Computational Neurobiology

Lecture 2: Neuron physiology and biophysics

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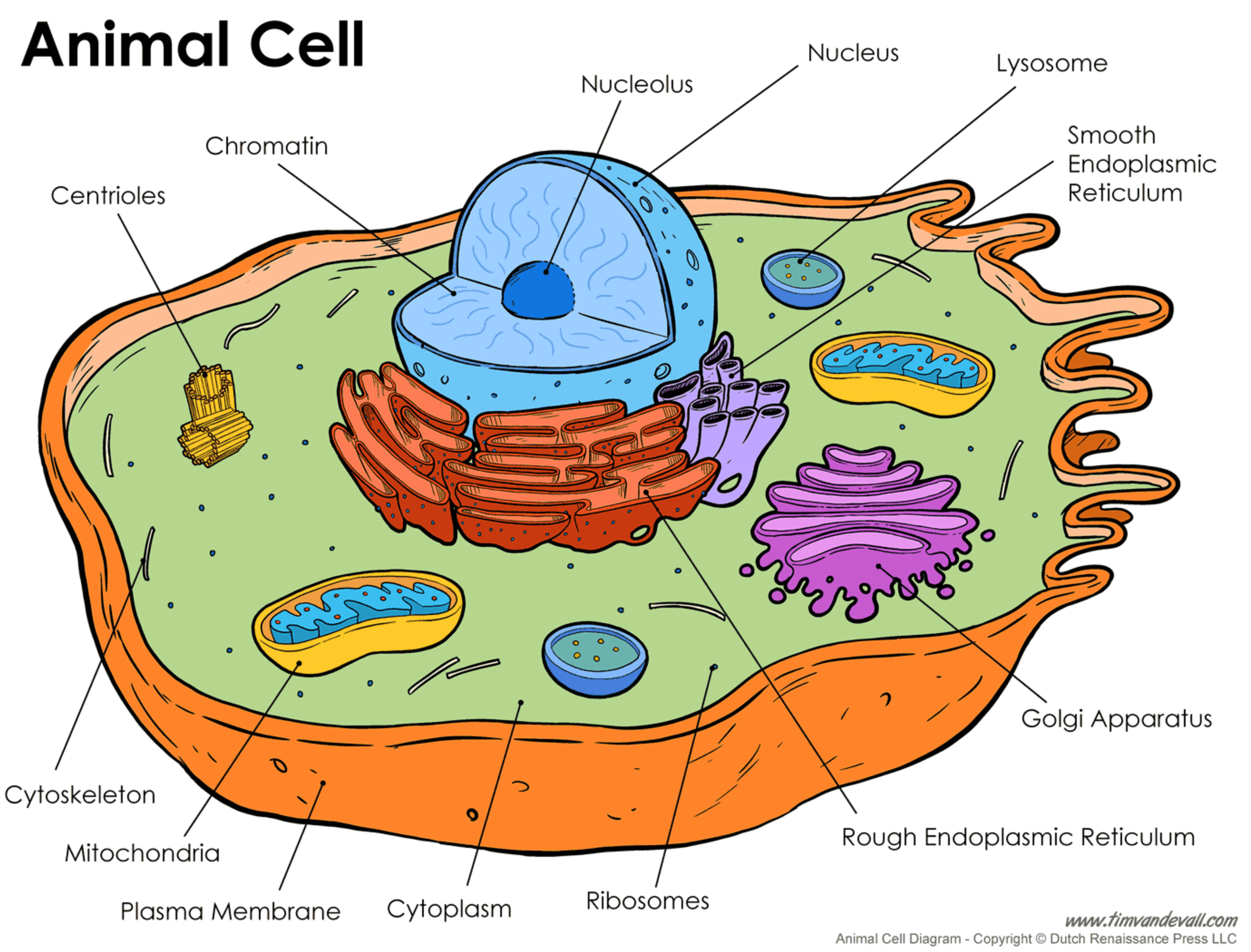
Syllabus

- Neuron morphological and functional structure
- How does neuron transmit signals
- Biophysics of neuron
- Electrochemical properties

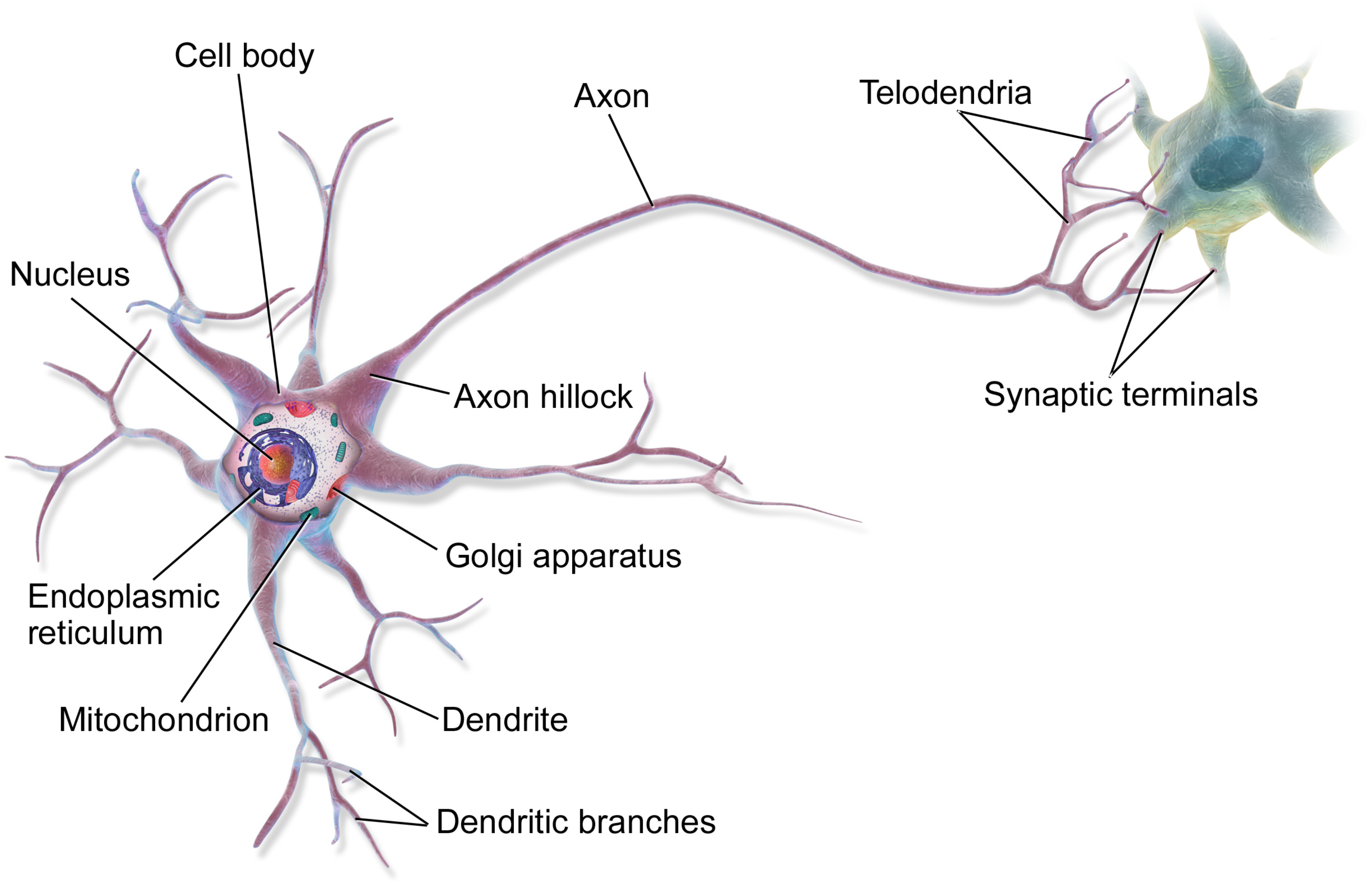
Neuron morphological and functional structure

- Neuron as a cell
- Neuron specific parts
- Morphology
- Functions
- Glial cells

