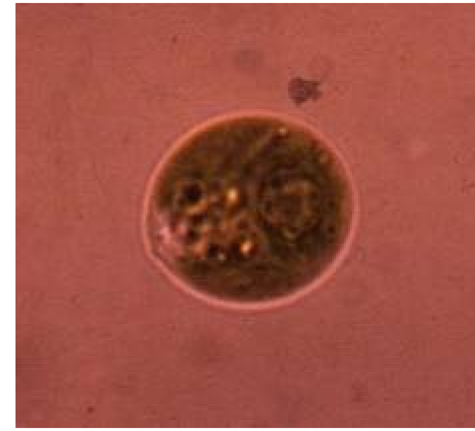
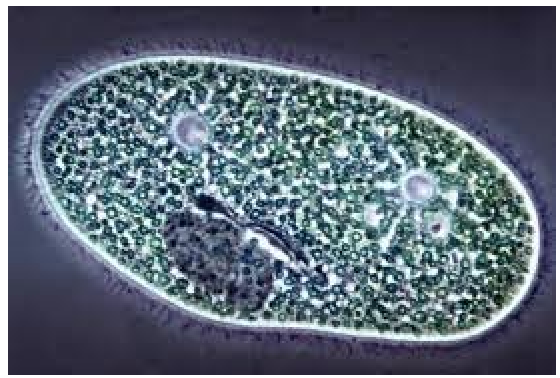
From Neuron to Brain: Pedagogic Approach

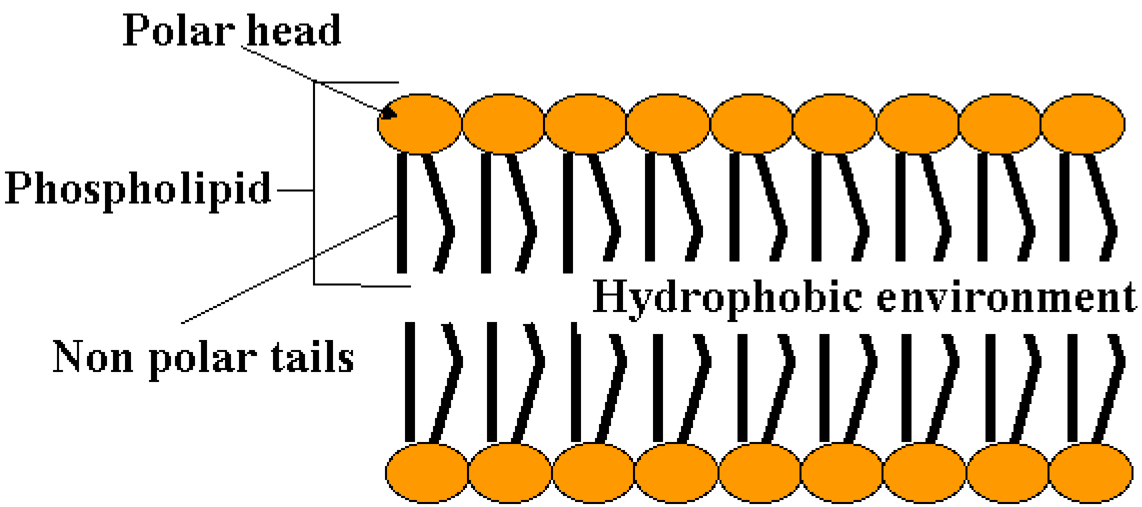
KAMALES BHAUMIK


(c) Amgueddfa Cymru - National Museum Wales





Plasma membrane



Movement of charged ions across the cell membrane

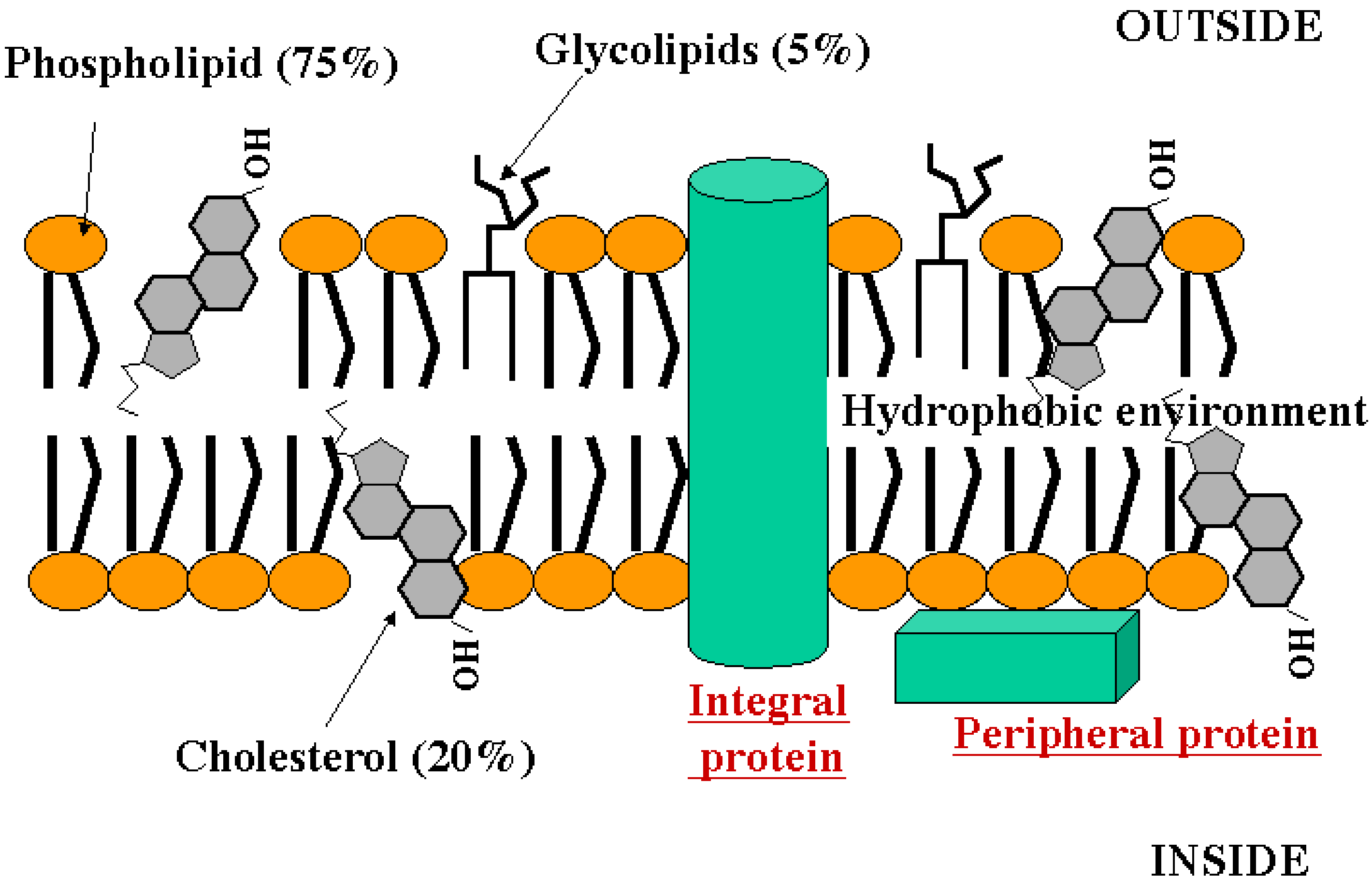
$$V = \frac{q}{\in a}$$

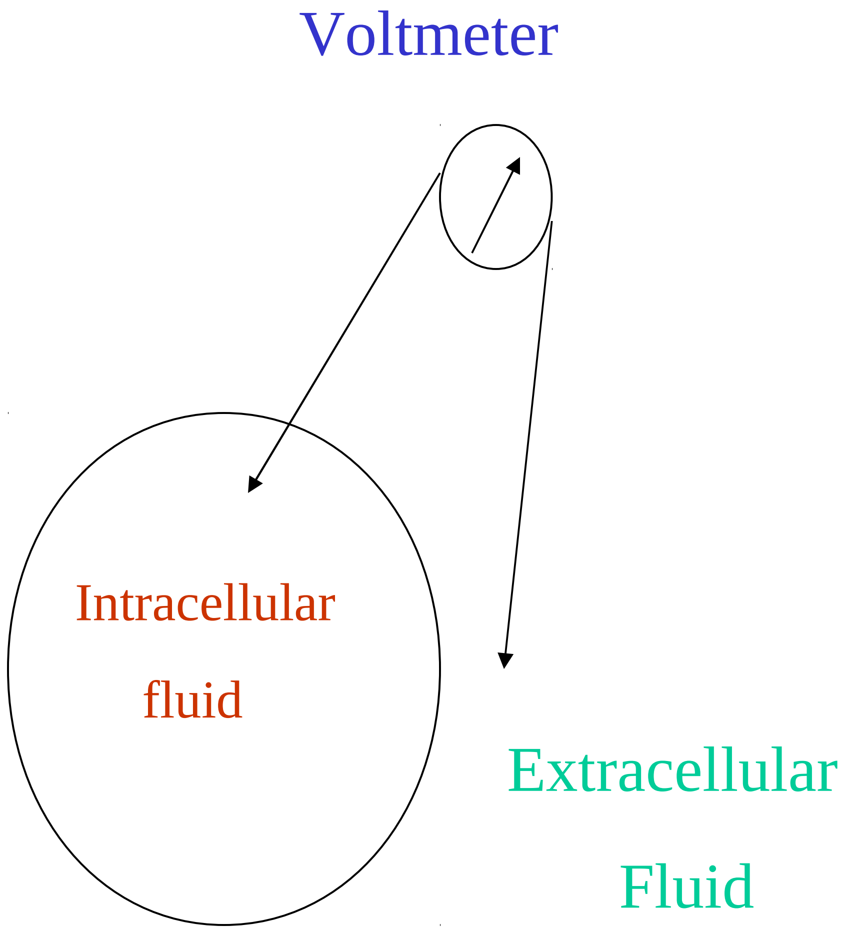
$$Capacitance \quad C = \frac{q}{V} = \in a$$

$$Self-energy \quad E = \frac{1}{2}CV^2 = \frac{q^2}{2a\in}\frac{1}{}$$

$$\in_{water} = 80 \quad \in_{lipid} \approx 4$$

Plasma membrane





Inside of the cell is negative with respect to outside.

Most of the cells have a resting membrane potential in the range of -30mV to -80mV

Resting Membrane Potential

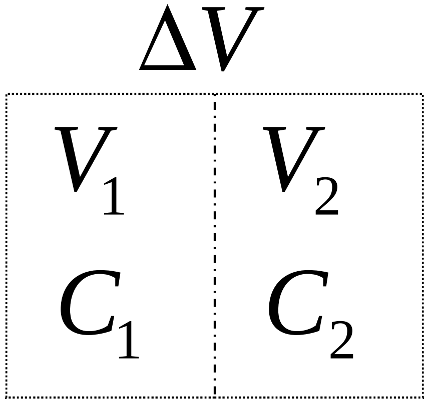
Nernst Potential

Nernst Potential

Chemical Potential = Partial Molar Gibbs Free Energy

Chemical Potential $\mu_c = \mu_c^0 + RT \ln C$

Electrochemical Potential $\mu = \mu_0 + RT \ln C + zFV$



$$RT \ln C_1 + zFV_1$$

$$= RT \ln C_2 + zFV_2$$

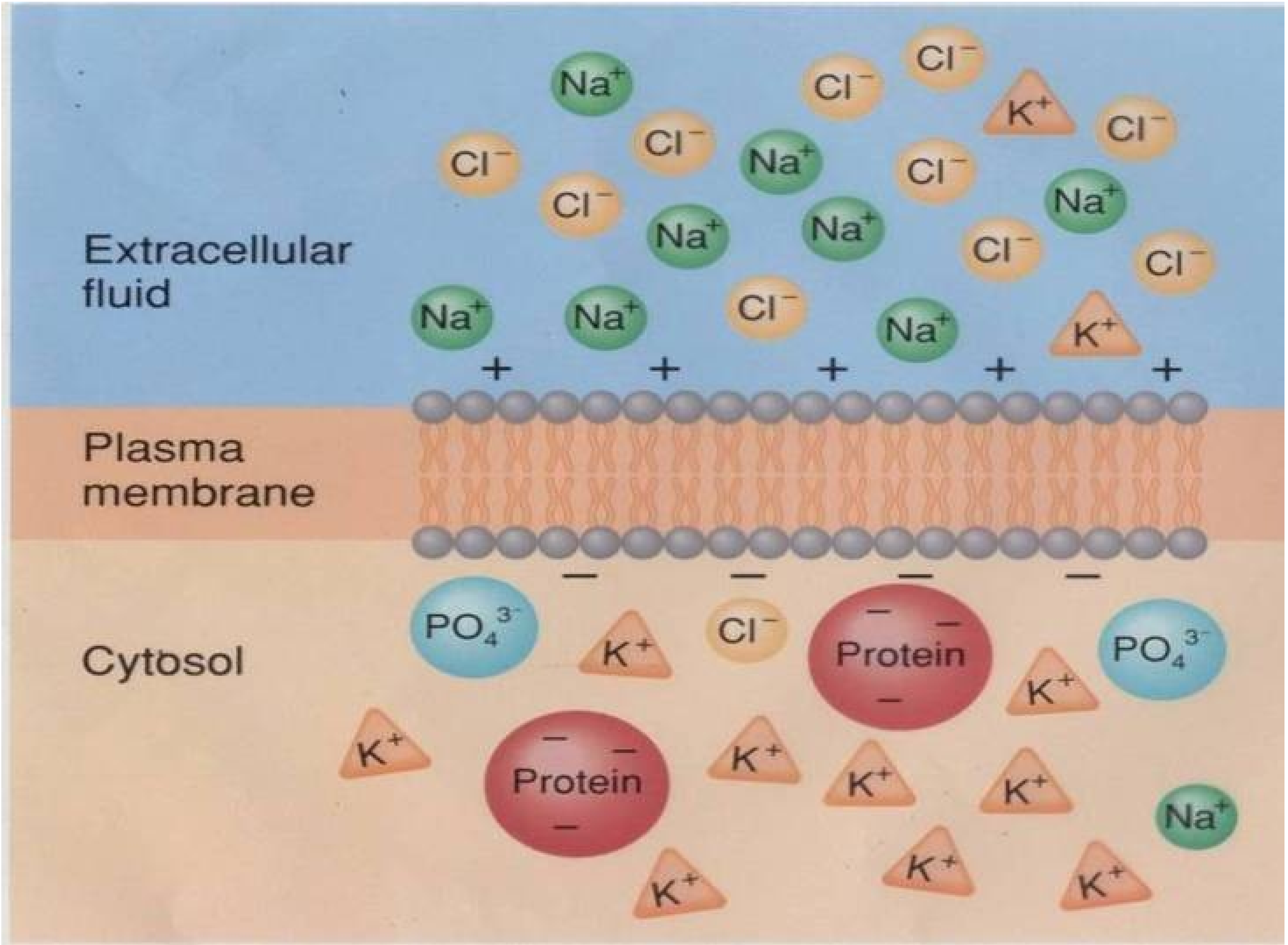
Nernst Potential

$$\Delta V = V_2 - V_1 = \frac{RT}{zF} \ln \frac{C_1}{C_2}$$

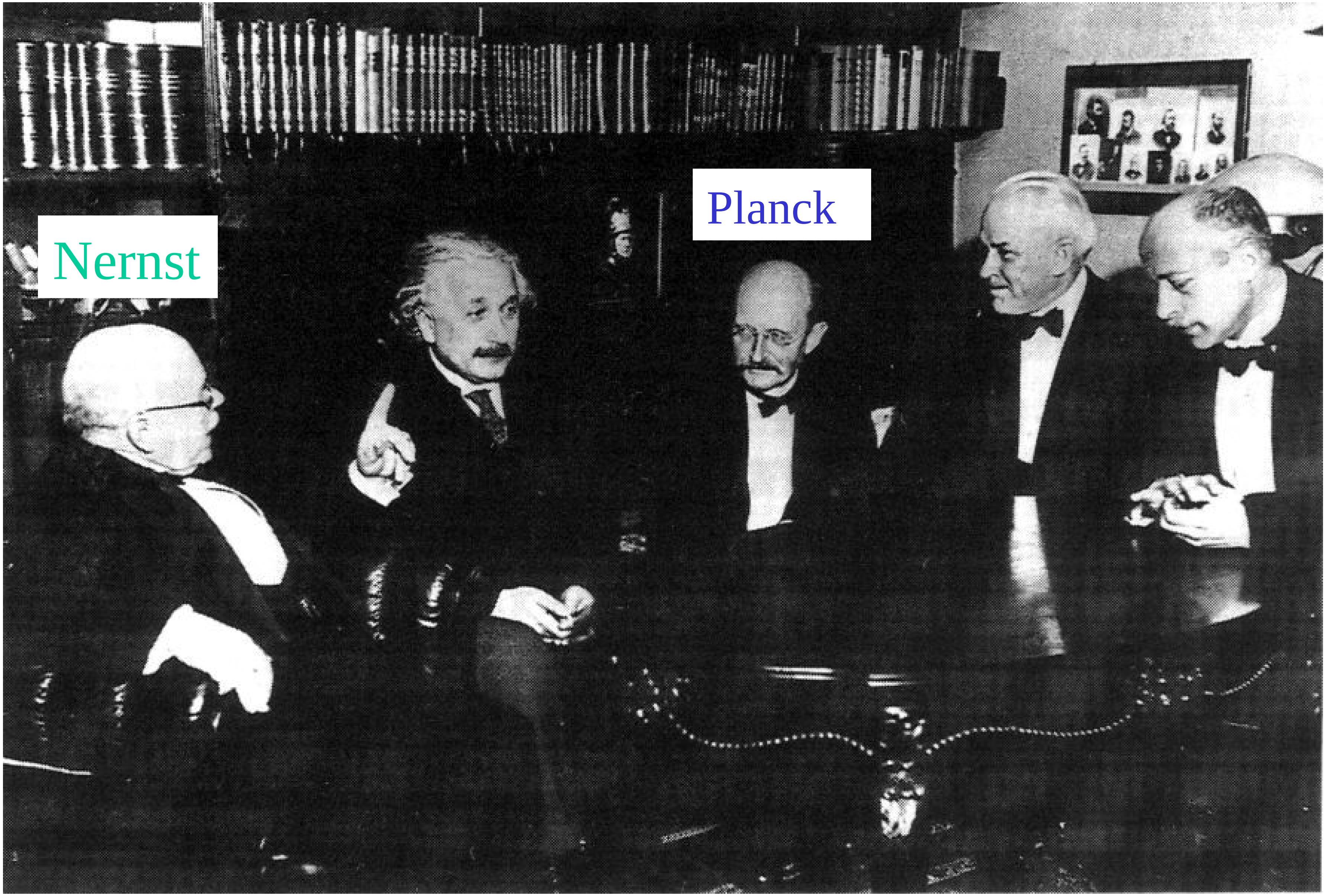
$$\frac{RT}{zF} = 25mV$$

$$\left(\Delta V\right)_{Na} = 25 \times 2.303 \log \frac{C_1}{C_2}$$

$$\approx 60 \log \frac{C_1}{C_2} mV$$


Extracellular fluid
Plasma membrane
Cytosol
Na^+
Cl^-
K^+
PO_4^{3-}
Protein

ION	CONCENTRATION (millimoles/liter) Extracellular	Intracellular	RELATIVE PERMEABILITY
Na^+	150	15	1
K^+	5	150	30
Cl^-	108	10	0.025
A^-	0	65	0


