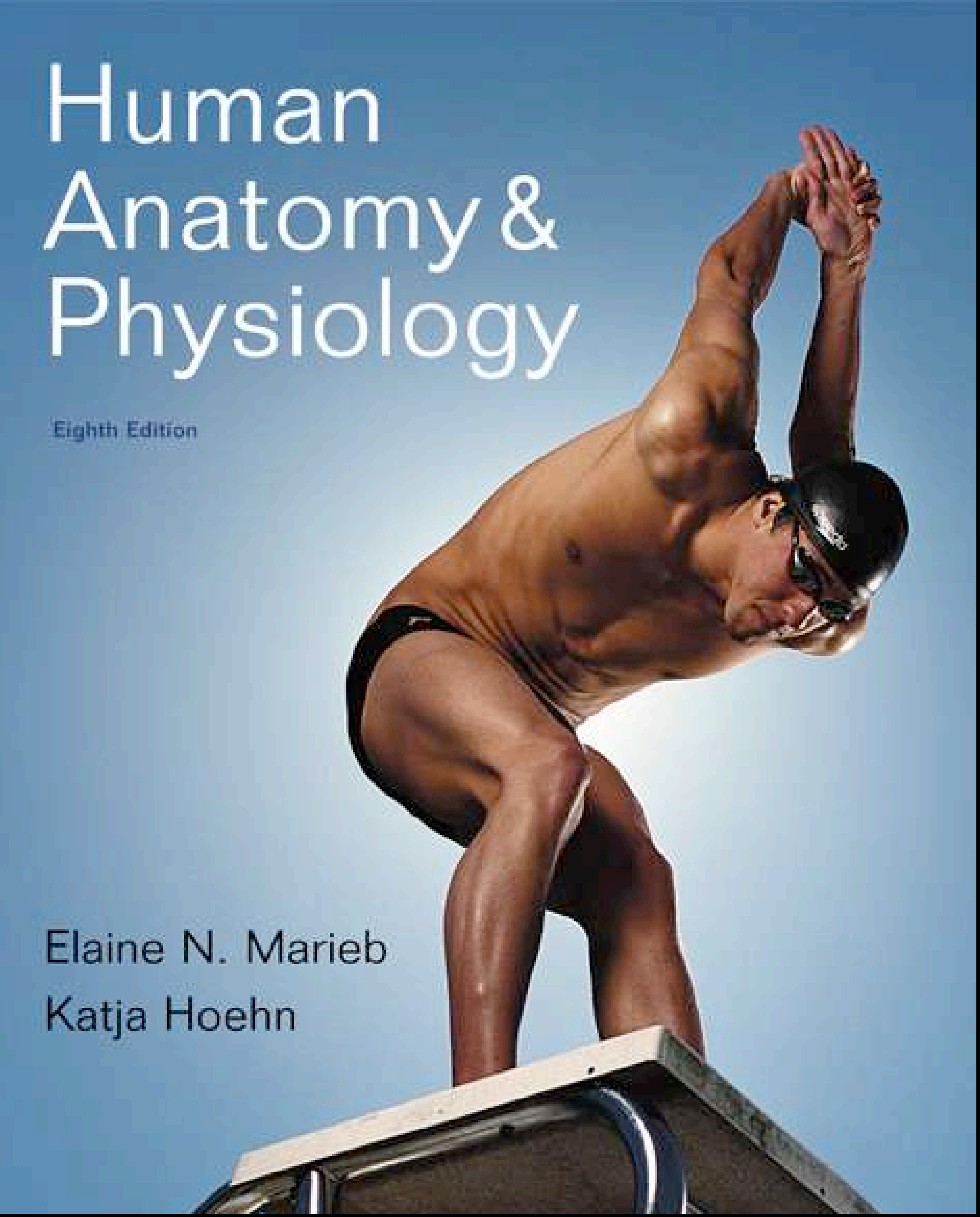

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PowerPoint® Lecture Slides
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Janice Meeking,
Mount Royal College

CHAPTER 11

Fundamentals of the Nervous System and Nervous Tissue: Part C

The Synapse

- A junction that mediates information transfer from one neuron:
  - To another neuron, or
  - To an effector cell

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The Synapse

- Presynaptic neuron—conducts impulses toward the synapse
- Postsynaptic neuron—transmits impulses away from the synapse

PLAY **Animation: Synapses**

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Types of Synapses

- Axodendritic—between the axon of one neuron and the dendrite of another
- Axosomatic—between the axon of one neuron and the soma of another
- Less common types:
  - Axoaxonic (axon to axon)
  - Dendrodendritic (dendrite to dendrite)
  - Dendrosomatic (dendrite to soma)

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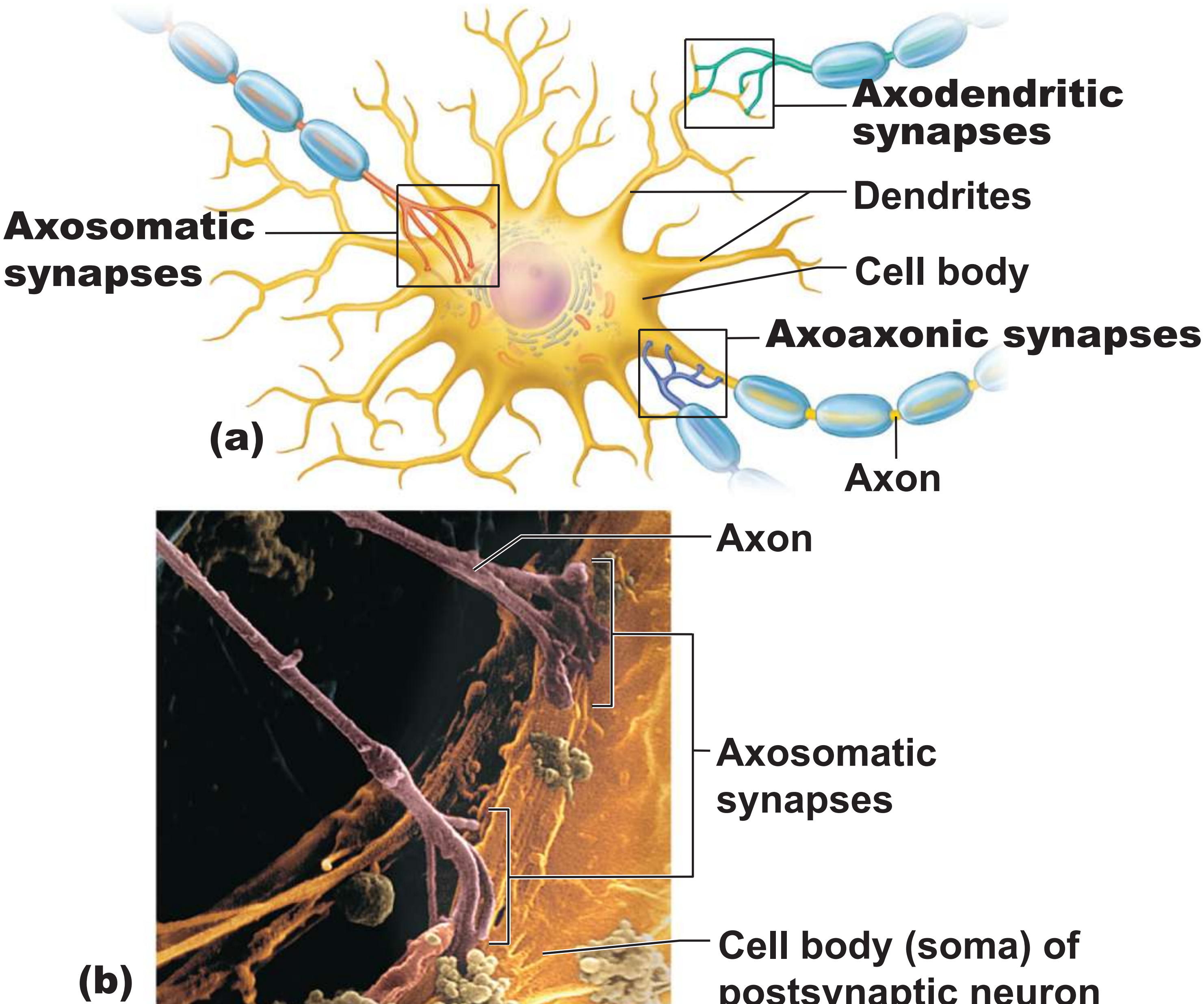

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Figure 11.16

Electrical Synapses

- Less common than chemical synapses
  - Neurons are electrically coupled (joined by gap junctions)
  - Communication is very rapid, and may be unidirectional or bidirectional
  - Are important in:
    - Embryonic nervous tissue
    - Some brain regions

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Chemical Synapses

- Specialized for the release and reception of neurotransmitters
- Typically composed of two parts
  - Axon terminal of the presynaptic neuron, which contains synaptic vesicles
  - Receptor region on the postsynaptic neuron

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Synaptic Cleft

- Fluid-filled space separating the presynaptic and postsynaptic neurons
- Prevents nerve impulses from directly passing from one neuron to the next
- Transmission across the synaptic cleft:
  - Is a chemical event (as opposed to an electrical one)
  - Involves release, diffusion, and binding of neurotransmitters
  - Ensures unidirectional communication between neurons

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Information Transfer

- AP arrives at axon terminal of the presynaptic neuron and opens voltage-gated Ca^{2+} channels
- Synaptotagmin protein binds Ca^{2+} and promotes fusion of synaptic vesicles with axon membrane
- Exocytosis of neurotransmitter occurs

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Information Transfer

- Neurotransmitter diffuses and binds to receptors (often chemically gated ion channels) on the postsynaptic neuron
- Ion channels are opened, causing an excitatory or inhibitory event (graded potential)

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Chemical synapses transmit signals from one neuron to another using neurotransmitters.

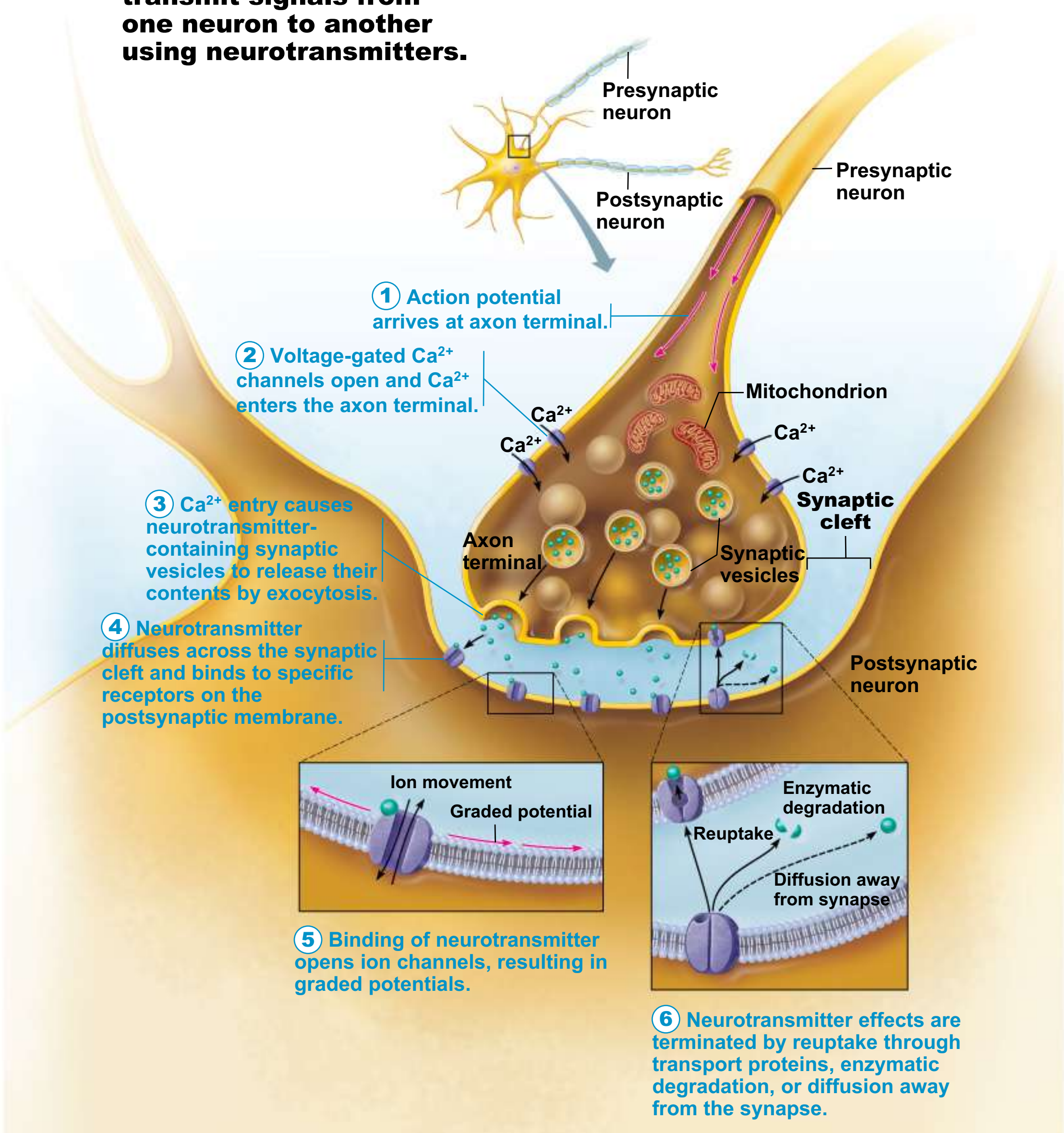

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Figure 11.17

Chemical synapses transmit signals from one neuron to another using neurotransmitters.

