THE ELEVEN SYSTEMS OF THE BODY

There are eleven systems in the human body, which we'll discuss over the next three chapters. Below is a brief summary of each, as well as the chapter in which it is covered.

Chapter 11

- The nervous system detects and interprets information from the surrounding environment. It essentially controls most body functions.
- The endocrine system controls body functions through the use of chemical messengers called hormones.

Chapter 12

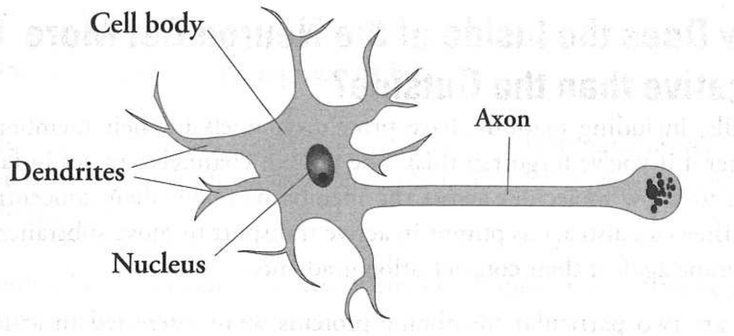
- The circulatory system transports needed materials to the cells and carries away waste materials.
- The lymphatic system recaptures and filters fluid from the tissues and returns it to the blood stream.
- The respiratory system takes oxygen into the body and releases carbon dioxide.

Chapter 13

- The digestive system takes food into the body, breaks it down, and absorbs the nutrients from the food.
- The urinary system removes metabolic wastes from the blood.
- The skeletal system supports the body, protects it, and allows movement (along with the muscular system).
- The muscular system makes it possible for the body to move.
- The skin protects the body and helps regulate body temperature.
- The reproductive system produces the cells necessary to produce offspring.

CONTROL OF THE BODY, PART 1—THE NERVOUS SYSTEM

The **nervous system** consists of billions of nerve cells. Nerve cells are also called **neurons**. Neurons are highly specialized cells that carry impulses—electrical signals—between body parts. Here's a typical neuron.



Neuron

The cell body (also called the **soma**) has all the usual cellular material. It has a nucleus, ribosomes, mitochondria, and all the rest of the organelles. Neurons are different from other cells because the cell body has structures sticking off of it in all directions. In the body, anything that sticks off something else is called a **process**, so we can say that the neuron has processes extending from the cell body. The processes are called **dendrites** and **axons.** Most neurons have several dendrites but only one axon. To be ready for the test, you should be able to identify the picture above as a neuron and be able to label the cell body, nucleus, dendrites, and axon.

What Neurons Do

We already said that neurons are specialized to carry impulses from one place to another. The impulse always follows the same path. A neuron *receives* impulses at its dendrites. It *transmits* the impulse through the cell body and down the axon.

The direction in which an impulse travels through a neuron is **dendrite → cell body → axon.**

What *Is* This Impulse?

We said that the impulse is an electrical signal. To understand this more completely, we have to take a closer look at the neuron. When a neuron is resting (i.e., not carrying an impulse), we describe it as being **polarized.** That means it's different on one side of its membrane than the other. The inside of the neuron is negatively charged when compared to the outside of the neuron.

The Resting Membrane Potential

All cells establish and maintain a **resting membrane potential** (RMP), wherein the inside of the cell is more negative than the outside. The RMP of most cells is around –70 mV; that is, the inside of the cells is about 70 mV more negative than the outside of the cell. The two membrane proteins that help set up and maintain the RMP are the Na^+/K^+ ATPase and the K^+ leak channel.

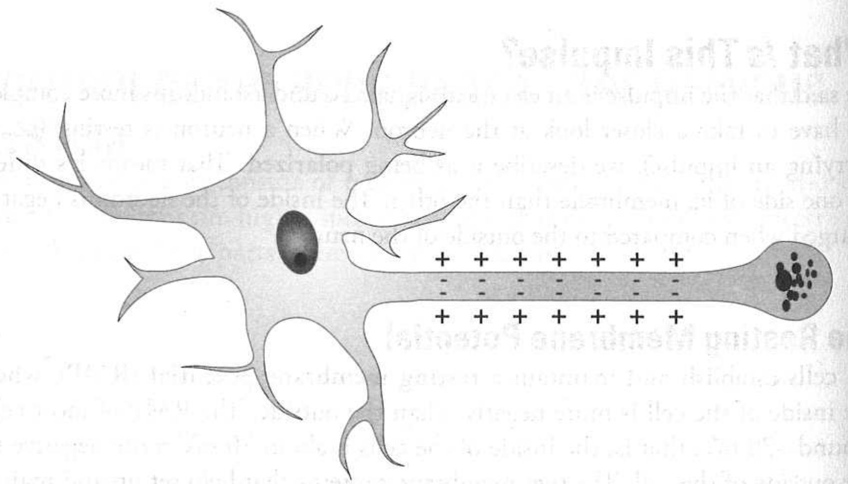
How Does the Inside of the Neuron Get More Negative than the Outside?

