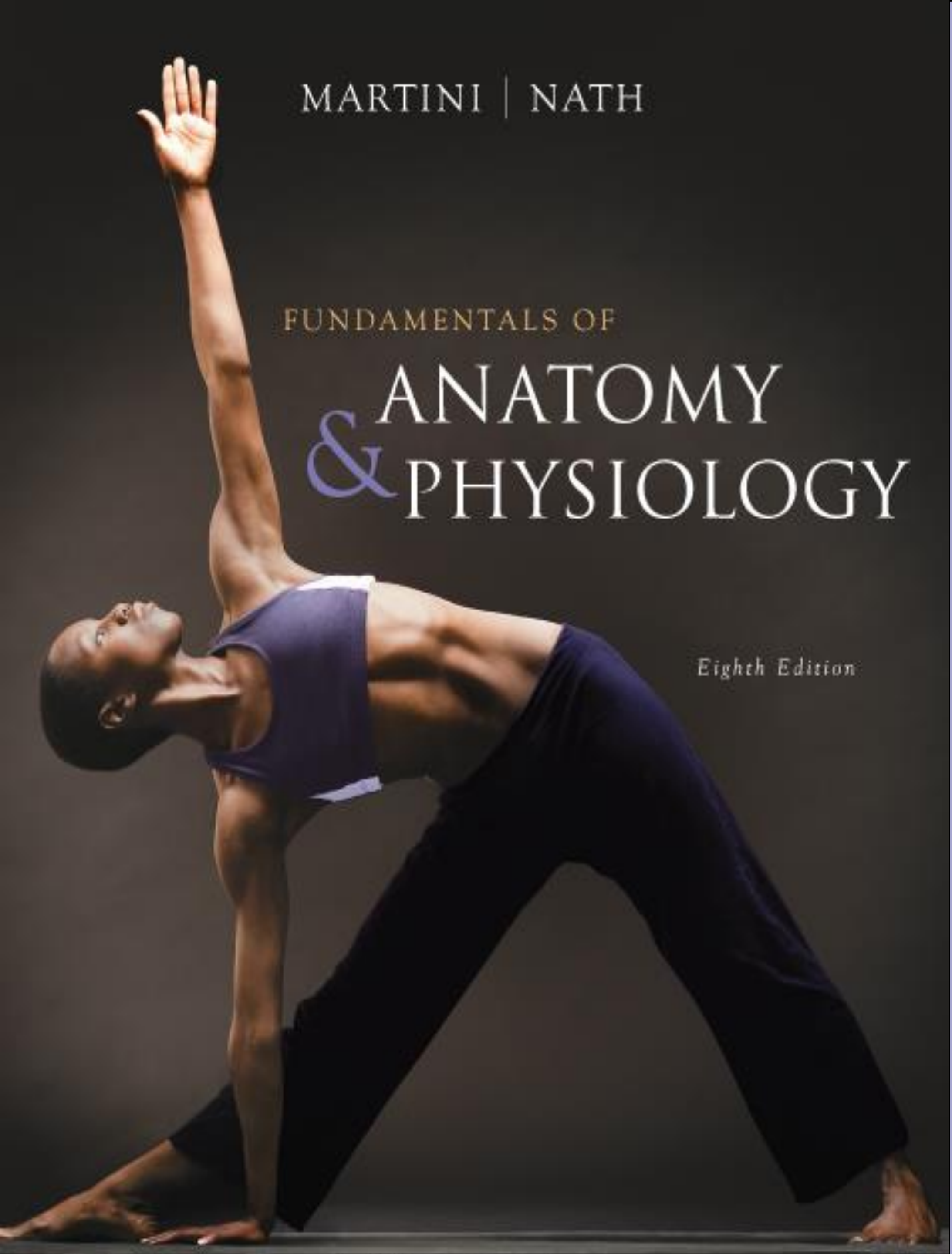


Chapter

12

Neural Tissue

PowerPoint® Lecture Slides
prepared by Jason LaPres
Lone Star College - North Harris

An Introduction to the Nervous System

- The Nervous System
  - Includes all **neural tissue** in the body

An Introduction to the Nervous System

- Neural Tissue
  - Contains two kinds of cells
    - **Neurons**:
      - – cells that send and receive signals
    - **Neuroglia** (glial cells):
      - – cells that support and protect neurons

An Introduction to the Nervous System

- Organs of the Nervous System
  - **Brain** and **spinal cord**
  - **Sensory receptors** of sense organs (eyes, ears, etc.)
  - **Nerves** connect nervous system with other systems

Divisions of the Nervous System

- Anatomical Divisions of the Nervous System
  - Central nervous system (CNS)
  - Peripheral nervous system (PNS)

Divisions of the Nervous System

- **The Central Nervous System (CNS)**
  - Consists of the spinal cord and brain
  - Contains neural tissue, connective tissues, and blood vessels
  - Functions of the CNS
    - Are to process and coordinate:
      - sensory data: from inside and outside body
      - motor commands: control activities of peripheral organs (e.g., skeletal muscles)
      - higher functions of brain: intelligence, memory, learning, emotion

Divisions of the Nervous System

- **The Peripheral Nervous System** (PNS)
  - Includes all neural tissue outside the CNS
  - Functions of the PNS
    - Deliver sensory information to the CNS
    - Carry motor commands to peripheral tissues and systems

Divisions of the Nervous System

- The Peripheral Nervous System (PNS)
  - **Nerves (also called *peripheral nerves*)**
    - Bundles of axons with connective tissues and blood vessels
    - Carry sensory information and motor commands in PNS:
      - **cranial nerves**—connect to brain
      - **spinal nerves**—attach to spinal cord

Divisions of the Nervous System

- Functional Divisions of the PNS
  - **Afferent division**
    - Carries sensory information
    - From PNS sensory receptors **to CNS**
  - **Efferent division**
    - Carries motor commands
    - **From CNS** to PNS muscles and glands

Divisions of the Nervous System

- Functional Divisions of the PNS
  - Receptors and effectors of afferent division
    - **Receptors**:
      - detect changes or respond to stimuli
      - neurons and specialized cells
      - complex sensory organs (e.g., eyes, ears)
    - **Effectors**:
      - respond to efferent signals
      - cells and organs

Divisions of the Nervous System

- Functional Divisions of the PNS
  - The efferent division
    - **Somatic nervous system** (SNS):
      - – controls skeletal muscle contractions: voluntary and involuntary (reflexes) muscle contractions
    - **Autonomic nervous system** (ANS):
      - – controls subconscious actions: contractions of smooth muscle and cardiac muscle and glandular secretions
      - – **sympathetic division**: has a stimulating effect
      - – **parasympathetic division**: has a relaxing effect

Neurons

- Neurons
  - The basic functional units of the nervous system

PLAY

Neurophysiology: Neuron Structure

Neurons

- The Structure of Neurons
  - The **multipolar neuron**
    - Common in the CNS:
      - **cell body** (soma)
      - short, branched **dendrites**
      - long, single **axon**

Neurons

- **Major Organelles of the Cell Body**
  - Large nucleus and nucleolus
  - **Perikaryon (**cytoplasm)
  - Mitochondria (produce energy)
  - RER and ribosomes (produce neurotransmitters)
  - Cytoskeleton
    - **Neurofilaments** and **neurotubules**: in place of microfilaments and microtubules
    - **Neurofibrils**: bundles of neurofilaments that provide support for dendrites and axon

Neurons

- The Structure of Neurons
  - **Nissl bodies**
    - Dense areas of RER and ribosomes
    - Make neural tissue appear gray (*gray matter*)
  - **Dendrites**
    - Highly branched
    - *Dendritic spines:*
      - – many fine processes
      - – receive information from other neurons
      - – 80–90% of neuron surface area

Neurons

- The Structure of Neurons
  - **The axon**
    - Is long
    - Carries electrical signal (*action potential*) to target
    - Axon structure is critical to function

Neurons

- Structures of the Axon
  - **Axoplasm**
    - Cytoplasm of axon
    - Contains neurotubules, neurofibrils, enzymes, organelles
  - **Axolemma**
    - Specialized cell membrane
    - Covers the axoplasm

Neurons

- Structures of the Axon
  - **Axon hillock**
    - Thick section of cell body
    - Attaches to initial segment
  - **Initial segment**
    - Attaches to axon hillock

Neurons

- Structures of the Axon
  - **Collaterals**
    - Branches of a single axon
  - **Telodendria**
    - Fine extensions of distal axon
  - **Synaptic terminals**
    - Tips of telodendria

Neurons

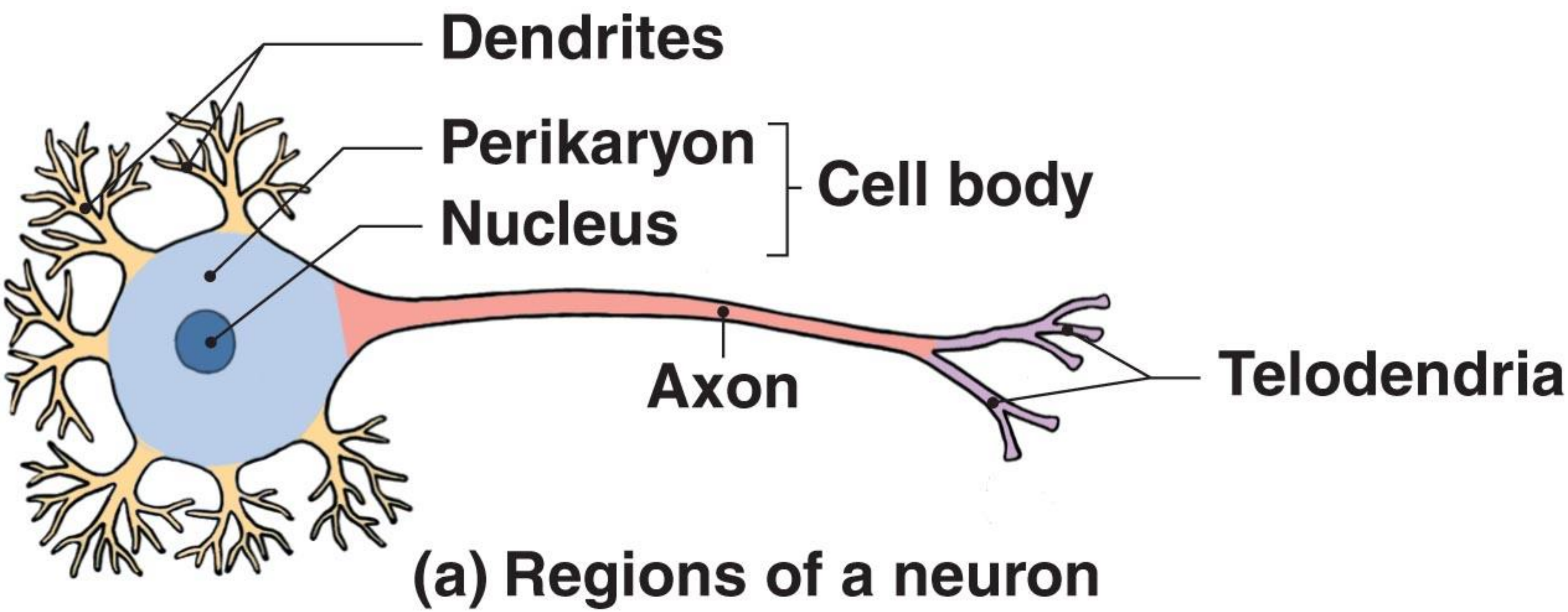


Figure 12–1a The Anatomy of a Multipolar Neuron.

Neurons

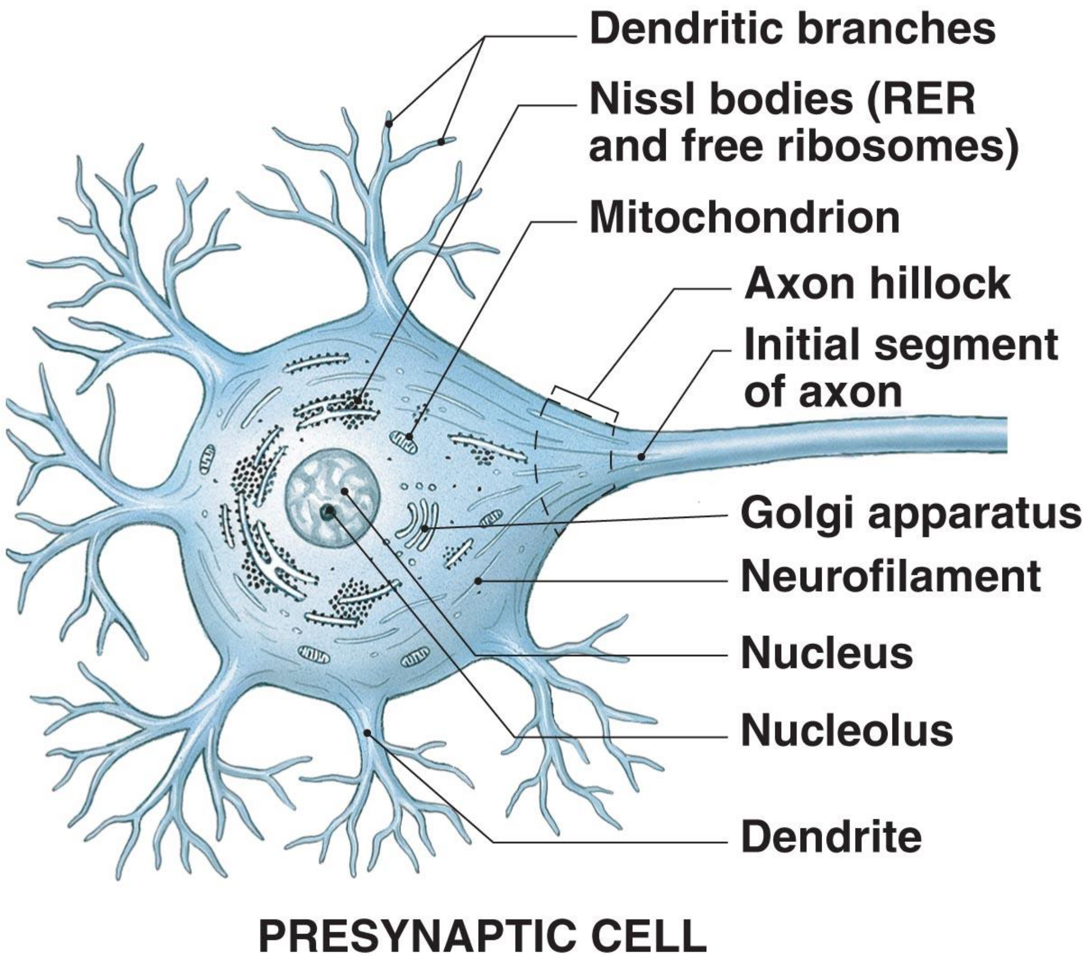


Figure 12–1b The Anatomy of a Multipolar Neuron.

Neurons

- The Structure of Neurons
  - The synapse
    - Area where a neuron communicates with another cell

PLAY

Neurophysiology: Synapse

Neurons

- The Structure of Neurons
  - The synapse
    - **Presynaptic cell:**
      - neuron that sends message
    - **Postsynaptic cell:**
      - cell that receives message
    - **The synaptic cleft:**
      - the small gap that separates the presynaptic membrane and the postsynaptic membrane

Neurons

- The Synapse
  - **The synaptic knob**
    - Is expanded area of axon of presynaptic neuron
    - Contains *synaptic vesicles* of **neurotransmitters**
    - Neurotransmitters:
      - are chemical messengers
      - are released at presynaptic membrane
      - affect receptors of postsynaptic membrane
      - are broken down by enzymes
      - are reassembled at synaptic knob

Neurons

- Recycling Neurotransmitters
  - **Axoplasmic transport**
    - Neurotubules within the axon
    - Transport raw materials
    - Between cell body and synaptic knob
    - Powered by mitochondria, *kinesin*, and *dynein*

Neurons

- Types of Synapses
  - **Neuromuscular junction**
    - Synapse between neuron and muscle
  - **Neuroglandular junction**
    - Synapse between neuron and gland

Neurons

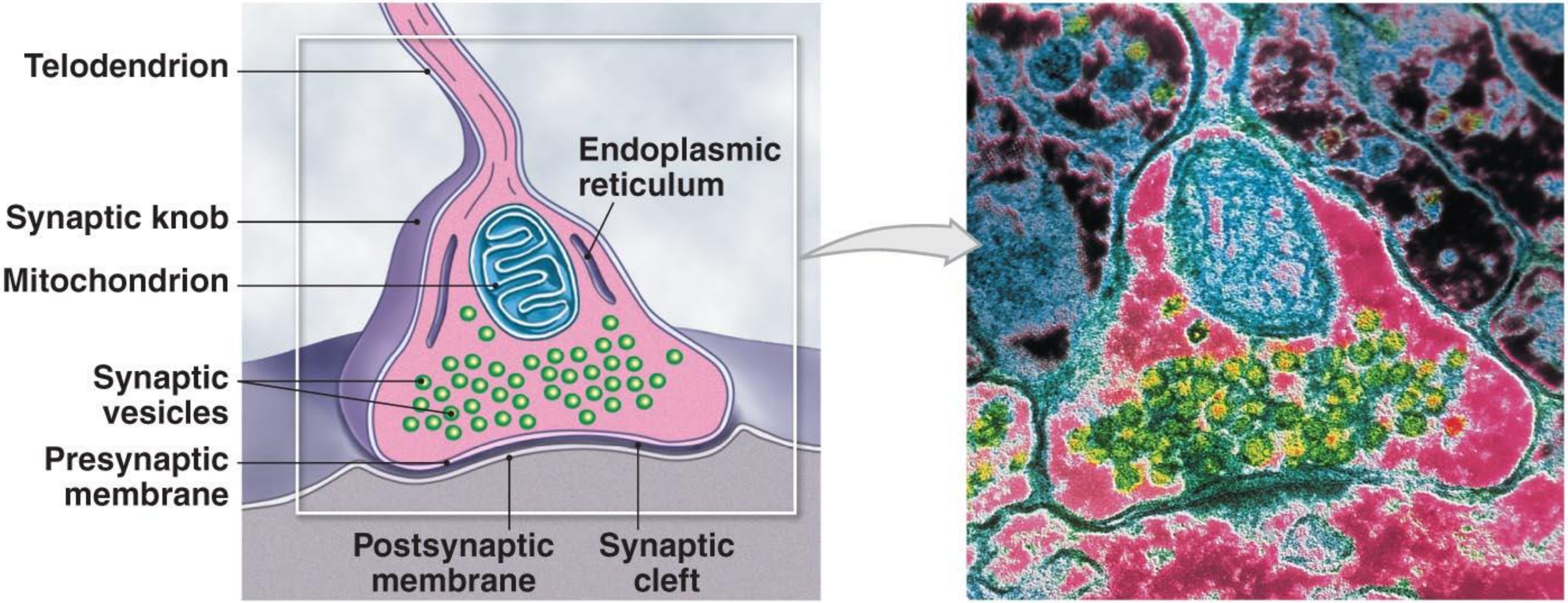


Figure 12–2 The Structure of a Typical Synapse.

Neurons

- Four Structural Classifications of Neurons
  - **Anaxonic neurons**
    - Found in brain and sense organs
  - **Bipolar neurons**
    - Found in special sensory organs (sight, smell, hearing)
  - **Unipolar neurons**
    - Found in sensory neurons of PNS
  - **Multipolar neurons**
    - Common in the CNS
    - Include all skeletal muscle motor neurons

Neurons

- **Anaxonic Neurons**
  - Small
  - All cell processes look alike
- **Bipolar Neurons**
  - Are small
  - One dendrite, one axon
- **Unipolar Neurons**
  - Have very long axons
  - Fused dendrites and axon
  - Cell body to one side
- **Multipolar Neurons**
  - Have very long axons
  - Multiple dendrites, one axon

Neurons

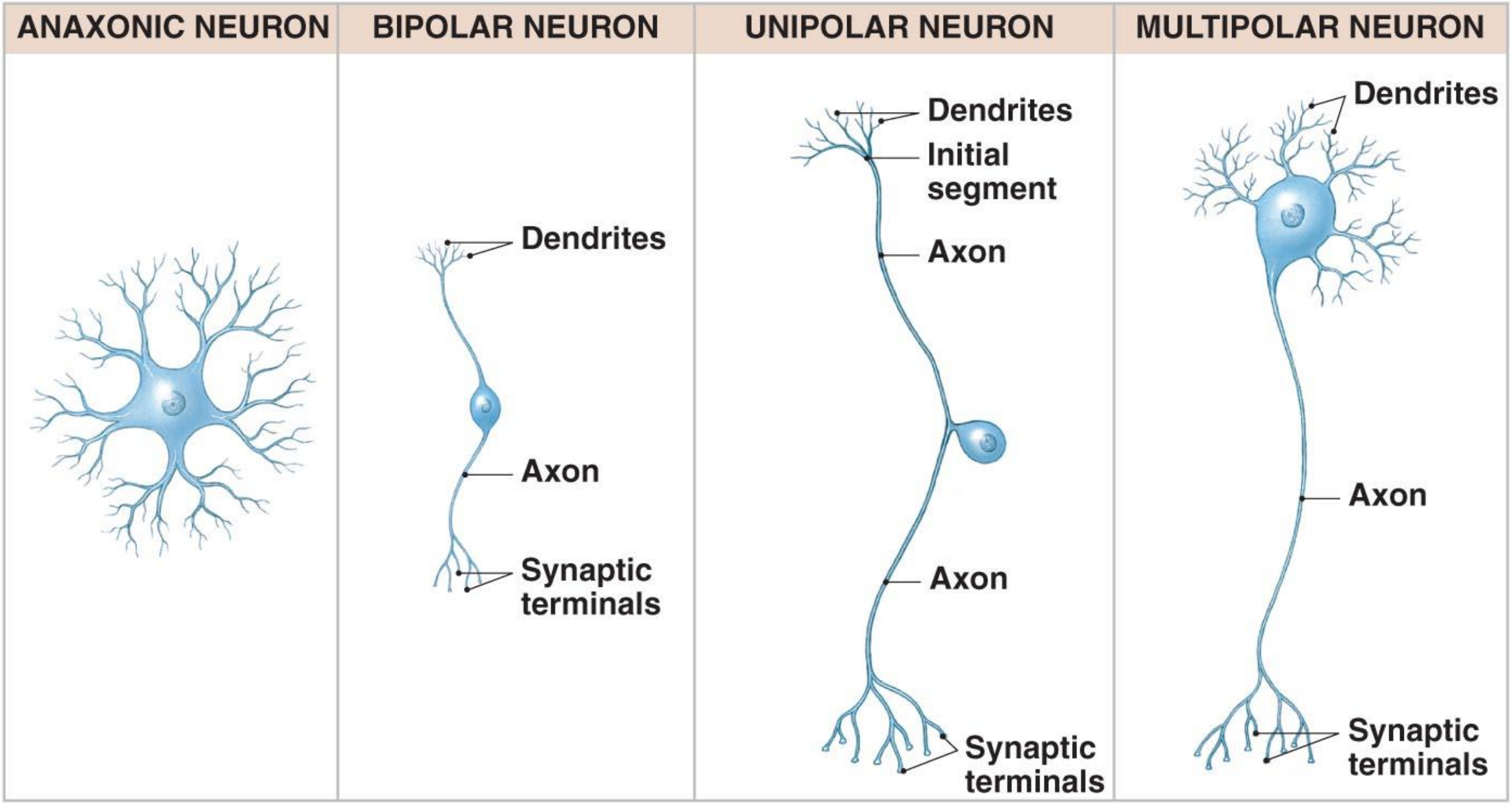


Figure 12–3 A Structural Classification of Neurons.