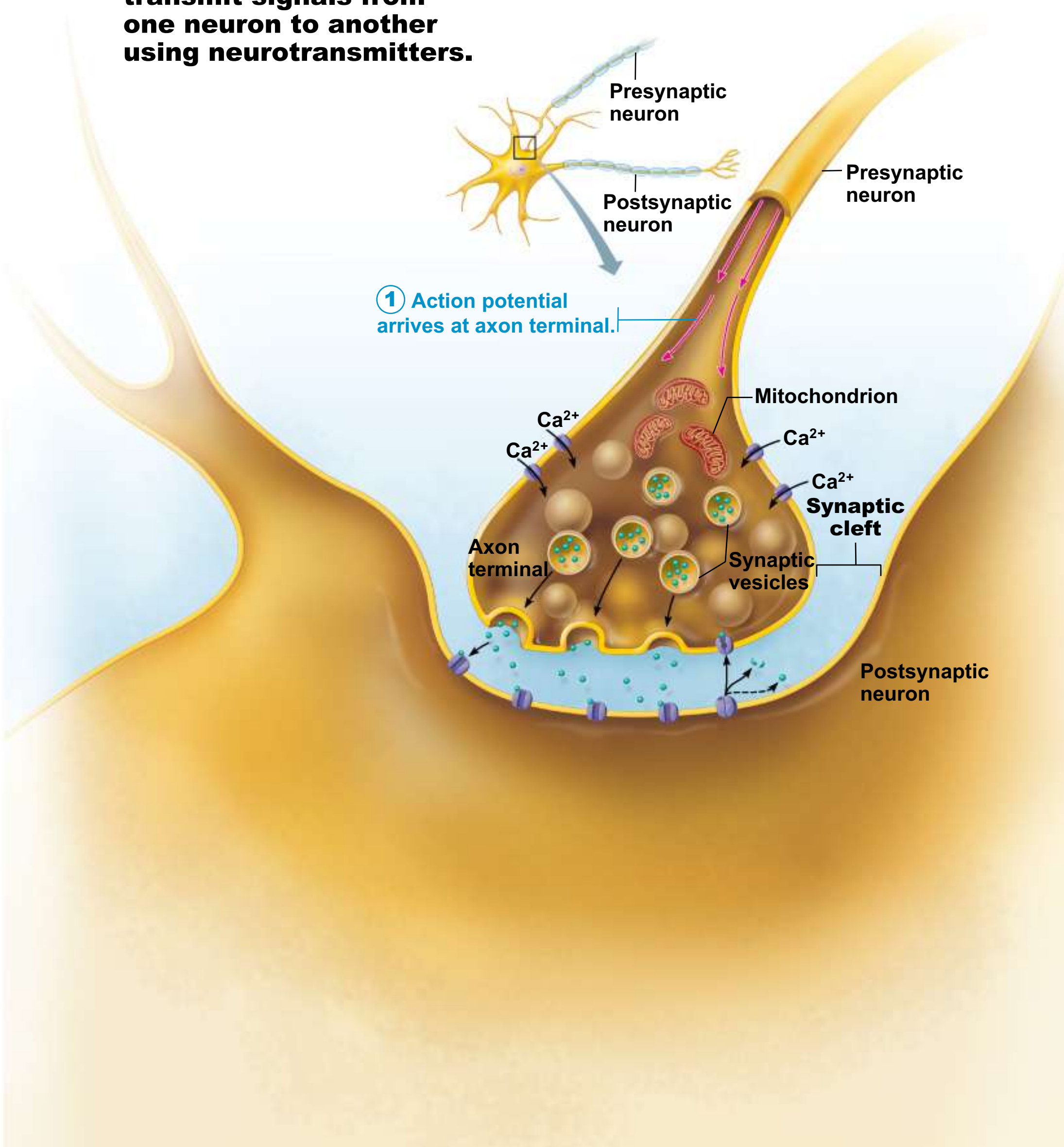

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Figure 11.17, step 1

Chemical synapses transmit signals from one neuron to another using neurotransmitters.

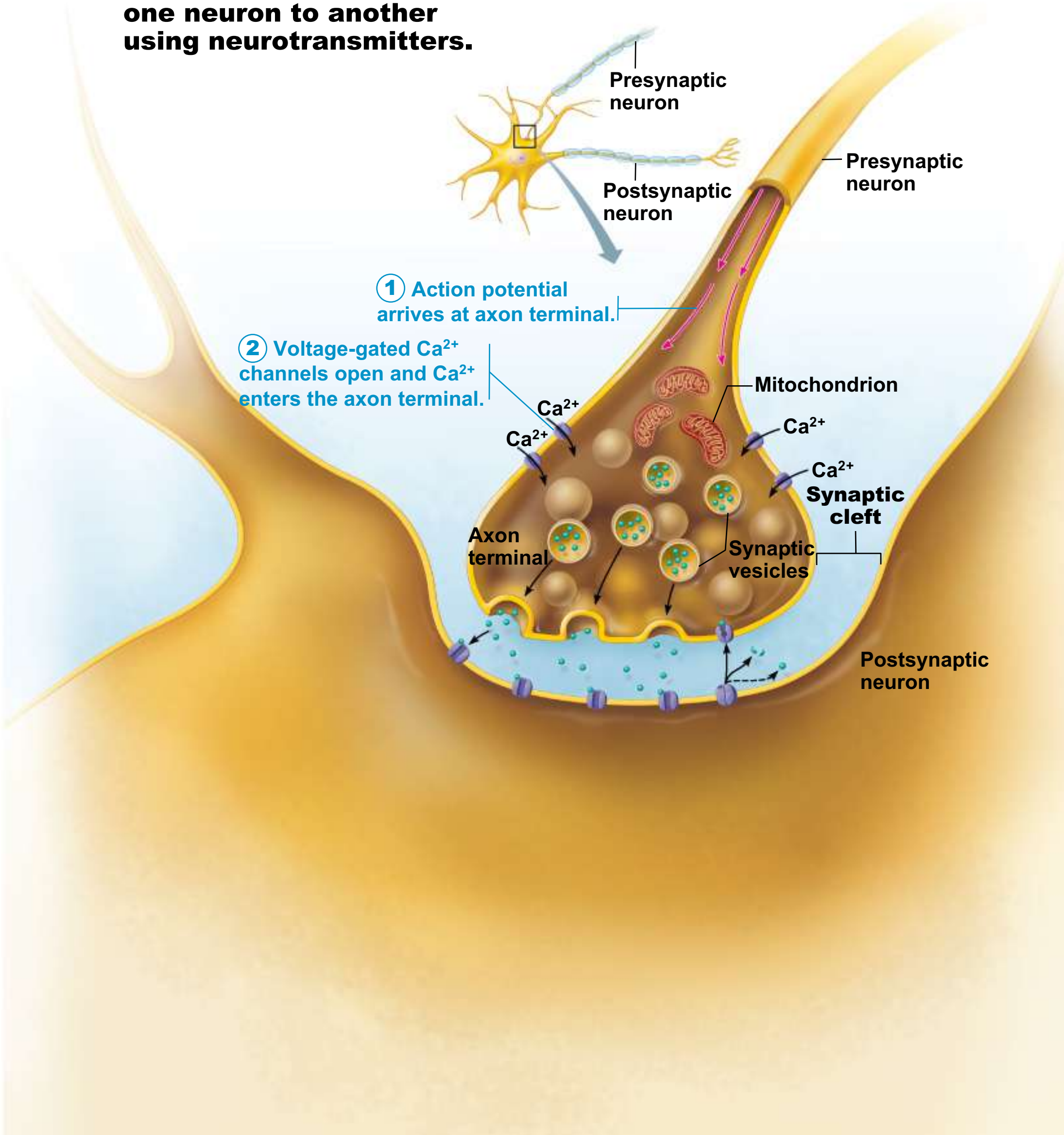

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Figure 11.17, step 2

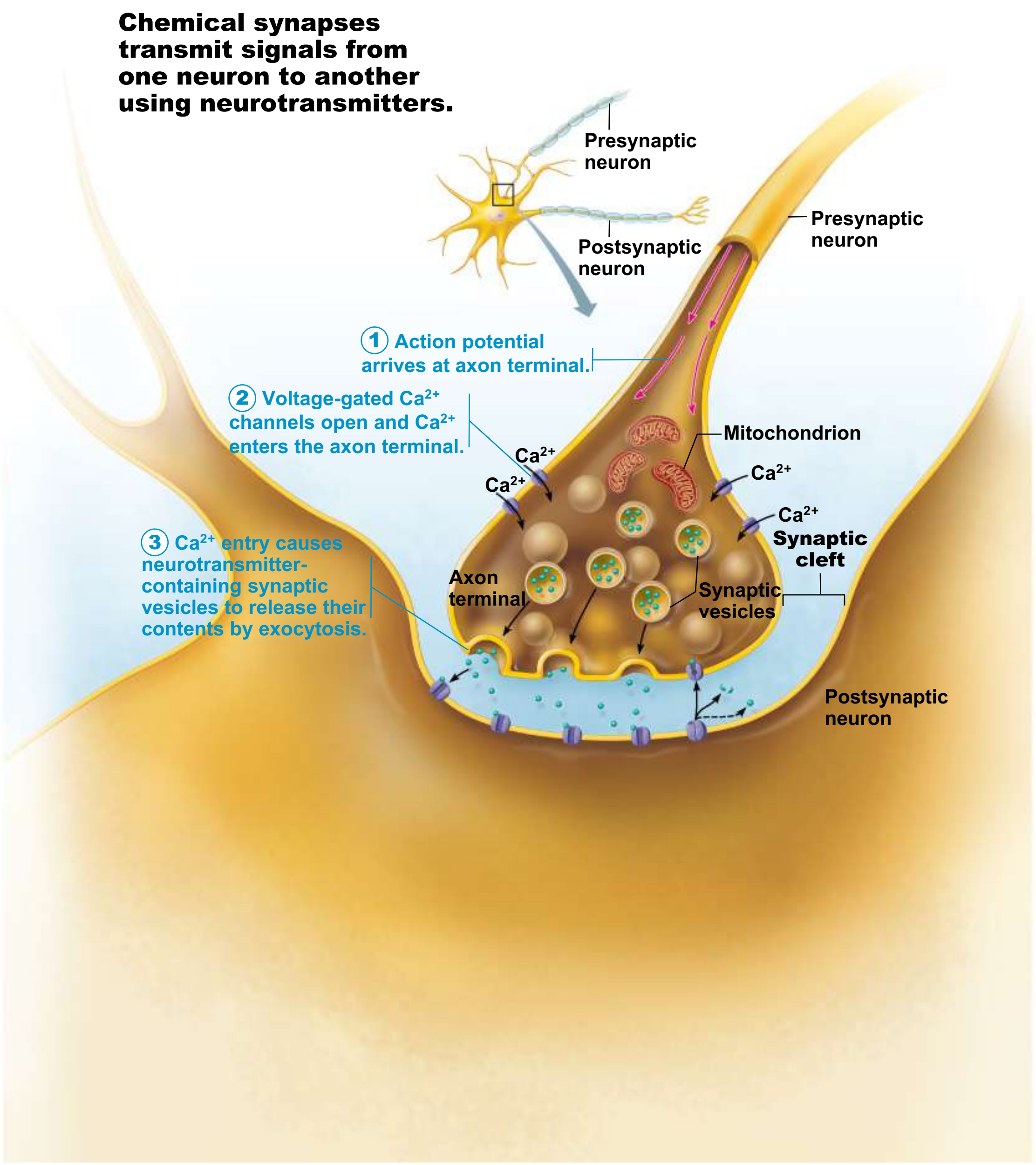

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Figure 11.17, step 3

Chemical synapses transmit signals from one neuron to another using neurotransmitters.

