XRAISE OUTREACH LABORATORY INVESTIGATION

Title:	**Biocircuits: Signal Loss in Cable Transmission**
Original: **Revision:** **Formatted:**	4 April 2009 15 April 2009 May 2015 by CLASSE Xraise
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Appropriate Level:	9-12 Regents Physics, AP Physics B
Abstract:	In this lab students will investigate a basic and important simple electric circuit and show how it can be used to model nerve conduction. They will use Ohm's law to predict voltage and current flow in a simple voltage divider. Students will build a model electrical cable using a series of voltage dividers and experiment with strategies to reduce current loss and voltage decay along the cable. Students will use the cable they build to show how the same strategies they discovered are used in nature to solve the very important problem of nerve conduction and appreciate how the cable model predicts problems associated with an important disease, *Multiple Sclerosis*.
NY Standards Met:	Physical Setting: Physics 4.1l All materials display a range of conductivity. At constant temperature, common metallic conductors obey Ohm's Law*. 4.1o Circuit components may be connected in series* or in parallel.* Schematic diagrams are used to represent circuits and circuit elements. 4.1m The factors affecting resistance in a conductor are length, area, temperature, and resistivity.* 5.1d An object in linear motion may travel with a constant velocity* or with acceleration*.(Note: Testing of acceleration will be limited to cases in which acceleration is constant.) Living Environment 1.2a Important levels of organization for structure and function and whole organisms. 1.2f Cells have particular structures that perform specific jobs. These structures perform the actual work of the cell. Just as systems are coordinated and work together, cell parts must also be coordinated and work together. 1.2g Each cell is covered by a membrane that performs a number of important functions for the cell. These include: separation from its outside environment controlling which molecules enter and leave the cell, and recognition of chemical signals. The processes of diffusion and active transport are important in the movement of materials in and out of cells.

Special Notes:	Created by the CNS Institute for Physics Teachers via the Nanoscale Science and Engineering Initiative under NSF Award # EEC-0117770, 0646547 and the NYS Office of Science, Technology & Academic Research under NYSTAR Contract # C020071

Pre-Lab: Signal Loss in Cable Transmission

Multiple sclerosis is a nerve conduction problem. The body is sending out a signal for something to happen and the message just isn't getting to the brain in time or at all. This is similar to the problem a communications engineer might experience with a data signal in a computer cable. The data goes in one end but by the time it gets to the other end the signal has become weak and noisy. This problem was originally encountered by the telegraph companies in the middle of the 1800s when they tried to lay cables across the English Channel and later across the Atlantic Ocean. How could they design a cable that could carry the signal without significant loss of data and at a cost that the companies and their customers could afford? Enter Lord Kelvin. You may have heard the name associated with temperature as in: “zero Kelvin,” *Absolute zero*, the coldest possible temperature.

Lord Kelvin, a Baron whose real name was William Thomson, is about as famous as they get in physics. Let's see how physics solved the problem of the transoceanic telegraph and how physicians used that knowledge to research multiple sclerosis.

Your challenge in this lab is to understand what a disease of the nervous system and the transatlantic cable have in common. The basic electrical unit that will be used to analyze both these things is the voltage divider, which is a basic electrical circuit used to create a smaller output voltage from a larger input voltage.

Section 1: Using Voltage Dividers To Analyze Signal Loss

Voltage dividers are used in electronics to reduce a fixed source voltage to an appropriate level for a particular task. For example, if you have a 12V battery and a lamp that can only handle 6V, you can use a voltage divider to drop the voltage to what is needed. A voltage divider is a simple circuit with 2 or more resistors added in series (Figure 1). We will put together a series of voltages dividers to model a voltage drop like the one that occurred on the transatlantic cable. We will then apply similar principles to model a biological system, specifically neurons in the nervous system.

> Interesting fact: Turns out the cable equations that Lord Kelvin derived in the 1800’s to explain signal loss in the transatlantic cable were found, almost a century later, able to describe conduction in the nervous system!

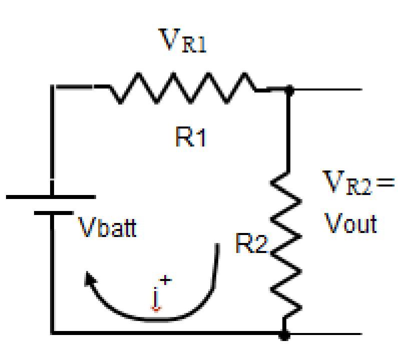


Figure 1. A simple voltage divider. Positive current (i^+) flows from the positive pole of the battery through two resistors in series to the negative pole of the battery.

According to Ohm's law (V=IR), when current flows through a resistor, a voltage equal to I*R appears across the resistor. In

Figure 1 this voltage is labeled V_{R1} for the voltage that appears across R_1 and V_{R2} for the **voltage drop** across R_2. **The total voltage drop across both resistors is equal to the voltage of the battery.**
$V_{batt} = V_{R1} + V_{R2}$

A voltage drop can occur, both in physical and biological systems, when the inherent properties of the system produce a voltage division that is NOT so helpful. These inherent properties can be caused by the internal resistance of the conducting material, weak resistance of the insulation material, resistance in connections or conductors, etc.