Neurons

- Three Functional Classifications of Neurons
  - **Sensory neurons**
    - *Afferent neurons* of PNS
  - **Motor neurons**
    - *Efferent neurons* of PNS
  - **Interneurons**
    - *Association neurons*

Neurons

- **Functions of Sensory Neurons**
  - Monitor internal environment **(visceral sensory neurons**)
  - Monitor effects of external environment (**somatic sensory neurons**)
  - Structures of sensory neurons
    - Unipolar
    - Cell bodies grouped in sensory ganglia
    - Processes (**afferent fibers**) extend from **sensory receptors** to CNS

Neurons

- Three Types of Sensory Receptors
  - **Interoceptors**
    - Monitor internal systems (digestive, respiratory, cardiovascular, urinary, reproductive)
    - Internal senses (taste, deep pressure, pain)
  - **Exteroceptors**
    - External senses (touch, temperature, pressure)
    - Distance senses (sight, smell, hearing)
  - **Proprioceptors**
    - Monitor position and movement (skeletal muscles and joints)

Neurons

- **Motor Neurons**
  - Carry instructions from CNS to peripheral effectors
  - Via **efferent fibers** (axons)
  - Two major efferent systems
    - Somatic nervous system (SNS):
      - includes all somatic motor neurons that innervate skeletal muscles
    - Autonomic (visceral) nervous system (ANS):
      - visceral motor neurons innervate all other peripheral effectors
      - e.g., smooth muscle, cardiac muscle, glands, adipose tissue

Neurons

- Motor Neurons
  - Two groups of efferent axons
    - Signals from CNS motor neurons to visceral effectors pass synapses at autonomic ganglia dividing axons into:
      – preganglionic fibers
      – postganglionic fibers

Neurons

- **Interneurons**
  - Most are located in brain, spinal cord, and autonomic ganglia
    - Between sensory and motor neurons
  - Are responsible for
    - Distribution of sensory information
    - Coordination of motor activity
  - Are involved in higher functions
    - Memory, planning, learning

Neuroglia

- Neuroglia
  - Half the volume of the nervous system
  - Many types of neuroglia in CNS and PNS

Neuroglia

- Four Types of Neuroglia in the CNS
  - **Ependymal cells:** cells with highly branched processes; contact neuroglia directly
  - **Astrocytes:** large cell bodies with many processes
  - **Oligodendrocytes:** smaller cell bodies with fewer processes
  - **Microglia:** smallest and least numerous neuroglia with many fine-branched processes

Neuroglia

- Four Types of Neuroglia in the CNS
  - **Ependymal cells**
    - Form epithelium called **ependyma**
    - Line central canal of spinal cord and ventricles of brain:
      - secrete **cerebrospinal fluid** (CSF)
      - have cilia or microvilli that circulate CSF
      - monitor CSF
      - contain stem cells for repair

Neuroglia

- Four Types of Neuroglia in the CNS
  - **Astrocytes**
    - Maintain blood–brain barrier (isolates CNS)
    - Create three-dimensional framework for CNS
    - Repair damaged neural tissue
    - Guide neuron development
    - Control interstitial environment
  - **Oligodendrocytes**
    - Processes contact other neuron cell bodies
    - Wrap around axons to form myelin sheaths

Neuroglia

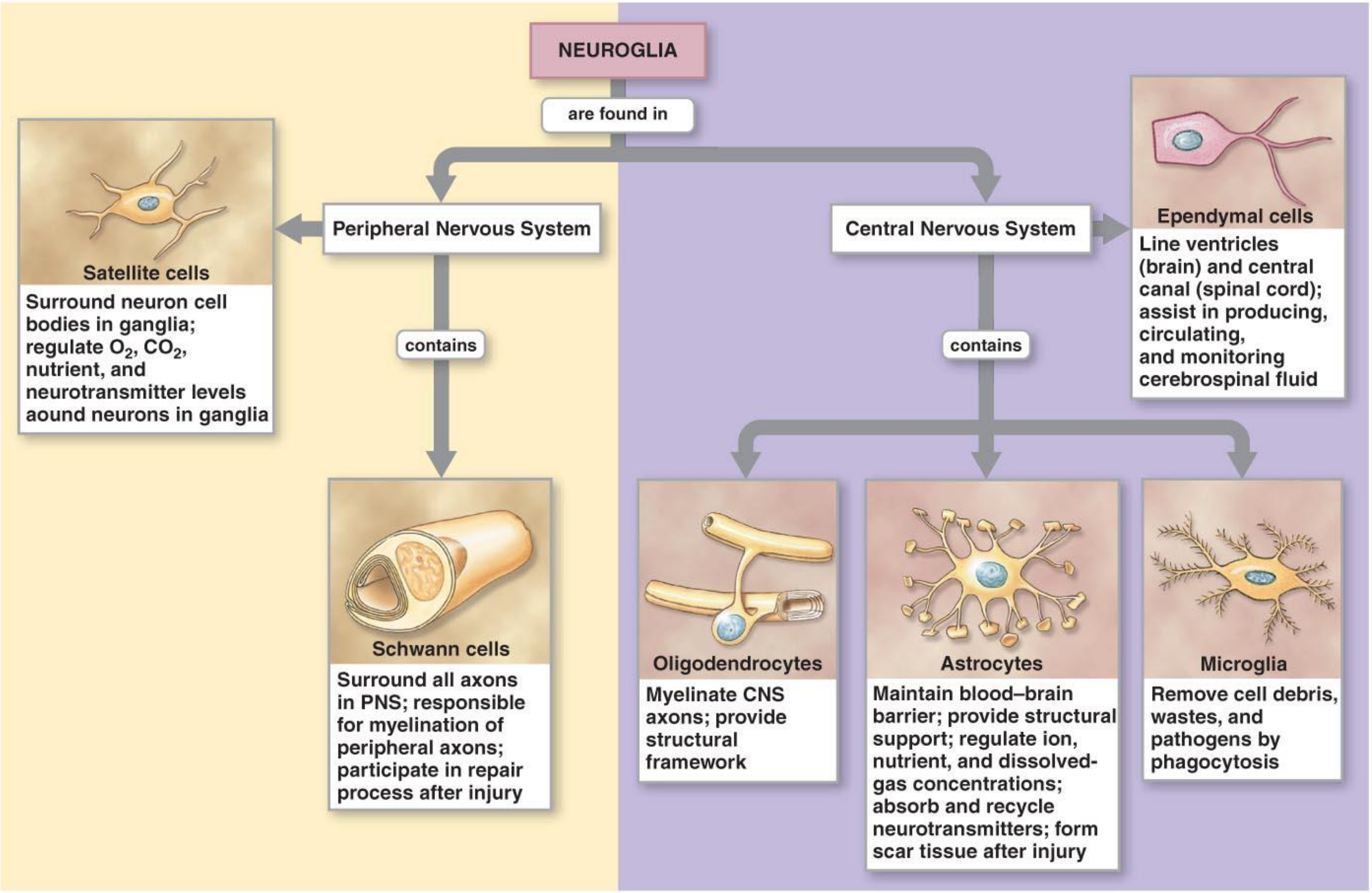


Figure 12–4 An Introduction to Neuroglia.

Neuroglia

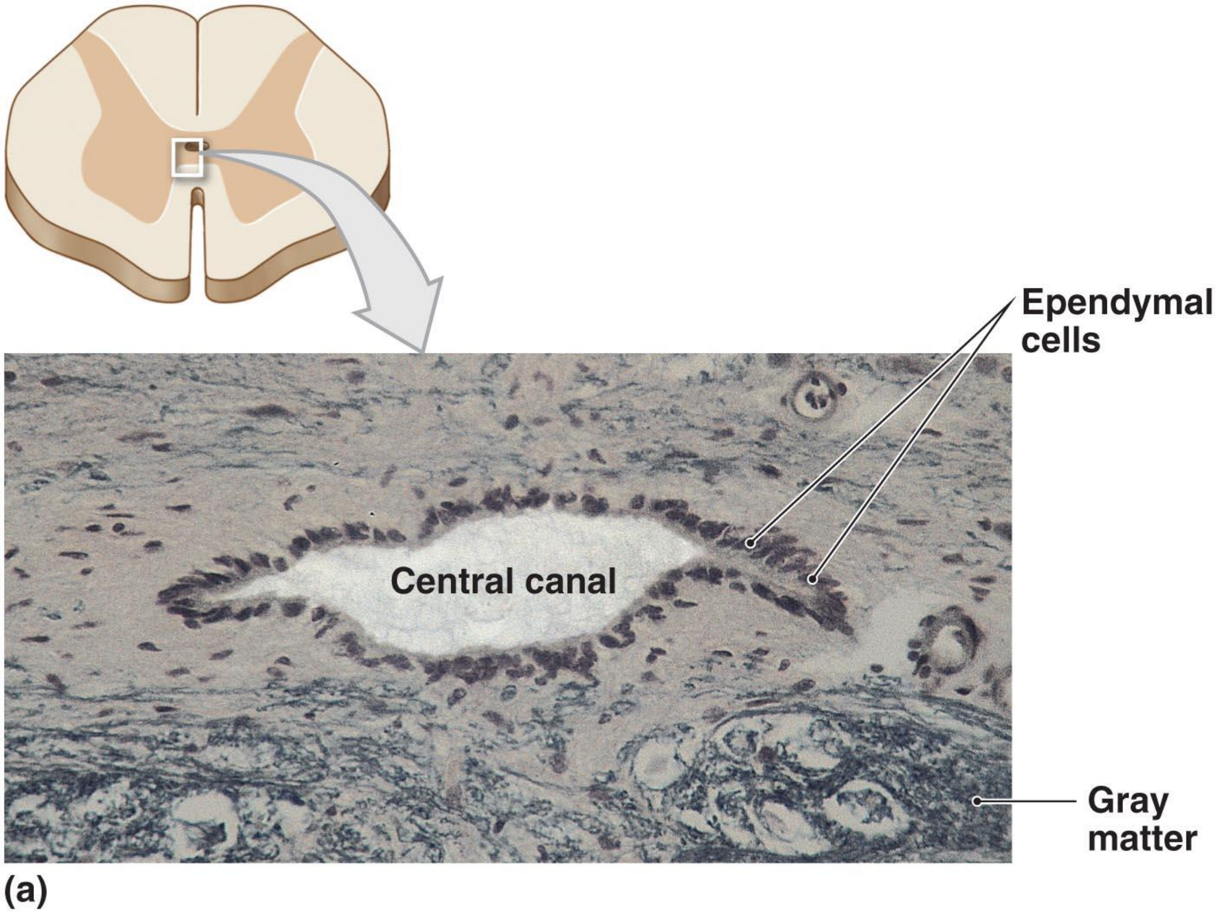


Figure 12–5a Neuroglia in the CNS.

Neuroglia

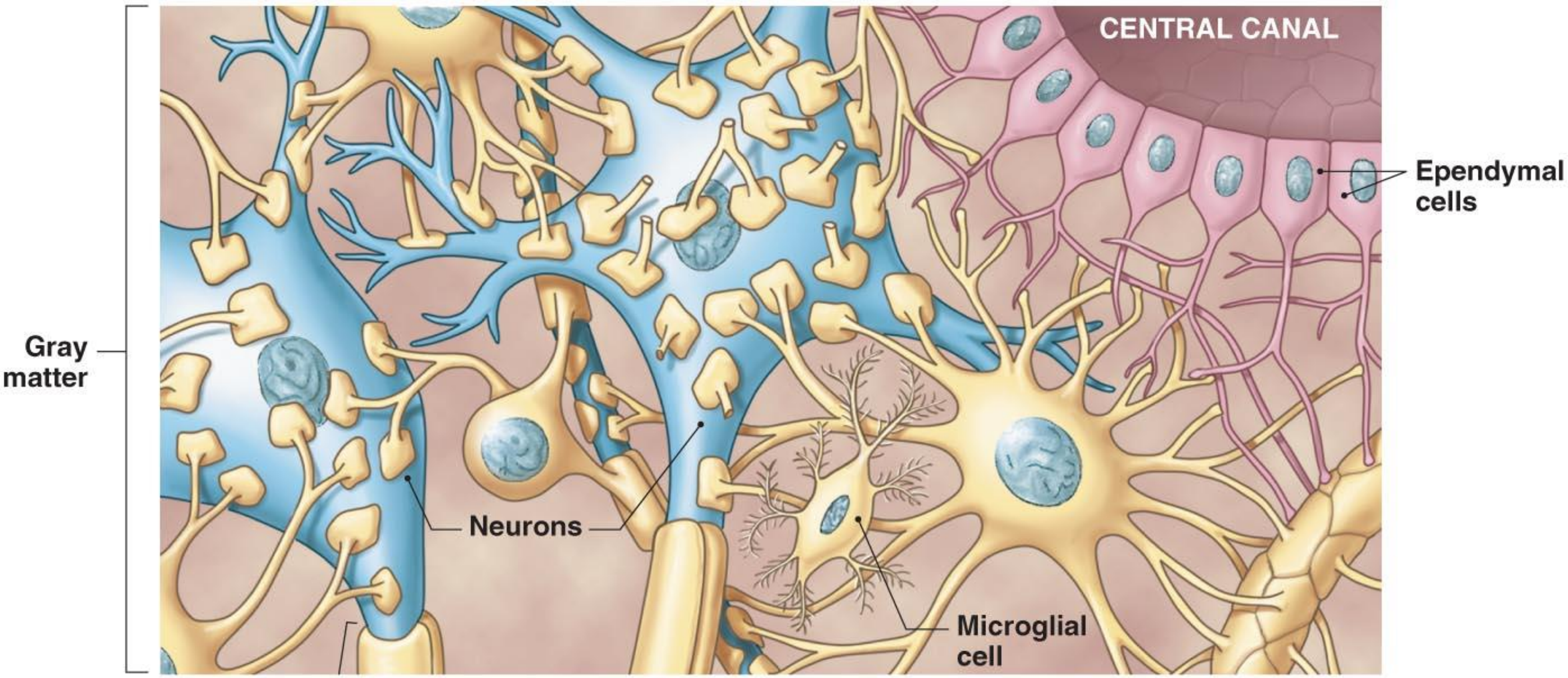
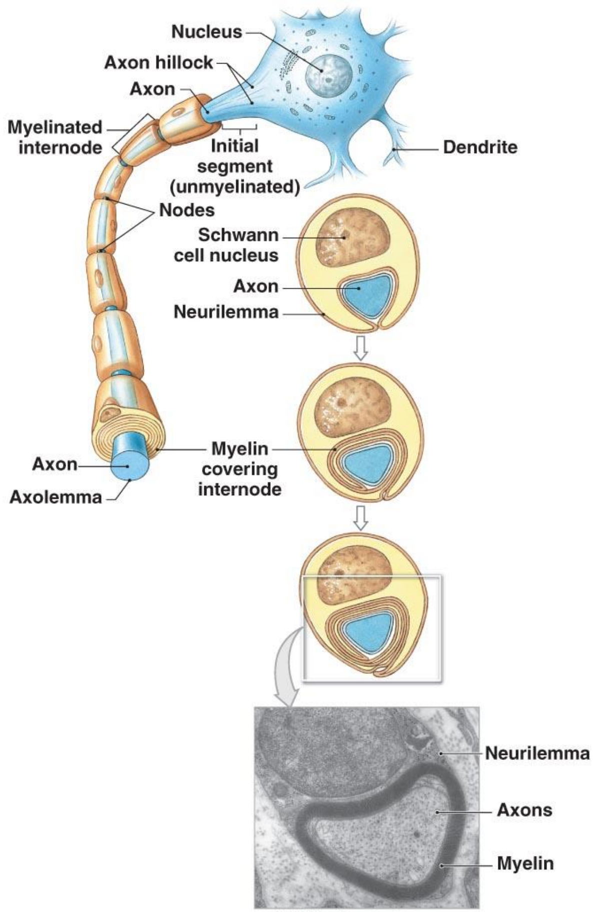


Figure 12–5b Neuroglia in the CNS.

Neuroglia

- Four Types of Neuroglia in the CNS
  - **Oligodendrocytes**
    - Myelination
      - – increases speed of action potentials
      - – myelin insulates myelinated axons
      - – makes nerves appear white
    - Nodes and internodes
      - – internodes: myelinated segments of axon
      - – **nodes** (also called *nodes of Ranvier)*
        - » gaps between internodes
        - » where axons may branch

Neuroglia



(a) Myelinated axon

Figure 12–6a Schwann Cells and Peripheral Axons.

Neuroglia

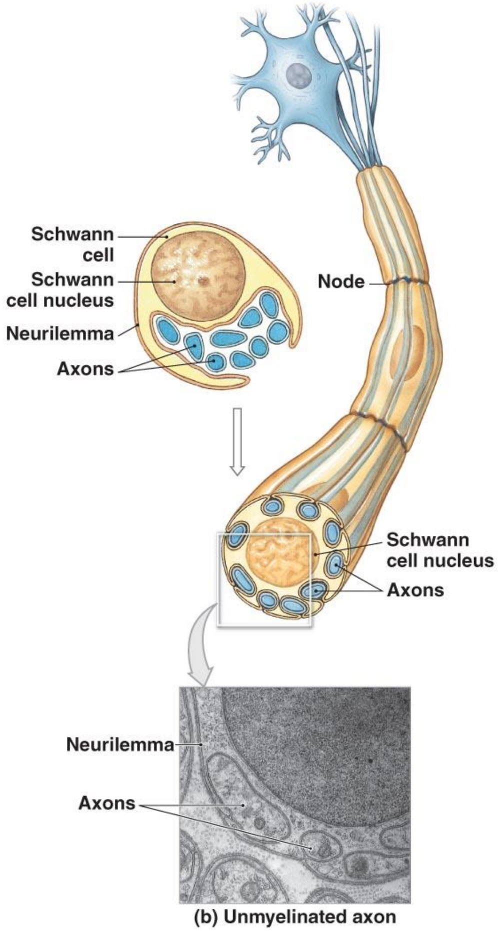


Figure 12–6b Schwann Cells and Peripheral Axons.

Neuroglia

- Four Types of Neuroglia in the CNS
  - Oligodendrocytes
    - Myelination
    - White matter:
      – regions of CNS with many myelinated nerves
    - Gray matter:
      – unmyelinated areas of CNS

Neuroglia

- Four Types of Neuroglia in the CNS
  - **Microglia**
    - Migrate through neural tissue
    - Clean up cellular debris, waste products, and pathogens

Neuroglia

- **Ganglia**
  - Masses of neuron cell bodies
  - Surrounded by neuroglia
  - Found in the PNS

Neuroglia

- Neuroglia of the Peripheral Nervous System
  - **Satellite cells**
    - Also called *amphicytes*
    - Surround ganglia
    - Regulate environment around neuron
  - **Schwann cells**
    - Also called *neurilemmocytes*
    - Form myelin sheath (**neurilemma**) around peripheral axons
    - One Schwann cell sheaths one segment of axon:
      – many Schwann cells sheath entire axon

Neuroglia

- Neurons perform all communication, information processing, and control functions of the nervous system
- Neuroglia preserve physical and biochemical structure of neural tissue and are essential to survival and function of neurons

Neuroglia

- **Neural Responses to Injuries**
  - Wallerian degeneration
    - Axon distal to injury degenerates
  - Schwann cells
    - Form path for new growth
    - Wrap new axon in myelin

Neuroglia

- Nerve Regeneration in CNS
  - Limited by chemicals released by astrocytes that
    - Block growth
    - Produce scar tissue

Neuroglia

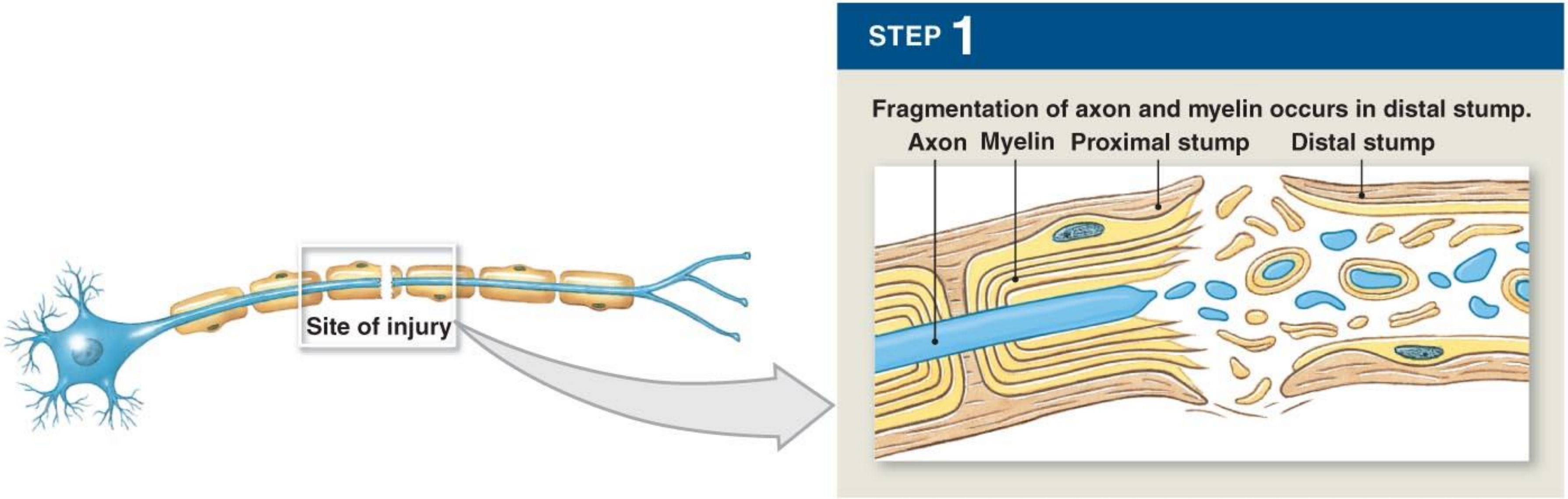


Figure 12–7 Peripheral Nerve Regeneration after Injury.

Neuroglia

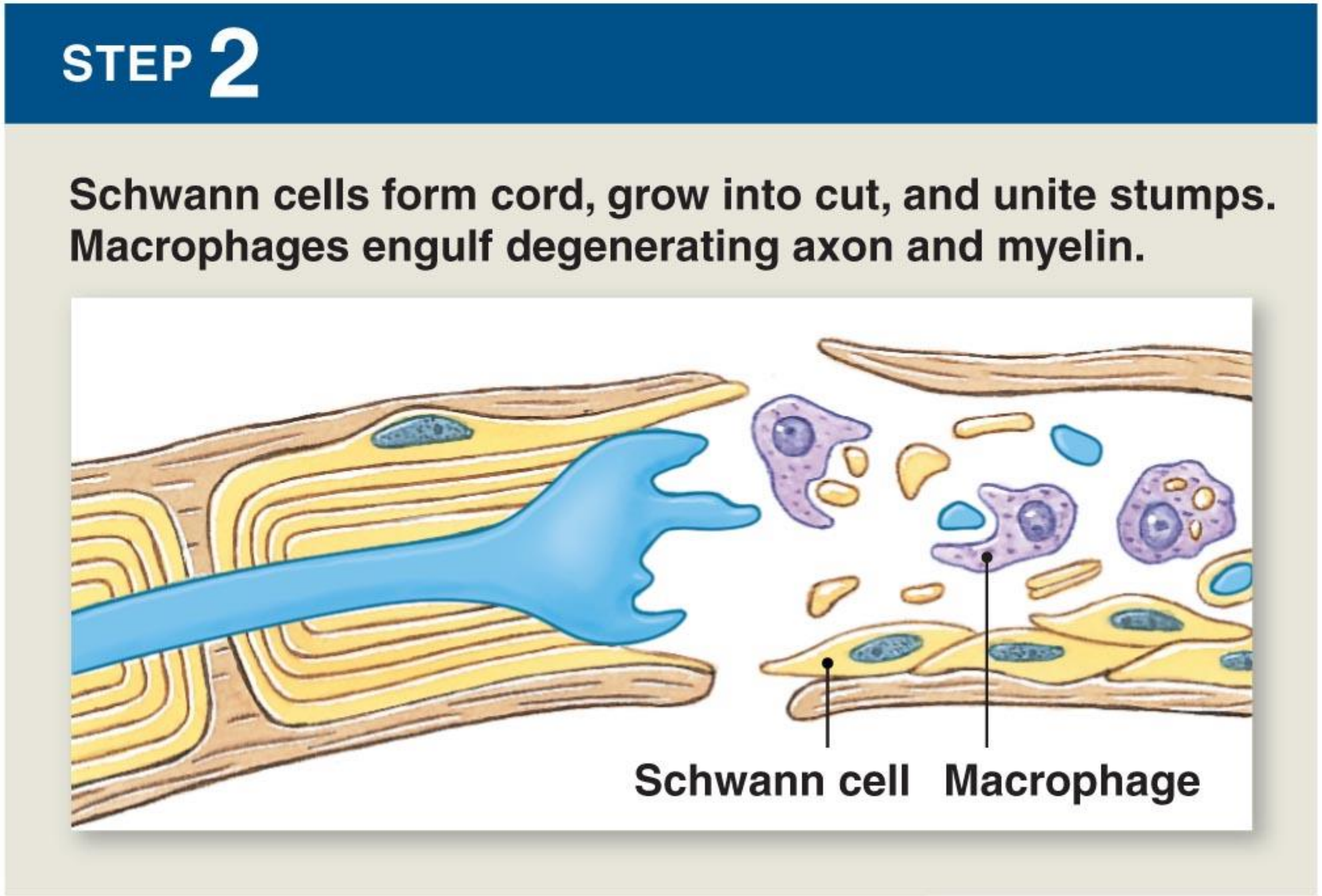


Figure 12–7 Peripheral Nerve Regeneration after Injury.

