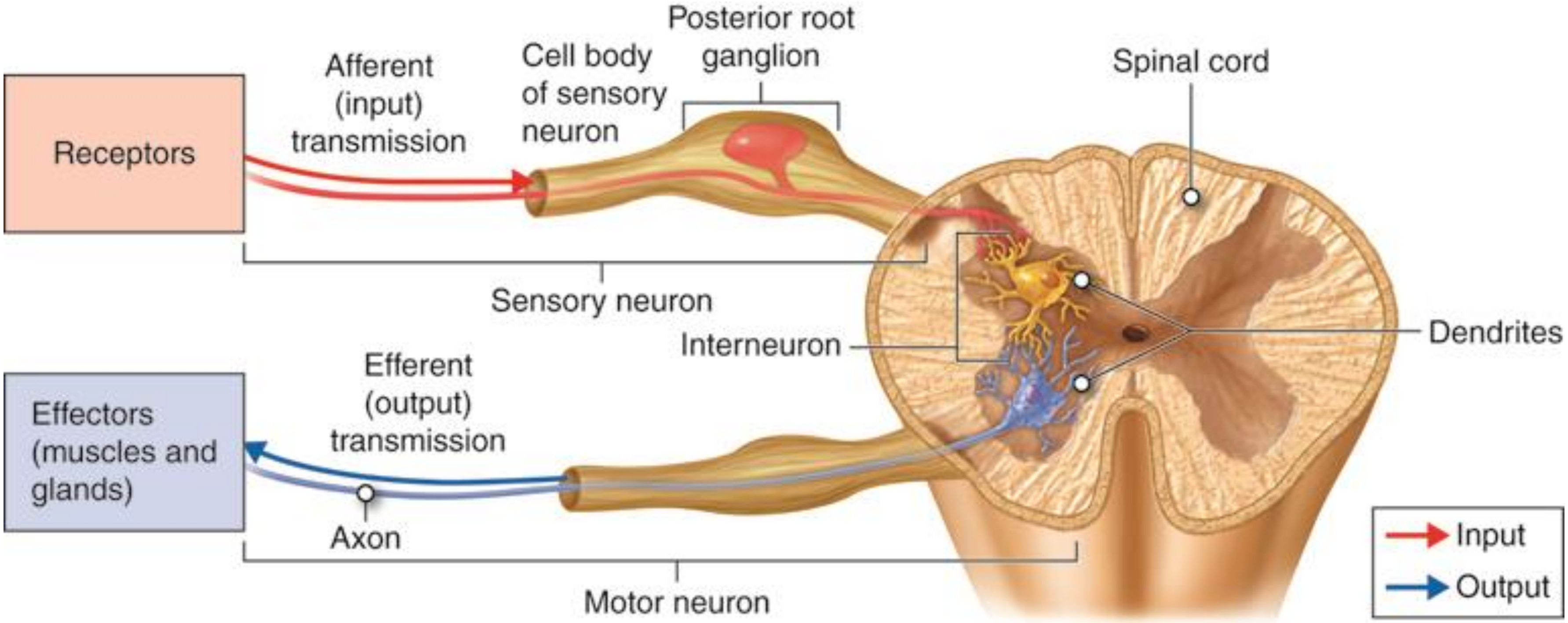
$V_C \to V_b$

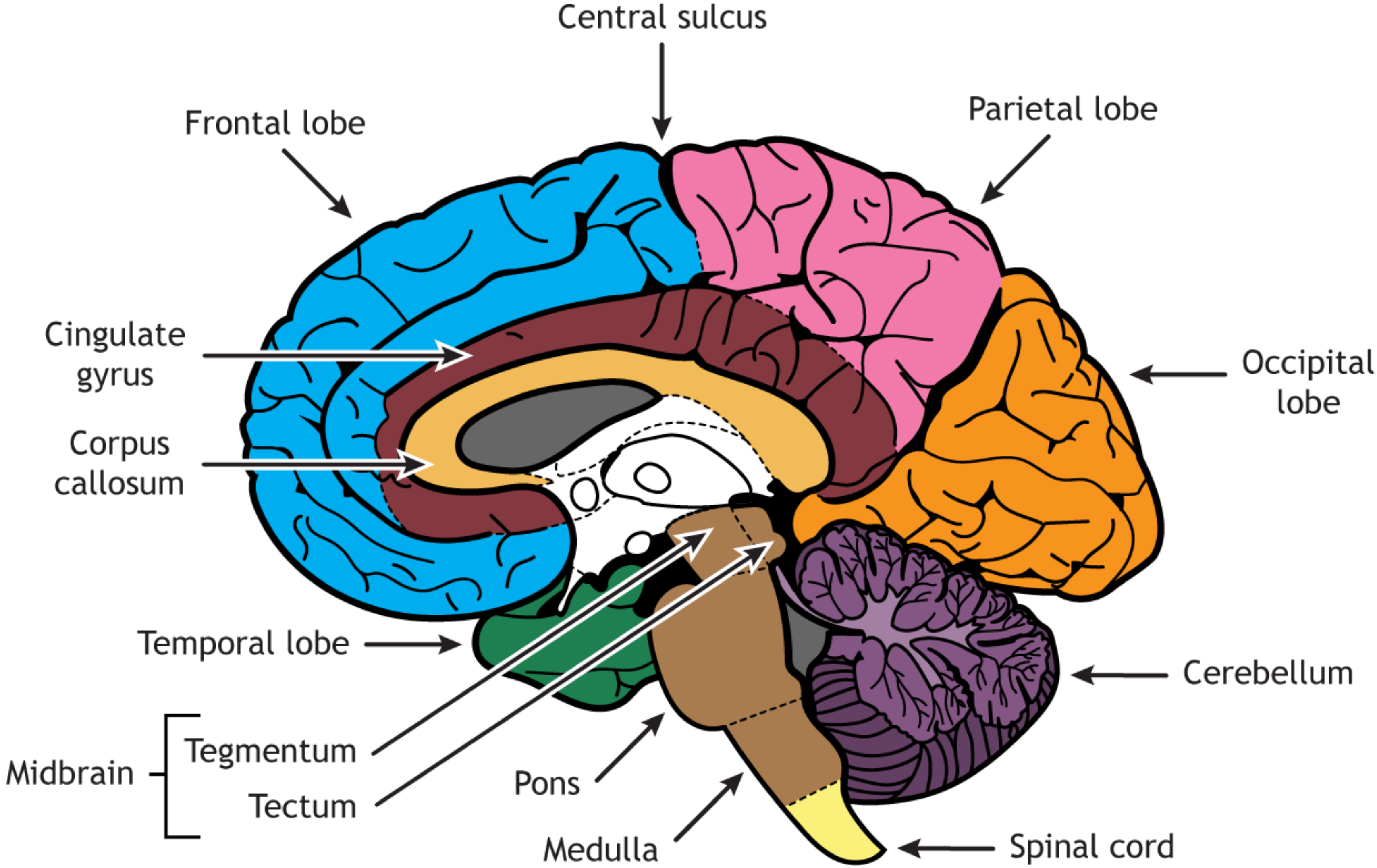
$I \to 0$



Central Nervous System
Brain
Spinal cord
(a)
Peripheral Nervous System
Nerve
(b)

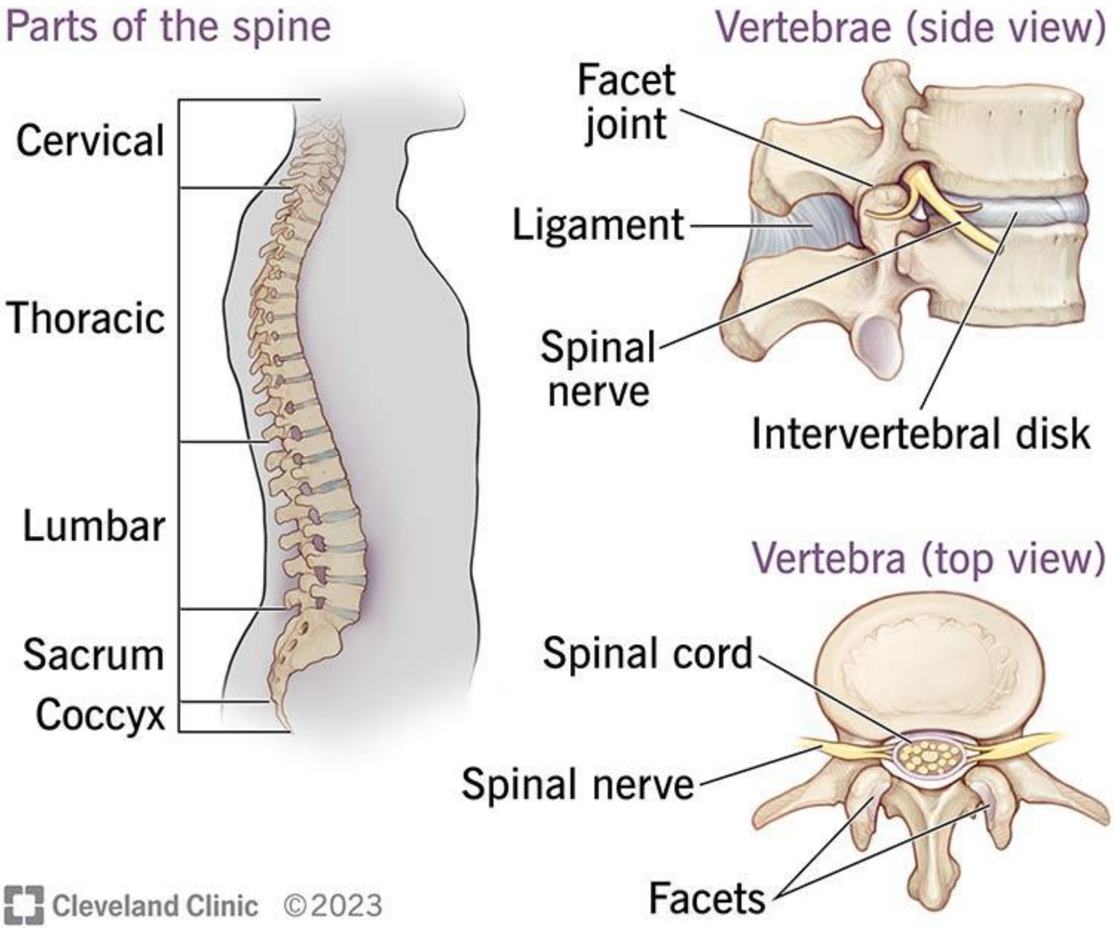

NERVOUS SYSTEM
CENTRAL NERVOUS SYSTEM
PERIPHERAL NERVOUS SYSTEM
BRAIN
SPINAL CORD
SOMATIC
Voluntary movement of skeletal muscle
AUTONOMIC
SYMPATHETIC
PARASYMPATHETIC
Involuntary movement of
* Smooth muscles
* Glands of organs