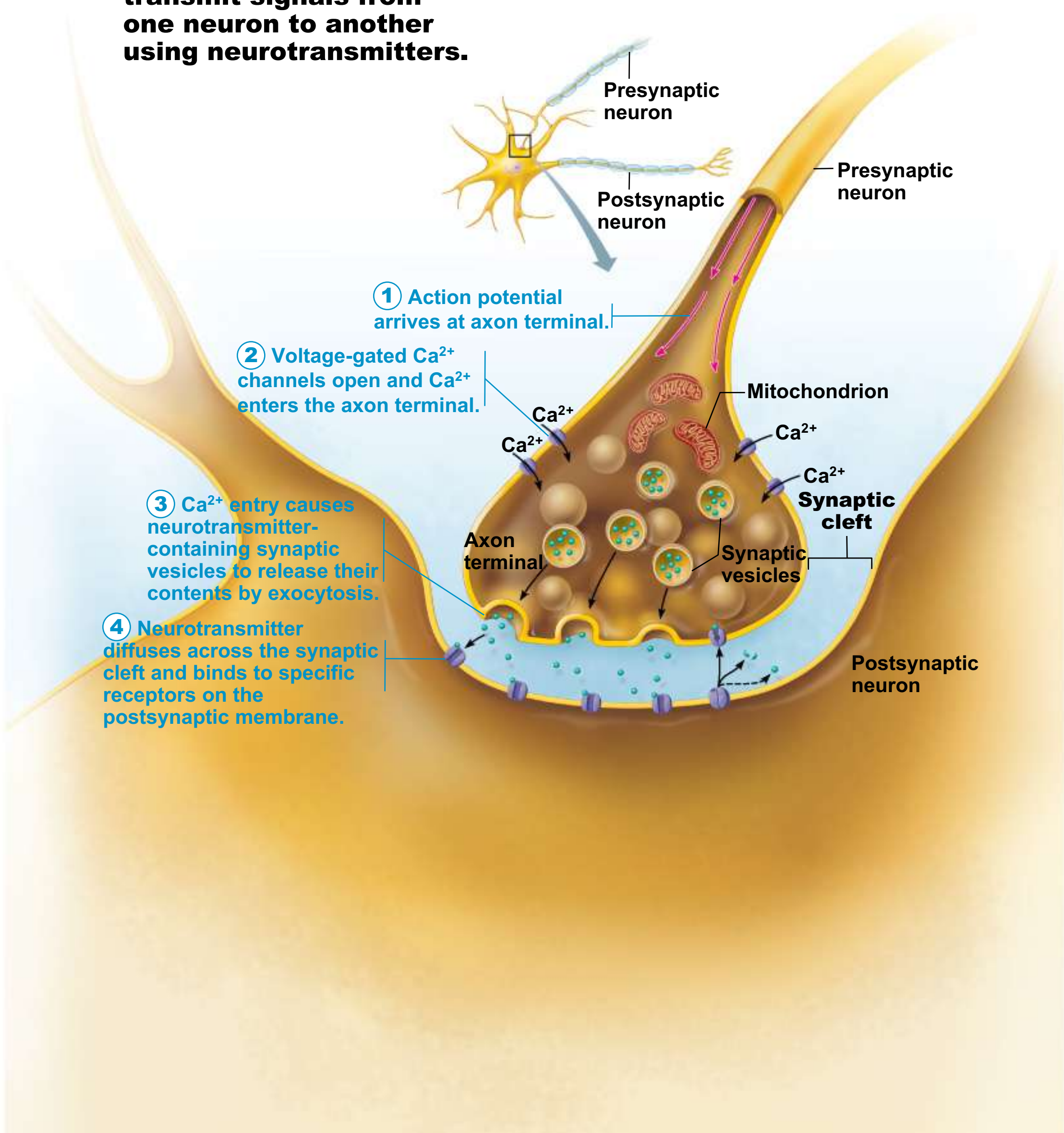

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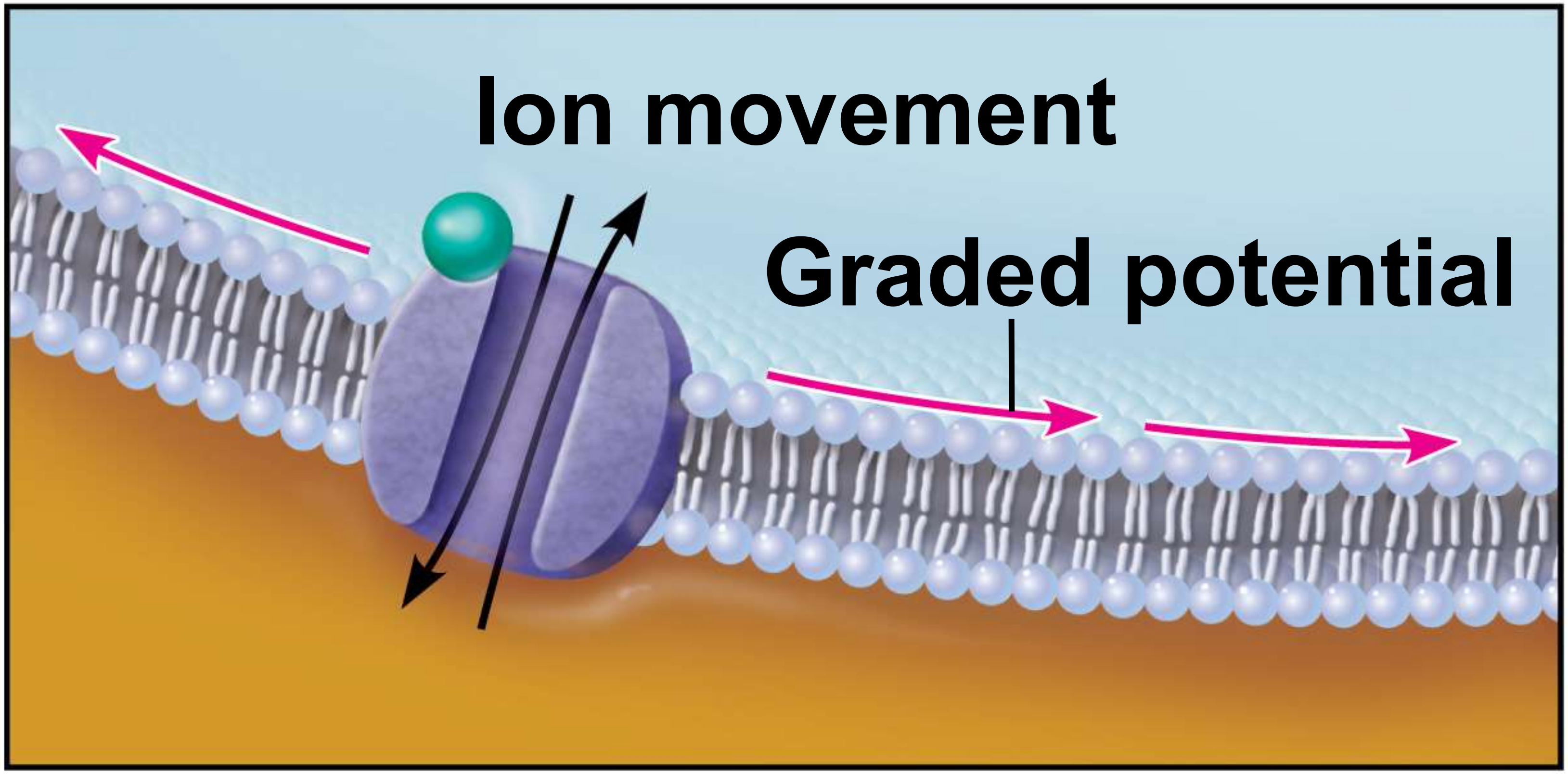
Figure 11.17, step 4



5 Binding of neurotransmitter opens ion channels, resulting in graded potentials.

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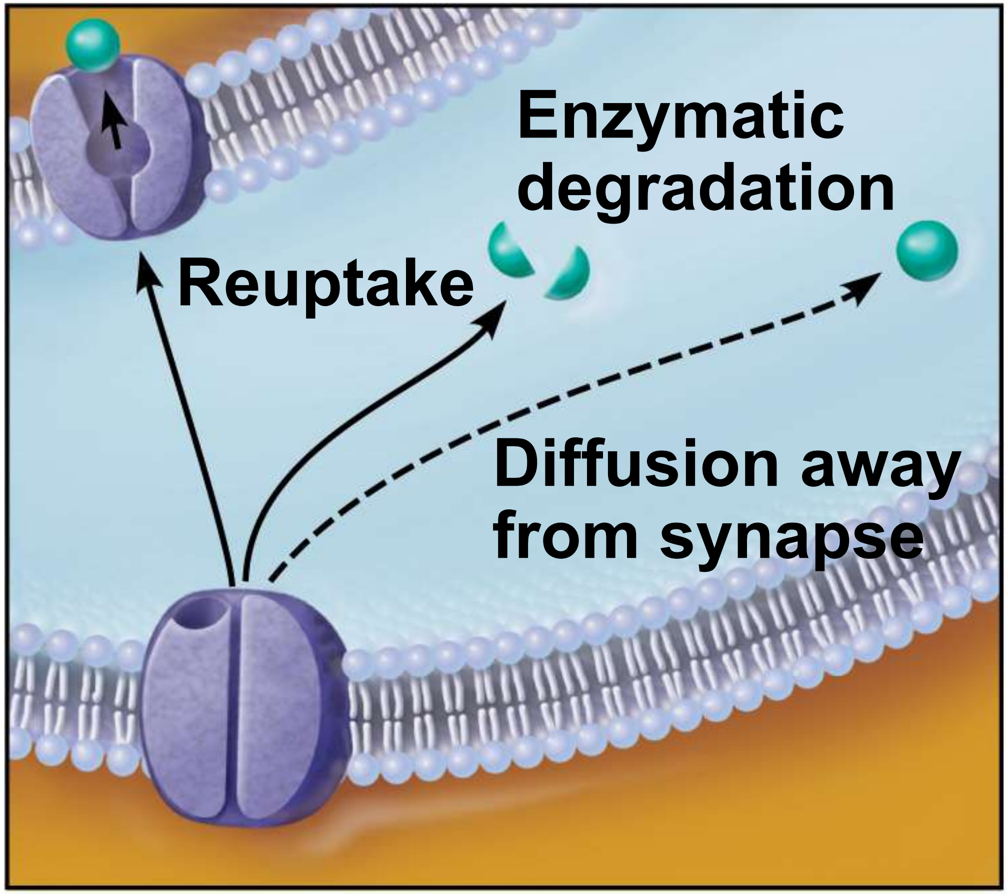
Figure 11.17, step 5



⑥ Neurotransmitter effects are terminated by reuptake through transport proteins, enzymatic degradation, or diffusion away from the synapse.

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Figure 11.17, step 6

Chemical synapses transmit signals from one neuron to another using neurotransmitters.

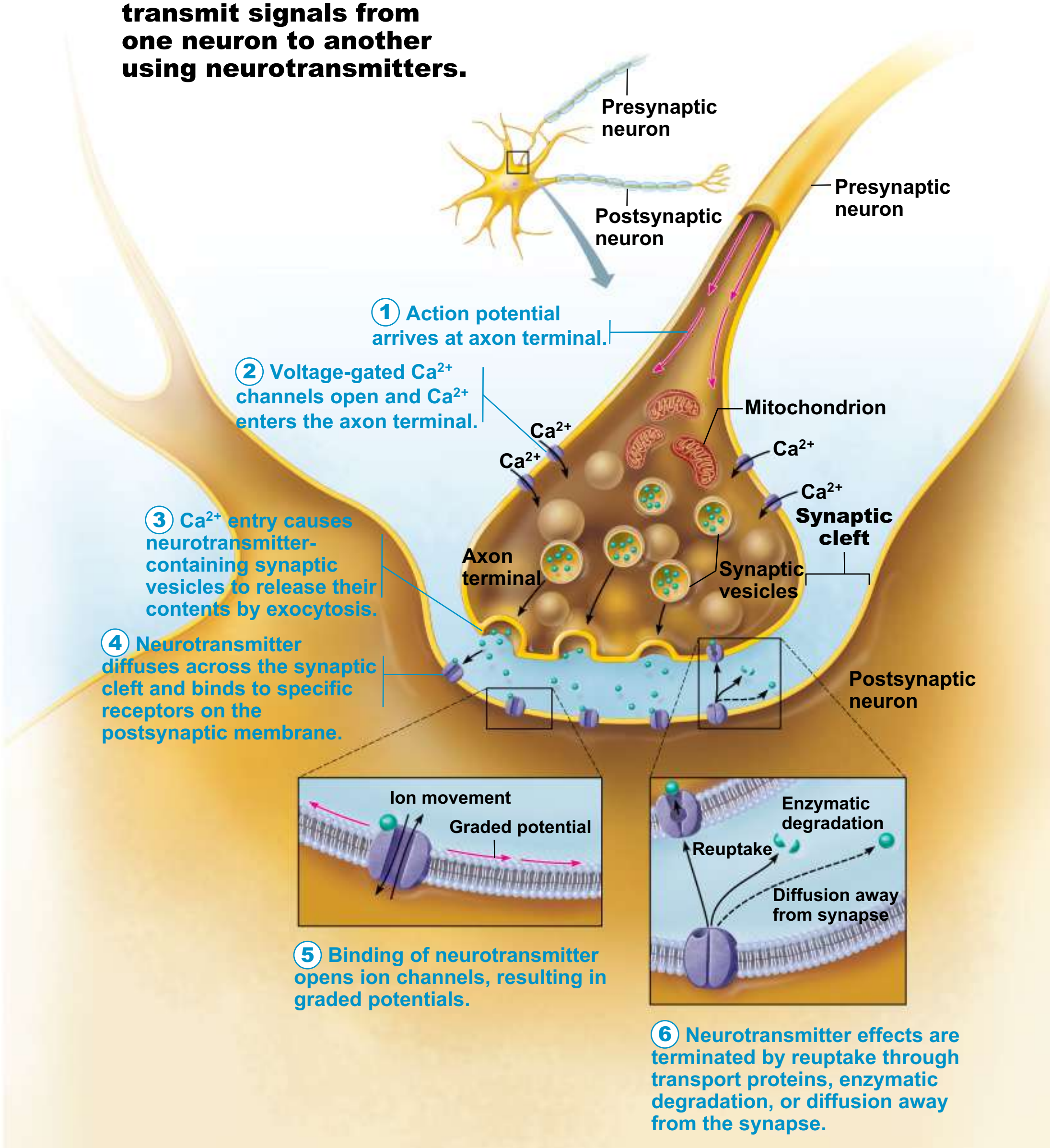

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Figure 11.17

Termination of Neurotransmitter Effects

- Within a few milliseconds, the neurotransmitter effect is terminated
  - Degradation by enzymes
  - Reuptake by astrocytes or axon terminal
  - Diffusion away from the synaptic cleft

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Synaptic Delay

- Neurotransmitter must be released, diffuse across the synapse, and bind to receptors
- Synaptic delay—time needed to do this (0.3–5.0 ms)
- Synaptic delay is the rate-limiting step of neural transmission

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Postsynaptic Potentials

- Graded potentials
- Strength determined by:
  - Amount of neurotransmitter released
  - Time the neurotransmitter is in the area
- Types of postsynaptic potentials
  1. EPSP—excitatory postsynaptic potentials
  2. IPSP—inhibitory postsynaptic potentials

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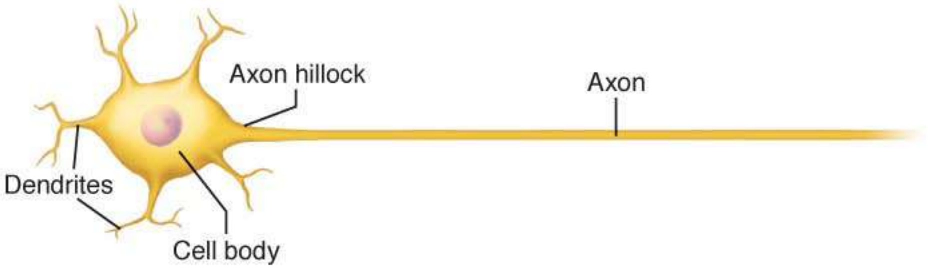
TABLE 11.2 Comparison of Action Potentials with Graded Potentials

	GRADED POTENTIAL (GP)	ACTION POTENTIAL (AP)
Location of event	Cell body and dendrites, typically	Axon hillock and axon



	GRADED POTENTIAL (GP)	ACTION POTENTIAL (AP)
Distance traveled	Short distance—typically within cell body to axon hillock (0.1–1.0 mm)	Long distance—from axon hillock through entire length of axon (a few mm to over a meter)

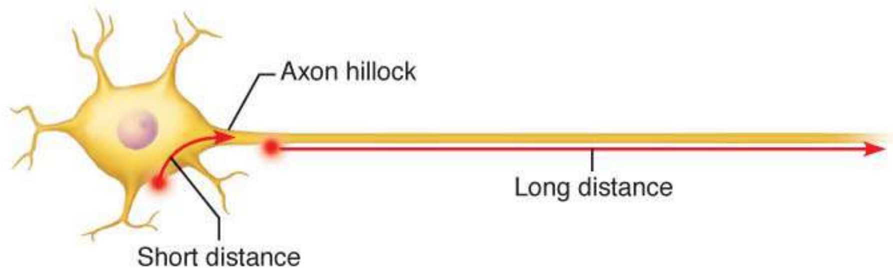


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TABLE 11.2 Comparison of Action Potentials with Graded Potentials *(continued)*

	GRADED POTENTIAL (GP)	ACTION POTENTIAL (AP)
Amplitude (size)	Various sizes (graded); declines with distance	Always the same size (all-or-none); does not decline with distance
Stimulus for opening of ion channels	Chemical (neurotransmitter) or sensory stimulus (e.g., light, pressure, temperature)	Voltage (depolarization, triggered by GP reaching threshold)
Positive feed-back cycle	Absent	Present
Repolarization	Voltage independent; occurs when stimulus is no longer present	Voltage regulated; occurs when Na^+ channels inactivate and K^+ channels open

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TABLE 11.2 Comparison of Action Potentials with Graded Potentials *(continued)*

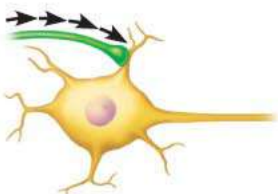
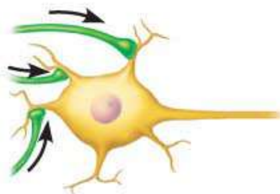
	GRADED POTENTIAL (GP)		ACTION POTENTIAL (AP)
Summation	Stimulus responses can be summed to increase amplitude of graded potential		Does not occur; an all-or-none phenomenon
	 Temporal: increased frequency of stimuli	 Spatial: stimuli from multiple sources	
	POSTSYNAPTIC POTENTIAL (A TYPE OF GP)		
	EXCITATORY (EPSP)	**INHIBITORY (IPSP)**	
Function	Short-distance signaling; depolarization that spreads to axon hillock; moves membrane potential *toward* threshold for generation of AP	Short-distance signaling; hyperpolarization that spreads to axon hillock; moves membrane potential *away from* threshold for generation of AP	Long-distance signaling; constitutes the nerve impulse