Neuroglia

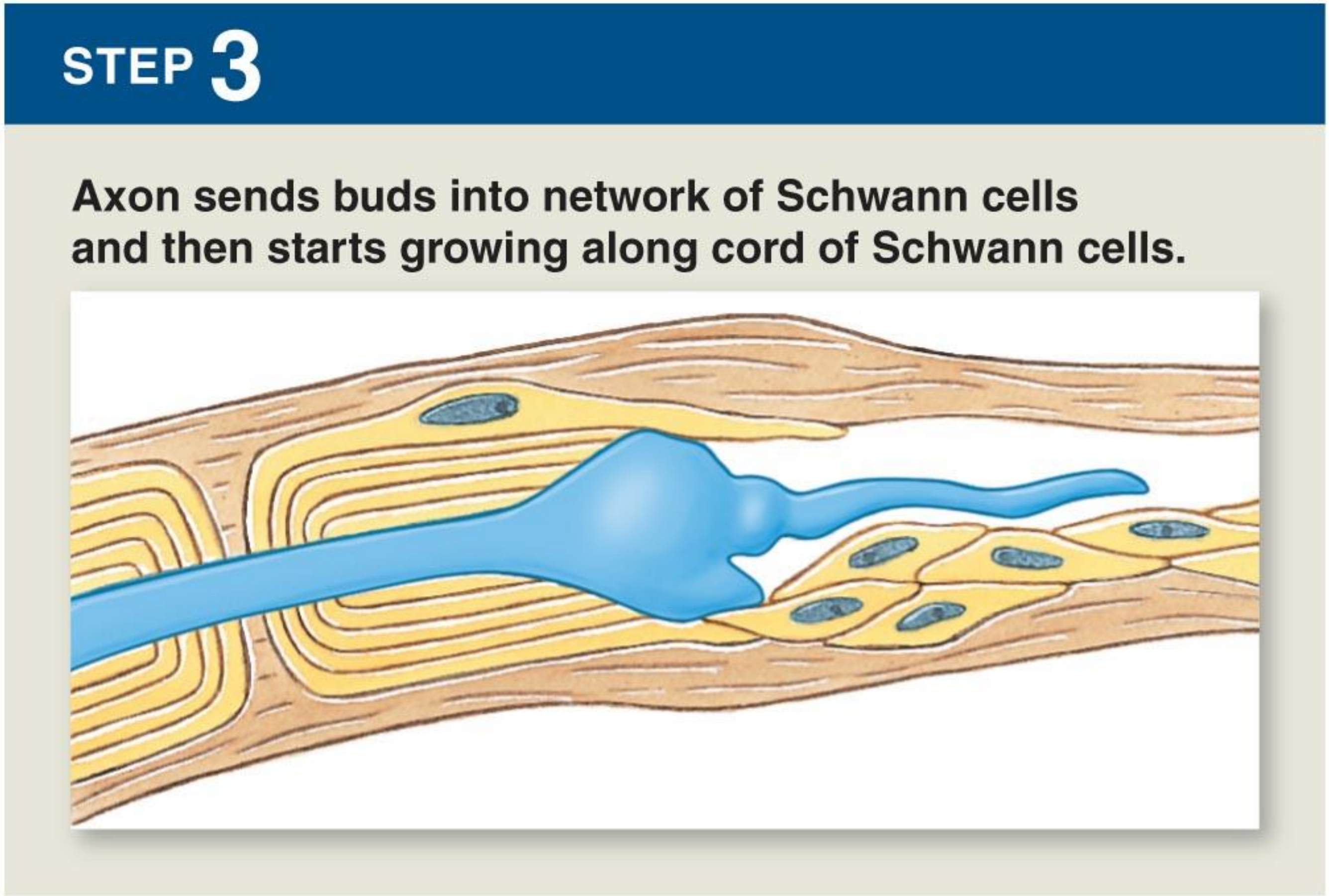


Figure 12–7 Peripheral Nerve Regeneration after Injury.

Neuroglia

STEP 4

Axon continues to grow into distal stump and is enclosed by Schwann cells.

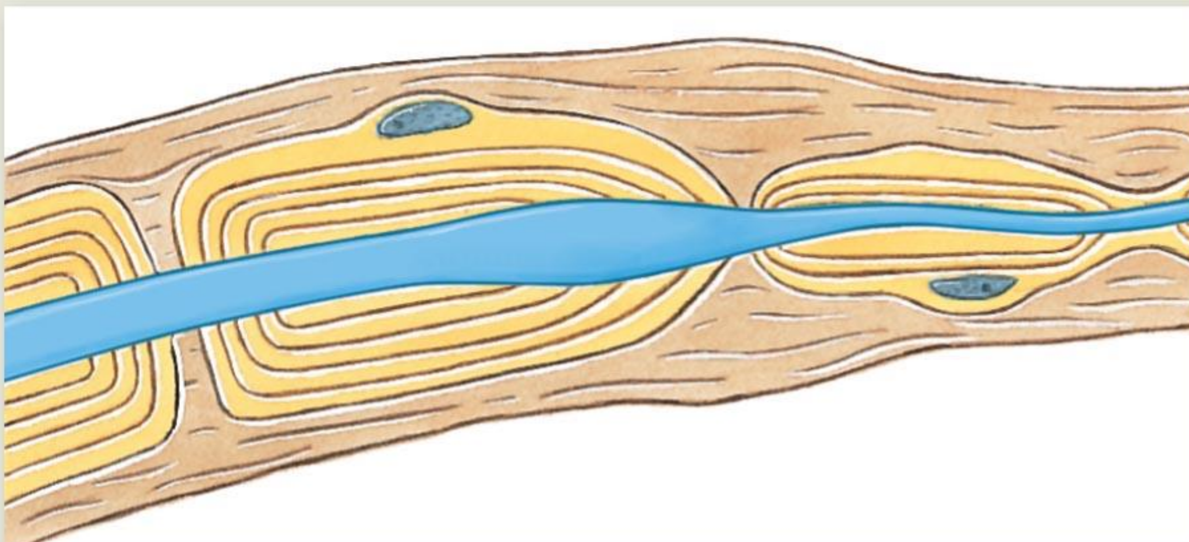


Figure 12–7 Peripheral Nerve Regeneration after Injury.

Transmembrane Potential

- Ion Movements and Electrical Signals
  - All plasma (cell) membranes produce electrical signals by ion movements
  - Transmembrane potential is particularly important to neurons

Transmembrane Potential

- Five Main Membrane Processes in Neural Activities
  - **Resting potential**
    - The transmembrane potential of resting cell
  - **Graded potential**
    - Temporary, localized change in resting potential
    - Caused by stimulus

Transmembrane Potential

- Five Main Membrane Processes in Neural Activities
  - **Action potential**
    - Is an electrical impulse
    - Produced by graded potential
    - Propagates along surface of axon to synapse

Neurophysiology: Action Potential

Transmembrane Potential

- Five Main Membrane Processes in Neural Activities
  - **Synaptic activity**
    - Releases neurotransmitters at presynaptic membrane
    - Produces graded potentials in postsynaptic membrane
  - **Information processing**
    - Response (integration of stimuli) of postsynaptic cell

Transmembrane Potential

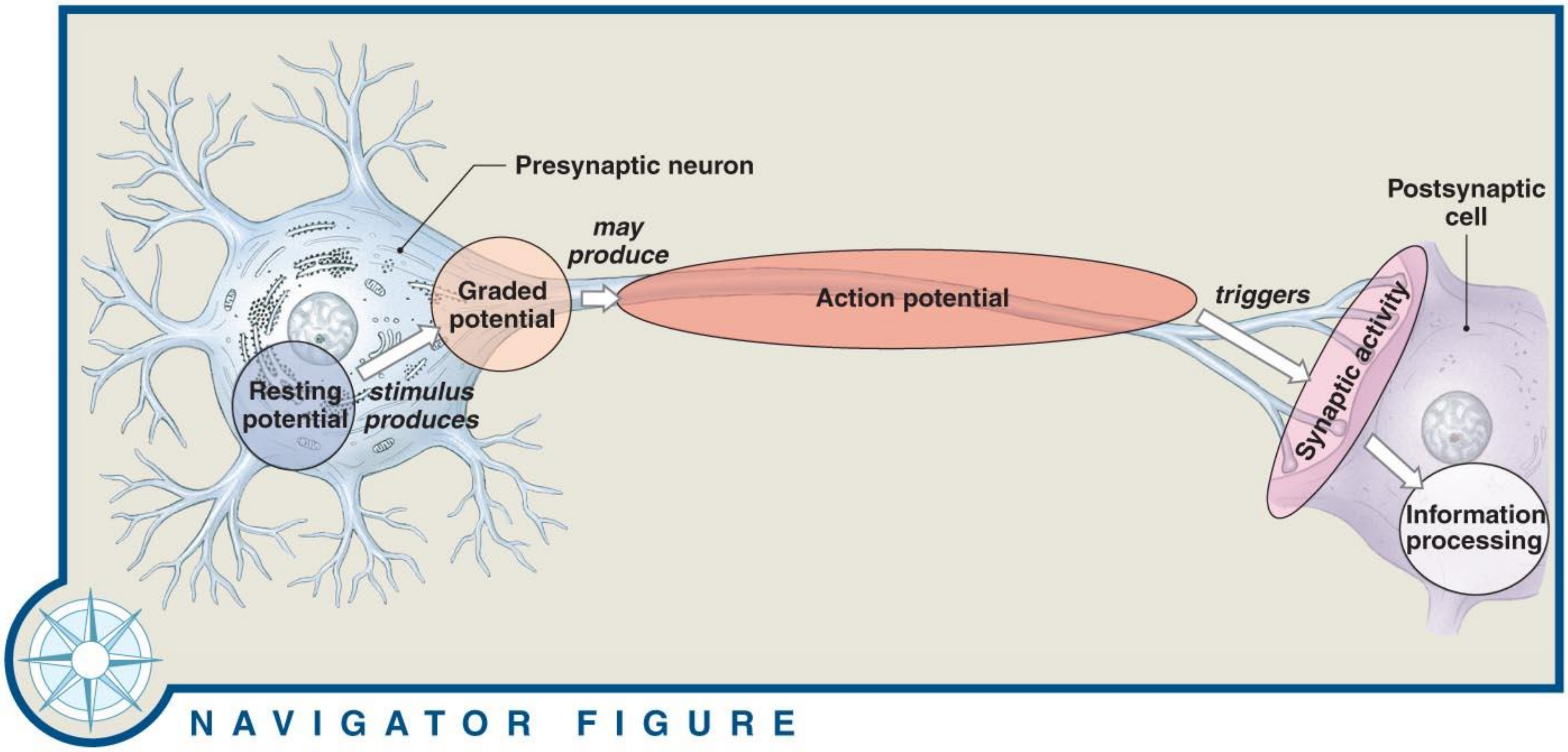


Figure 12–8 An Overview of Neural Activities.

Transmembrane Potential

- Three Requirements for Transmembrane Potential
  - Concentration gradient of ions (Na^+, K^+)
  - Selectively permeable through channels
  - Maintains charge difference across membrane (resting potential –70 mV)

Transmembrane Potential

- Passive Forces Acting Across the Membrane
  - **Chemical gradients**
    - Concentration gradients of ions (Na^+, K^+)
  - **Electrical gradients**
    - Separate charges of positive and negative ions
    - Result in *potential difference*

Transmembrane Potential

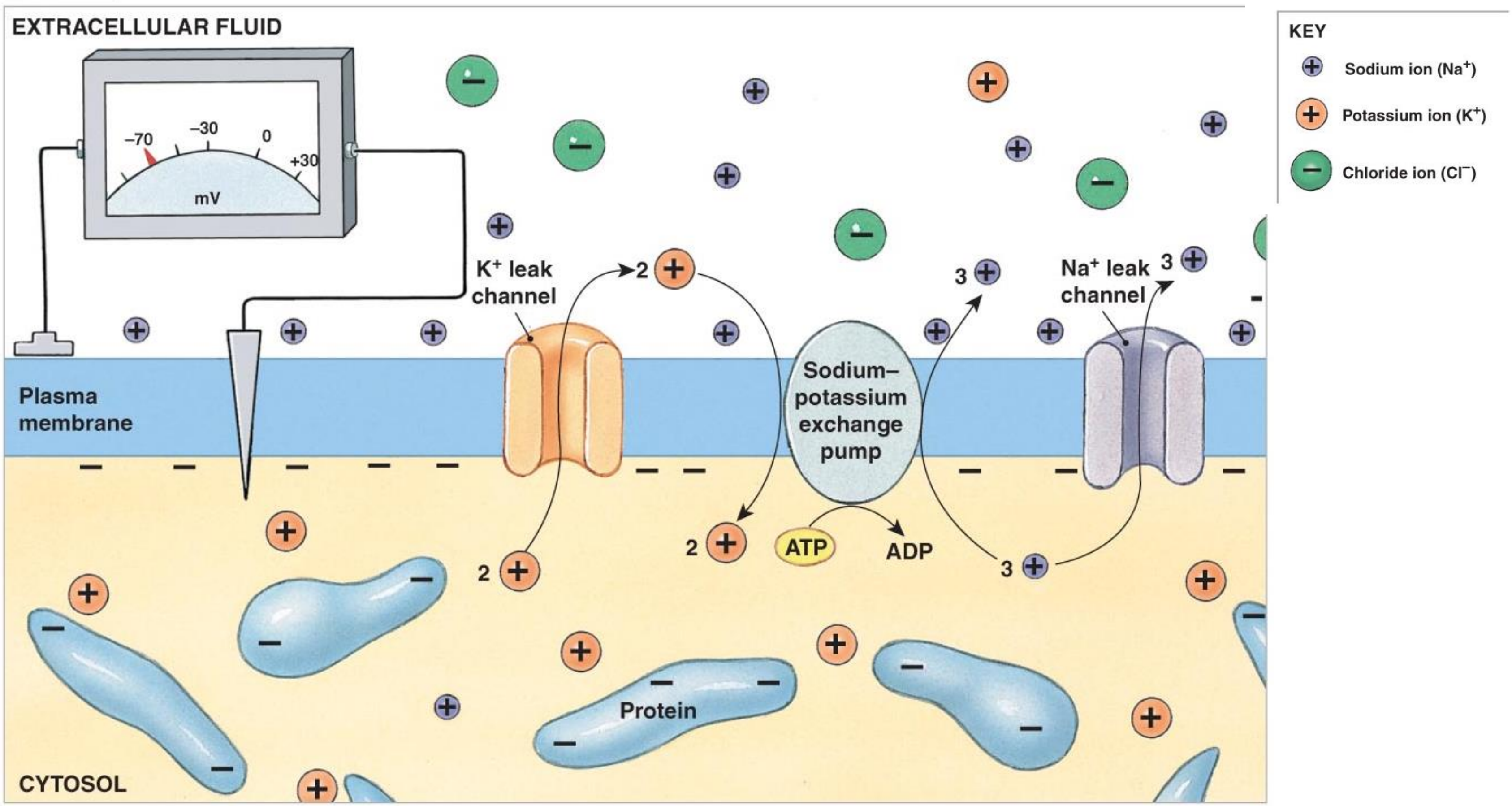


Figure 12–9 An Introduction to the Resting Potential.

Transmembrane Potential

- **Electrical Currents and Resistance**
  - Electrical current
    - Movement of charges to eliminate potential difference
  - Resistance
    - The amount of current a membrane restricts
- **Electrochemical Gradient**
  - For a particular ion (Na^+, K^+) is
    - The sum of chemical and electrical forces
  - Acting on the ion across a plasma membrane
    - A form of *potential energy*

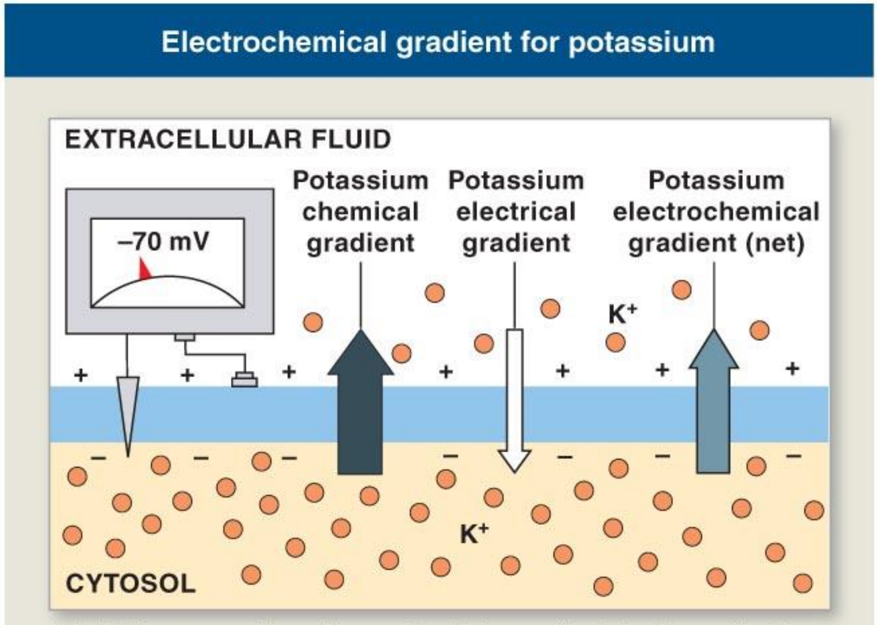
Transmembrane Potential

- **Equilibrium Potential**
  - The transmembrane potential at which there is no net movement of a particular ion across the cell membrane
  - Examples

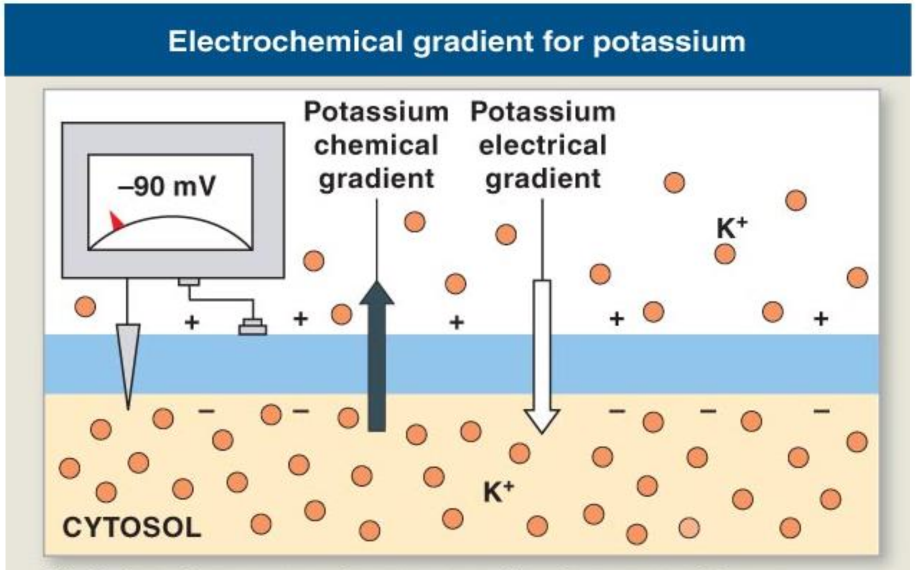
    $K^+ = –90$ mV

    $Na^+ = +66$ mV

Transmembrane Potential



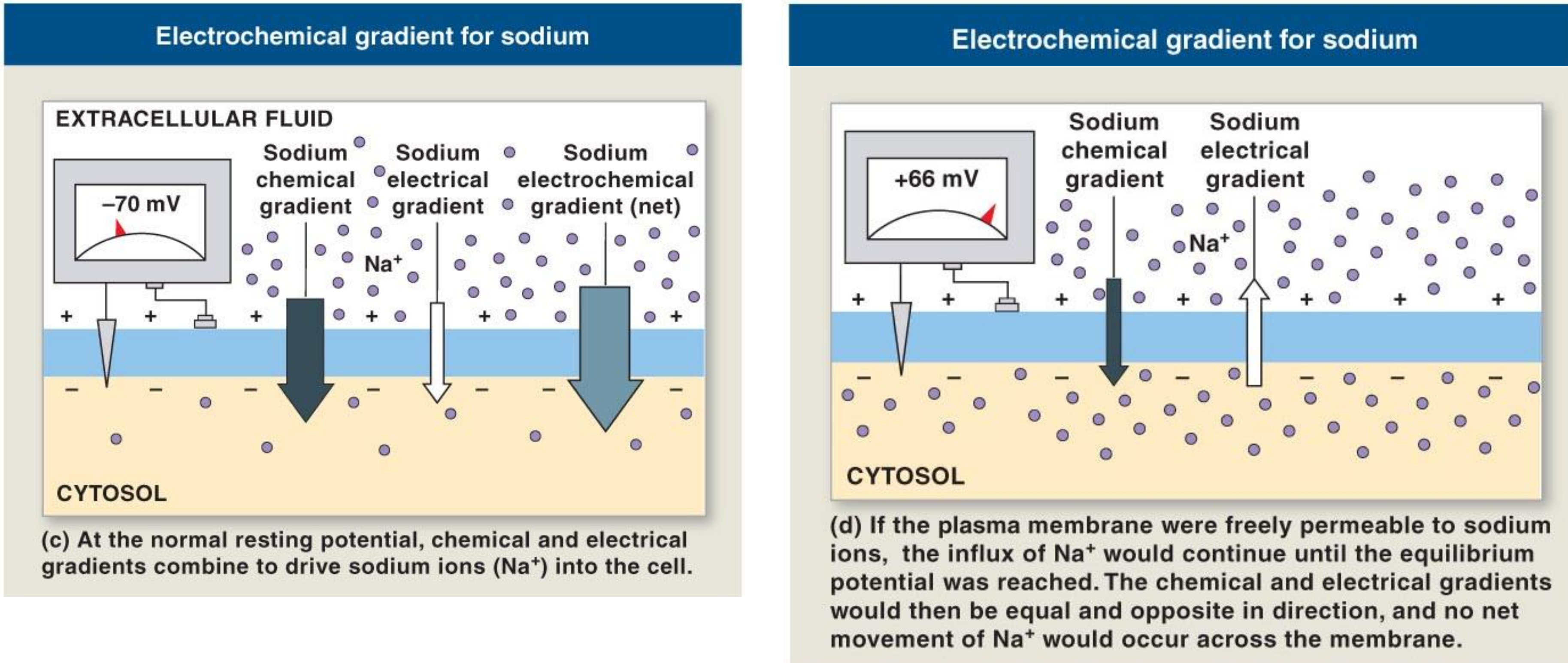
(a) At the normal resting potential, an electrical gradient opposes the chemical gradient for potassium ions (K^+). The net electrochemical gradient tends to force potassium ions out of the cell.



(b) If the plasma membrane were freely permeable to potassium ions, the outflow of K^+ would continue until the equilibrium potential was reached.

Figure 12–10 Electrochemical Gradients for Potassium and Sodium Ions.

Transmembrane Potential



(c) At the normal resting potential, chemical and electrical gradients combine to drive sodium ions (Na^+) into the cell.

(d) If the plasma membrane were freely permeable to sodium ions, the influx of Na^+ would continue until the equilibrium potential was reached. The chemical and electrical gradients would then be equal and opposite in direction, and no net movement of Na^+ would occur across the membrane.

Figure 12–10 Electrochemical Gradients for Potassium and Sodium Ions.

