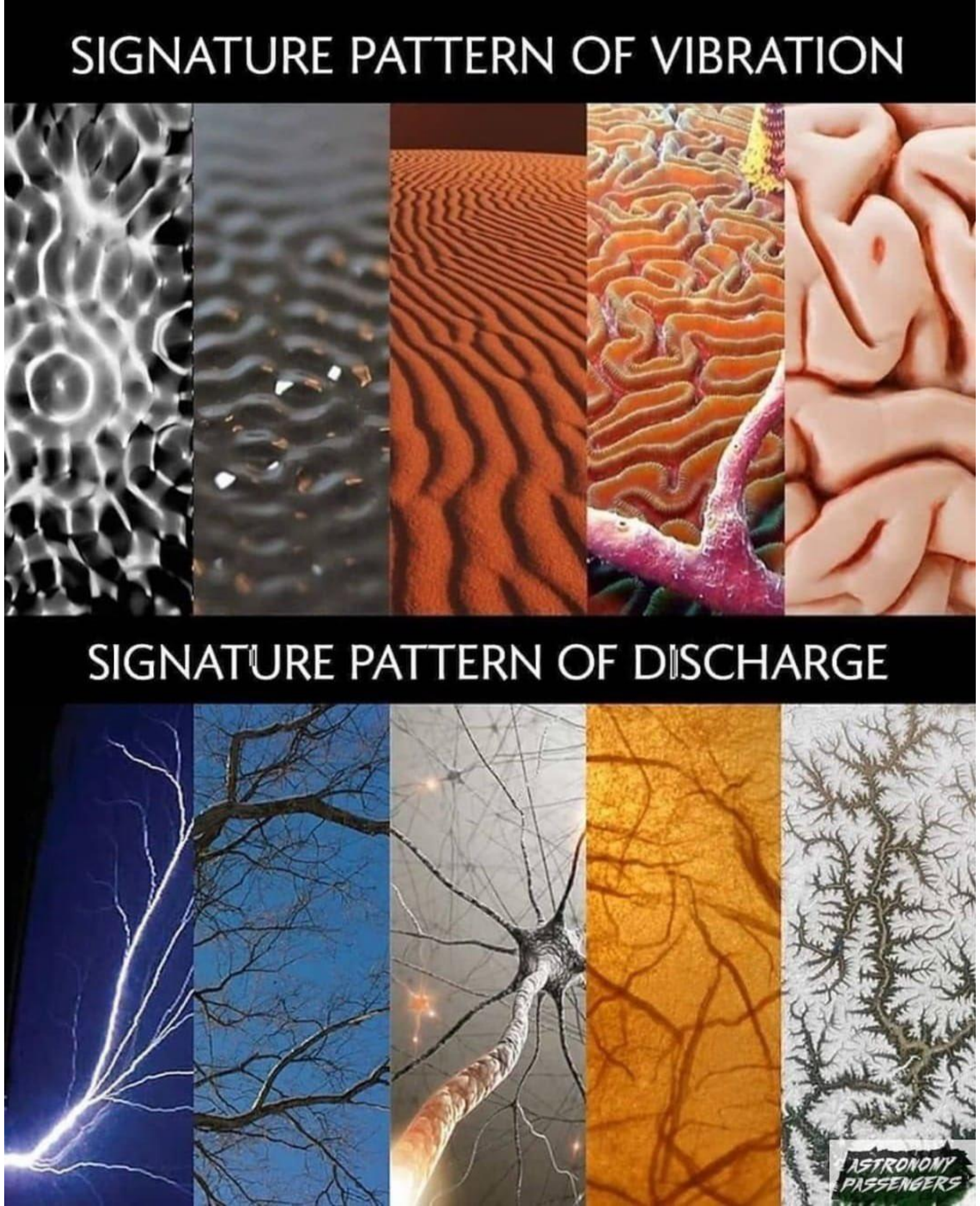
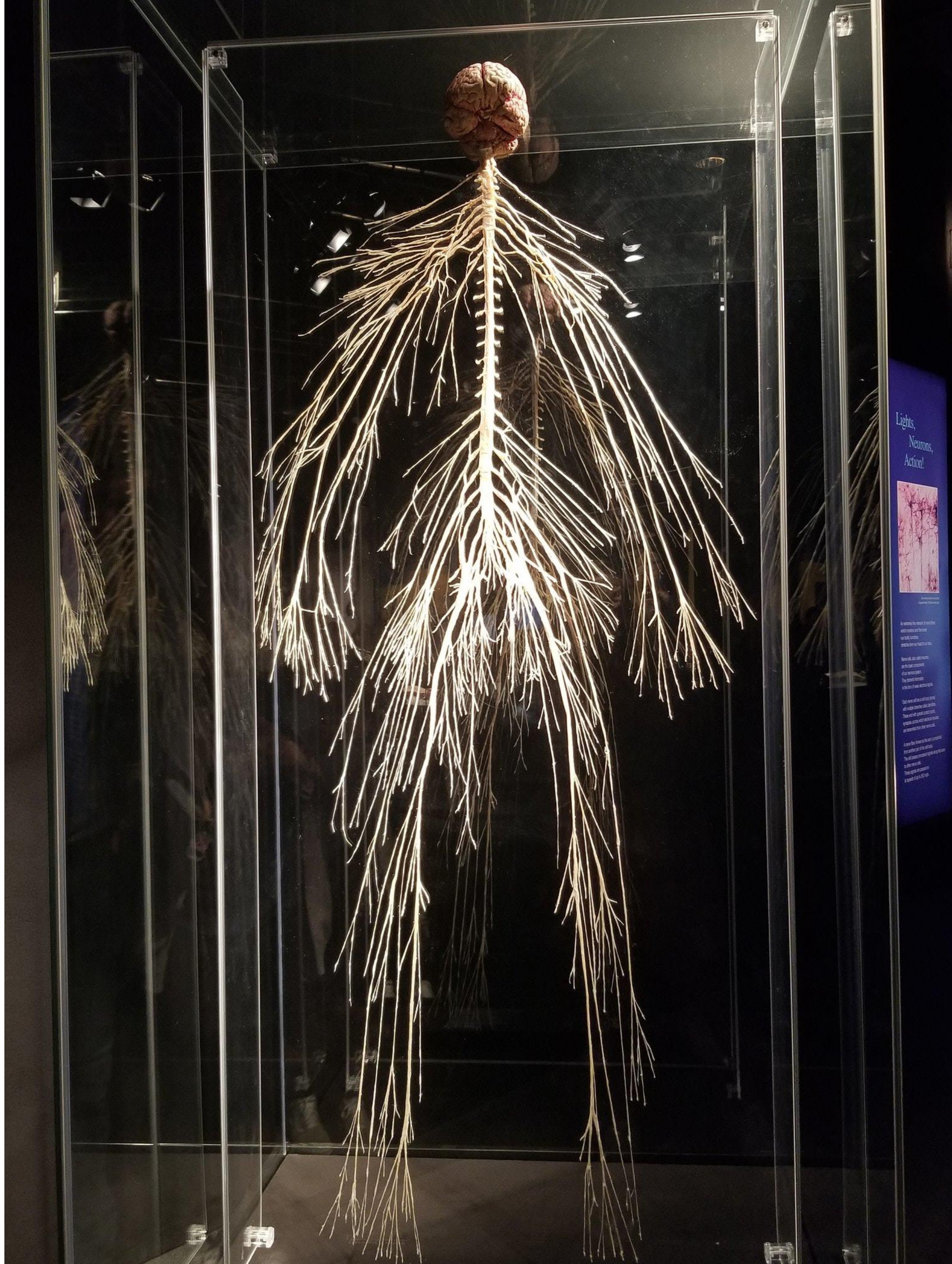
Neural Anatomy -- Neurons

9/3/2024



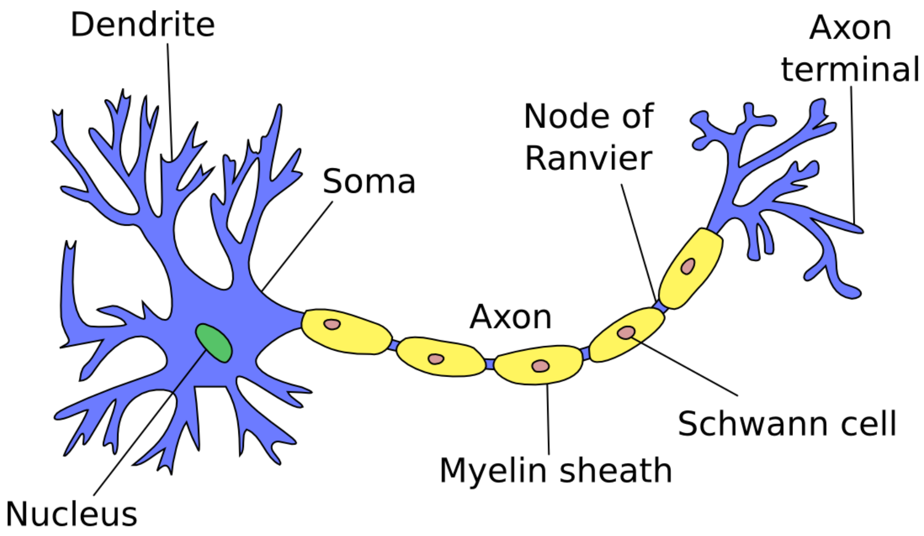
The nervous system

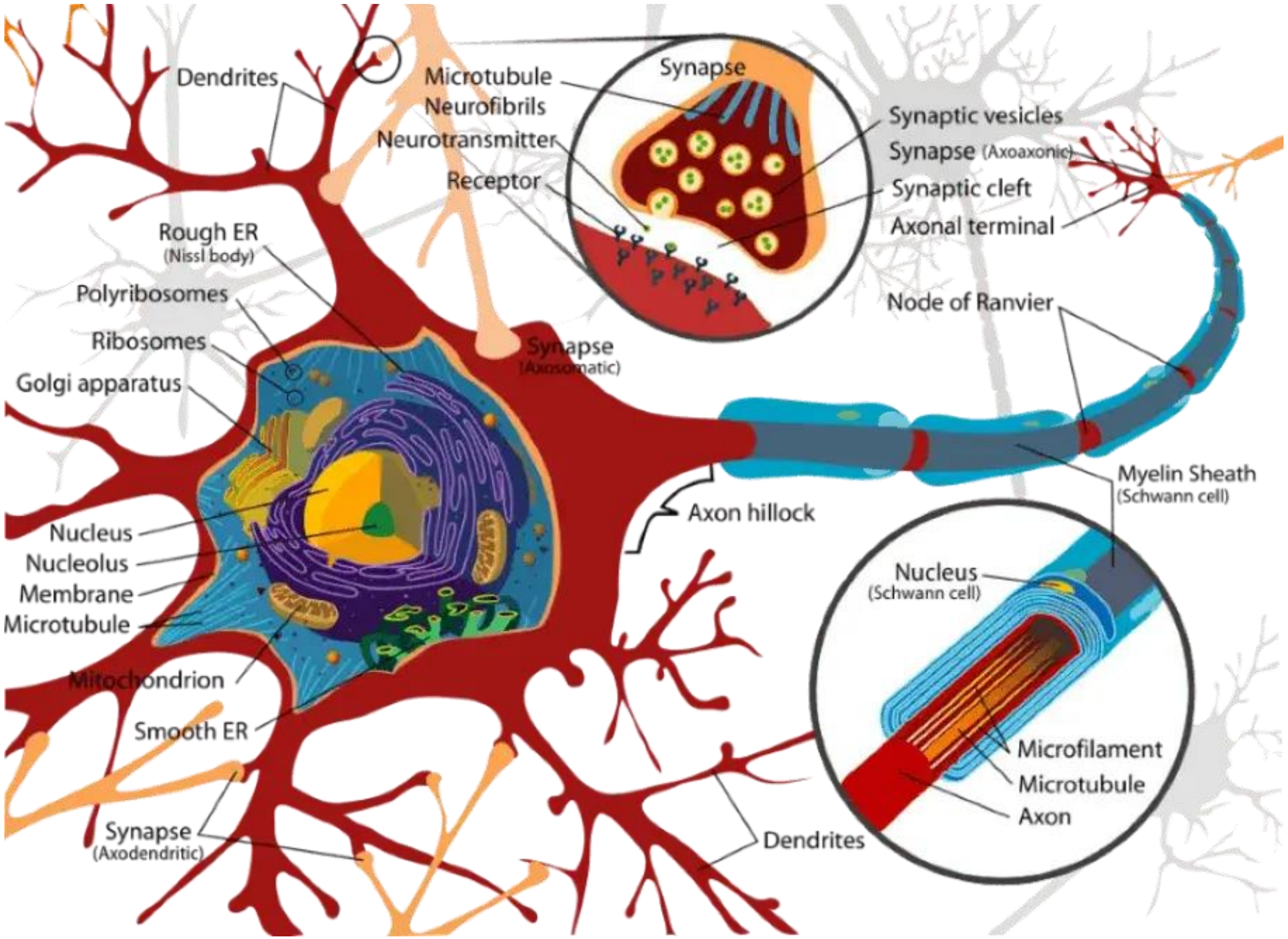
- Two main sections:
- Central nervous system (CNS)
  - Brain and spinal cord
  - Approximately 86 billion neurons + the same number of glia
- Peripheral nervous system (PNS)
  - The rest of the body
  - Hundreds of millions of neurons, 45 miles of nervous tissue
- Somehow responsible for sensory interface with the world, internal feeling, cognitive processing, internal signal coordination, and motor control



