LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 48

Neurons, Synapses, and Signaling

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Lines of Communication

- The cone snail kills prey with venom that disables neurons
- **Neurons** are nerve cells that transfer information within the body
- Neurons use two types of signals to communicate: electrical signals (long-distance) and chemical signals (short-distance)

- Interpreting signals in the nervous system involves sorting a complex set of paths and connections
- Processing of information takes place in simple clusters of neurons called **ganglia** or a more complex organization of neurons called a **brain**

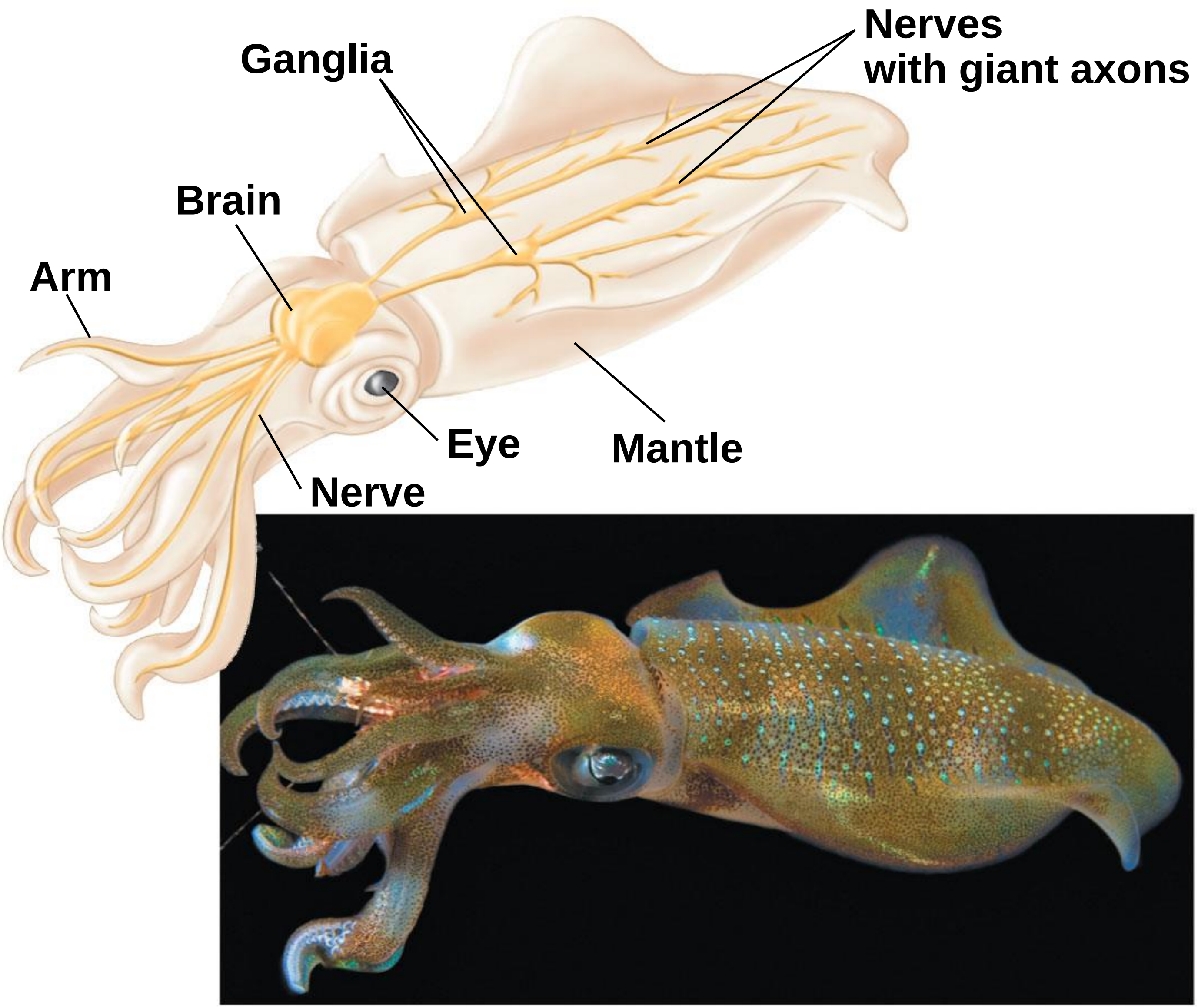
Concept 48.1: Neuron organization and structure reflect function in information transfer

- The squid possesses extremely large nerve cells and has played a crucial role in the discovery of how neurons transmit signals

Introduction to Information Processing

- Nervous systems process information in three stages: sensory input, integration, and motor output

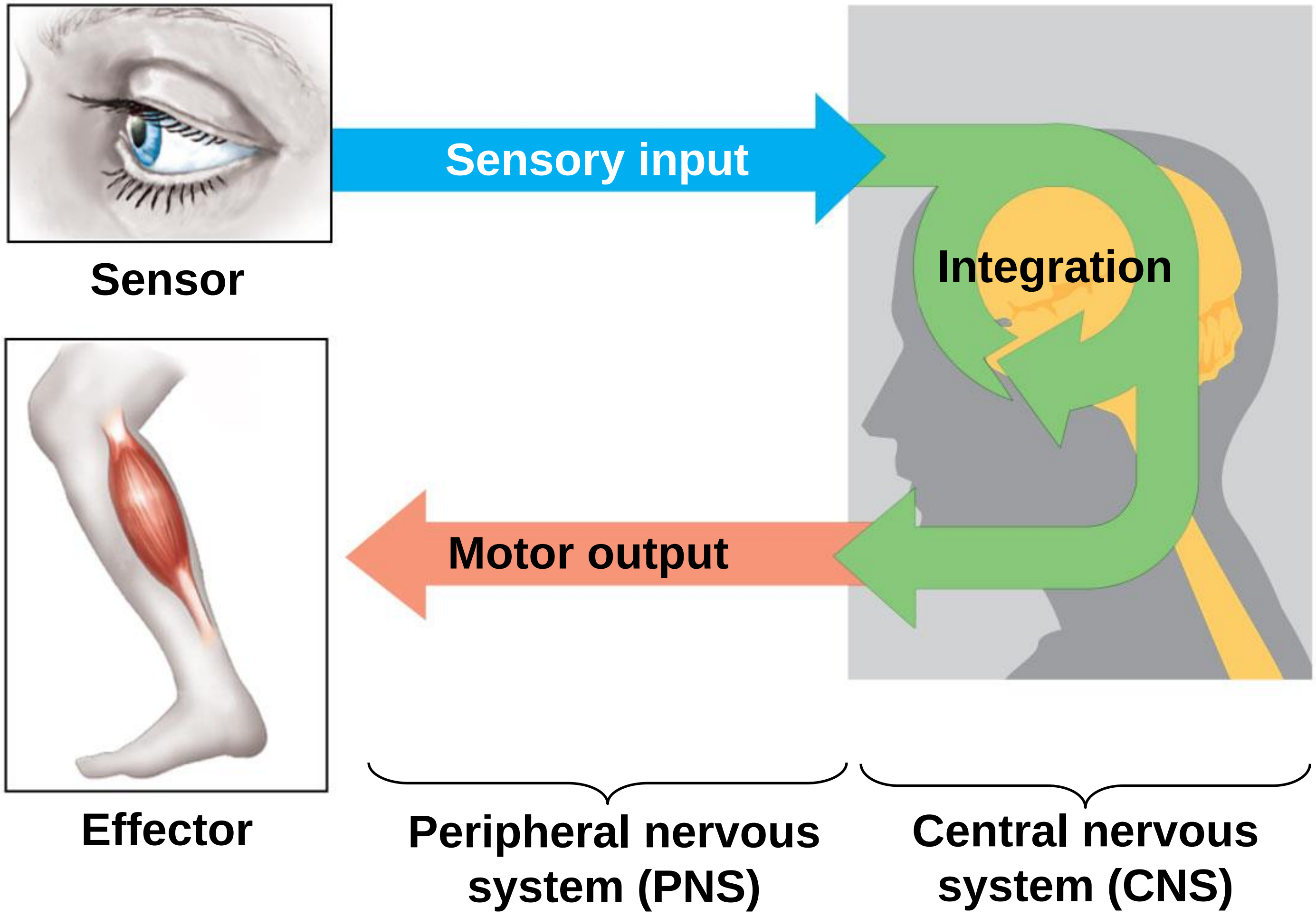
Figure 48.2



- Sensors detect external stimuli and internal conditions and transmit information along **sensory neurons**
- Sensory information is sent to the brain or ganglia, where **interneurons** integrate the information
- Motor output leaves the brain or ganglia via **motor neurons**, which trigger muscle or gland activity

- Many animals have a complex nervous system that consists of
  - A **central nervous system (CNS)** where integration takes place; this includes the brain and a nerve cord
  - A **peripheral nervous system (PNS)**, which carries information into and out of the CNS
  - The neurons of the PNS, when bundled together, form **nerves**