All cells, including neurons, have protein channels in their membranes (review Chapter 4 if you've forgotten this). The protein channels can act in facilitated diffusion to allow molecules across the membrane down their concentration gradients. They can also act as pumps in active transport to move substances across the membrane against their concentration gradients.

There are two particular membrane proteins we're interested in at the moment. The first is the **sodium-potassium pump** (**Na^+/K^+ ATPase**), which uses a molecule of ATP to move three sodium ions *out* of the cell and (simultaneously) two potassium ions *into* the cell. After these pumps run for a while, there is plenty of sodium outside the cell (and not much inside) and plenty of potassium inside the cell (and not much outside). Remember, because these molecules are charged (they're *ions*), they cannot simply cross the membrane. So once the sodium is out, it's *out.* And once the potassium is in, it's *in.* Unless of course, there's a sodium or potassium **channel** that can allow them to cross the membrane again, according to their gradients.

There are no sodium channels in the membrane, but there *are* potassium channels. This is the second protein we're interested in. These particular potassium channels are referred to as **leak channels**, because they are always open and will always allow potassium to leak out of the cell, according to its gradient. (Remember, because of the ATPase, there is more potassium *inside* the cell than outside, so potassium will leak *out* of the cell.)

The bottom line is that many positively charged ions are being let out of the cell. Sodium ions are being pumped out, and potassium ions are leaking out. Many negatively charged things are left behind, inside the cell. Things like DNA and RNA and proteins. *Because a lot of positive stuff is leaving the cell and a lot of negative stuff is staying behind, the cell is more negative on the inside, compared to the outside;* 70 millivolts more negative, in fact, so that when we look at a cell we say that it rests at –70 mV.



Resting Neuron

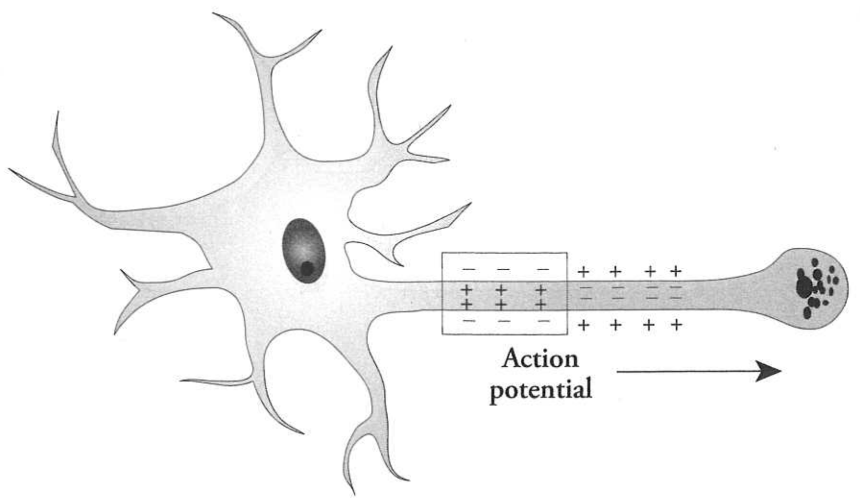
VOLTAGE-GATED CHANNELS

Neurons, in addition to the two membrane proteins we discussed above (the Na^+/K^+ ATPase and the potassium leak channels), have **voltage-gated channels** in their membranes. Voltage-gated channels are channels that open when the cell membrane reaches a particular voltage. At the normal resting potential of the cell, –70 mV, the voltage-gated channels are closed. But if the cell membrane could reach –50 mV, these channels would open. This potential, the potential at which the voltage-gated channels open, is known as the **threshold potential.** (Don't worry just yet about how the cell reaches threshold; we'll talk about this a bit later.) There are two types of voltage-gated channels in neuron cell membranes: **sodium voltage-gated channels** and **potassium voltage-gated channels.**