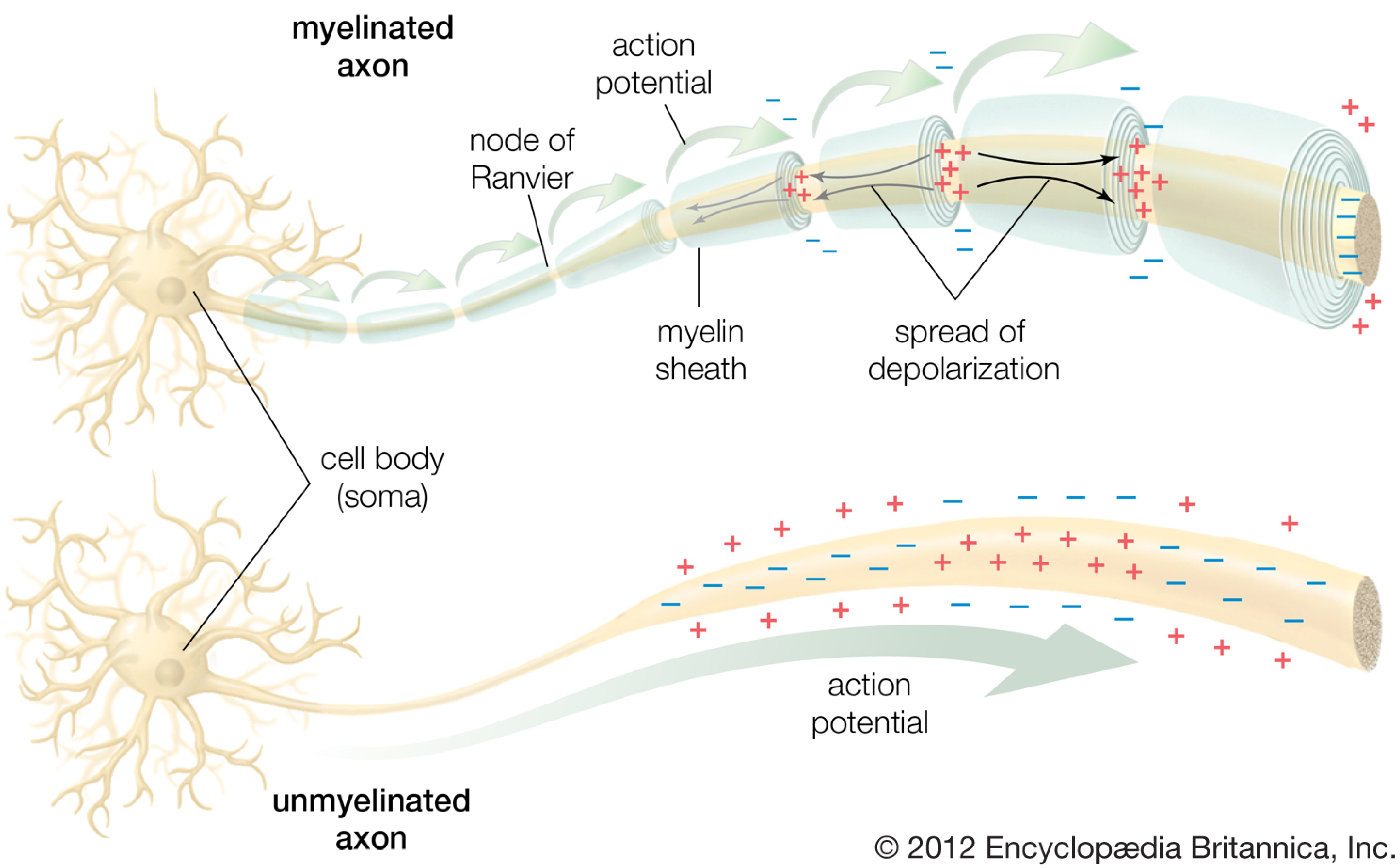
Neuron as a cell



Neuron specific parts

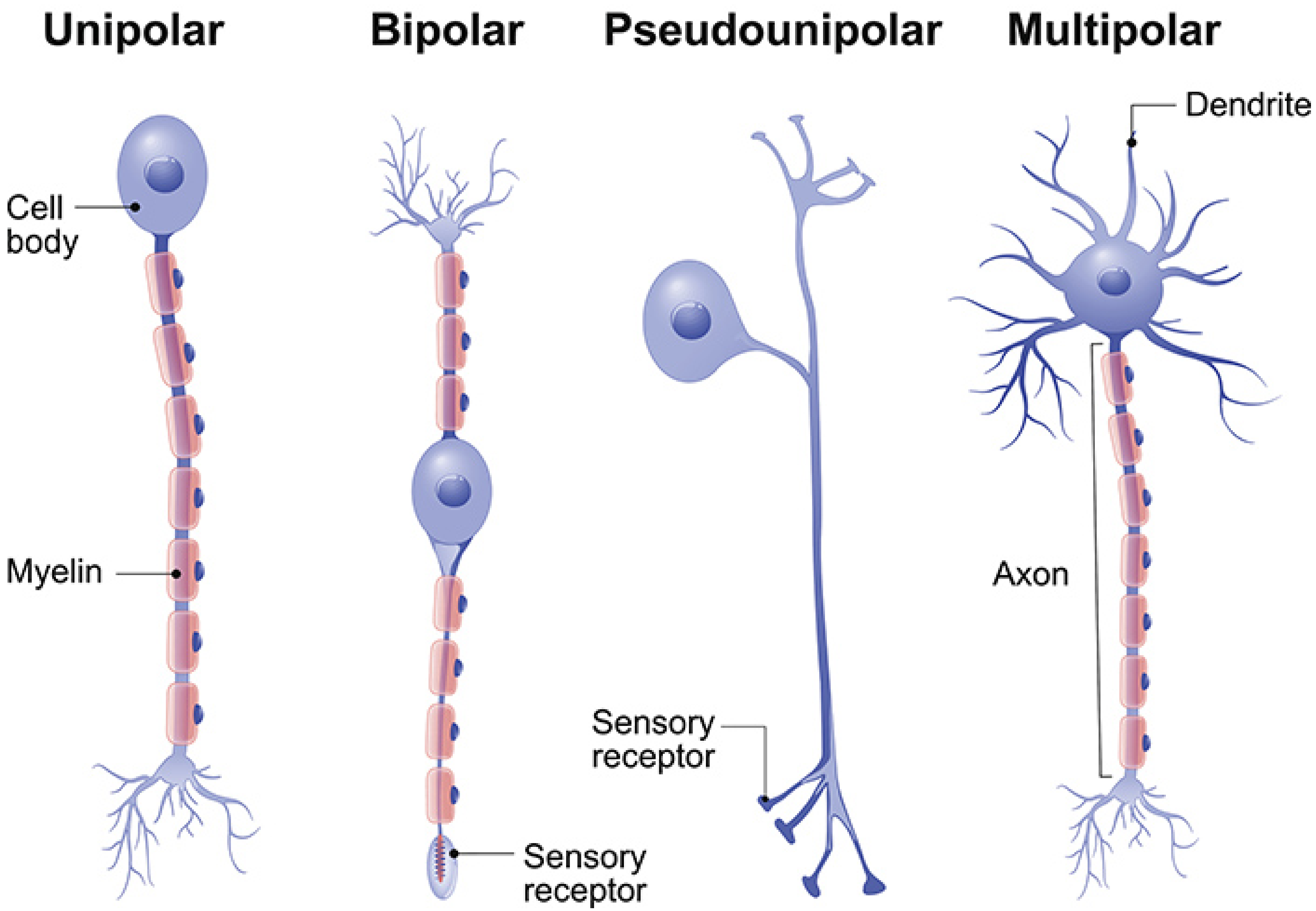


Axons

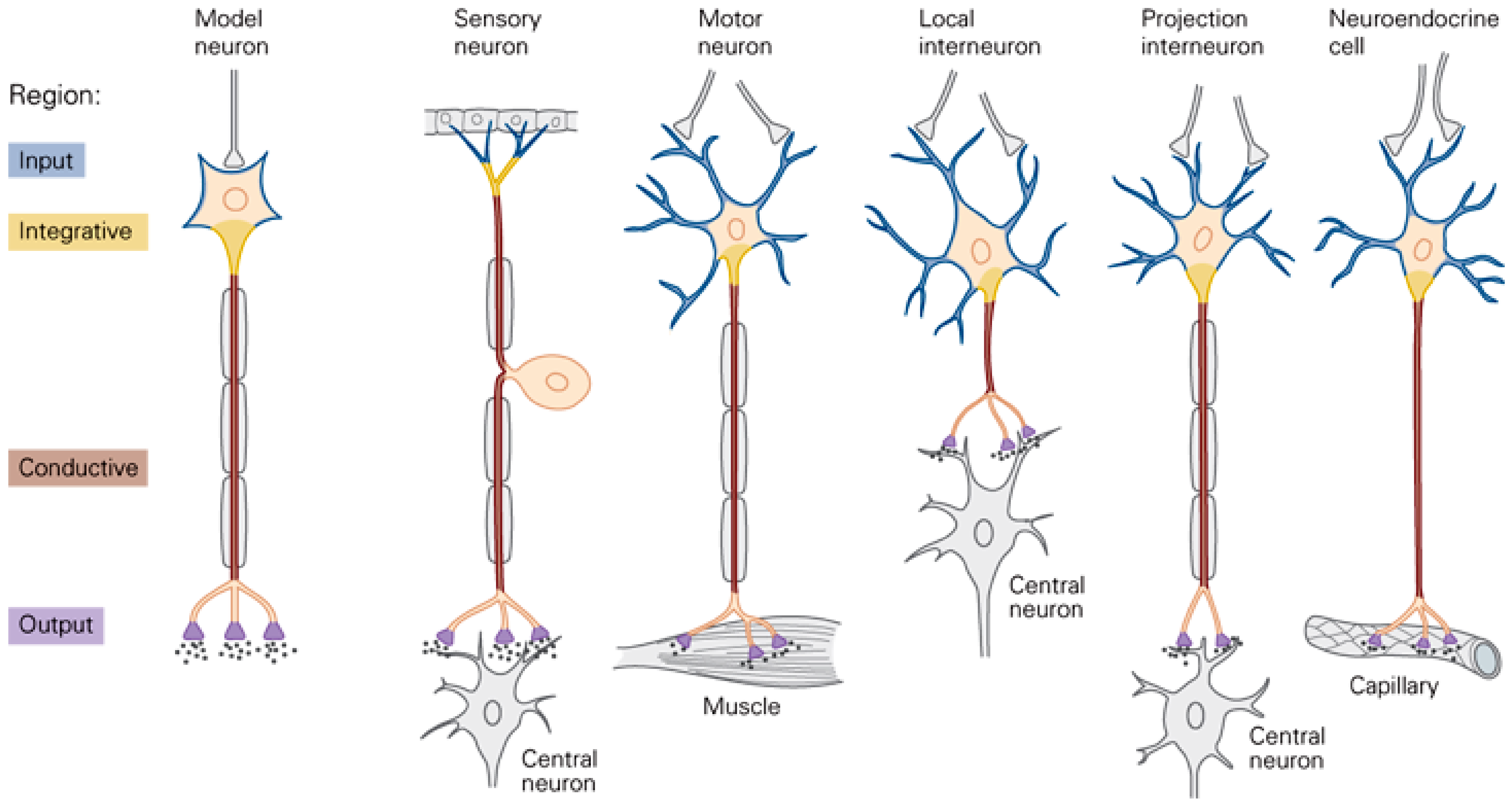


myelinated axon
action potential
node of Ranvier
myelin sheath
spread of depolarization
cell body (soma)
action potential
unmyelinated axon

Morphology

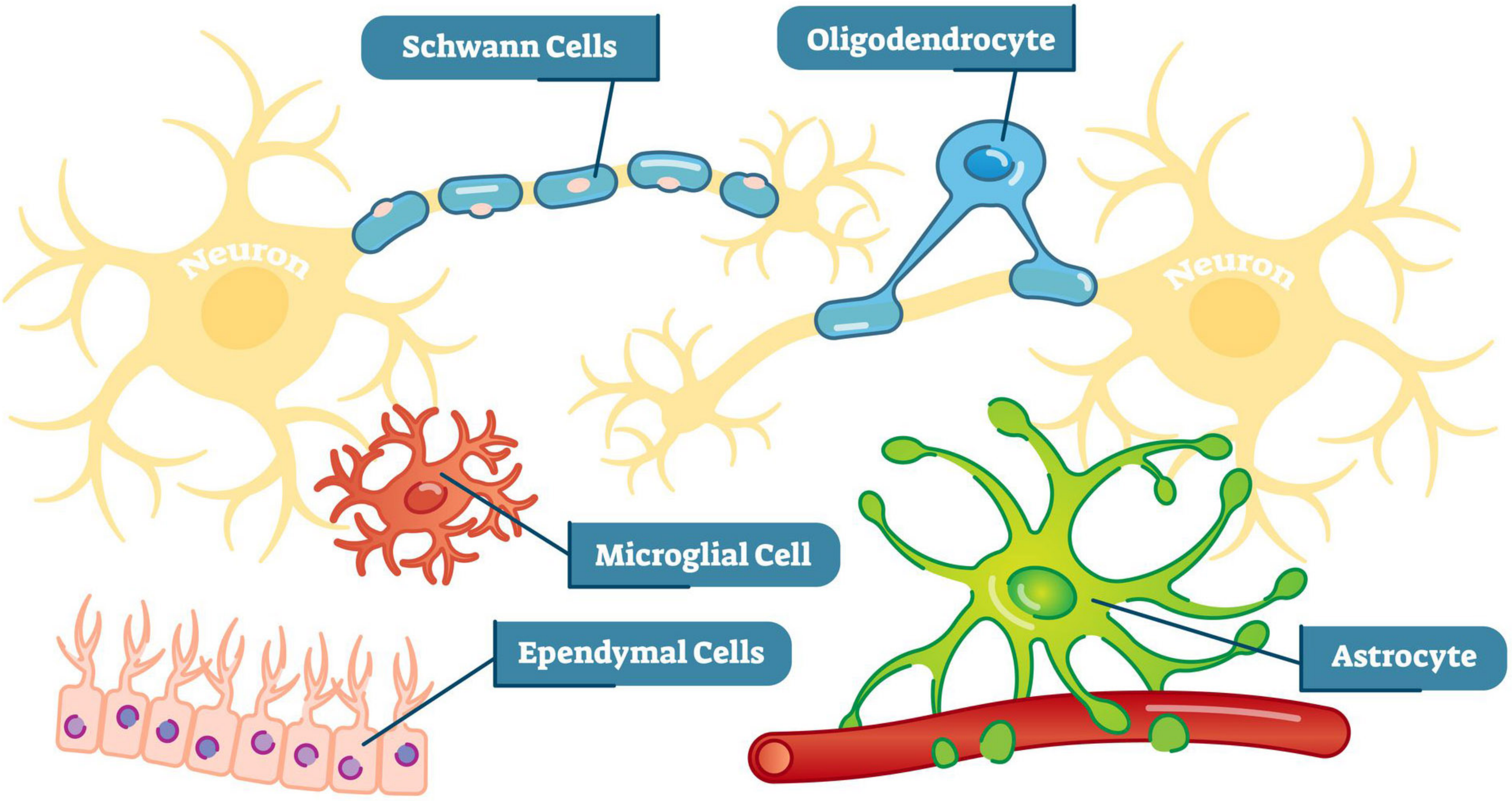

Unipolar
Bipolar
Pseudounipolar
Multipolar
Dendrite
Cell body
Myelin
Axon
Sensory receptor
Sensory receptor

Functions



Model neuron
Sensory neuron
Motor neuron
Local interneuron
Projection interneuron
Neuroendocrine cell
Region:
Input
Integrative
Conductive
Output
Central neuron
Muscle
Central neuron
Central neuron
Capillary