For the first part of the lab, you will be modeling the transatlantic cable, which for simplicity; will consist of a copper wire wrapped in a certain insulating material. The copper wire will have an inherent core resistance R_c and the insulating material will also have an inherent resistance, called leak resistance, R_L.

- **Core resistance of a wire**: When current flows through a wire it encounters a resistance that is a function of the material from which the wire is made and the wire geometry. This resistance is called the 'core' resistance (R_{core} or R_C).
  A high core resistance means that the wire is not a good electrical conductor.
  A low core resistance means that the wire is a good electrical conductor.

- **Leak resistance of insulation:** At the same time, some of the current will not flow along the wire, but will leak to ground. The better the wire is insulated, the less current will be leaked. The resistance of the insulation to this current leakage is called the 'leak' resistance (R_{leak} or R_L).
  A well insulated wire has a high leak resistance.
  A poorly insulated wire has a low leak resistance.

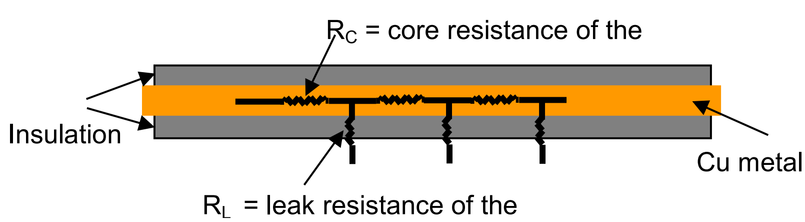


Figure 2. Cross-section of an insulated metal wire.

- If the signal leaks to ground as it travel down the cable, then only part of the original signal will be available at the other end of the cable to do useful work. **Figure 3** shows a voltage divider model of a wire that is similar to what Lord Kelvin developed to solve the problem of transmitting telegraph signals across the English Channel.

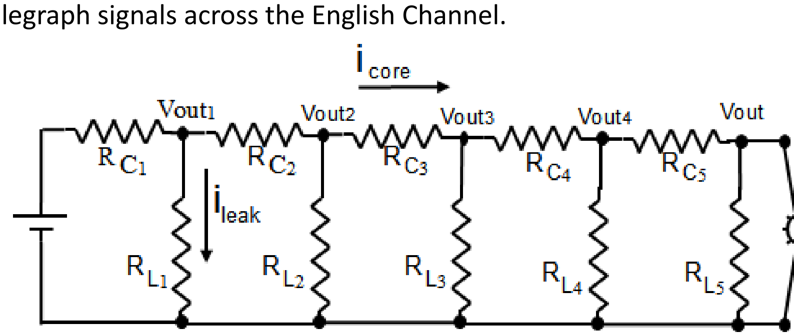


Figure 3. Circuit model for signal losses along a cable

- You will test this voltage divider model using different combinations of core and leak resistances. **Study the figure and be sure you can identify the voltage dividers. Note that the output of the first divider in the Figure 3 is the input to the second one, and so on.**

Section 2: Experimental Section

Activity 1:
In this activity you will measure the voltage drop across different voltage divider set-ups and compare your output voltages.

Materials:

- **Project Board** (Disclaimer: This project board was designed to show a Multipolar or Motor Neuron so that later in this lab we can emphasize the connection between physics and biology. For more details about the board please refer to the Appendix).
- **Multimeter**
- **9V battery**
- **Screwdriver (will help opening the slots to insert the leads of the resistors)**
- **LED**
- **Resistors (set of 5 of the 6 resistors shown in Table 1.)**

Table 1: Resistor Values and Corresponding Color Codes

	HI	**MED**	**LO**
Core resistance, R_C, of the Cu wire	Red (400 Ω)	Blue (200Ω)	Green (100Ω)
Leak resistance, R_L, of the insulation	Yellow (7,500Ω)	Brown (2,200Ω)	Black (1,500 Ω)

Procedure:

- Get your project board out. Note that this is designed to show a Multipolar or Motor Neuron and will be discussed later in the lab. For more info on the board, refer to Appendix.
- Measure the actual voltage of your battery and record it in Table 2.
- On your project board, assemble the circuit shown in Figure 4, using R_c=R_L = 1,500 Ω (black). The left hand image is the circuit schematic and the right hand image shows how you build this circuit on your project board. The right hand image also shows how to measure the voltage across a resistor.
- The 9V battery is connected to the board using the double clip leads.
  TIP: Use the screwdriver or wooden ruler to depress the lever and insert the resistor leads.

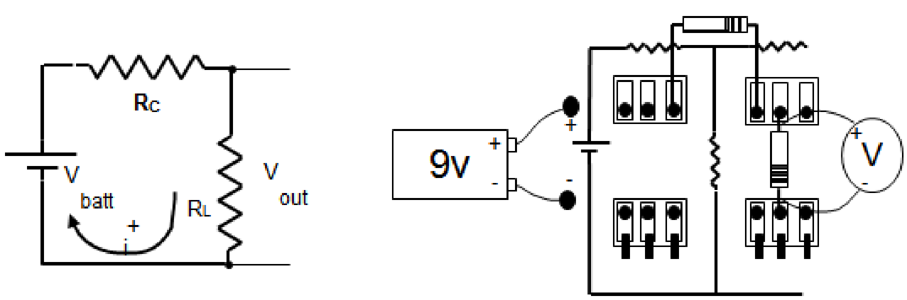


Figure 4. Voltage divider circuit and project board wiring diagram.