Action Potentials

Imagine the scene: A barrier separates the inside of the cell from the outside. Sodium ions, plentiful on the outside, long to get in. But they can't cross the barrier. Potassium ions, plentiful on the inside, long to get out. Some of them do, through the leak channels. But many potassium ions stay behind. All of a sudden, the cell potential reaches –50 mV! Sodium voltage-gated channels slam open, and now sodium has a way to get across the barrier. Sodium ions flood into the cell from the outside! The inside of the cell gets very positive, until finally, at around +35 mV, the sodium channels close. Now the potassium voltage-gated channels open! Potassium has a way to get across the barrier, and potassium ions flood out of the cell; they carry a positive charge, which makes the inside of the cell more negative again. At around –90 mV, the potassium voltage-gated channels close, and the only channels left running are the Na^+/K^+ ATPase and the potassium leak channels. The pump restores the balance of sodium and potassium, and the cell membrane potential again rests at –70 mV.

The sequence of events we've just described is known as an **action potential.** An action potential occurs at only a small portion of the neuron's membrane.



Let's take a quick look at some terms and definitions.

Polarized: the state of the membrane at rest, negative on the inside and positive on the outside.

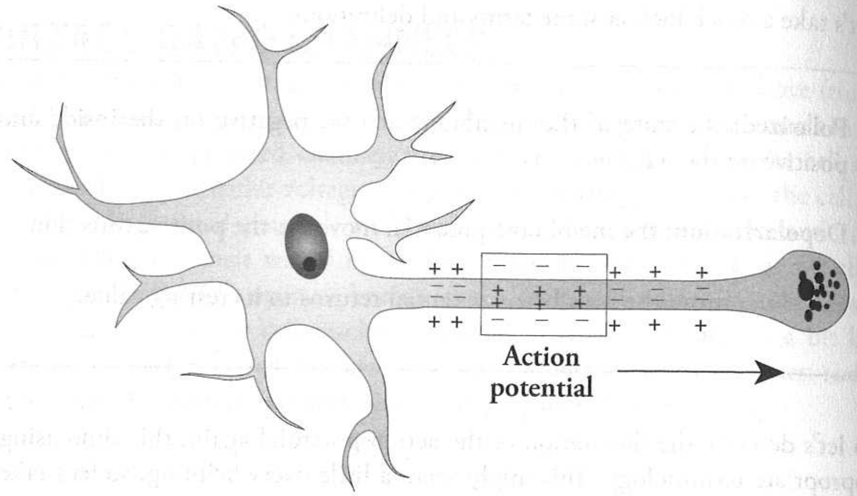
Depolarization: the membrane potential moves in the positive direction.

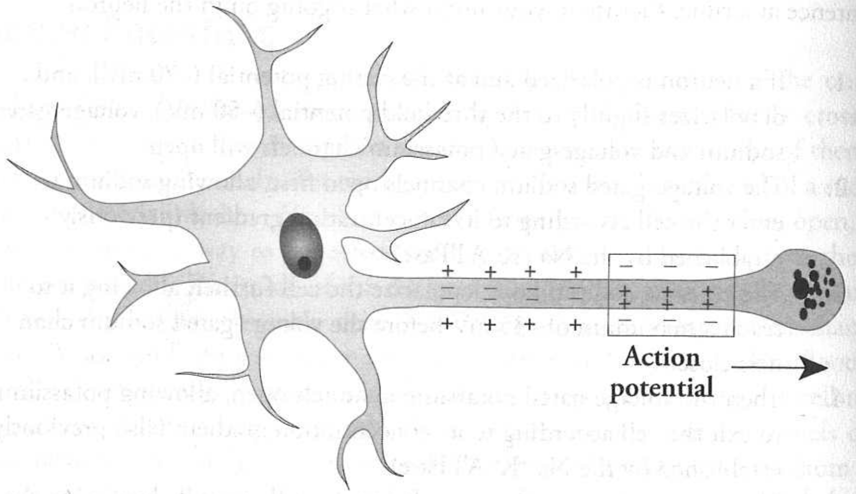
Repolarization: the membrane potential returns to its resting value.

So let's describe the illustration of the action potential again, this time using the appropriate terminology. This might seem a little overwhelming, so let's take it a sentence at a time. Picture in your mind what is going on in the neuron.

