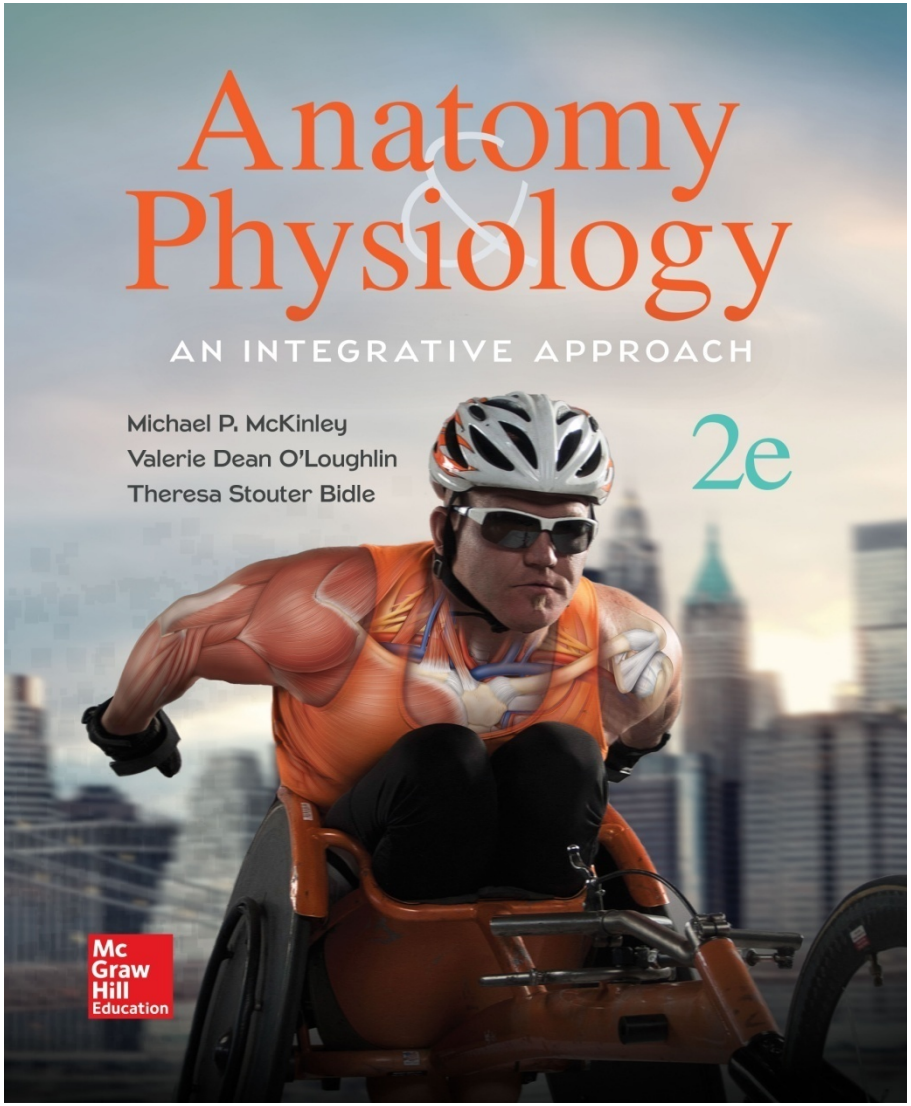
Chapter 12
Lecture Outline

See separate PowerPoint slides for all figures and tables pre-inserted into PowerPoint without notes.



12.1 Introduction to the Nervous System

Learning Objectives:

1. Describe the three general functions of the nervous system.
2. Identify the structural components included in the CNS and those in the PNS.
3. Explain the functional organization of the nervous system.

12.1a General Functions of the Nervous System

- Nervous system: communication and control system
  - Collects information
    - Receptors detect stimuli and send sensory signals to spinal cord and brain
  - Processes and evaluates information
    - Brain and spinal cord determine response to sensory input
  - Initiates response to information
    - Brain and spinal send motor output via nerves to effectors (muscles or glands)

12.1b Organization of the Nervous System

How is the nervous system organized structurally?

CNS = brain + spinal cord

PNS = nerves (fiber bundles) + ganglia (clusters of cell bodies along nerves)

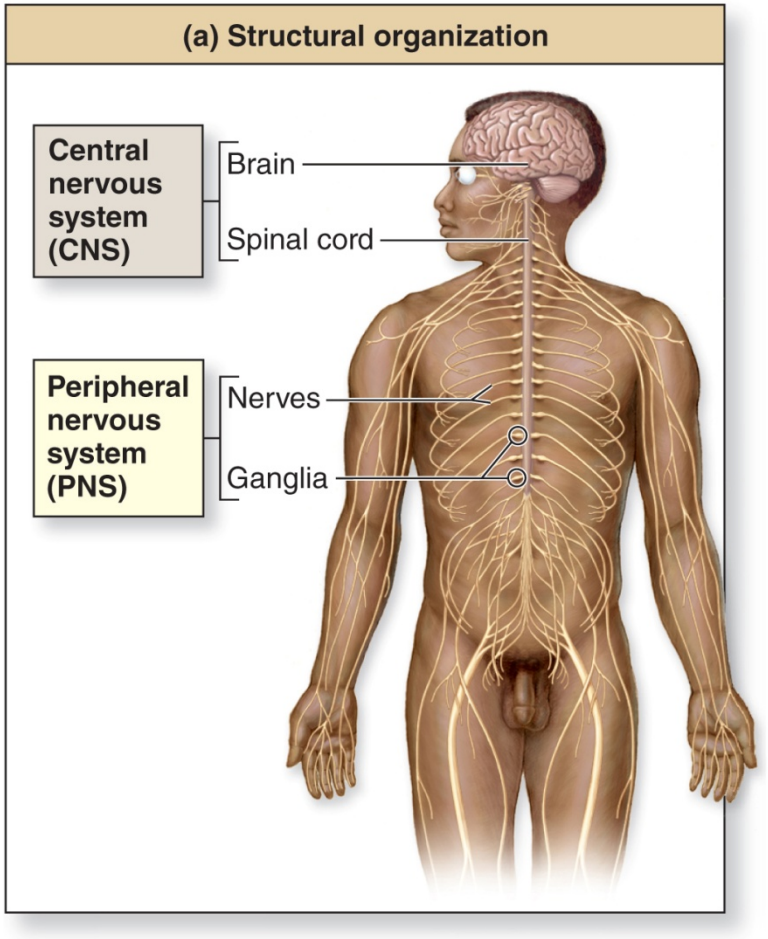


Figure 12.1a

12.1b Organization of the Nervous System

- Functional organization: sensory versus motor
  - **Sensory nervous system** = afferent nervous system
    - Receives sensory information from receptors and transmits it to CNS
    - **Somatic sensory system** detects stimuli we consciously perceive
    - **Visceral sensory system** detects stimuli we typically do not perceive
      - E.g., signals from the heart or kidneys
  - **Motor nervous system** = efferent nervous system
    - Initiates motor output and transmits it from CNS to effectors
    - **Somatic motor system** sends voluntary signals to skeletal muscles
    - **Autonomic motor system** (visceral motor) sends involuntary commands to heart, smooth muscle, and glands
      - Has **sympathetic** and **parasympathetic** divisions

Organization of the Nervous System

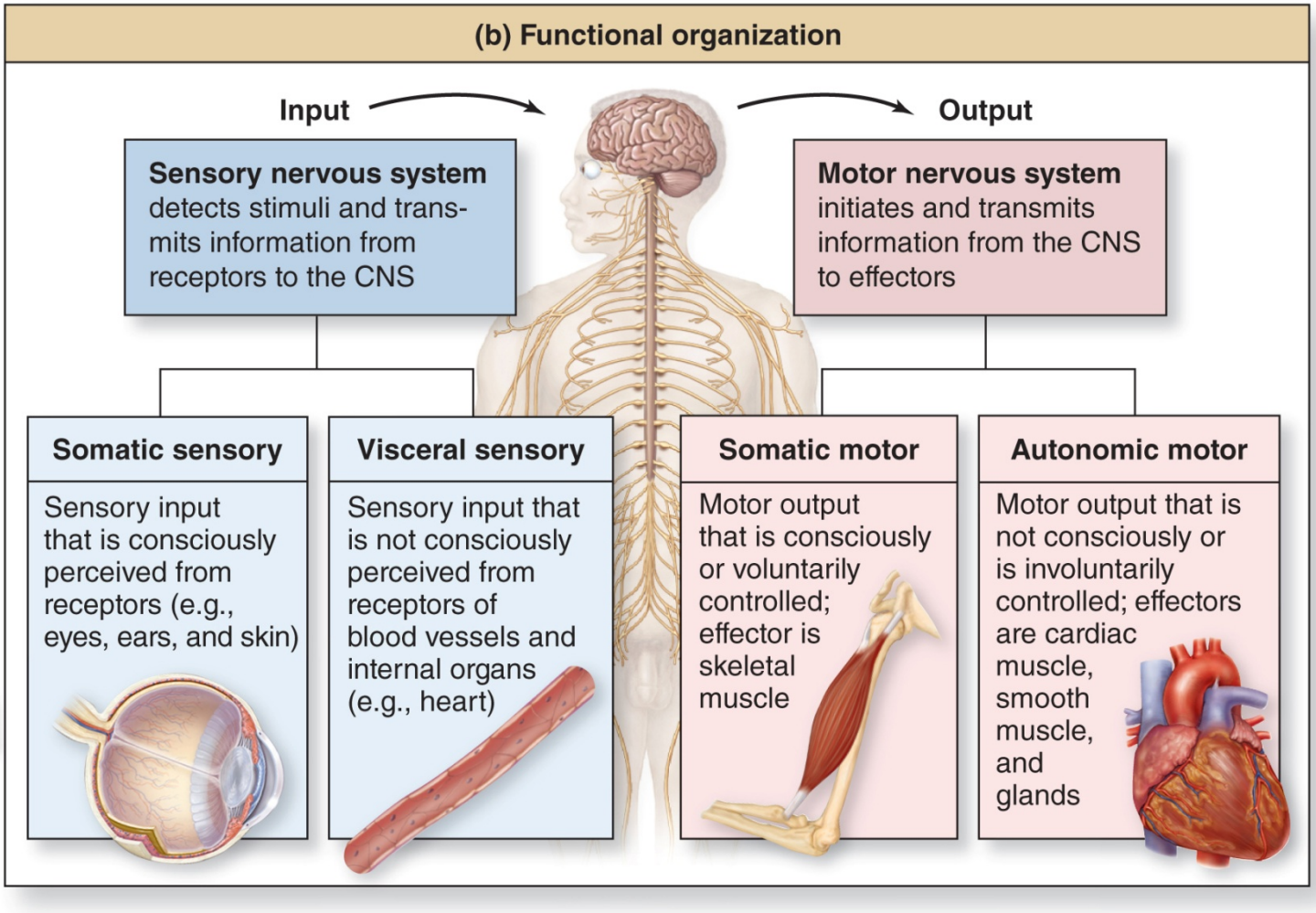


Figure 12.1b

What did you learn?

- What function is served by somatic sensory nerves?
- Are nerves located in the CNS or PNS?
- Is the autonomic nervous system considered a sensory system or a motor system?

12.2 Nervous Tissue: Neurons

Learning Objectives:

1. Describe five distinguishing features common to all neurons.
2. Describe the three basic anatomic features common to most neurons.
3. Identify and describe the structures unique to neurons.
4. Distinguish between fast axonal transport and slow axonal transport, and give examples of the different substances moved by each.

12.2 Nervous Tissue: Neurons

Learning Objectives:

5. Name and describe the four structural categories of neurons.
6. Identify the three functional categories of neurons and where each is primarily located.
7. Describe the structure of a nerve, including the three layers of connective tissue wrappings.
8. Explain how nerves are classified structurally and functionally.

12.2a General Characteristics of Neurons

- Neurons (nerve cells) have certain traits
  - Excitability: responsiveness to a stimulus
    - Stimulus causes change in cell's membrane potential
  - Conductivity: ability to propagate electrical signal
    - Voltage-gated channels along membrane open sequentially
  - Secretion: release of neurotransmitter in response to conductive activity
    - Messenger is released from vesicle to influence target cell
  - Extreme longevity: cell can live throughout person's lifetime
  - Amitotic: After fetal development, mitotic activity is lost in most neurons

12.2b Neuron Structure

- Parts of a neuron
  - **Cell body** (*soma*)
    - Plasma membrane encloses cytoplasm **(perikaryon)**
    - Contains nucleus
    - Initiates some graded potentials, receives others from dendrites; conducts these potentials to axon
    - Contains **chromatophilic substance** (*Nissl bodies*) made of ribosomes (free and bound)
  - **Dendrites**
    - Short, unmyelinated processes branching off cell body
    - Receive input and transfer it to cell body

12.2b Neuron Structure

- **Parts of a neuron** (*continued*)
  - **Axon**
    - Long process emanating from cell body
    - Makes contact with other neurons, muscle cells, or glands
    - Attaches to cell body at **axon hillock** (triangular region of soma)
    - Cytoplasm called **axoplasm;** membrane called **axolemma**
    - Splits into branches called **axon collaterals**
    - Ends in several **telodendria** (*axon terminals*)
    - Tips of telodendria are **synaptic knobs** (*terminal boutons*)
    - Synaptic knobs house **synaptic vesicles** containing neurotransmitter
    - Axons function to conduct action potentials and then release neurotransmitter at synaptic knobs

12.2b Neuron Structure

- **Parts of a neuron** (*continued*)
  - **Cytoskeleton**
    - Composed of microfilaments, intermediate filaments, microtubules
    - Intermediate filaments, termed **neurofilaments**
      - Aggregate to form bundles, **neurofibrils**
      - Provide tensile strength

Structures in a Typical Neuron

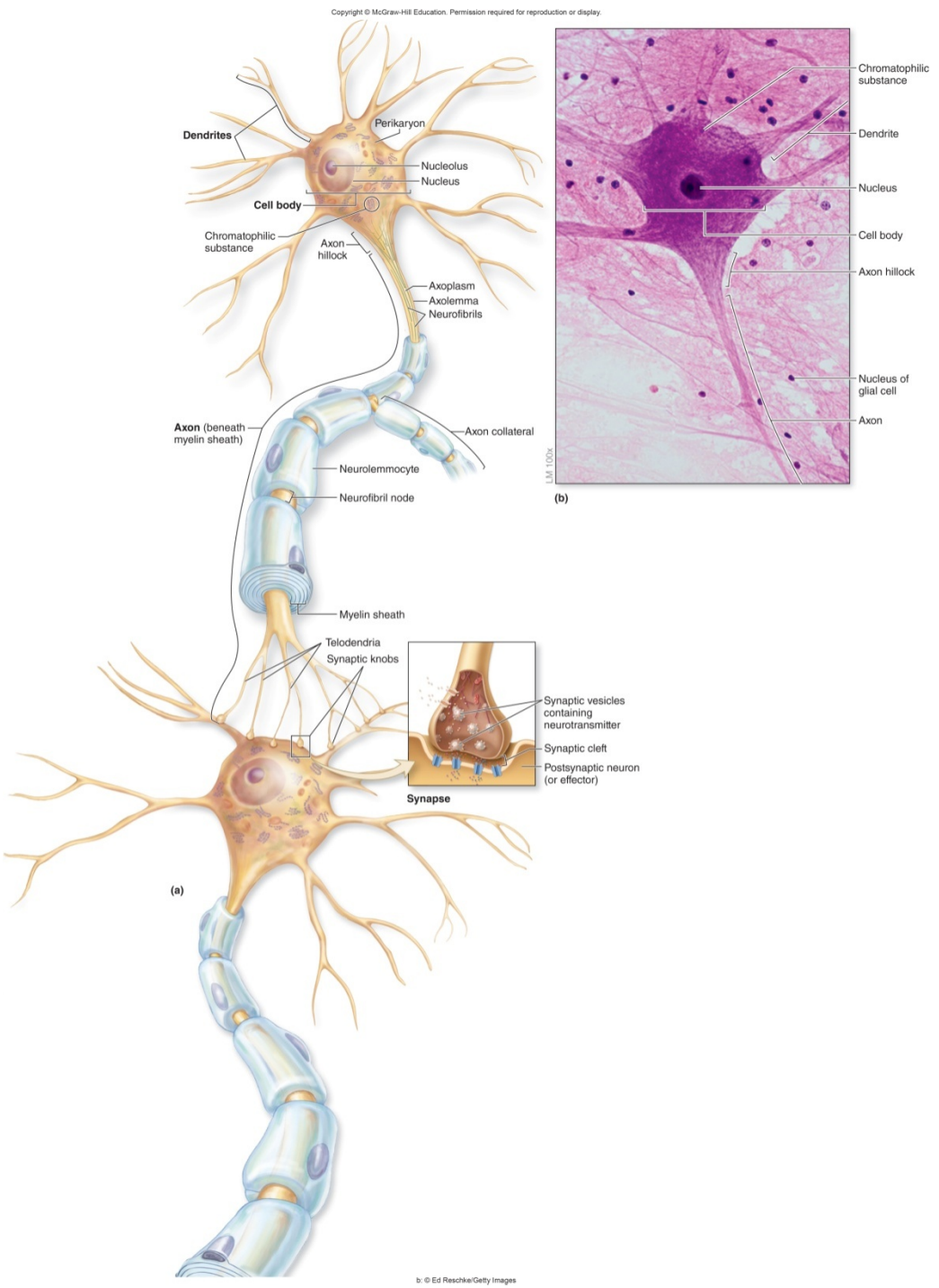


Figure 12.2

12.2c Neuron Transport

- Axons move material to and from the cell body
  - **Anterograde transport:** from cell body
    - Moves newly synthesized material toward synaptic knobs
  - **Retrograde transport:** to cell body
    - Moves used materials from axon for breakdown and recycling in soma
  - This can occur by **fast axonal transport** or slow **axonal transport**

12.2c Neuron Transport

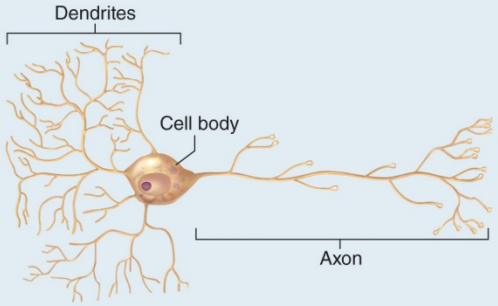
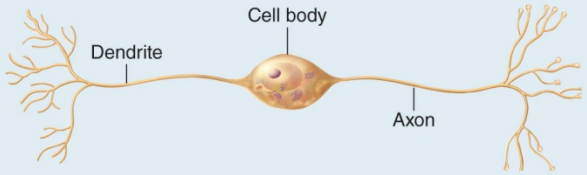
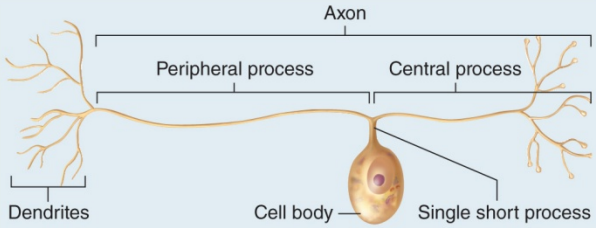
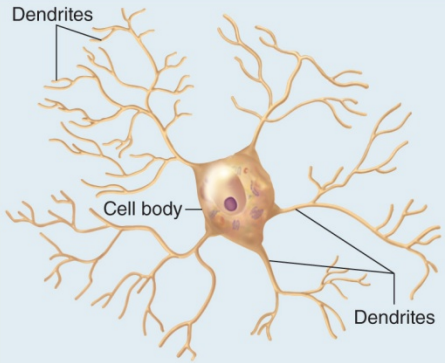
- **Fast axonal transport**
  - Occurs at about 400 mm per day
  - Involves movement along microtubules
  - Powered by motor proteins that split ATP
  - Anterograde or retrograde motion possible
    - Anterograde transport of vesicles, organelles, glycoproteins
    - Retrograde transport of used vesicles, potentially harmful agents
- **Slow axonal transport**
  - Occurs at about 0.1 to 3 mm per day
  - Results from flow of axoplasm
  - Substances only moved from cell body toward knob
    - Enzymes, cytoskeletal components, new axoplasm

12.2d Classification of Neurons

- Structural classification (by number of processes coming off soma)
  - **Multipolar neurons:** many dendrites, one axon extend from soma
    - Most common type
  - **Bipolar neurons:** one dendrite and one soma extend from soma
    - Limited number; e.g., in retina of the eye
  - **Unipolar neurons (pseudounipolar):** one axon extends from soma
    - Axon splits in two processes
      - **Peripheral process** splits into several receptive dendrites
      - **Central process** leads to synaptic knobs in CNS
  - **Anaxonic neurons:** have dendrites but no axons