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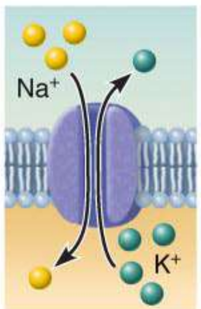
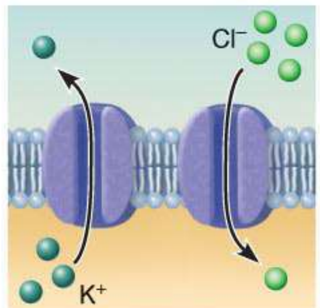
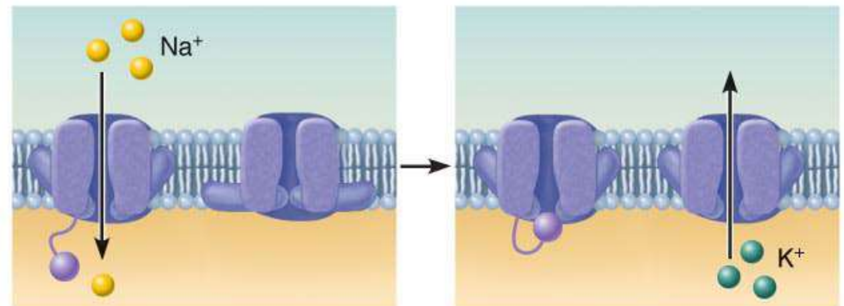
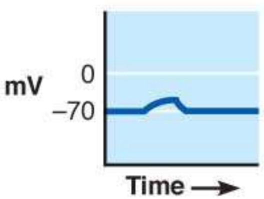
TABLE 11.2 Comparison of Action Potentials with Graded Potentials *(continued)*

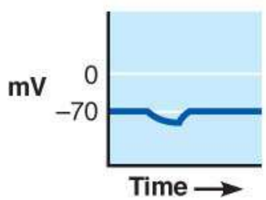
	GRADED POTENTIAL (GP)		ACTION POTENTIAL (AP)
Initial effect of stimulus	Opens channels that allow simultaneous Na^+ and K^+ fluxes	Opens K^+ or Cl^- channels	First opens Na^+ channels, then K^+ channels
Peak membrane potential	Becomes depolarized; moves toward 0 mV	Becomes hyperpolarized; moves toward −90 mV	+30 to +50 mV

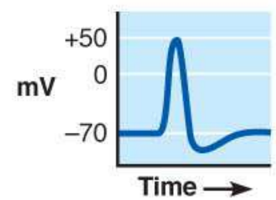












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Excitatory Synapses and EPSPs

- Neurotransmitter binds to and opens chemically gated channels that allow simultaneous flow of Na^+ and K^+ in opposite directions
- Na^+ influx is greater that K^+ efflux, causing a net depolarization
- EPSP helps trigger AP at axon hillock if EPSP is of threshold strength and opens the voltage-gated channels

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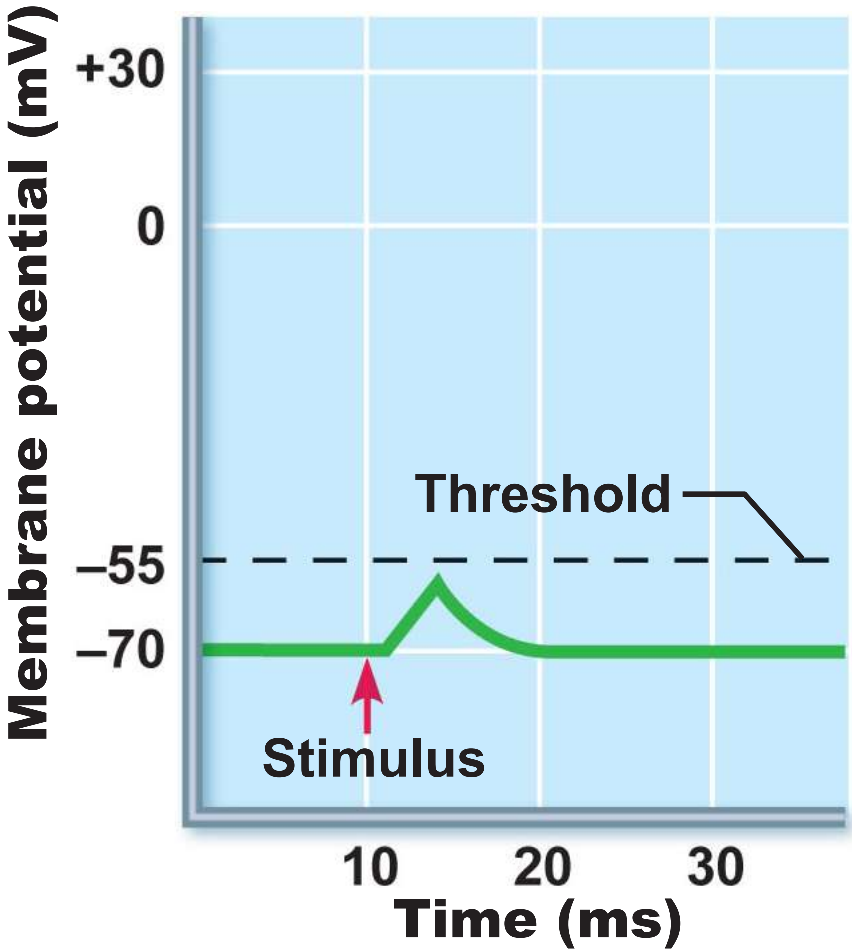

An EPSP is a local depolarization of the postsynaptic membrane that brings the neuron closer to AP threshold. Neurotransmitter binding opens chemically gated ion channels, allowing the simultaneous passage of Na^+ and K^+.

(a) Excitatory postsynaptic potential (EPSP)

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Figure 11.18a

Inhibitory Synapses and IPSPs

- Neurotransmitter binds to and opens channels for K^+ or Cl^-
- Causes a hyperpolarization (the inner surface of membrane becomes more negative)
- Reduces the postsynaptic neuron's ability to produce an action potential

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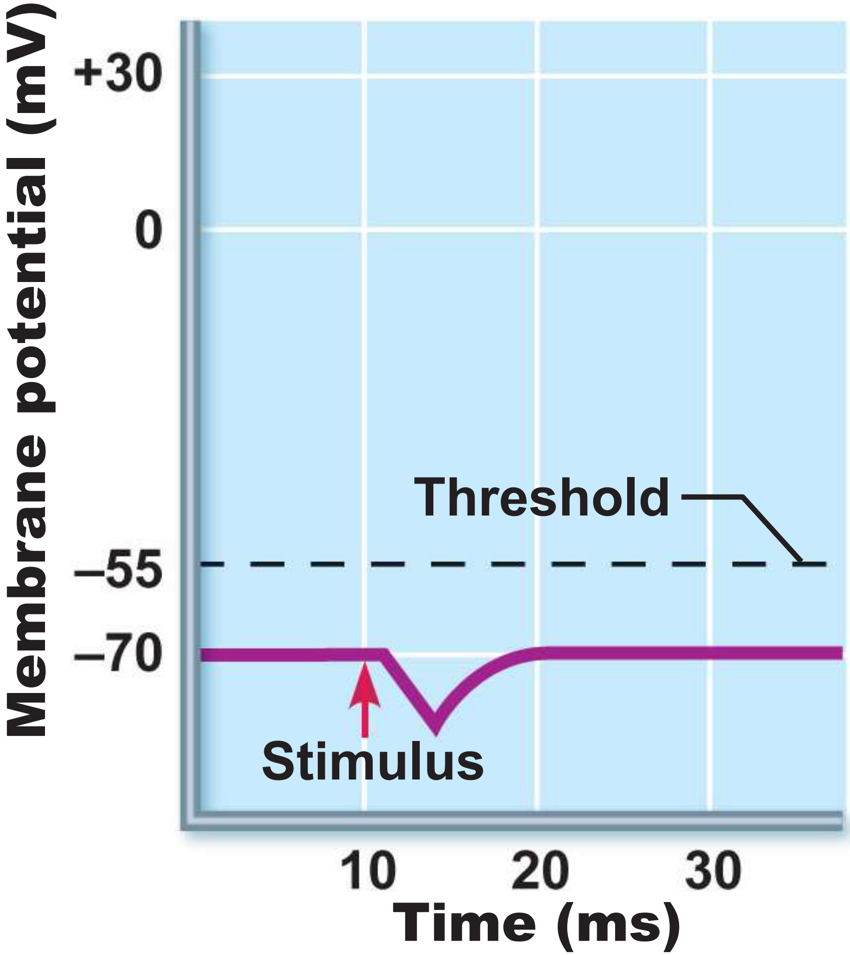

An IPSP is a local hyperpolarization of the postsynaptic membrane and drives the neuron away from AP threshold. Neurotransmitter binding opens K^+ or Cl^- channels.

(b) Inhibitory postsynaptic potential (IPSP)

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Figure 11.18b

Integration: Summation

- A single EPSP cannot induce an action potential
- EPSPs can summate to reach threshold
- IPSPs can also summate with EPSPs, canceling each other out

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Integration: Summation

- Temporal summation
  - One or more presynaptic neurons transmit impulses in rapid-fire order
- Spatial summation
  - Postsynaptic neuron is stimulated by a large number of terminals at the same time

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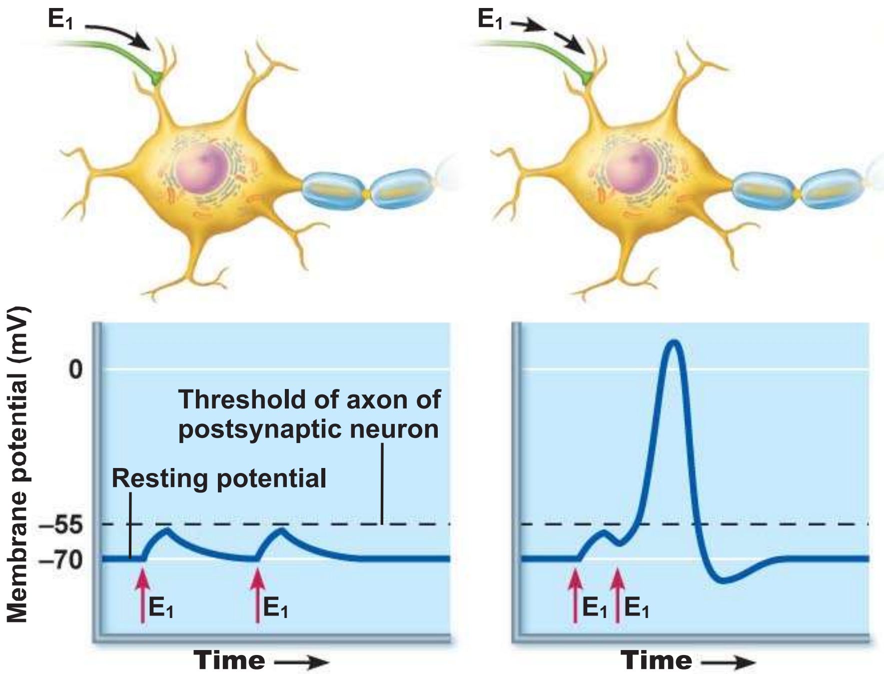

(a) No summation: 2 stimuli separated in time cause EPSPs that do not add together.

(b) Temporal summation: 2 excitatory stimuli close in time cause EPSPs that add together.

Excitatory synapse 1 (E_1)

Excitatory synapse 2 (E_2)

Inhibitory synapse (I_1)

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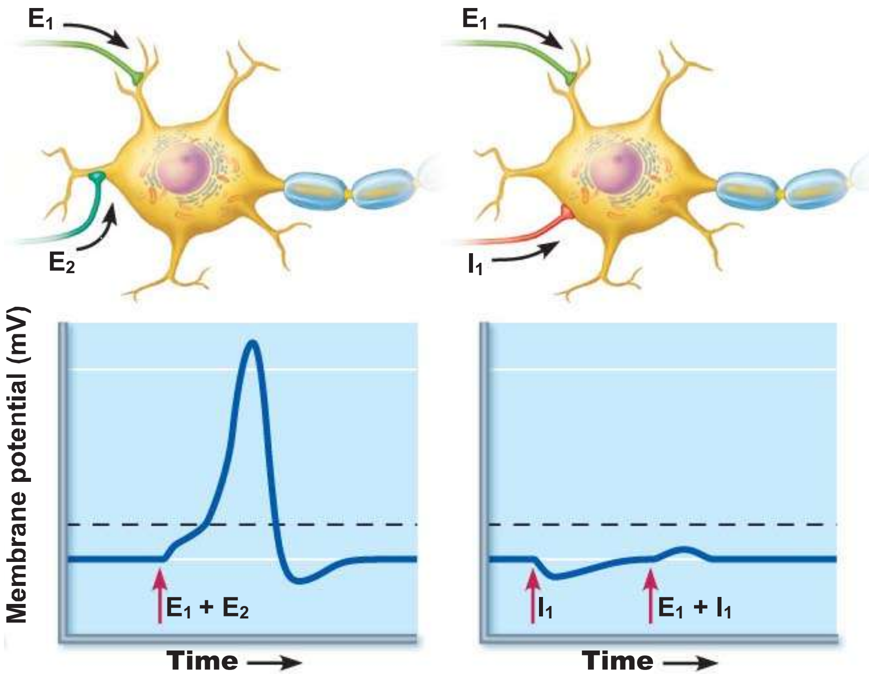
Figure 11.19a, b



(c) Spatial summation: 2 simultaneous stimuli at different locations cause EPSPs that add together.

(d) Spatial summation of EPSPs and IPSPs: Changes in membane potential can cancel each other out.

