Chapter 48

Neurons, Synapses, and Signaling

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp

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)

Fig. 48-1

- The transmission of information depends on the path of neurons along which a signal travels
- 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 is a good model for studying neuron function

Introduction to Information Processing

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

Fig. 48-2

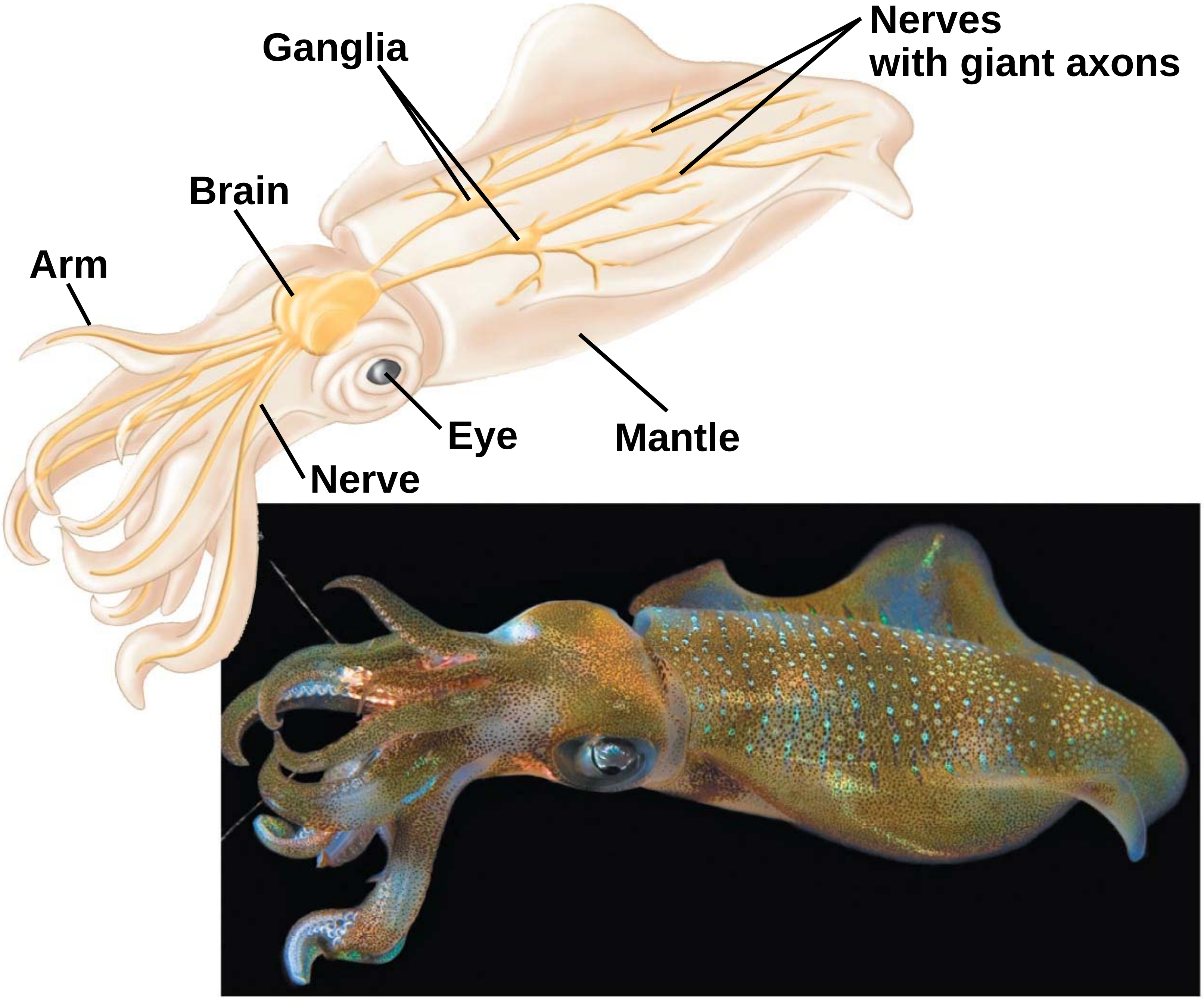
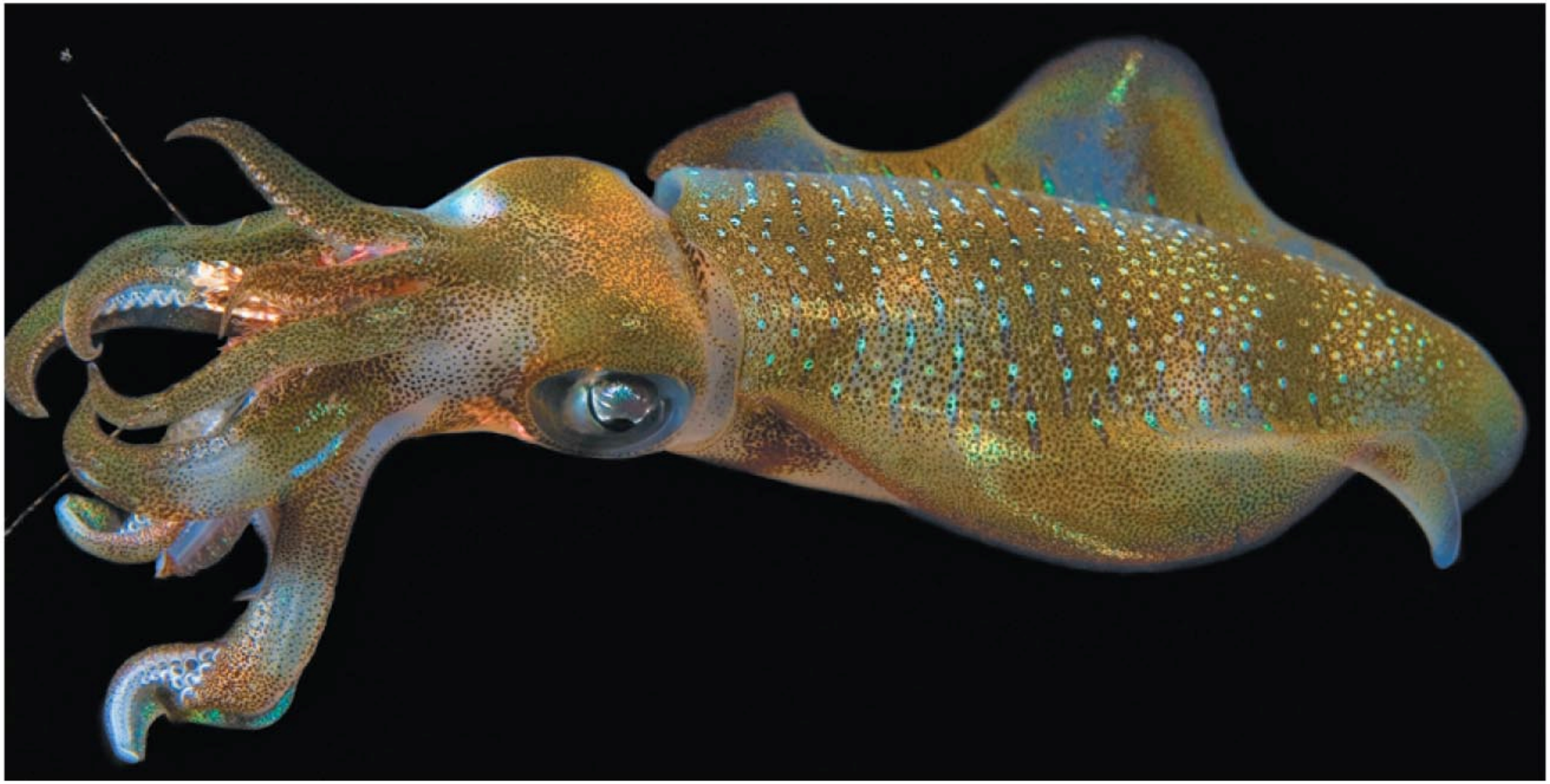


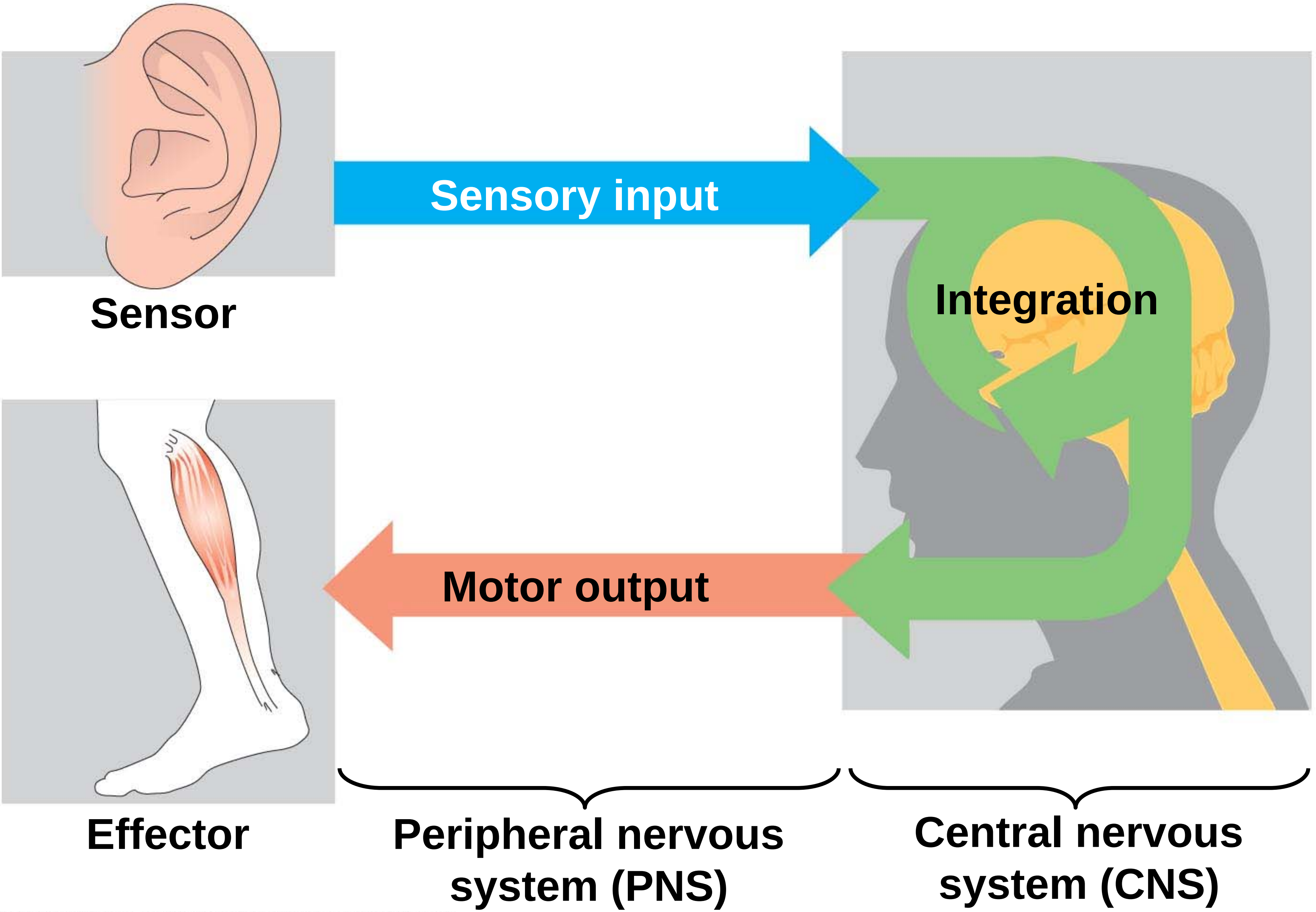
Fig. 48-2a



- 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 which 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 brings information into and out of the CNS

Fig. 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
- An axon joins the cell body at the **axon hillock**

Fig. 48-4

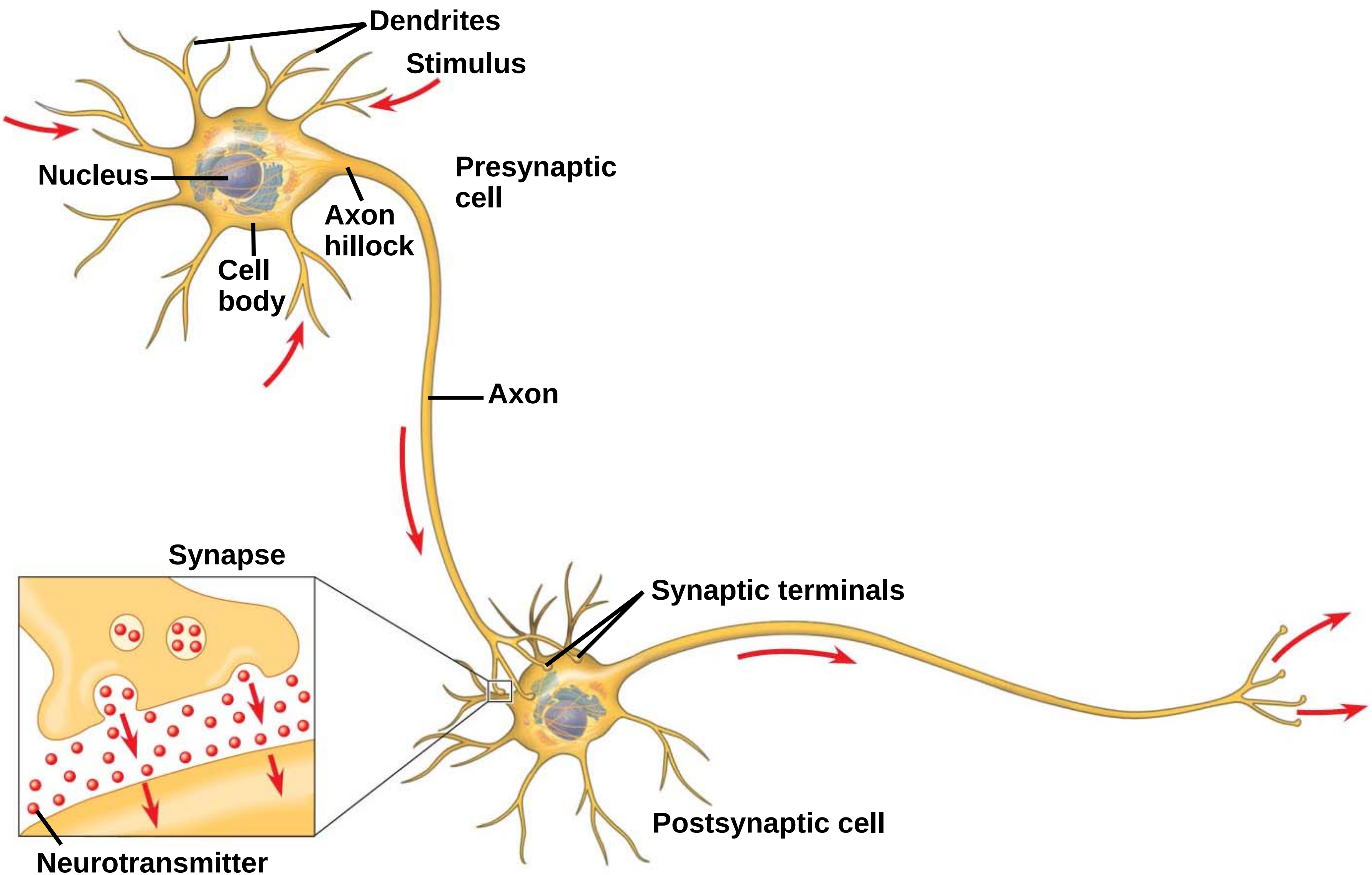
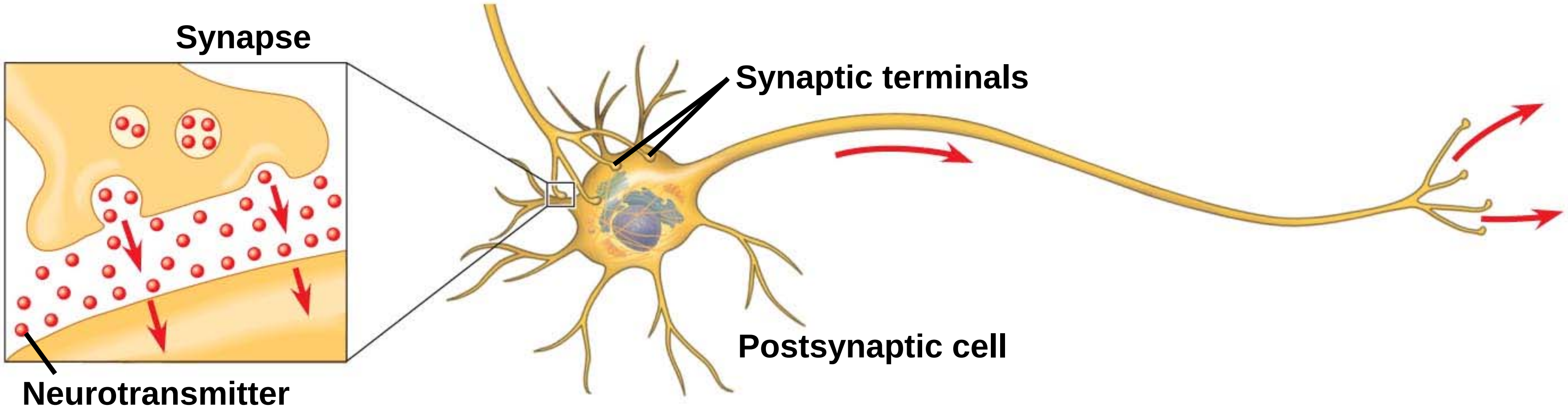

Dendrites
Stimulus
Nucleus
Presynaptic cell
Axon hillock
Cell body
Axon
Synapse
Synaptic terminals
Postsynaptic cell
Neurotransmitter