Transmembrane Potential

- **Active Forces Across the Membrane**
  - *Sodium–potassium ATPase* (exchange pump)
    - Is powered by ATP
    - Carries 3 Na^+ out and 2 K^+ in
    - Balances passive forces of diffusion
    - Maintains *resting potential* (–70 mV)

Transmembrane Potential

SUMMARY TABLE 12–1 The Resting Potential
• Because the plasma membrane is highly permeable to potassium ions, the resting potential is fairly close to −90 mV, the equilibrium potential for K^+.
• Although the electrochemical gradient for sodium ions is very large, the membrane's permeability to these ions is very low. Consequently, Na^+ has only a small effect on the normal resting potential, making it just slightly less negative than it would be otherwise.
• The sodium–potassium exchange pump ejects 3 Na^+ ions for every 2 K^+ ions that it brings into the cell. It thus serves to stabilize the resting potential when the ratio of Na^+ entry to K^+ loss through passive channels is 3:2.
• At the normal resting potential, these passive and active mechanisms are in balance. The resting potential varies widely with the type of cell. A typical neuron has a resting potential of approximately −70 mV.

Transmembrane Potential

- Changes in Transmembrane Potential
  - Transmembrane potential rises or falls
    - In response to temporary changes in membrane permeability
    - Resulting from opening or closing specific membrane channels

Transmembrane Potential

- Sodium and Potassium Channels
  - Membrane permeability to Na^+ and K^+ determines transmembrane potential
  - They are either **passive** or **active**
    - Passive channels (also called **leak channels**):
      - are always open
      - permeability changes with conditions
    - Active channels (also called **gated channels**):
      - open and close in response to stimuli
      - at resting potential, most gated channels are closed

Transmembrane Potential

- Three *Conditions* of Gated Channels
  - Closed, but capable of opening
  - Open (activated)
  - Closed, not capable of opening (inactivated)

Transmembrane Potential

- Three *Classes* of Gated Channels
  - **Chemically gated channels**
    - Open in presence of specific chemicals (e.g., ACh) at a binding site
    - Found on neuron cell body and dendrites
  - **Voltage-gated channels**
    - Respond to changes in transmembrane potential
    - Have activation gates (opens) and inactivation gates (closes)
    - Characteristic of excitable membrane
    - Found in neural axons, skeletal muscle sarcolemma, cardiac muscle
  - **Mechanically gated channels**
    - Respond to membrane distortion
    - Found in sensory receptors (touch, pressure, vibration)

Transmembrane Potential

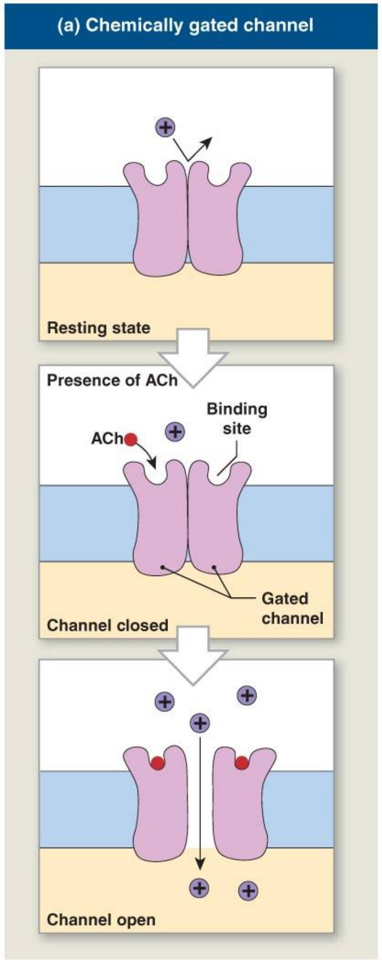


Figure 12–11a Gated Channels.

Transmembrane Potential

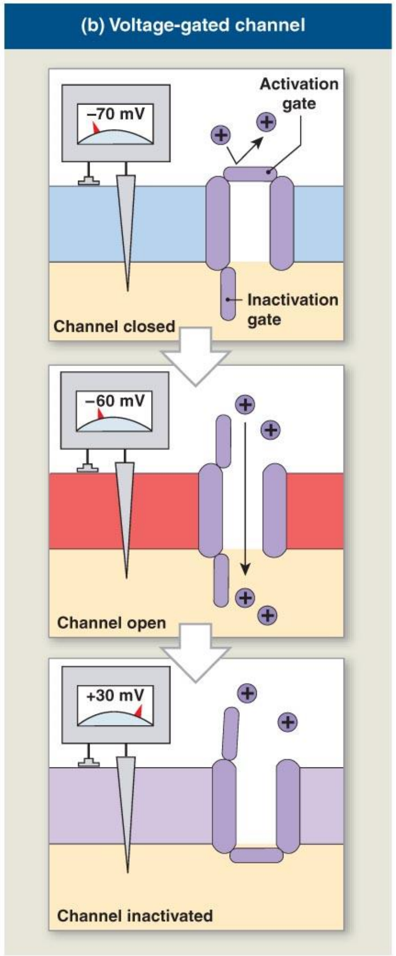


Figure 12–11b Gated Channels.

Transmembrane Potential

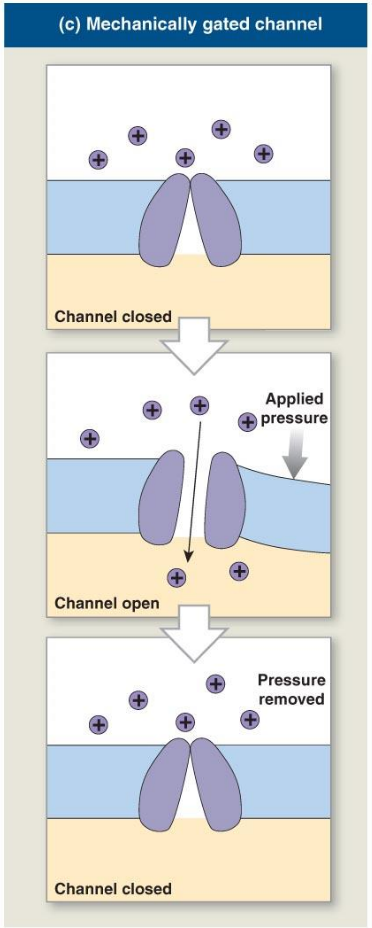


Figure 12–11c Gated Channels.

Transmembrane Potential

- **Transmembrane potential exists across plasma membrane because**
  - Cytosol and extracellular fluid have different chemical/ionic balance
  - The plasma membrane is selectively permeable
- **Transmembrane potential**
  - Changes with plasma membrane permeability
  - In response to chemical or physical stimuli

Transmembrane Potential

- **Graded Potentials**
  - Also called *local potentials*
  - Changes in transmembrane potential
    - That cannot spread far from site of stimulation
  - Any stimulus that opens a gated channel
    - Produces a graded potential

Transmembrane Potential

- Graded Potentials
  - **The Resting state**
    - Opening sodium channel produces graded potential:
      - resting membrane exposed to chemical
      - sodium channel opens
      - sodium ions enter the cell
      - transmembrane potential rises
      - **depolarization** occurs

Transmembrane Potential

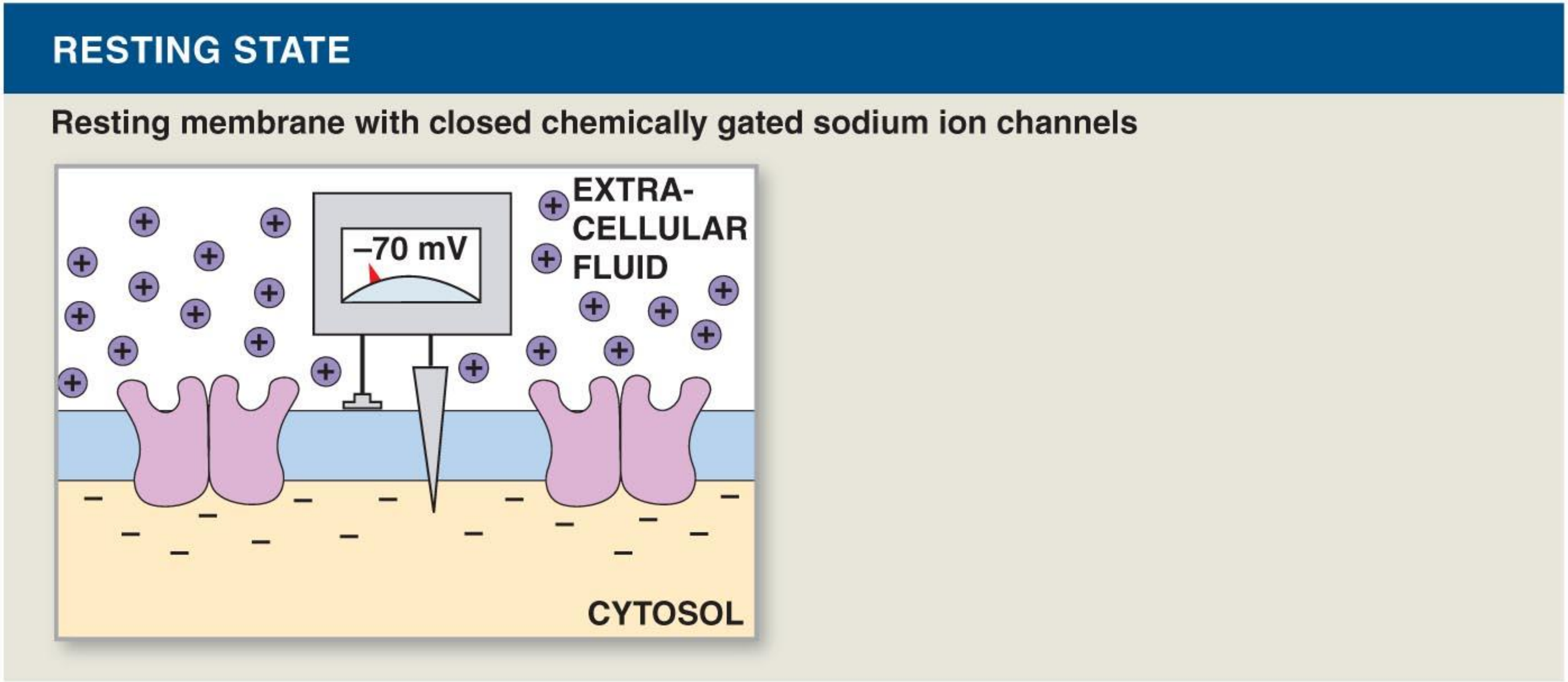


Figure 12–12 Graded Potentials (Resting State).

Transmembrane Potential

- Graded Potentials
  - **Depolarization**
    - A shift in transmembrane potential toward 0 mV:
      - movement of Na^+ through channel
      - produces **local current**
      - depolarizes nearby plasma membrane (**graded potential**)
      - change in potential is proportional to stimulus

Transmembrane Potential

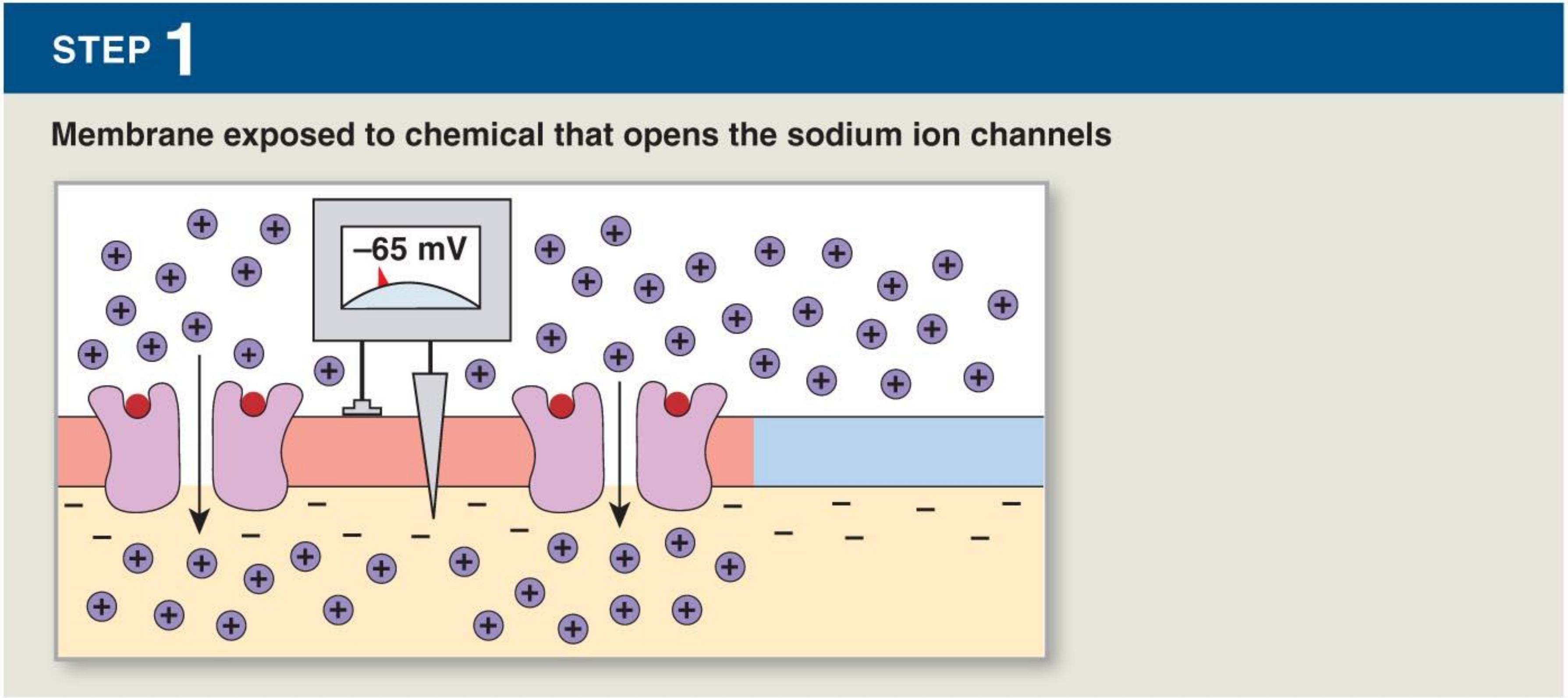


Figure 12–12 Graded Potentials (Step 1).

Transmembrane Potential

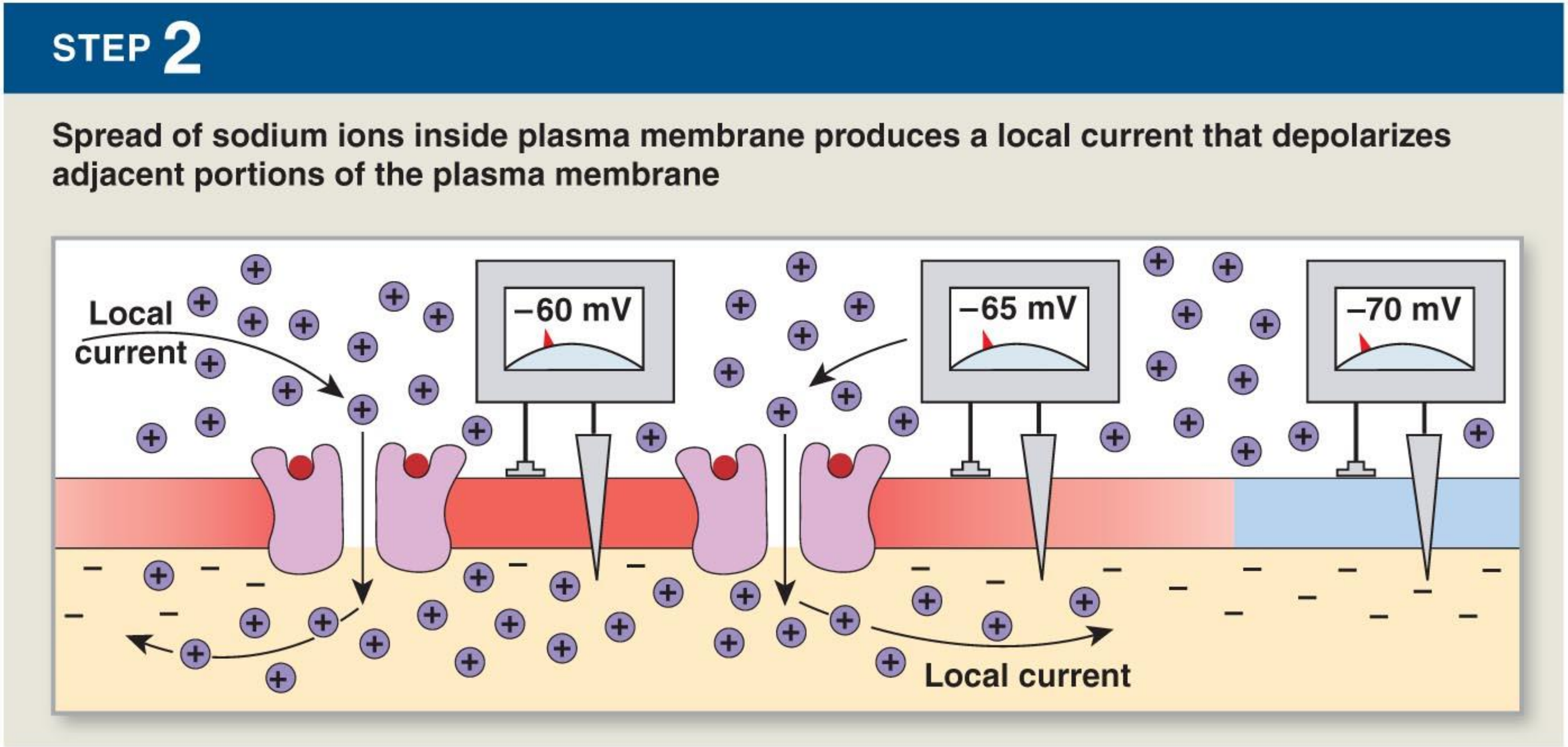


Figure 12–12 Graded Potentials (Step 2).

Transmembrane Potential

SUMMARY TABLE 12–2 Graded Potentials

Graded potentials, whether depolarizing or hyperpolarizing, share four basic characteristics:

1. The transmembrane potential is most affected at the site of stimulation, and the effect decreases with distance.
2. The effect spreads passively, owing to local currents.
3. The graded change in membrane potential may involve either depolarization or hyperpolarization. The nature of the change is determined by the properties of the membrane channels involved. For example, in a resting membrane, the opening of sodium channels will cause depolarization, whereas the opening of potassium channels will cause hyperpolarization. That is, the change in membrane potential reflects whether positive charges enter or leave the cell.
4. The stronger the stimulus, the greater is the change in the transmembrane potential and the larger is the area affected.

Transmembrane Potential

- Graded Potentials
  - **Repolarization**
    - When the stimulus is removed, transmembrane potential returns to normal
  - **Hyperpolarization**
    - Increasing the negativity of the resting potential
    - Result of opening a potassium channel
    - Opposite effect of opening a sodium channel
    - Positive ions move out, not into cell

Transmembrane Potential

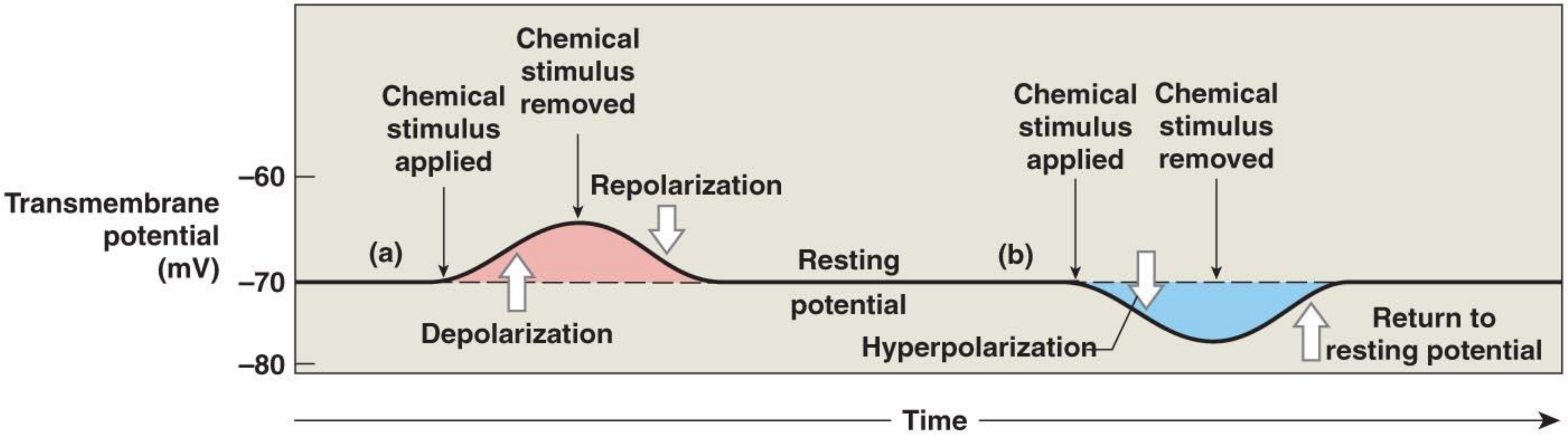


Figure 12–13 Depolarization, Repolarization, and Hyperpolarization.

Transmembrane Potential

- Graded Potentials
  - **Effects of graded potentials**
    - At cell dendrites or cell bodies:
      - – trigger specific cell functions
      - – e.g., exocytosis of glandular secretions
    - At motor end plate:
      - – releases ACh into synaptic cleft

Action Potential

- Action Potentials
  - Propagated changes in transmembrane potential
  - Affect an entire excitable membrane
  - Link graded potentials at cell body with motor end plate actions

Action Potential

- Initiating Action Potential
  - **Initial stimulus**
    - A graded depolarization of axon hillock large enough (10 to 15 mV) to change resting potential (−70 mV) to threshold level of voltage-gated sodium channels (–60 to –55 mV)

Action Potential

- Initiating Action Potential
  - **All-or-none principle**
    - If a stimulus exceeds threshold amount:
      – the action potential is the same
      – no matter how large the stimulus
    - Action potential is either triggered, or not

Action Potential

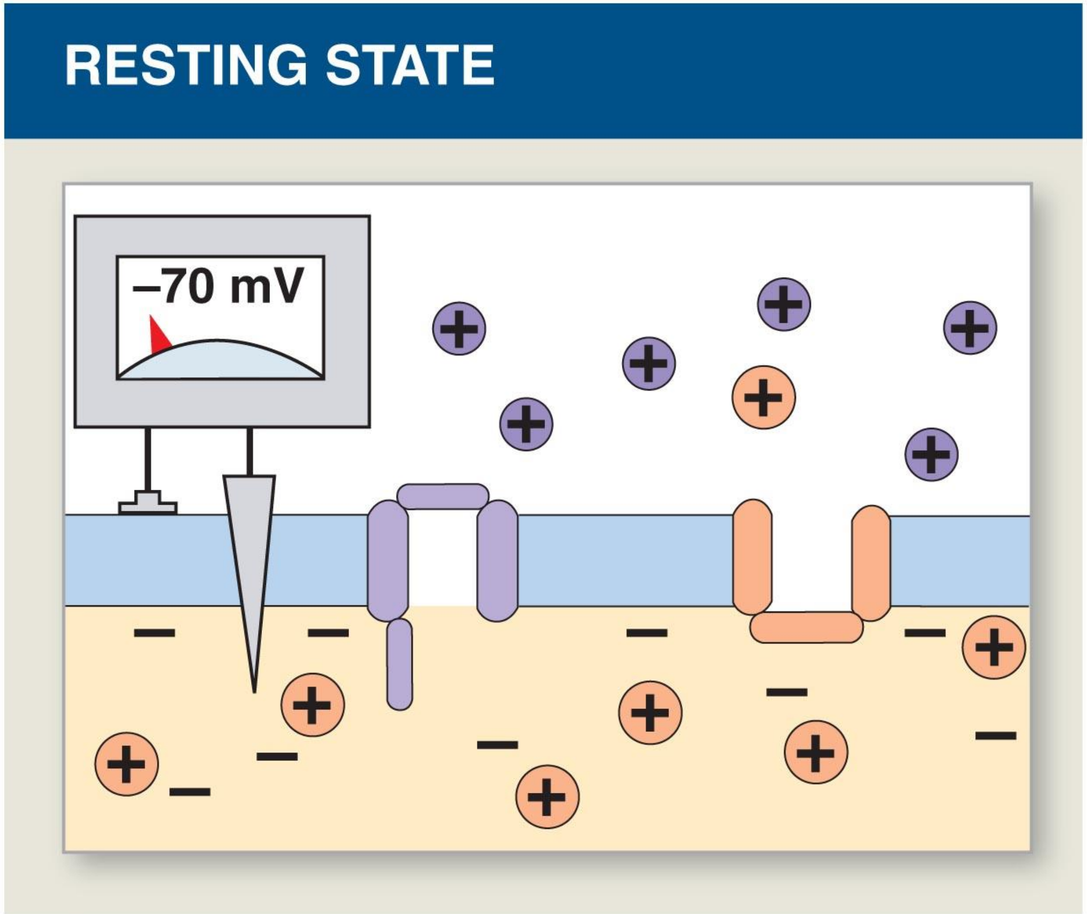


Figure 12–14 The Generation of an Action Potential (Resting State).

