Functional Organization of Nervous Tissue
Chapter 11

FUNCTIONS OF THE NERVOUS SYSTEM

1. *Sensory input*. Sensory receptors detects external and internal stimuli.

2. *Integration*. The brain and spinal cord process sensory input and produce responses.

3. *Homeostasis*. The nervous system coordinates the activities of other systems in order to maintain homeostasis.

4. *Mental activities*. "I say to myself, Self? What do you think?"

5. *Controls muscles and glands*.

DIVISIONS OF THE NERVOUS SYSTEM

FIGURE 11.1

1. The nervous system can be divided into subdivisions based on structure and on function. Each of the these subdivisions are referred to as separate nervous systems. However, keep in mind that the subdivisions are all part of a single nervous system.

2. **Central nervous system (CNS)**.
   A. The CNS consists of the **brain** and **spinal cord**.

   B. The CNS is enclosed by bone (the skull and vertebrae).

3. **Peripheral nervous system (PNS)**.
   A. The PNS consists of sensory receptors, nerves, ganglia, and plexuses.

   B. **Sensory receptors** are the endings of nerve cells or separate, specialized cells. They detect stimuli, such as temperature, touch, pain, etc.

   C. **Nerves** are bundles of axons that connect the CNS to sensory receptors, muscles, and glands. Nerves are divided into two groups.
      1) **Cranial nerves**. Twelve pairs arise from the brain and exit through foramina in the skull.

      2) **Spinal nerves**. Thirty one pairs arise from the spinal cord and exit through the intervertebral or sacral foramina.

   D. A **ganglion** is a collection of neuron cell bodies in the PNS.

   E. A **plexus** is an extensive network of axons, and in some cases neuron cell bodies, in the PNS.

4. The PNS can be divided into two parts.

FIGURE 11.2

A. The **sensory,** or **afferent, division** carries action potentials TO the CNS.
   1) Sensory input can be at the conscious level, such as touch, taste, smell, sight, etc.

   2) Sensory input can be at the unconscious level, such as blood pressure, blood oxygen levels, etc.

B. The **motor,** or **efferent, division** carries action potentials FROM the CNS to effector organs and can be divided into two parts.
   1) The **somatic nervous system** innervates skeletal muscle. It is usually under voluntary conscious control, although reflexes are involuntary.

   2) The **autonomic nervous system (ANS)** innervates smooth muscle, cardiac muscle, and glands. It is usually under involuntary control, although biofeedback and meditation techniques can produce voluntary control of normally involuntary functions. The ANS can be divided into three parts.
      a. The **sympathetic division** prepares the body for physical activity.

      b. The **parasympathetic division** maintains normal resting functions, such as digestion of food.

      c. The **enteric nervous system** consists of plexuses in the wall of the digestive tract. Although it has sympathetic and parasympathetic neurons, it has its own neurons and can function independently of the CNS.

5. The central nervous system receives input from the PNS, integrates the input and causes a response. The CNS is the integrative and control center of the nervous system. The peripheral nervous system receives stimuli from the environment and conducts action potentials to and from the CNS.

FIGURE 11.3

CELLS OF THE NERVOUS SYSTEM

1. **Neurons** receive stimuli and conduct action potentials.

2. **Neuroglia** are support cells that perform a variety of functions. Neuroglia cells account for over half the brain's weight. There can be 10 to 50 times more neuroglia cells than neurons in various locations in the brain.

Neurons

FIGURE 11.4

1. The **neuron cell body** contains the nucleus, and the cell body is the site of manufacture of proteins (enzymes) necessary for neuron function.

2. **Dendrites** are short, cytoplasmic extensions from the neuron cell body. They are specialized to receive stimuli, which can result in the production of an action potential in the neuron.

3. **Axons**, or **nerve fibers**, are long cytoplasmic extensions from the neuron cell body.
   A. The axon arises from an enlarged area of the neuron cell body called the **axon hillock**. The beginning of the axon is called the **initial segment**. The **trigger zone** consists of the axon hillock and initial segment. It is where action potentials are generated.

   B. Axons are specialized to conduct action potentials to their ends, the **presynaptic terminals**. **Neurotransmitters** are chemicals released from the presynaptic terminals.

Types of Neurons

FIGURE 11.5

1. There are three types of neurons based on their structure.
   A. **Multipolar neurons** have several dendrites and one axon.

   B. **Bipolar neurons** have one dendrite and one axon.

   C. **Unipolar neurons** have one axon.
      1) During development unipolar neurons were originally bipolar neurons.

      2) The dendrite and axon migrated around the cell body and fused together.

      3) Usually the fused processes divide into two processes that are morphologically identical to axons, so both processes are called axons.

2. Types of neurons according to function.
   A. **Sensory neurons** transmit action potentials TO the CNS. Most are unipolar, but a few sensory neurons associated with the senses of sight, taste, hearing, and smell are bipolar.

   B. **Motor neurons** transmit action potentials AWAY FROM the CNS. They are multipolar.

   C. **Interneurons** transmit impulses from one neuron to another neuron. They are multipolar.

Neuroglia of the CNS
Astrocytes

FIGURE 11.6

1. **Astrocytes** have extensions that cover the surfaces of blood vessels and neurons.

2. Astrocytes function as a nonrigid supporting matrix for blood vessels and neurons in the brain.

3. Astrocytes help to regulate the composition of the extracellular fluid around neurons.
   A. Astrocytes remove and/or process materials that pass through blood vessels into the extracellular fluid.

   B. Astrocytes influence the formation of tight junctions between the epithelial cells of blood vessels. The epithelial cells form the **blood-brain barrier**, which controls what substances can enter the central nervous system.

Ependymal Cells

FIGURE 11.7

1. **Ependymal cells** line the cavities of the brain and spinal cord.

2. In specialized areas called the **choroid plexuses** they produce cerebrospinal fluid.

Microglia

FIGURE 11.8

1. **Microglia** are phagocytic cells in the CNS.

2. They engulf microbes or damaged tissue.

Oligodendrocytes

FIGURE 11.9

1. **Oligodendrocytes** surround axons in the central nervous system.

2. If the plasma membrane of an oligodendrocyte wraps many times around an axon, it forms a **myelin sheath**. Analogy: the axon is the cardboard center of a role of toilet paper, and the plasma membrane is the toilet paper.

3. The plasma membrane of an oligodendrocyte forms a myelin sheath around **more than one** axon.

Neuroglia of the PNS

FIGURE 11.10

1. **Schwann cells**, or **neurolemmocytes** surround axons in the peripheral nervous system.

2. If the plasma membrane of a Schwann cell wraps many times around an axon, it forms a myelin sheath.

3. The plasma membrane of a Schwann cell forms a myelin sheath around **one** axon.

4. **Satellite cells** are specialized Schwann cells that surround the cell bodies of neurons in the peripheral nervous system. They provide support and nutrients.

Myelinated and Unmyelinated Axons

FIGURE 11.11

1. **Myelin** is a lipoprotein (phospholipids, cholesterol, and proteins) in the plasma membrane. Myelin protects and electrically insulates axons.

4. Axons are **myelinated** when the axons are surrounded by myelin sheaths.
   A. The **node of Ranvier** is a gap in-between adjacent the myelin sheaths. It is a bare area of the axon.

   B. The myelin sheath in-between two nodes of Ranvier is called an **internode**.

   C. Oligodendrocytes form myelin sheaths in the CNS. Each oligodendrocyte forms a myelin sheath around several axons. Each myelin sheath formed by an oligodendrocyte is an internode. Thus oligodendrocytes form several internodes.

   D. Schwann cells form myelin sheaths in the PNS. Each Schwann cell surrounds one axon. Each Schwann cell is an internode.