Nernst
Planck

Nernst-Planck Equation

$$\mu_i = \mu_i^0 + RT \ln C_i + z_i FV$$

$$J_i = Flux \quad mol\ L^{-2}\ T^{-1}$$

$$J_i = -u_i C_i \frac{d\mu_i}{dx}$$

FICK's Law

$$J_i = -u_i RT \frac{\partial C_i}{\partial x} - u_i C_i z_i F \frac{\partial V}{\partial x}$$

OHM's Law

$$D_i = u_i RT \quad Einstein's\ \mathrm{Re}lation$$

Integration of Nernst Planck Equation

CONSTANT FIELD MODEL

Goldmann Hodgkin Katz (GHK) Model

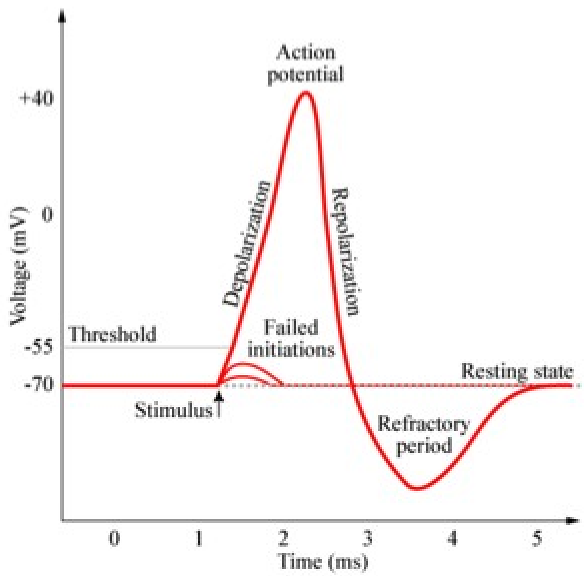
$$V = \frac{RT}{F} \ln \frac{P_{Na}C_{Na}^{1} + P_{K}C_{K}^{1} + P_{Cl}C_{Cl}^{2}}{P_{Na}C_{Na}^{2} + P_{K}C_{K}^{2} + P_{Cl}C_{Cl}^{1}}$$

Excitation of cells at resting membrane potential

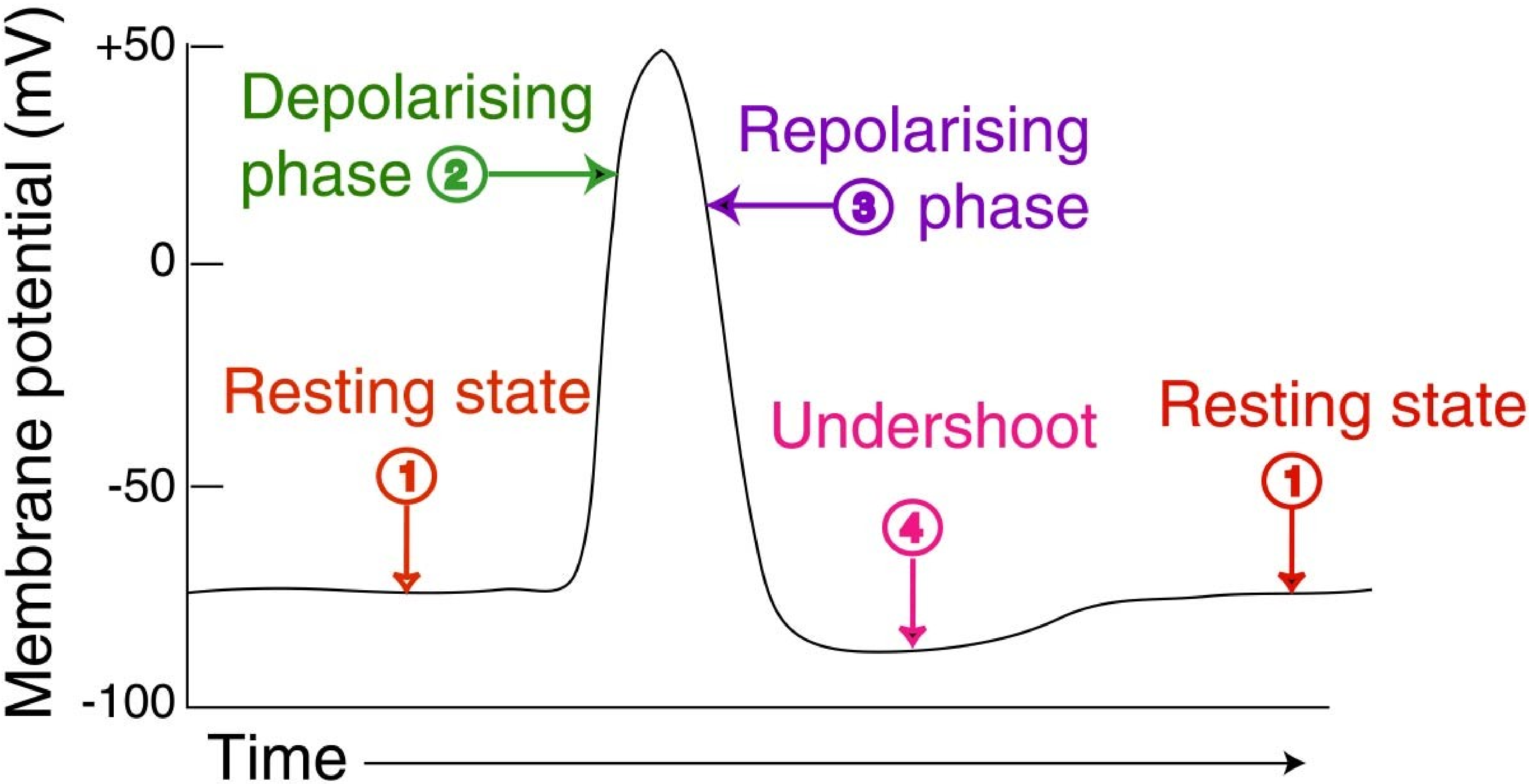
Passive Response

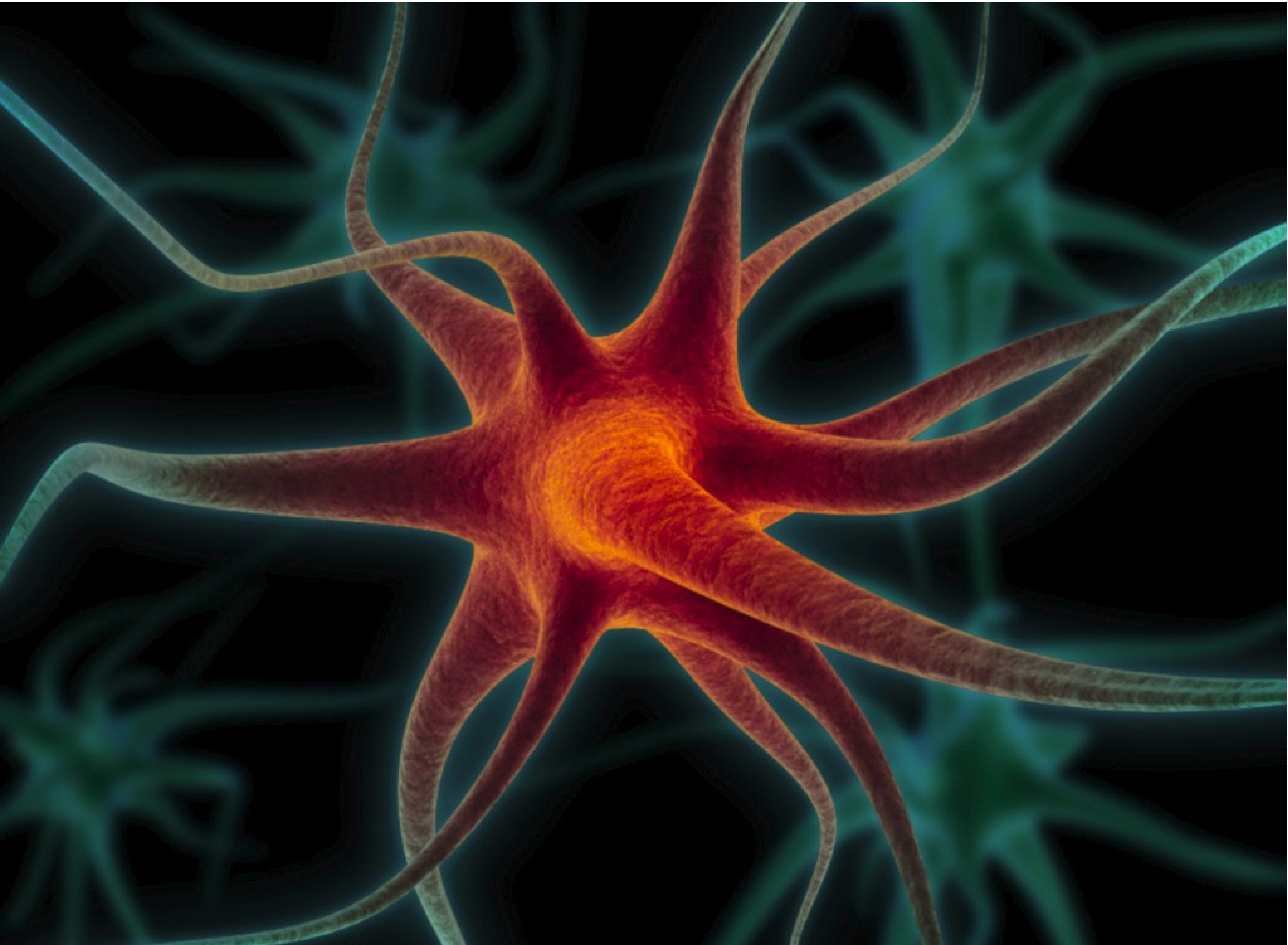
Excitable Cells

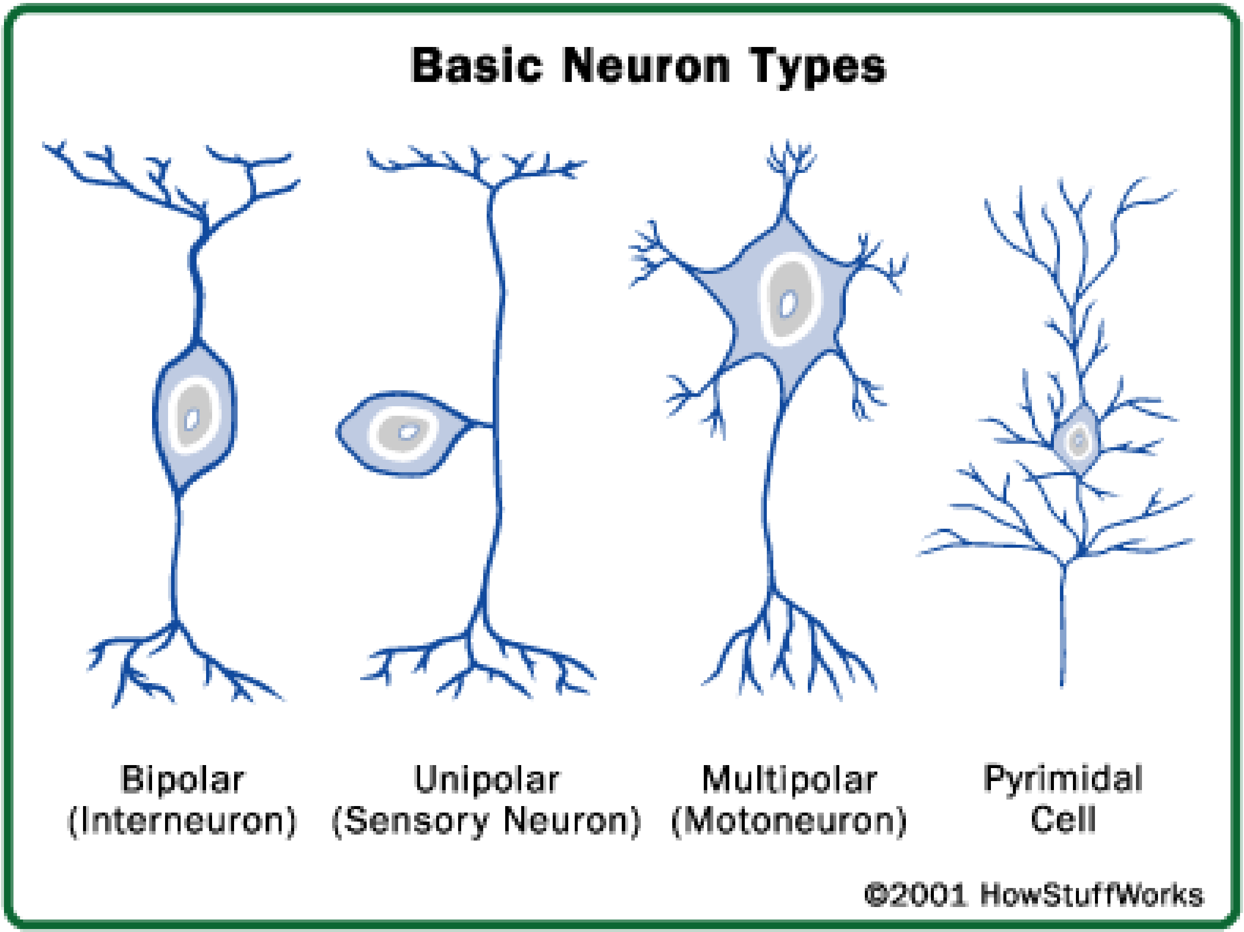
Action Potential



All or None response


Membrane potential (mV)
+50
0
-50
-100
Depolarising phase ②
Repolarising ③ phase
Resting state ①
Undershoot ④
Resting state ①
Time