Figure 48.3

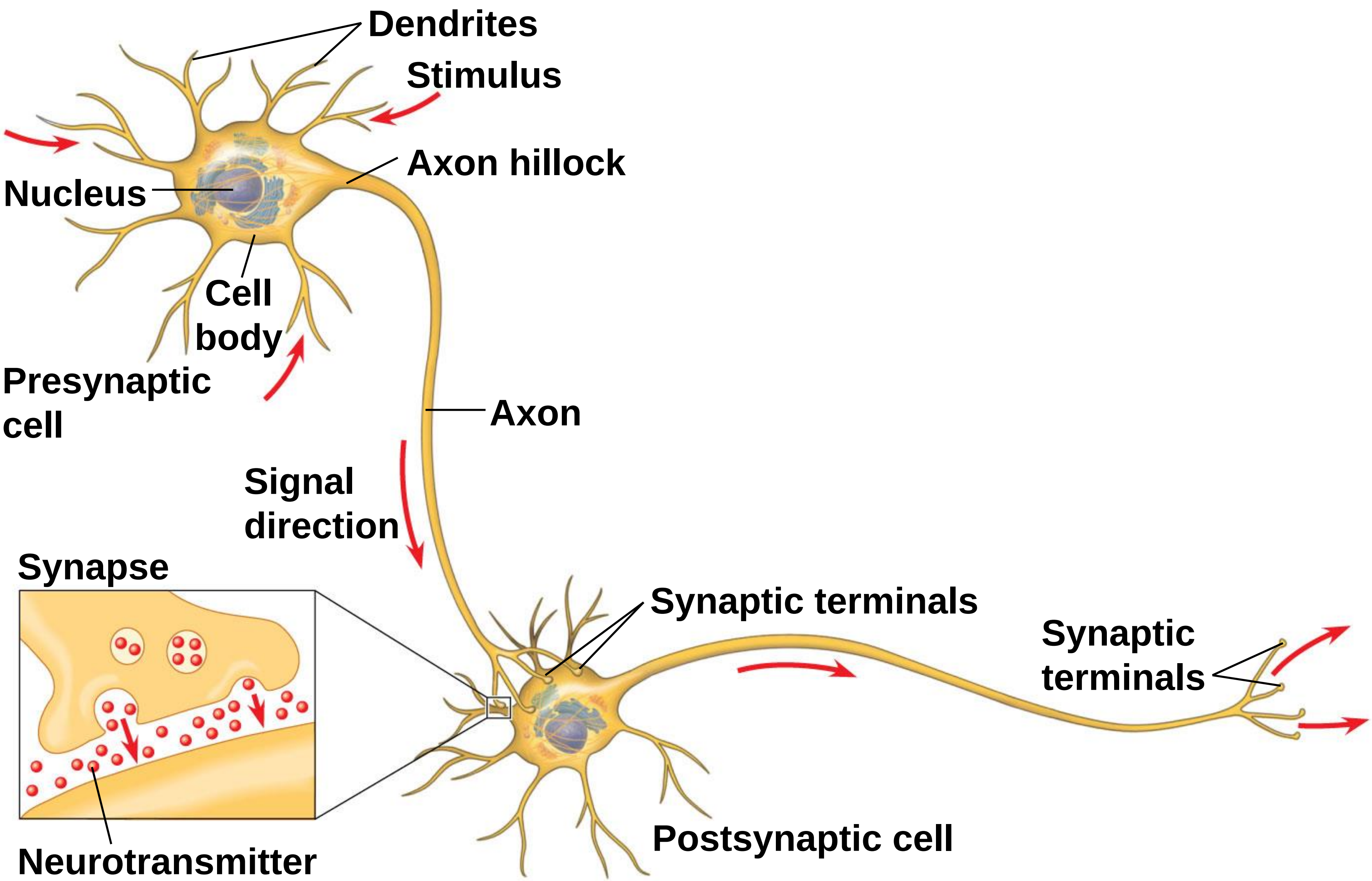


Sensory input
Sensor
Integration
Motor output
Effector
Peripheral nervous system (PNS)
Central nervous system (CNS)

Neuron Structure and Function

- Most of a neuron's organelles are in the **cell body**
- Most neurons have **dendrites**, highly branched extensions that *receive* signals from other neurons
- The **axon** is typically a much longer extension that transmits signals to other cells at synapses
- The cone-shaped base of an axon is called the **axon hillock**

Figure 48.4

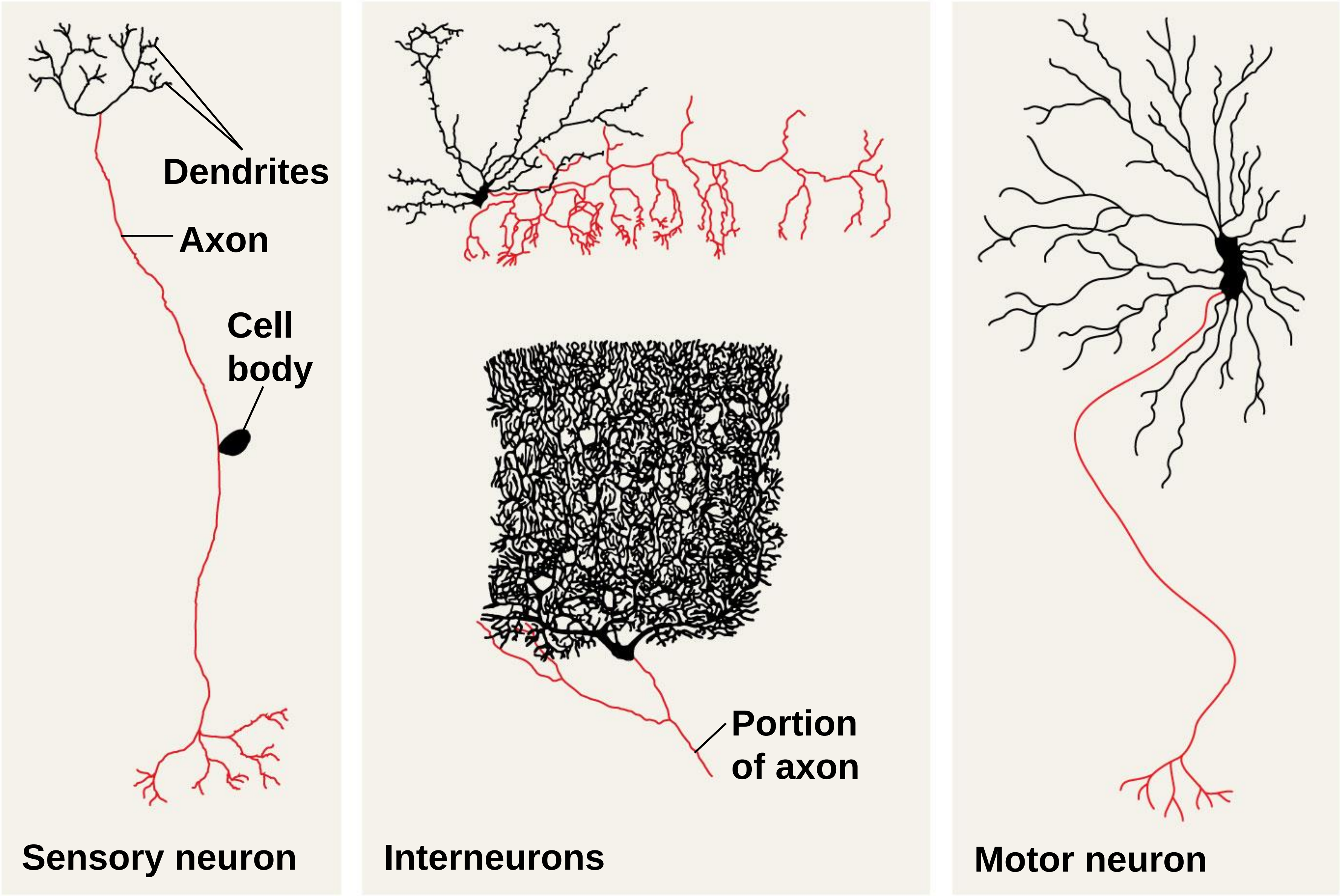


Dendrites
Stimulus
Axon hillock
Nucleus
Cell body
Presynaptic cell
Axon
Signal direction
Synapse
Synaptic terminals
Synaptic terminals
Postsynaptic cell
Neurotransmitter

- The **synaptic terminal** of one axon passes information across the synapse in the form of chemical messengers called **neurotransmitters**
- A **synapse** is a junction between an axon and another cell

- Information is transmitted from a **presynaptic cell** (a neuron) to a **postsynaptic cell** (a neuron, muscle, or gland cell)
- Most neurons are nourished or insulated by cells called **glia**

