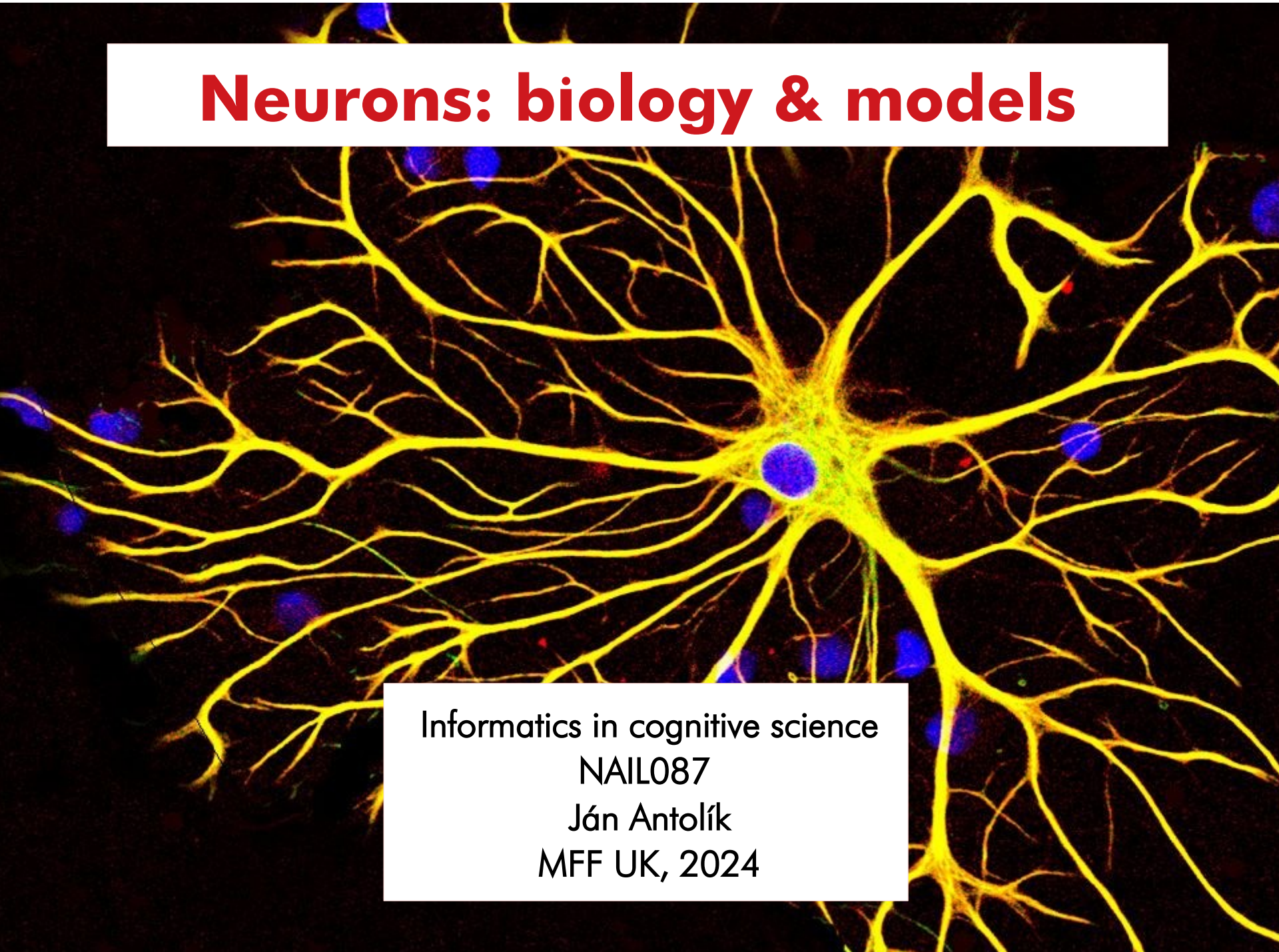
Neurons: biology & models



Informatics in cognitive science
NAIL087
Ján Antolík
MFF UK, 2024

Lecture Outline

- Little recap
- Axons, dendrites, soma
- Neuronal Membrane
- Synapses and synaptic transmission
- Neuron as a signal integration element
- Integrate & Fire abstraction of neural operation
- Outlook

Little recap

How did we simplify brain?

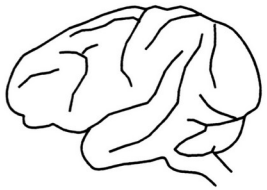
Little recap

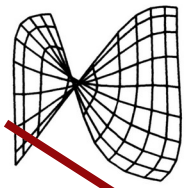
What could be the elementary units from which to build our understanding of neural computation?

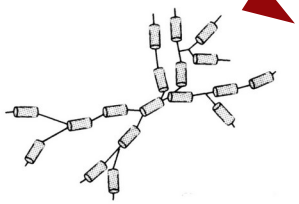
Why do we care about neurons?

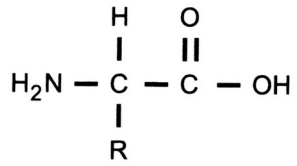
Neurons, axons, dendrites and synapses are to neuroscience what atoms and electrons are to physics.

Brain as a multi–scale system









1 m CNS

10 cm System

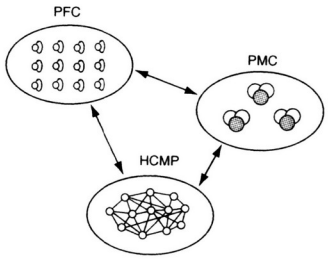
1 cm Maps

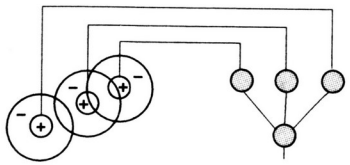
1 mm Networks

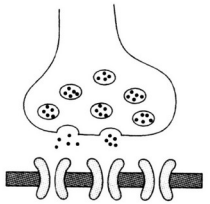
100 µm Neurons

1 µm Synapses

1 Å Molecules



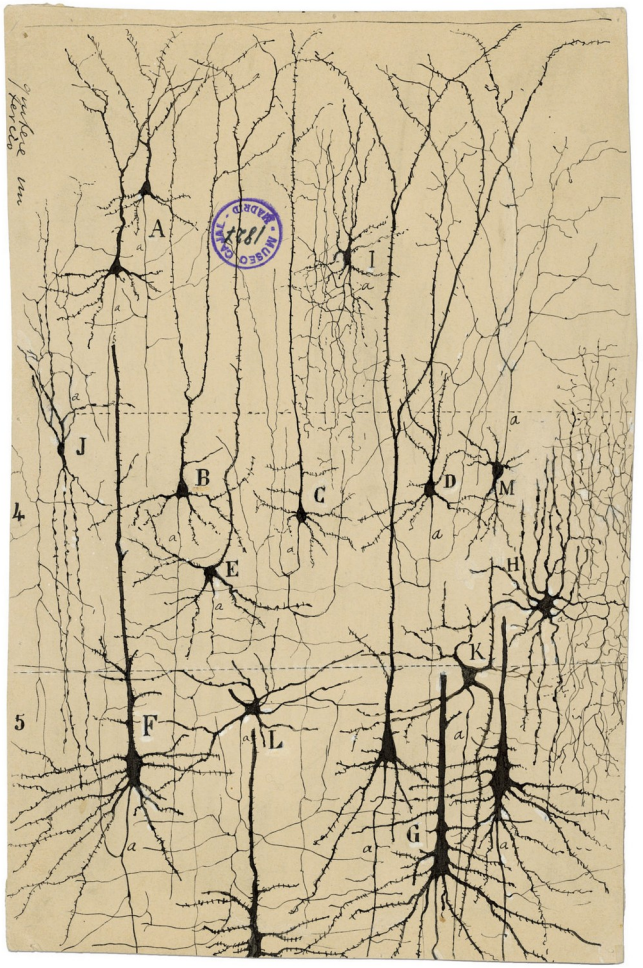




In this and next lecture we will work here

The discovery of neuron

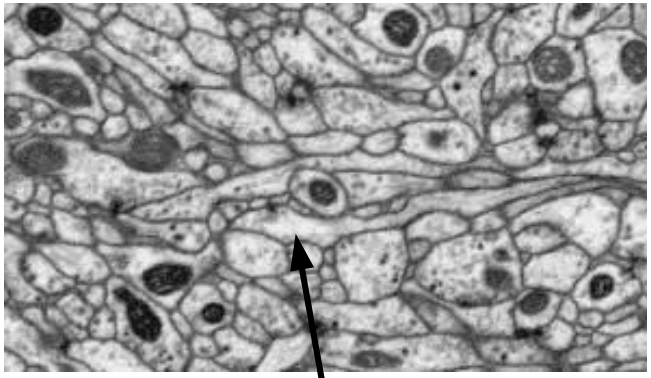
- Glogi's method of silver staining
- Discovered by S.R. Cajal
- The dye is injected in the neural tissue
- It stains the neurons which can then be viewed under optical microscope



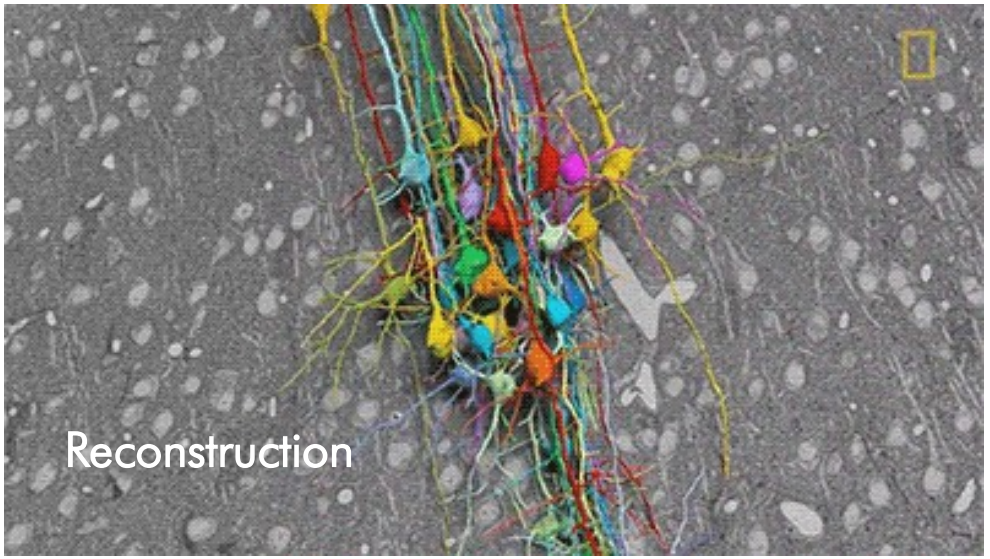
Santiago Ramón y Cajal

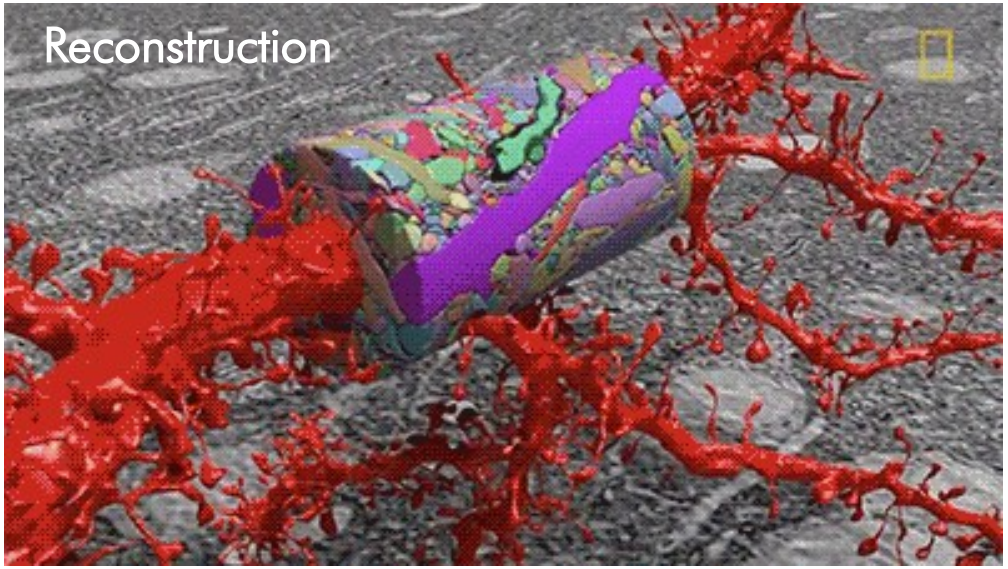
Ways to look at it

Electron microscope view



Apropo 3km of wires: each delineated region here here belongs to a different cell.





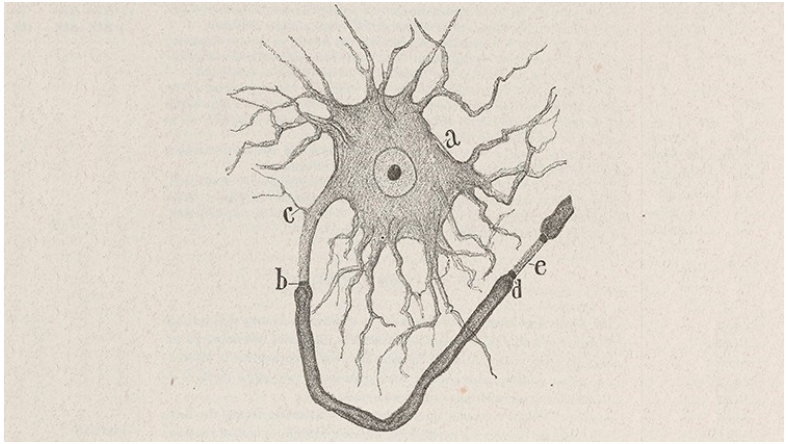
Compromises between different methods of studying neurons:

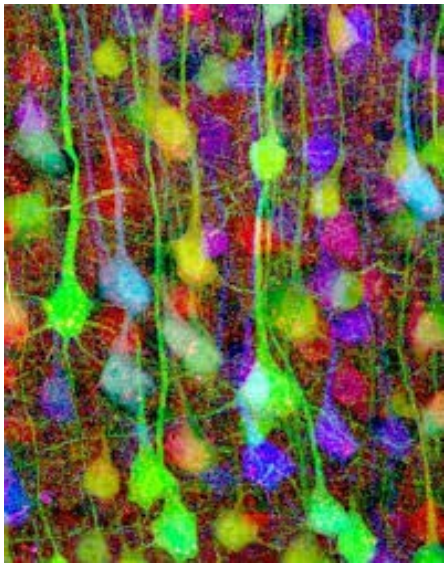
* spatial resolution
* recording length
* fixed/in-vitro/in-vivo tissue

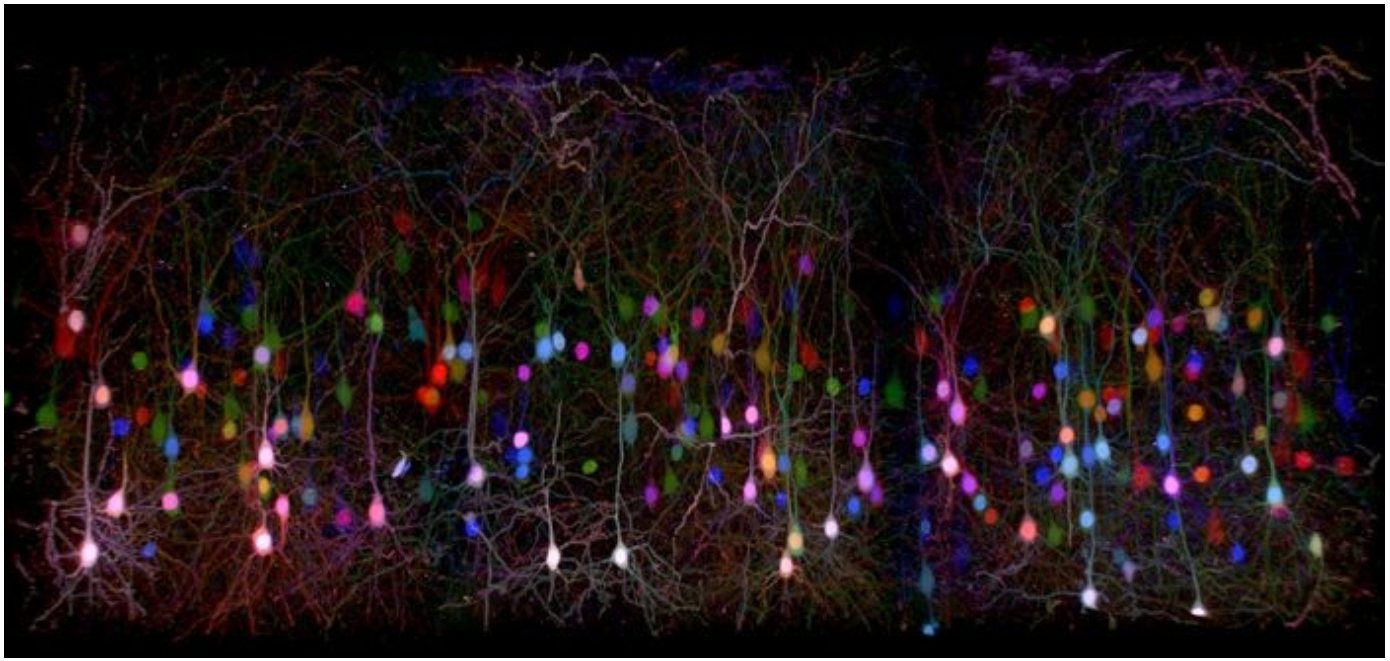
in-vitro vs. in-vivo

What's the difference?