Structural Classification of Neurons

Table 12.1 Structural Classification of Neurons

Neuron Type	Structure	Description	Examples of Functional Types
Multipolar Neuron		Multiple processes extend directly from the cell body; typically many dendrites and one axon; most common type of neuron	All motor neurons; most interneurons
Bipolar Neuron		Two processes extend directly from the cell body; one dendrite and one axon; relatively uncommon	Some special sense neurons (e.g., retina of eye, olfactory epithelium in nose)
Unipolar Neuron		Single short process extends directly from the cell and looks like a T as a result of the fusion of two processes into one long axon	Most sensory neurons
Anaxonic Neuron		Processes are only dendrites; no axon present	Interneurons of the central nervous system (CNS)

12.2d Classification of Neurons

- Functional classification
  - **Sensory neurons** (*afferent neurons*)
    - Conduct input from somatic and visceral receptors to CNS
    - Most are unipolar (a few bipolar)
  - **Motor neurons** (*efferent neurons*)
    - Conduct output from CNS to somatic and visceral effectors
    - All are multipolar
  - **Interneurons** (*association neurons*)
    - Receive, process, and integrate information from many other neurons
    - Communicate between sensory and motor neurons
    - Located within CNS; make up 99% of our neurons
    - Generally are multipolar

Functional Classification of Neurons

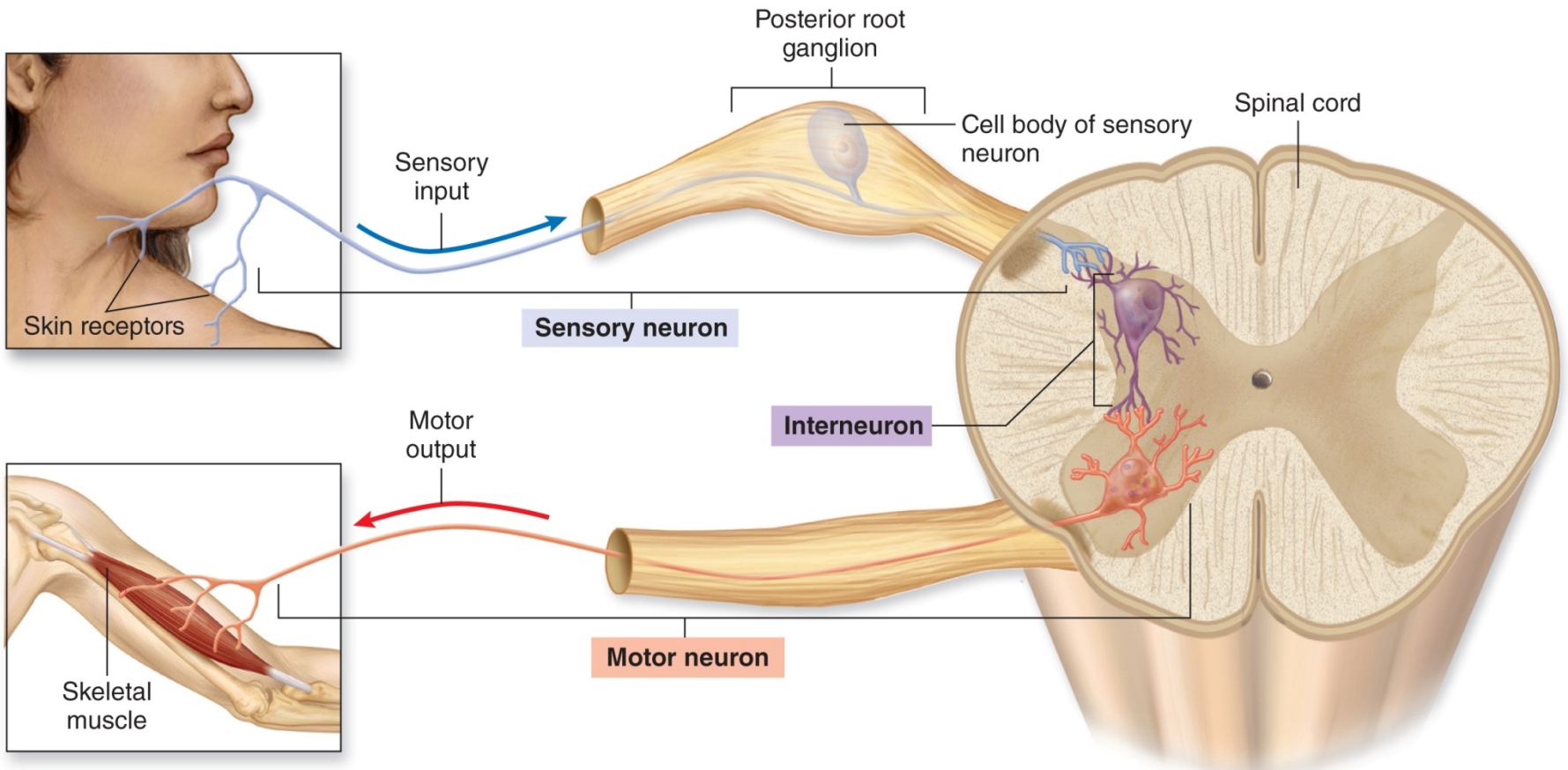


Figure 12.3

12.2e Relationship of Neurons and Nerves

- **Nerve:** a bundle of parallel axons in the PNS
- Nerves have connective tissue wrappings
  - **Epineurium:** encloses entire nerve
    - Thick layer of dense irregular connective tissue
  - **Perineurium:** wraps fascicle (small bundle of axons in nerve)
    - Layer of dense irregular connective tissue
  - **Endoneurium:** wraps an individual axon
    - Delicate layer of areolar connective tissue
    - Separates and electrically insulates each axon

Structure of a Nerve and Ganglion

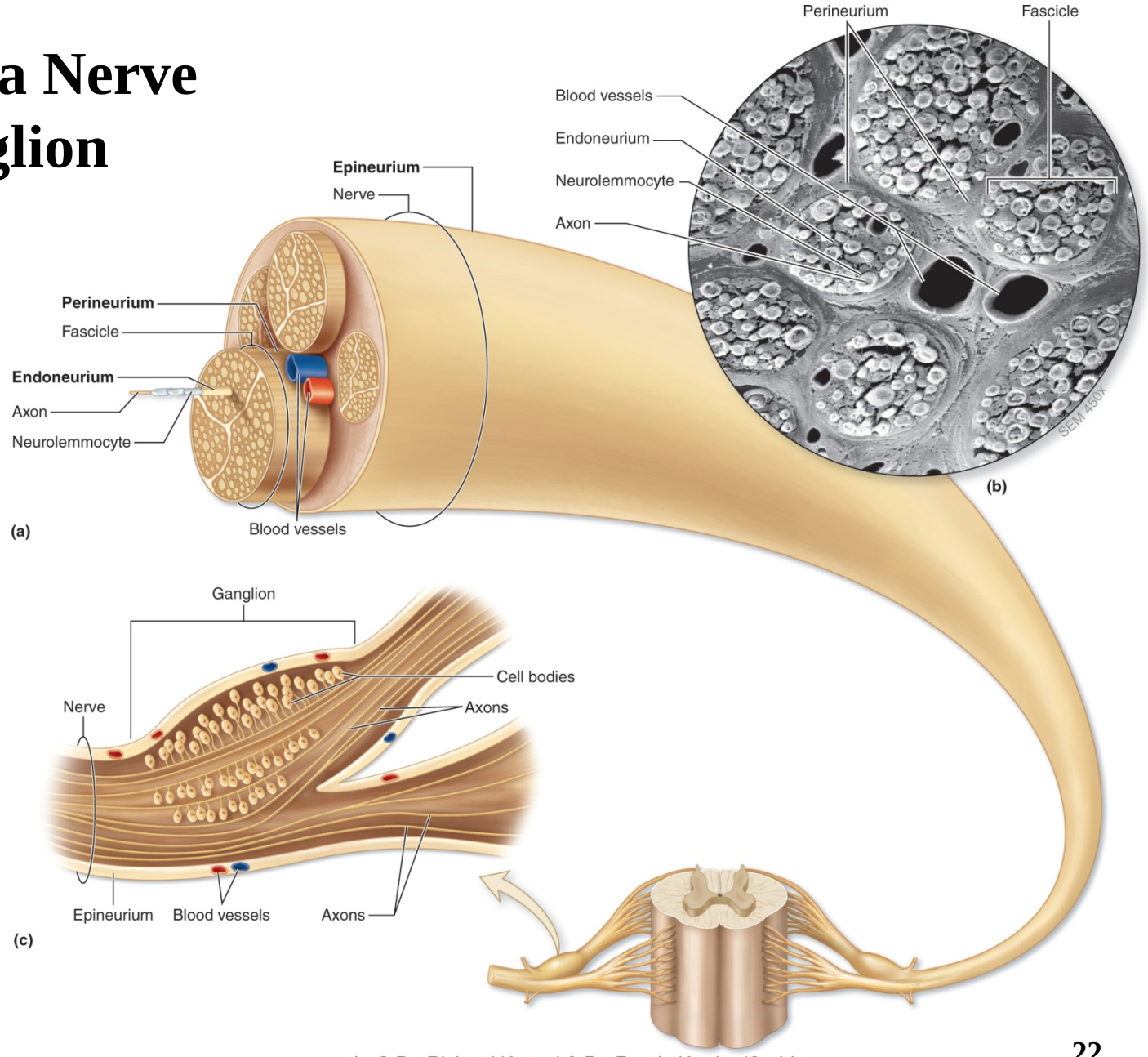


Figure 12.4

b: © Dr. Richard Kessel & Dr. Randy Kardon/Corbis

12.2e Relationship of Neurons and Nerves

- Structural classification of nerves
  - **Cranial nerves:** extend from brain
  - **Spinal nerves:** extend from spinal cord
- Functional classification of nerves
  - **Sensory nerves** contain sensory neurons sending signals to CNS
  - **Motor nerves** contain motor neurons sending signals from CNS
  - **Mixed nerves** contain both sensory and motor neurons
    - Most named nerves are in this category
    - Individual axons in these nerves transmit only one type of information

What did you learn?

- What is the difference between an axon and a dendrite?
- What is the most common structural class of neuron?
- What is the most common functional class of neuron?
- What is a perineurium?

12.3 Synapses

Learning Objectives:

1. Define a synapse.
2. Describe the essential structural and functional differences between a chemical synapse and an electrical synapse.

12.3 Synapses

- **Synapse:** place where a neuron connects to another neuron or an effector
  - Two types: chemical and electrical
    - Chemical synapses are far more common than electrical synapses
- **Electrical synapse**
  - Presynaptic and postsynaptic neurons bound together by gap junctions
  - Fast: no synaptic delay in passing electrical signal

12.3 Synapses

- **Chemical synapse**
  - **Presynaptic neuron**'s axon terminal produces signal
  - **Postsynaptic neuron** receives signal
    - Most commonly with one of its dendrites
  - **Synaptic cleft:** small fluid-filled gap between the two neurons
  - Events of synaptic communication
    - Neurotransmitter molecules released from vesicles of synaptic knob into cleft
    - Transmitter diffuses across cleft and binds to postsynaptic receptors
    - Binding of transmitter to receptor initiates postsynaptic potential (a graded potential)
    - **Synaptic delay:** time it takes for all of these events

What did you learn?

- What are synaptic vesicles and how are they involved in exocytosis?
- Which part of a presynaptic neuron participates in the synapse?

12.4 Nervous Tissue: Glial Cells

Learning Objectives:

1. List the distinguishing features of glial cells.
2. Describe structure and function of the four types of glial cells within the CNS, and the two types of glial cells of the PNS.
3. Define myelination, and describe the composition and function of a myelin sheath.
4. Distinguish between the myelination process carried out by neurolemmocytes in the PNS and by oligodendrocytes in the CNS.

12.4a General Characteristics of Glial Cells

- **Glial cells** (*neuroglia*)
  - Nonexcitable, support cells found in CNS and PNS
  - Smaller, but far outnumber neurons; account for about half the volume of nervous system
  - Capable of mitosis
  - Protect and nourish neurons
  - Provide physical scaffolding for nervous tissue
    - Guide migrating neurons during development
  - Critical for normal function at neural synapses

12.4b Types of Glial Cells

Glial cells of the CNS

- **Astrocytes** (star-shaped cells)
  - Have processes that end in perivascular feet
  - Most abundant glial cell in CNS
  - Help form **blood-brain barrier** by wrapping feet around brain capillaries
    - Controls which substances enter brain's nervous tissue from blood
  - Regulate tissue fluid composition (chemical environment around neurons)
    - E.g., can absorb K^+ and regulate its concentration
  - Form structural framework: strong cytoskeleton helps support nearby neurons
  - Assist development by secreting chemicals that regulate synapse formation
  - Occupy the space of neurons that have died

12.4b Types of Glial Cells

Glial cells of the CNS (*continued*)

- Ependymal cells
  - Line internal cavities of brain and spinal cord
  - Ciliated simple cuboidal or simple columnar epithelial cells
  - Form *choroid plexus* with nearby blood capillaries
    - Helps produce cerebrospinal fluid
      - Liquid that bathes CNS and fills its cavities
  - Have cilia to help circulate CSF

12.4b Types of Glial Cells

Glial cells of the CNS (*continued*)

- **Microglia**
  - Small, rare cells that wander CNS and replicate in infection
  - Phagocytic cells of immune system that engulf infectious agents
  - Remove debris from damaged CNS tissue
- **Oligodendrocytes**
  - Large cells with slender extensions
  - Extensions wrap around axons of neurons forming myelin sheath
    - Myelin insulation allows for faster action potential propagation

Cellular Organization of Nervous Tissue: CNS Glial Cells

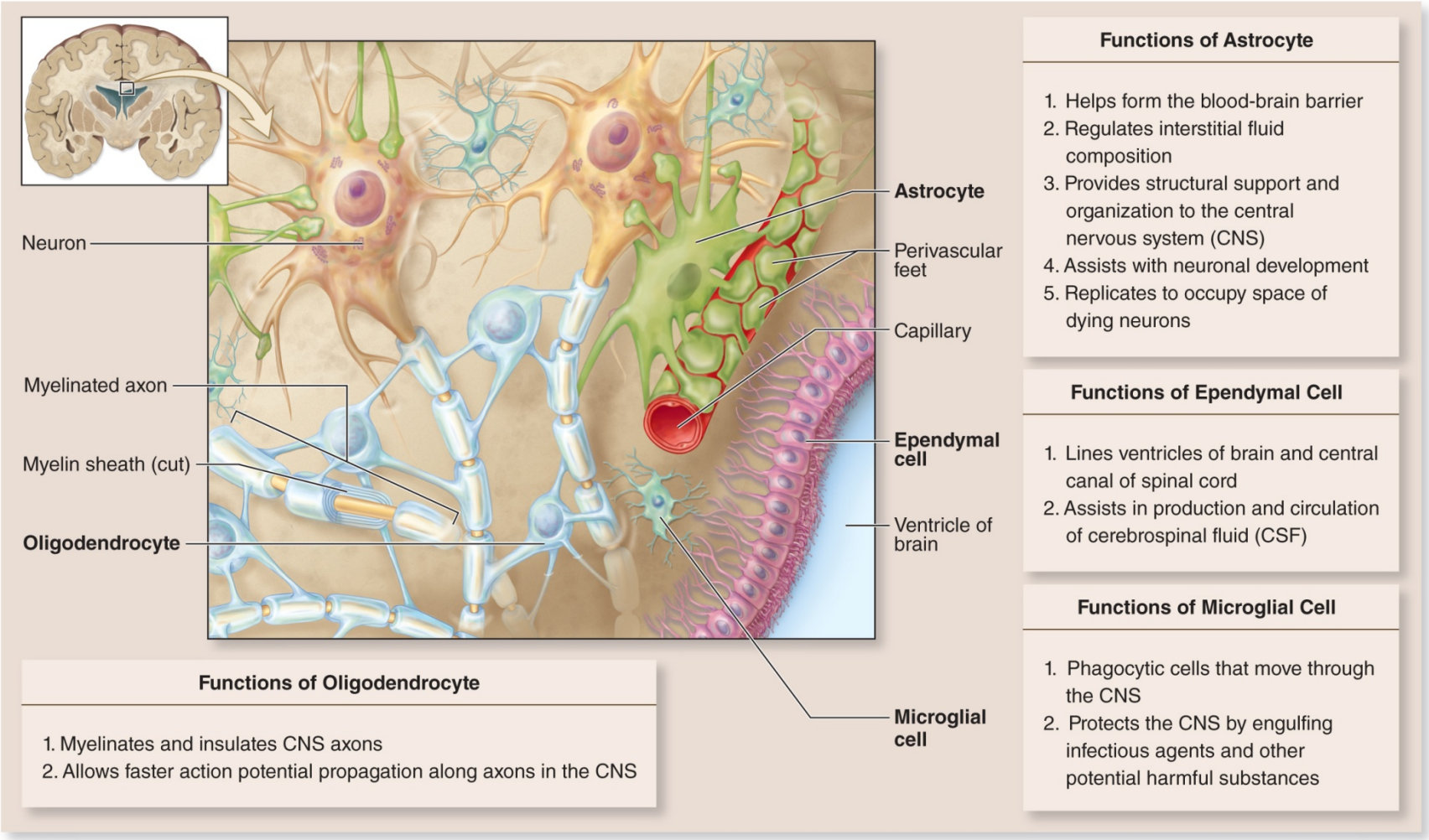


Figure 12.5a

12.4b Types of Glial Cells

Glial cells of the PNS

- **Satellite cells**
  - Arranged around neuronal cell bodies in a ganglion
  - Electrically insulate and regulate the exchange of nutrients and wastes
- **Neurolemmocytes** (*Schwann cells*)
  - Elongated, flat cells that ensheath PNS axons with myelin
  - Allows for faster action potential propagation

Glial Cells of the PNS

Functions of Satellite Cell

1. Electrically insulates PNS cell bodies.
2. Regulates nutrient and waste exchange for cell bodies in ganglia

Functions of Neurolemmocyte

1. Myelinates and insulates PNS axons
2. Allows for faster action potential propagation along an axon in the PNS

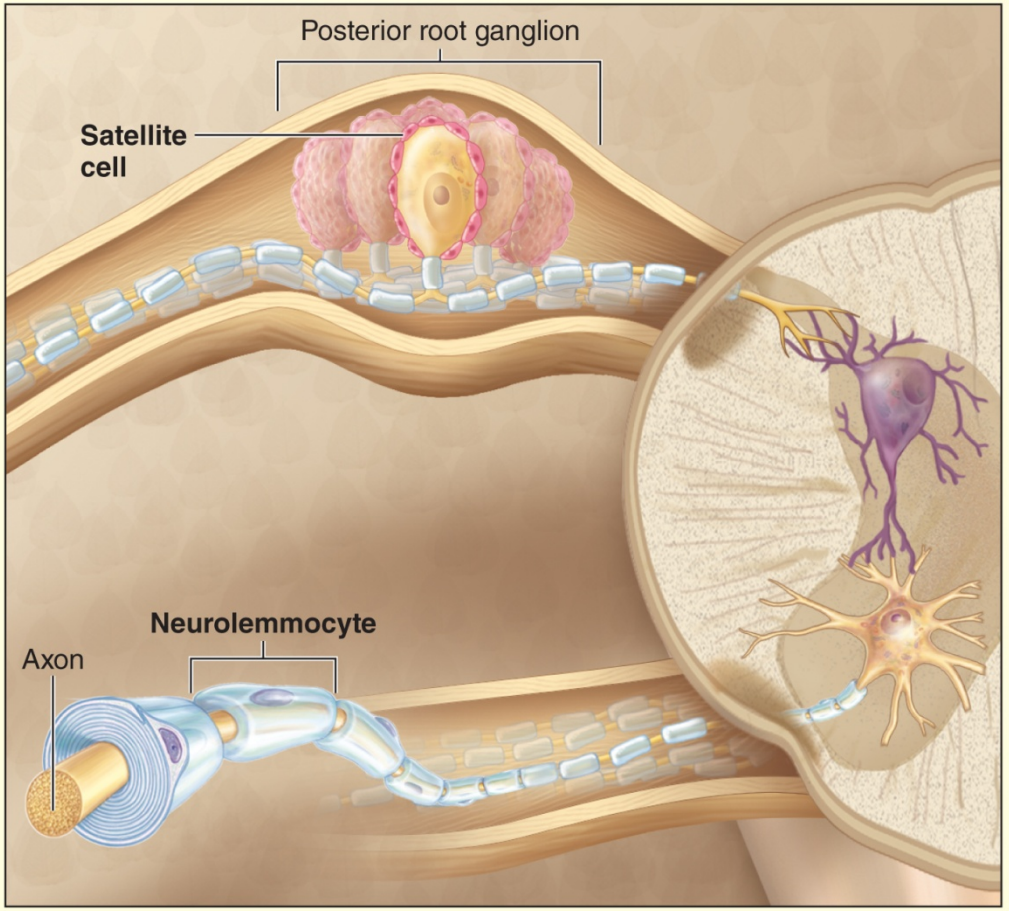


Figure 12.6

Clinical View: Tumors of the Central Nervous System

- Neoplasms from unregulated cell growth, **tumors**
- Sometimes occur in CNS
- Tumors originating from the brain, primary brain tumors
- Typically originate in supporting tissues
  - Tissues with capacity to undergo mitosis
  - From meninges (protective membranes of CNS) or glial cells
- **Gliomas,** glial cell tumors
  - May be relatively benign
  - May be malignant, capable of metastasizing

