Sending a Signal

Exploration - How Does a Neuron Transmit a Signal?

Electrical processes are essential to the working of the human body. The transmission of information in the body is an electrical phenomenon. For example, sensory information is transmitted from the skin of your foot to your spinal column via nerves. Each nerve consists of a bundle of nerve cells where each nerve cell is called a neuron. Here is an example of an artist's rendering of a neuron. A similar drawing can be found on page 611 of your textbook.

A neuron receives stimuli at the input end and creates a signal that is transmitted across the axon to the output end. The length of the axon varies considerably, depending on its function and placement in the body. The neuron that extends from the foot to the spinal column may have an axon that is 1-m long!

The axon membrane is usually positive on the outside and negative on the inside (as modeled in Lesson 60). The potential difference between the membrane is typically about 70 mV. However, when a stimuli (such as the sensation of heat) interacts with the neuron, the potential difference rapidly changes so that the inside of the membrane has a potential of about 40 mV higher than the outside. This new potential difference rapidly decreases to its original value, sending a wave pulse along the axon.

1. Considering the neuron membrane as a kind of capacitor in series with the length of the axon over which the signal is transmitted, what factors do you think could affect the time it takes for the signal (wave pulse) to be transmitted from the input end to the output end? Explain your ideas.
Application #1 - Modeling the Rapid Change of the Potential in a Nerve Signal

During this lab, you will model the behavior of neurons as they transmit electrical signals. To do this, you will build a circuit containing a capacitor, resistance, and an initial potential difference.

**Equipment:** Battery set, Plastic circuit block, One assorted resistor, One assorted capacitor, Key switch, Banana leads, Digital multimeter (DMM), Capacitance meter, MBL voltage sensor

**Experiment #1 – Classifying the circuit components and physically building the model**

In preparation for your experiments today, you should measure and record the following quantities. Write a brief description of how you made your measurements in your logbook. In addition, be sure to record and clearly label all measured values.

**Resistor**
- Using the information in Lesson 62 (p. 6), record and interpret the color code of the resistor. What is its labeled resistance value? Identify this resistor as $R_1$.
- What is the resistance of the resistor as measured by the DMM?

**Capacitor**
- Record the stated capacitance value given on the capacitor. Identify the capacitor as $C_1$.
- What is the capacitance as measured by the capacitance meter? **Be careful to place the capacitor in the circuit with the (-) and (+) in the correct orientation!**

**Battery set**
- Record the stated potential difference value given for two batteries in series.
- What is the potential difference value of two batteries in series as measured by the DMM? Make sure they are in the range of 2.7-3.2 V. If they are below 2.7 V, then ask your instructor for new batteries before continuing.

**Internal resistance of the measuring device(s)**
- What is the internal resistance of the MBL voltage sensor system as measured by the DMM?

2. In general, how good would you say the "given" values are for these different circuit components? Are they always exactly right or do you think it is important to measure them instead of relying on the given stated values? Explain.
Build the following RC circuit, hooking the MBL voltage sensor at points A and B.

\[ V_0 = 2 \text{ batteries in series} \]
\[ R = R_1 \]
\[ C = C_1 \]

**Warnings!**

- Be careful to place the capacitor in the circuit with the (-) and (+) in the correct orientation!
- Have your instructor verify your circuit before you close the key switch!

3. **Discuss** in your group the following questions. Record a summary of your responses and explanations. Do not close the key switch in your circuit until after you answer these questions (and have the circuit inspected by your instructor).

(a) If you closed the key switch, what potential difference \( V_{AB} \) would result on the capacitor after it was "charged up"?

(b) Suppose you placed the MBL voltage sensor at locations A and B (to measure \( V_{AB} \)). Would the internal resistance of the MBL voltage sensor be in parallel or in series with the resistor \( R \)? Why?

(c) Based on your answer to (b), what would be the equivalent resistance (\( R_p \) or \( R_s \)) of the circuit?

Note: The equivalent resistance of a series circuit, \( R_s \), can be calculated by
\[ R_s = R_1 + R_2 + R_3 + \ldots \]

The equivalent resistance of a parallel circuit, \( R_p \), can be calculated by
\[ \frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \]

Draw a large, clear picture of the circuit in your logbook. Include the voltage sensor (along with its internal resistance) connected to measure \( V_{AB} \) in your drawing. Clearly label all relevant quantities.
In the following experiment, you will use the energy of the batteries to put an excess of charges on the two plates of the capacitor. This is like the potential difference across the cell membrane before it is depolarized in one spot and the depolarized wave pulse is transmitted. After the plates are charged up, you will disconnect the battery by opening the switch. The two plates will be connected electrically through a circuit containing resistance. You will measure the resulting potential difference across the plates as a function of time using the MBL voltage sensor.

You will use your data to answer the question:

How long does it take for electric potential to drop to the initial value?