Neurons

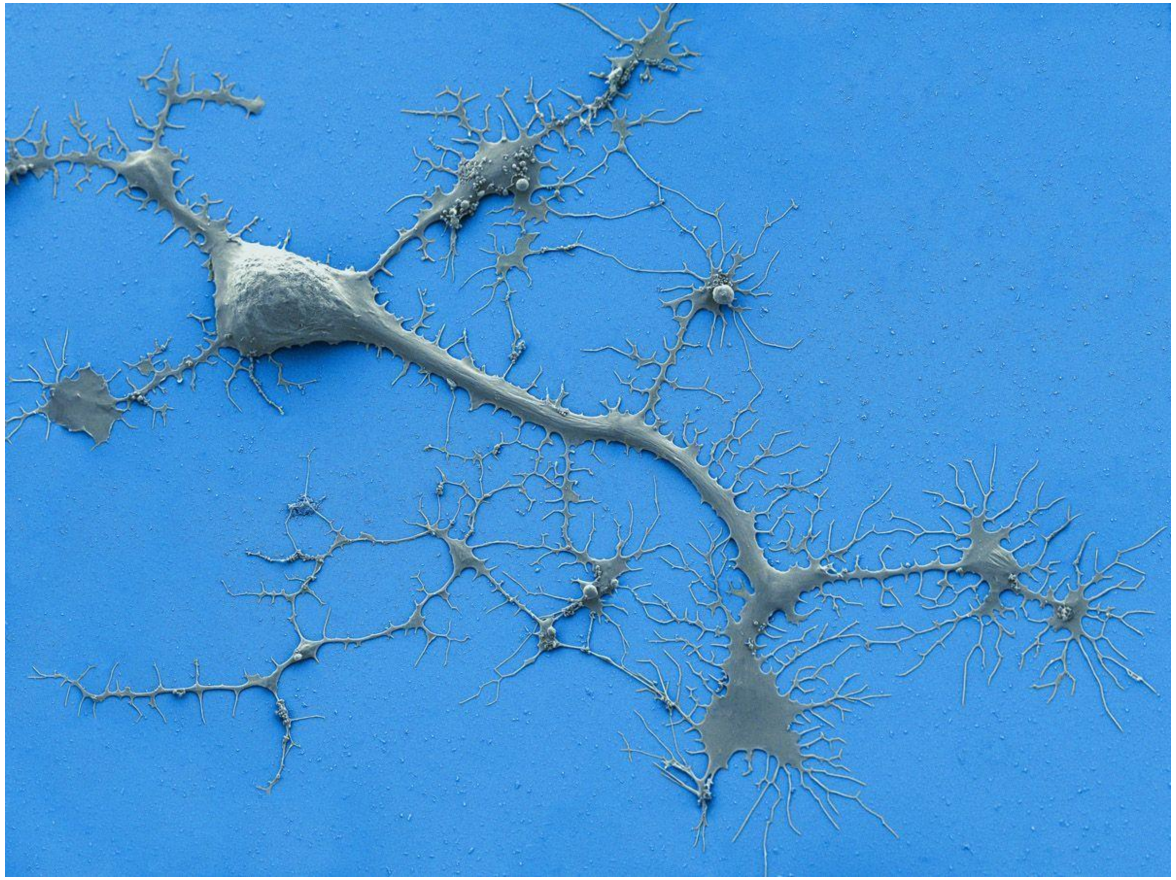
Diagrams

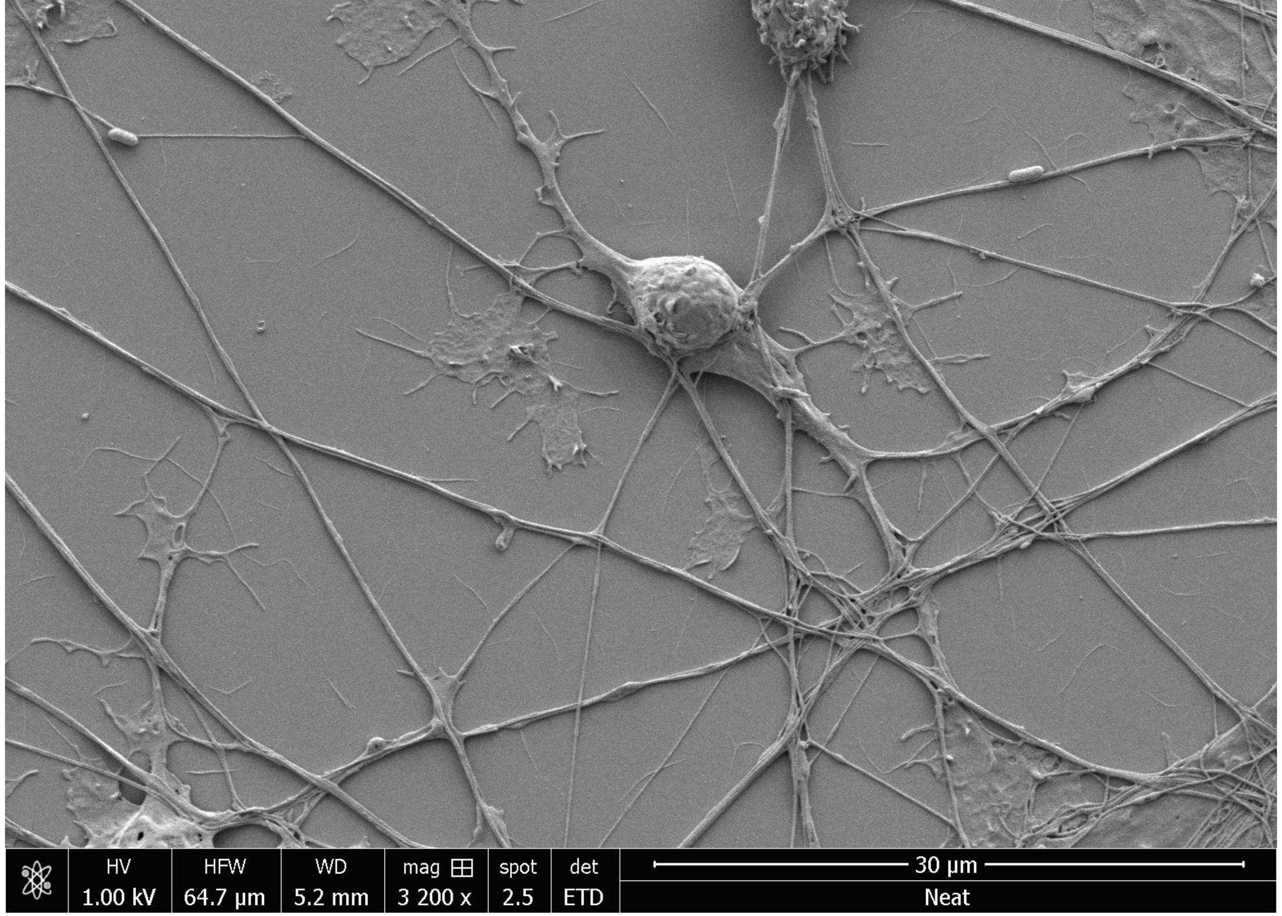




Neurons

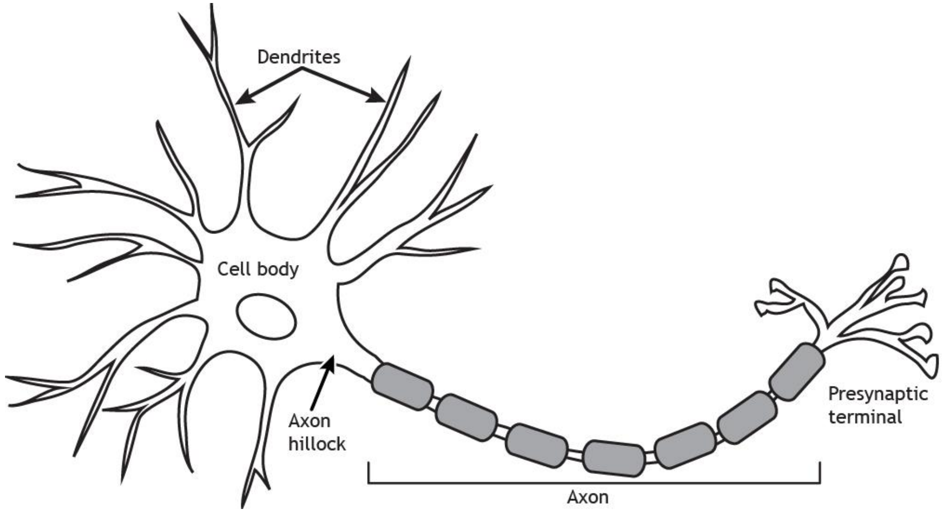
Electron microscope images

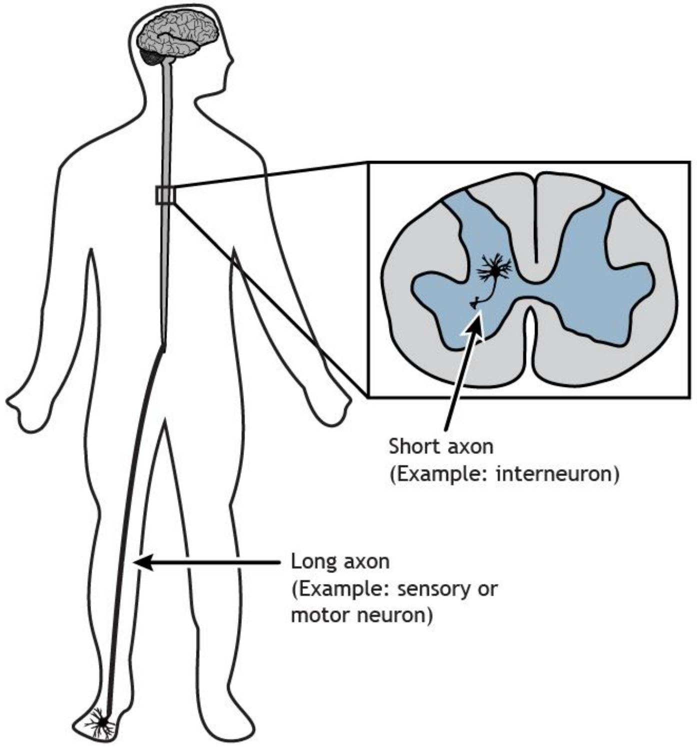




Neurons

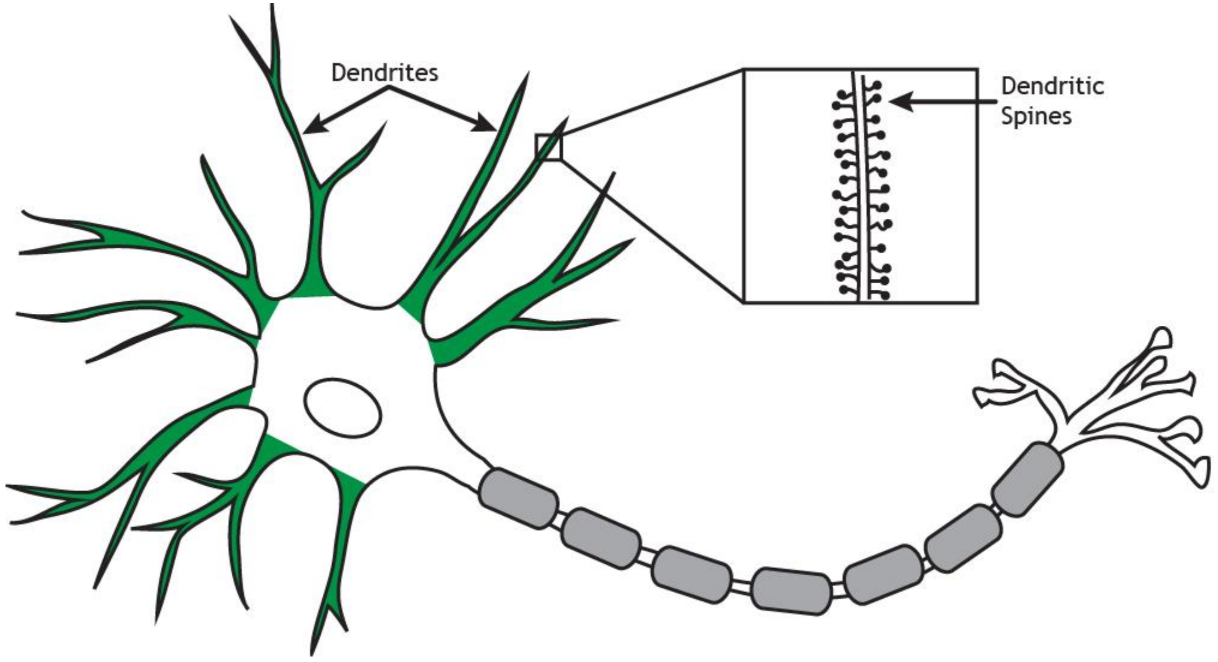
- Neurons are the central units of the brain
- The use **electrochemical signaling** to send, receive, and process information between each other
- The relationship between structure and function in neurons is highly interdependent
    - Structure often determines function
    - But functional demands can lead to structural changes!