Fig. 48-4a


Synapse
Synaptic terminals
Postsynaptic cell
Neurotransmitter

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

- 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**

Fig. 48-5

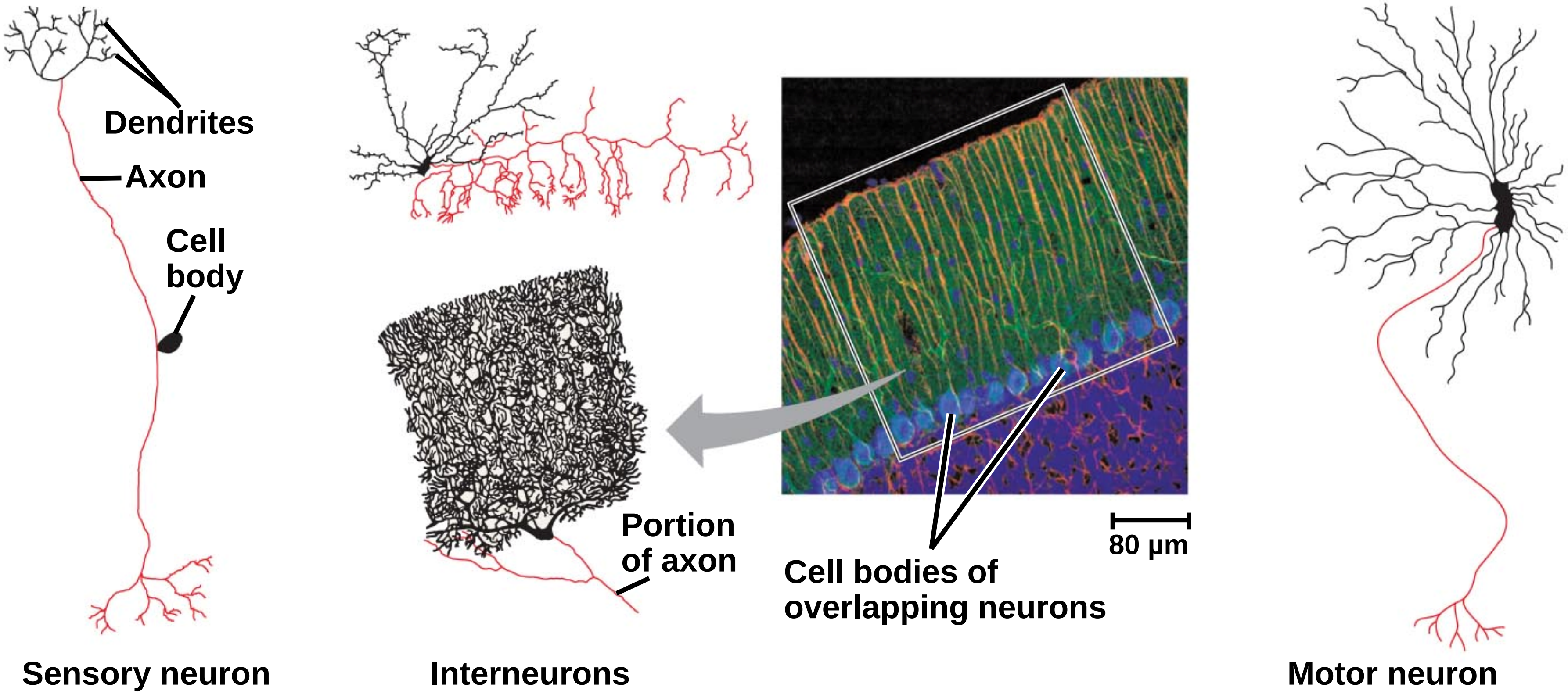
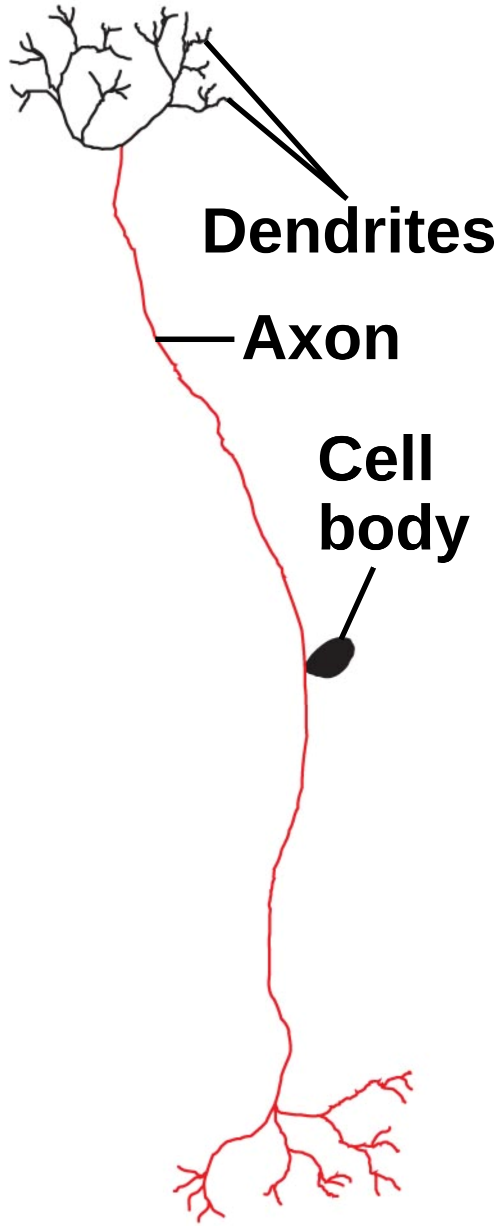
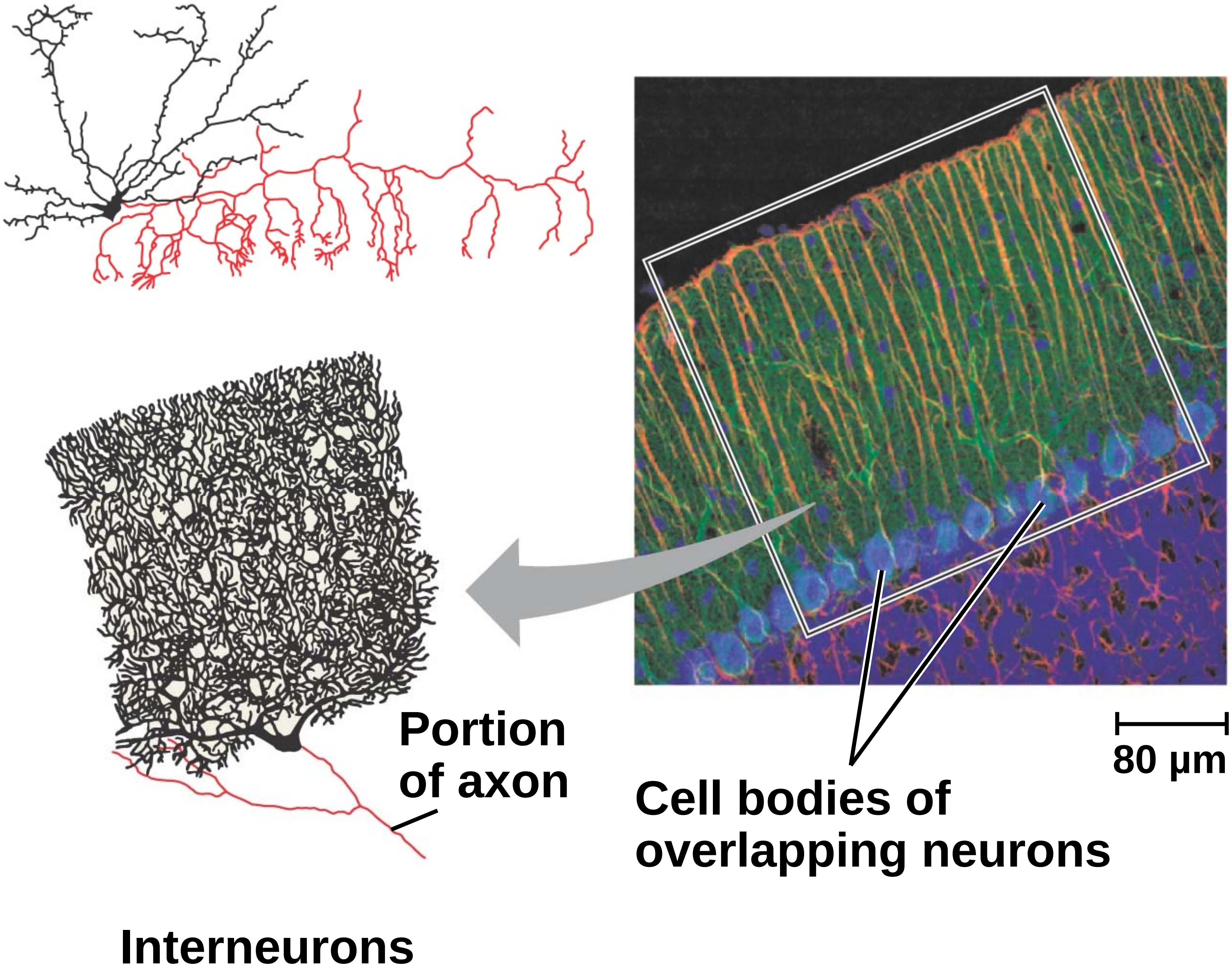

Dendrites
Axon
Cell
body
Portion
of axon
Cell bodies of
overlapping neurons
80 µm
Sensory neuron
Interneurons
Motor neuron

Fig. 48-5a



Sensory neuron

Fig. 48-5b



Portion
of axon
Cell bodies of
overlapping neurons
80 µm
Interneurons

Fig. 48-5c

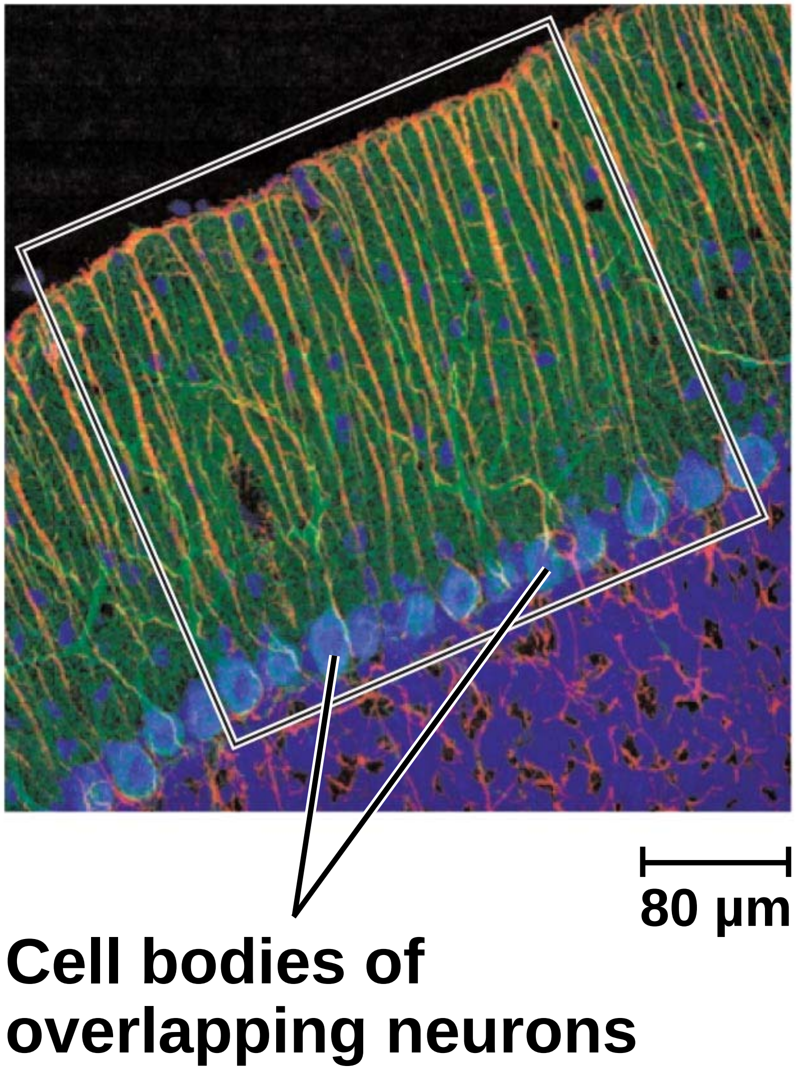
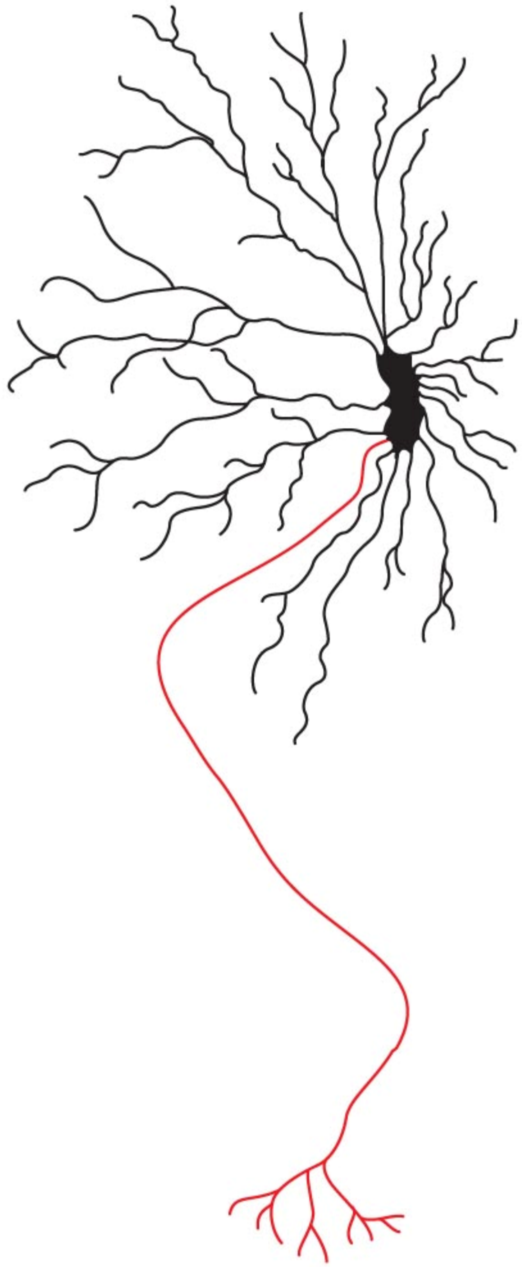


Fig. 48-5d



Motor neuron

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

- Every cell has a voltage (difference in electrical charge) across its plasma membrane called a **membrane potential**
- Messages are transmitted as changes in membrane potential
- The **resting potential** is the membrane potential of a neuron not sending signals

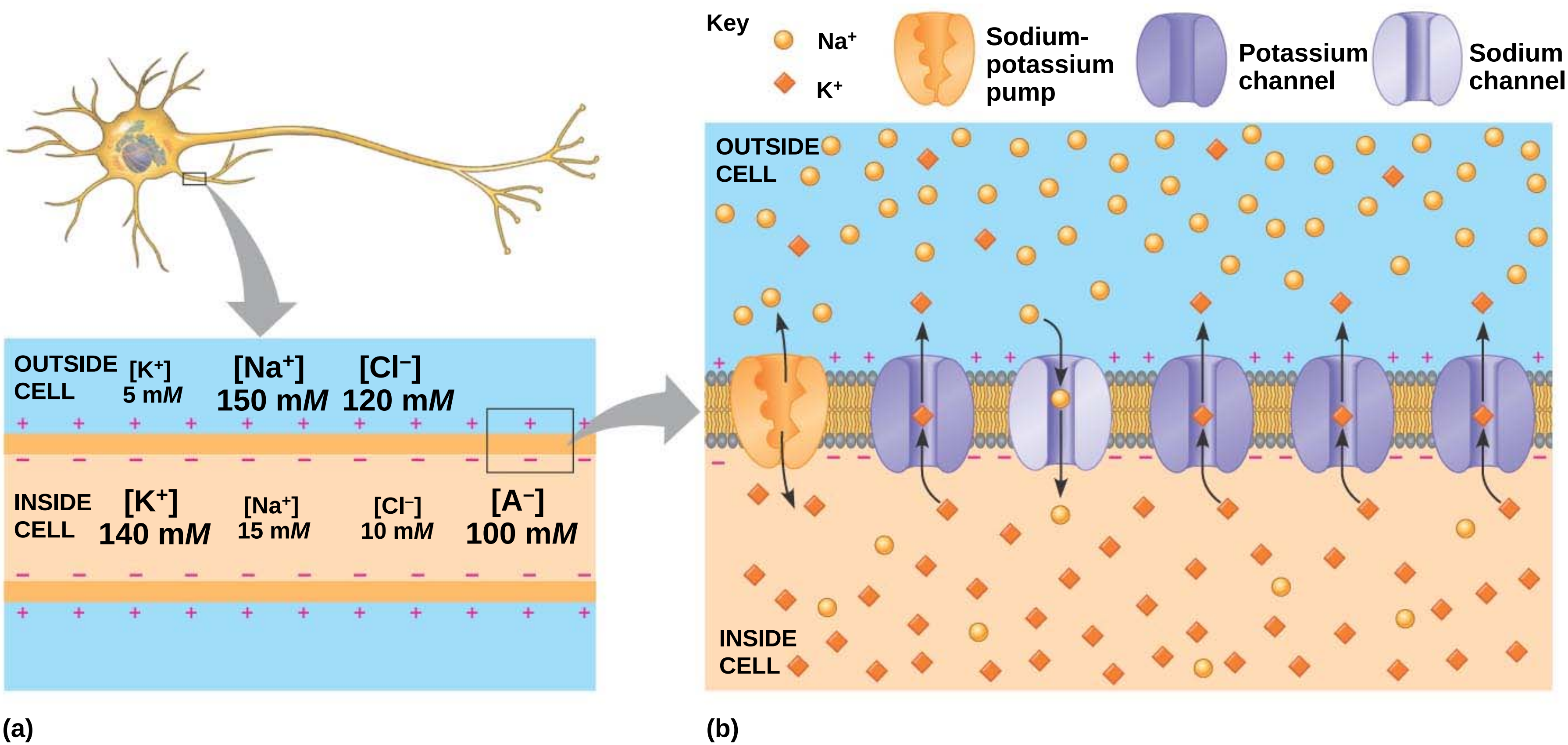
Formation of the Resting Potential

- In a mammalian neuron at resting potential, the concentration of K^+ is greater inside the cell, while the concentration of Na^+ is greater 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
- Anions trapped inside the cell contribute to the negative charge within the neuron

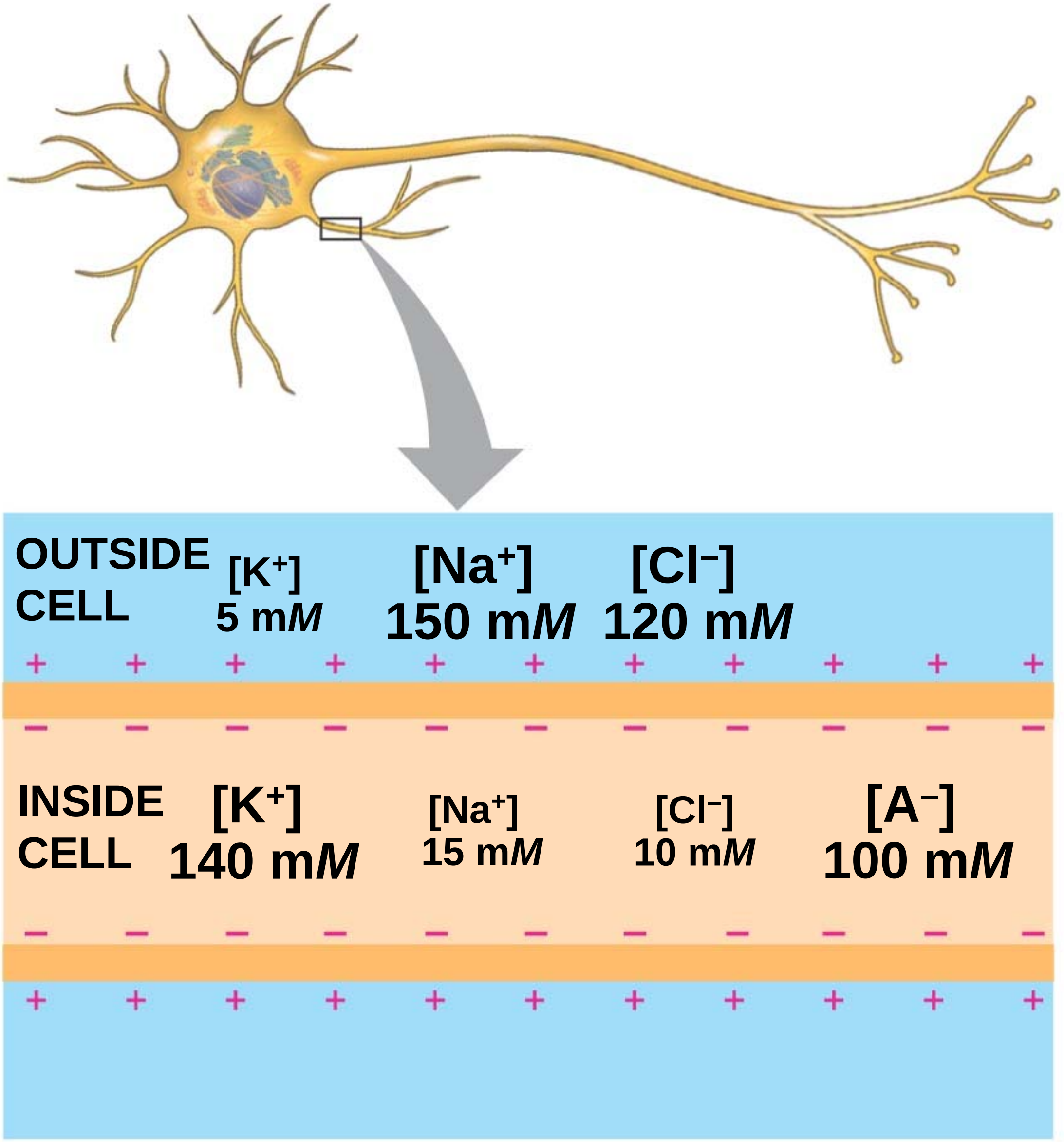
PLAY Animation: Resting Potential

Fig. 48-6



OUTSIDE CELL
[K+] 5 mM
[Na+] 150 mM
[Cl–] 120 mM
INSIDE CELL
[K+] 140 mM
[Na+] 15 mM
[Cl–] 10 mM
[A–] 100 mM
(a)
Key
Na+
K+
Sodium-potassium pump
Potassium channel
Sodium channel
OUTSIDE CELL
INSIDE CELL
(b)