1. If a neuron is polarized and at the resting potential (–70 mV), and depolarizes slightly to the threshold potential (–50 mV), voltage-gated sodium and voltage-gated potassium channels will open.
2. The voltage-gated sodium channels open first, allowing sodium to enter the cell according to its concentration gradient (previously established by the Na^+/K^+ ATPase).
3. The entering sodium ions depolarize the cell further, allowing it to reach a maximum of +35 mV before the voltage-gated sodium channels close.
4. Then the voltage-gated potassium channels open, allowing potassium to exit the cell according to its concentration gradient (also previously established by the Na^+/K^+ ATPase).
5. The exiting potassium ions repolarize the cell, actually bypassing the resting membrane potential, to a minimum of –90 mV before the voltage-gated potassium channels close.
6. Finally, the Na^+/K^+ ATPase and the potassium leak channels return the membrane to its resting polarized state.

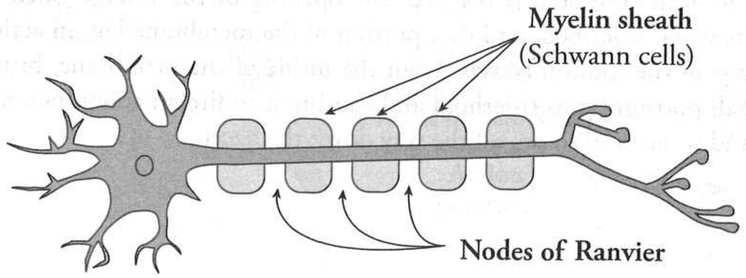
We said earlier that the function of a neuron is to transmit impulses—electrical signals. This "impulse" is nothing more than a traveling action potential. When one small portion of a neuron's membrane fires an action potential, some of the sodium that rushes in from the opening of the voltage-gated channels travels down the inside of the membrane, bringing the next small portion up to threshold. As soon as threshold is reached, the opening of the voltage-gated channels occurs as we've described, and that portion of the membrane has an action potential. Some of the sodium travels down the inside of the membrane, bringing the next small portion up to threshold and causing it to fire an action potential. And so on, and so on, and so on, all the way down the axon.



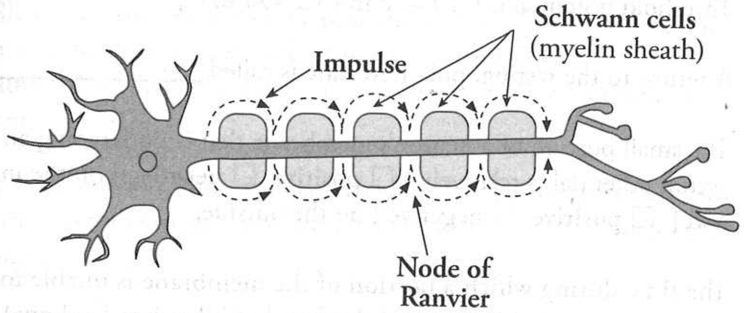


Very Fast Impulse Speeds: Myelin Sheath and Schwann Cells

In some neurons, the axon is wrapped with special cells called **Schwann cells.** This Schwann cell "wrapping" is called a **myelin sheath.** Many Schwann cells can sit on a single axon. The spaces between the Schwann cells are called **nodes of Ranvier.**



Myelin increases the speed at which an impulse can travel down the axon because not all portions of the axon have to fire an action potential. The only portions that fire action potentials are the nodes of Ranvier. So the impulse seems to "jump" down the axon from node to node, and this increases the rate at which it reaches the end of the axon. This "jumping" type of conduction is called **saltatory conduction,** from the Latin word *saltar* meaning "to jump." The largest myelinated neurons can conduct impulses at the speed of 100 meters per second (100 m/sec). That's a little more than the length of a football field in one second—virtually instantaneous.



