Electrical Properties of the Human Nervous System

University Physics II Honors Project

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I. Introduction

Electromagnetism is the field of physics that examines the far-reaching effects of one of the most fundamental properties of the universe: charge. Charge is a property that comes with matter, and the microscopic interactions between charges are of great importance not only in physics but also in chemistry, biology, and physiology. The human body is composed of many charged particles, referred to as electrolytes, and one of the most important organ systems in the body is based entirely on the use of electricity: the nervous system. The nervous system is a system of cells called neurons that conduct messages throughout the body nearly instantaneously in the form of electrical impulses (McCall, 2010). The electromagnetic laws that describe electric fields and potentials are greatly present in nerve function and describe the reasons and mechanism of the propagation of an action potential down a neuron, which is the basis of nerve impulse transmission throughout the body. This paper seeks to understand the electrical properties of the human body, especially as they relate to the nervous system, and use qualitative and quantitative explanations for the functioning of the human body at the deepest level.

II. Ionic Properties of the Human Body

The human body is a large example of an aqueous solution, wherein certain solutes are dissolved in water. Salts and other such ionic compounds are easily dissolved in water. When they are dissolved, they distribute charged ions in the solution. Within the human body, these ions are very important and are referred to as electrolytes. Sources of electrolytes are important to intake for normal body functioning: some essential electrolytes, which are electrolytes that are necessary for the survival and growth of an organism, include sodium, potassium, and calcium ions (Mertz, 1981). These ions are also essential for the functioning of the nervous system,

especially in how they move during the action potential stage, and their functions will be revisited later.

The human body is composed of many such ions in solution at the same time, and the interplay between these ions results in the biochemical framework of life. Therefore, it is important to understand the electrical behavior of these ions in solution before we continue. Positive charges and negative charges attract one another, and this electrostatic attraction is the basis for chemical reactions that occur in the physiological environment. The physical reason for this attraction is the generation of an electric field by each ion. The charged ions may best be approximated as point charges, and so the electric field is given by Coulomb's Law for point charges (Equation 1).

$$E = \frac{kq_1}{d}, \text{ where d is distance, and q is charge intensity} \qquad (1)$$

The electric field produced by a positive ion (such as Na^+ or K^+), would have field lines pointing away from the ion, radiating outward to infinity, while the electric field of a negatively-charged ion (such as Cl^-) would have field lines pointing toward the ion, still radial at infinity. Notice that this means that the field of the positive charge would exert an outward force on a nearby positive charge, but an inward force on a nearby negative charge. This is the physical basis of attraction of unlike particles. In the world of biochemistry, these ions attract and combine in order to decrease separation of charge as much as possible. The force between two point charges is given by Equation 2, which includes a new value, κ, which is the dielectric constant of the medium.

$$F = \frac{kq_1q_2}{d\kappa} \qquad (2)$$

Thus, the force between two ions is directly proportional to the charge magnitudes and inversely proportional to the distance between them: meaning that the fields decay as you move

further from the point charges. The remainder of the equation is a very important point, however, especially in physiological systems. The κ is a dielectric constant, a constant that varies with the material between the point charges. In a solution, this material is the solvent. One important distinction is the benefit of water as a solvent in the human body. Water has a much higher dielectric constant (κ=80) than other organic solvents, such as cyclohexane (κ=2). Water therefore acts to thin the fields of the ions and therefore lower the attractive force between them. Since many biochemical reactions depend on the components being able to separate and make the reactions reversible, this decreasing of the intensity of forces is very useful (Berg et al., 2012). In other solvents, ion-ion interactions can be permanent and irreversible due to the high amount of force between two ions. In water, however, these reactions are more able to find an equilibrium, where they bind for a brief period of time and then can more easily be separated by the solvent. These are just a few examples of the electrical behavior of ions in solution. In a physiological scenario, ions can also interact with cell membranes in applicable ways. One place where these interactions are of vital importance is the nervous system.