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Figure 11.19c, d

Integration: Synaptic Potentiation

- Repeated use increases the efficiency of neurotransmission
- Ca^{2+} concentration increases in presynaptic terminal and ostsynaptic neuron
- Brief high-frequency stimulation partially depolarizes the postsynaptic neuron
  - Chemically gated channels (NMDA receptors) allow Ca^{2+} entry
  - Ca^{2+} activates kinase enzymes that promote more effective responses to subsequent stimuli

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Integration: Presynaptic Inhibition

- Release of excitatory neurotransmitter by one neuron may be inhibited by the activity of another neuron via an axoaxonic synapse
- Less neurotransmitter is released and smaller EPSPs are formed

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Neurotransmitters

- Most neurons make two or more neurotransmitters, which are released at different stimulation frequencies
- 50 or more neurotransmitters have been identified
- Classified by chemical structure and by function

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Chemical Classes of Neurotransmitters

- Acetylcholine (Ach)
  - Released at neuromuscular junctions and some ANS neurons
  - Synthesized by enzyme choline acetyltransferase
  - Degraded by the enzyme acetylcholinesterase (AChE)

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Chemical Classes of Neurotransmitters

- Biogenic amines include:
  - Catecholamines
    - Dopamine, norepinephrine (NE), and epinephrine
  - Indolamines
    - Serotonin and histamine
- Broadly distributed in the brain
- Play roles in emotional behaviors and the biological clock

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Chemical Classes of Neurotransmitters

- Amino acids include:
  - GABA—Gamma (γ)-aminobutyric acid
  - Glycine
  - Aspartate
  - Glutamate

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Chemical Classes of Neurotransmitters

- Peptides (neuropeptides) include:
  - Substance P
    - Mediator of pain signals
  - Endorphins
    - Act as natural opiates; reduce pain perception
  - Gut-brain peptides
    - Somatostatin and cholecystokinin

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Chemical Classes of Neurotransmitters

- Purines such as ATP:
    - Act in both the CNS and PNS
    - Produce fast or slow responses
    - Induce Ca^{2+} influx in astrocytes
    - Provoke pain sensation

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Chemical Classes of Neurotransmitters

- Gases and lipids
  - Nitric oxide (NO)
    - Synthesized on demand
    - Activates the intracellular receptor guanylyl cyclase to cyclic GMP
    - Involved in learning and memory
  - Carbon monoxide (CO) is a regulator of cGMP in the brain

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Chemical Classes of Neurotransmitters

- Gases and lipids
  - Endocannabinoids
    - Lipid soluble; synthesized on demand from membrane lipids
    - Bind with G protein–coupled receptors in the brain
    - Involved in learning and memory

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Functional Classification of Neurotransmitters

- Neurotransmitter effects may be excitatory (depolarizing) and/or inhibitory (hyperpolarizing)
  - Determined by the receptor type of the postsynaptic neuron
  - GABA and glycine are usually inhibitory
  - Glutamate is usually excitatory
  - Acetylcholine
    - Excitatory at neuromuscular junctions in skeletal muscle
    - Inhibitory in cardiac muscle

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Neurotransmitter Actions

- Direct action
  - Neurotransmitter binds to channel-linked receptor and opens ion channels
  - Promotes rapid responses
  - Examples: ACh and amino acids

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Neurotransmitter Actions

- Indirect action
  - Neurotransmitter binds to a G protein-linked receptor and acts through an intracellular second messenger
  - Promotes long-lasting effects
  - Examples: biogenic amines, neuropeptides, and dissolved gases

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Neurotransmitter Receptors

- Types
  1. Channel-linked receptors
  2. G protein-linked receptors

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Channel-Linked (Ionotropic) Receptors

- Ligand-gated ion channels
- Action is immediate and brief
- Excitatory receptors are channels for small cations
- Na^+ influx contributes most to depolarization
- Inhibitory receptors allow Cl^- influx or K^+ efflux that causes hyperpolarization

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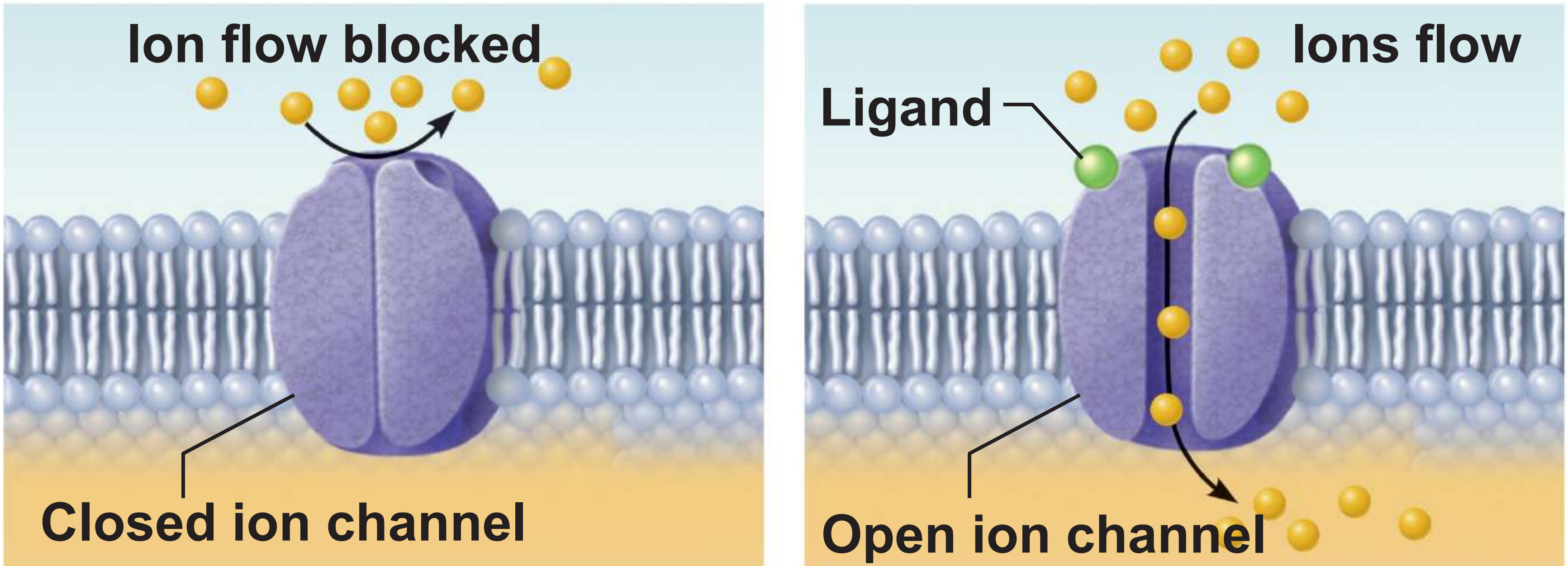

(a) Channel-linked receptors open in response to binding of ligand (ACh in this case).

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Figure 11.20a

G Protein-Linked (Metabotropic) Receptors

- Transmembrane protein complexes
- Responses are indirect, slow, complex, and often prolonged and widespread
- Examples: muscarinic ACh receptors and those that bind biogenic amines and neuropeptides

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G Protein-Linked Receptors: Mechanism

- Neurotransmitter binds to G protein–linked receptor
- G protein is activated
- Activated G protein controls production of second messengers, e.g., cyclic AMP, cyclic GMP, diacylglycerol or Ca^{2+}

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G Protein-Linked Receptors: Mechanism

- Second messengers
  - Open or close ion channels
  - Activate kinase enzymes
  - Phosphorylate channel proteins
  - Activate genes and induce protein synthesis

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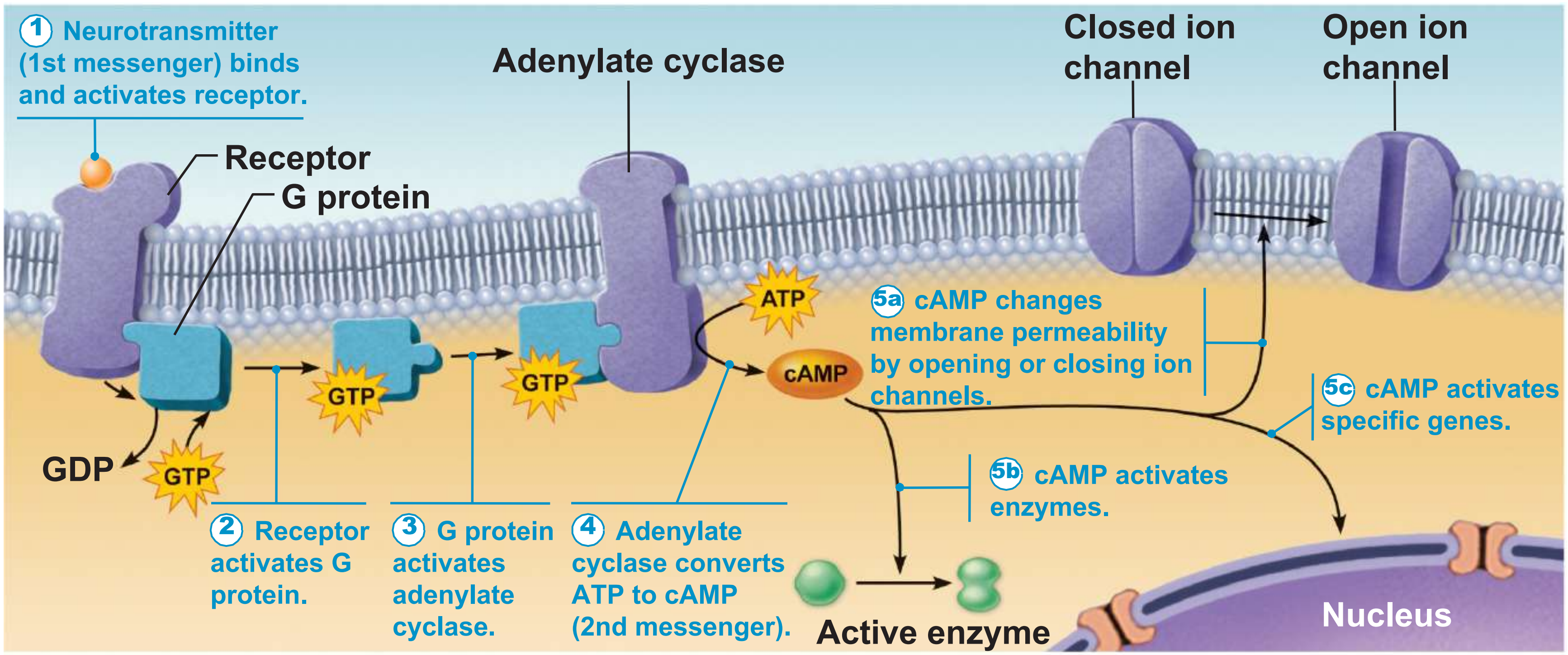

(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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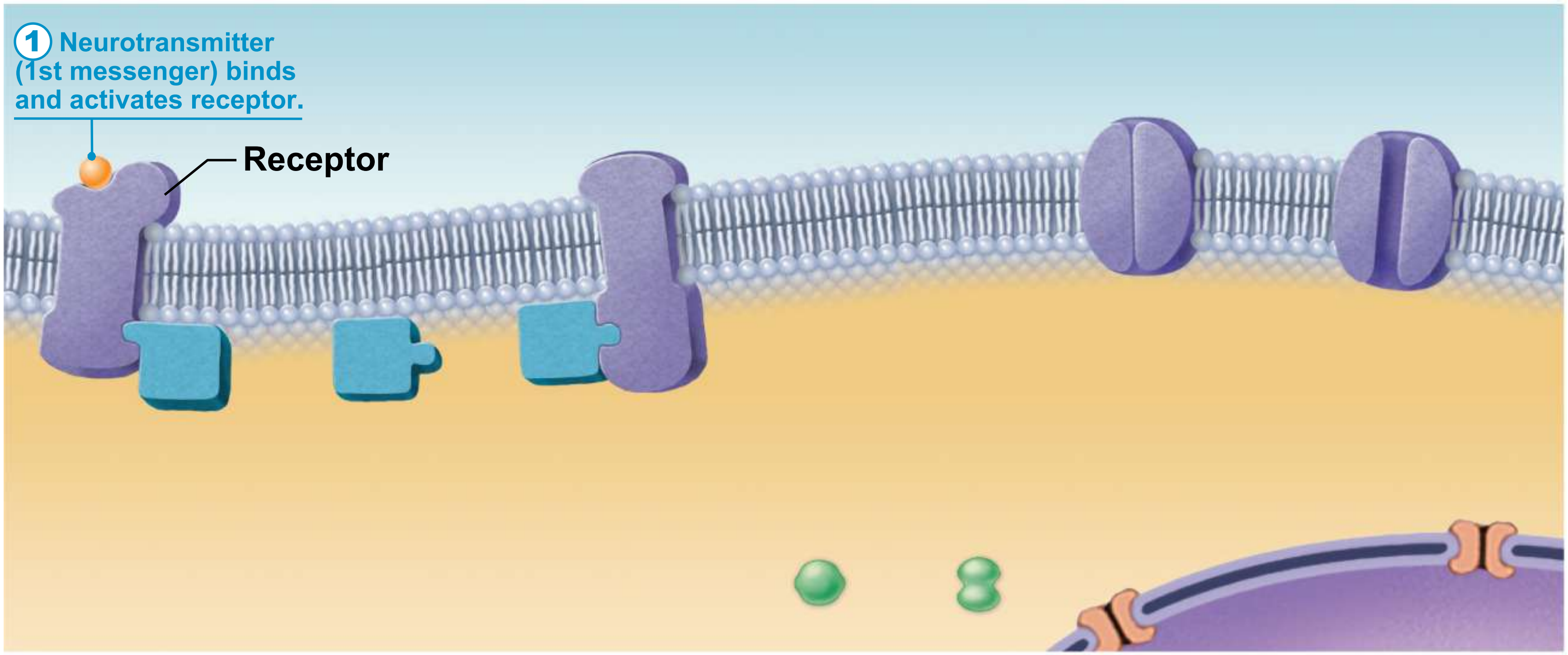

(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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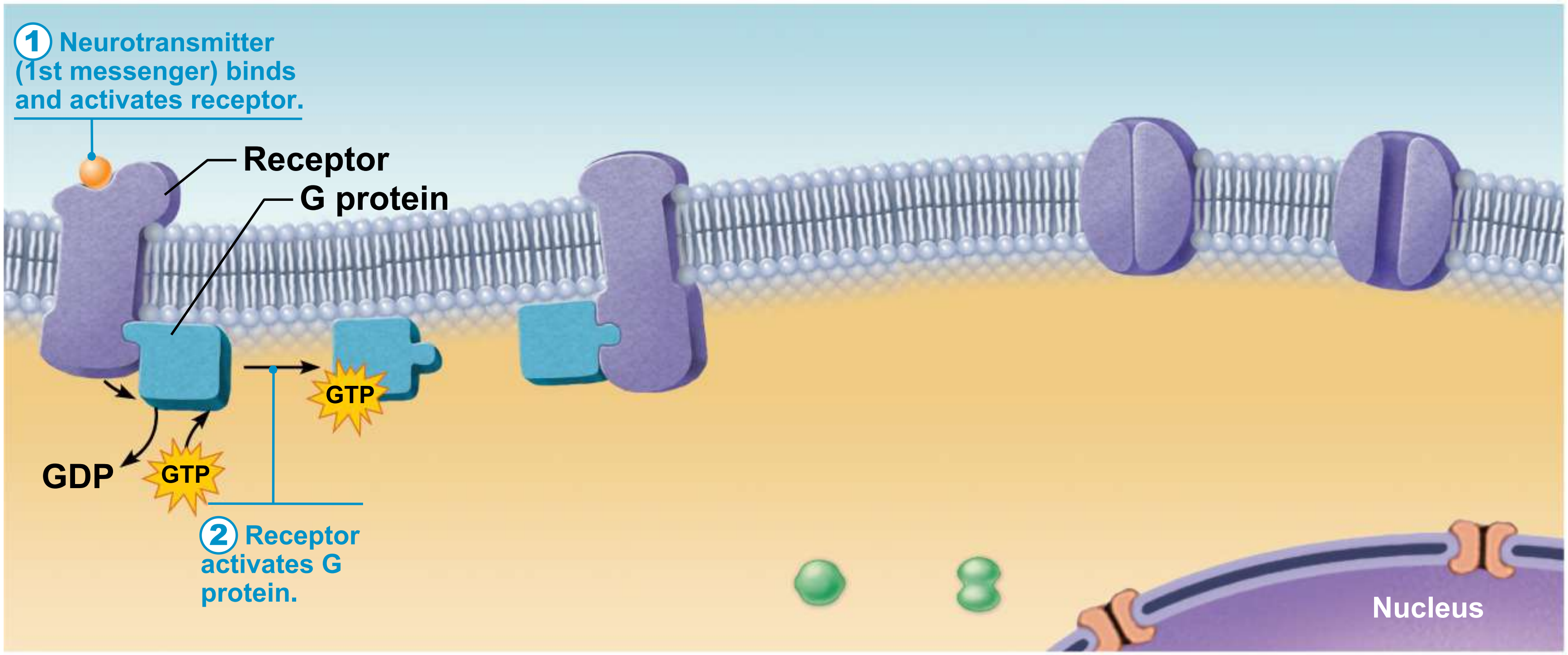
Figure 11.17b, step 1