5. Axons are **unmyelinated** when they rest in an invagination of an oligodendrocyte or Schwann cell.
   A. The plasma membrane does **NOT wrap** around the axon many times. Analogy: the plasma membrane is like the last layer of toilet paper that sticks to the cardboard (axon).

   B. Note that the plasma membrane of the oligodendrocyte and Schwann cells surrounds **more than one** axon.

   C. There is no gap or space in-between adjacent oligodendrocytes or Schwann cells. There are no nodes of Ravier in unmyelinated axons.

6. Myelinated axons conduct action potentials more rapidly than do unmyelinated axons.

The Role of Schwann Cells in Nerve Repair

FIGURE 11A, p. 395
(see Clinical Focus Essay)

1. Following injury to a nerve the axon distal to the injury degenerates.

☞ Explain why the distal part of the axon degenerates.

2. Schwann cells distal to the injury degenerate (lose their myelin sheath), divide, and form a column of cells.

3. The axon proximal to the injury grows through the column of Schwann cells and reinnervates structures distal to the injury.

4. Reinnervation depends upon the Schwann cell columns. If the column does not align with the growing axon, reinnervation does not occur.

5. In the CNS, regeneration of axons is very poor compared to the PNS. Following injury the oligodendrocytes do not form columns to guide the axon.

ORGANIZATION OF NERVOUS TISSUE

1. **Gray matter** is collections of neuron cell bodies and unmyelinated axons. **White matter** is collections of myelinated axons (myelin sheaths appear white).

2. Central nervous system.
   A. Gray matter forms the **cortex** (outer surface of the brain), **nuclei** (discrete collections of neuron cell bodies), and the **central area of the spinal cord**.

   B. **Nerve tracts** are collections of axons in the CNS. Nerve tracts can be myelinated or unmyelinated.

3. Peripheral nervous system.
   A. A **ganglion** (plural = ganglia) is a collection of neuron cell bodies in the PNS.

   B. A **nerve** is a collection of axons in the PNS. Nerves can be myelinated or unmyelinated.

ELECTRIC SIGNALS

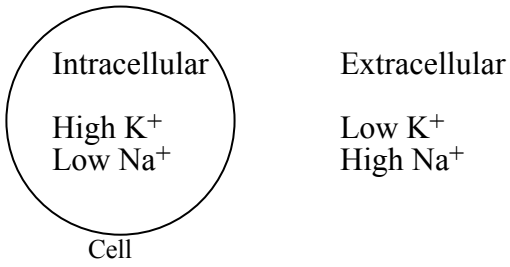
1. Cells can communicate using electric signals called action potentials.

2. To understand action potentials, it is first necessary to understand that the electrical properties of cells result from (1) the concentration differences of ions across the plasma membrane, and (2) the permeability characteristics of the plasma membrane.

Concentration Differences Across the Plasma Membrane

1. **Intracellular fluid** is the fluid inside cells and accounts for about two thirds of the body's fluids. The remaining one third is **extracellular fluid,** which consists mostly of interstitial fluid (around cells, also called intercellular fluid), lymph, and plasma.

2. The concentration of potassium ions (K^+) is higher inside cells (intracellular fluid) than outside cells (extracellular fluid). The concentration of sodium ions (Na^+) is higher outside cells than inside cells.

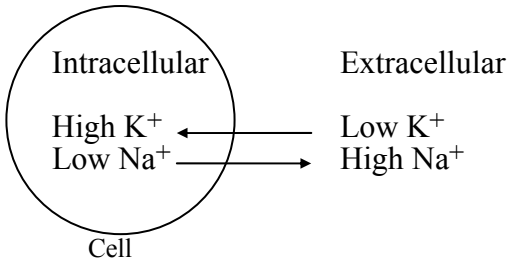


The Na^+ - K^+ Pump

FIGURE 3.21. p. 72

1. The Na^+ - K^+ pump maintains the concentration difference of Na^+ and K^+ across the plasma membrane.

2. The Na^+ - K^+ pump uses active transport to move Na^+ out of the cell and K^+ into the cell against their concentration gradients.



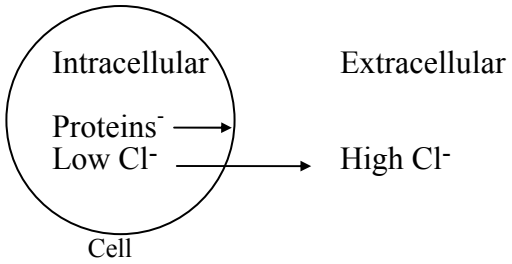
Permeability Characteristics of the Plasma Membrane

FIGURE 11.12

1. The plasma membrane is selectively permeable, allowing some substances to pass through the membrane, but not others.

2. For example, the proteins synthesized within the cell are too large to pass through membrane channels and are not soluble in the phospholipid portion of the membrane. It makes sense to keep these proteins within the cell because they are necessary for cell function.

3. Some ions can pass through membrane channels. For example, K^+, Na^+, and Cl^-. Because the negatively charged Cl^- are repelled by the negatively charged proteins, the Cl^- move out of the cell and are in a higher concentration outside the cell than inside.



Leak Channels

1. **Leak channels (leak channels)** are always open and are responsible for the permeability characteristics of the resting plasma membrane.

2. Each leak channel is (mostly) specific for one ion. For example, there are K^+, Na^+, and Cl^- leak channels.

3. The membrane is much more permeable to K^+ and Cl^- than Na^+ because there are many more K^+ and Cl^- leak channels than Na^+ leak channels.

Gated Ion Channels

1. **Gated ion channels** can open and close in response to stimuli. By opening and closing, they change the permeability characteristics of the plasma membrane.

2. There are three kinds of gated ion channels.
   A. **Ligand-gated ion channels** open or close as a result of a ligand binding to its receptor. The ligands that stimulate ion channels in the human body are often neurotransmitters released from nerve endings. Thus, the nervous system can cause ion channels to open or close.

FIGURE 3.10, p. 63

B. **Voltage-gated ion channels** open and close in response to small voltage changes across the plasma membrane. The small voltages are measured in units called **millivolts**. A millivolt (mV) is 1/1000 of a volt. This type of ion channel is important in the production of action potentials.

C. **Other gated ion channels** open or close in response to stimuli such as temperature and pressure.

The Resting Membrane Potential

FIGURE 11.13

1. The kinds of ions and proteins in the intracellular fluid are different from those in the extracellular fluid. SEE TABLE 11.1. For example, the concentrations of Na^+ and K^+ are different.

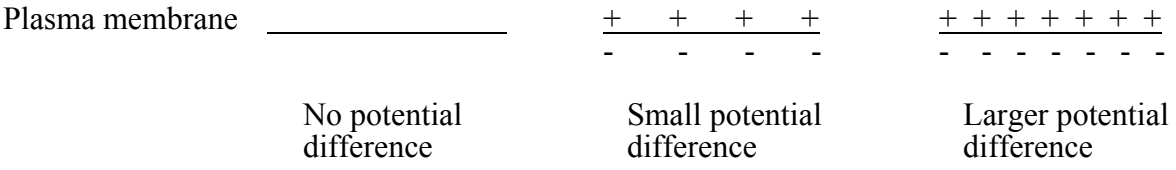
2. The intracellular and extracellular fluids are electrically neutral.
   A. In the intracellular fluid, the number of plus charges equals the number of minus charges.