Figure 48.5



Dendrites
Axon
Cell body
Sensory neuron
Portion of axon
Interneurons
Motor neuron

Concept 48.2: Ion pumps and ion channels establish the resting potential of a neuron

- Every cell has a voltage (difference in electrical charge) across its plasma membrane called a **membrane potential**
- The **resting potential** is the membrane potential of a neuron not sending signals
- Changes in membrane potential act as signals, transmitting and processing information

Formation of the Resting Potential

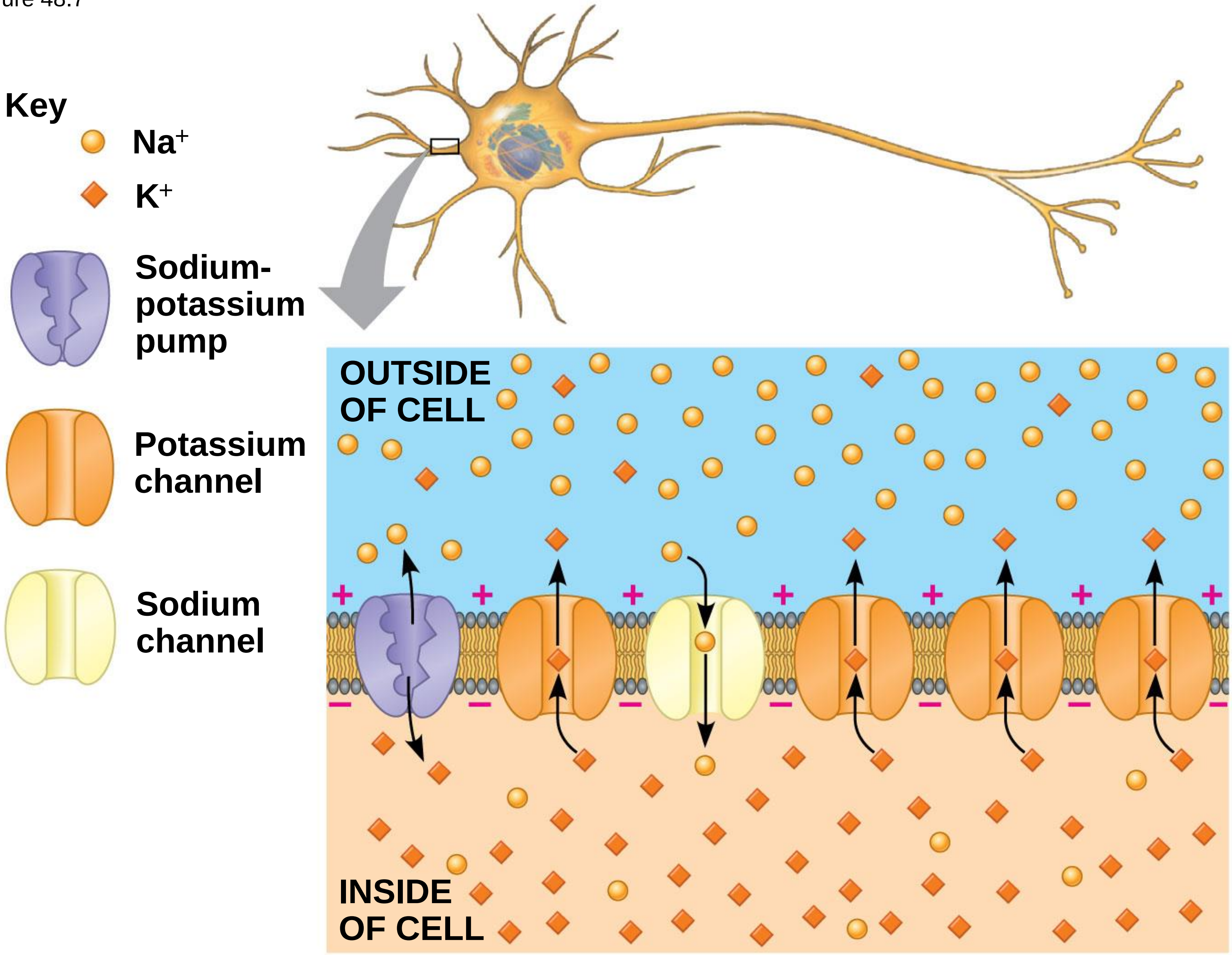
- In a mammalian neuron at resting potential, the concentration of K^+ is highest inside the cell, while the concentration of Na^+ is highest outside the cell
- Sodium-potassium pumps use the energy of ATP to maintain these K^+ and Na^+ gradients across the plasma membrane
- These concentration gradients represent chemical potential energy

- The opening of **ion channels** in the plasma membrane converts chemical potential to electrical potential
- A neuron at resting potential contains many open K^+ channels and fewer open Na^+ channels; K^+ diffuses out of the cell
- The resulting buildup of negative charge within the neuron is the major source of membrane potential

Table 48.1 Ion Concentrations Inside and Outside of Mammalian Neurons

Ion	Intracellular Concentration (m*M*)	Extracellular Concentration (m*M*)
Potassium (K^+)	140	5
Sodium (Na^+)	15	150
Chloride (Cl^-)	10	120
Large anions (A^-) inside cell, such as proteins	100	(not applicable)

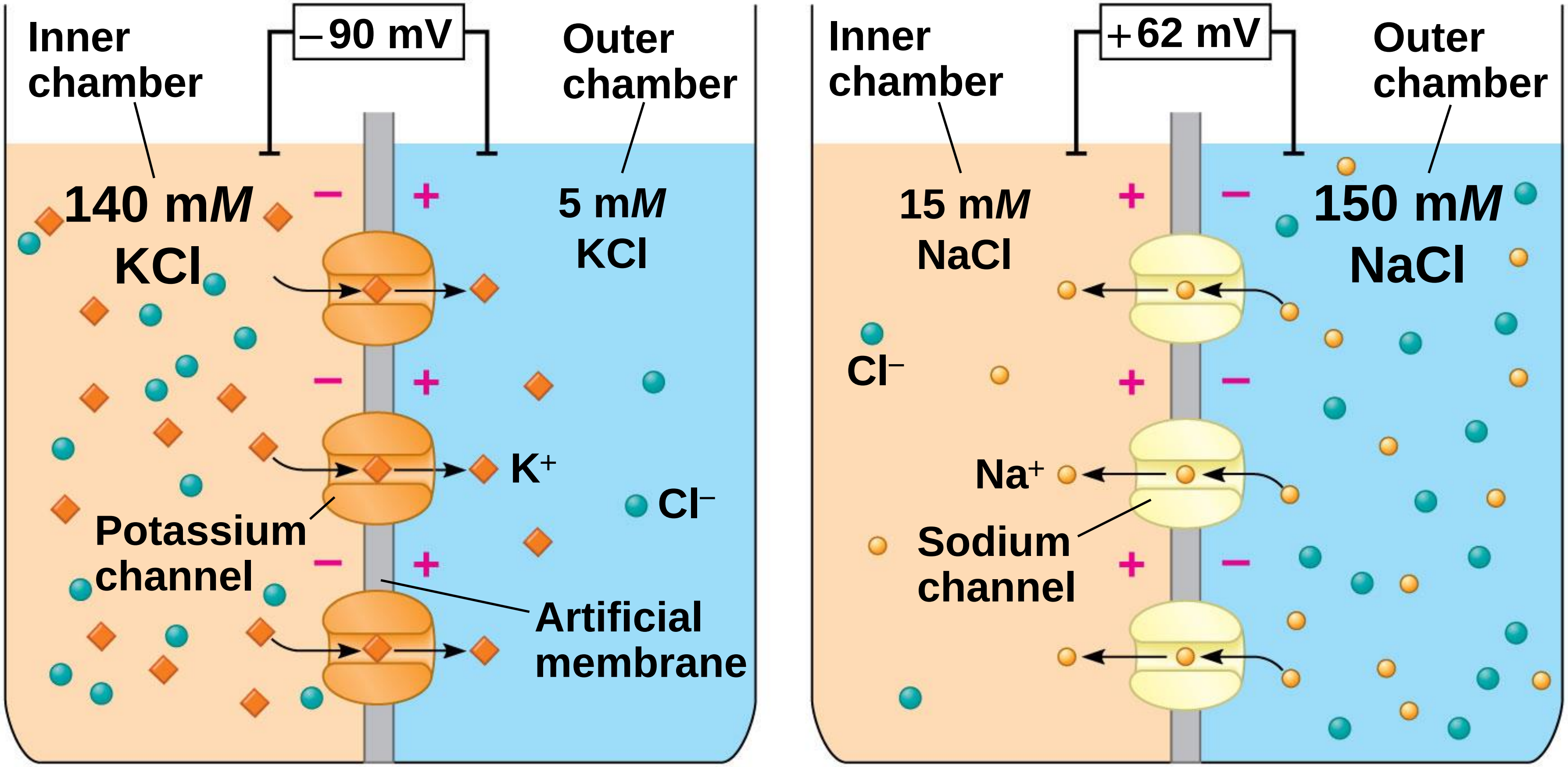
Figure 48.7


Key
Na+
K+
Sodium-potassium pump
Potassium channel
Sodium channel
OUTSIDE OF CELL
INSIDE OF CELL

