

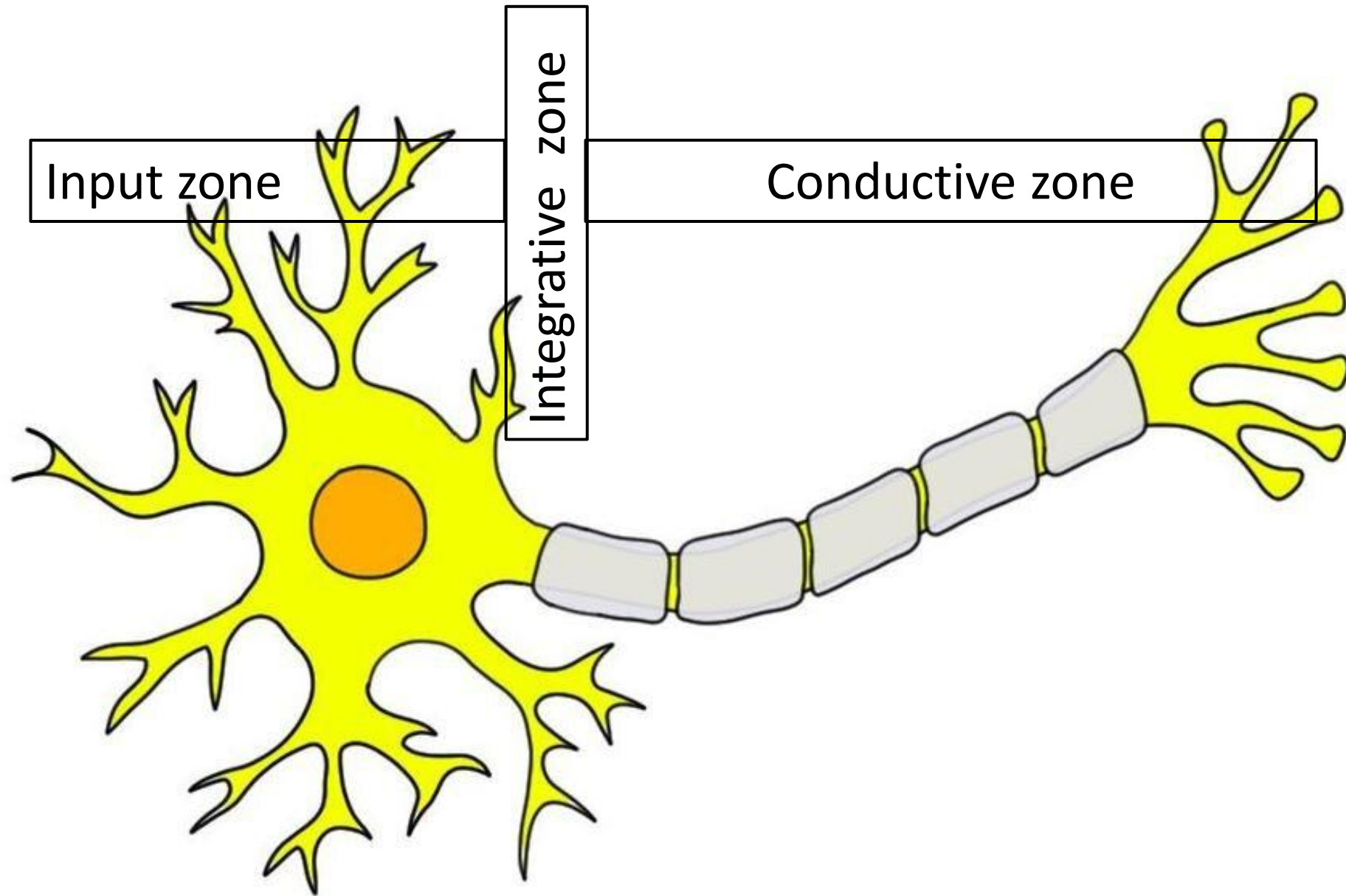
# Introduction to Neurophysiology 4

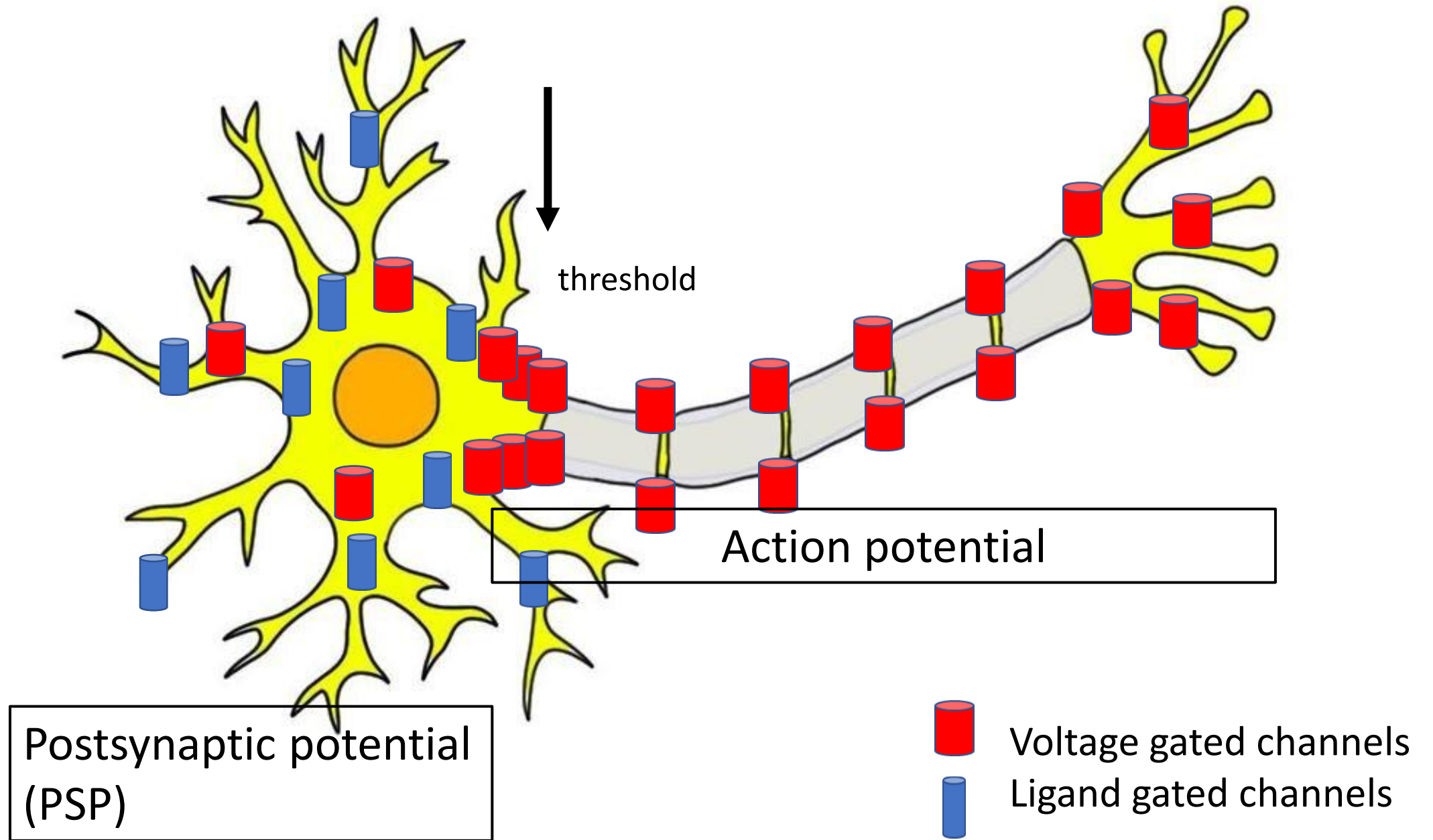
## Neural circuits

Fatima Ryalat, MD, PhD

Assistant Professor, Physiology and Biochemistry Department,  
School of Medicine, The University of Jordan

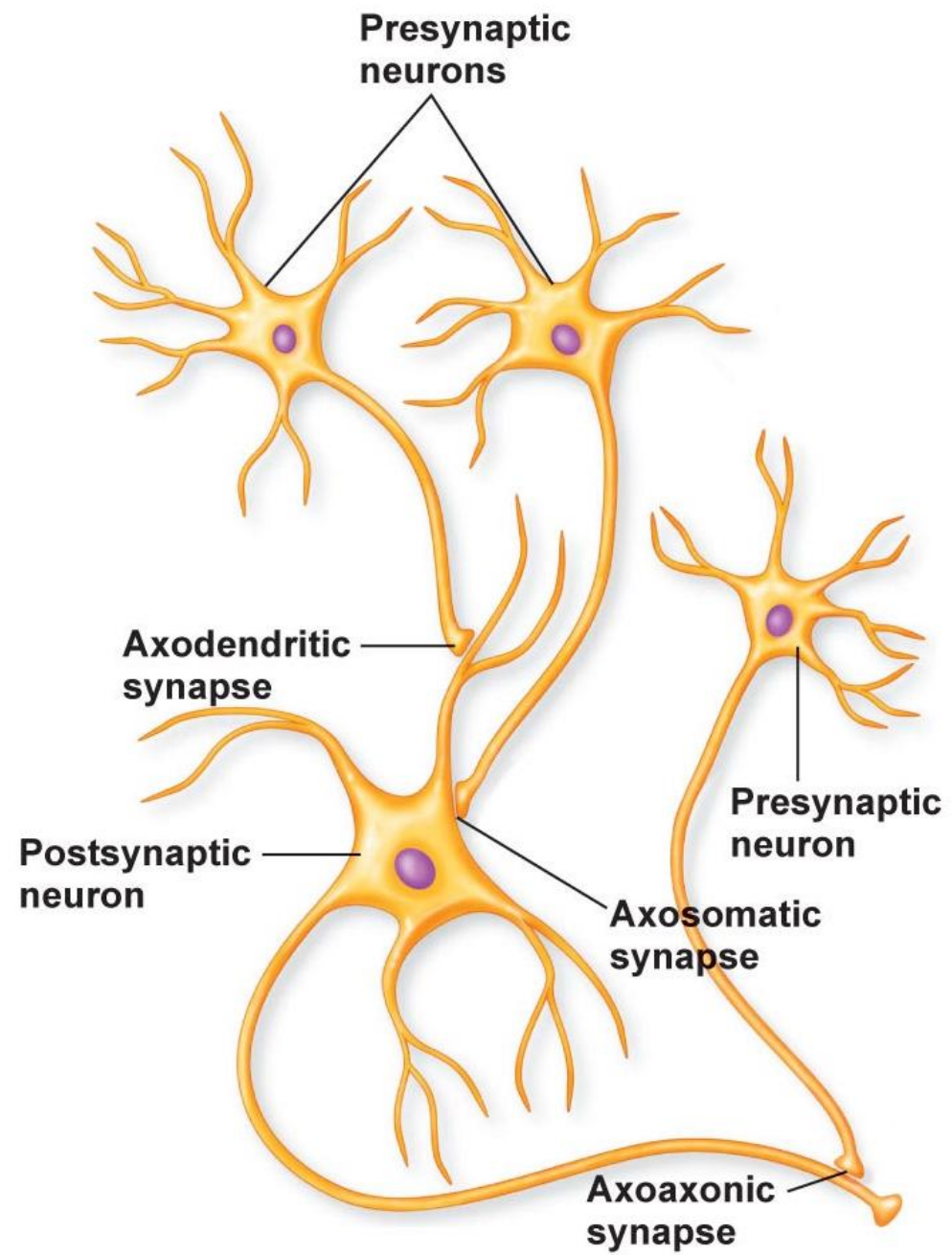






# Signal Transmission in Neurons

- **Synaptic Transmission:** Chemical synapses are unidirectional (from presynaptic to postsynaptic). Signals arrive via dendrites, soma, or axon and propagate to axon terminals.
- **Postsynaptic Potentials (PSPs):** Can be excitatory (EPSP) or inhibitory (IPSP) and are graded potentials, not action potentials.
- **Action Potential Generation:** Occurs at the **axon hillock** (integrative zone) due to a high density of **voltage-gated Na<sup>+</sup> channels**, unlike dendrites and soma that mainly have **ligand-gated channels**.
- **Saltatory Conduction:** Myelinated axons conduct signals faster due to jumping from one node to another.



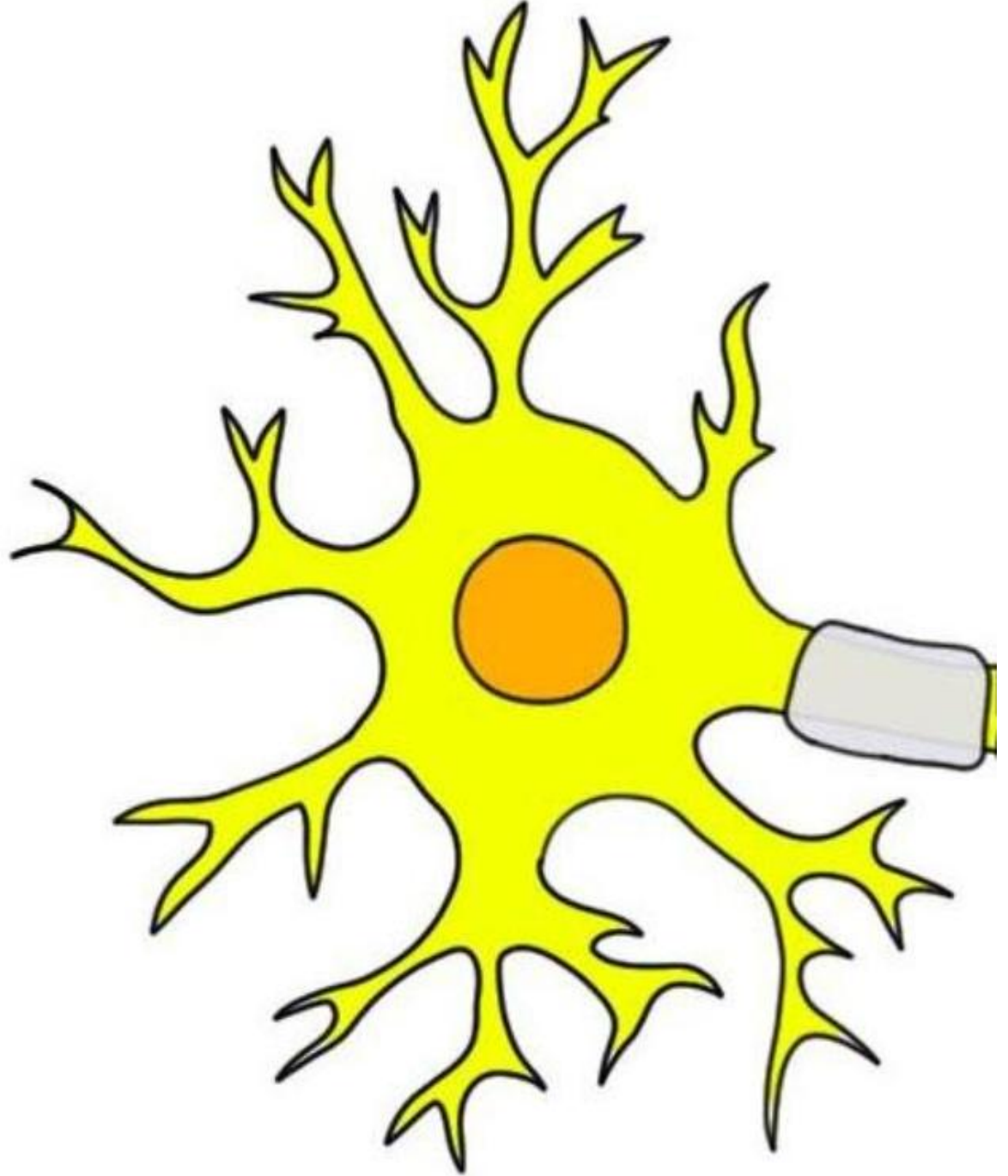
# Synapse Types

- **Axodendritic:** Most common; synapse on dendrites.
- **Axosomatic:** Synapse on the soma.
- **Axoaxonal:** Synapse on the axon of another neuron.