Ways to look at it

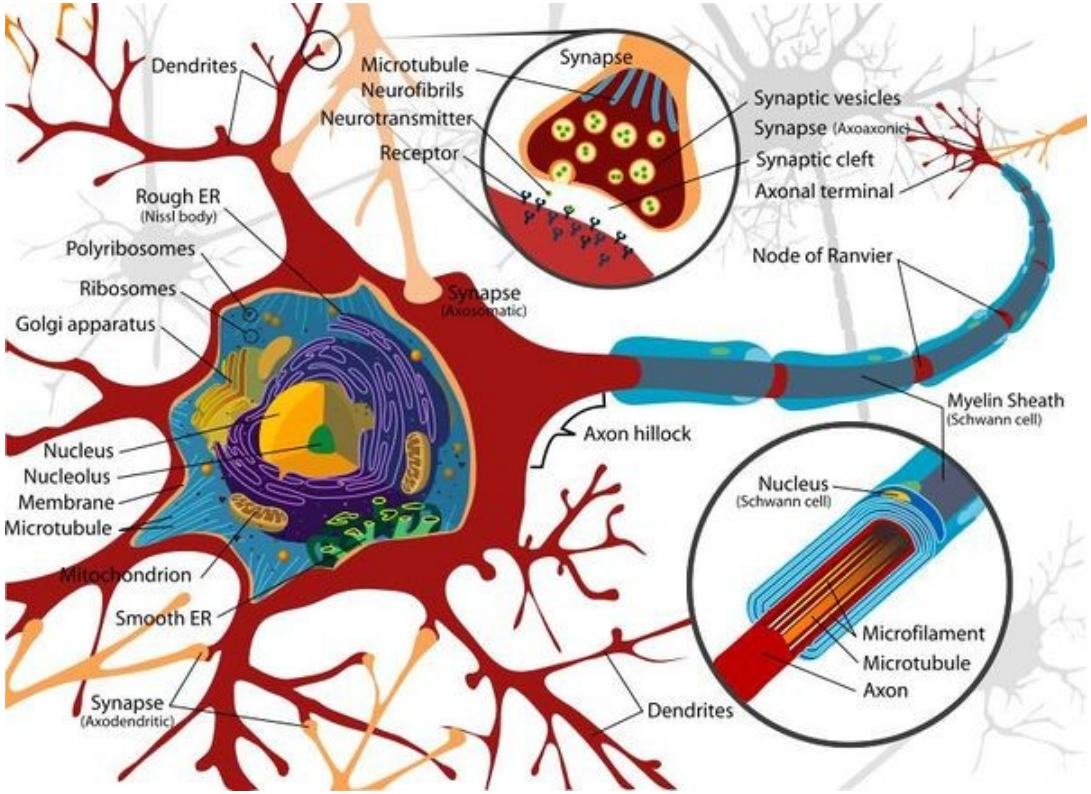






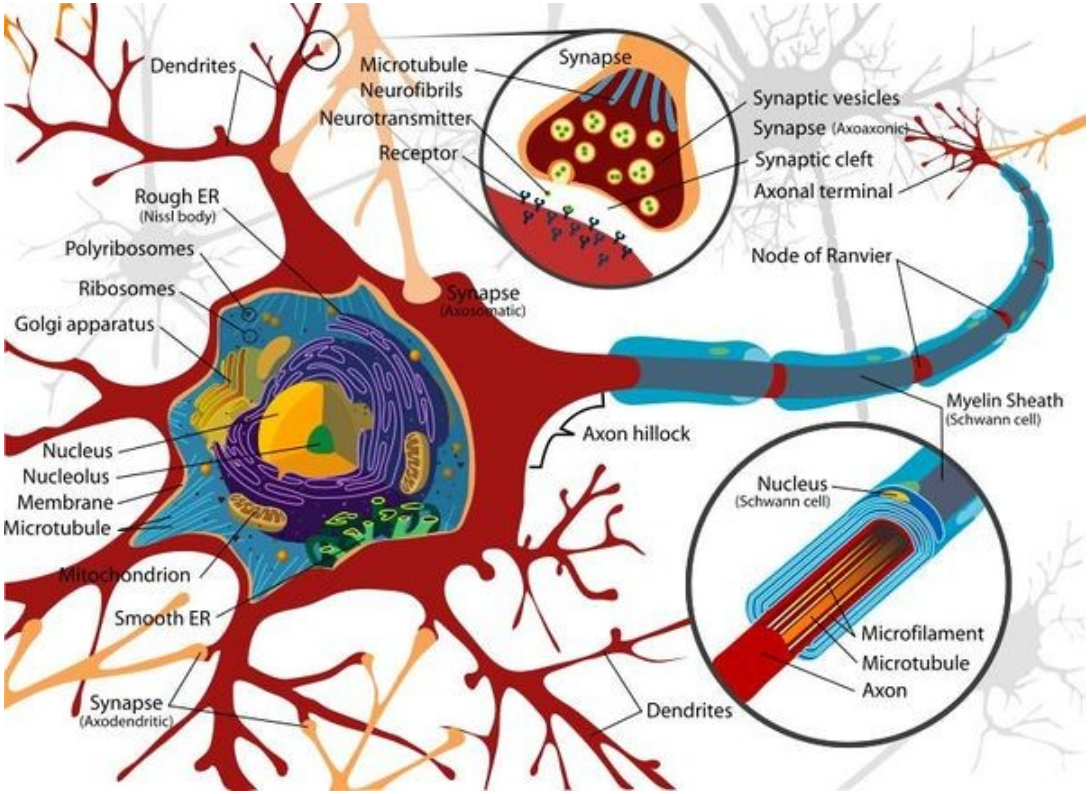
Neuron is just another cell

- Nucleus
- Ribosome
- Mitochondrias
- Cytoskeleton
- Endopl. reticulum

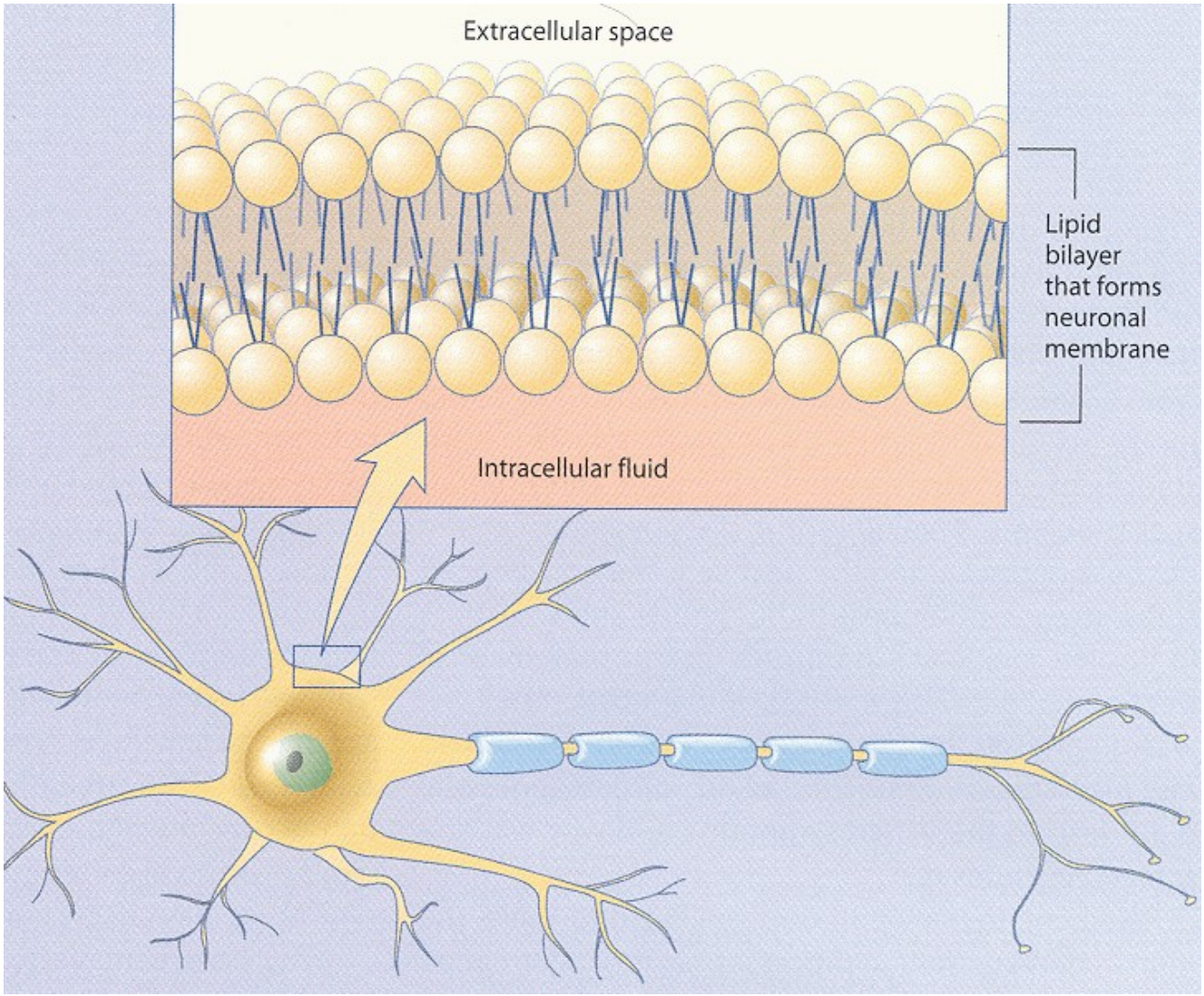


The key components

- Membrane
- Dendrites
- Soma
- Axon
- Synapses
- Spines



Neural membrane



Membrane potential (single ion)

Blackboard time

Nernst equation

$$E_X = \frac{RT}{zF} \ln \frac{[X]_{out}}{[X]_{in}}$$

$$E_X = \frac{58}{z} \log \frac{[X]_{out}}{[X]_{in}}$$

R : Gas constant
T : Absolute temperature
F : Faraday constant
z : Valence

Equilibrium potential for K^+

- Concentration inside: 150 mMol/L
- Concentration outside: 5 mMol/L

$[K^+]_{in} = 130\ mM$ $[K^+]_{out} = 5\ mM$ $z = +1$

$$E_{K^+} = \frac{58\ mV}{1} \log \frac{5}{130} = -82\ mV$$

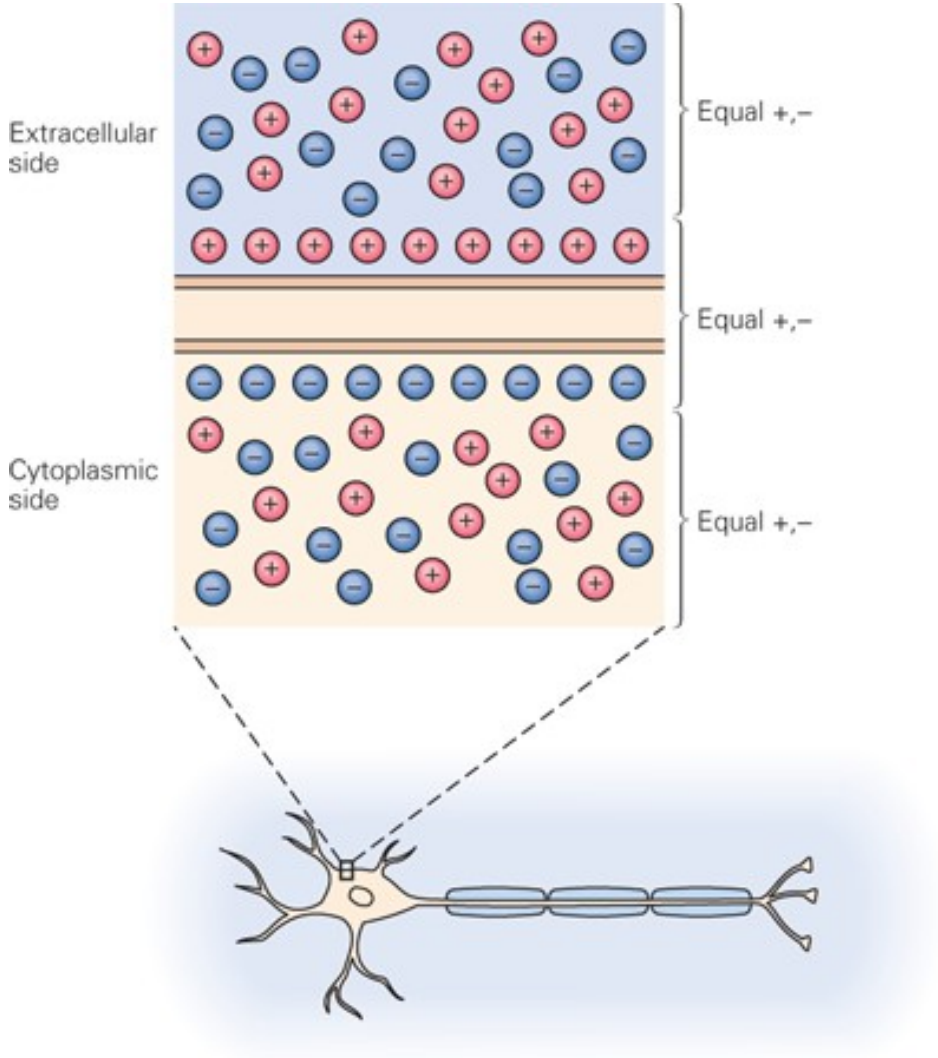
Membrane potential (multiple ions)

Blackboard time

How can neurons change their membrane potential?

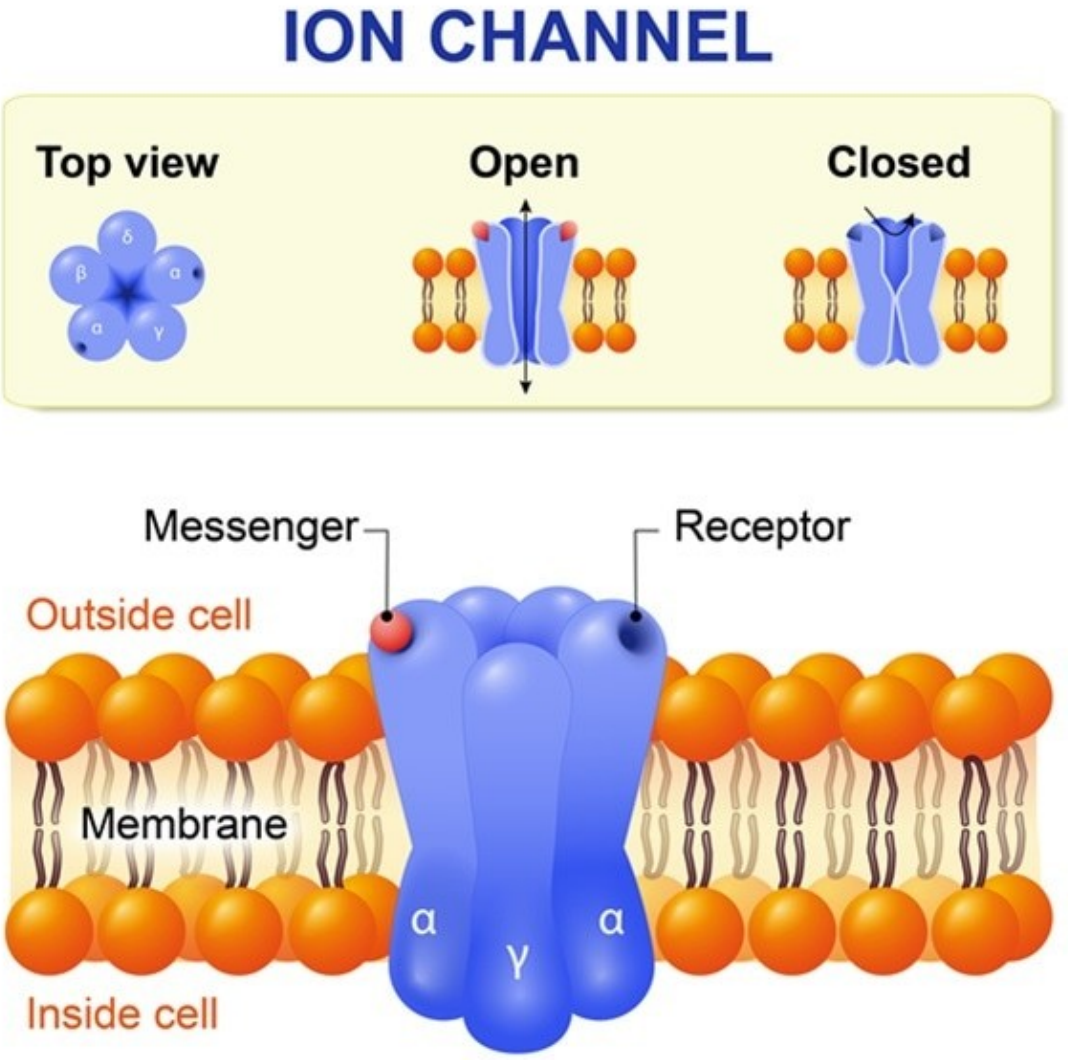
Membrane potential summary

- Equilibrium potential
  - single ion
  - concentration gradient
    - remains constant
  - difference of charge
  - permeability
- Membrane potential
  - Equilibrium potential across all ions



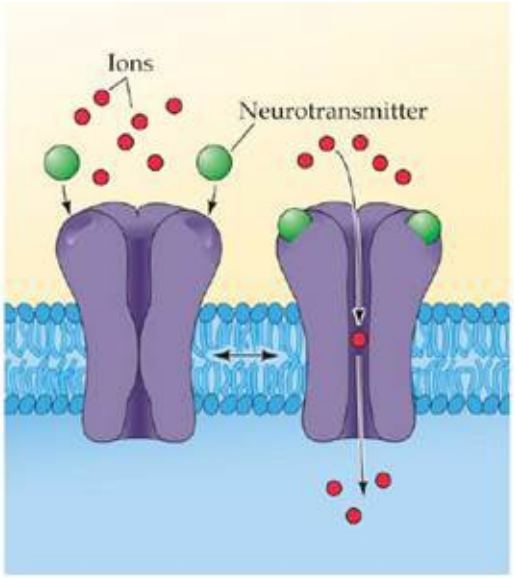
How can cell change its membrane permeability?