12.4c Myelination

- **Myelination:** process of wrapping an axon with myelin
  - Myelin: several layers of membrane of glial cells
    - High lipid content gives it glossy-white appearance and insulates axon
    - The glia are neurolemmocytes in PNS; oligodendrocytes in CNS
  - In the PNS
    - Neurolemmocyte encircles neuron axon and wraps it in layers forming **myelin sheath**
    - Neurolemmocyte's cytoplasm and nucleus are pushed to periphery forming **neurilemma**
    - A neurolemmocyte can myelinate only 1 mm of axon, so several are needed for one axon
      - Gaps between neurolemmocytes are **neurofibril nodes** (*nodes of Ranvier*)

Myelination of PNS Axons

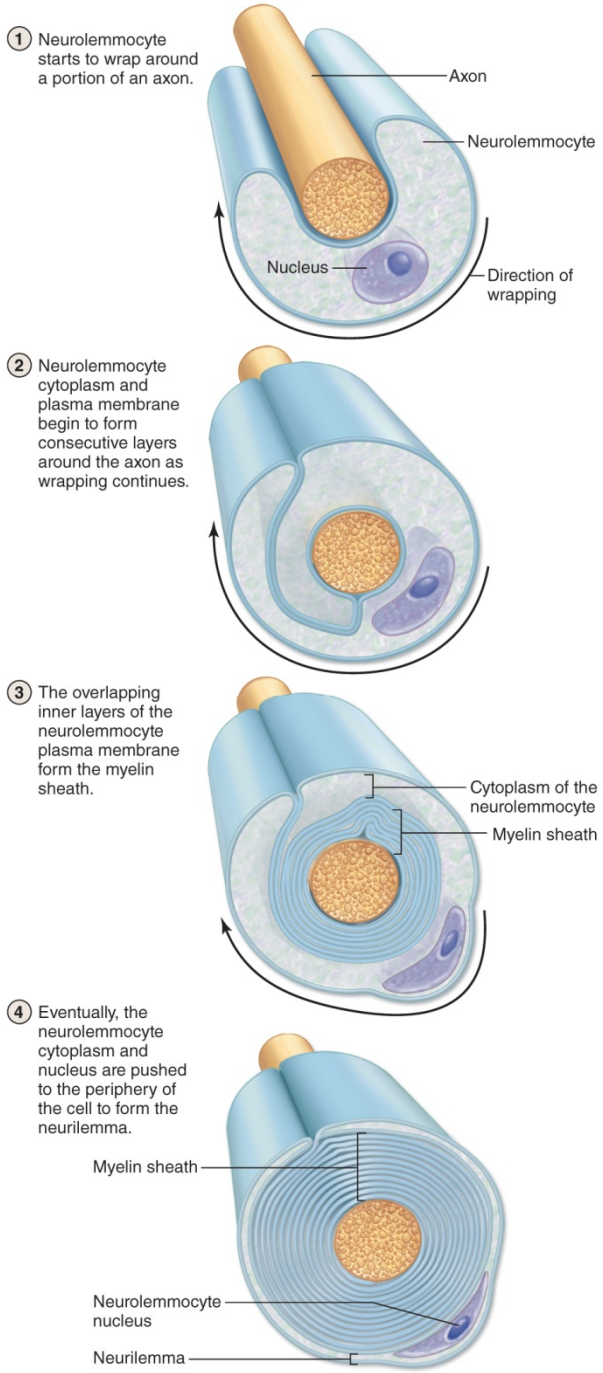
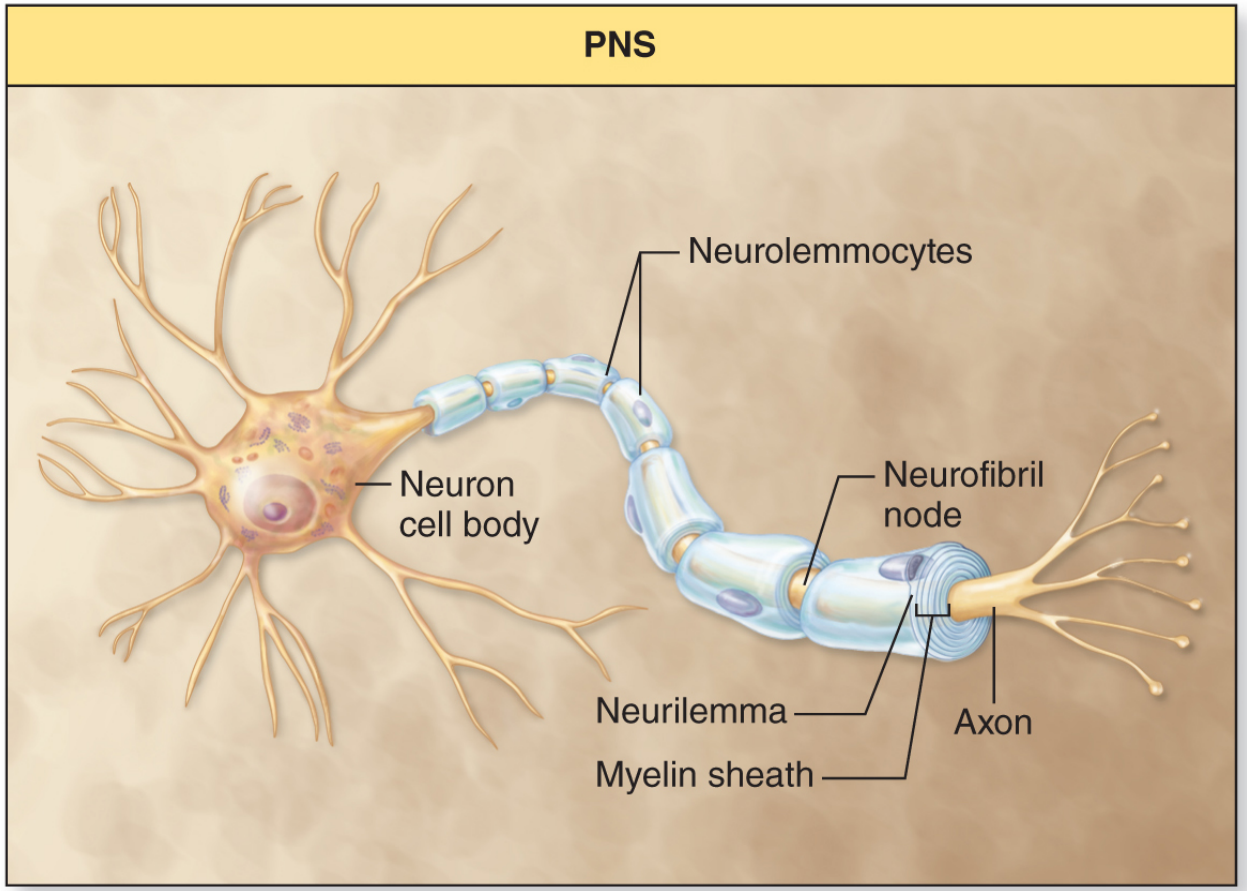


Figure 12.7

Myelin Sheath in the PNS



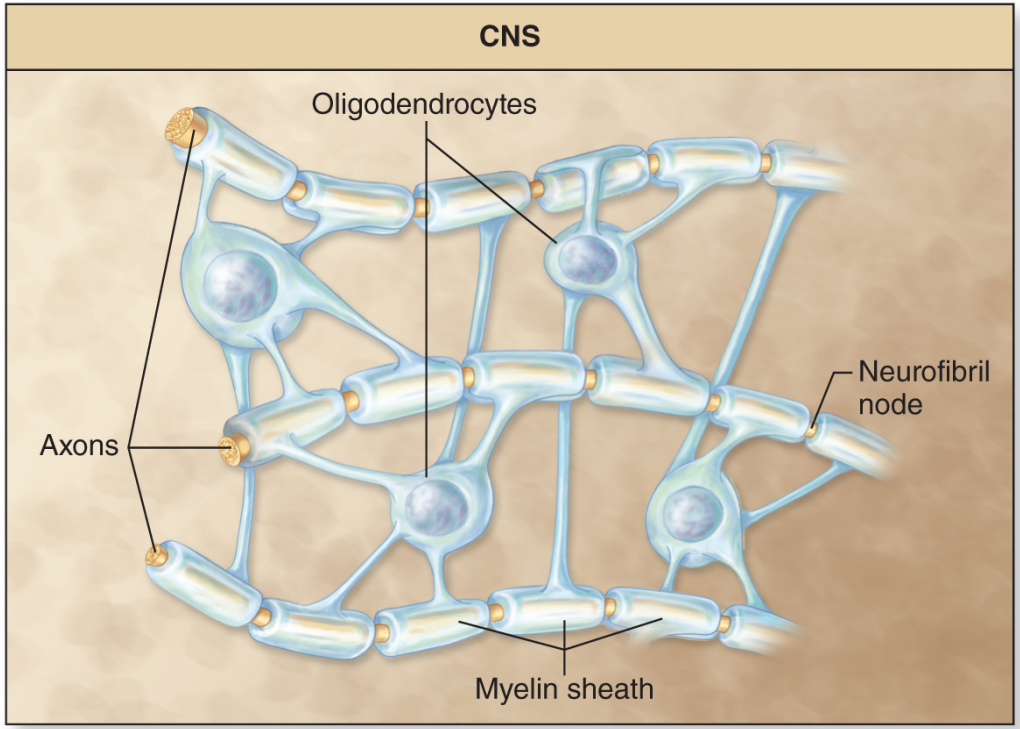
(a) Myelination by neurolemmocytes

Figure 12.8a

Myelin Sheath in the CNS

Myelination (*cont'd*)

- In the CNS
  - One oligodendrocyte can myelinate 1 mm of multiple axons, each at multiple spots
  - No neurilemma formed
  - Neurofibril nodes between adjacent wrapped segments



(b) Myelination by oligodendrocytes

Figure 12.8b

12.4c Myelination

- **Unmyelinated axons** exist in PNS and CNS
  - In PNS
    - Axon sits in depressed portion of neurolemmocyte
      - Not fully ensheathed by it
  - In CNS
    - Unmyelinated axons not associated with oligodendrocytes

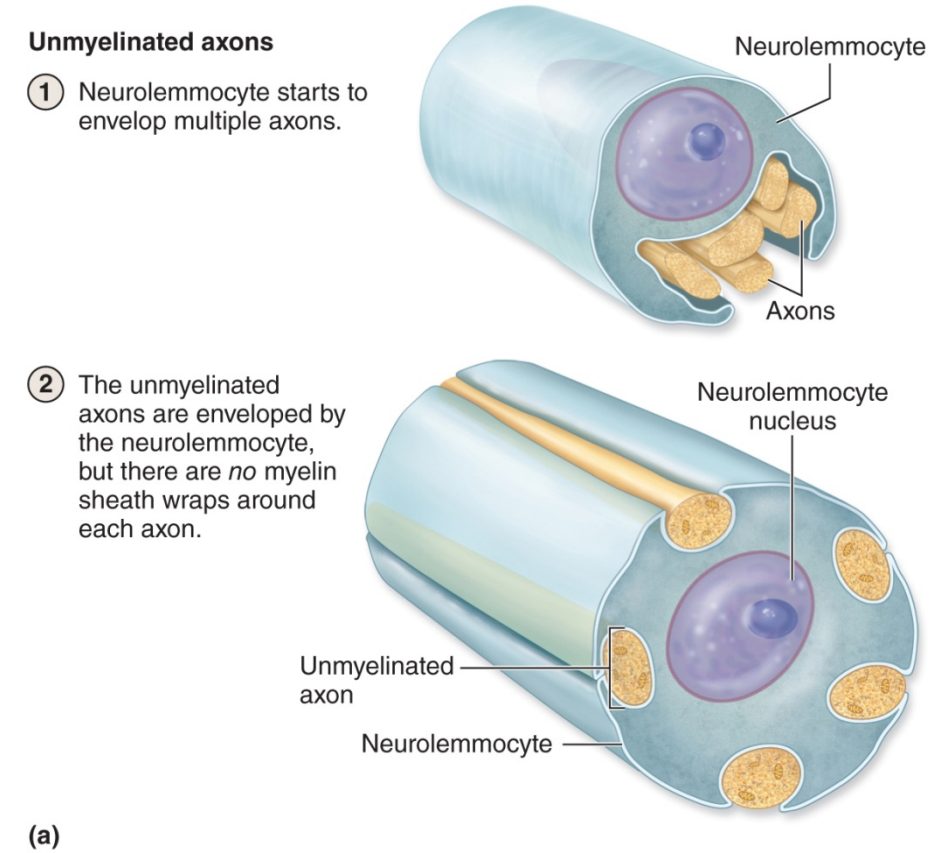


Figure 12.9a

Clinical View: Nervous System Disorders Affecting Myelin

- **Multiple sclerosis**
  - Progressive demyelination of neurons in CNS
  - Autoimmune disorder: oligodendrocytes attacked by immune cells
  - Repeated inflammatory events causing scarring and permanent loss of function
- **Guillain-Barré syndrome**
  - Loss of myelin from peripheral nerves due to inflammation
  - Muscle weakness begins in distal limbs, advances to proximal muscles
  - Most function recovered with little medical intervention

What did you learn?

- Which type of glial cell scavenges the CNS for debris and helps fight pathogens?
- What is the function of a satellite cell?
- Are oligodendrocytes in the CNS, PNS, or both?
- What is a neurilemma?

12.5 Axon Regeneration

Learning Objectives:

1. Identify factors that influence regeneration of PNS axons, and explain why axon regeneration in the CNS is limited.
2. Describe the events of Wallerian degeneration and axon regrowth.

12.5 Axon Regeneration

- After traumatic injuries, PNS axons can regenerate
  - Regeneration is possible if
    - Neuron cell body is intact
    - Enough neurilemma remains
  - Regeneration success is more likely if
    - Amount of damage is less extensive
    - Distance between site of damage and structure it innervates is shorter

12.5 Axon Regeneration

- Steps of axon regeneration
  1) Axon severed by trauma
  2a) Proximal to the cut: the axon seals off and swells
  2b) Distal to the cut: the axon and sheath degenerate **(Wallerian degeneration)** but the neurilemma survives
  3) Neurilemma and endoneurium form a regeneration tube
  4) Axon regenerates guided by nerve growth factors released by neurolemmocytes
  5) Axon reinnervates original effector or sensory receptor

Regeneration of PNS axons

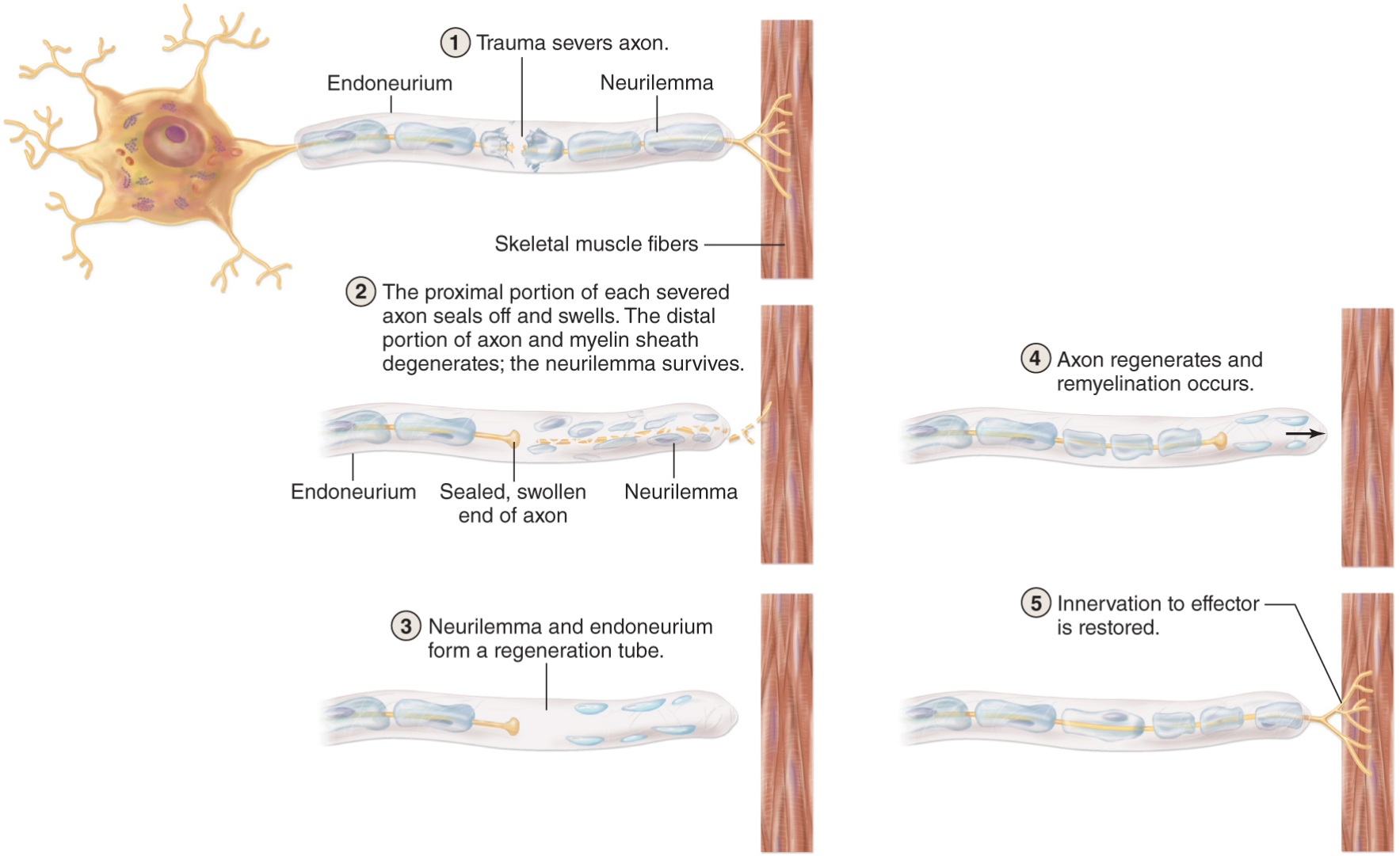


Figure 12.10

12.5 Axon Regeneration

- CNS axon regeneration is extremely limited
  - Oligodendrocytes secrete growth-inhibiting molecules; not growth factors
  - Large number of axons crowd the CNS
  - Regrowth obstructed by scars from astrocytes and connective tissue

What did you learn?

- In which part of the nervous system is axon regeneration more likely—CNS or PNS?
- What structures help form a regeneration tube?

12.6 Plasma Membrane of Neurons

Learning Objectives:

1. Distinguish between a pump and a channel, and describe the three specific states of a voltage-gated Na^+ channel.
2. List the channels and pumps that are located along the entire neuron, and identify the general function of each.
3. Identify and describe the four functional neuron segments, including the distribution of channels and pumps in each.