(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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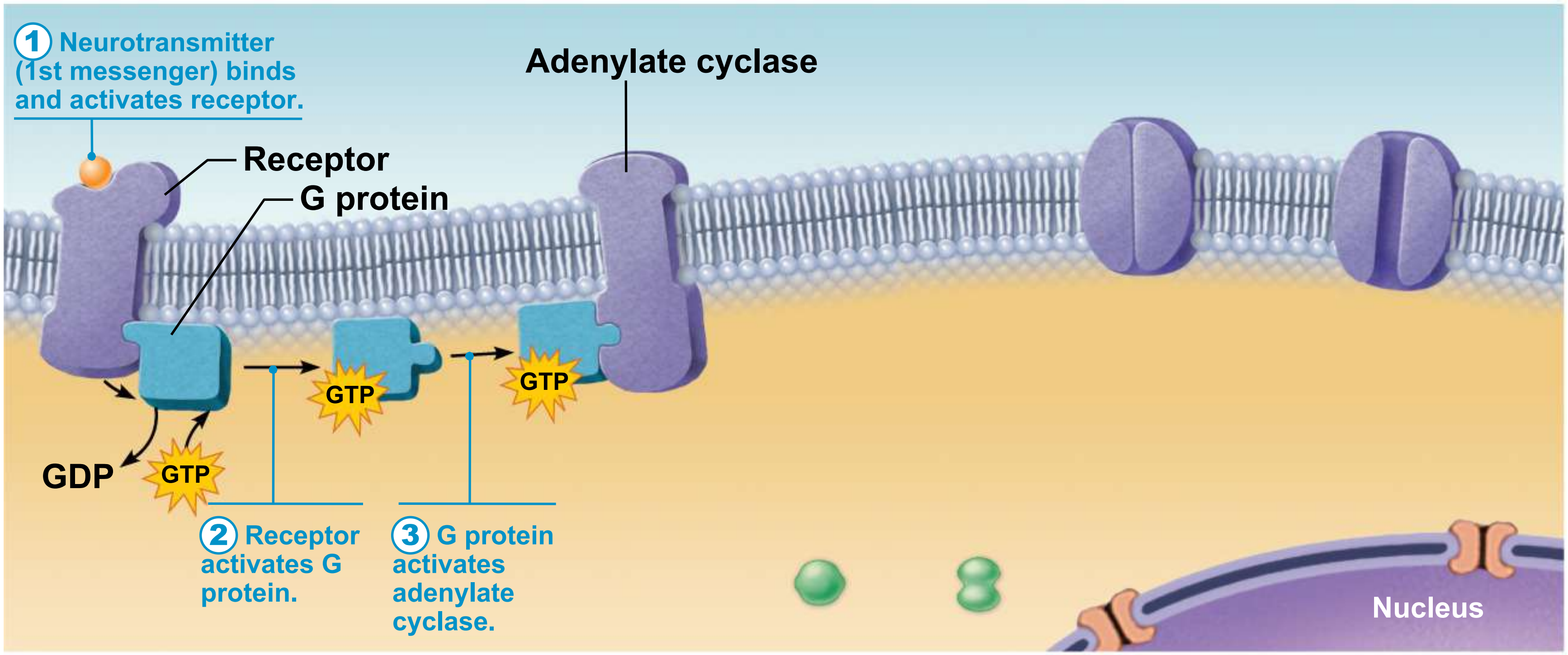
Figure 11.17b, step 2



(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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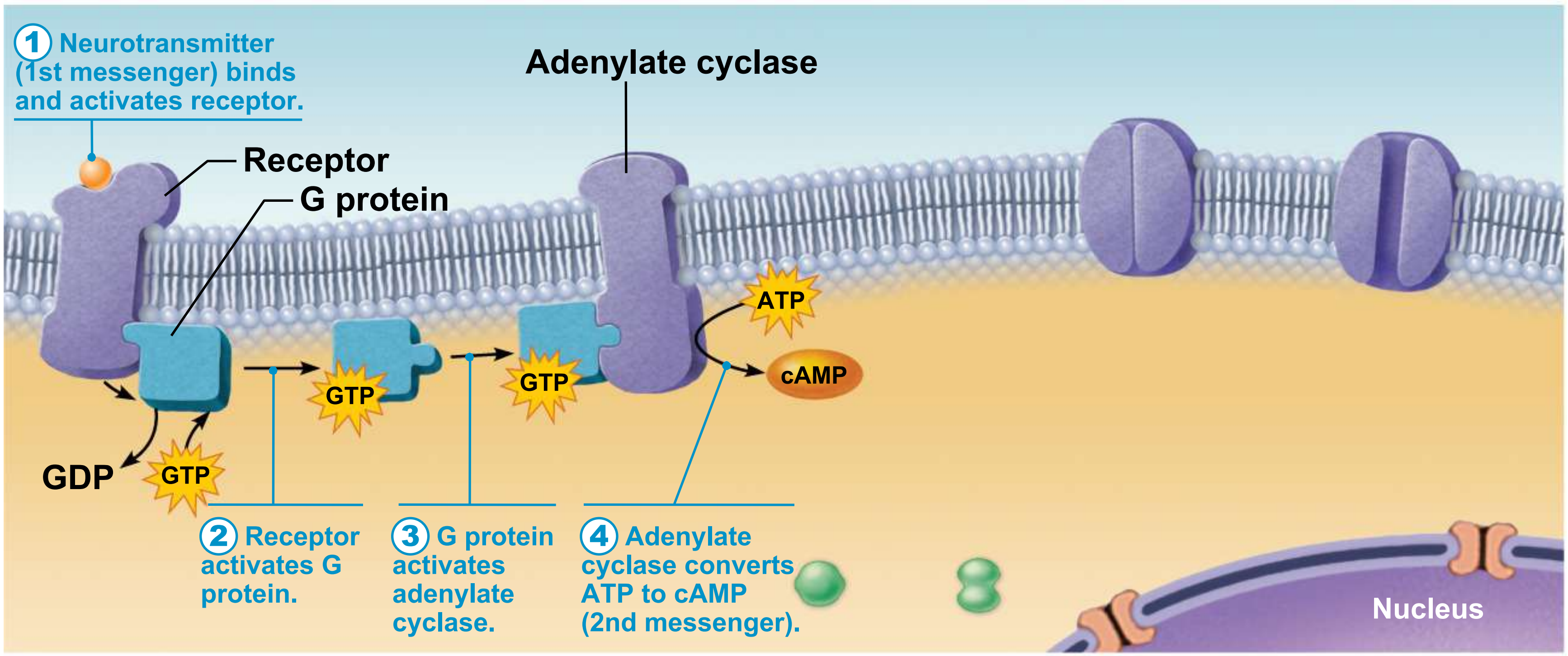
Figure 11.17b, step 3



(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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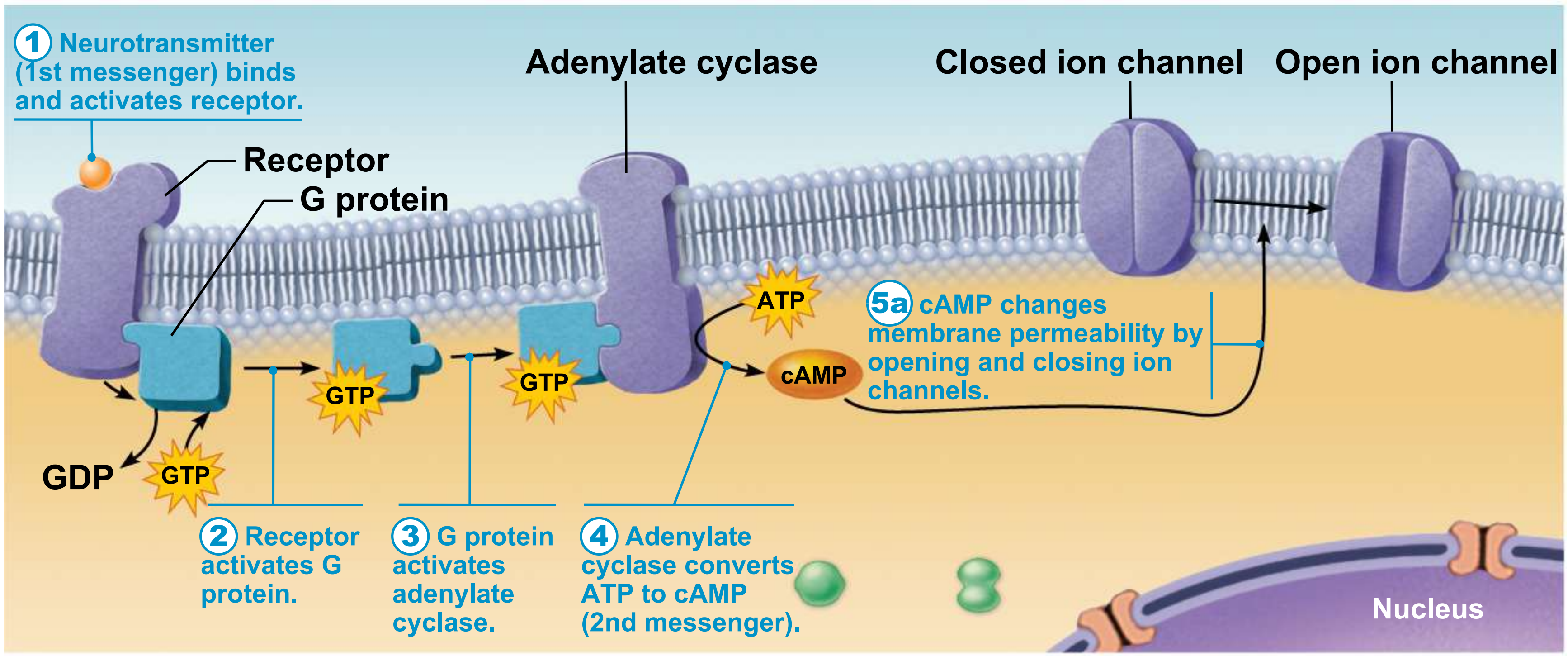

(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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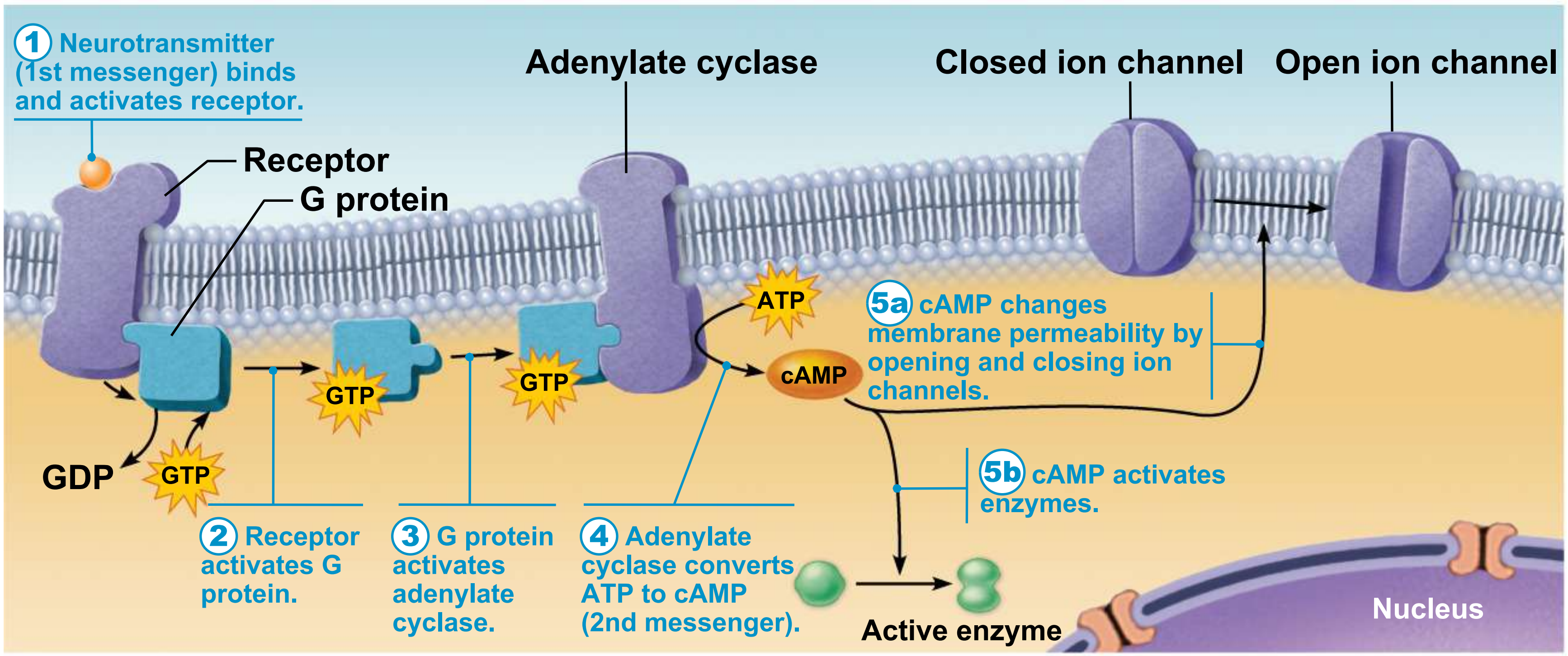
Figure 11.17b, step 5a