Receptors
Afferent (input) transmission
Cell body of sensory neuron
Posterior root ganglion
Spinal cord
Sensory neuron
Interneuron
Dendrites
Effectors (muscles and glands)
Efferent (output) transmission
Axon
Motor neuron
Input
Output

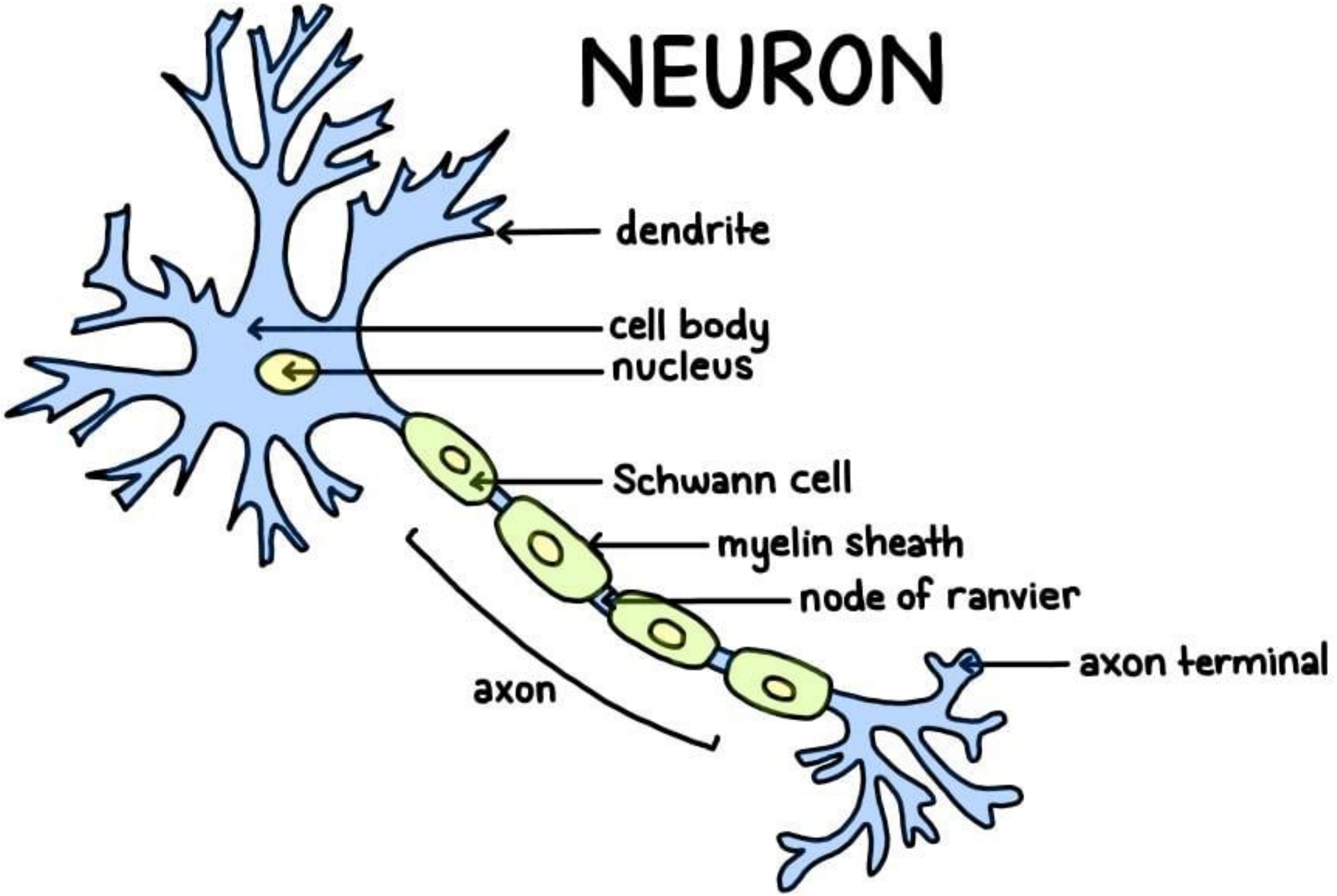


Central sulcus
Frontal lobe
Parietal lobe
Cingulate gyrus
Corpus callosum
Occipital lobe
Temporal lobe
Cerebellum
Midbrain
Tegmentum
Tectum
Pons
Medulla
Spinal cord

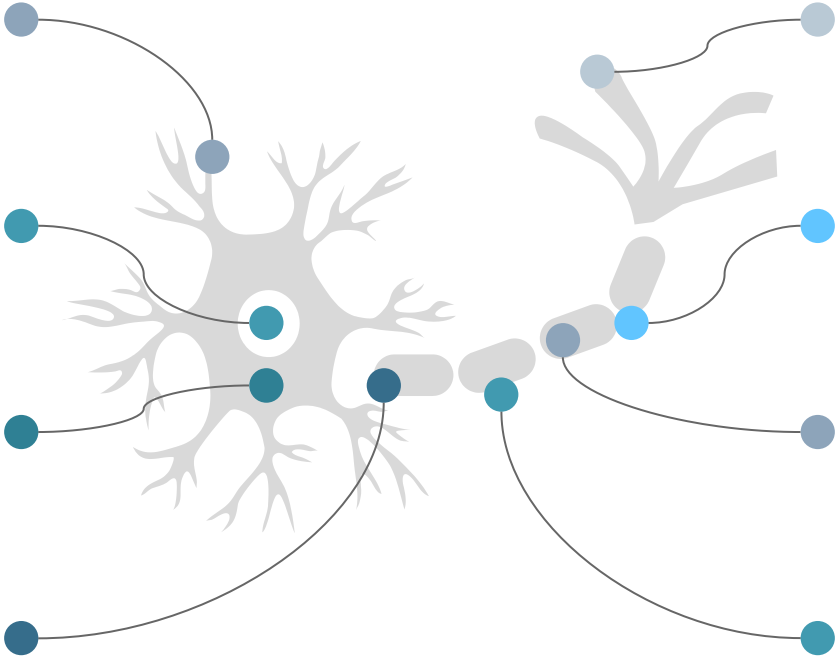
Spine (backbone)



NEURON


dendrite
cell body
nucleus
Schwann cell
myelin sheath
node of ranvier
axon terminal
axon