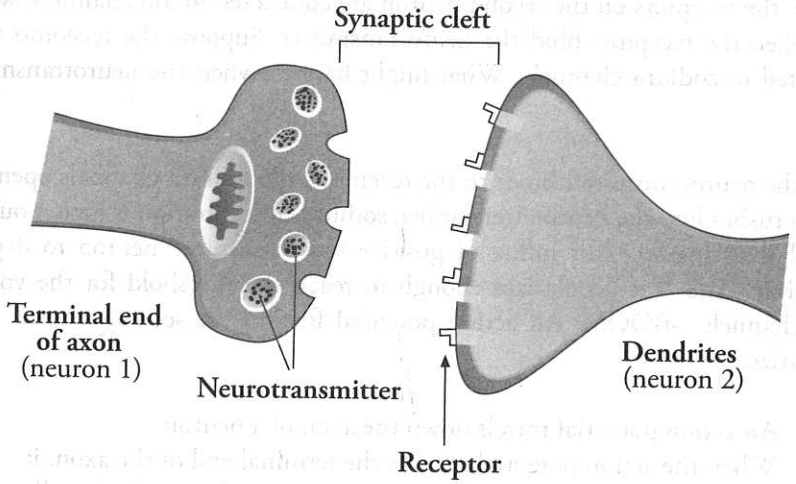
One last thing: For a very short while after firing an action potential, that portion of the membrane is not able to fire a second action potential (that is, until the sodium and potassium channels reset and the membrane is again at the resting potential). In any case, that short period of time is known as the **refractory period.** Having a short refractory period in the portion of the membrane that has just fired an action potential ensures that the action potential (the impulse) will only travel in one direction down the axon—away from the cell body.

SYNAPSES: WHEN THE IMPULSE (ACTION POTENTIAL) REACHES THE END OF THE AXON

When the nerve impulse reaches the end of an axon, it will either get transferred to another neuron's dendrites, or it will get transferred to an organ (which will exhibit some effect because of being stimulated by the neuron). The point where the impulse gets transferred is called a **synapse.** A synapse is nothing more than a neuron-to-neuron junction or a neuron-to-organ junction.

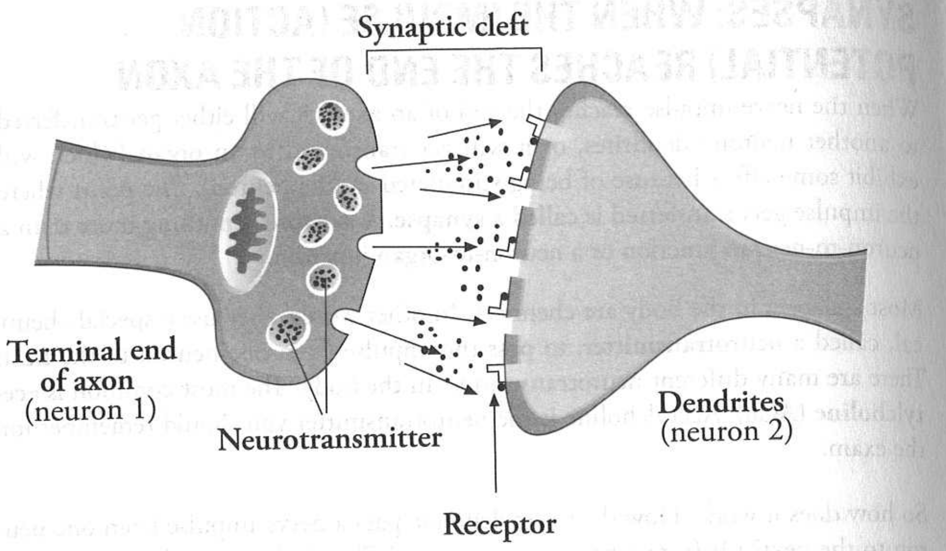
Most synapses in the body are chemical. In other words, they use a special chemical, called a **neurotransmitter**, to pass the impulse from one neuron to the next. There are many different neurotransmitters in the body. The most common is **acetylcholine** (ACh). Acetylcholine is the neurotransmitter you should remember for the exam.

So how does it work? How does acetylcholine pass a nerve impulse from one neuron to the next? Or from a neuron to an organ? First, let's take a close-up look at the synapse itself.



The axon of the first neuron doesn't actually contact the dendrites of the second neuron. There is a small gap between them called the **synaptic cleft**. In the terminal end of the axon are vesicles that contain the chemical neurotransmitter. On the dendrites are receptors that can bind to that neurotransmitter.

When an action potential reaches the terminal end of an axon, it causes the vesicles to fuse with the cell membrane. The neurotransmitter is released into the synaptic cleft by exocytosis. It diffuses instantly across the (very small) synaptic cleft where it binds to the receptors on the dendrites of the next neuron.



Usually, the receptors on the second neuron are connected to ion channels, which open when the receptors bind the neurotransmitter. Suppose the receptors were connected to sodium channels. What might happen when the neurotransmitter binds?

When the neurotransmitter binds to the receptors, the sodium channels open and sodium rushes into the neuron (remember, sodium concentration is higher outside the cell than inside). This influx of positive ions causes the neuron to depolarize slightly. And if it depolarizes enough to reach the threshold for the voltage-gated channels—BOOM! An action potential fires in the second neuron. Let's summarize.