## **Dendrites:**

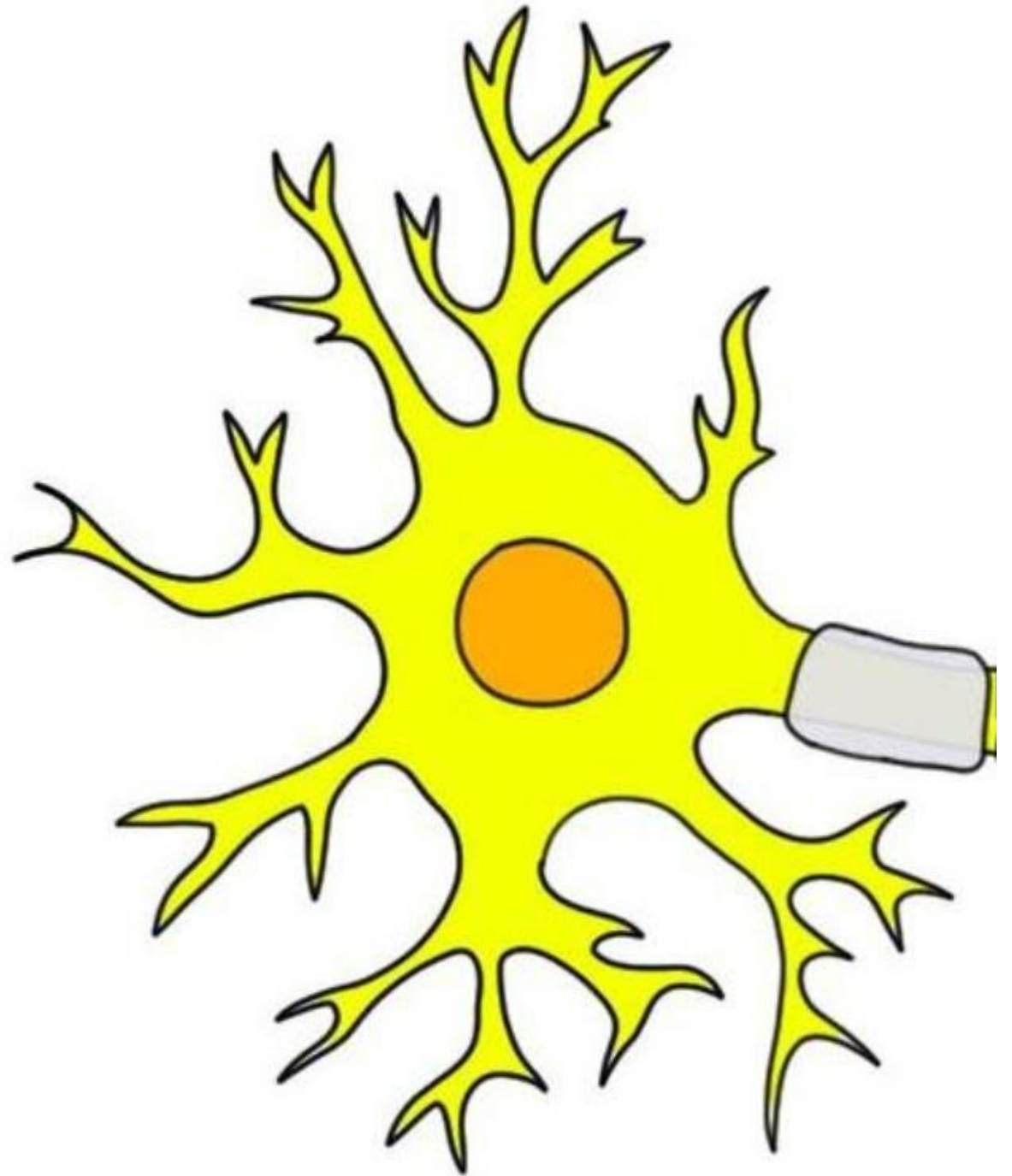
Large spatial field of excitation.

A great opportunity for summation of signals from many neurons.





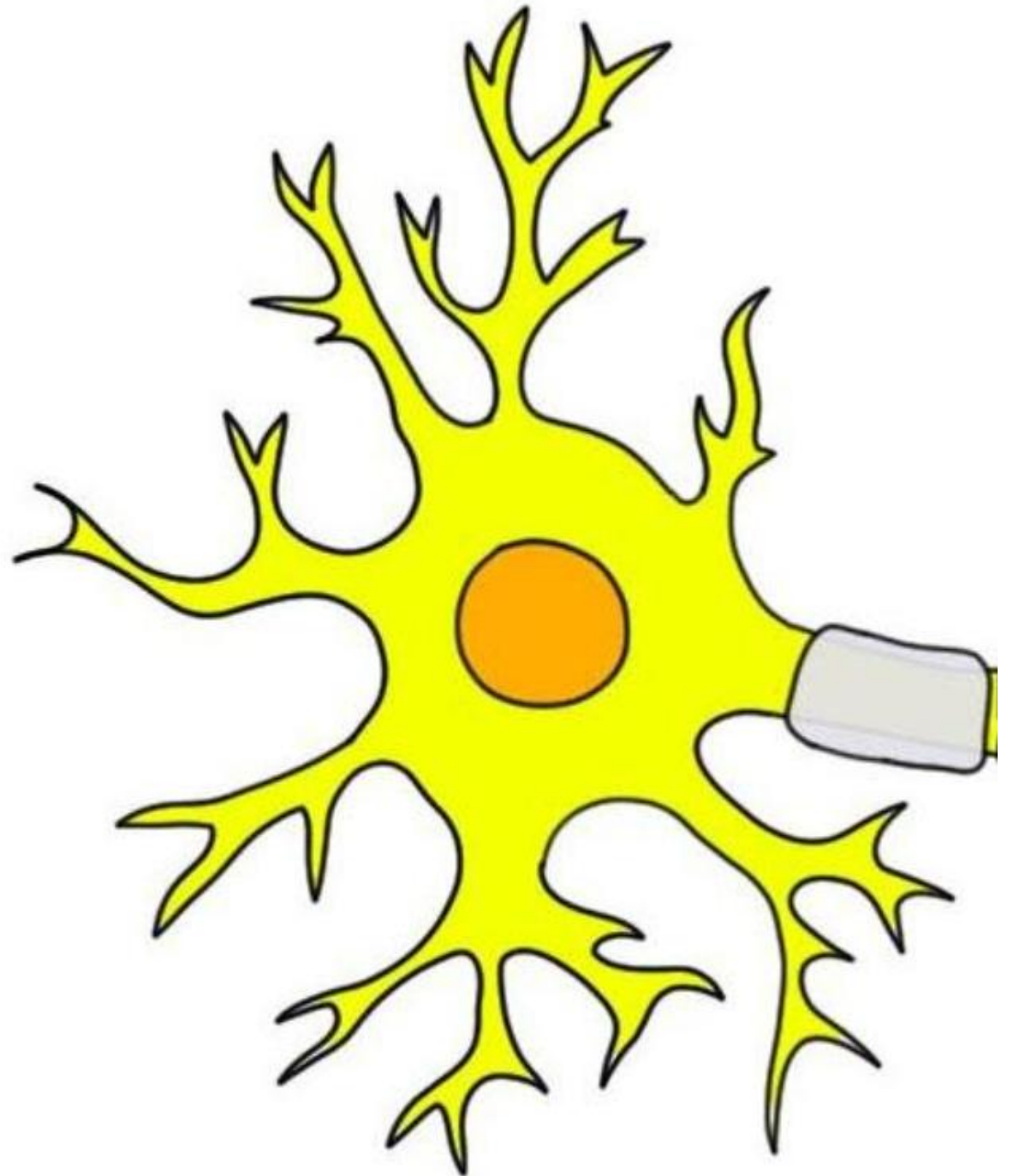
Most dendrites fail to transmit action potentials because their membranes have relatively few voltage-gated sodium channels, and their thresholds for excitation are too high for action potentials to occur.





## **Decremental conduction**

The synapses that lie near the soma have far more effect in causing neuron excitation or inhibition than those that lie far away from the soma.



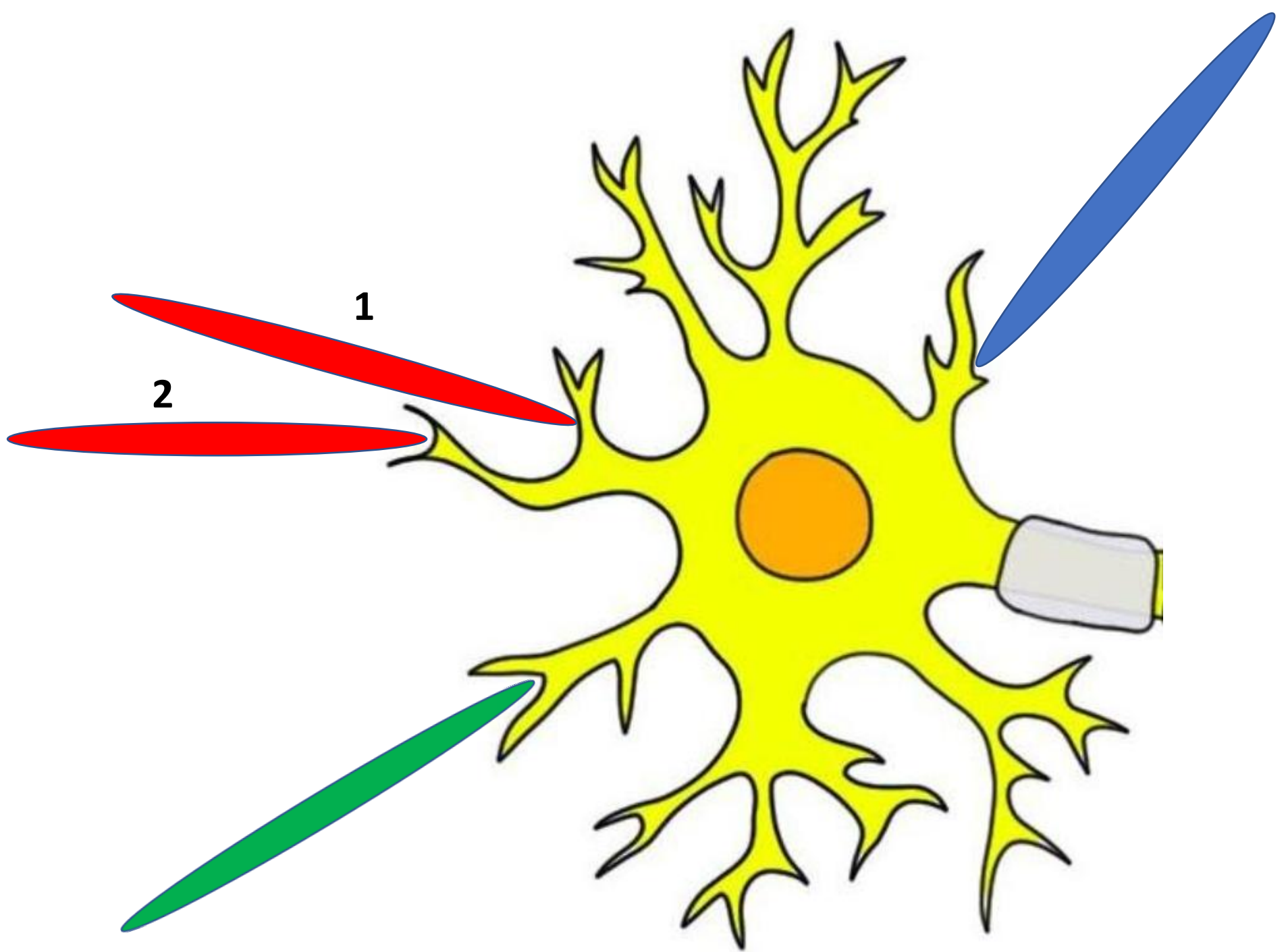
# Action potential in the axon

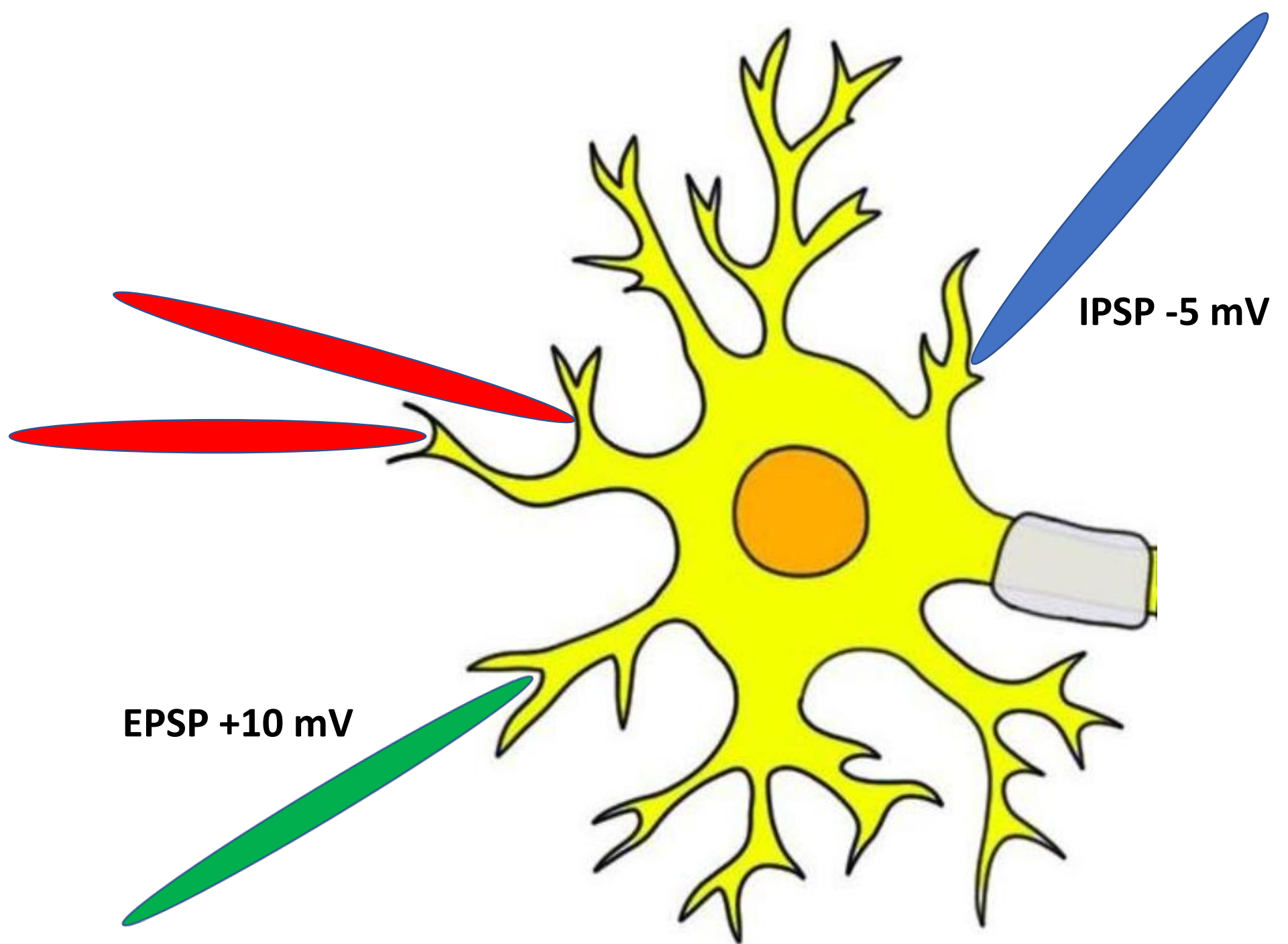
Action potential does not begin adjacent to the excitatory synapses. Instead, it begins in the initial segment of the axon.

The main reason is that the soma has relatively few voltage gated sodium channels in its membrane, which makes it difficult for the EPSP to open the required number of sodium channels to elicit an action potential.

# Action potential in the axon

- The membrane of the initial segment of the axon has 7 times as great a concentration of voltage-gated  $\text{Na}^+$  channels as does the soma and, therefore, can generate an action potential with much greater ease than can the soma.
- The threshold is lower in the axon initial segment than the soma.





# Examples of Summation

- EPSP +10 mV + IPSP -5 mV = Net +5 mV → Not enough for AP.
- Multiple excitatory inputs needed to reach threshold.
- One EPSP alone (e.g. +10 mV) is usually insufficient.



# Excitatory postsynaptic potential (EPSP)

- This positive increase in voltage above the normal resting neuronal potential— that is, to a less negative value—is called the excitatory postsynaptic potential (or **EPSP**), because if this potential rises high enough in the positive direction, it will elicit an action potential in the postsynaptic neuron, thus exciting it.
- EPSP is +20 millivolts means 20 millivolts more positive than the resting value.

# Inhibitory postsynaptic potential (IPSP)

- Opening potassium or chloride channels.
- An increase in negativity beyond the normal resting membrane potential level is called an inhibitory postsynaptic potential (IPSP).
- IPSP is -20 millivolts means 20 millivolts more negative than the resting value.