Neuron infographics



Dendrite

Nucleus

Cell body

Axon

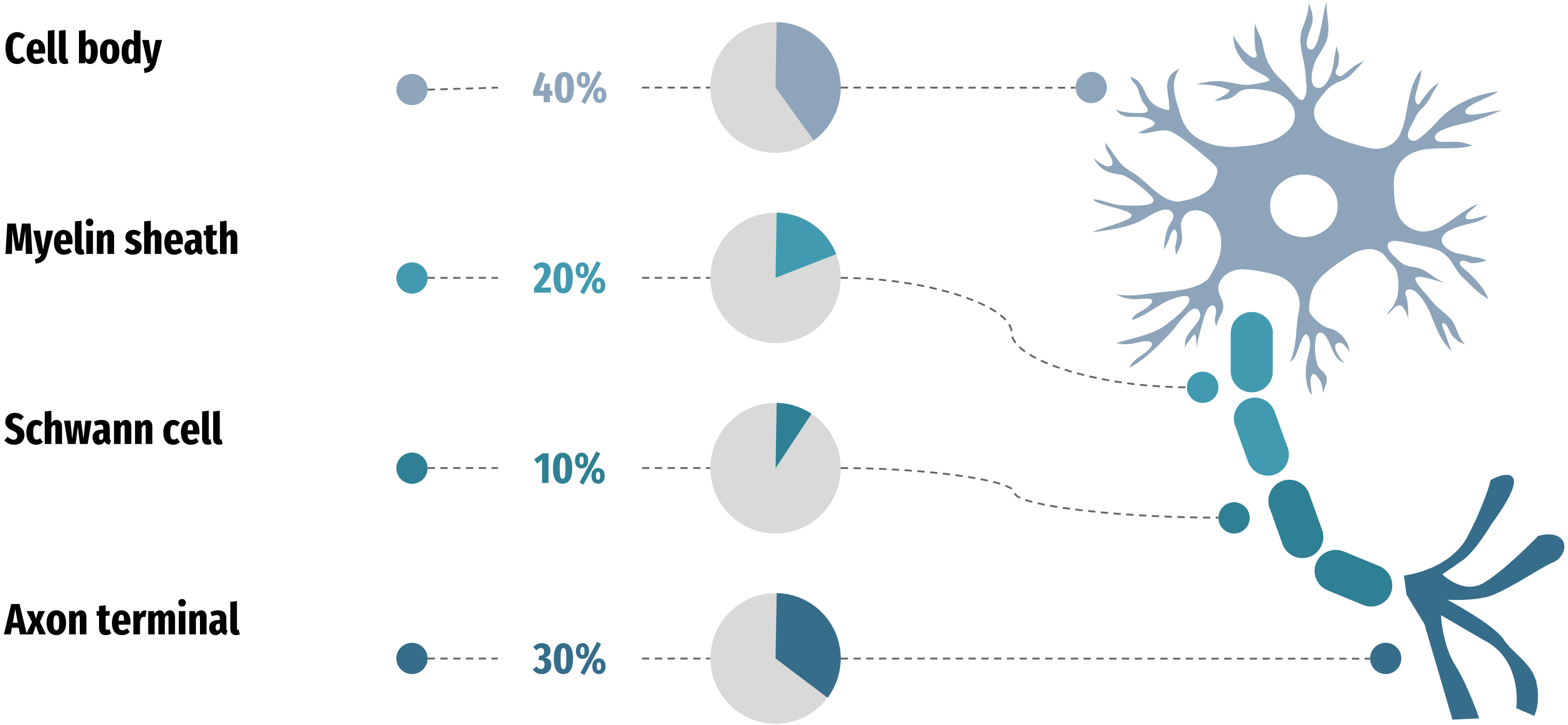
Axon terminal

Node of Ranvier

Schwann cell

Myelin sheath

Neuron infographics



Neuron infographics

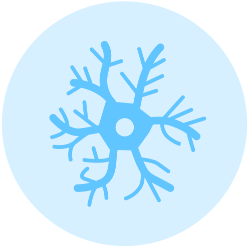
Sensory

Motor

Pyramidal

Astrocyte

Betz cell



Microglia

Neuron infographics

01

Sensory

02

Pyramidal

03

Betz cell

Neuron infographics

Motor neurons

Neuron infographics

01

Sensory neurons

02

Motor neurons

03

Interneurons

Neuron infographics

Sensory neuron

Physical inputs

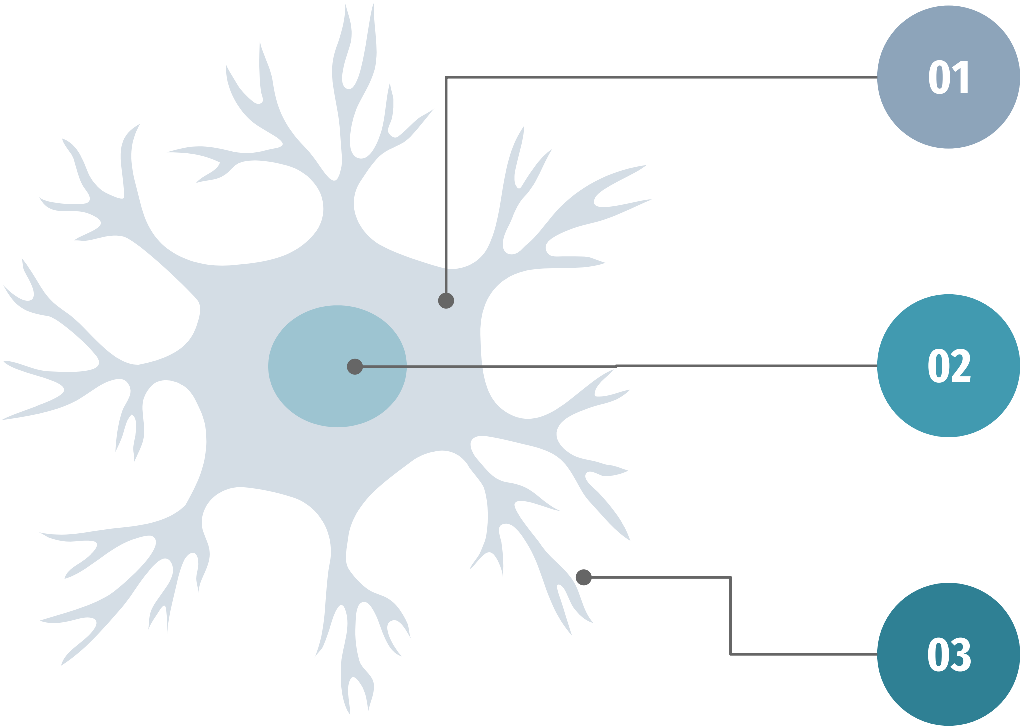
- Light
- Sound

Chemical inputs

- Smell
- Taste

Response

Neuron infographics



Cell body

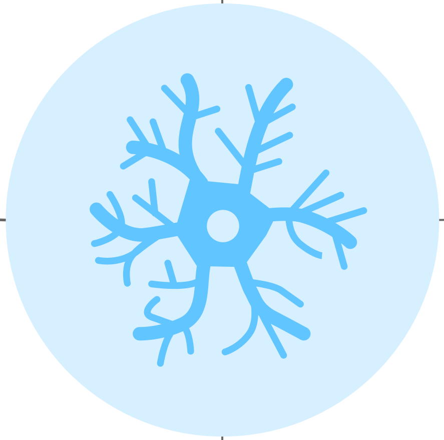
Nucleus

Axon

Neuron infographics

Microglia

Resident cells of the brain