Glial cells

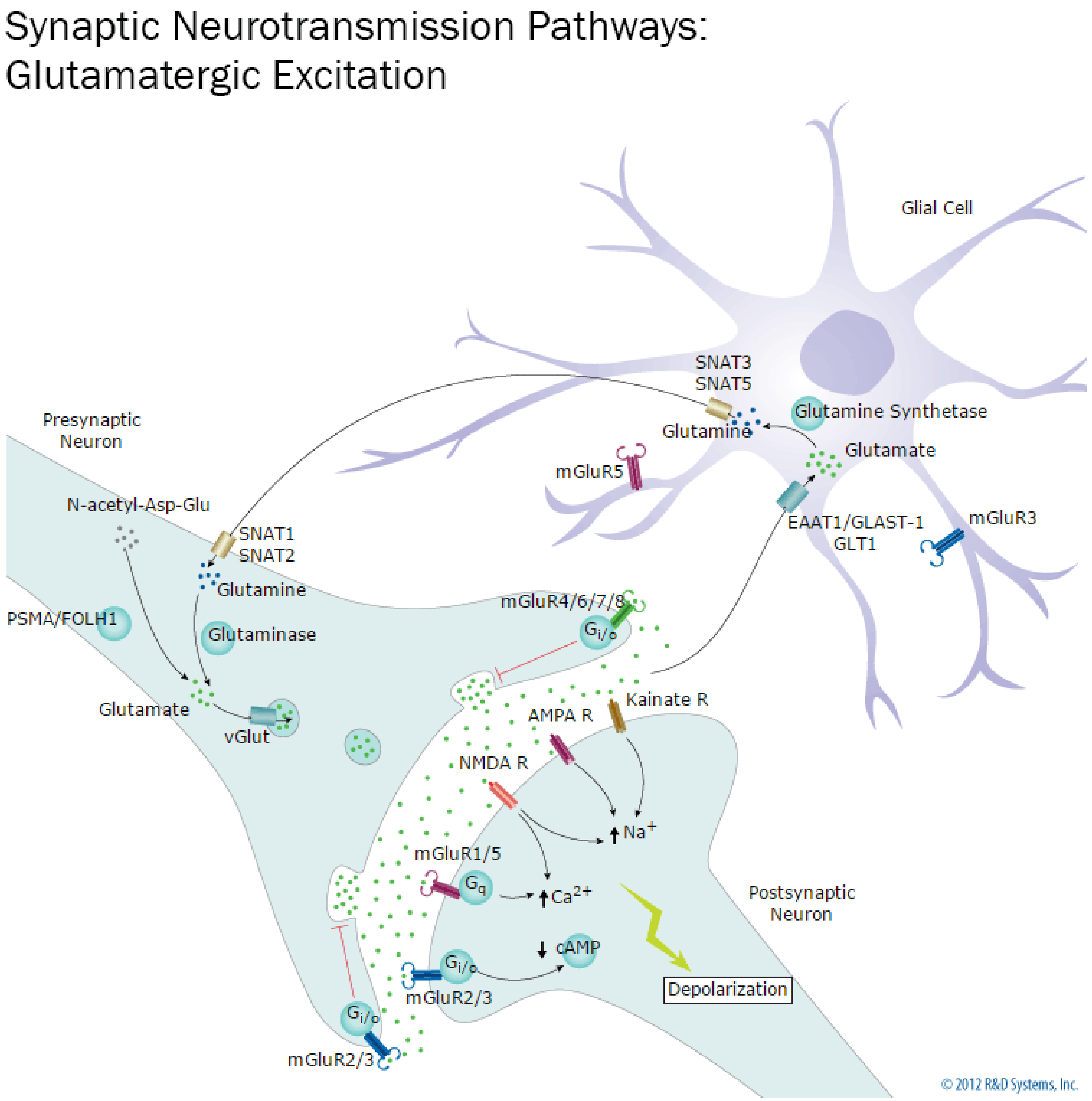


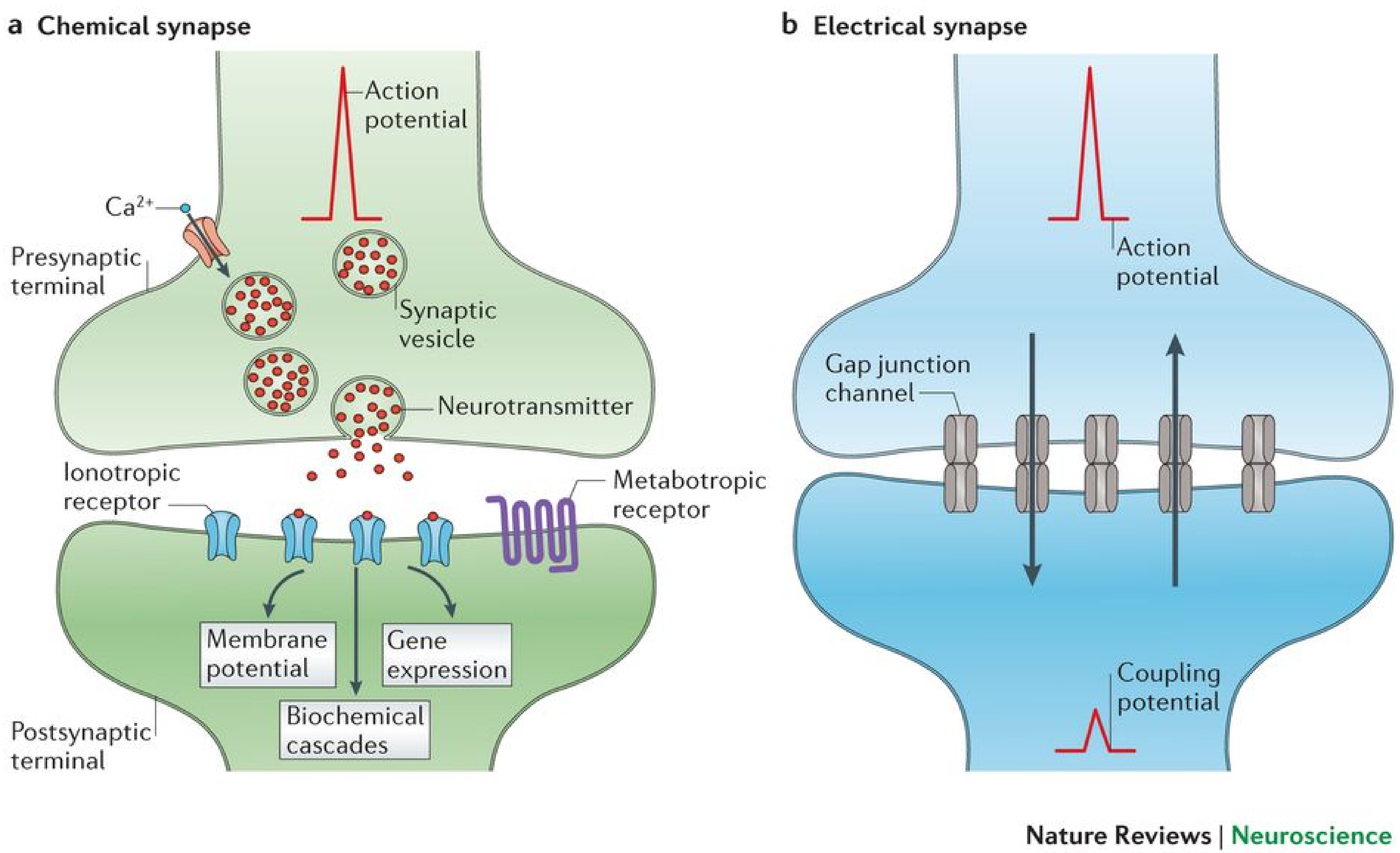
Schwann Cells
Oligodendrocyte
Neuron
Neuron
Microglial Cell
Ependymal Cells
Astrocyte

How does neuron transmit signals

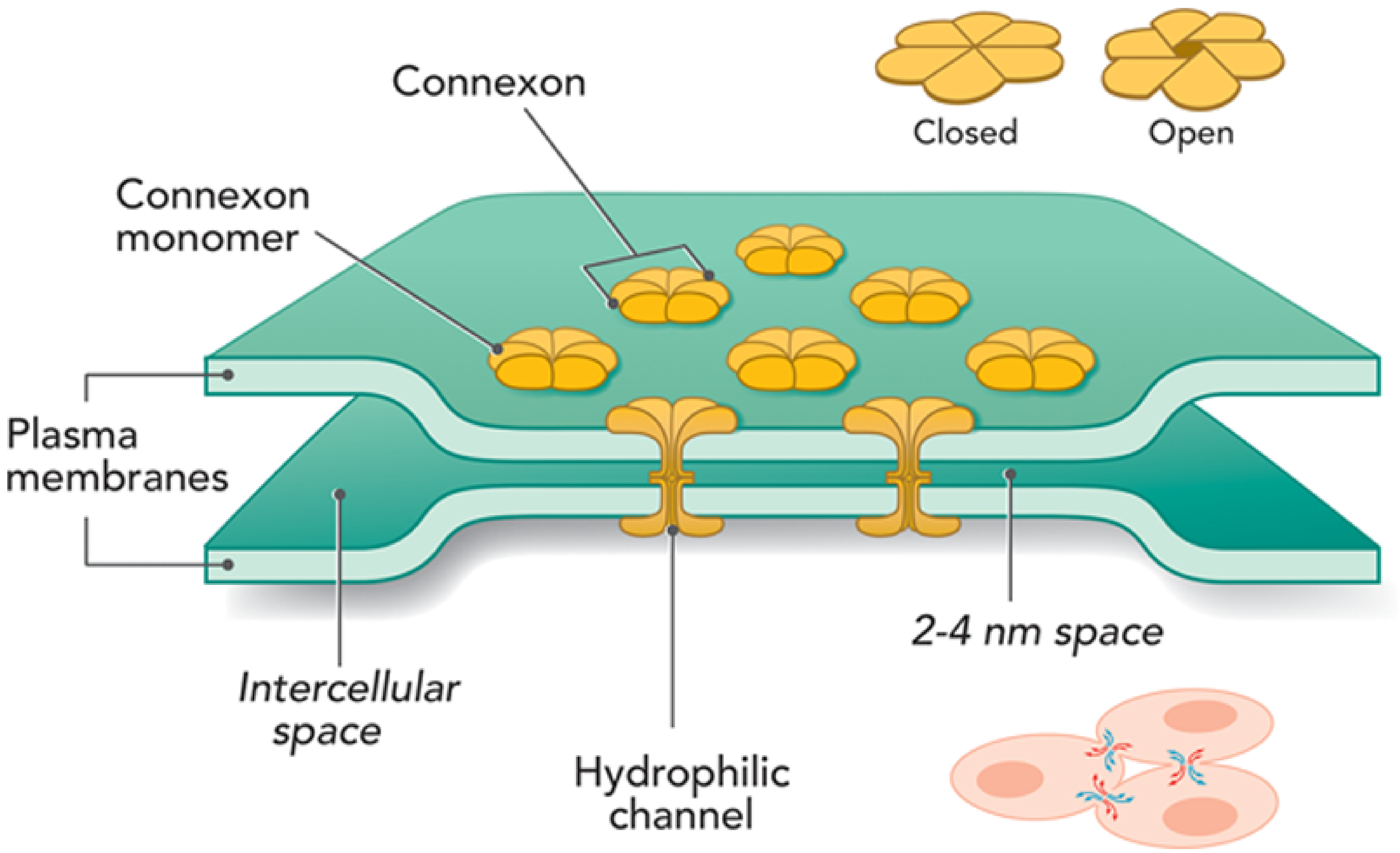
- Connections (synapses, gap junctions)
- Excitation/Inhibition

Connections (synapses, gap junctions)