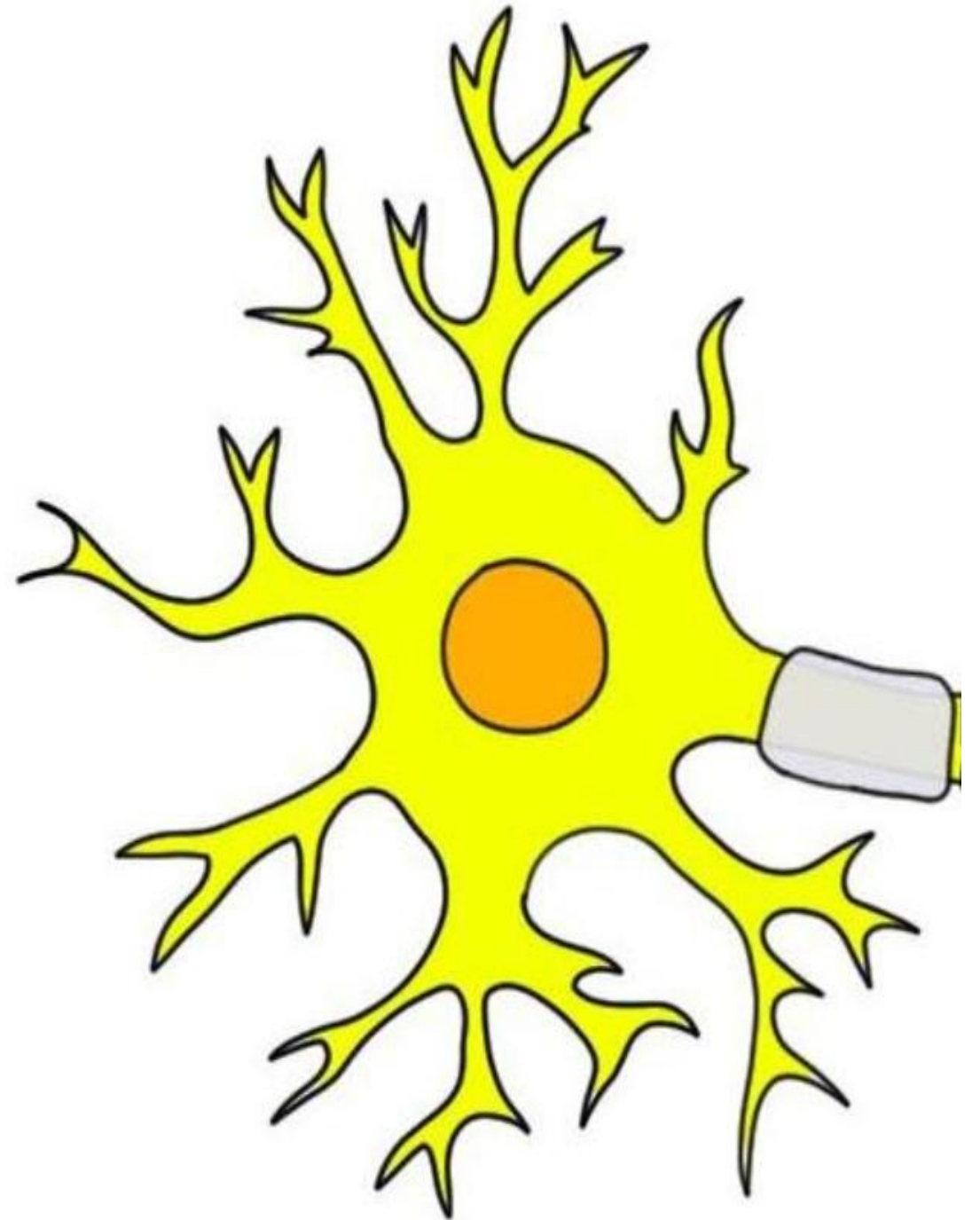
## **Soma:**

uniform distribution of electrical potential:

Large diameter (less resistance to conductance).

Highly conductive electrolytic fluid.

(change in membrane potential will be transmitted equally to all parts of the soma.)

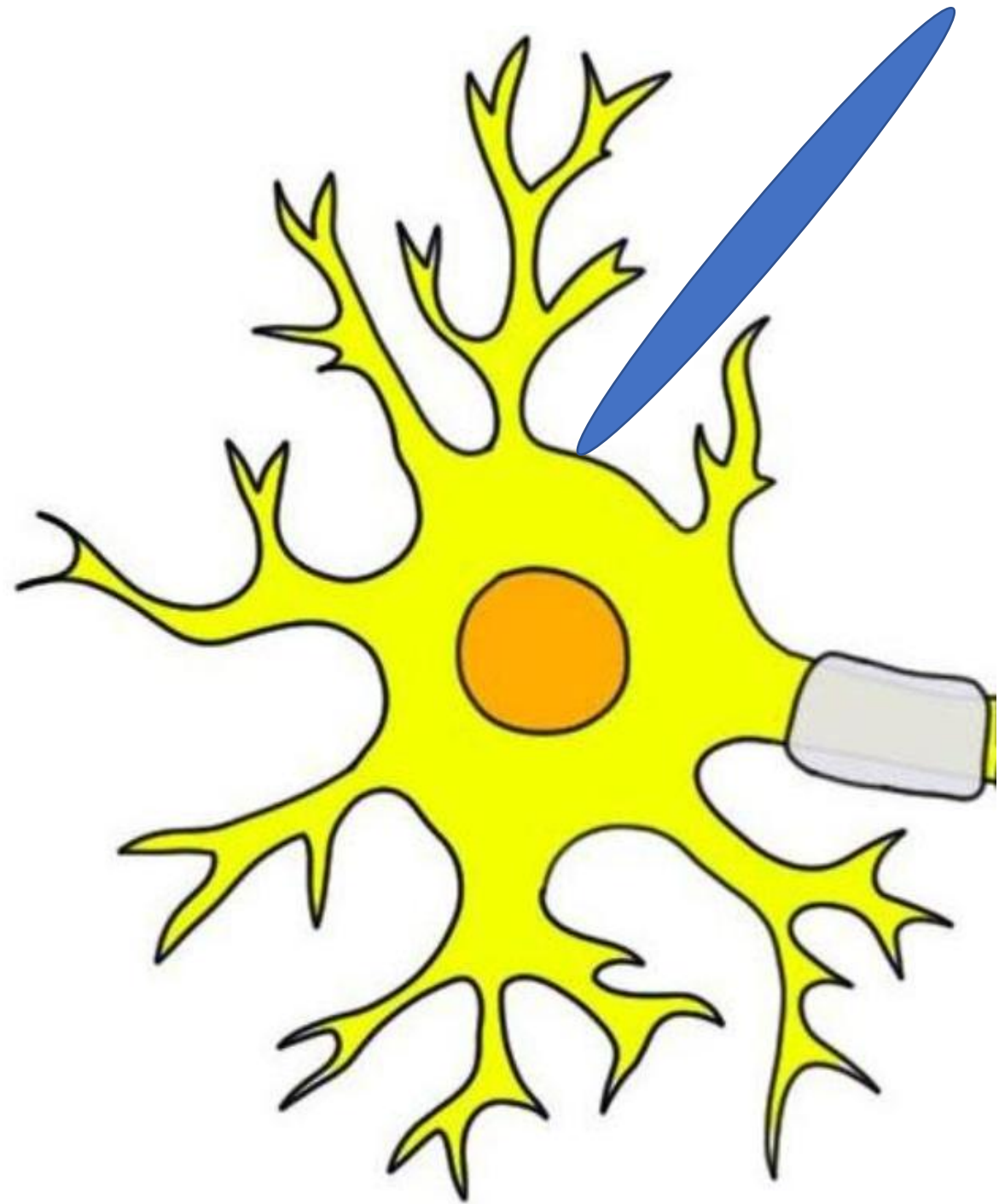


# Resting membrane potential of neuronal soma

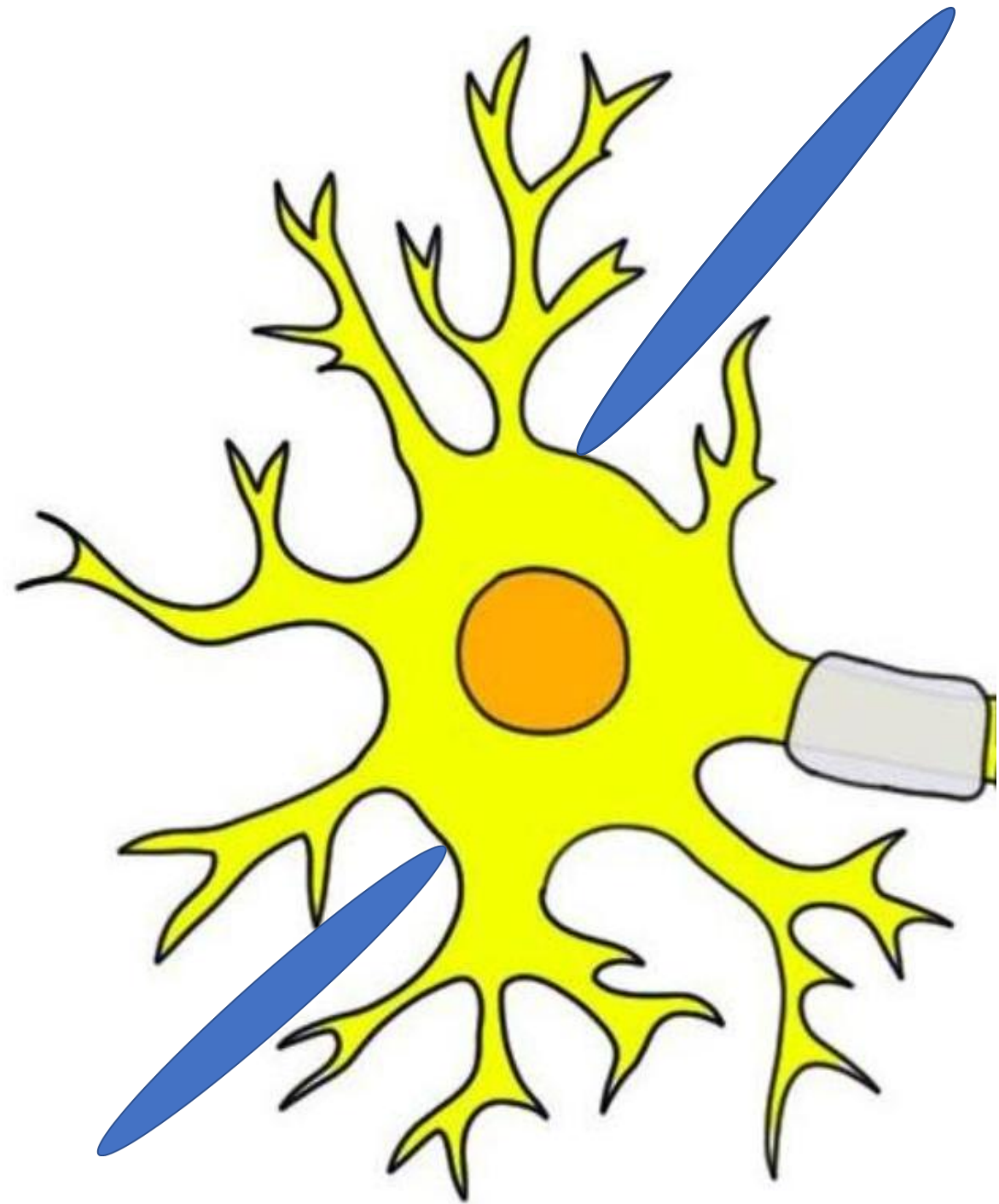
- Any change in potential in any part of the intra-somal fluid causes an almost exactly equal change in potential at all other points inside the soma.
- This principle is important because it plays a major role in “summation” of signals entering the neuron from multiple sources.