Basic Neuron Types
Bipolar
(Interneuron)
Unipolar
(Sensory Neuron)
Multipolar
(Motoneuron)
Pyrimidal
Cell
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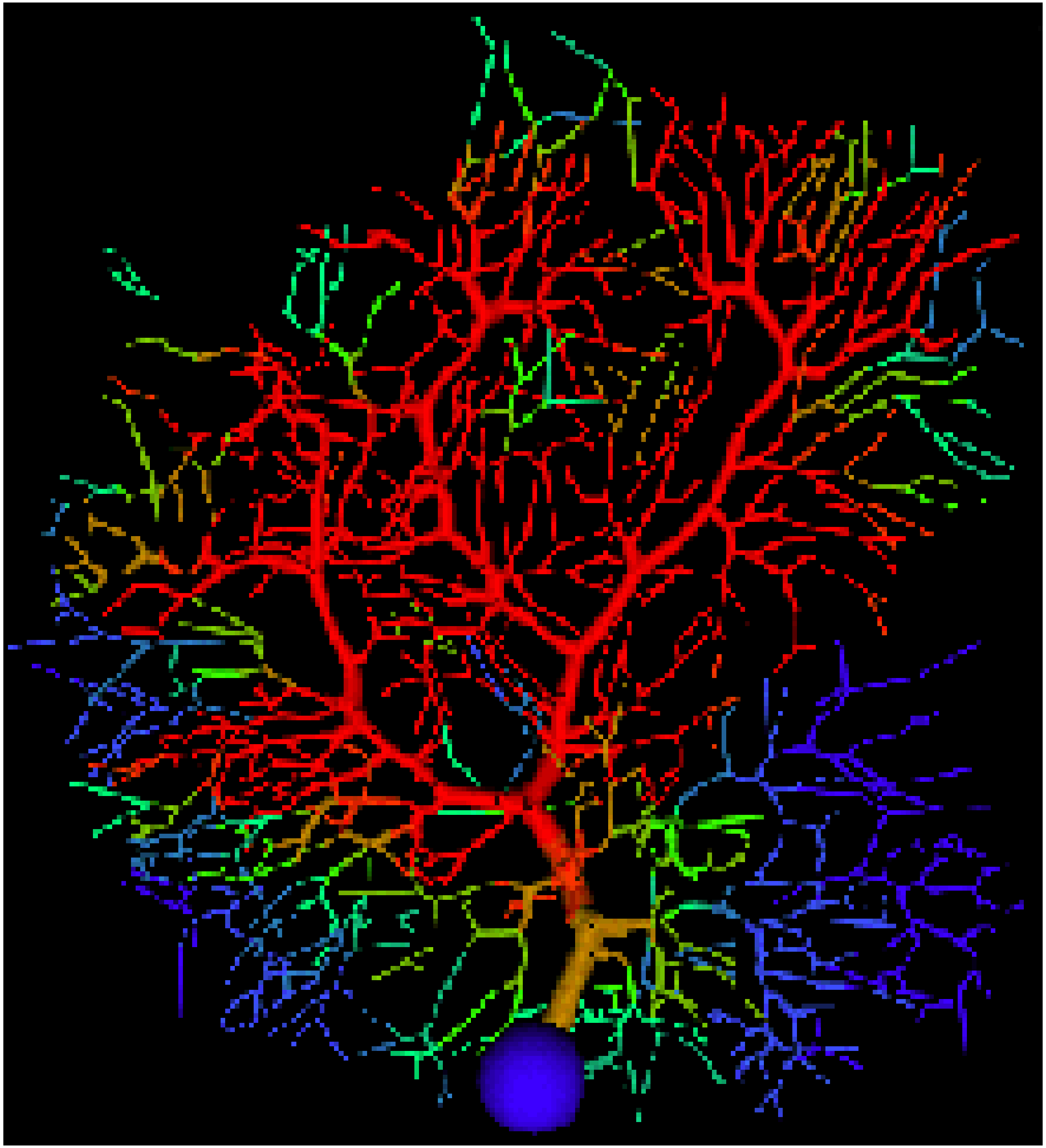
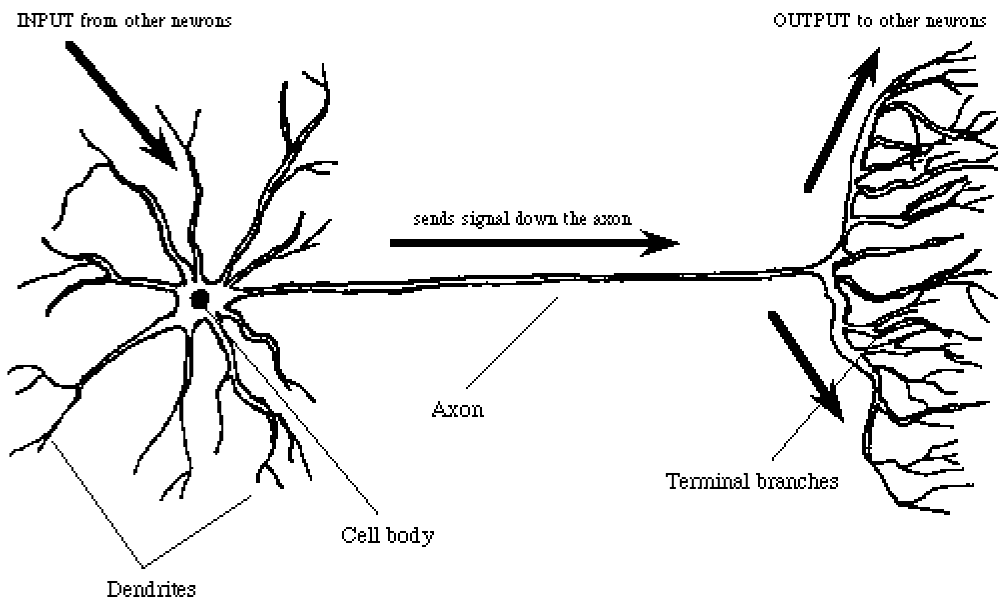
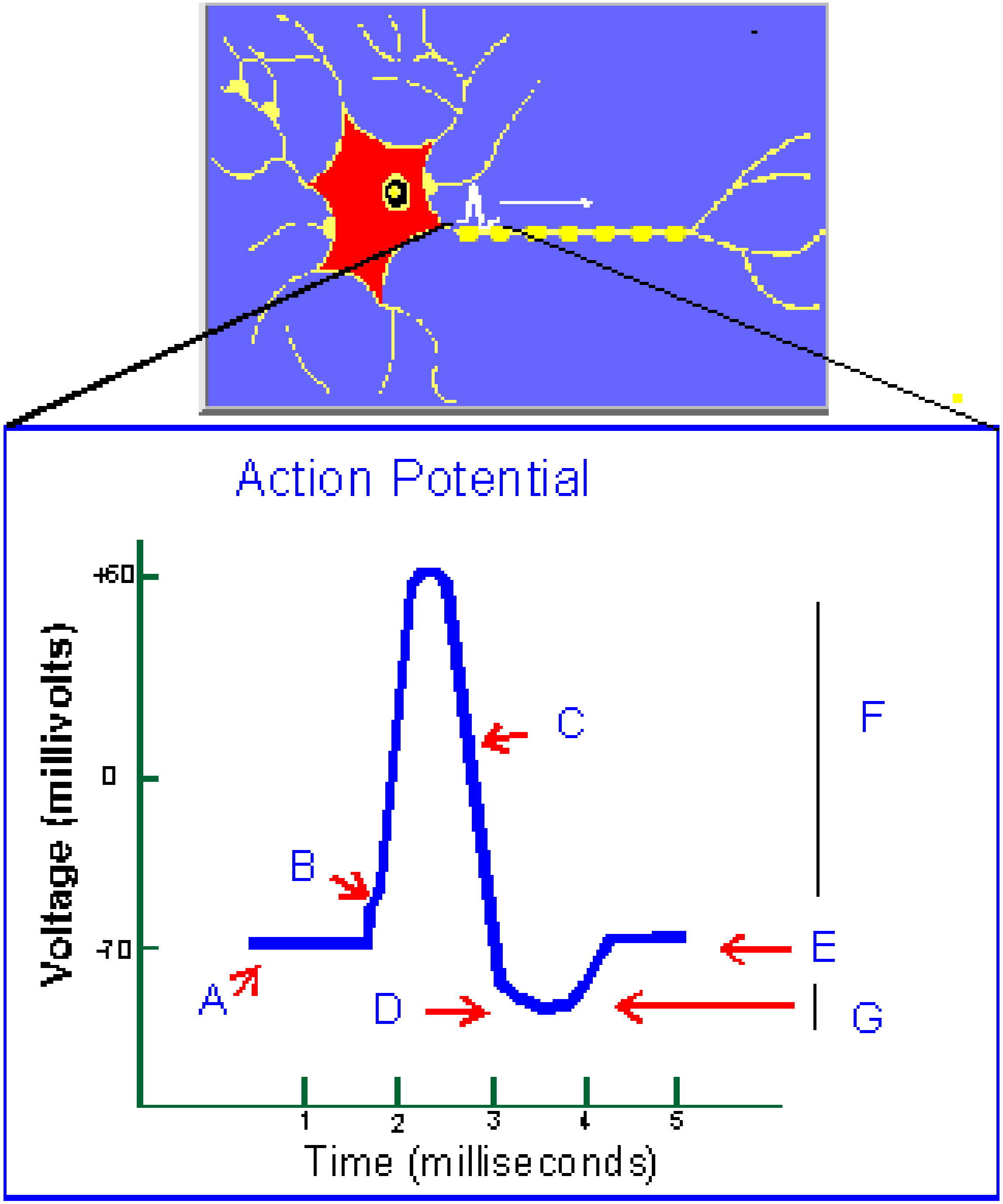



INPUT from other neurons
OUTPUT to other neurons
sends signal down the axon
Axon
Terminal branches
Cell body
Dendrites


Action Potential
Voltage (millivolts)
+60
0
-70
Time (milliseconds)
1
2
3
4
5
A
B
C
D
E
F
G

Currents Flowing in and out of the membrane During Action Potential

Capacitative current $$C_m \frac{dV}{dt}$$

Resting membrane potential = K-Nernst potential

Peak of action potential = Na-Nernst Potential

Nonlinearity in the current flow

Necessity of a voltage clamp machine

Separation of ionic currents

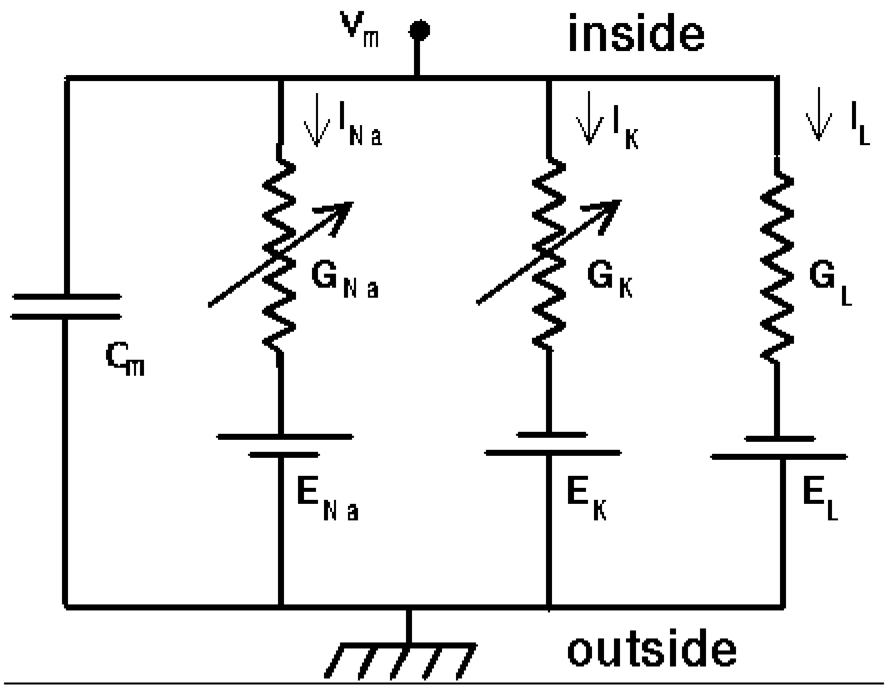
TTX (Tetrodotoxin) Na-Channel Blocker

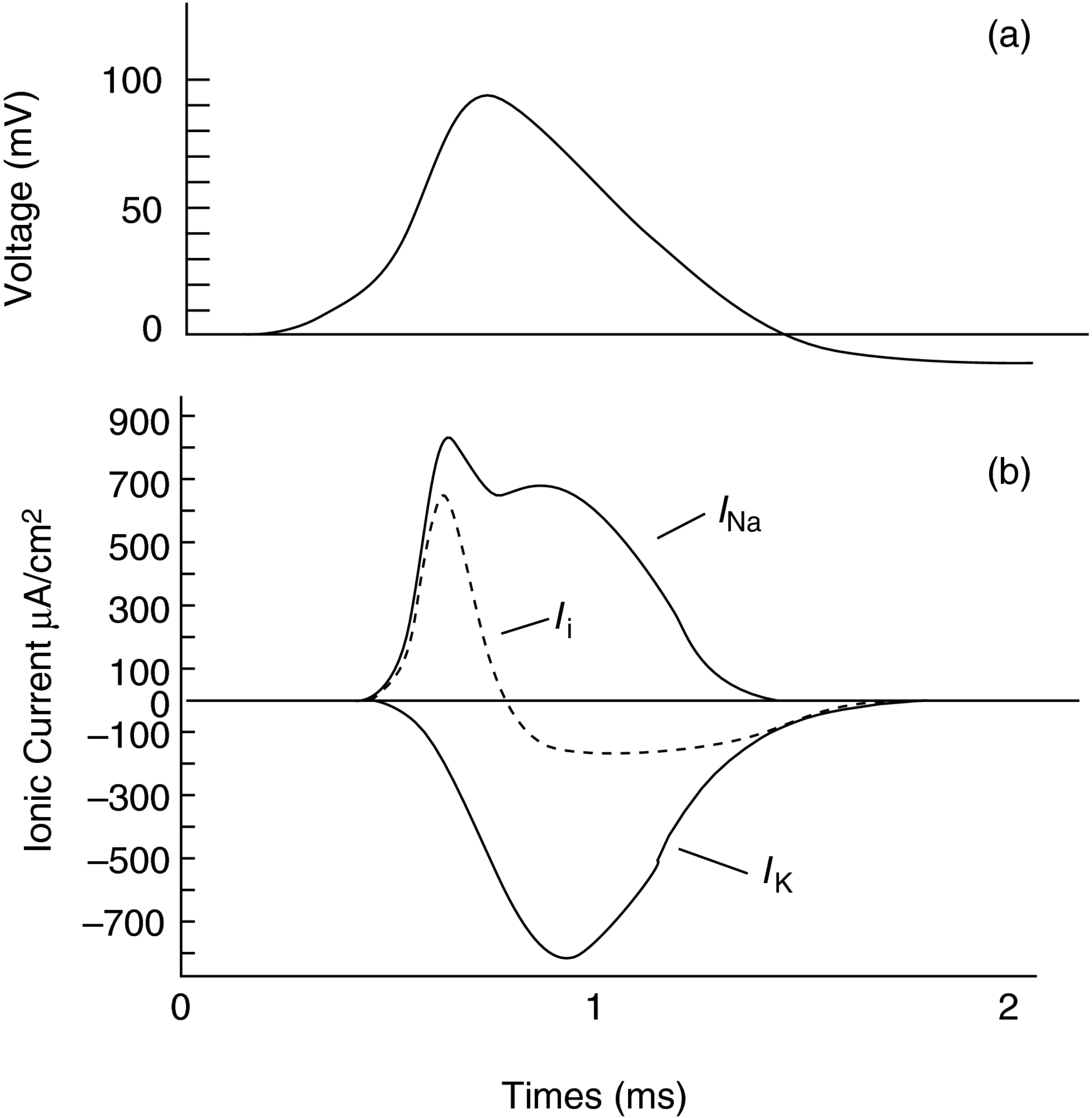
TEA (Tetra-ethyl-ammonium)   K-channel blocker

Na and K channel conductance depends on membrane voltage

Chloride and non-specific ions follow Ohm's law

Equivalent Circuit





(a)
Voltage (mV)
100
50
0
(b)
Ionic Current μA/cm²
900
700
500
300
100
0
–100
–300
–500
–700
I_{Na}
I_i
I_K
0
1
2
Times (ms)

$$I = C_M \frac{dV}{dT} + \bar{g}_K n^4 (V - V_K) + \bar{g}_{Na} m^3 h (V - V_{Na}) + \bar{g}_l (V - V_l)$$

$$\frac{dn}{dt} = \alpha_n (1 - n) - \beta_n n$$

$$\frac{dm}{dt} = \alpha_m (1 - m) - B_m m$$

$$\frac{dh}{dt} = \alpha_h (1 - h) - \beta_h h$$

$$\alpha_n = \frac{0.01(V + 10)}{e^{\frac{V-10}{10}} - 1}$$

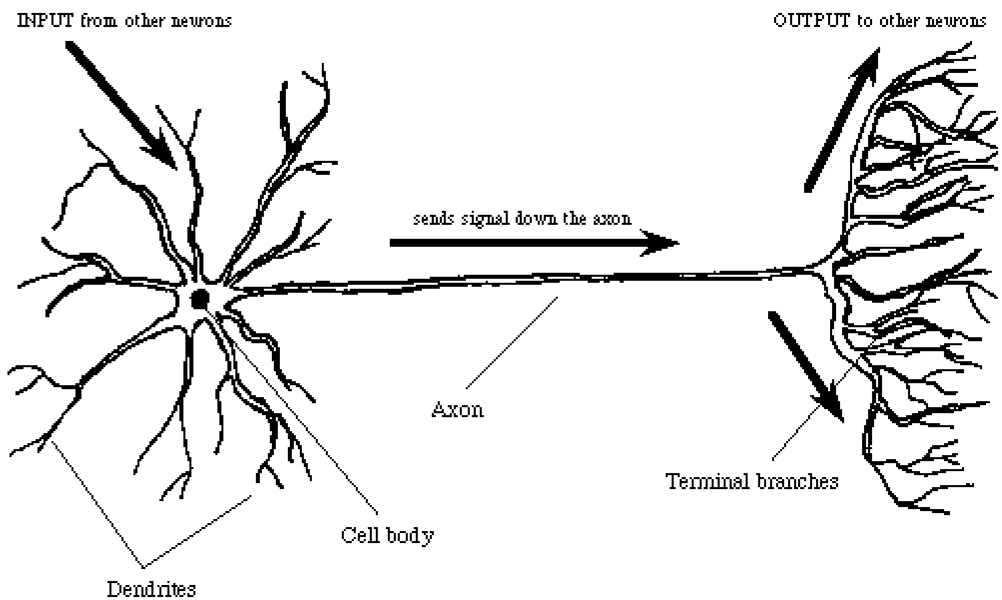
$$\beta_n = 0.125 e^{(V/80)}$$

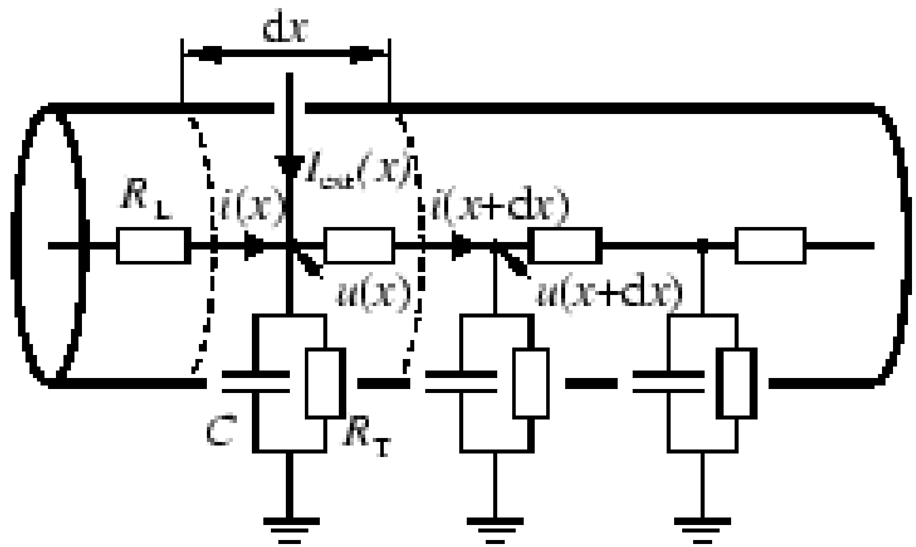
$$\alpha_m = \frac{0.1(V + 25)}{e^{\frac{V+25}{10}} - 1}$$