1. An action potential travels down the axon of a neuron.
2. When the action potential reaches the terminal end of the axon, it causes vesicles containing a neurotransmitter to fuse with the cell membrane.
3. The neurotransmitter is released into the synaptic cleft by exocytosis.
4. The neurotransmitter diffuses across the cleft where it binds to receptors on the dendrites of the next neuron.
5. Binding of the neurotransmitter to the receptors opens ion channels in the next neuron.
6. If the ion channels allow sodium to enter the neuron, it will depolarize.
7. If the neuron depolarizes to threshold, voltage-gated channels will open, causing an action potential to fire.

Not All Neurotransmitters Are the Same

Not all neurotransmitters cause a cell to be **stimulated** (depolarize toward threshold). Some cause a cell to be **inhibited**, in other words, to move away from threshold. And don't forget, a single neuron may receive impulses from many, many other neurons. Some impulses will cause the neuron to be stimulated, some will cause it to be inhibited. The neuron will take all the stimulatory input and all the inhibitory input and "add them up." If there are more stimulatory inputs than inhibitory, the neuron will most likely fire an action potential. If there are more inhibitory inputs than stimulatory, the cell will NOT fire an action potential. This is called **summation.**

The Nervous System's Job As a Whole

So far we've only looked at the nervous system at the cellular level—the neuron level. But all of an organism's neurons are put together into a complicated network. If an organism were a city's entire electrical system, a neuron would be a single wire. The nervous system would be all of the wires in the whole city—on every street, on every power line and pole, in every wall of every floor of every building and home. In the human nervous system, billions of neurons run every which way, with synapses all over the place, carrying impulses here, there, everywhere.

The brain and the spinal cord are made completely out of neurons. The brain and the spinal cord are referred to as the **central nervous system** (CNS). Any neurons outside of the brain and spinal cord, like those in our organs and skin, are part of the **peripheral nervous system** (PNS).

This, then, is the true function of the nervous system as a whole. It receives information from the body's sense organs (eyes, ears, etc.). This sensory information is carried by the PNS to the CNS, where it is processed and integrated with other information. The CNS makes some decisions and sends commands out to the body through the PNS. There are three types of neurons involved here.

The CNS is like a command station at a military base. Decisions are made here, and information is processed here. The PNS is like a network of phone lines that connect the command station to all other centers on the base. Information from the command station is sent along these phone lines to all other centers so that orders are carried out. New information can be sent to the command station from other centers along these same phone lines. That new information will be processed, decisions will be made, and new orders will be sent along the phone lines.

PNS	**1. Sensory neurons**	These neurons are involved in sending information to the CNS from the sensory organs of the body.
	2. Motor neurons	These neurons are involved in sending information from the CNS to the organs of the body such as muscles and glands.
CNS	**3. Interneurons**	Neurons that are completely within the brain and spinal cord are called interneurons. They often connect sensory and motor neurons.

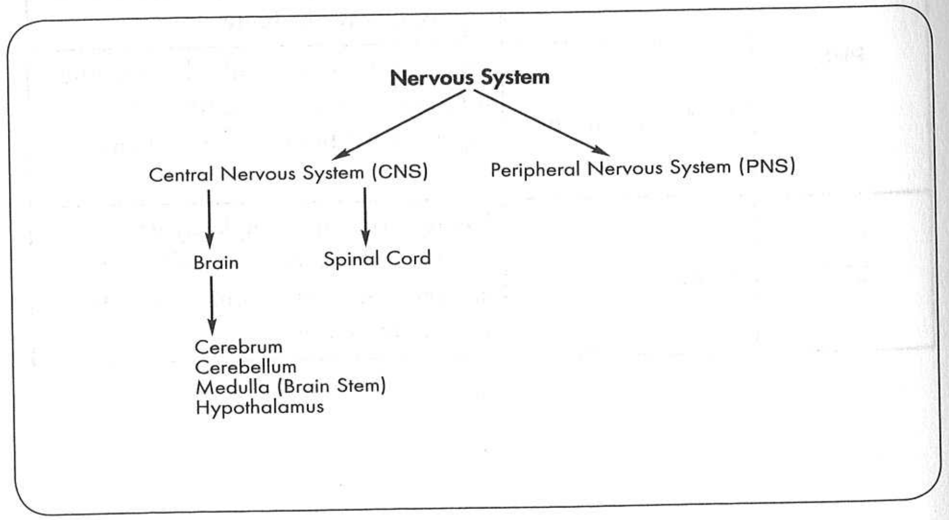
Here is something to remember about all of the neurons in the nervous system: They all fire the same type of action potential. In other words, *all action potentials are exactly alike.* There is no such thing as a "big" action potential or a "small" action potential. There is no such thing as a "short" action potential or a "long" action potential. As soon as threshold is reached and the voltage-gated channels open, the action potential occurs automatically, in exactly the same way it did the last time the neuron reached threshold and in exactly the same way it will the next time the neuron reaches threshold.