Action Potential

- Four Steps in the Generation of Action Potentials
  - **Step 1: Depolarization to threshold**
  - **Step 2: Activation of Na^+ channels**
    - Rapid depolarization
    - Na^+ ions rush into cytoplasm
    - Inner membrane changes from negative to positive

Action Potential

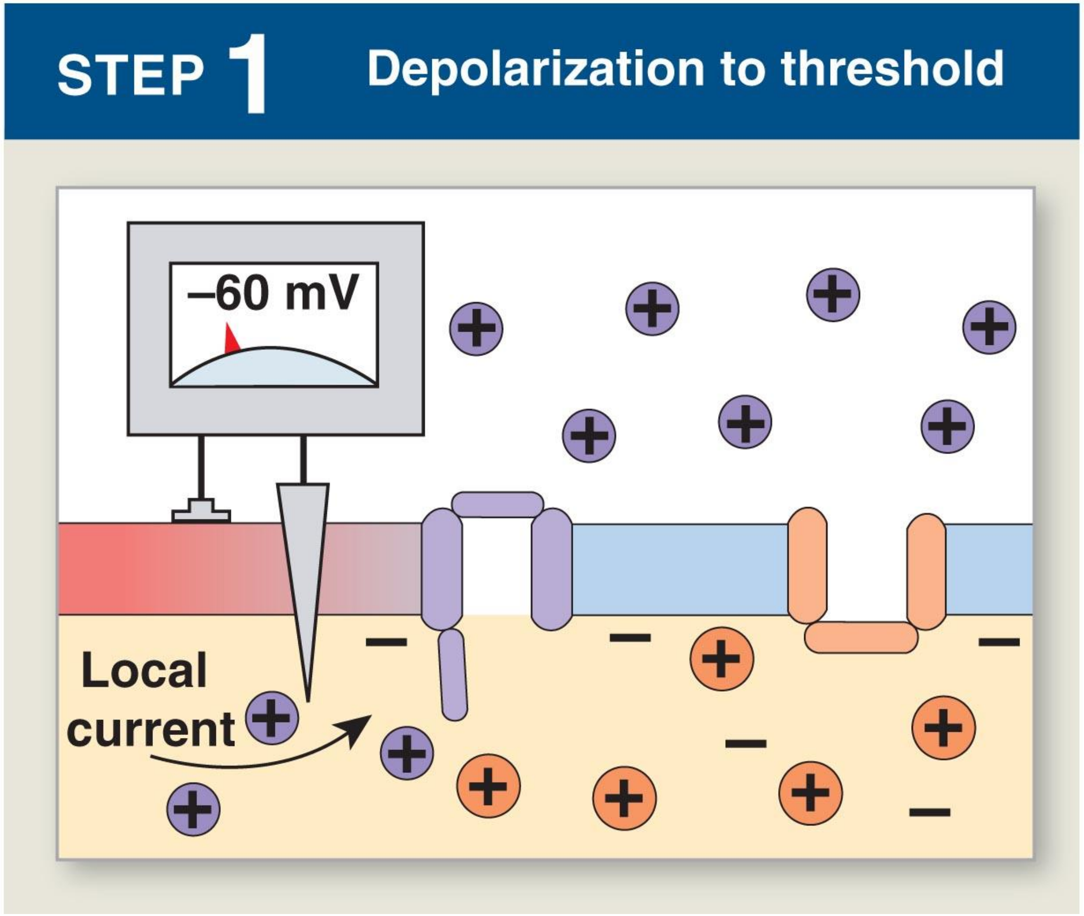


Figure 12–14 The Generation of an Action Potential (Step 1).

Action Potential

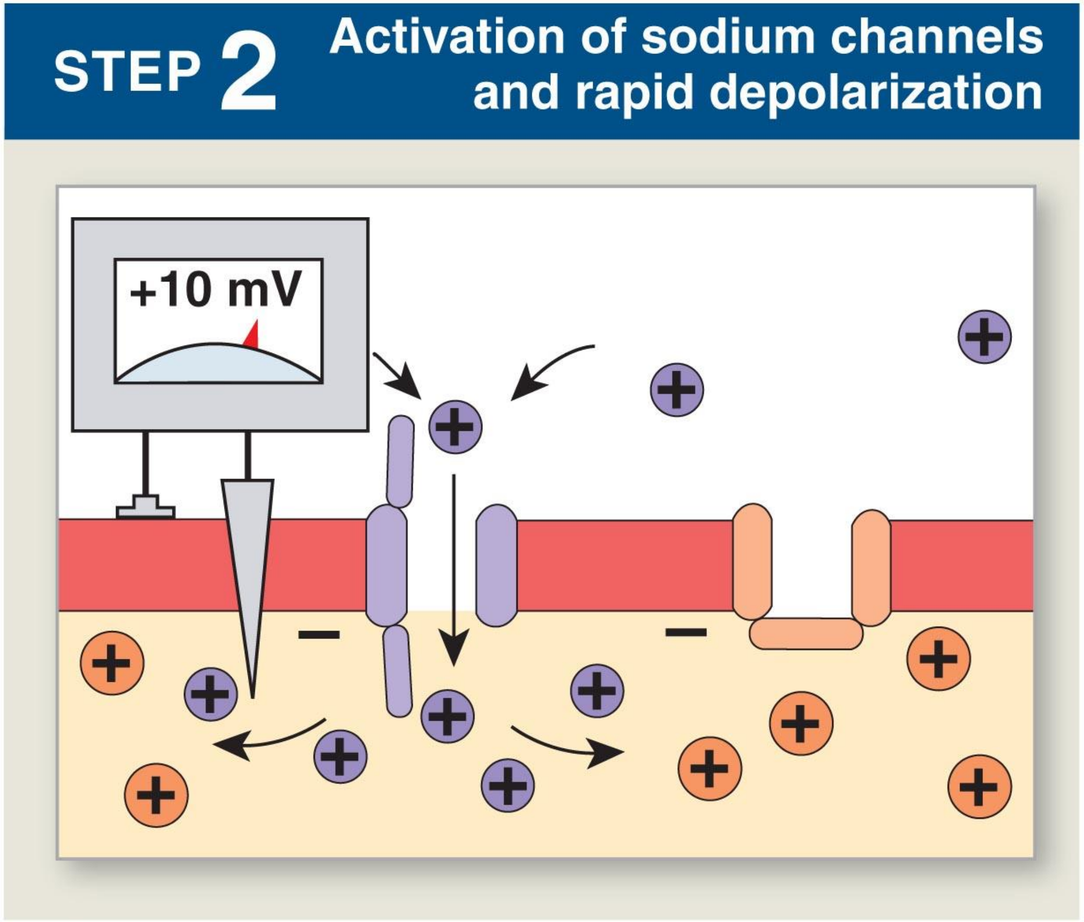


Figure 12–14 The Generation of an Action Potential (Step 2).

Action Potential

- Four Steps in the Generation of Action Potentials
  - **Step 3: Inactivation of Na^+ channels, activation of K^+ channels**
    - At +30 mV
    - Inactivation gates close (Na^+ channel inactivation)
    - K^+ channels open
    - Repolarization begins

Action Potential

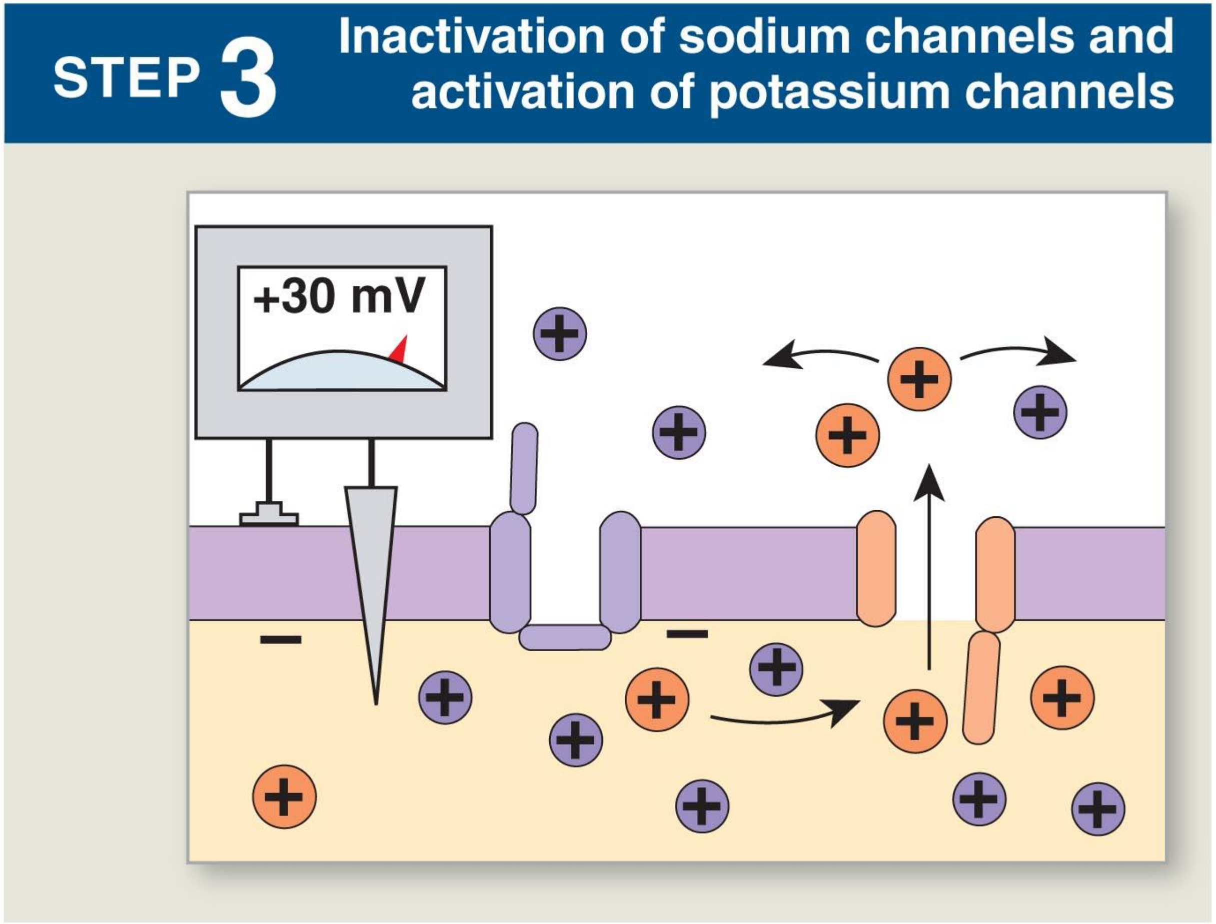


Figure 12–14 The Generation of an Action Potential (Step 3).

Action Potential

- Four Steps in the Generation of Action Potentials
  - **Step 4: Return to normal permeability**
    - K^+ channels begin to close:
      - when membrane reaches normal resting potential (–70 mV)
    - K^+ channels finish closing:
      - membrane is hyperpolarized to -90 mV
      - transmembrane potential returns to resting level:
      - action potential is over

Action Potential

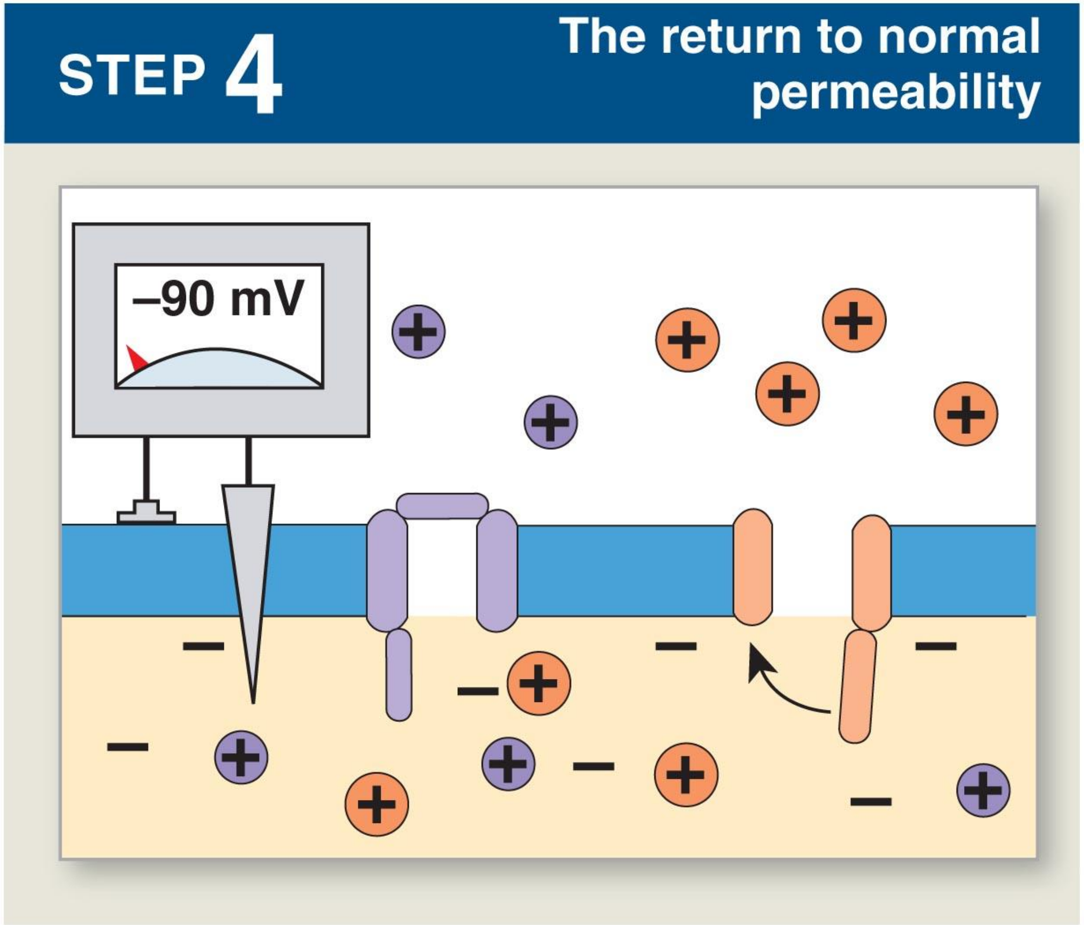


Figure 12–14 The Generation of an Action Potential (Step 4).

Action Potential

- The Refractory Period
  - **The time period**
    - From beginning of action potential
    - To return to resting state
    - During which membrane will not respond normally to additional stimuli
  - **Absolute refractory period**
    - Sodium channels open or inactivated
    - No action potential possible
  - **Relative refractory period**
    - Membrane potential almost normal
    - Very large stimulus can initiate action potential

Action Potential

- Powering the Sodium-Potassium Exchange Pump
  - To maintain concentration gradients of Na^+ and K^+ over time
    - Requires energy (1 ATP for each $2K^+/3\ Na^+$ exchange)
  - Without ATP
    - Neurons stop functioning

Action Potential

SUMMARY TABLE 12–3 Generation of Action Potentials

STEP 1: Depolarization to threshold

- A graded depolarization brings an area of excitable membrane to threshold (−60 mV).

STEP 2: Activation of sodium channels and rapid depolarization

- The voltage-gated sodium channels open (sodium channel activation).
- Sodium ions, driven by electrical attraction and the chemical gradient, flood into the cell.
- The transmembrane potential goes from −60 mV (the threshold level), toward +30 mV (the sodium equilibrium potential).

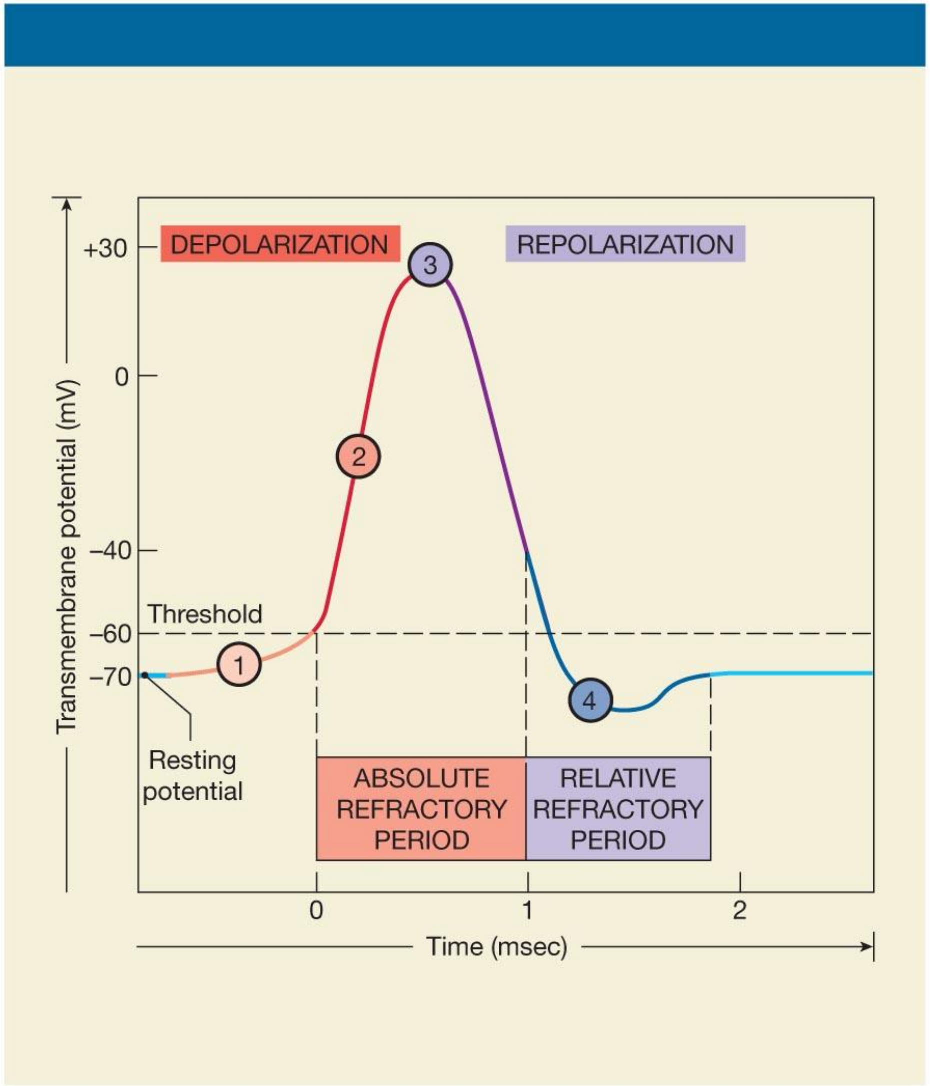
STEP 3: Inactivation of sodium channels and activation of potassium channels

- The voltage-gated sodium channels close (sodium channel inactivation occurs) at +30 mV.
- The voltage-gated potassium channels are now open, and potassium ions diffuse out of the cell.
- Repolarization begins.

STEP 4: Return to normal permeability

- The voltage-gated sodium channels regain their normal properties in 0.4–1.0 msec. The membrane is now capable of generating another action potential if a larger-than-normal stimulus is provided.
- The voltage-gated potassium channels begin closing at −70 mV. Because they do not all close at the same time, potassium loss continues and a temporary hyperpolarization to approximately −90 mV (the potassium equilibrium potential) occurs.
- At the end of relative refractory period, all voltage-gated channels have closed and the plasma membrane is back to its resting state.

Action Potential



Action Potential

- Propagation of Action Potentials
  - **Propagation**
    - Moves action potentials generated in axon hillock
    - Along entire length of axon
    - A series of repeated actions, not passive flow
  - **Two methods of propagating action potentials**
    - Continuous propagation: unmyelinated axons
    - Saltatory propagation: myelinated axons

Action Potential

- **Continuous Propagation**
  - Of action potentials along an unmyelinated axon
  - Affects one segment of axon at a time
  - Steps in a propagation
    - Step 1: Action potential in segment 1:
      - depolarizes membrane to +30 mV
      - local current
    - Step 2: Depolarizes second segment to threshold:
      - second segment develops action potential

Action Potential

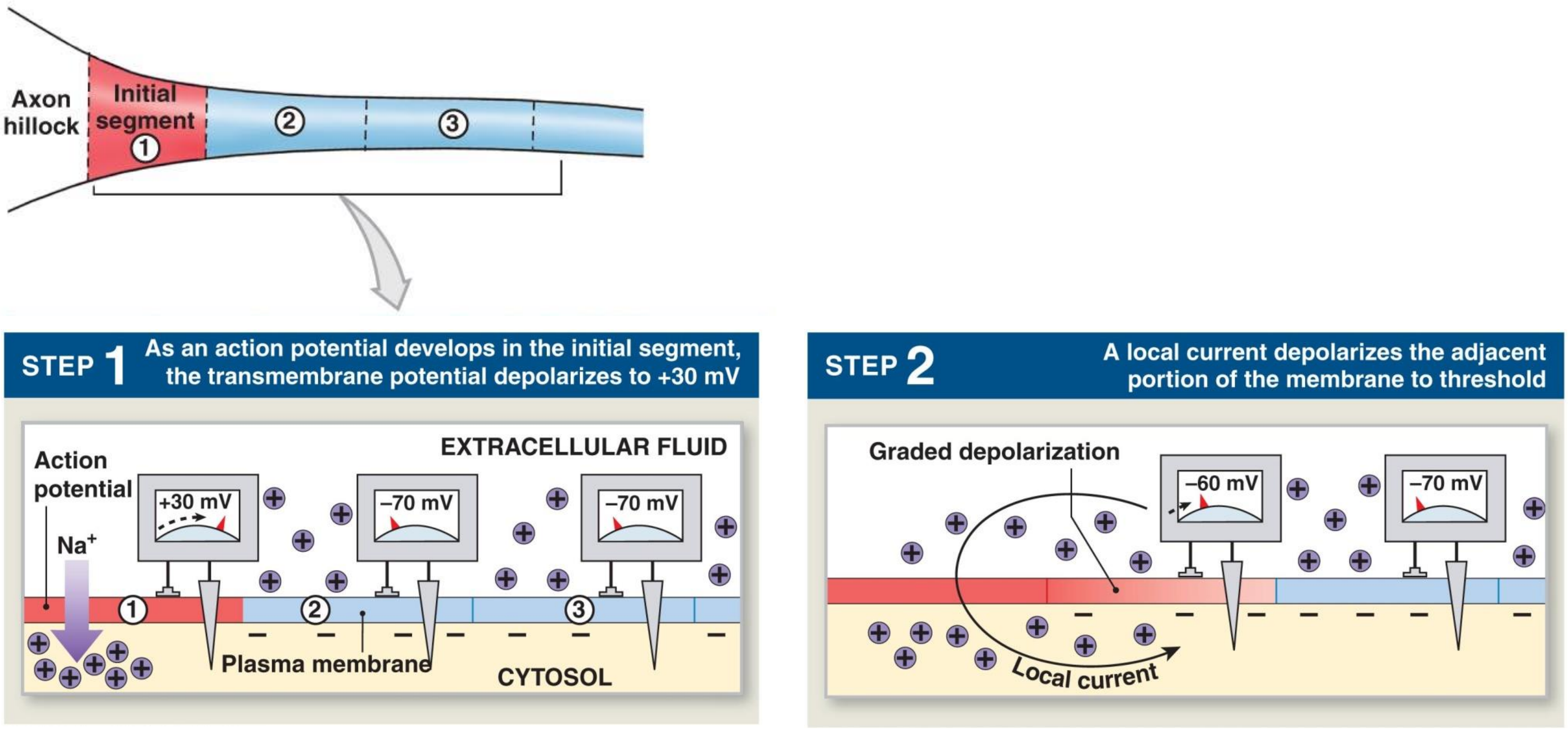


Figure 12–15 Continuous Propagation of an Action Potential along an Unmyelinated Axon (Steps 1 and 2).