(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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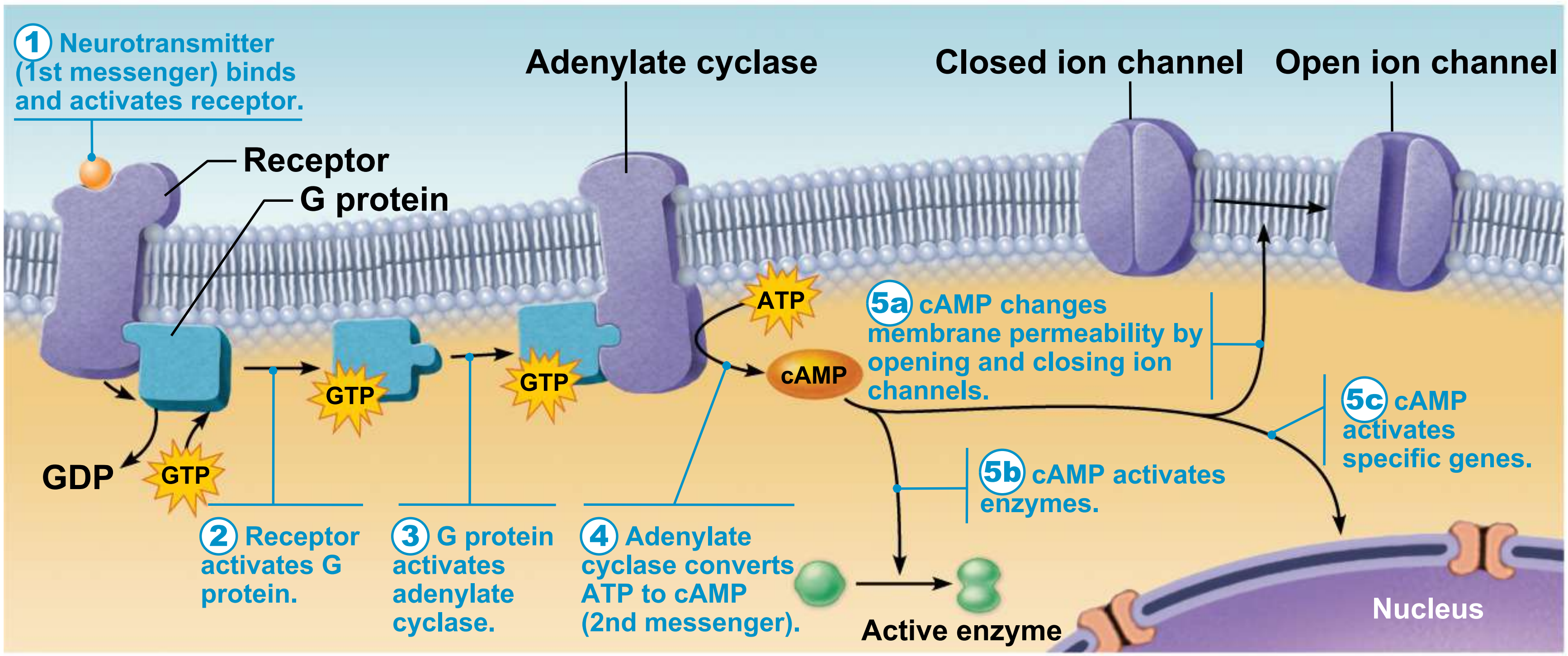
Figure 11.17b, step 5b



(b) G-protein linked receptors cause formation of an intracellular second messenger (cyclic AMP in this case) that brings about the cell's response.

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Figure 11.17b, step 5c

Neural Integration: Neuronal Pools

- Functional groups of neurons that:
  - Integrate incoming information
  - Forward the processed information to other destinations

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Neural Integration: Neuronal Pools

- Simple neuronal pool
  - Single presynaptic fiber branches and synapses with several neurons in the pool
  - Discharge zone—neurons most closely associated with the incoming fiber
  - Facilitated zone—neurons farther away from incoming fiber

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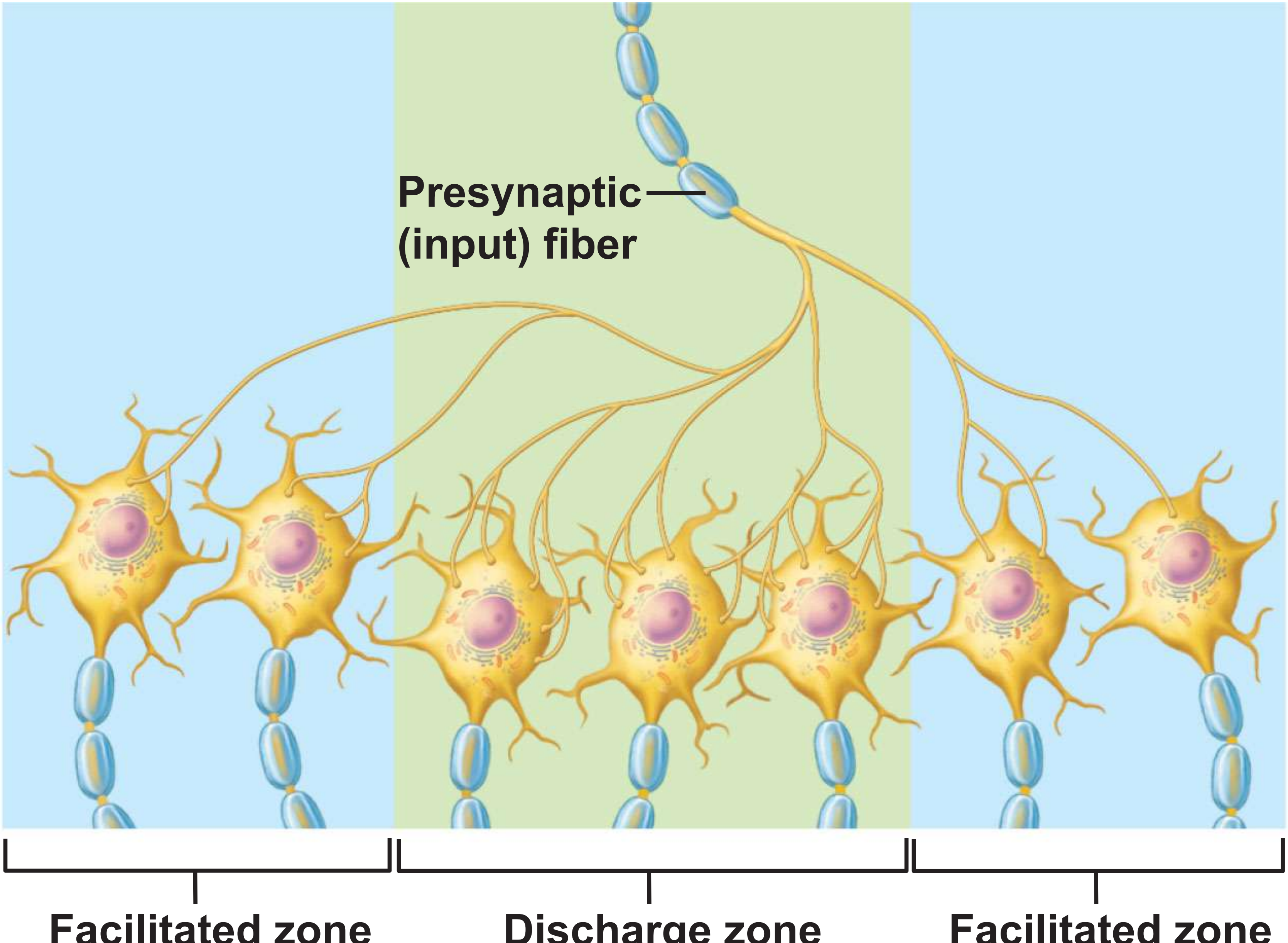

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Figure 11.21

Types of Circuits in Neuronal Pools

- Diverging circuit
  - One incoming fiber stimulates an ever-increasing number of fibers, often amplifying circuits
  - May affect a single pathway or several
  - Common in both sensory, motor, and reflex systems

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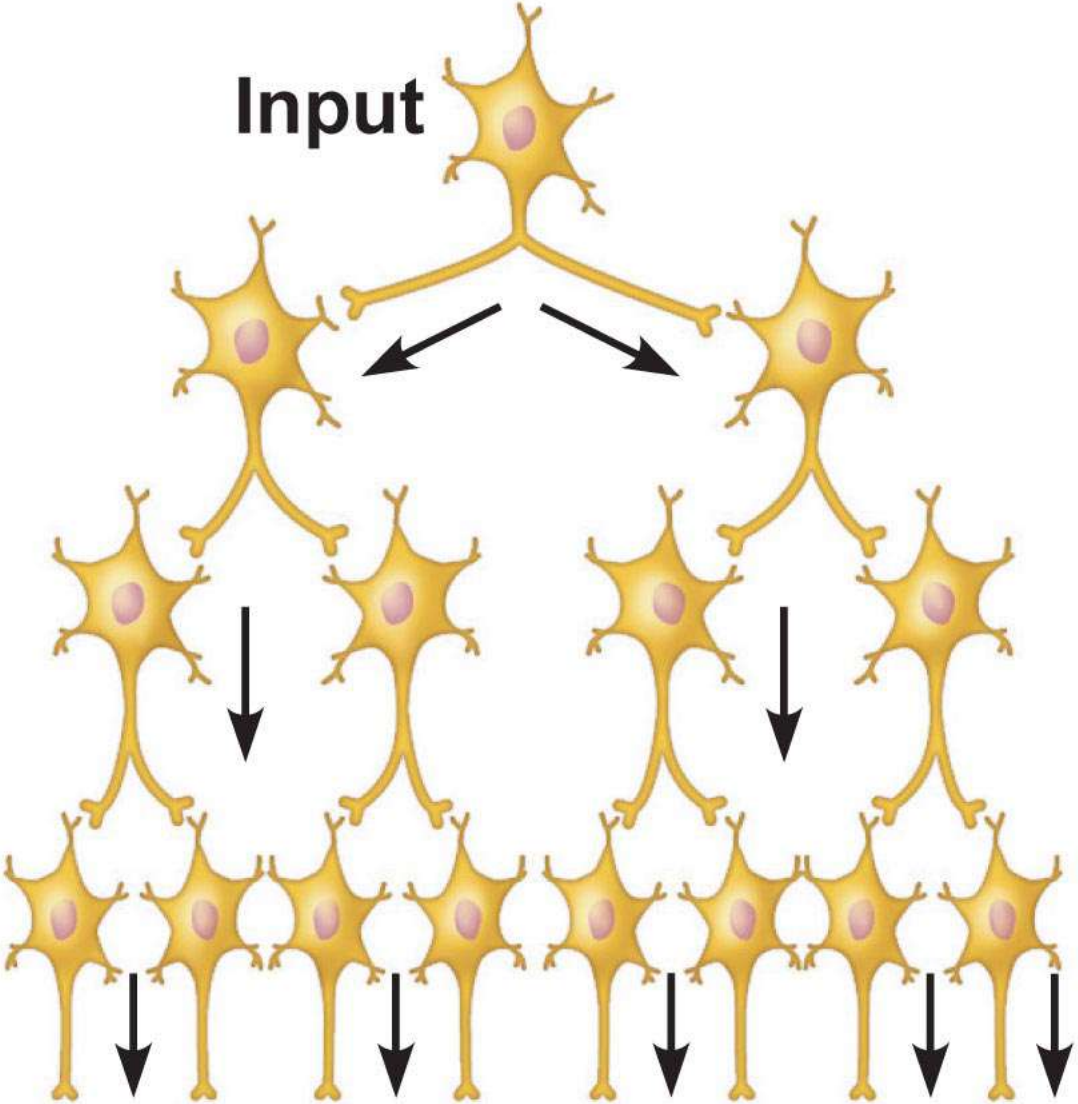

(a) Divergence in same pathway

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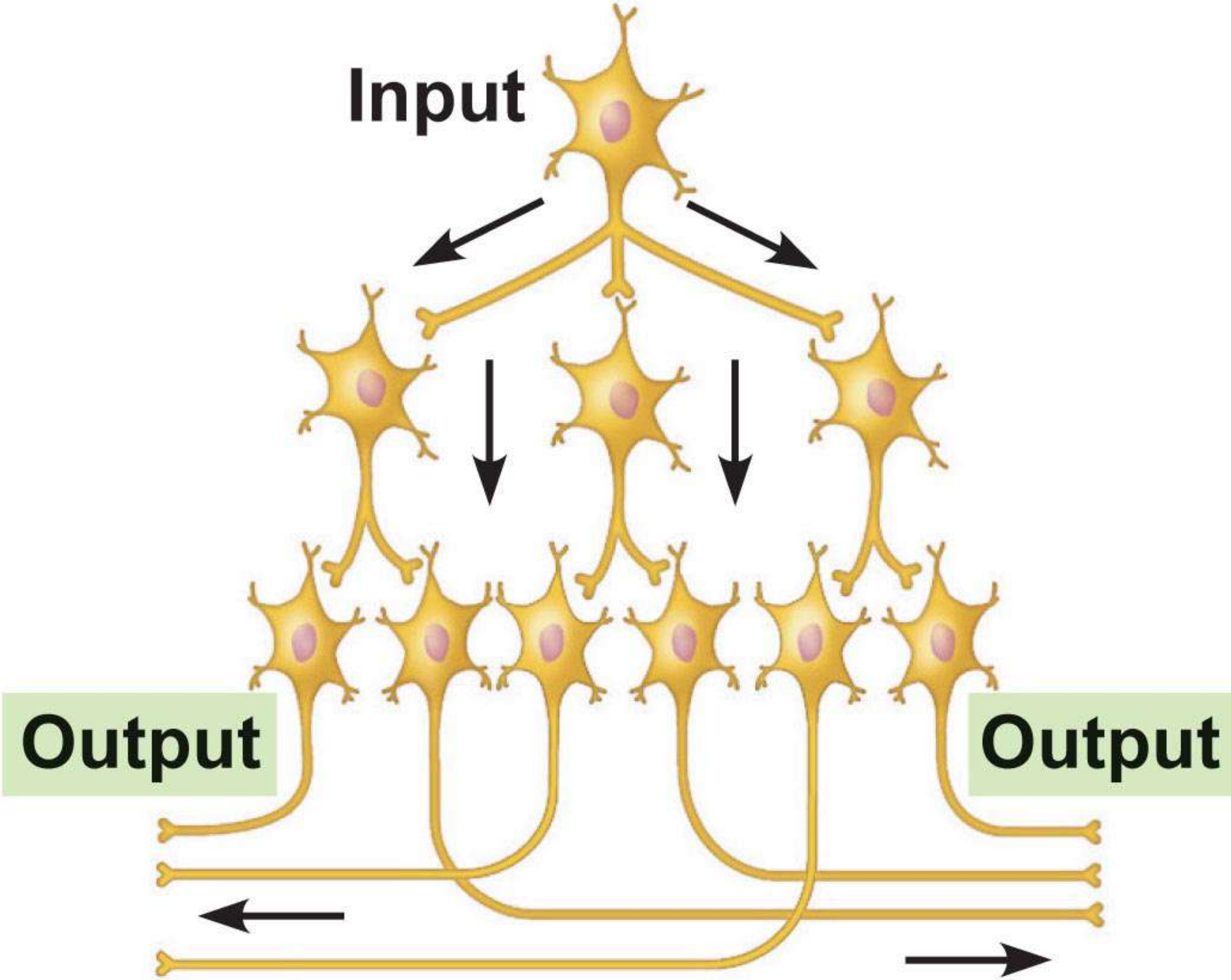
Figure 11.22a