However, the sensations picked up by the sensory neurons and sent to the CNS certainly DO differ in strength. We might sense something as a little bit warm or as too hot to touch. The prick of a pin is hardly irritating, but a broken ankle is excruciatingly painful. If all action potentials are the same, how does the CNS "know" when a sensation is strong or weak?

The answer lies in how frequently threshold is reached and, thus, how frequently action potentials are fired. Weak stimuli might cause the neuron to fire two action potentials in a one-second period, while strong stimuli might cause the neuron to fire 20 action potentials in the same one-second period. Very frequent action potentials are interpreted by the CNS as a strong sensation, whereas less frequent action potentials are interpreted as weak sensations.

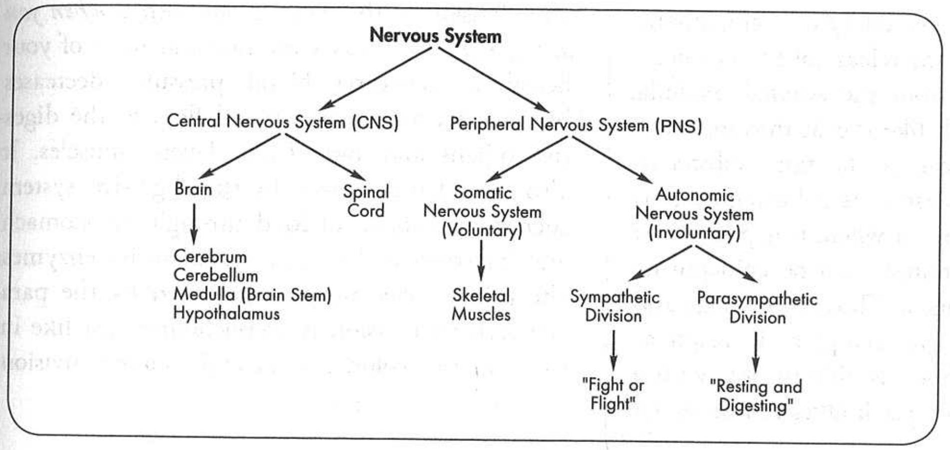
SUBDIVISIONS OF THE NERVOUS SYSTEM

So far, we've looked at two of the subdivisions of the nervous system, the CNS and the PNS. Let's take a closer look at the central nervous system.



- **Spinal cord:** The spinal cord is primarily involved in primitive, reflex actions.
- **Cerebrum:** The cerebral cortex is our conscious mind. This is where voluntary actions occur such as movement, speech, and problem solving. This is where we have conscious awareness of sensations such as smells, sights, hot, and cold.
- **Cerebellum:** The cerebellum coordinates muscle movement and balance so that movement is smooth and coordinated.
- **Medulla:** Involuntary acts originate here such as breathing and blood pressure regulation. This is a relatively primitive region.
- **Hypothalamus:** The hypothalamus maintains body homeostasis—a constant internal environment regardless of changing external conditions. It monitors things like hormone levels, electrolyte balance, and temperature. It also controls the pituitary gland.

Now let's take a closer look at the peripheral nervous system (PNS).



The PNS has two subdivisions: the somatic nervous system and the autonomic nervous system. The **somatic nervous system** is a *voluntary system*, meaning that we have conscious control over the organs that this subdivision controls. The only organs controlled and monitored by the somatic system are the skeletal muscles. The somatic nervous system uses acetylcholine (ACH) as a neurotransmitter. In other words, to stimulate a skeletal muscle, a somatic motor neuron releases a little ACh onto the muscle. The ACh binds to receptors on the muscle, and this causes the muscle to depolarize and contract.

The **autonomic nervous system** (ANS), as its name implies, is an autonomous, or *involuntary system*. We do NOT have conscious control over the organs controlled by this subdivision. Some examples of the organs controlled by the autonomic nervous system are the heart, the digestive organs, the blood vessels, and the pancreas. The autonomic nervous system can be further subdivided into the sympathetic division (which tends to increase body activity) and the parasympathetic division (which tends to decrease body activity).