- The average neuron makes 1,000-10,000 connections

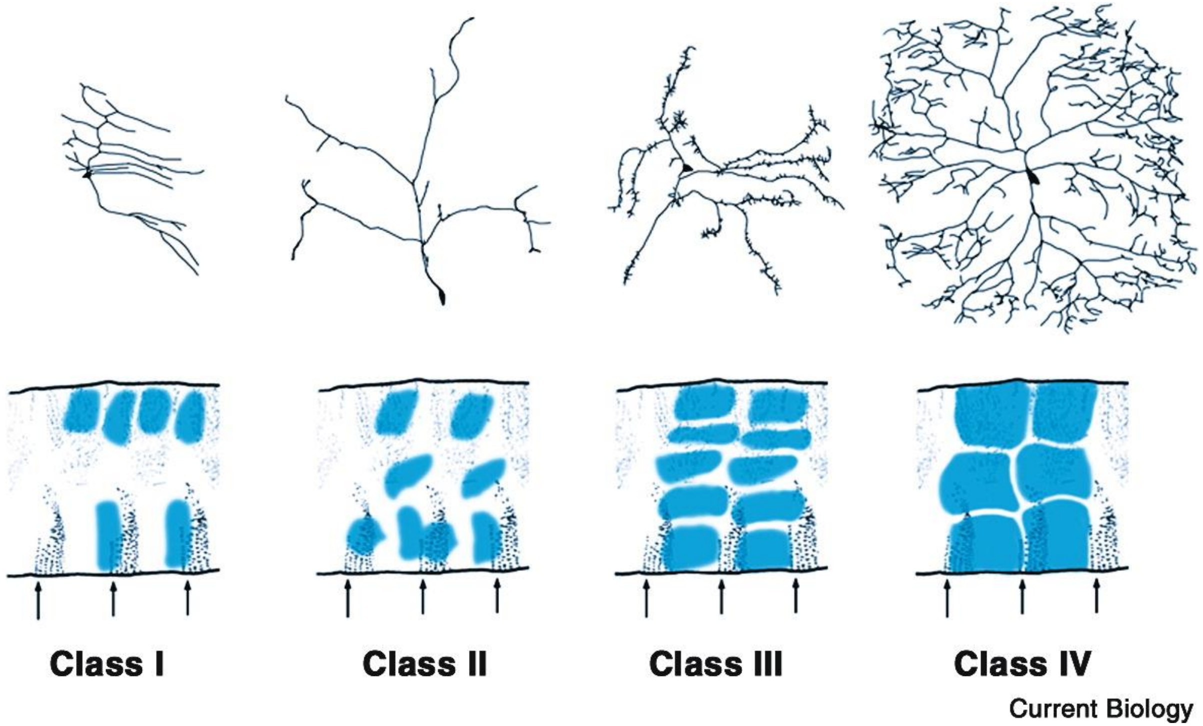




Dendrites

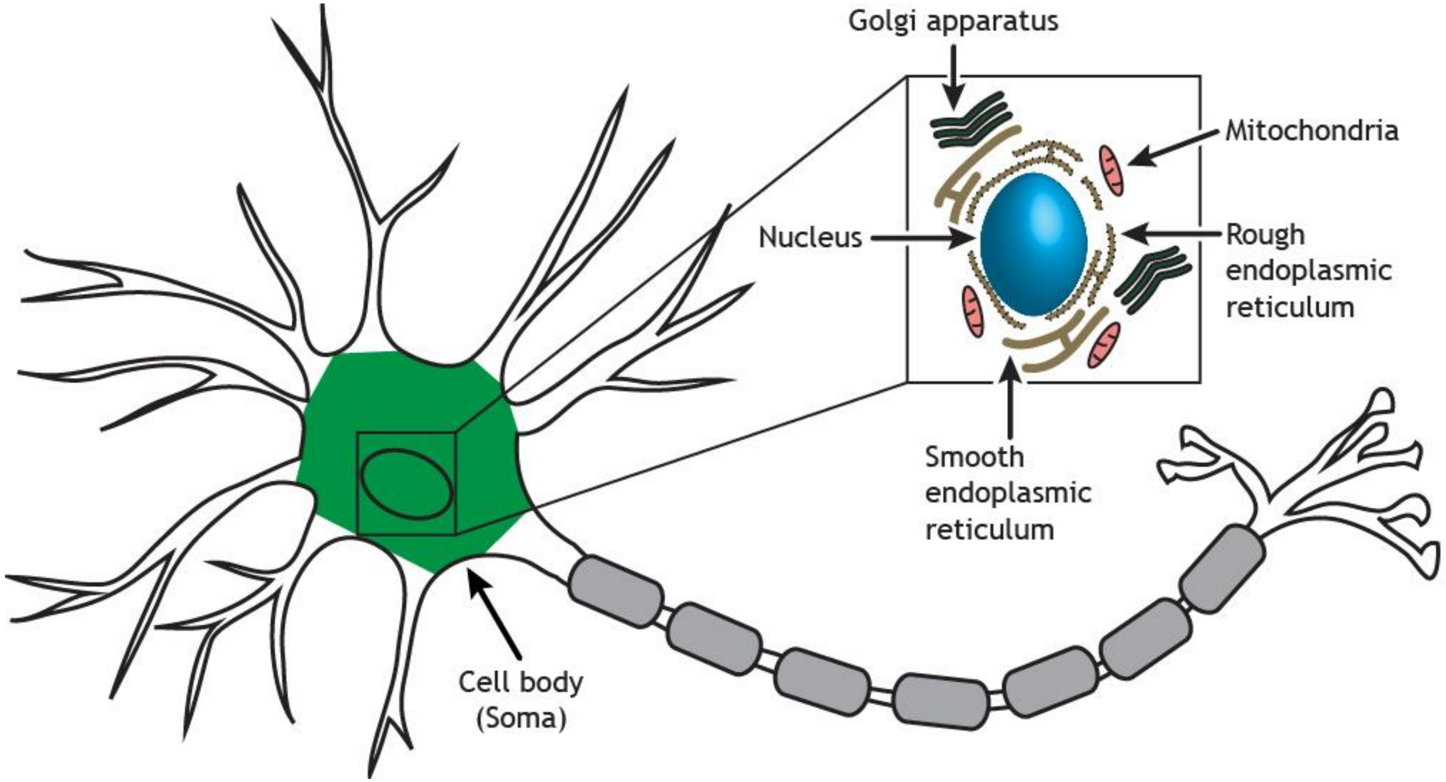
- **Dendrites** are processes that branch out in a tree-like fashion from the cell
- They are usually the main target for receiving incoming signals
- **Dendritic spines** increase the surface area of the **dendritic arbor** (the tree-like structure), allowing cells to make more connections
- Different types of neurons will have different types of dendritic arbors





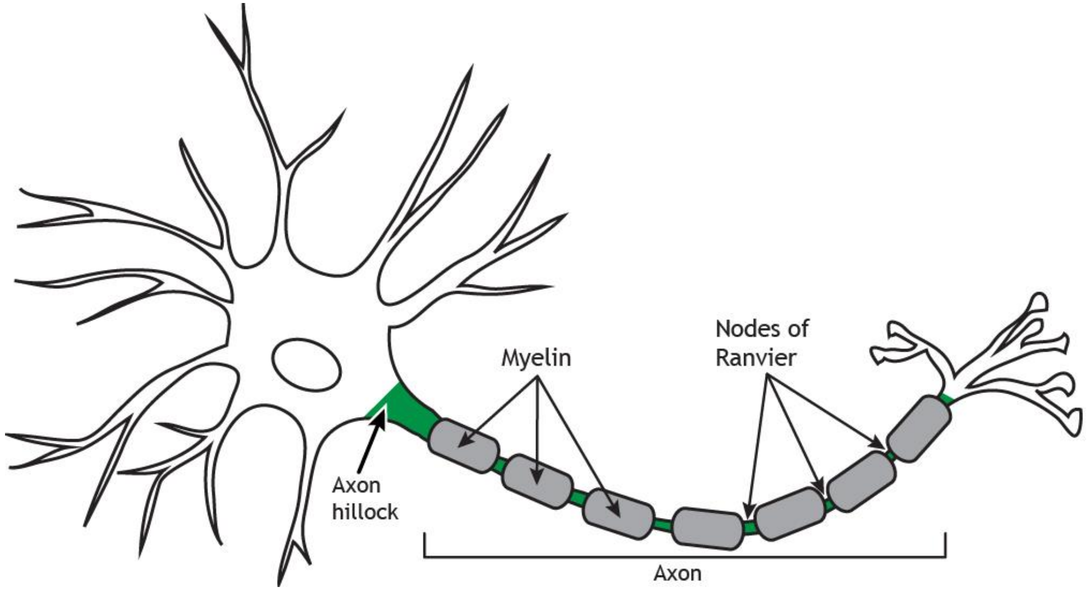
Cell Body (Soma)