Memrane Channels

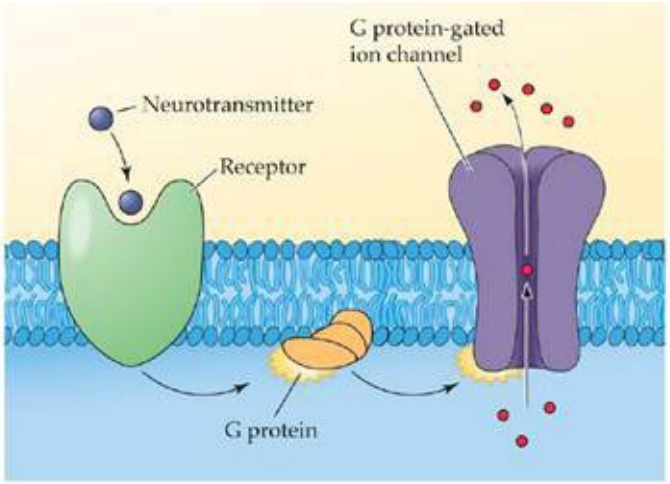


Design a channel that will depolarize a cell?

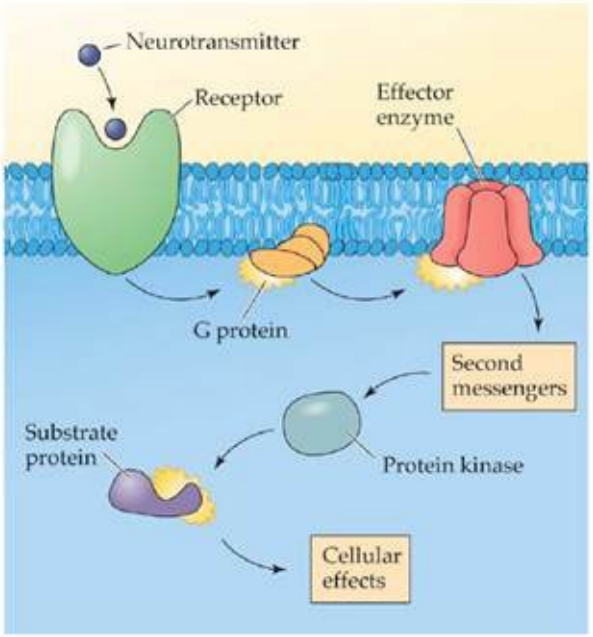
Channel Types



(A) An ionotropic receptor, which allows ions into the cell directly

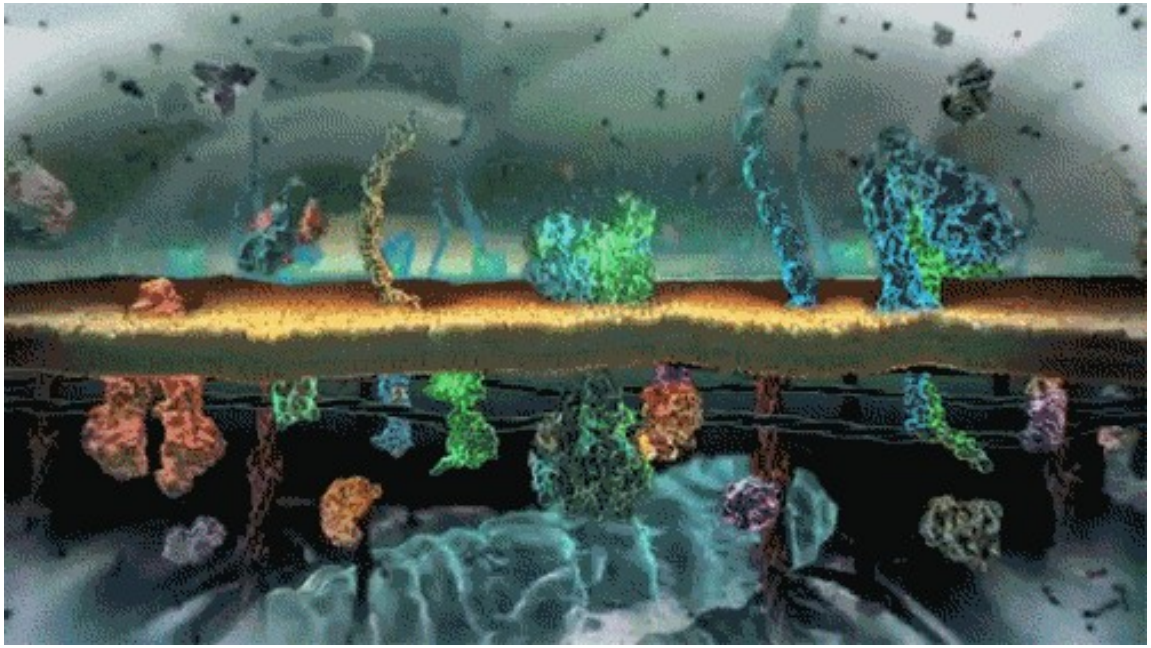


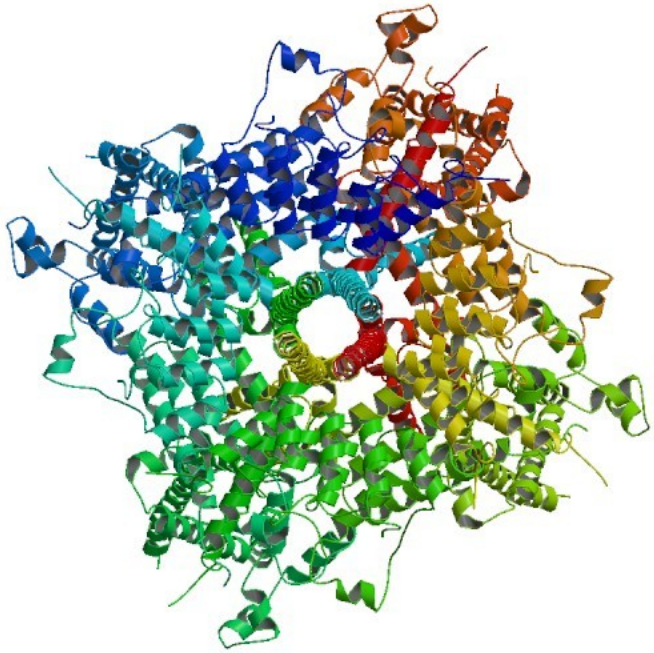
(B) A metabotropic receptor, which uses a G protein to activate an ion channel and let ions into the cell



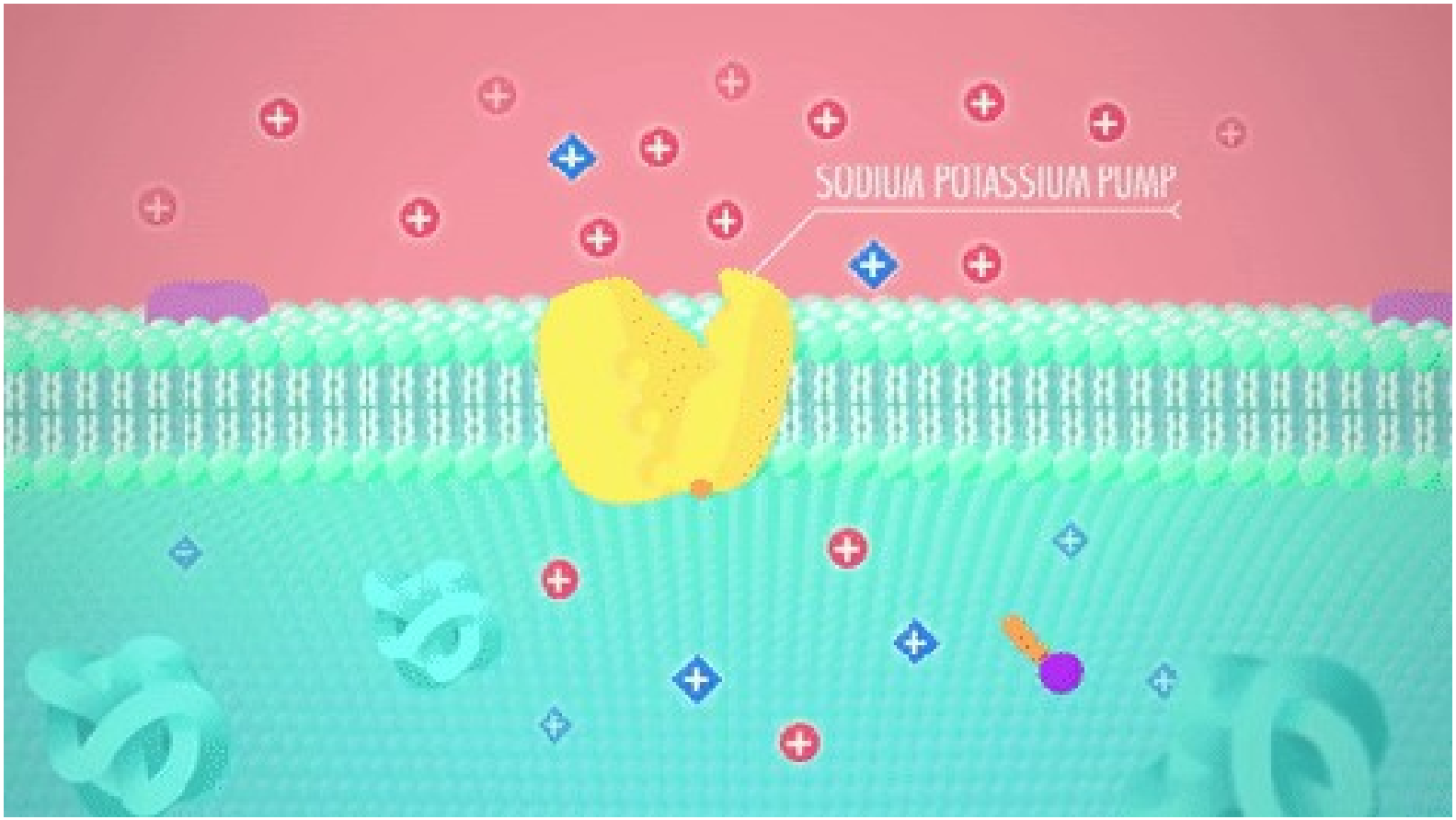
(C) A metabotropic receptor which uses G proteins to create a signalling cascade