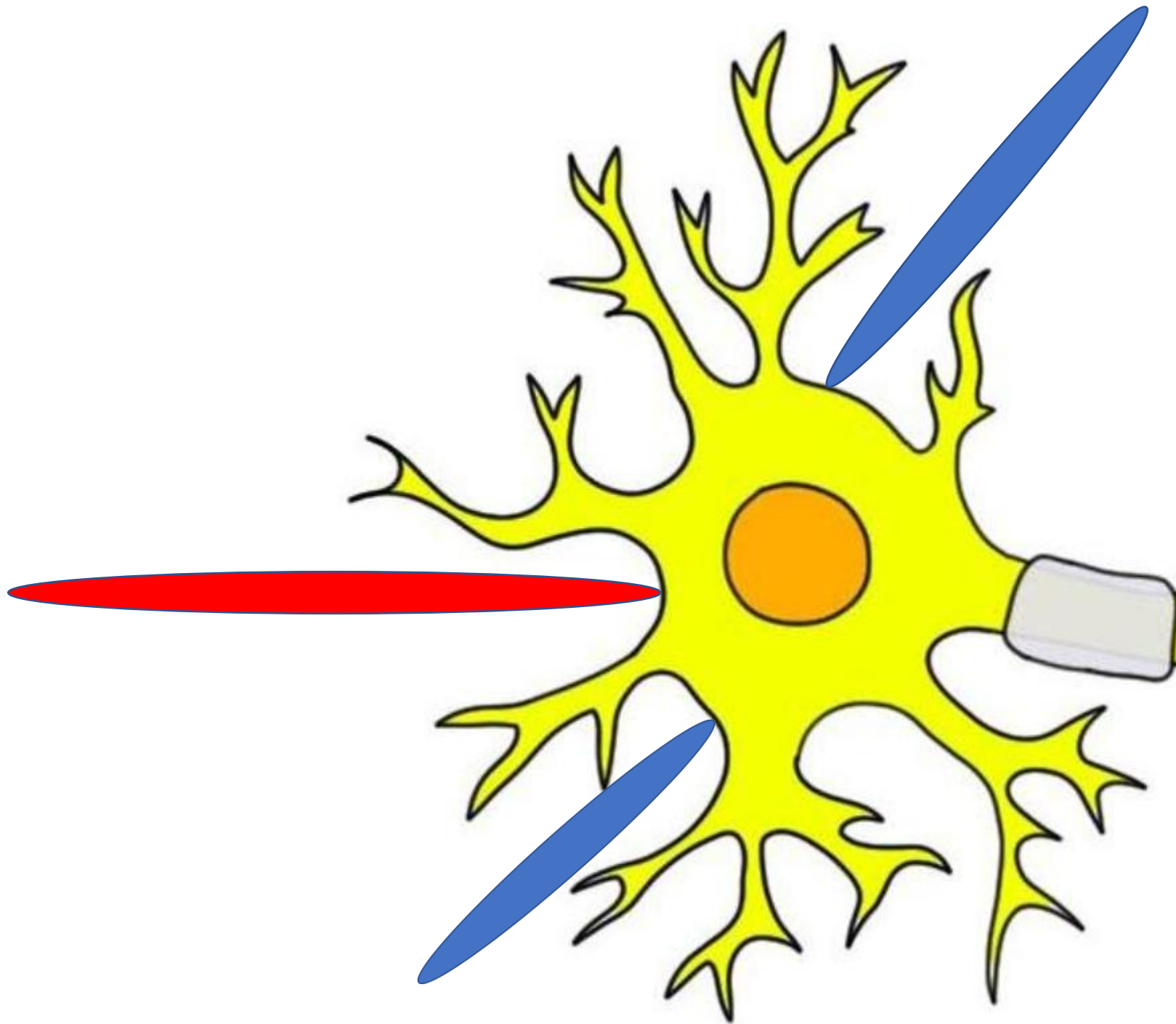
# Summation in neurons

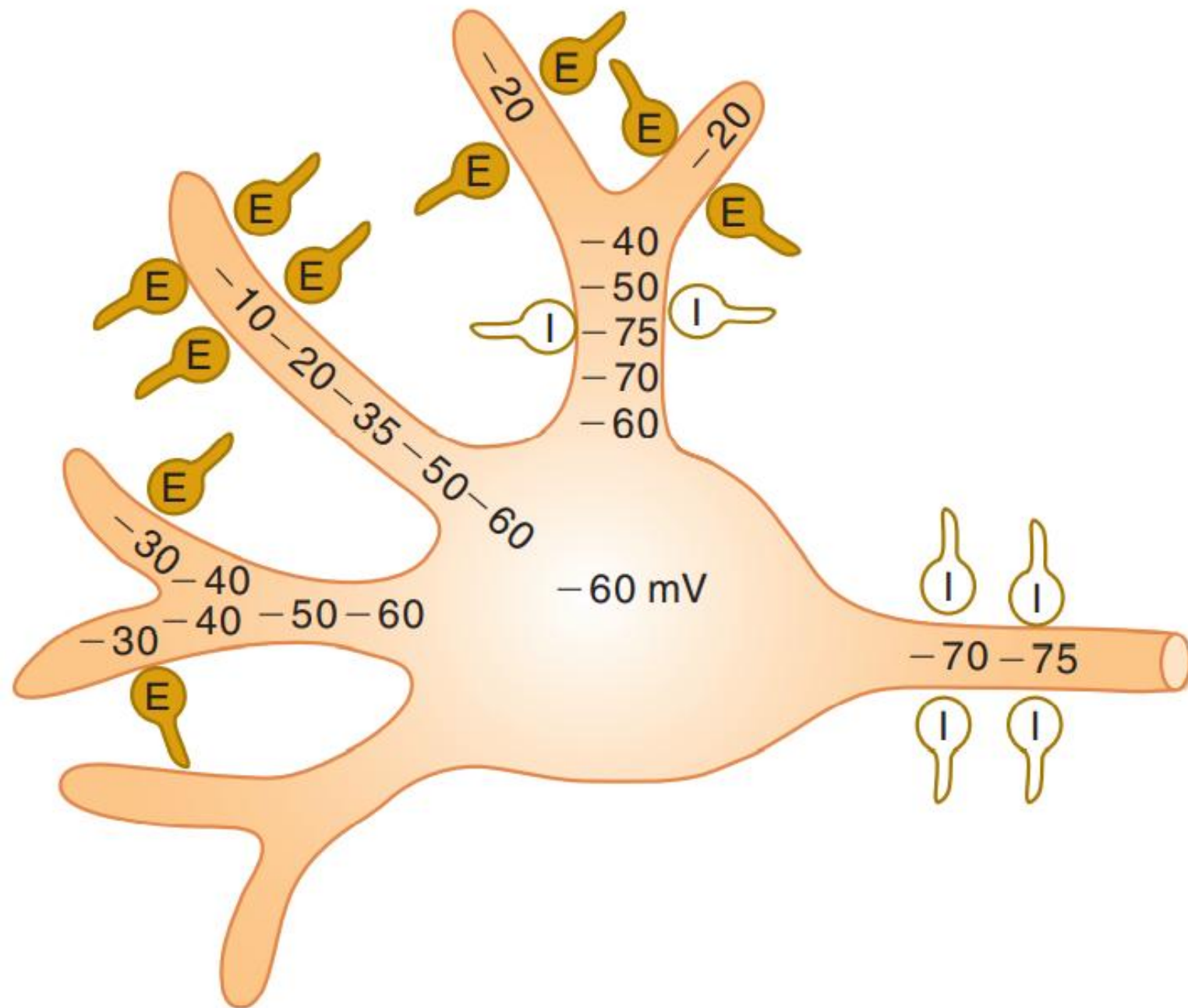
- Excitation of a single presynaptic terminal on the surface of a neuron almost never excites the neuron.
- The reason is that the amount of transmitter substance released by a single terminal to cause an EPSP is usually no greater than 0.5 to 1 millivolt, instead of the 10 to 20 millivolts normally required to reach threshold for excitation.











# Presynaptic inhibition

- In addition to inhibition caused by inhibitory synapses operating at the neuronal membrane, which is called **postsynaptic inhibition**.
- **Presynaptic inhibition** is caused by release of an inhibitory substance onto the outsides of the presynaptic nerve fibrils before their own endings terminate on the postsynaptic neuron.
- In most instances, the inhibitory transmitter substance is GABA.
- This release has a specific effect of opening anion channels, allowing large numbers of Cl<sup>-</sup> ions to diffuse into the terminal fibril.

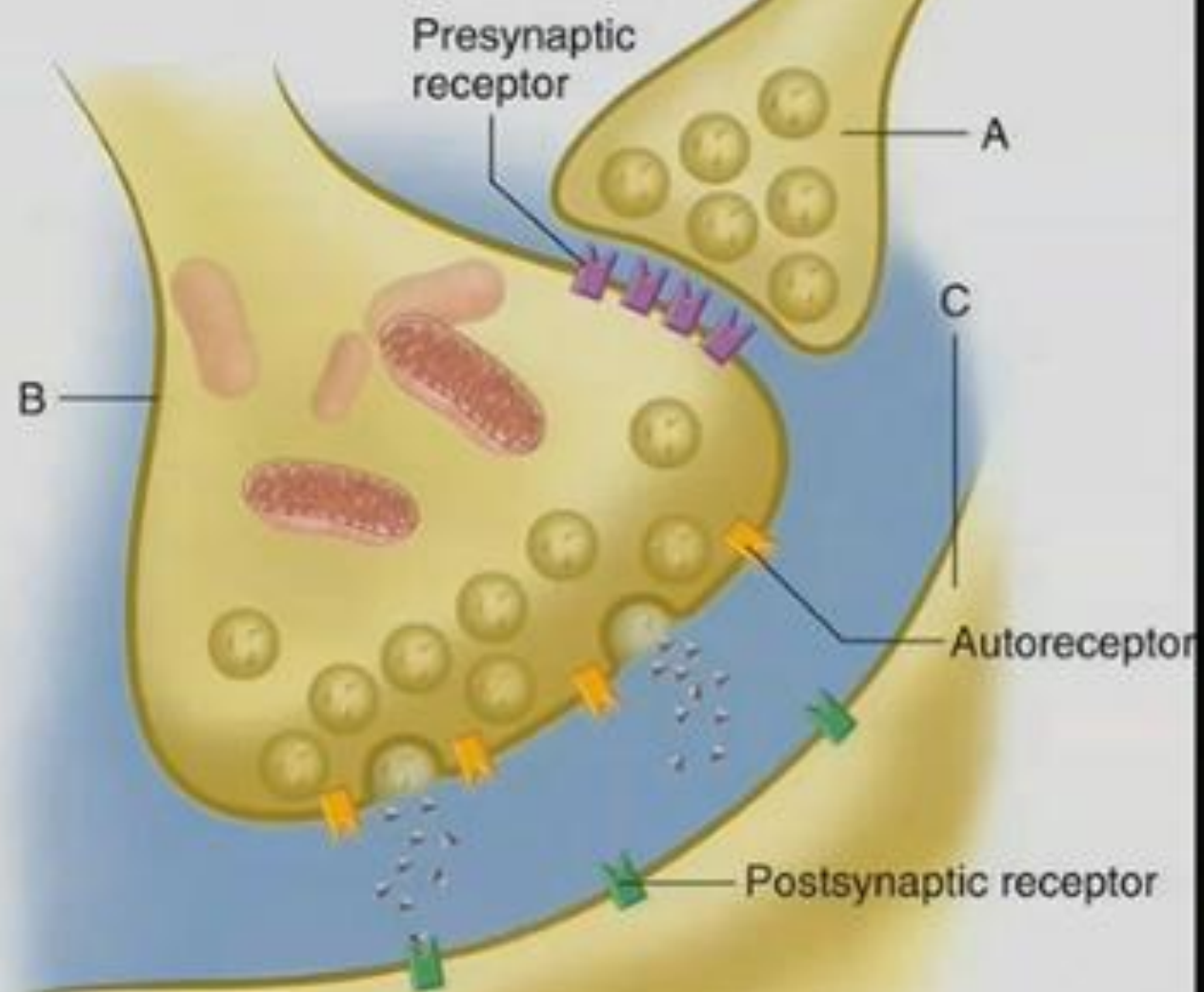


Fig. 6.33V

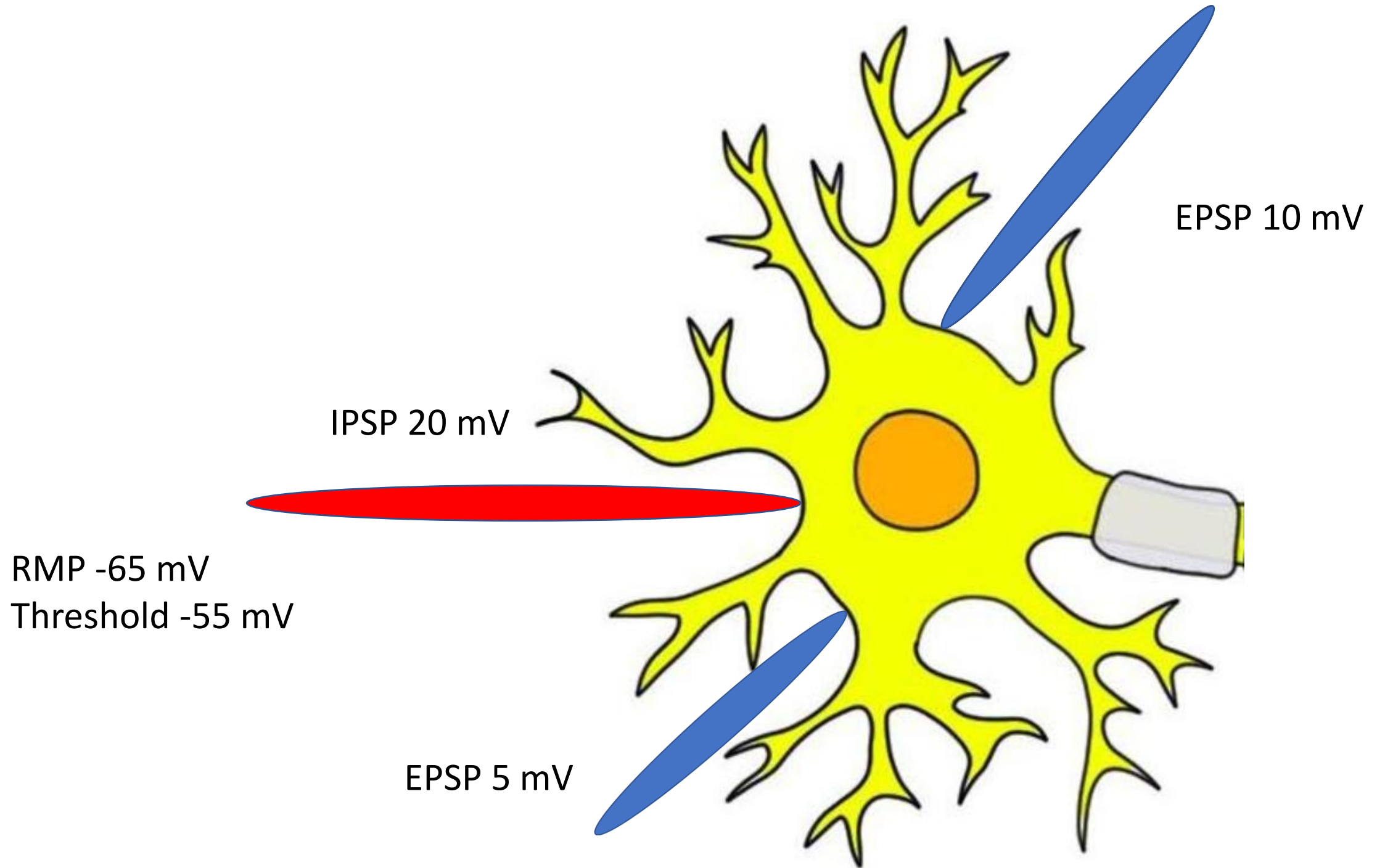
# Presynaptic inhibition

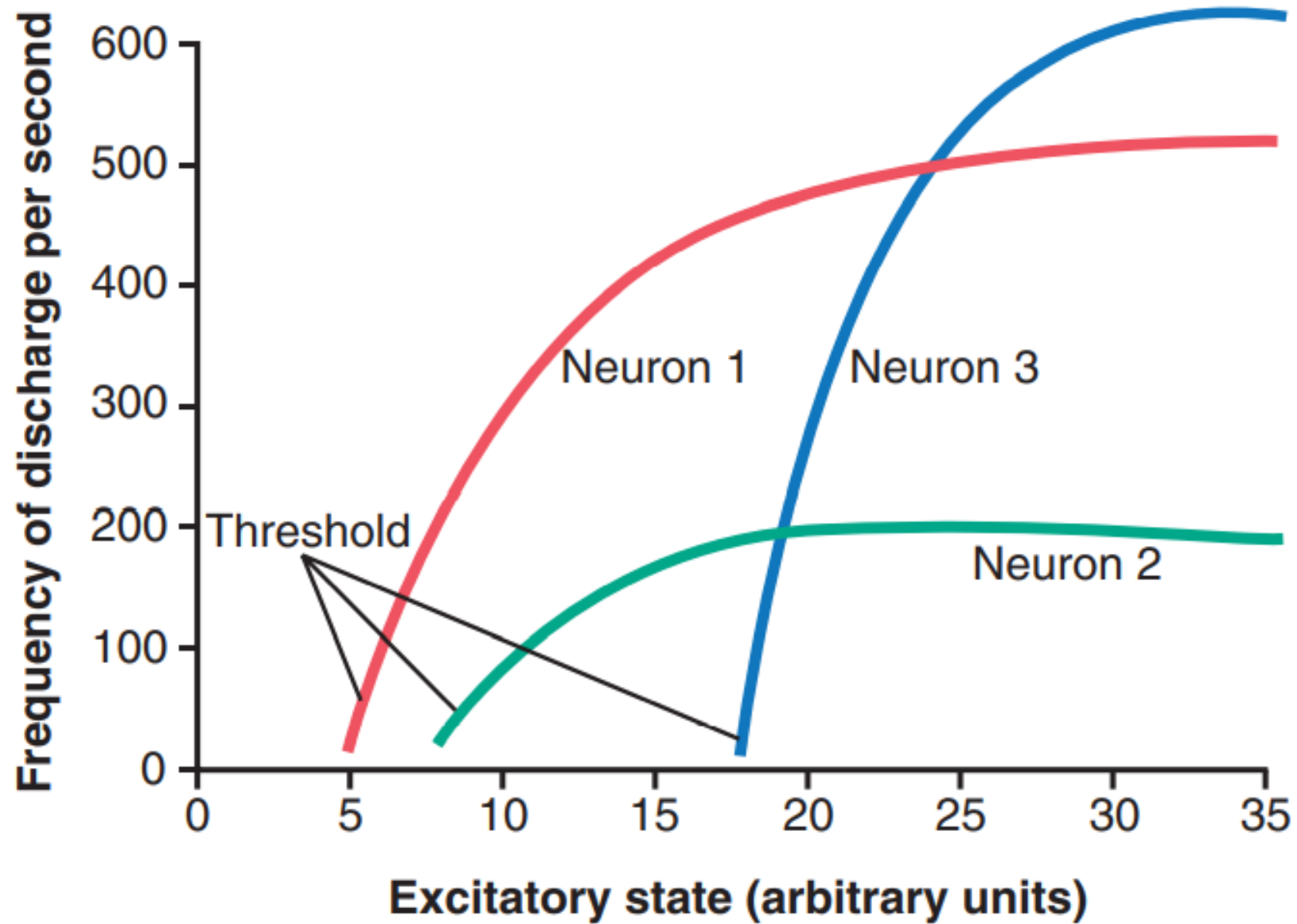
- Presynaptic inhibition occurs in many of the sensory pathways in the nervous system, such as, adjacent sensory nerve fibers often mutually inhibit one another, which minimizes sideways spread and mixing of signals in sensory tracts.