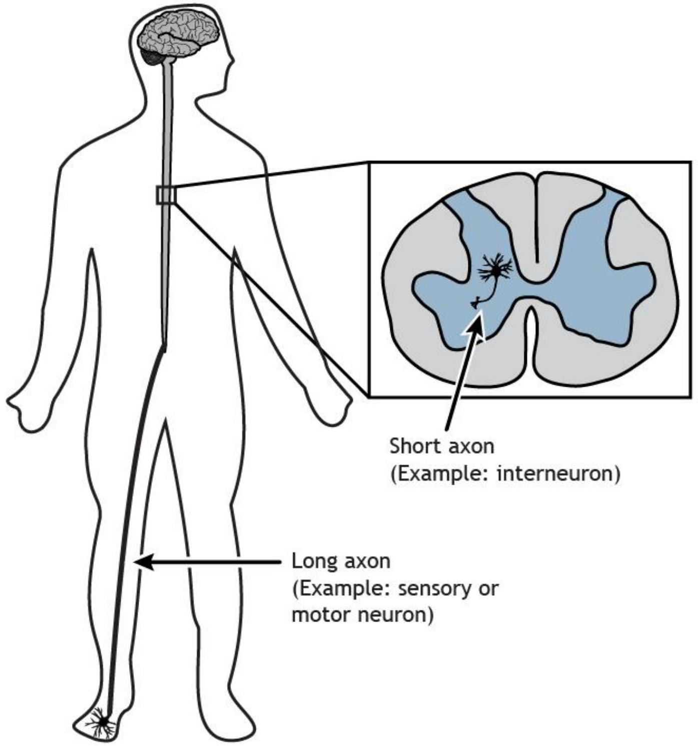
- The **soma** contains the nucleus and cellular organelles
- Where protein synthesis and cellular respiration occur
- It is also usually where signals from the dendritic arbor will combine (more on that later)



Axon

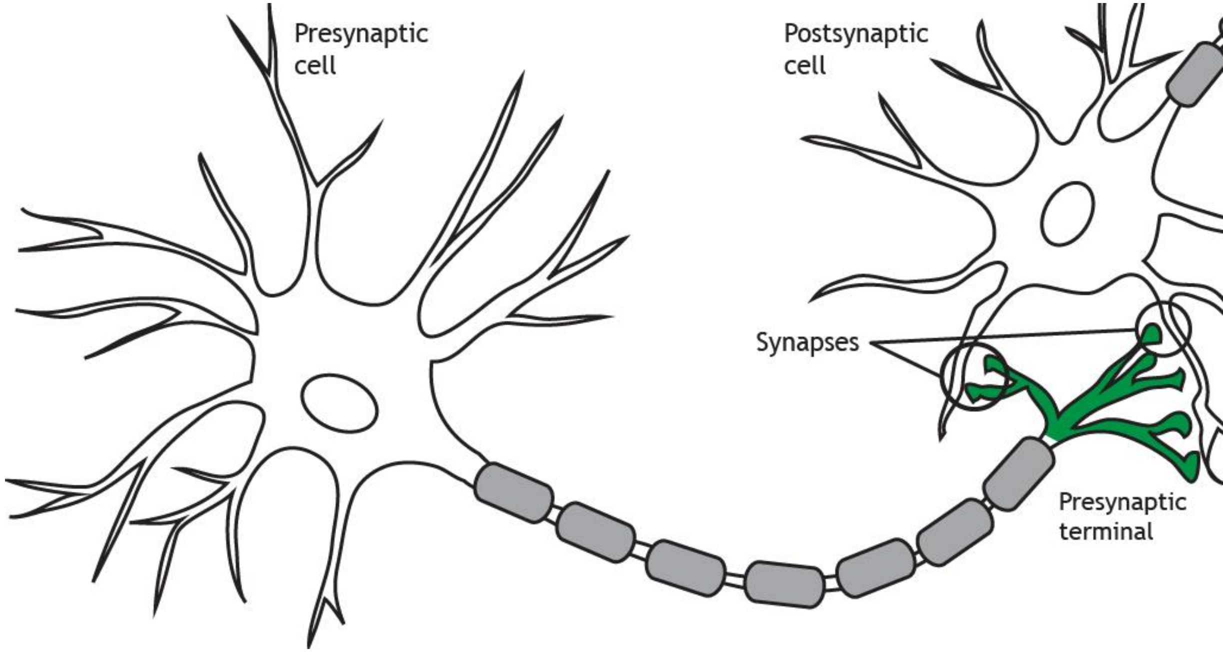
- The **axon** is usually a long, single process that begins at the **axon hillock** and extends out to a series of **axon terminals**
- Communication signals known as **action potentials** propagate down the axon through **saltatory conduction**
- Some neurons have a **myelin sheath** around their axons, which provides fatty insulation to improve the speed and efficiency of the action potential
- Gaps between the myelin are called **nodes of Ranvier**, which action potentials will “jump” through
- Some axons extend across entire limbs to the spinal cord





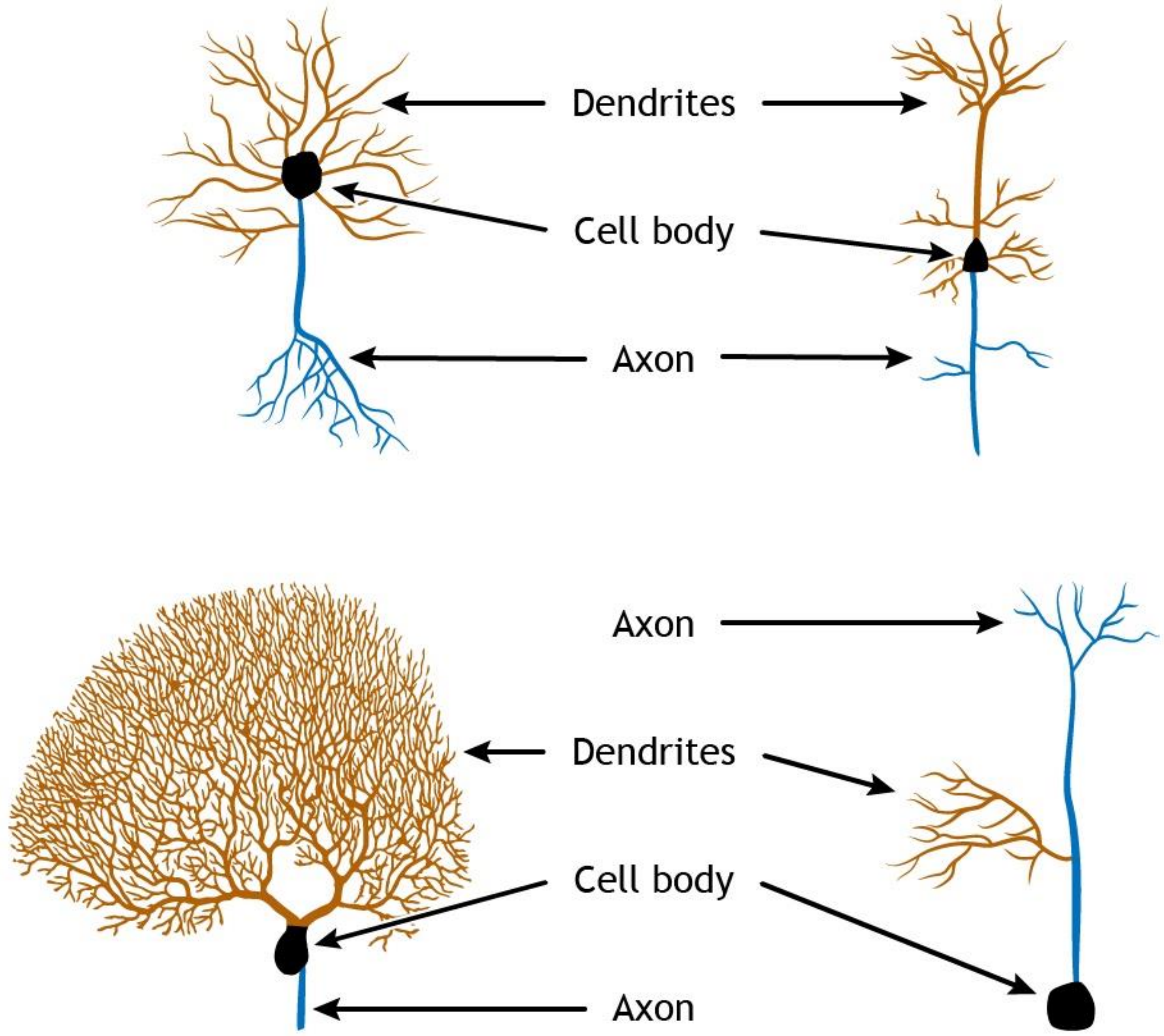
Presynaptic Terminals

- The axon terminates at **presynaptic terminals**, which form **synapses** with another neuron or cell, known as the **postsynaptic cell**
- Terminals release **neurotransmitters** into the synapse to send a **chemical signal** to the postsynaptic cell
- Usually, axon terminals synapse with dendrites, but they can also synapse with cell bodies or axons



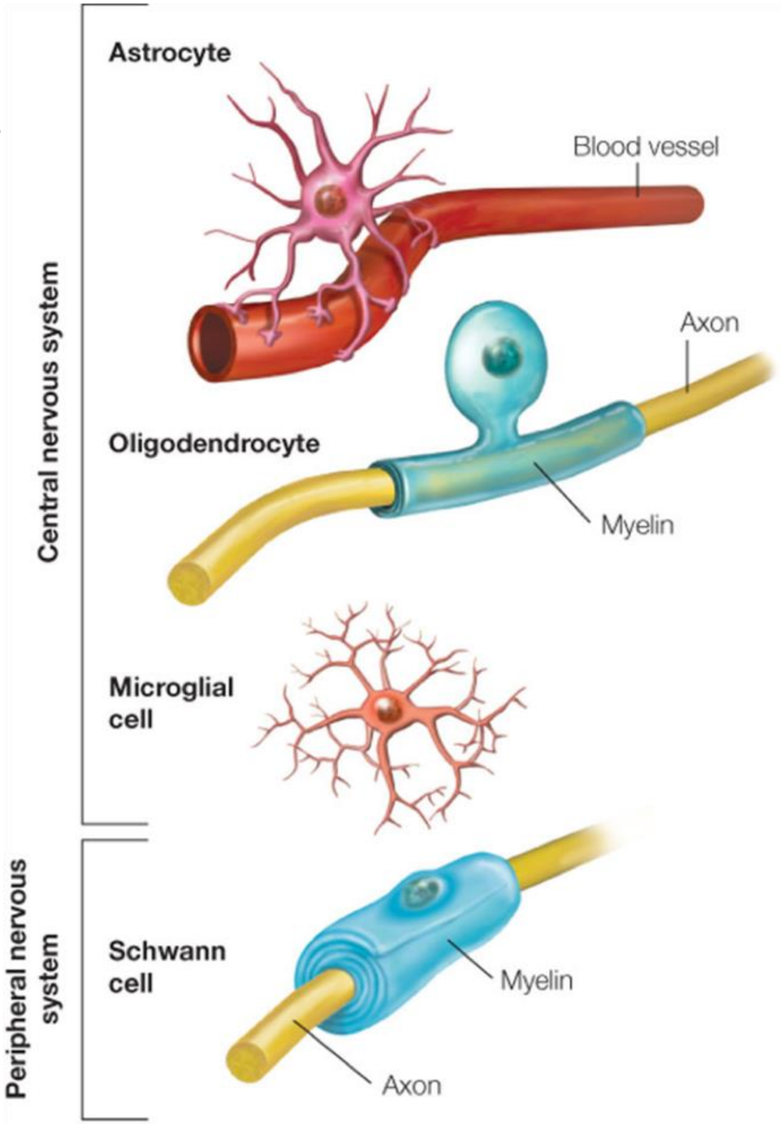
Neurons come in many shapes and sizes, but these components are common