- Measure the voltage across R_C and R_L (V_{out}). Record these values in Table 2. Note that V_{RC} and V_{RL} must total V_{batt}.
- Complete the data table using the other 3 combinations of resistors listed.

Table 2. Voltage Divider Data

V_{batt}	R_c Ω color	R_L Ω color	V_{RC}	V_{RL} (V_{out})
	1500 (black)	1500 (black)		
	1500 (black)	100 (green)		
	100 (green)	1500 (black)		
	100 (green)	200 (blue)		

Questions:

- Based on your calculations: How would you pick R_C and R_L to make V_{out} close to V_{batt}?

- How about V_{out} much smaller than V_{batt}?

Activity 2:

In this activity you will investigate the problem of transmitting electrical signals over long distances. In addition to modeling the performance of a cable, you will conduct an engineering assessment of the cost/benefit analysis for cable design.

Materials:

- **Same as above**

Procedure:

- Assemble the circuit shown in Figure 3 by using the resistors values shown in the first two columns of Table 3.
- **All of the resistors used for R_C must be of the same value, because the wire is homogenous along its length. Similarly, all resistors used for R_L must be of the same value, because the insulating material is also uniform along the length of the cable.**
- Connect the battery and measure the voltage across the 5 R_L or “leak” resistors (R_{L1} to R_{L5}). Enter the values in Table 3.
- After you have recorded your data connect the LED by touching its leads to the leads of the leak resistor R_{L5}. Record whether or not the LED lights in Table 3.

- NOTE: It isn't necessary to actually connect the LED to the board. You can just touch the LED leads to the resistor leads.
- NOTE: LEDs have polarity. Try the LED on both leads to make sure you are reading it correctly.
- Repeat the procedure using the other values for R_C and R_L in Table 3.
- Data for the six possible configurations is plotted in Figure 5. Note that the uniformity of R_C and R_L create an exponential decrease of voltage over distance from the battery that can be described by a "space or length" constant.
- Using your data and the data in Figure 5, determine which combination of core and leak resistances lead to cables capable of lighting an LED. Summarize this information in Table 4 by writing "ON" if a particular combination of core and leak resistances can light the LED and writing "OFF" it is cannot. Test your predictions for the combinations not included in Figure 5.

Table 3: Voltage Divider Network Data

R_C	R_L	V_{out1}	V_{out2}	V_{out3}	V_{out4}	V_{out5}	LED (on/off)
LO core resistance *(green)*	MED leak resistance *(brown)*						
LO core resistance *(green)*	LO leak resistance *(black)*						
HI core resistance *(red)*	LO leak resistance *(black)*						

