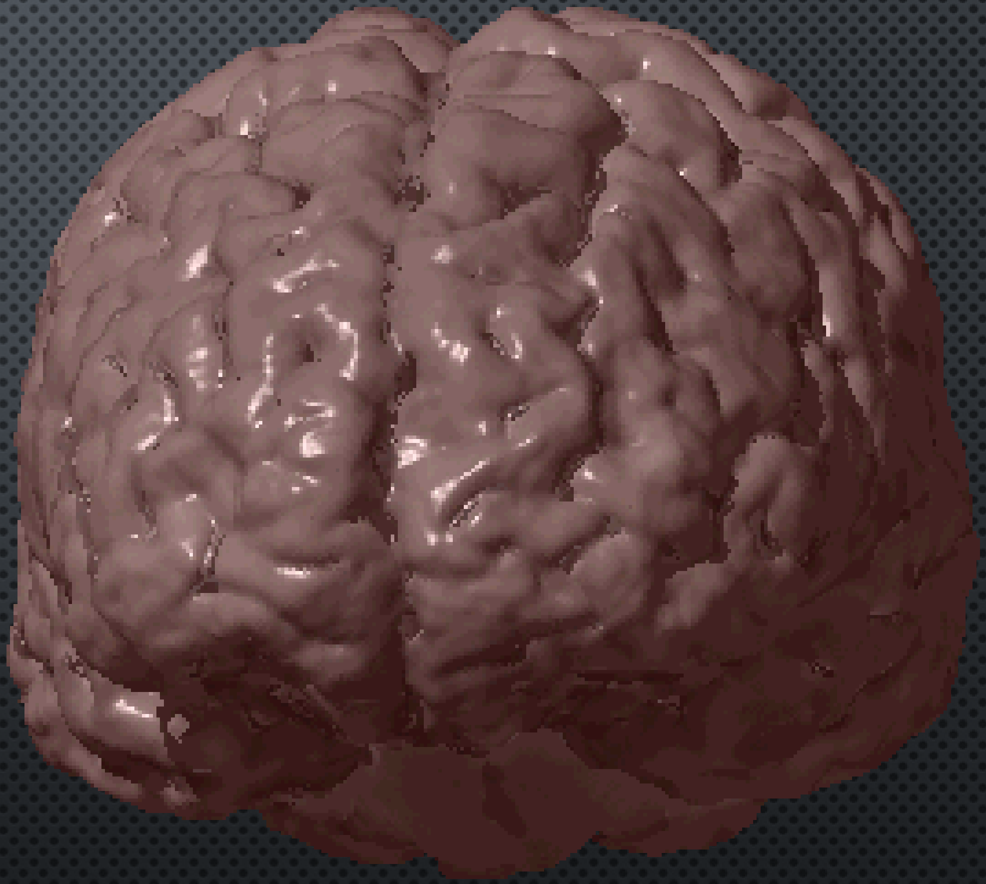
2 Biological neurons and their functional engineering models

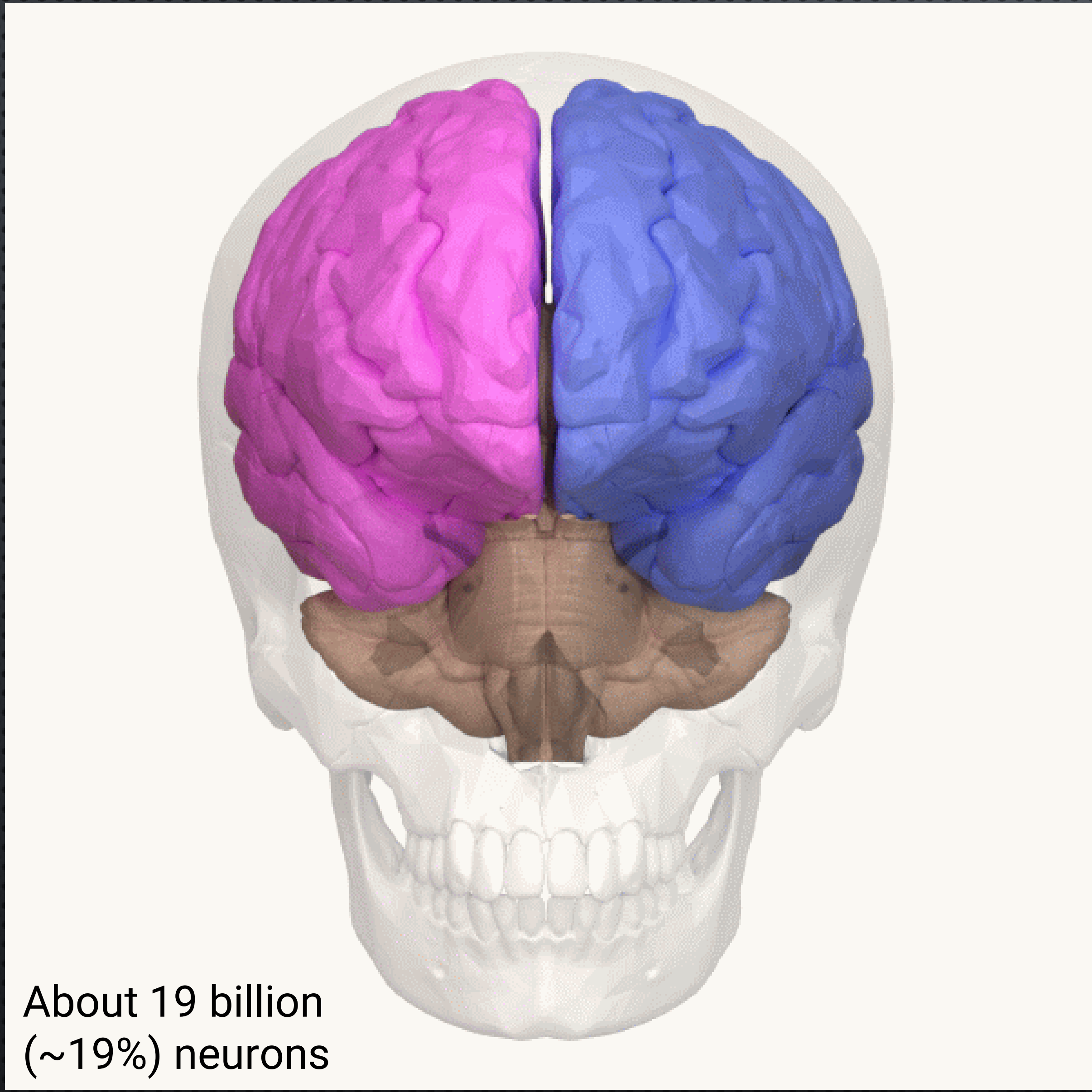
Neurobiology ahead
(get used to it)

The human brain

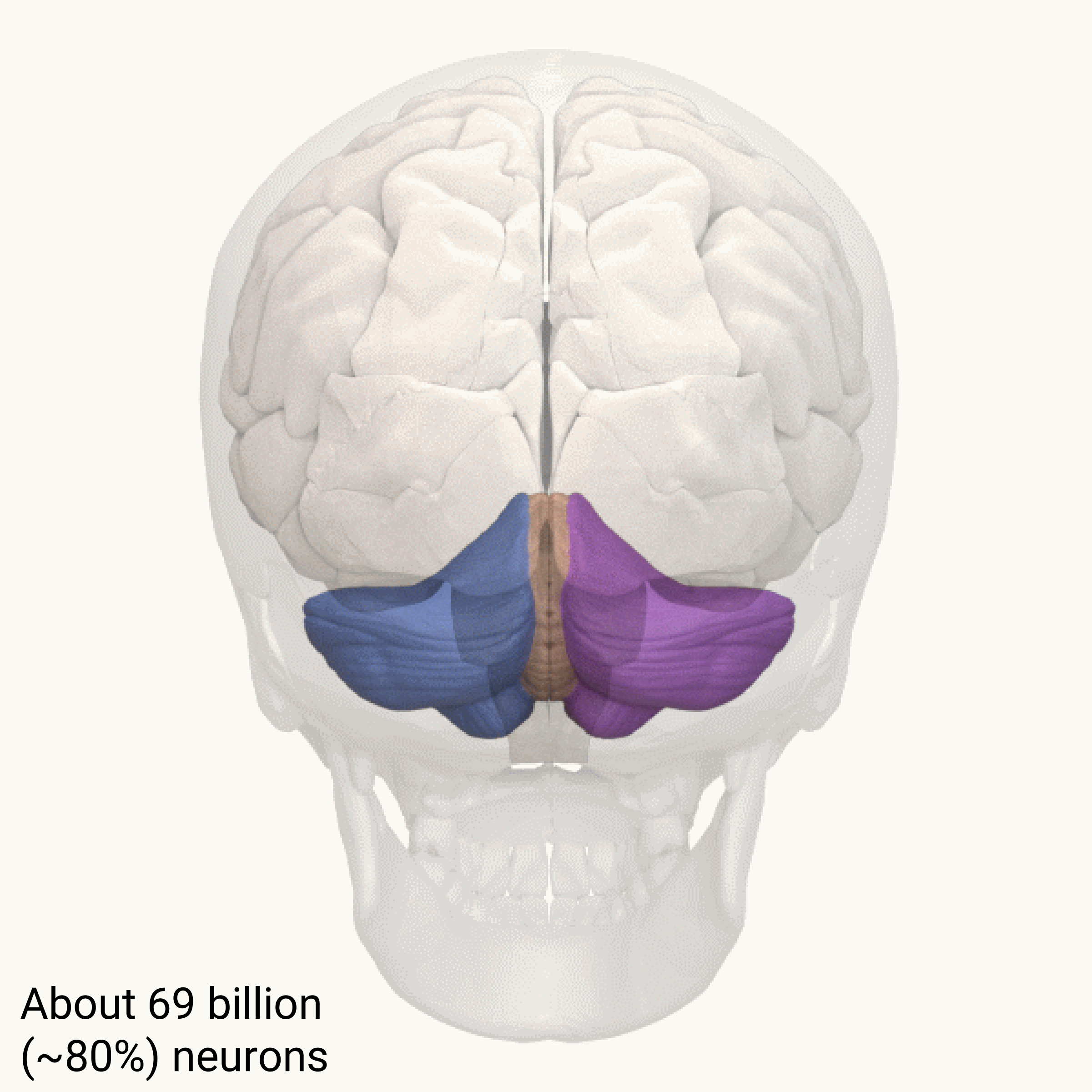
- Represents only 2% of the body weight (1.2 - 1.4 kg) but receives 15% of the cardiac output, 20% of total body oxygen consumption, and 25% of total body glucose utilization
- Composed of neurons, glial cells, neural stem cells, and blood vessels
- Contains about 86 ± 8 billion neurons and 85 ± 10 billion non-neuronal cells



What makes the brain so special?

