Overview: Lines of Communication

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

The cone snail is a deadly predator. Why?

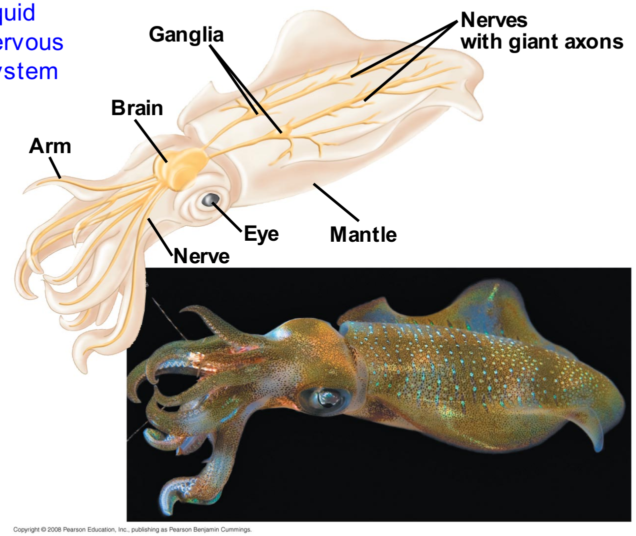
Signals Travel along a Path

- The transmission of information depends on the path of neurons along which a signal travels.
- Processing of information takes place in simple clusters of neurons called **ganglia** or a more complex organization of neurons called a **brain**.

Neuron organization and structure reflect function in information transfer

- The squid possesses extremely large nerve cells and is a good model for studying neuron function.
- Nervous systems process information in three stages: ***sensory input***, ***integration***, and ***motor output***.

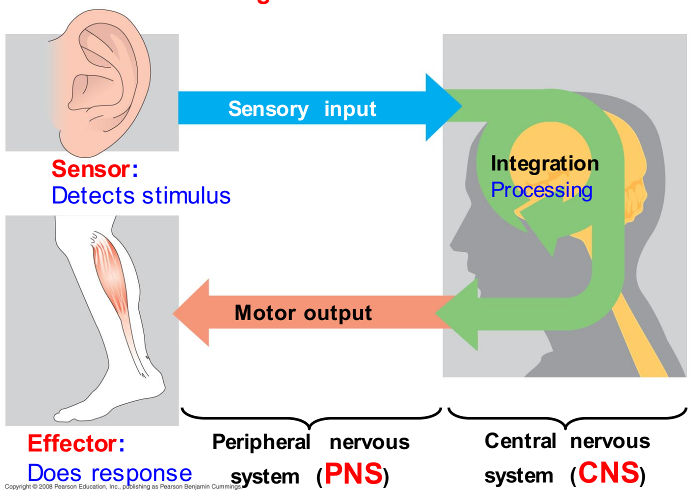
Squid Nervous System



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

- Many animals have a complex nervous system which consists of:
  - A **central nervous system (CNS)** where integration takes place; this includes the brain and a nerve cord.
  - A **peripheral nervous system (PNS)**, which brings information into and out of the CNS.

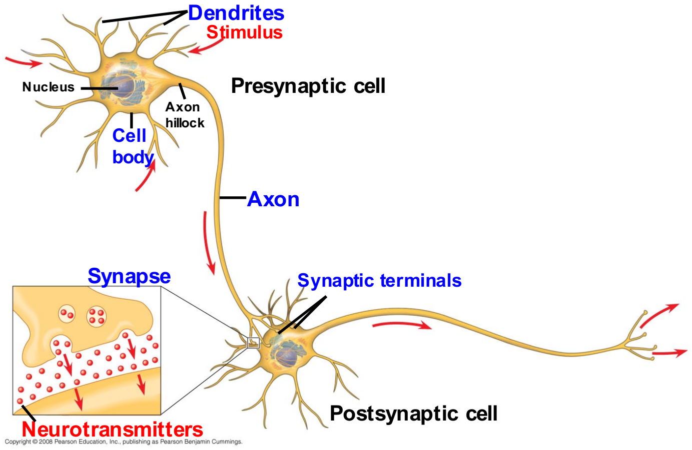
Information Processing



Neuron - Structure / Function Signal Transmission

- Most of a neuron’s organelles are in the **cell body**.
- Most neurons have **dendrites**, highly branched extensions that *receive* signals from other neurons.
- The **axon** is typically a much longer extension that *transmits* signals from its terminal branches to other cells at **synapses**.
- An axon joins the cell body at the **axon hillock.**