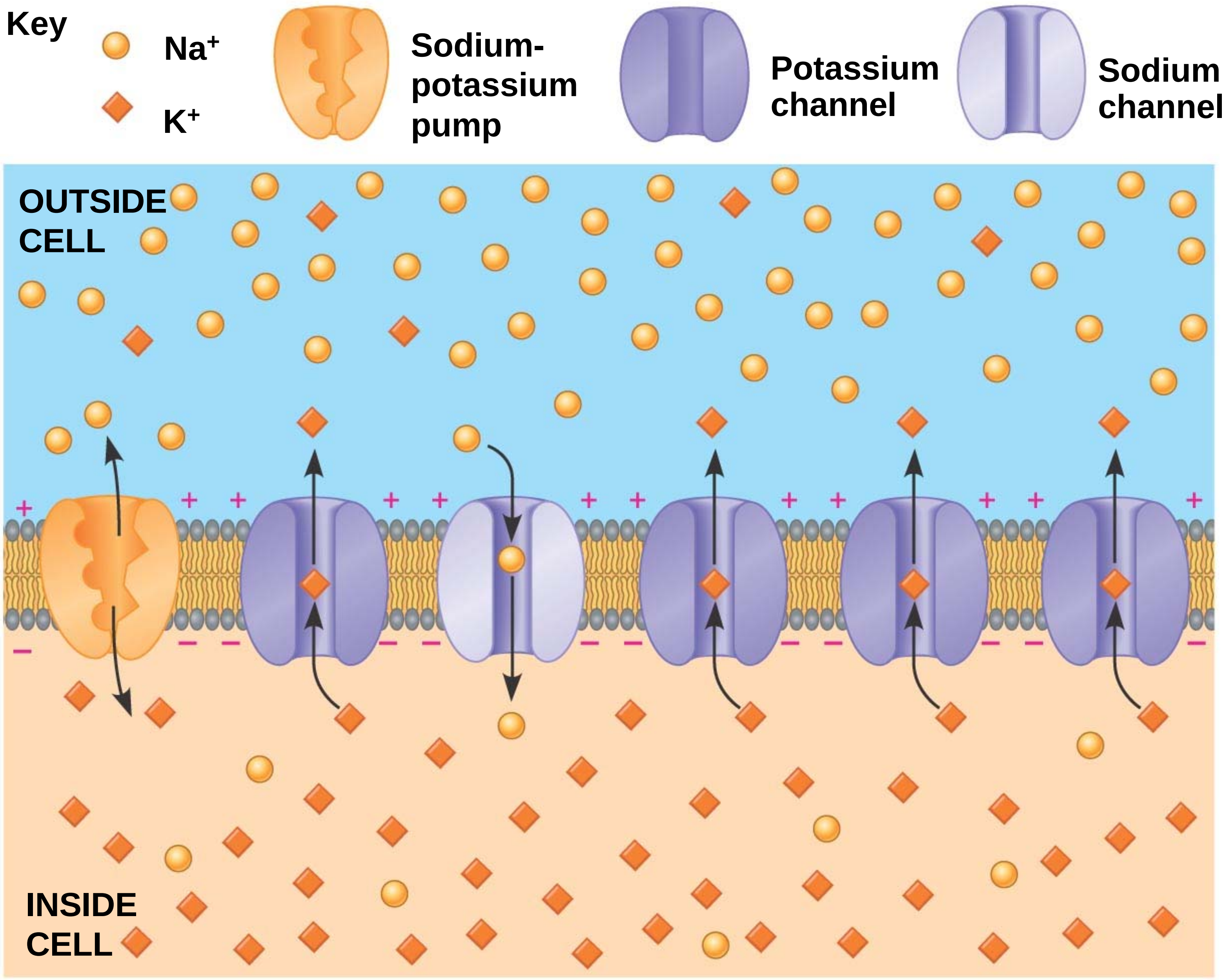
Fig. 48-6a



OUTSIDE CELL
[K+] 5 mM
[Na+] 150 mM
[Cl–] 120 mM
INSIDE CELL
[K+] 140 mM
[Na+] 15 mM
[Cl–] 10 mM
[A–] 100 mM

(a)

Fig. 48-6b



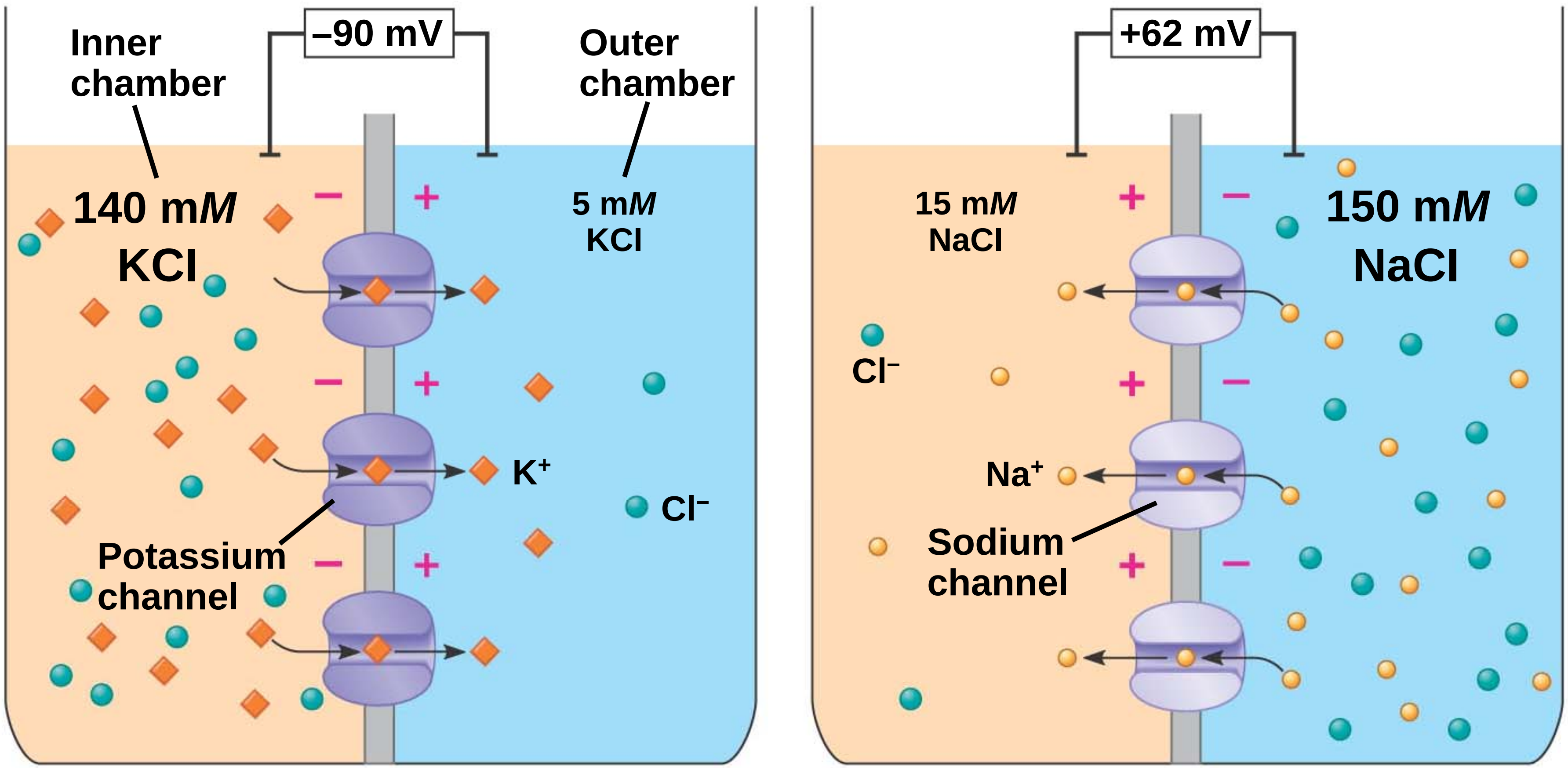
Key
Na+
K+
Sodium-potassium pump
Potassium channel
Sodium channel
OUTSIDE CELL
INSIDE CELL

(b)

Modeling of 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 builds up in the inner chamber
- At equilibrium, both the electrical and chemical gradients are balanced

Fig. 48-7



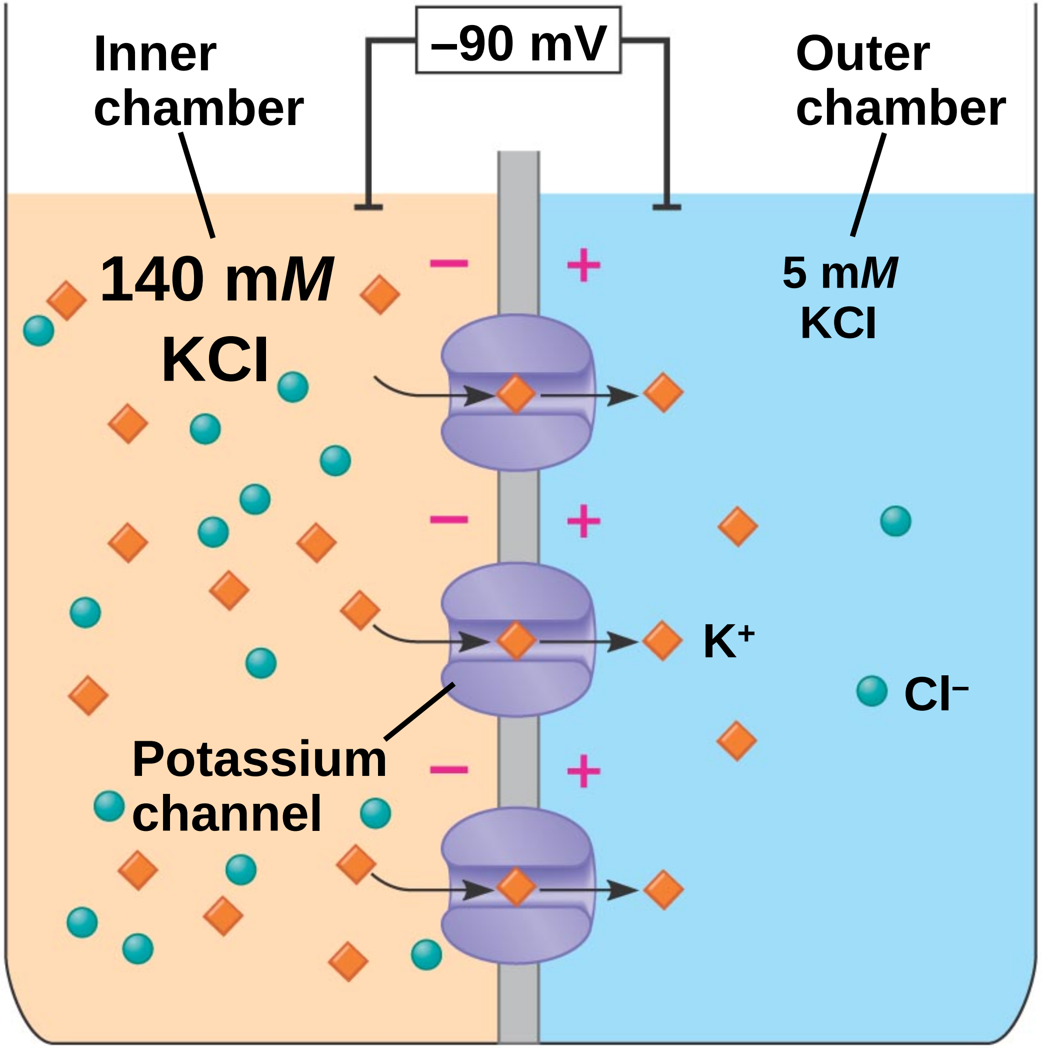
(a) Membrane selectively permeable to K^+

(b) Membrane selectively permeable to Na^+

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

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

Fig. 48-7a



(a) Membrane selectively permeable to K^+

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

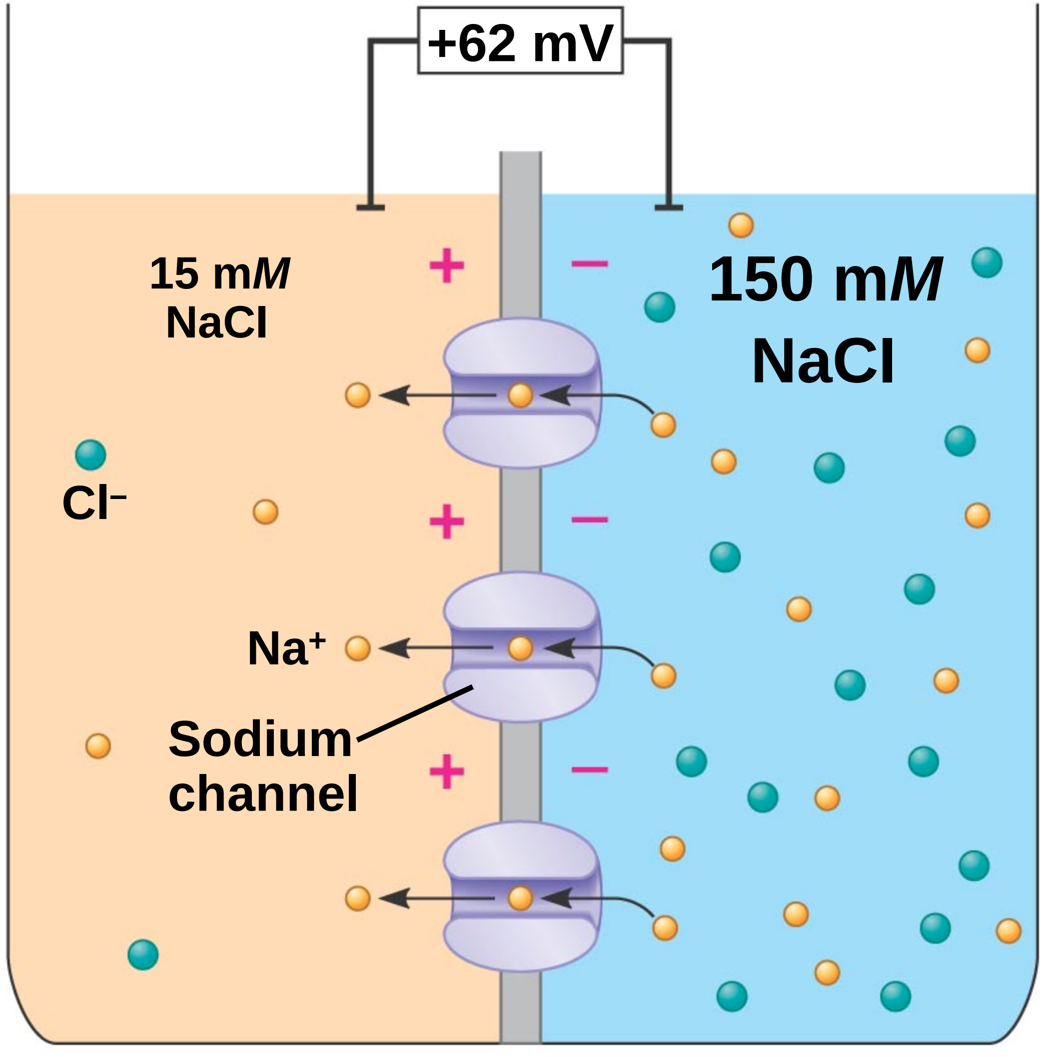
- The **equilibrium potential (E_{ion})** is the membrane voltage for a particular ion at equilibrium and can be calculated using the Nernst equation:

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

- 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

Fig. 48-7b



(b) Membrane selectively permeable to Na^+

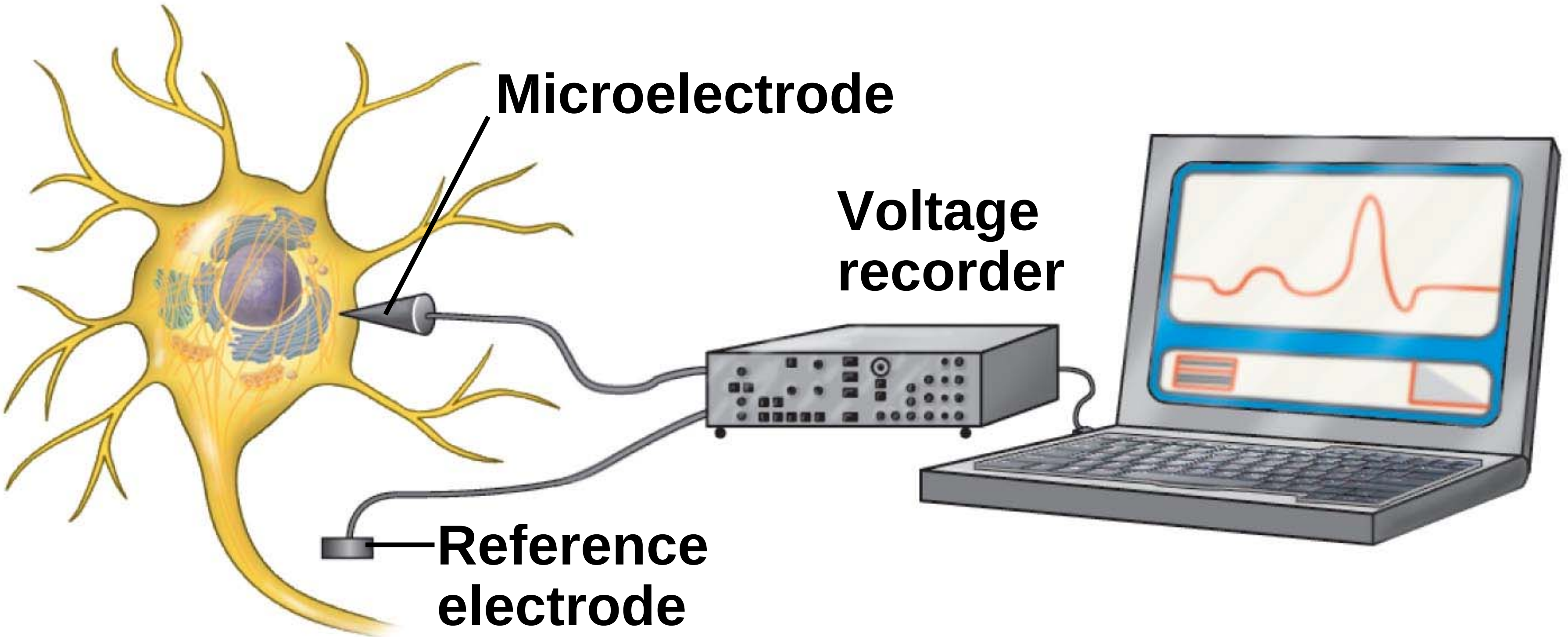
$$E_{Na} = 62\ \text{mV} \left(\log \frac{150\ mM}{15\ mM}\right) = +62\ \text{mV}$$