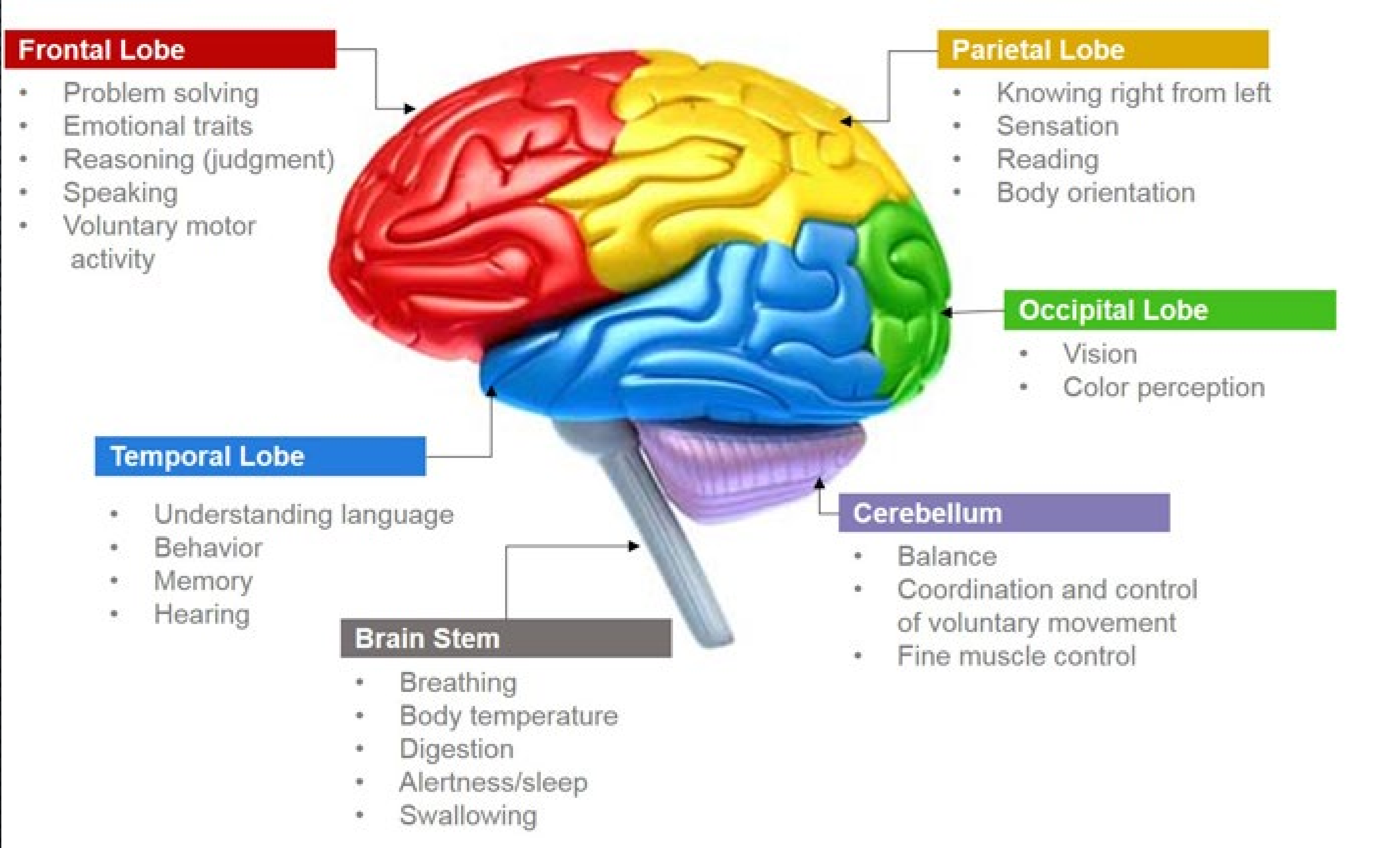


Cerebrum

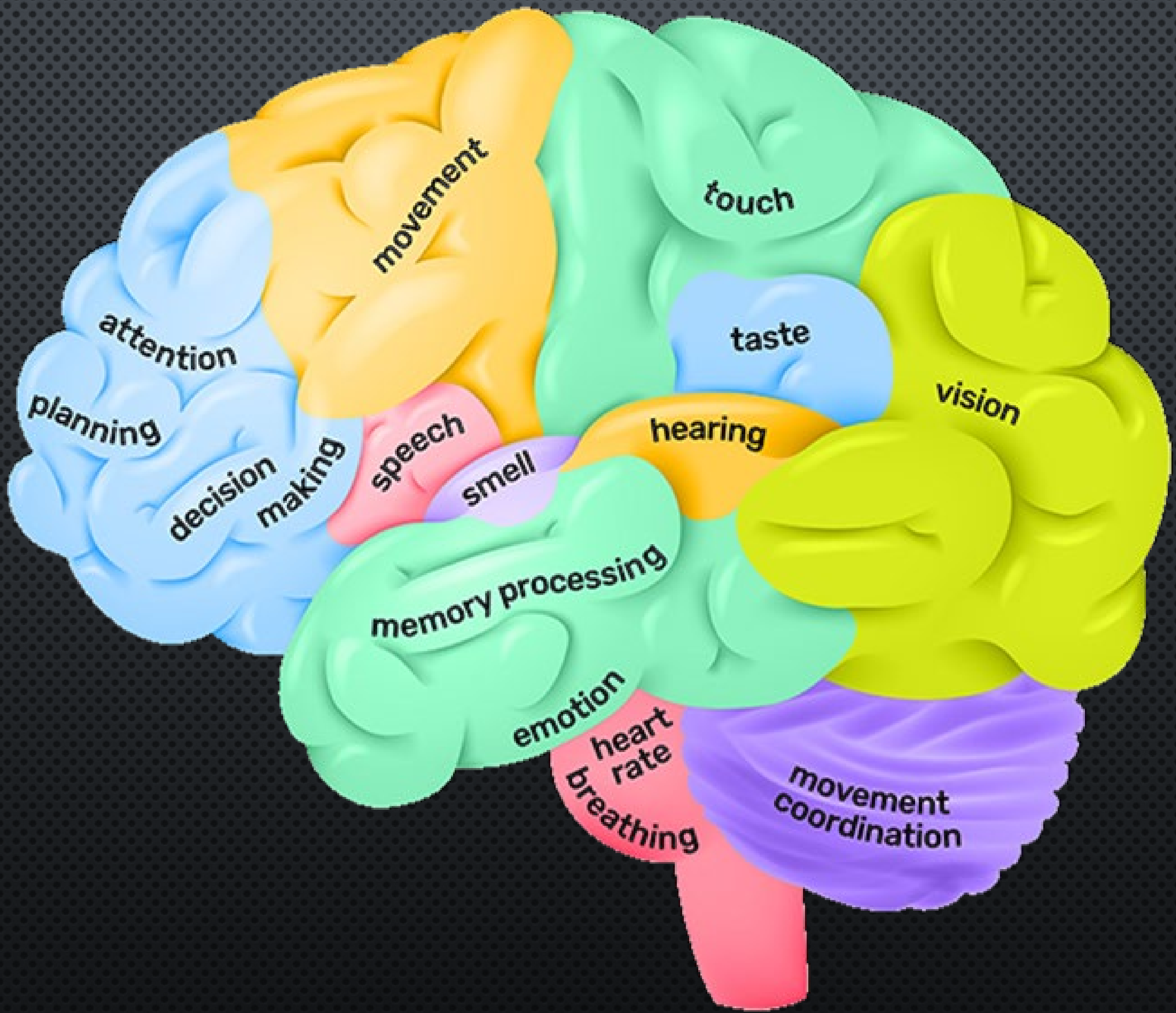


Cerebellum

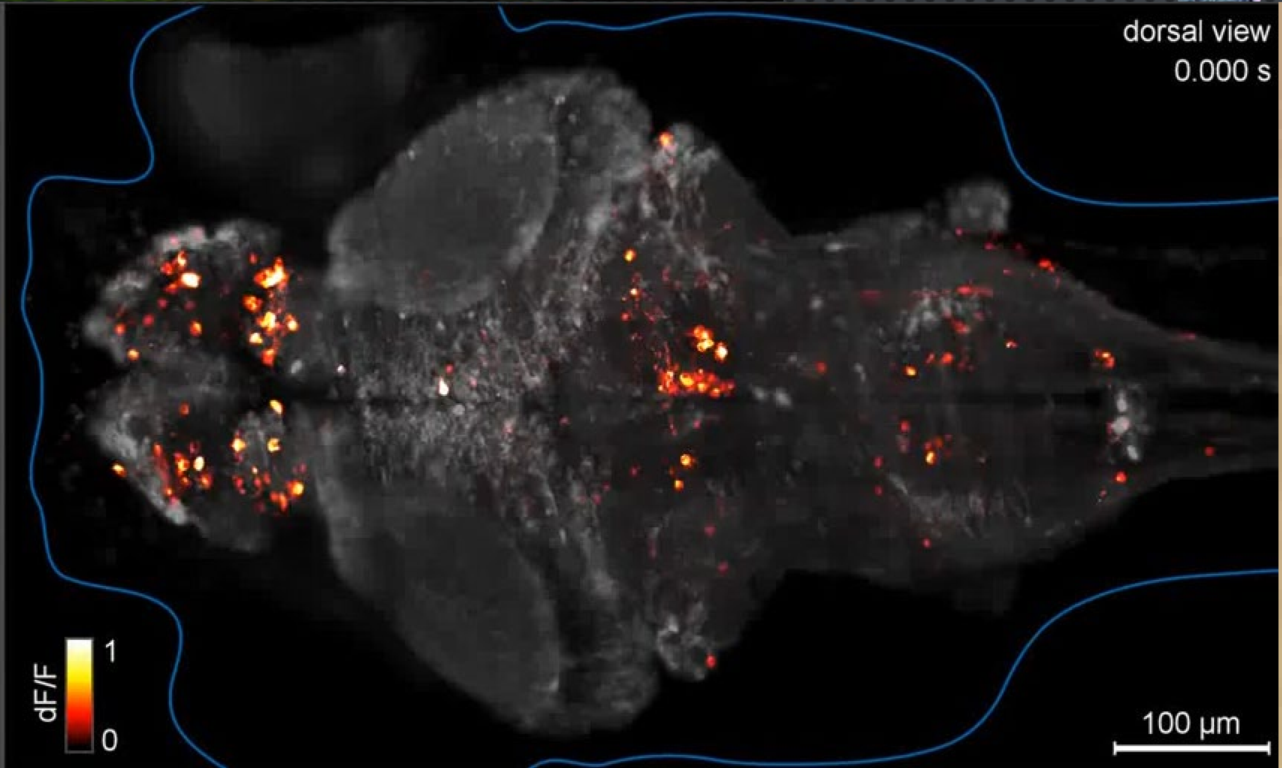
Brain anatomy and function



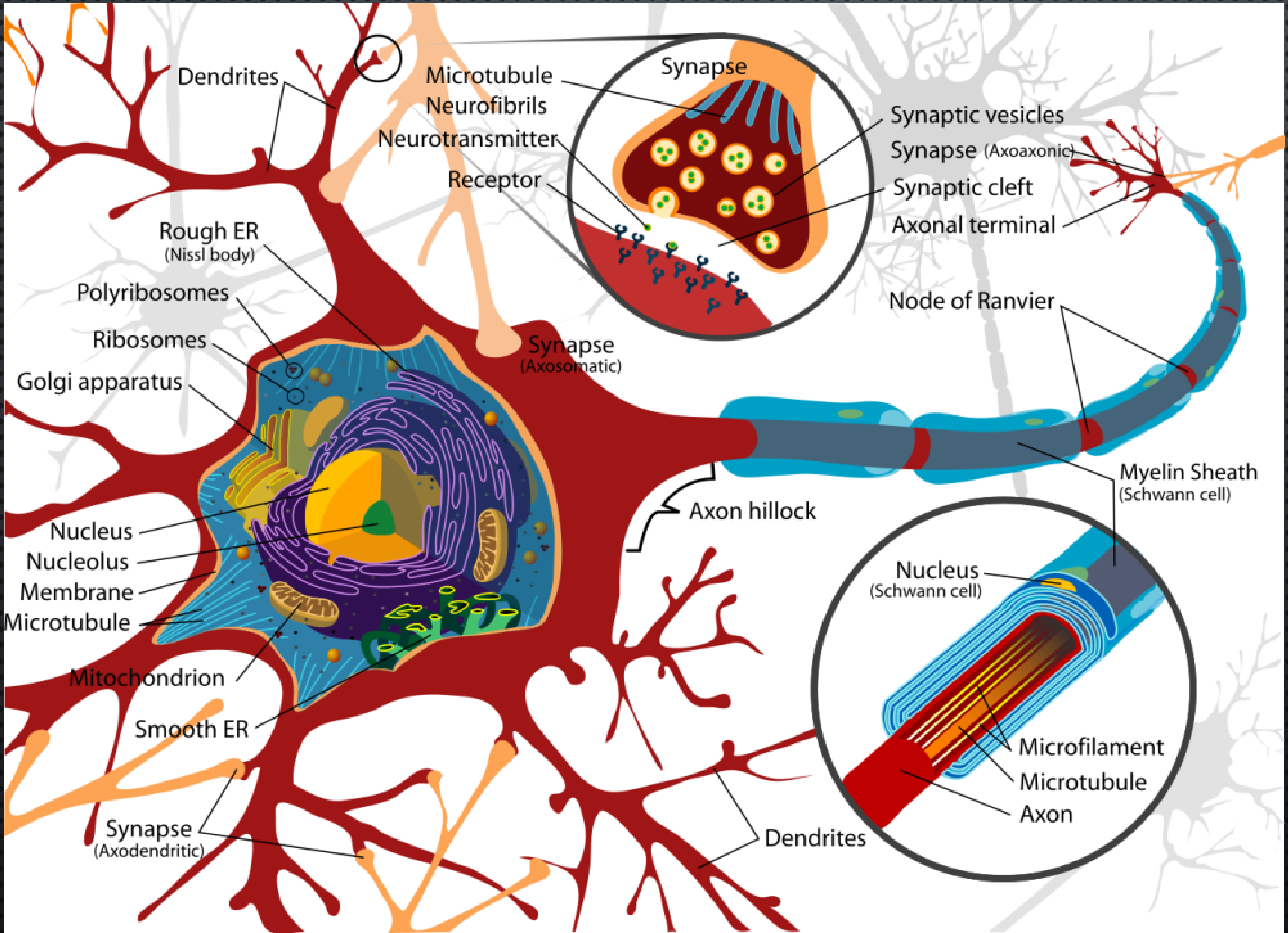
Implications for robotics

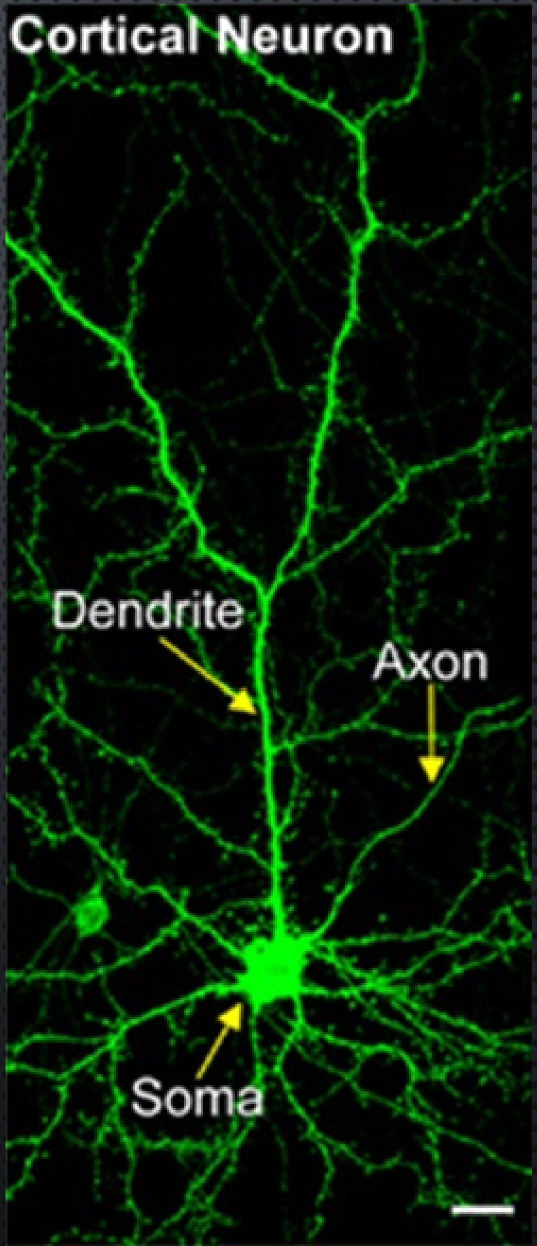


Visualising the brain



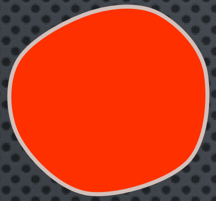
What is a neuron?

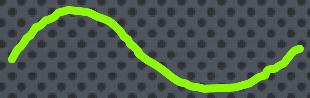


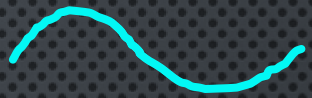


Basic types of neurons

 Nucleus

 Cell body

 Axon/synapses

 Dendrites