Regulate brain development

Maintenance of neuronal networks

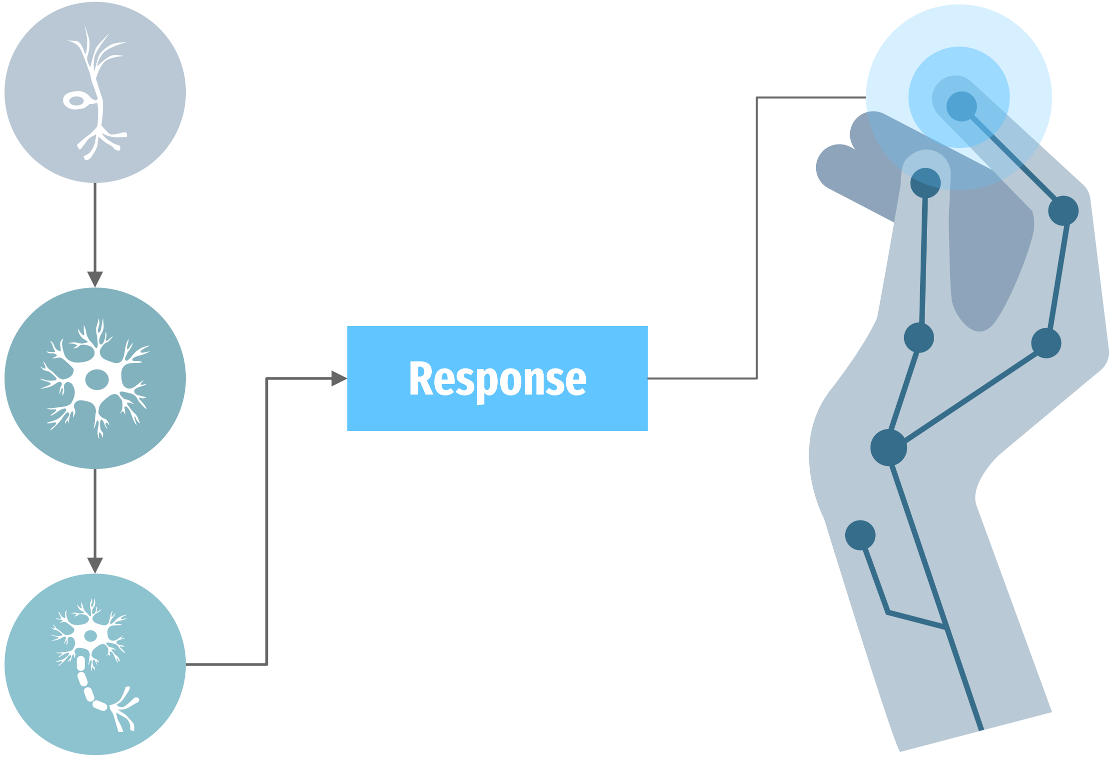
Injury repair

Neuron infographics

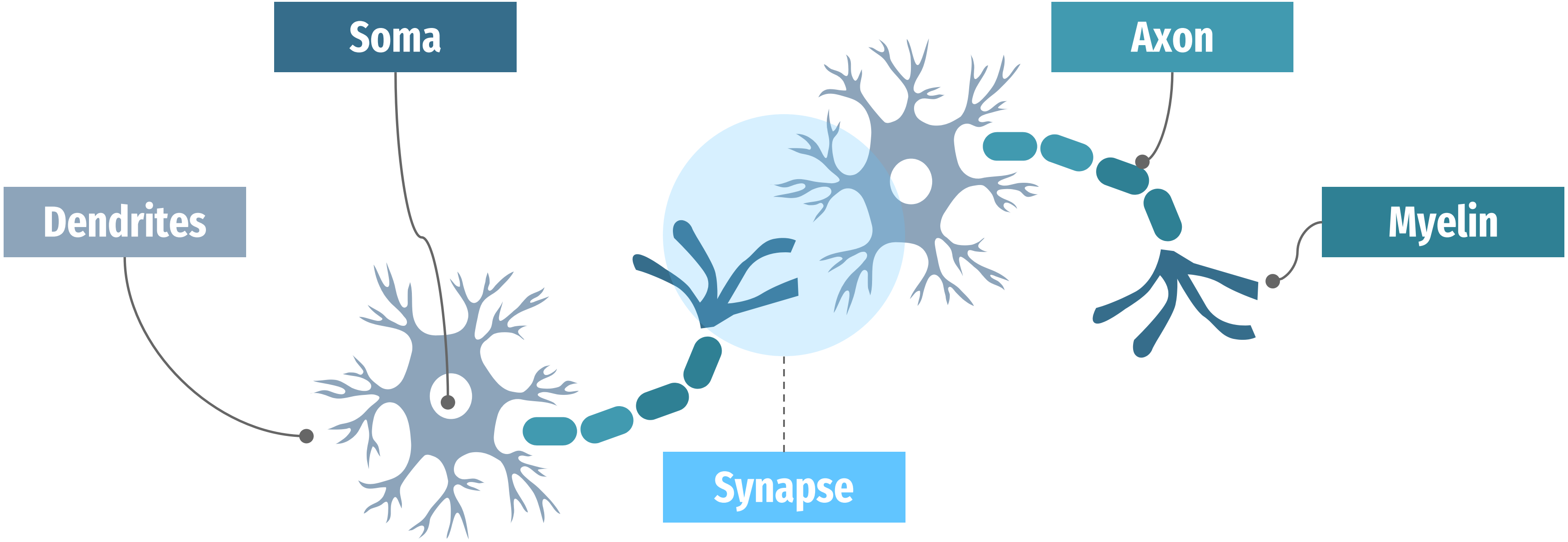
Sensory neurons

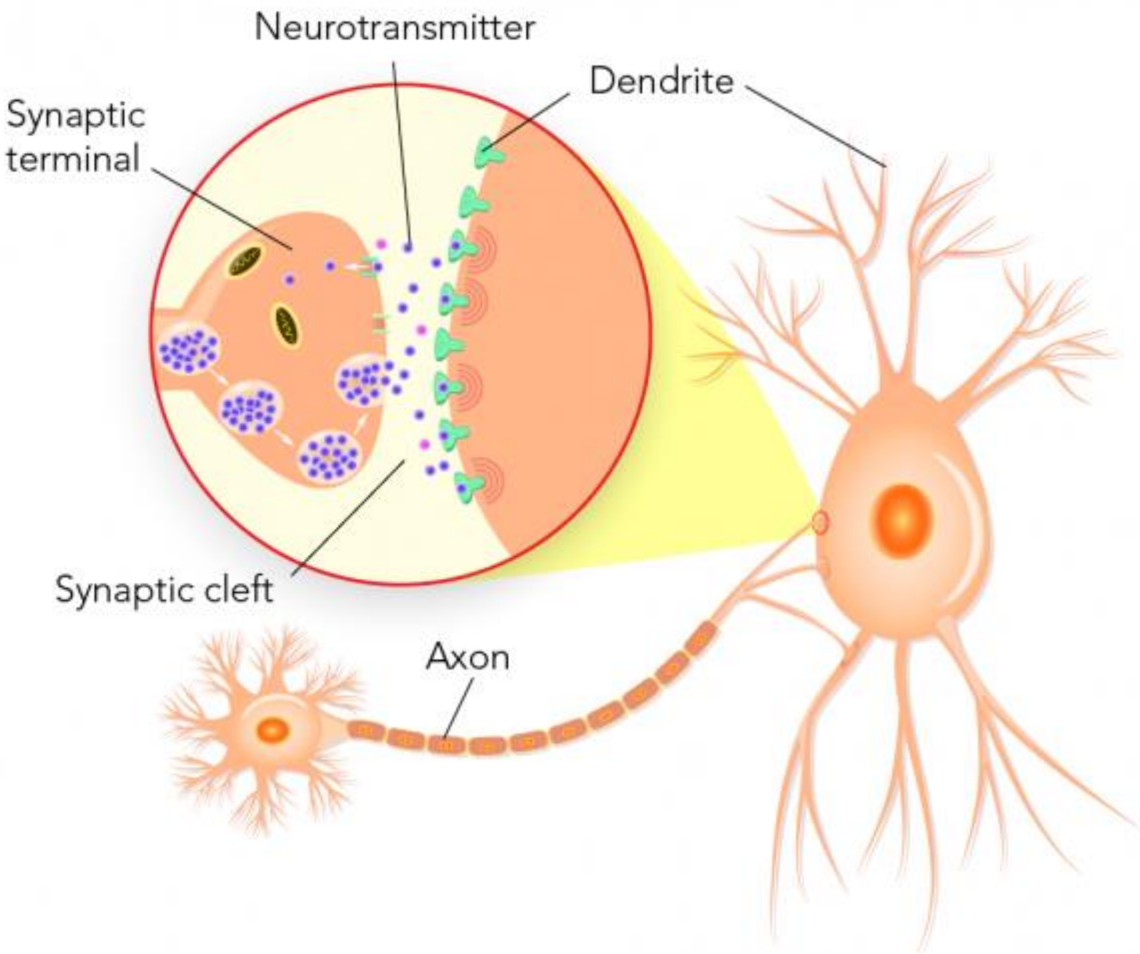
Interneurons

Motor neurons

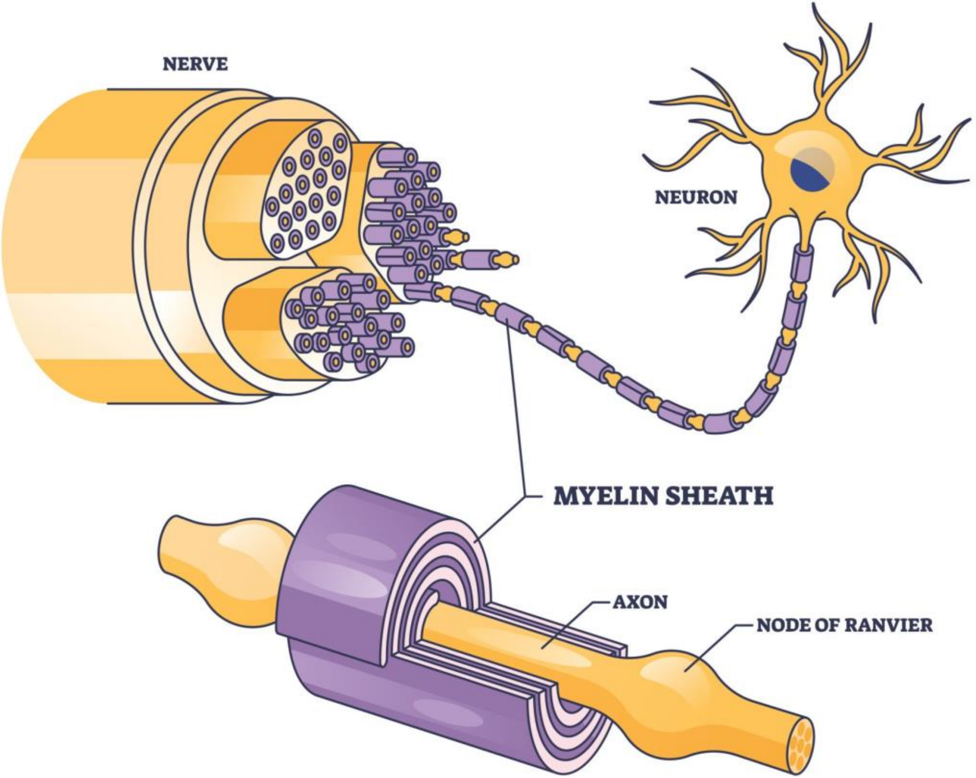


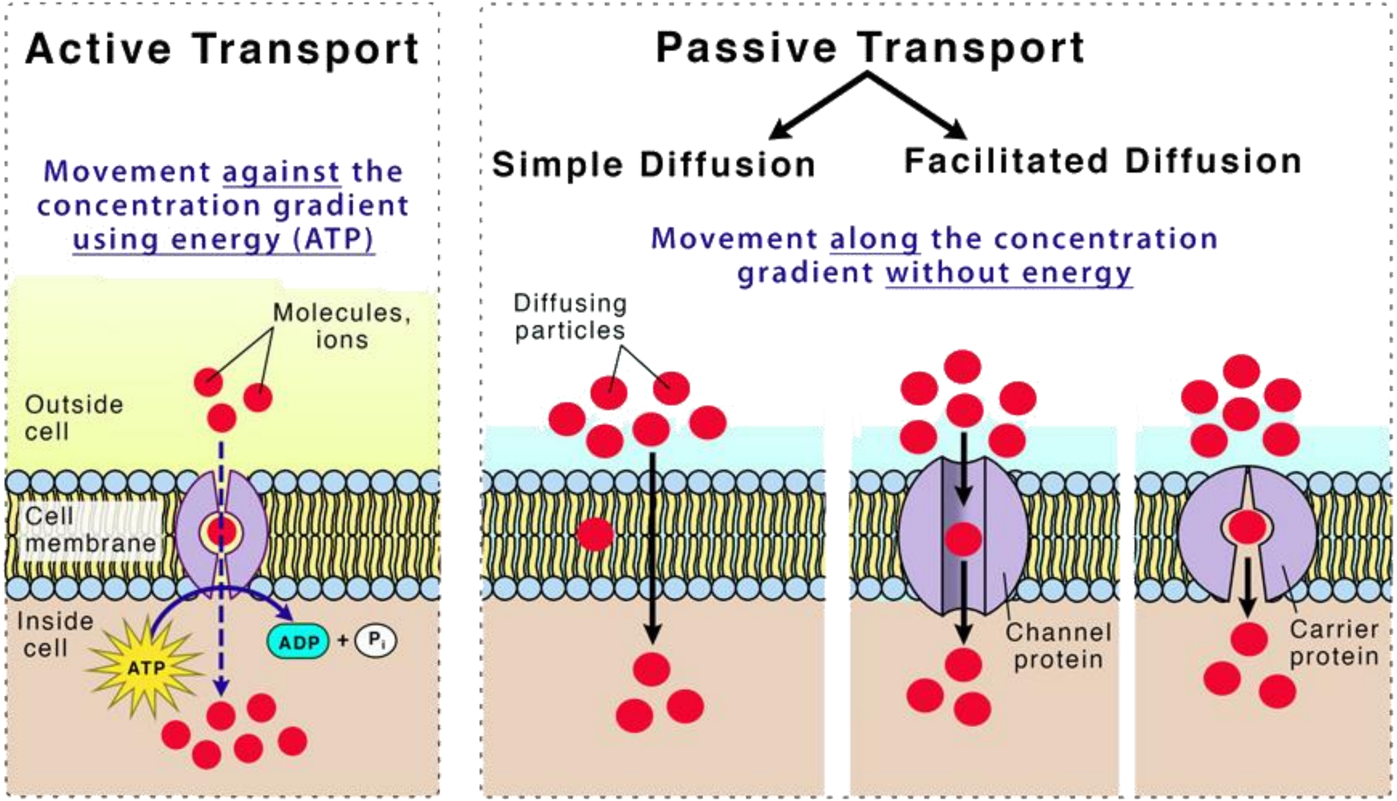
Neuron infographics




Neurotransmitter
Dendrite
Synaptic
terminal
Synaptic cleft
Axon

MYELIN SHEATH





Active Transport
Movement against the concentration gradient using energy (ATP)
Molecules, ions
Outside cell
Cell membrane
Inside cell
ATP
ADP
+
P_i
Passive Transport
Simple Diffusion
Facilitated Diffusion
Movement along the concentration gradient without energy
Diffusing particles
Channel protein
Carrier protein