Structural Variability



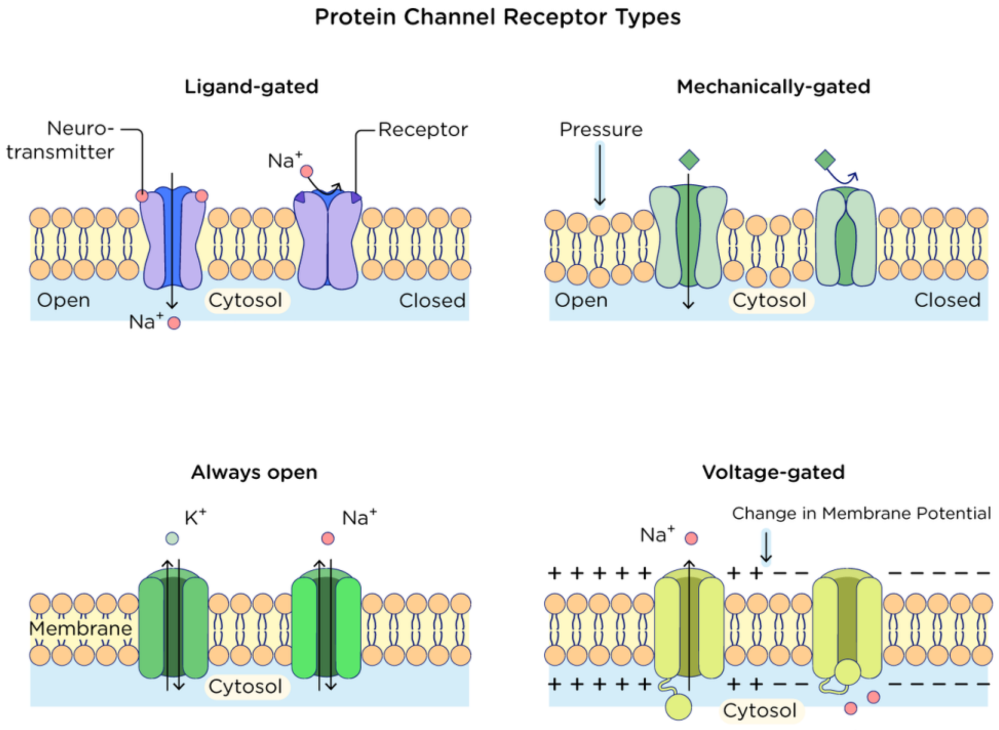
Glial cells

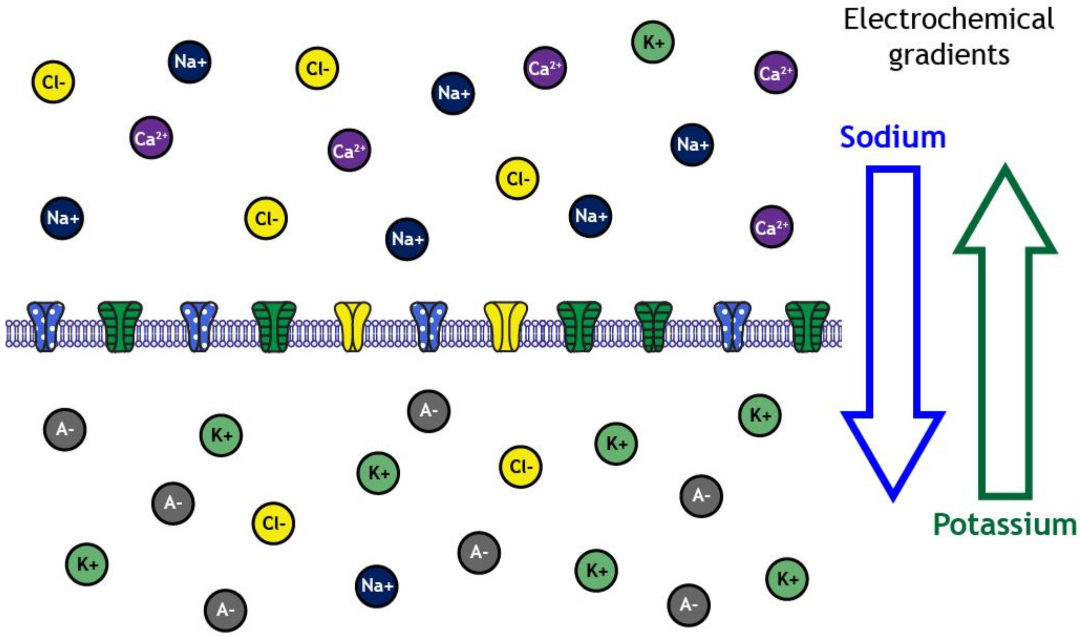
- **Glia** (or neuroglia) – non-neuronal cells that provide critical support to neurons and their environment
- **Astrocyte** (CNS)
  - Provide structural support to neurons
  - Maintain the **blood-brain barrier**, which regulates what substances can transfer between blood vessels and the brain
  - Regulate the extracellular environment, including ion balance and neurotransmitter levels
  - Support repair processes after injury
- **Oligodendrocyte** (CNS)
  - Produce myelin sheath
  - Maintain health of axons
- **Microglia** (CNS)
  - Primary immune cell of the CNS
  - Engulf and remove debris, pathogens, and dead neurons through **phagocytosis**
  - Support injury and disease response by promoting inflammation
- **Schwann cell** (PNS)
  - Produce myelin sheath
  - Guide and support axonal regrowth in case of damage

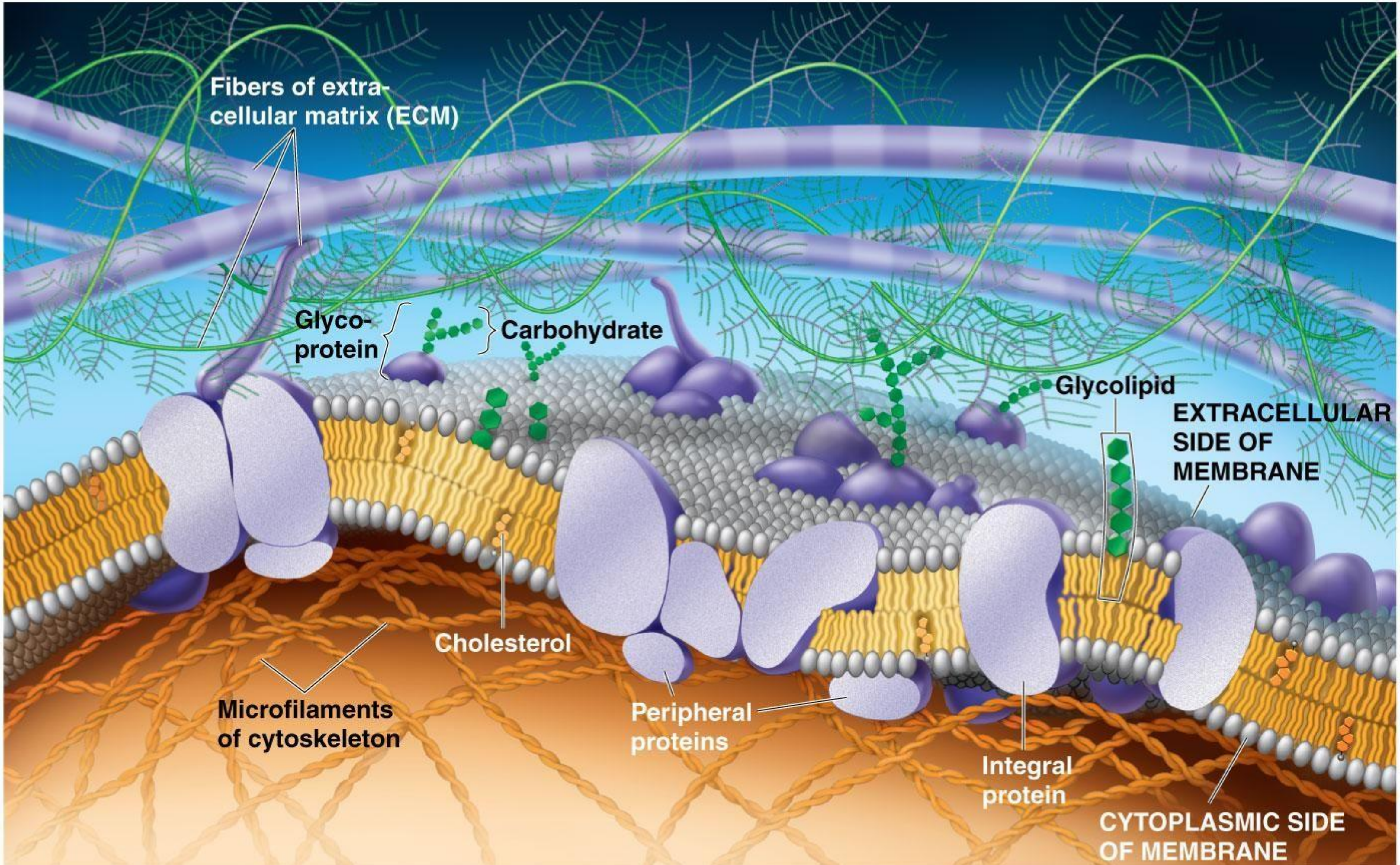


The Neuronal Membrane

- The **membrane** of a cell (not just neurons) is the key structure that dictates how that cell interacts with its neighbors and its environment
- **Receptors** to receive signals
- **Ion channels** regulate ion concentrations in the cell
  - Na^+, K^+, Cl^-, and Ca^{2+} are the main ions of concern in neuroscience
  - Their concentrations inside the cell are very carefully managed
- At rest, there is more K^+ inside the cell, and more Na^+, Cl^-, and Ca^{2+} outside the cell
  - A difference in ion distribution between different regions creates an **electrochemical gradient** – the ion wants to travel from high to low concentration