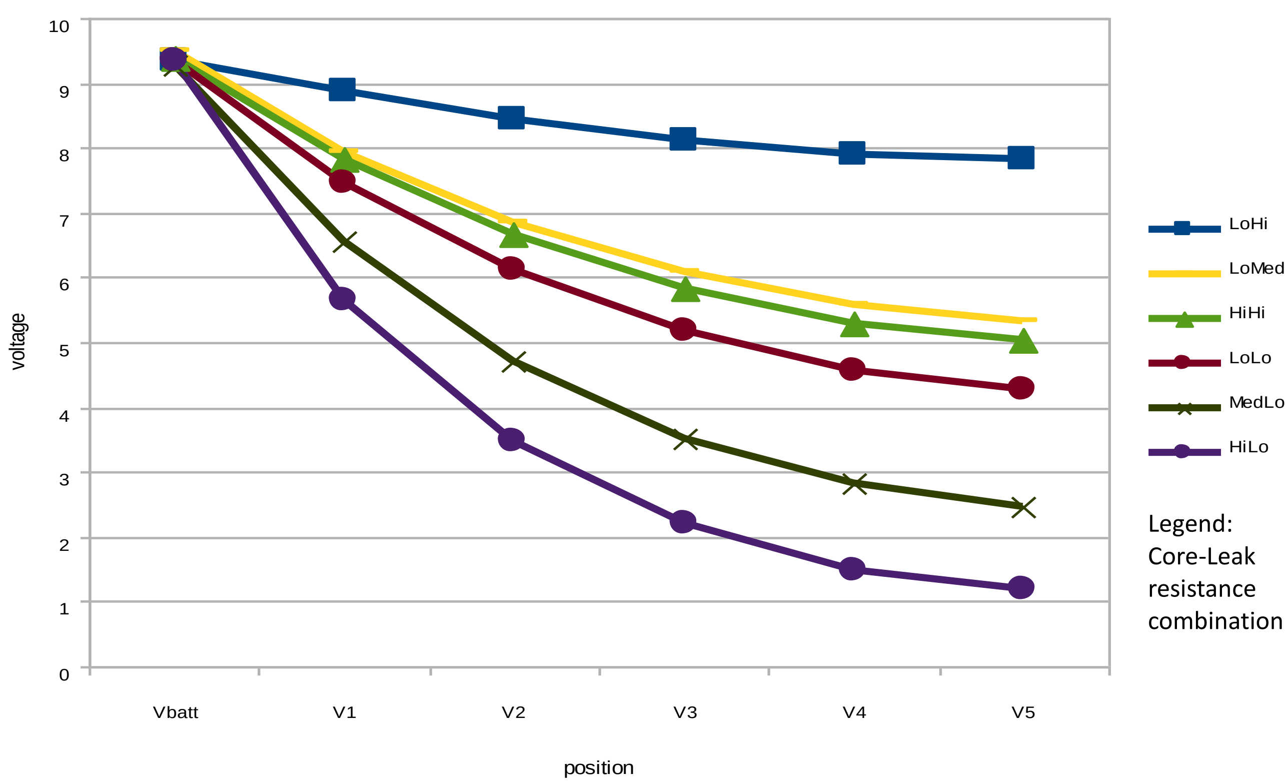


Figure 5: Voltage Divider Data for Different Resistor Combinations. The core resistance is listed first and the leak resistance is listed second.

Table 4: Summary showing which cables could light the LED.

		Core Resistance		
		High	Med	Low
Leak Resistance	Low			
	Med			
	High			

Questions:

- What trends do you notice in this table?

In the real world, engineers rarely have the luxury of building the best possible system since materials cost money and customers desire a working and reliable solution that is economically viable.

For the cable, the core resistance models the resistance of the wire itself. This follows the equation:

$$R = \rho L/A$$

- For a given material (with resistivity ρ) and a given length wire (L), how do you make a wire with a low core resistance?

- How do you make a cable with a high leak resistance?

- Given this information, which cable configurations do you think are the least and most expensive to produce and why?

Historical data shows that the cost of the transatlantic cable was approximately £400/nautical mile in British Pounds, £. Table 5 has estimates for the cost of the various core and leak resistances/nautical mile of cable. The total cost per nautical mile is the sum of the cost of the core and leak resistances.

Table 5: Estimated material cost per nautical mile (in British Pounds) as a function of material quality

	HIGH	MED	LOW
Core resistance, R_C of the wire	£100.00	£200.00	£400.00
Leak resistance, R_L of the insulation	£200.00	£150.00	£50.00

- **Assume that your voltage divider circuit is a good model for the design and function of the transatlantic cable.**
  - Based on your LED model and the data in Table 5, determine the cost per nautical mile of each working model for the transatlantic cable. Show your work.
  - If you were the engineer responsible for the project, which combination of core and leak resistances would you decide to construct the cable from? Why?

Section 3: Finding Physics in a Biology Problem

Activity 3: Physics in Biology

In the pre-lab you were introduced to a serious disease that is caused by a failure of nerves to properly carry signals throughout the body. Our success as animals depends on the ability of these nerves to conduct signals efficiently and often rapidly. You have probably had the experience of a painful stimulus causing you to quickly, without even thinking, pull your hand away. Figure 6 shows the nerves (electric wires) used to transmit signals between your limbs and central nervous system (CNS) in the withdrawal reflex. The little square in this diagram represents an area of skin on your hand containing sensory neurons that are sensitive to painful stimuli. The part of a neuron that carries the signal over long distances is a long thin process called the axon. The sensory signal from the pain travels along an axon toward the CNS. In the spinal cord, the signal is transferred to another neuron (motor neuron) and travels along its axon back to the muscles in your arm causing the withdrawal. **The axons in this biological circuit are analogous to the wires in an electric circuit.** The term nerve is often used instead of axon. A nerve is composed of a bundle of many axons packaged together; much like an electrical cable is composed of a bundle of wires. In this lab we are studying axonal conduction.

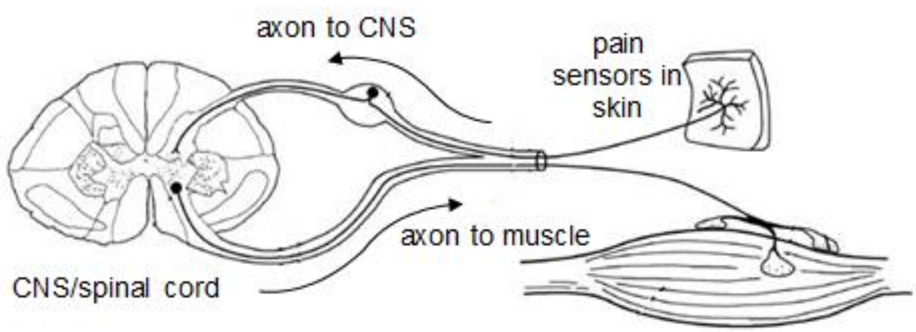


Figure 6. Neural circuit of the withdrawal reflex.