   B. In the extracellular fluid, the number of plus charges equals the number of minus charges.

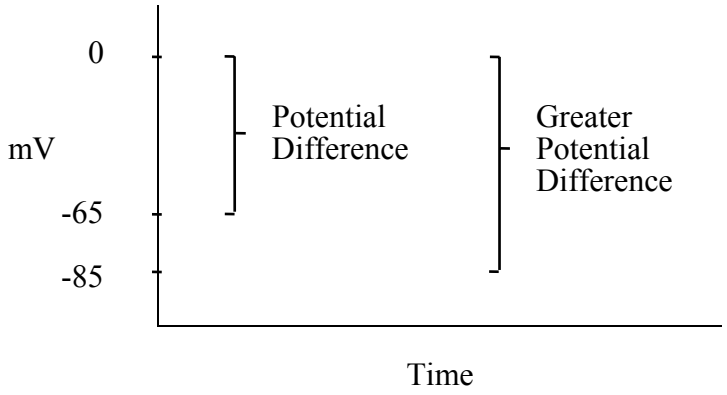
3. An electrical charge difference, called a **potential difference**, exists across the plasma membrane. The potential difference can be measured by placing microelectrodes on either side of the plasma membrane.
   A. The potential is reported as a negative number. The negative number indicates that the inside of the plasma membrane is negative compared to the outside of the plasma membrane.

   B. The potential is a measure of the number of plus and minus charges separated across the plasma membrane. Analogy: the plasma membrane with a resting membrane potential is like a battery with a plus pole and a minus pole.
      1) If there are no separated plus and minus charges across the plasma membrane, the potential difference is zero.

      2) The greater the number of separated plus and minus charges, the greater is the potential difference.



4. Note that the larger the negative number, the greater the potential difference.



5. In an unstimulated cell, the potential difference is called the **resting membrane potential (RMP)**. Examples of resting membrane potentials:

Nerve cell	-40	to	-70 mV
Skeletal muscle cell	-70	to	-90 mV
Gland cell	-30	to	-90 mV

Establishing the Resting Membrane Potential

FIGURE 11.14

SEE ALSO TABLE 11.2

1. The resting membrane potential results primarily from the accumulation of K^+ on the outside of the plasma membrane.

2. There is a higher concentration of K^+ inside the cell than outside. Therefore, K^+ diffuse out of the cell through K^+ leak channels. Thus, there is a slight <u>leakage</u> of K^+ out of the cell.

3. Negatively charged proteins, which are contained within the cell, attract the positively charge K^+ back toward the cell. At equilibrium, the tendency for the K^+ to diffuse down their concentration gradient out of the cell is counteracted by the tendency of the K^+ to be attracted back into the cell by the negatively charged proteins.

4. Big picture: The greater the number of K^+ on the outside of the plasma membrane, the greater is the resting membrane potential.

5. Although K^+ are the most important ions for establishing the resting membrane potential, other ions, such as Na^+ play a role.

FIGURE 11.14

   A. The Na^+ - K^+ pump functions to maintain the K^+ and Na^+ concentration gradients across the plasma membrane.

   B. Three Na^+ are pumped out of the cell for every two K^+ pumped into the cell. As a result, the outside of the plasma membrane becomes slightly more positive. Thus the Na^+ - K^+ pump contributes to the hyperpolarization of the plasma membrane.

Changing the Resting Membrane Potential

1. The resting membrane potential can depolarize or hyperpolarize.

FIGURE 11.15

   A. **Depolarization** occurs when the resting membrane potential becomes smaller (less negative, the graph line moves up toward zero).

   B. **Hyperpolarization** occurs when the membrane potential becomes larger (more negative, the graph line moves down away from zero).

Potassium Ions

1. Hyperpolarization results from the increased movement of K^+ out of cells. Increased movement of K^+ out of cells results in more K^+ on the outside of the membrane, a larger membrane potential, and hyperpolarization.
   A. Increase the K^+ concentration gradient by decreasing the extracellular K^+ concentration or by increasing the intracellular K^+ concentration.

   B. Increase membrane permeability to K^+. For example, by opening voltage-gated K^+ channels during the repolarization phase of the action potential.

2. Depolarization results from the decreased movement of K^+ out of cells. Decreased movement of K^+ out of cells results in fewer K^+ on the outside of the membrane, a smaller membrane potential, and depolarization.
   A. Decrease the K^+ concentration gradient by increasing the extracellular K^+ concentration or by decreasing the intracellular K^+ concentration.

   B. Decrease membrane permeability to K^+.

Sodium Ions

1. Depolarization can result from the increased movement of positively charged ions into the cell.

2. Increase membrane permeability to Na^+ by opening ligand-gated Na^+ channels or voltage-gated Na^+ channels. For example, at the neuromuscular junction.

Calcium Ions

1. Depolarization can result from the increased movement of positively charged ions into the cell. The role of Ca^{2+} and gated Ca^{2+} channels in cardiac muscle membrane potentials will be covered in Bio 202.

2. Calcium ion concentrations can affect membrane potentials by altering Na permeability.
   A. Ca^{2+} are bound to voltage-gated Na^+ channels.

   B. When extracellular Ca^{2+} decreases, Ca^{2+} unbinds from voltage-gated Na^+ channels and they open. The increased movement of Na^+ into cells causes depolarization.

   C. When extracellular Ca^{2+} increases, Ca^{2+} binds to voltage-gated Na^+ channels and they close. The decreased movement of Na^+ into cells causes hyperpolarization.

Chloride ions

1. The movement of negatively charged Cl^- into cells can make the inside of the membrane more negative, resulting in hyperpolarization.

2. Membrane permeability to Cl^- increases when gated Cl^- channels open.

Graded Potentials

TABLE 11.3

1. A stimulus applied to the plasma membrane can cause a **graded potential**, which is a change in the resting membrane potential that can vary from small to large.

FIGURE 11.16

   A. Stimulus strength: A weak stimulus produces a small graded potential, whereas a stronger stimulus produces a larger graded potential.

   B. Stimulus frequency: If stimuli (of the same strength) are applied rapidly, one after the other, the effect of the second stimulus **summates**, or accumulates, producing a larger graded potential than would a single stimulus.

2. Graded potentials can result from ligands binding to their receptors. We have seen that one consequence of a ligand, such as acetylcholine, binding to its receptor, is the opening of a ligand-gated Na^+ channel. When Na^+ diffuse into the cell, they cause depolarization, that is, a graded potential.

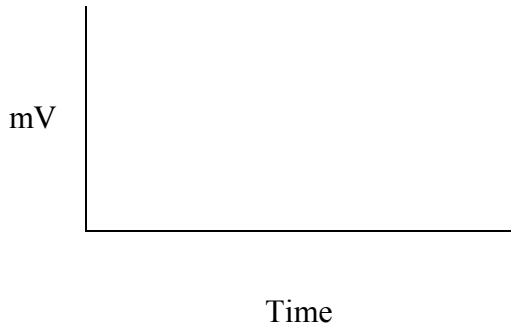
3. Other causes of graded potentials are changes in the voltage difference across the plasma membrane, mechanical stimulation, temperature changes, and spontaneous changes in membrane permeability.

4. Graded potentials are also called **local potentials** because they are confined to a small area of the plasma membrane.

5. Graded potentials spread over the surface of the plasma membrane in a **decremental fashion**, meaning that the magnitude of the graded potential decreases as it spreads. Analogy: When shouting at someone, the sound is loud close up, but fades the farther away you get. No sound is heard far away (the graded potential is confined to a small area of the plasma membrane).

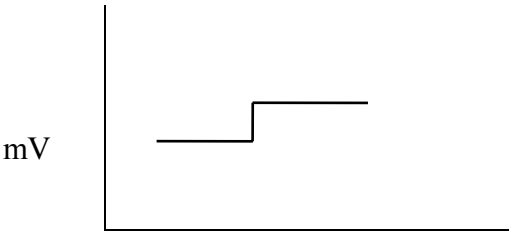
6. A graded potential can be a depolarization or a hyperpolarization.

☞ If membrane permeability to K^+ increased would you expect the graded potential to be a depolarization or a hyperpolarization. Explain.