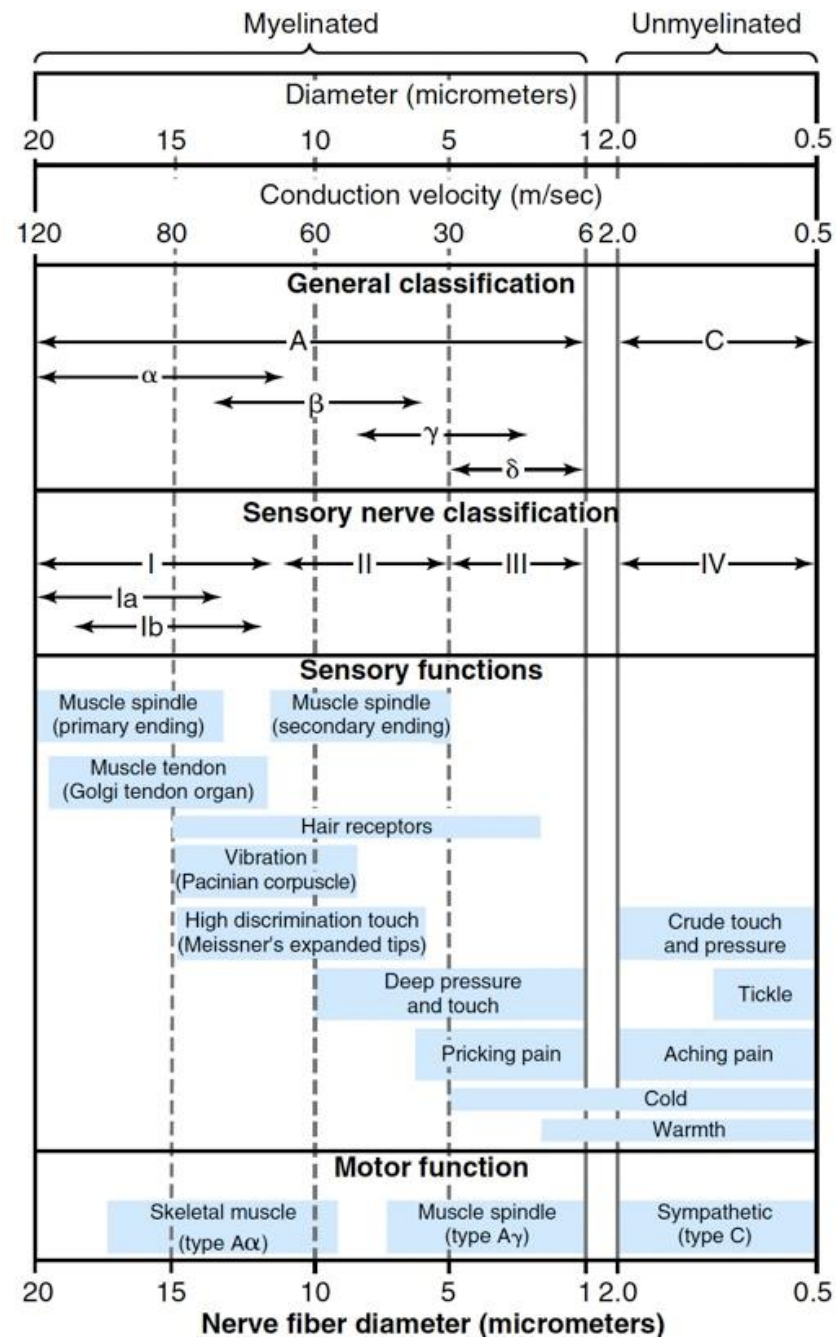


# Facilitation of neurons

- Often the summated postsynaptic potential is excitatory but has not risen high enough to reach the threshold for firing by the postsynaptic neuron.
- When this situation occurs, the neuron is said to be facilitated.
- That is, its membrane potential is nearer the threshold for firing than normal but is not yet at the firing level.
- Consequently, another excitatory signal entering the neuron from some other source can then excite the neuron very easily.







- **Fiber Type Classification Based on Myelination, Diameter, and Conduction Velocity**
- **Myelinated Fibers**
- **Fiber diameter:** 1.0 to 20 micrometers
- **Conduction velocity:** 2.0 to 120 m/sec
- **Unmyelinated Fibers**
- **Fiber diameter:** 0.4 to 1.2 micrometers
- **Conduction velocity:** 0.5 to 2.0 m/sec

# General Classification of Nerve Fibers

Type	Subtype	Diameter ( $\mu\text{m}$ )	Velocity (m/s)
A	$\alpha$	13–20	80–120
A	$\beta$	6–12	35–90
A	$\gamma$	5–8	10–45
A	$\delta$	1–6	5–35
C	—	0.4–1.2	0.5–2.0



# Sensory Nerve Classification

Type	Subtype	Diameter (μm)	Velocity (m/s)
I	a	17–20	80–120
I	b	14–17	80–120
II	—	6–12	33–80
III	—	1–6	3–30
IV	—	0.4–1.2	0.5–2.0

# Sensory Functions and Associated Fiber Types

- **Muscle spindle (primary ending):** Type Ia fibers (myelinated, fast, large diameter)
- **Muscle tendon (Golgi tendon organ):** Type Ib fibers (myelinated)
- **Muscle spindle (secondary ending):** Type II fibers
- **Hair receptors:** Type II fibers
- **Vibration (Pacinian corpuscle):** Type II fibers
- **High-discrimination touch (Meissner's corpuscle):** Type II fibers
- **Deep pressure and touch:** Type III fibers
- **Pricking pain:** Type III fibers
- **Crude touch and pressure:** Type IV (unmyelinated, slow)
- **Tickle:** Type IV fibers
- **Aching pain:** Type IV fibers
- **Cold:** Type III and IV fibers
- **Warmth:** Type IV fibers

# Motor Function and Associated Fiber Types

- **Skeletal muscle (type A $\alpha$ ):** Large, myelinated, fast conduction
- **Muscle spindle (type A $\gamma$ ):** Smaller than A $\alpha$ , myelinated
- **Sympathetic (type C):** Smallest, unmyelinated, slowest

- Inhibition and Facilitation

Postsynaptic Inhibition: IPSPs generated at postsynaptic membrane.

Presynaptic Inhibition: Inhibitory neurotransmitter (e.g., GABA) released at presynaptic terminal, prevents neurotransmitter release.

Facilitation: Neuron is near threshold but not firing; easier to excite with another input.

Presynaptic Facilitation: Enhances neurotransmitter release.

- Functional Differences Between

Neurons Differ in threshold, conduction speed, firing frequency.

Fast signaling neurons: Low threshold, quick response.

High-frequency neurons: May have higher threshold but sustain rapid firing.

Myelination and Diameter: Increase conduction velocity.

Type A fibers (large, myelinated): Fast (e.g., reflexes).

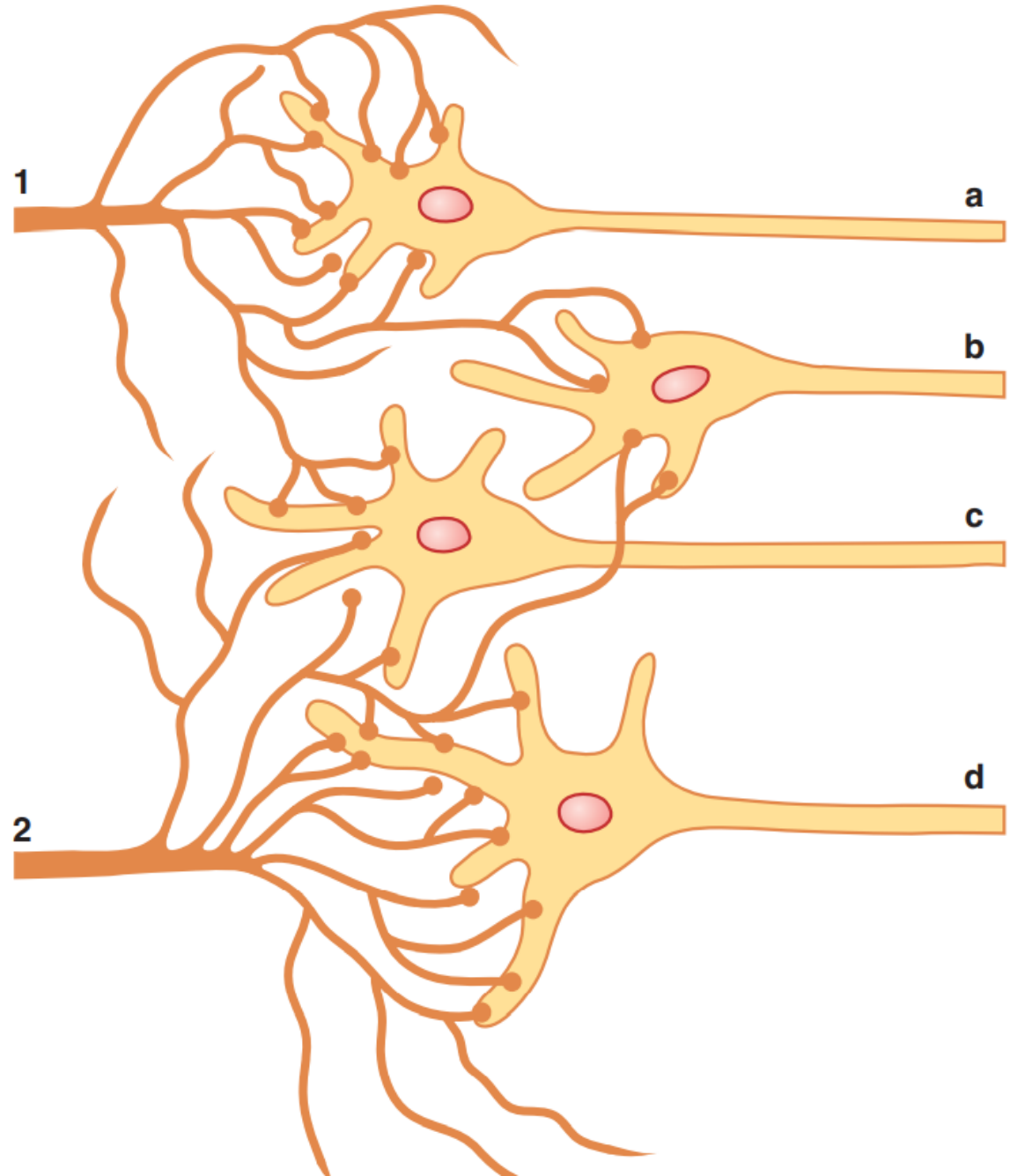
Type C fibers (small, unmyelinated): Slow (e.g., itch).

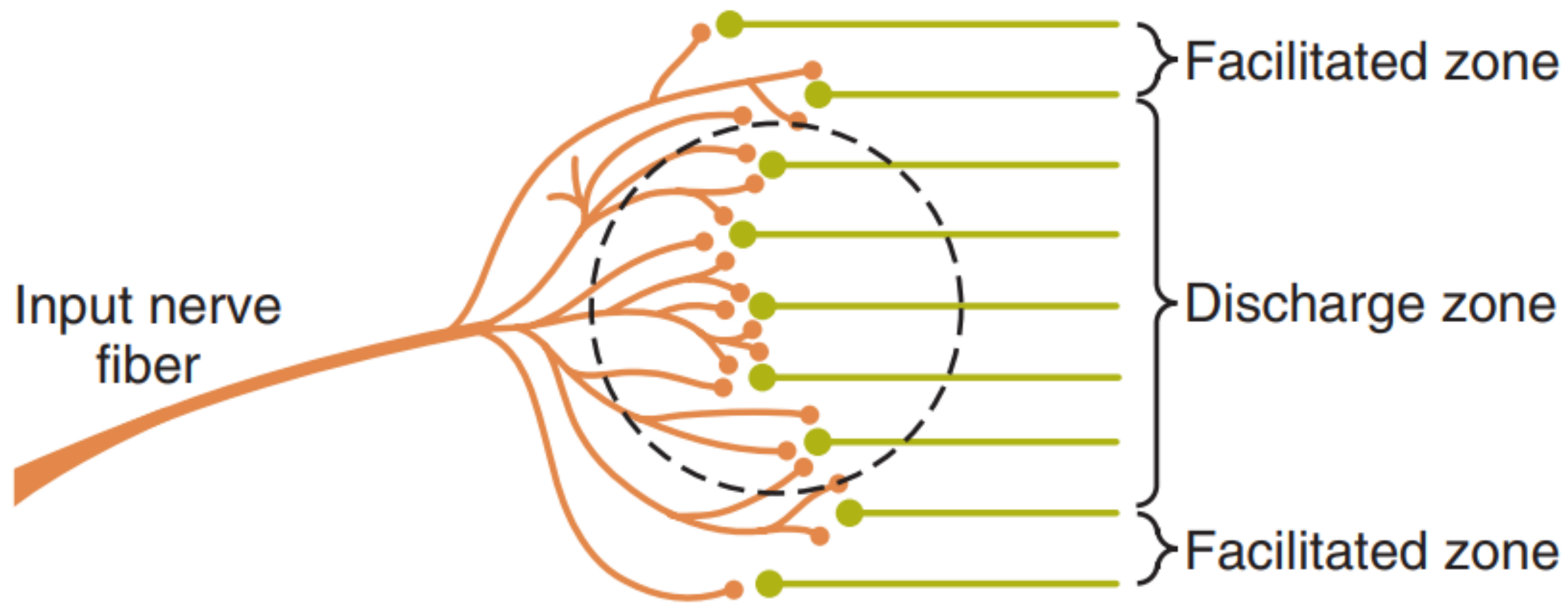
# Neuronal pools

- Functional groups of neurons occurring in the grey matter of the brain and spinal cord, which process and integrate incoming information received from other sources, such as the sense organs, and transmit the processed information to other destinations. (oxfordreference.com)
- Each neuronal pool has its own special organization that causes it to process signals in its own unique way and perform certain function.

Stimulatory field:

The neuronal area  
stimulated by each  
incoming nerve fiber.