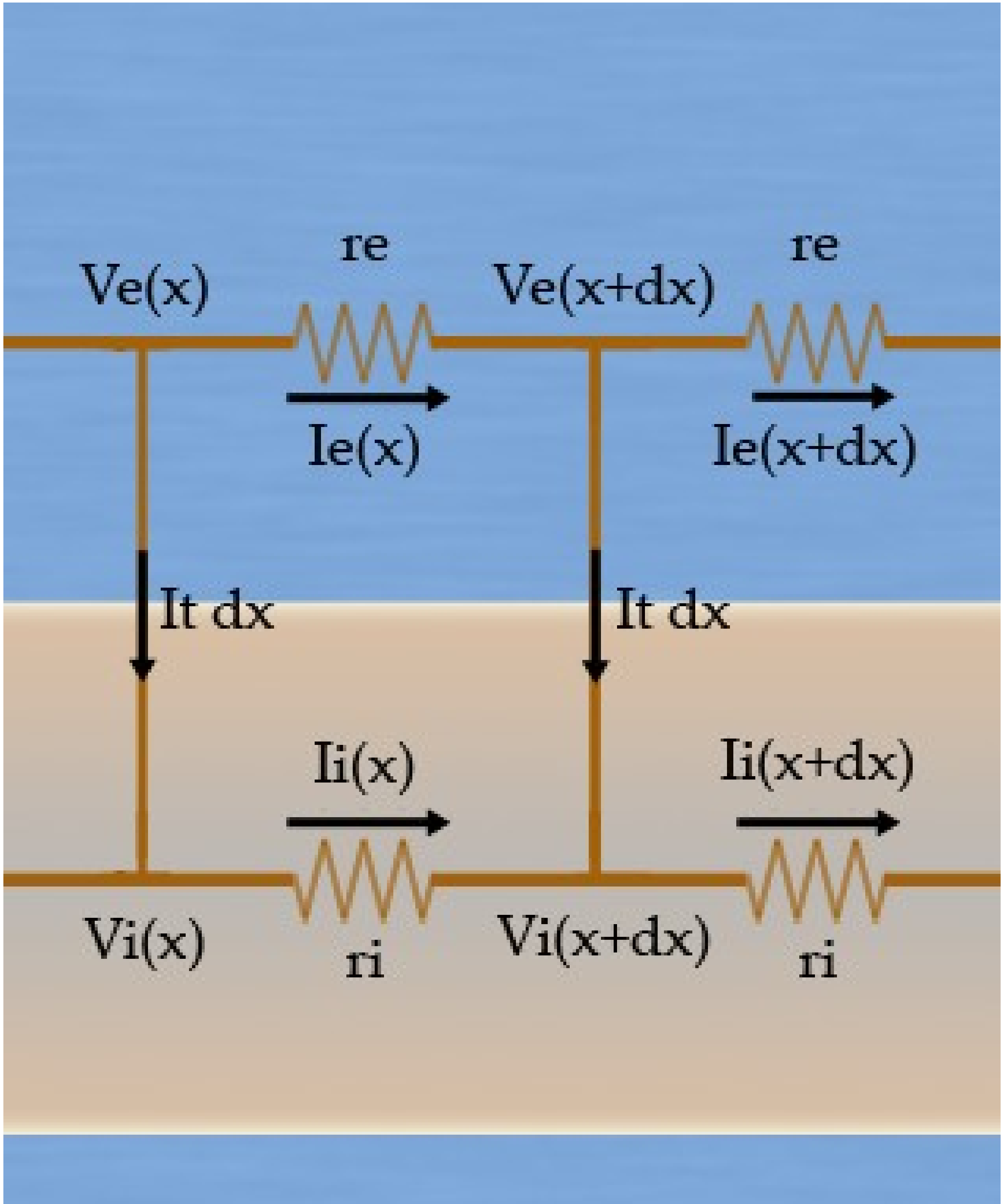
$$\beta_m = 4 e^{(V/18)}$$

$$\alpha_h = 0.07 e^{\frac{V}{20}}$$

$$\beta_h = \frac{1}{e^{\frac{V+30}{10}} + 1}$$


INPUT from other neurons
OUTPUT to other neurons
sends signal down the axon
Axon
Terminal branches
Cell body
Dendrites


dx
$I_{out}(x)$
R_L
$i(x)$
$i(x+dx)$
$u(x)$
$u(x+dx)$
C
R_T

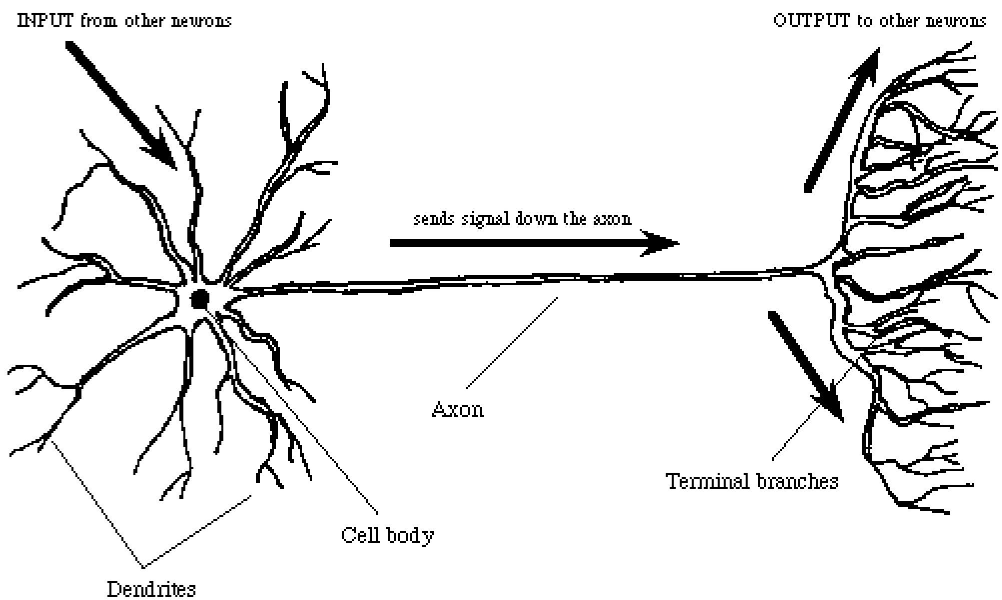

re
re
Ve(x)
Ve(x+dx)
Ie(x)
Ie(x+dx)
It dx
It dx
Ii(x)
Ii(x+dx)
Vi(x)
Vi(x+dx)
ri
ri

Propagation of Axon Potential

$$\frac{1}{factor}\frac{\partial^2 V}{\partial x^2} = I_m$$

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$

$$\frac{1}{factor}\frac{1}{v^2}\frac{\partial^2 V}{\partial t^2} = I_m = C_m\frac{\partial V}{\partial t} + \sum_i I_i$$


INPUT from other neurons
OUTPUT to other neurons
sends signal down the axon
Axon
Terminal branches
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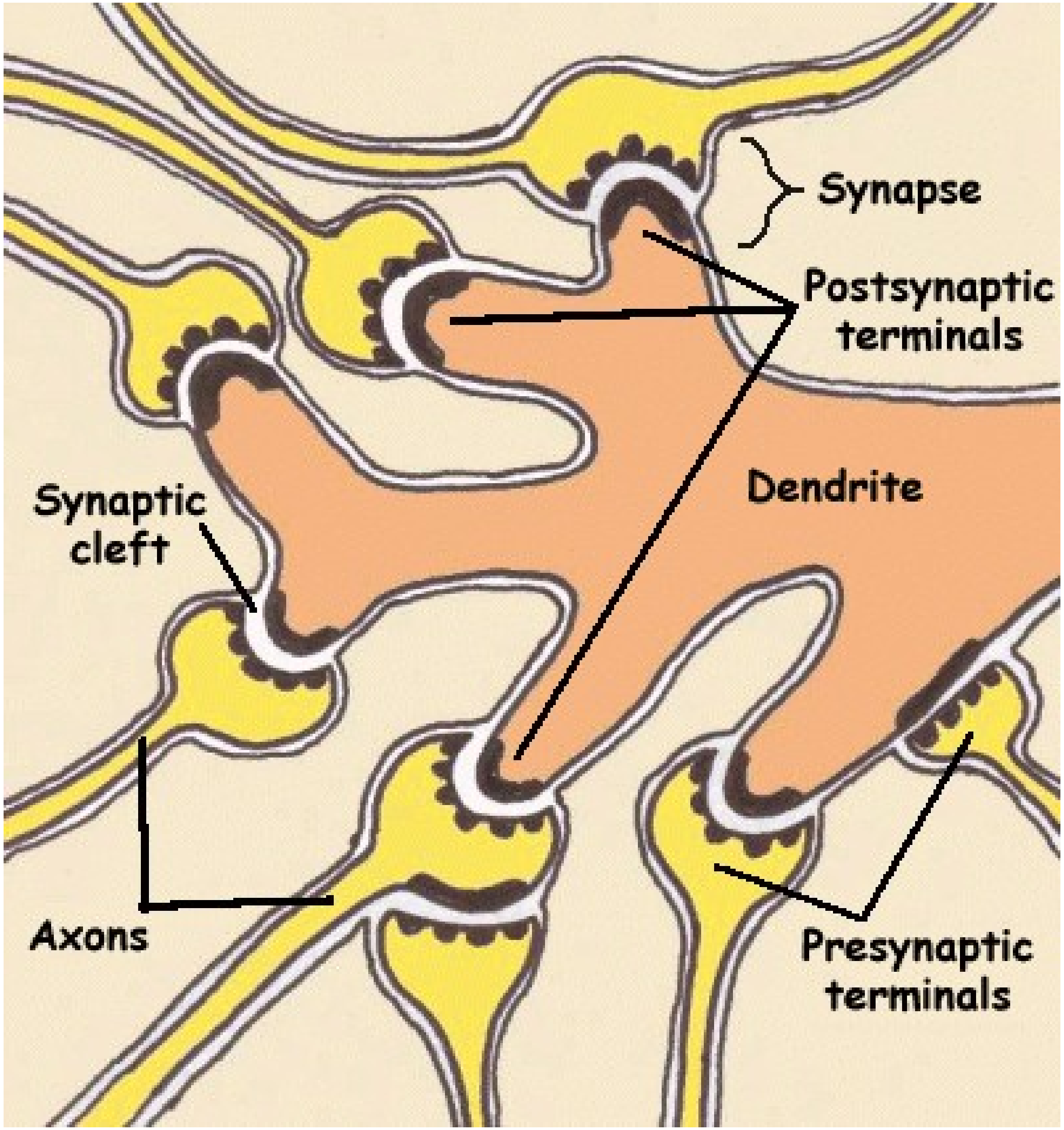
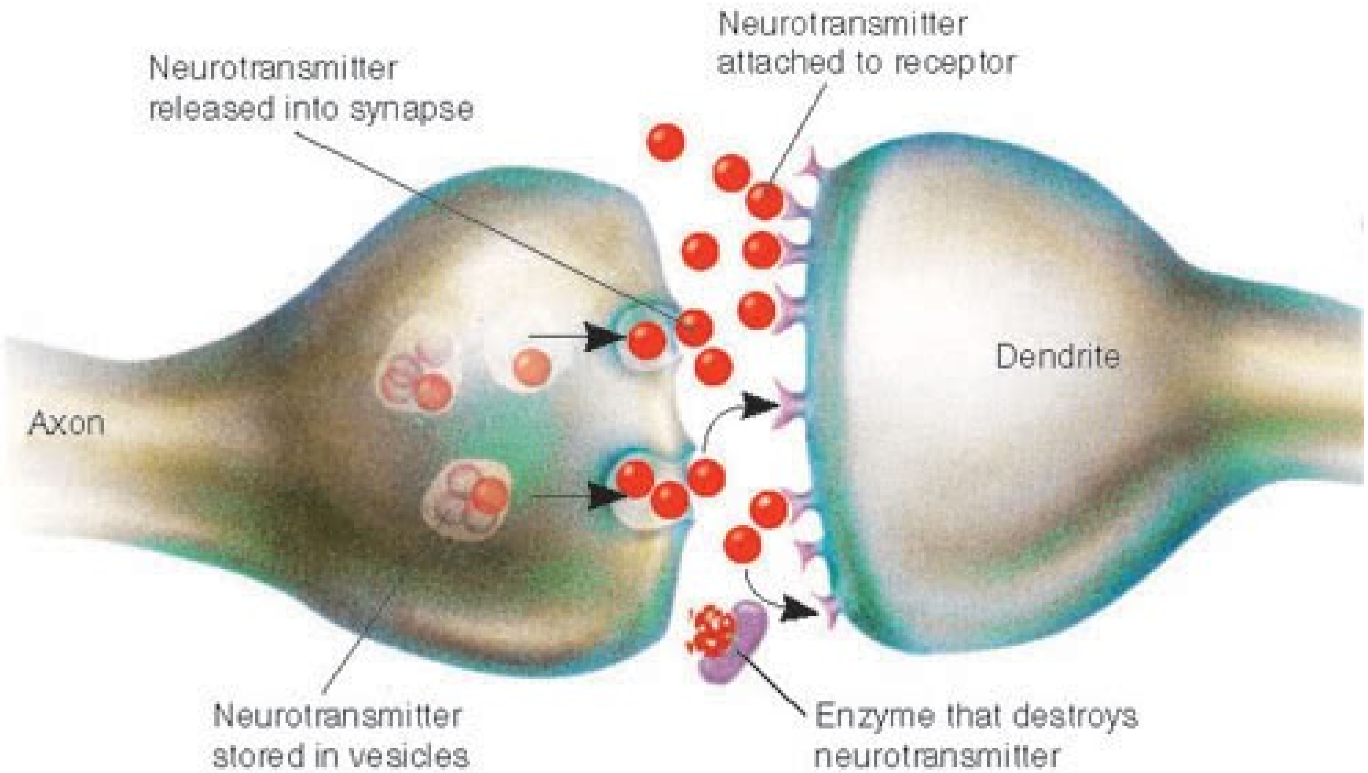
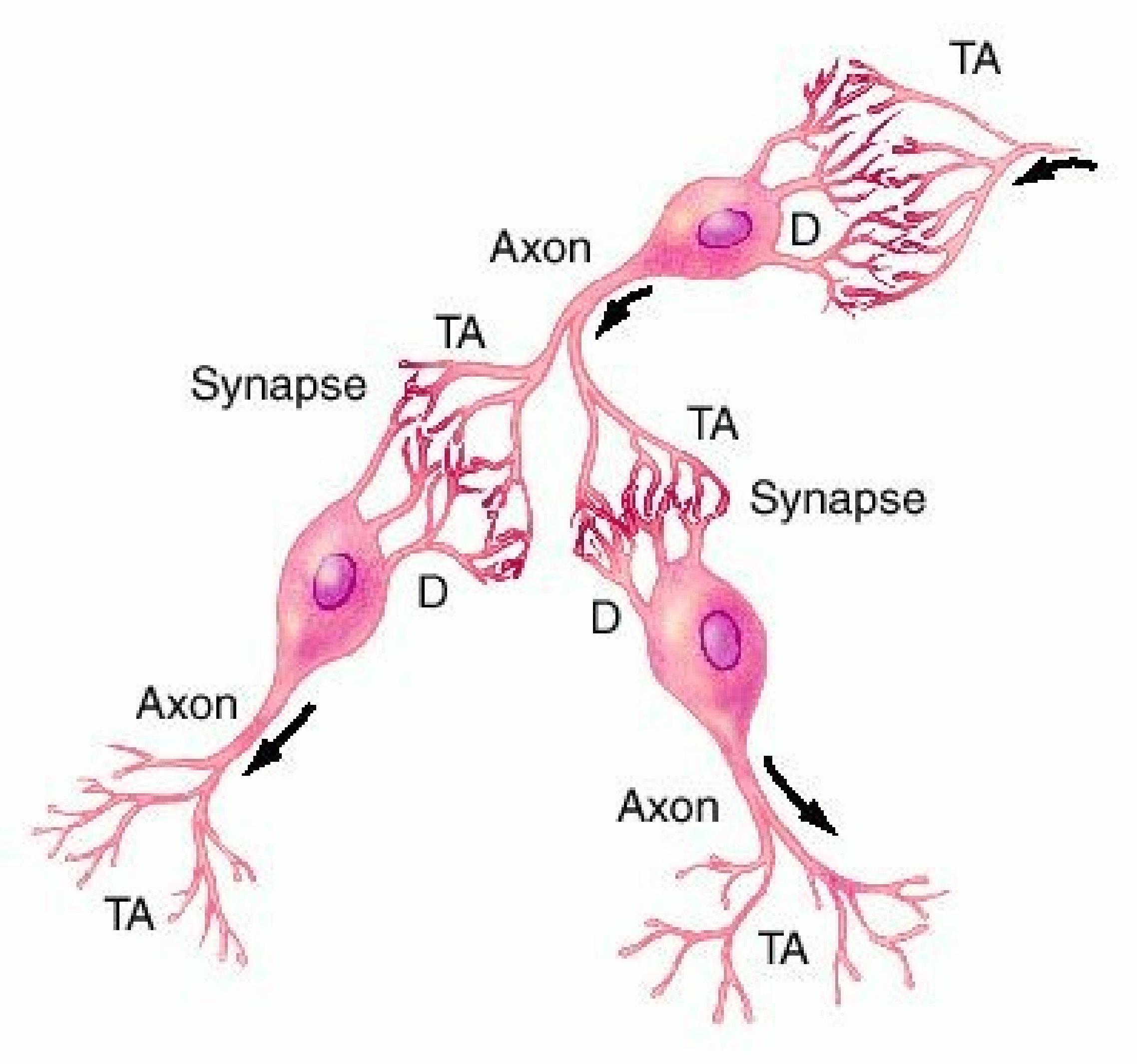
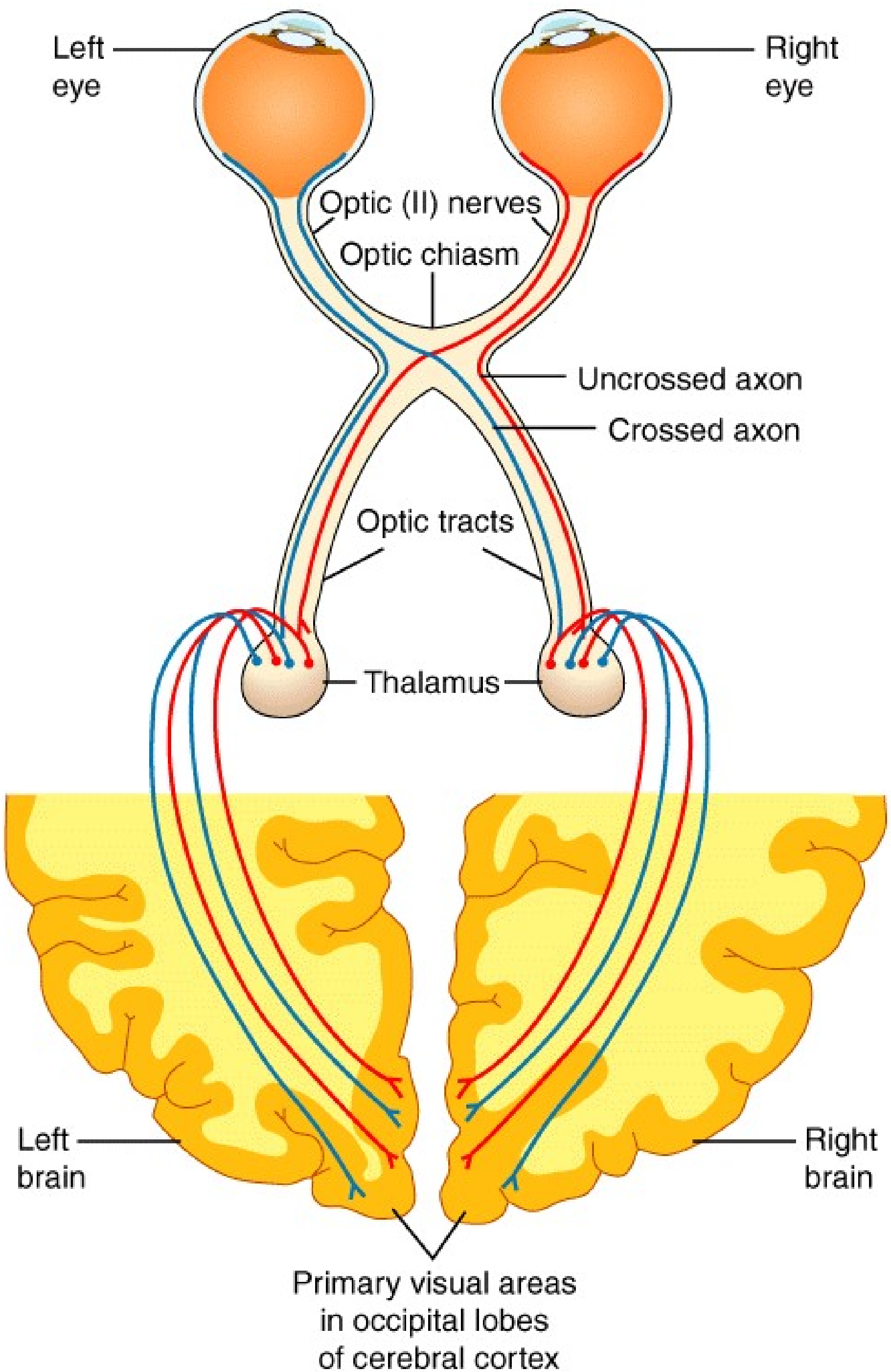
Dendrites