Modeling the Resting Potential

- Resting potential can be modeled by an artificial membrane that separates two chambers
  - The concentration of KCl is higher in the inner chamber and lower in the outer chamber
  - K^+ diffuses down its gradient to the outer chamber
  - Negative charge (Cl^-) builds up in the inner chamber
- At equilibrium, both the electrical and chemical gradients are balanced

Figure 48.8



(a) Membrane selectively permeable to K^+

(b) Membrane selectively permeable to Na^+

$$E_K = 62 \text{ mV} \left(\log \frac{5 \text{ m}M}{140 \text{ m}M} \right) = -90 \text{ mV}$$

$$E_{Na} = 62 \text{ mV} \left(\log \frac{150 \text{ m}M}{15 \text{ m}M} \right) = +62 \text{ mV}$$

- The **equilibrium potential (E_{ion})** is the membrane voltage for a particular ion at equilibrium and can be calculated using the Nernst equation

$$E_{ion} = 62 \text{ mV } (\log[\text{ion}]_{outside}/[\text{ion}]_{inside})$$

- The equilibrium potential of K^+ (E_K) is negative, while the equilibrium potential of Na^+ (E_{Na}) is positive

- In a resting neuron, the currents of K^+ and Na^+ are equal and opposite, and the resting potential across the membrane remains steady

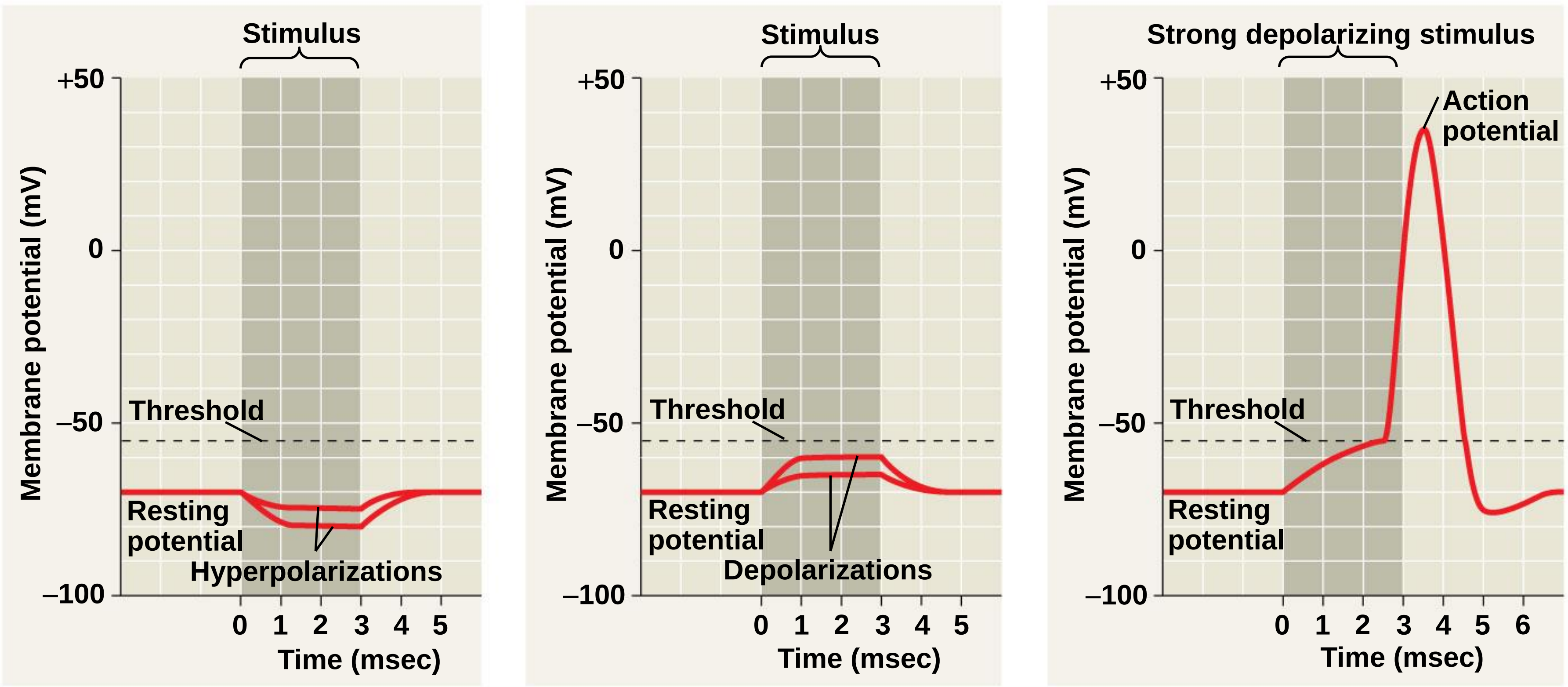
Concept 48.3: Action potentials are the signals conducted by axons

- Changes in membrane potential occur because neurons contain **gated ion channels** that open or close in response to stimuli

Hyperpolarization and Depolarization

- When gated K^+ channels open, K^+ diffuses out, making the inside of the cell more negative
- This is **hyperpolarization**, an increase in magnitude of the membrane potential

Figure 48.10



(a) **Graded hyperpolarizations produced by two stimuli that increase membrane permeability to K^+**

(b) **Graded hyperpolarizations produced by two stimuli that increase membrane permeability to Na^+**

(c) **Action potential triggered by a depolarization that reaches the threshold**

- Opening other types of ion channels triggers a **depolarization**, a reduction in the magnitude of the membrane potential
- For example, depolarization occurs if gated Na^+ channels open and Na^+ diffuses into the cell

Graded Potentials and Action Potentials

- **Graded potentials** are changes in polarization where the magnitude of the change varies with the strength of the stimulus
- These are not the nerve signals that travel along axons, but they do have an effect on the generation of nerve signals

- If a depolarization shifts the membrane potential sufficiently, it results in a massive change in membrane voltage called an **action potential**
- Action potentials have a constant magnitude, are all-or-none, and transmit signals over long distances
- They arise because some ion channels are **voltage-gated**, opening or closing when the membrane potential passes a certain level

Generation of Action Potentials: *A Closer Look*

- An action potential can be considered as a series of stages
- At resting potential
    1. Most voltage-gated sodium (Na^+) channels are closed; most of the voltage-gated potassium (K^+) channels are also closed

- When an action potential is generated
    2. Voltage-gated Na^+ channels open first and Na^+ flows into the cell
    3. During the *rising phase*, the threshold is crossed, and the membrane potential increases
    4. During the *falling phase*, voltage-gated Na^+ channels become inactivated; voltage-gated K^+ channels open, and K^+ flows out of the cell

5. During the *undershoot*, membrane permeability to K^+ is at first higher than at rest, then voltage-gated K^+ channels close and resting potential is restored