Unipolar

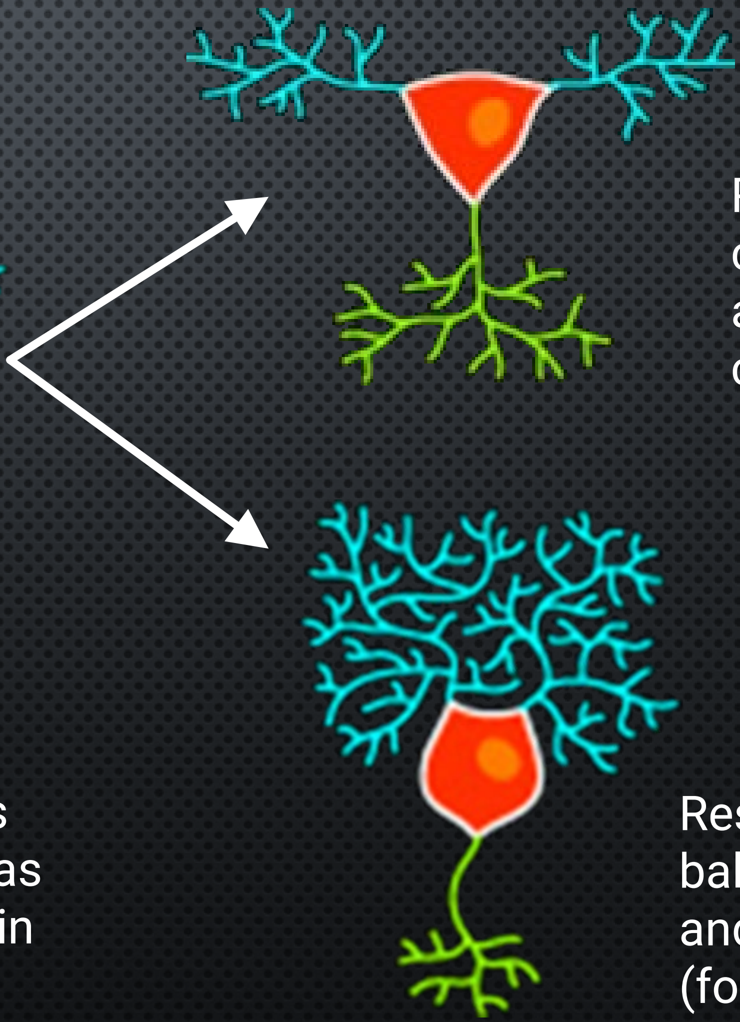
Transmit signals from outside of body to brain (found in insect brains)

Bipolar

Transmit signals from sensory appendages (eyes, ears etc.) to brain

Multipolar

Transmit signals within the brain as well as from brain to muscles



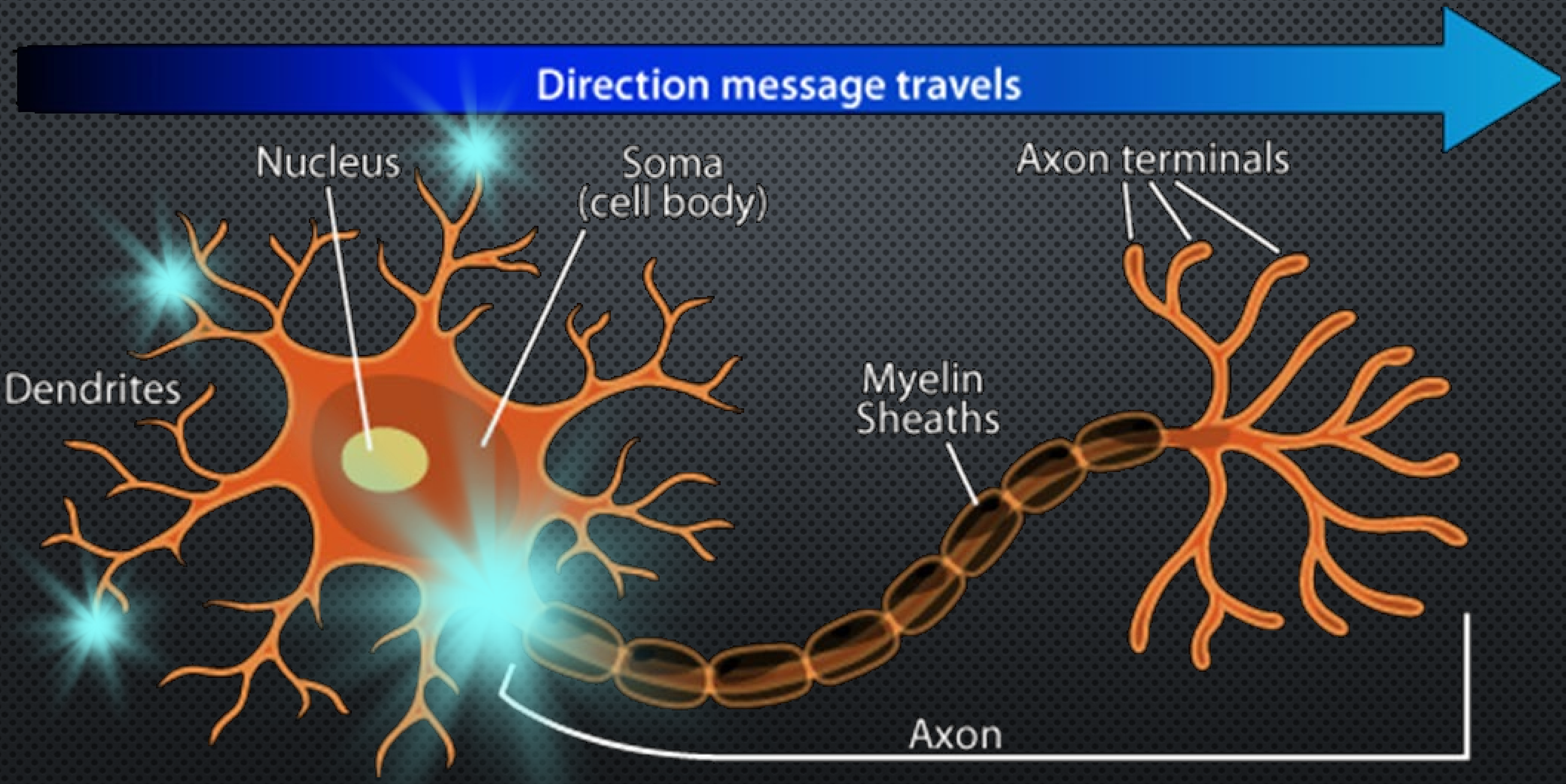
Pyramidal

Responsible for complex cognitive abilities (found in cerebrum)

Purkinje

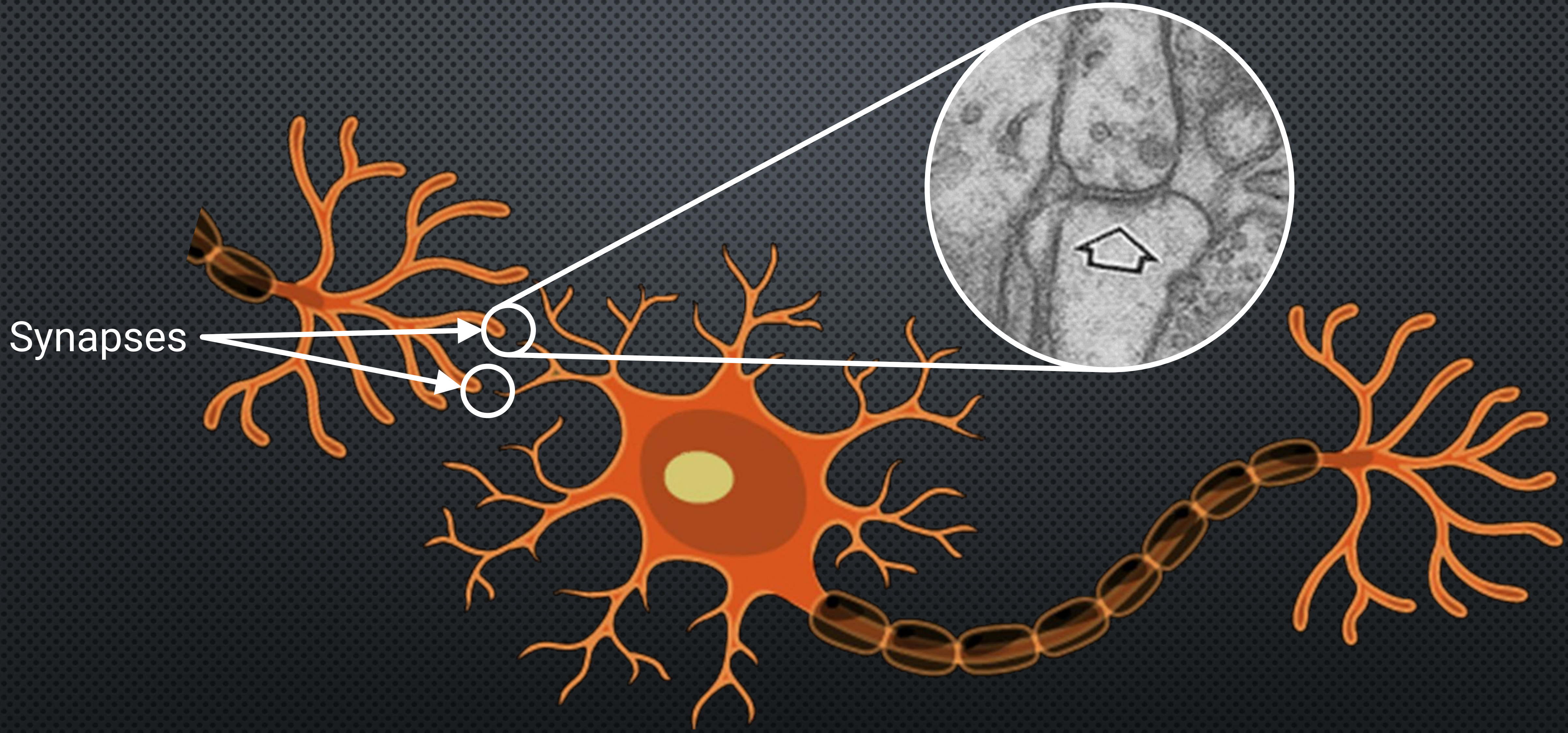
Responsible for balance, coordination and timing of actions (found in cerebellum)