III. The Neuron at Rest

The basic cell in the nervous system is called a neuron. A diagram of the structure of the neuron is illustrated in Figure 1. Neurons have smaller processes called dendrites that pick up information and electrical signals from the previous neurons in the pathway. This electrical signal is propagated from the cell body, along a long process called an axon, and then finally across the synapse to the next neuron (Brodal, 2010). The neurons are structured so that each collection of nerve cells will only go in one direction. Sensory pathways are pointed with the axons toward the brain, while motor neurons (those responsible for performing body

movements) have the axons pointed away from the brain, toward the effector, the tissue that will act on the nerve impulse. The exact mechanism of this impulse transduction along the axon to the next neuron is mediated by the generation of an electric field by moving ions. Figure 2 illustrates the basic system at the membrane, or cell boundary, of the neuron. Integrated into the neuronal bilayer are protein structures, including the sodium-potassium pump. This pump is a transmembrane channel that uses energy to push sodium ions out of the cell and potassium ions into the cell, both against their concentration gradients, meaning the opposite of the way they would flow normally by diffusion. The pump sends three sodium (Na^+) ions out of the membrane, and brings in two potassium (K^+) ions for every ATP molecule hydrolyzed for energy (Morth et al., 2007). The physiological significance of this action is great, for it allows for the region outside the cell to be more positive than the region just inside. The two regions can be approximated as parallel plates of charge, and so the region between the two "plates" is expected to have an electric field. Figure 3 shows a diagram of the field, which acts across the membrane in the direction that pushes positive charges into the cell. Related to an electric field is also a potential. For a parallel plate approximation, the voltage is given by Equation 3.

$V = Ed$, where d is the distance between the plates (3)

The uneven distribution of positive charge maintained by the sodium-potassium pump creates a voltage across the membrane of a nerve cell even when the cell is at rest. This voltage is called resting potential, and in a neuron it is measured at −70 mV (Schadé and Ford, 1973). This is a sort of baseline potential, the voltage that signifies that a neuron is in equilibrium and not firing. Other ions are involved in the resting potential, including chloride ions (Cl^-) and other negative ions, but sodium and potassium are the two major players, and the two that the neuron will manipulate during the time when it is stimulated.

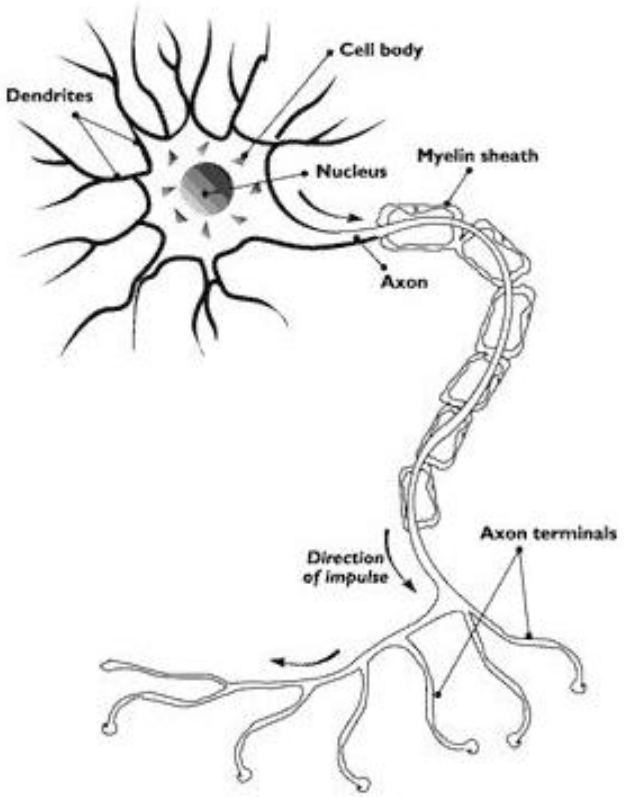

Figure 1: A diagram of a neuron, showing the direction of impulse transmission and pertinent structures on the cell.