Concept 48.3: Action potentials are the signals conducted by axons

- Neurons contain **gated ion channels** that open or close in response to stimuli

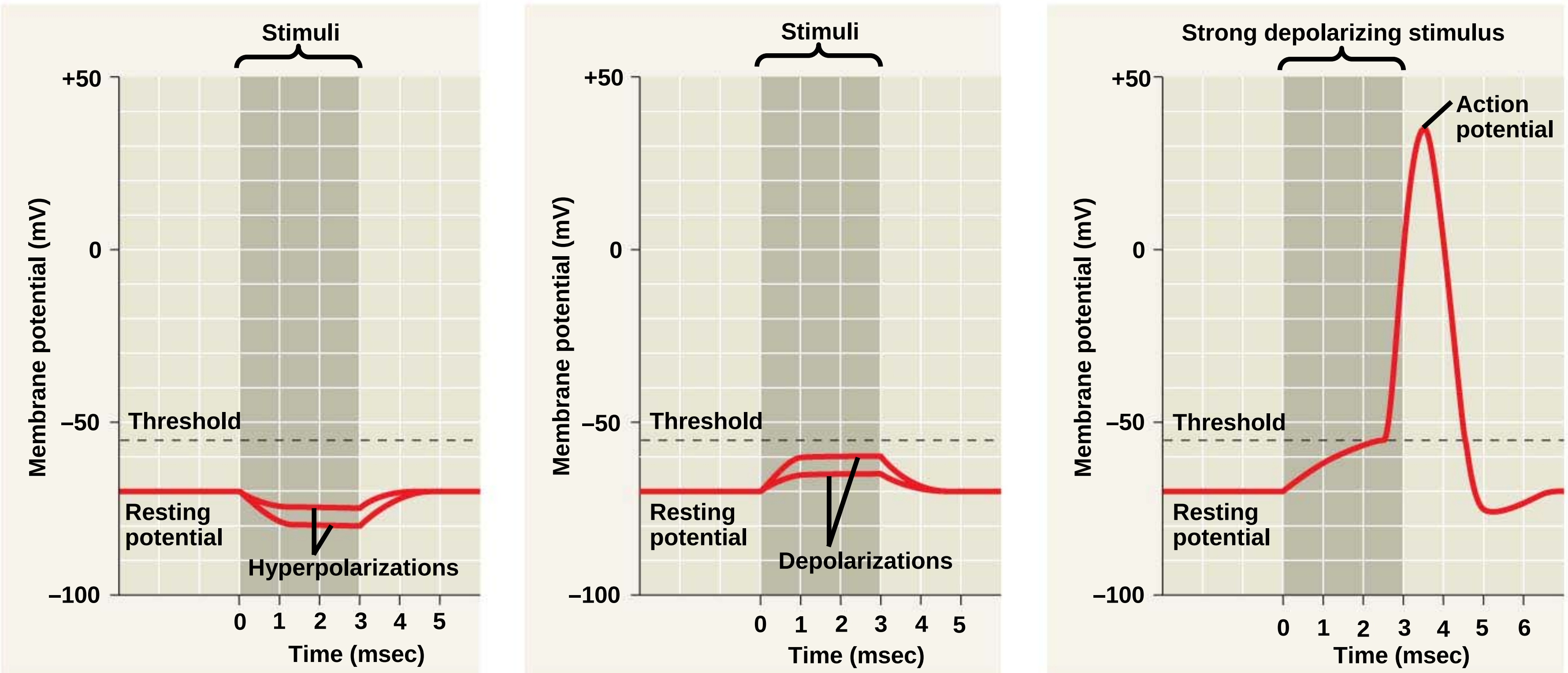
Fig. 48-8

TECHNIQUE



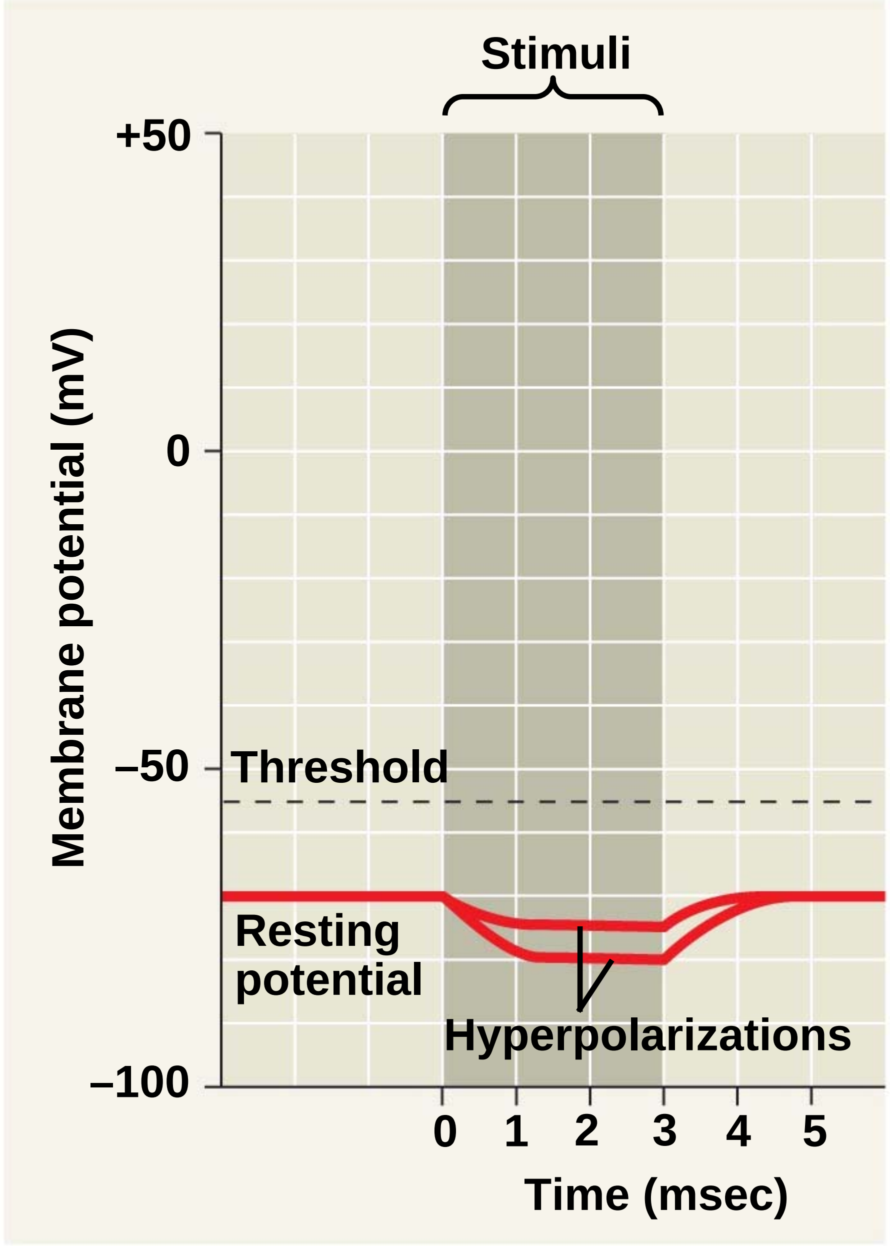
- Membrane potential changes in response to opening or closing of these channels
- When gated K^+ channels open, K^+ diffuses out, making the inside of the cell more negative
- This is **hyperpolarization**, an increase in magnitude of the membrane potential

Fig. 48-9



(a) Graded hyperpolarizations (b) Graded depolarizations (c) Action potential

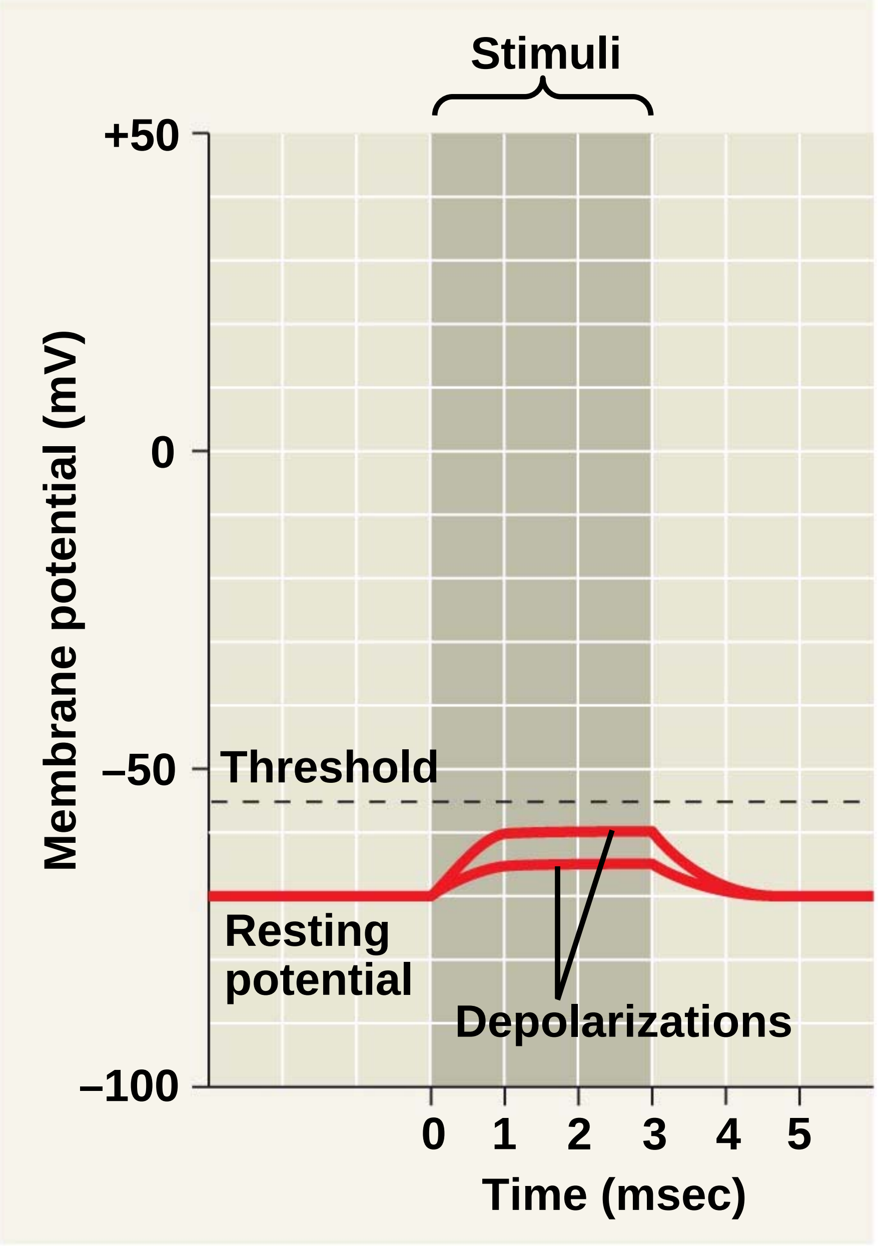
Fig. 48-9a



(a) Graded hyperpolarizations

- Other stimuli trigger 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 are changes in polarization where the magnitude of the change varies with the strength of the stimulus

Fig. 48-9b

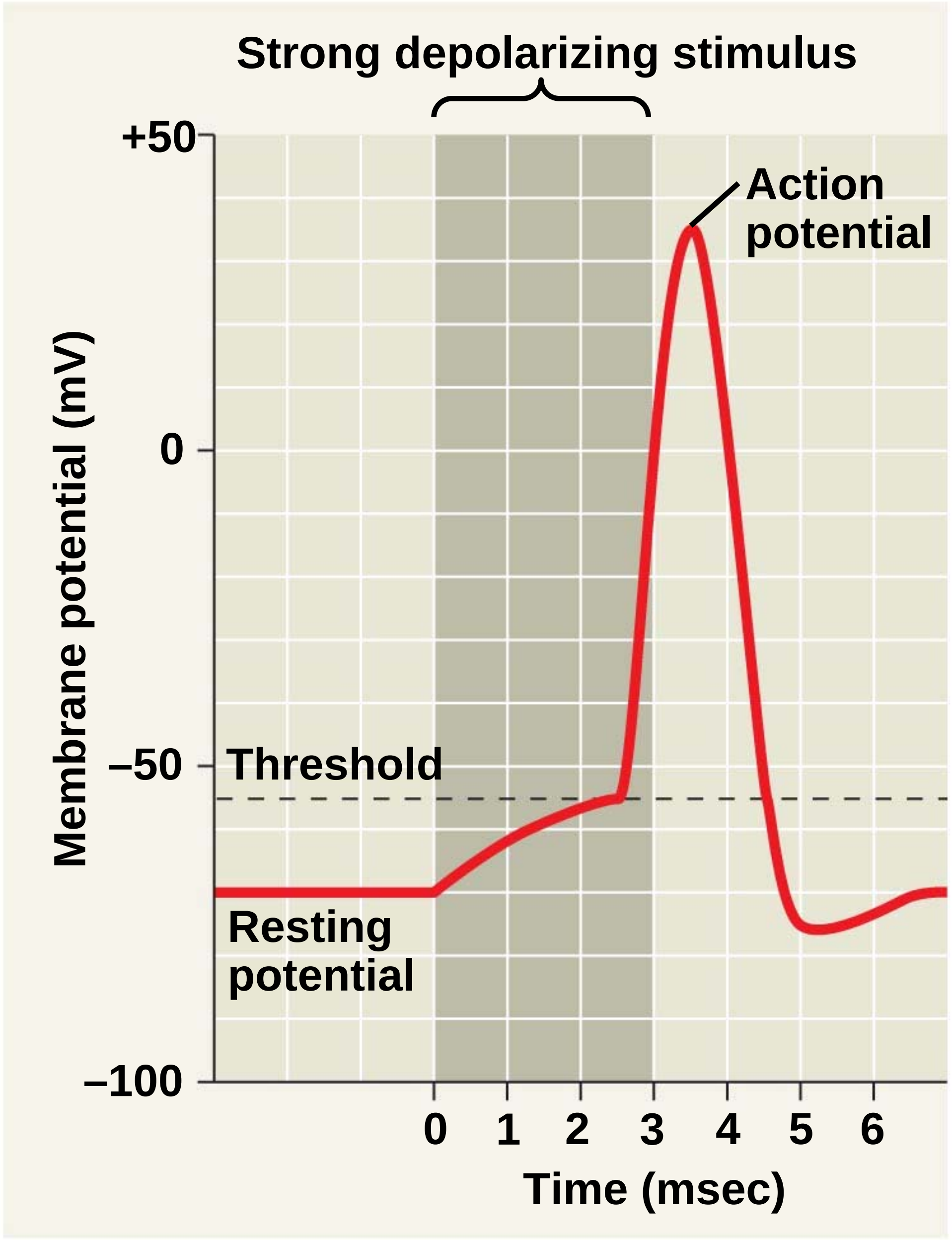


(b) Graded depolarizations

Production of Action Potentials

- **Voltage-gated** Na^+ and K^+ channels respond to a change in membrane potential
- When a stimulus depolarizes the membrane, Na^+ channels open, allowing Na^+ to diffuse into the cell
- The movement of Na^+ into the cell increases the depolarization and causes even more Na^+ channels to open
- A strong stimulus results in a massive change in membrane voltage called an **action potential**

Fig. 48-9c



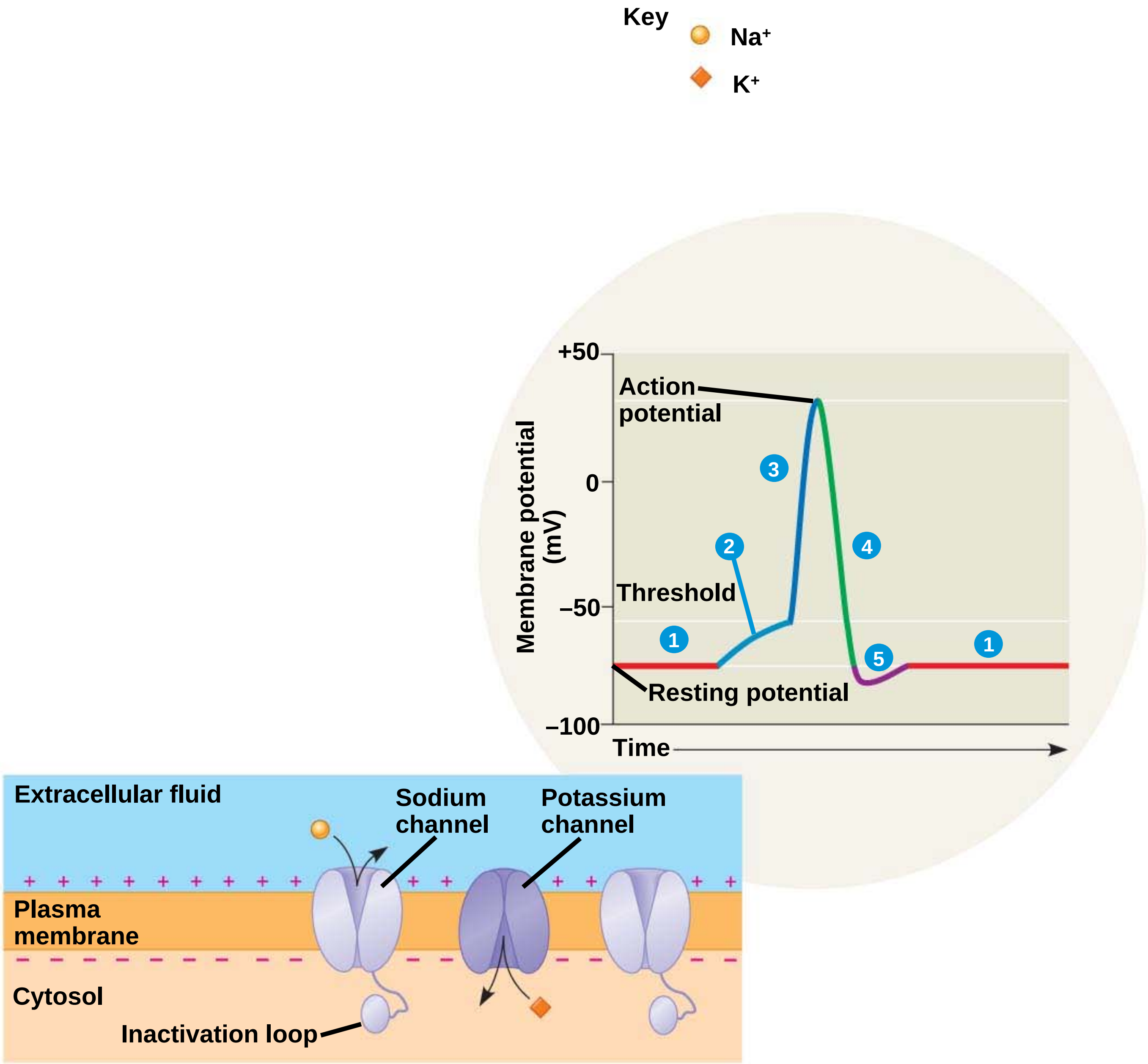
(c) Action potential

- An action potential occurs if a stimulus causes the membrane voltage to cross a particular **threshold**
- An action potential is a brief all-or-none depolarization of a neuron’s plasma membrane
- Action potentials are signals that carry information along axons