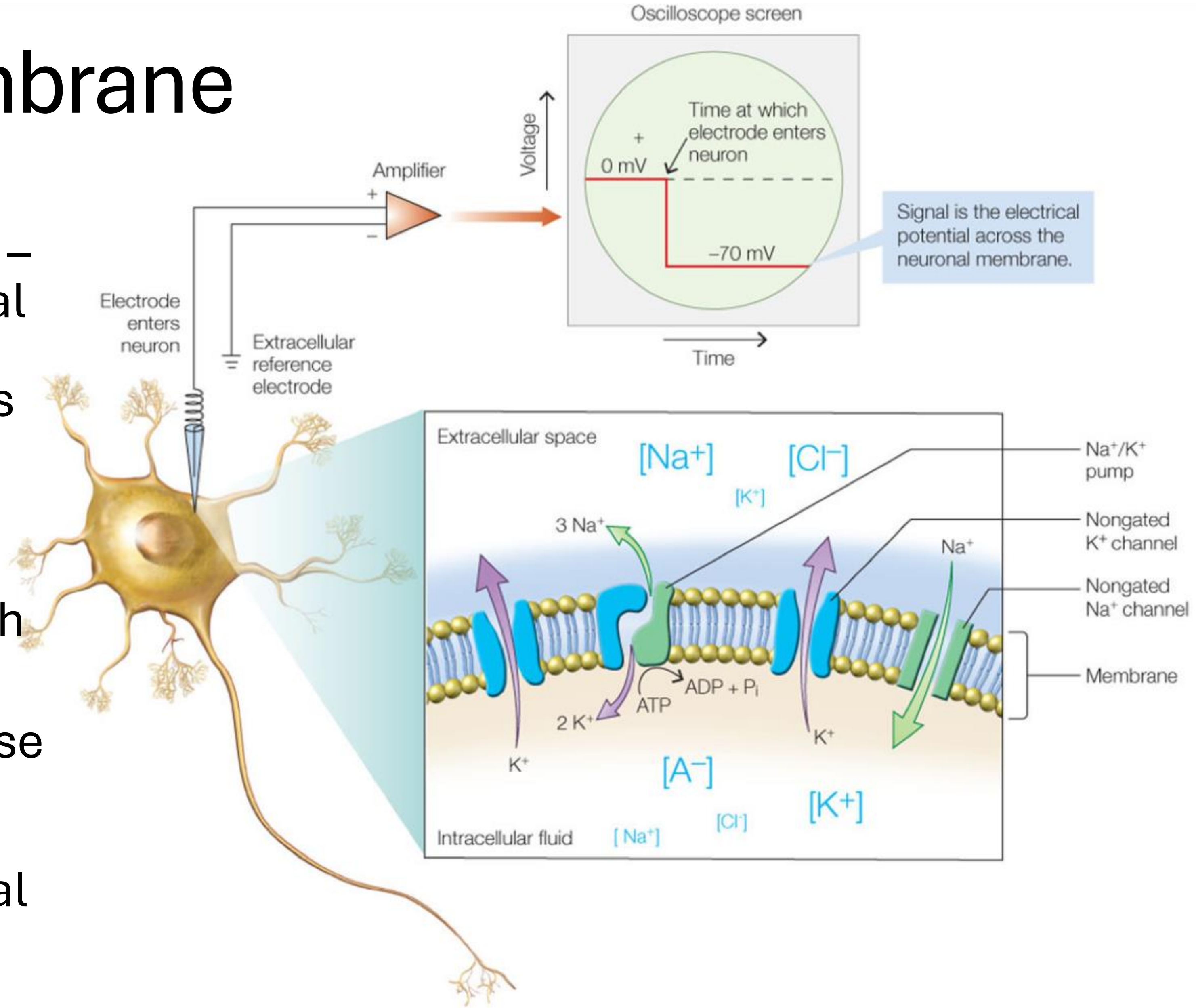


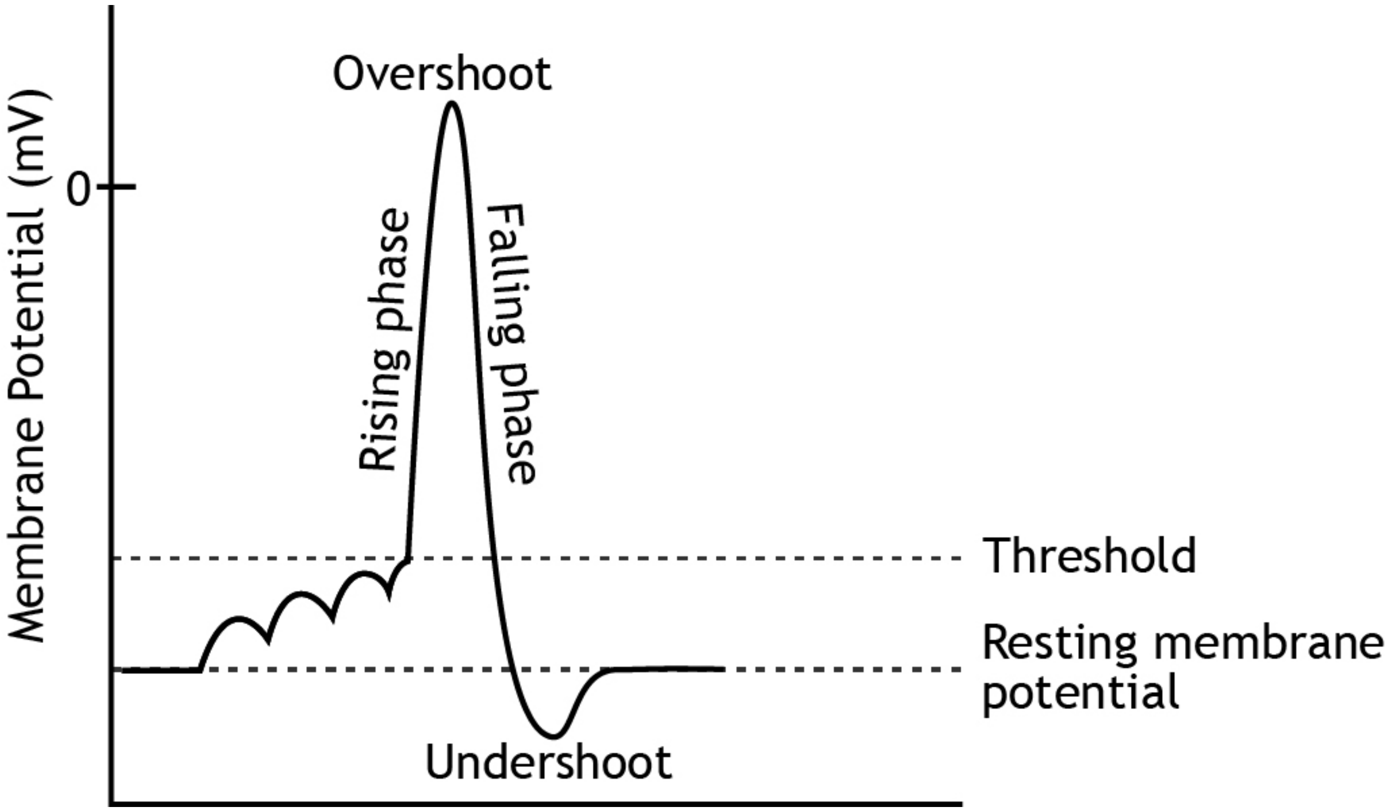



Fibers of extra-
cellular matrix (ECM)
Glyco-
protein
Carbohydrate
Glycolipid
EXTRACELLULAR
SIDE OF
MEMBRANE
Cholesterol
Microfilaments
of cytoskeleton
Peripheral
proteins
Integral
protein
CYTOPLASMIC SIDE
OF MEMBRANE

The Neuronal Membrane

- **Resting membrane potential** – the voltage across the neuronal membrane when it is at equilibrium (no net flow of ions in or out). The inside is more negative than the outside, approximately -70 mV
- Ions are always flowing through non-gated leak channels
- **Sodium-potassium pumps** use ATP to pump ions against their gradients, in order to regulate the resting membrane potential



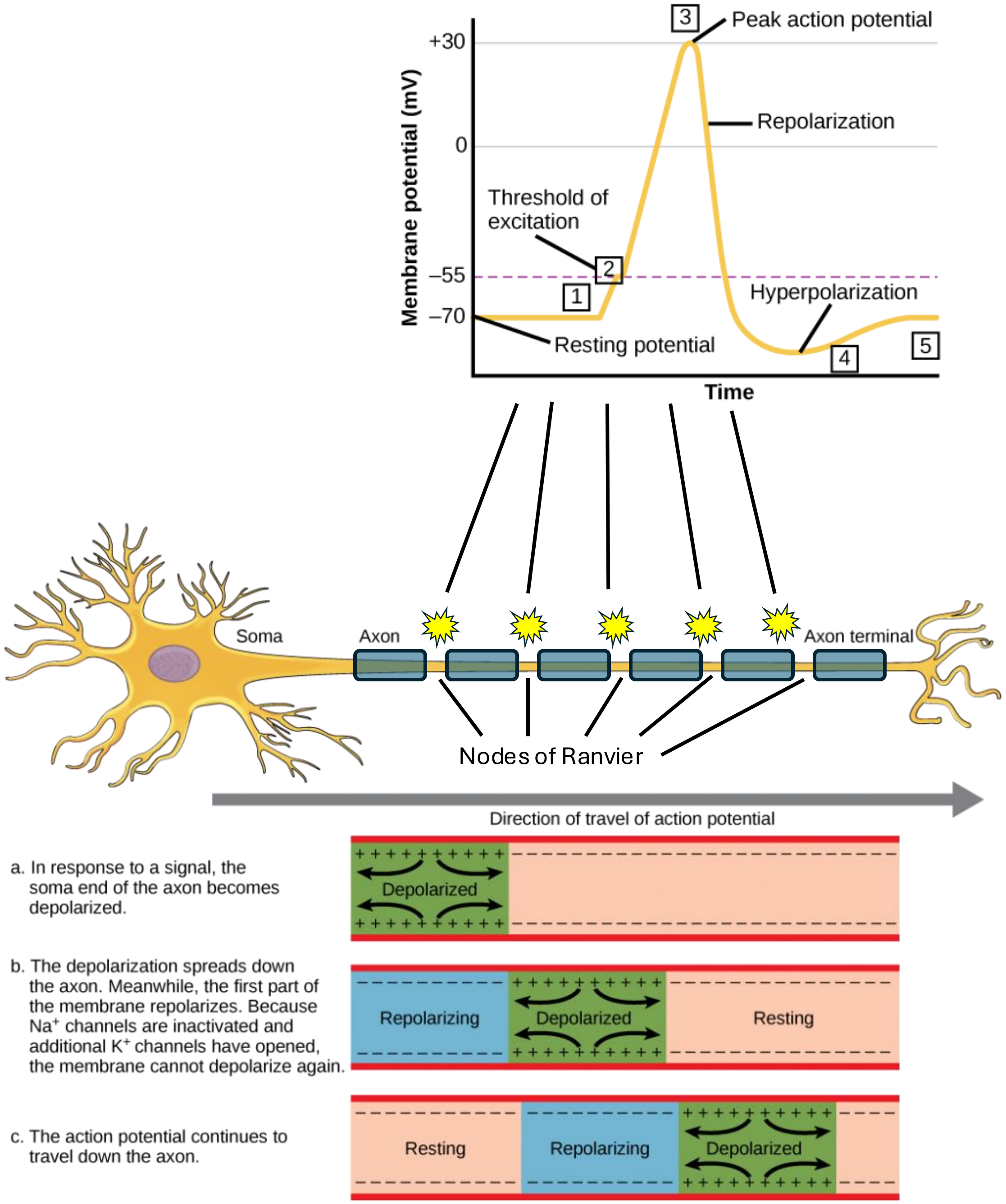


The Action Potential

Happens along the cell membrane of the axon when the neuron fires

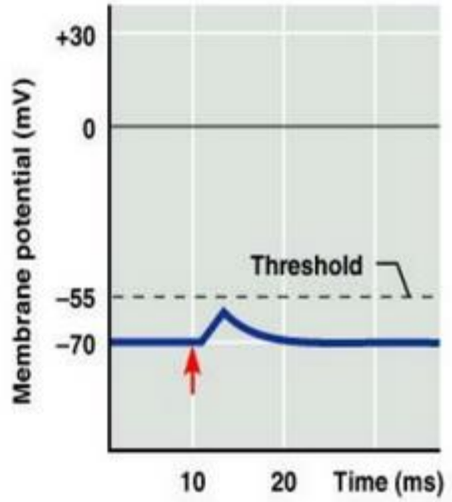
The Action Potential

- The **action potential** – a brief (roughly 3-4 ms) positive spike in the membrane potential that moves down the axon
- Some rules:
    - The neuron either fires or it doesn't
    - Action potential does not lose strength down the axon, regardless of length
    - It propagates only in one direction, towards the terminals; no back-propagation
- In **unmyelinated** axons, the action potential travels smoothly down the axon
- In **myelinated** axons, it jumps to the nodes of Ranvier, allowing the signal to jump down the axon more quickly

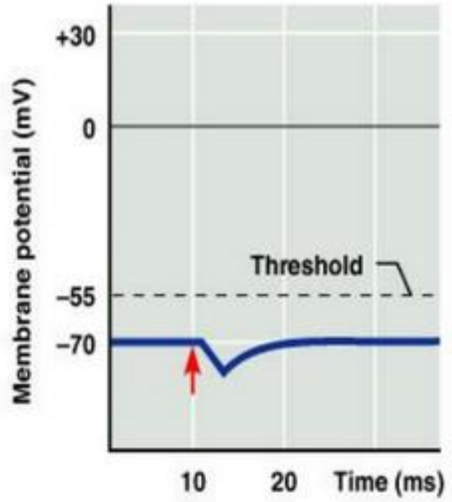


Postsynaptic Potentials

- Changes in membrane potential that move the cell away from its resting state
- **Excitatory** – receiving neuron will be **depolarized**, making it *more likely* to fire
  - Na+ channels open
- **Inhibitory** – receiving neuron will be **hyperpolarized**, making it *less likely* to fire
  - Cl- channels open
- **Summation** of inputs from multiple sources across time and space accumulate to determine whether neuron will fire