Review of Important Points:

Location of the higher concentration of K^+?	Inside cell, outside cell
Charge on the outside of the plasma membrane?	Positive, negative
Charge on the outside of the plasma membrane results <u>primarily</u> from what type of ion?	K^+, Na^+
Result of decreasing the number of K^+ on the outside of the plasma membrane?	Depolarization, hyperpolarization
What is the change on the graph below called?	Depolarization, hyperpolarization



Effect of decreasing the K^+ concentration gradient?	Depolarization, hyperpolarization
Effect of decreasing K^+ membrane permeability?	Depolarization, hyperpolarization

Action Potentials

TABLE 11.4

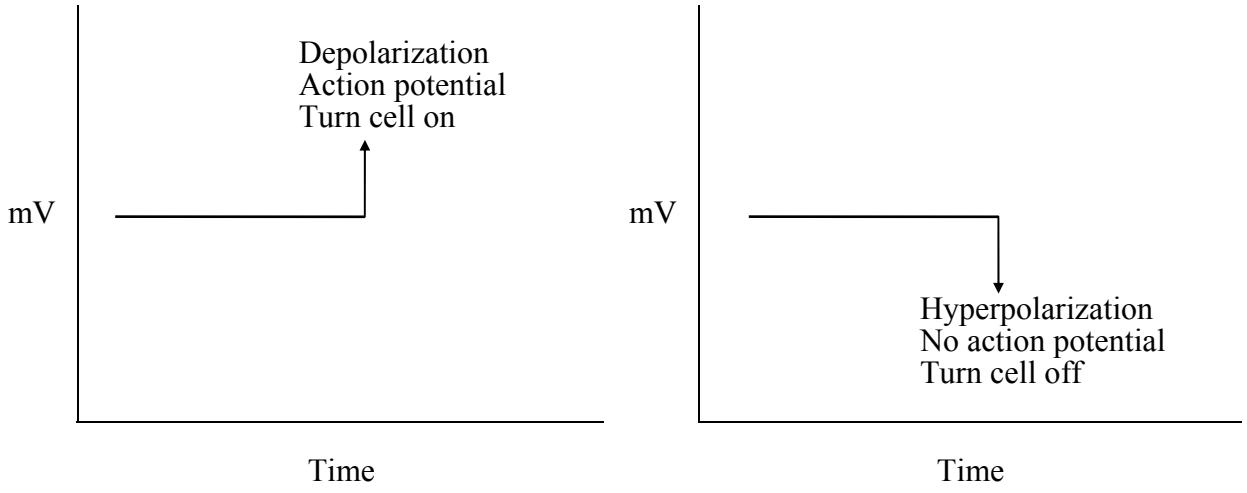
1. An **action potential** is a signal that causes a cell to increase or decrease an activity. For example, an action potential in a muscle cell results in muscle cell contraction.

2. In the brain and spinal cord, action potentials are responsible for the interactions between nerve cells that result in thoughts, sensations, and the ability to control body movements. An **electroencephalogram (EEG)** measures the action potentials of the brain.

3. In nerves, a propagated action potential is what is commonly called a **nerve impulse**. Thus, action potentials are a means of communicating between the brain and other cells of the body. We are aware of stimuli because receptor cells generate action potentials that are propagated to our brain. Our brain is able to generate action potentials that stimulate muscles to contract or glands to secrete.

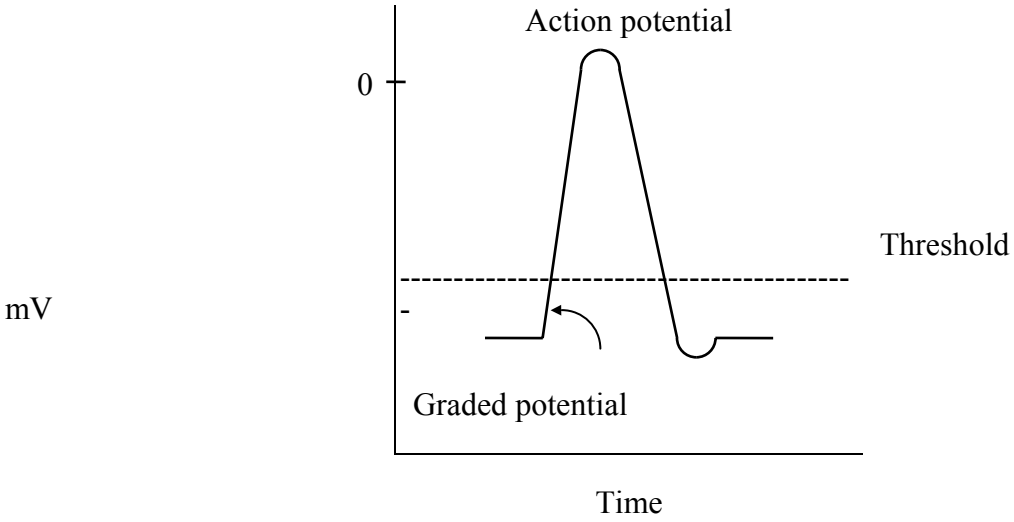
4. Stimuli can cause a change in the resting membrane potential, that is, stimuli can cause a graded potential that is a depolarization or hyperpolarization.
   A. A depolarizing graded potential of sufficient magnitude can produce an action potential.

   B. A hyperpolarizing graded potential can never produce an action potential.



   C. Analogy. The resting membrane potential is like constructing a light switch. There must be something capable of being changed in response to a stimulus. When the switch is in the off position (resting membrane potential), flipping the switch up (depolarization) turns on the light (produces an action potential), which is a signal to the cell that leads to a cellular response. When the switch is in the off position, flipping it down even more (hyperpolarization) does not turn on the light.

5. When the graded potential depolarizes to a level called the **threshold potential** an action potential results. The graded potential is now the beginning of the action potential.

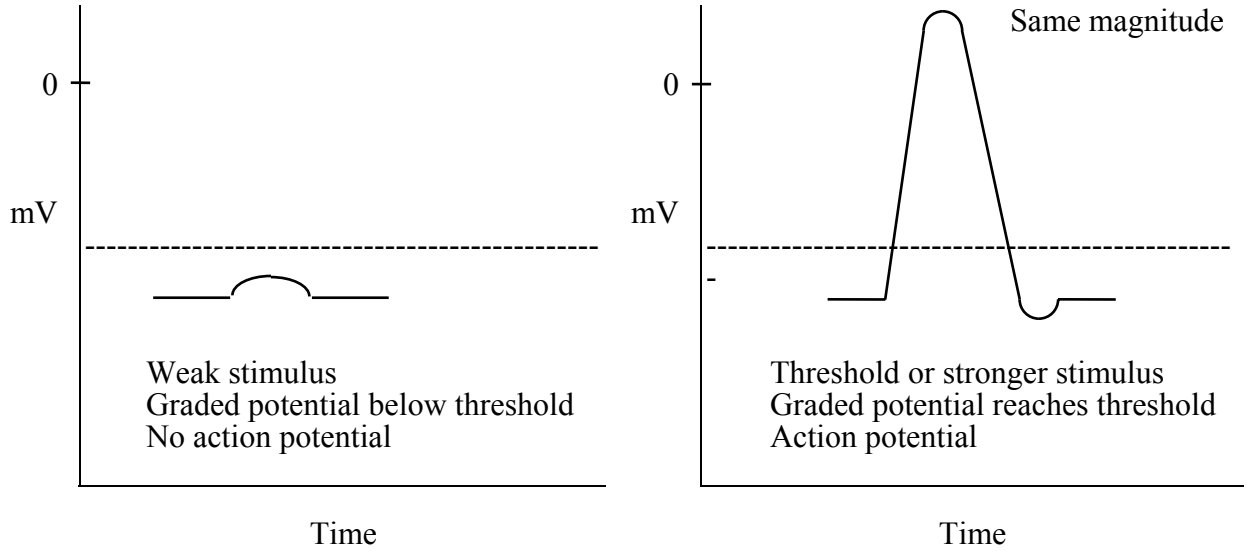


6. The **all-or-none law of action potentials**: When a cell is stimulated, it either produces an action potential of the same magnitude or it does not produce an action potential.
   A. If the graded potential does not reach threshold there is no action potential. This is the "none" part of the all-or-none law.