Neurons integrate and transmit information



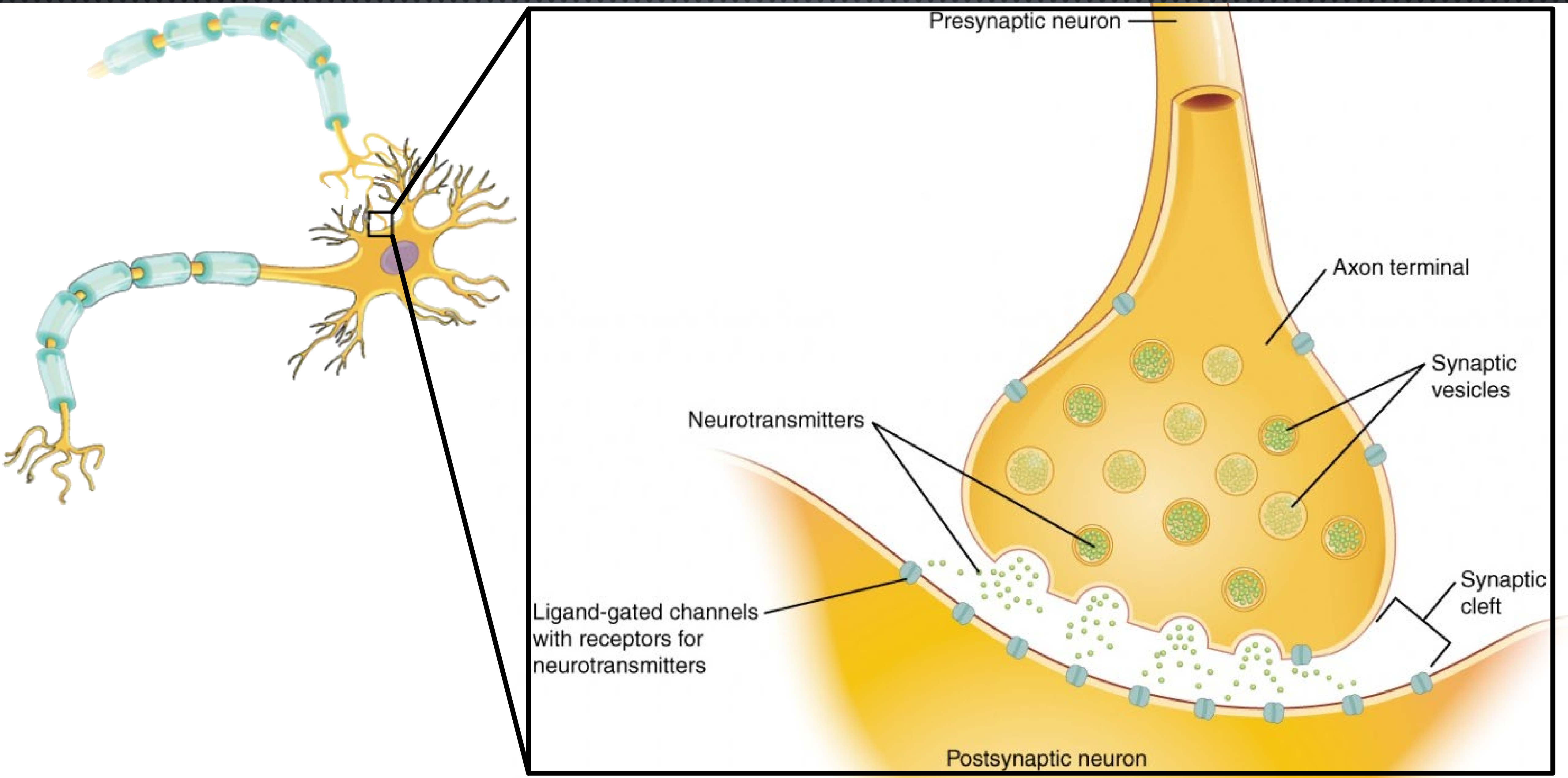
Neurons collect electrical signals (called action potentials) from other neurons via synapses and transmit them to other neurons via the axon

Synapses bridge neurons together

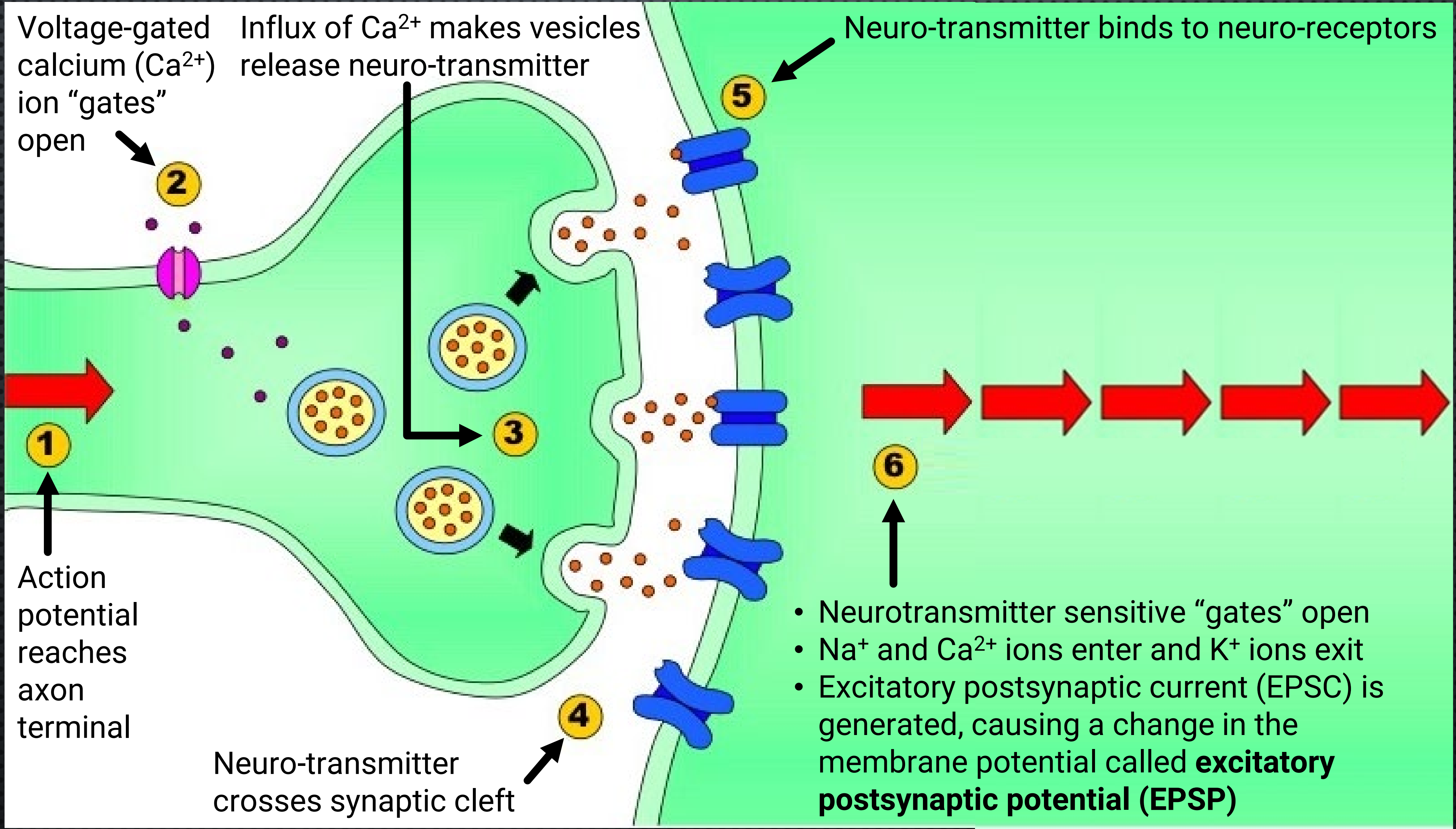


A synapse is a structure that permits a neuron to pass an electrical or chemical signal to another neuron.