Fick's First Law

Movement of particles (diffusion flux) from high to low concentration is directly proportional to the particle's concentration gradient

$$J \propto \frac{d\varphi}{dx} \quad \text{or} \quad J = -D\,\frac{d\varphi}{dx}$$

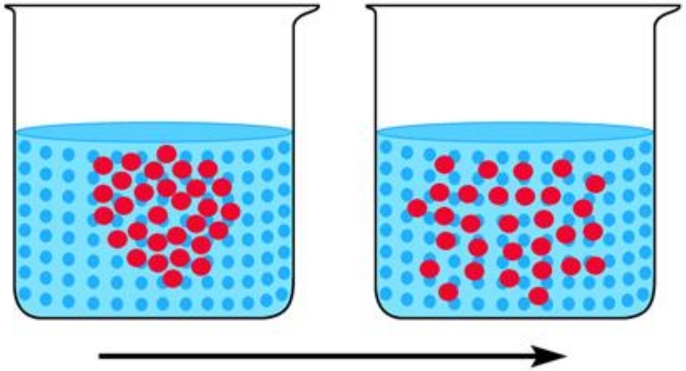
J = diffusion flux

D = diffusion coefficient or diffusivity

$d\varphi$ = change in concentration of the particle

dx = change in position

$\frac{d\varphi}{dx}$ = concentration gradient of the particle



Particles diffusing from high to low concentration

$$E = -\frac{dV}{dx}$$

$$J_{elect} = nv_{drift} = n\mu E$$

$$\mu = \frac{qD_{diff}}{k_B T}$$

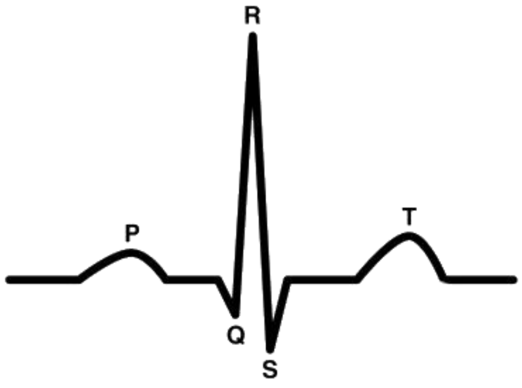
$$J_{diff} + J_{elect} = 0$$

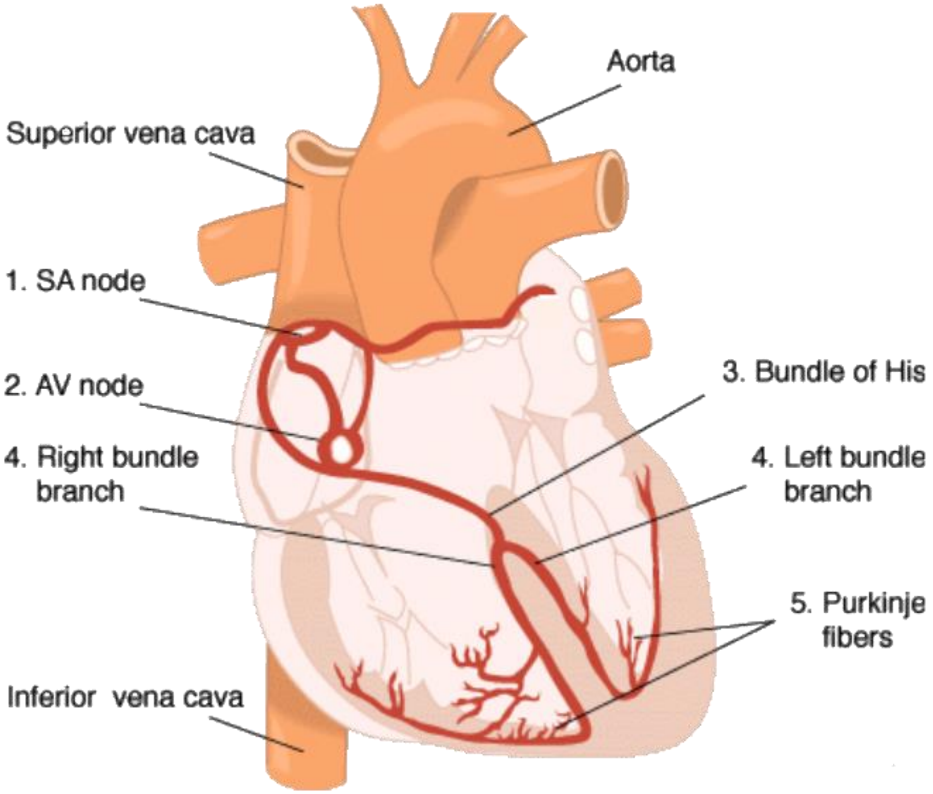
$$D_{diff}\frac{dn}{dx} = n\mu E$$

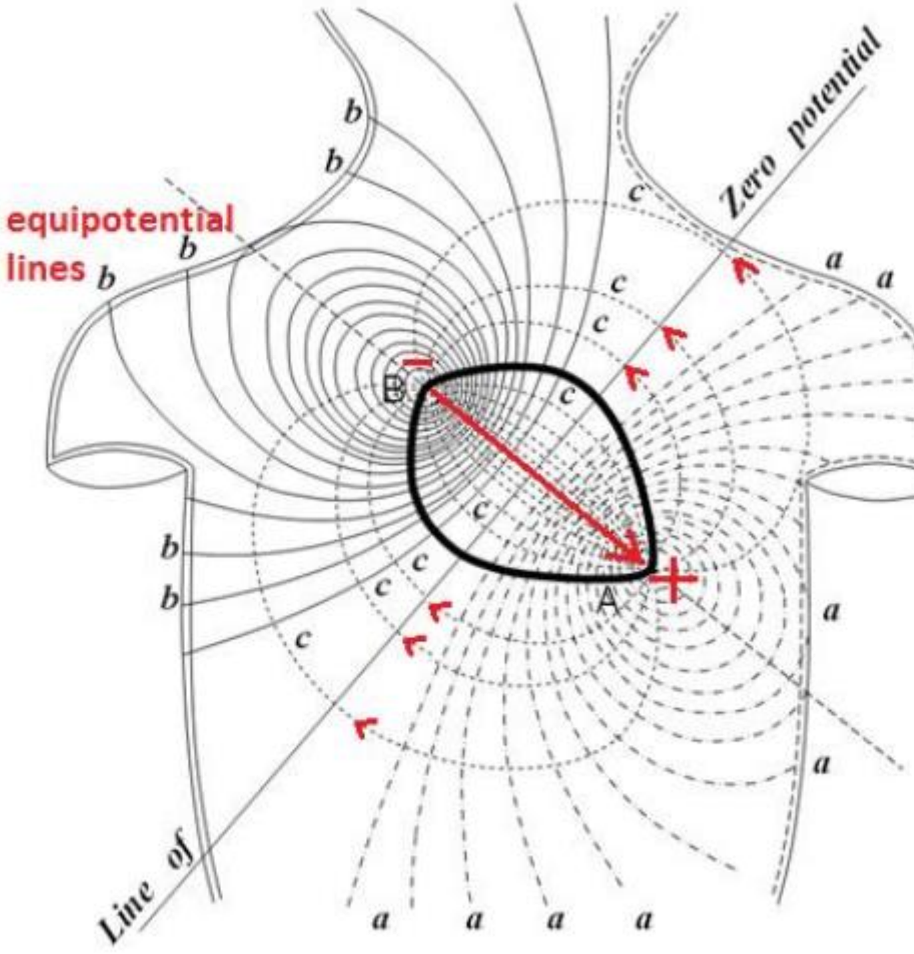
$$\Delta V = -\frac{k_B T}{q}\ln\frac{n_i}{n_o} \times (\frac{1}{z})$$

$$\Delta V = -\frac{k_B T}{q}\ \ln\frac{p_{Na}n_{Na}, i + p_k n_k, i + p_{Cl}n_{Cl}, o}{p_{Na}n_{Na}, o + p_k n_k, o + p_{Cl}n_{Cl}, i}$$