12.6a Types of Pumps and Channels

- **Pumps**
  - Membrane proteins that maintain a concentration gradient by moving substances against their concentration gradient
  - Require cellular energy
  - Neurons have sodium-potassium pumps and calcium pumps in their membranes

12.6a Types of Pumps and Channels

- **Channels**
  - Protein pores in the membrane that allow ions to move down their concentration gradients (into or out of the cell)
    - When open they allow a specific type of ion to diffuse
  - **Leak** (*passive*) **channels** are always open for continuous diffusion
  - **Chemically gated channels** are normally closed, but open when neurotransmitter binds
  - **Voltage-gated channels** are normally closed, but open when membrane charge changes

12.6a Types of Pumps and Channels

- Voltage-gated sodium channels have two gates; they can be in three states

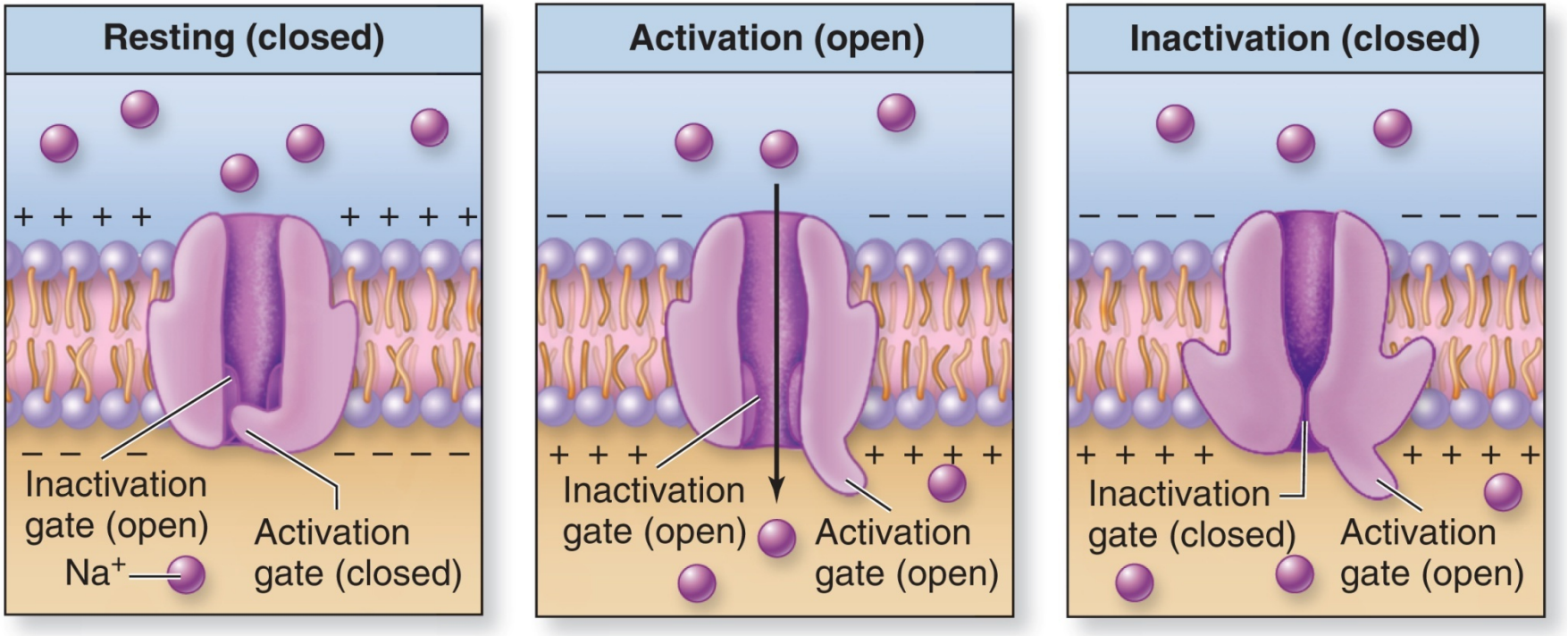


Figure 12.11

12.6a Types of Pumps and Channels

- Three states of voltage-gated Na^+ channels
  1. **Resting state**
     - Activation gate closed; inactivation gate open
     - Entry of Na^+ prevented
  2. **Activation state**
     - Activation gate open (due to voltage change); inactivation gate open
     - Na^+ moves through channel
  3. **Inactivation state**
     - Activation gate open; inactivation gate closed
     - Entry of Na^+ prevented
     - This state lasts a short time—the channel quickly resets to resting state

12.6a Types of Pumps and Channels

- **Modality gated channels**
  - Normally closed, but open in response to a stimulus other than a chemical or a voltage change
  - Found in membranes of sensory neurons that respond to changes in their environment
    - E.g., some receptor neurons of the skin have mechanically gated channels that sense pressure

12.6b Distribution of Pumps and Channels

- Entire plasma membrane of neuron
  - Leak channels (e.g., K^+ leak channels)
  - Na^+/K^+ pumps
  - Maintain resting membrane potential

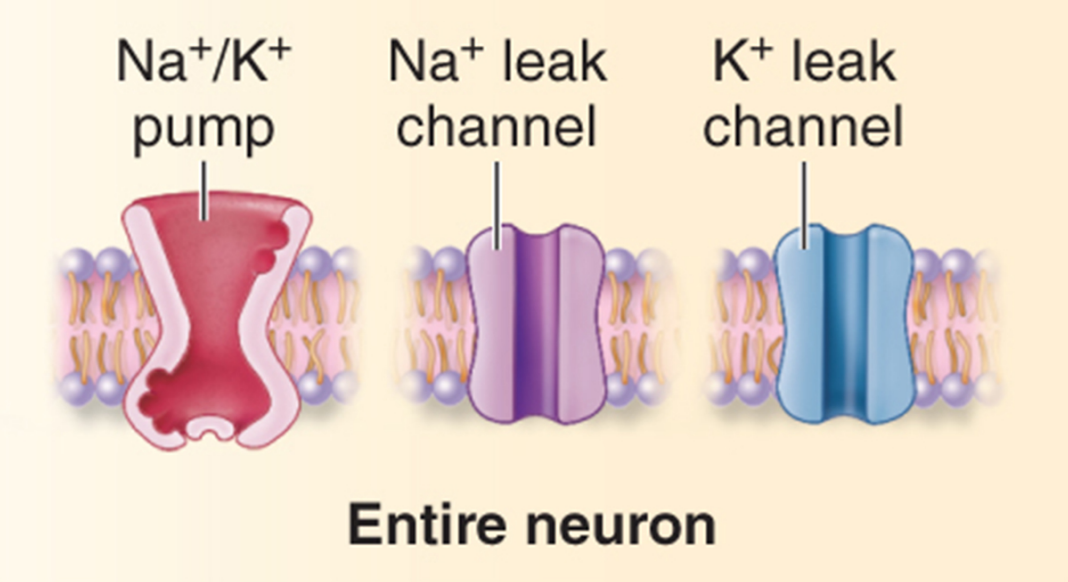


Figure 12.12a

12.6b Distribution of Pumps and Channels

- Functional segments of neuron have additional channels and/or pumps
  - **Receptive segment** (dendrite and cell body)
    - Chemically gated channels (e.g., chemically gated Cl^- channels)
  - **Initial segment** (*axon hillock*)
    - Voltage-gated Na^+ channels and voltage-gated K^+ channels
  - **Conductive segment** (axon and its branches)
    - Voltage-gated Na^+ channels and voltage-gated K^+ channels
  - **Transmissive segment** (synaptic knobs)
    - Voltage-gated Ca^{2+} channels and Ca^{2+} pumps

Distribution of Pumps and Channels in the Plasma Membrane of a Neuron

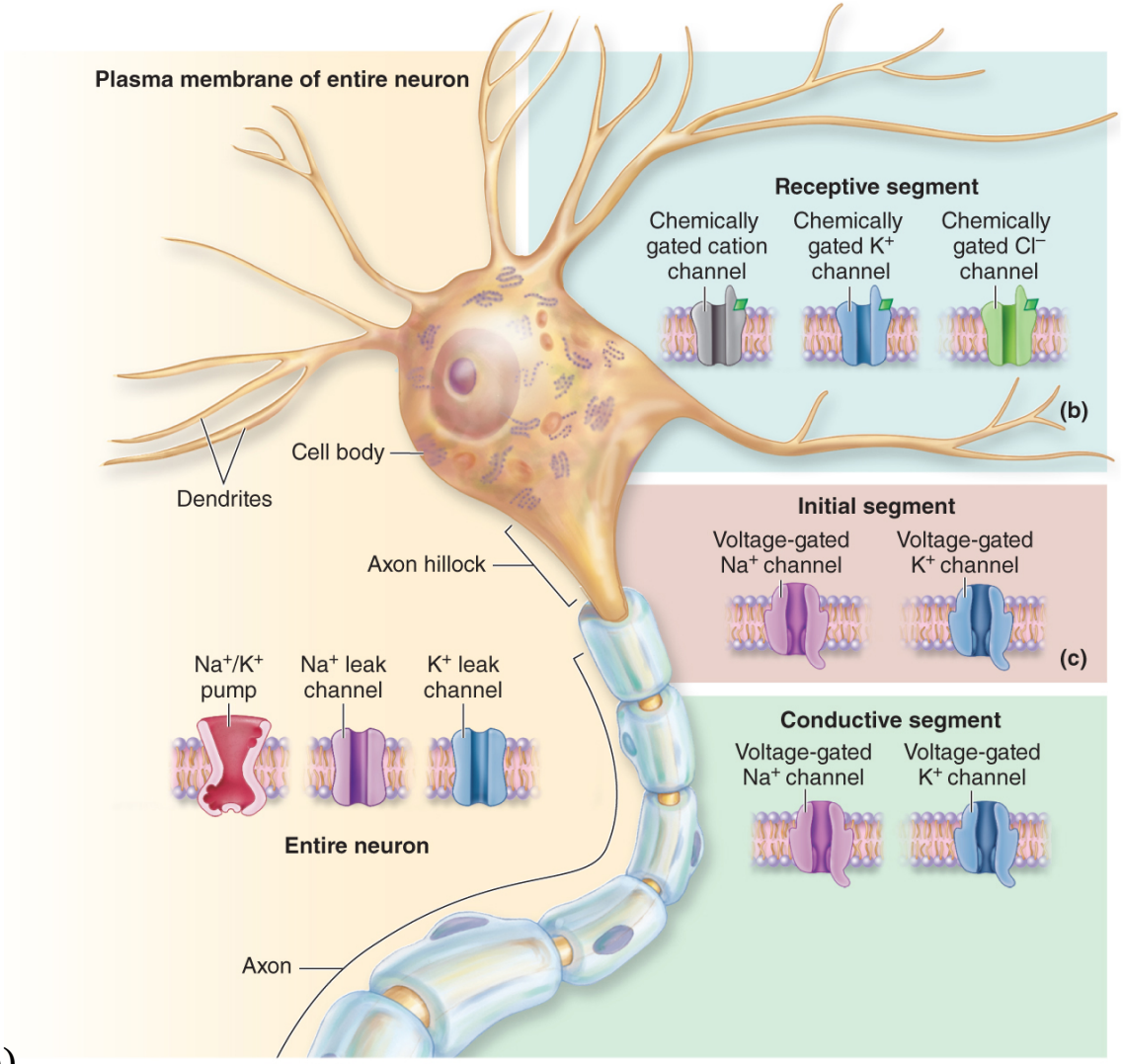


Figure 12.12 (top)

Distribution of Pumps and Channels in the Plasma Membrane of a Neuron

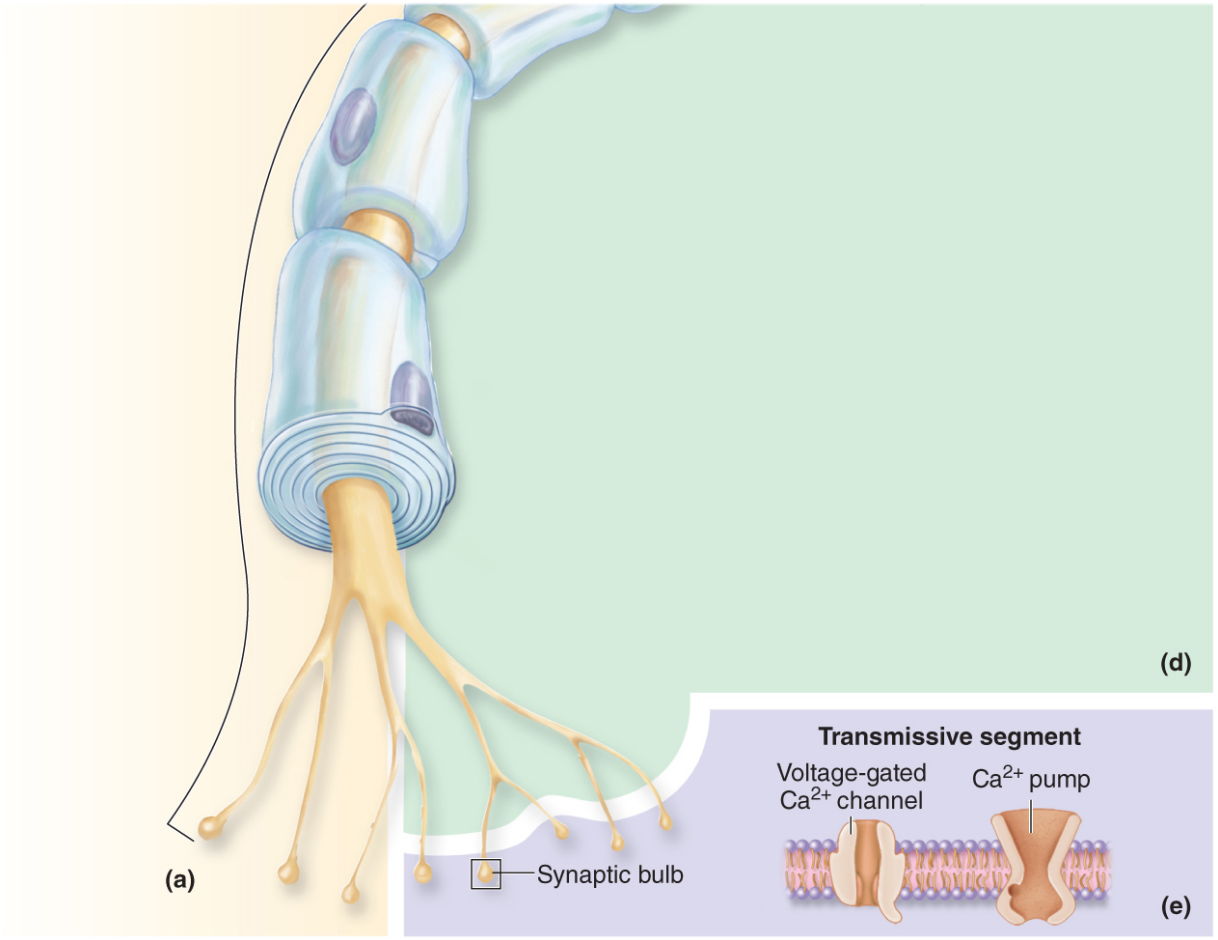


Figure 12.12 (bottom)

What did you learn?

- Which type of membrane protein, channel, or pump requires cellular energy?
- What part of a neuron contains chemically gated ion channels?
- What types of channels are found along the length of the axon? (Hint: Don’t forget those found on entire neuron.)

12.7 Introduction to Neuron Physiology

Learning Objectives:

1. Integrate the concepts of voltage, current, and resistance with neuron structure and function.
2. Describe the conditions of a neuron at rest.
3. Define resting membrane potential, and state its typical value for neurons.
4. Explain how the resting membrane potential is established and maintained in neurons.

12.7a Neurons and Ohm's Law

- Neuron activity dependent upon electrical current
  - **Voltage** (potential energy)
    - Amount of difference in electrical charge between two places
    - Measured in volts or millivolts
  - **Current**
    - Movement of charged particles across barrier separating them
    - Can be harnessed to do work
  - **Resistance**
    - Opposition to movement of charged particles (i.e., the barrier)
    - An increase in resistance lowers the current

12.7a Neurons and Ohm's Law

- **Ohm's law**
  - Current = voltage/resistance
  - Current increases with larger voltage and smaller resistance
- As applied to neurons
  - Charged particles are ions, and current is generated when ions diffuse through channels
  - Voltage exists across the membrane due to unequal distribution of ions
  - The membrane offers resistance to ion flow, and this resistance changes due to the actions of gated channels
    - Resistance decreases when channels open

12.7b Neurons at Rest

- Characteristics of resting neurons
  - Ions are unevenly distributed across the plasma membrane due to the actions of pumps
    - Higher concentration of K^+ in cytosol verses interstitial fluid (IF)
    - Higher concentrations of Na^+, Cl^-, Ca^{2+} in IF than in cytosol
  - Gated channels are closed in the functional segments of the cell
  - There is an electrical charge difference across the membrane
    - Cytosol is relatively negative compared to IF
    - **Resting membrane potential (RMP)** is typically –70 mV
    - This difference can be measured with microelectrodes (one inside cell; one outside) and a voltmeter

Neuron at Rest

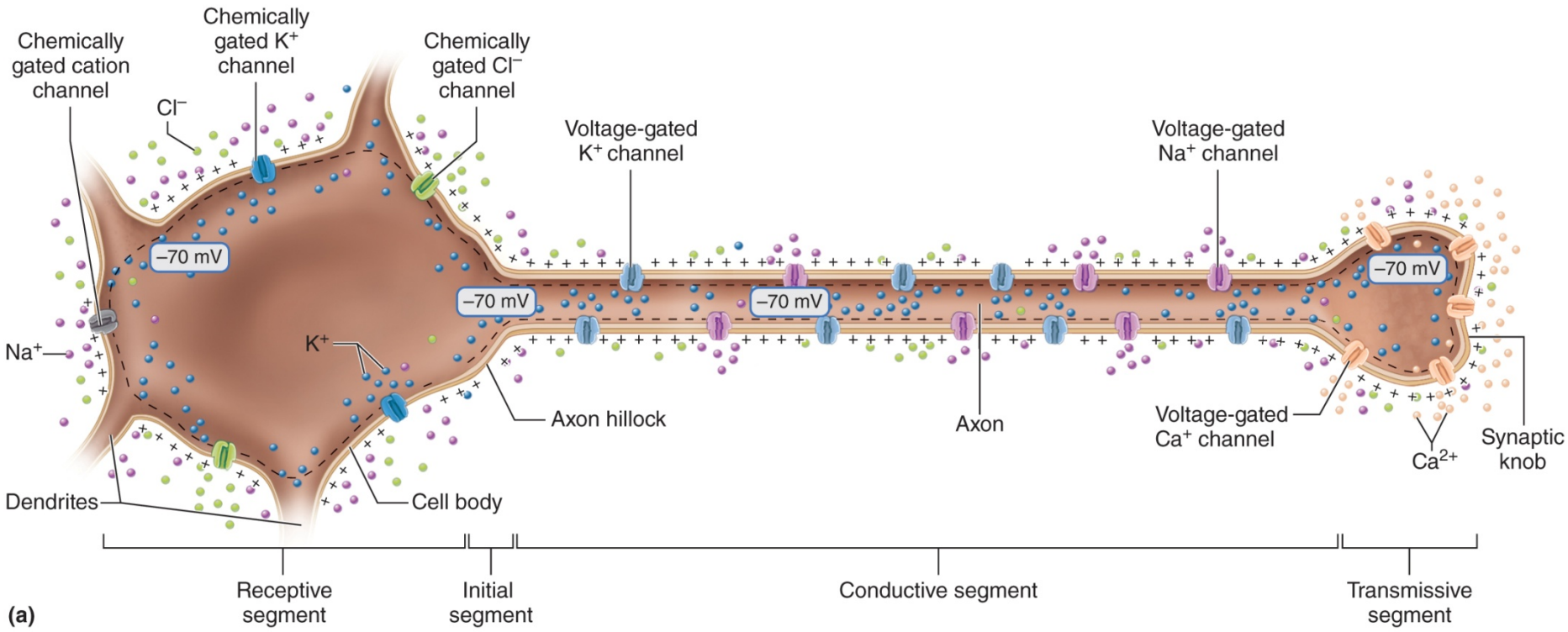


Figure 12.13a

Neuron at Rest

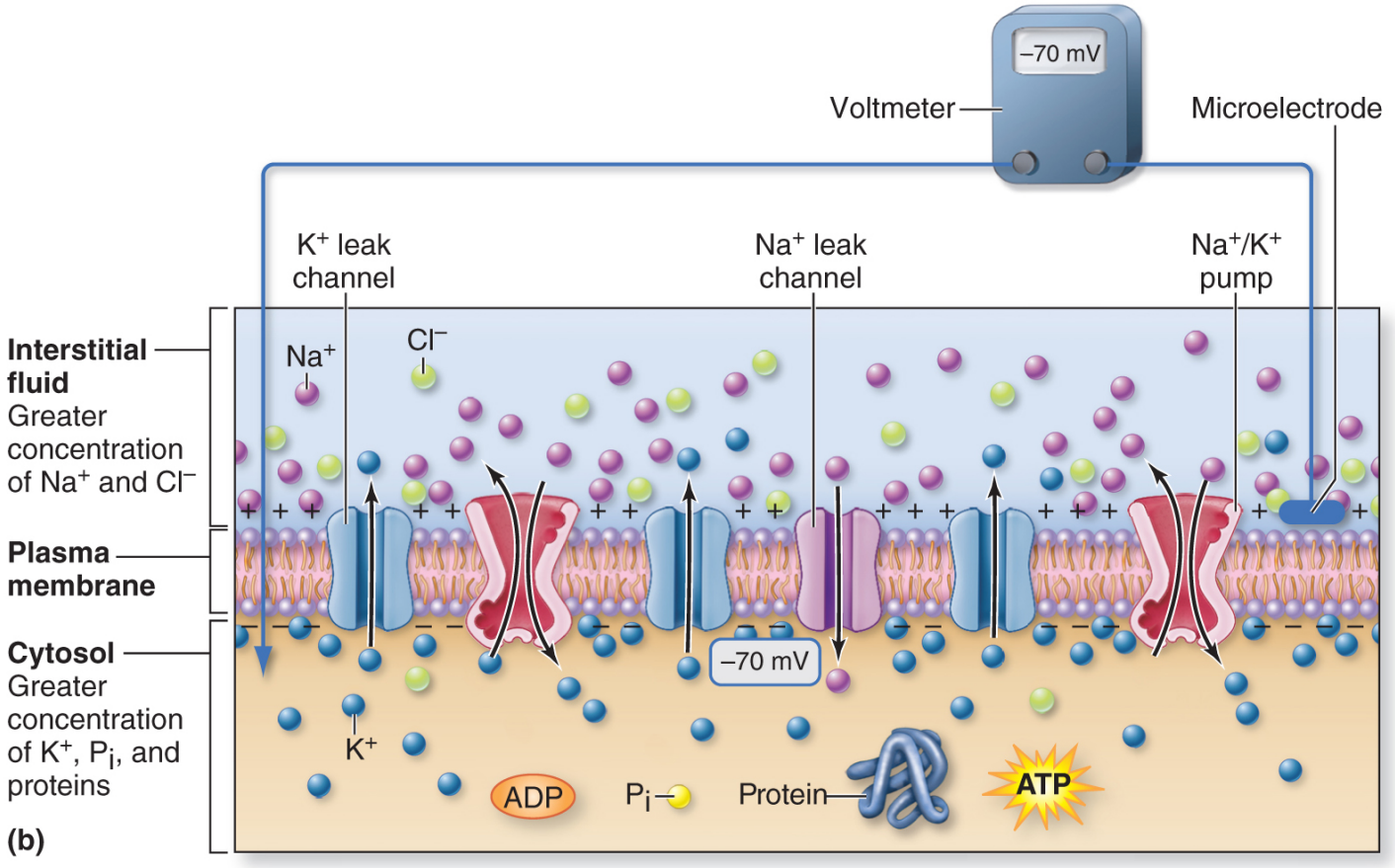


Figure 12.13b

12.7b Neurons at Rest

Resting membrane potential (RMP)