Generation of Action Potentials: *A Closer Look*

- A neuron can produce hundreds of action potentials per second
- The frequency of action potentials can reflect the strength of a stimulus
- An action potential can be broken down into a series of stages

Fig. 48-10-1



1 Resting state

Fig. 48-10-2

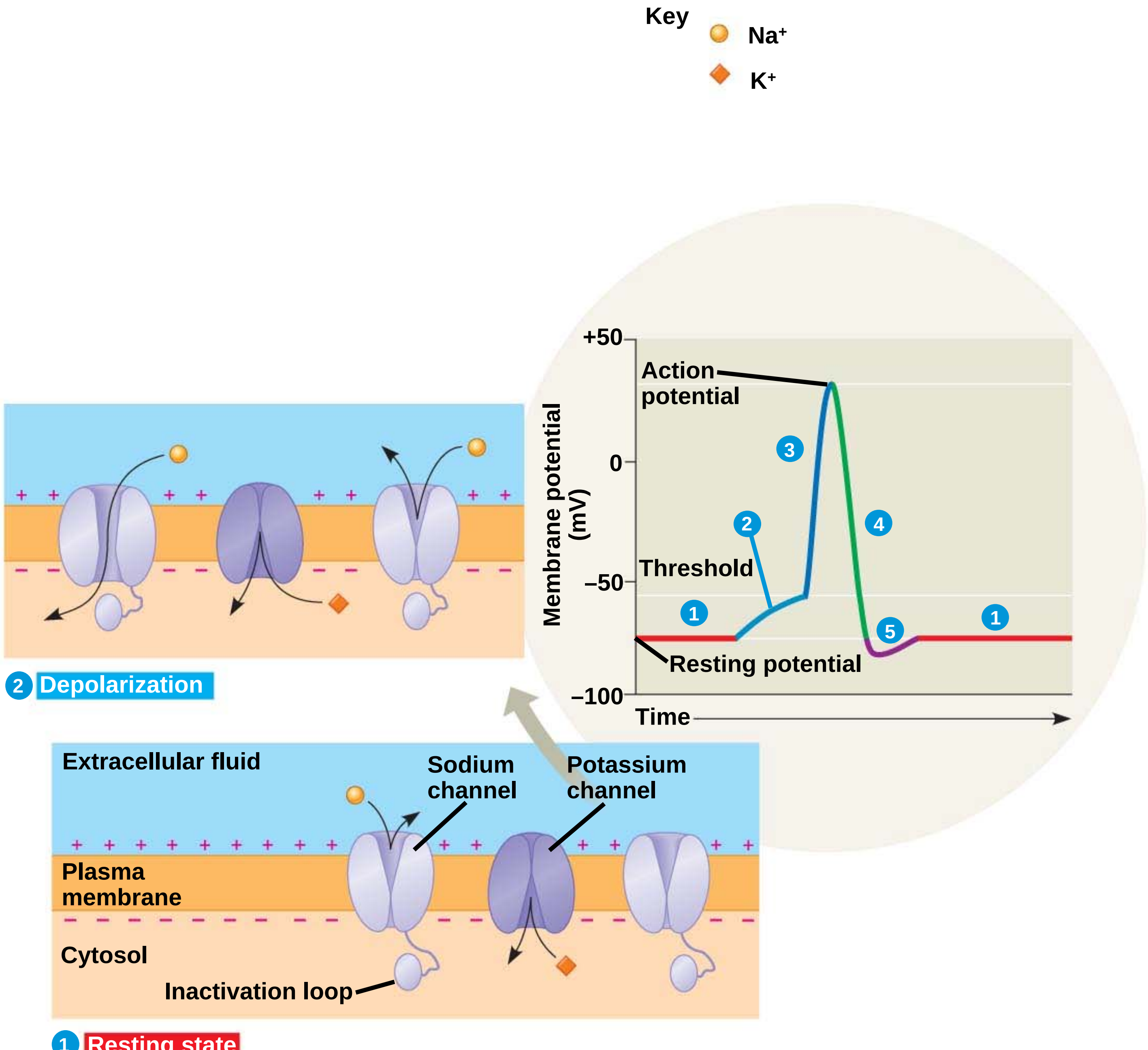
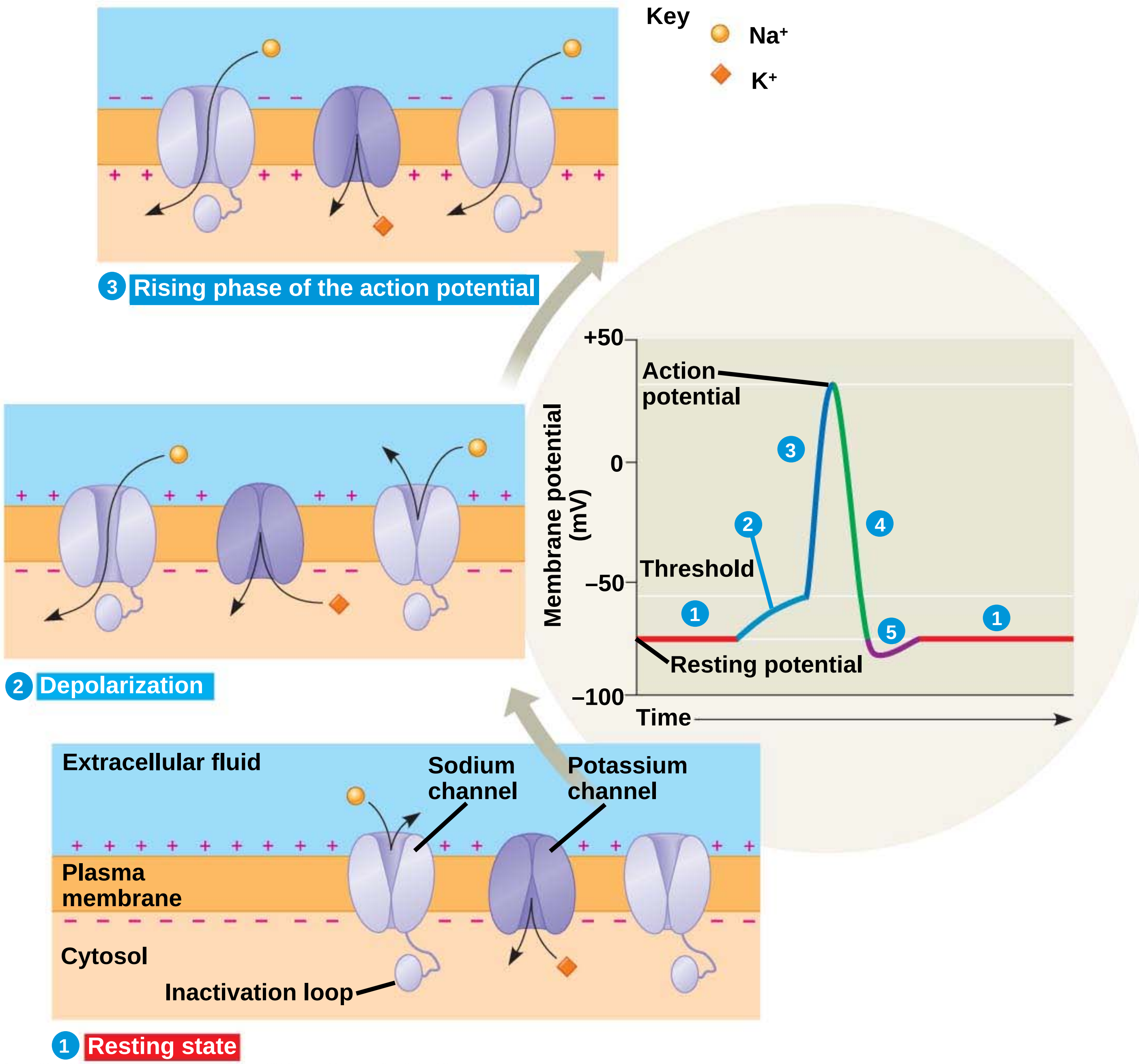
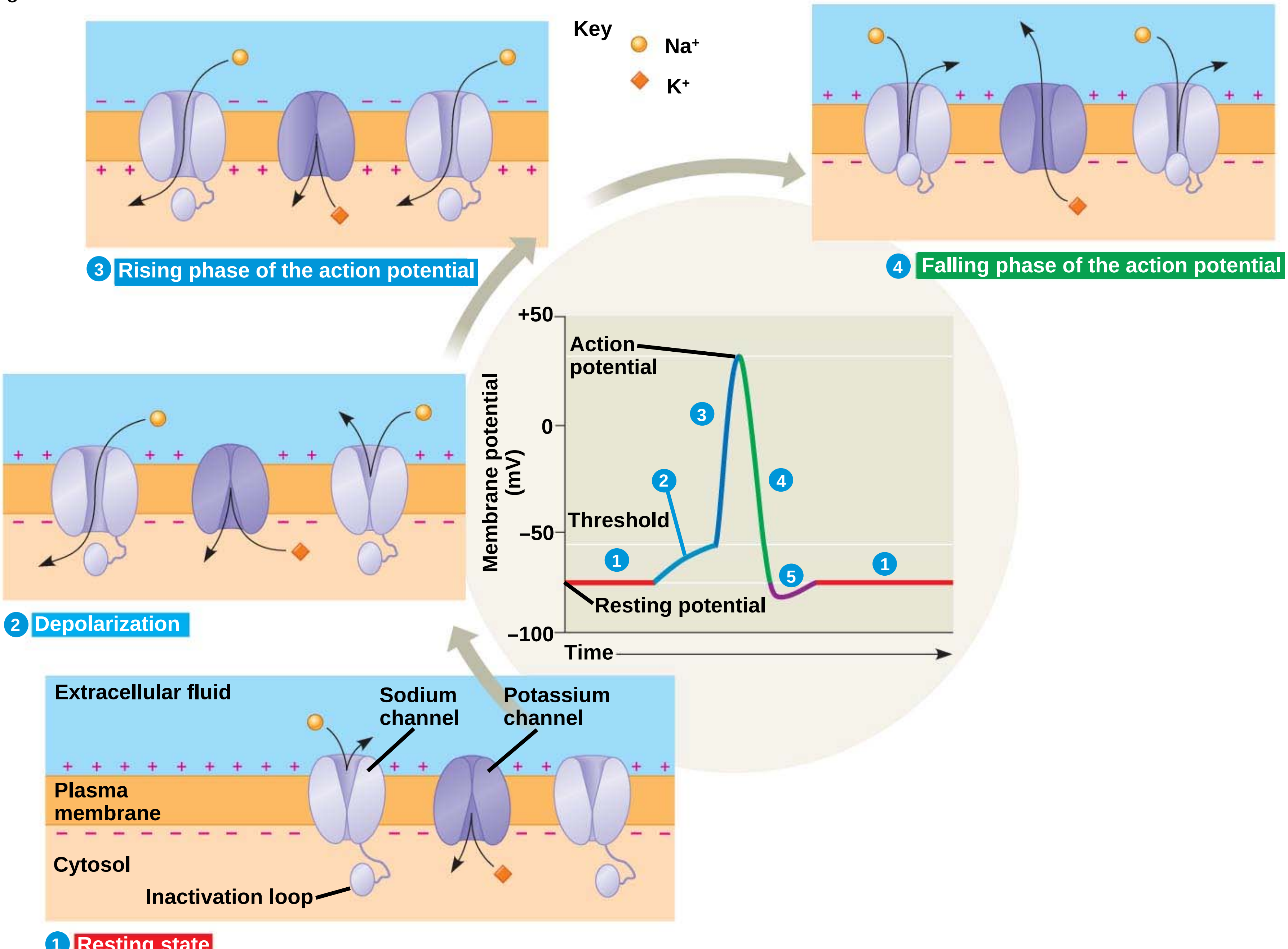

Key
Na+
K+
+50
0
–50
–100
Membrane potential (mV)
Action potential
Threshold
Resting potential
Time
1
2
3
4
5
1
2 Depolarization
Extracellular fluid
Sodium channel
Potassium channel
Plasma membrane
Cytosol
Inactivation loop
1 Resting state

Fig. 48-10-3



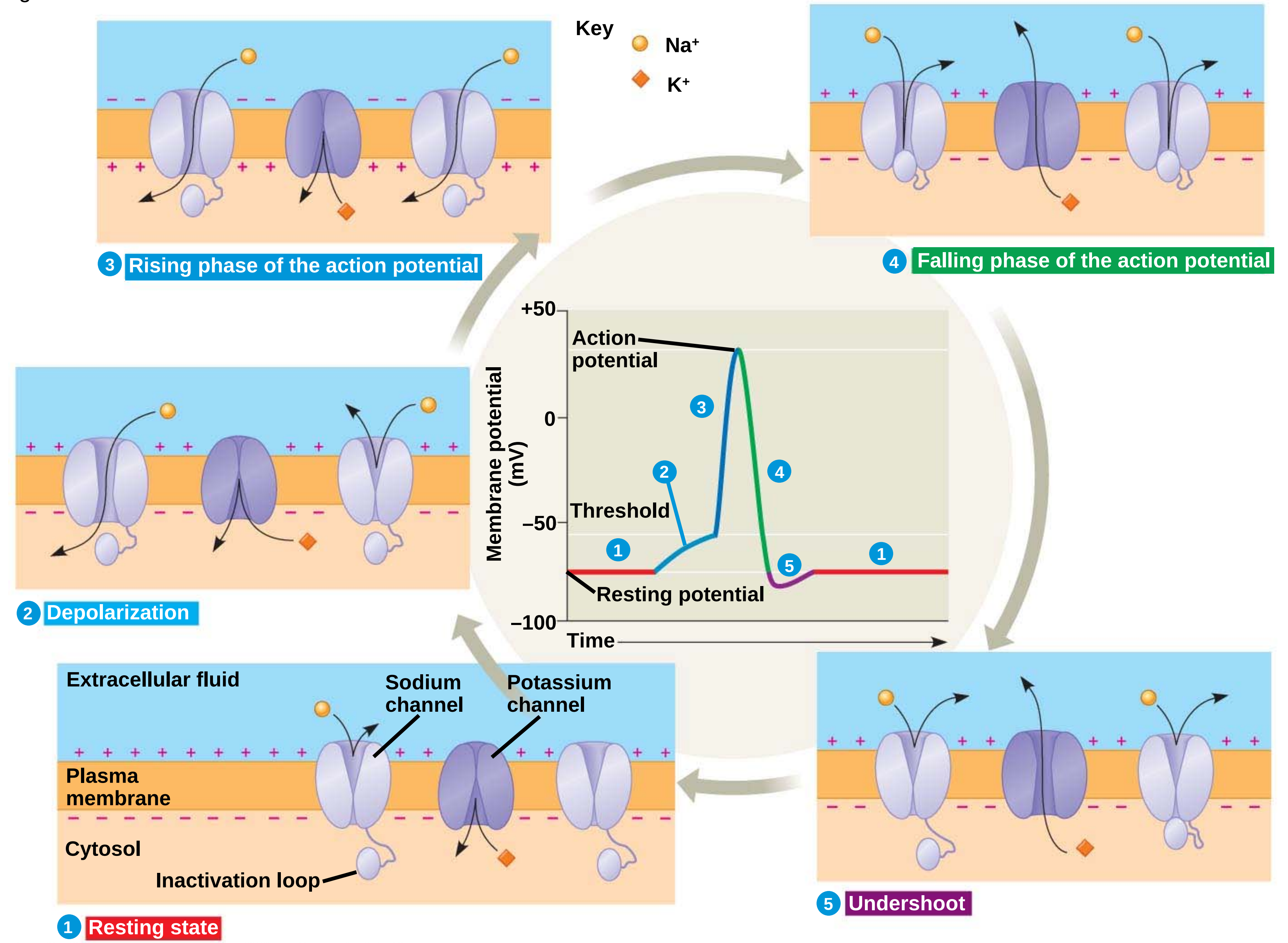
Key
Na+
K+
Rising phase of the action potential
3
Depolarization
2
Membrane potential (mV)
+50
0
–50
–100
Action potential
Threshold
Resting potential
Time
1
2
3
4
5
1
Extracellular fluid
Sodium channel
Potassium channel
Plasma membrane
Cytosol
Inactivation loop
Resting state
1

Fig. 48-10-4



Key
Na+
K+
3 Rising phase of the action potential
4 Falling phase of the action potential
+50
0
–50
–100
Membrane potential (mV)
Action potential
Threshold
Resting potential
Time
1
2
3
4
5
1
2 Depolarization
Extracellular fluid
Sodium channel
Potassium channel
Plasma membrane
Cytosol
Inactivation loop
1 Resting state

Fig. 48-10-5



Key
Na+
K+
3 Rising phase of the action potential
4 Falling phase of the action potential
2 Depolarization
Membrane potential (mV)
+50
0
–50
–100
Action potential
Threshold
Resting potential
Time
1
2
3
4
5
1
Extracellular fluid
Sodium channel
Potassium channel
Plasma membrane
Cytosol
Inactivation loop
1 Resting state
5 Undershoot

- At resting potential

  1. Most voltage-gated Na^+ and K^+ channels are closed, but some K^+ channels (not voltage-gated) are open

- 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; resting potential is restored

- 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

PLAY BioFlix: How Neurons Work

PLAY Animation: Action Potential

Conduction of Action Potentials

- An action potential can travel long distances by regenerating itself along the axon
- At the site where the action potential is generated, usually the axon hillock, an electrical current depolarizes the neighboring region of the axon membrane

- Inactivated Na^+ channels behind the zone of depolarization prevent the action potential from traveling backwards
- Action potentials travel in only one direction: toward the synaptic terminals