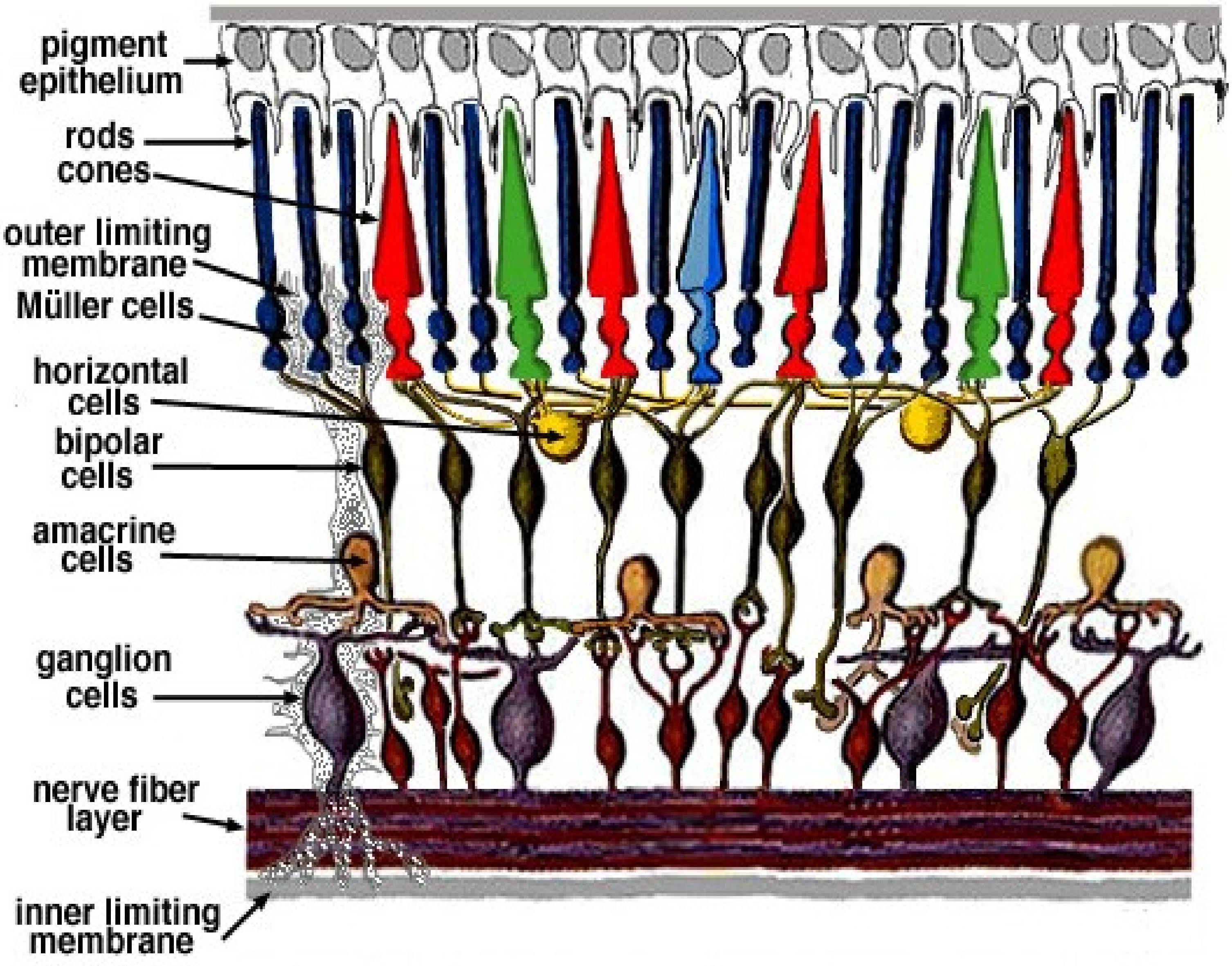
Synapse
Postsynaptic terminals
Dendrite
Synaptic cleft
Axons
Presynaptic terminals

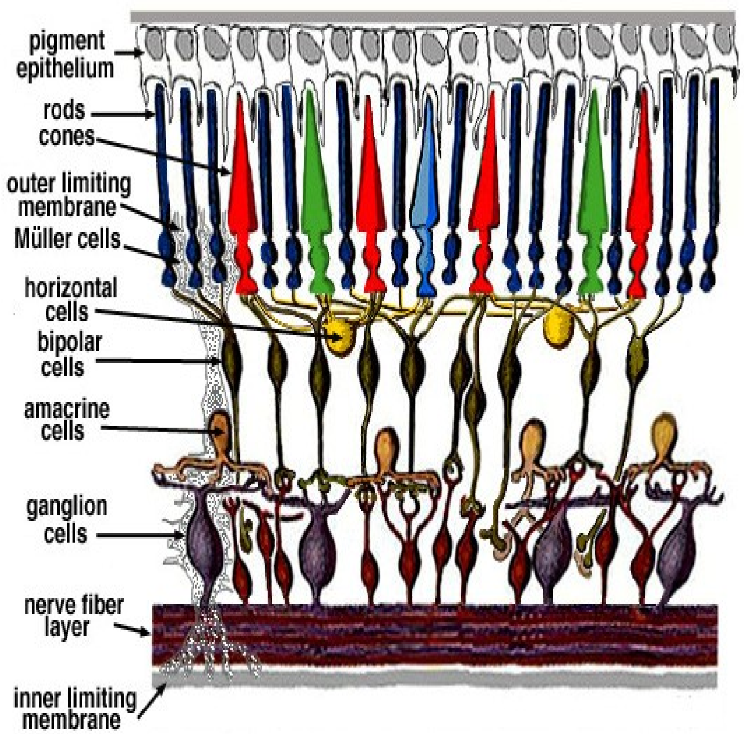

Neurotransmitter
released into synapse
Neurotransmitter
attached to receptor
Dendrite
Axon
Neurotransmitter
stored in vesicles
Enzyme that destroys
neurotransmitter

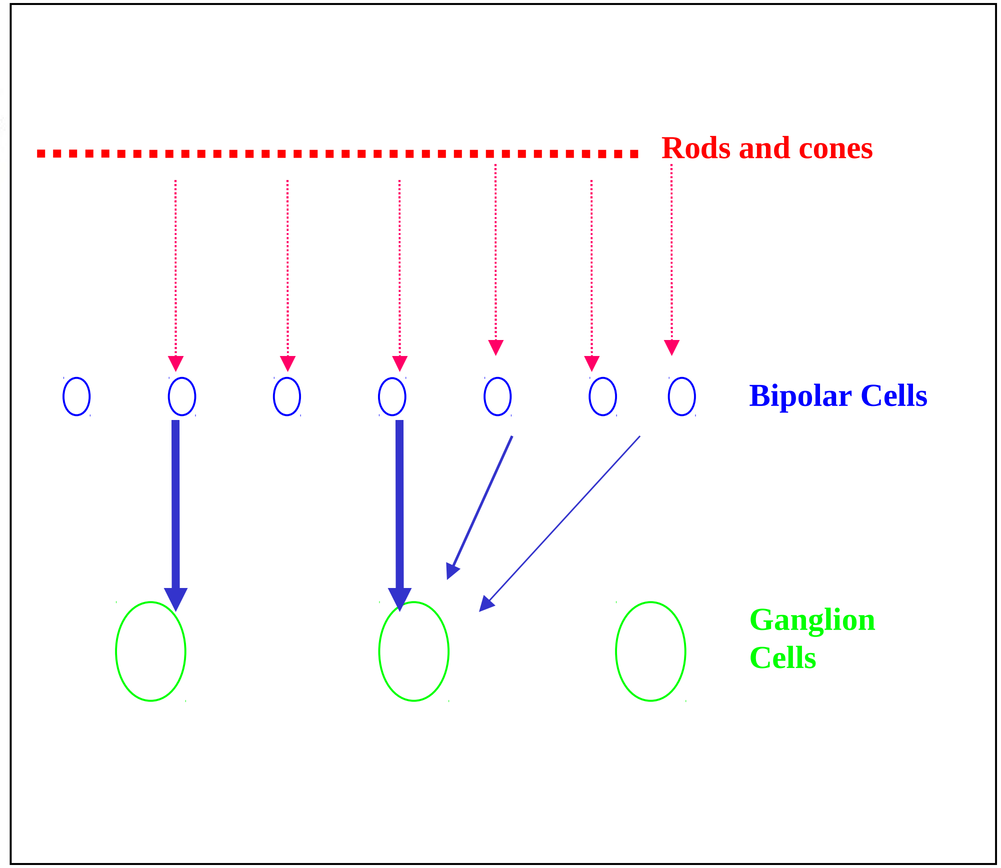

TA
D
Axon
TA
Synapse
TA
Synapse
D
D
Axon
Axon
TA
TA



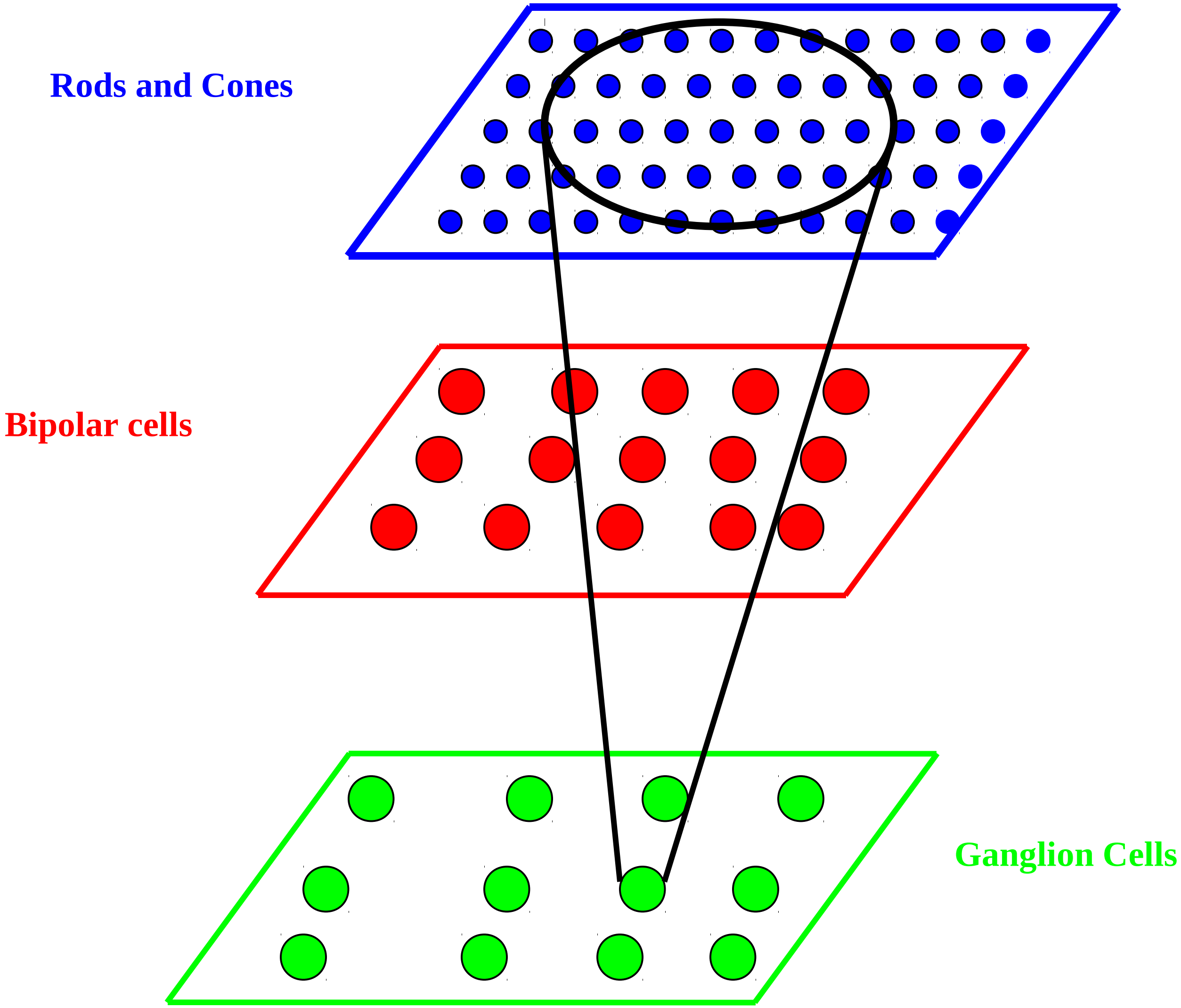
Left eye
Right eye
Optic (II) nerves
Optic chiasm
Uncrossed axon
Crossed axon
Optic tracts
Thalamus
Left brain
Right brain
Primary visual areas in occipital lobes of cerebral cortex