Figure 48.11-5

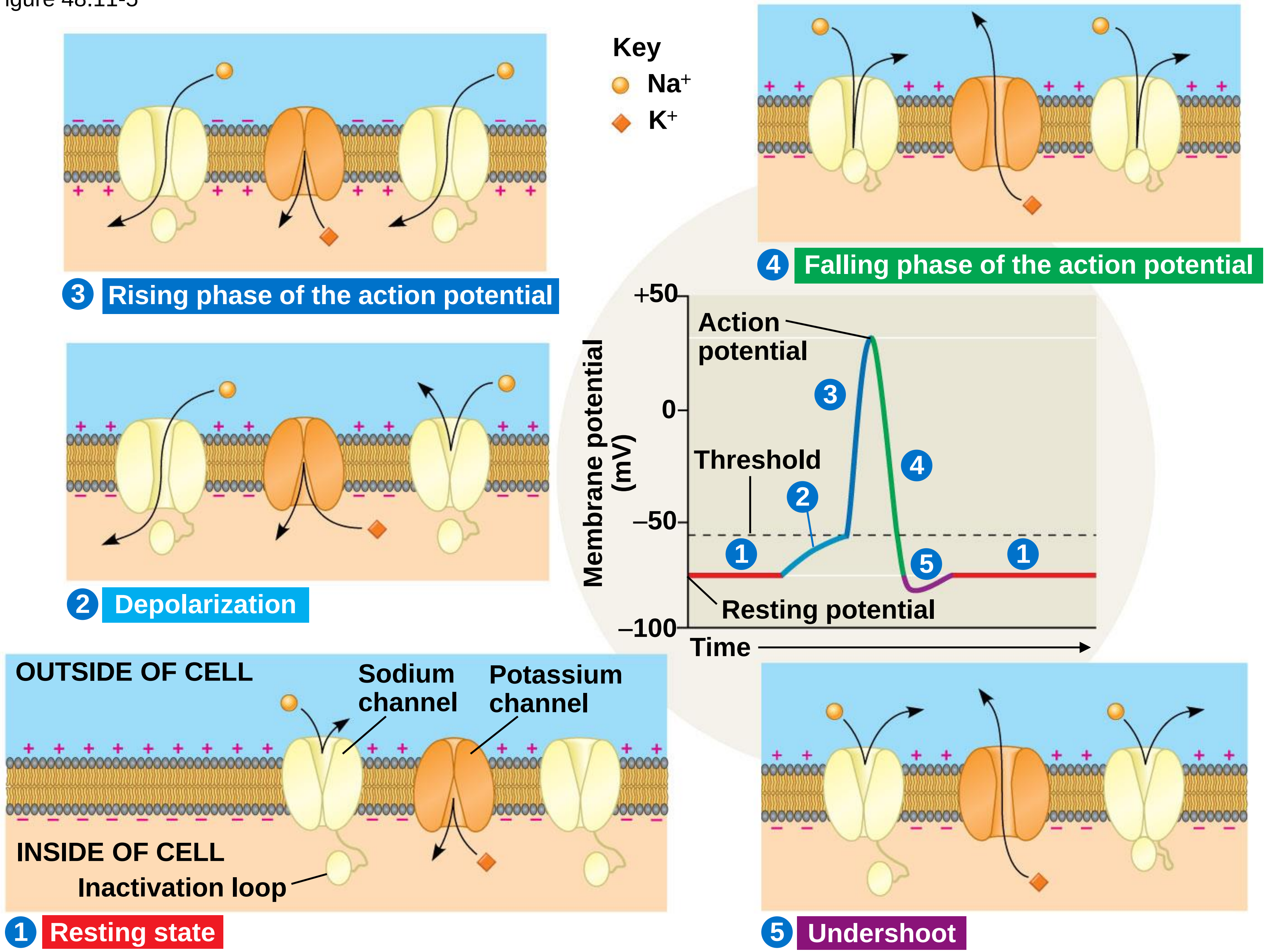
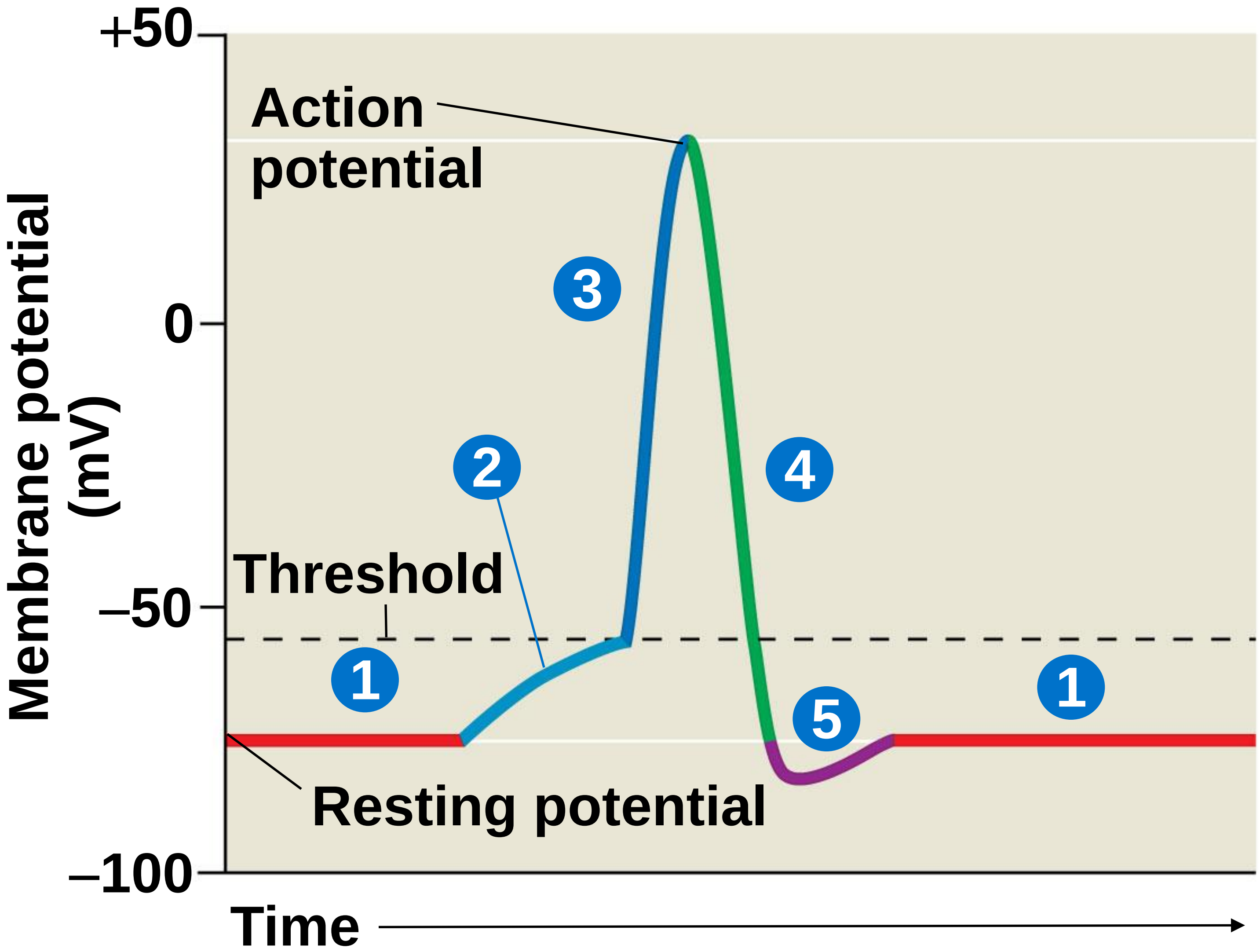


Figure 48.11a



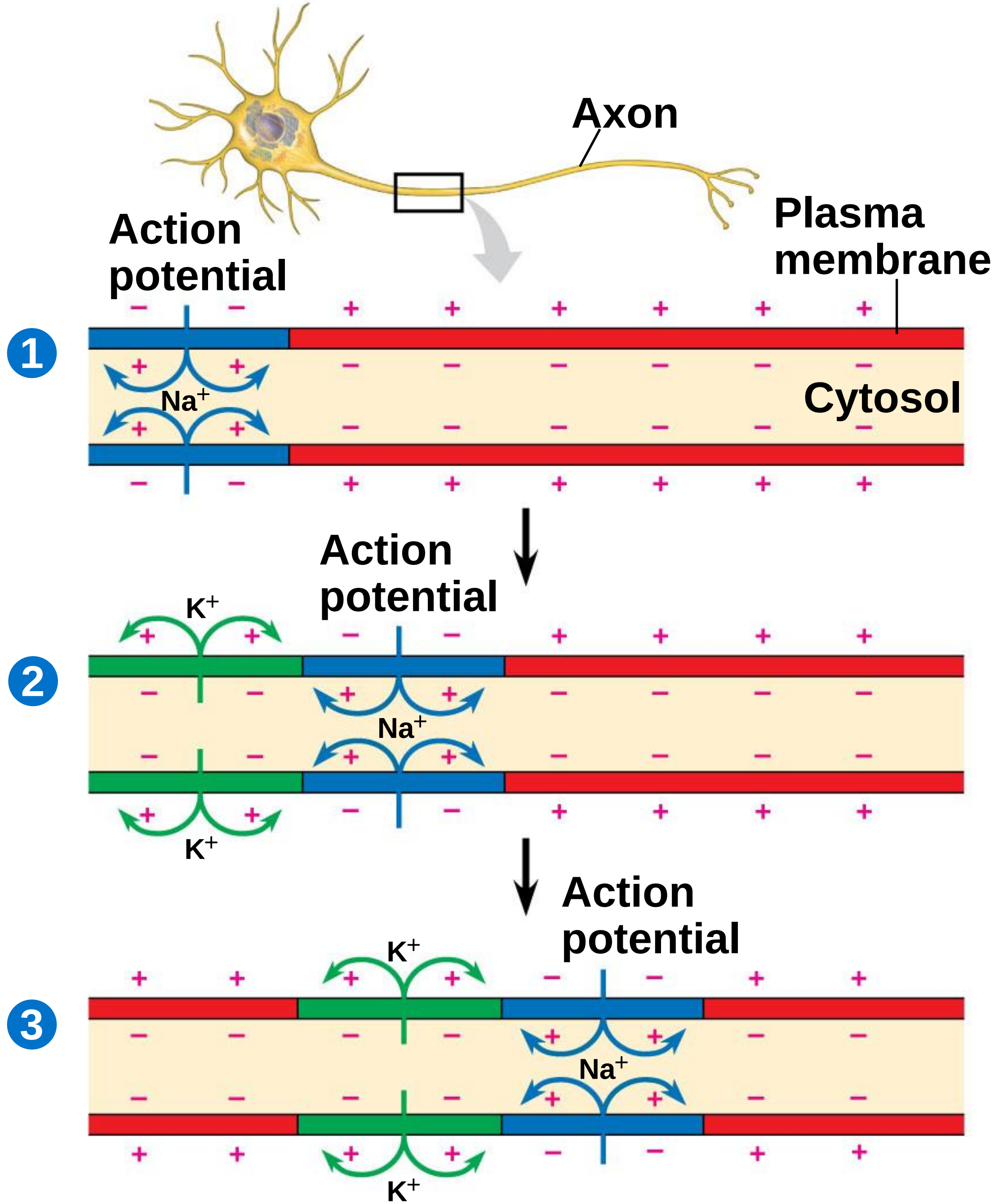
- During the **refractory period** after an action potential, a second action potential cannot be initiated
- The refractory period is a result of a temporary inactivation of the Na^+ channels