Structure of a chemical synapse



Signal transmission in synapses



Action potential

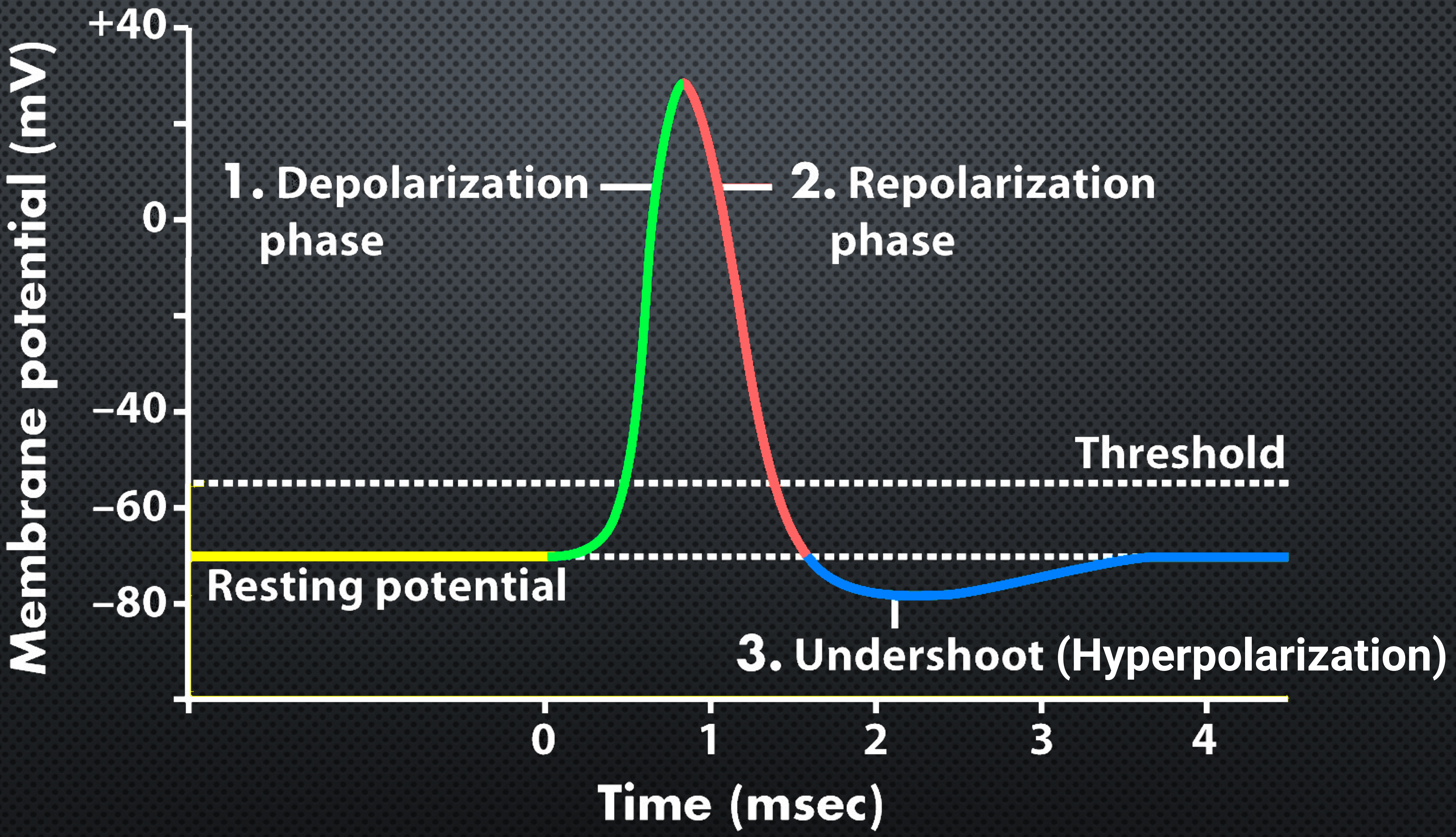
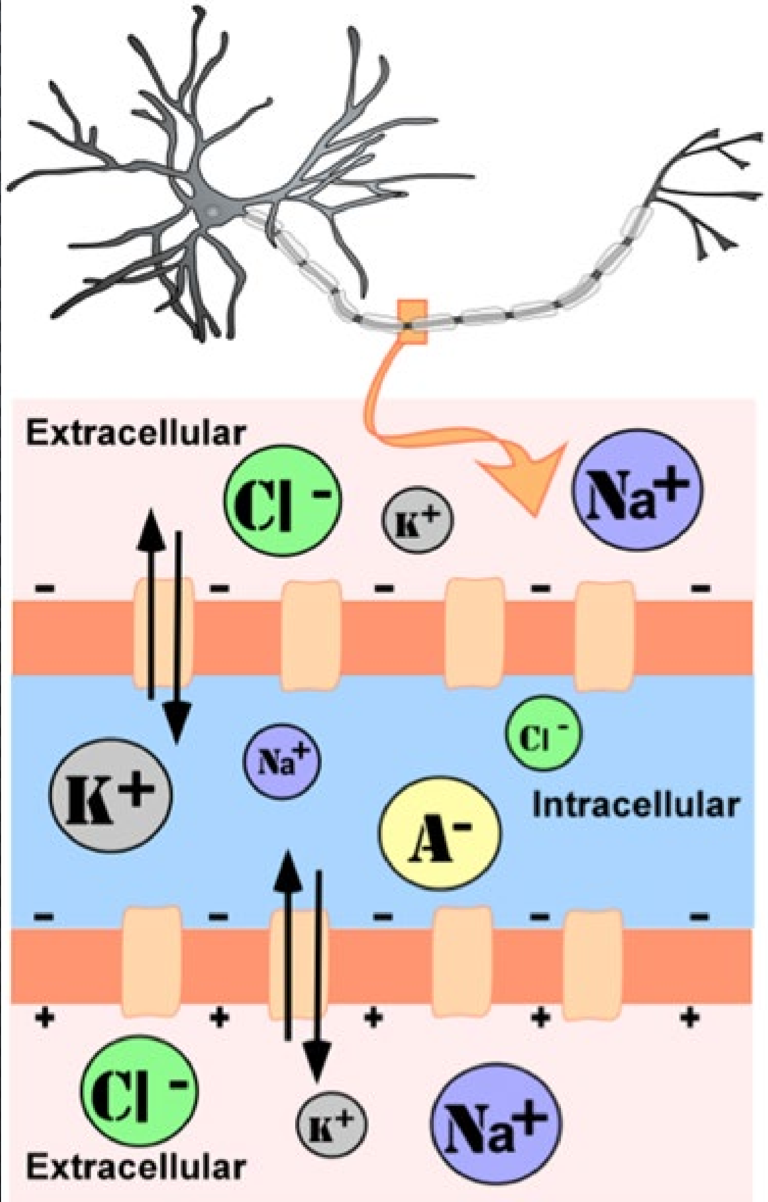
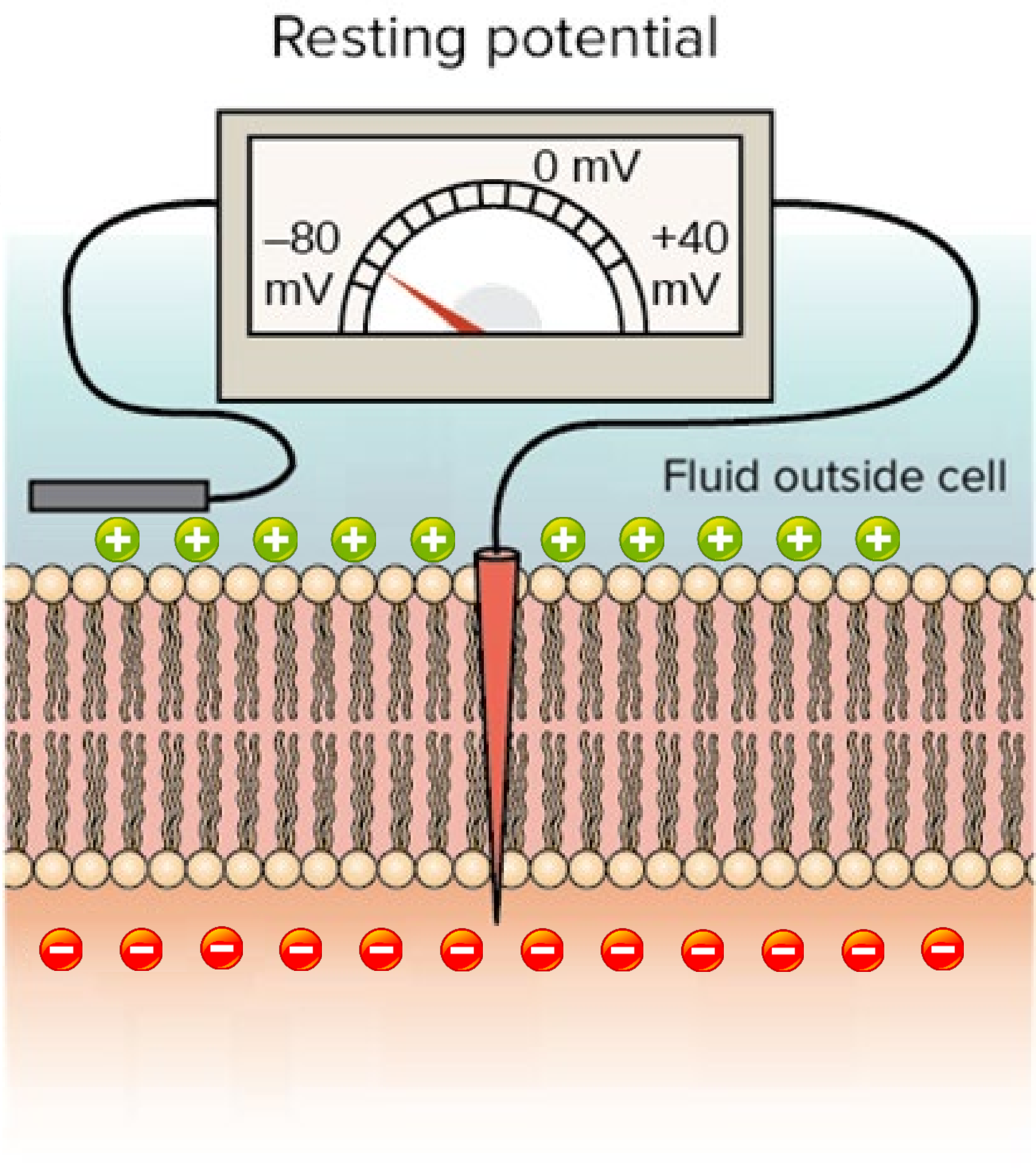


Figure 45-5 Biological Science, 2/e

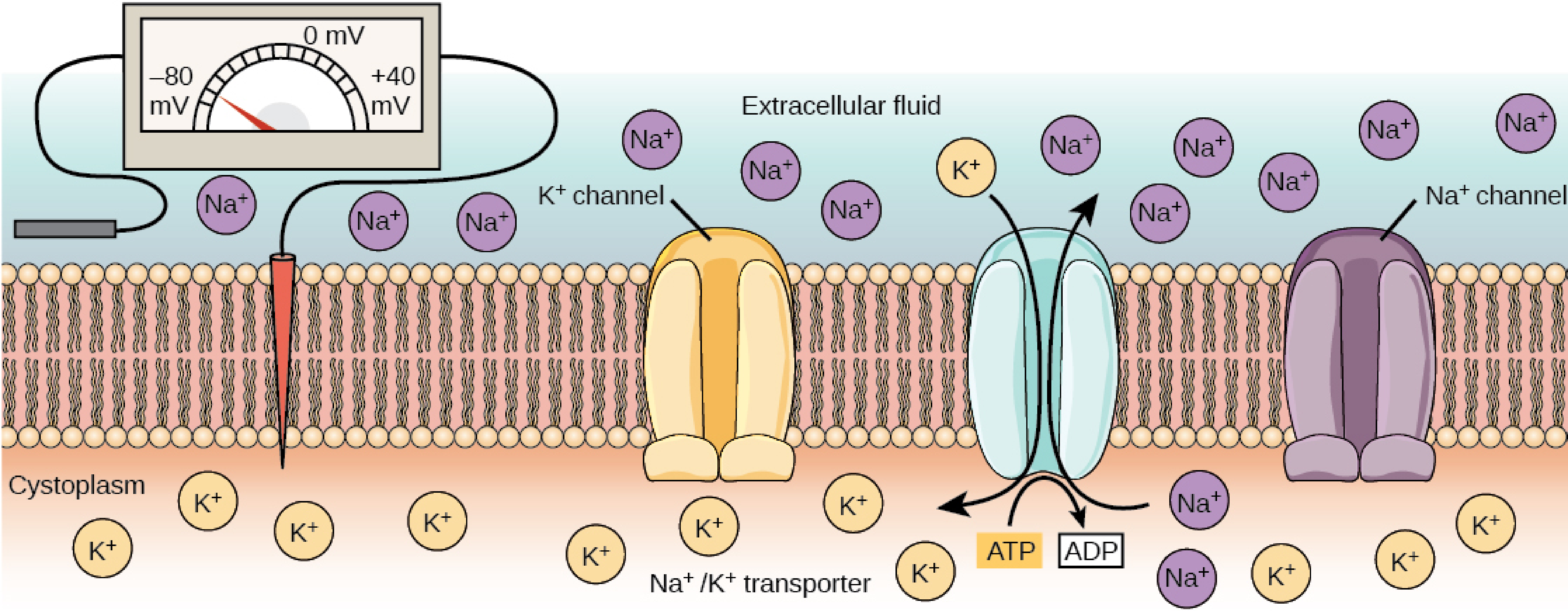
Resting membrane potential: default state of a neuron

- Difference between electric potential inside and outside a neuron, due to different ion concentration
- Potassium (K^+) ions have higher concentration inside
- Sodium (Na^+) ions have higher concentration outside
- Leakage of K^+ to outside leaves excess negative charge inside and excess positive charge outside
- Ion leakage sets resting membrane potential to around −65 mV to -70 mV