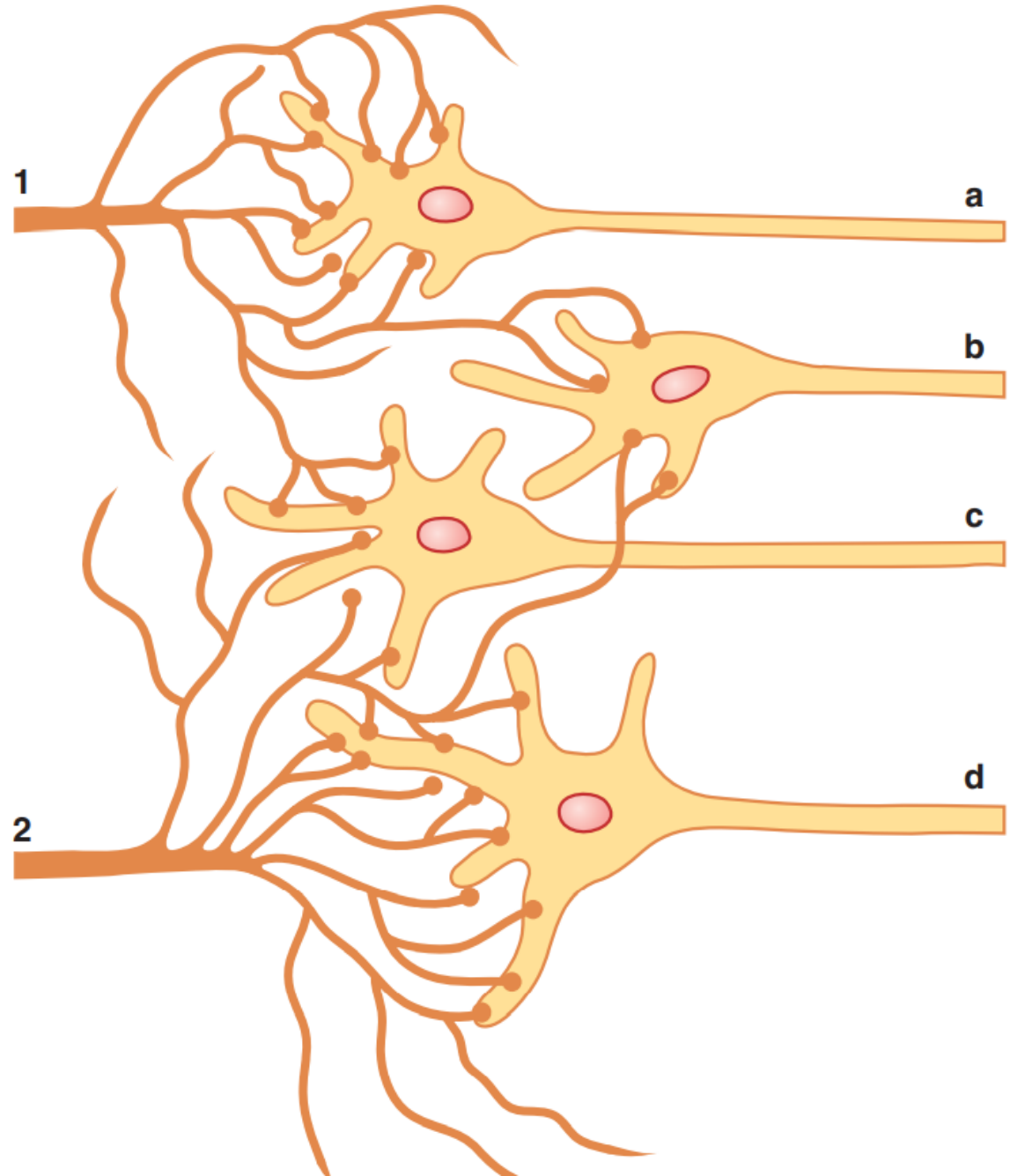






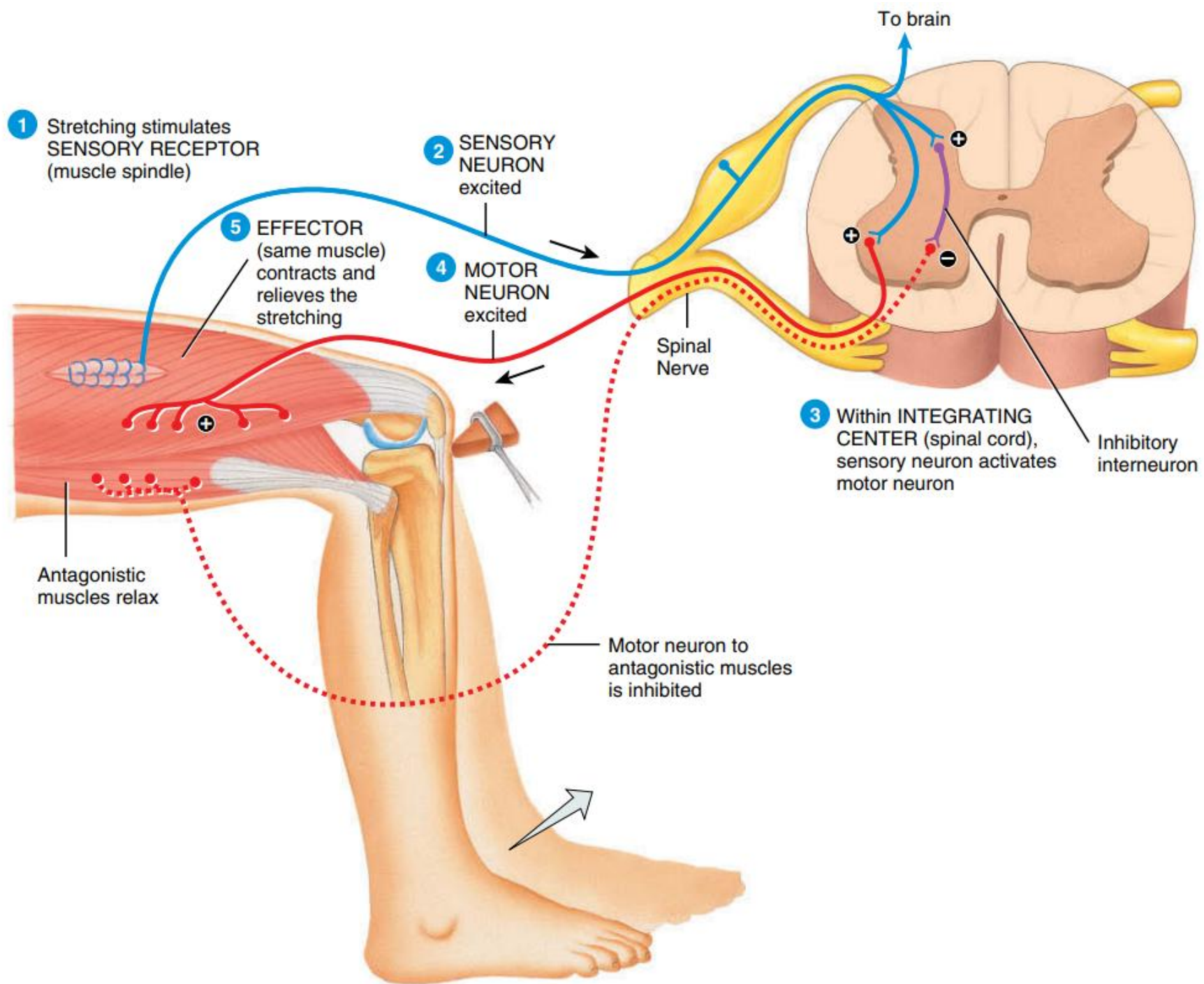
Inhibitory zone:

Greatest inhibition in the  
center of the zone.



# Neuronal circuits

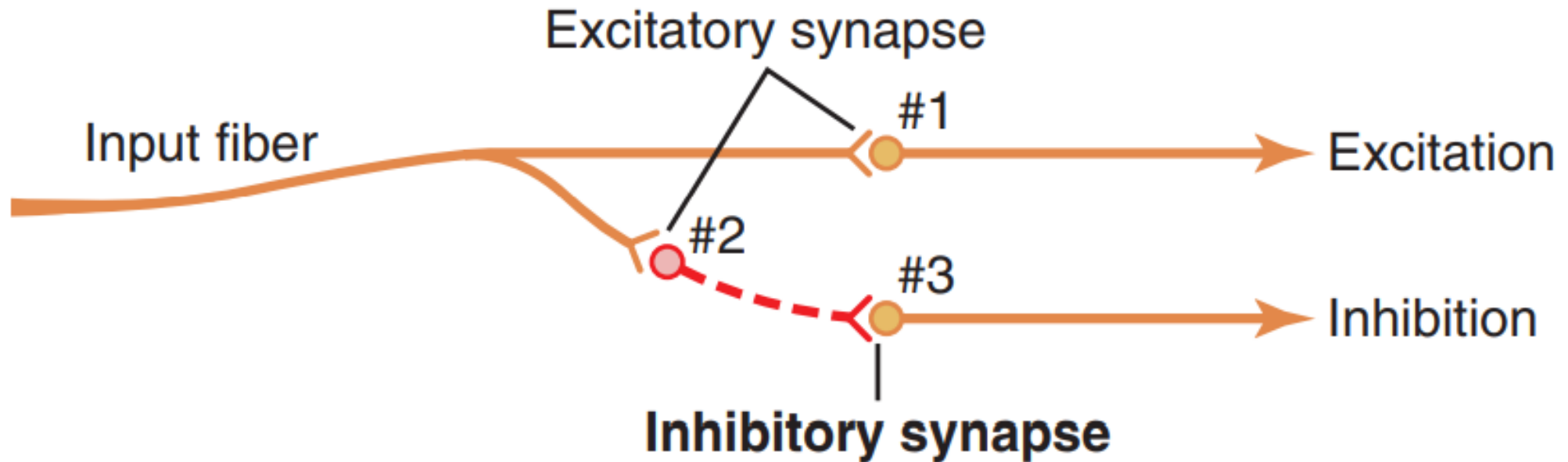
- A group of interconnected neurons that perform certain function.

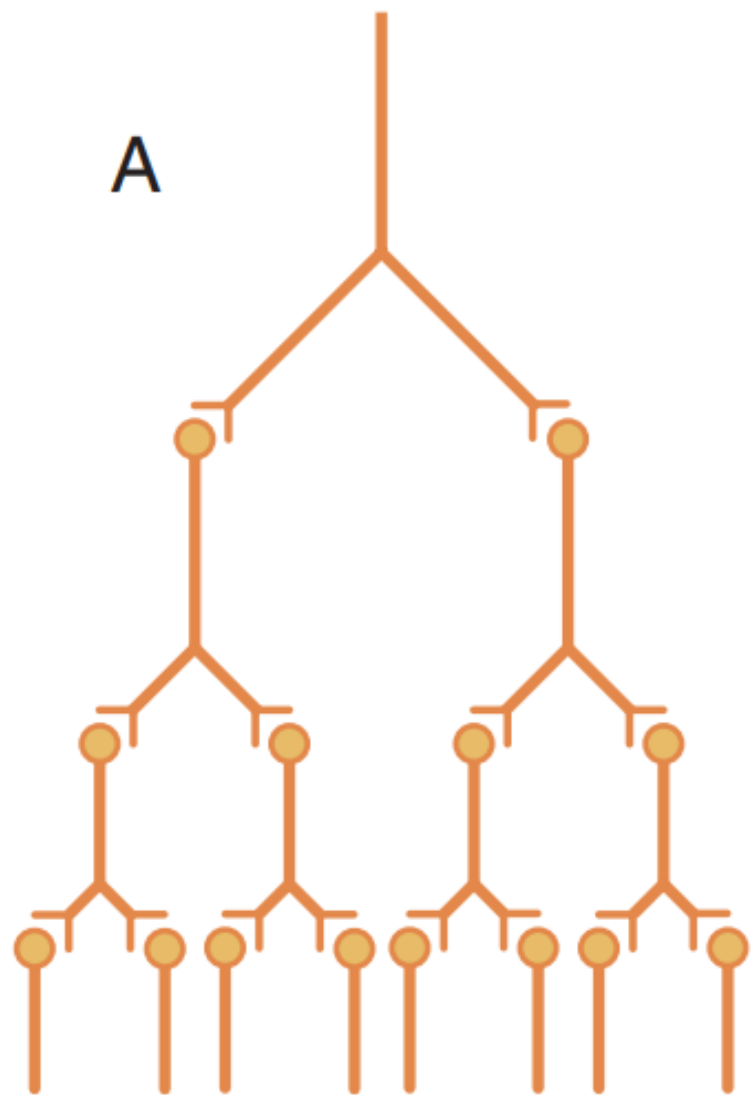


# Reciprocal inhibition

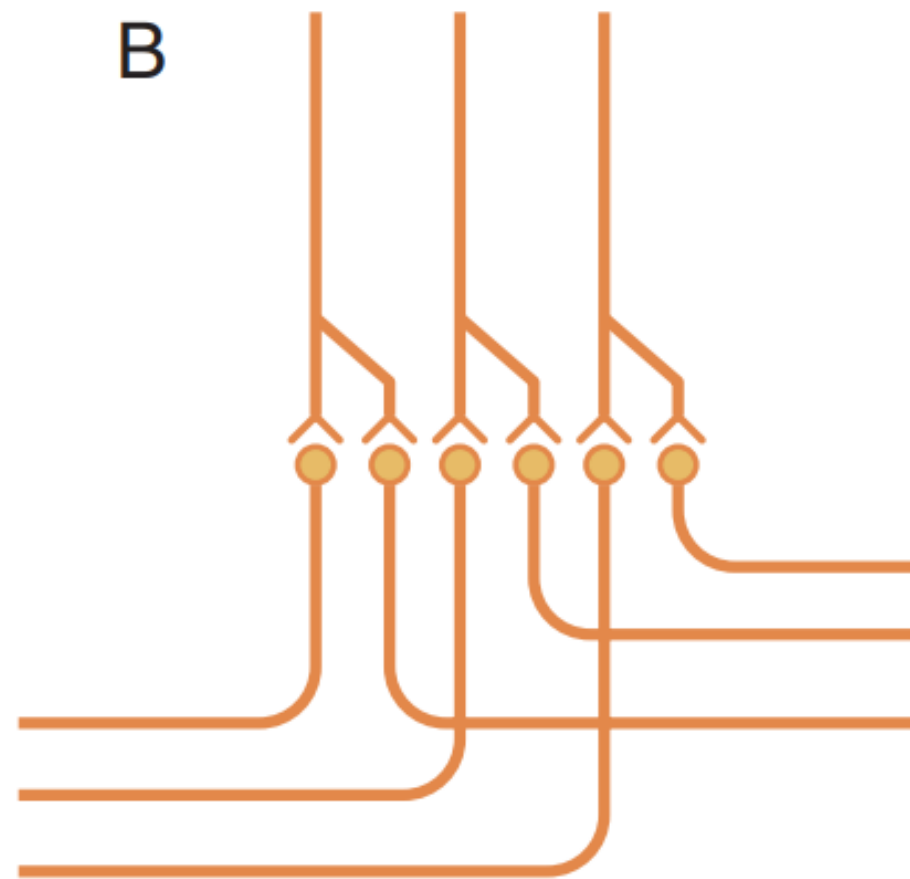
- Sometimes an incoming signal to a neuronal pool causes an output excitatory signal going in one direction and at the same time an inhibitory signal going elsewhere.
- This type of circuit is characteristic for controlling all antagonistic pairs of muscles.