The **sympathetic division** is sometimes known as the **"fight or flight"** system. This division of the ANS *helps prepare your body for stress situations* by increasing the rate and force of your heartbeat, increasing blood pressure, increasing breath rate, and diverting blood flow away from your digestive organs and toward skeletal muscles. The primary neurotransmitter used by the sympathetic division is **norepinephrine**.

The **parasympathetic division** is sometimes known as the **"resting and digesting"** system. This division of the ANS is *most active when you are at rest*. It decreases the rate and force of your heartbeat, decreases blood pressure, decreases breath rate, and diverts blood flow to the digestive organs and away from skeletal muscles. It also stimulates activity in the digestive system such as movement of food through the stomach and intestines and secretion of digestive enzymes. The primary neurotransmitter used by the parasympathetic division is acetylcholine, just like in the somatic (voluntary skeletal muscle) division.

A Neuro-Endocrine Connection

One of the first things triggered by the sympathetic "fight or flight" system is the release of the hormone *epinephrine* (adrenaline) from the adrenal medulla. Epinephrine is very much like the neurotransmitter norepinephrine, and it causes the same effects in the body. However, because it is a hormone, it is released into the bloodstream where it is present for a much longer time (minutes) than norepinephrine is at a synapse (milliseconds). Thus, it prolongs and enhances the effects of the sympathetic response, making sure that your body is able to deal with a stressful situation for as long as it takes to resolve it.

Not Just for Humans

Much of this discussion about the nervous system relates to humans. The nervous system in other organisms of the **vertebrate group**, such as fish, amphibians, and birds, is very similar. In all these organisms, the central nervous system is made up of the brain and spinal cord. Nerves transmit impulses to and from the brain and spinal cord and make up the peripheral nervous system.

The nervous systems of **arthropods** (such as many of the insects we see) and **annelids** (segmented worms) are made up of a ventral nerve cord and a brain. There are a series of **ganglia** (clusters of nerve cell bodies) along the nerve cord and neurons branch from the ganglia.

CONTROL OF THE BODY, PART 2—THE ENDOCRINE SYSTEM

We've seen how the nervous system helps to control body functions. The nervous system is extremely fast. Action potentials last only about two to three milliseconds, so actions controlled by the nervous system are virtually instantaneous. Consider a pain withdrawal reflex (controlled by the nervous system). If you touch something painful, like a hot stove, your hand immediately pulls back, even before you consciously realize you've touched something hot.

Endocrine System

Consider some of the things controlled by the endocrine system.

- **Ejection of breast milk:** 1–2 minutes
- **Regulation of blood glucose:** about 15 minutes
- **Regulation of extracellular sodium:** about 1–2 hours
- **Female reproductive cycle:** average of 28 days
- **Puberty:** average of 5 years

The **endocrine system** is also a control system of the body, but it operates on a much slower time scale than the nervous system.

How does the endocrine system control the body? Through the use of **hormones.** Hormones are chemicals made by special glands (called endocrine glands), which are then secreted (released) into the bloodstream. Once a hormone is in the blood, it goes everywhere in the body; however, it has effects on only some of the organs in the body. What makes some organs respond to a hormone and other organs ignore the same hormone? For a hormone to have an effect on an organ, that organ must have receptors for the hormone. No receptors, no effect. The organs that are affected by a particular hormone are called target organs for that hormone.

Peptides and Steroids

Hormones come in two classes: **peptide hormones** (which are amino acid-based) and **steroid hormones** (which are cholesterol-based). These general classes of hormones act in slightly different ways. Let's take a look.

Peptide hormones are made from amino acids. They are essentially protein molecules, but some are very small and are referred to as peptides. Because they cannot cross cell membranes, peptide hormones must bind to receptors outside the cell (on the extracellular surface). Peptide hormones generally cause their effects rapidly. They do this by turning existing enzymes in the cell on or off. Some examples of peptide hormones are insulin, prolactin, and glucagon.

Steroid hormones are made from cholesterol. They are lipids and can easily cross the cell membrane, so they bind to receptors inside the cell (intracellular). Steroid hormones generally cause their effects more slowly than peptide hormones. They cause their effects by binding to DNA and changing which genes get transcribed. Some examples of steroids are aldosterone, estrogen, and testosterone.