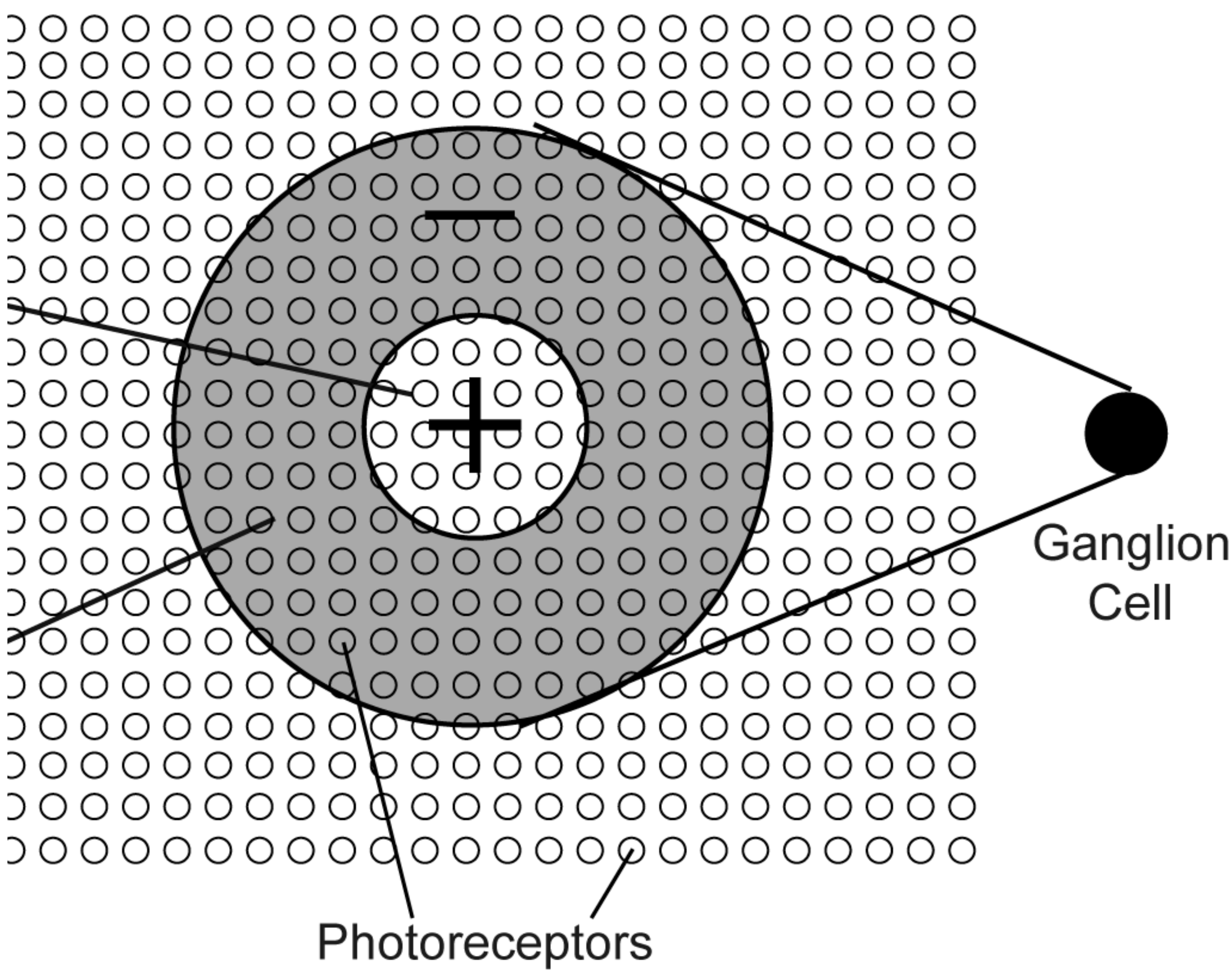

pigment
epithelium
rods
cones
outer limiting
membrane
Müller cells
horizontal
cells
bipolar
cells
amacrine
cells
ganglion
cells
nerve fiber
layer
inner limiting
membrane


pigment epithelium
rods
cones
outer limiting membrane
Müller cells
horizontal cells
bipolar cells
amacrine cells
ganglion cells
nerve fiber layer
inner limiting membrane