Channel structure

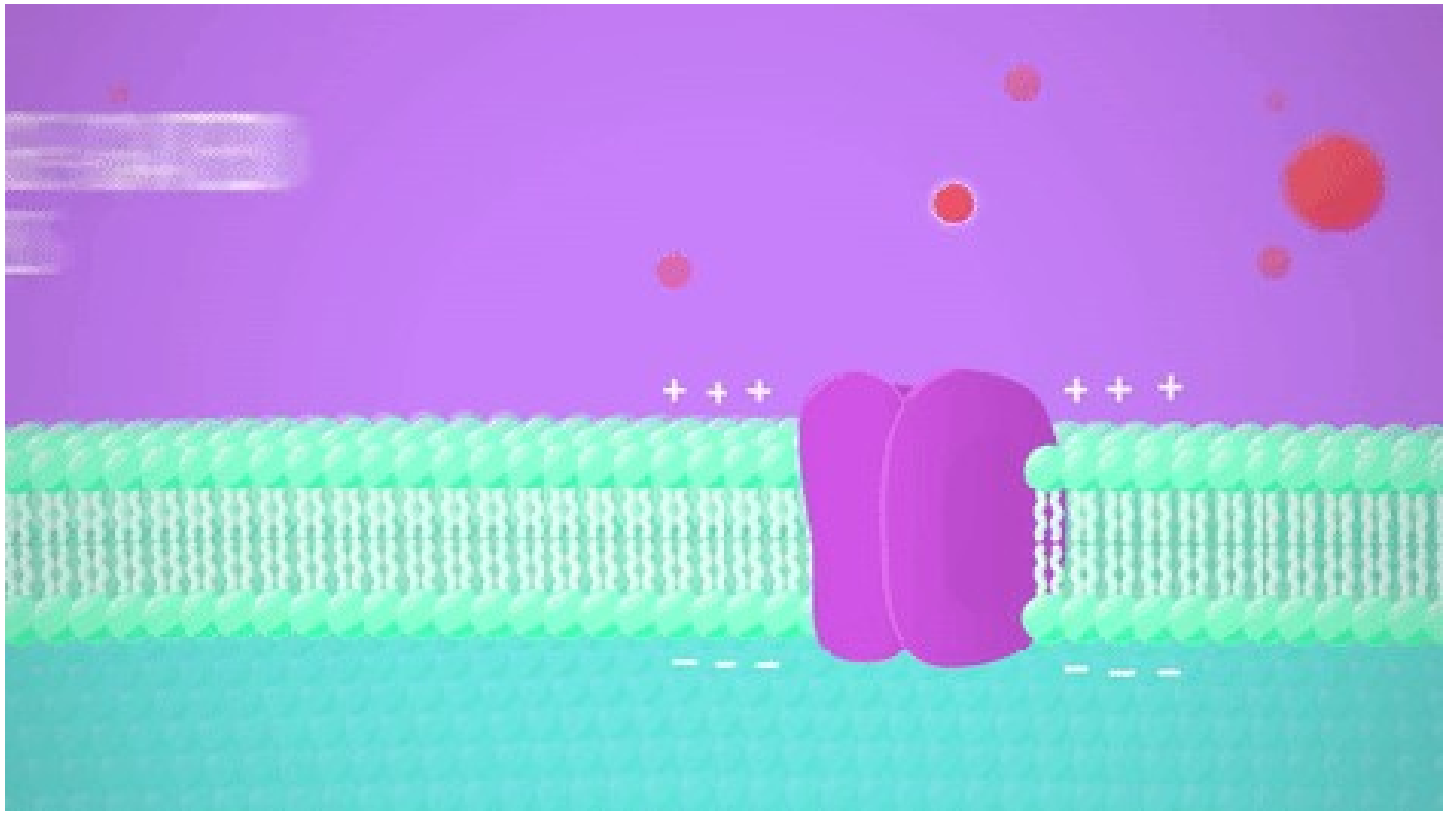




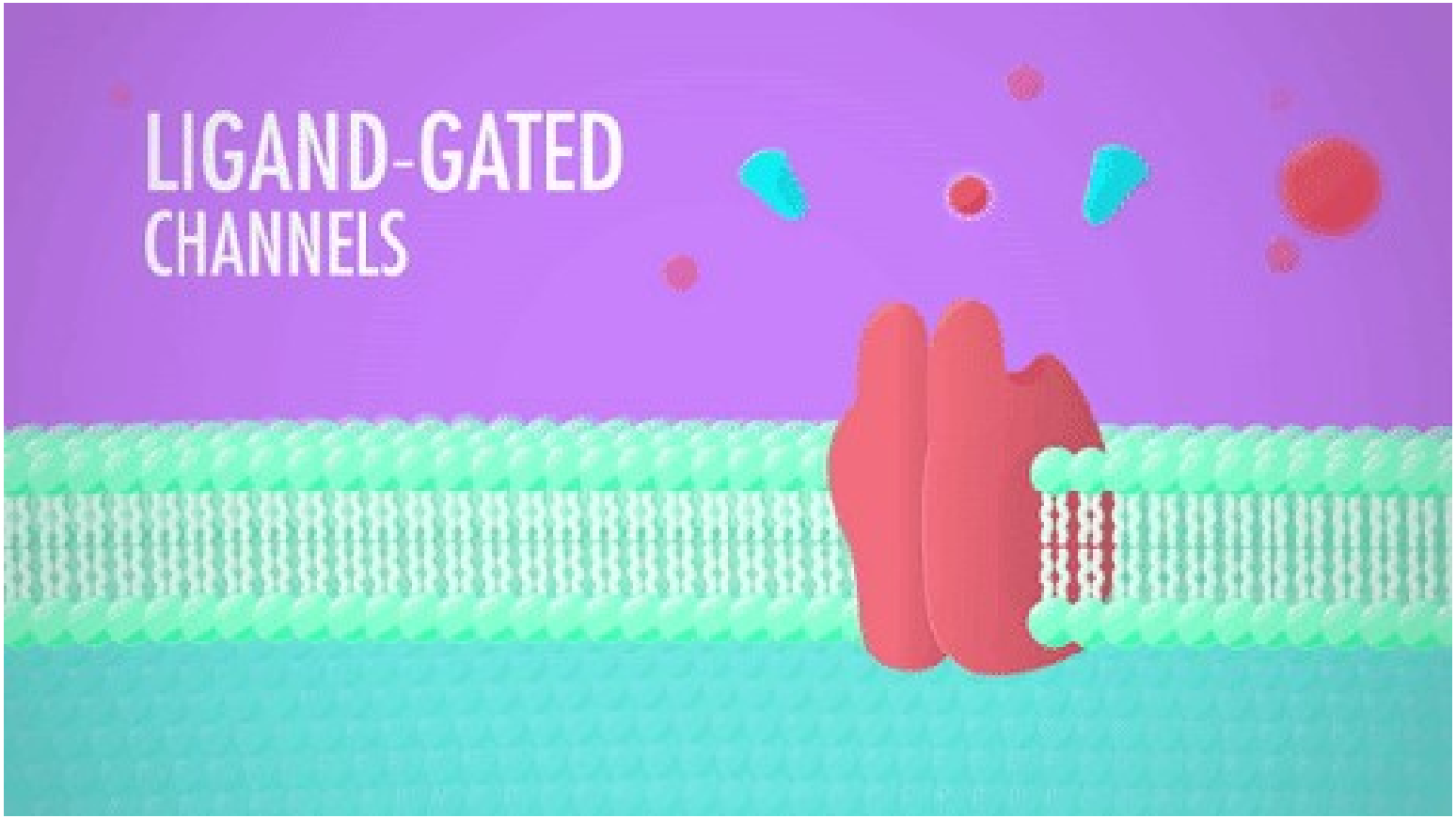
Sodium – Potassium Channels



Voltage gated channels

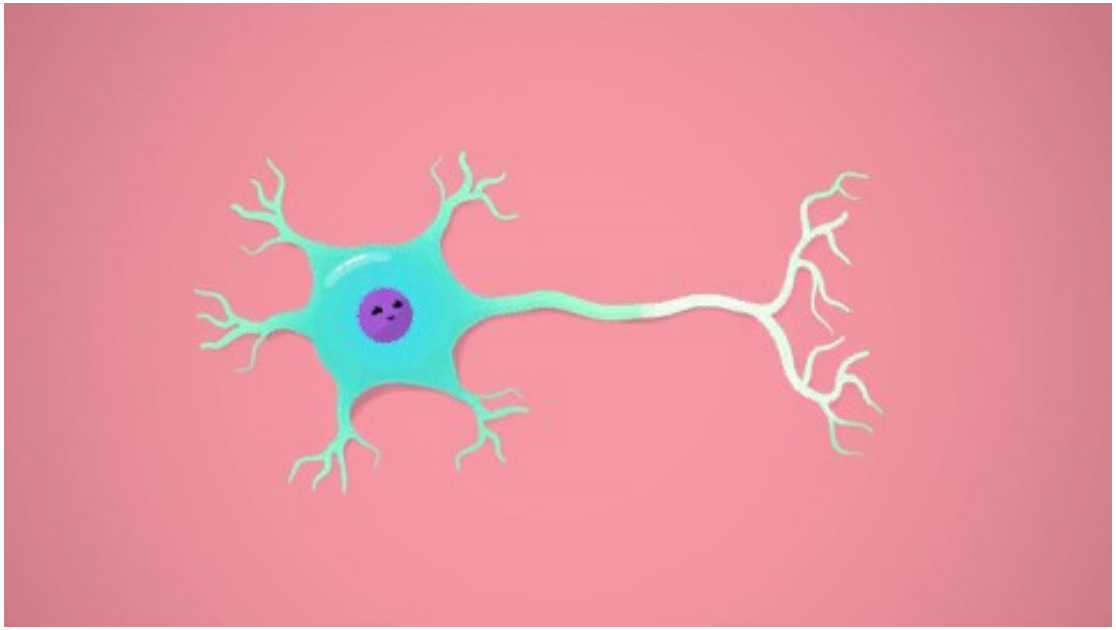


Ligand Gated Channels

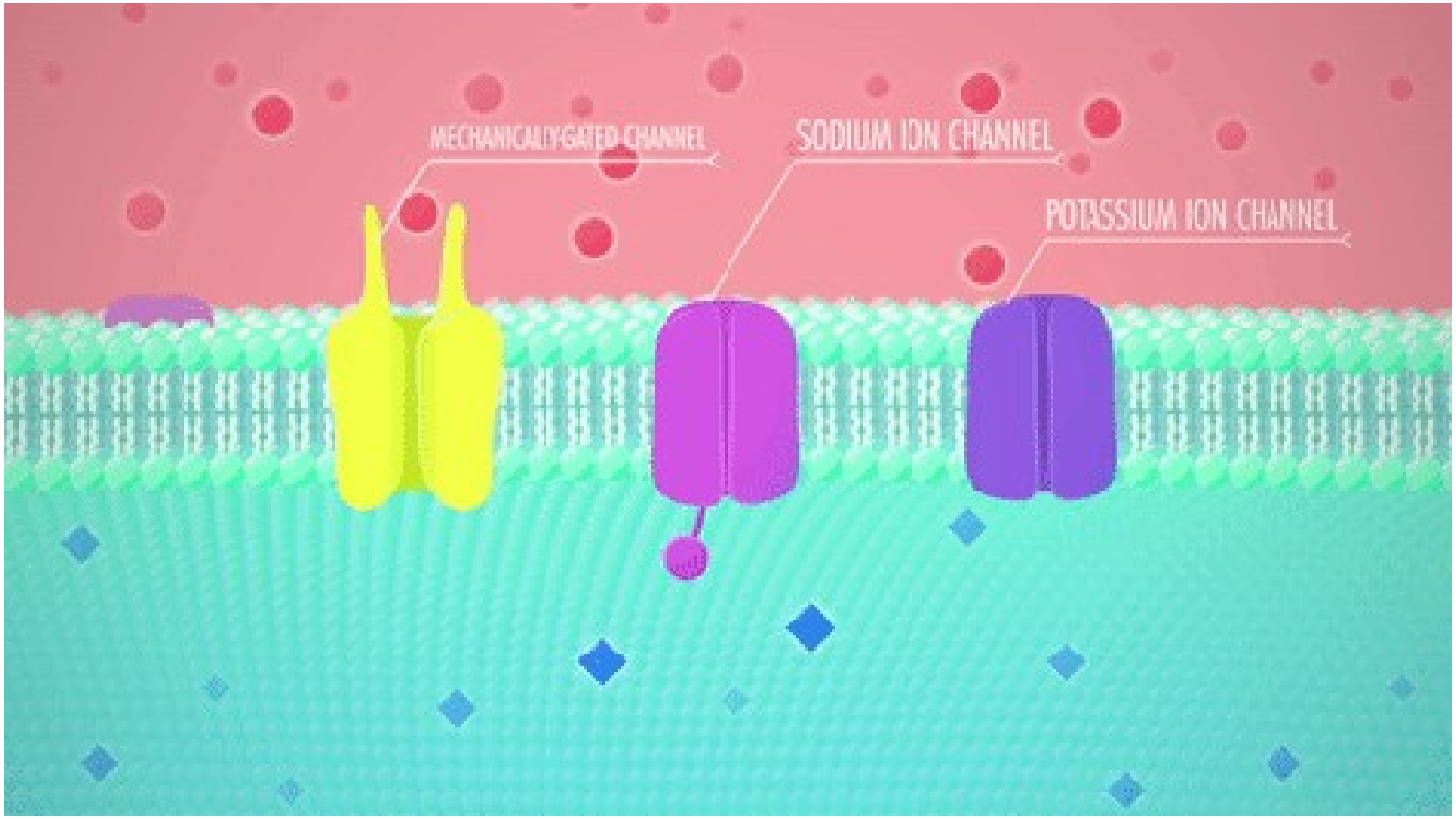


How to transmit information using membrane potential?

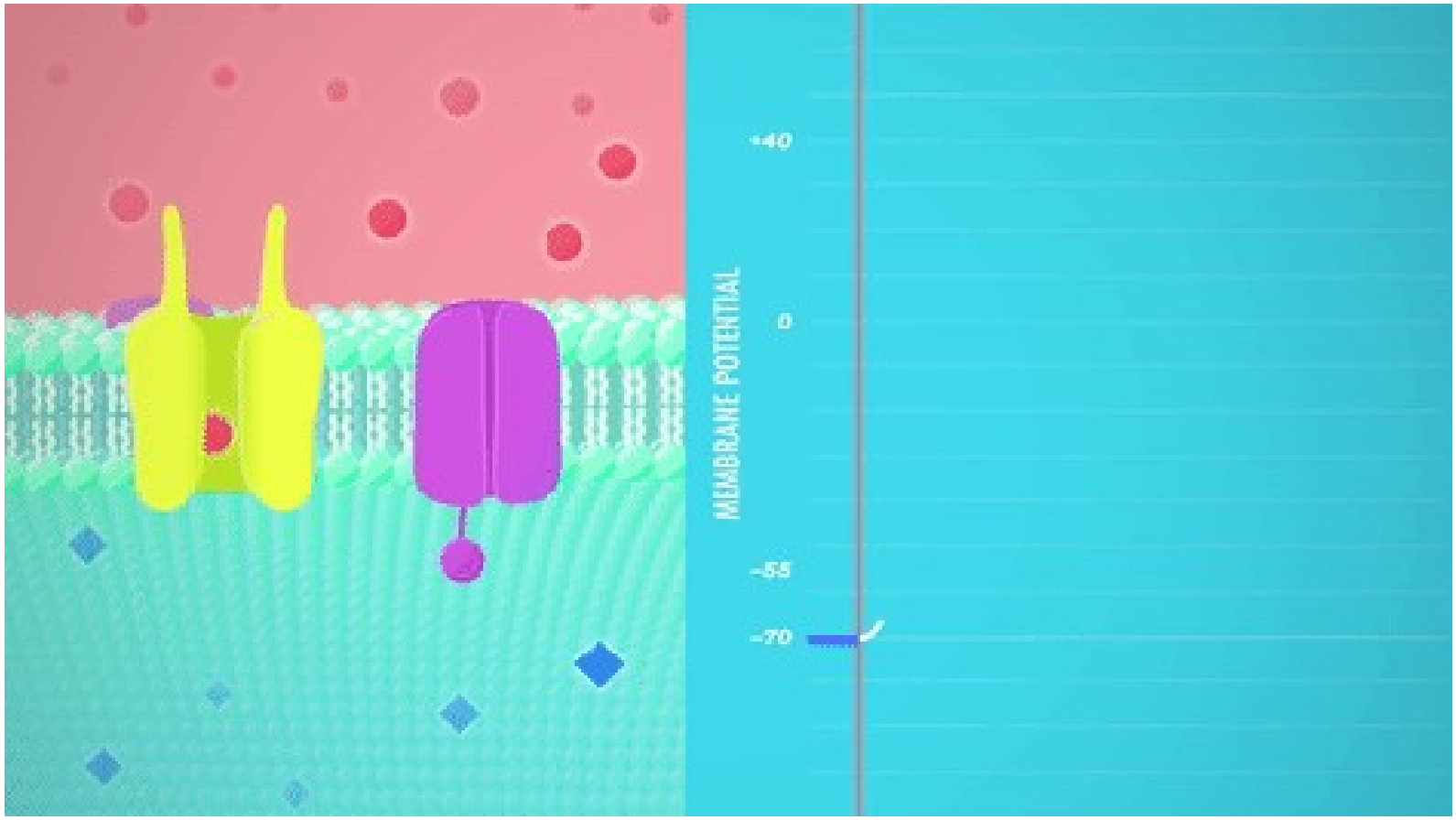
Action Potential



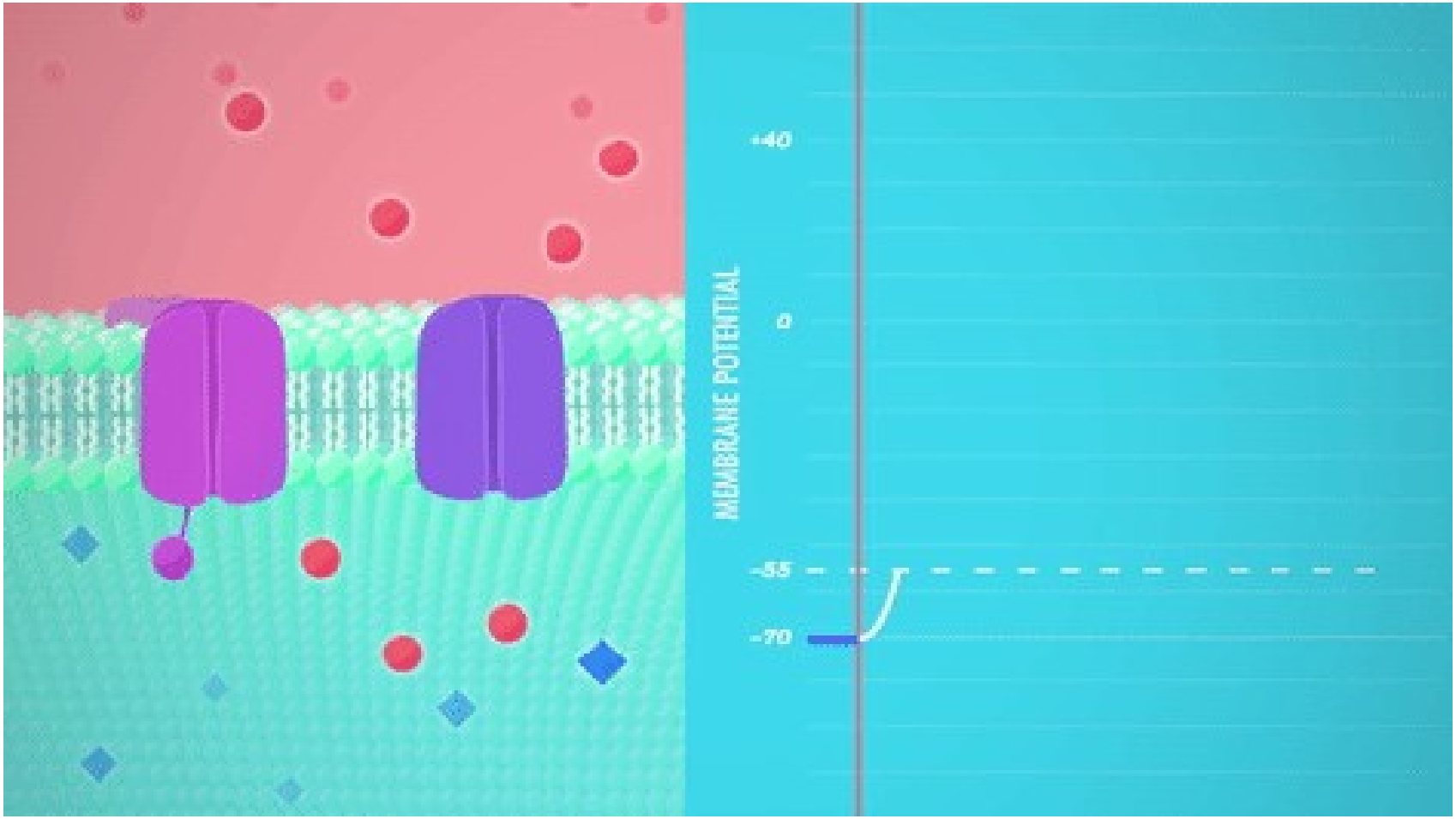
Resting membrane potential



Its all about getting to −55mV

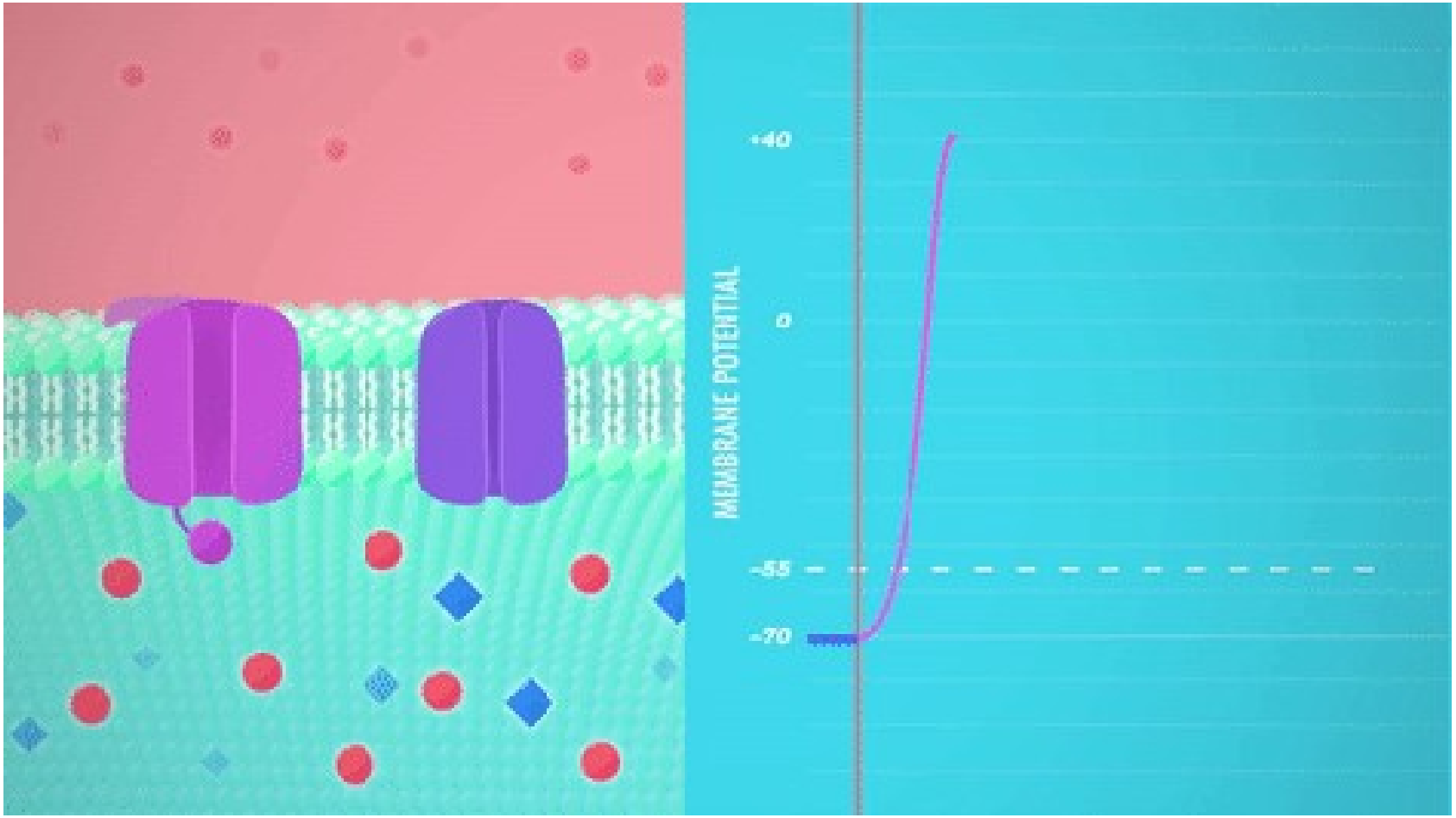


Depolarization



Why does membrane potential go all the way to positive?