Materials:
- Wooden ruler or meter stick
- calculator

Procedure:
- Vertically hold a ruler between your fingers and record the position of your fingers on the ruler. This is x_1.
- Open and close your fingers as fast as you can. Record the new position of your fingers. This is x_2.
- $x_2 - x_1 = d$, the distance the ruler fell. Record your values in the Table 6.
- Calculate the time it took for your hands to open and close using the following equation. Solve for Δt in seconds and record this value in Table 6.

$$d = \frac{1}{2}a(\Delta t)^2$$

Where: d is the distance the rule moved (m), a is the acceleration of gravity (9.8m/sec^2) and Δt is the time it took to open and close your hand (sec)

Estimate Δx, the total distance the signal must travel for you to open and close your hand by first measuring the distance from your fingers to the center of your spine at the level of your shoulder blades. What you are actually measuring are two signals: 0ne to release the ruler and the other to squeeze it. Double your value for Δx to account for this. Input this value into Table 6.

- Calculate the velocity using the equation in the table and enter the value in Table 6. This is a rough estimate because we are ignoring the timing of the brain commands to get to the spinal cord.

Table 6: Calculation of motor neuron transmission speed.

Initial ruler Position, x_1 (m)	Final ruler position, x_2 (m)	$d = x_2 - x_1$ (m)	Time, Δt (sec)	Δx = nerve pathway length, (m)	$v_{nerve} = \Delta x/\Delta t$ (m/sec)

- Think about experiences in your daily life – or those of other creatures you know – and make a list of situations where fast response is crucial. Make a separate list of situations where fast reactions are less important.

Fast	Not so fast
______________________________	____________________________
______________________________	____________________________
______________________________	____________________________

- Do you think that the axons making up the neural circuits required for producing the behaviors in these two lists have the same or different physical properties? Explain which properties, specifically, are similar and different, addressing at least R_C and R_L.

Activity 4: Cable Conduction in Biology

In Activity 1 and 2 you modeled the transatlantic cable as a series of voltage dividers. The reason you did that on a project board with a picture of a nerve cell is that the same voltage divider model applies to signal transmission in the nervous system. To convert from metal cables to the biological system, we just need to redefine the variables:

- **Core resistance of an axon**

When a signal travels along a nerve axon it encounters a resistance that is a function of nerve geometry.

A high core resistance means that the nerve is thin (small cross sectional area)

A low core resistance means that the nerve is thick (large cross sectional area).

- **Leak resistance of an axon: the myelin sheath**

Insulation of axons is provided by a layer of myelin. A schematic of a neuron with a myelinated axon is shown in Figure 9. *Myelin is used to insulate nerve axons whenever fast conduction speed is needed.* Not all axons are myelinated.

A well insulated axon with a thick myelin layer has a high leak resistance.

An axon with no myelin sheath has a low leak resistance.

The graphs below (Figures 7 and 8) show the effects of reducing the core resistance (Rc) of an axon by increasing its diameter and the effects of decreasing the leak resistance (RL) of a neuron on the voltage spread from a source. Do these graphs have any similarities to the data in Figure 5? Does it look like cable transmission in an axon is similar to that in the transatlantic cable? What does this say about the uniformity of R_C and R_L in animal "wires"? Axon membranes also have a "space" constant for passive voltage spread.

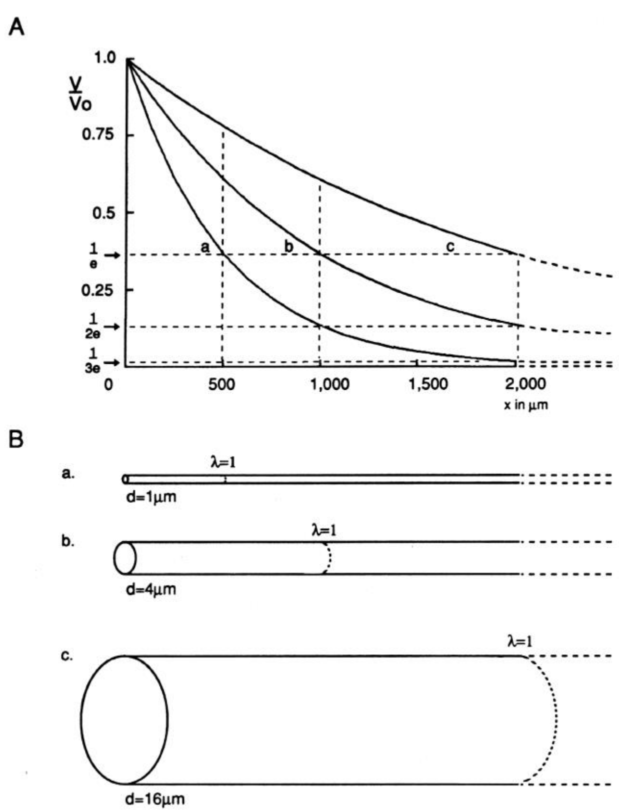


Figure 7. Graph showing the effects of reducing the core resistance (Rc) of an axon by increasing its diameter