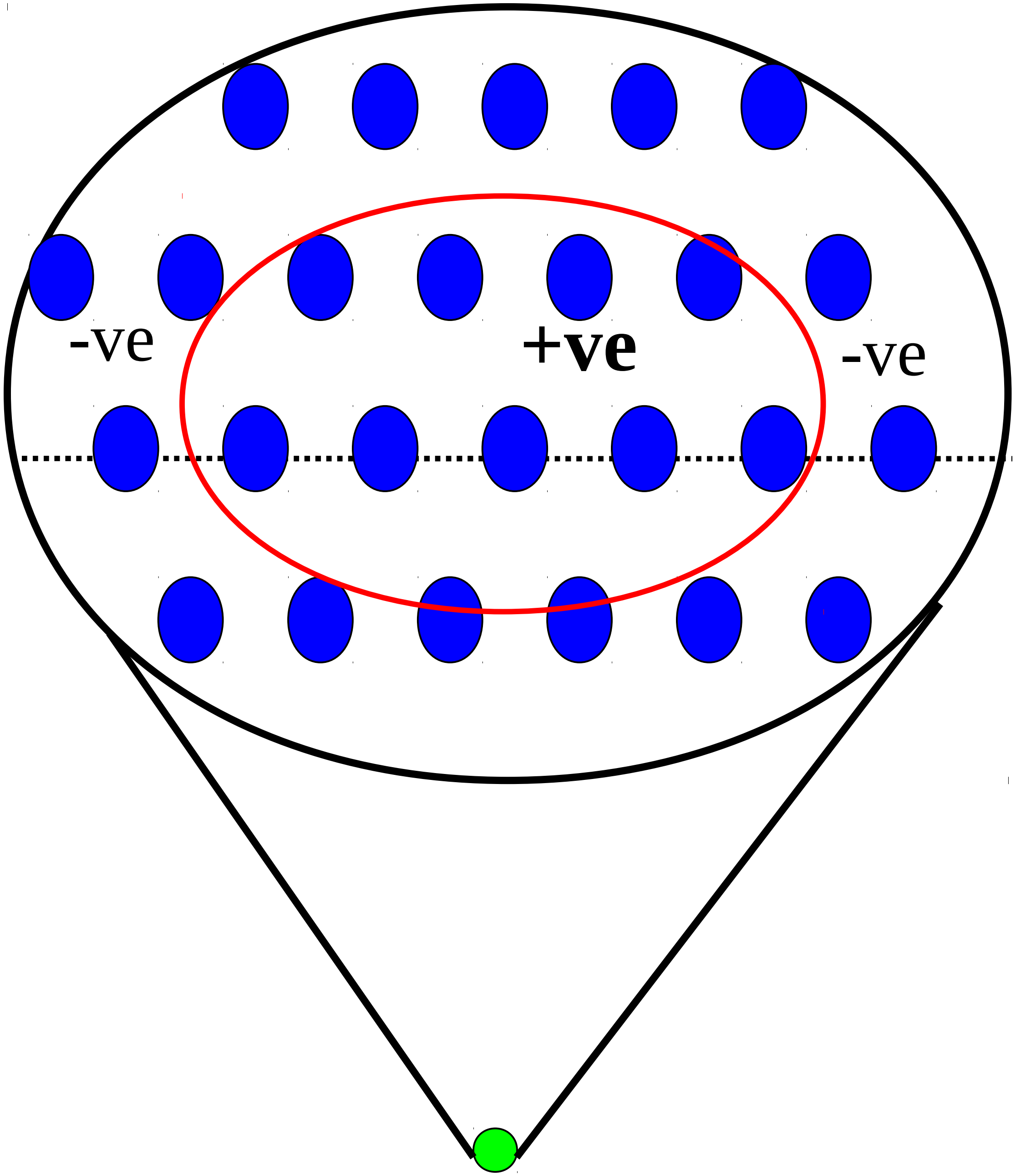

Rods and cones
Bipolar Cells
Ganglion Cells

Receptive field of Ganglion cell

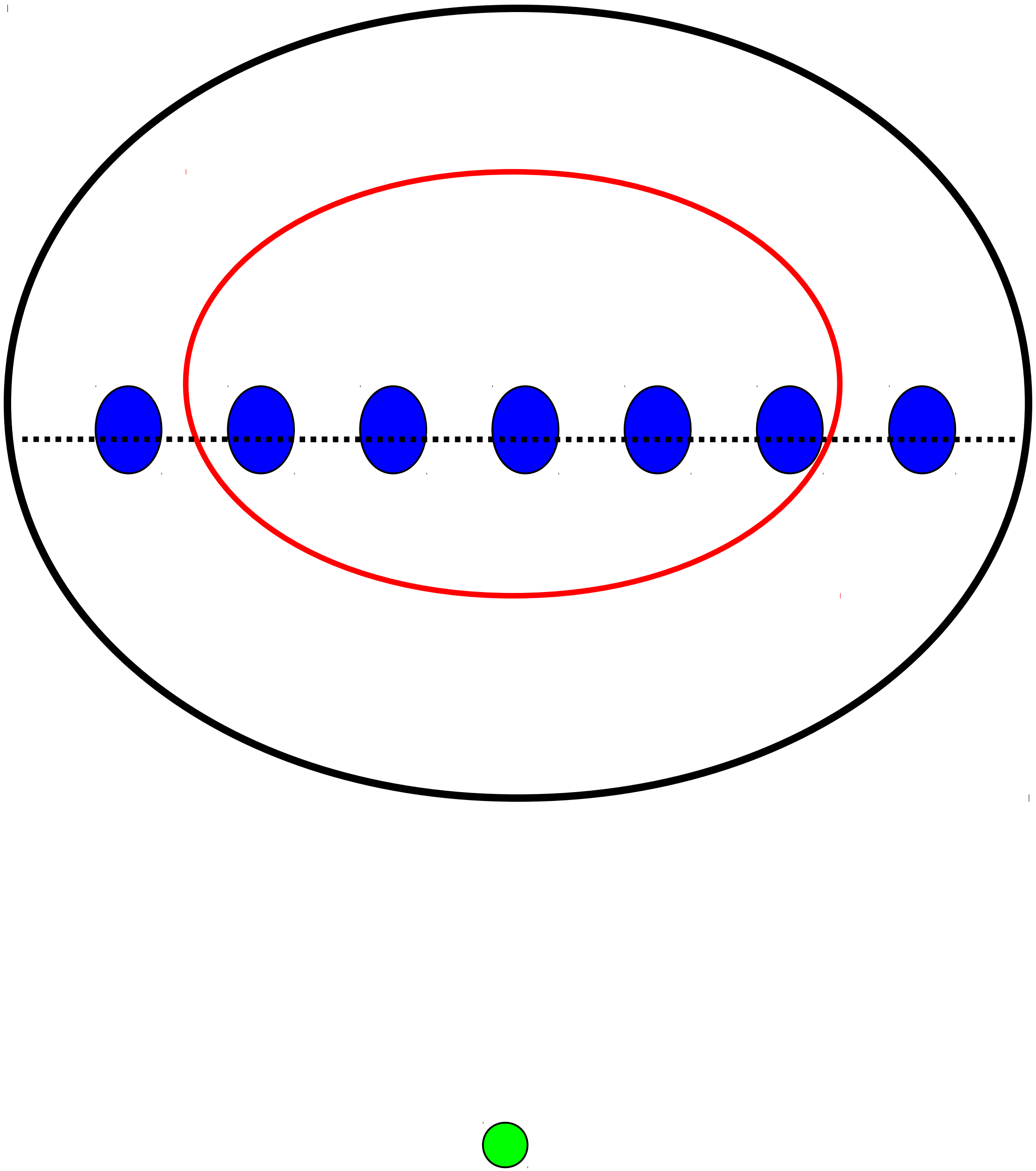


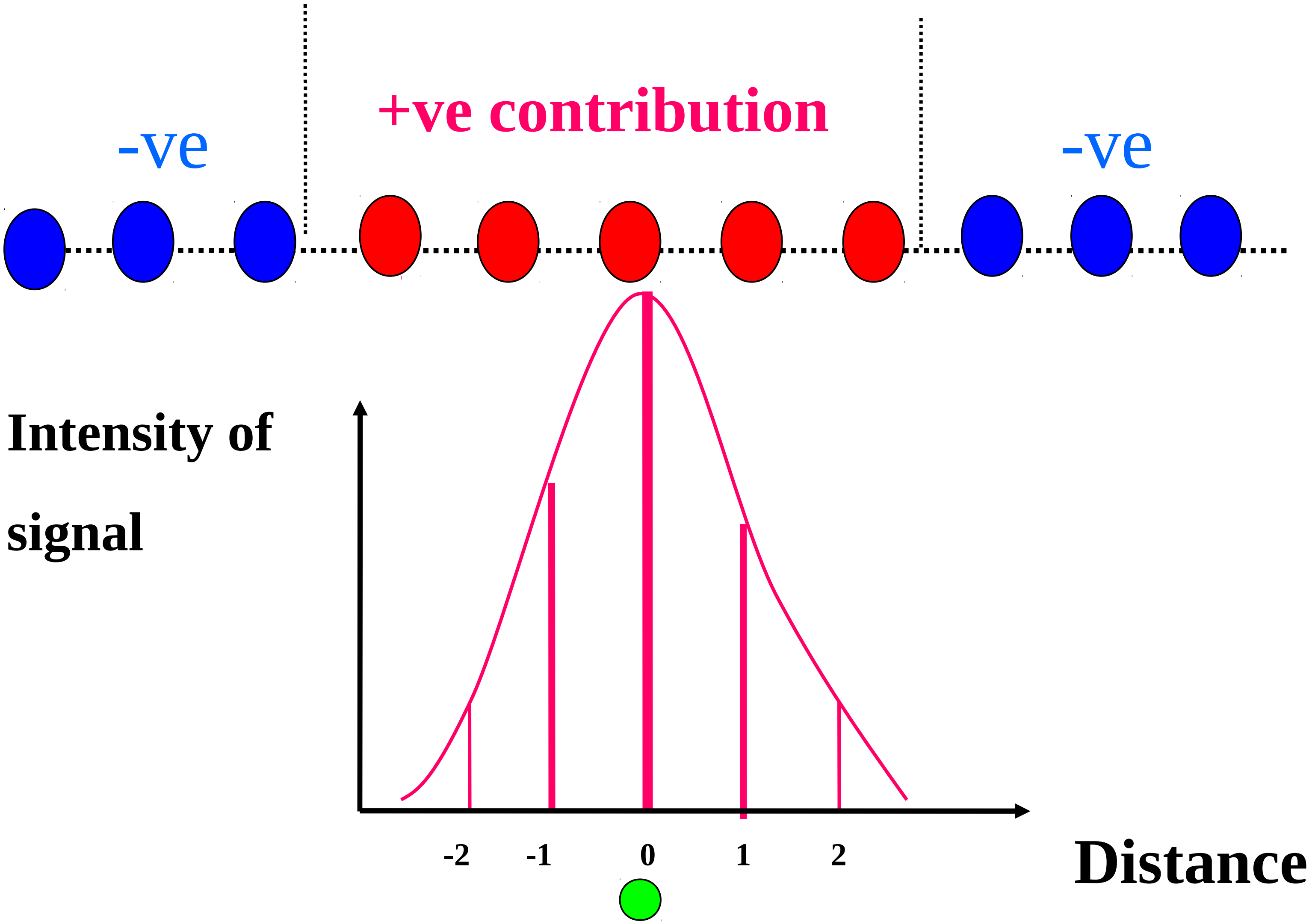


−
+
Ganglion Cell
Photoreceptors



-ve
+ve
-ve



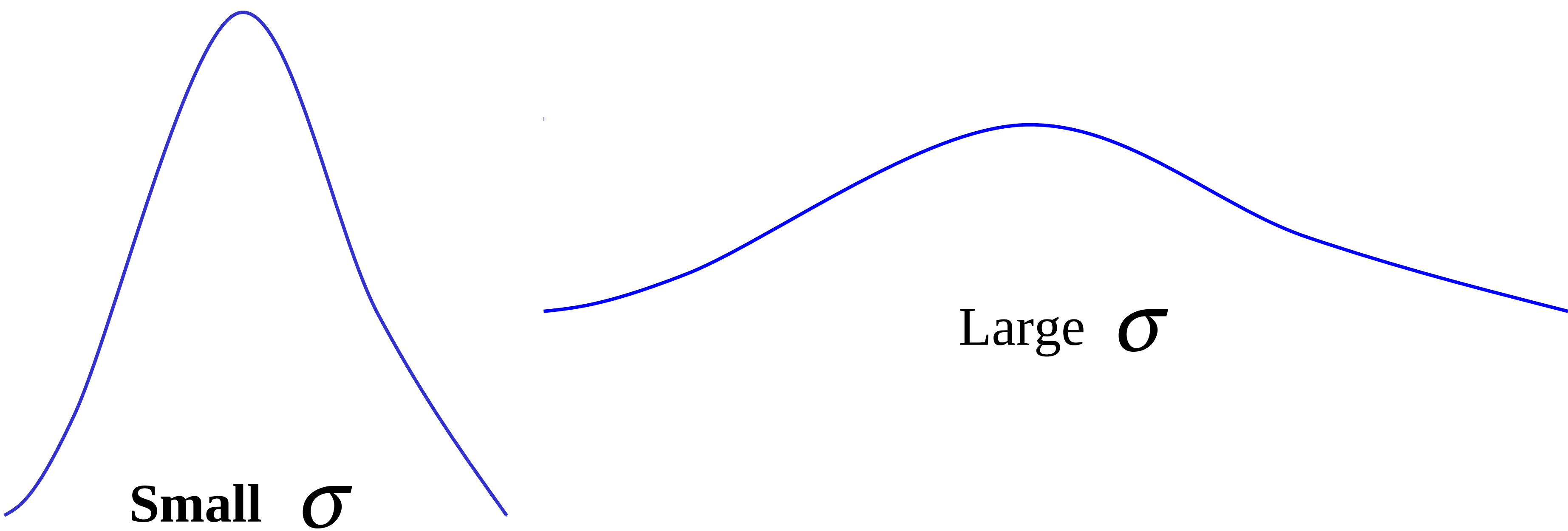


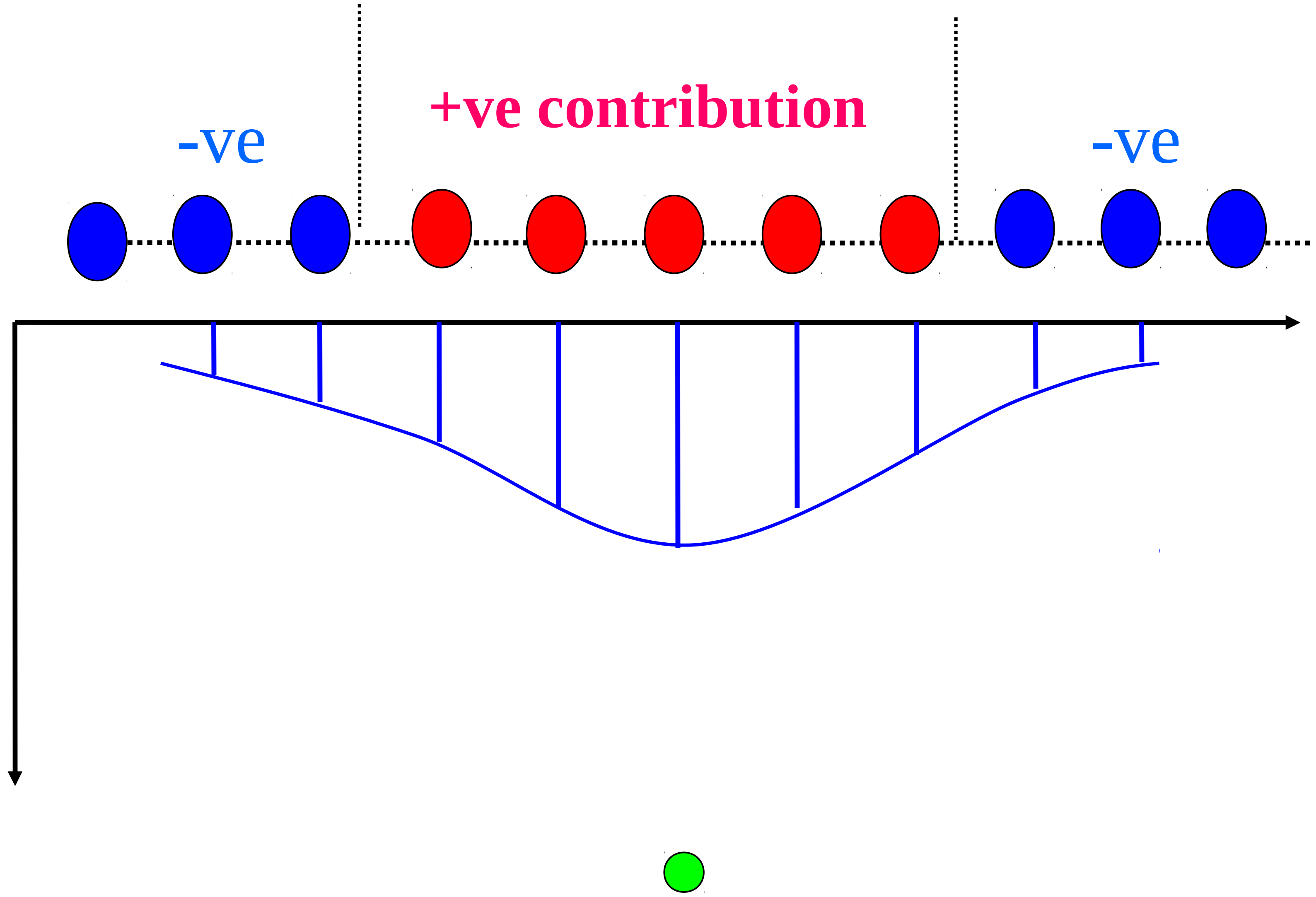
+ve contribution
-ve
-ve
Intensity of
signal
-2
-1
0
1
2
Distance

A Gaussian function, whose mean value is kept at zero, is given by:

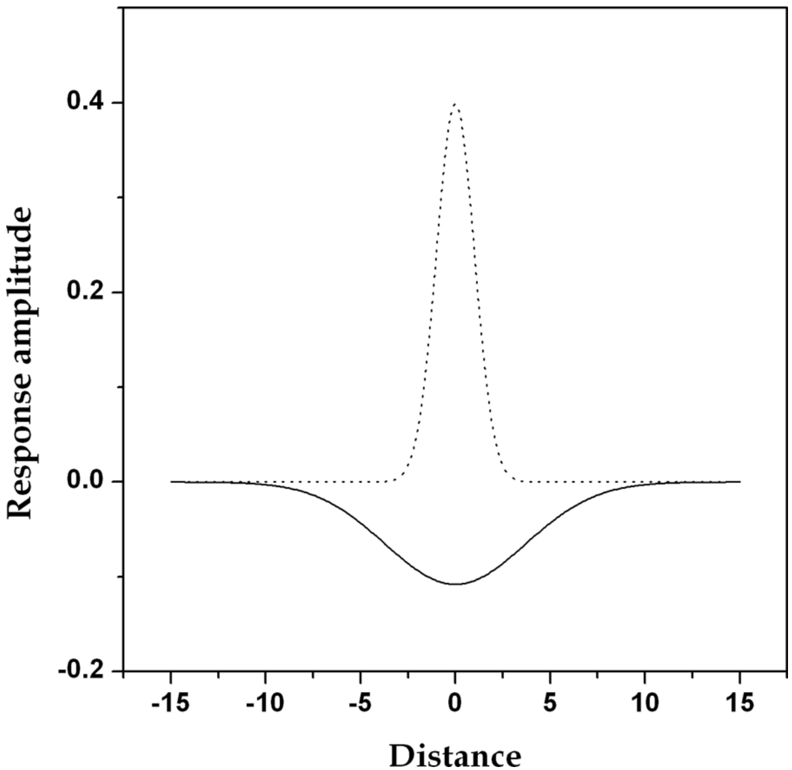
$$g(x,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{x^2}{2\sigma^2})$$

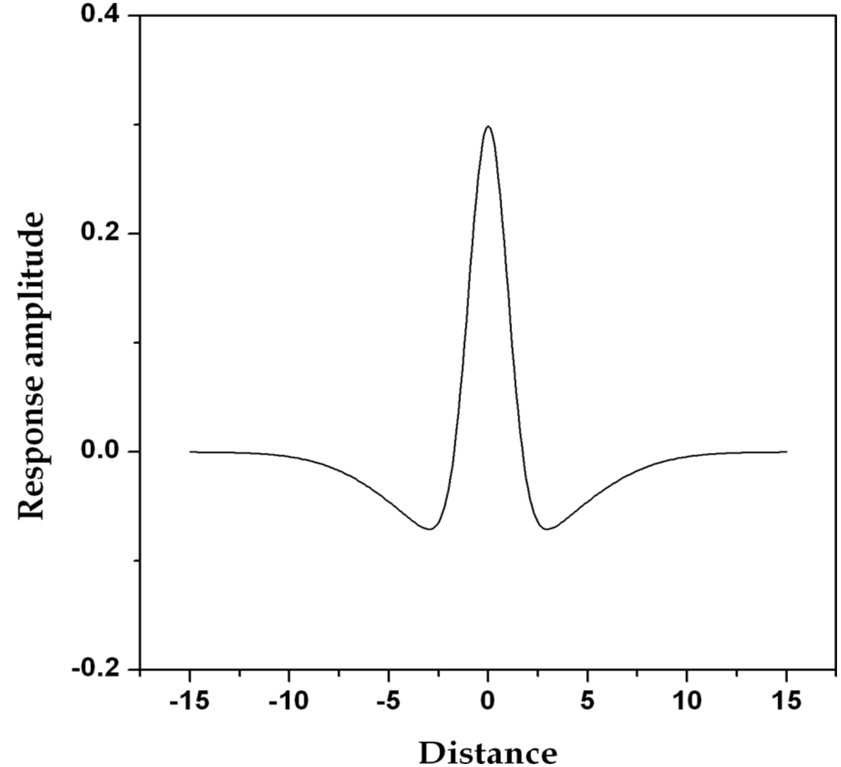
where σ is called the standard deviation