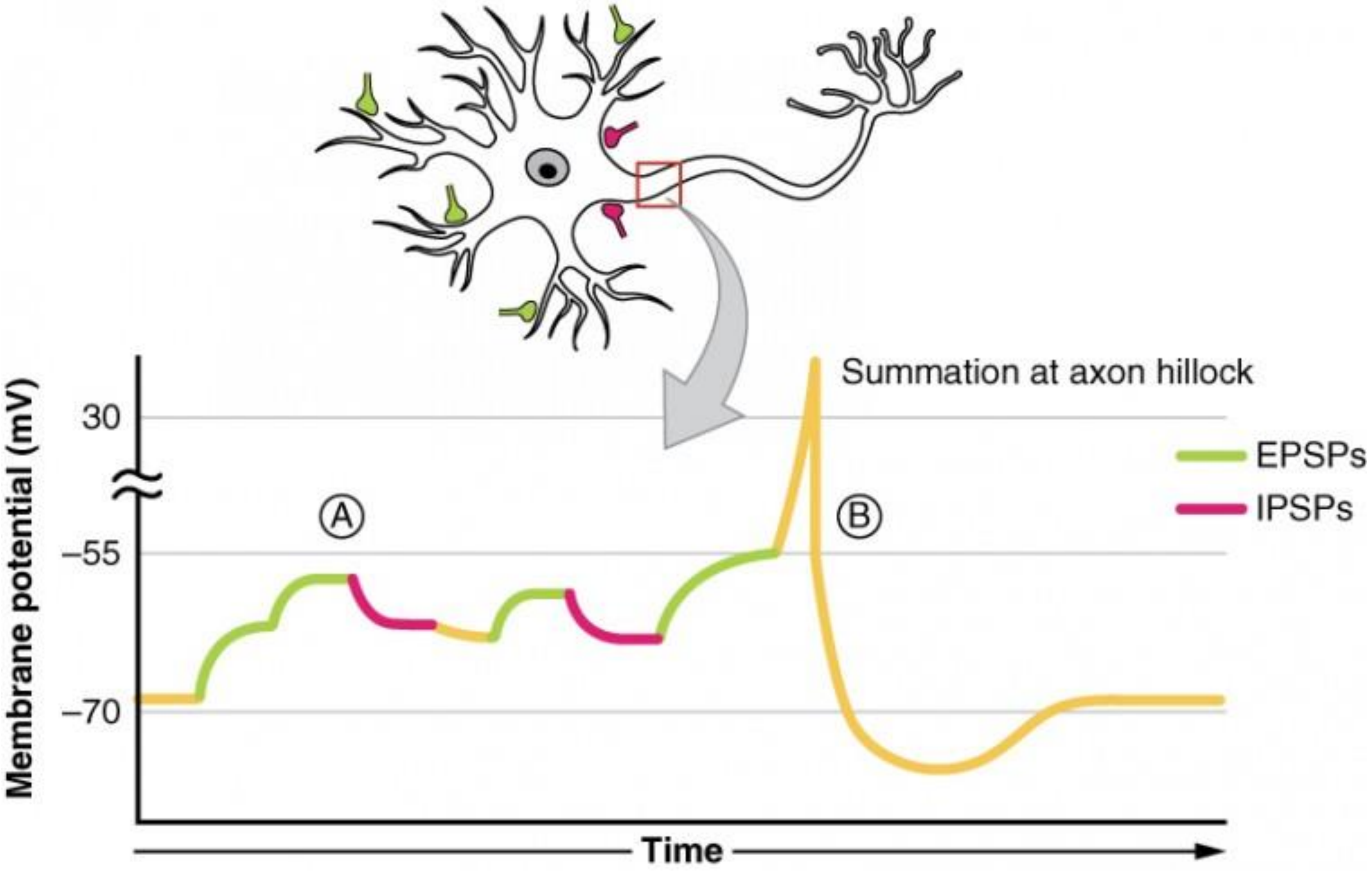
(a) Excitatory postsynaptic potential (EPSP)



(b) Inhibitory postsynaptic potential (IPSP)

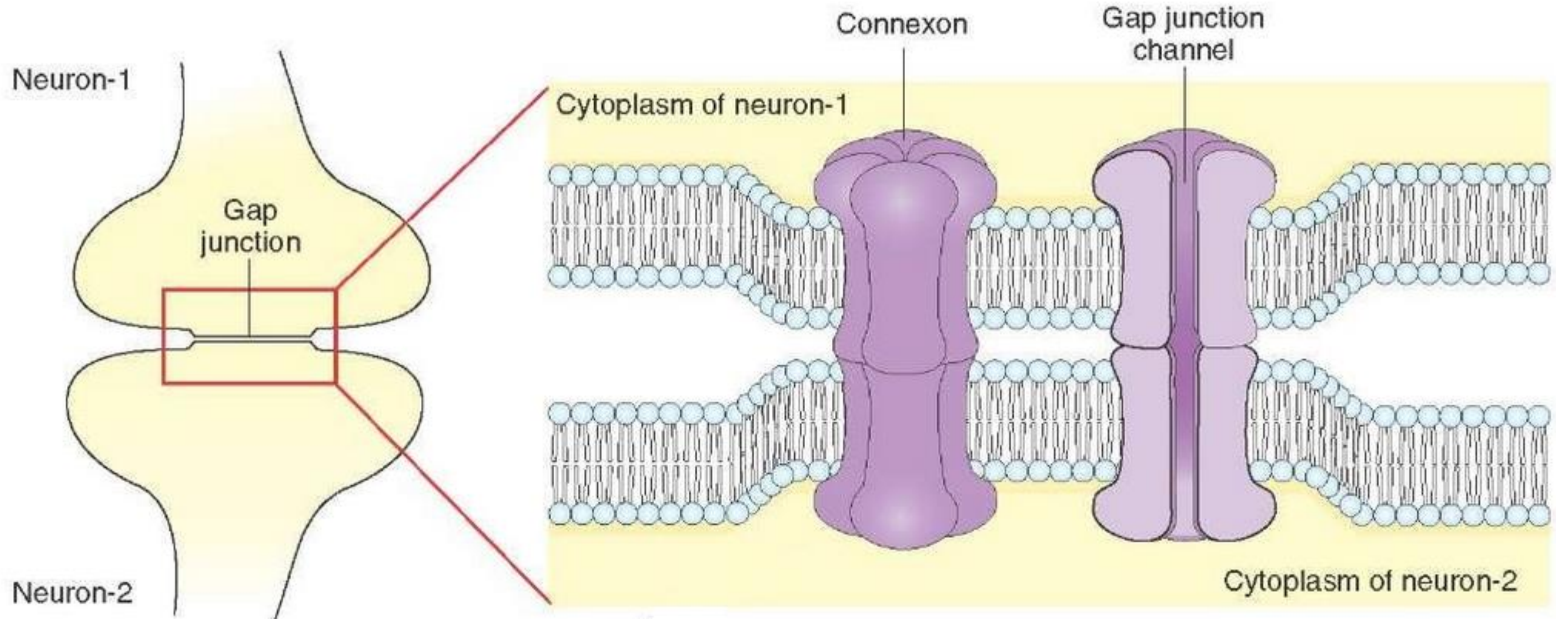
Postsynaptic potentials initiate or inhibit action potentials

- Activity of ion channels changes the membrane potential
- Timing and spatial positioning affects its influence on the action potential
- Ion channels can be affected by: intra- and extra-cellular factors, mechanical stress, temperature change, lipids, oxidative stress, and ligands binding to receptors (neurotransmitters)



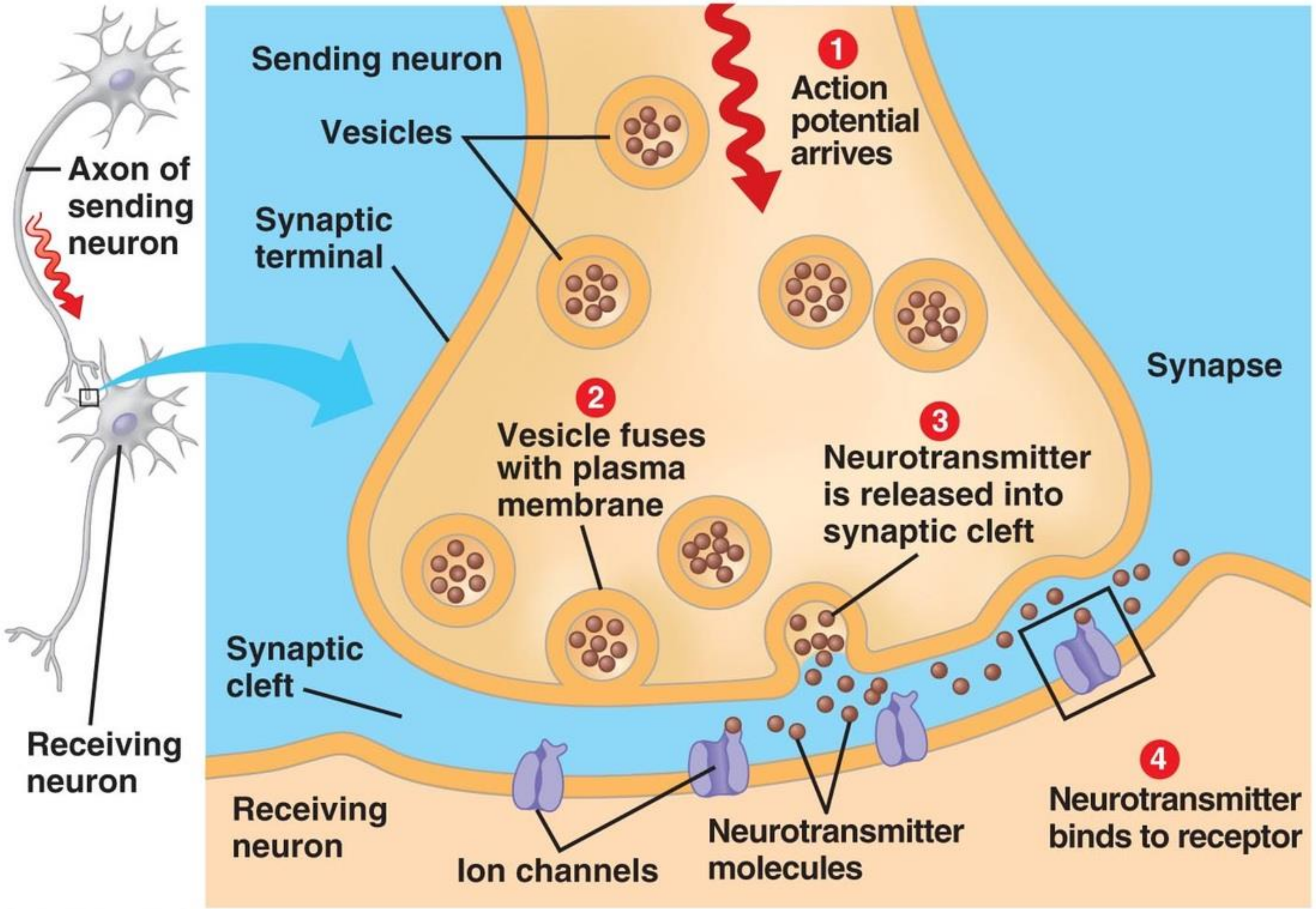
Gap Junctions

- **Gap junctions** allow current to flow between cells using **connexons**, proteins that span across the two cell membranes enabling ions to flow between the two cells
- Faster than chemical synapses, and **bidirectional**, gap junctions can occur anywhere on the membrane of either neuron
- Allows for highly synchronous activity. Seen in:
  - Smooth cardiac muscle or reflexes
  - Brain regions like hippocampus where coherent oscillations are important
  - Areas where local processing is important – **dendritic trees** can exchange and process information before action potentials even occur!