Action Potential

- Continuous Propagation
  - Steps in propagation
    - Step 3: First segment enters refractory period
    - Step 4: Local current depolarizes next segment
  - Cycle repeats
    - Action potential travels in one direction (1 m/sec)

Action Potential

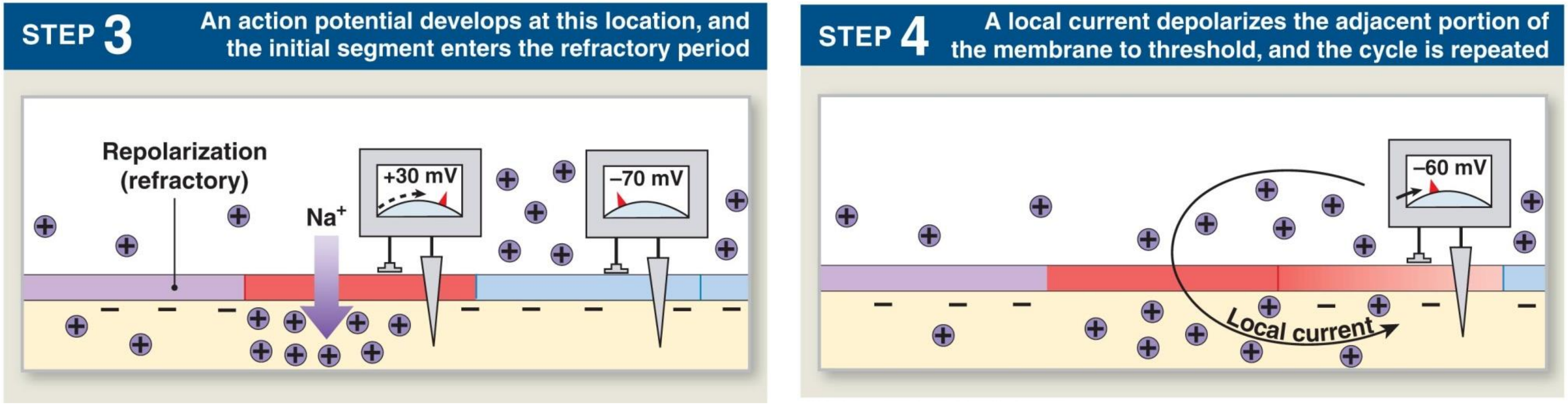


Figure 12–15 Continuous Propagation of an Action Potential along an Unmyelinated Axon (Steps 3 and 4).

Action Potential

- **Saltatory Propagation**
  - Action potential along myelinated axon
  - Faster and uses less energy than continuous propagation
  - Myelin insulates axon, prevents continuous propagation
  - Local current “jumps” from node to node
  - Depolarization occurs only at nodes

Action Potential

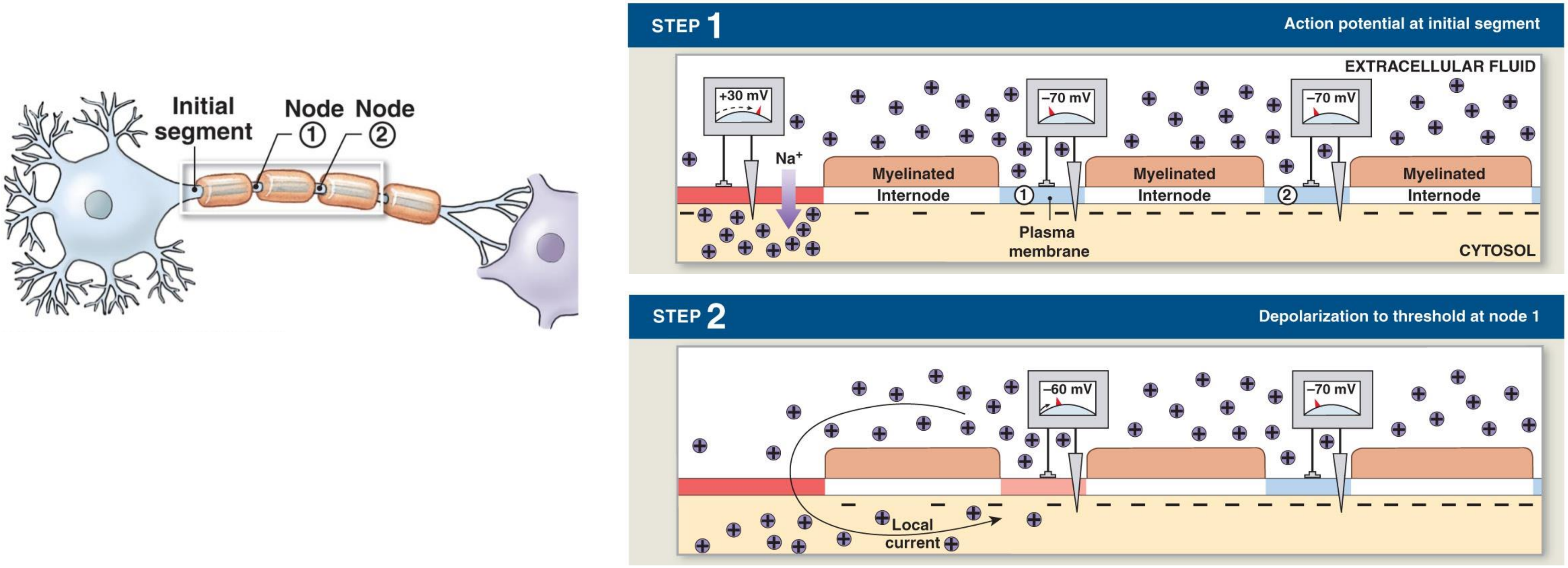


Figure 12–16 Saltatory Propagation along a Myelinated Axon (Steps 1 and 2).

Action Potential

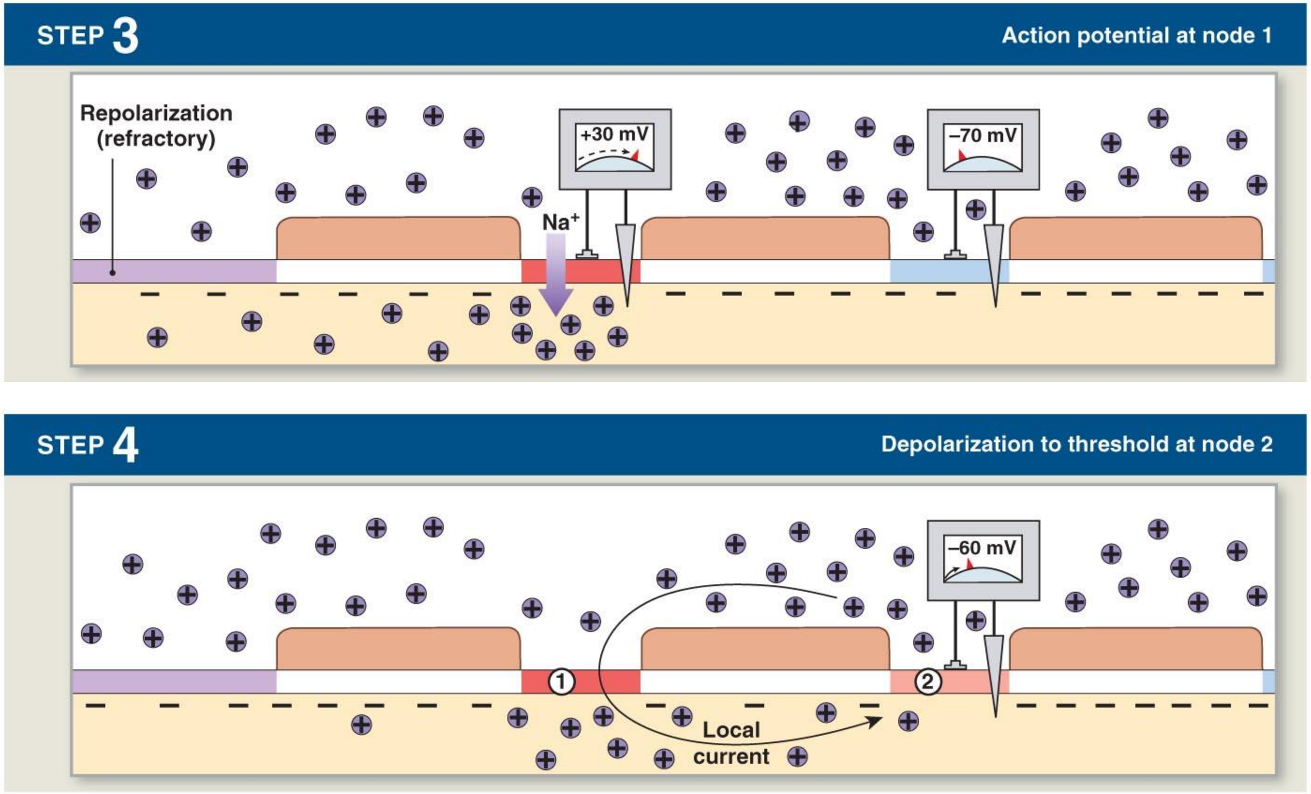


Figure 12–16 Saltatory Propagation along a Myelinated Axon (Steps 3 and 4).

Action Potential

TABLE 12–4 A Comparison of Graded Potentials and Action Potentials

Graded Potentials	Action Potentials
Depolarizing or hyperpolarizing	Always depolarizing
No threshold value	Depolarization to threshold must occur before action potential begins
Amount of depolarization or hyperpolarization depends on intensity of stimulus	All-or-none phenomenon; all stimuli that exceed threshold will produce identical action potentials
Passive spread from site of stimulation	Action potential at one site depolarizes adjacent sites to threshold
Effect on membrane potential decreases with distance from stimulation site	Propagated along entire membrane surface without decrease in strength
No refractory period	Refractory period occurs
Occur in most plasma membranes	Occur only in excitable membranes of specialized cells such as neurons and muscle cells

Axon Diameter and Speed

- **Axon Diameter and Propagation Speed**
  - Ion movement is related to cytoplasm concentration
  - Axon diameter affects action potential speed
  - The larger the diameter, the lower the resistance

Axon Diameter and Speed

- **Three Groups of Axons**
  - Type A fibers
  - Type B fibers
  - Type C fibers
- **These groups are classified by**
  - Diameter
  - Myelination
  - Speed of action potentials

Axon Diameter and Speed

- **Type A Fibers**
  - Myelinated
  - Large diameter
  - High speed (140 m/sec)
  - Carry rapid information to/from CNS
  - For example, position, balance, touch, and motor impulses

Axon Diameter and Speed

- **Type B Fibers**
  - Myelinated
  - Medium diameter
  - Medium speed (18 m/sec)
  - Carry intermediate signals
  - For example, sensory information, peripheral effectors

Axon Diameter and Speed

- **Type C Fibers**
  - Unmyelinated
  - Small diameter
  - Slow speed (1 m/sec)
  - Carry slower information
  - For example, involuntary muscle, gland controls

Axon Diameter and Speed

- “Information” travels within the nervous system as propagated electrical signals (action potentials)
- The most important information (vision, balance, motor commands) is carried by large-diameter, myelinated axons

Synapses

- Synaptic Activity
  - Action potentials (**nerve impulses**)
    - Are transmitted from **presynaptic neuron**
    - To **postsynaptic neuron** (or other postsynaptic cell)
    - Across a **synapse**

Synapses

- Two Types of Synapses
  - **Electrical synapses**
    - Direct physical contact between cells
  - **Chemical synapses**
    - Signal transmitted across a gap by chemical neurotransmitters

Synapses

- **Electrical Synapses**
  - Are locked together at **gap junctions** (*connexons*)
  - Allow ions to pass between cells
  - Produce continuous local current and action potential propagation
  - Are found in areas of brain, eye, ciliary ganglia

Synapses

- **Chemical Synapses**
  - Are found in most synapses between neurons and all synapses between neurons and other cells
  - Cells not in direct contact
  - Action potential *may* or *may not* be propagated to postsynaptic cell, depending on
    - Amount of neurotransmitter released
    - Sensitivity of postsynaptic cell

Synapses

- Two Classes of Neurotransmitters
  - **Excitatory neurotransmitters**
    - Cause depolarization of postsynaptic membranes
    - Promote action potentials
  - **Inhibitory neurotransmitters**
    - Cause hyperpolarization of postsynaptic membranes
    - Suppress action potentials

Synapses

- The Effect of a Neurotransmitter
  - On a postsynaptic membrane
    - Depends on the receptor
    - Not on the neurotransmitter
  - For example, **acetylcholine** (ACh)
    - Usually promotes action potentials
    - But inhibits cardiac neuromuscular junctions

Synapses

- **Cholinergic Synapses**
  - Any synapse that releases ACh
    - All neuromuscular junctions with skeletal muscle fibers
    - Many synapses in CNS
    - All neuron-to-neuron synapses in PNS
    - All neuromuscular and neuroglandular junctions of ANS parasympathetic division

Synapses

- **Events at a Cholinergic Synapse**
  - Action potential arrives, depolarizes synaptic knob
  - Calcium ions enter synaptic knob, trigger exocytosis of Ach
  - ACh binds to receptors, depolarizes postsynaptic membrane
  - AChE breaks ACh into **acetate** and **choline**

Synapses

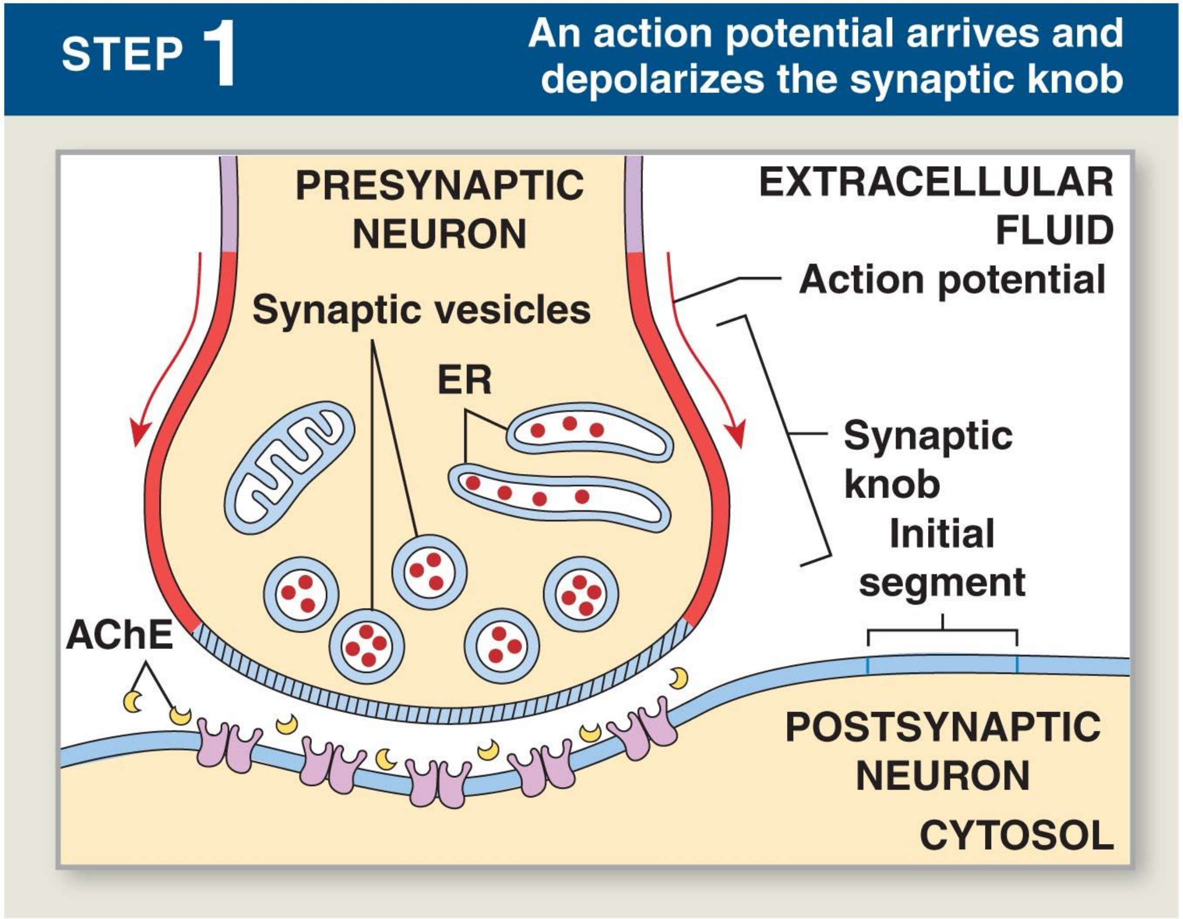


Figure 12–17 Events in the Functioning of a Cholinergic Synapse (Step 1).

Synapses

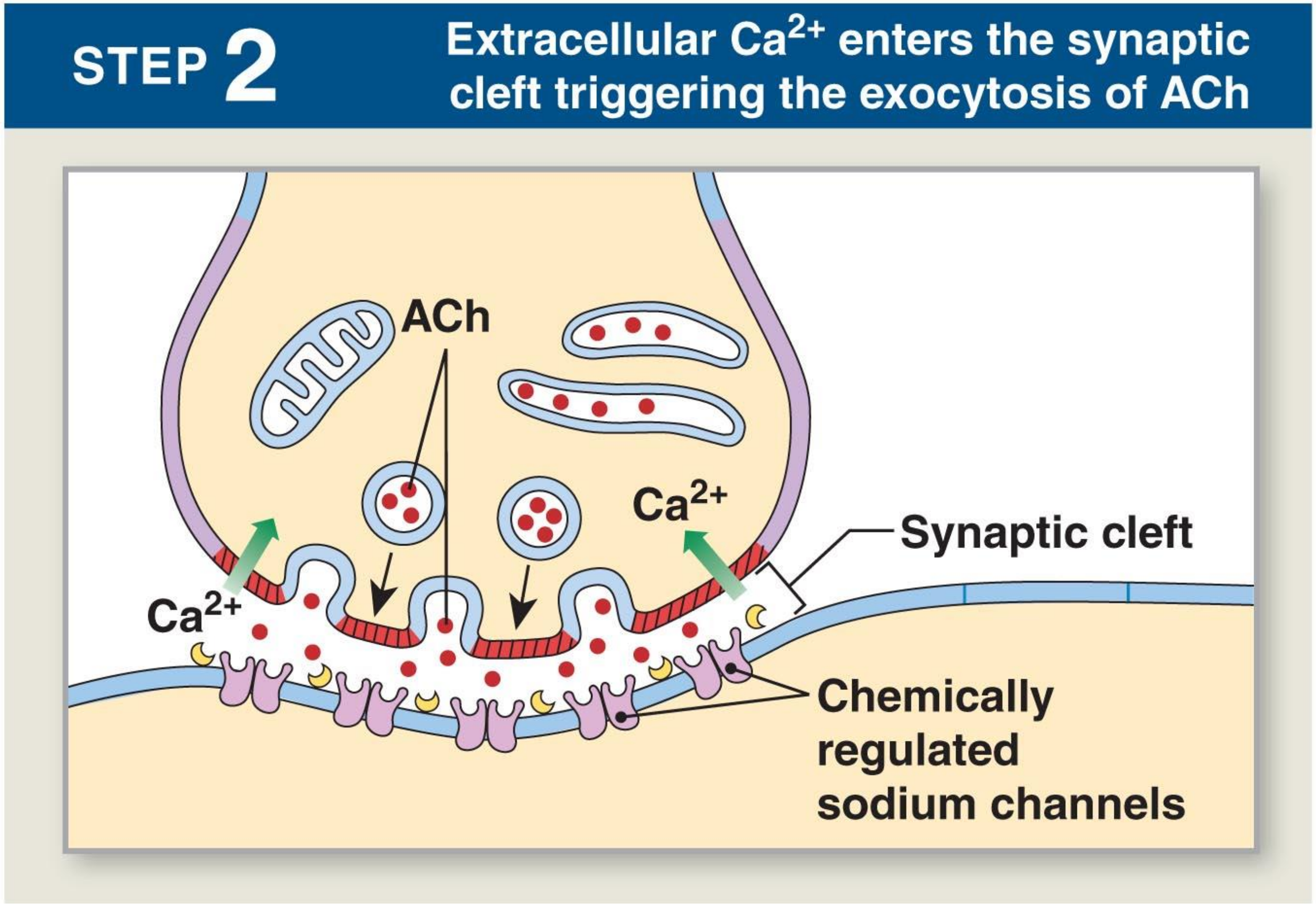


Figure 12–17 Events in the Functioning of a Cholinergic Synapse (Step 2).

Synapses

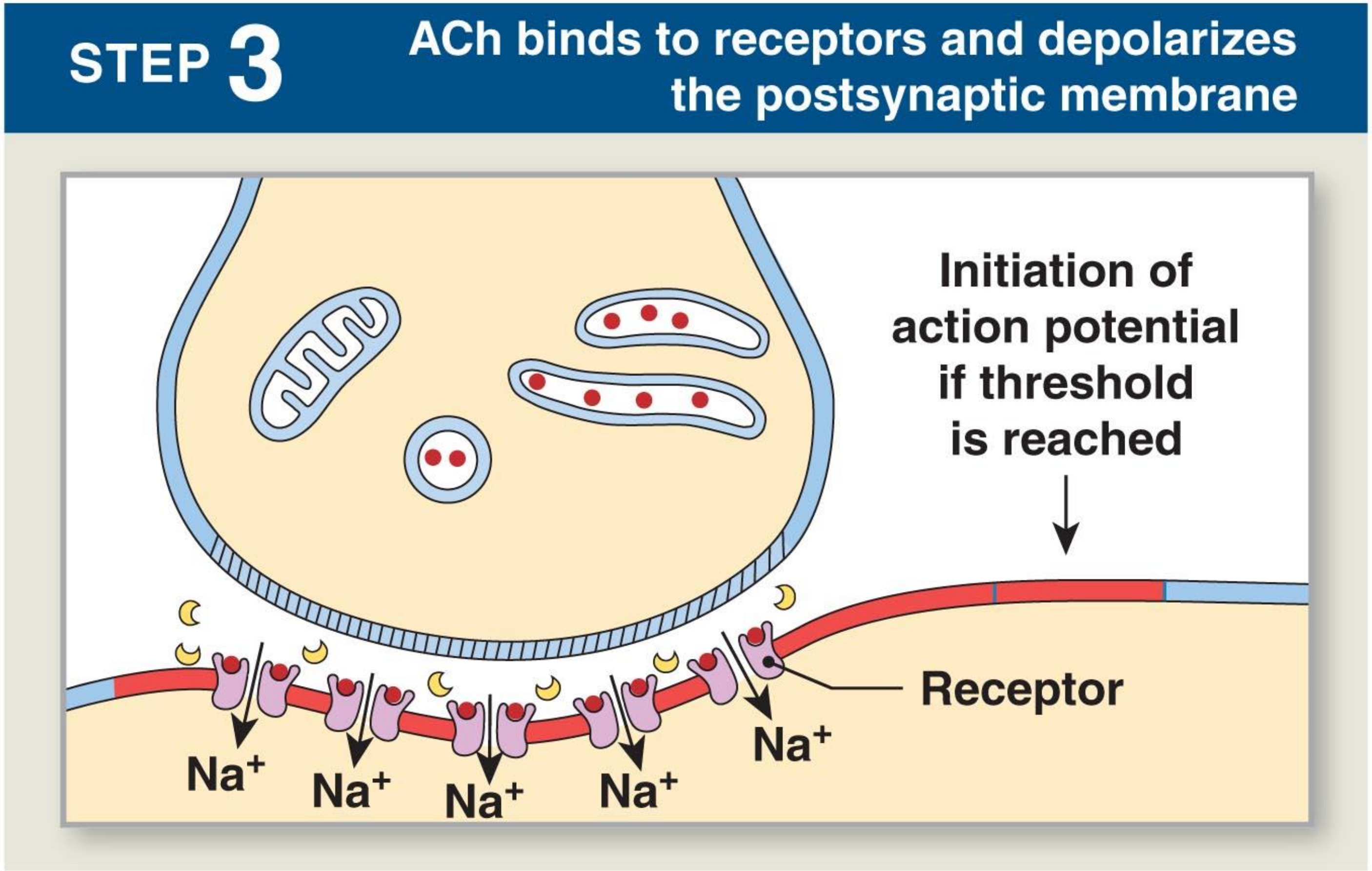


Figure 12–17 Events in the Functioning of a Cholinergic Synapse (Step 3).