Credit: National Institute on Drug Abuse

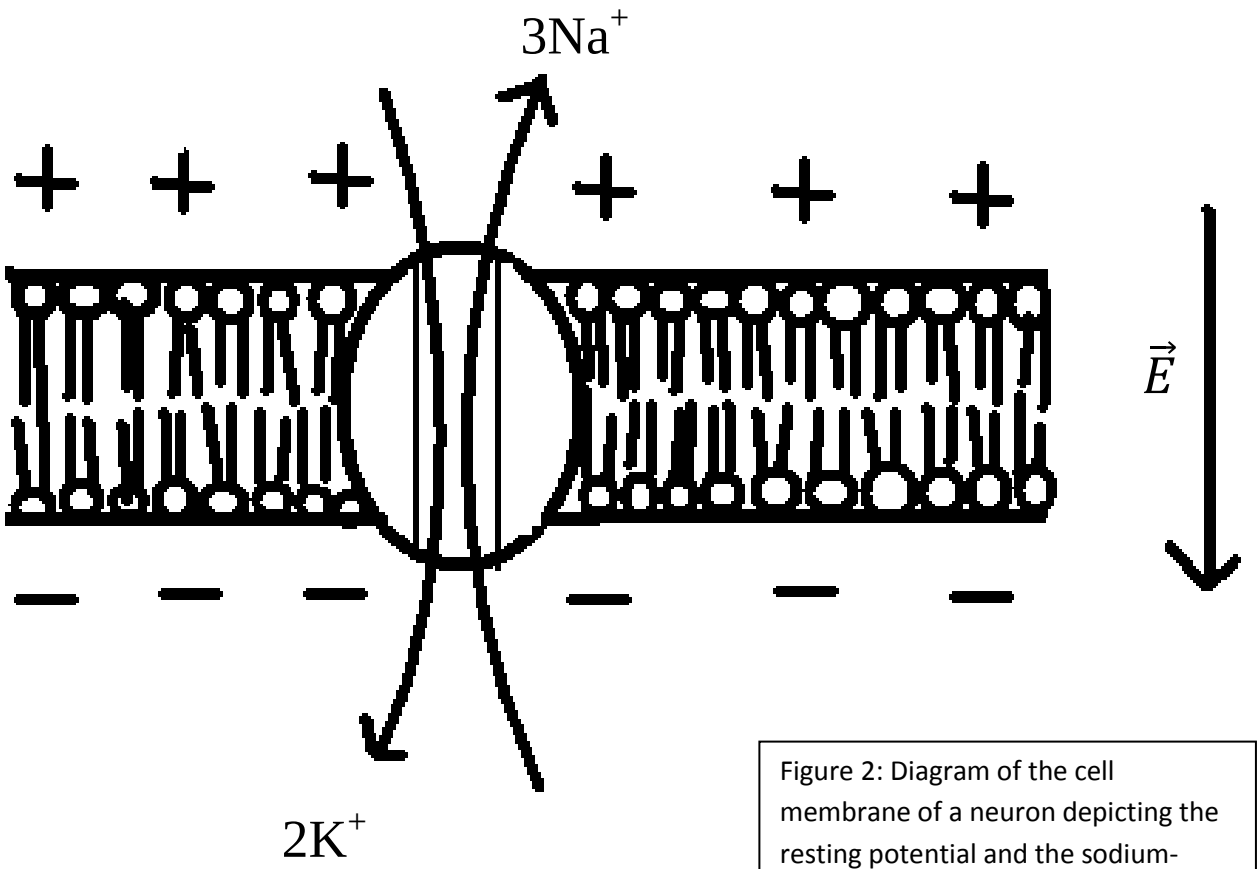

Figure 2: Diagram of the cell membrane of a neuron depicting the resting potential and the sodium-potassium pump

IV. Neuronal Function

The resting potential is the default state of the neuron when nothing in its environment is causing it to transmit a signal. Nerves send signals− for example, signals for muscle fibers to contract in order to move the body− by way of electricity (Barnes and Beutner, 1946). The actual generation of this electricity is based on the deviation from the resting potential by neurons along the path. The current produced by the neuron in order to transmit the electricity is very different from the current experienced in circuits and wires. In such systems, the current flow is composed of electrons that are delocalized in the metal wire and move along the axis of the wire. In a neuron, while the propagation of the signal moves in the direction parallel to the axis of the axon, most of the charged ions that move during the propagation of the signal do so in a direction *perpendicular* to the axis of the neuron (McCall, 2010). The perpendicular motion of some particles induces nearby particles to do the same, resulting in a wave of perpendicular motion, propagating in the parallel direction. The electrical aspect to this phenomenon describes it as the rapid changes in polarization of the membrane, called an action potential. One reason for the poor behavior of the axon as a traditional wire lies in the inefficiency of the membrane for transmitting current. Compared to standard copper wire, the membrane of the axon is 1,000,000 times more likely to leak electrical current to the surroundings resulting in a loss. The interior of the axon is not a better option: the interior has a resistance that is over 10,000,000 times greater than copper wire (Schadé and Ford, 1973).