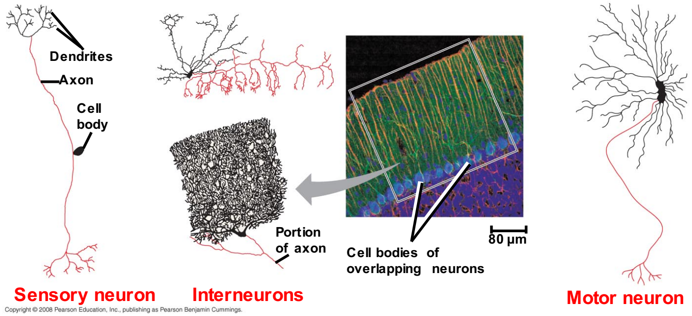
Neurons



A **synapse** is a junction between cells.

- The **synaptic terminal** of one axon passes information across the synapse in the form of chemical messengers called **neurotransmitters.**
- Information is transmitted from a **presynaptic cell** (a neuron) to a **postsynaptic cell** (a neuron, muscle, or gland cell).
- Most neurons are nourished or insulated by cells called **glia.**

Structural diversity of neurons



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

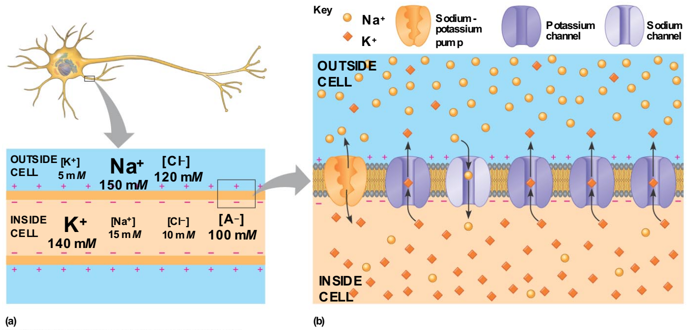
- Every cell has a voltage (**difference** in electrical charge) across its plasma membrane called a **membrane potential.**
- Messages are transmitted as changes in membrane potential.
- The **resting potential** is the membrane potential of a neuron not sending signals.

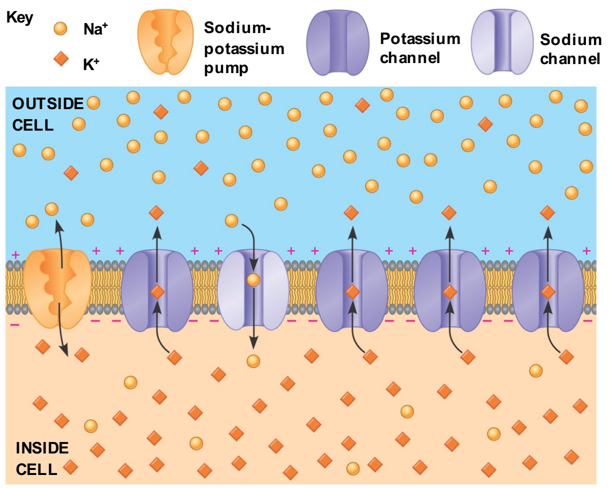
Formation of the Resting Potential

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

- The opening of **ion channels** in the plasma membrane converts chemical potential to electrical potential.
- A neuron at resting potential contains many open K^+ channels and fewer open Na^+ channels; K^+ diffuses out of the cell.
- Anions trapped inside the cell contribute to the negative charge within / inside the neuron.

The Basis of the Membrane Potential





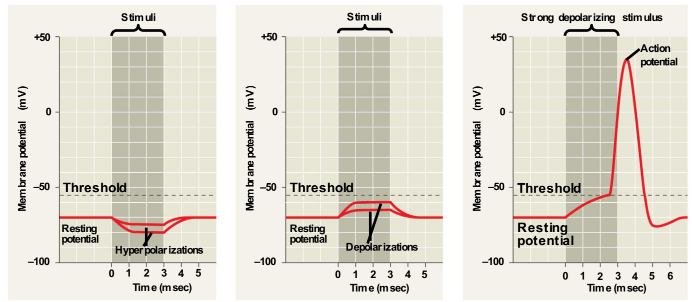
Modeling of the Resting Potential

- Resting potential can be modeled by an artificial membrane that separates two chambers.
- *At equilibrium, both the electrical and chemical gradients are balanced*.
- In a resting neuron, the currents of K^+ and Na^+ are equal and opposite, and the resting potential across the membrane remains steady.