   B. The action potential results from ion channels opening and allowing ion movement. Because all the channels open, the resulting action potential is always of the same magnitude (for a given condition). This is the "all" part of the all-or-none law.

   C. In contrast to graded potentials, action potentials are <u>not</u> graded.

   D. Analogy: the resting membrane potential is like a light switch. Movement toward the on position does not turn on the light (none part). When contact is made the light goes on (all part). Each time the light is on, the brightness is the same (same magnitude). But conditions can change the magnitude, for example, use a 25 watt versus 100 watt bulb.



7. The action potential has two phases.

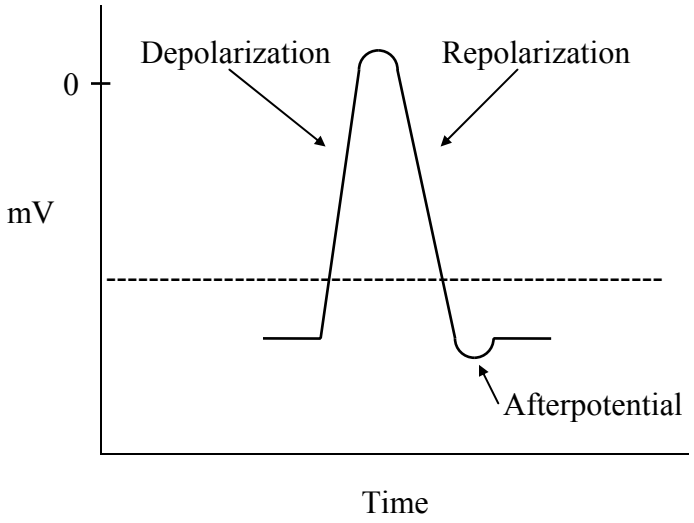
FIGURE 11.17 and 11.18

   A. In **depolarization** the membrane potential moves away (becomes more positive) from the resting membrane potential. Usually the membrane potential switches polarity from a negative to a positive value.

   B. In **repolarization** the membrane potential returns to the resting state.

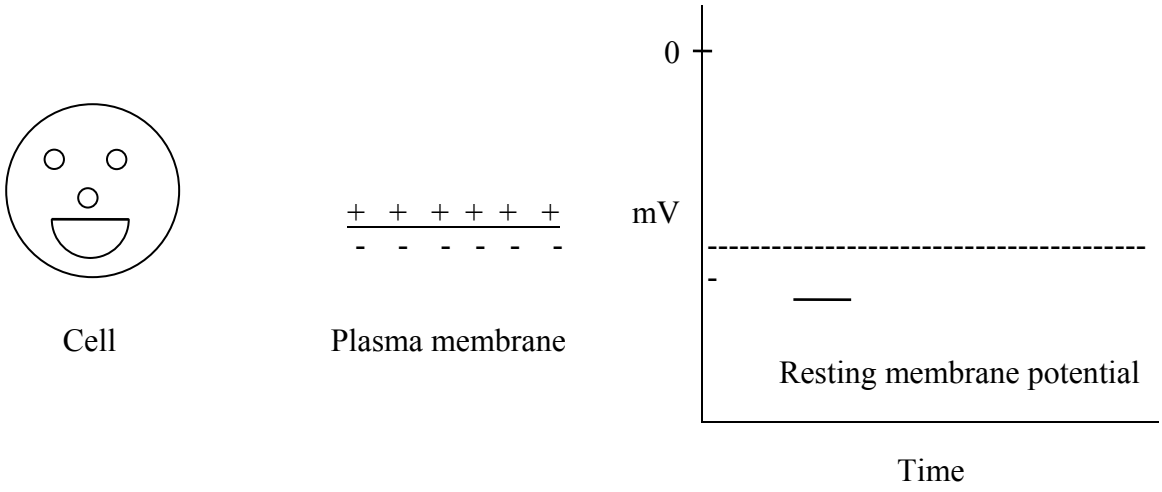
   C. The action potential takes approximately 1 to 2 msec (1 msec is 1/1000 of a second).

8. After repolarization, the membrane can be slightly <u>hyperpolarized</u> for a short period called the **afterpotential**, before polarity returns to the resting state.



Depolarization Phase

1. The resting membrane potential before stimulation.

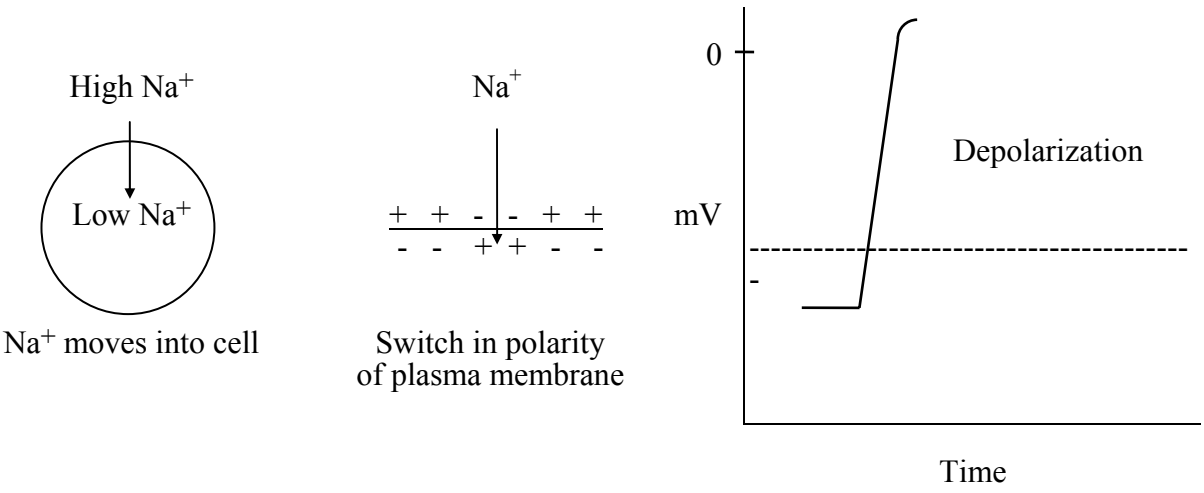


2. Depolarization.
   A. A stimulus causes a few Na^+ channels to open. Na^+ move into the cell producing a graded potential.

   B. The graded potential causes the **activation gates** of voltage-gated Na^+ channels to open. More Na^+ move into the cell and the graded potential reaches threshold.

   C. At threshold, most of the voltage-gated Na^+ channels open and depolarization results.

   D. The graded potential also causes voltage-gated K^+ channels to open, but they open more slowly than the voltage-gated Na^+ channels. Consequently, few K^+ move through the membrane during depolarization.