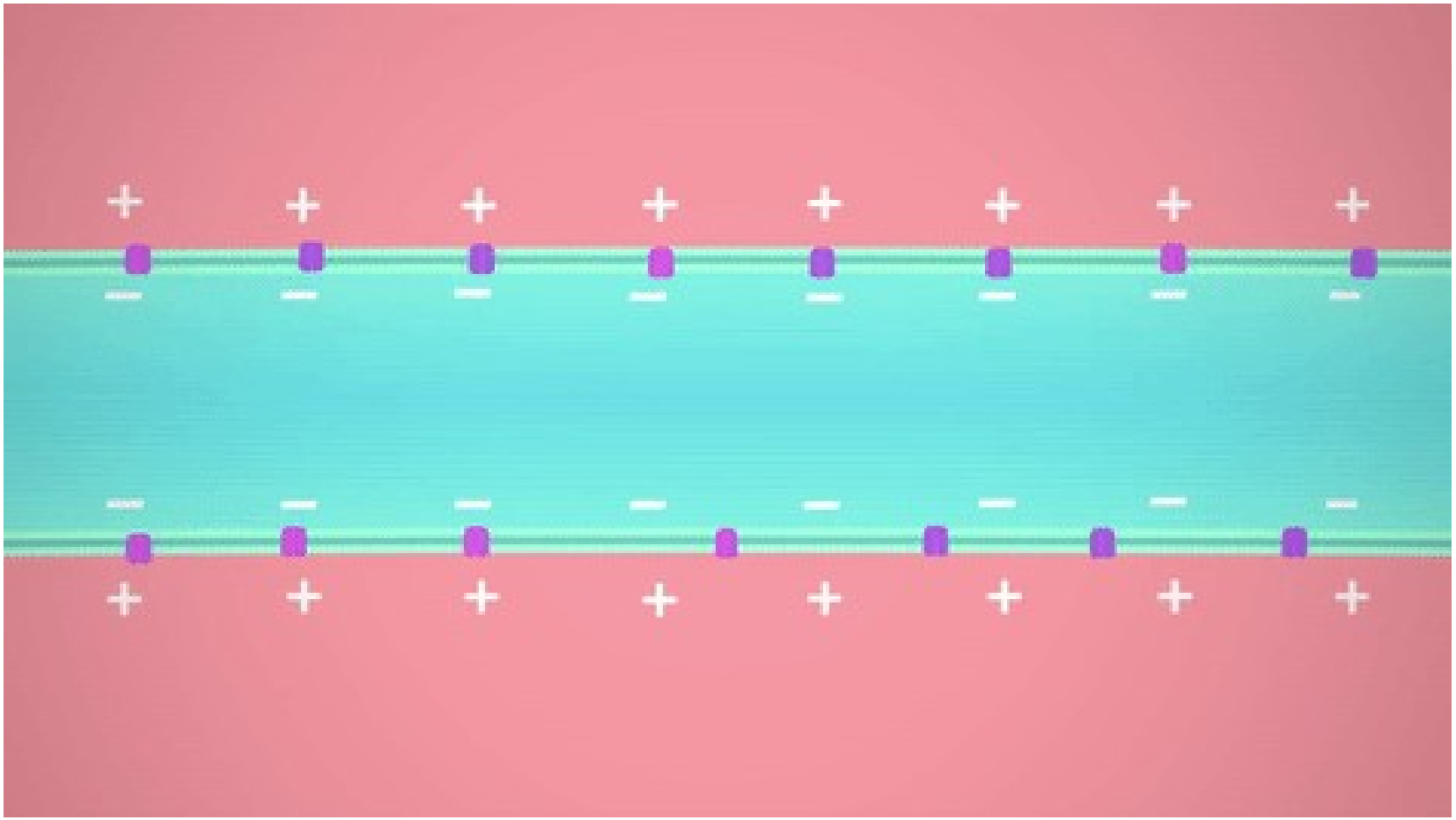
Repolarization



OK, we have evoked depolarization in a bit of membrane.

But how does the signal get further?

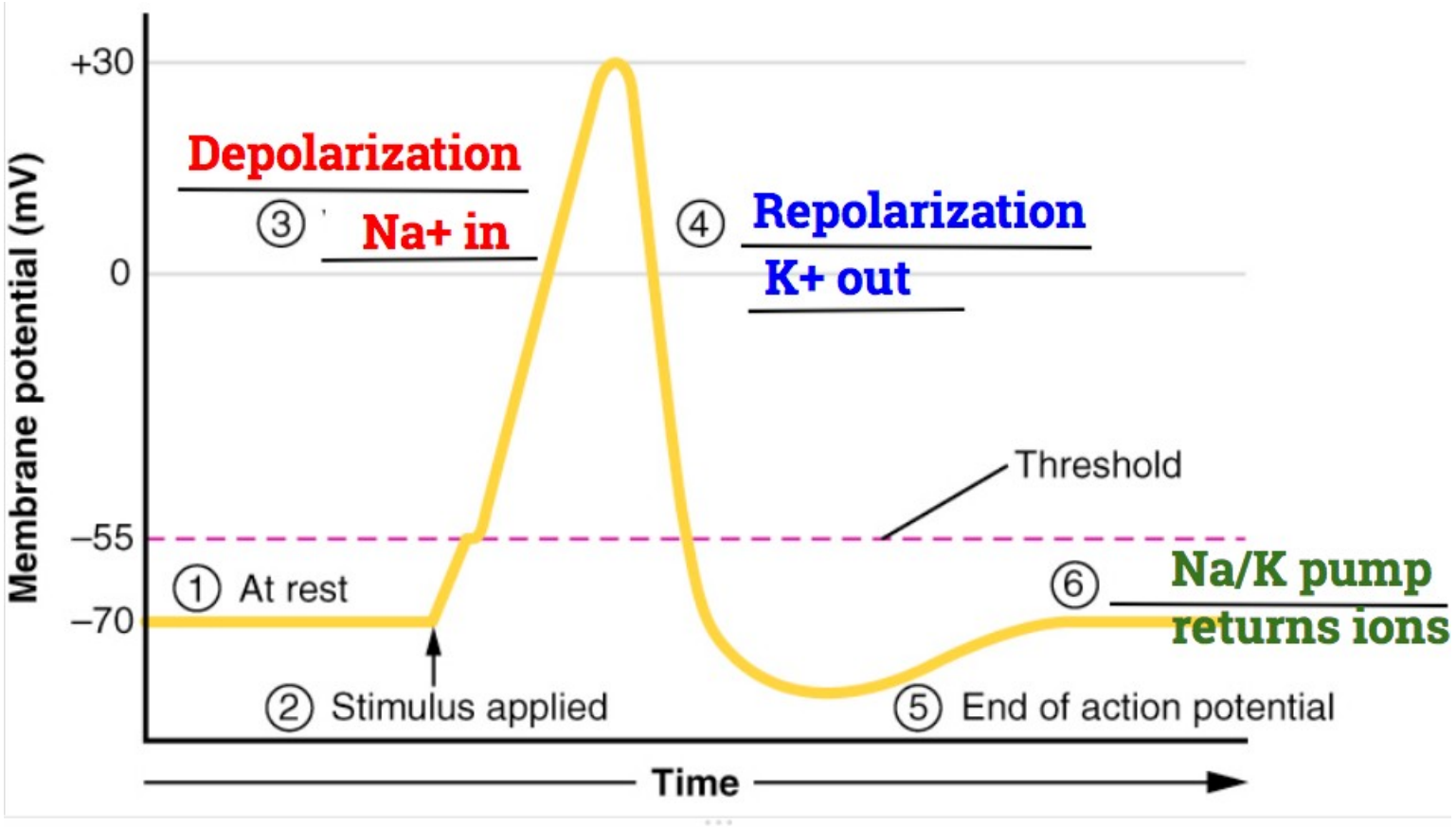
Action Potential



OK we have Action Potantial wave.

Is the mechanism we have described complete/self-consistent?

Action Potential summary



We are transmitting signals.

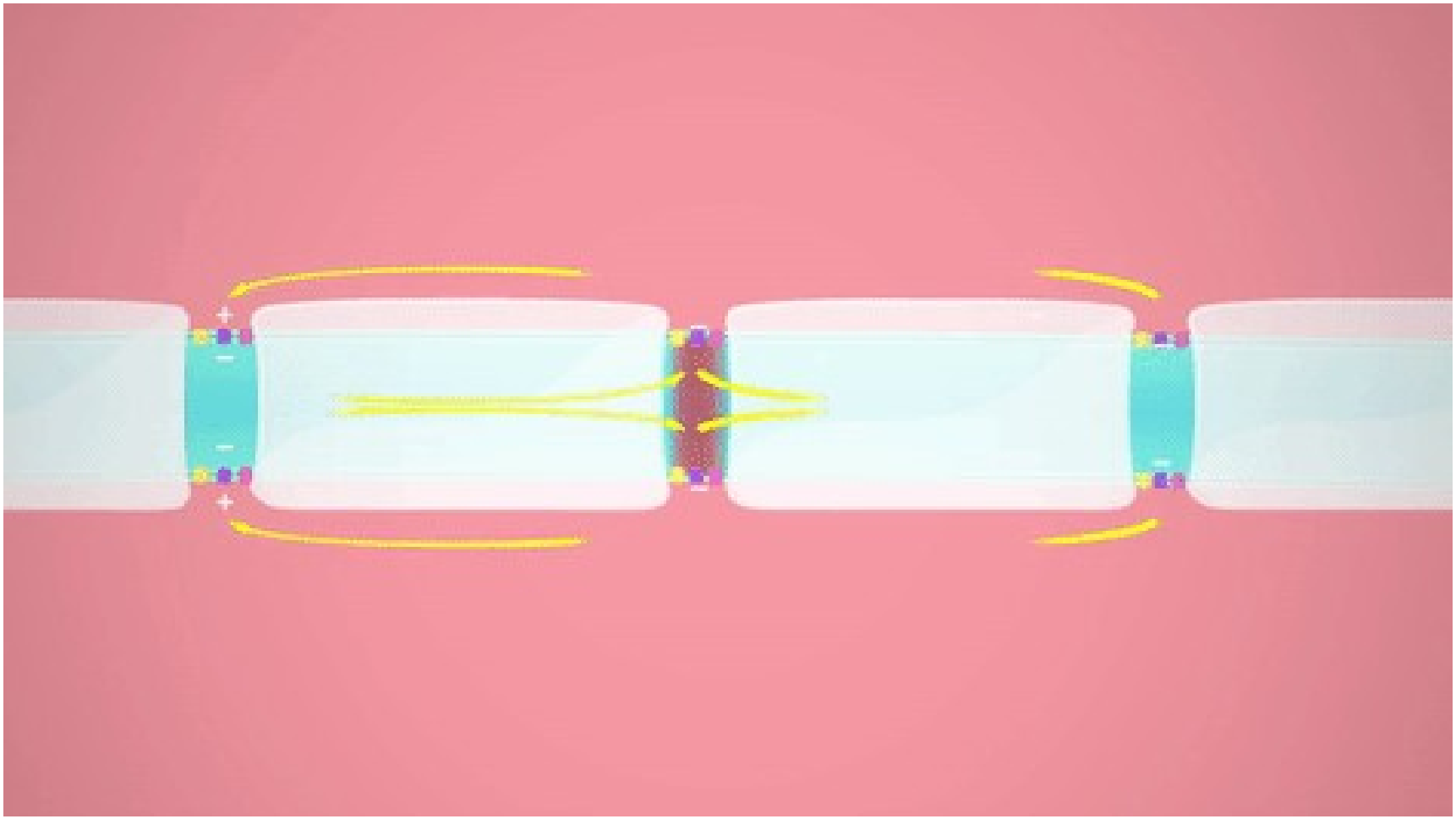
Are we doing it for free?

As much as 20–40% of brains' energy expenditure is due to maintenance of membrane potential

All this ion pumping seems quite inefficient and slow.

Can we do something about it?

Myelinated axon



Now we know how information comes out.

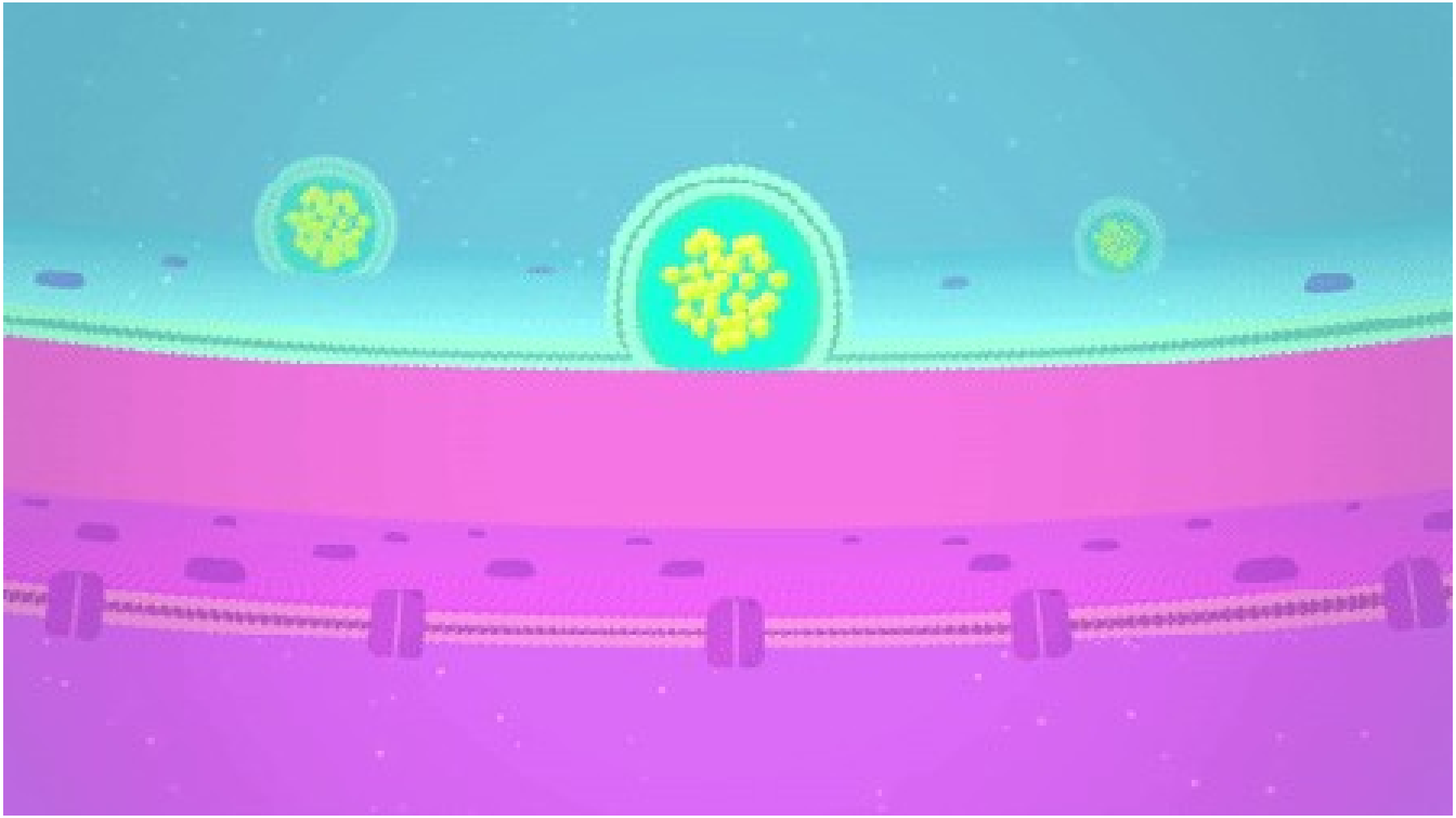
How does it come in?