# Reciprocal inhibition

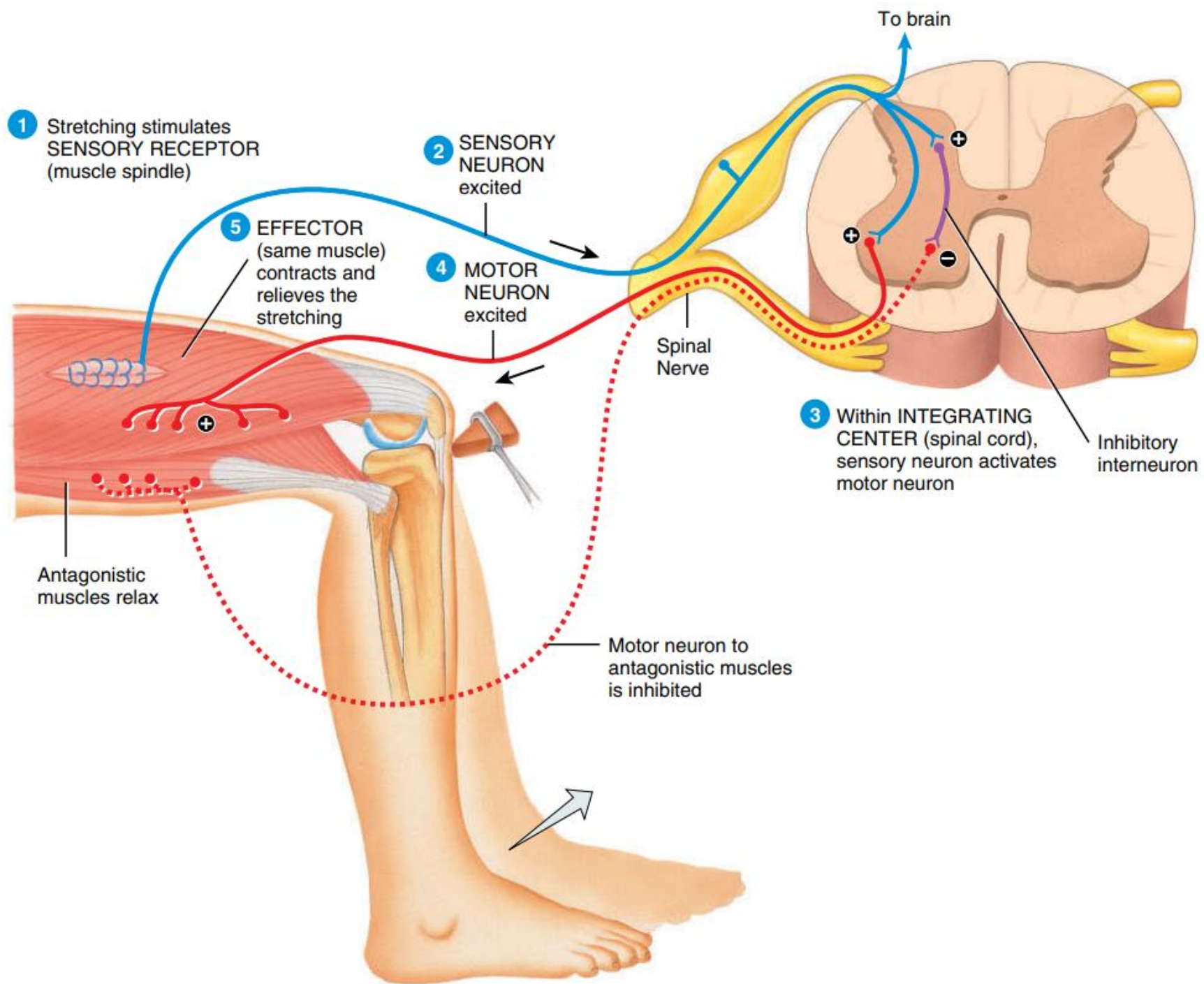




Divergence in same tract

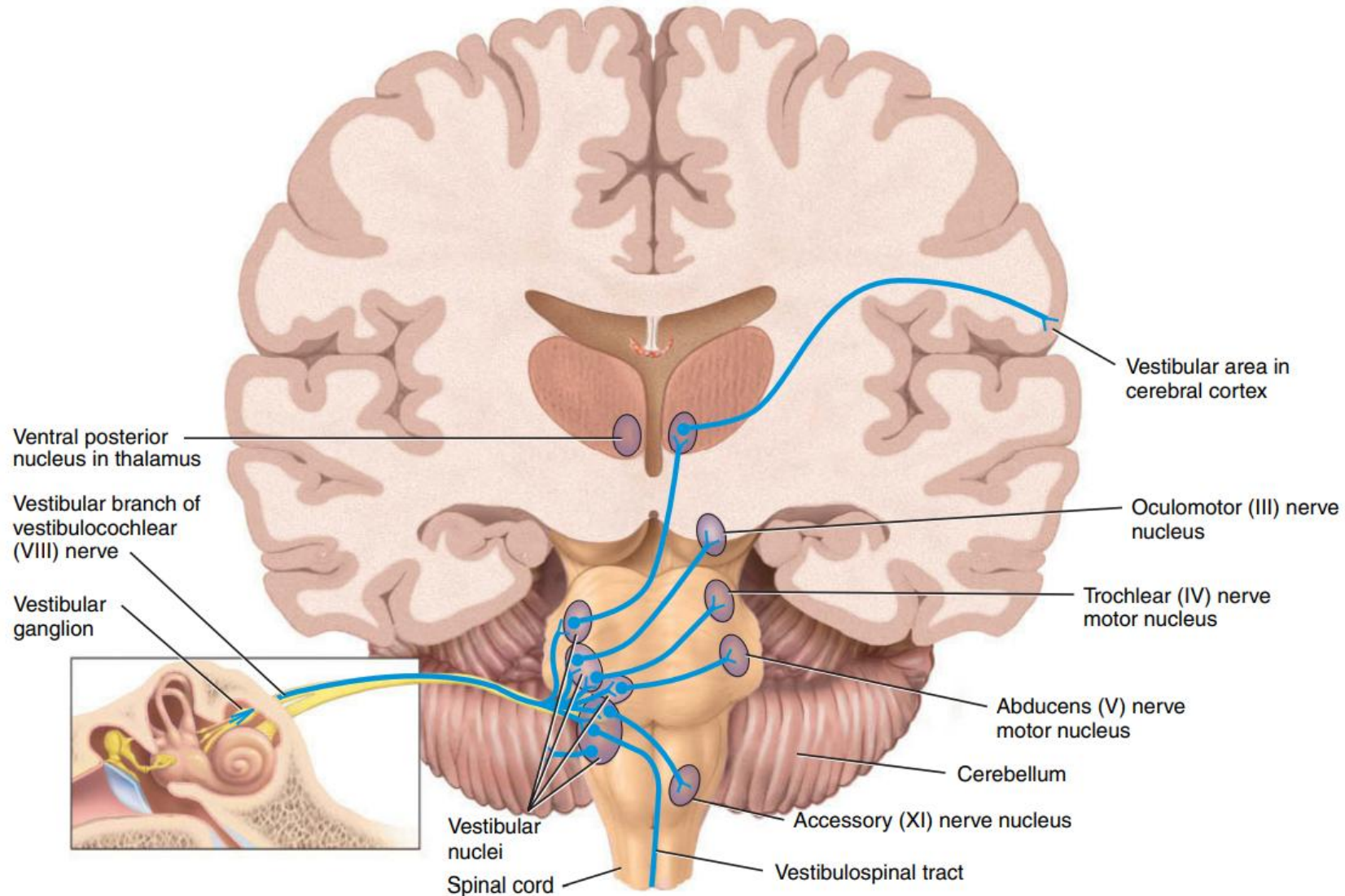


Divergence into multiple tracts





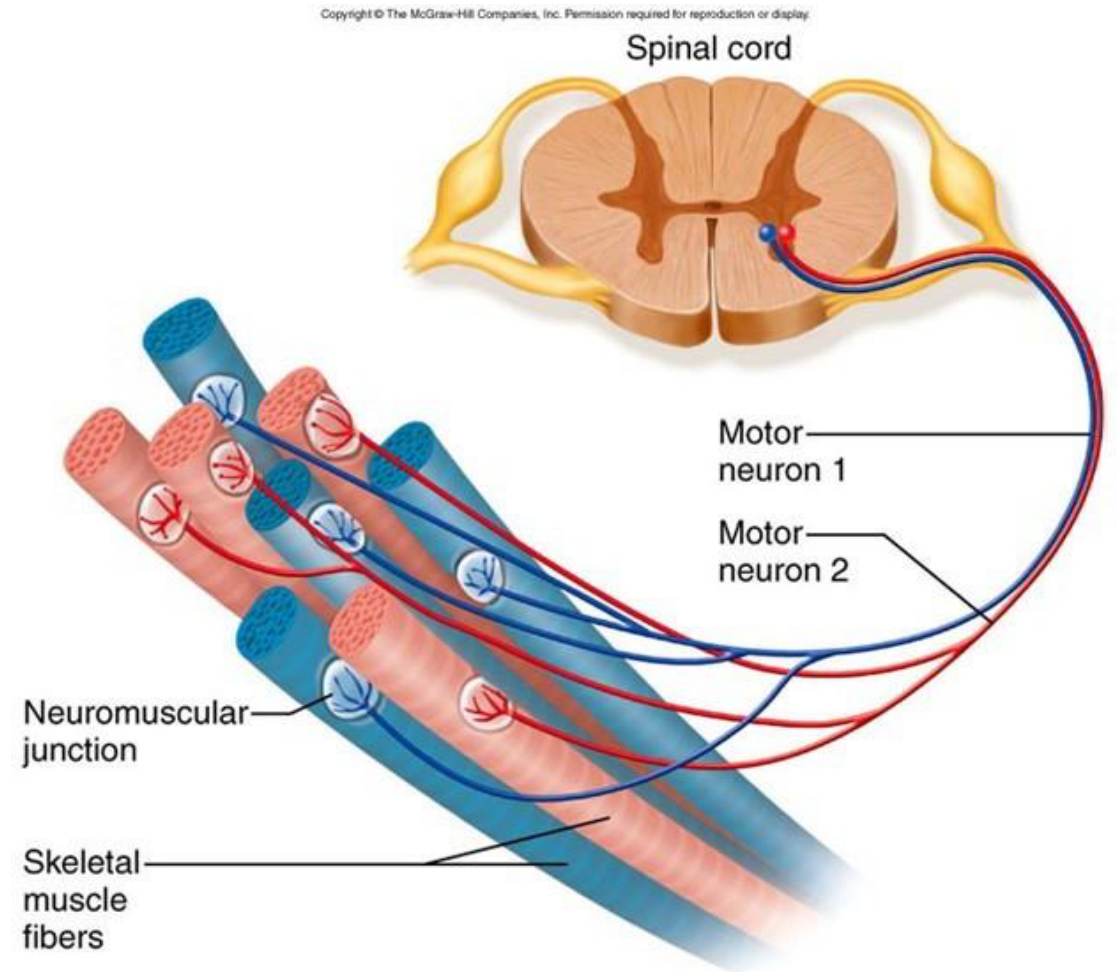
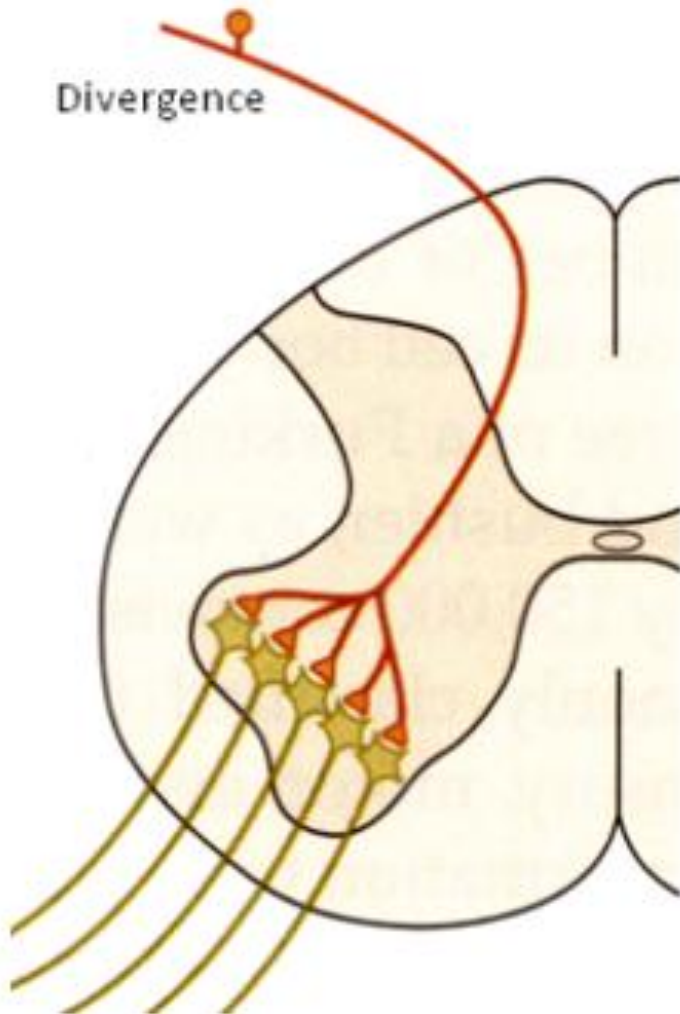
# Divergence into multiple tracts



# Amplifying divergence

- Amplifying divergence means simply that an input signal spreads to an increasing number of neurons as it passes through successive orders of neurons in its path.

# Amplifying divergence



# Convergence

- Convergence means signals from multiple inputs uniting to excite a single neuron.
- The importance of this type is summation.
- Convergence is one of the important means by which the central nervous system correlates, summates, and sorts different types of information

A Source



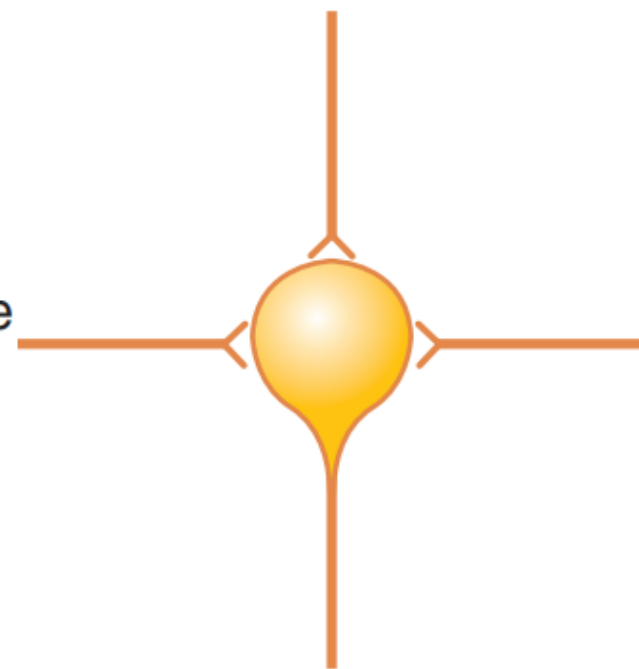
Convergence from a  
single source

B

Source  
#1

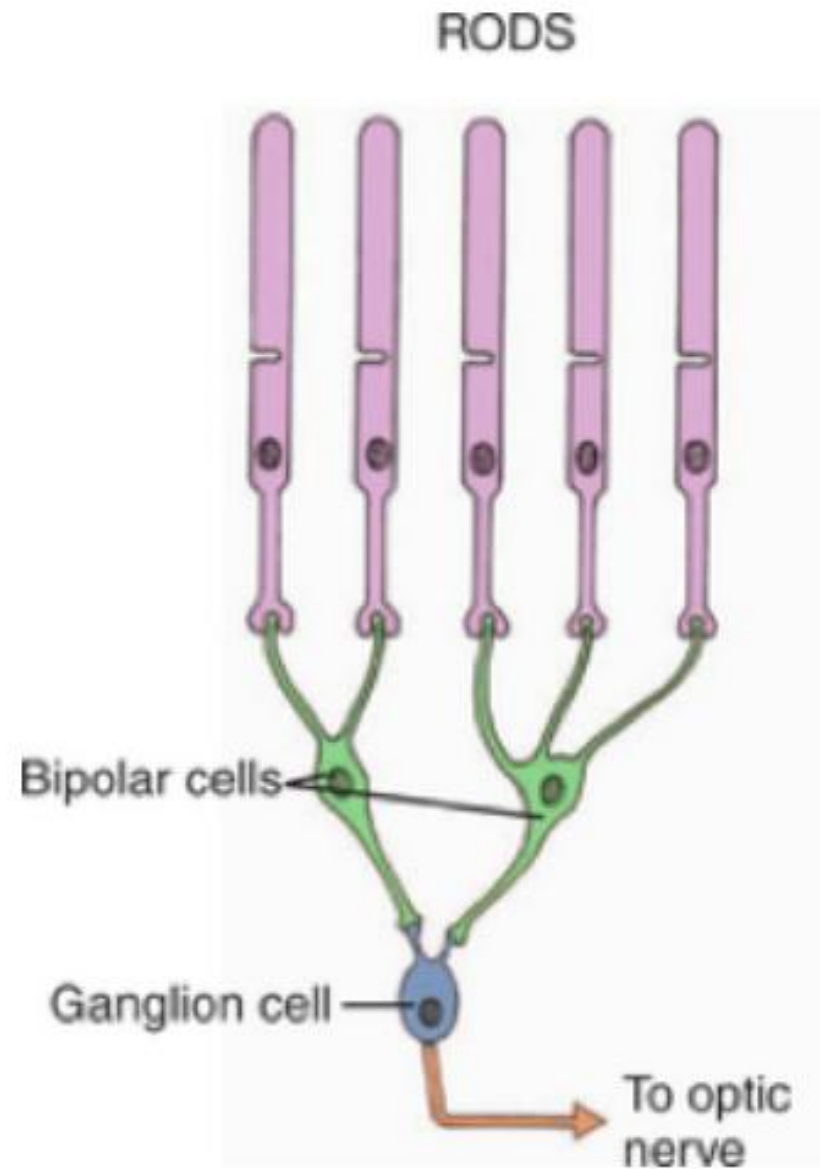
Source  
#2

Source  
#3



Convergence from  
multiple separate sources

# Convergence in photoreceptors (Rods)



- **Summary of Circuit Types**
- **1. Monosynaptic Reflex (Stretch Reflex)**
- E.g., Patellar reflex: Sensory neuron → Motor neuron → Muscle contraction.
- **Reciprocal Inhibition:** Inhibitory interneuron relaxes antagonist muscle using glycine.
- **2. Divergence**
- One neuron → Multiple outputs (e.g., vestibular system).
- **Amplifying Divergence:** One input excites many outputs (e.g., motor units).
- **3. Convergence**
- Multiple inputs → One neuron (e.g., rods in retina).
- Important for **summation** and detecting weak signals.

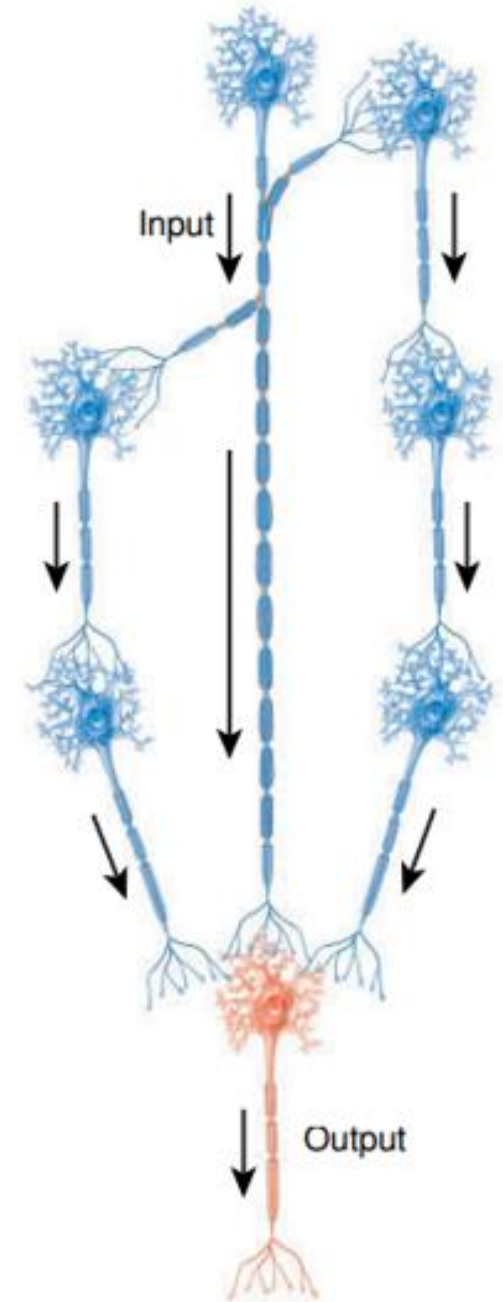


# After-discharge

- A signal entering a pool causes a prolonged output discharge.
- **Synaptic afterdischarge:** as in some neuropeptides.

# Parallel afterdischarge

- Continued firing after the stimulus has stopped, so prolonged output discharge.
- a neuron inputs to several chains of neurons.
- Each chain is made up of a different number of neurons, but their signals converge onto one output neuron.
- Reach output at varying times.
- No feedback loop as in the reverberating circuit.