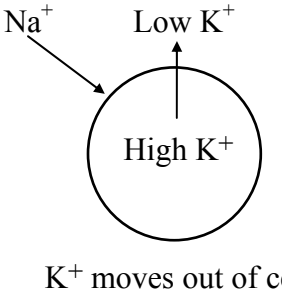


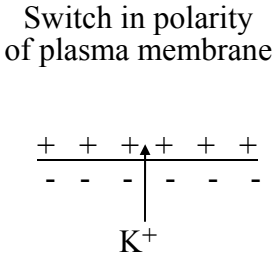
Repolarization Phase

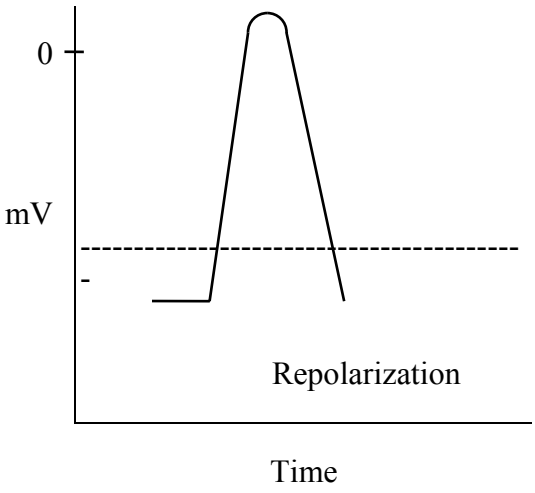
1. The **inactivation gates** of voltage-gated Na^+ channels close and Na^+ movement into the cell stops.

2. The voltage-gated K^+ channels continue to open and K^+ move out of the cell producing repolarization.

3. Closing the activation gates and opening the inactivation gates returns the voltage-gated Na^+ channels to their resting condition.



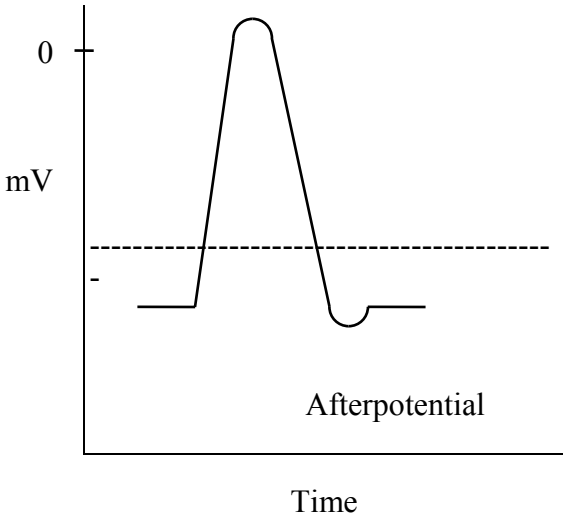




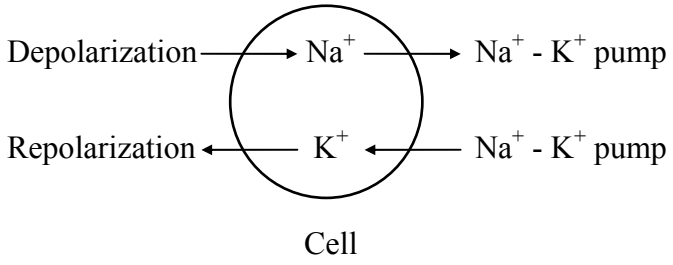
Afterpotential

1. In many cells, following repolarization there is a short period of hyperpolarization called the **afterpotential**.

☞ Explain how the afterpotential is produced? (Hint: membrane permeability)



2. One problem remains. During the action potential Na^+ moved into the cell and K^+ moved out. This changes the normal ionic balance. The Na^+ - K^+ pump restores ion balance by moving Na^+ out of the cell and K^+ back into the cell.



Refractory Period

FIGURE 11.19

1. The ability of a plasma membrane to respond to a stimulus is affected by its refractory periods.

2. During the **absolute refractory period**, a second stimulus, no matter how strong, will NOT be able to stimulate a second action potential.
   A. Depolarization ends when the inactivation gates close.

   B. The absolute refractory period ends when the activation gates close and the inactivation gates open. That is, when the voltage-gated Na^+ channels return to their resting condition.

3. During the **relative refractory period** a stronger than threshold stimulus is required to produce a second action potential.
   A. The relative refractory period ends when the voltage-gated K^+ channels close. That is, when they return to their resting condition.

   B. Note that an action potential produced during the relative refractory period is the same magnitude as the original action potential because of the all-or-none law of action potentials.

Action Potential Frequency

FIGURE 11.20

1. The total number of action potentials generated by a cell depends upon the strength of the stimulus and the length of time the stimulus is applied.

2. The strength of the stimulus determines the **action potential frequency**, that is, the number of action potentials produced per unit of time.
   A. A **subthreshold stimulus** does not produce an action potential. This occurs because the graded potential produced by the stimulus does not reach threshold.

   B. A **threshold stimulus** produces a single action potential. The graded potential reaches threshold.

   C. A **maximal stimulus** produces a maximum frequency of action potentials. The stimulus is so strong that, after one action potential is produced, another is immediately produced.

   D. A **submaximal stimulus** is between a threshold and maximal stimulus in strength and produces an intermediate frequency of action potentials.

   E. A **supramaximal stimulus** is a stronger stimulus than a maximal stimulus, but it still produces the same frequency of action potentials as a maximal stimulus. You can't produce more than a maximum frequency.

☞ What determines the maximum frequency of action potentials that can be generated by a cell?

☞ A low frequency of action potentials from touch receptors in the skin is interpreted by the brain as a light touch, whereas a high frequency of action potentials is interpreted as a heavy touch. Why can't the brain rely upon the magnitude of the action potential to determine if there was a light touch or a heavy touch?

Propagation of Action Potentials

FIGURE 11.21

1. Action potentials move, or **propagate**, along the plasma membrane. An action potential at one point on the plasma membrane is a stimulus that causes voltage-gated Na^+ channels in adjacent areas to open, resulting in an action potential in the adjacent area.

2. Action potentials are typically generated at the trigger zone and propagate in one direction along the axon.

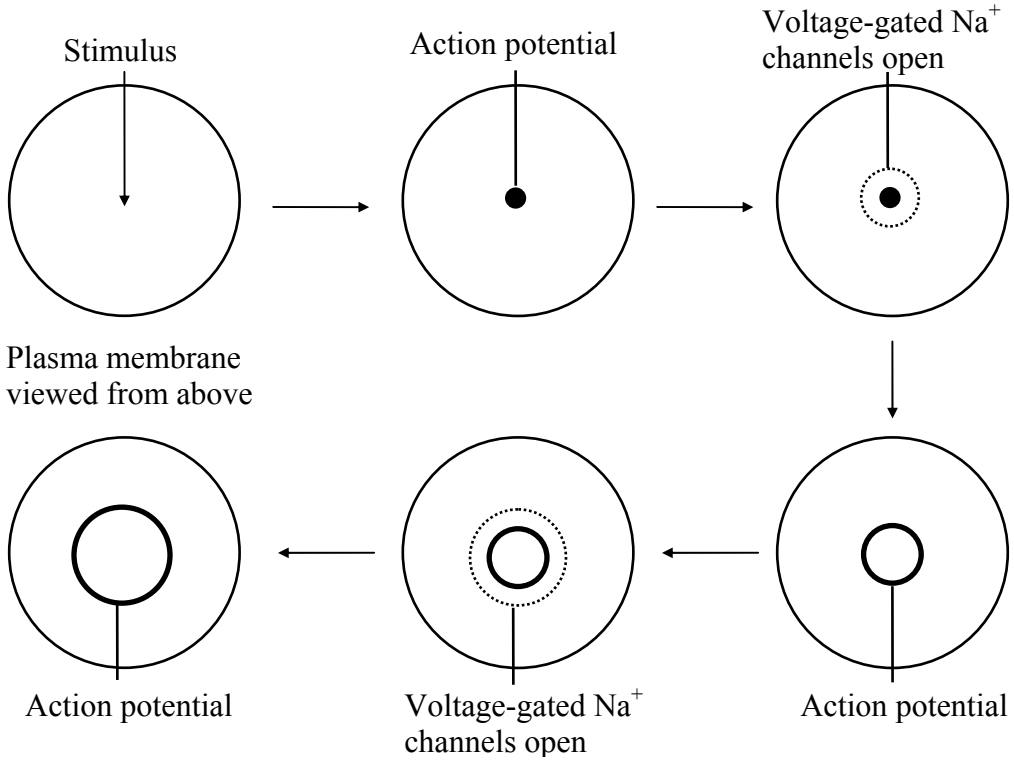
3. The locations in axons at which action potentials are generated is different for unmyelinated and myelinated axons.