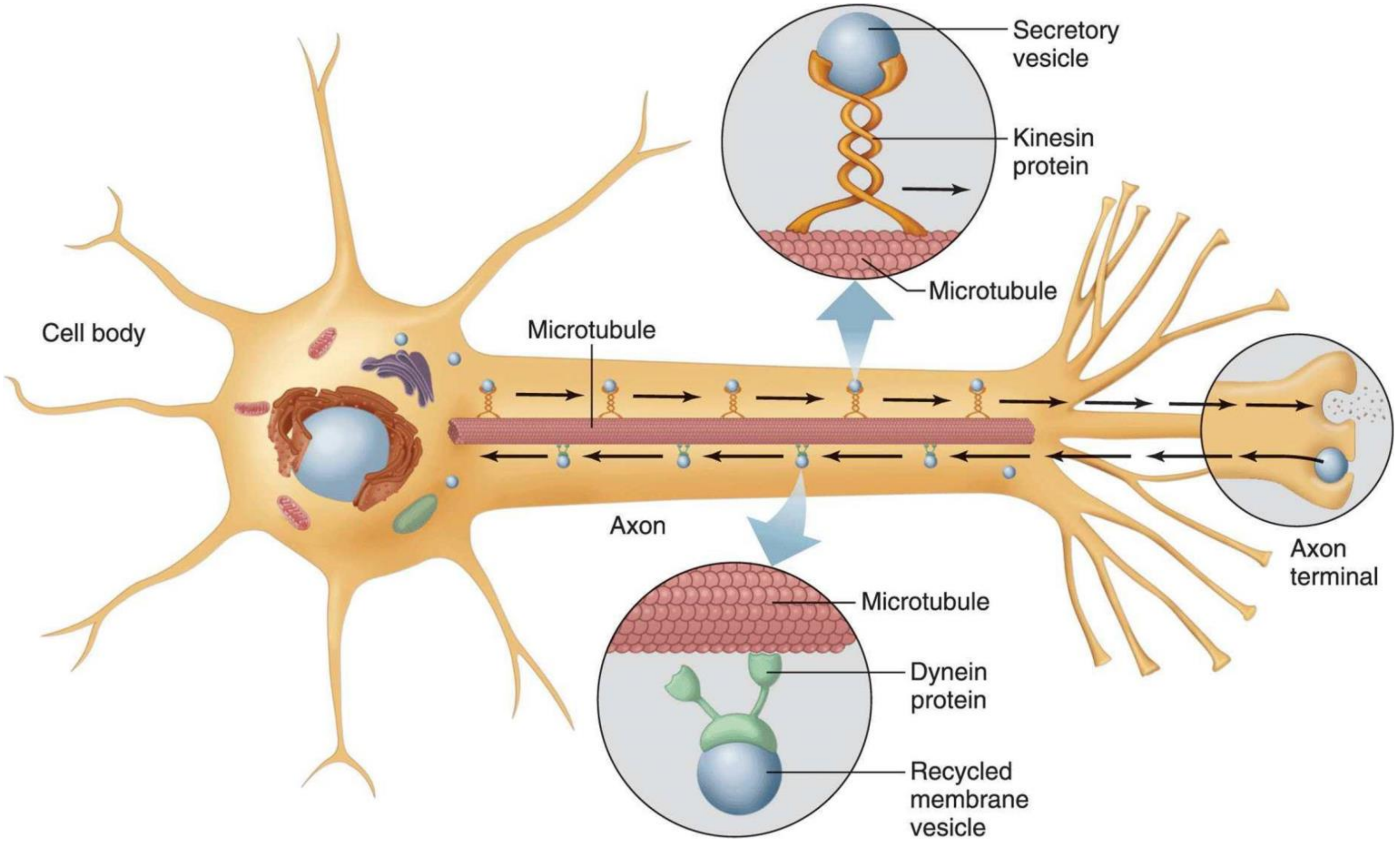
Chemical Synaptic Transmission

- **Synapse** – the gap connecting the **axon terminal** of one neuron to the **dendrite** of another, where the signal is transmitted across cells
- **Neurotransmitter** – a chemical messenger that used to transmit across a **synaptic cleft**
- The neurotransmitter binds to the **receptor** on the receiving cell, causing it to open or close an ion channel, thus changing the postsynaptic potential. The effect can be:
- After binding, the neurotransmitter has three possible destinations:
  - **Reuptake** back into the presynaptic terminal
  - **Enzymatic breakdown** in the synaptic cleft
  - **Diffusion** away from the synapse



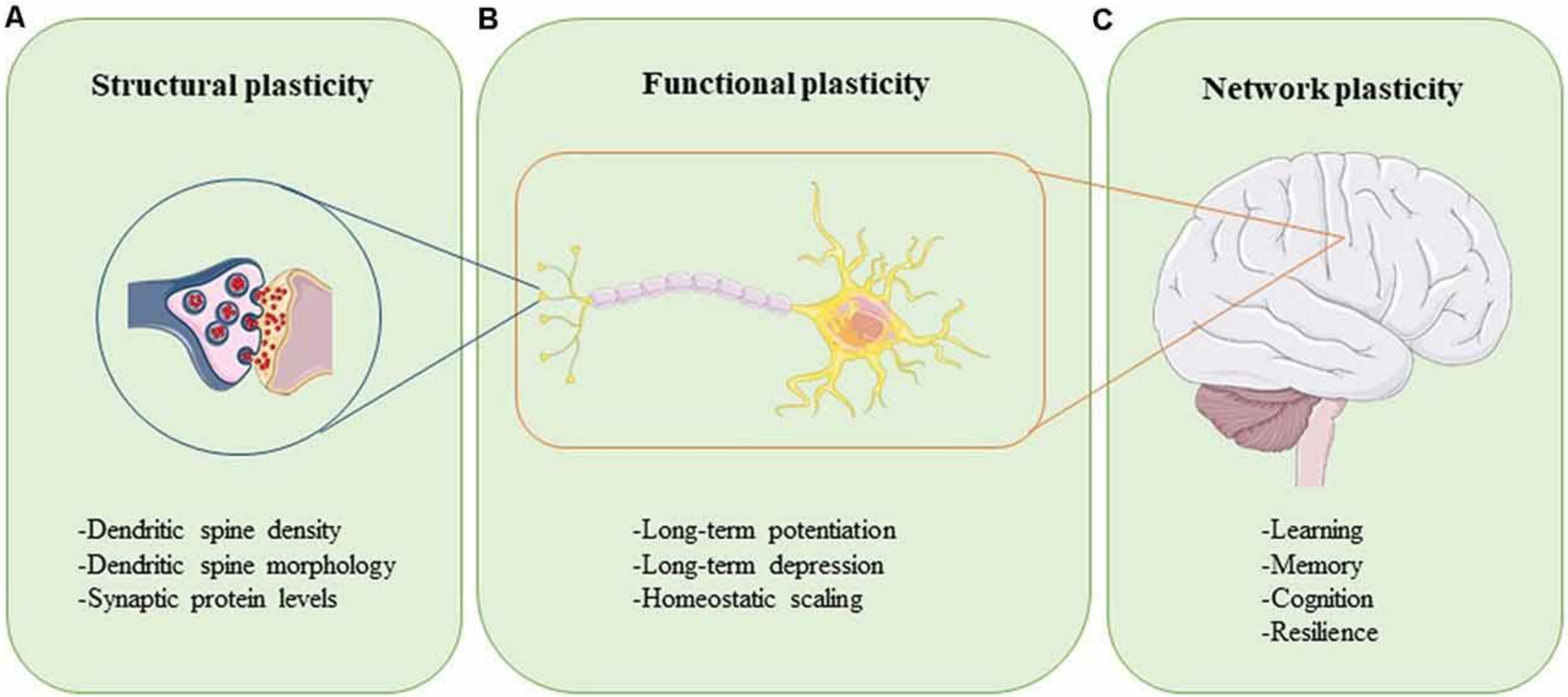
Quantum?

- Quantum coherence effects have been reported in microtubules and myelin
  - Coherent light – like a laser
- Microtubules support the architecture of axons and dendrites
- This may be the basis for deeper levels of cognition inside the cell, and for consciousness



Neuroplasticity

- The brain's ability to reorganize itself by changing its neural connections throughout the lifespan
- This is how the brain learns and remembers, changing in response to new experiences, injury, age, repetition, or medical treatment
- Neurons that fire together, wire together – use it or lose it!



Neurotransmitter	Effect	CNS Functions	PNS Functions
Acetylcholine	Excitatory	Attention, memory, learning, synaptic plasticity	Muscle activation, PNS regulation
Norepinephrine	Excitatory	Arousal, alertness reset, focus, mood regulation	Fight-or-flight response, increases heart rate and blood pressure
Epinephrine	Excitatory	Limited CNS role, arousal and fight-or-flight, emotional memory formation	Fight-or-flight response, increases heart rate, blood flow to muscles
Serotonin	Inhibitory	Mood regulation, appetite, sleep, anxiety, social rank	Regulation of gut motility and function
Glutamate	Excitatory	Learning, memory, synaptic plasticity, synaptic pruning	Limited PNS role, pain transmission, gut motility and function
Gamma-aminobutyric acid (GABA)	Inhibitory	Main inhibitory neurotransmitter in the CNS, reducing neuronal excitability	Limited PNS role, gut motility and secretion, immune modulation, muscle tone
Dopamine	Both	Reward, motivation, motor control, reinforcement learning, prediction error	Blood vessel function modulation, kidney function, and norepinephrine precursor
Histamine	Excitatory	Regulation of sleep-wake cycles, arousal, and alertness, food intake	Immune response regulation, allergic reactions
Melatonin	Modulatory	Regulation of sleep-wake cycle (circadian rhythm) and seasonal rhythms	Limited PNS role, antioxidant, anti-inflammatory agent, gut motility
Endorphin	Inhibitory	Natural painkiller, involved in pleasure and well-being, “runner’s high” euphoria	Limited PNS role, pain modulation, immune response
Oxytocin	Modulatory	Social bonding, sexual reproduction, childbirth, in-group favoritism	Uterine contractions during childbirth, milk ejection during breastfeeding
Vasopressin	Modulatory	Social behavior, sexual motivation, pair bonding, territorial behavior	Water retention in kidneys, regulation of blood pressure, vasoconstriction

ADRENALINE for Fight or Flight	Also known as 'epinephrine', releases in response to stress. It increases heart rate, blood pressure, glucose metabolism to boost physical reflexes.
NORADRENALINE for Attention & Focus	Also known as 'norepinephrine', affects brain activity, contracts blood vessels, controls blood flow, regulates heartbeat and liver function.
ENDORPHIN for Pain Management	Releases during exercise, excitement, and sex. Produces the feeling of well-being, euphoria, and involved in pain management.
ACETYLCHOLINE for Memory & Learning	Linked with thought, learning, and memory. Stimulates muscle function, contractions of the digestive tract. Involved with focus and alertness.
HISTAMINE for Immune Protection	Controls vasodilation, inflammation, and immune response. Regulates metabolism, body temperature, hormone function, and sleep-wake cycle.
DOPAMINE for Repeat Behavior	Provides pleasure and motivation, motor control and movement. Responsible for any repeat behavior such as addiction.
GABA for Motor Control	High levels improve focus and low levels cause anxiety. Calms the firing nerves and contributes to motor control and vision.
SEROTONIN for Calming & Sleep	Helps in sleep, memory, mood, and relaxation. Affected by exercise and light exposure. Also released in the digestive tract and regulates appetite.