- K^+ diffusion is the most important factor in setting RMP
  - K^+ diffuses out of the cell due to its concentration gradient
  - K^+ diffusion out is limited by the electrical gradient (the pull of the negative RMP on the positive ion)
  - If K^+ were the only ion that leaked, RMP would be where the K^+ concentration and electrical gradients are at equilibrium (–90 mV)
- Since there are a few Na^+ leak channels, Na^+ also influences RMP
  - Na^+ diffuses in due to its concentration gradient and the electrical gradient
  - This small Na^+ leakage means RNP is less negative (–70 mV)

12.7b Neurons at Rest

Resting membrane potential (RMP) (*continued*)

- The role of Na^+/K^+ pumps
  - By pushing 3 positive charges out and pushing in only 2, the pump contributes about –3 mV (of the –70 mV total)
  - More importantly, it maintains the concentration gradients for these ions

What did you learn?

- According to Ohm’s law, what happens to current flow when resistance increases?
- What happens to membrane resistance when channels close?
- In which direction does potassium diffuse through leakage channels at rest?

12.8 Physiologic Events in the Neuron Segments

Learning Objectives:

1. Describe a postsynaptic potential.
2. Compare and contrast the action of neurotransmitters in developing both excitatory and inhibitory postsynaptic potentials (graded potentials) in the receptive segment.
3. Graph and explain an excitatory postsynaptic potential (EPSP) and an inhibitory postsynaptic potential (IPSP).
4. Define summation, and describe the two types of summation that can occur in the initial segment.

12.8 Physiologic Events in the Neuron Segments (*continued*)

Learning Objectives:

5. Describe and graph an action potential.
6. Explain propagation of an action potential in both unmyelinated and myelinated axons.
7. Define refractory period, and explain the difference between the absolute refractory period and relative refractory period associated with transmitting an action potential.
8. Describe events that occur when the propagated action potential reaches the transmissive segment.
9. Explain the general role of Ca^{2+} in neurotransmitter release.

12.8a Receptive Segment

- Reception of neurotransmitter triggers postsynaptic potential
  - Neurotransmitter binds to chemically gated ion channels and opens them
  - Ions diffuse across membrane changing its electrical potential
  - The voltage change is a **graded potential:** it can vary in size (from a few mV to many mV)
  - It is a local potential: it starts at dendrites or soma and does not go far
  - The direction of the potential depends on what type of ion channel opens
    - If Na^+ channels open, Na^+ diffuses in and membrane becomes less negative
    - If Cl^- channels open, Cl^- diffuses in and membrane becomes more negative
    - If K^+ channels open, K^+ diffuses out and membrane becomes more negative
    - When a cell is less negative than RMP it is **depolarized**; when it is more negative it is **hyperpolarized**
  - It is a short-lived potential (lasting only milliseconds)

Postsynaptic Potentials in the Receptive Segment

Excitatory postsynaptic potentials (EPSPs) are depolarizations caused by cation entry

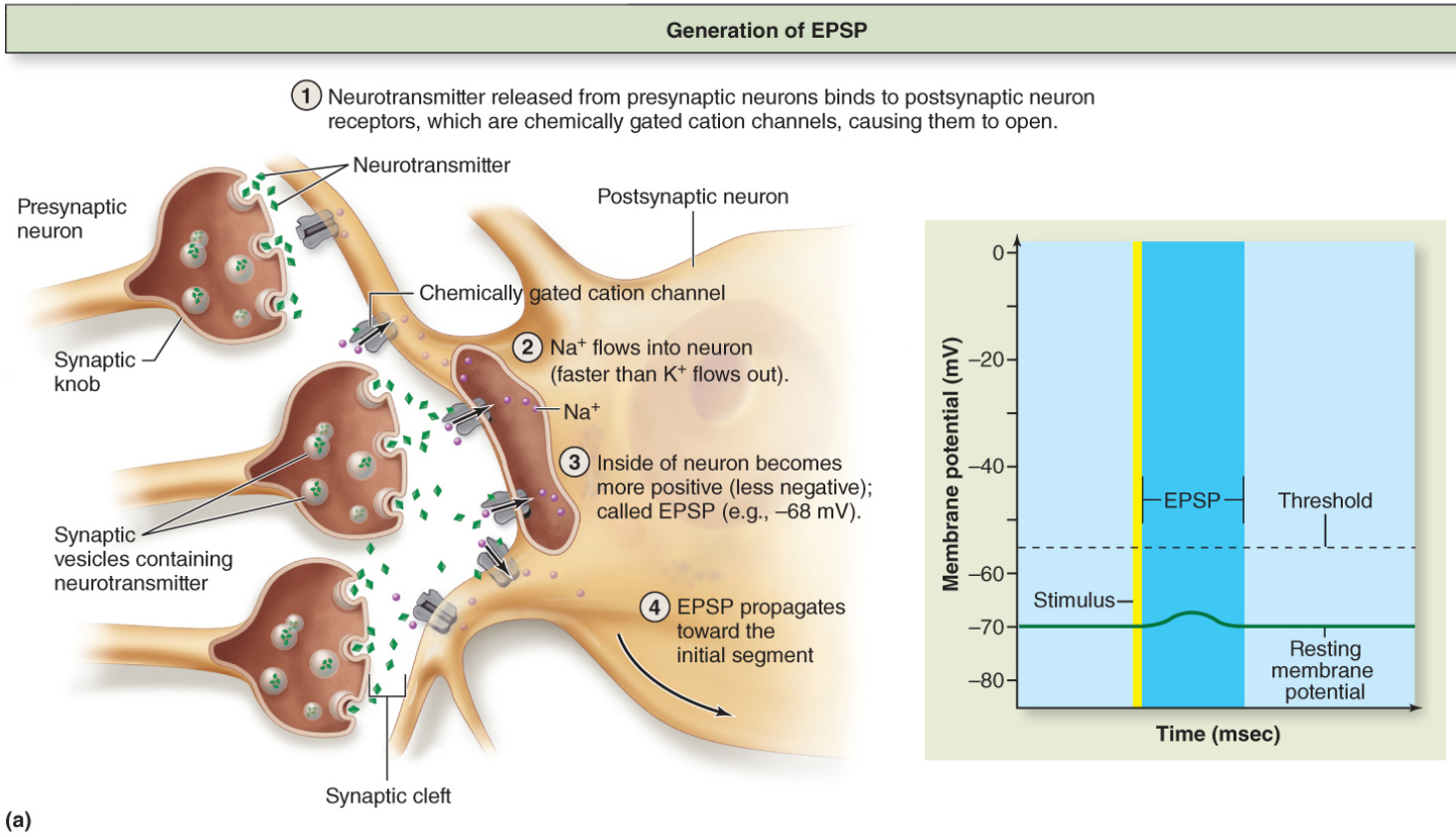


Figure 12.15a

Postsynaptic Potentials in the Receptive Segment

Inhibitory postsynaptic potentials (IPSPs) are hyperpolarizations caused by cation exit or anion entry

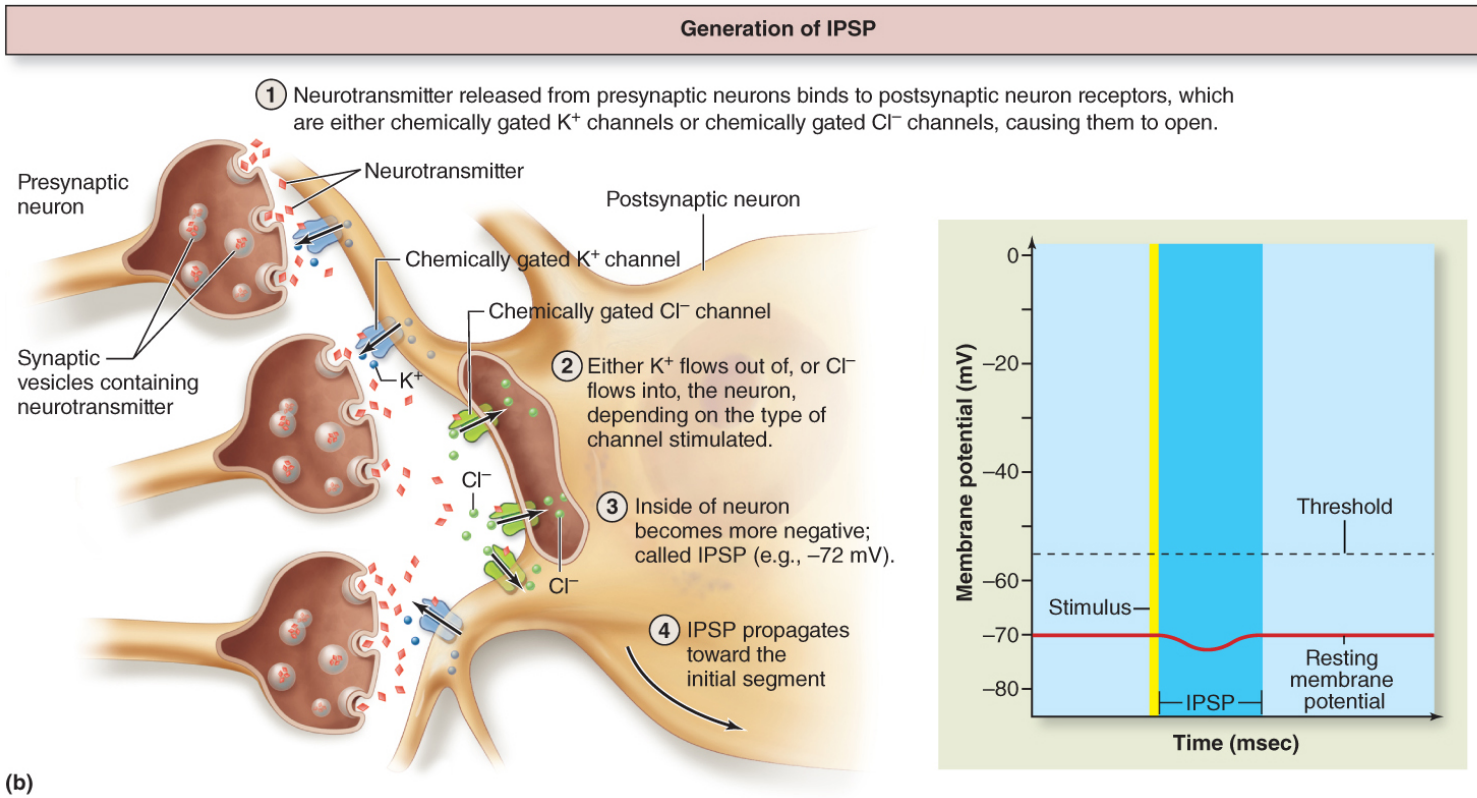


Figure 12.15b

Several Presynaptic Neurons with a Postsynaptic Neuron

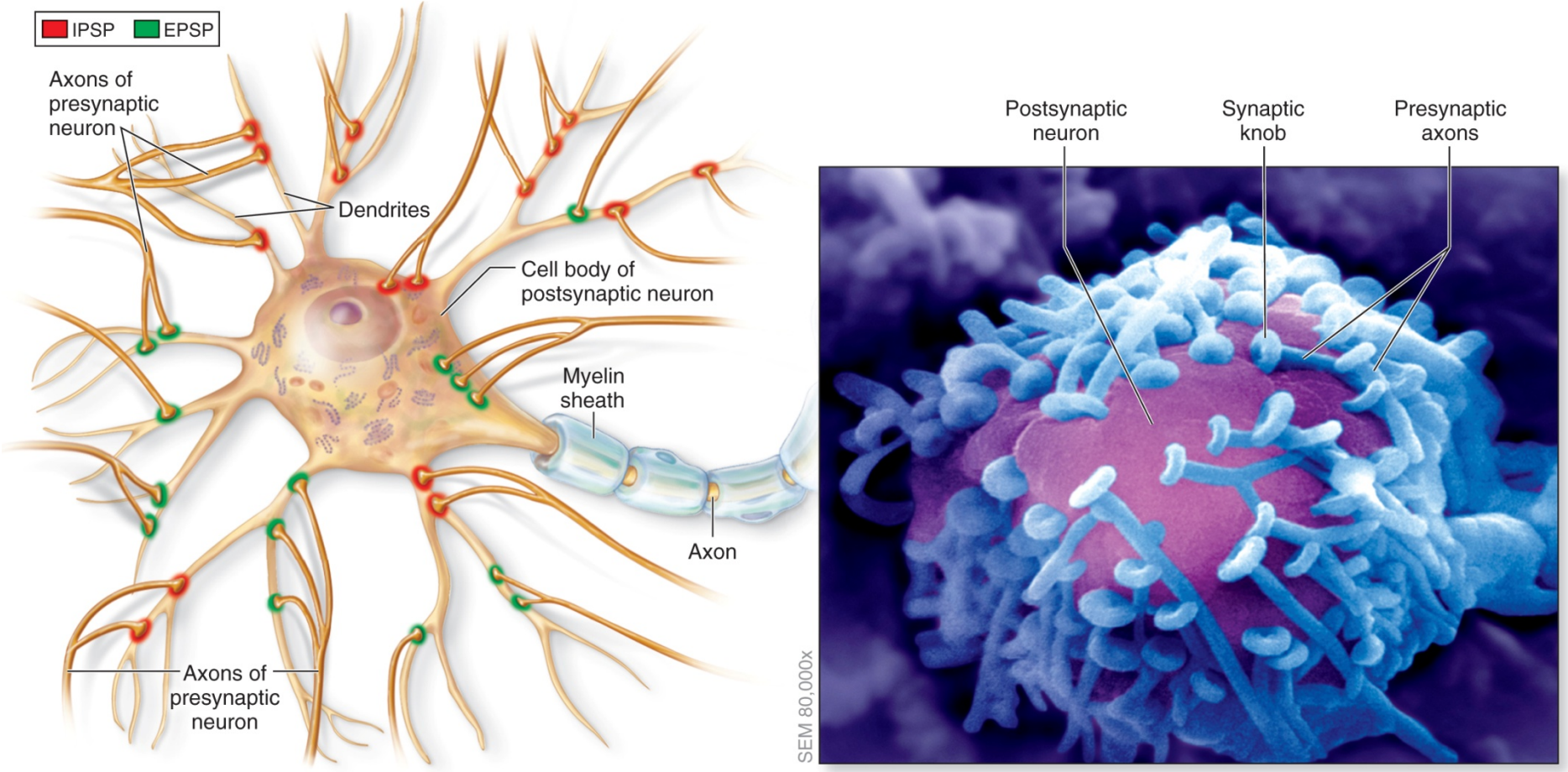


Figure 12.16

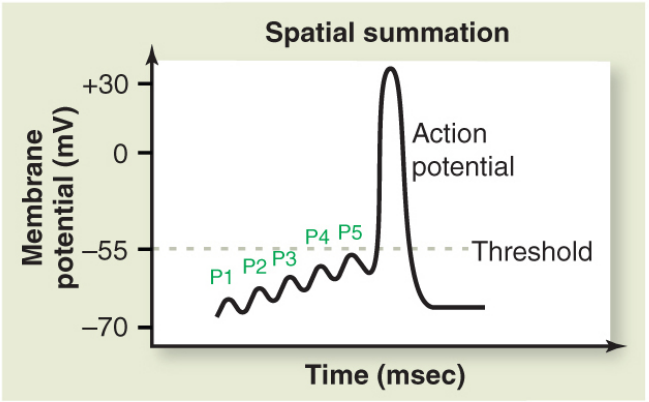
12.8b Initial Segment

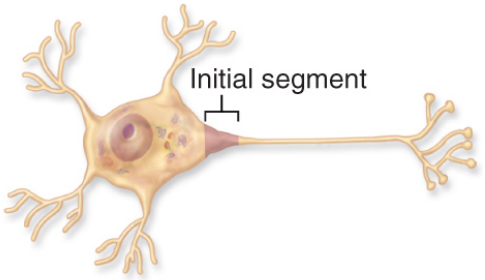
- **Summation** of EPSPs and IPSPs occurs at axon hillock
  - Voltage changes from the dendrites and soma are added
  - The sum may or may not reach **threshold membrane potential** for initiating an action potential
    - Threshold is the minimum voltage change required
    - Typically, threshold is about –55 mV
    - Generally, multiple EPSPs must be added to reach threshold
  - If threshold is reached at the axon hillock (initial segment)
    - Voltage-gated channels open, and an action potential is generated

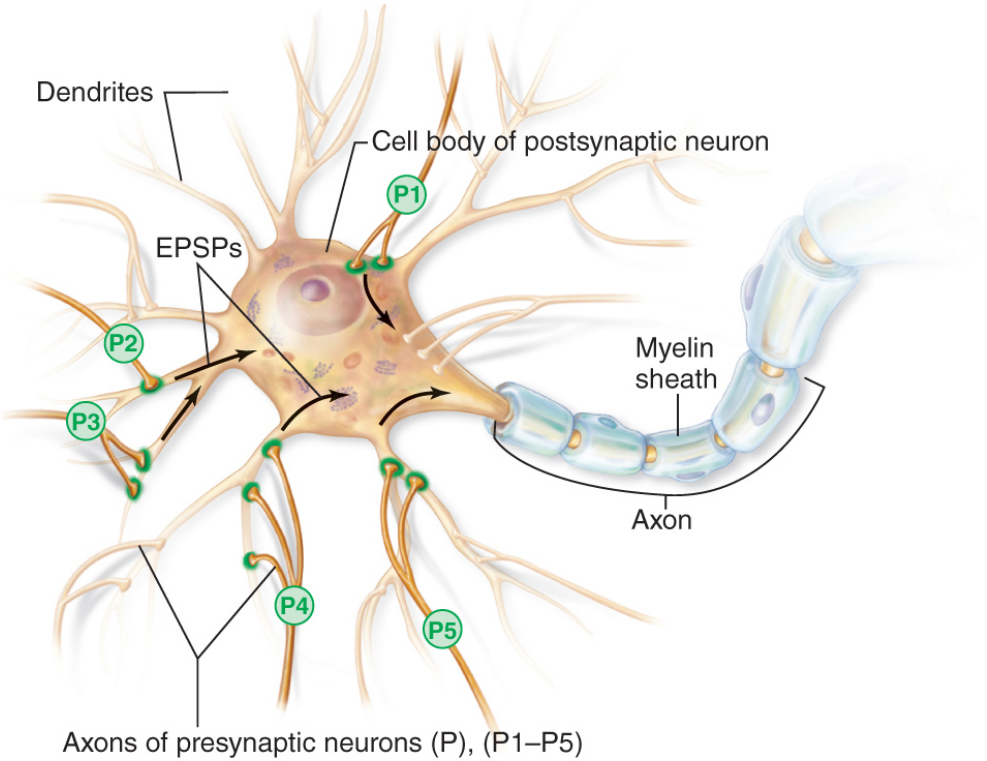
12.8b Initial Segment

- Summation occurs across space and time
  - Spatial summation
    - Multiple locations on cell's receptive regions receive neurotransmitter simultaneously and generate postsynaptic potentials
  - Temporal summation
    - A single presynaptic neuron repeatedly releases neurotransmitter and produces multiple EPSPs within a very short period of time