Conduction of Action Potentials

- At the site where the action potential is generated, usually the axon hillock, an electrical current depolarizes the neighboring region of the axon membrane
- Action potentials travel in only one direction: toward the synaptic terminals

- Inactivated Na^+ channels behind the zone of depolarization prevent the action potential from traveling backwards

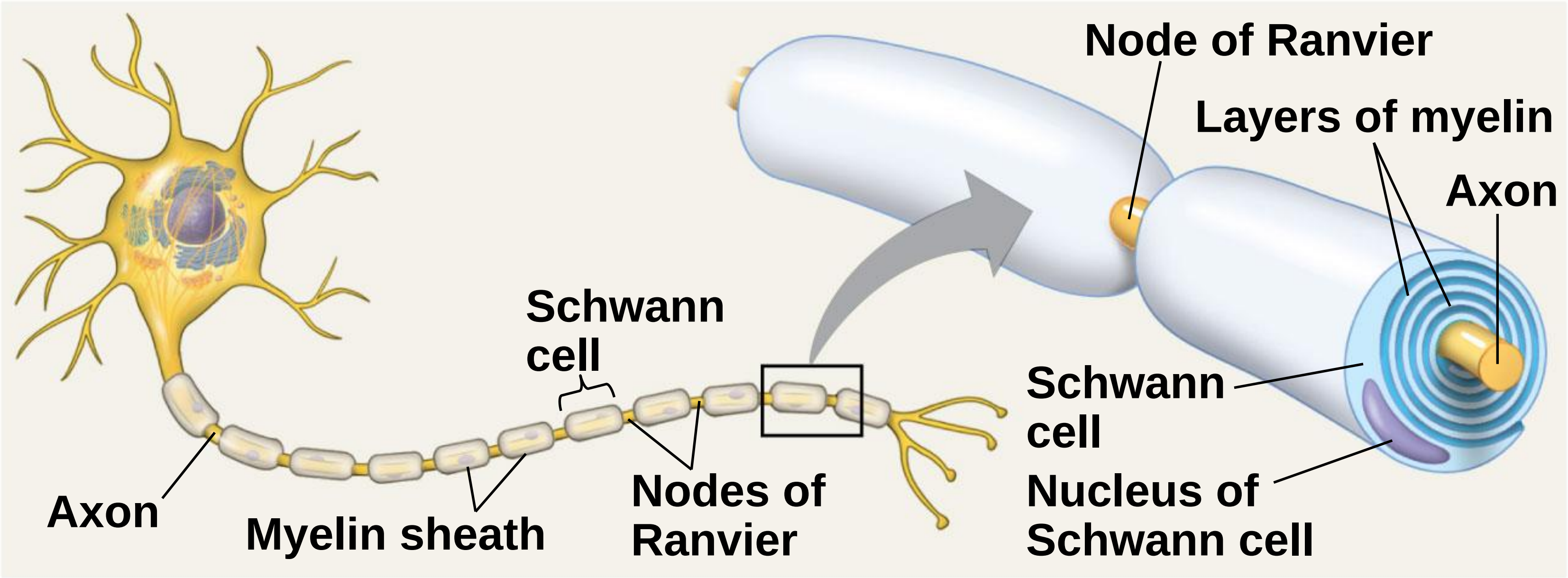
Figure 48.12-3



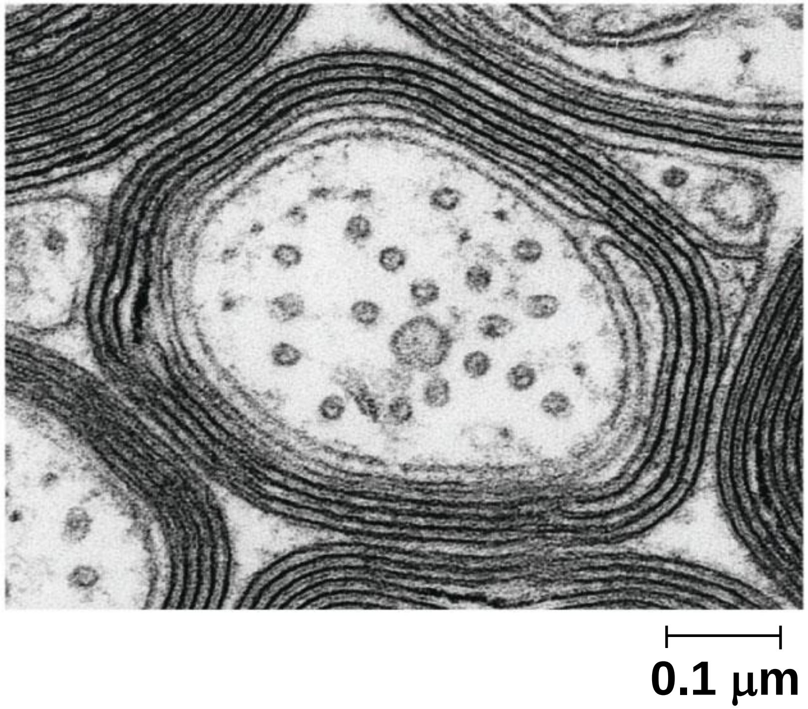
Evolutionary Adaptation of Axon Structure

- The speed of an action potential increases with the axon's diameter
- In vertebrates, axons are insulated by a **myelin sheath**, which causes an action potential's speed to increase
- Myelin sheaths are made by glia—**oligodendrocytes** in the CNS and **Schwann cells** in the PNS

Figure 48.13



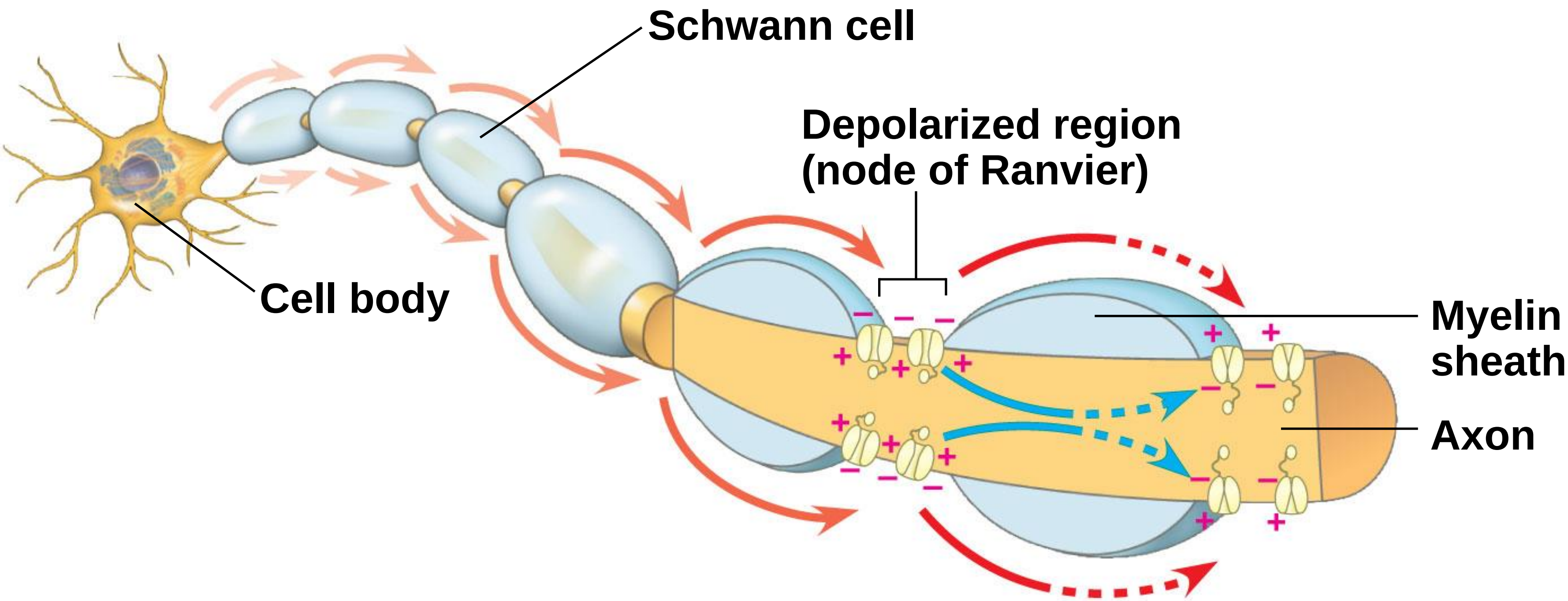
Node of Ranvier
Layers of myelin
Axon
Schwann cell
Schwann cell
Nucleus of Schwann cell
Axon
Myelin sheath
Nodes of Ranvier