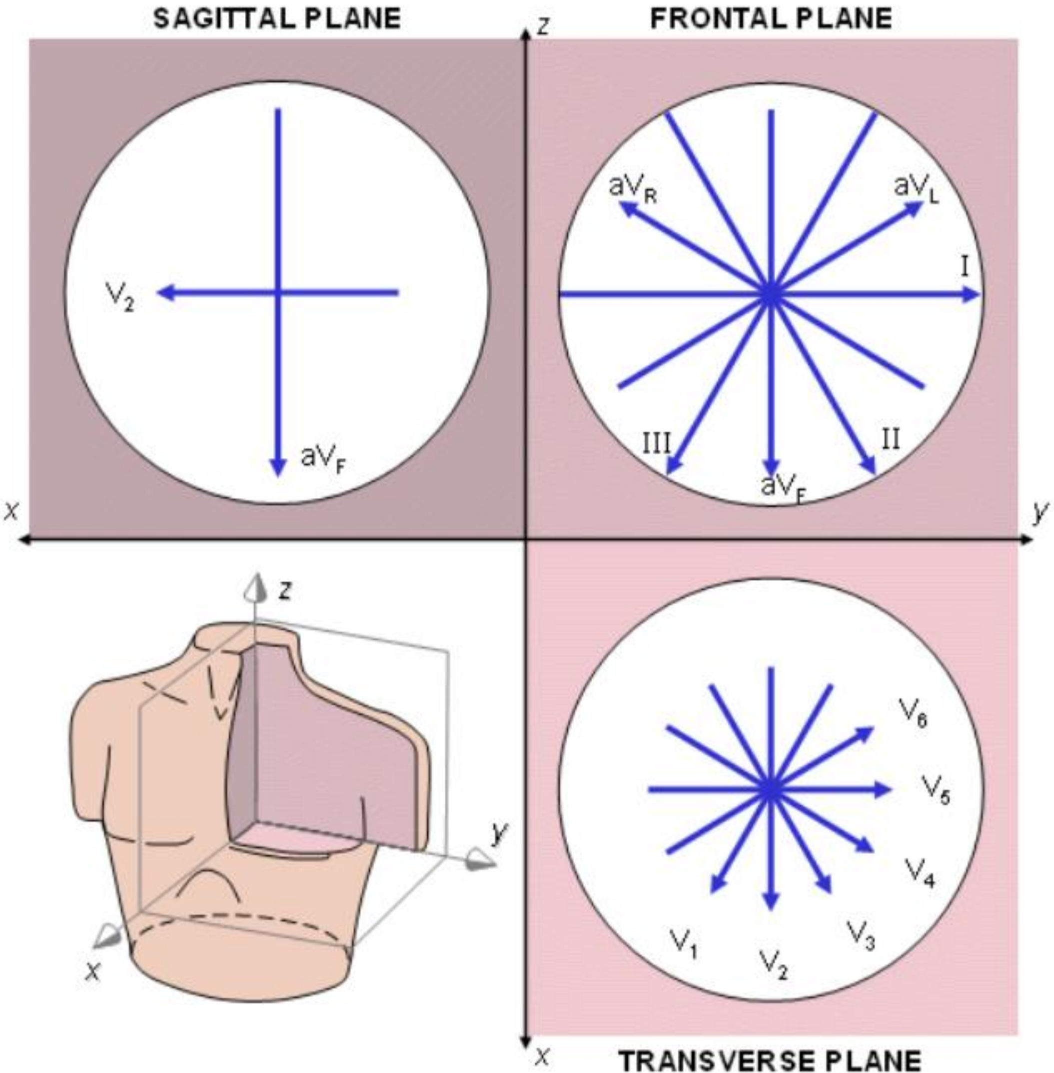
$$\rightarrow \frac{kT}{q}\ \ln\frac{[Na^+]_o + [k^+]_o + [Cl^-]_i}{[Na^+]_i + [k^+]_i + [Cl^-]_o}$$


R
P
T
Q
S

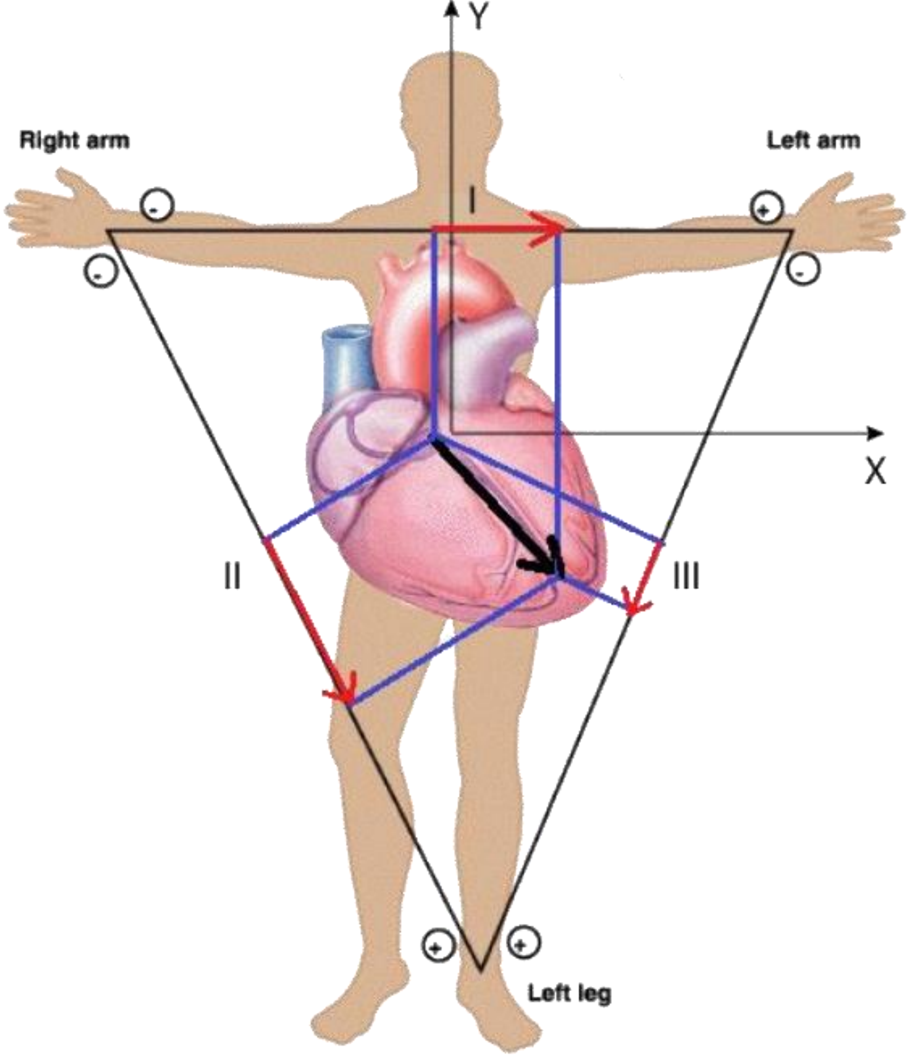

Aorta
Superior vena cava
1. SA node
2. AV node
3. Bundle of His
4. Right bundle branch
4. Left bundle branch
5. Purkinje fibers
Inferior vena cava



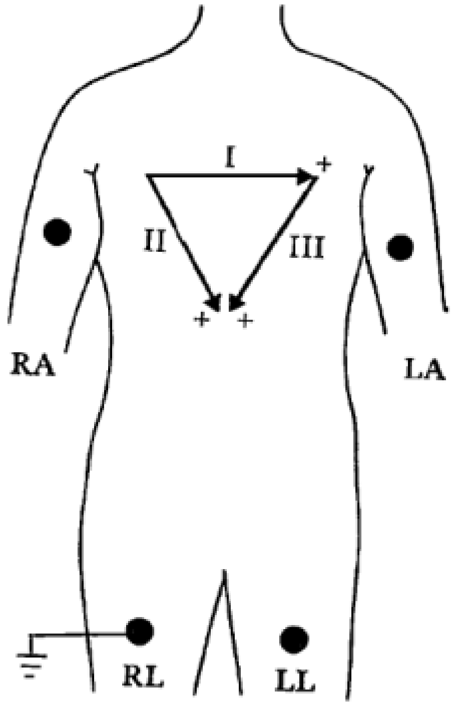
equipotential lines
Zero potential
Line of
B
A
−
+
a
b
c



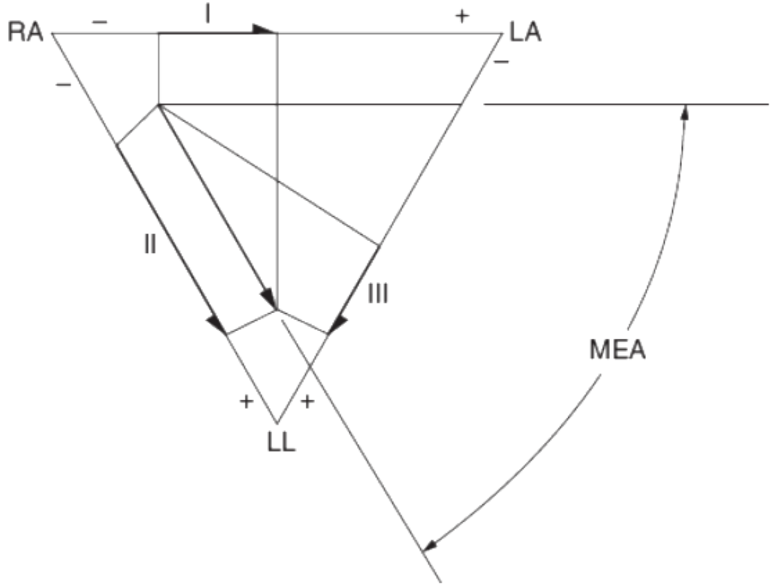
SAGITTAL PLANE
FRONTAL PLANE
TRANSVERSE PLANE
z
x
y
V_2
aV_F
aV_R
aV_L
I
II
III
aV_F
V_1
V_2
V_3
V_4
V_5
V_6
z
y
x
x