Action potentials are the signals conducted by axons

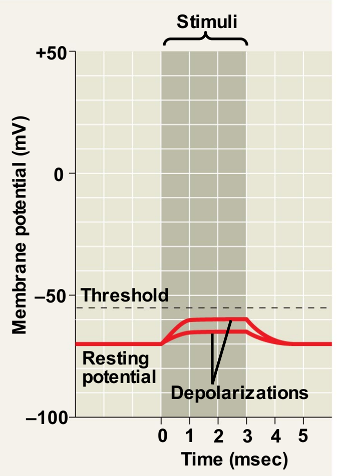
- Neurons contain **gated ion channels** that open or close in response to stimuli.
- Membrane potential changes in response to opening or closing of these channels.
- When gated K^+ channels open, ***K^+ diffuses out***, **making the inside of the cell more negative**. This is **hyperpolarization**, an increase in magnitude of the membrane potential / increase in difference between sides / farther from threshold.

Graded potentials and an action potential in a neuron



(a) Graded Hyperpolarizations (b) Graded Depolarizations (c) Action potential

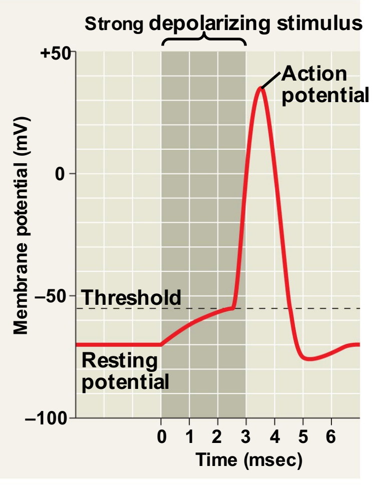
- Other stimuli trigger a **depolarization**, a reduction in the magnitude of the membrane potential.
- For example, *depolarization occurs if gated Na^+ channels open and Na^+ diffuses into the cell*.
- Graded potentials are changes in polarization where the magnitude of the change varies with the strength of the stimulus.



(b) Graded depolarizations – magnitude of the change varies with the strength of the stimulus.

Production of Action Potentials

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



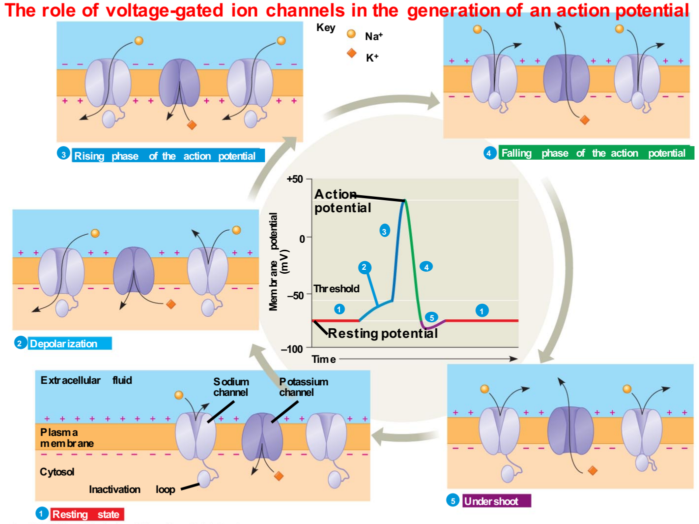
(c) Action potential = change in membrane voltage

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

Generation of Action Potentials: *A Closer Look*

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

The role of voltage-gated ion channels in the generation of an action potential



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

When an action potential is generated

2. Voltage-gated Na^+ channels open first and Na^+ flows into the cell.
3. During the *rising phase*, the threshold is crossed, and the membrane potential increases.
4. During the *falling phase*, voltage-gated Na^+ channels become inactivated; voltage-gated K^+ channels open, and K^+ flows out of the cell.
5. Cell is now repolarized but is not normal until Na^+ K^+ pump restores original resting potential.