The action potential is the time when the neuron is functional. Figure 3 depicts the action potential from several perspectives. Imagine a neuron in a relay sequence that is taking sensory information back to the brain. It senses a painful stimulus in the outside environment and now must alert the brain. How does it do this? It has everything to do with the membrane potential.

The dendrites are the site on the neuron where stimuli act. It is the dendrite of this neuron that first senses the pain. Neurons act according to the all-or-none principle. If a stimulus passes a certain threshold, then it will generate an impulse of a certain size, and the neuron will never fire more or less than with that intensity: any smaller stimulus will not cause the nerve fiber to transmit an impulse (Adrian, 1914). Therefore, once the stimulus reaches a certain intensity, then the dendrites are alerted and the signal begins. The "excitability" of the neuron refers to its ability to activate according to an outside stimulus. The excited dendrite has sensors that pick up the stimulus and transmit the information to the nucleus in the cell body. It is of vital importance for the message to be passed on to the next neuron, a process that involves transmitting the impulse down the axon. This begins with the depolarization of the axon in the region where the axon meets the cell body, called the axon hillock. On Figure 3A, depolarization is represented by the period of upward slope before the peak. During depolarization, the potential generated across the membrane is disturbed, as sodium channels open on the membrane that are normally closed (Schadé and Ford, 1973). The sodium ions use these channels to flow into the neuron through the membrane, thus causing a rapid change in the potential. Figure 3C shows the permeability increase of Na^+ that corresponds to this potential shift. The channels used by sodium ions are called voltage-gated channels, so named because changes in membrane voltage cause them to open, and this opening is very important in the production of an action potential (Hirakawa et al., 2012).

Voltage-gated sodium channels are sensitive to changes in the membrane voltage nearby, and open in response to changes. This behavior is crucial to the propagation of the action potential. Figure 3B shows the inversion of membrane potential created by the influx of sodium ions through an open voltage-gated channel. For the action potential to continue down the length