0.1 μm

- Action potentials are formed only at **nodes of Ranvier**, gaps in the myelin sheath where voltage-gated Na^+ channels are found
- Action potentials in myelinated axons jump between the nodes of Ranvier in a process called **saltatory conduction**

Figure 48.14

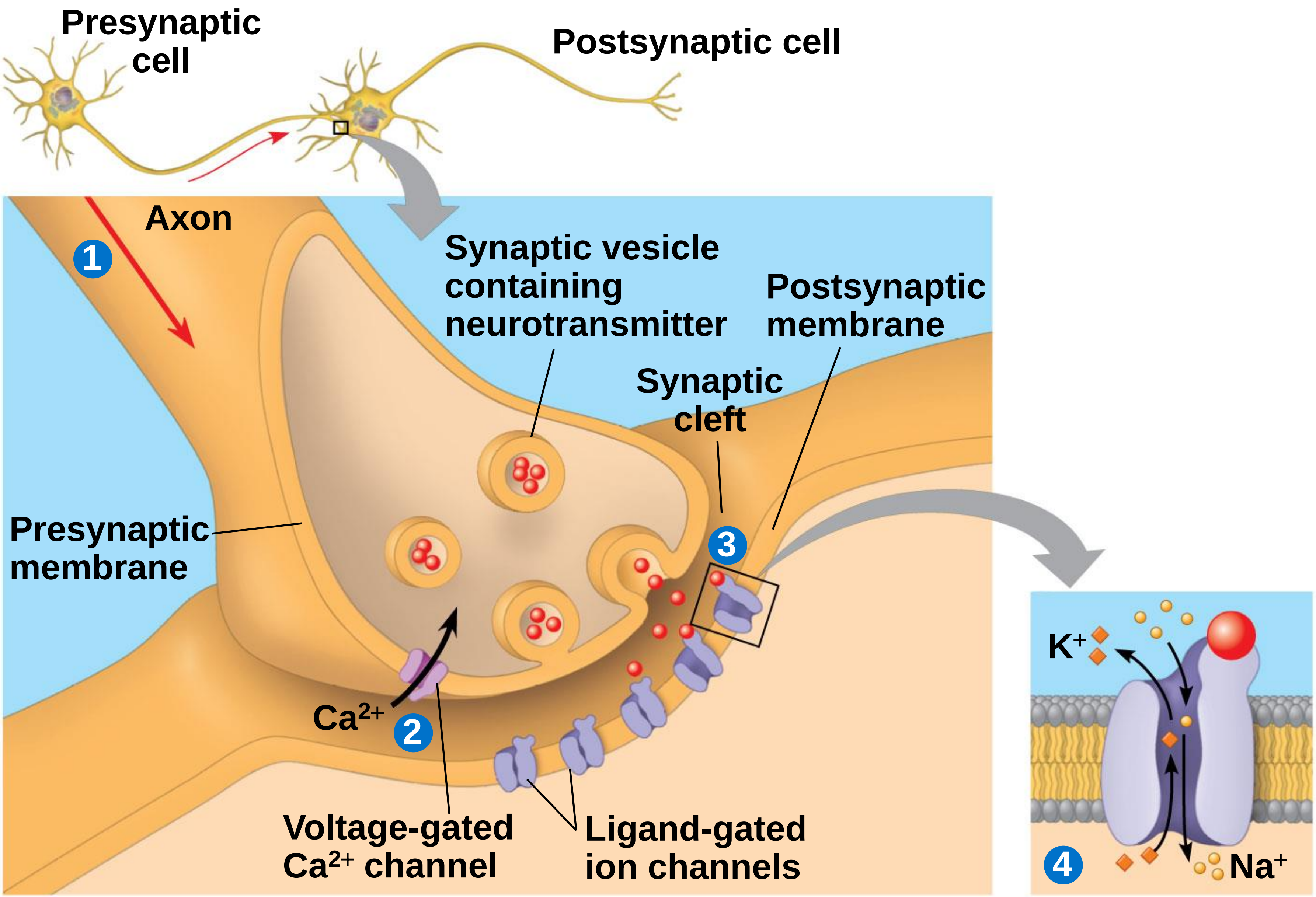

Schwann cell
Depolarized region
(node of Ranvier)
Cell body
Myelin
sheath
Axon

Concept 48.4: Neurons communicate with other cells at synapses

- At electrical synapses, the electrical current flows from one neuron to another
- At chemical synapses, a chemical neurotransmitter carries information across the gap junction
- Most synapses are chemical synapses

- The presynaptic neuron synthesizes and packages the neurotransmitter in **synaptic vesicles** located in the synaptic terminal
- The action potential causes the release of the neurotransmitter
- The neurotransmitter diffuses across the **synaptic cleft** and is received by the postsynaptic cell

Figure 48.15



Presynaptic cell
Postsynaptic cell
Axon
1
Synaptic vesicle containing neurotransmitter
Postsynaptic membrane
Synaptic cleft
Presynaptic membrane
3
Ca2+
2
Voltage-gated Ca2+ channel
Ligand-gated ion channels
K+
Na+
4

Generation of Postsynaptic Potentials

- Direct synaptic transmission involves binding of neurotransmitters to **ligand-gated ion channels** in the postsynaptic cell
- Neurotransmitter binding causes ion channels to open, generating a postsynaptic potential

- Postsynaptic potentials fall into two categories
  - **Excitatory postsynaptic potentials (EPSPs)** are depolarizations that bring the membrane potential toward threshold
  - **Inhibitory postsynaptic potentials (IPSPs)** are hyperpolarizations that move the membrane potential farther from threshold

- After release, the neurotransmitter
  - May diffuse out of the synaptic cleft
  - May be taken up by surrounding cells
  - May be degraded by enzymes

Summation of Postsynaptic Potentials

- Most neurons have many synapses on their dendrites and cell body
- A single EPSP is usually too small to trigger an action potential in a postsynaptic neuron