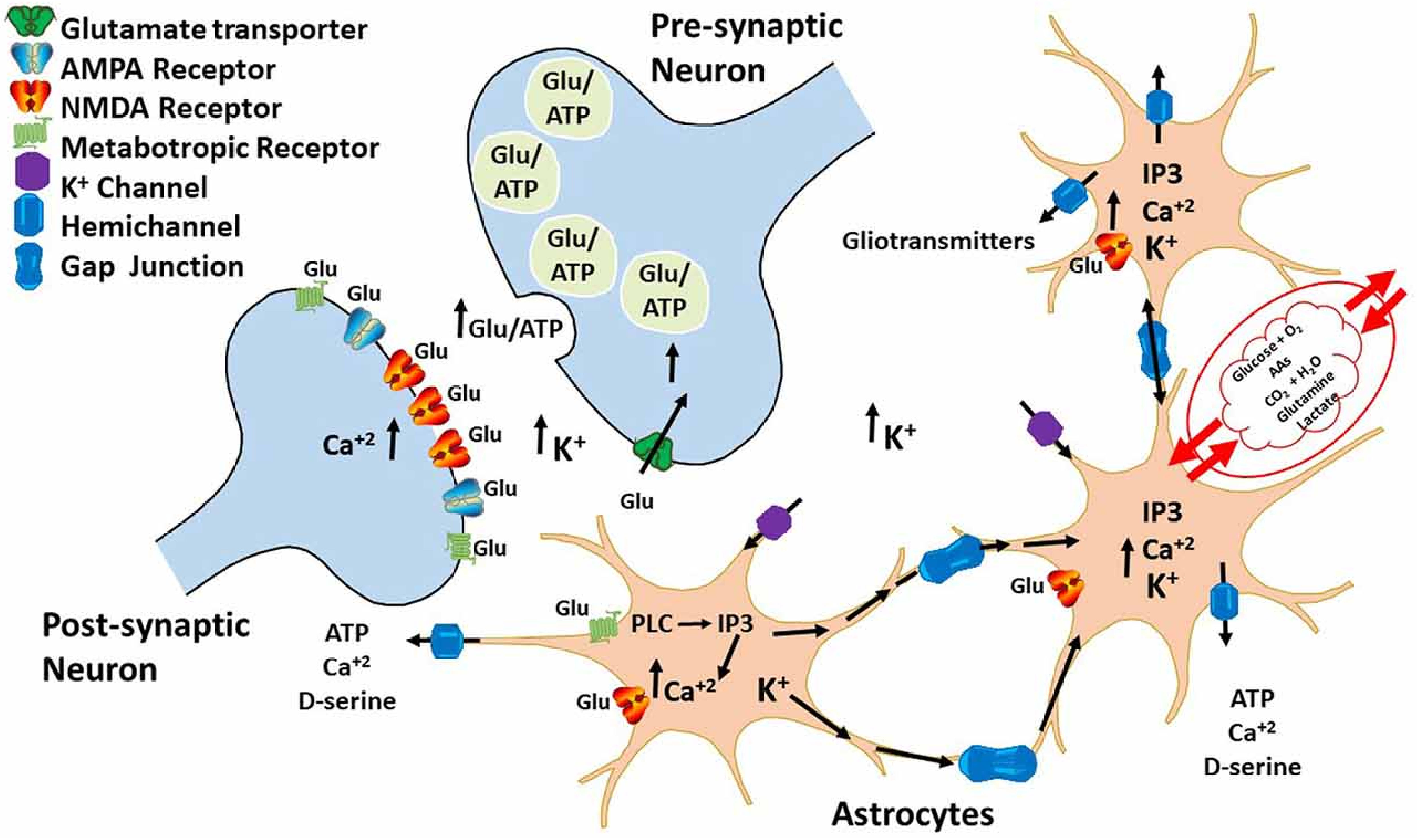




Differences between electrical and chemical synapses

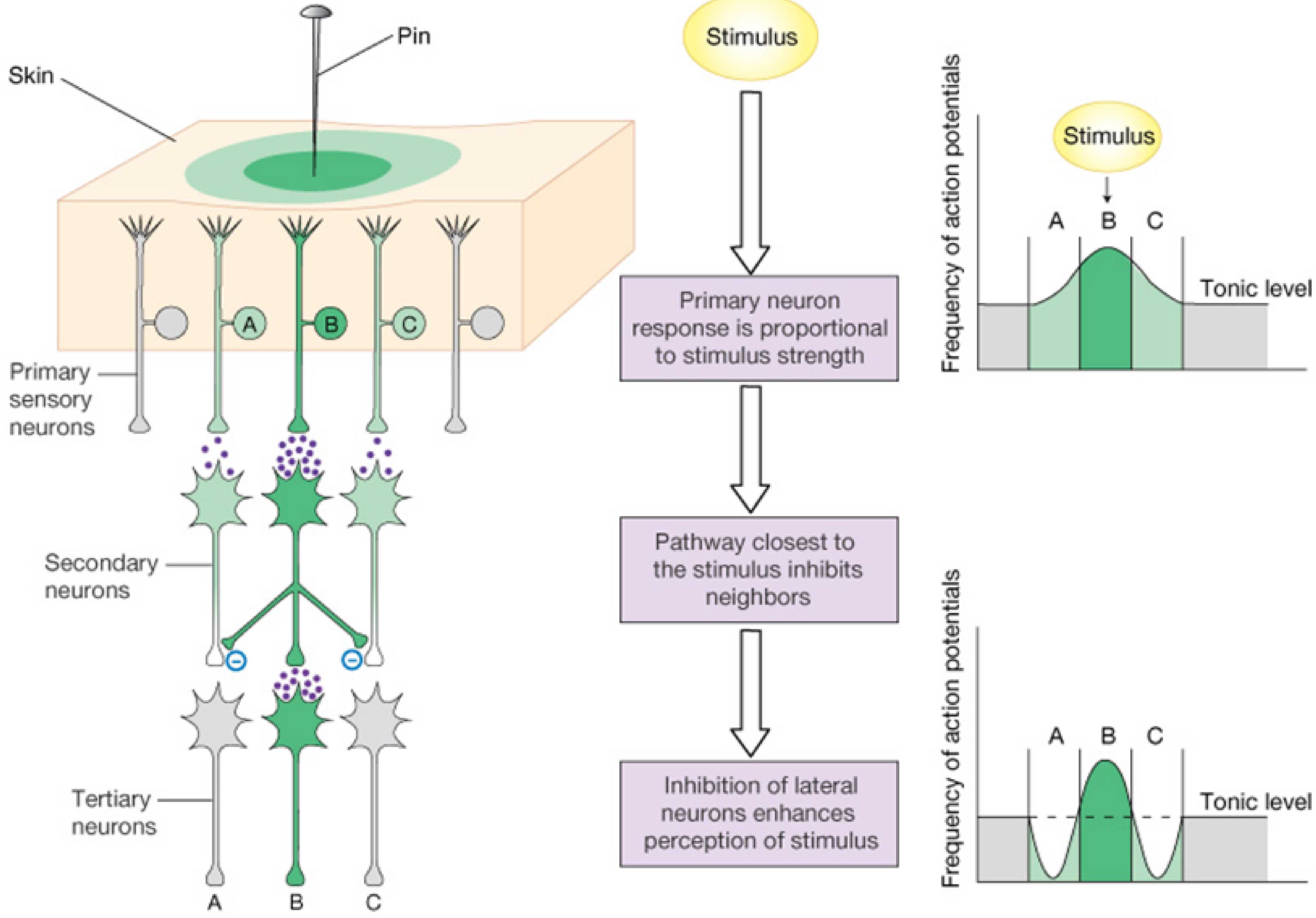


Gap junction scheme



Diversity of connections

Excitation/Inhibition



Lateral inhibition in sensory processing

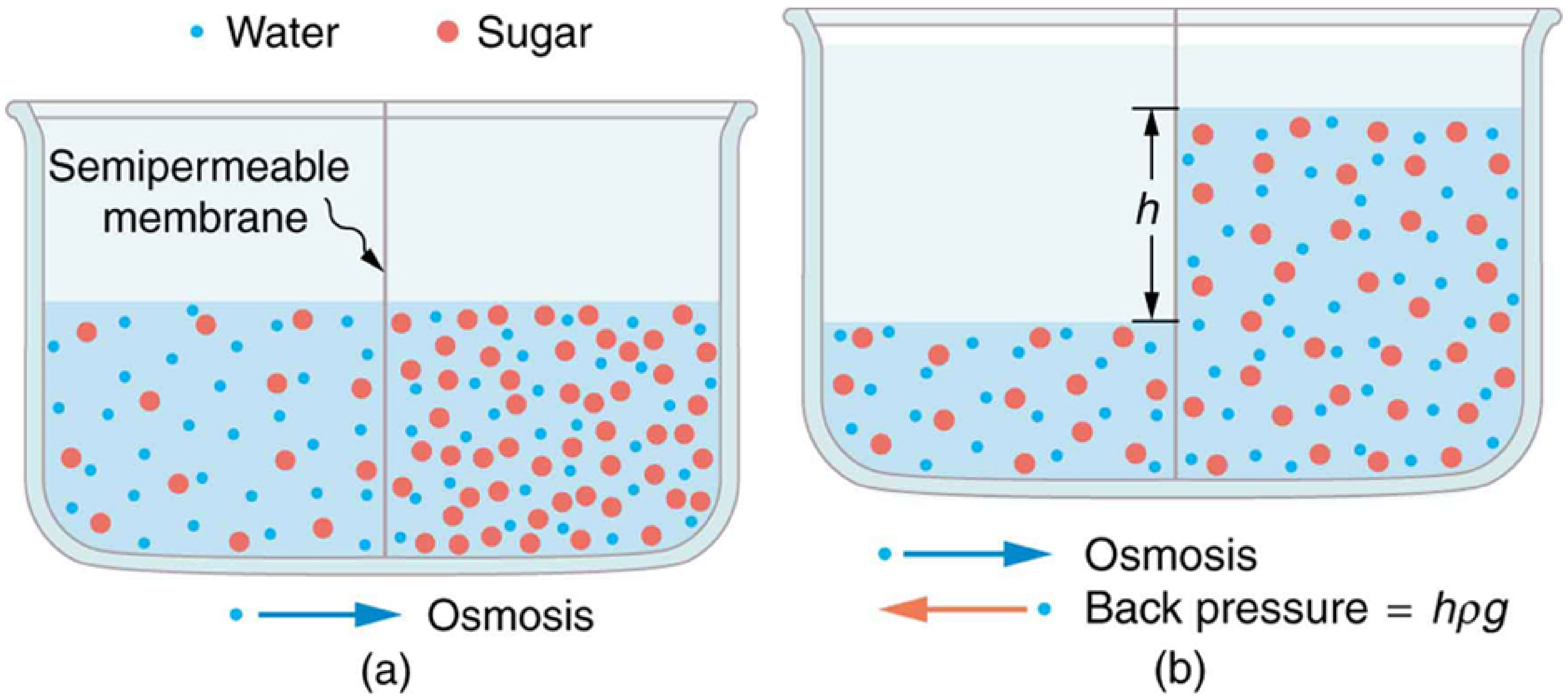
Biophysics of neuron

- Membrane and potential
- Osmotic effect
- Ion gradient (electrochemical gradient)
- Ion pumps (active transport)
- Ion channels (passive transport)
- Leakage

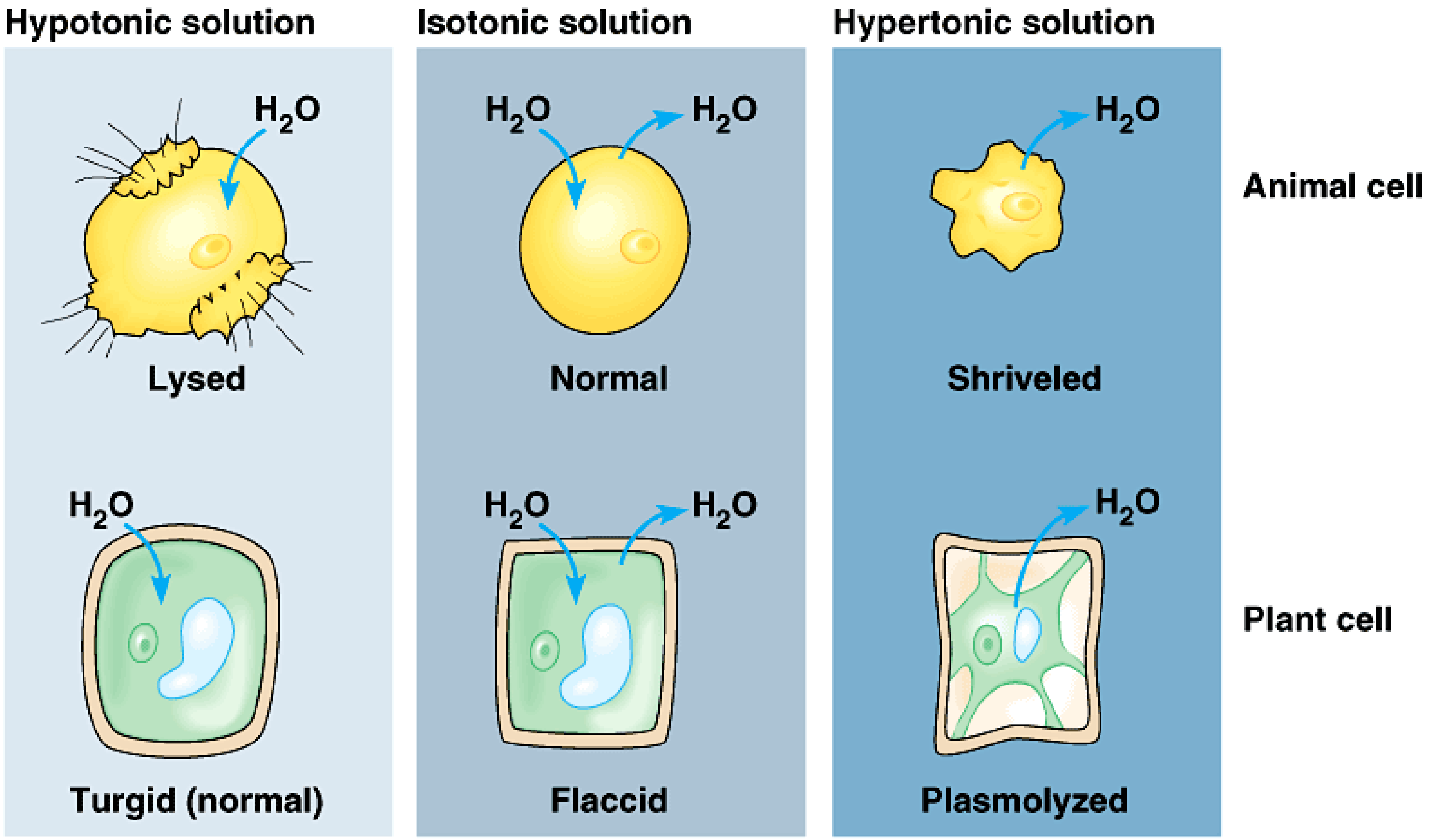
Membrane and potential

- A cubic micron of cytoplasm might contain, for example, 10^{10} water molecules, 10^{8} ions, 10^{7} small molecules such as amino acids and nucleotides, and 10^{5} proteins
- Cell membrane acts as a capacitor by separating the charges lying along its interior and exterior surfaces
- Almost all plasma membranes have an electrical potential across them, with the inside usually negative with respect to the outside
- In electrically excitable cells such as neurons and muscle cells, it is used for transmitting signals between different parts of a cell
- The membrane potential in a cell derives ultimately from two factors: electrical force! and diffusion!