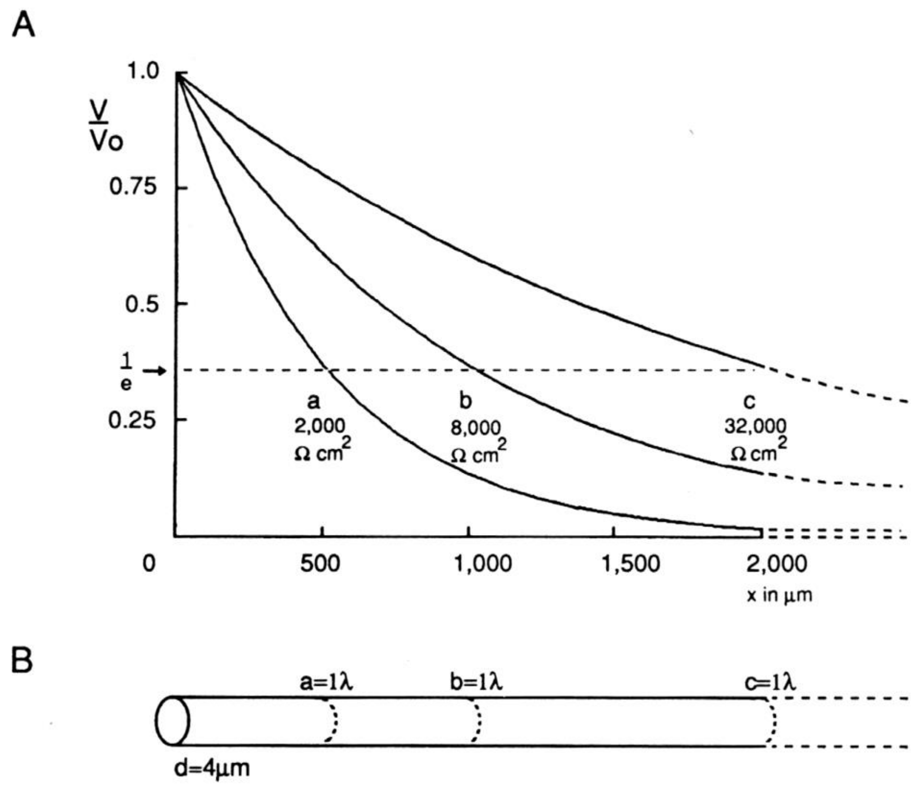
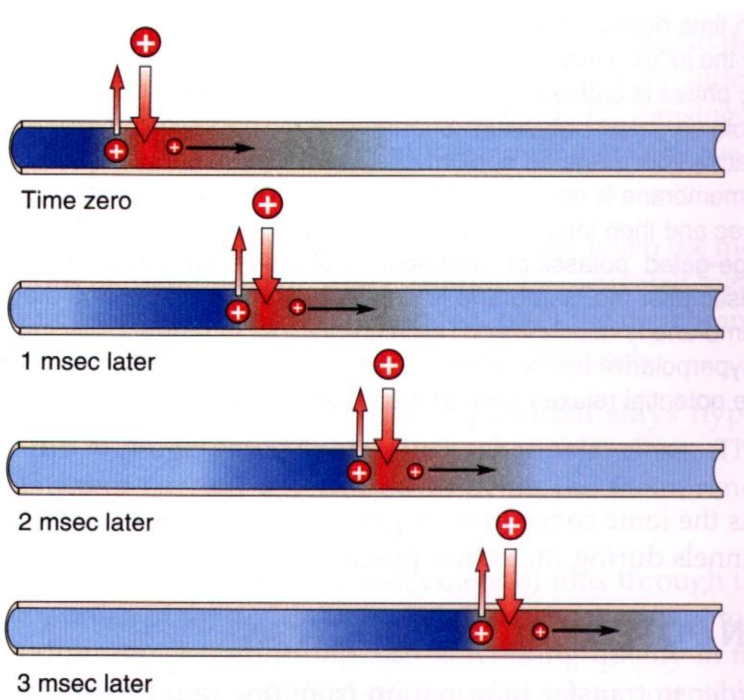