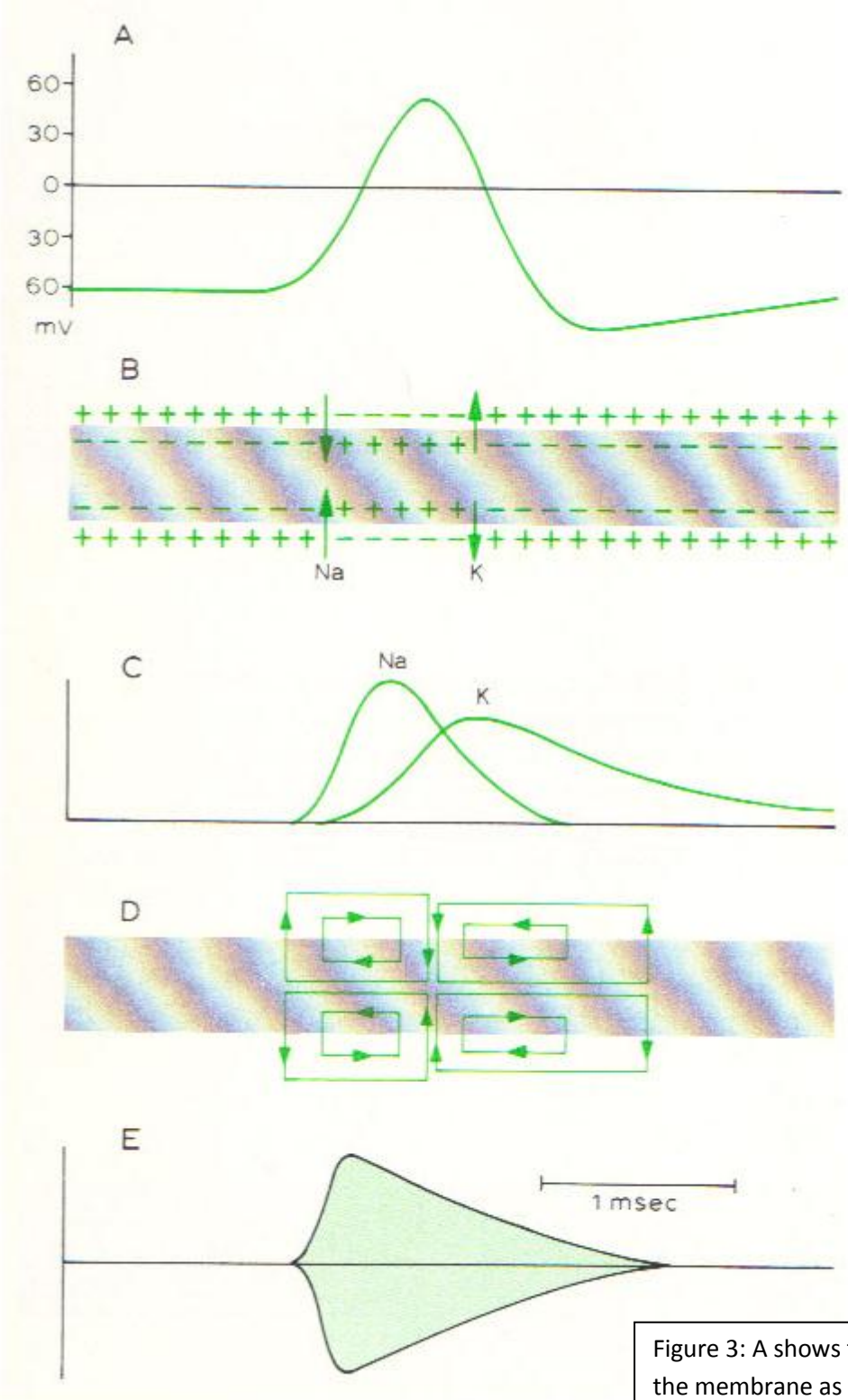

Figure 3: A shows the potential change across the membrane as a function of time. B shows the action potential at a point on the membrane. C shows the rates of sodium and potassium diffusion through voltage-gated channels as a function of time. D shows the local current movements. E shows the variation in membrane conductance as a function of time.

of the axon, the nearby membrane must react to the progressing signal. Voltage-gated sodium channels adjacent to the action potential position respond to the changing polarity of the membrane and open, causing the action potential to propagate further along the axon. This accounts for the movement of the signal, which sets up the local currents seen in Figure 3D. However, the neuron must be able to regain the polarity of the resting potential; otherwise the signal would never stop. Potassium voltage-gated channels also exist along the membrane, and they become active when the potential reaches its most positive value. These channels trigger the release of potassium ions into the extracellular space, equilibrating the potential change and starting the reversion to the resting potential. This process is called repolarization (Schadé and Ford, 1973). Repolarization marks the downward slope after the peak on Figure 3A, where the potential is returning to the resting state. Once the voltage drops enough, both sets of channels close, and the sodium-potassium pump helps the membrane equilibrate to the resting potential. At this point, the neuron would be ready to fire again, to report another stimulus.

The action potential occurs very quickly: the average duration of an action potential is about 1-3 ms. This short time is a product of how quickly the signal can move along the axon. In spite of the poor cable properties of the axon, the signal can still proceed at speeds up to 120 m/s in myelinated fibers. So, for example, in a person about 6’2”, a signal would travel roughly 1.8m to reach the brain from the foot. The high speed of impulse conduction results in a time of 0.015 s or 15 ms. Therefore, nerve signals and thereby action potentials occur very quickly. One way the body increases the speed of the impulse is by using myelination. In this process, a thick myelin sheath surrounds the axon, with small openings called nodes of Ranvier appearing. The membrane depolarization and repolarization cycles of the action potential exhibit salutatory conduction: where the signal jumps quickly between nodes (Pereira et al., 2012). The membrane

needs to go through the cycles of opening and closing channels only in a few places, instead of down the entire length. When the potential has moved to the end of the axon, it reaches a structure called the terminal button, which responds to the potential change by releasing chemical compounds into the synaptic cleft between the terminal button and the dendrite of the next neuron in the sequence. This begins a chain that carries a nerve impulse all the way to either the brain or its effector tissue.