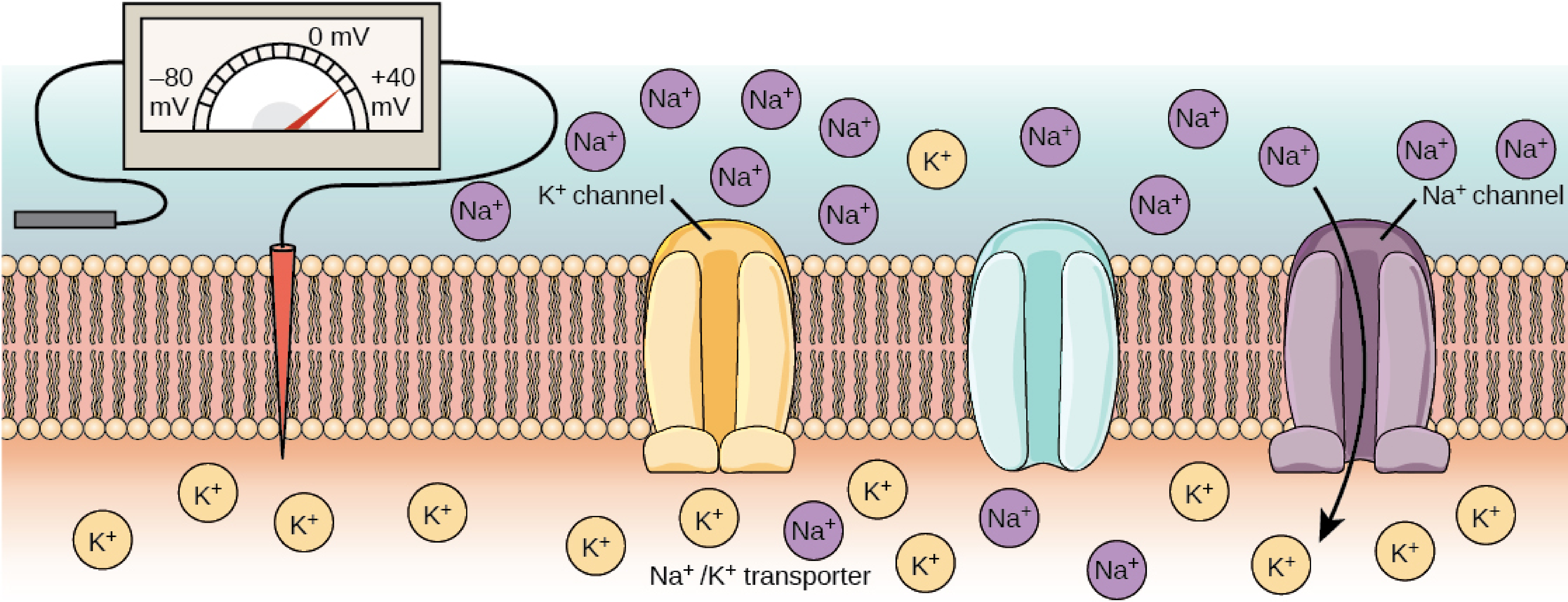


Resting membrane potential: default state of a neuron



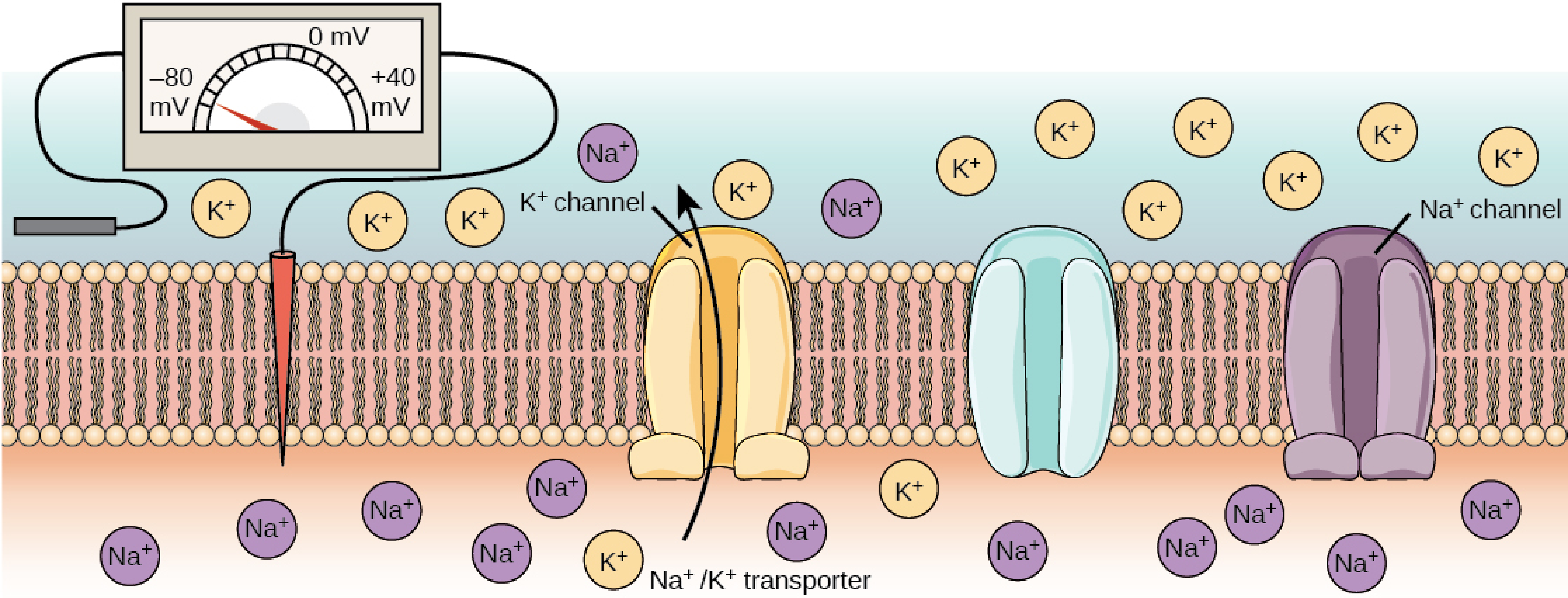
At the resting potential, all voltage-gated Na^+ channels and most voltage-gated K^+ channels are closed. The Na^+/K^+ transporter pumps K^+ ions into the cell and Na^+ ions out.

De-polarisation



In response to a depolarization, some Na^+ channels open, allowing Na^+ ions to enter the cell. The membrane starts to depolarize (the charge across the membrane lessens). If the threshold of excitation is reached, all the Na^+ channels open.

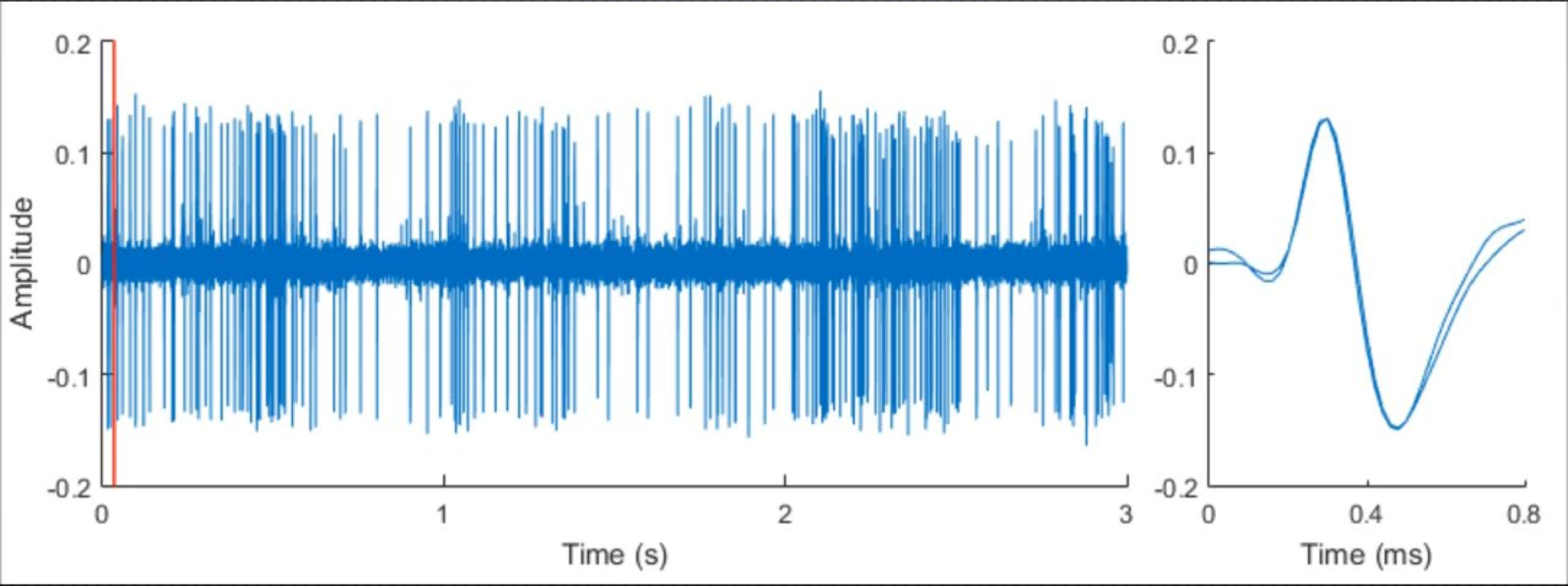
Hyper-polarisation



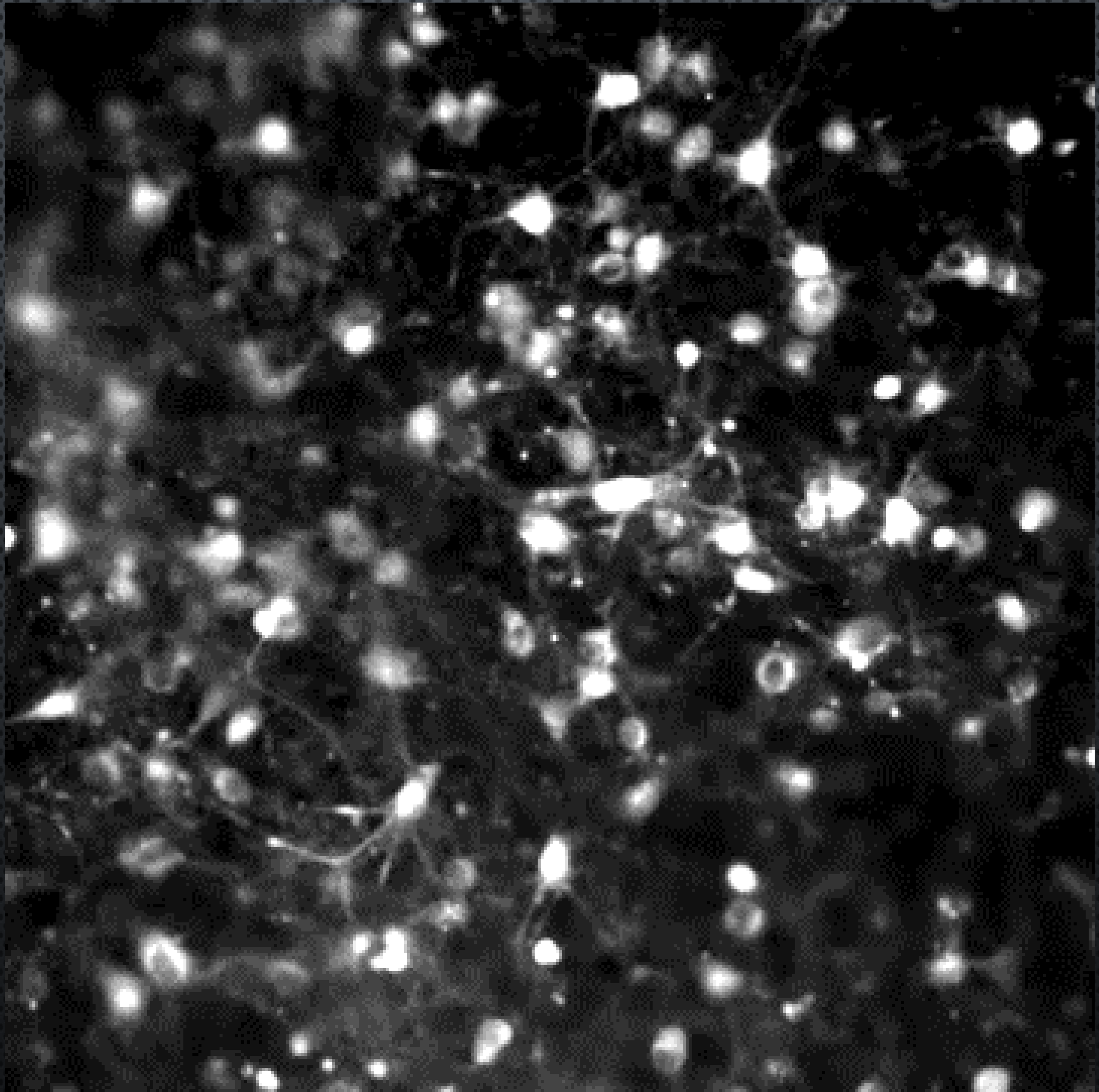
At the peak action potential, Na^+ channels close while K^+ channels open. K^+ leaves the cell, and the membrane eventually becomes hyperpolarized.

How is action potential actually measured?