Fig. 48-11-1

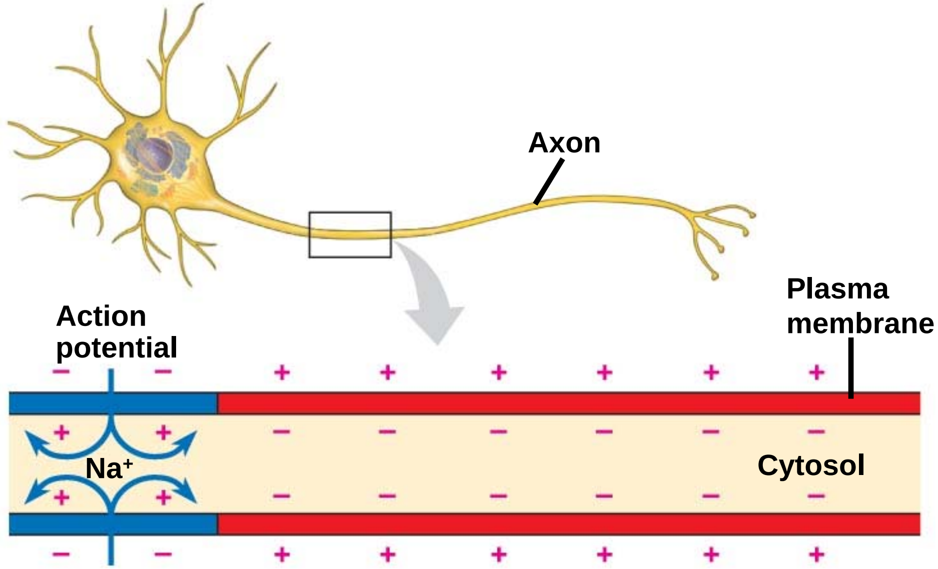


Fig. 48-11-2

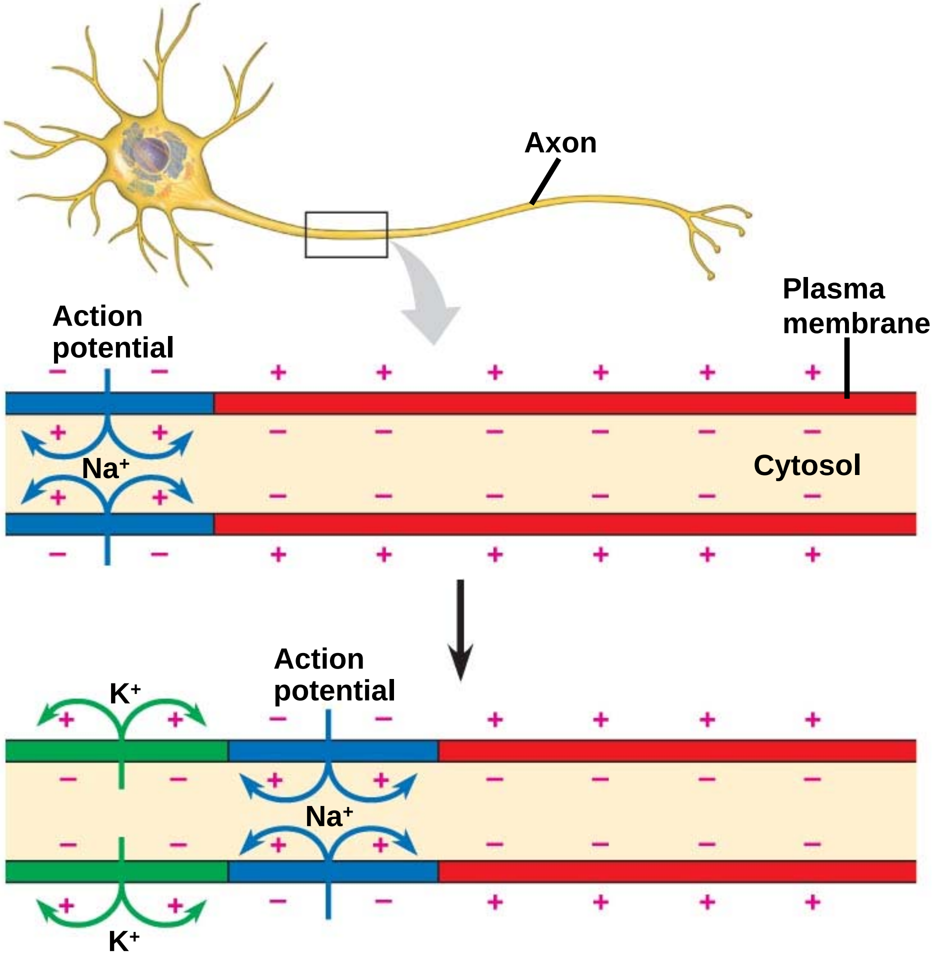
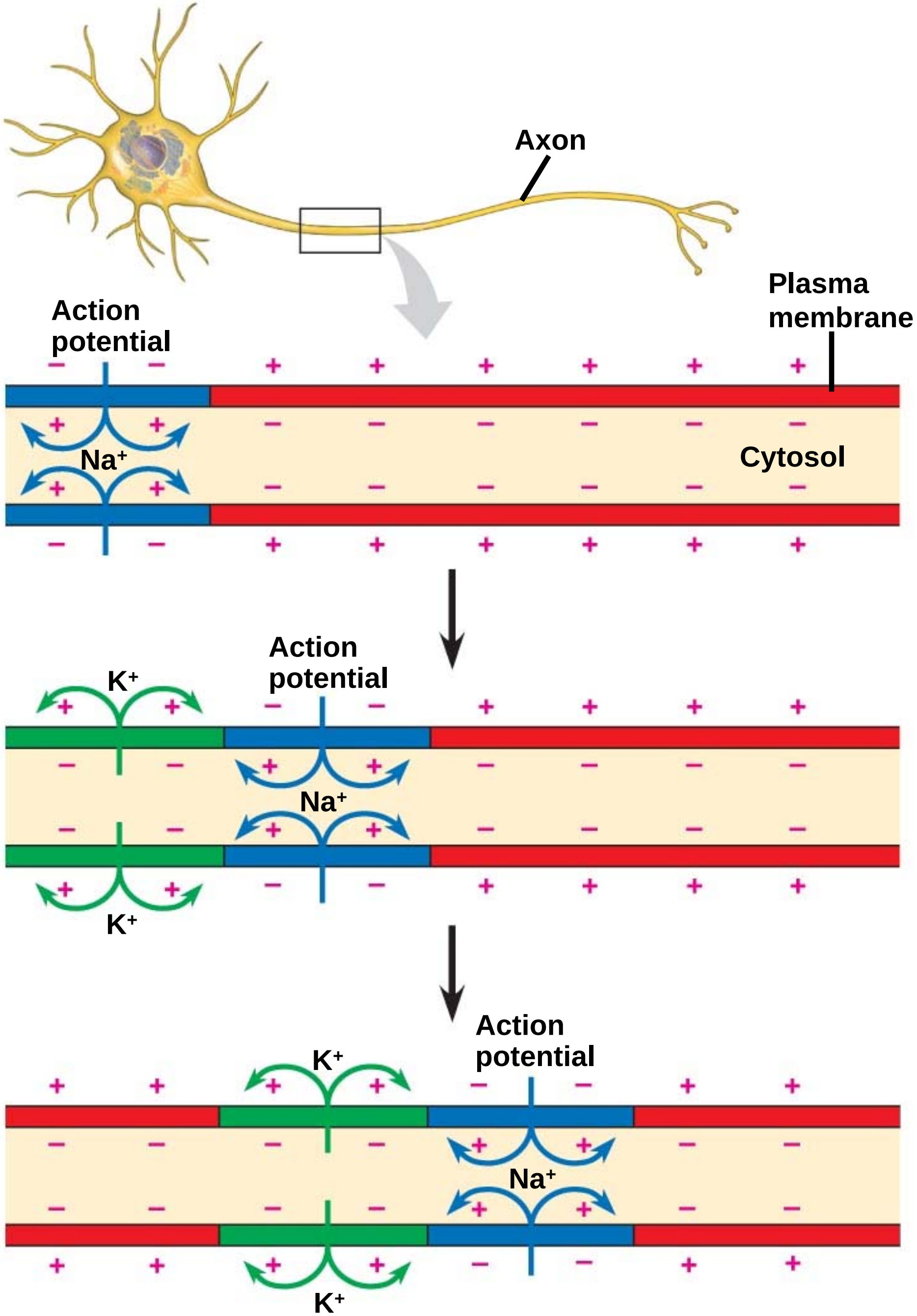

Axon
Plasma membrane
Action potential
Na+
Cytosol
Action potential
K+
Na+
K+

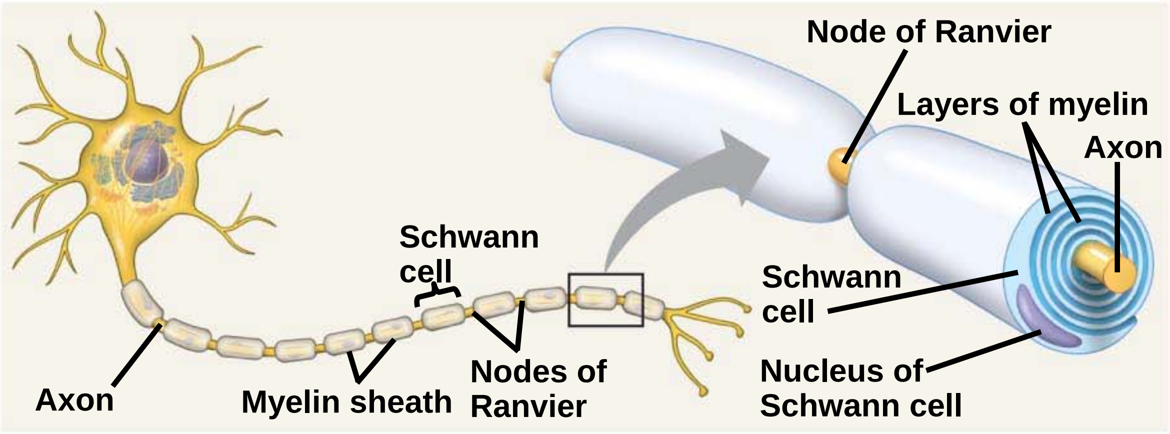
Fig. 48-11-3


Axon
Plasma membrane
Action potential
Na+
Cytosol
Action potential
K+
Na+
K+
Action potential
K+
Na+
K+

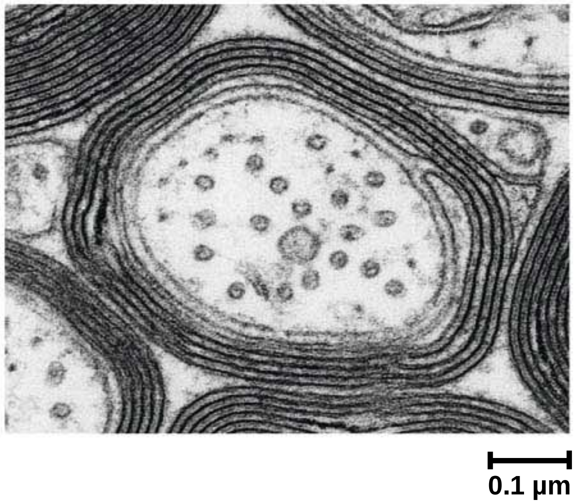
Conduction Speed

- 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

Fig. 48-12



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



0.1 µm

Fig. 48-12a

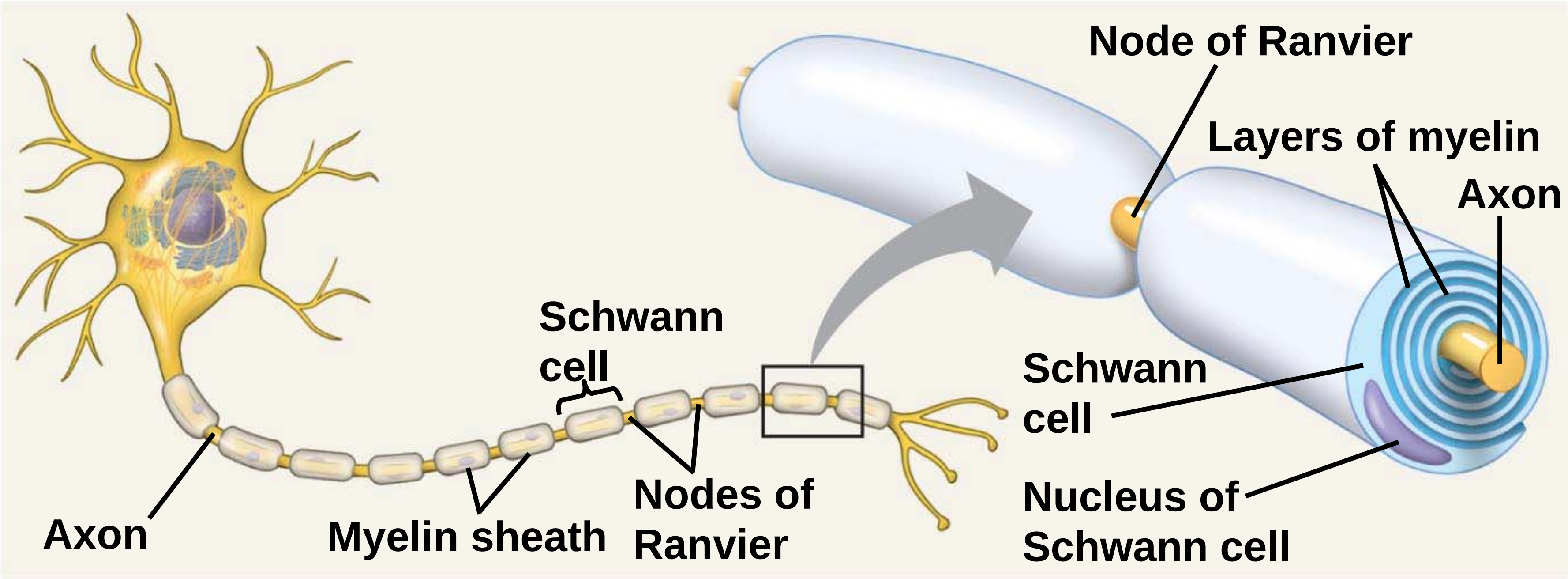
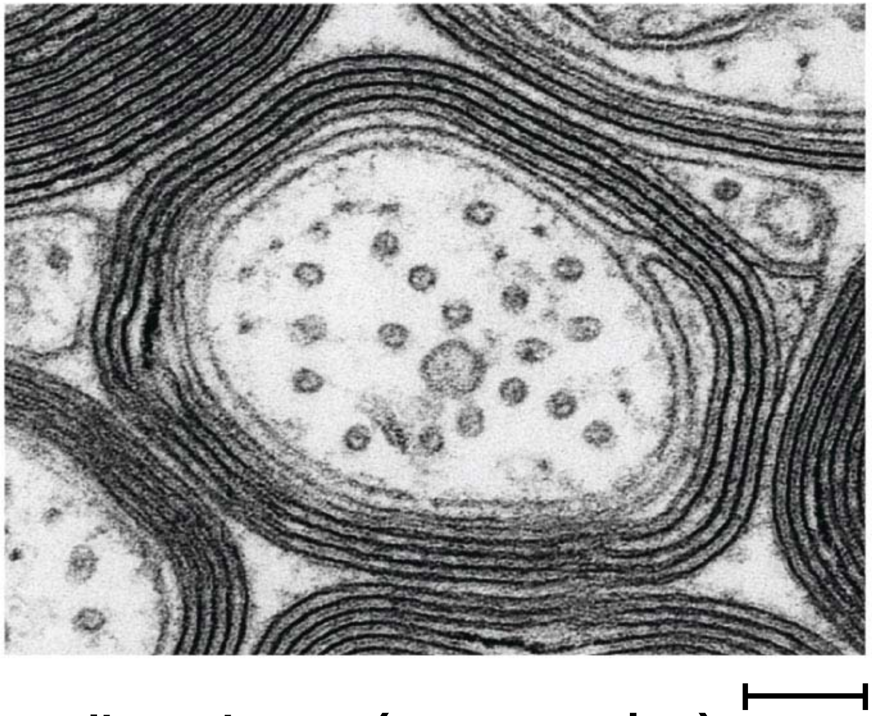

Node of Ranvier
Layers of myelin
Axon
Schwann cell
Schwann cell
Nucleus of Schwann cell
Axon
Myelin sheath
Nodes of Ranvier

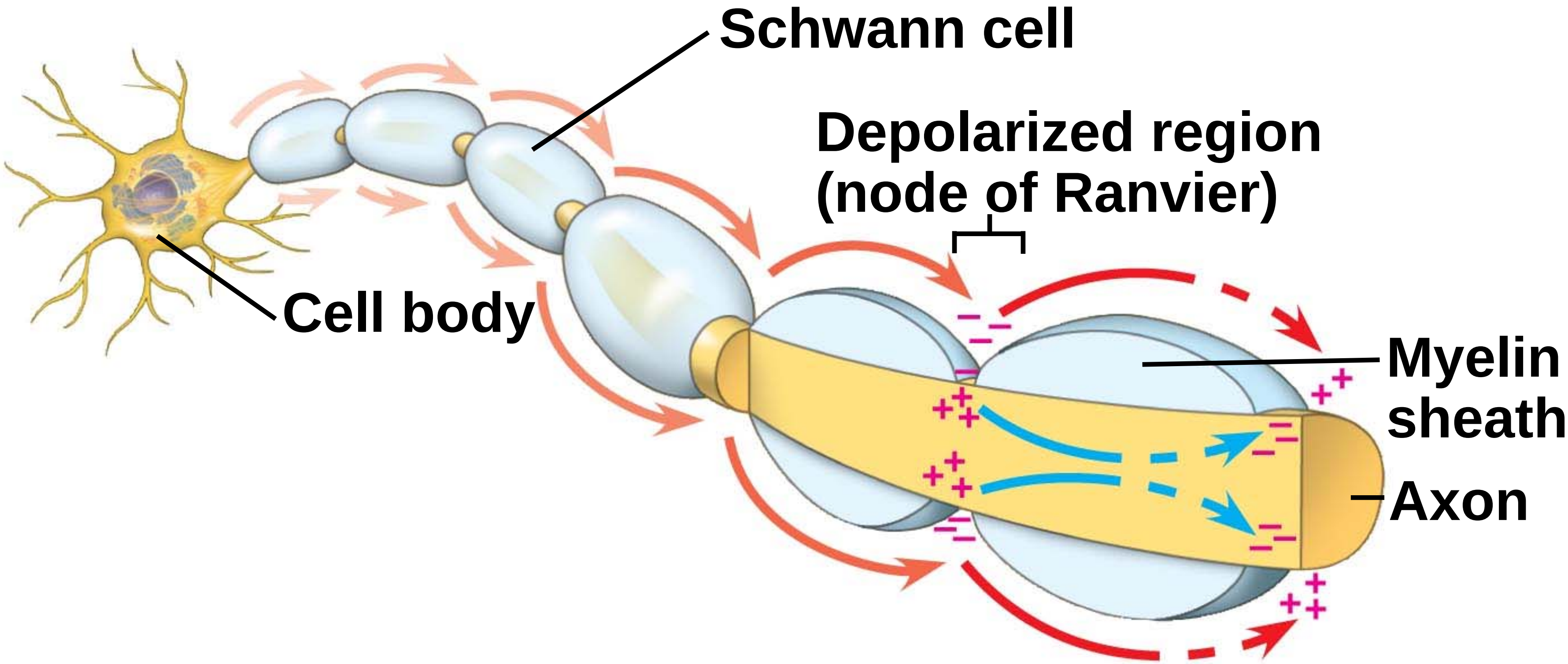
Fig. 48-12b



Myelinated axon (cross section)