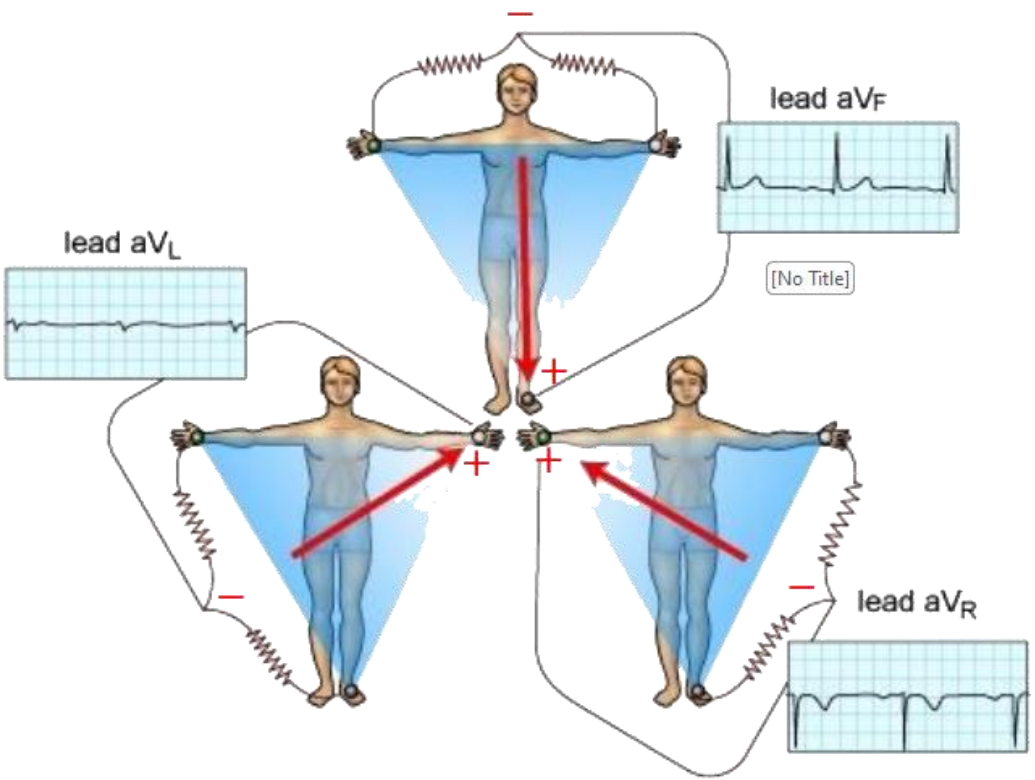
Y
Right arm
Left arm
I
-
+
-
-
X
II
III
+
+
Left leg



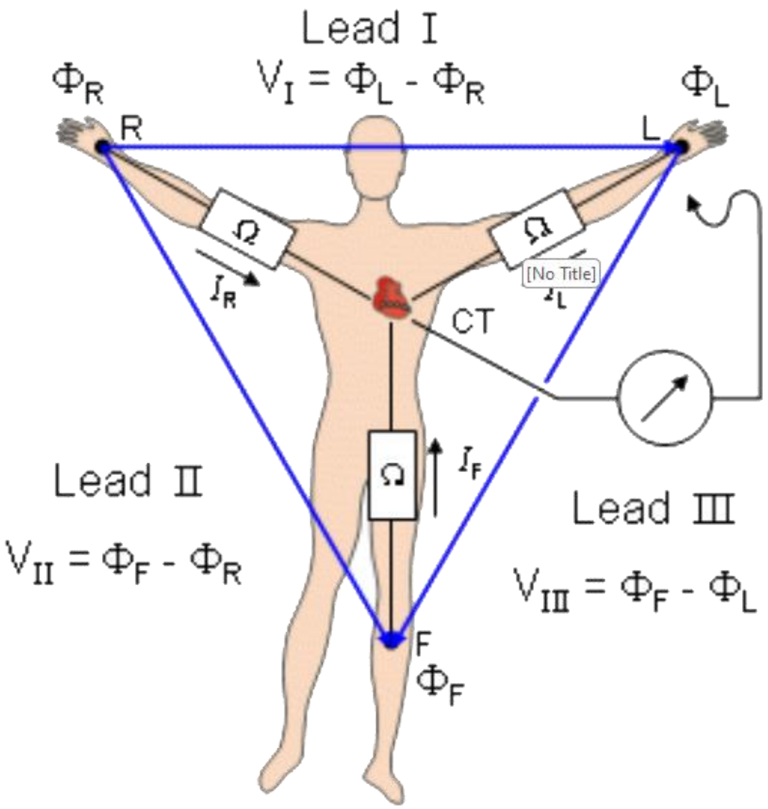
I
+
II
III
+
+
RA
LA
RL
LL



RA
−
I
+
LA
−
−
II
III
+
+
LL
MEA



lead aVF
lead aVL
lead aVR
[No Title]



$V_I = aVL - aVR$

$V_{II} = aVF - aVR$

$V_{III} = aVF - aVL$

$$\Phi_{CT} = \frac{\Phi_R + \Phi_L + \Phi_F}{3}$$

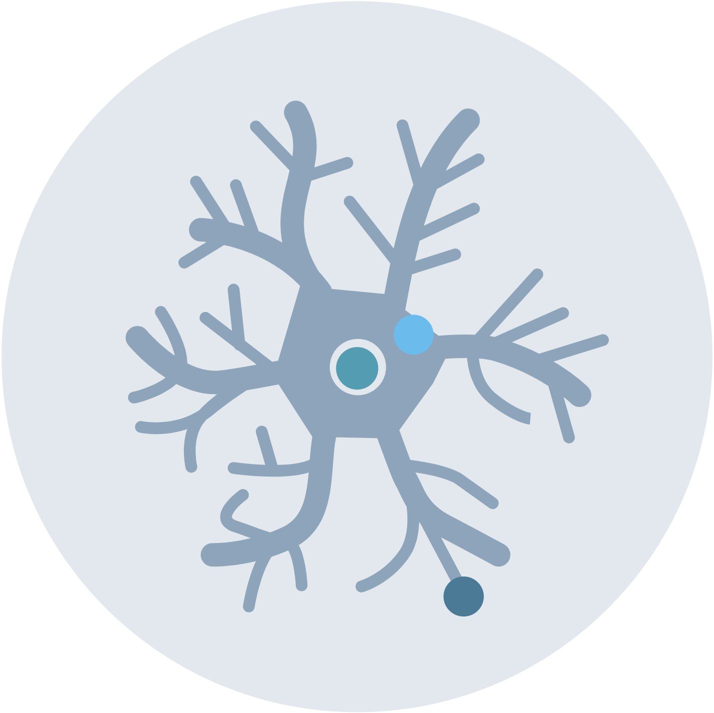
Wilson Central Terminal (WCT)

$aVL + aVF + aVR = 0$

$V_{II} - V_{III} = V_I$

03

Examples



Example 6-1

A. Calculate the Nernst potential for each ion as well as the membrane potential assuming the following permeability coefficients.

B. If the active sodium-potassium pump in this cell fails due to a chemical drug, assuming that the membrane potential does not change much, calculate the new sodium ion concentration outside and inside the cell. (Hint: consider the volume of intracellular and extracellular fluid to be almost equal and use the law of conservation of mass.)

Ion	Intracellular concentration	Extracellular concentration	Permeability coefficient
Na^+	50	440	0.04
K^+	400	20	1
Cl^-	52	560	0.45

Example 6-1

Answer

A)

$$V_{Na} = \frac{kT}{q} \ln \frac{[Na^+]_o}{[Na^+]_i} = 25 \times \ln \frac{440}{50} = 54.4\, mV$$

$$V_k = \frac{kT}{q} \ln \frac{[k^+]_o}{[k^+]_i} = 25 \times \ln \frac{20}{400} = -74.8\, mV$$

$$V_{Na} = \frac{kT}{q} \ln \frac{[Cl^-]_i}{[Cl^-]_o} = 25 \times \ln \frac{52}{560} = -59.4\, mV$$

$$V_{total} = \frac{kT}{q} \ln \frac{[Na^+]_o + [k^+]_o + [Cl^-]_i}{[Na^+]_i + [k^+]_i + [Cl^-]_o} = 25 \times \ln \frac{20 + 0.04 \times 440 + 0.45 \times 52}{400 + 0.04 \times 50 + 0/45 \times 560} = -59.1\, mV$$

Example 6-1

Answer

B)

When the pump is broken, Nernst potential and membrane potential will be equal:

$$\left.\begin{aligned}\frac{[k^+]_o}{[k^+]_i} &= \frac{61}{654}\\ 420 - [k^+]_o &= [k^+]_i\end{aligned}\right\} \frac{x}{420-x} = \frac{61}{654} \rightarrow x = 35.9 = [k^+]_o \rightarrow [k^+]_i = 420 - 35.9 = 384.1\ mM$$

Example 6-2

The cell membrane is permeable to k and cl ions and not permeable to R ions. Find the concentration of ions at equilibrium. The concentration of ions before equilibrium is as follows.

$[Kcl]_o = 400\ mM$
$[Kcl]_i = 100\ mM$
$[Rcl]_i = 500\ mM$

Example 6-2

Answer

$$\left.\begin{aligned} [k^+]_o + [k^+]_i &= 500 \\ [Cl^-]_i + [Cl^-]_o &= 1000 \\ [Cl^-]_i = [k^+]_i &+ 500 \\ [k^+]_o &= [Cl^-]_o \\ E_{cl} &= E_K \end{aligned}\right\} 26 \ln \frac{[Cl^-]_i}{[Cl^-]_o} = 26 \ln \frac{[k^+]_o}{[k^+]_i} \rightarrow \frac{[k^+]_o}{[k^+]_i} = \frac{[Cl^-]_i}{[Cl^-]_o}$$

$$\left.\begin{aligned} [k^+]_i &= 500 - [k^+]_o \\ [Cl^-]_i &= 1000 - [Cl^-]_o \\ [k^+]_o &= [Cl^-]_o \end{aligned}\right\} \rightarrow x^2 = (500 - x) \times (1000 - x)$$

$$x = 333$$
$$[k^+]_i = 167\ mM$$
$$[Cl^-]_i = 667\ mM$$
$$[k^+]_o = [Cl^-]_o = 333 mM$$

Example 6-3

The potential recorded from two lead II, aVF is as follows. Calculate the MEA and electrical Doppler vector of the heart. Is the MEA in the normal range? What kind of deviation does it have?