Sights and sounds of neuronal recordings

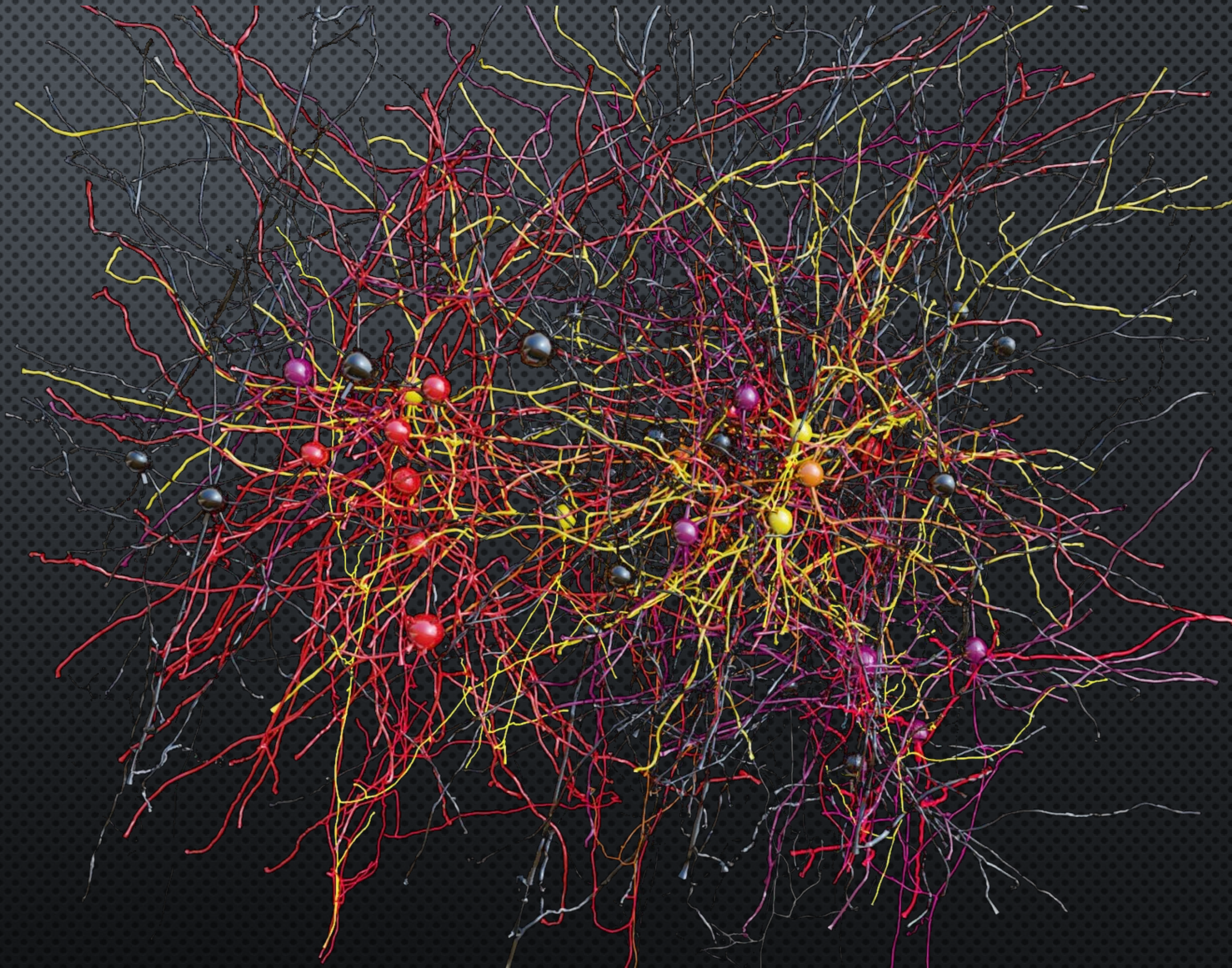


Neuronal firing

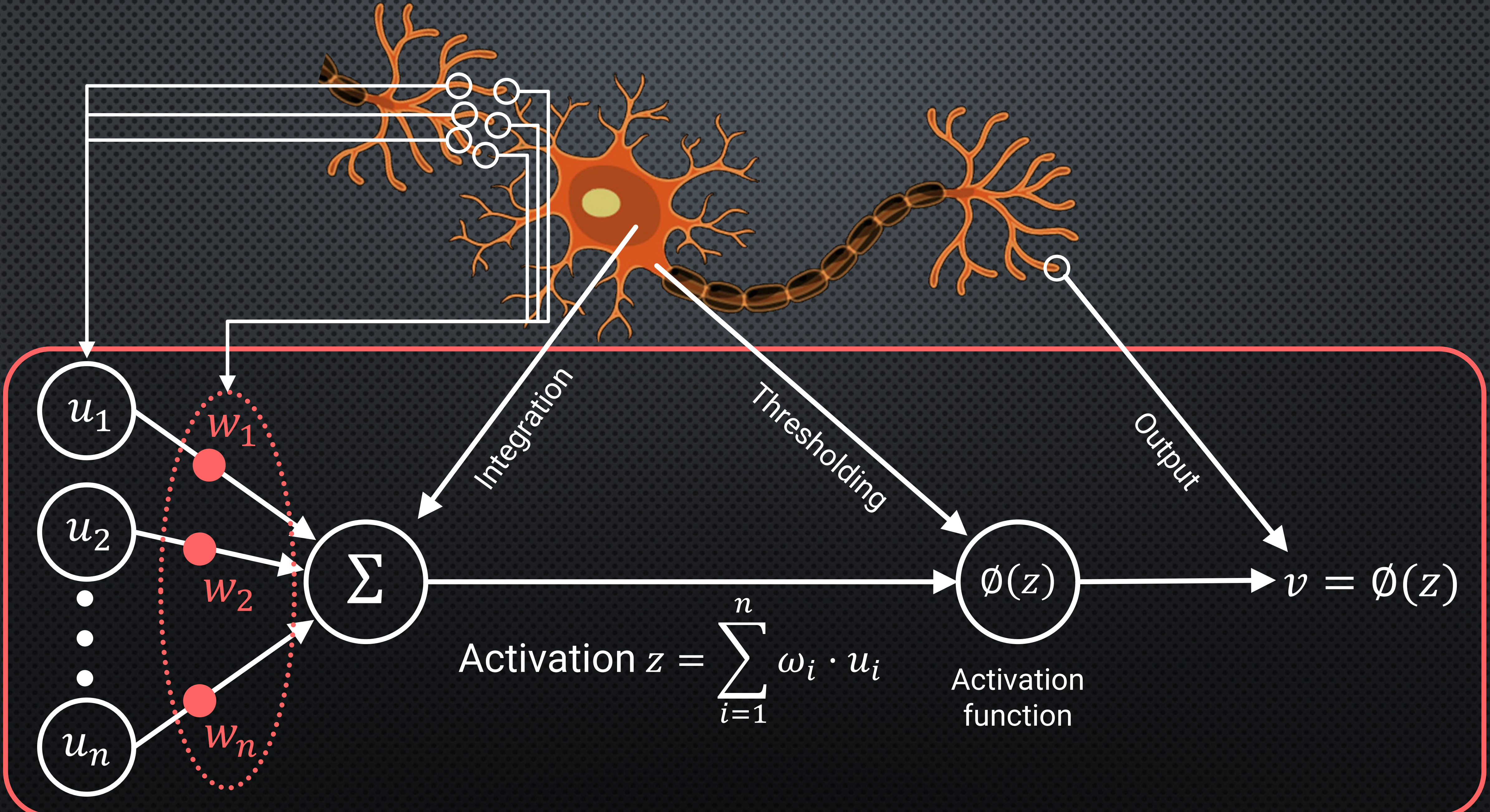


Neural connectivity is very complex!

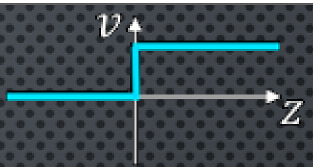
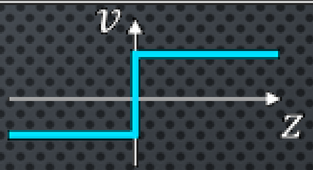
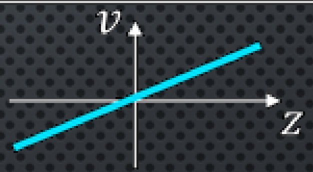
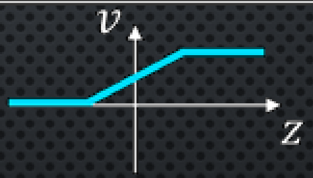
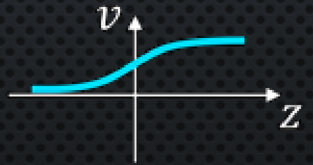
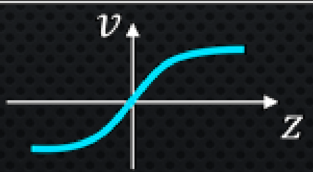
- A typical neuron may receive inputs from on the order of 10,000 neurons
- Pyramidal cells in the hippocampus can receive on the order of 50,000 inputs
- There are an estimated 1000 trillion synapses in the human brain
- Although neural connectivity is highly dense, the brain is not a fully connected network



Perceptrons: from real to artificial neurons



Common activation functions

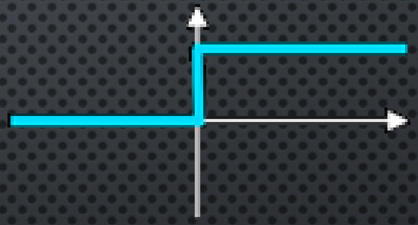
Activation function	Equation	Example	1D Graph
Unit step (Heaviside) Threshold Logic Unit (TLU)	$\phi(z) = \begin{cases} 0, & z < 0, \\ 0.5, & z = 0, \\ 1, & z > 0, \end{cases}$	Perceptron variant	
Sign (Signum)	$\phi(z) = \begin{cases} -1, & z < 0, \\ 0, & z = 0, \\ 1, & z > 0, \end{cases}$	Perceptron variant	
Linear	$\phi(z) = z$	Adaline, linear regression	
Piece-wise linear	$\phi(z) = \begin{cases} 1, & z \geq \frac{1}{2}, \\ z + \frac{1}{2}, & -\frac{1}{2} < z < \frac{1}{2}, \\ 0, & z \leq -\frac{1}{2}, \end{cases}$	Support vector machine	
Logistic (sigmoid)	$\phi(z) = \frac{1}{1 + e^{-z}}$	Logistic regression, Multi-layer NN	
Hyperbolic tangent	$\phi(z) = \frac{e^{z} - e^{-z}}{e^{z} + e^{-z}}$	Multi-layer NN	

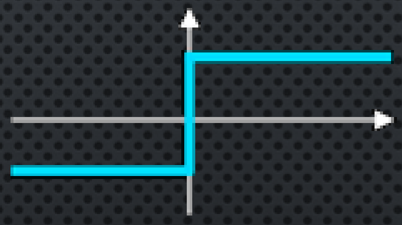
Which activation function to choose?

- Activation function decides what output the perceptron produces

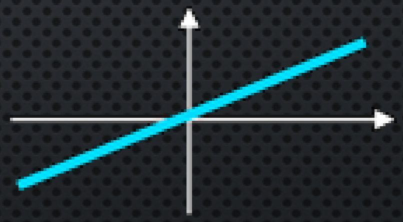
- Choose an AF based on what you want your output to look like. For example, if your output:

  - can only be 0 or 1 (-1 or 1), choose TLU or sign
    - Good for binary classification problems but bad for everything else

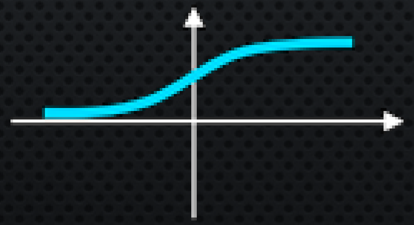


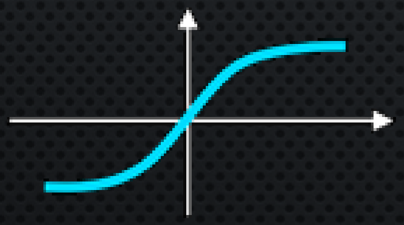


  - can be any value between $-\infty$ to $+\infty$, choose linear
    - Almost always a bad choice so try to avoid using it