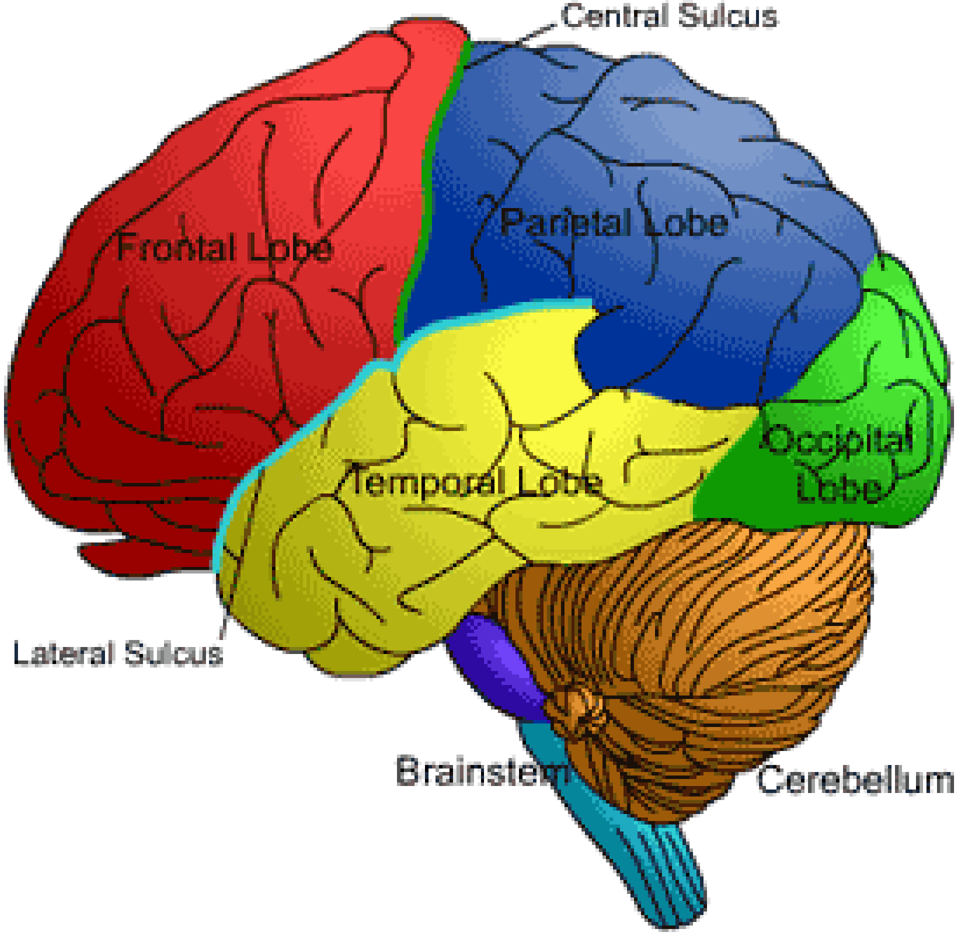


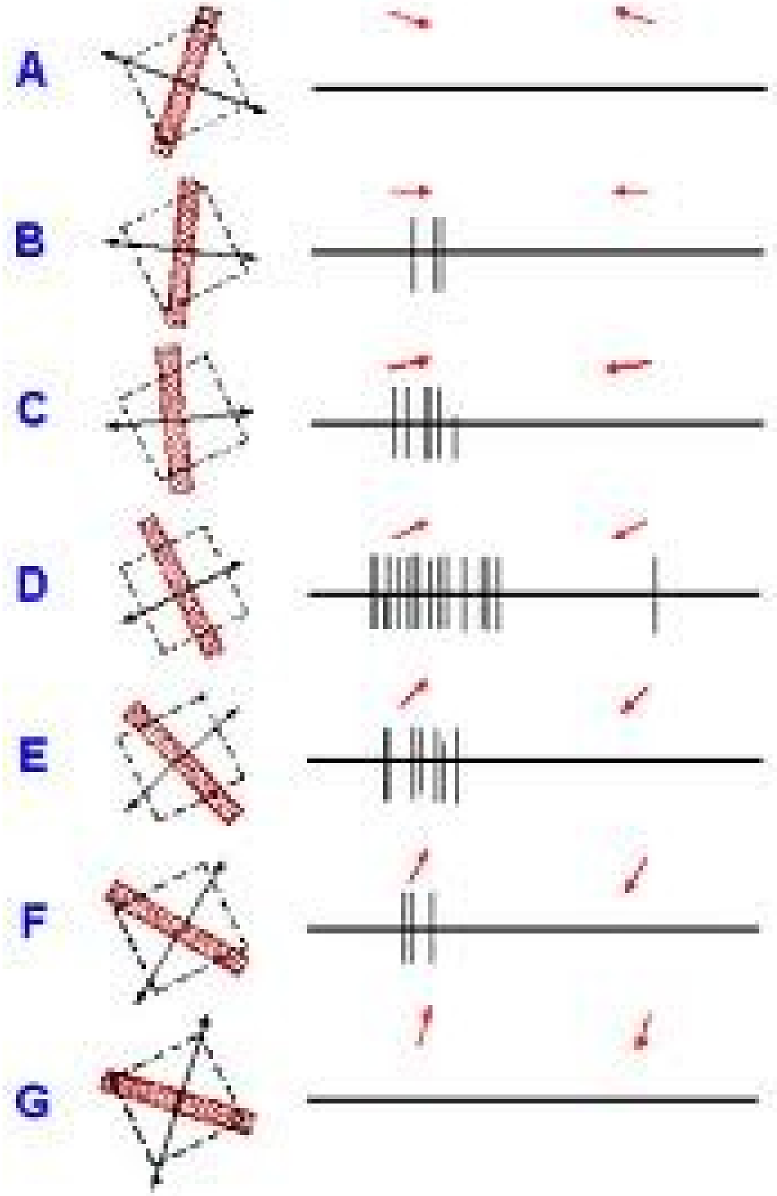
+ve contribution
-ve
-ve

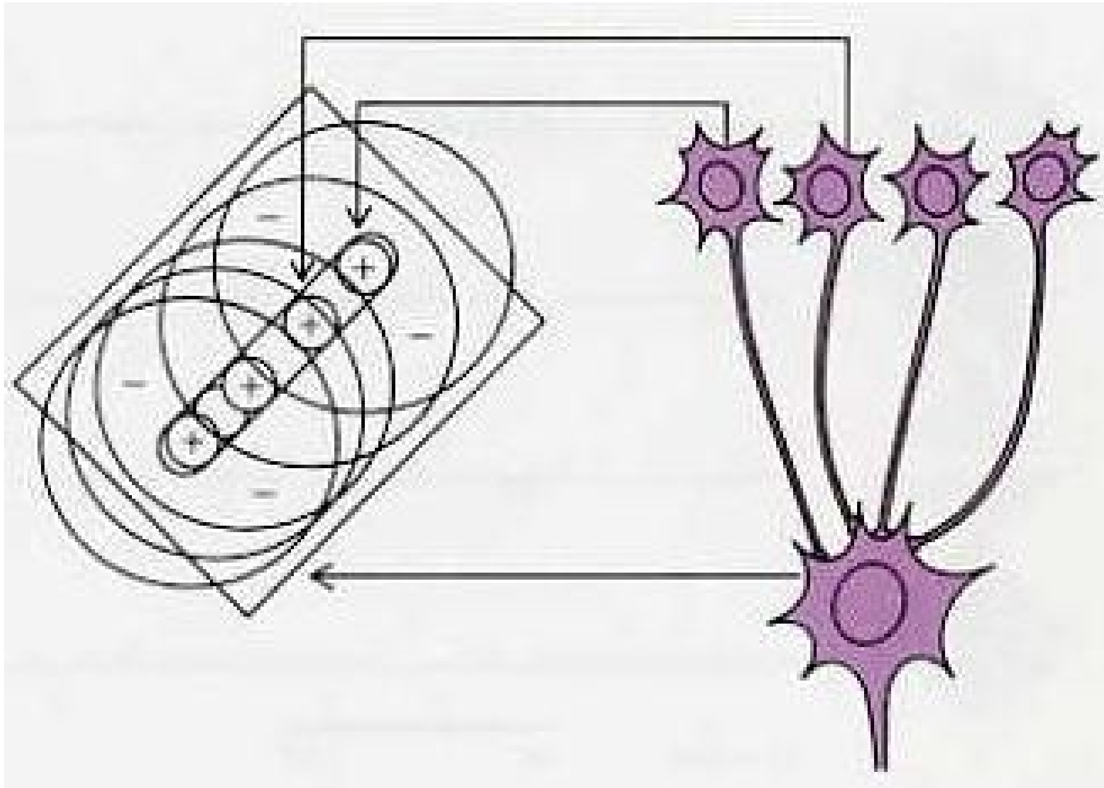


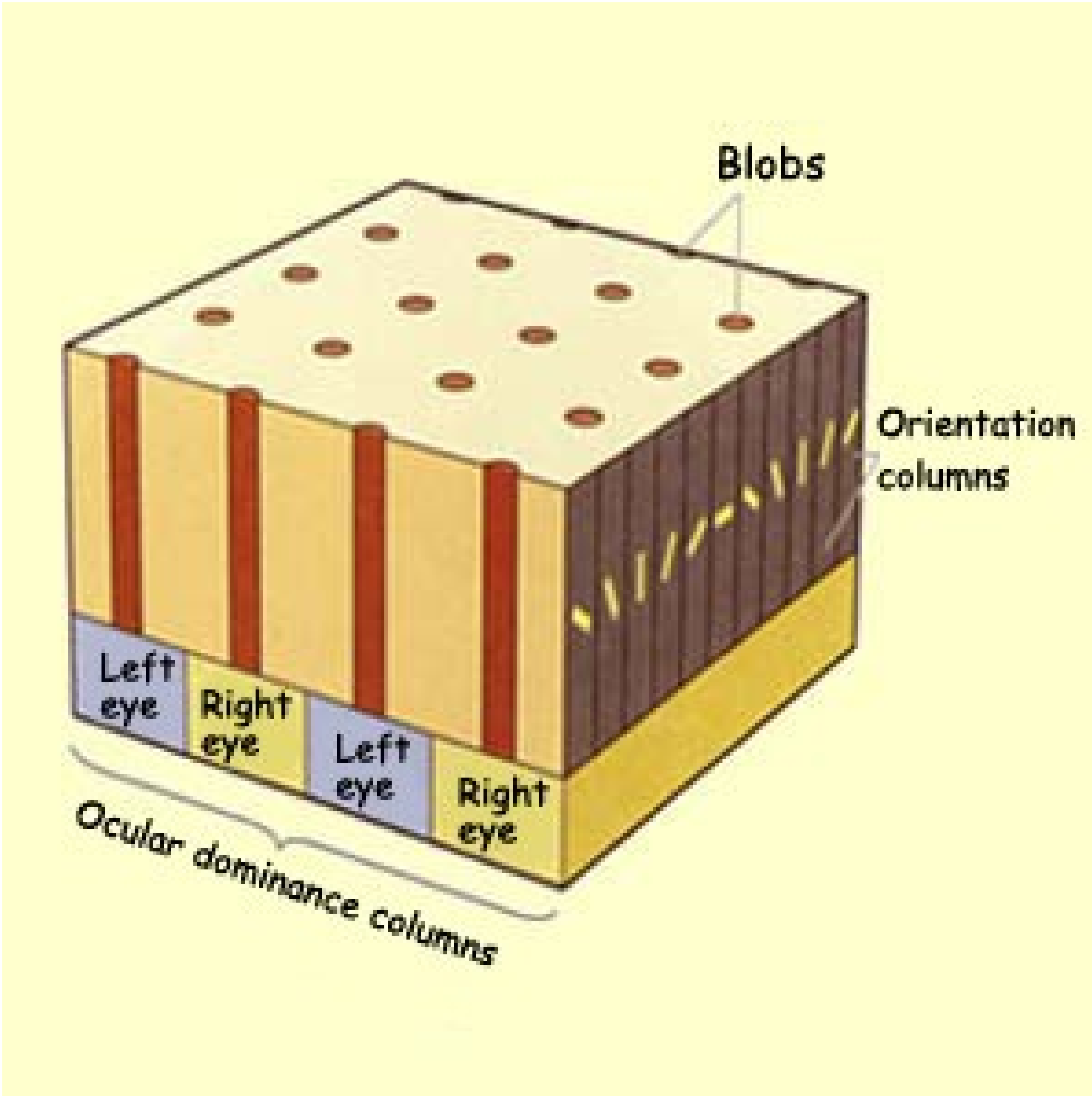


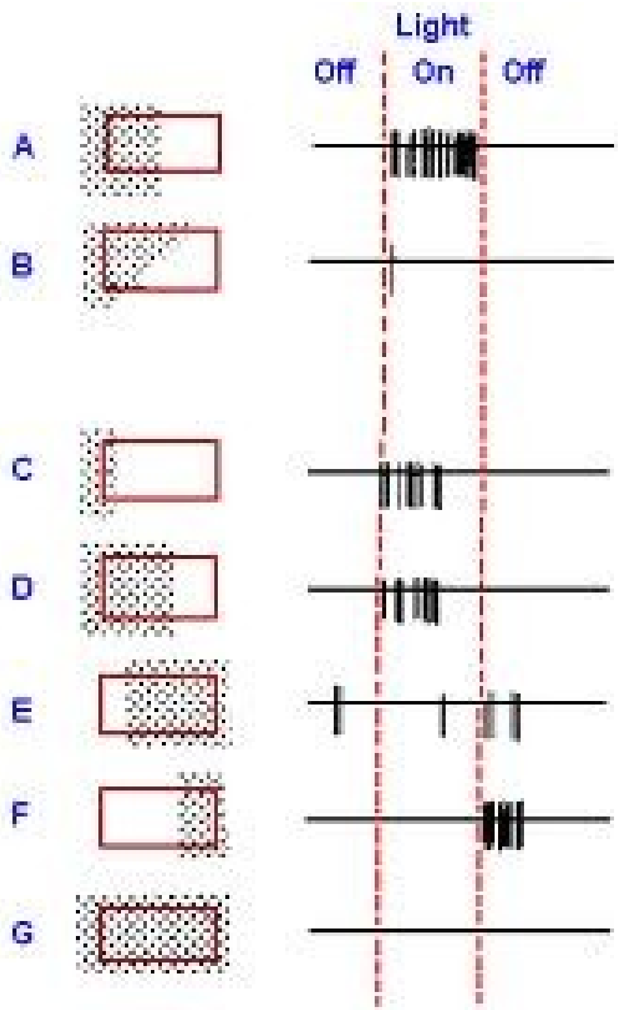
$$DOG(\sigma_1, \sigma_2) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} - \frac{1}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$


Central Sulcus
Frontal Lobe
Parietal Lobe
Temporal Lobe
Occipital Lobe
Lateral Sulcus
Brainstem
Cerebellum

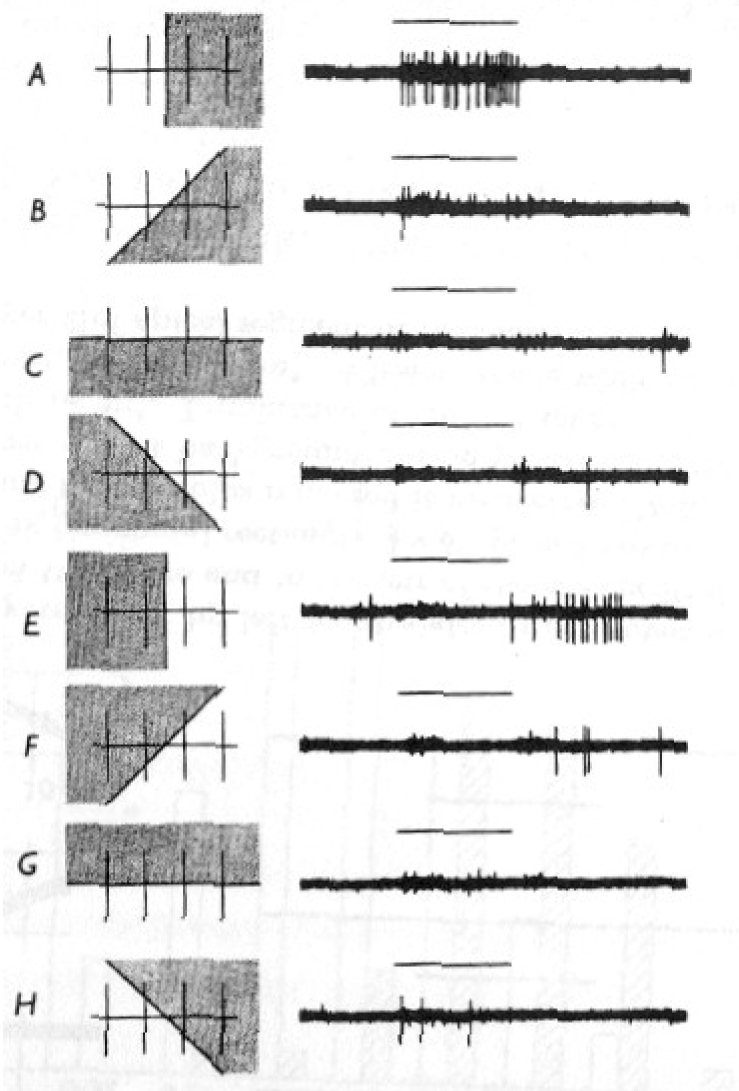

A
B
C
D
E
F
G

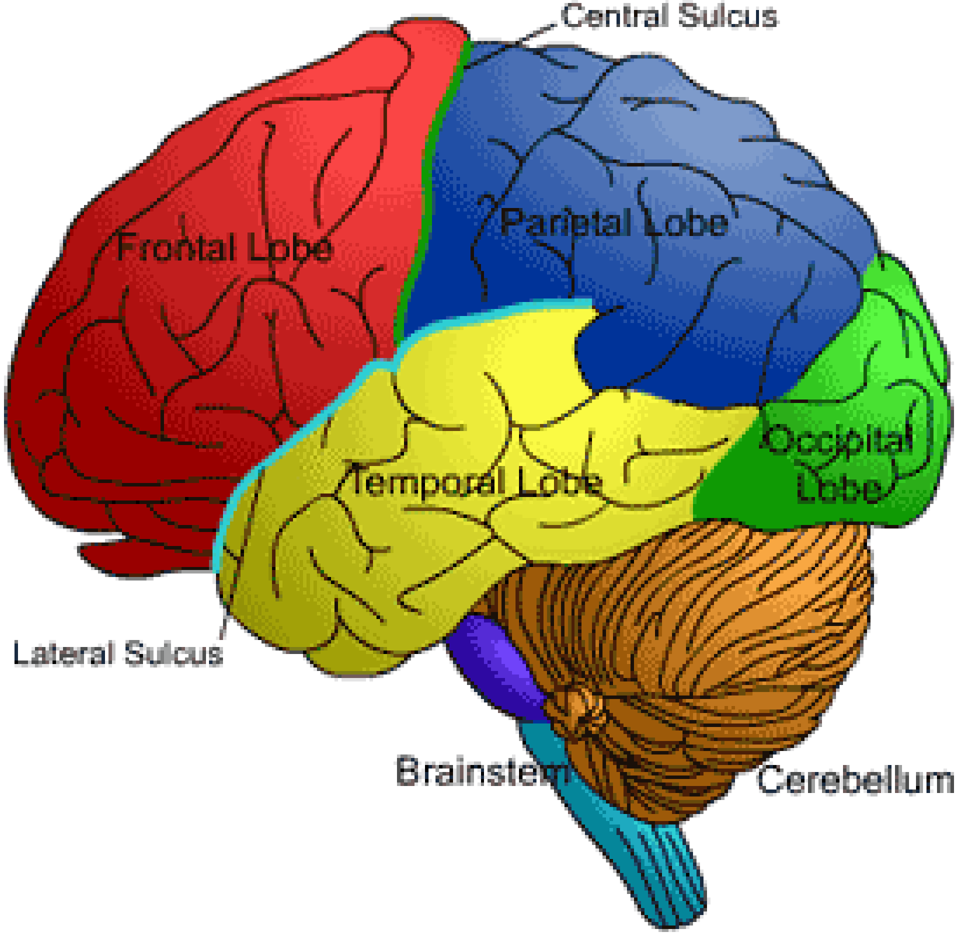


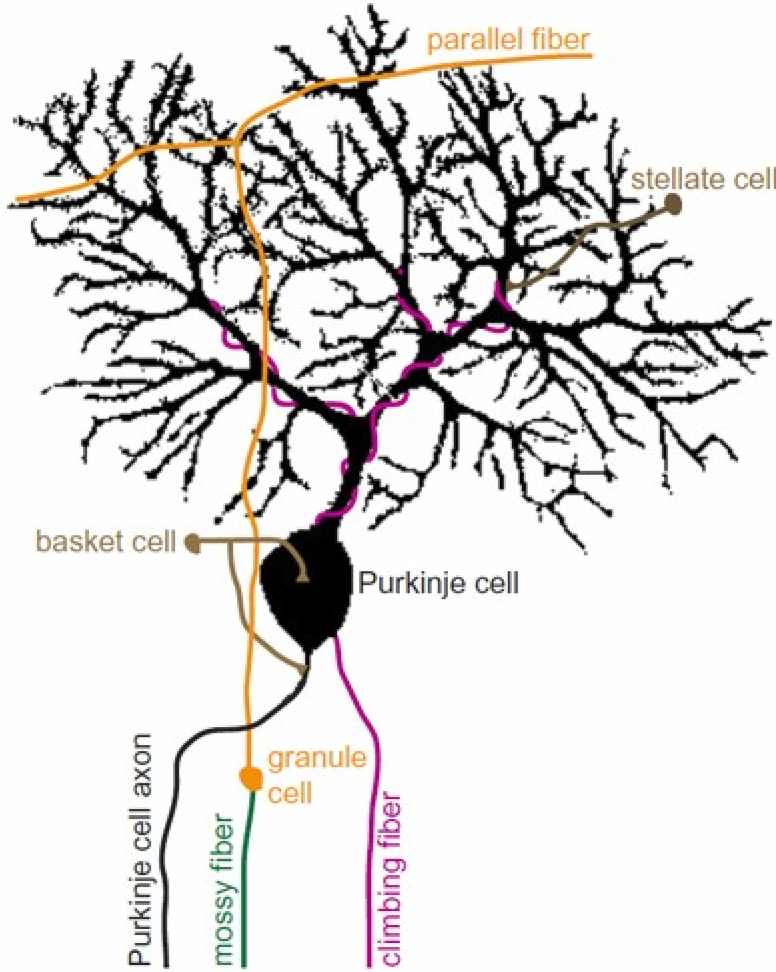

Blobs
Orientation columns
Left eye
Right eye
Left eye
Right eye
Ocular dominance columns



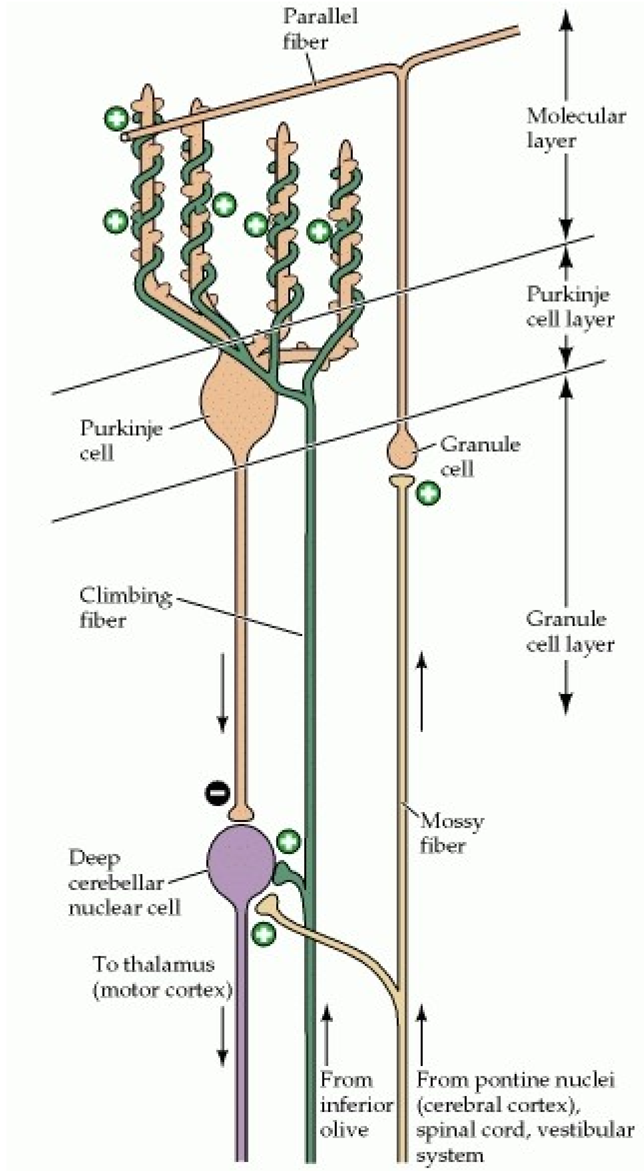
Light
Off
On
Off
A
B
C
D
E
F
G


A
B
C
D
E
F
G
H

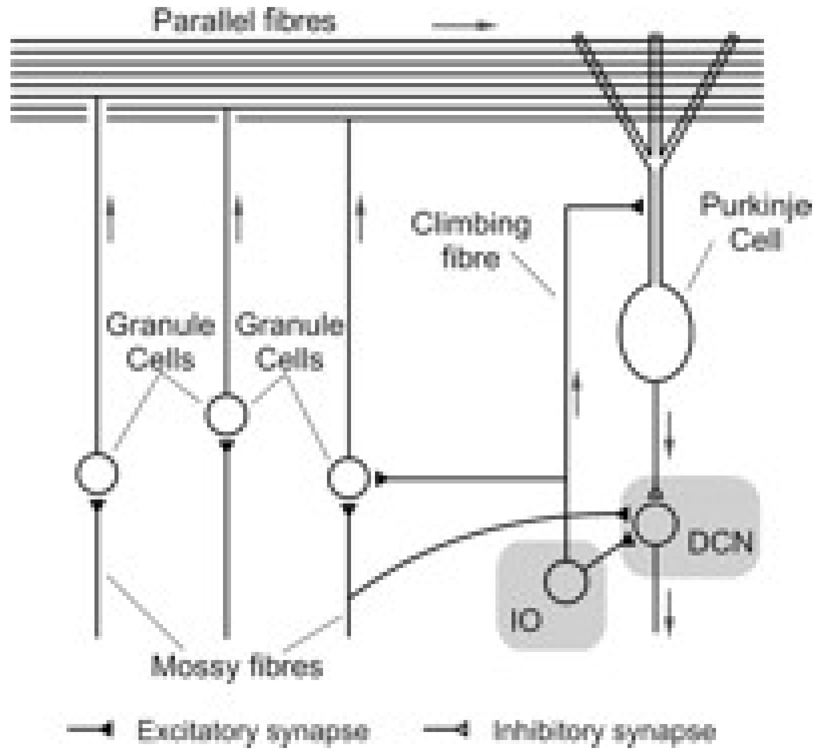

Central Sulcus
Parietal Lobe
Frontal Lobe
Occipital
Lobe
Temporal Lobe
Lateral Sulcus
Brainstem
Cerebellum



parallel fiber
stellate cell
basket cell
Purkinje cell
granule cell
Purkinje cell axon
mossy fiber
climbing fiber



Parallel fiber
Molecular layer
Purkinje cell layer
Purkinje cell
Granule cell
Granule cell layer
Climbing fiber
Mossy fiber
Deep cerebellar nuclear cell
To thalamus (motor cortex)
From inferior olive
From pontine nuclei (cerebral cortex), spinal cord, vestibular system


Parallel fibres
Climbing fibre
Purkinje Cell
Granule Cells
Granule Cells
DCN
IO
Mossy fibres
Excitatory synapse
Inhibitory synapse

Thank you