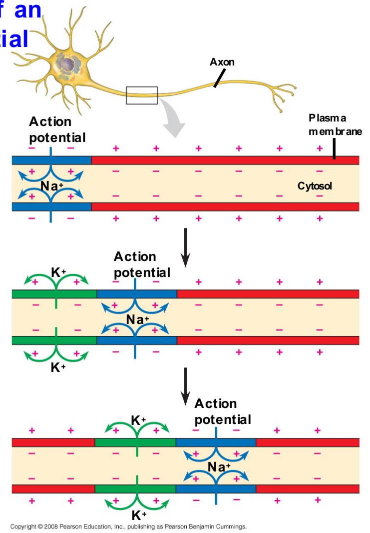
- During the **refractory period** after an action potential, a second action potential cannot be initiated. This ensures that an impulse moves along the axon in one direction only.
- The refractory period is a result of a temporary inactivation of the Na^+ channels.
- The **refractory period** is a period of "normal" repolarization when the **Na^+ K^+ pump restores the membrane to its <u>original</u> polarized condition**.

Conduction of Action Potentials

- An **action potential** can travel long distances by regenerating itself along the axon.
- At the site where the action potential is generated, usually the axon hillock, an electrical current **depolarizes** the neighboring region of the axon membrane.
- Inactivated **Na^+ channels** behind the zone of **depolarization** prevent the action potential from traveling backwards. *Action potentials travel in only one direction: toward the synaptic terminals.*

Conduction of an Action Potential

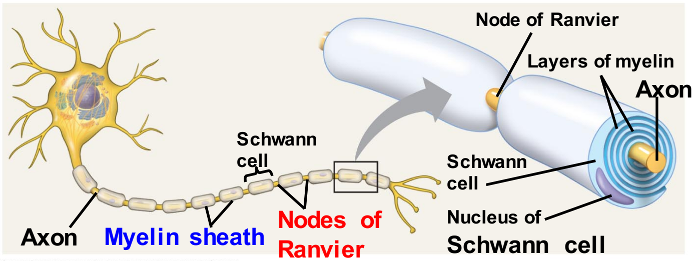
Signal Transmission



Conduction Speed

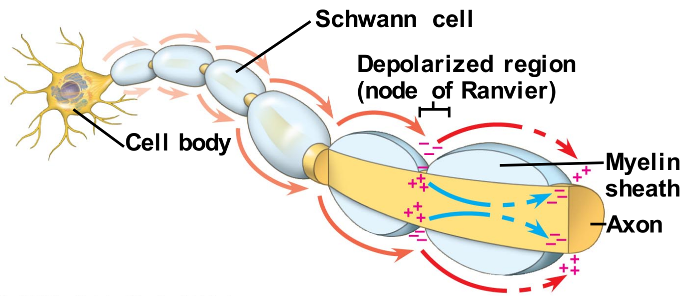
- The speed of an action potential increases with the axon's diameter.
- In vertebrates, axons are insulated by a **myelin sheath**, which causes an action potential's speed to increase.
- Myelin sheaths are made by glia—**oligodendrocytes** in the CNS and **Schwann cells** in the PNS.

Schwann cells and the myelin sheath



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

Saltatory conduction

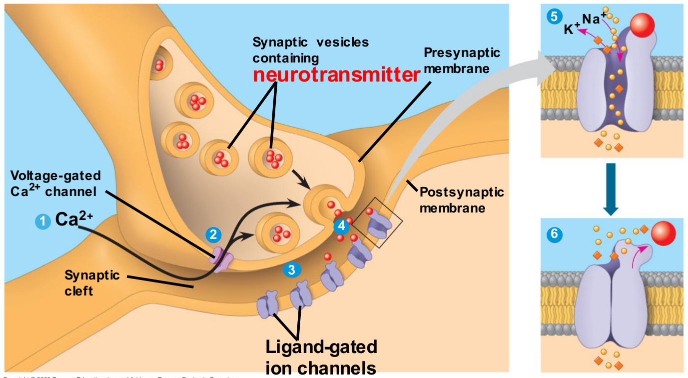


Neurons communicate with other cells at synapses

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

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

Chemical synapse



Generation of Postsynaptic Potentials

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

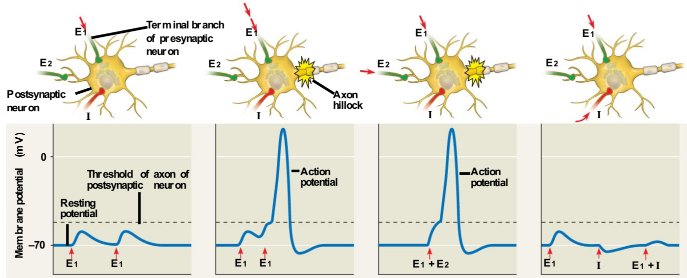
- **Postsynaptic potentials** fall into two categories:
  - **Excitatory postsynaptic potentials (EPSPs)** are depolarizations that bring the membrane potential toward threshold.
  - **Inhibitory postsynaptic potentials (IPSPs)** are hyperpolarizations that move the membrane potential farther from threshold.