- 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**

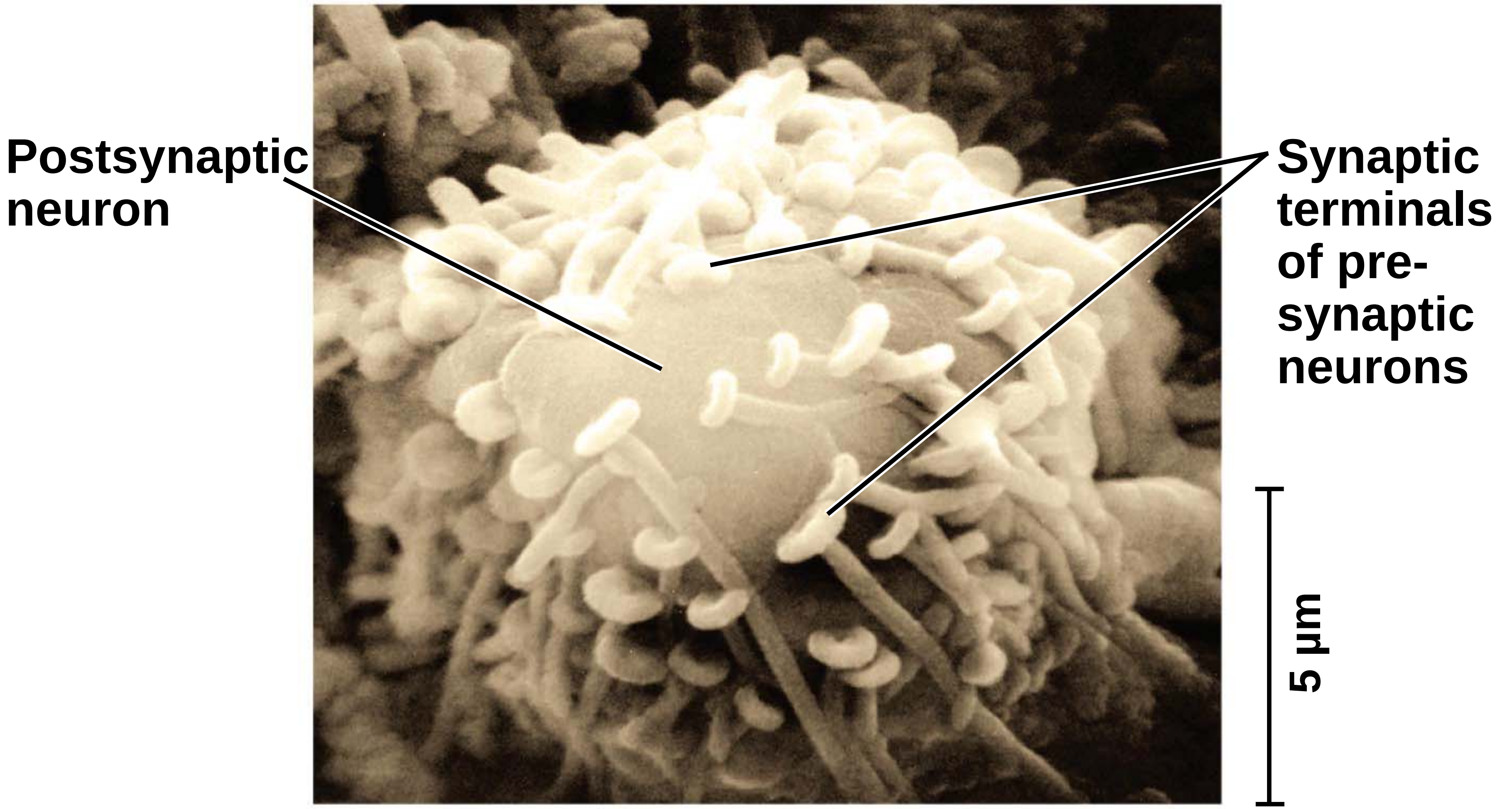
Fig. 48-13


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

Fig. 48-14

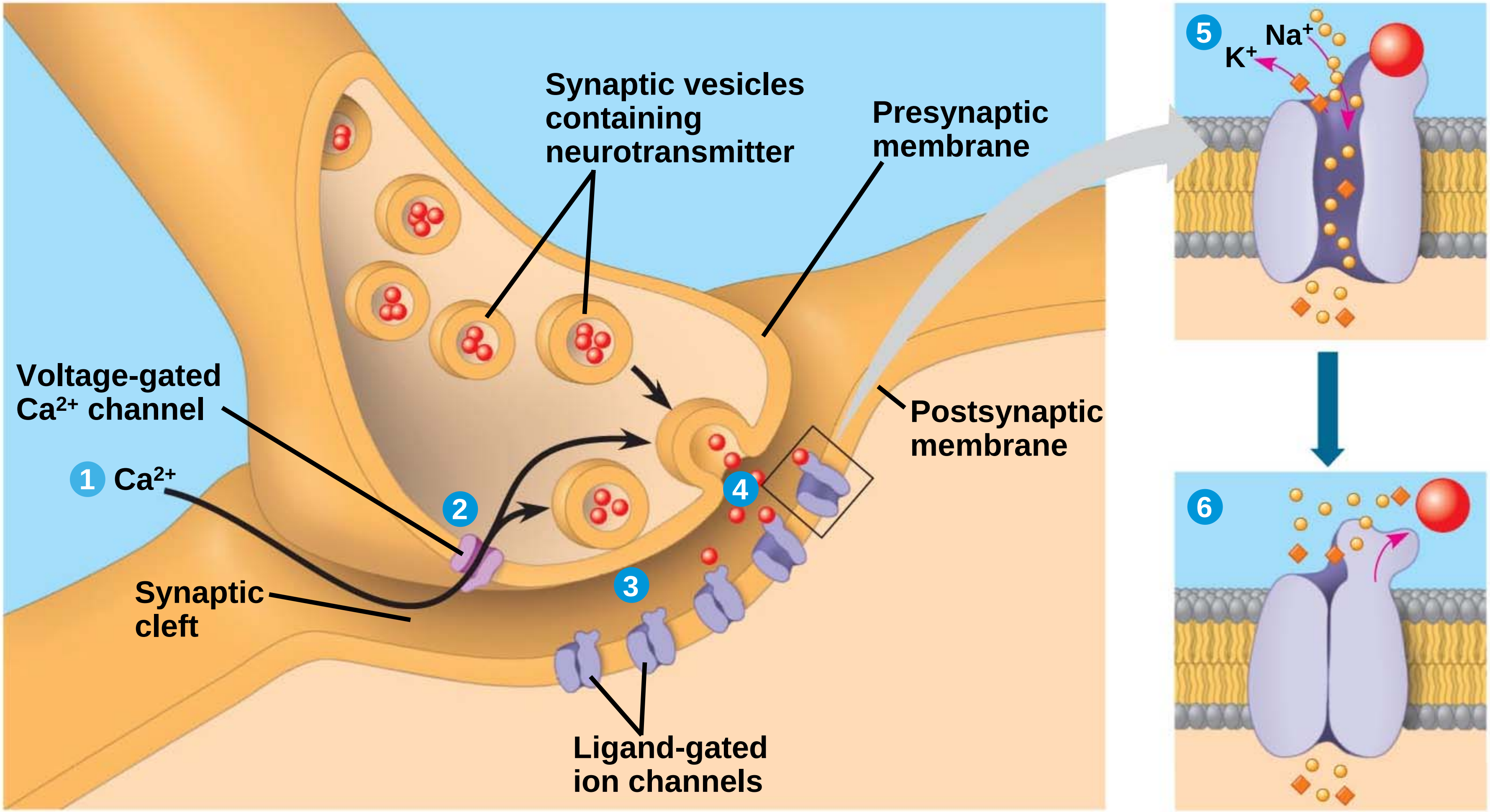


Postsynaptic neuron
Synaptic terminals of pre-synaptic neurons
5 µm

- 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

PLAY Animation: Synapse

Fig. 48-15



Synaptic vesicles containing neurotransmitter
Presynaptic membrane
Voltage-gated Ca^{2+} channel
1 Ca^{2+}
2
3
4
5
6
Na^+
K^+
Postsynaptic membrane
Synaptic cleft
Ligand-gated ion channels

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*

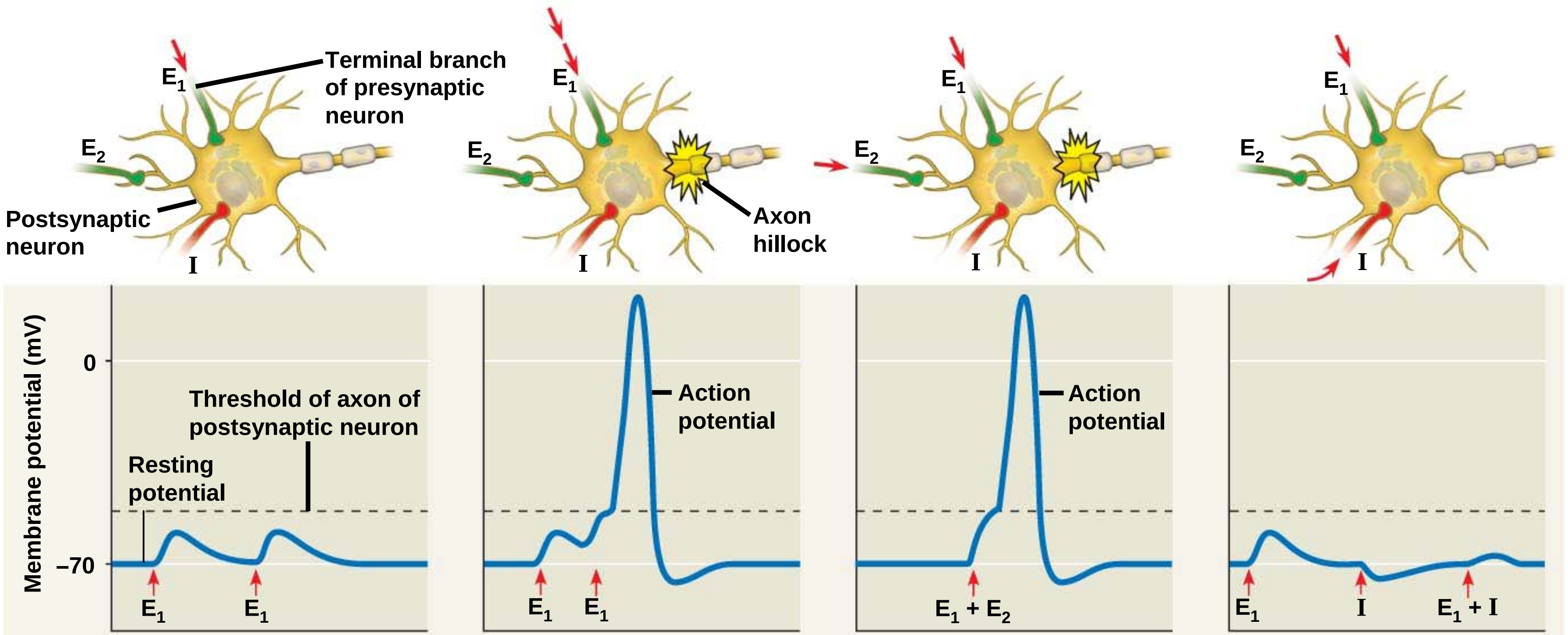
- Postsynaptic potentials fall into two categories:
  - **Excitatory postsynaptic potentials (EPSPs)** are depolarizations that bring the membrane potential toward threshold
  - **Inhibitory postsynaptic potentials (IPSPs)** are hyperpolarizations that move the membrane potential farther from threshold

- 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

- Unlike action potentials, postsynaptic potentials are graded and do not regenerate
- 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
- If two EPSPs are produced in rapid succession, an effect called **temporal summation** occurs

Fig. 48-16



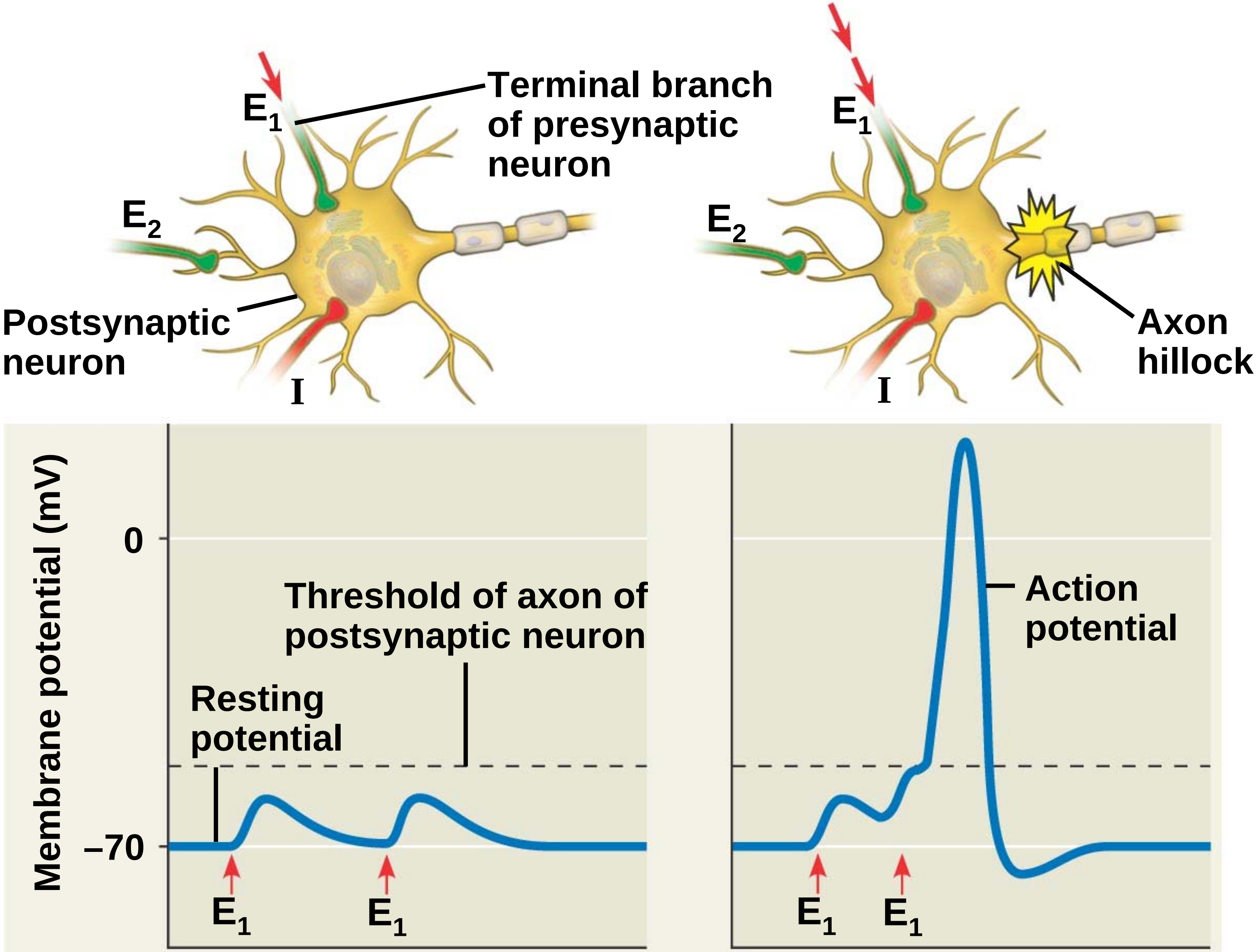
(a) Subthreshold, no summation

(b) Temporal summation

(c) Spatial summation

(d) Spatial summation of EPSP and IPSP

Fig. 48-16ab

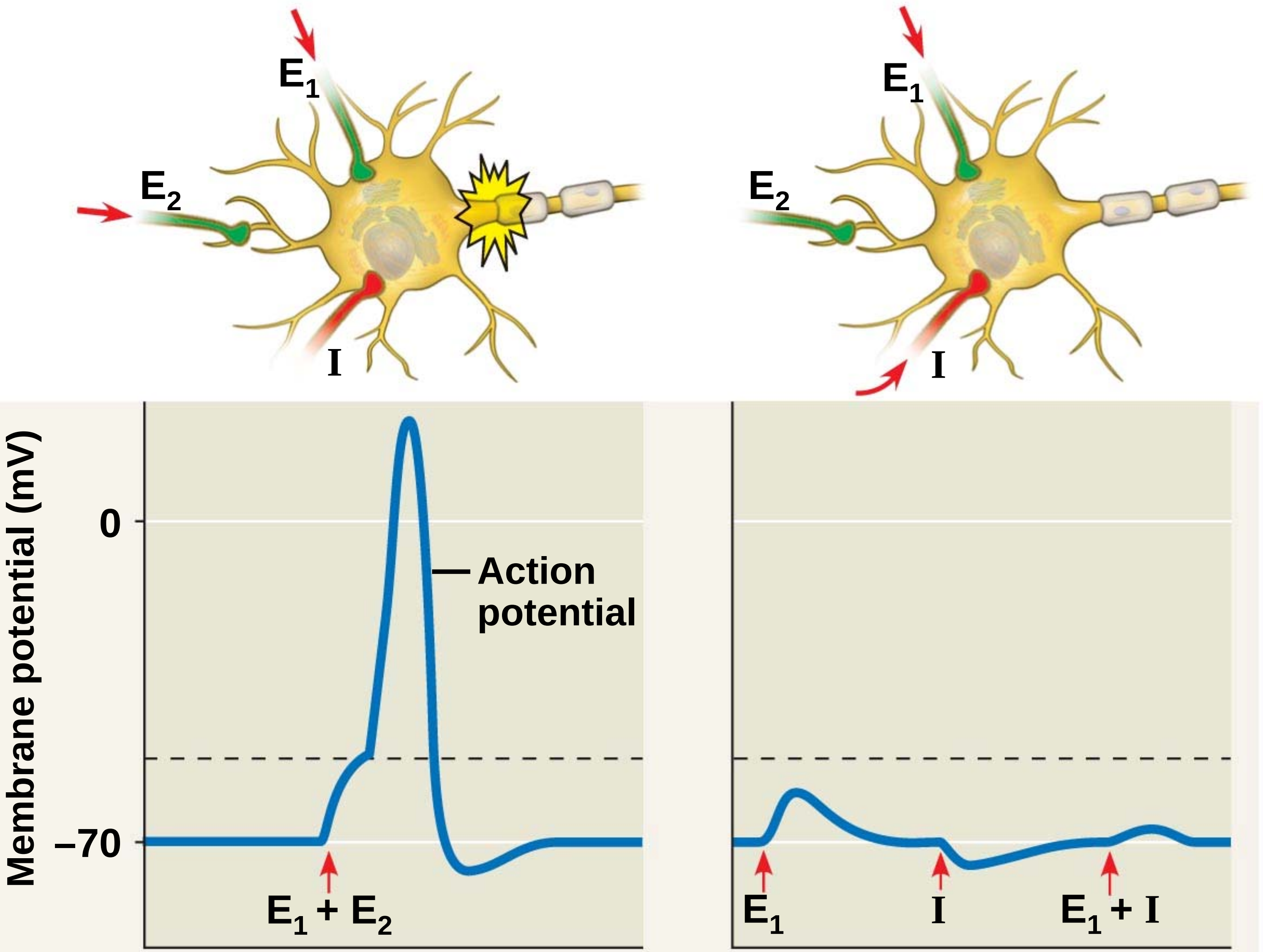


(a) Subthreshold, no summation

(b) Temporal summation

- 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

Fig. 48-16cd



(c) Spatial summation

(d) Spatial summation of EPSP and IPSP

- 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 Synaptic Transmission

- In indirect synaptic transmission, a neurotransmitter binds to a receptor that is not part of an ion channel
- This binding activates a signal transduction pathway involving a second messenger in the postsynaptic cell
- Effects of indirect synaptic transmission have a slower onset but last longer

Neurotransmitters

- The same neurotransmitter can produce different effects in different types of cells
- There are five major classes of neurotransmitters: acetylcholine, biogenic amines, amino acids, neuropeptides, and gases

Table 48-1

Table 48.1 Major Neurotransmitters

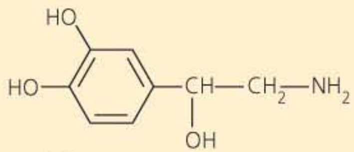
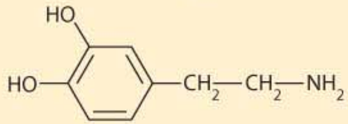
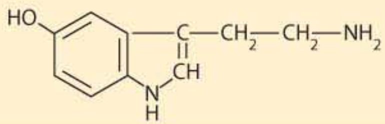
Neurotransmitter	Structure	Functional Class	Secretion Sites
Acetylcholine	$H_3C-C(=O)-O-CH_2-CH_2-N^+-[CH_3]_3$	Excitatory to vertebrate skeletal muscles; excitatory or inhibitory at other sites	CNS; PNS; vertebrate neuromuscular junction
Biogenic Amines			
Norepinephrine		Excitatory or inhibitory	CNS; PNS
Dopamine		Generally excitatory; may be inhibitory at some sites	CNS; PNS
Serotonin		Generally inhibitory	CNS
Amino Acids			
GABA (gamma-aminobutyric acid)	$H_2N-CH_2-CH_2-CH_2-COOH$	Inhibitory	CNS; invertebrate neuromuscular junction
Glutamate	$H_2N-CH(COOH)-CH_2-CH_2-COOH$	Excitatory	CNS; invertebrate neuromuscular junction
Glycine	H_2N-CH_2-COOH	Inhibitory	CNS
Neuropeptides (a very diverse group, only two of which are shown)			
Substance P	Arg—Pro—Lys—Pro—Gln—Gln—Phe—Phe—Gly—Leu—Met	Excitatory	CNS; PNS
Met-enkephalin (an endorphin)	Tyr—Gly—Gly—Phe—Met	Generally inhibitory	CNS
Gases			
Nitric oxide	N═O	Excitatory or inhibitory	PNS