Osmotic effect



Diffusion and osmosis



Osmosis in biological cells

Ion gradient (electrochemical gradient)

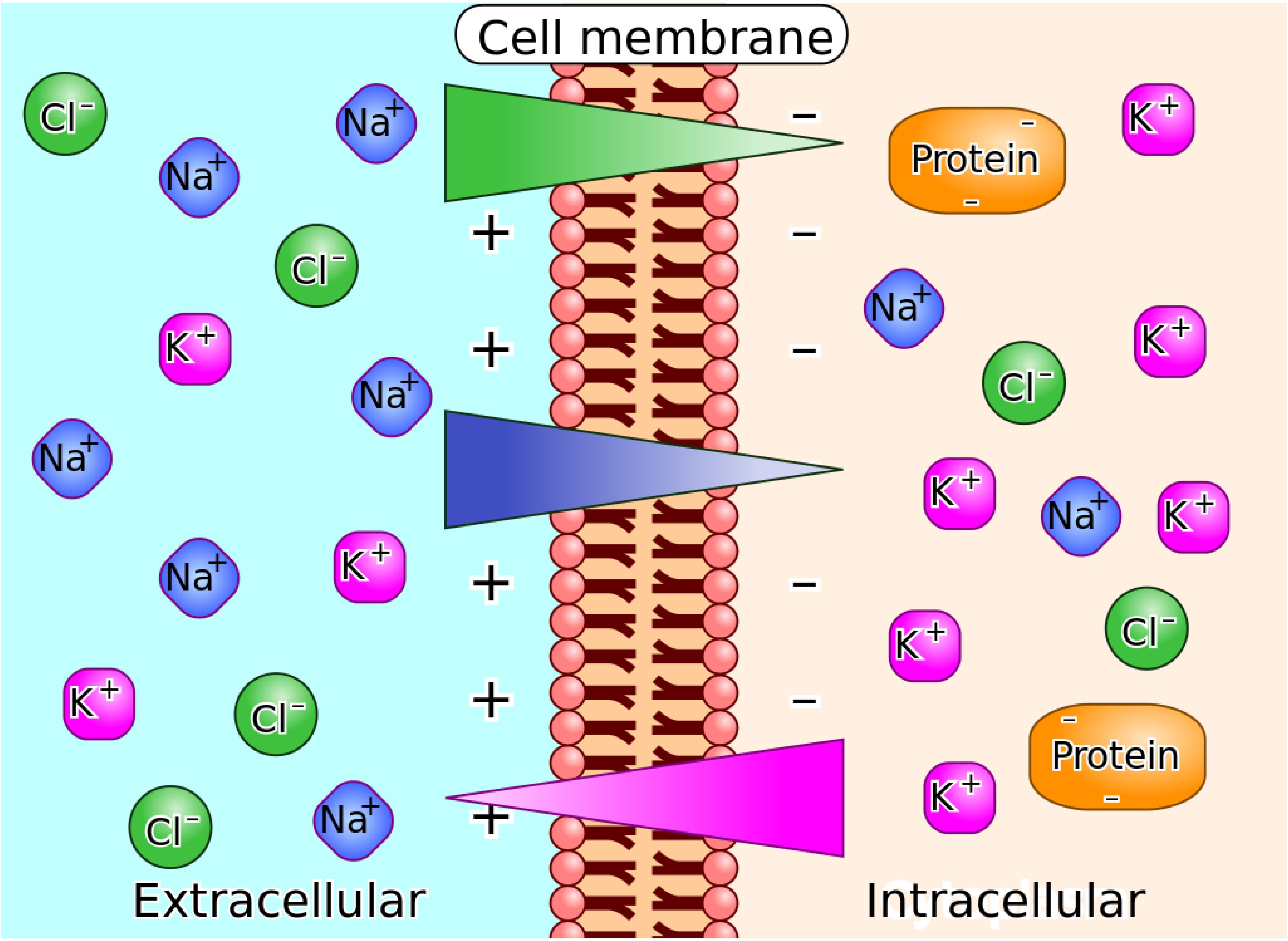
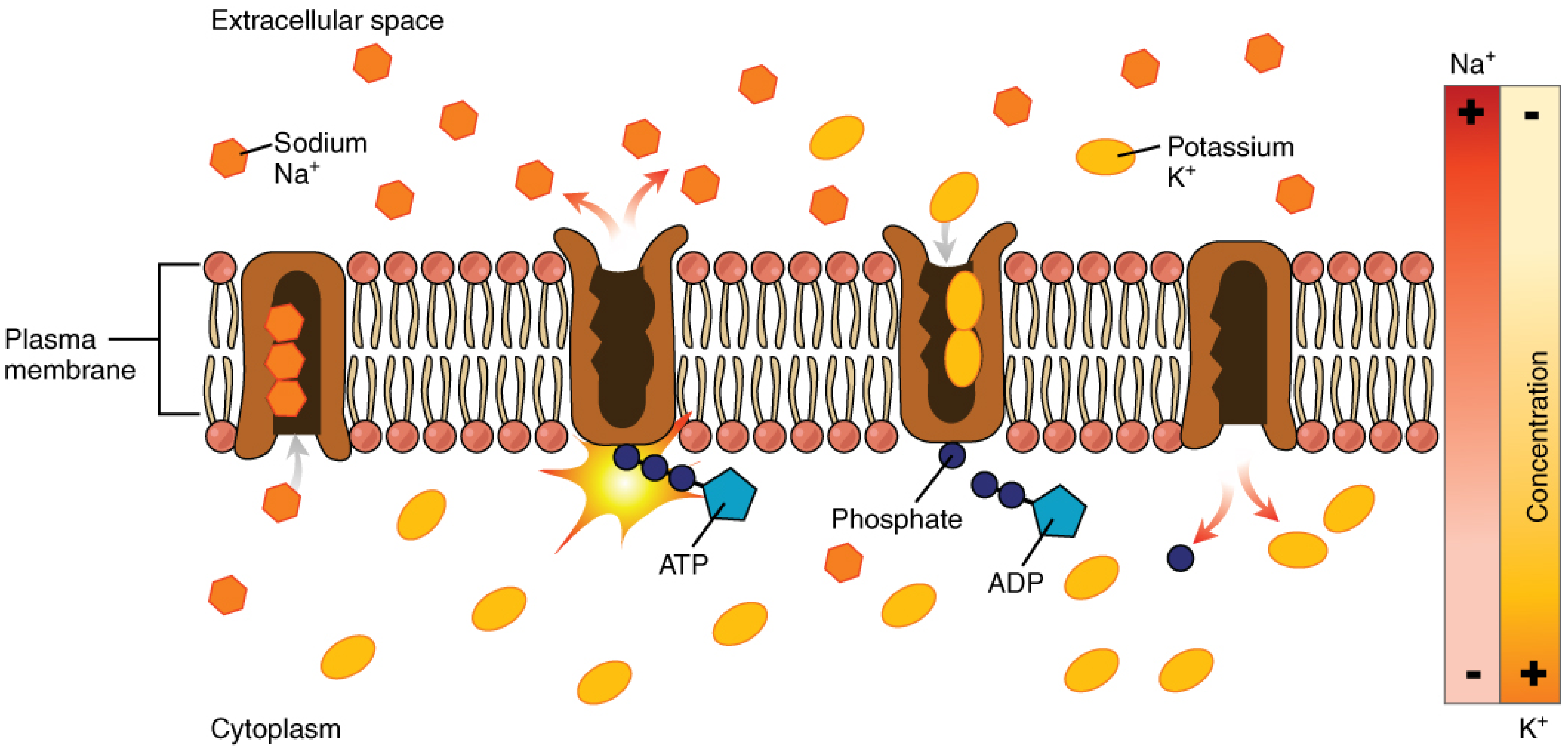


Diagram of ion concentrations and charge across a semi-permeable cellular membrane

Ion pumps (active transport)

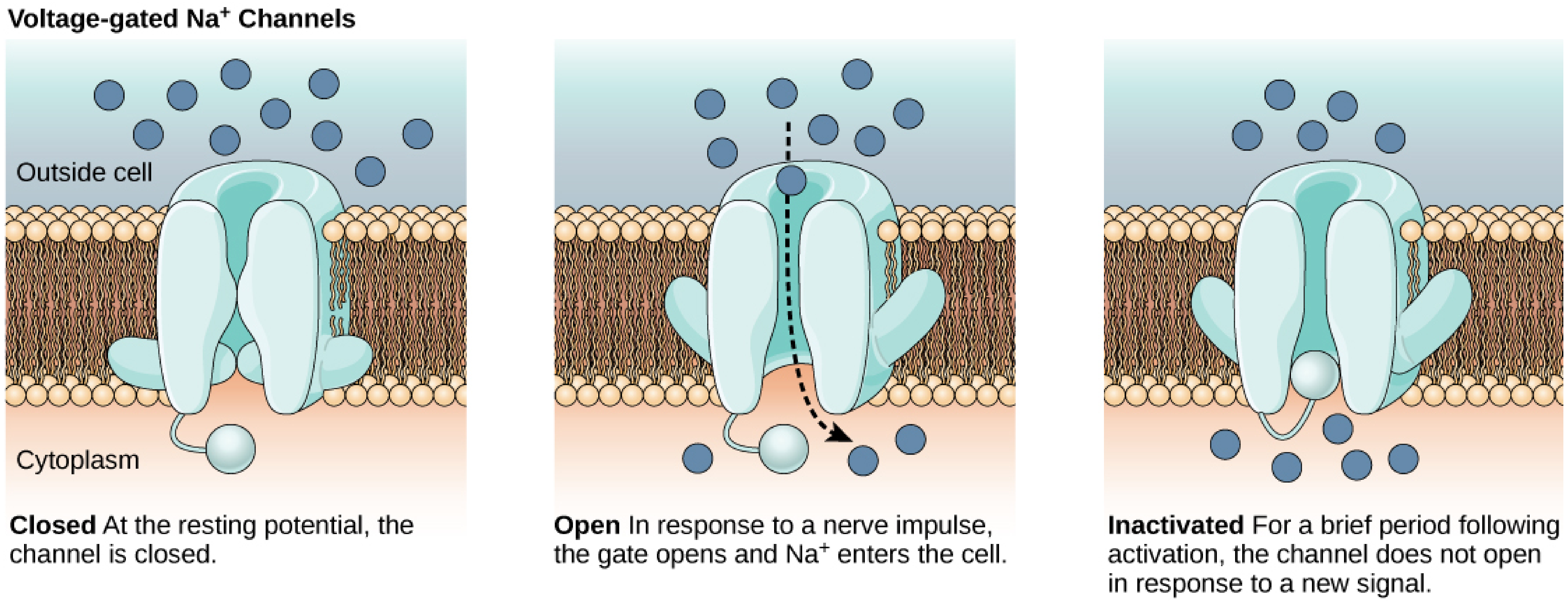
Na^+/K^+-ATPase (Na^+/K^+ adenosine triphosphatase) found in the plasma membrane of all animal cells.