4. In unmyelinated axons, the another action potential is generated in the area immediately adjacent to an action potential.
   A. An action potential results in the inside of the membrane becoming positively charged.

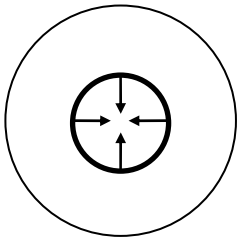
   B. An **ionic current** is the movement of positively charged ions. During an action potential, Na^+ flow into the cell at the site of the action potential. On the inside of the plasma membrane, some of the Na^+ are attracted to the negative charges in the part of the membrane adjacent to the site of the action potential.

   C. The ionic current (movement of Na^+) causes the adjacent area to become more positively charged. That is, it produces a depolarizing graded potential.

   D. When the graded potential reaches threshold, it stimulates voltage-gated Na^+ channels to open and an action potential is produced. Analogy: pebble in a pond.



☞ Why doesn't the action potential propagate back in the direction it just came from?



5. Action potentials are conducted down myelinated axons by **saltatory conduction**.

FIGURE 11.22

   A. An action potential at one node of Ranvier produces an ionic current that flows to the next adjacent node where it causes the production of an action potential.

   B. The myelin sheath acts as an insulator that forces the ionic current to flow to the next node.

6. Speed of action potential conduction.
   A. Myelinated nerve fibers conduct action potentials faster than unmyelinated fibers. Analogy: myelinated conduction is like a cricket jumping, whereas unmyelinated conduction is like a cricket walking.

   B. Large diameter nerve fibers conduct action potentials faster than small diameter axons.

7. Types of nerve fibers.

Fiber Type	Diameter	Sheath	Conduction Rate (m/sec)
Type A	Large	Myelinated	15 to 120 (1 s goal post to goal post)
Type B	Medium	Myelinated	3 to 15
Type C	Small	Unmyelinated	0.5 to 2 (4 min goal post to goal post)

8. Distribution of fiber types.
   A. Motor neurons to skeletal muscles are the largest, most heavily myelinated followed by most sensory neurons. These are type A fibers.

   B. Motor neurons of the ANS to cardiac muscle, smooth muscle, and glands are mostly type B and C fibers.

   C. The size and myelination of fibers is related to their function:
      1) The larger diameter and myelination of type A fibers allows rapid input of sensory information and rapid response by skeletal muscles. This ensures a rapid response to the external environment, which is necessary for survival. However, these neurons take up more space and require more maintenance.

      2) ANS functions, such as digestion and defecation don't require as rapid a response. Therefore smaller type B and C fibers are adequate, and these fibers don't take up as much space and require less maintenance..

   D. There are two types of pain fibers: A and C.
      1) Type A fibers transmit action potentials that are perceived as a sharp, localized pricking pain sensation. As a result, there is a rapid response to the pain stimulus.

      2) Type C fibers transmit action potentials that are perceived as a burning, aching pain. Awareness of the pain prevents further damage. For example, you "favor" an injured part of the body.

THE SYNAPSE

1. A **synapse** is the junction between two cells.

2. The **presynaptic cell** carries action potentials toward the synapse and the **postsynaptic cell** carries them away.

Electrical Synapses

1. **Electrical synapses** are low electrical resistance **gap junctions** between the plasma membranes of adjacent cells, such as between smooth muscle cells or between cardiac muscle cells.

2. The ionic current produced by an action potential in one cell passes through the gap junction to a second cell, causing an action potential in the second cell.

FIGURE 11.23

Chemical Synapses

1. A **chemical synapse** consists of a **presynaptic terminal** (end of an axon), **synaptic cleft** (small space), and **postsynaptic membrane** (specialized part of the plasma membrane of the postsynaptic cell).

FIGURE 11.24

2. Most synapses are **chemical synapses**, e.g., between nerve cells and between nerve cells and muscle cells.

Neurotransmitter Release

1. Action potentials arrive at the presynaptic terminal and cause voltage-gated Ca^{2+} channels to open.

2. Ca^{2+} diffuses into the cell and cause the release of neurotransmitters from synaptic vesicles by exocytosis. For example, the neurotransmitter acetylcholine.

3. The neurotransmitter molecules diffuse across the synaptic cleft.

4. The neurotransmitter binds to its receptor in the postsynaptic membrane, causing ion channels to open or close, depending on the type of neurotransmitter and receptor. As a result, the postsynaptic membrane can depolarize or hyperpolarize.

5. Note that the action potential does not <u>directly</u> pass from one cell to another in a chemical synapse.

Neurotransmitter Removal

1. Neurotransmitters have short-term effects on postsynaptic membranes because they are rapidly broken down or removed from the synaptic cleft.

FIGURE 11.25

2. Acetylcholine is broken down by acetylcholinesterase. The choline is taken up by the presynaptic terminal and used to make acetylcholine.

3. Many neurotransmitters are taken up intact by the presynaptic terminal and repackaged into synaptic vesicles. For example, norepinephrine.

4. Diffusion of neurotransmitters away from the synaptic cleft also limits their effect on the postsynaptic membrane. Neurotransmitters that enter the blood are broken down in the liver and kidneys.

5. Drugs can affect the nervous system by activating or blocking receptors in the synapse, by inhibiting or promoting the breakdown of neurotransmitters, by inhibiting or promoting the uptake of neurotransmitters by the presynaptic terminal, or by inhibiting or promoting the production of neurotransmitters in the presynaptic terminal.

Receptor Molecules in Synapses

1. Receptors bind only to specific neurotransmitters or closely related substances, for example drugs.

2. Any given cell has only certain receptors. Therefore a given cell responds only to certain neurotransmitters.

3. More than one type of receptor molecule exists for a given neurotransmitter. For example NE can combine with one type of receptor to cause depolarization, whereas NE can combine with a different type of receptor to cause hyperpolarization. Thus, NE can be excitatory or inhibitory.

Neurotransmitters and Neuromodulators

1. Usually a neuron releases only one type of neurotransmitter. Some neurons release two or more neurotransmitters. At this time the interactive role of the neurotransmitters is not clearly understood.

2. Some of the substances released from neurons are **neuromodulators**. A neuromodulator can increase or decrease the likelihood of producing an action potential in the postsynaptic membrane, but by itself does not have a very big effect (compared to a neurotransmitter).

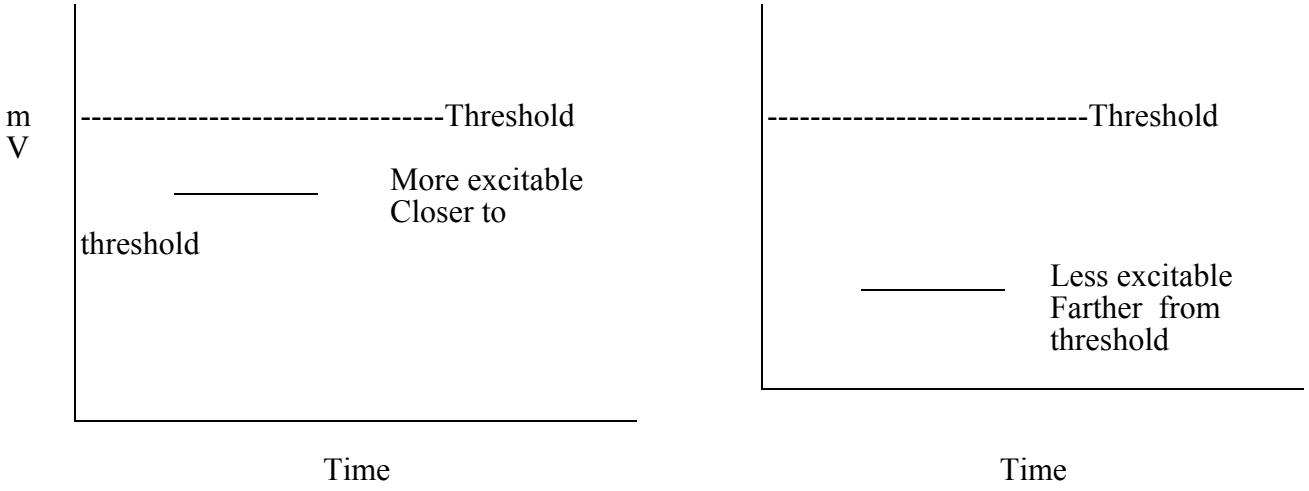
3. See Table 11.5 (p. 399) in the text for examples of neurotransmitters and neuromodulators.