Initial Segment: Spatial Summation

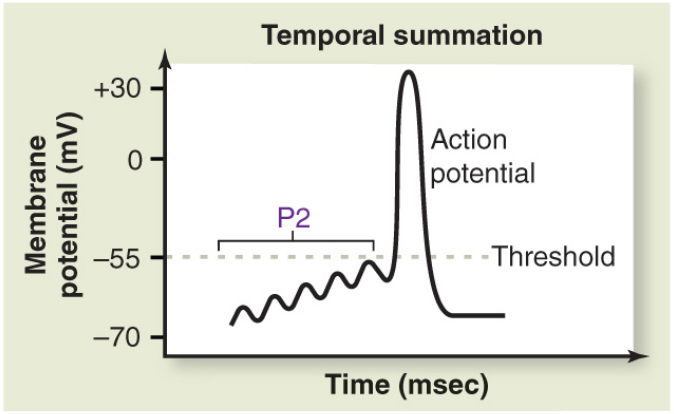






(a) Spatial summation

Figure 12.17a



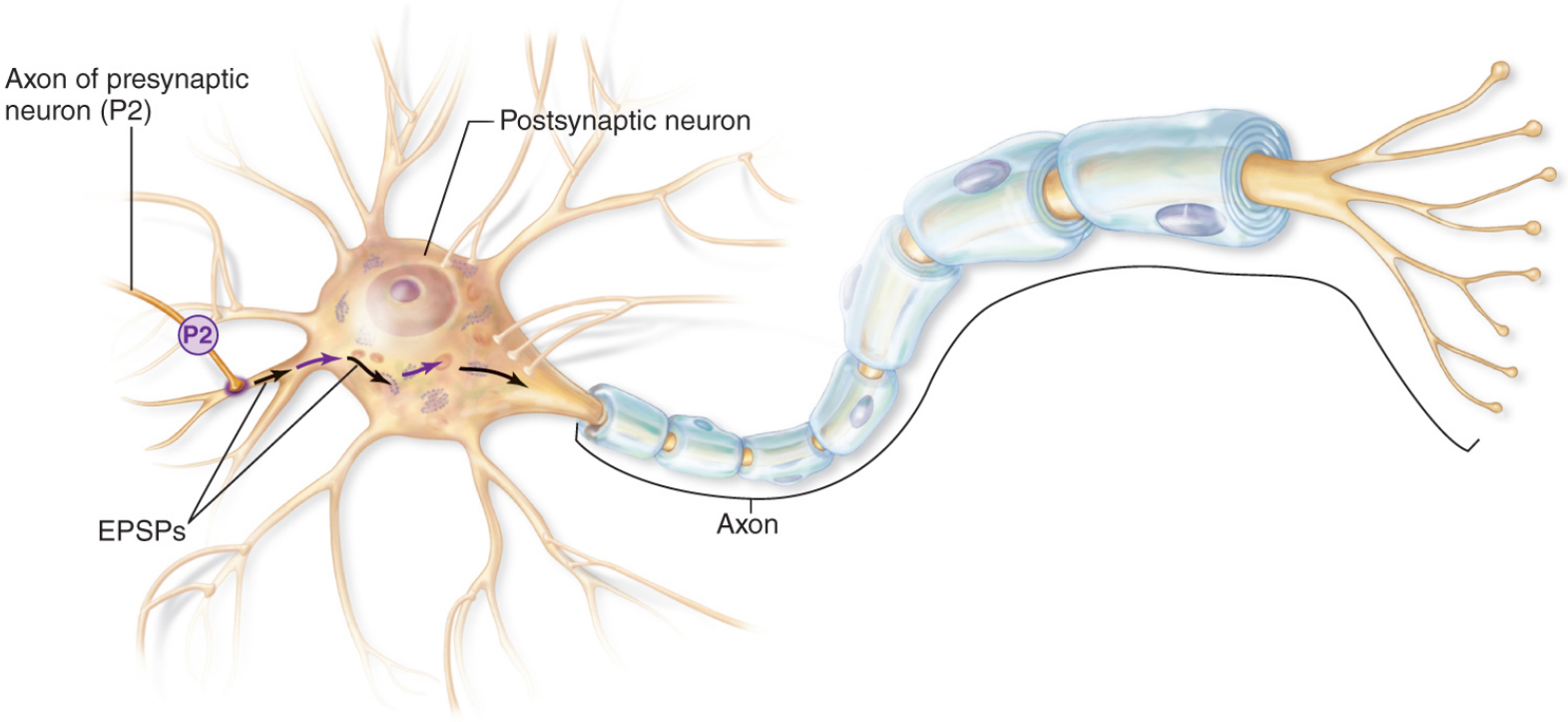


Figure 12.17b

(b) Temporal summation

12.8b Initial Segment

- **All or none law**
  - If threshold reached, action potential generated and propagated down axon without any loss in intensity
  - If threshold not reached, (stimulus is **subthreshold**), voltage-gated channels stay closed, no action potential
  - The axon shows same intensity of response to values greater than threshold
  - Similar to what occurs with a gun
    - With sufficient pressure on trigger, gun fired
    - With insufficient pressure on trigger, not fired
    - Firing is the same even if trigger squeezed very hard

12.8c Conductive Segment

- The axon conducts action potentials
- **Action potential** involves depolarization and repolarization
  - Depolarization is gain of positive charge as Na^+ enters through voltage-gated Na^+ channels
  - Repolarization is return to negative potential as K^+ exits through voltage-gated K^+ channels
- Action potential is propagated down axon to synaptic knob
  - Voltage-gated channels open sequentially down axolemma
  - Propagation is called an impulse or **nerve signal**

Generation of an Action Potential—Depolarization

Action potential: steps in depolarization

1. At RMP, voltage-gated channels are closed

2. As Na^+ enters from adjacent region, voltage-gated Na^+ channels open

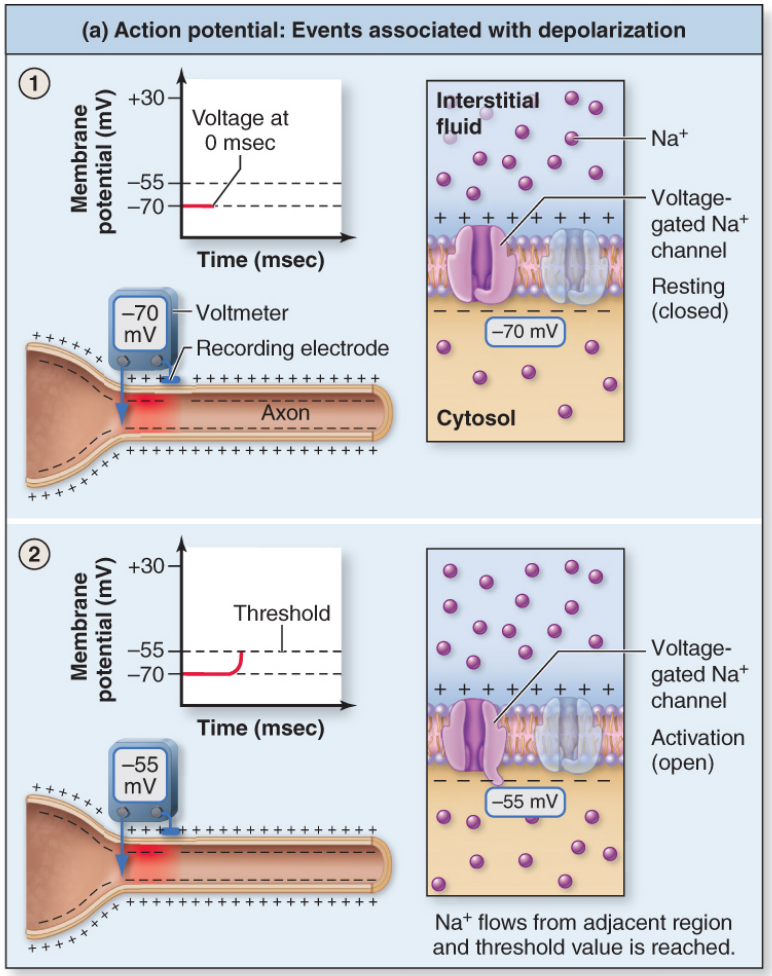


Figure 12.18a (part)

Generation of an Action Potential--Depolarization

Action potential: steps in depolarization (*continued*)

3.Na^+ enters the axon causing the membrane to have a positive potential

4.Na^+ channels close becoming inactive (unable to open) for a time

Steps 1–4 repeat in adjacent regions and the impulse moves toward synaptic knob

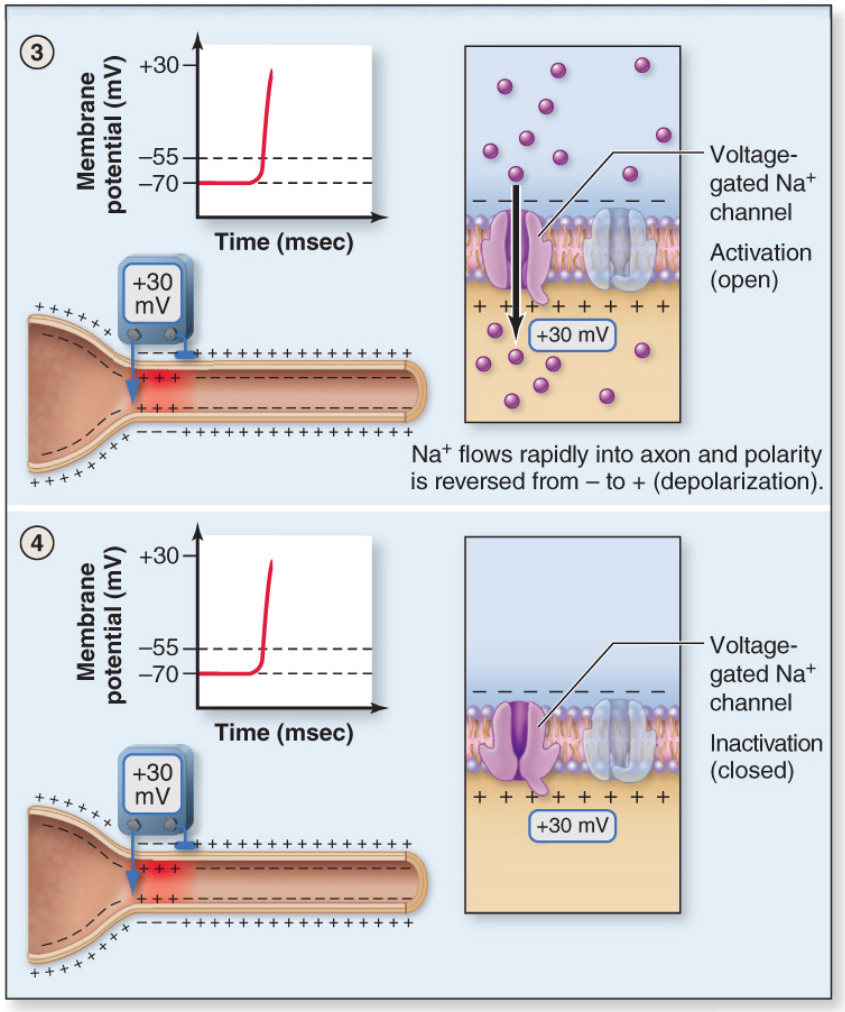


Figure 12.18a (part)

Generation of an Action Potential—Repolarization

Action potential: steps in repolarization

5. Depolarization slowly opens K^+ channels, and K^+ diffuses out, causing negative membrane potential

6. K^+ channels stay open for a longer time, so K+ exit makes cell more negative than RMP

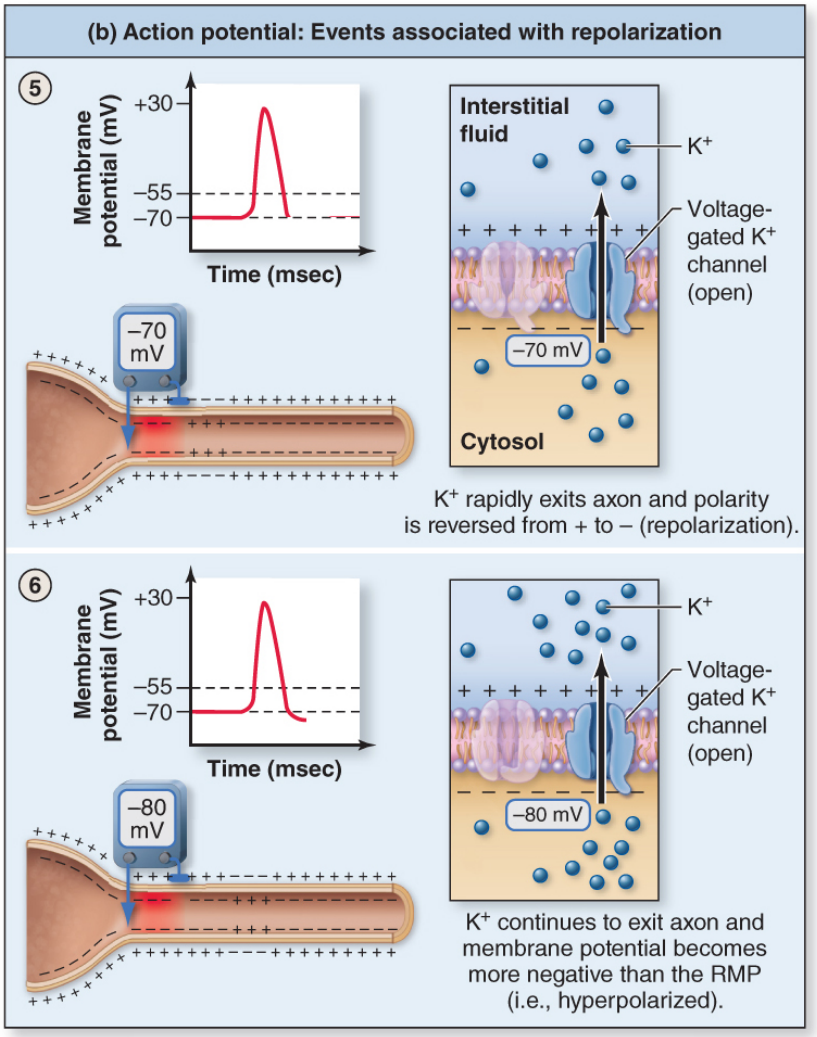


Figure 12.18b (part)

Generation of an Action Potential--Repolarization

Action potential: steps in repolarization (*continued*)

7.K+ channels eventually close and RMP is reestablished

Steps 5–7 repeat in adjacent regions as the impulse moves toward synaptic knob

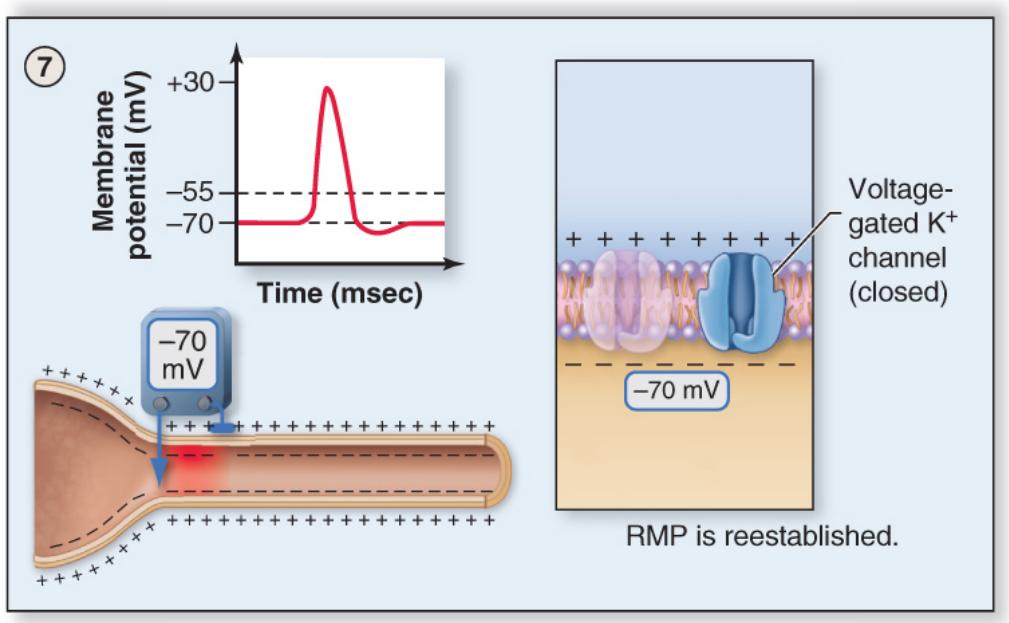
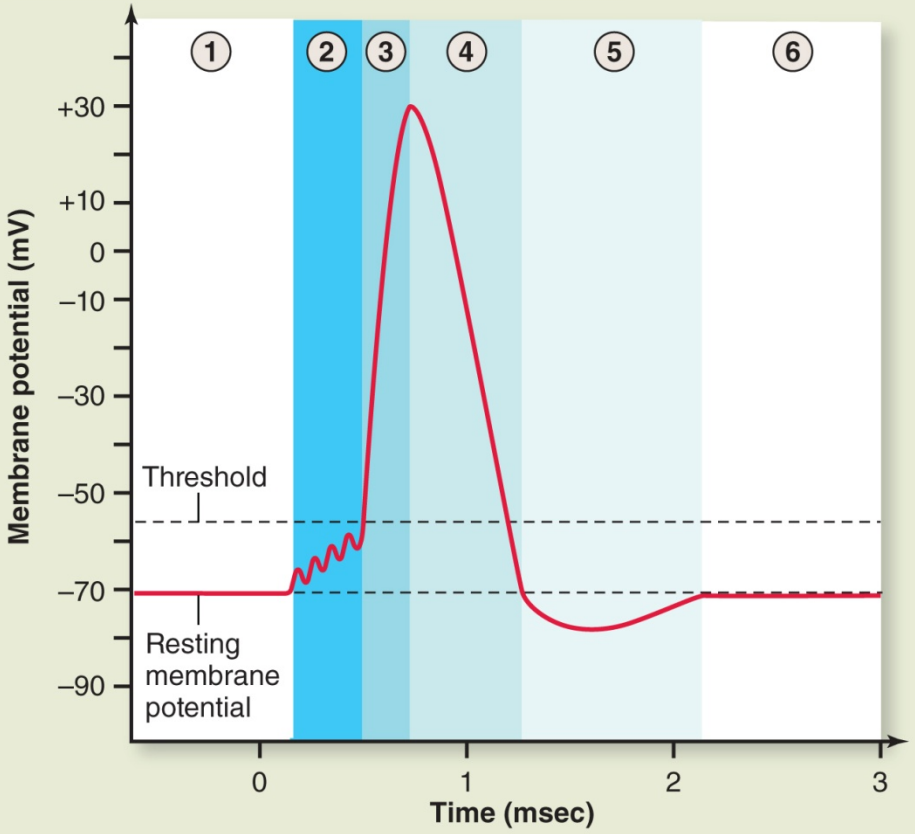


Figure 12.18b(part)

Events of an Action Potential



1. The unstimulated axon has a resting membrane potential of –70 mV.
2. Graded potentials reach the initial segment and are added together (–70 mV ➔ –55 mV).
3. **Depolarization** occurs when the threshold (–55 mV) is reached; voltage-gated Na^+ channels open and Na^+ enters rapidly, reversing the polarity from negative to positive (–55 mV ➔ +30 mV).
4. **Repolarization** occurs due to closure of voltage-gated Na^+ channels (inactivation state) and opening of voltage-gated K^+ channels. K^+ moves out of the cell and polarity is reversed from positive to negative (+30 mV ➔ –70 mV).
5. **Hyperpolarization** occurs when voltage-gated K^+ channels stay open longer than the time needed to reach the resting membrane potential; during this time the membrane potential is less than the resting membrane potential (–70 mV ➔ –80 mV).
6. Voltage-gated K^+ channels are closed, and the plasma membrane has returned to resting conditions by activity of Na^+/K^+ pumps (–80 mV ➔ –70 mV).