Once the synapse is passed on to the next neuron, a phenomenon occurs in the next neuron called an excitatory post-synaptic potential (EPSP). This phenomenon occurs on the dendrites of the neuron, and results in a higher likelihood of the neuron firing. It is a potential that is applied to the membrane by the flow of positive ions into the cell due to the opening of ligand-gated channels (which open due to the chemical signals released in the synapse). This potential generates a current and an electric field. An equation that measures the electric field intensity generated by the EPSP is given as Equation 4, where V_0 is the initial voltage applied, λ is the space constant (for a dendrite of diameter 1 μm, it is found to be −353 μm), and τ is the time constant for the voltage change in the dendrite (about 30 ms) (Georgiev, 2003).

$$\vec{E} = -\frac{dV}{dt} = \frac{1}{\lambda} V_0 (e^{\frac{-x}{\lambda}})(e^{\frac{-t}{\tau}}) \qquad (4)$$

Using this equation, it is discovered that the intensity of the electric field in the neuron that has an EPSP of 0.2mV delivered to it is about 0.57 V/m. The current that runs through the dendrite under the same conditions is also found to be 0.45 pA (Georgiev, 2003). This is consistent with the normal current expected in the dendrites, the range of which is 20 pA to 100 pA. This represents the current generated by the movement of ions across the membrane in the dendrite during the acceptance of the signal by the neuron. This precedes the generation of the action potential and propagation along the axon.

Current is nothing more than moving charge. One property of moving charge in the universe is that it generates a magnetic field. Magnetic field lines exist perpendicular to the movement of the charge. Previous calculations were performed using Equations 5 and 6, where H is the magnetic intensity, d is the diameter of the dendrite, and μ_{eff} is the effective magnetic permeability in the ferrofluid formed by the water and the microtubules, roughly 10.

$$H = \frac{current}{\pi d} \quad (5)$$

$$B = \mu_{eff}\mu_0 H \quad (6)$$

Calculations were performed using for reference a dendrite with a 1 μm diameter and 100 pA current, and the magnetic field was found to have a magnitude of 4×10^{-10} T, compared to a 1.6×10^{-7} T value for an axon magnetic field, generated by a similar phenomenon (Georgiev, 2003). This shows that the neurons produce a relatively weak magnetic field (compared to the Earth's magnetic field), but still produce one, as would be expected due to the moving charge contained within the neurons.

Since individual neurons produce magnetic fields, it would be expected that the largest mass of them in the body would produce a significant magnetic field. Therefore, at low frequencies of brain dynamics, magnetic fields in the brain are due only to currents, and so the magnitude of the field can be determined by using the Biot-Savart Law, in Equation 7, where H is the magnitude of the magnetic field.

$$\vec{B} = \mu_0 \frac{I\vec{l} \times \vec{r}}{4\pi r^3} \quad (7)$$

For example, if the current magnitude were 4π μA, then at a distance r=1 cm away (perpendicular distance to the axis of the neuron), then the magnetic field would have the magnitude 0.01 μA/mm^2 (Nunez and Srinivasan, 2006). For the current amount calculated before for a dendrite, 100 pA, and a distance 1 cm from the brain neuron would have a magnetic

field of magnitude 1×10^{-13} T. These properties of the brain are exploited in medical techniques: for example, electroencephalography (EEG) uses the electric fields and voltage fluctuations in the brain to diagnose brain disorders and study the brain. Magnetoencephalography (MEG) is an analogous technique; instead using the magnetic fields produced by current within brain neurons, and is primarily used for research into brain activity. These two techniques make use of the electromagnetic properties of neurons in order to gain a greater insight into the human nervous system.

The neuron is a vastly complicated, highly specialized cell that is used to transmit information throughout the body. The very basis for this system's function is the phenomenon of electromagnetism. The nervous system is based heavily on these physical laws that dictate how charge behaves, both in electric field, using potentials and electric force, and in magnetic field. These laws help students learn more about why the body behaves the way it does, and it sheds light on how all the worlds of physics, biology, and chemistry intertwine to create one of the most complicates life systems known.

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