3 sodium ions ↑ of the cell and two potassium ions ↓

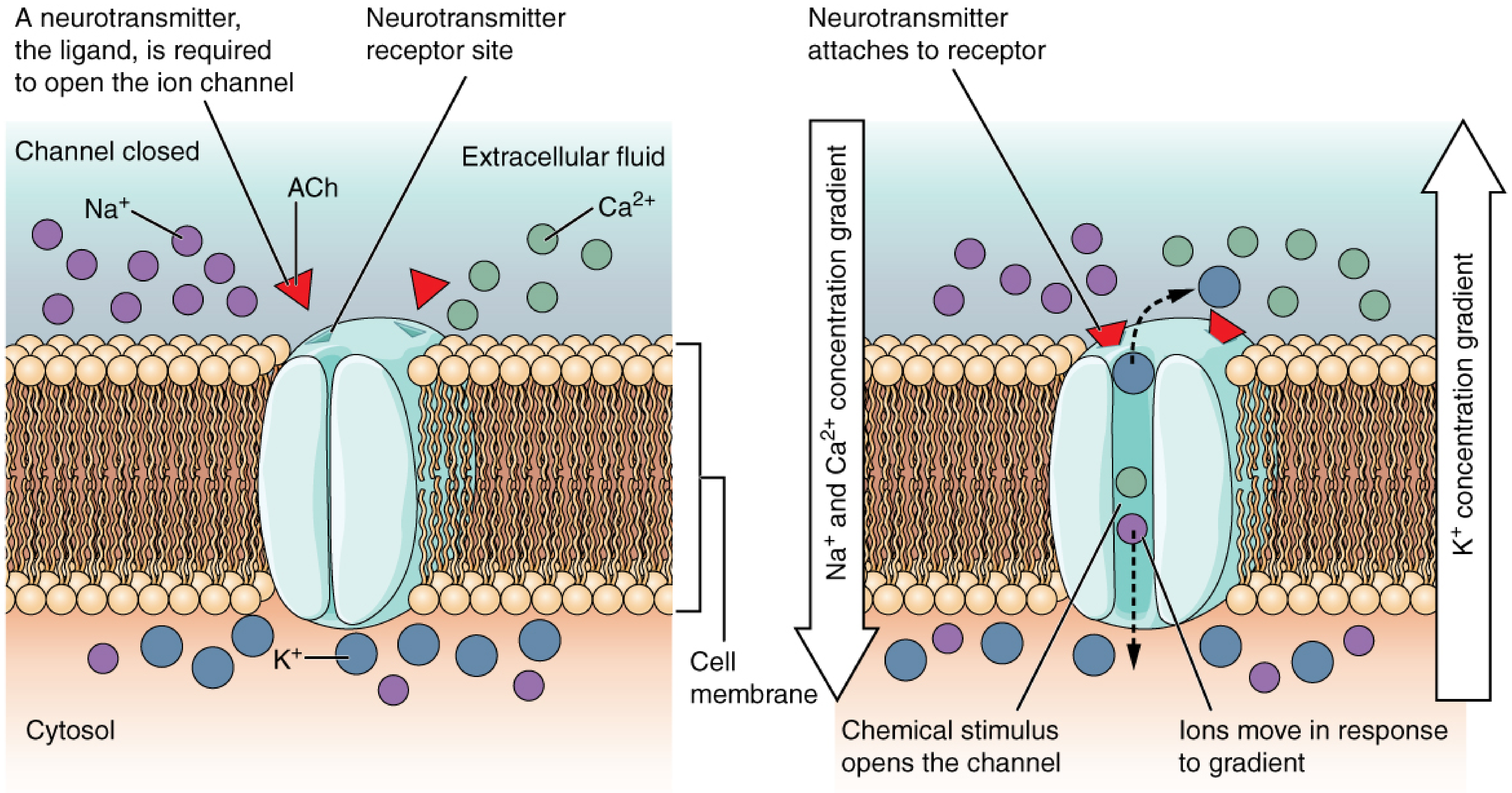


Sodium–potassium pump @ Wikipedia

Ion channels (passive transport)

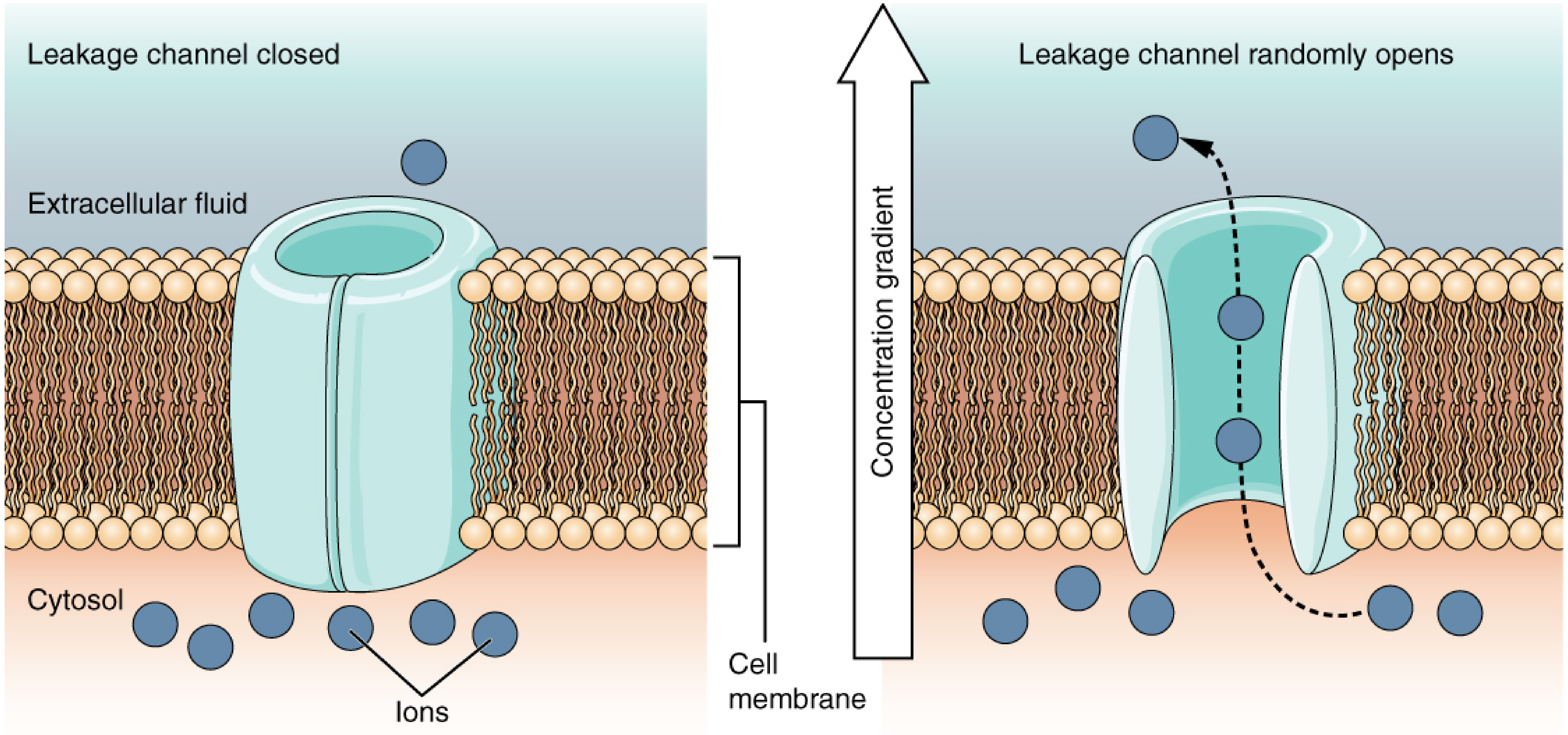


Voltage-gated Na^+ channel example



Ligand-gated ACh channel example

Leakage



Leakage channel example

Electrochemical properties

- Nernst equation
- Reversal potential (equilibrium)
- Resting potential
- Action potential
- Detection methods. Pros and Cons

Boltzmann distribution

Boltzmann distribution: $n \propto e^{-\frac{E}{kT}}$, n - density, E - energy, k - Boltzmann's constant, T - temperature

Energy: $E = qu$, E - energy, q - charge, u - potential

$$\frac{n_2}{n_1} = e^{\frac{1}{kT}(E_1 - E_2)} = e^{\frac{q}{kT}(u_1 - u_2)}$$

$\ln \frac{n_2}{n_1} = \frac{q}{kT}\Delta u \implies \Delta u = \frac{kT}{q}\ln \frac{n_2}{n_1}$, where $\Delta u = u_1 - u_2$ and

u_1 - potential inside, u_2 - potential outside, n_1 - concentration inside, n_2 - concentration outside,

Nernst equation

$$E_m = \frac{kT}{q} \ln \frac{[outside]}{[inside]} = \frac{RT}{F} \ln \frac{[outside]}{[inside]}, \text{ where}$$

T - the absolute temperature, measured in kelvins

R - the universal gas constant, equal to 8.314 joules $\cdot K^{-1} \cdot \mathrm{mol}^{-1}$

F - the Faraday constant, equal to 96,485 C $\cdot\ \mathrm{mol}^{-1}$

Reversal potential (equilibrium)

The reversal potential (or equilibrium potential) of an ion is the value of transmembrane voltage at which diffusive and electrical forces counterbalance, so that there is no net ion flow across the membrane.

E_K in $[-90; -70]$ mV for K^+

$E_{Na} > 50$ mV for Na^+

$E_{Ca} \approx 150$ mV for Ca^{2+}

E_{Cl} in $[-65; -60]$ mV for Cl^-

Resting potential

When the membrane potential of a cell goes for a long period of time without changing significantly, it is referred to as a resting potential or resting voltage. This term is used for the membrane potential of non-excitable cells, but also for the membrane potential of excitable cells in the absence of excitation.

- The Nernst equation applies for one type of ion to pass through membrane
- Some ion channels are not so selective
- Membrane potential as a weighted average of the reversal potentials for the individual ion types, weighted by permeability

Goldman Equation

$$E_m = \frac{RT}{F} \ln\left(\frac{P_K[K^+]_{out} + P_{Na}[Na^+]_{out} + P_{Cl}[Cl^-]_{in}}{P_K[K^+]_{in} + P_{Na}[Na^+]_{in} + P_{Cl}[Cl^-]_{out}}\right)$$, where

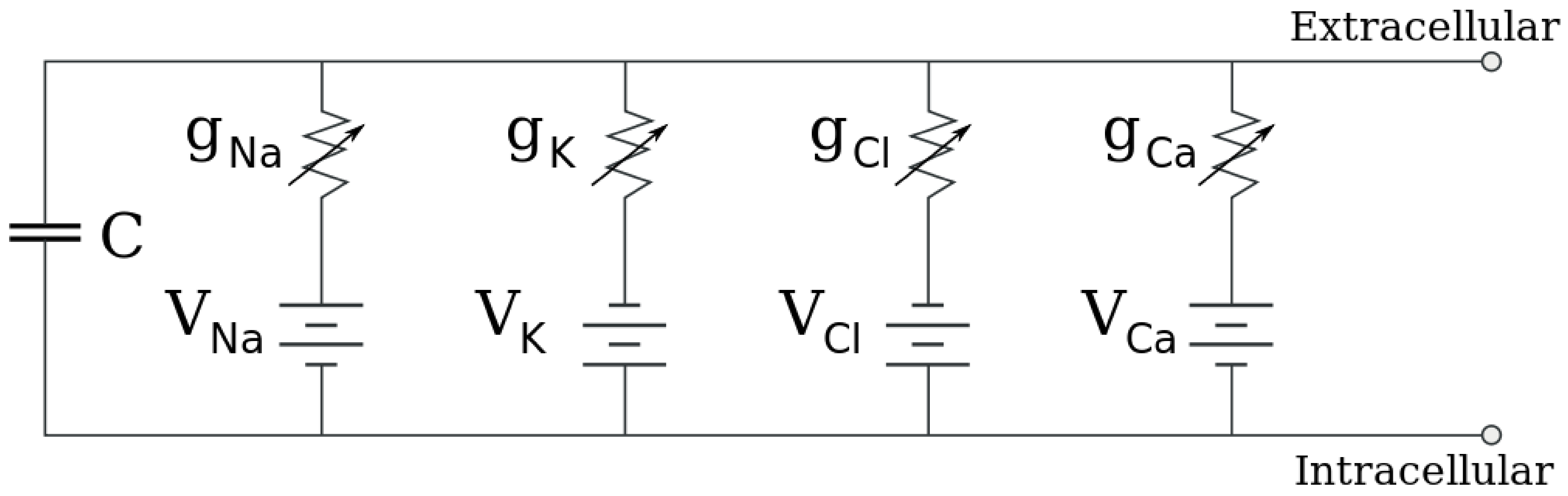
P_{ion} - the permeability or selectivity for that ion type

$[\mathrm{ion}]_{out}$ - the extracellular concentration of that ion (in moles per cubic meter)

$[\mathrm{ion}]_{in}$ - the extracellular concentration of that ion (in moles per cubic meter)

Cl^- conductances, with reversal potentials near the resting potential, may pass little net current. Instead, their primary impact is to change the membrane resistance of the cell.