Figure 12.19

12.8c Conductive Segment

- Refractory period
  - Period of time after start of action potential when it is impossible or difficult to fire another action potential
  - **Absolute refractory period** (about 1 ms)
    - No stimulus can initiate another action potential
    - Na^+ channels are open, then inactivated
    - Ensures propagation goes toward synaptic knob; doesn't reverse direction
  - **Relative refractory period** (just after absolute)
    - Another action potential is possible (Na^+ channels have reset) but the minimum stimulus strength is now greater
    - Some K^+ channels are still open; cell is slightly hyperpolarized and further from threshold

12.8c Conductive Segment

- Continuous vs. saltatory conduction
  - **Continuous conduction** occurs on unmyelinated axons
    - Charge opens voltage-gated channels, which allows charge to enter, which spreads to adjacent region and opens more channels, sequentially

12.8c Conductive Segment

- Continuous vs. saltatory conduction (*continued*)
  - **Saltatory conduction** occurs on myelinated axons
    - Action potential occurs only at neurofibril nodes, which is where the axon's voltage-gated channels are concentrated
    - After Na^+ enters at a node it starts a rapid positive current down the inside of the axon's myelinated region
    - The current becomes weaker with distance, but still strong enough to open voltage-gated channels at the next node
    - Full action potential occurs at the node, and the process repeats: impulse seemingly jumping from node to node
    - Saltatory conduction is much faster than continuous conduction and myelinated cells use less ATP to maintain resting membrane potential

12.8d Transmissive Segment

- Activity at the synaptic knob
  - Arrival of action potential opens voltage-gated Ca^{2+} channels
    - Ca^{2+} diffuses into knob (Ca^{2+} pumps had established gradient)
  - Ca^{2+} binds to proteins associated with synaptic vesicles and triggers exocytosis
    - Vesicles fuse with membrane and neurotransmitter released into cleft
    - (Subsequently, transmitter binds to postsynaptic receptors)
    - Historically, it was believed that one neuron releases only one type of transmitter, but recent research indicates more options are possible

Transmissive Segment: Release of Neurotransmitter

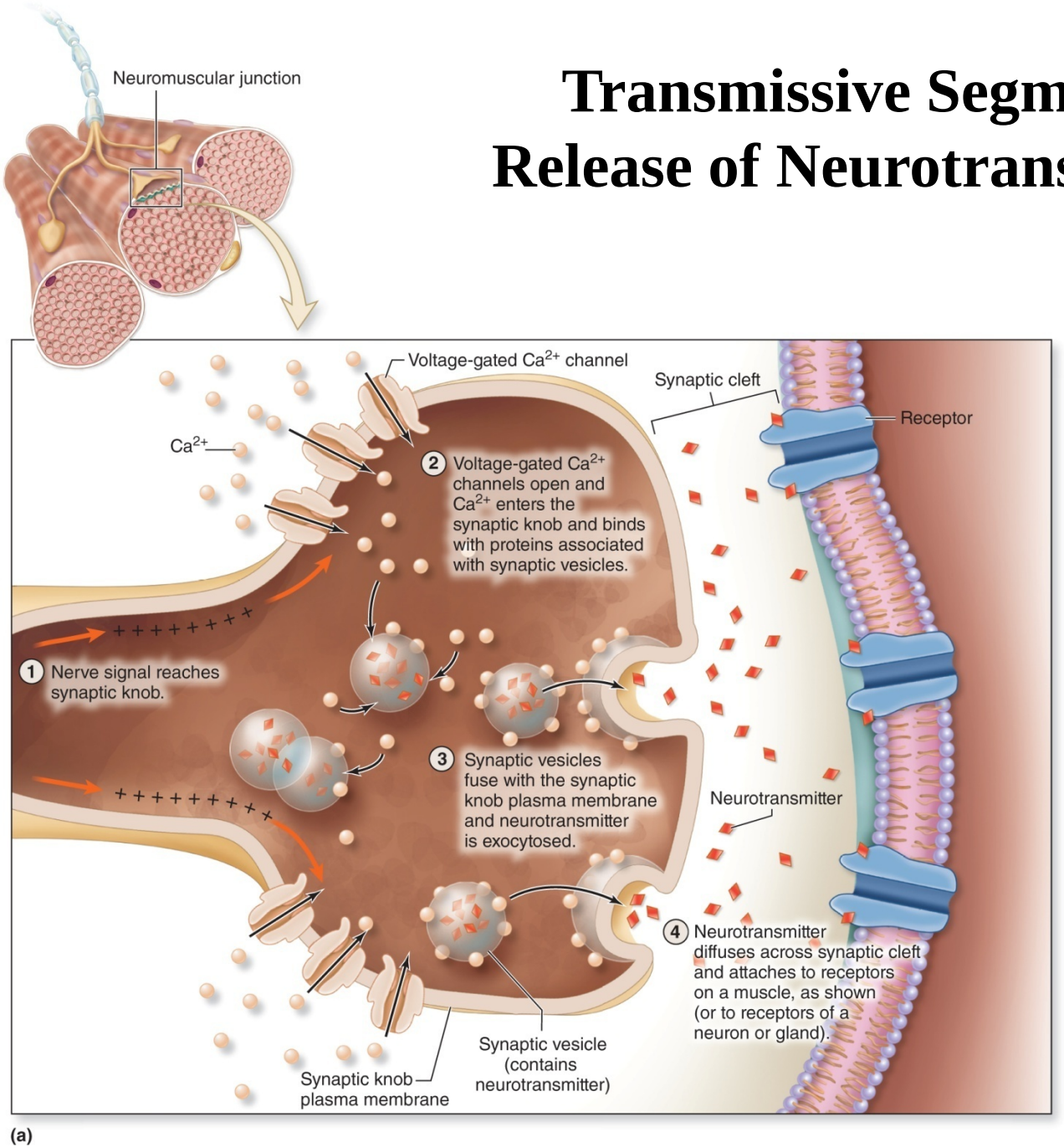


Figure 12.22a

Events of Neuron Physiology

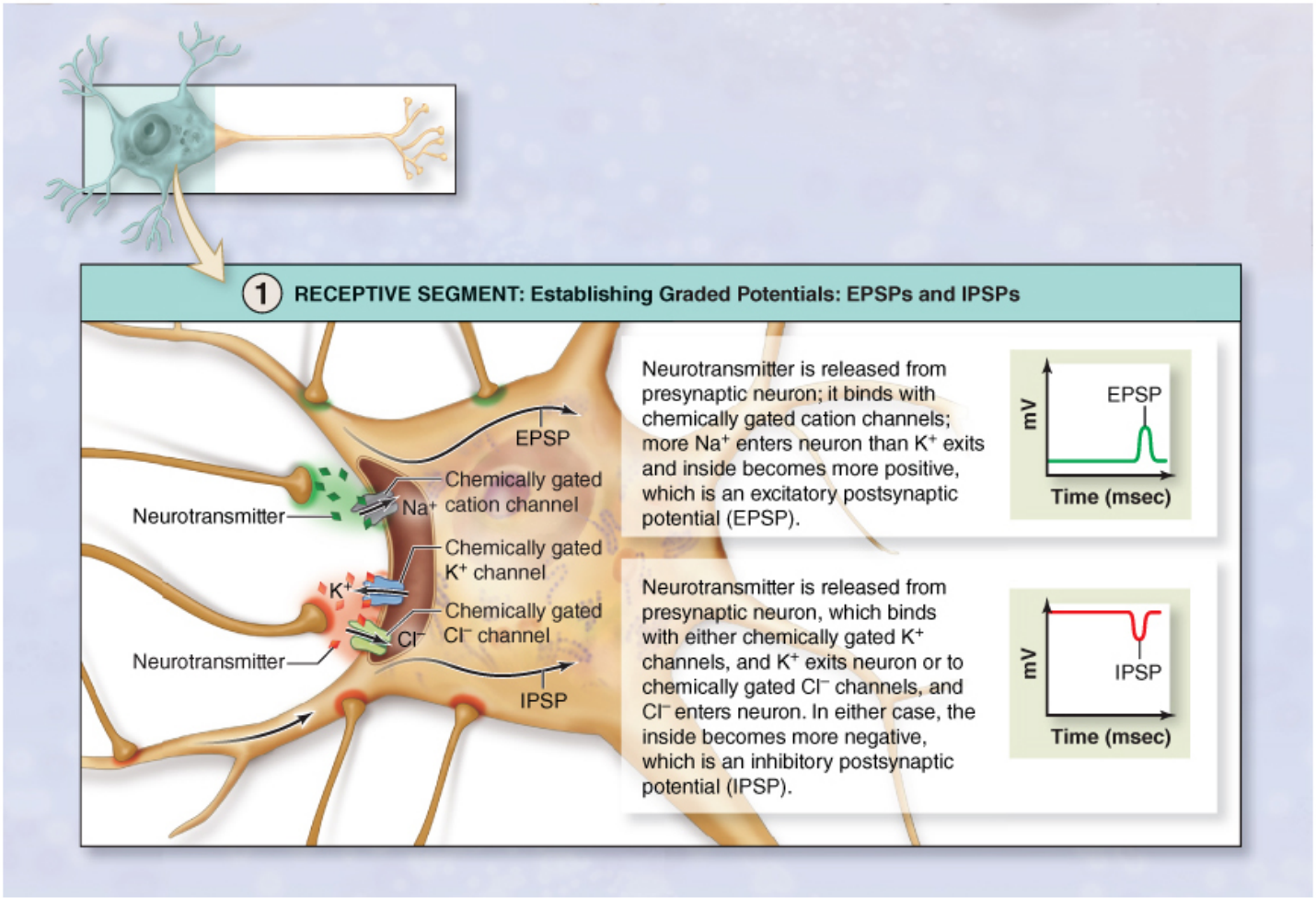


Figure 12.23, Panel 1

Events of Neuron Physiology

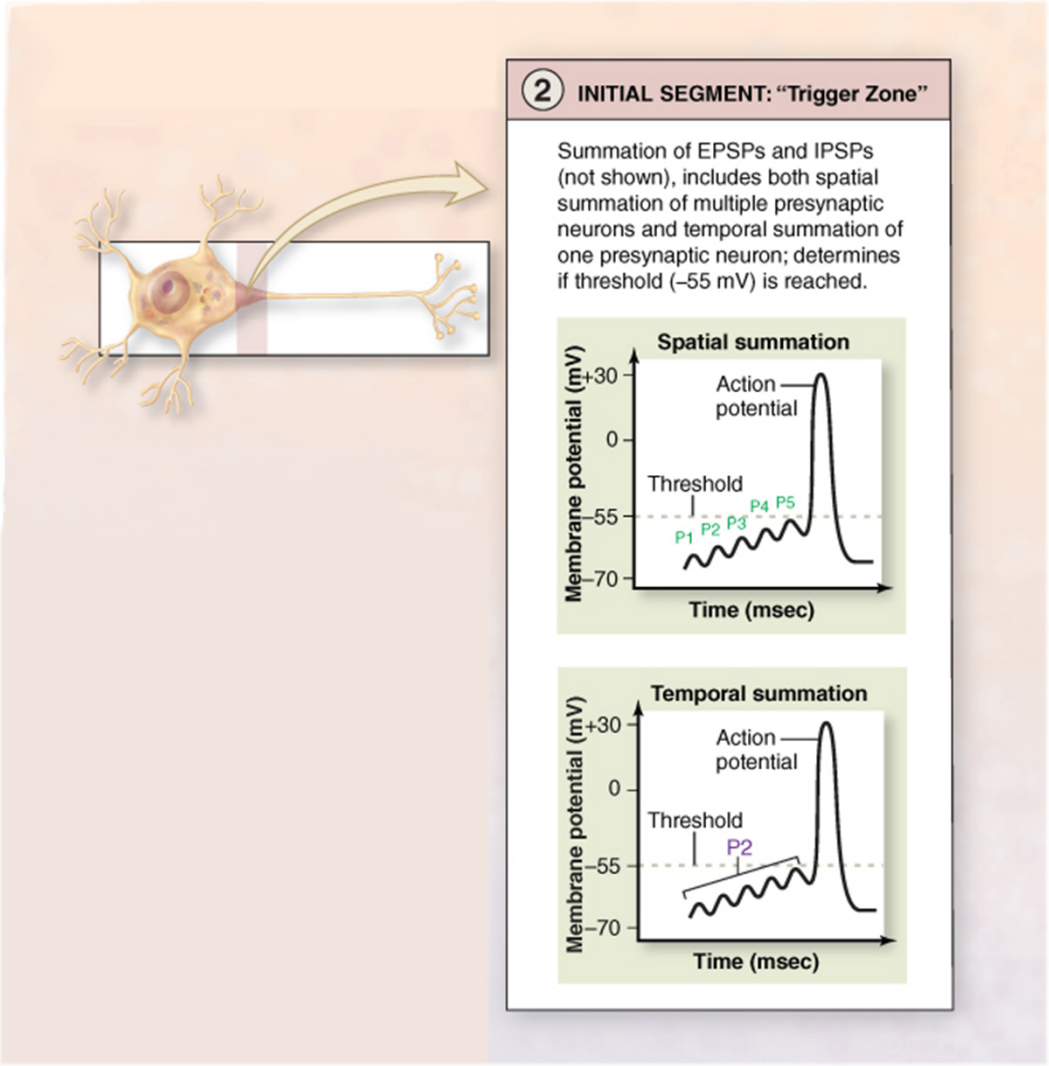


Figure 12.23, Panel 2

Events of Neuron Physiology

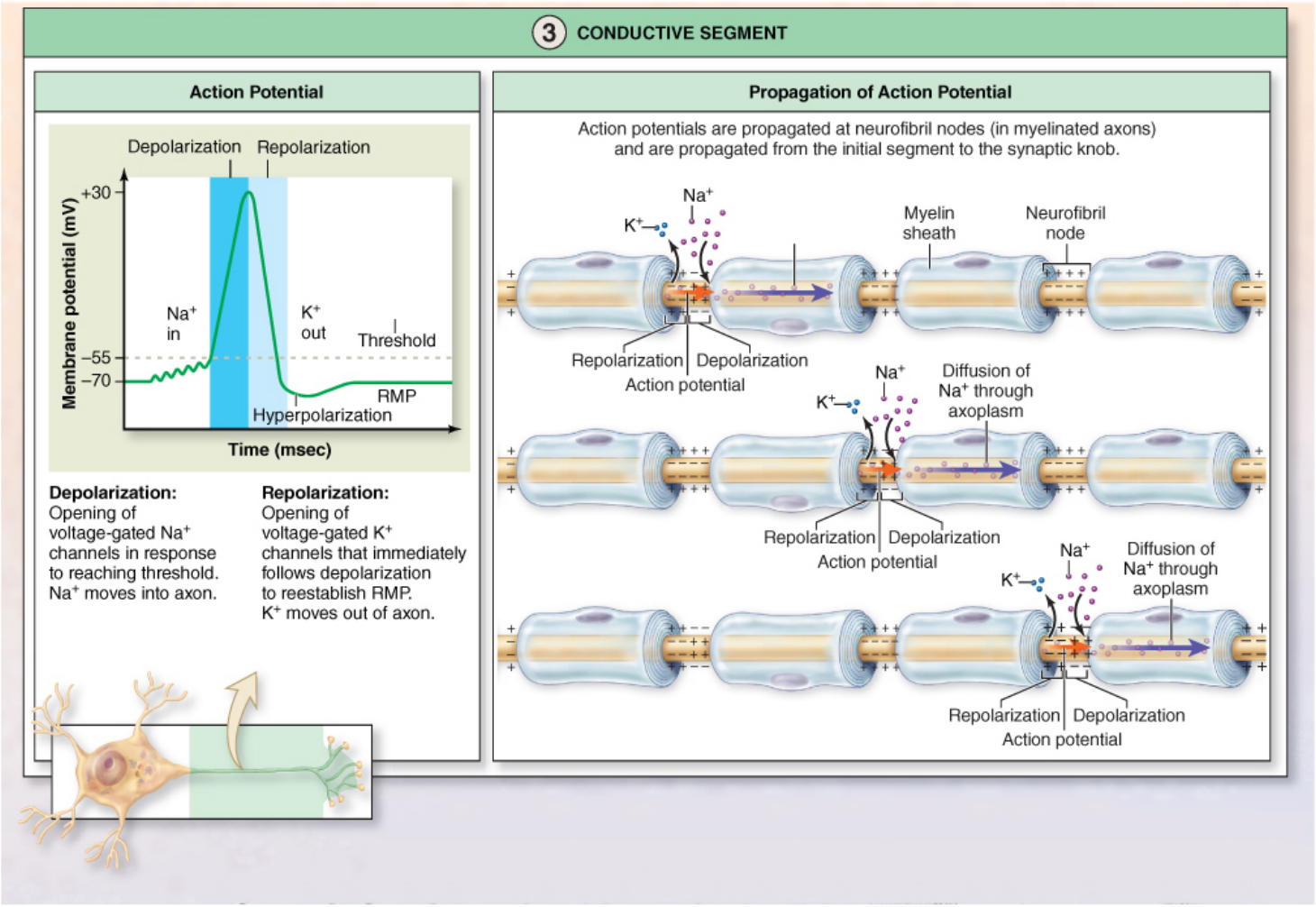


Figure 12.23, Panel 3

Events of Neuron Physiology

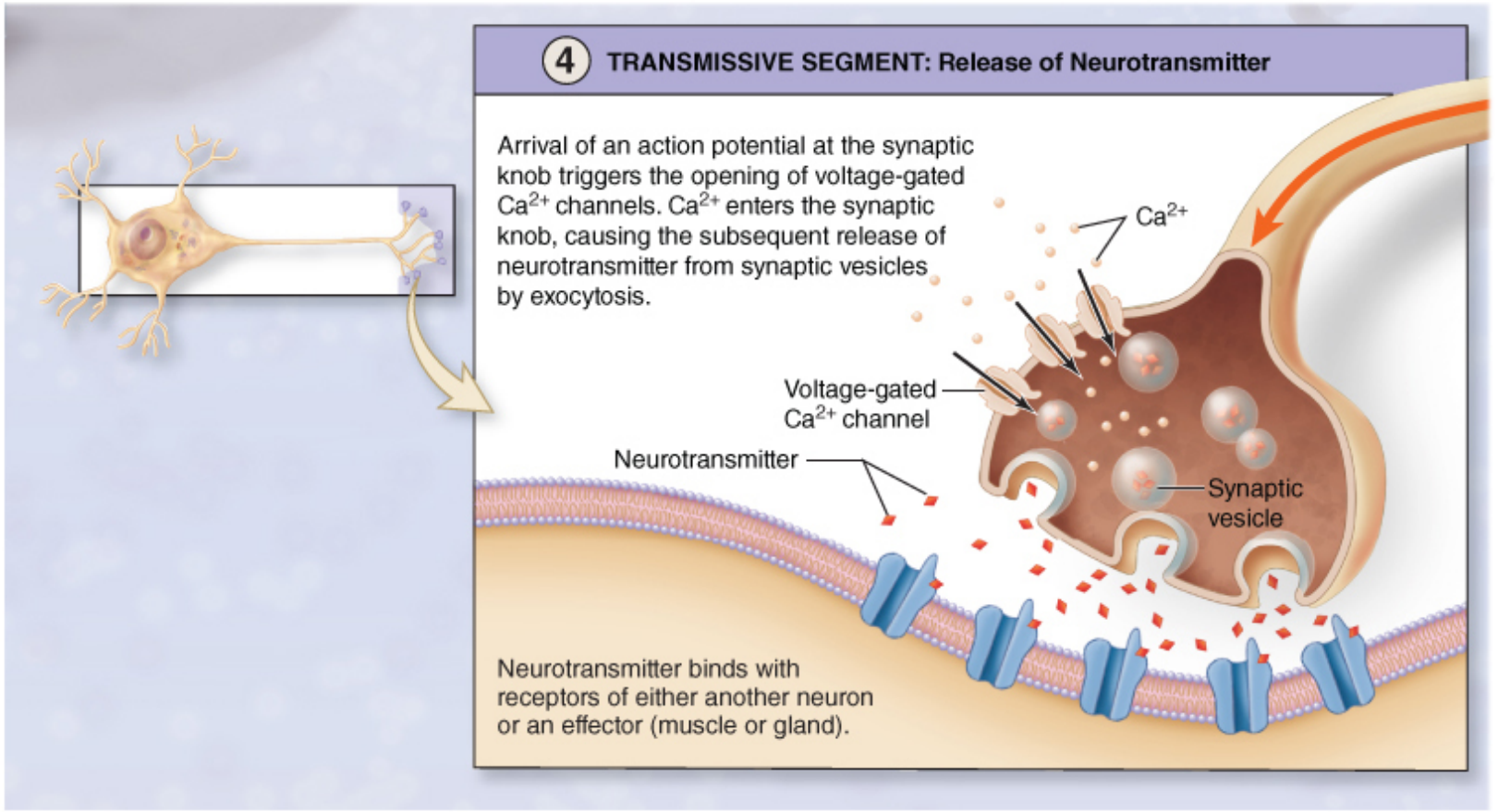


Figure 12.23, Panel 4

What did you learn?