Chemical synapses

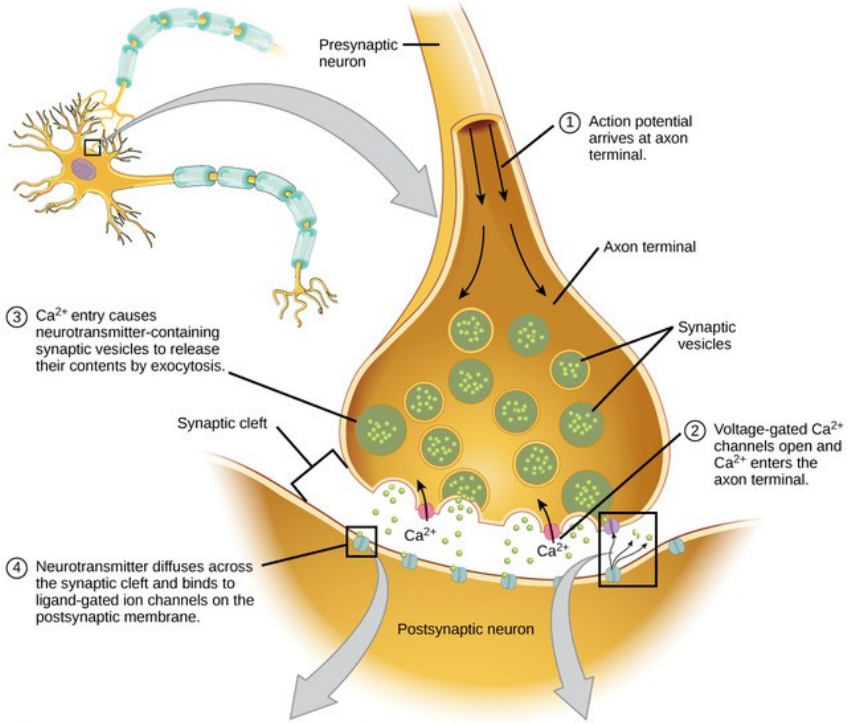
- Communication within neurons is electrical
- Communication between neurons is chemical
- **Neurotransmitters** are the molecules that act as chemical signals between neurons

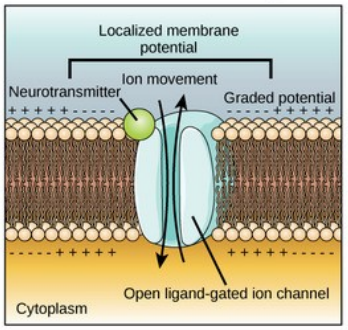
Pre–synaptic neurotransmitter release

Synaptic cleft

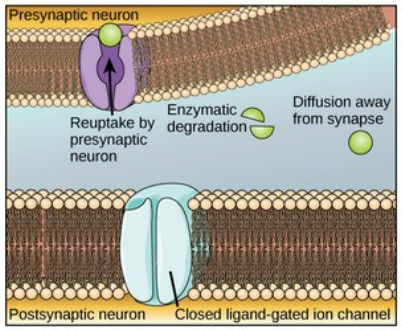


Chemical Synapses

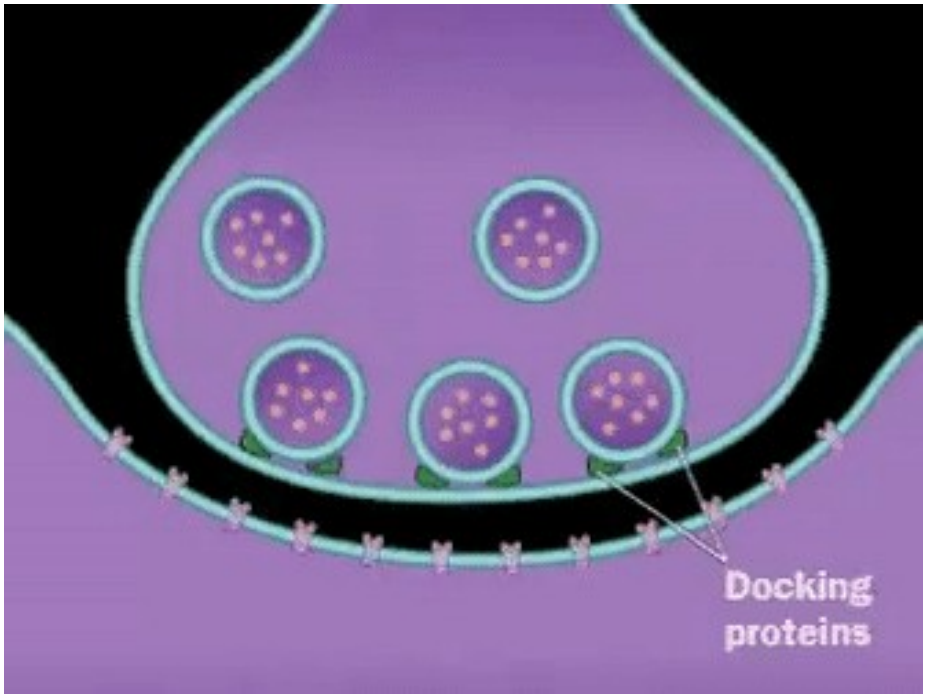




5 Binding of neurotransmitter opens ligand-gated ion channels, resulting in graded potentials.



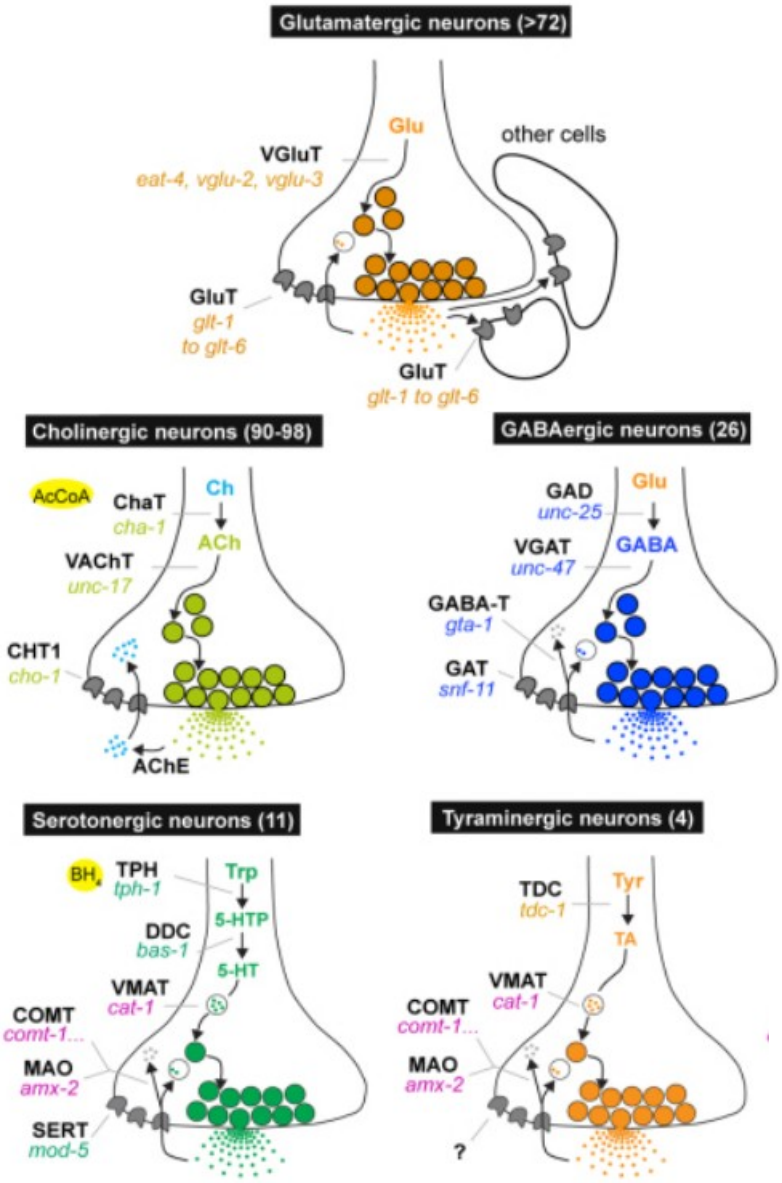
6 Reuptake by the presynapic neuron, enzymatic degradation, and diffusion reduce neurotransmitter levels, terminating the signal.



- Vesicles
- Calcium

Neurotransmitter

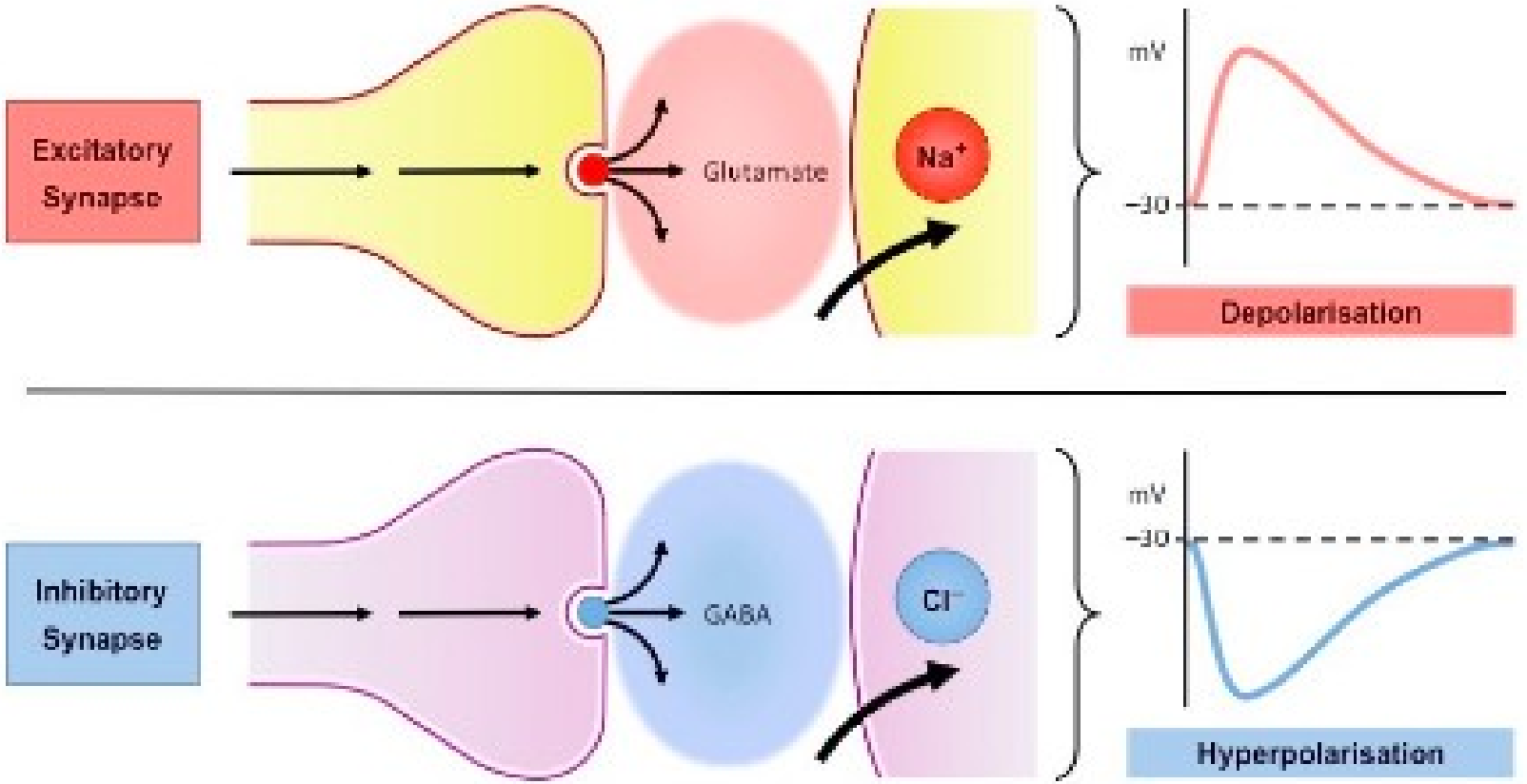
- Various types
  - Glutamate
  - GABA
  - Serotinin (5HT)
- Typically one neuron = 1 neurotransmitter
- But neurotransmitters are not exclusive to receptors



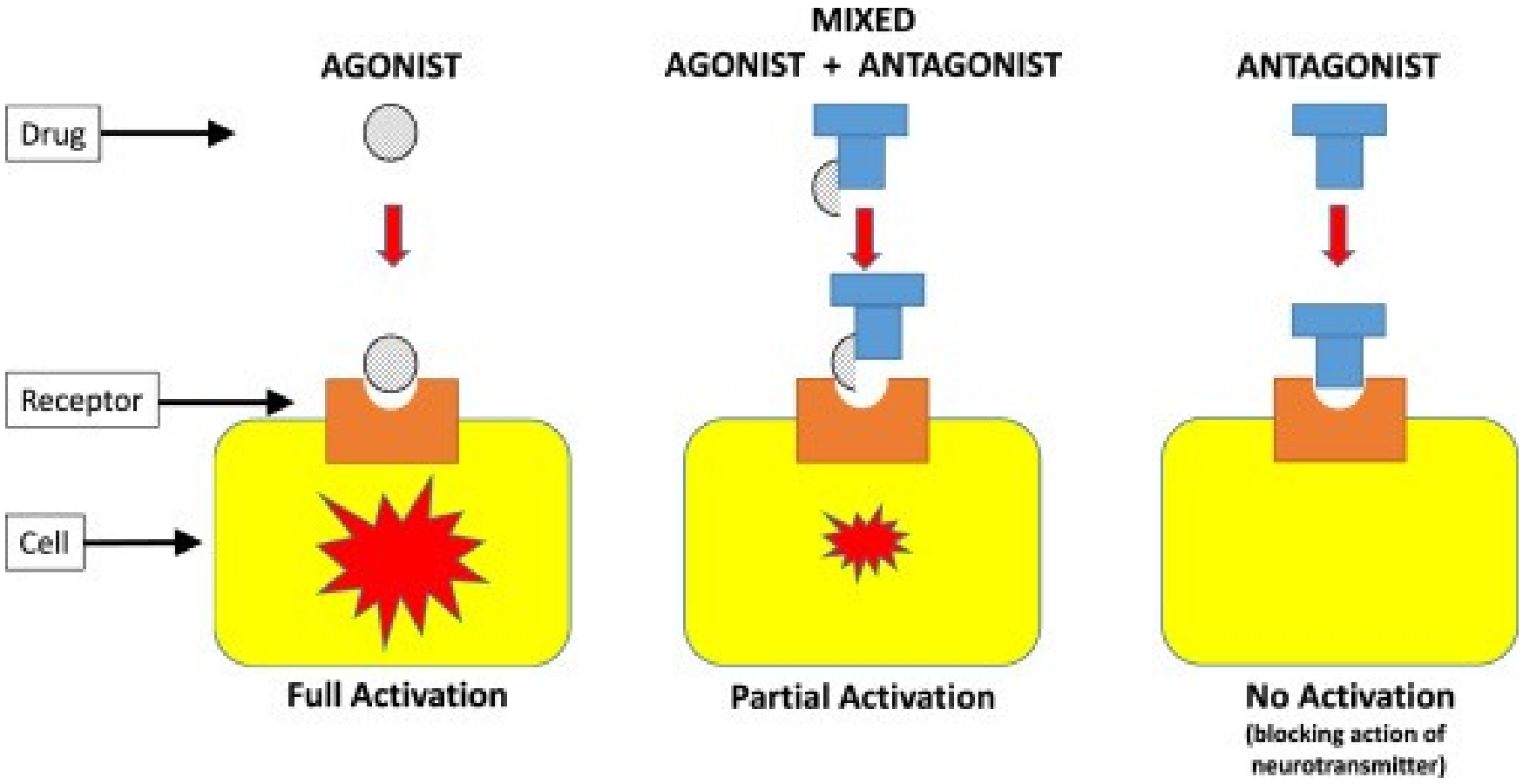
In ANNs we have positive and negative connections.

How would you design them in the brain?