Equivalent circuit

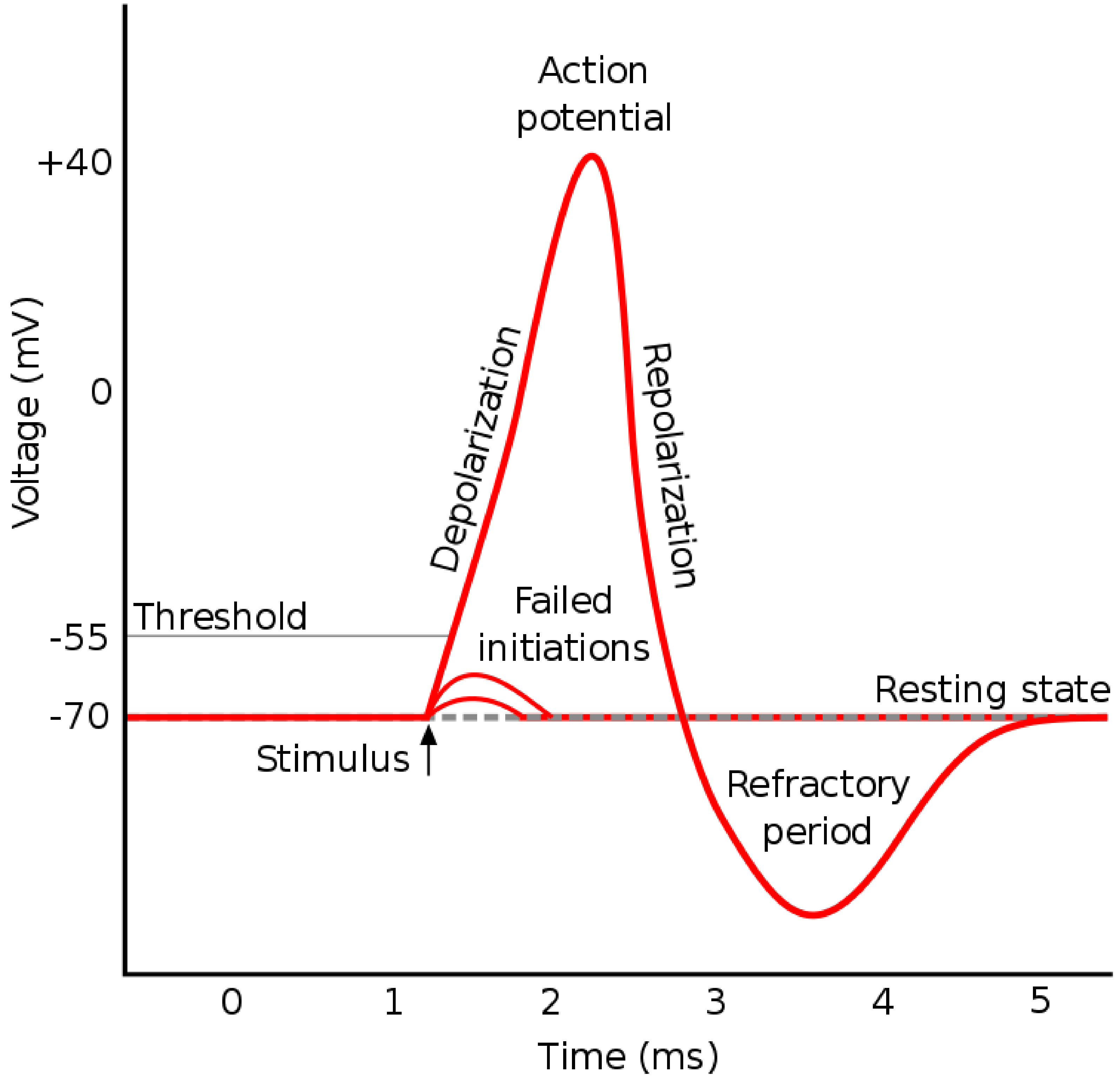


Resistance-capacitance or RC circuit in electrical terms

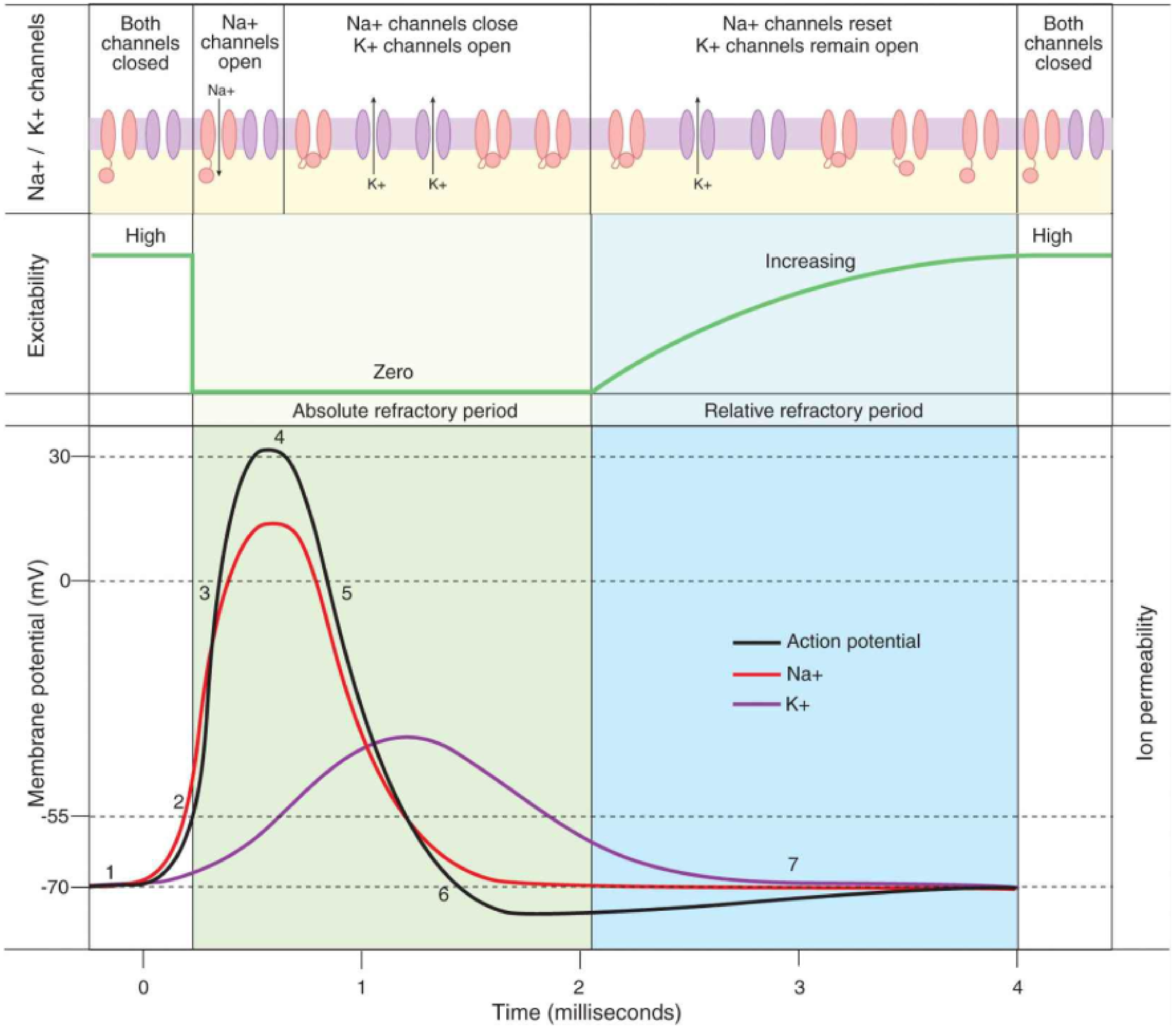
Summary of resting potential values in different types of cells

Cell types	Resting potential
Skeletal muscle cells	-95 mV
Astroglia	-80 to -90 mV
Neurons	-60 to -70 mV
Smooth muscle cells	-60 mV
Aorta Smooth muscle tissue	-45 mV
Photoreceptor cells	-40 mV
Hair cell (Cochlea)	-15 to -40mV
Erythrocytes	-8.4 mV
Chondrocytes	-8 mV