(b) Divergence to multiple pathways

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Figure 11.22b

Types of Circuits in Neuronal Pools

- Converging circuit
  - Opposite of diverging circuits, resulting in either strong stimulation or inhibition
  - Also common in sensory and motor systems

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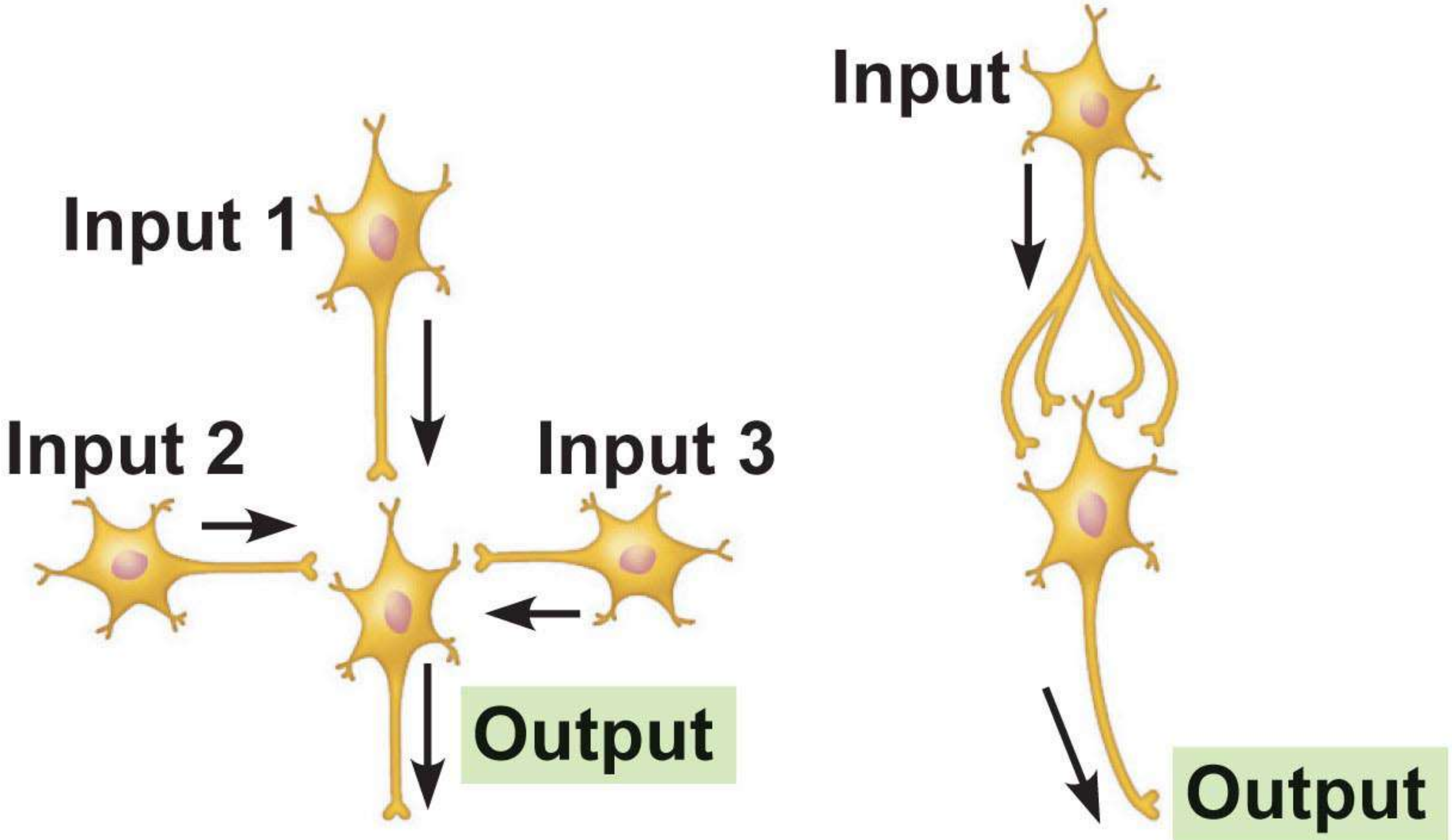

(c) Convergence, multiple sources

(d) Convergence, single source

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Figure 11.22c, d

Types of Circuits in Neuronal Pools

- Reverberating (oscillating) circuit
  - Chain of neurons containing collateral synapses with previous neurons in the chain

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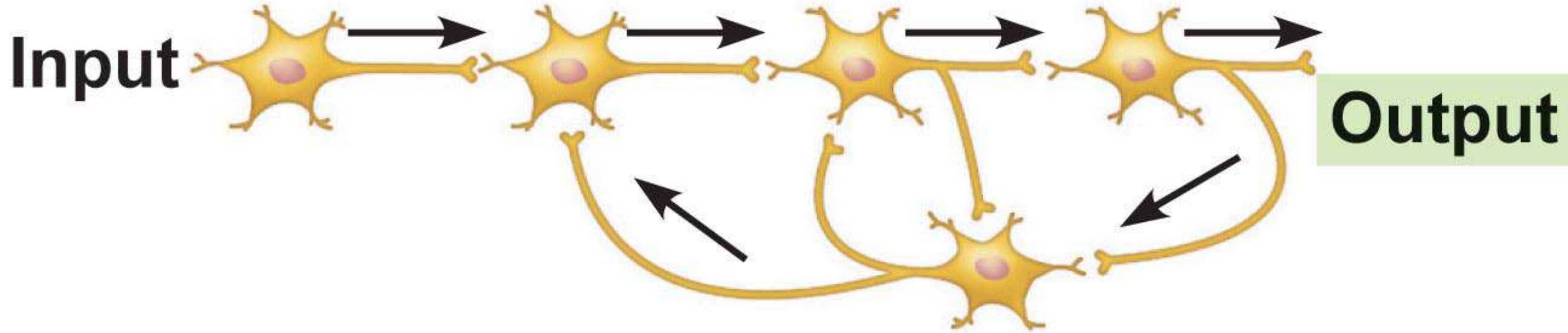

(e) Reverberating circuit

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Figure 11.22e

Types of Circuits in Neuronal Pools

- Parallel after-discharge circuit
  - Incoming fiber stimulates several neurons in parallel arrays to stimulate a common output cell

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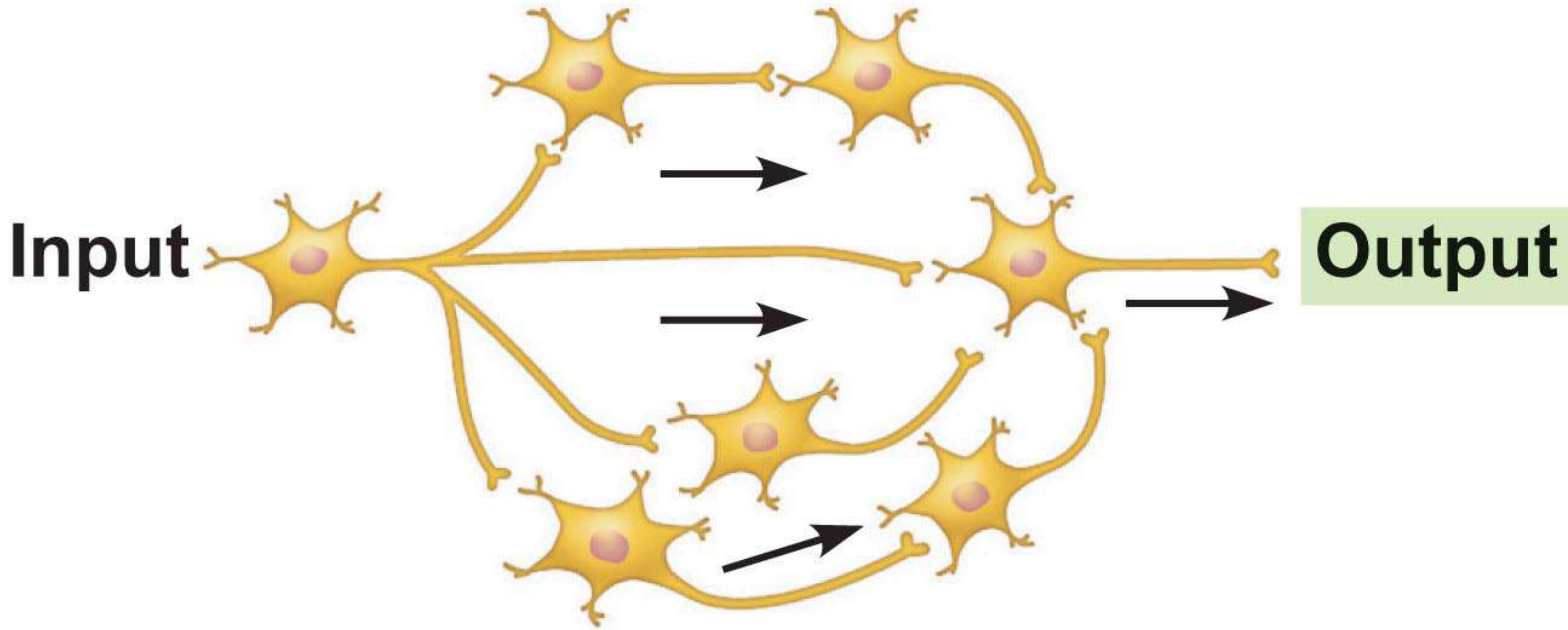

(f) Parallel after-discharge circuit

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Figure 11.22f

Patterns of Neural Processing

- Serial processing
  - Input travels along one pathway to a specific destination
  - Works in an all-or-none manner to produce a specific response
  - Example: reflexes—rapid, automatic responses to stimuli that always cause the same response
  - Reflex arcs (pathways) have five essential components: receptor, sensory neuron, CNS integration center, motor neuron, and effector

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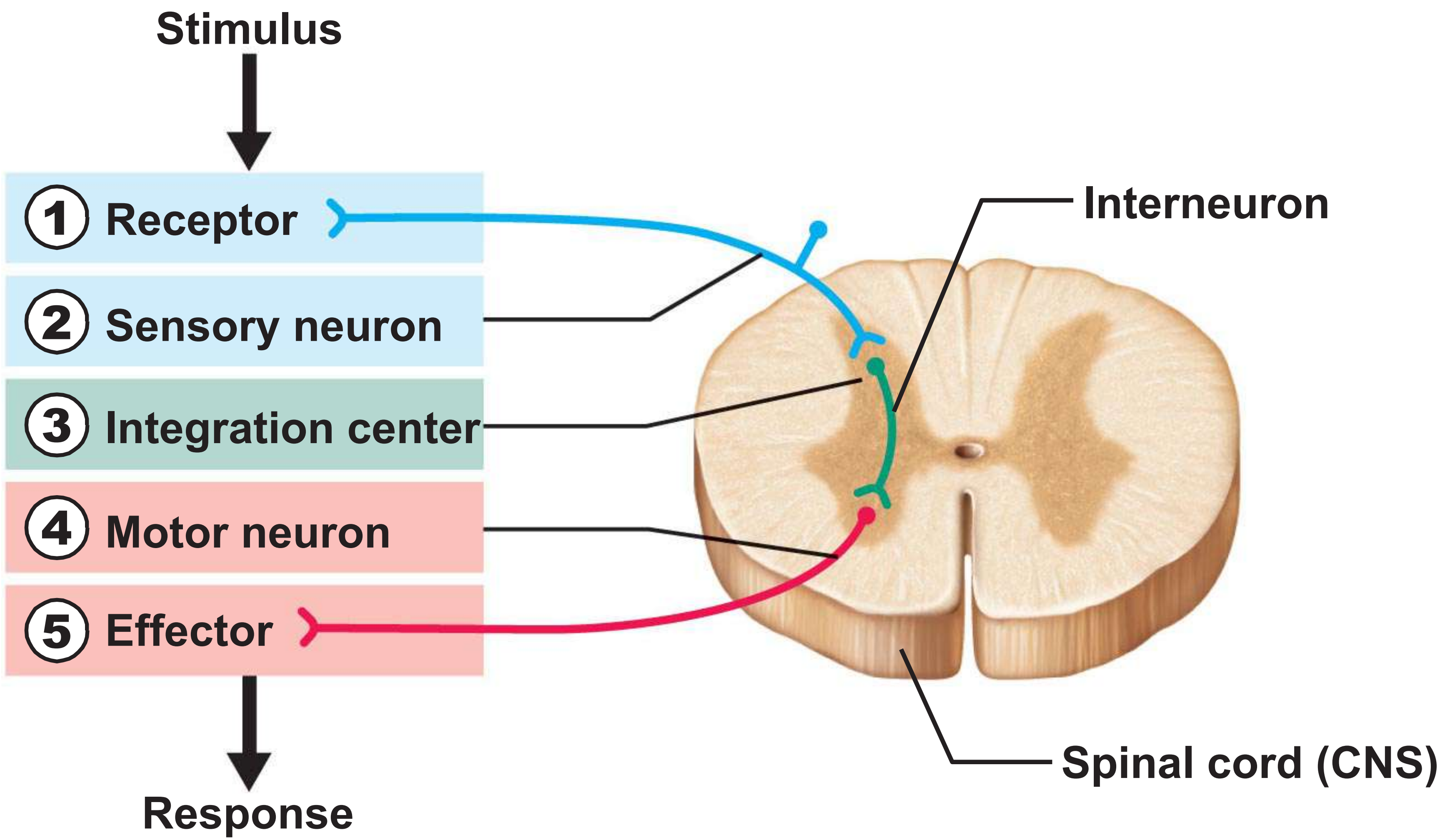

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Figure 11.23

Patterns of Neural Processing

- Parallel processing
  - Input travels along several pathways
  - One stimulus promotes numerous responses
  - Important for higher-level mental functioning
- Example: a smell may remind one of the odor and associated experiences

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Developmental Aspects of Neurons

- The nervous system originates from the neural tube and neural crest formed from ectoderm
- The neural tube becomes the CNS
  - Neuroepithelial cells of the neural tube undergo differentiation to form cells needed for development
  - Cells (neuroblasts) become amitotic and migrate
  - Neuroblasts sprout axons to connect with targets and become neurons

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Axonal Growth

- Growth cone at tip of axon interacts with its environment via:
  - Cell surface adhesion proteins (laminin, integrin, and nerve cell adhesion molecules or N-CAMs)
  - Neurotropins that attract or repel the growth cone
  - Nerve growth factor (NGF), which keeps the neuroblast alive
- Astrocytes provide physical support and cholesterol essential for construction of synapses

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Cell Death

- About 2/3 of neurons die before birth
  - Death results in cells that fail to make functional synaptic contacts
  - Many cells also die due to apoptosis (programmed cell death) during development

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