Excitatory and Inhibitory Postsynaptic Potentials

1. A cell is excitable if a stimulus causes the production of an action potential.
   A. If a small stimulus causes the production of an action potential, the cell is said to be <u>more excitable</u> than if a larger stimulus is required to produce an action potential.

   B. If a large stimulus is required to produce an action potential, a cell is said to be <u>less excitable</u> then if a smaller stimulus is required.

2. The excitability of a cell is determined by how close the resting membrane potential is to threshold.



3. Remember that <u>graded potentials</u> are <u>graded</u>. That is, a weak stimulus produces a small graded potential, whereas a stronger stimulus produces a larger graded potential.
   A. When the membrane potential of a cell is close to threshold, a weak stimulus can produce a graded potential that reaches threshold. The cell is very excitable because a weak stimulus produces a response (action potential).

   B. When the membrane potential of a cell is far from threshold, it takes a strong stimulus to produce a graded potential that reaches threshold. The cell is less excitable because a strong stimulus is necessary to produce a response (action potential).

4. When a neurotransmitter binds to a receptor it can either depolarize or hyperpolarize the postsynaptic membrane.

FIGURE 11.26

5. **Excitatory postsynaptic potential (EPSP)**. The resting membrane potential of the postsynaptic membrane depolarizes.
   A. The depolarization results from increased membrane permeability to Na^+.

   B. The postsynaptic cell is more excitable, i.e., more likely to have an action potential, because depolarization causes the membrane potential to be closer to threshold, The more excitable cell is said to be **facilitated**.

C. A neuron that releases a neurotransmitter that facilitates a postsynaptic cell is called an **excitatory neuron**.

6. **Inhibitory postsynaptic potential (IPSP)**. The resting membrane potential of the postsynaptic membrane hyperpolarizes.
   A. The hyperpolarization results from an increased membrane permeability to K^+ or Cl^-.

   B. The postsynaptic cell is less excitable, i.e., less likely to have an action potential, because the resting membrane potential is further from threshold. The less excitable cell is said to be **inhibited**.

   C. A neuron that release a neurotransmitter that inhibits a postsynaptic cell is called an **inhibitory neuron**.

7. Factors that increase cell excitability.
   A. Excitatory postsynaptic potentials.

   B. Increased extracellular K^+ concentrations cause the resting membrane potential to depolarize, which moves the resting membrane potential closer to threshold.

   C. Decreased extracellular Ca^{2+} concentrations causes voltage-gated Na^+ channels to open.

8. Factors that decrease cell excitability.
   A. Inhibitory postsynaptic potentials.

   B. Decreased extracellular K^+ concentrations cause the resting membrane potential to hyperpolarize, which moves the resting membrane potential farther from threshold.

   C. Increased extracellular Ca^{2+} concentrations causes voltage-gated Na^+ channels to close.

	More Excitable	Less Excitable
EPSP		
IPSP		
Increased extracellular K^+		
Decreased extracellular K^+		
Increased K^+ permeability		
Decreased K^+ permeability		
Increased extracellular Ca^{2+}		
Decreased extracellular Ca^{2+}		

☞ A patient is suffering from rickets. Would you expect the patient to have flaccid muscles or muscles that undergo spasms of contractions.

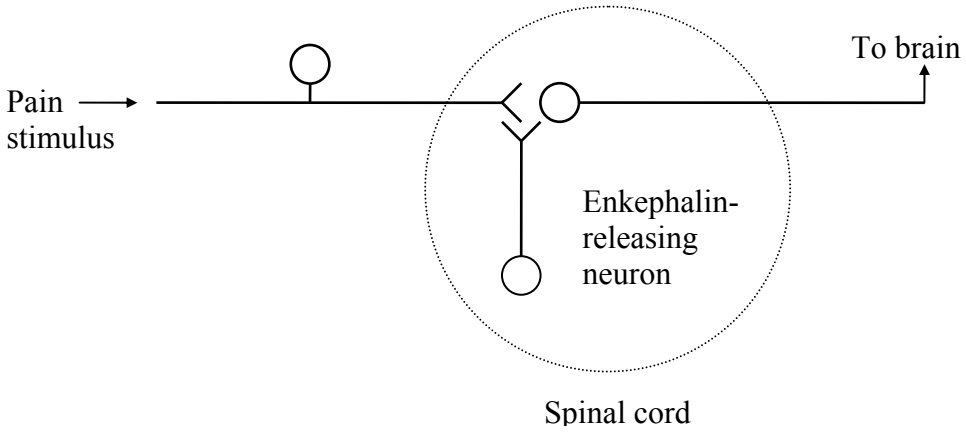
Presynaptic Inhibition and Facilitation

FIGURE 11.27

1. Many CNS synapses are **axo-axonic synapses**, in which the axon of one neuron synapses with the presynaptic terminal (axon) of another neuron.

2. In **presynaptic inhibition,** a neuromodulator decreases neurotransmitter release by the presynaptic terminal. This decreases the likelihood an action potential is produced in the postsynaptic membrane.
   A. Endorphins and enkephalins are neuromodulators that inhibit neurotransmitter release.

   B. Endorphins and enkephalins can block the transmission of pain signals.



3. In **presynaptic facilitation,** a neuromodulator released onto the presynaptic terminal increases the release of neurotransmitter. This increases the likelihood an action potential is produced in the postsynaptic membrane.

Spatial and Temporal Summation

FIGURE 11.28

1. Normally a single presynaptic action potential does not result in a postsynaptic action potential.

2. Graded potentials, produced by stimulating the dendrites, can combine at the trigger zone in a process called **summation** to produce an action potential.
   A. **Spatial summation** occurs when two action potentials arrive at different presynaptic terminals at the same time.

   B. **Temporal summation** occurs when two action potentials arrive in close succession at the same presynaptic terminal.

3. Excitatory and inhibitory neurons can both synapse with the same neuron. An action potential can result if the EPSPs are stronger than the IPSPs.

NEURONAL PATHWAYS AND CIRCUITS

FIGURE 11.29

1. In **convergent circuits,** many presynaptic neurons synapse with a smaller number of postsynaptic neurons. In converging circuits spatial summation can occur. Thus, input from many different parts of the nervous system can affect a neuron.

2. In **divergent circuits,** a small number of presynaptic neurons synapse with a larger number of postsynaptic neurons. Thus output from a neuron can affect more than one part of the nervous system.

3. In **oscillating circuits,** the neurons are arranged in a circular fashion, which allows action potentials entering the circuit to cause a neuron further along in the circuit to produce an action potential more than once. This response is called **after discharge**.

   A. Oscillating circuits function to produce a prolonged response. Once started they continue until the synapses fatigue or until the neurons are inhibited by other neurons.

   B. Oscillating circuits are important for continuous or cyclic events, such as heart rate and respiration. They may also be involved in memory (called a memory engram).