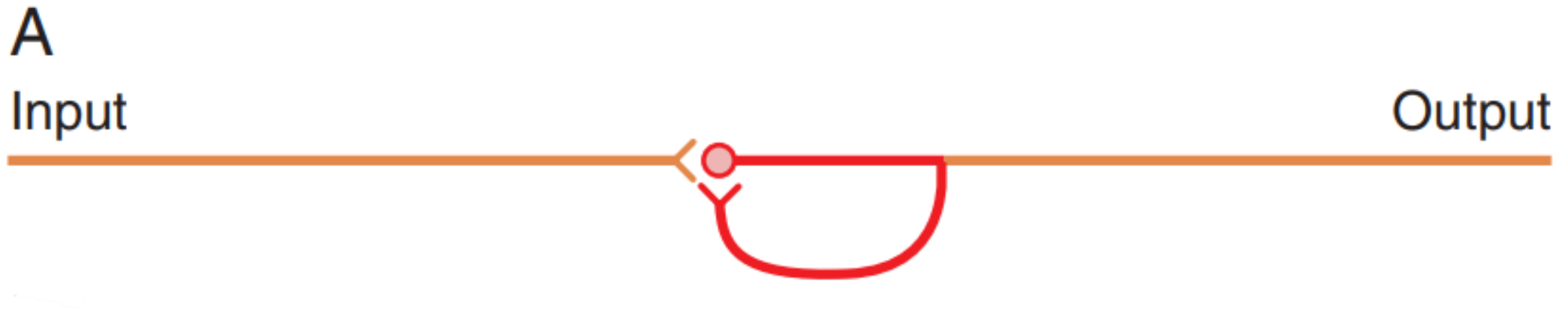
- **After-Discharge Circuits**
- **Synaptic Afterdischarge:** Sustained output after stimulus via neuropeptides.
- **Parallel After-Discharge:**
  - Input neuron → Multiple chains → Single output neuron.
  - Different delays → Prolonged output.
  - No feedback loop (unlike reverberation).

# Reverberatory (Oscillatory) circuits

- One of the most important circuits in the nervous system.
- Caused by positive feedback within the neuronal circuit that feeds back to re-excite the input of the same circuit.
- Consequently, once stimulated, the circuit may discharge repetitively for a long time.

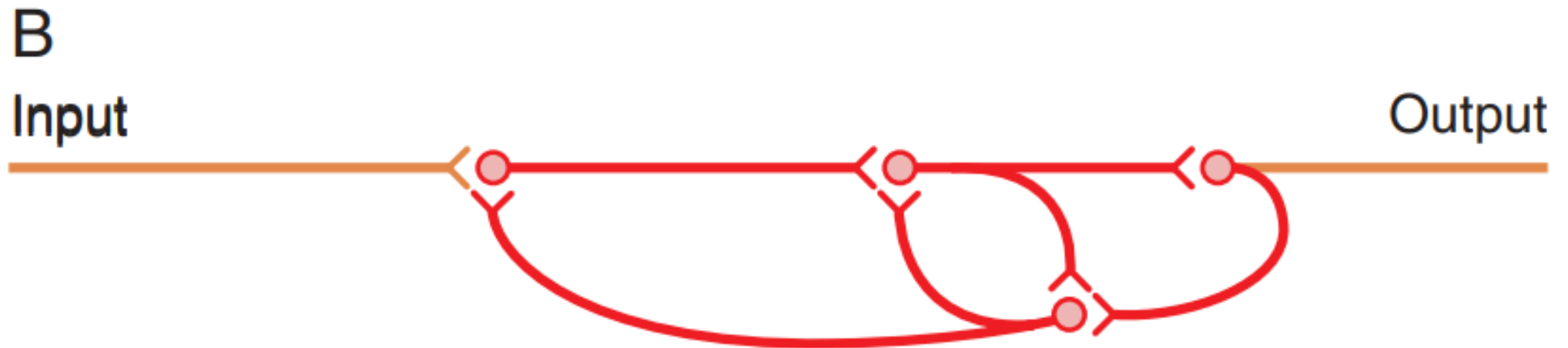
# Reverberatory circuits

The output neuron sends a collateral nerve fiber back to its own dendrites or soma to restimulate itself.

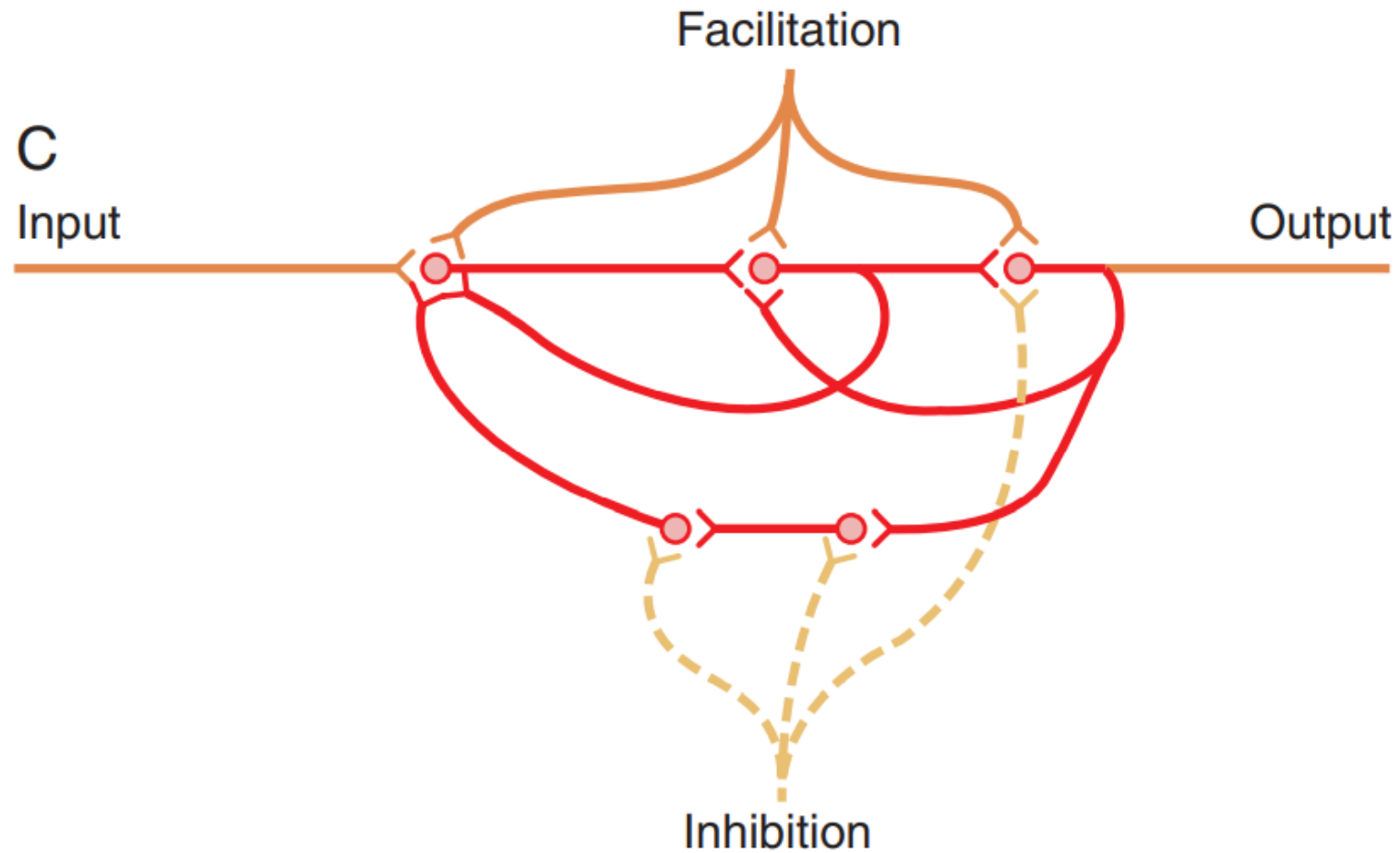


# Reverberatory circuits

A few additional neurons in the feedback circuit, which causes a longer delay between initial discharge and the feedback signal.



A facilitatory signal enhances the intensity and frequency of reverberation, whereas an inhibitory signal depresses or stops the reverberation.



- **Reverberatory Circuits**
- **Positive Feedback Loop:** Output neuron re-stimulates itself via collateral branches.
- **Used for continuous output** (e.g., respiratory rhythm).
- **Modulated by:** Facilitation (enhances) or inhibition (decreases output).



# Continuous signal output

- Some neuronal circuits emit output signals continuously, even without excitatory input signals.
- At least two mechanisms can cause this effect:
  - (1) continuous intrinsic neuronal discharge
  - (2) continuous reverberatory signals

- **Continuous Signal Output**
- **Sources:**
  - Intrinsic discharge (spontaneous).
  - Reverberatory circuits.

# Stability of neuronal circuits

- Almost every part of the brain connects either directly or indirectly with every other part, which creates a serious challenge.
- Two basic mechanisms that stabilize the central nervous system:
  - (1) inhibitory circuits
  - (2) fatigue of synapses.

# Stability of neuronal circuits

## **INHIBITORY CIRCUITS**

Two types of inhibitory circuits in widespread areas of the brain help prevent excessive spread of signals:

- (1) inhibitory feedback circuits that return from the termini of pathways back to the initial excitatory neurons of the same pathways (like in sensory nervous pathways).

# Stability of neuronal circuits

## **INHIBITORY CIRCUITS**

(2) some neuronal pools that exert gross inhibitory control over widespread areas of the brain (for instance, many of the basal nuclei exert inhibitory influences throughout the muscle control system).

- **Stability of Neuronal Circuits**
- CNS is highly interconnected → Needs stability via:
  - **Inhibitory Circuits:**
    - Feedback inhibition (e.g., sensory pathways).
    - Global inhibition (e.g., basal ganglia to motor cortex).
  - **Fatigue of Synapses:**
    - Neurotransmitter depletion.
    - Receptor desensitization.
    - Ion concentration shifts.

# Fatigue of synaptic transmission

- Depletion of transmitter stores.
- Progressive inactivation of postsynaptic membrane receptors.
- Slow development of abnormal concentrations of ions inside the postsynaptic neuronal cell.

# Effect of alkalosis on synaptic transmission

- **Most neurons are highly responsive to changes in pH** of the surrounding interstitial fluids.
- **Alkalosis increases neuronal excitability** and may cause cerebral **epileptic seizures**.
- In a person who is predisposed to epileptic seizures, even a short period of hyperventilation, which lowers CO<sub>2</sub> and elevates the pH, may precipitate an epileptic attack.



# Effect of acidosis on synaptic transmission

- Conversely, **acidosis greatly depresses neuronal activity**; a fall in pH may cause a comatose state.
- For instance, in very severe **diabetic or uremic acidosis**, **coma** almost always develops.

# Effect of hypoxia on synaptic transmission

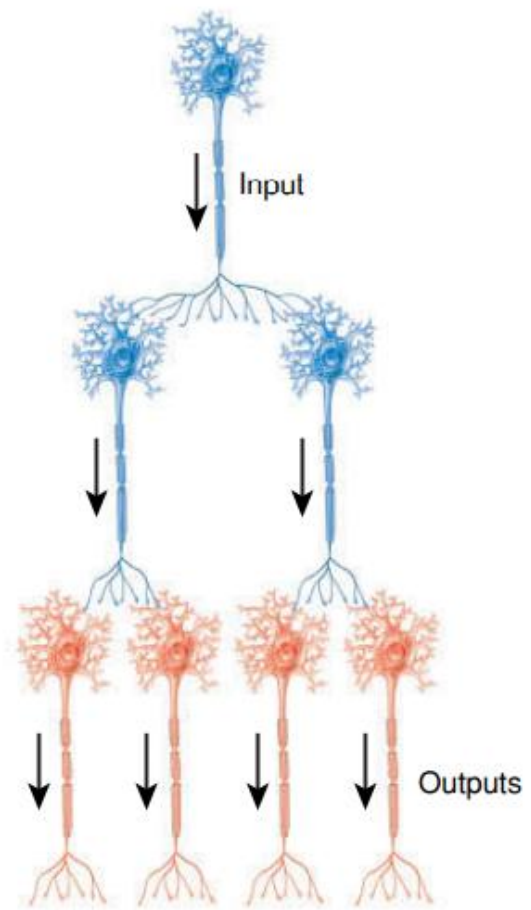
- Neuronal excitability is also highly dependent on an adequate supply of oxygen.
- **Cessation of oxygen for only a few seconds can cause complete inexcitability of some neurons.**
- This effect is observed when the brain's blood flow is temporarily interrupted because within 3 to 7 seconds, the person becomes unconscious.

# Effect of drugs on synaptic transmission

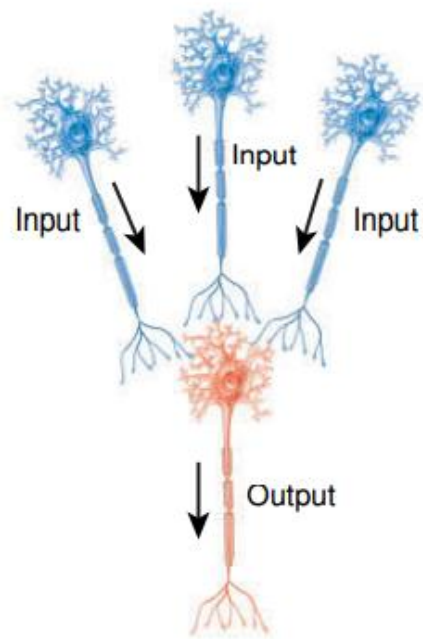
- Many drugs are known to increase the excitability of neurons, and others are known to decrease excitability.
- For instance, **caffeine, theophylline, and theobromine**, which are found in coffee, tea, and cocoa, respectively, all **increase neuronal excitability**, presumably by reducing the threshold for excitation of neurons.

# Effect of drugs on synaptic transmission

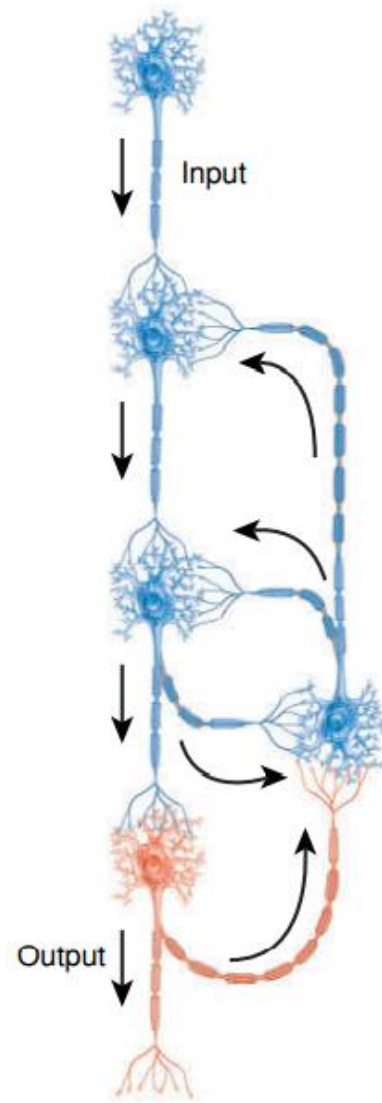
- Most **anesthetics** increase the neuronal membrane threshold for excitation and thereby **decrease synaptic transmission** at many points in the nervous system.



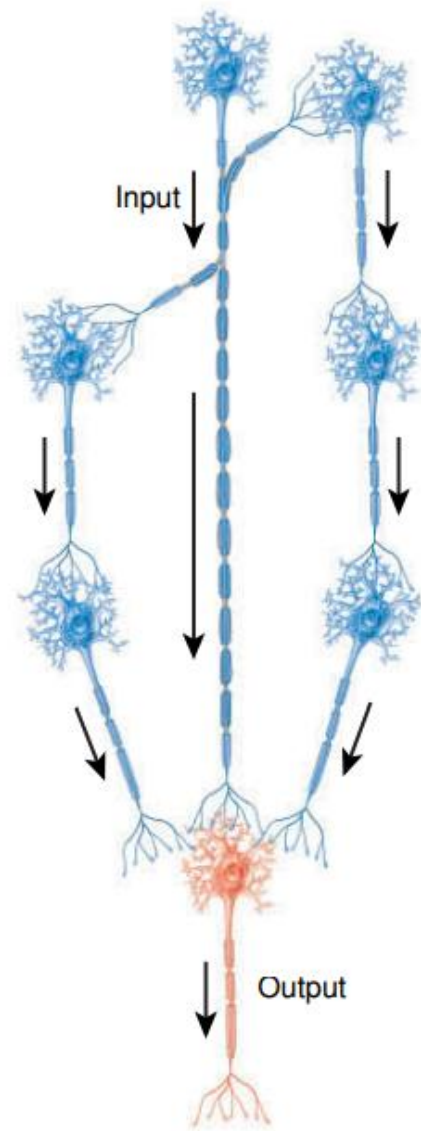
**A**



**B**



**C**



**D**

- **Pathophysiology of Circuit Dysfunction**
- **Alkalosis:** ↑ neuronal excitability, can cause seizures (e.g., via hyperventilation).
- **Acidosis:** ↓ neuronal activity, may cause coma (e.g., diabetic ketoacidosis).
- **Hypoxia:** Few seconds of O<sub>2</sub> loss → Unconsciousness.
- **Drugs:**
  - Stimulants (caffeine, theophylline): ↓ threshold → ↑ excitability.
  - Anesthetics: ↑ threshold → ↓ excitability.