Figure 48.16

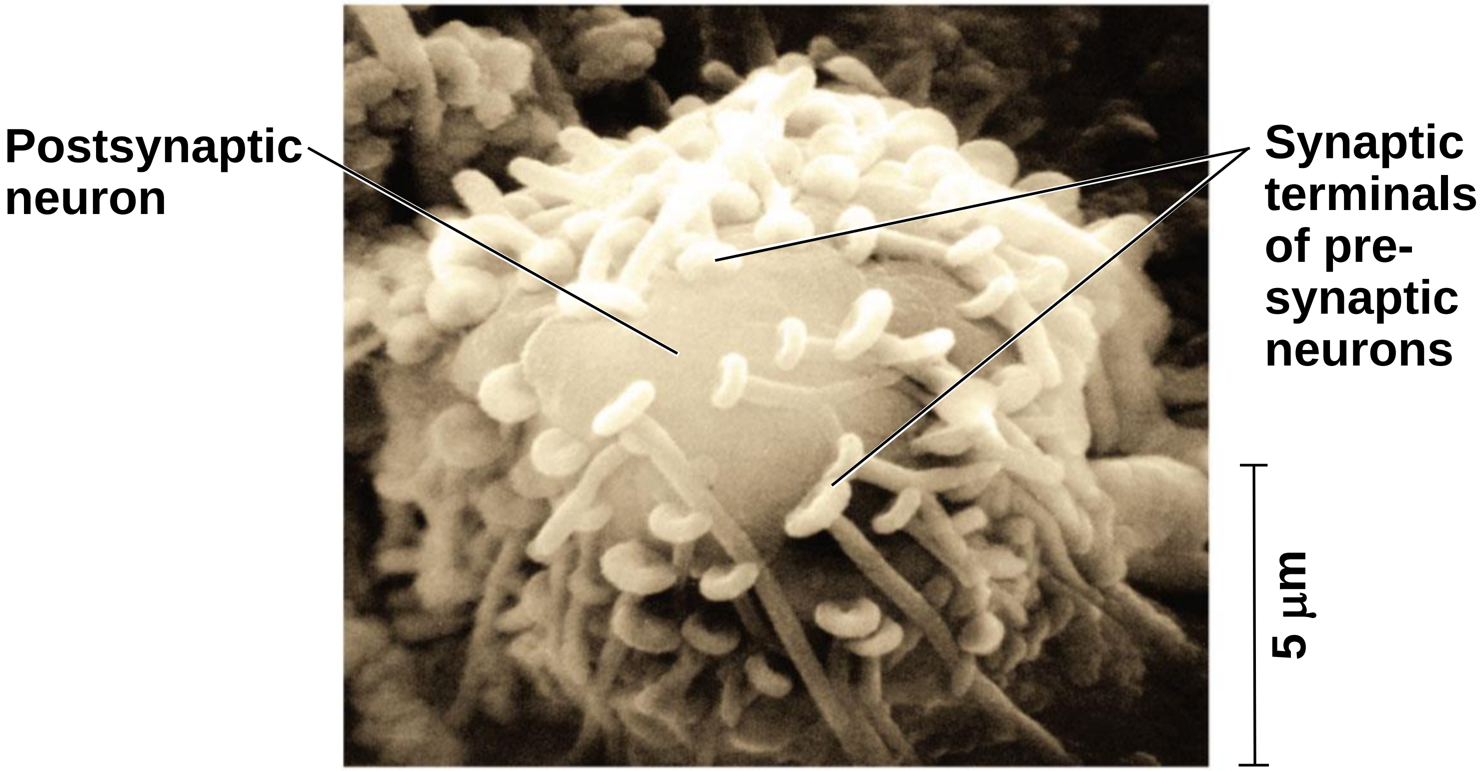
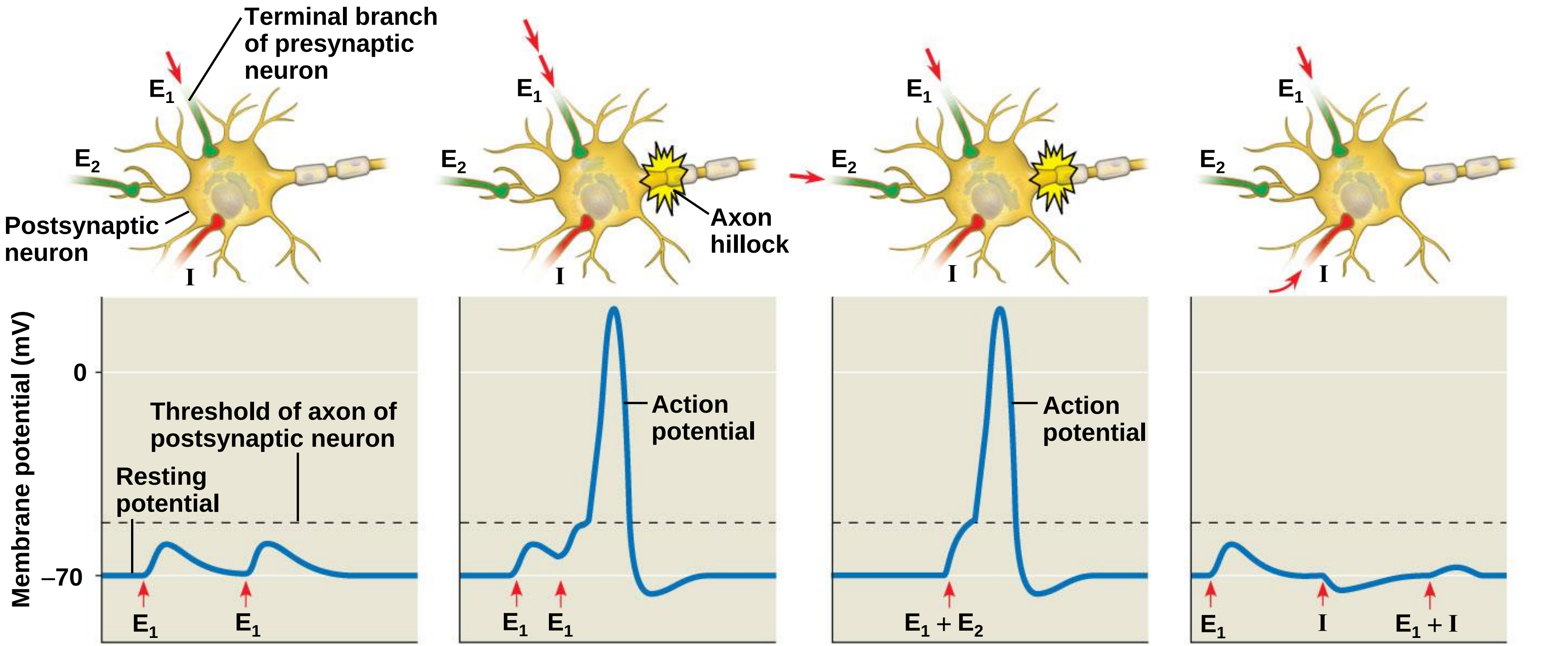

Postsynaptic neuron
Synaptic terminals of pre-synaptic neurons
5 µm

Figure 48.17



(a) Subthreshold, no summation

(b) Temporal summation

(c) Spatial summation

(d) Spatial summation of EPSP and IPSP

- If two EPSPs are produced in rapid succession, an effect called **temporal summation** occurs

- In **spatial summation**, EPSPs produced nearly simultaneously by different synapses on the same postsynaptic neuron add together
- The combination of EPSPs through spatial and temporal summation can trigger an action potential

- Through summation, an IPSP can counter the effect of an EPSP
- The summed effect of EPSPs and IPSPs determines whether an axon hillock will reach threshold and generate an action potential

Modulated Signaling at Synapses

- In some synapses, a neurotransmitter binds to a receptor that is metabotropic
- In this case, movement of ions through a channel depends on one or more metabolic steps

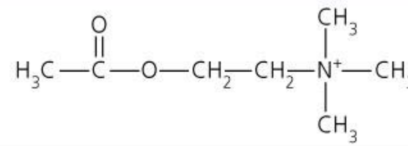
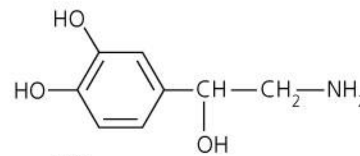
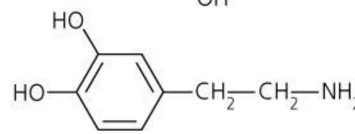
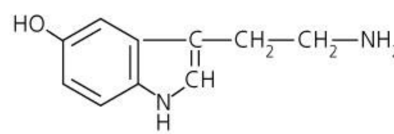
- Binding of a neurotransmitter to a metabotropic receptor activates a signal transduction pathway in the postsynaptic cell involving a second messenger
- Compared to ligand-gated channels, the effects of second-messenger systems have a slower onset but last longer

Neurotransmitters

- There are more than 100 neurotransmitters, belonging to five groups: acetylcholine, biogenic amines, amino acids, neuropeptides, and gases
- A single neurotransmitter may have more than a dozen different receptors

Table 48.2

Table 48.2 Major Neurotransmitters

Neurotransmitter	Structure
Acetylcholine	
Amino Acids	
GABA (gamma-aminobutyric acid)	$H_2N—CH_2—CH_2—CH_2—COOH$
Glutamate	$H_2N—CH(COOH)—CH_2—CH_2—COOH$
Glycine	$H_2N—CH_2—COOH$
Biogenic Amines	
Norepinephrine	
Dopamine	
Serotonin	
Neuropeptides (a very diverse group, only two of which are shown)	
Substance P	Arg—Pro—Lys—Pro—Gln—Gln—Phe—Phe—Gly—Leu—Met
Met-enkephalin (an endorphin)	Tyr—Gly—Gly—Phe—Met
Gases	
Nitric oxide	N═O

Acetylcholine

- **Acetylcholine** is a common neurotransmitter in vertebrates and invertebrates
- It is involved in muscle stimulation, memory formation, and learning
- Vertebrates have two major classes of acetylcholine receptor, one that is ligand gated and one that is metabotropic

Amino Acids

- Amino acid neurotransmitters are active in the CNS and PNS
- Known to function in the CNS are
  - **Glutamate**
  - **Gamma-aminobutyric acid (GABA)**
  - Glycine

Biogenic Amines

- **Biogenic amines** include
  - **Epinephrine**
  - **Norepinephrine**
  - **Dopamine**
  - **Serotonin**
- They are active in the CNS and PNS

Neuropeptides

- Several **neuropeptides**, relatively short chains of amino acids, also function as neurotransmitters
- Neuropeptides include substance P and **endorphins**, which both affect our perception of pain
- Opiates bind to the same receptors as endorphins and can be used as painkillers

Gases

- Gases such as nitric oxide and carbon monoxide are local regulators in the PNS