EPSP vs. IPSP

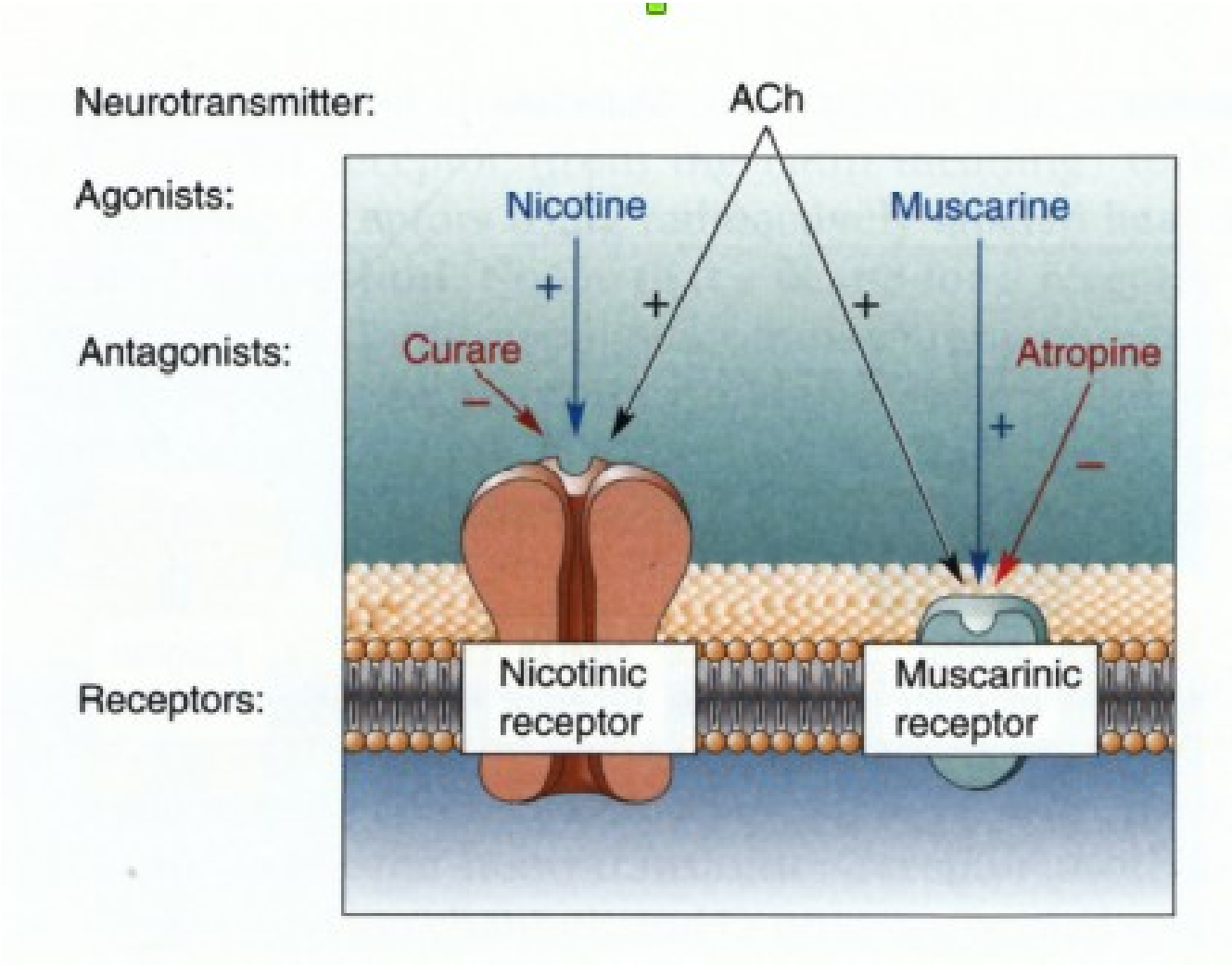

Excitatory Synapse
Glutamate
Na+
mV
-70
Depolarisation
Inhibitory Synapse
GABA
Cl-
mV
-70
Hyperpolarisation

Antagonists vs. agonists



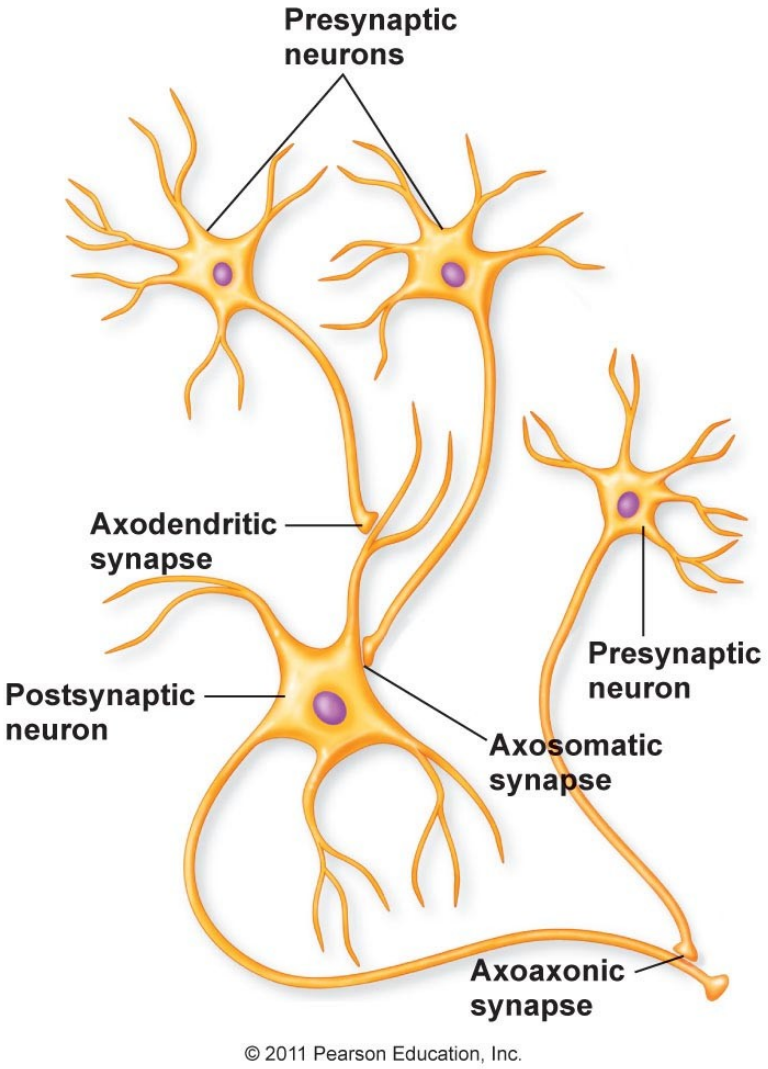
Do you know of real–world examples where agonists/antagonists play a role?

Antagonists vs. agonists

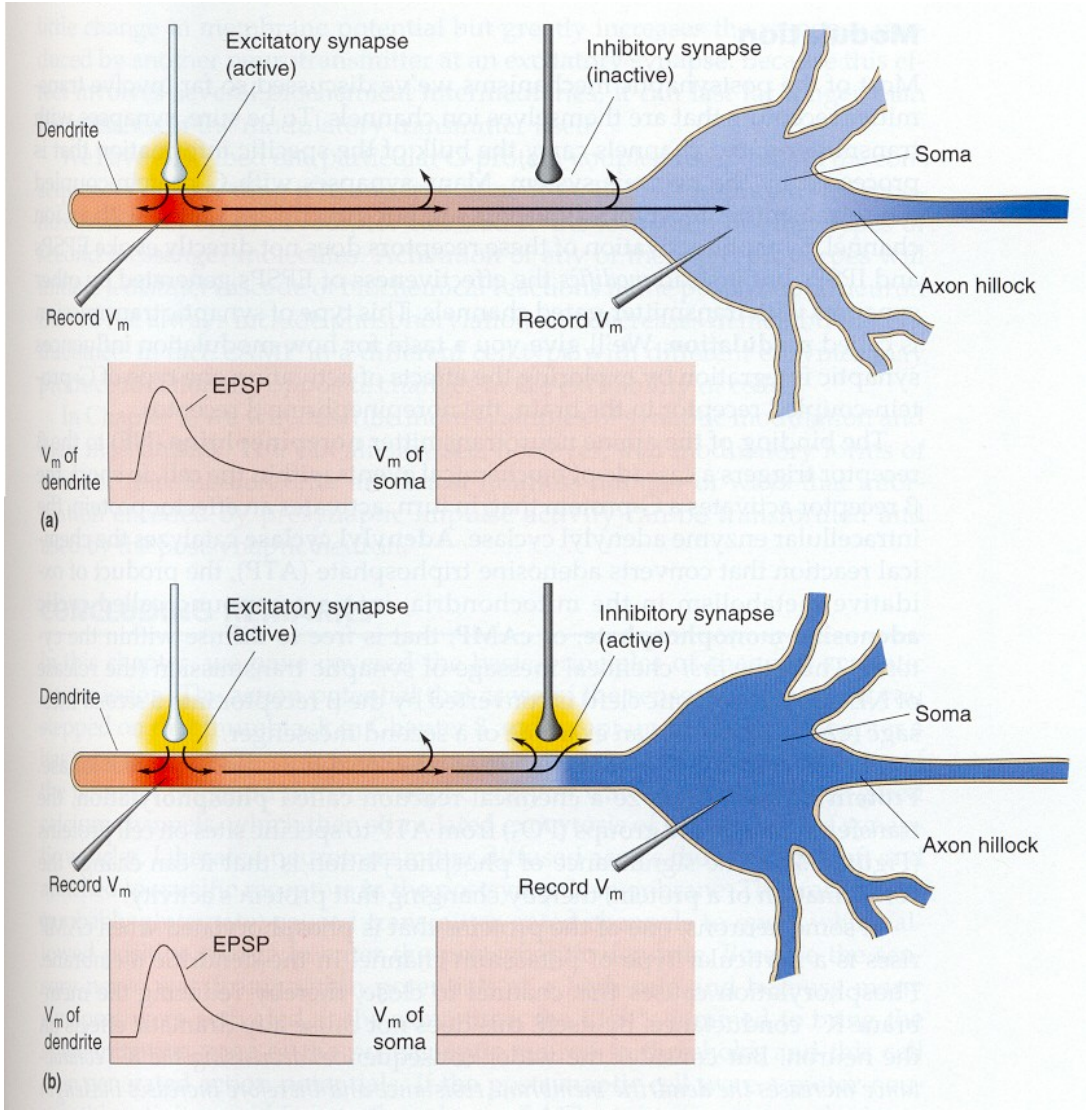


Types of connections

- Axo-dendritic
- Axo-axonal
- Axo-somatic



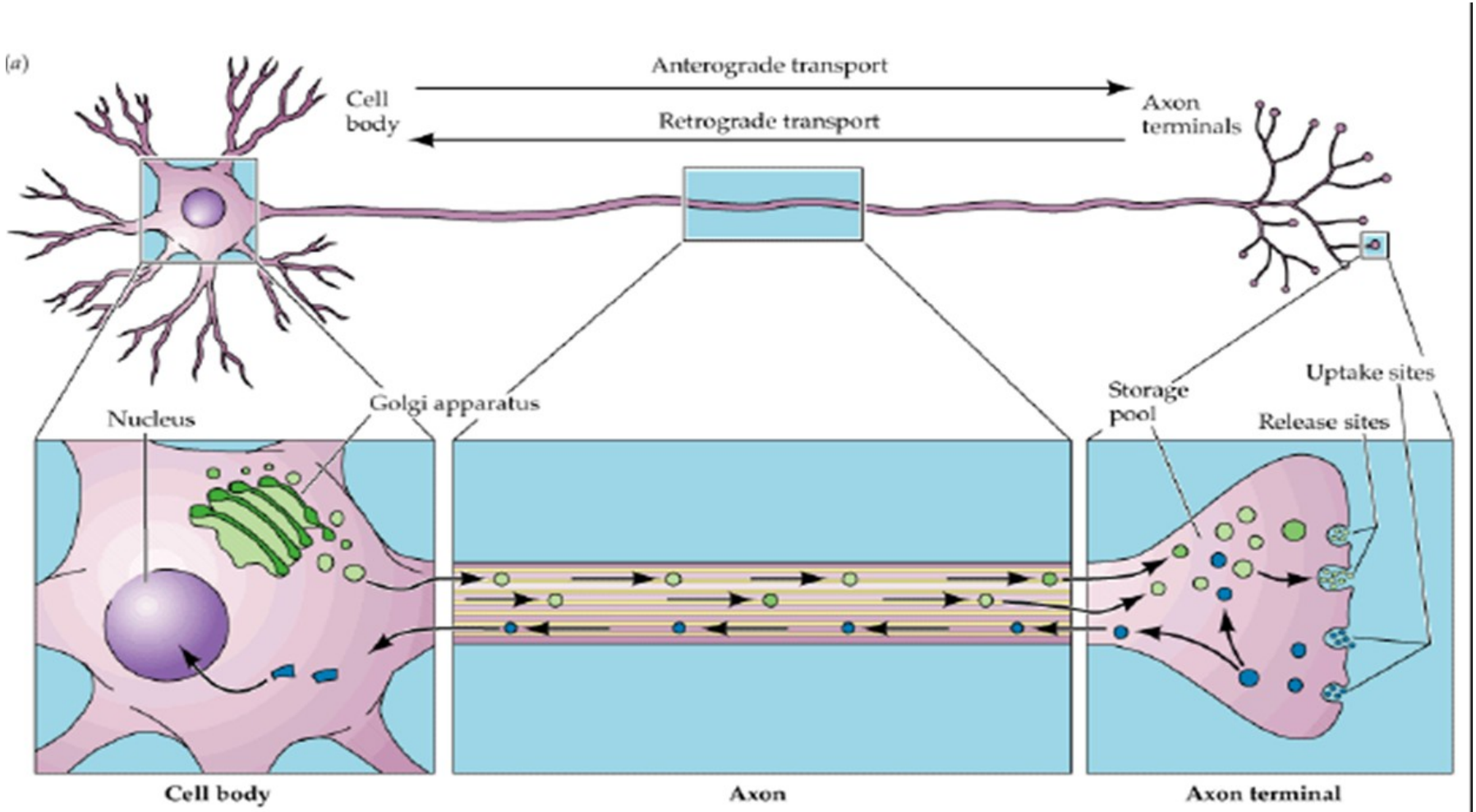
Shunting inhibition



Shunting inhibition

Implications for Artificial Neural Networks?

Axonal transport



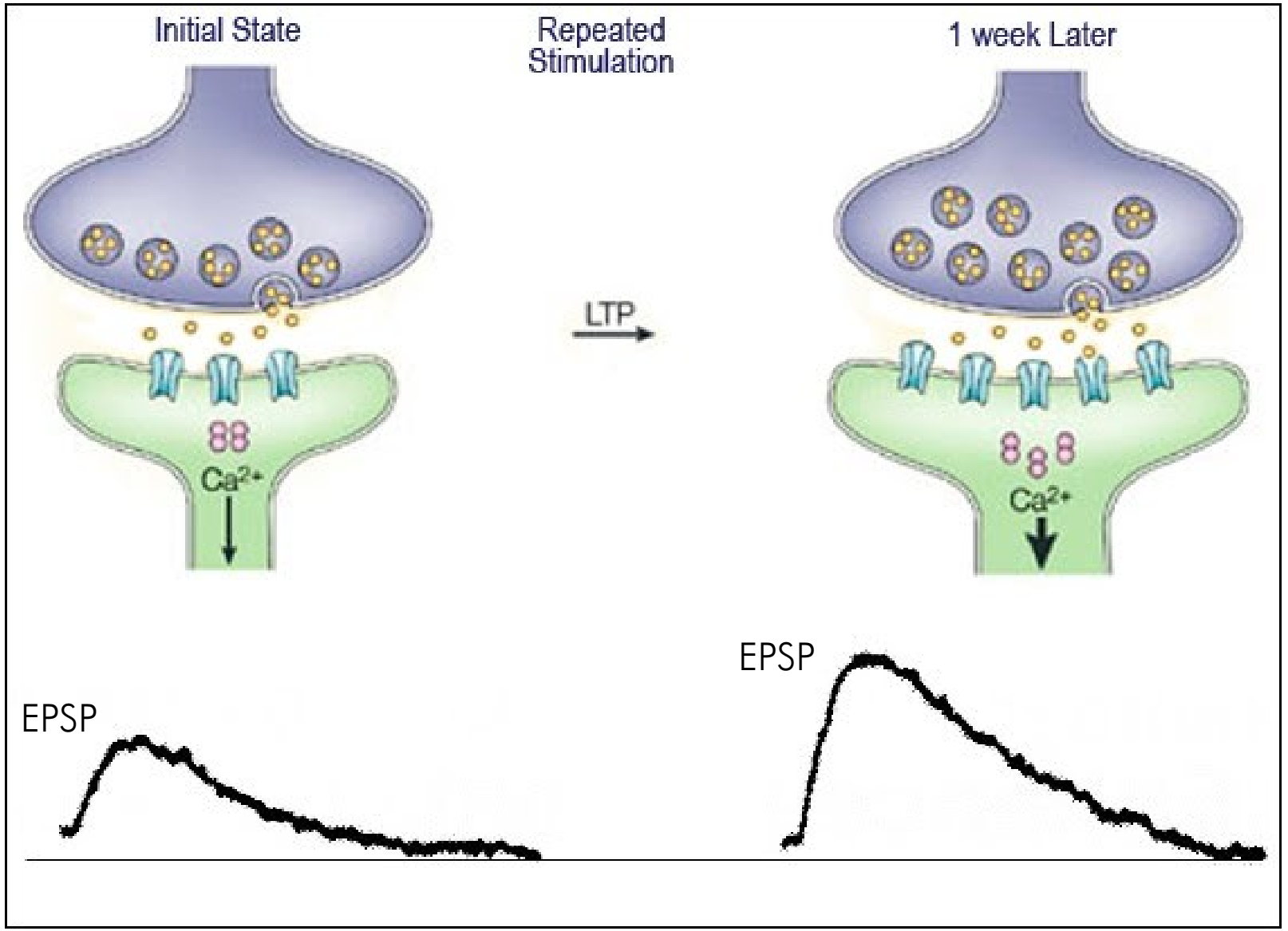
Slow: 1-10mm/day

Fast: ~1000mm/day

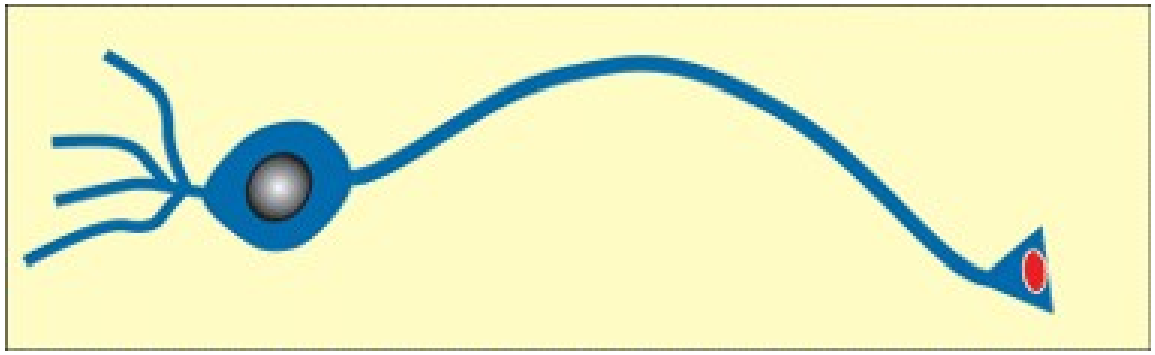
The most important property of ANNs is that they learn.