- Where do postsynaptic potentials occur? How do EPSPs and IPSPs differ?
- What is typically required in order for a cell to reach threshold?
- What is the all or none law?
- How does the distribution of voltage-gated channels differ between myelinated and unmyelinated axons?

12.9 Characteristics of Action Potentials

Learning Objectives:

1. Compare graded potentials and action potentials.
2. Describe the two primary factors that influence the velocity of action potential propagation.
3. Identify the criteria used to distinguish the groups of nerve fibers.
4. Describe how action potentials vary in frequency.

12.9a Graded Potentials Versus Action Potentials

- **Graded potentials**
  - Occur in neuron's receptive region due to ion flow through chemically gated channels
  - Can be positive or negative changes in charge
  - Are graded: have larger potential change to stronger stimulus
  - Are local (travel only a short distance)
- **Action potentials**
  - Occur on neuron's conductive region (axon) due to ion flow through voltage-gated channels
  - Involve depolarization (Na^+ in) then repolarization (K^+ out)
  - Are all or none once threshold is reached
  - Propagate down entire axon to synaptic knob

12.9b Velocity of Action Potential Propagation

- Conduction speed depends on axon thickness and myelination
  - Thicker fibers conduct faster than thin ones
    - Thick axons offer less resistance to current flow down the axon
  - Myelinated fibers conduct much faster than unmyelinated ones
    - Current flow under myelin (between nodes) is very fast

12.9b Velocity of Action Potential Propagation

- Nerve fiber groups
  - Nerve fiber: an axon and its myelin sheath
  - Group A: conduction velocity as fast as 150 m/sec
    - Large diameter, myelinated fibers
    - E.g., most somatic sensory neurons; all somatic motor neurons
  - Group B conducts at 15 m/sec; Group C at 1 m/sec
    - Small diameter and/or unmyelinated
    - E.g., some visceral neurons; some somatic sensory neurons from skin

12.9c Frequency of Action Potentials

- Impulse frequency (action potentials per second) varies
  - Although impulse amplitude is constant, firing frequency varies with stimulus strength (up to a max)
  - Bright lights cause faster firing frequency on the optic nerve than dim lights
  - When motor nerves fire at faster frequency it causes muscle to generate more tension
  - For neurons that can use different transmitter, the firing frequency can influence the type of transmitter released

What did you learn?

- What does the word “graded” mean in the context of receptor potentials?
- Which have faster conduction velocity—thick or thin axons?
- Which group of nerve fibers (designated by letter) is the slowest conducting?

12.10 Neurotransmitters and Neuromodulation

Learning Objectives:

1. Identify the four classes of neurotransmitters based upon chemical structure.
2. Describe how neurotransmitters are classified based upon function.
3. Describe how acetylcholine functions as a neurotransmitter.
4. Discuss the different mechanisms for removing neurotransmitter from the synaptic cleft.
5. Define neuromodulation including its function in facilitation and inhibition.
6. Describe how nitric oxide and endocannabinoids function as neuromodulators.

12.10a Classification of Neurotransmitters

- What are neurotransmitters?
  - Small organic compounds synthesized by neurons
  - Stored in vesicles in synaptic knobs
  - Released by exocytosis when action potential triggers calcium entry into knob
  - Trigger a physiologic response in target cell
  - Approximately 100 different ones have been named and classified into groups

12.10a Classification of Neurotransmitters

- Four main chemical classes of neurotransmitters
  - **Acetylcholine**
    - Structure differs substantially from other transmitters
  - **Biogenic amines** (*monoamines*)
    - An amino acid is slightly modified to synthesize the transmitter
    - **Catecholamines** (e.g., dopamine) are made from tyrosine
    - **Indolamines** (e.g., seratonin) are made from histidine or tryptophan
  - **Amino acids**
    - Include common transmitters glutamate, glycine, GABA
  - **Neuropeptides**
    - Chains of amino acids (2 to 40 amino acids long) including endorphins, substance P

12.10a Classification of Neurotransmitters

- Neurotransmitters are also classified by function
- Classes by effect
  - **Excitatory** transmitters cause EPSPs; **inhibitory** transmitters cause IPSPs
    - But some transmitters can excite some targets and inhibit others depending on target cells' receptors
- Classes by action
  - **Direct** transmitters bind to receptors that are chemically gated channels (immediate postsynaptic potential)
  - **Indirect** transmitters bind to receptors that involve G-proteins and second messengers in order to cause postsynaptic potential

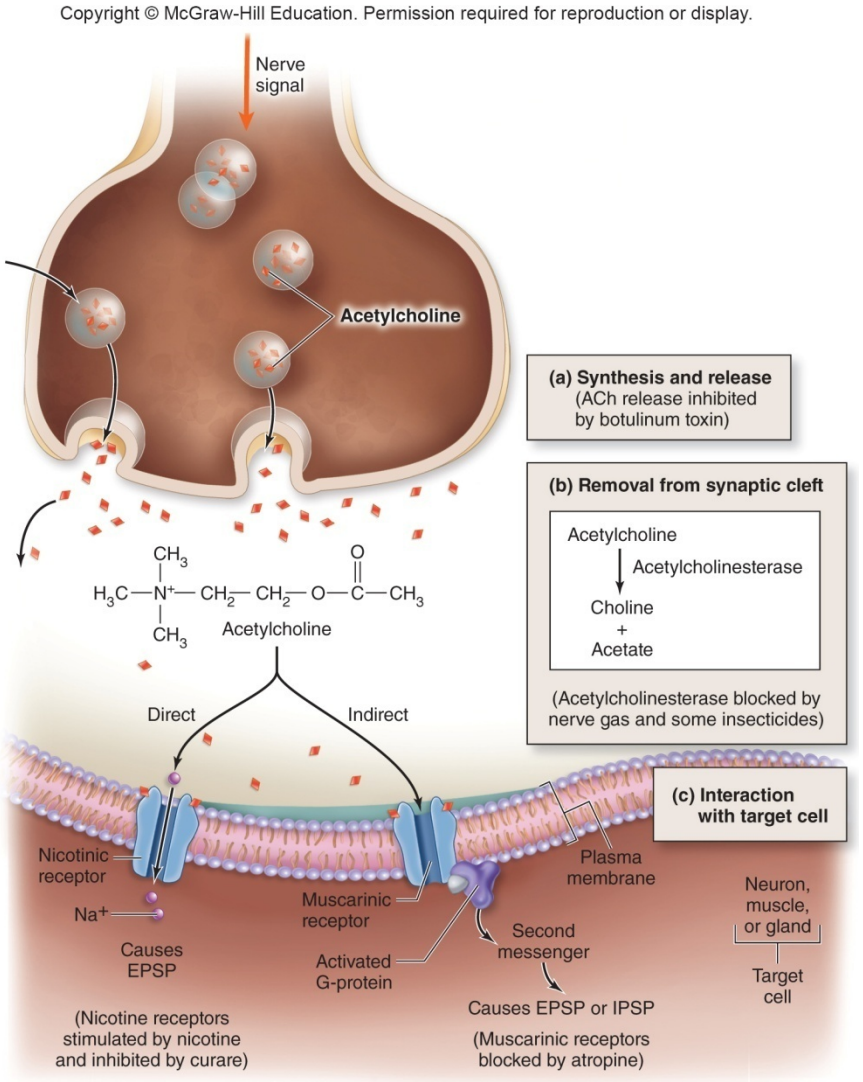
12.10b Features of Neurotransmitters

- Acetylcholine (ACh) is the best characterized transmitter
  - Used in PNS to stimulate skeletal muscle; used in the CNS to increase arousal
  - Synthesized from acetate and choline; stored in synaptic vesicles
  - Action potential triggers its release into cleft
  - Some ACh attaches (briefly) to postsynaptic receptor
  - ACh is cleared from cleft by being broken down to acetate and choline by acetylcholinesterase
  - Acetate and choline are taken up by presynaptic cell for recycling

12.10b Features of Neurotransmitters

- Removal of neurotransmitter from the synaptic cleft can occur in varied ways
  - Enzymes might degrade transmitter
  - Presynaptic transporters might import transmitter (“reuptake”)
  - Some transmitter diffuses away from synapse, reabsorbed by glia
- Some drugs have their effect by influencing transmitter removal
  - E.g., selective serotonin reuptake inhibitors treat depression
  - E.g., galantamine hydrobromide is an acetylcholinesterase inhibitor used to treat Alzheimer disease

Ach Release, Removal from Synaptic Cleft, and Action



- ACh effect on target cell depends on receptor
  - **Nicotinic receptor** directly causes EPSP
  - **Muscarinic receptor** engages G protein and 2nd messenger
    - Indirectly leads to either EPSP or IPSP

Figure **12.25**

12.10c Neuromodulation

- **Neuromodulators—**chemicals that alter responses of local neurons
- Modulation
  - **Facilitation**
    - Modulation that causes greater response in postsynaptic neuron
    - May increase amount of neurotransmitter in cleft or number of postsynaptic receptors
  - **Inhibition**
    - Modulation that causes weaker response
    - May decrease amount of neurotransmitter in cleft or number of postsynaptic receptors

12.10c Neuromodulation

- **Nitric oxide**
  - Might be a transmitter or a modulator
  - Is a short-lived, nonpolar gas
  - Made and released by postsynaptic neurons in brain where it is believed to strengthen memory by affecting presynaptic cells
  - Effects in the PNS include blood vessel dilation
- **Endocannabinoids**
  - Influence same receptors that marijuana does
  - Small, nonpolar molecules
  - Made and released by postsynaptic neurons
  - Have effects on presynaptic transmitter release
  - Influence memory, appetite

What did you learn?

- What structural category does dopamine fit into?
- How do indirect neurotransmitters influence their target cells?
- How is ACh cleared from the synaptic cleft?
- How might a neuromodulator inhibit neurotransmission?

12.11 Neural Integration and Neuronal Pools of the CNS

Learning Objectives:

1. Identify the four different types of neuronal pools, and explain how they function.

12.11 Neural Integration and Neuronal Pools of the CNS

- **Neuronal pools** (*neuronal circuits*)
  - Groups of neurons arranged in specific patterns
  - Four types of circuits
    - Converging
    - Diverging
    - Reverberating
    - Parallel-after-discharge
  - Pool may be localized or distributed in several regions of CNS

Neuronal Pools

- Types of circuits
  - **Converging circuit**
    - Input converges at a single postsynaptic neuron
    - E.g., multiple sensory inputs synapse on neurons in the salivary nucleus. Sights, sounds, and smells of cooking lead to one output: salivation.

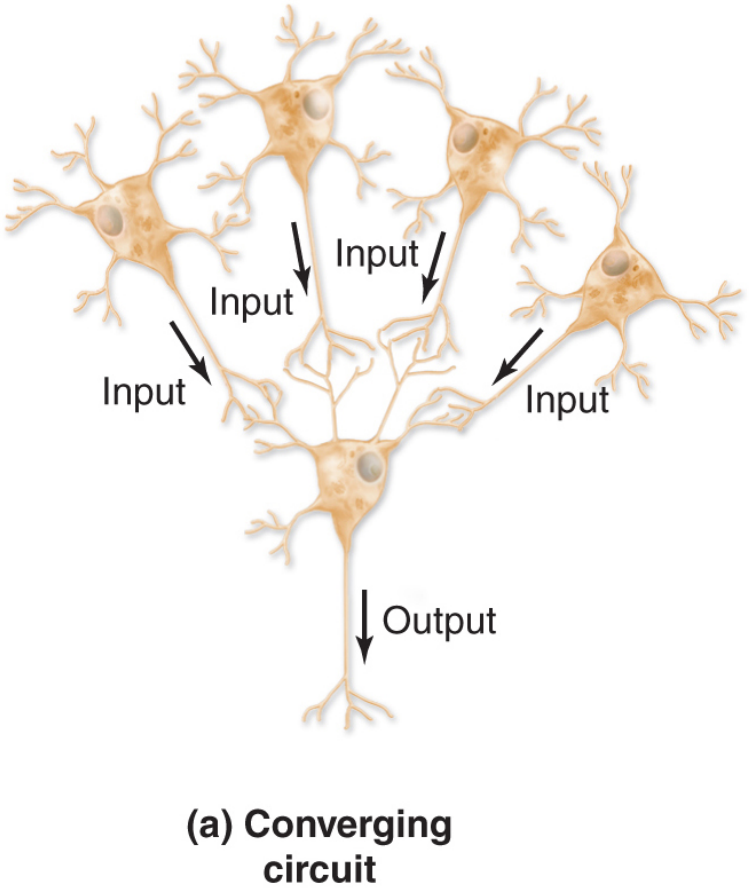
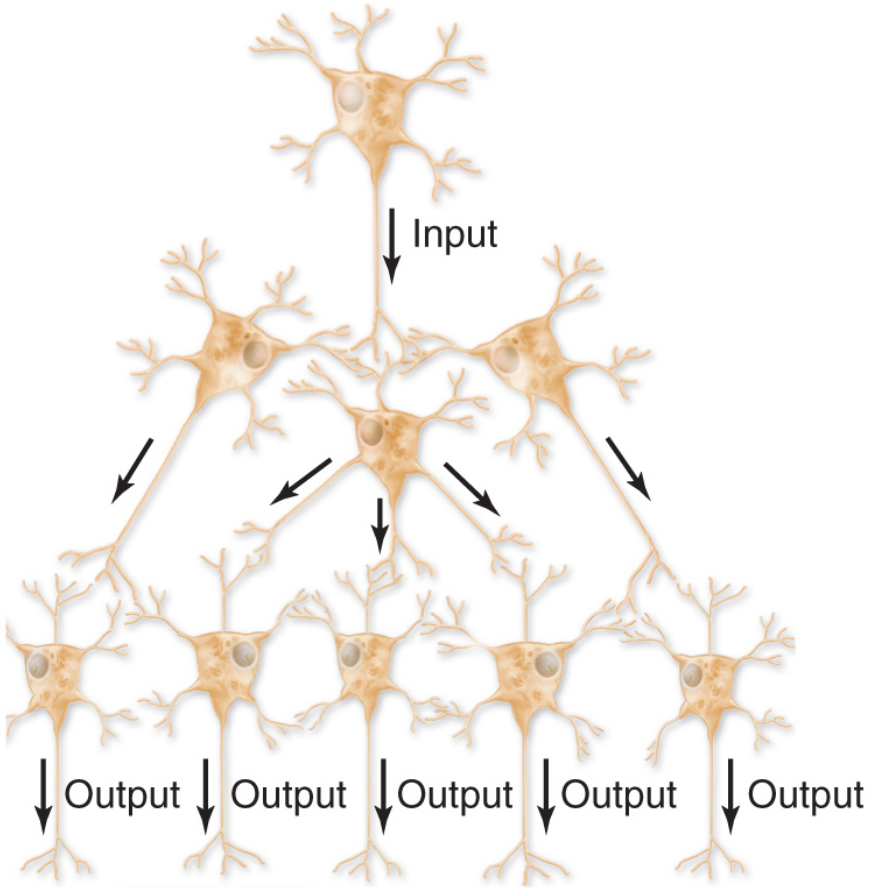


Figure 12.26a

Neuronal Pools

- Types of circuits (*continued*)
  - **Diverging circuit**
    - Spreads information from one presynaptic neuron to several postsynaptic neurons
    - E.g., neurons in the brain that control walking send commands to several different muscles for proper balance, posture, and motion

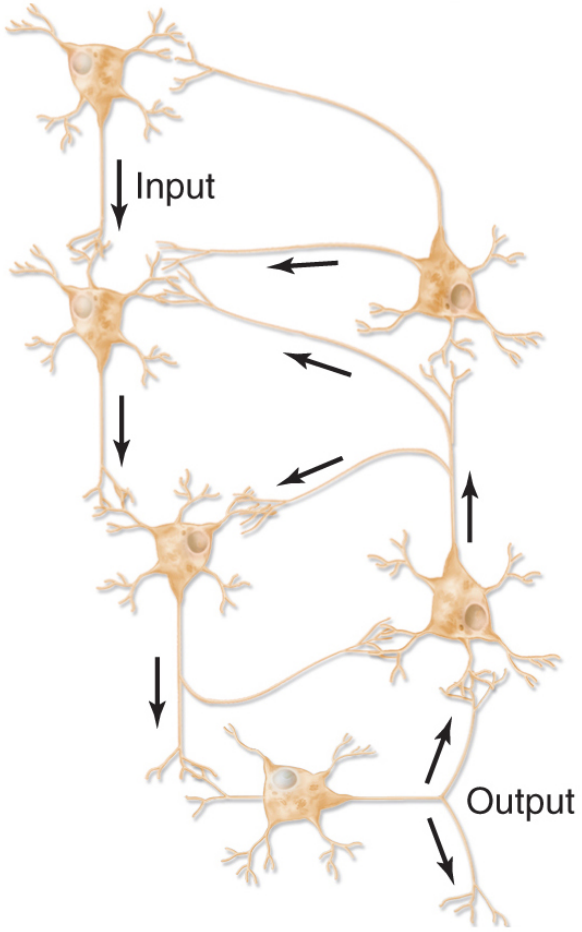


(b) Diverging circuit

Figure 12.26b

Neuronal Pools

- Types of circuits (*continued*)
  - **Reverberating circuits**
    - Use feedback to produce repeated, cyclical activity
    - Once started, it stays active until there is an inhibitory stimulus or synaptic fatigue
    - E.g., circuits that keep us breathing regularly during sleep

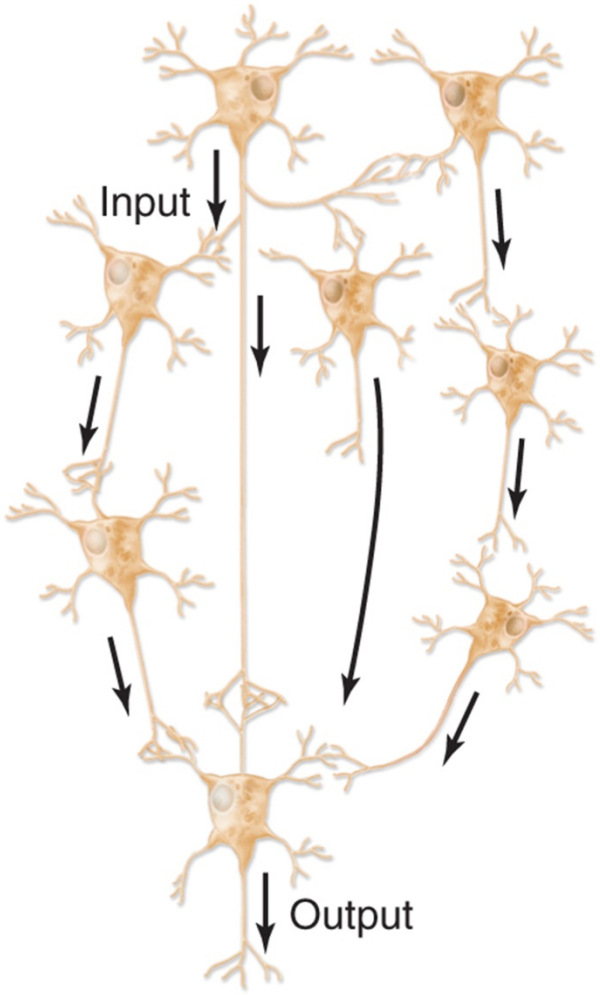


(c) Reverberating circuit

Figure 12.26c

Neuronal Pools

- Types of circuits (*continued*)
  - **Parallel-after-discharge circuits**
    - Input transmitted simultaneously along several paths to a postsynaptic cell
    - Since paths vary in number of synapses, signal arrives at postsynaptic cell at various times
    - Believed to be involved in higher-order thinking



(d) Parallel-after-discharge circuit

Figure 12.26d

What did you learn?

- What type of circuit involves a small number of presynaptic neurons communicating with a large number of postsynaptic neurons?