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

Summation of Postsynaptic Potentials

- Unlike action potentials, postsynaptic potentials are graded and do not regenerate.
- Most neurons have many synapses on their dendrites and cell body.
- A single EPSP is usually too small to trigger an action potential in a postsynaptic neuron.
- If two EPSPs are produced in rapid succession, an effect called **temporal summation** occurs.

Summation of postsynaptic potentials



(a) Subthreshold, no summation (b) Temporal summation (c) Spatial summation (d) Spatial summation of EPSP and IPSP

- In spatial **summation**, EPSPs produced nearly simultaneously by different synapses on the same postsynaptic neuron **add together**. The combination of EPSPs through spatial and temporal summation can trigger an action potential.
- Through summation, an IPSP can counter the effect of an EPSP. The **summed effect** of EPSPs and IPSPs determines whether an axon hillock will reach threshold and generate an action potential.

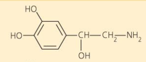
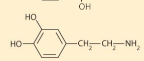
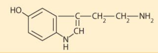
Modulated / Indirect Synaptic Transmission

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

Neurotransmitters

- The same neurotransmitter can produce different effects in different types of cells.
- There are five major classes of neurotransmitters: **acetylcholine**, **biogenic amines**, **amino acids**, **neuropeptides**, and **gases**.
- **Gases** such as nitric oxide and carbon monoxide are **local regulators** in the **PNS**.

Table 48.1 Major Neurotransmitters

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

Acetylcholine

- **Acetylcholine** is a common neurotransmitter in vertebrates and invertebrates.
- In vertebrates it is usually an excitatory transmitter.
- Common at the neuro-muscular junction.

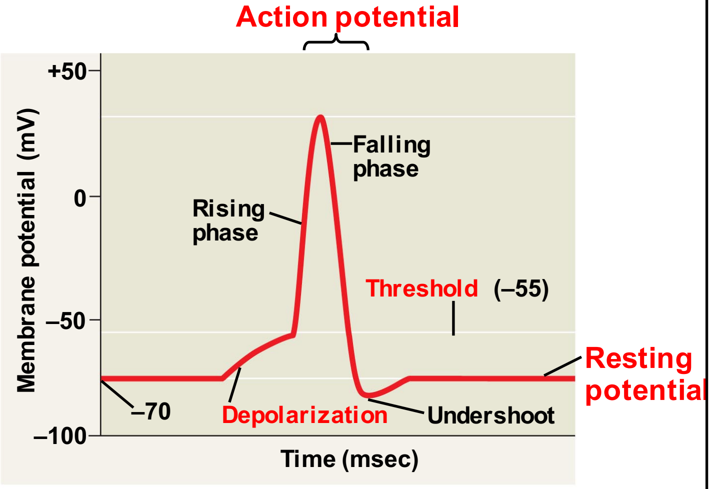
Biogenic Amines & Amino Acids

- **Biogenic amines** include **epinephrine**, **norepinephrine**, **dopamine**, and **serotonin**. They are active in the **CNS** and PNS.
- Two amino acids are known to function as *major neurotransmitters* in the **CNS**: **gamma-aminobutyric acid** (***GABA***) and ***glutamate***.

Neuropeptides

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

Review



You should now be able to:

1. Distinguish among the following sets of terms: sensory neurons, interneurons, and motor neurons; membrane potential and resting potential; ungated and gated ion channels; electrical synapse and chemical synapse; EPSP and IPSP; summation.
2. Explain the role of the sodium-potassium pump in maintaining the resting potential.

3. Describe the stages of an action potential; explain the role of voltage-gated ion channels in this process.
4. Explain why the action potential cannot travel back toward the cell body.
5. Describe saltatory conduction.
6. Describe the events that lead to the release of neurotransmitters into the synaptic cleft.

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