How would you design that in a biological neuron?

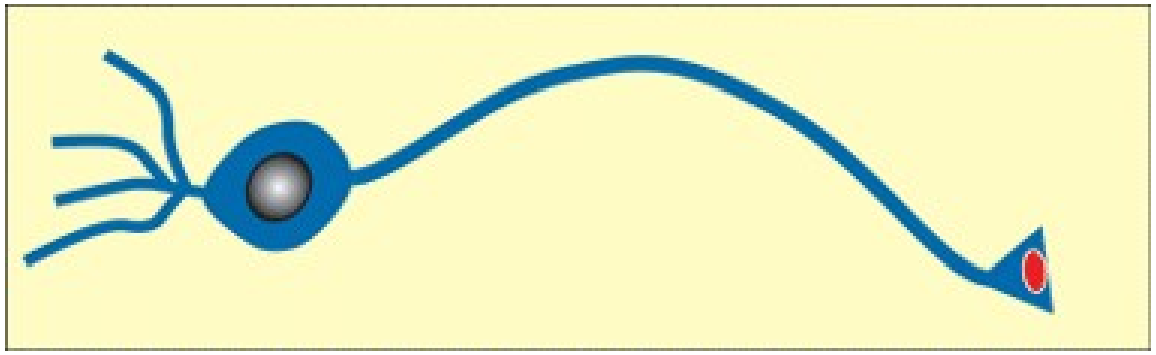
Synapses and learning

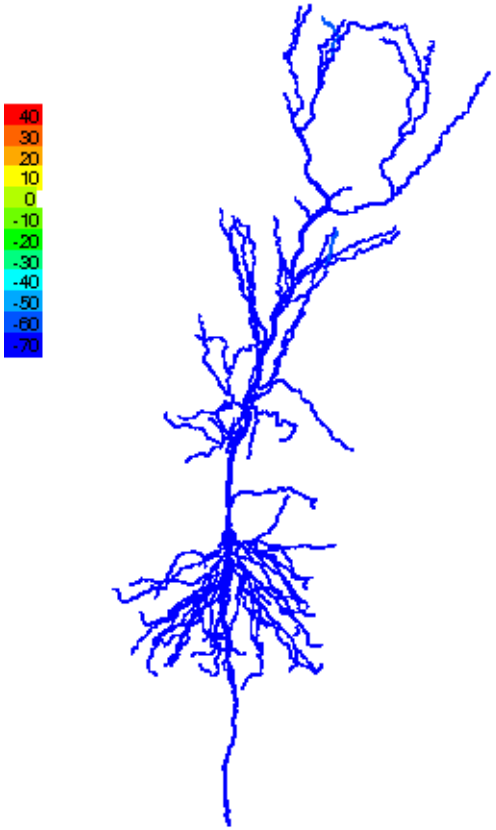


Signal integration in a neuron



Signal integration in a neuron

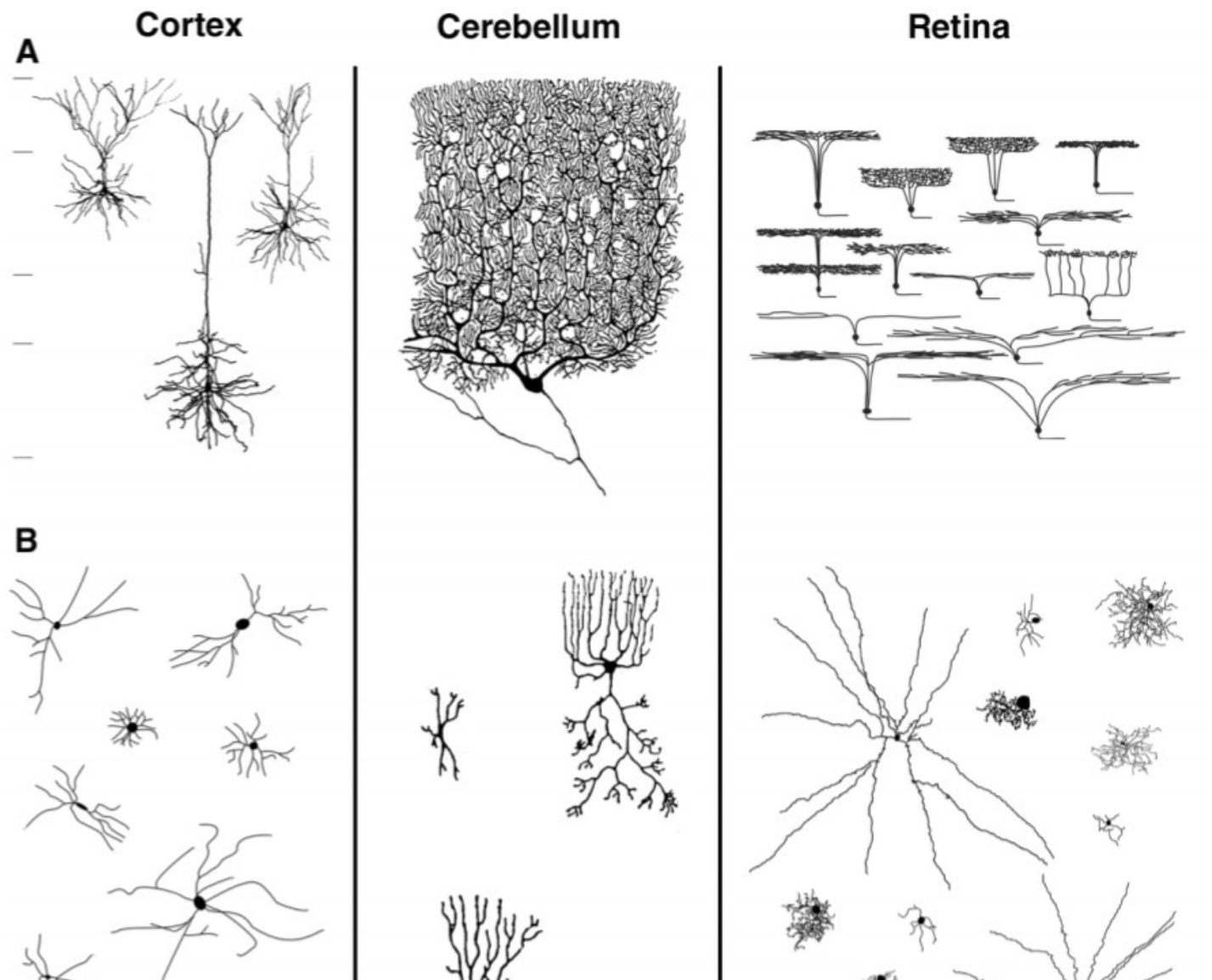




Basic parameters

- 10 – 100 μm
- Cerebellum ~10^9 granule cells
- Cat visual cortex, 1 mm^3
  - ~50 000 neurons
    - each ~6 000 synapses
    - ~84% Type I, ~16% Type II
- Human (extrapolation from cat)
  - Surface of one hemisphere ~100 000 mm^2
  - ~10^9 neurons
  - ~60.10^{12} synapses

Many types of cells

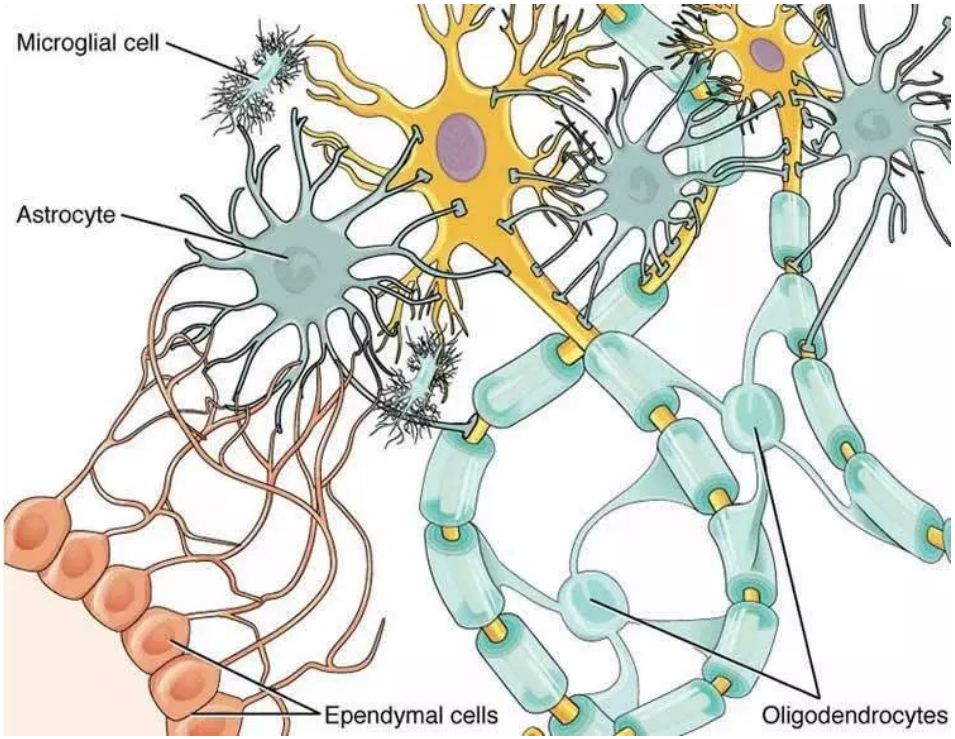


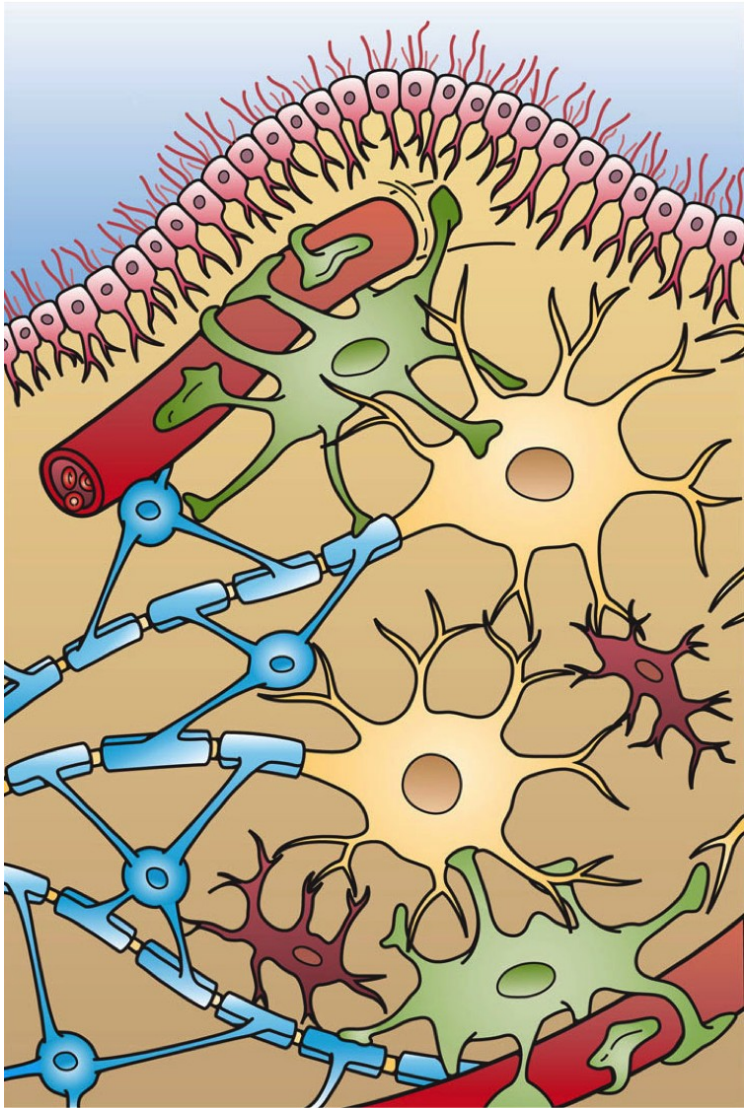
Caveats

Other cells in CNS

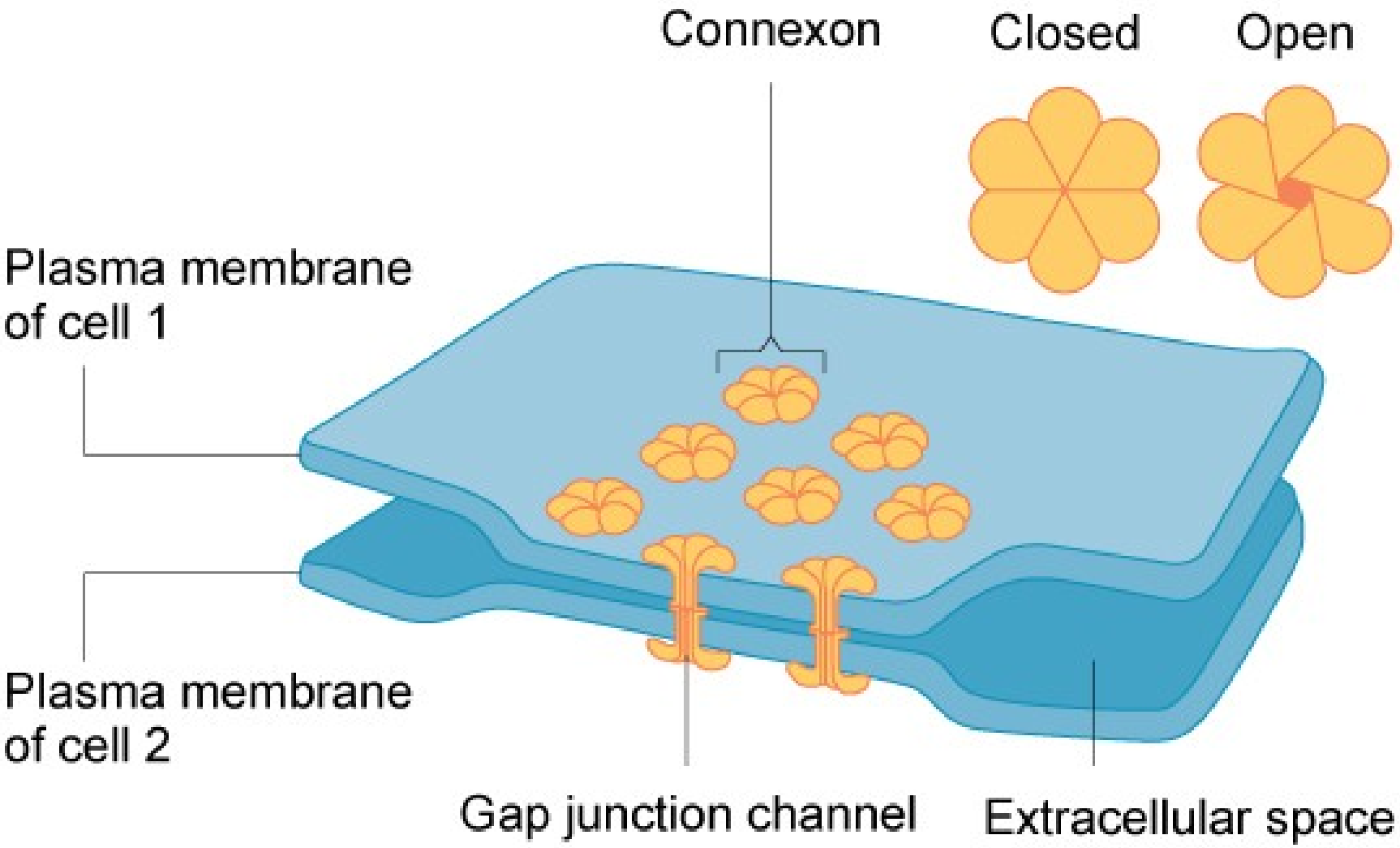
- Neurons: 10%
- Glia: 90%
  - astrocytes: cca 80%
  - ependymal cells: cca 5%
  - oligodendrocytes: cca 5%
  - mikroglia: cca 10%
- Glia as a support system for neural substrate

Glia


Microglial cell
Astrocyte
Ependymal cells
Oligodendrocytes



Gap junctions



Gap junctions

- Present throughout neural system
- Hypothesized in formation of neural rythms
- Weak neural-to-glial coupling via gap junctions
- Astrocytes and Oligodendrocytes coupled via gap junctions

Other

- Probabilistic nature of vesicle release – failure to initiate PSP
- Threshold is not fixed
- Dendritic integration