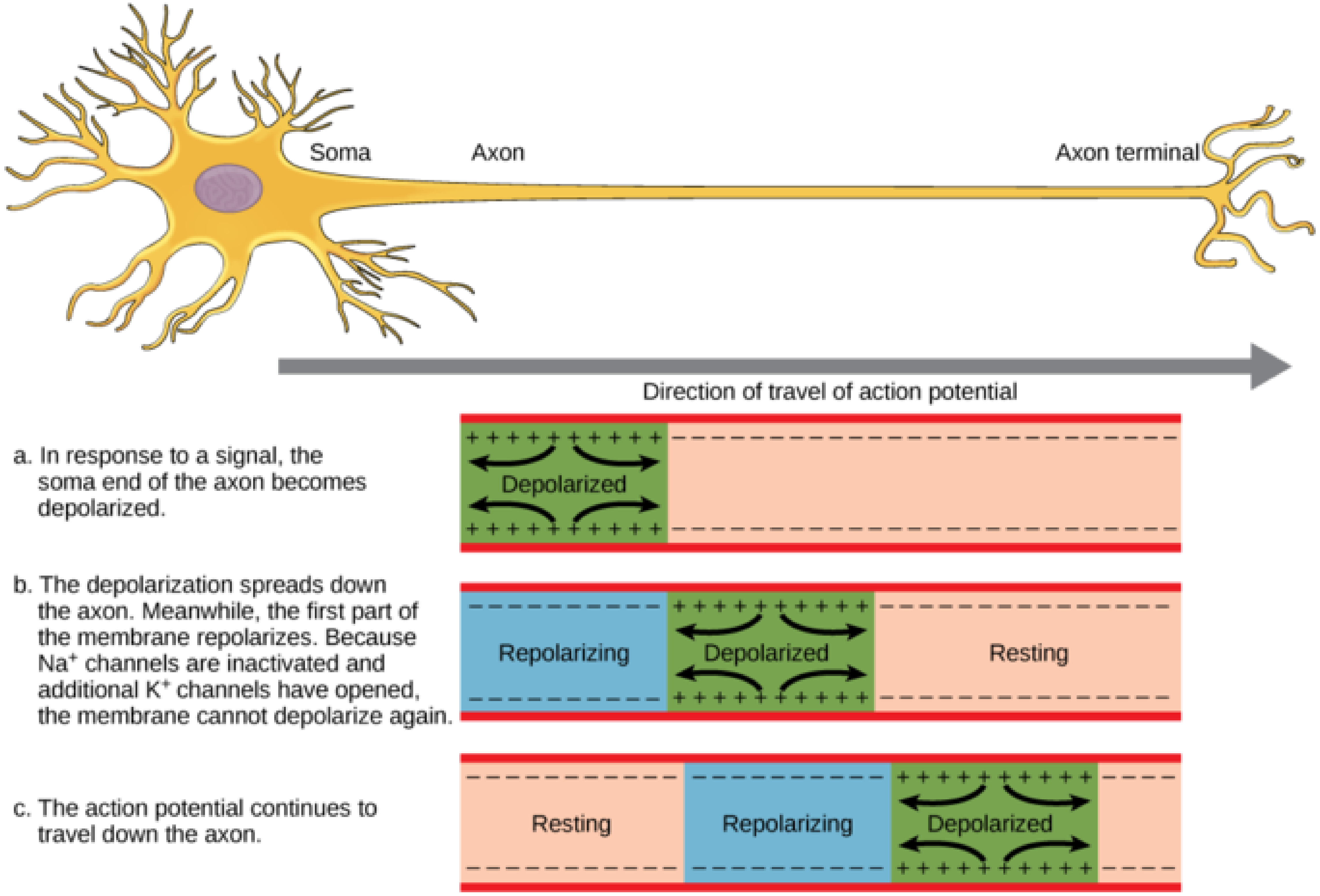
Action potential



Approximate plot of a typical action potential

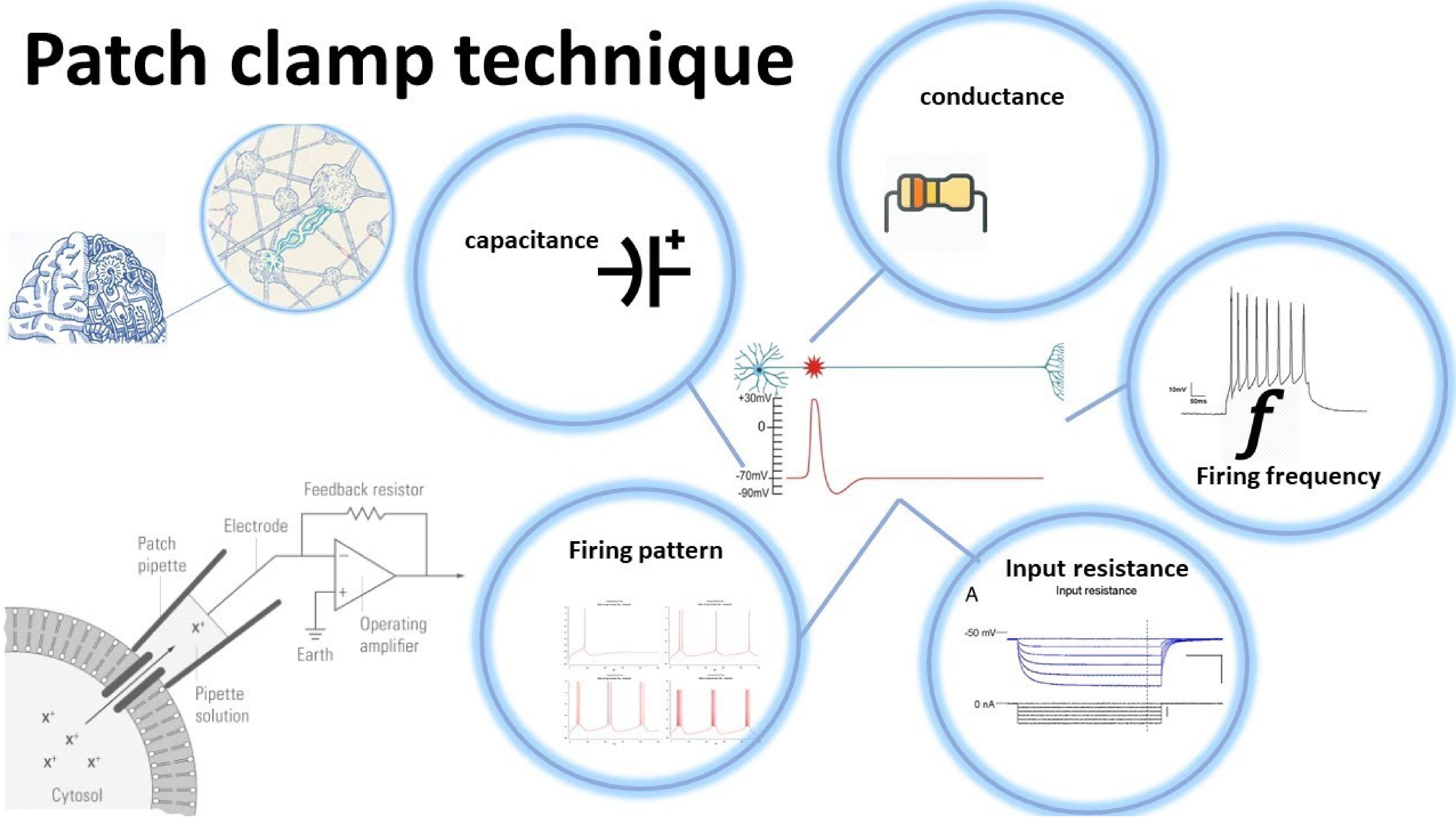


Action potential, ion permeability dynamics, excitability dynamics

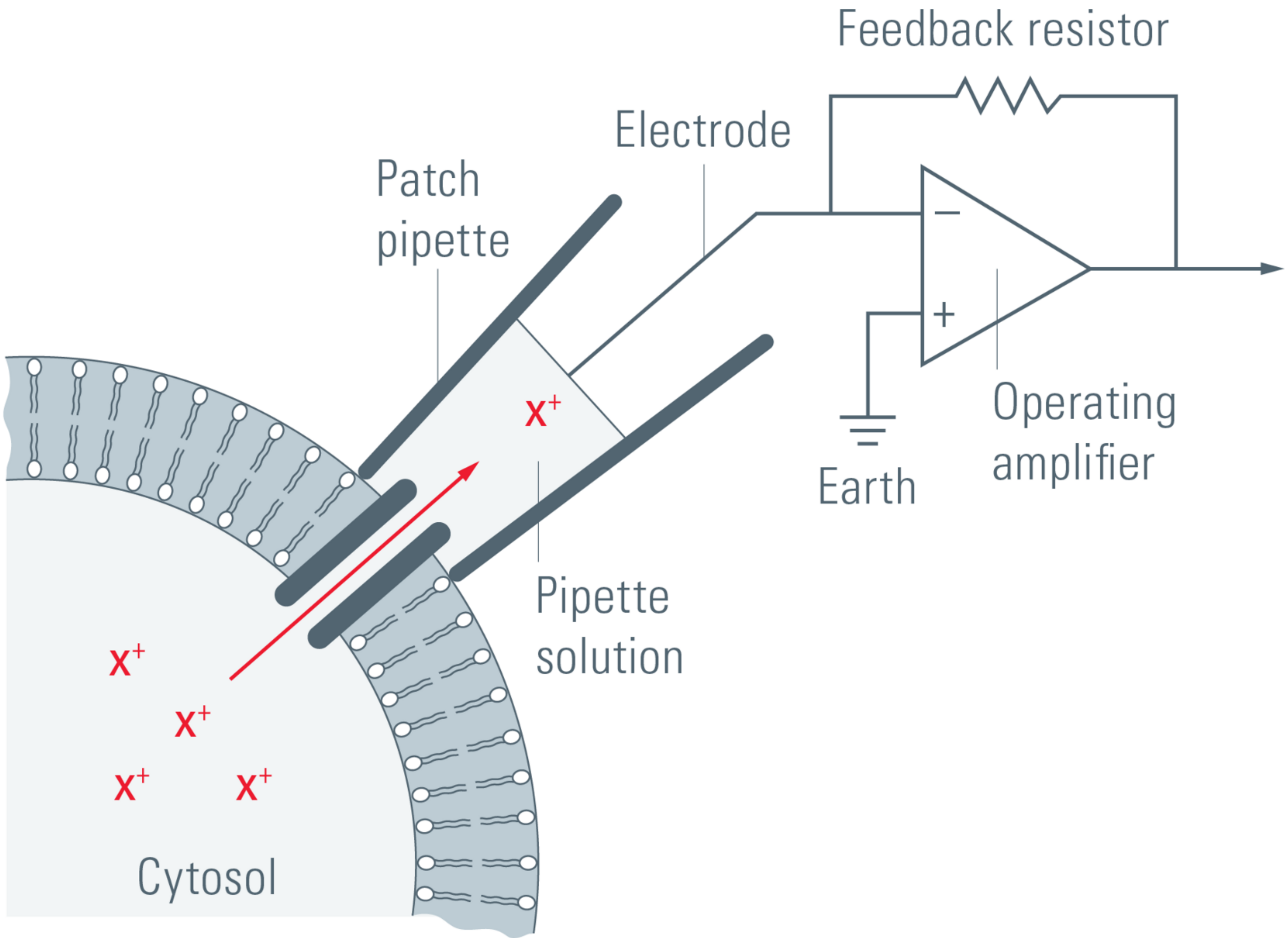


Action potential propagation along an axon

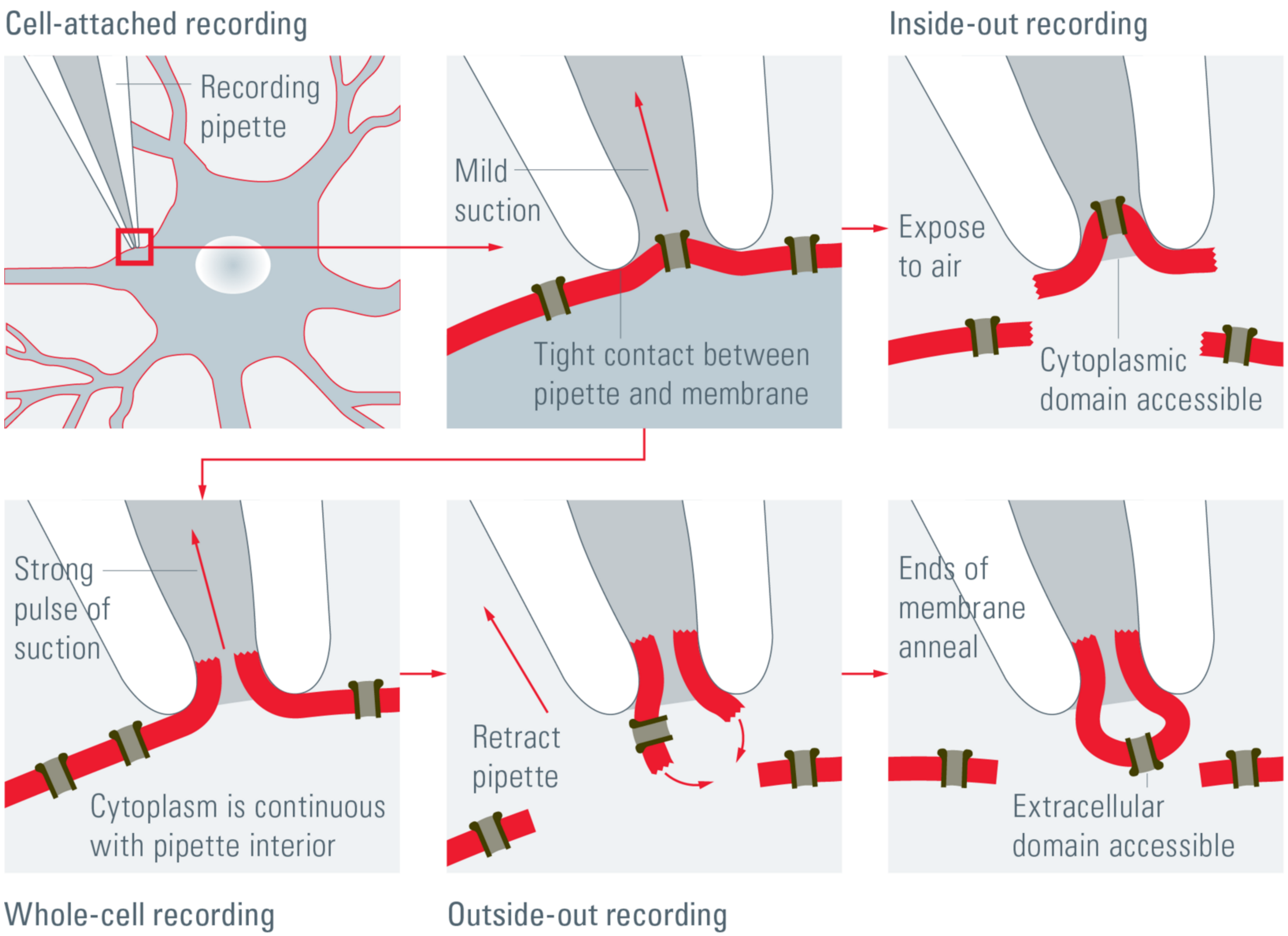
Detection methods. Pros and Cons



What we can see with patch clamp



Patch clamp principal scheme



Patch clamp configurations