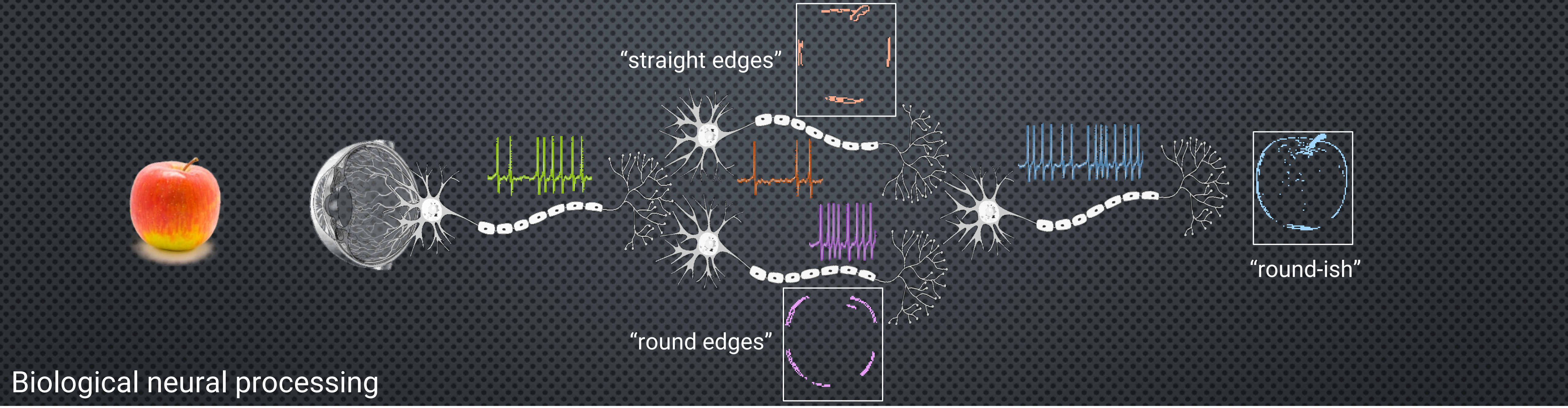


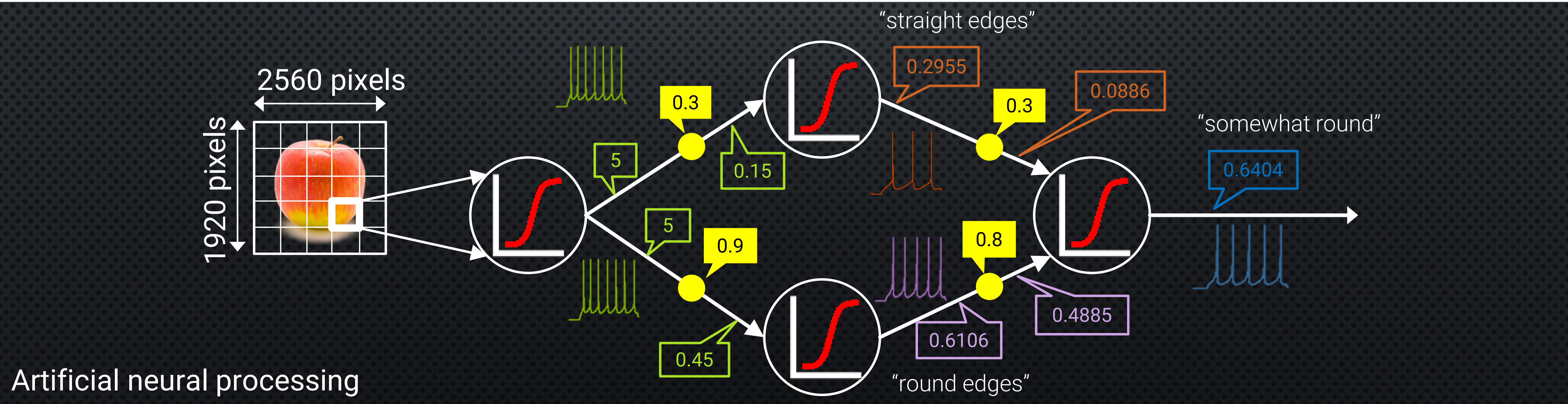
  - can be any value between 0 or 1 (-1 or 1), choose logistic or hyperbolic tangent
    - Almost always the best choice for most ML problems



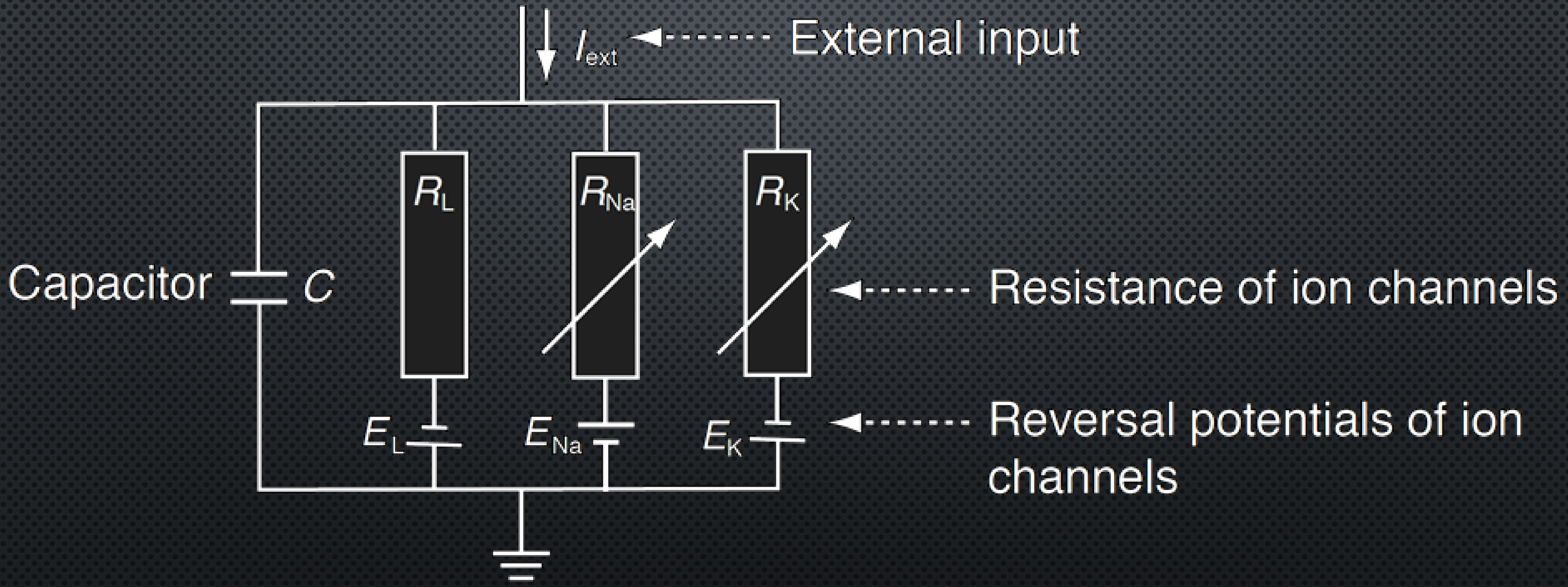


Biologically-inspired computation





A biologically realistic neuron model: Hodgkin-Huxley model



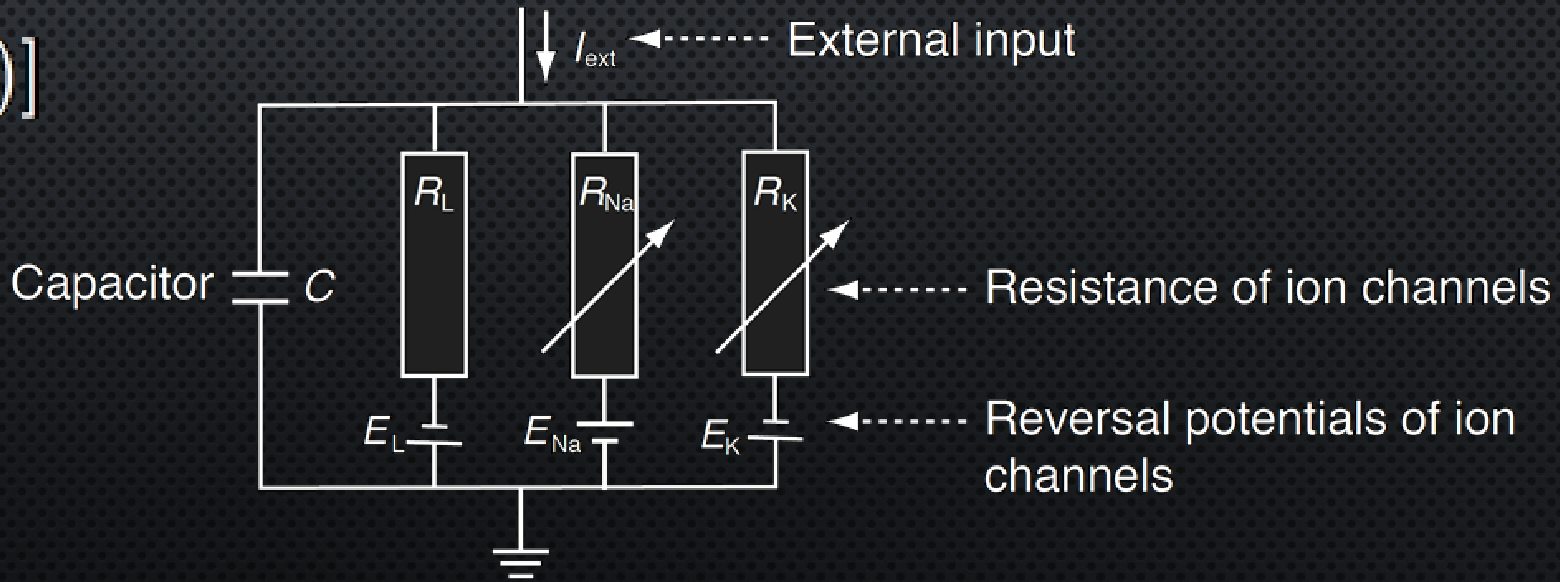
A biologically realistic neuron model: Hodgkin-Huxley model

$$C\frac{\mathrm{d}V}{\mathrm{d}t} = -g_{\mathrm{K}}n^4(V - E_{\mathrm{K}}) - g_{\mathrm{Na}}m^3h(V - E_{\mathrm{Na}}) - g_{\mathrm{L}}(V - E_{\mathrm{L}}) + I(t)$$

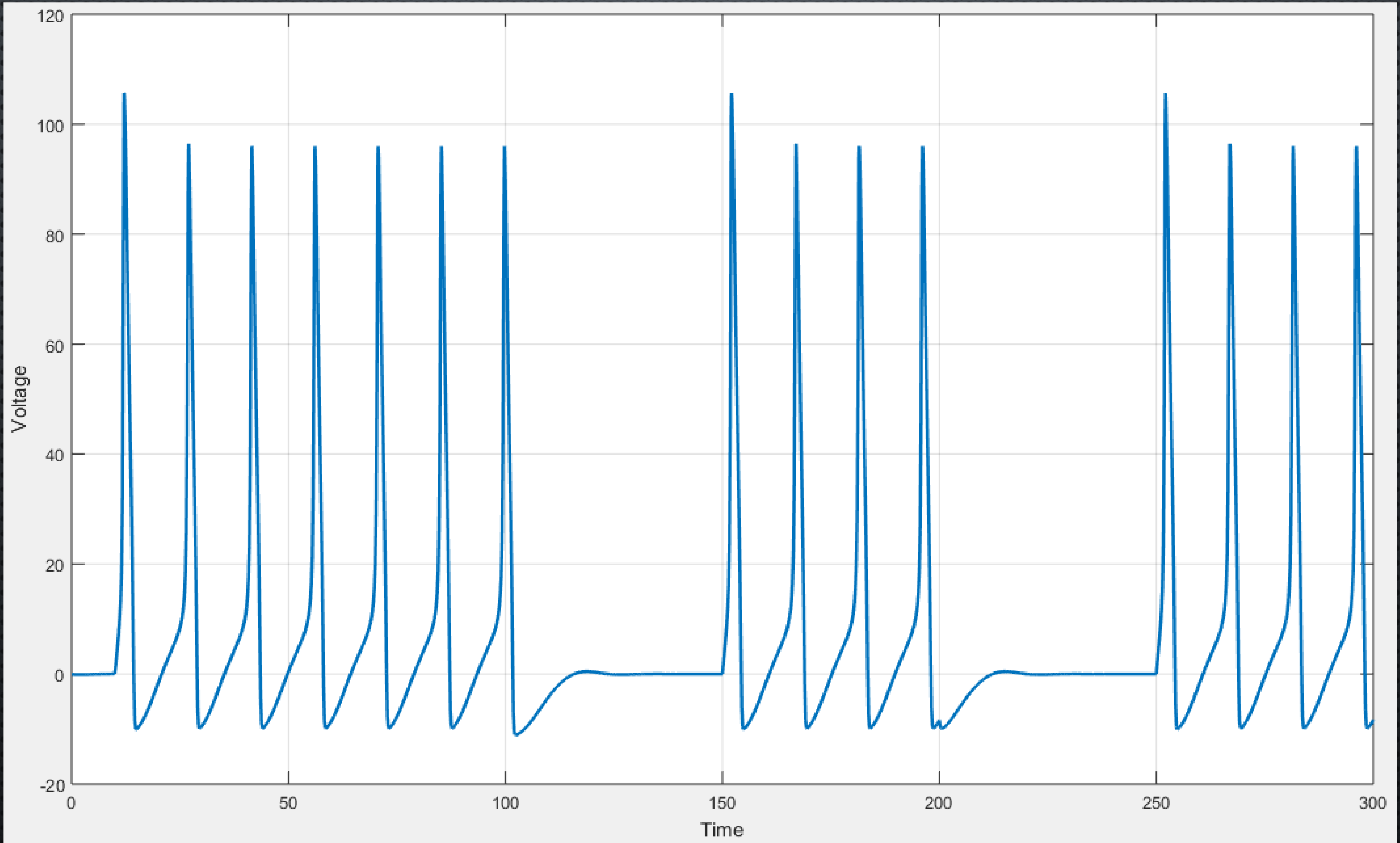
$$\tau_{\mathrm{n}}(V)\frac{\mathrm{d}n}{\mathrm{d}t} = -[n - n_0(V)]$$

$$\tau_{\mathrm{m}}(V)\frac{\mathrm{d}m}{\mathrm{d}t} = -[m - m_0(V)]$$

$$\tau_{\mathrm{h}}(V)\frac{\mathrm{d}h}{\mathrm{d}t} = -[h - h_0(V)]$$



A biologically realistic neuron model: Hodgkin-Huxley model



Matlab exercises

- Download “Assignment 1.pdf” from Itslearning and follow the instructions in it.