Example 6-3

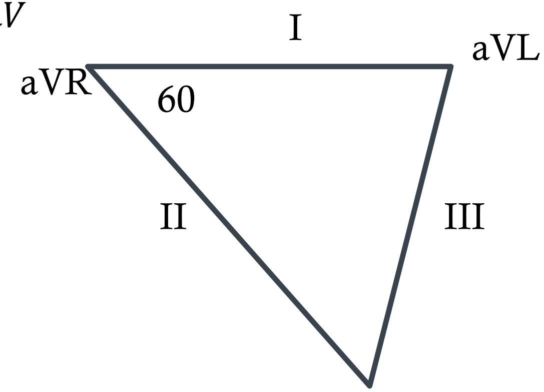
Answer

$aVF = 5.5\ mV\ , V_{II} = 3.5\ mV\ , V_{II} = aVF\ - aVR\ \rightarrow 3.5 = 5.5\ - aVR\ \rightarrow aVR = 2\ mV$

$\frac{(aVF + aVR + aVL)}{3} = 0\ \rightarrow (5.5 + 2 + aVL) = 0\ \rightarrow aVL = -7.5\ mV$

$V_I = aVL\ - aVR = -7.5\ - 2 = -9.5\ mV : M_x\vec{\imath}$

$\vec{M} = \left(-9.5\,\vec{\imath} + M_y\vec{\jmath}\right)$



$V_{II} = \vec{M}.(\cos60\,\vec{\imath} - \sin60\,\vec{\jmath})$

$3.5 = \left(-9.5\,\vec{\imath} + M_y\vec{\jmath}\right).\left(\frac{1}{2}\,\vec{\imath} - 0.86\vec{\jmath}\right) = M_y = -9.6\ mV$

$\vec{M} = (-9.5\,\vec{\imath} + -9.6\vec{\jmath})\ , \theta =\ \tan^{-1}\frac{9.6}{9.5} =\ 45.2^o\ \rightarrow MEA = 134.8$

$120 < MEA < 180\ \rightarrow RAD$

Example 6-4

A. If the resting potential is -52 mV at room temperature, find the concentration of potassium in the cytoplasm.

B. Find the Nernst potential of each ion.

C. Is the membrane potential equal to the ionic Nernst potential? What factor can cause equality, and in this case, what is the flow of each of the ions? Explain

Ion	Cytoplasm	outside the cell	Permeability ratio
Na^+	41	276	0.017
K^+	؟	4	1
Cl^-	52	340	0.412

Example 6-4

Answer

A)

$$V_{total} = \frac{kT}{q}\ln\frac{[Na^+]_o + [k^+]_o + [Cl^-]_i}{[Na^+]_i + [k^+]_i + [Cl^-]_o} = -52 = 26\, ln\left(\frac{4 + 17 \times 276 + 412 \times 10^{-3}\ \times 52}{x + 17 \times 10^{-3} \times 41 + 412 \times 10^{-3} \times 340}\right)$$

$$\rightarrow x = 81.76\ mM$$

B)

$$V_{Na} = \frac{kT}{q}\ln\frac{[Na^+]_o}{[Na^+]_i} = 26 \times \ln\frac{276}{41} = 49.577\ mV$$

$$V_k = \frac{kT}{q}\ln\frac{[k^+]_o}{[k^+]_i} = -78.95\ mV$$

$$V_{Na} = \frac{kT}{q}\ln\frac{[Cl^-]_i}{[Cl^-]_o} = 26 \times \ln\frac{52}{340} = -46.82\ mV$$

C)

What do you think about this one? This one will be left as your HWc05

Example 6-5

Consider a membrane that has a passive channel for chlorine ions and an active pump for potassium ions separate from the potassium channel. If the concentration of [KCl] is not in equilibrium on both sides of the membrane of this cell, find an expression for the current of the potassium pump.
(Hint: Use the proof of existing relationships for the flow of ions.)

Example 6-5

Answer

$$J_k = J_p - \mu_k Z_k [k^+] \frac{dV}{dx} - \frac{kT}{q} \mu_k \frac{d[k^+]}{dx}$$

$$J_{Cl} = -\mu_{Cl} Z_{Cl} [Cl^-] \frac{dV}{dx} - \frac{kT}{q} \mu_{Cl} \frac{d[Cl^-]}{dx}$$

$$\rightarrow \frac{dV}{dx} = \frac{kT}{q[Cl^-]} \frac{d[Cl^-]}{dx} \xrightarrow{[Cl^-]=[k^+]} \frac{dV}{dx} = \frac{kT}{q[k^+]} \frac{d[k^+]}{dx}$$

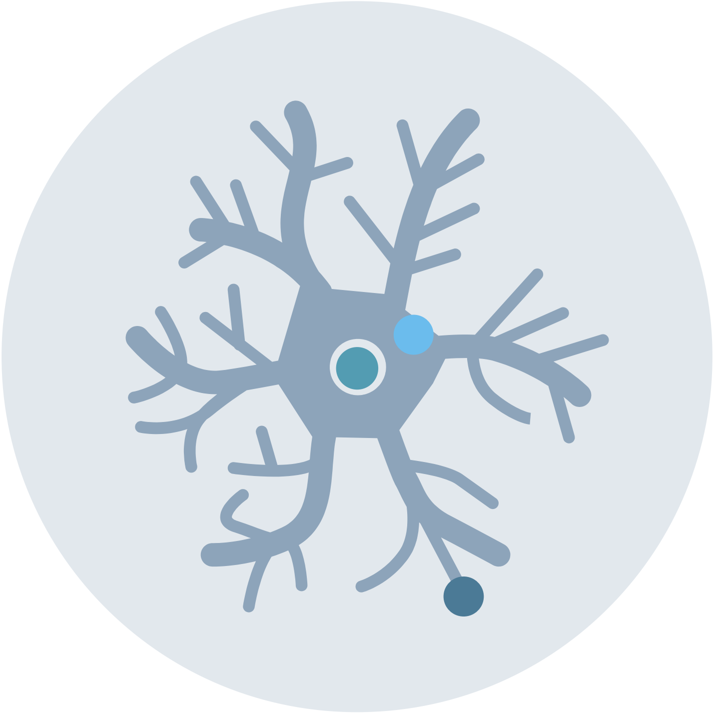
$$Steady\ State: J_k = 0 = J_p - \mu_k Z_k [k^+] \frac{dV}{dx} - \frac{kT}{q} \mu_k \frac{d[k^+]}{dx}$$

$$= J_p - \mu_k [k^+] \frac{kT}{q[k^+]} \frac{d[k^+]}{dx} - \frac{kT}{q} \mu_k \frac{d[k^+]}{dx} \rightarrow J_p - \frac{2kT\mu_k}{q} \frac{d[k^+]}{dx}$$

$$-\int_0^{\delta} J_p dx = -\frac{2kT\mu_k}{q} \int_{[k^+]_i}^{[k^+]_o} d[k^+] \rightarrow J_p = \frac{2kT\mu_k}{q} ([k^+]_o - [k^+]_i)$$

04

Assignment



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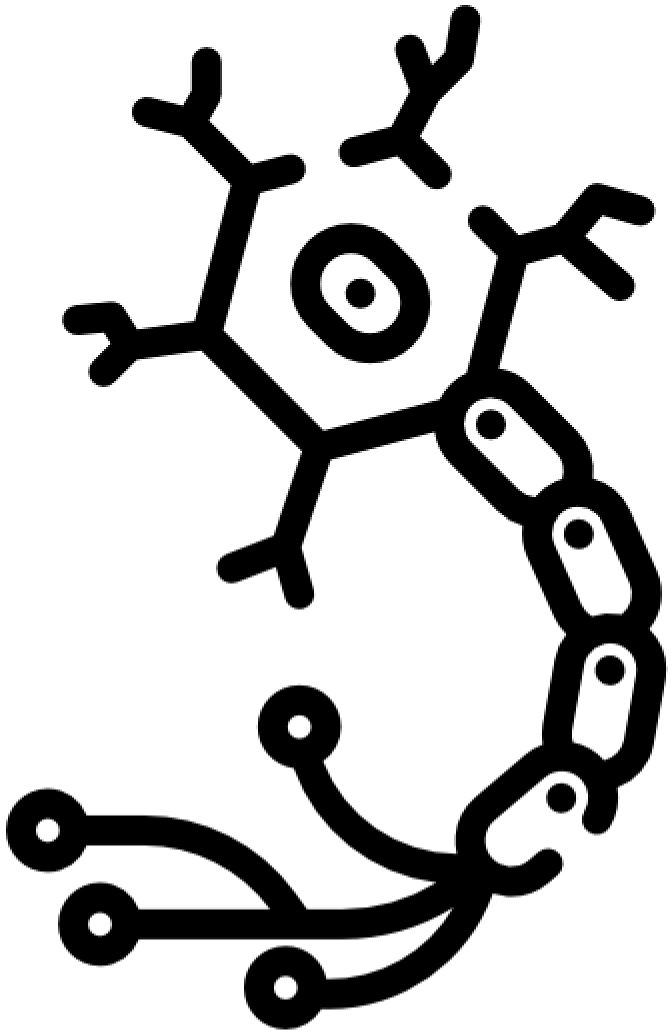

Resources

Dr. Malikeh Nabaei:

- Slides
- Classes

Faezeh Jahani:

- Slides

biological and medical physics, biomedical engineering

- The reference book

Thanks!

Does anyone have any questions?

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Have a good afternoon