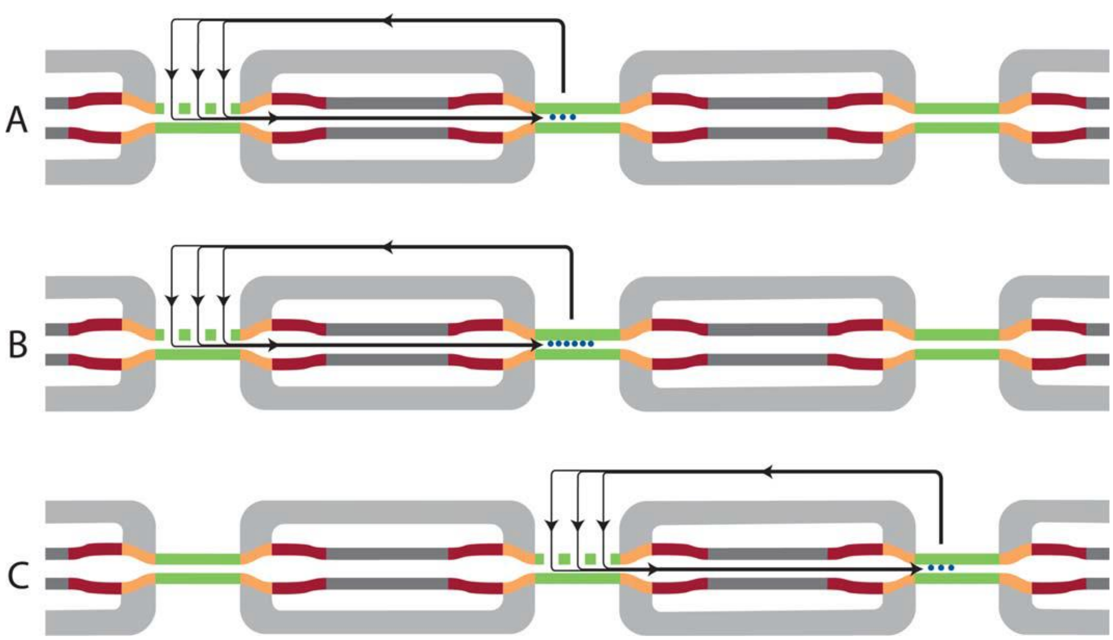
Figure 8. Graph showing the effects of decreasing the leak resistance (RL) of a neuron on the voltage spread from a source

In most parts of the nervous system distances are too long for signal transmission to be effective by cable properties alone. For example, consider the signal transmission in a motor neuron axon going from the spinal cord down to a toe muscle in a basketball player (or a giraffe!). Voltage sensitive booster stations in axons create sparks of electricity called Action Potentials (APs) which then become the voltage source to passively transmit the signal like in a cable down the axon to ignite the next AP, and so on and so on.

In unmyelinated axons, APs are ignited continuously when the passive voltage spread is large enough (long space constant) to activate the next booster system as shown below. It takes time to generate each AP and the passive voltage spreads very quickly. So if the initial voltage stays strong and spreads further, fewer APs have to be initiated in the same length of axon and so signal transmission will be faster.



In myelinated axons (Figure 9) and below, the AP is only ignited at the bare internode (green) regions and the myelinated regions (gray) conduct the voltage spread passively like a cable to the next AP generation area. It would be more consistent to number these figures too and give them a figure legend, but it’s fine for now.



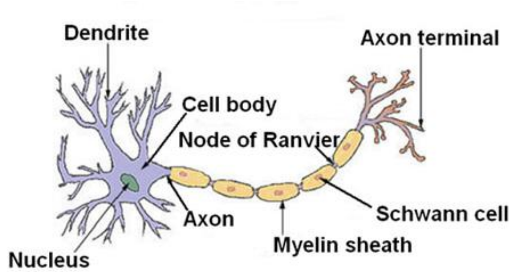


Figure 9. Schematic representation of a multipolar neuron with myelinated axon.

How fast is fast?

Questions:

- In nature, animals rely on fast reactions for survival. Based on your understanding of cables and nerves, speculate about strategies nature could use to increase the speed of conduction. Give your answer in terms of both R_C and R_L for axons. Make sure to explain what these values mean in terms of the axon structure.

- Not all axons are myelinated. If myelin makes nerve signal transmission faster, why wouldn't all axons be myelinated? Consider that evolution also makes a cost/benefit analysis when adjusting electrical parameters that affects the speed of signal transmission.

- Many invertebrate animals do have relatively fast signal conduction that are not insulated with myelin. Based on your understanding of cable conduction, what must be a common physical characteristic of these unmyelinated neurons to enable them to transmit signals so quickly?

- How fast were your neurons? To get a better sense of this, convert your neuron speed from m/sec into miles/hour. Show your work.

> Fun Fact: The ratio of the diameter to the length of the transatlantic cable is similar to that of a long alpha motor neuron. Engineering produced the same solution as biology!

Here are some examples of unmyelinated axons in invertebrates:

- The squid contracts its mantle providing a jet powered escape mechanism using a signal from an axon known as the squid giant axon. It's so big you can dissect it without using a microscope.
- The cockroach has a pair of hairs on its tail end called cerci. Large unmyelinated axons carry information from these hairs to its brain about air currents coming from behind it.
- The crayfish uses rapid beats of its tail to dart away for cover. This movement is stimulated by large unmyelinated axons.

- Which of these neurons do you think would have myelinated axons? Explain your reasoning.

Table 7.

Nerve Type	Axon Diameter (µm)	Signal Velocity (m/s)	Myelinated? Yes or No	Explanation
Squid Giant Axon	500	19		
α-motor neuron (skeletal muscle)	10	120		
Sensory neuron (stimulus response)	1-5	30		
c-fiber pain (not sudden)	0.2 – 1.5	0.5 – 2.0		

Fun Fact: The neurons in your brain have myelinated axons to assure fast conduction. If they were not, to achieve the same transmission speed, the nerves would have to be much larger in diameter. In fact, your head would have to be the size of a beach ball!

Multiple Sclerosis

What happens in your body if you have Multiple Sclerosis? This is an autoimmune disease, which means your body attacks itself. In multiple sclerosis the core resistance of your nerves is not affected.