Synapses

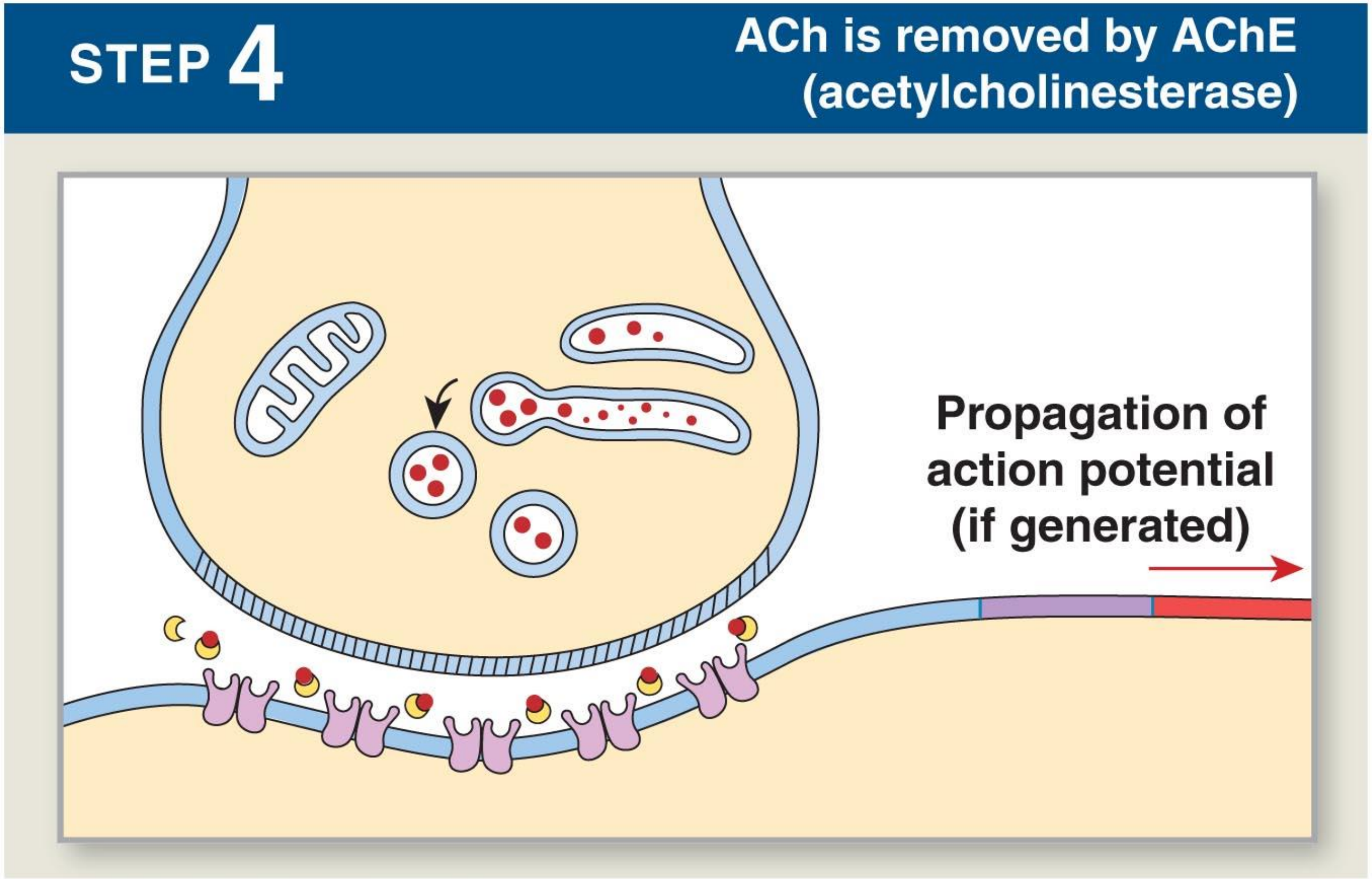


Figure 12–17 Events in the Functioning of a Cholinergic Synapse (Step 4).

Synapses

- **Synaptic Delay**
  - A synaptic delay of 0.2–0.5 msec occurs between
    - Arrival of action potential at synaptic knob
    - And effect on postsynaptic membrane
  - Fewer synapses mean faster response
  - Reflexes may involve only one synapse

Synapses

- **Synaptic Fatigue**
  - Occurs when neurotransmitter cannot recycle fast enough to meet demands of intense stimuli
  - Synapse inactive until ACh is replenished

Synapses

SUMMARY TABLE 12–5 Synaptic Activity

THE SEQUENCE OF EVENTS AT A TYPICAL CHOLINERGIC SYNAPSE:

STEP 1

- An arriving action potential depolarizes the synaptic knob.

STEP 2

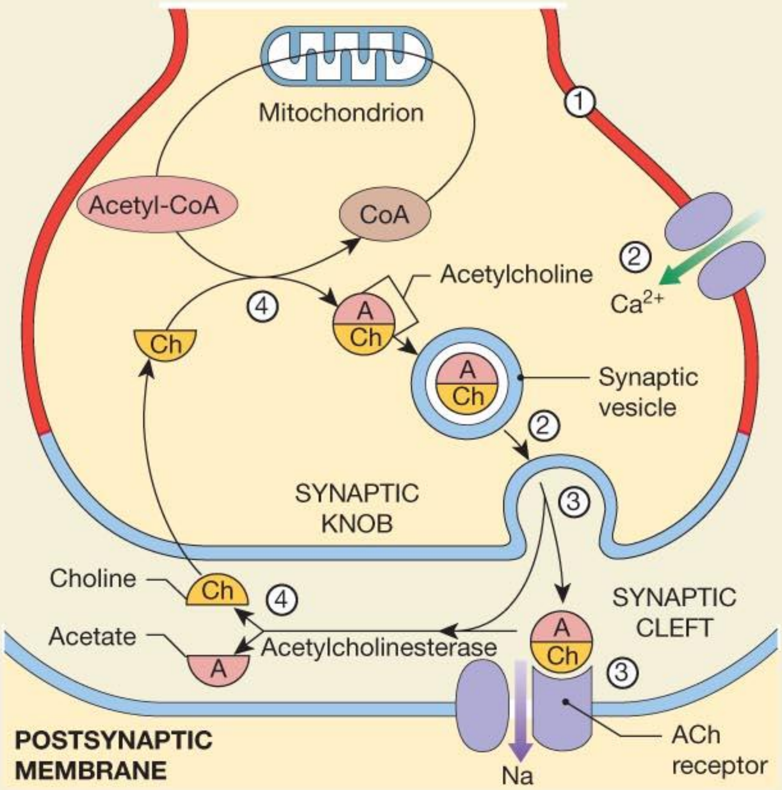
- Calcium ions enter the cytoplasm of the synaptic knob.
- ACh is released through exocytosis of neurotransmitter vesicles.

STEP 3

- ACh diffuses across the synaptic cleft and binds to receptors on the postsynaptic membrane.
- Chemically gated sodium channels on the postsynaptic surface are activated, producing a graded depolarization.
- ACh release ceases because calcium ions are removed from the cytoplasm of the synaptic knob.

STEP 4

- The depolarization ends as ACh is broken down into acetate and choline by AChE.
- The synaptic knob reabsorbs choline from the synaptic cleft and uses it to resynthesize ACh.



Neurotransmitters and Neuromodulators

- Other Neurotransmitters
  - At least 50 neurotransmitters other than ACh, including
    - Some amino acids
    - Peptides
    - Prostaglandins
    - ATP
    - Some dissolved gases

Neurotransmitters and Neuromodulators

- Important Neurotransmitters
  - Other than acetylcholine
    - Norepinephrine (NE)
    - Dopamine
    - Serotonin
    - Gamma aminobutyric acid (GABA)

Neurotransmitters and Neuromodulators

- **Norepinephrine (NE)**
  - Released by **adrenergic synapses**
  - Excitatory and depolarizing effect
  - Widely distributed in brain and portions of ANS
- **Dopamine**
  - A CNS neurotransmitter
  - May be excitatory or inhibitory
  - Involved in Parkinson disease, cocaine use

Neurotransmitters and Neuromodulators

- **Serotonin**
  - A CNS neurotransmitter
  - Affects attention and emotional states
- **Gamma Aminobutyric Acid (GABA)**
  - Inhibitory effect
  - Functions in CNS
    - Not well understood

Neurotransmitters and Neuromodulators

- **Chemical synapse**
  - The synaptic terminal releases a neurotransmitter that binds to the postsynaptic plasma membrane
  - Produces temporary, localized change in permeability or function of postsynaptic cell
  - Changes affect cell, depending on nature and number of stimulated receptors
- **Many drugs**
  - Affect nervous system by stimulating receptors that respond to neurotransmitters
  - Can have complex effects on perception, motor control, and emotional states

Neurotransmitters and Neuromodulators

- **Neuromodulators**
  - Other chemicals released by synaptic knobs
  - Similar in function to neurotransmitters
  - Characteristics of neuromodulators
    - Effects are long term, slow to appear
    - Responses involve multiple steps, intermediary compounds
    - Affect presynaptic membrane, postsynaptic membrane, or both
    - Released alone or with a neurotransmitter

Neurotransmitters and Neuromodulators

- **Neuropeptides**
  - Neuromodulators that bind to receptors and activate enzymes
- **Opioids**
  - Neuromodulators in the CNS
  - Bind to the same receptors as opium or morphine
  - Relieve pain

Neurotransmitters and Neuromodulators

- **Four Classes of Opioids**
  - Endorphins
  - Enkephalins
  - Endomorphins
  - Dynorphins

Neurotransmitters and Neuromodulators

- How Neurotransmitters and Neuromodulators Work
  - **Direct effects on membrane channels**
    - For example, ACh, glutamate, aspartate
  - **Indirect effects via G proteins**
    - For example, E, NE, dopamine, histamine, GABA
  - **Indirect effects via intracellular enzymes**
    - For example, lipid-soluble gases (NO, CO)

Neurotransmitters and Neuromodulators

- **Direct Effects**
  - *Ionotropic effects*
  - Open/close gated ion channels
- **Indirect Effects: G Proteins**
  - Work through *second messengers*
  - Enzyme complex that binds GTP
  - Link between neurotransmitter (first messenger) and second messenger
  - Activate enzyme **adenylate cyclase**
    - Which produces second messenger *cyclic AMP*

Neurotransmitters and Neuromodulators

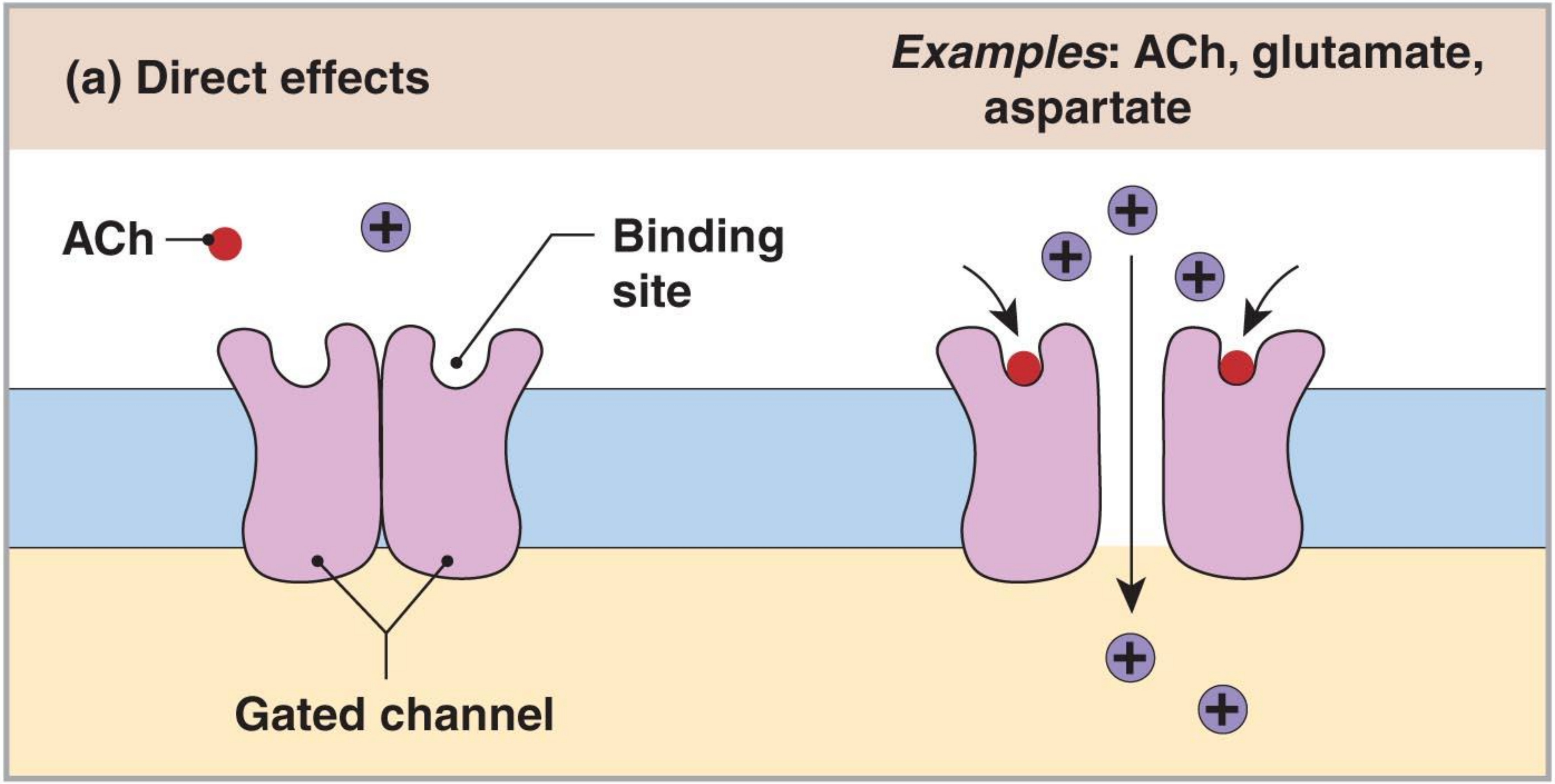


Figure 12–18a Mechanisms of Neurotransmitter Function.

Neurotransmitters and Neuromodulators

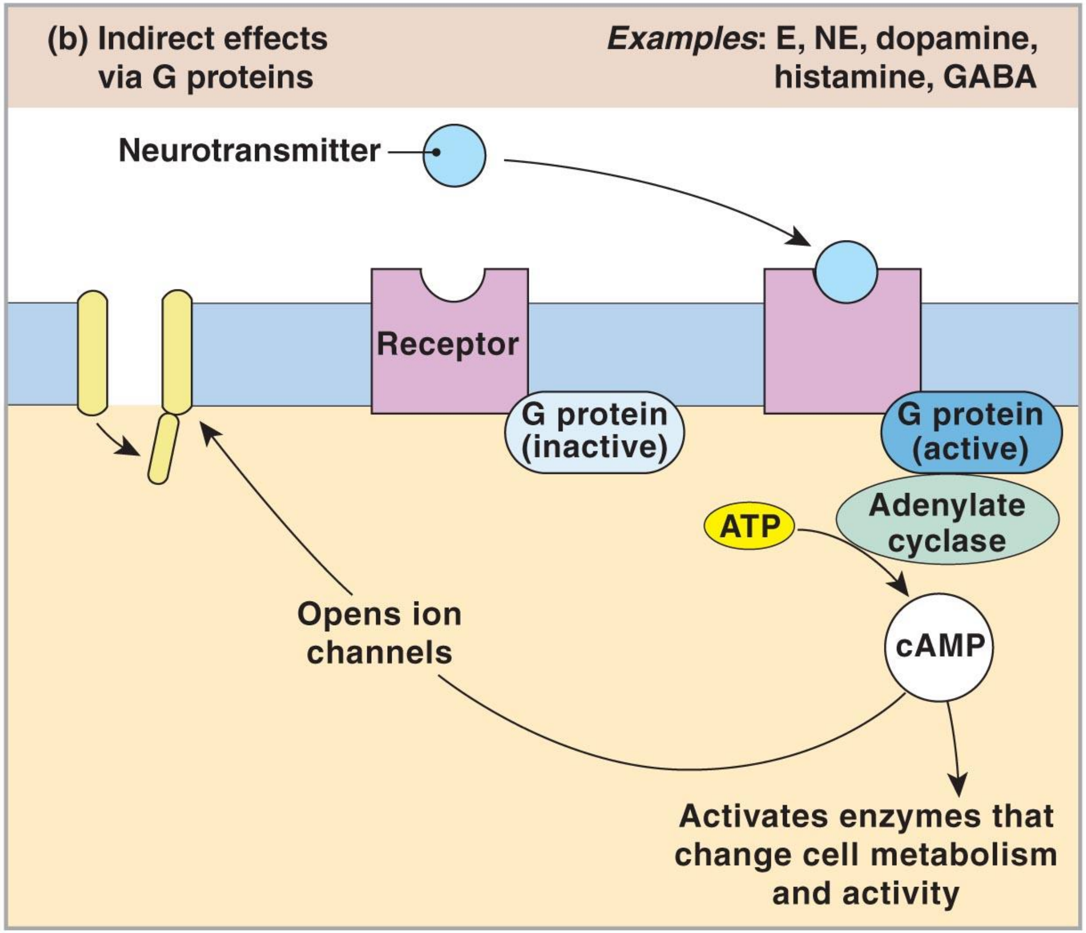


Figure 12–18b Mechanisms of Neurotransmitter Function.

Neurotransmitters and Neuromodulators

- Indirect Effects: Intracellular receptors
  - Lipid–soluble gases (NO, CO)
  - Bind to enzymes in brain cells

Neurotransmitters and Neuromodulators

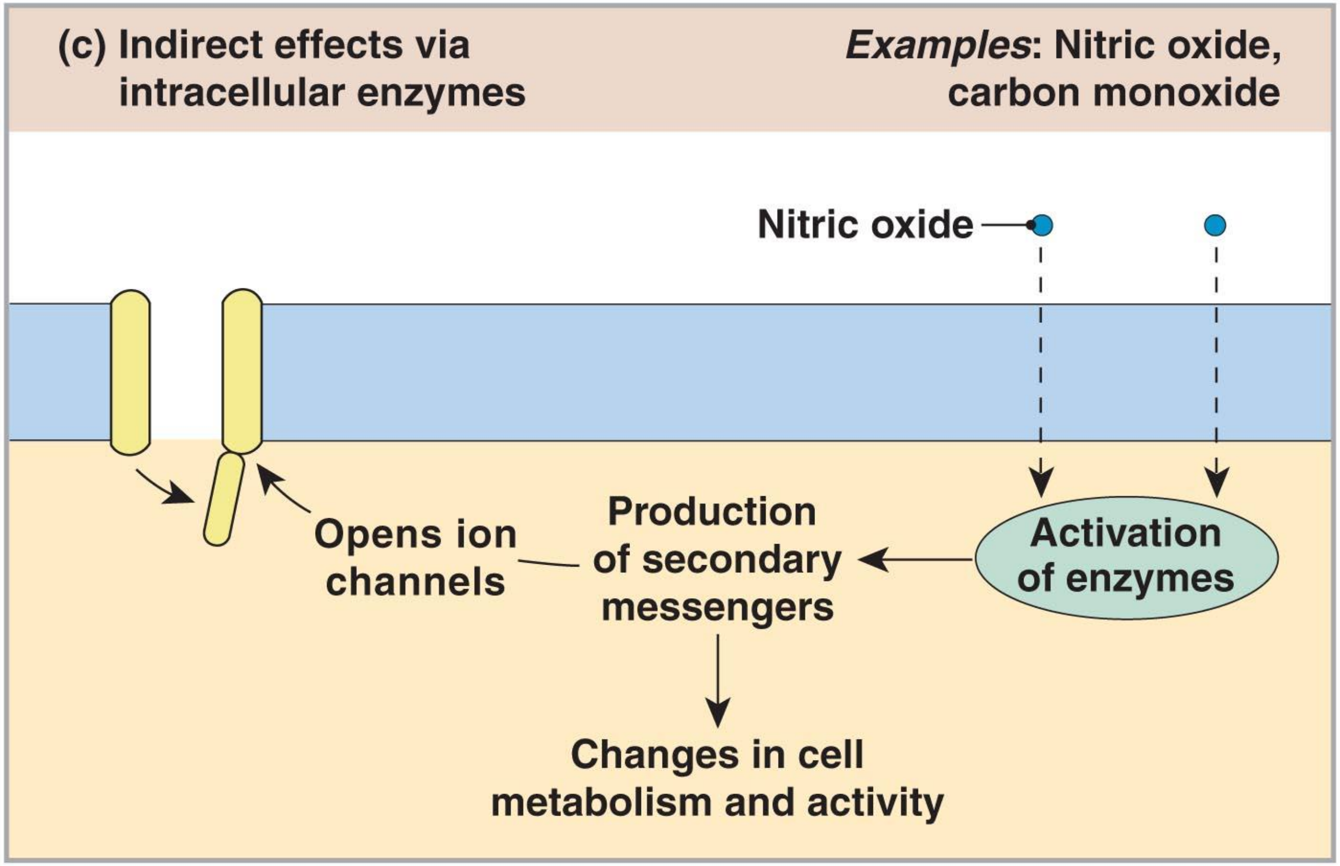
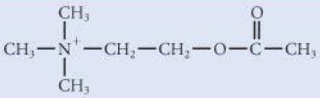


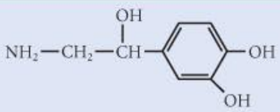
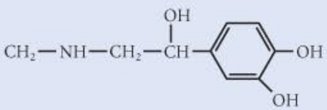
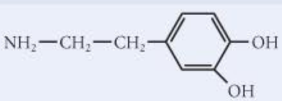
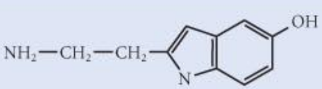
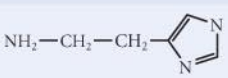
Figure 12–18c Mechanisms of Neurotransmitter Function.

Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators				
Class and Neurotransmitter	**Chemical Structure**	**Mechanism of Action**	**Location(s)**	**Comments**
Acetylcholine		Primarily direct, through binding to chemically gated channels	CNS: Synapses throughout brain and spinal cord PNS: Neuromuscular junctions; preganglionic synapses of ANS; neuroglandular junctions of parasympathetic division and (rarely) sympathetic division of ANS; amacrine cells of retina	Widespread in CNS and PNS; best known and most studied of the neurotransmitters

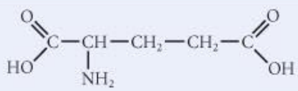
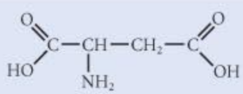
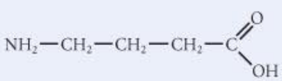
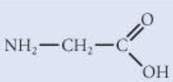
Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators

Class and Neurotransmitter	Chemical Structure	Mechanism of Action	Location(s)	Comments
Norepinephrine		Indirect: G proteins and second messengers	CNS: Cerebral cortex, hypothalamus, brain stem, cerebellum, spinal cord PNS: Most neuromuscular and neuroglandular junctions of sympathetic division of ANS	Involved in attention and consciousness, control of body temperature, and regulation of pituitary gland secretion
Epinephrine		Indirect: G proteins and second messengers	CNS: Thalamus, hypothalamus, midbrain, spinal cord	Uncertain functions
Dopamine		Indirect: G proteins and second messengers	CNS: Hypothalamus, midbrain, limbic system, cerebral cortex, retina	Regulation of subconscious motor function; receptor abnormalities have been linked to development of schizophrenia
Serotonin		Primarily indirect: G proteins and second messengers	CNS: Hypothalamus, limbic system, cerebellum, spinal cord, retina	Important in emotional states, moods, and body temperature; several illicit hallucinogenic drugs, such as Ecstasy, target serotonin receptors
Histamine		Indirect: G proteins and second messengers	CNS: Neurons in hypothalamus, with axons projecting throughout the brain	Receptors are primarily on presynaptic membranes; functions in sexual arousal, pain threshold, pituitary hormone secretion, thirst and blood pressure control

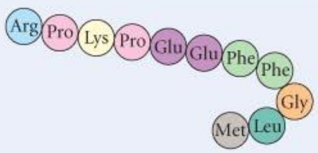
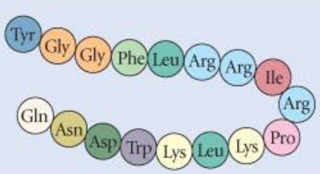
Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators

Class and Neurotransmitter	Chemical Structure	Mechanism of Action	Location(s)	Comments
AMINO ACIDS				
Excitatory: **Glutamate**		Indirect: G proteins and second messengers Direct: opens calcium/ sodium channels on pre- and postsynaptic membranes	CNS: Cerebral cortex and brain stem	Important in memory and learning; most important excitatory neurotransmitter in the brain
Aspartate		Direct or indirect (G proteins), depending on type of receptor	CNS: Cerebral cortex, retina, and spinal cord	Used by pyramidal cells that provide voluntary motor control over skeletal muscles
Inhibitory: **Gamma-aminobutyric acid (GABA)**		Direct or indirect (G proteins), depending on type of receptor	CNS: Cerebral cortex, cerebellum, interneurons throughout brain and spinal cord	Direct effects: open Cl^- channels; indirect effects: open K^+ channels and block entry of Ca^{2+}
Glycine		Direct: Opens Cl^- channels	CNS: Interneurons in brain stem, spinal cord, and retina	Produces postsynaptic inhibition; the poison *strychnine* produces fatal convulsions by blocking glycine receptors

Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators

Class and Neurotransmitter	Chemical Structure	Mechanism of Action	Location(s)	Comments
NEUROPEPTIDES				
Substance P		Indirect: G proteins and second messengers	CNS: Synapses of pain receptors within spinal cord, hypothalamus, and other areas of the brain PNS: Enteric nervous system (network of neurons along the digestive tract)	Important in pain pathway, regulation of pituitary gland function, control of digestive tract reflexes
Neuropeptide Y	*36-amino-acid peptide*	As above	CNS: hypothalamus PNS: sympathetic neurons	Stimulates appetite and food intake
Opioids **Endorphins**	*31-amino-acid peptide*	Indirect: G proteins and second messengers	CNS: Thalamus, hypothalamus, brain stem, retina	Pain control; emotional and behavioral effects poorly understood
Enkephalins		As above	CNS: Basal nuclei, hypothalamus, midbrain, pons, medulla oblongata, spinal cord	As above
Endomorphin	*9- or 10-amino-acid peptide*	As above	CNS: Thalamus, hypothalamus, basal nuclei	As above
Dynorphin		As above	CNS: Hypothalamus, midbrain, medulla oblongata	As above

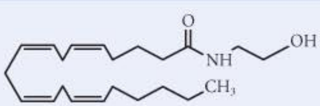
Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators

Class and Neurotransmitter	Chemical Structure	Mechanism of Action	Location(s)	Comments
PURINES				
ATP, GTP	*(see Figure 2–24)*	Direct or indirect (G proteins), depending on type of receptor	CNS: Spinal cord PNS: Autonomic ganglia	
Adenosine	*(see Figure 2–24)*	Indirect: G proteins and second messengers	CNS: Cerebral cortex, hippocampus, cerebellum	Produces drowsiness; stimulatory effect of caffeine is due to inhibition of adenosine activity
HORMONES				
ADH, oxytocin, insulin, glucagon, secretin, CCK, GIP, VIP, inhibins, ANP, BNP, and many others	Peptide containing fewer than 200 amino acids	Typically indirect: G proteins and second messengers	CNS: Brain (widespread)	Numerous, complex, and incompletely understood

Neurotransmitters and Neuromodulators

TABLE 12–6 Representative Neurotransmitters and Neuromodulators

Class and Neurotransmitter	Chemical Structure	Mechanism of Action	Location(s)	Comments
GASES				
Carbon monoxide (CO)	C = O	Indirect: By diffusion to enzymes activating second messengers	CNS: Brain PNS: Some neuromuscular and neuroglandular junctions	Localization and function poorly understood
Nitric oxide (NO)	N = O	As above	CNS: Brain, especially at blood vessels PNS: Some sympathetic neuromuscular and neuroglandular junctions	
LIPIDS				
Anandamide		Indirect: G proteins and second messengers	CNS: cerebral cortex, hippocampus, cerebellum	Euphoria, drowsiness, appetite; receptors are targeted by the active ingredient in marijuana

Information Processing

- Information Processing
  - At the simplest level (individual neurons)
    - Many dendrites receive neurotransmitter messages simultaneously
    - Some excitatory, some inhibitory
    - Net effect on axon hillock determines if action potential is produced

Information Processing

- **Postsynaptic Potentials**
  - Graded potentials developed in a postsynaptic cell
    - In response to neurotransmitters
- **Two Types of Postsynaptic Potentials**
  - Excitatory postsynaptic potential (EPSP)
    - Graded depolarization of postsynaptic membrane
  - Inhibitory postsynaptic potential (IPSP)
    - Graded hyperpolarization of postsynaptic membrane

Information Processing

- **Inhibition**
  - A neuron that receives many IPSPs
    - Is **inhibited** from producing an action potential
    - Because the stimulation needed to reach threshold is increased
- **Summation**
  - To trigger an action potential
    - One EPSP is not enough
    - EPSPs (and IPSPs) combine through summation:
      - temporal summation
      - spatial summation

Information Processing

- **Temporal Summation**
  - Multiple times
  - Rapid, repeated stimuli at one synapse
- **Spatial Summation**
  - Multiple locations
  - Many stimuli, arrive at multiple synapses

Information Processing

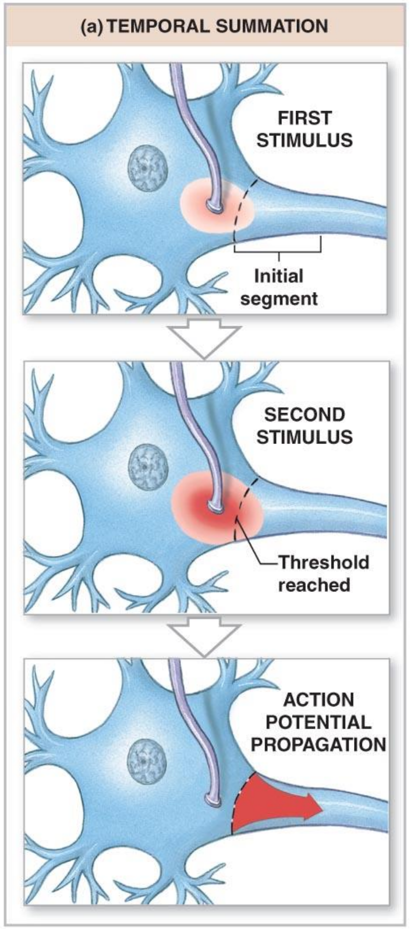


Figure 12–19 Temporal and Spatial Summation.

Information Processing

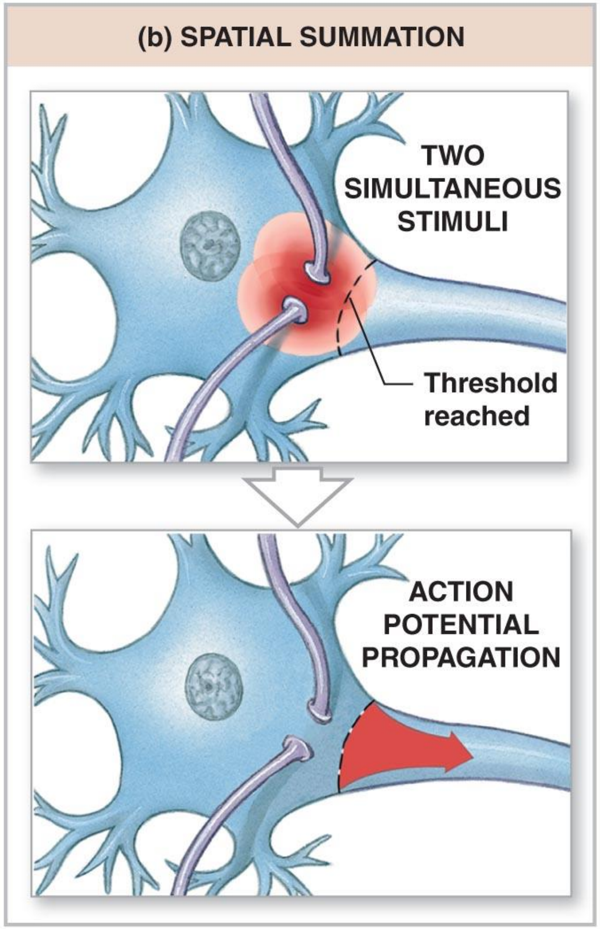


Figure 12–19 Temporal and Spatial Summation.

Information Processing

- Facilitation
  - A neuron becomes **facilitated**
    - As EPSPs accumulate
    - Raising transmembrane potential closer to threshold
    - Until a small stimulus can trigger action potential

Information Processing

- Summation of EPSPs and IPSPs
  - Neuromodulators and hormones
    - Can change membrane sensitivity to neurotransmitters
    - Shifting balance between EPSPs and IPSPs

Information Processing

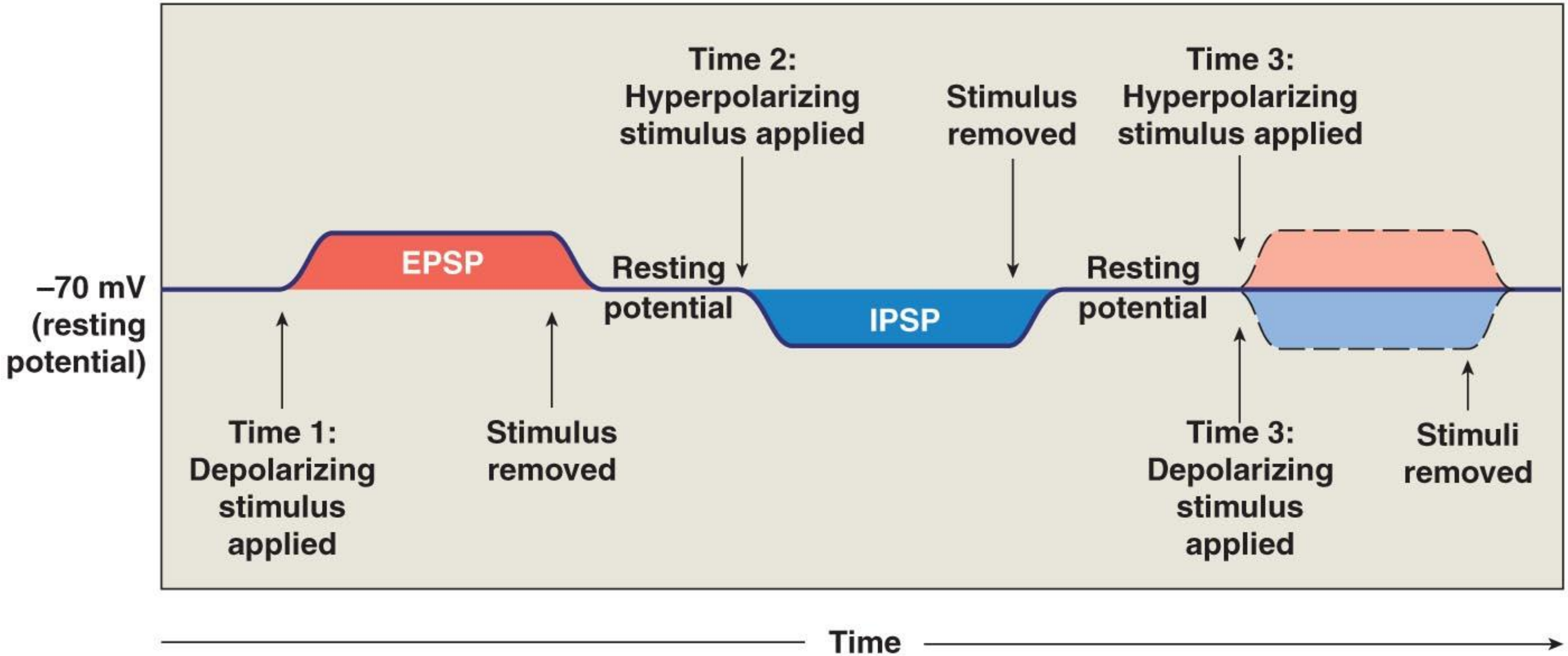


Figure 12–20 Interactions between EPSPs and IPSPs.

Information Processing

- Axoaxonic Synapses
  - Synapses between the axons of two neurons
  - **Presynaptic inhibition**
    - Action of an axoaxonic synapse at a synaptic knob:
      - that *decreases* the neurotransmitter released by presynaptic membrane
  - **Presynaptic facilitation**
    - Action of an axoaxonic synapse at a synaptic knob:
      - that *increases* the neurotransmitter released by presynaptic membrane

Information Processing

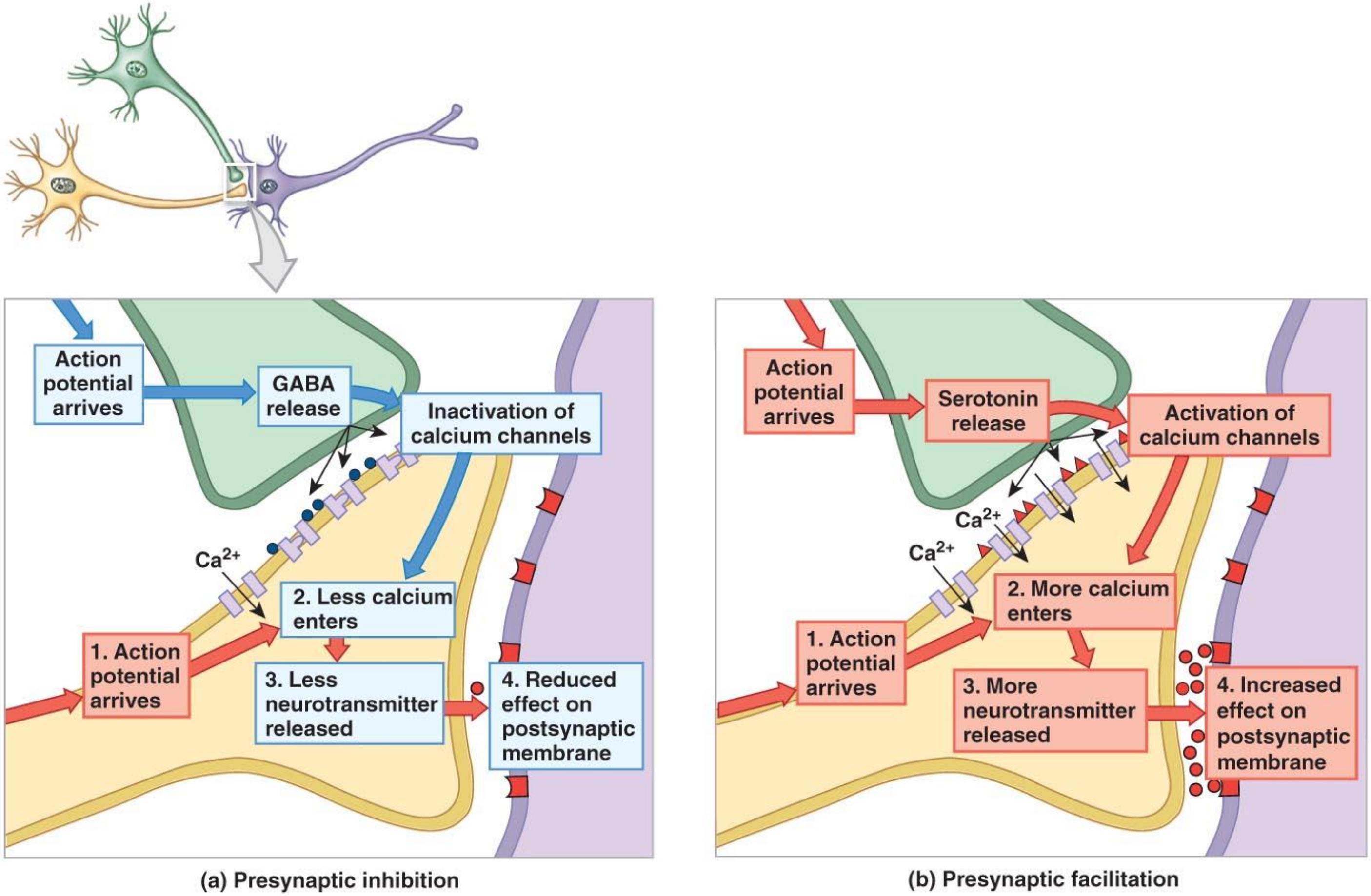
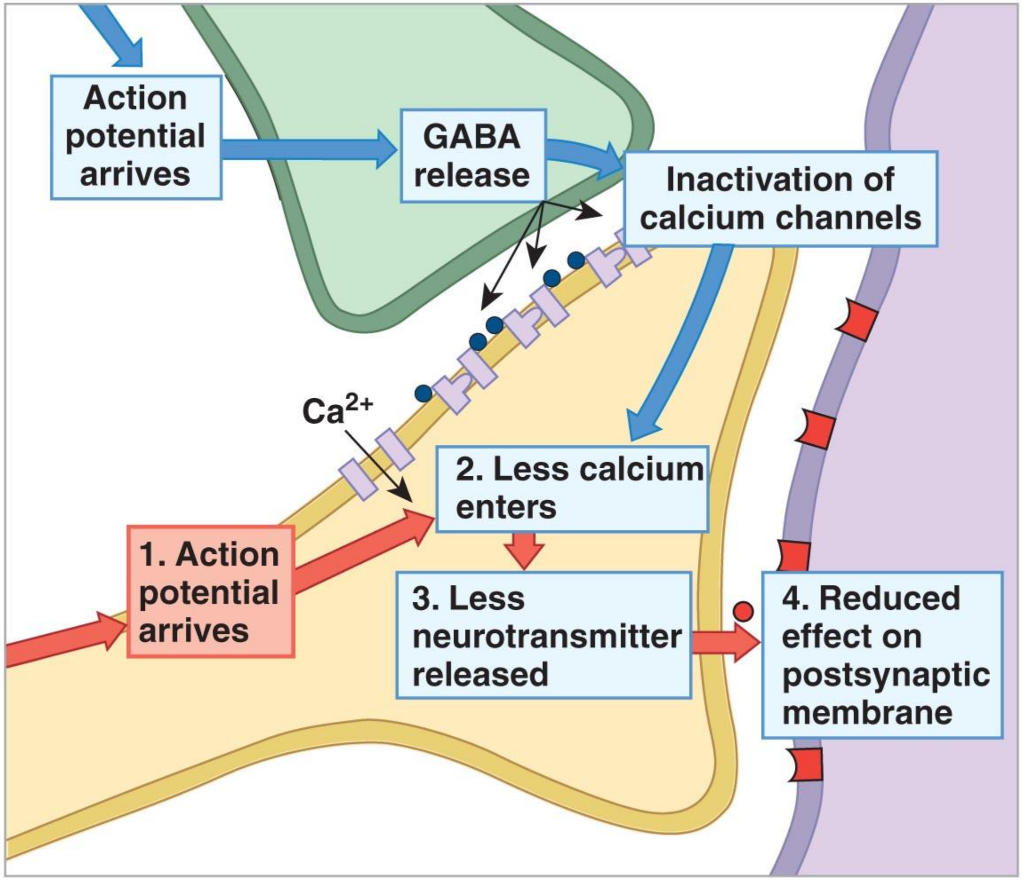


Figure 12–21 Presynaptic Inhibition and Presynaptic Facilitation.

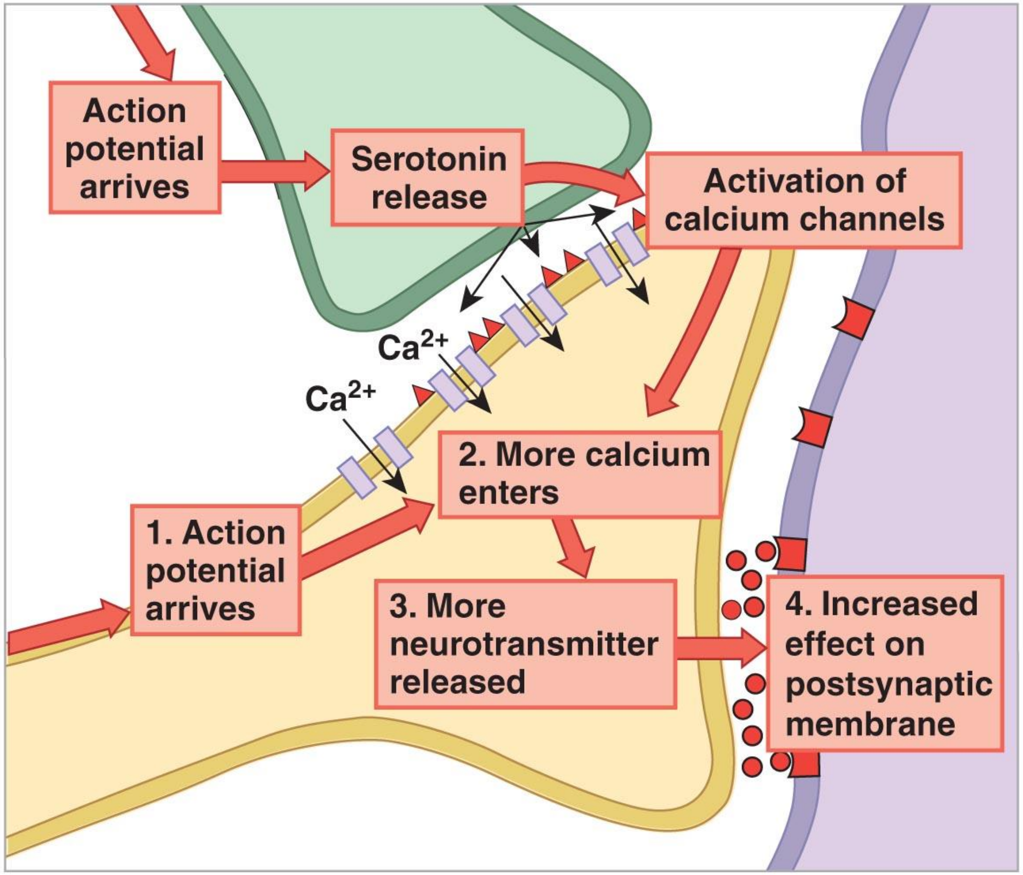
Information Processing



(a) Presynaptic inhibition

Figure 12–21a Presynaptic Inhibition and Presynaptic Facilitation.

Information Processing



(b) Presynaptic facilitation

Figure 12–21b Presynaptic Inhibition and Presynaptic Facilitation.

Information Processing

- **Frequency of Action Potentials**
  - Information received by a postsynaptic cell may be simply the frequency of action potentials received
- **Rate of Generation of Action Potentials**
  - Frequency of action potentials
    - Depends on degree of depolarization above threshold
  - Holding membrane above threshold level
    - Has same effect as a second, larger stimulus
    - Reduces relative refractory period

Information Processing

- In the nervous system
  - A change in transmembrane potential that determines whether or not action potentials are generated is the simplest form of information processing

Information Processing

SUMMARY TABLE 12–7 Information Processing

- The neurotransmitters released at a synapse may have either excitatory or inhibitory effects. The effect on the axon's initial segment reflects a summation of the stimuli that arrive at any moment. The frequency of generation of action potentials is an indication of the degree of sustained depolarization at the axon hillock.
- Neuromodulators can alter either the rate of neurotransmitter release or the response of a postsynaptic neuron to specific neurotransmitters.
- Neurons may be facilitated or inhibited by extracellular chemicals other than neurotransmitters or neuromodulators.
- The response of a postsynaptic neuron to the activation of a presynaptic neuron can be altered by (1) the presence of neuromodulators or other chemicals that cause facilitation or inhibition at the synapse, (2) activity under way at other synapses affecting the postsynaptic cell, and (3) modification of the rate of neurotransmitter release through presynaptic facilitation or presynaptic inhibition. Information is relayed in the form of action potentials. In general, the degree of sensory stimulation or the strength of the motor response is proportional to the frequency of action potentials.