Table 48-1a

Table 48.1 Major Neurotransmitters

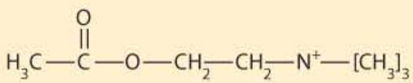
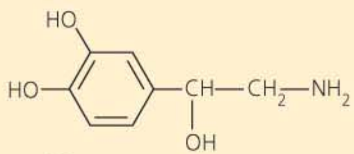
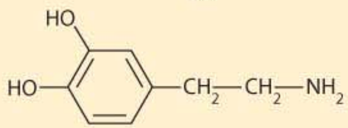
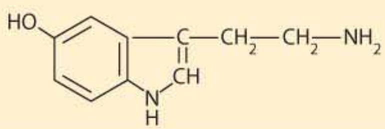
Neurotransmitter	Structure	Functional Class	Secretion Sites
Acetylcholine		Excitatory to vertebrate skeletal muscles; excitatory or inhibitory at other sites	CNS; PNS; vertebrate neuromuscular junction
Biogenic Amines			
Norepinephrine		Excitatory or inhibitory	CNS; PNS
Dopamine		Generally excitatory; may be inhibitory at some sites	CNS; PNS
Serotonin		Generally inhibitory	CNS

Table 48-1b

Table 48.1 Major Neurotransmitters

Neurotransmitter	Structure	Functional Class	Secretion Sites
Amino Acids			
GABA (gamma-aminobutyric acid)	$H_2N-CH_2-CH_2-CH_2-COOH$	Inhibitory	CNS; invertebrate neuromuscular junction
Glutamate	$H_2N-CH(COOH)-CH_2-CH_2-COOH$	Excitatory	CNS; invertebrate neuromuscular junction
Glycine	H_2N-CH_2-COOH	Inhibitory	CNS
Neuropeptides (a very diverse group, only two of which are shown)			
Substance P	Arg—Pro—Lys—Pro—Gln—Gln—Phe—Phe—Gly—Leu—Met	Excitatory	CNS; PNS
Met-enkephalin (an endorphin)	Tyr—Gly—Gly—Phe—Met	Generally inhibitory	CNS
Gases			
Nitric oxide	N=O	Excitatory or inhibitory	PNS

Acetylcholine

- **Acetylcholine** is a common neurotransmitter in vertebrates and invertebrates
- In vertebrates it is usually an excitatory transmitter

Biogenic Amines

- **Biogenic amines** include **epinephrine**, **norepinephrine**, **dopamine**, and **serotonin**
- They are active in the CNS and PNS

Amino Acids

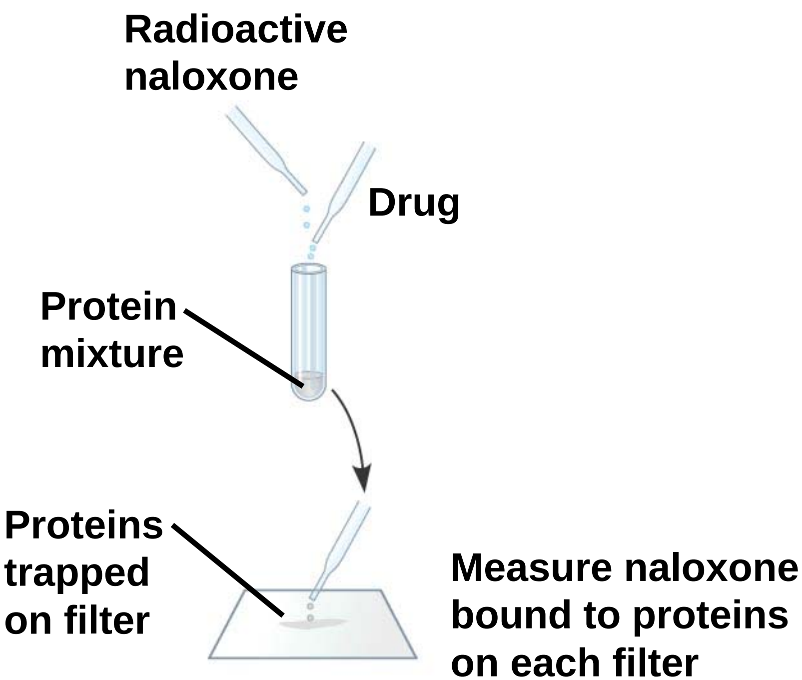
- Two amino acids are known to function as major neurotransmitters in the CNS: **gamma-aminobutyric acid** (**GABA**) and **glutamate**

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

Fig. 48-17

EXPERIMENT



RESULTS

Drug	Opiate	Concentration That Blocked Naloxone Binding
Morphine	Yes	6×10^{-9} *M*
Methadone	Yes	2×10^{-8} *M*
Levorphanol	Yes	2×10^{-9} *M*
Phenobarbital	No	No effect at 10^{-4} *M*
Atropine	No	No effect at 10^{-4} *M*
Serotonin	No	No effect at 10^{-4} *M*

Fig. 48-17a

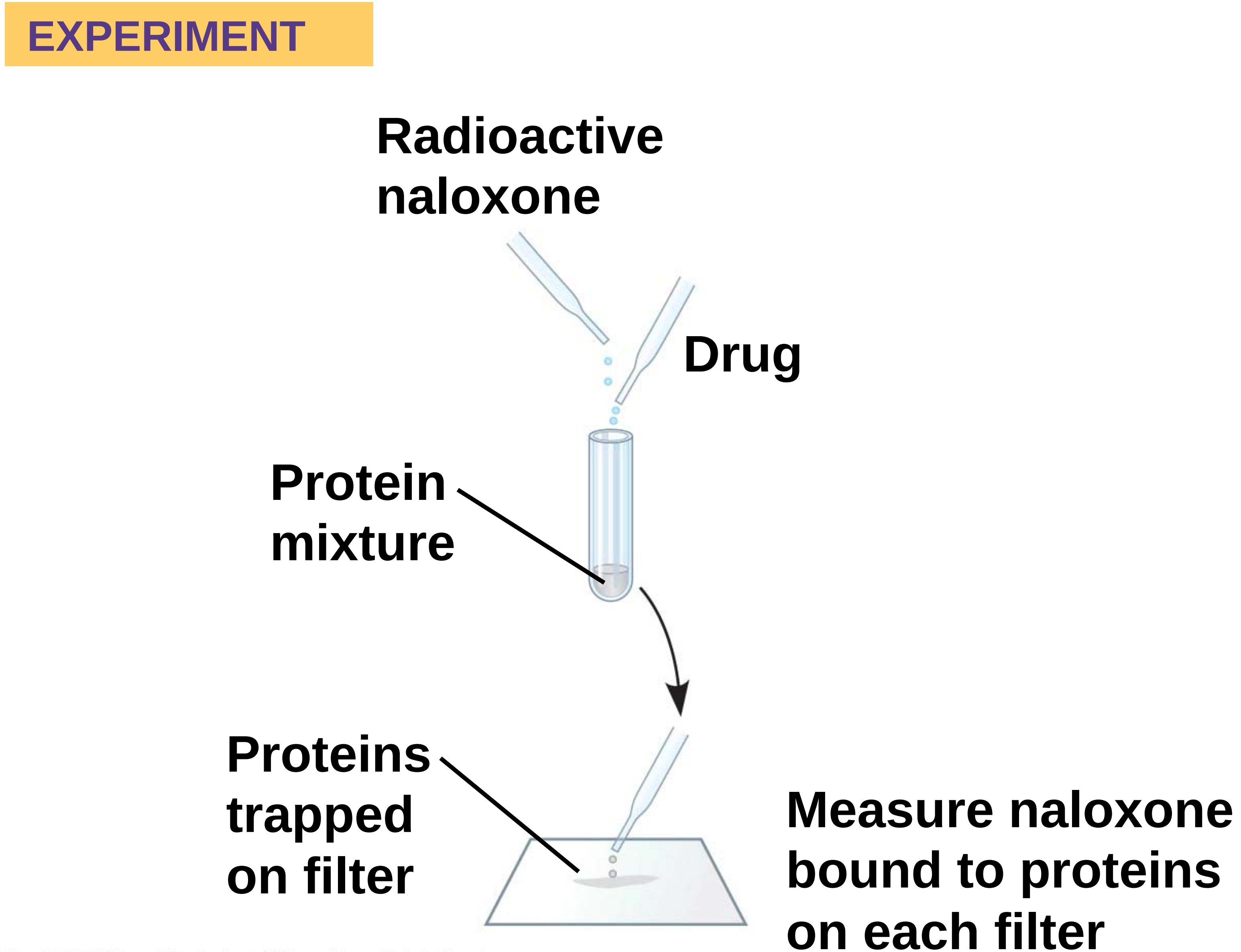

EXPERIMENT
Radioactive naloxone
Drug
Protein mixture
Proteins trapped on filter
Measure naloxone bound to proteins on each filter

Fig. 48-17b

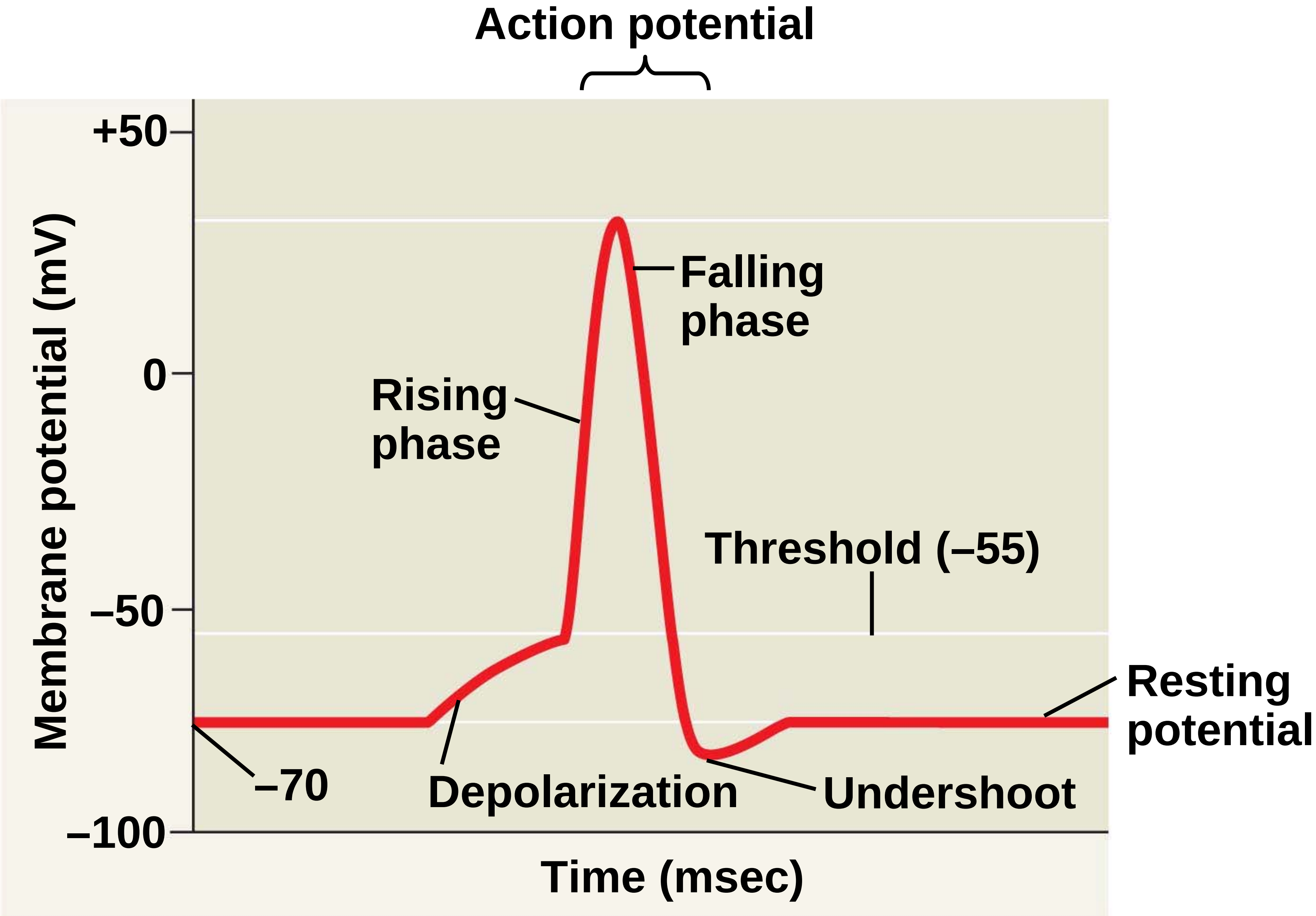
RESULTS

Drug	Opiate	Concentration That Blocked Naloxone Binding
Morphine	Yes	6×10^{-9} *M*
Methadone	Yes	2×10^{-8} *M*
Levorphanol	Yes	2×10^{-9} *M*
Phenobarbital	No	No effect at 10^{-4} *M*
Atropine	No	No effect at 10^{-4} *M*
Serotonin	No	No effect at 10^{-4} *M*

Gases

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

Fig. 48-UN1



Action potential
+50
0
–50
–100
Membrane potential (mV)
Falling phase
Rising phase
Threshold (–55)
Resting potential
–70
Depolarization
Undershoot
Time (msec)

Fig. 48-UN2

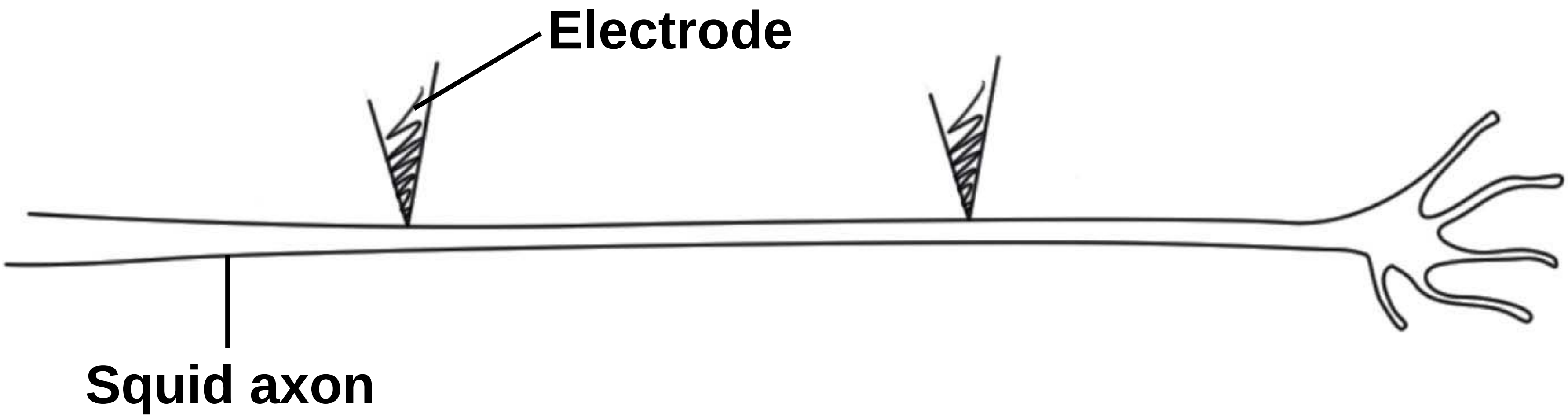
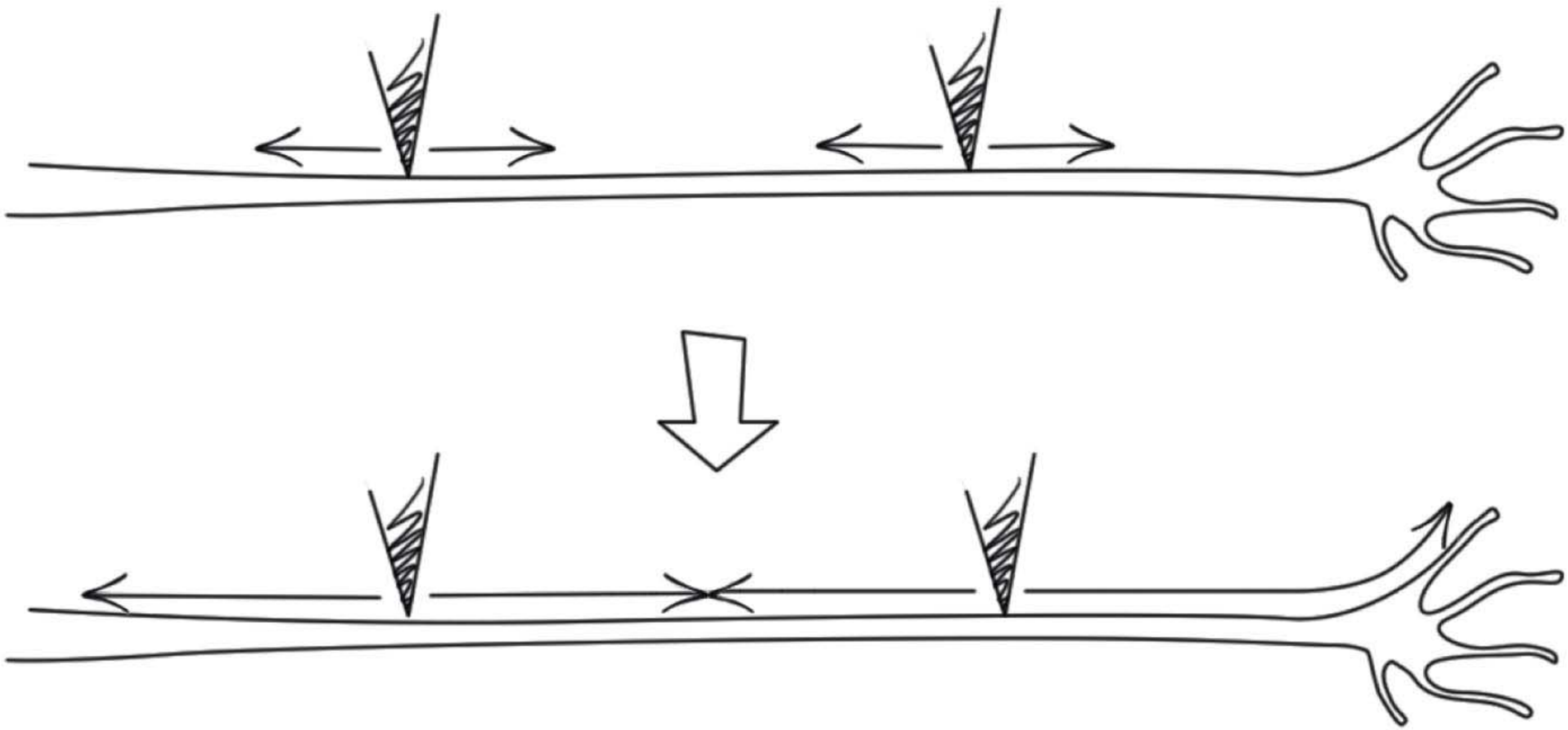


Fig. 48-UN3



You should now be able to:

1. Distinguish among the following sets of terms: sensory neurons, interneurons, and motor neurons; membrane potential and resting potential; ungated and gated ion channels; electrical synapse and chemical synapse; EPSP and IPSP; temporal and spatial summation

2. Explain the role of the sodium-potassium pump in maintaining the resting potential

3. Describe the stages of an action potential; explain the role of voltage-gated ion channels in this process

4. Explain why the action potential cannot travel back toward the cell body

5. Describe saltatory conduction

6. Describe the events that lead to the release of neurotransmitters into the synaptic cleft

7. Explain the statement: “Unlike action potentials, which are all-or-none events, postsynaptic potentials are graded”
8. Name and describe five categories of neurotransmitters