- According to what you have learned in this lab, describe the type of damage that occurs to a person's nervous system as a result of having Multiple Sclerosis. How might this cause AP signal transmission to be slowed or fail.

Refer to the Figure 10 below for a hint. Consider how the space constant for the passive voltage spread down the axon might be affected in the internode region.

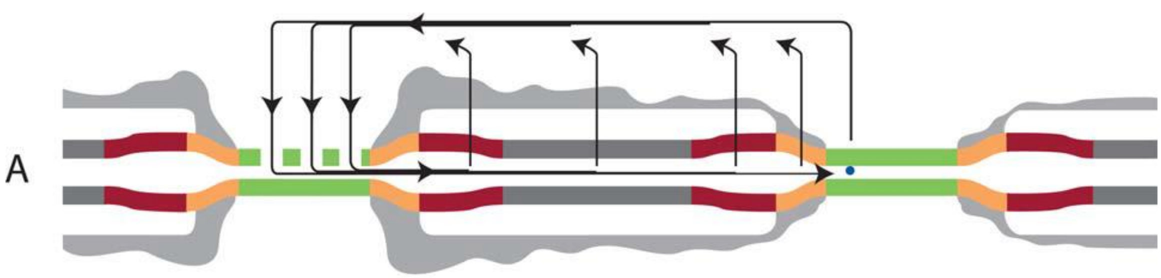


Figure 10.

- Science has not figured out how to cure this disease. How could stem cell research lead to a potential cure for this disease? The axonal membrane has many ion channels through which charged ions like sodium and potassium flow. If we could block some of these ion channels with a drug, how might this help MS patients? What electrical parameter of the membrane would be affected?

Appendix

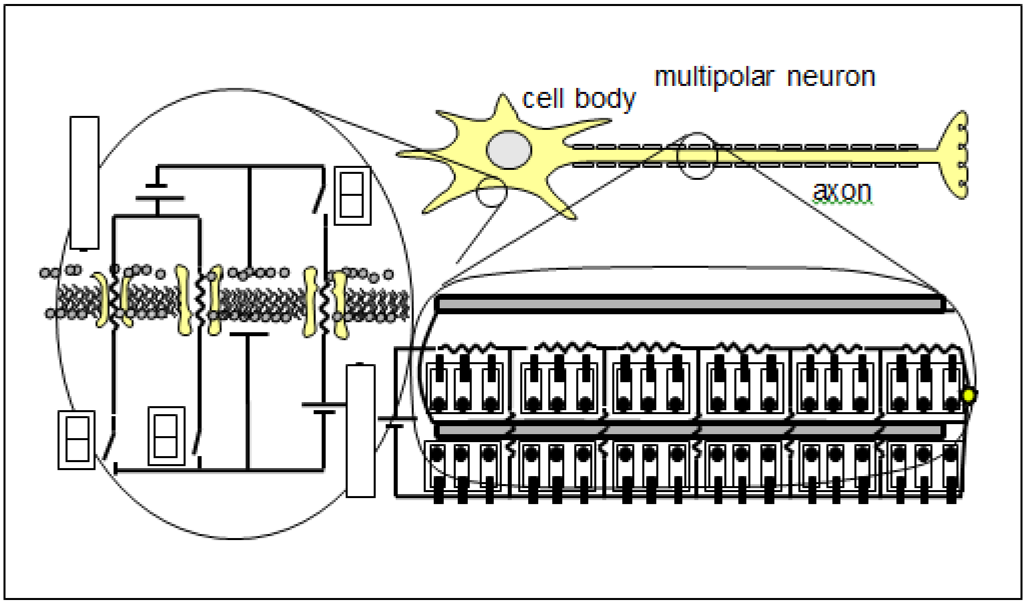


Figure 11. The Cable Transmission Project Board

Even though most of the work done in lab will concern conventional electric circuits, the project board used was designed to emphasize the connection between physics and biology.

There are 3 main areas on the board.

- At the top and to the right is a diagram of a multipolar neuron. This is the type of neuron called a motor neuron that is used to carry signals to muscles. When activated, these neurons cause muscles to contract.
- On the left side of the board in the large circle is a detailed diagram of a section of the cell body and the circuit that describes the action potential. The cell body is where the neuron makes the decision as to whether or not it should fire an action potential. It will not be used in this activity.
- At the bottom and to the right is a detailed diagram of a segment of axon. The axon is the structure that transmits the action potential generated in the cell body and carries it to the muscle. On the left side of this diagram is a symbol for a battery. This is where you will attach your signal source, a 9V dry cell battery. On the far right is an LED. The LED will be used as the signal that the circuit you've constructed works.

Study the diagram and see if you can find any voltage dividers in the circuit between the battery and the LED.

References:

1. Facts about MS. (n.d.). Retrieved from http://www.msfocus.org/Facts-About-MS.aspx - See more at: http://www.healthline.com/health/multiple-sclerosis/facts-statistics-infographic#sthash.icgOCW2K.dpuf
2. http://www.nlm.nih.gov/medlineplus/multiplesclerosis.html