Experiment #2 – Studying the discharge of a charged capacitor (Using $R_1$ and $C_1$)

Data Collection Procedure:

- Be sure your instructor has checked your circuit.
- Open the file: MBL - Voltage – Delayed Start. This software has been setup with a "delayed start" to make your data analysis easier later in lab.
- Charge up the capacitor’s plates by holding down the key switch.
- While still holding down the key switch, one person should click on the START button. Once this button is clicked, wait two seconds. Then, the other person should let go of the key switch.
- The capacitor will now discharge through the circuit’s resistor.
- Stop recording data once the electric potential across the capacitor’s plates has clearly returned to zero.

Evaluating the Collected Data:

- If the decay curve was very fast and the computer only collected very few data points during the decay, then you should increase the sampling rate to an appropriate value and repeat the Data Collection Procedures. Be sure to note your sampling rate in your log report (whether you changed it or left it unchanged).
- Use the "zoom select" tool to inspect the resulting signal decay curve. If the curve is relatively smooth, then you are ready to move on.
- If there are spikes and bumps in the decay curve, then try repeating the experiment. Be careful to cleanly release the key switch.

Data Saving Procedure:

- Once you have a good set of data for this circuit, then save the file in the User Folder giving it an appropriate name.
- Record the name of this data file in your logbook and the relevant run number.
**Speed of propagation of nerve signal**

Two primary factors affect the speed of propagation of the action potential, the electrical resistance $R$ within the core of the axon and the capacitance $C$ (related to the charge stored) across the membrane. The time $t$ needed to charge or discharge a simple series electrical circuit containing resistance and capacitance has an exponential functional form of $\exp(-t/RC)$. The time constant $t$ is the value of $t$ when it equals $RC$, $t = RC$. A decrease in either $R$ or $C$ will decrease the time constant and the capacitor will charge or discharge faster.

The conduction speed of an action potential depends on the rate of charging or discharging an $R$-$C$ circuit. The internal resistance of an axon, decreases as its diameter increases. For two axons with similar properties differing only in diameter, the larger diameter axon will have a faster conduction speed than an axon with a smaller diameter.

The greater the capacitance (or stored charge) of a membrane, the longer it takes to depolarize it, thus the slower the propagation speed. The myelin sleeve is a good insulator and this part of the axon has very low capacitance. Because of the low capacitance, the charge stored is very small compared to an unmyelinated section of a nerve with the same diameter and length. The conduction speed in myelinated fibers is much faster than in unmyelinated fibers. The unmyelinated squid axons (~1 mm in diameter) have propagation speeds of 20 to 50 m/s, whereas the myelinated fibers in man (about 10 mm in diameter) have propagation speeds of around 100 m/s. This large conduction speed results mainly from the very small capacitance of the myelinated axons.

The action potential travels very fast in the myelinated portion and much slower in the unmyelinated sections (nodes of Ranvier). The action potential is reduced in amplitude in the myelinated segment, but restored to full size in the unmyelinated section. Under these two conditions, the action potential travels very fast in the myelinated sections and much slower in the nodes; it thus appears to jump from one node of Ranvier to the next. This is called saltatory (leaping) conduction.

The advantage of myelinated nerves in man is their high propagation velocities in axons of small diameter. A large number of nerve fibers can thus be packed into a small bundle to provide many signal channels. For example, 10,000 myelinated fibers of 10 gm in diameter can be carried in a bundle with a cross-sectional area of 1 to 2 mm$^2$, whereas 10,000 unmyelinated fibers with the same conduction speed would be a bundle with a cross-sectional area of approximately 100 cm$^2$, or about 10,000 times larger.

4. (a) What is the advantage of myelinated nerves over unmyelinated nerves?

(b) What is the typical resting potential of a cell?

(c) What is the typical conduction velocity of the action potential in a nerve cell? What factors contribute to the conduction velocity?
Data Analysis Procedure:

Once you have collected a "good" set of data, you are ready to analyze it. Since you want to answer the question of how long it takes the potential difference to return to its initial value, you will want to measure a meaningful time. But what is a meaningful time...?

As introduced in Appendices B1 and B3, this data resembles an exponential decay curve. One property of exponential decay functions is that the time it takes for the variable of interest to decrease by 50% is a constant. This constant is often referred to as the half-life time, or, more simply, \( T_{1/2} \).

In order to estimate values of \( T_{1/2} \), use the DataStudio tools to make careful measurements from the graph and a data table such as the following. Estimate \( T_{1/2} \) three different times for this data.

Hint! You may want to "zoom" in on each point of interest to improve your ability to estimate the values from the graph.

Sample Data Table for Determining \( T_{1/2} \):

<table>
<thead>
<tr>
<th>Trial</th>
<th>Electric Potential (V)</th>
<th>Time (s)</th>
<th>( T_{1/2} = T_B - T_A ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Point A ( V_A = 2.50 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point B ( V_B = (0.5) V_A = 1.25 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Point A ( V_A = 2.00 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point B ( V_B = (0.5) V_A = 1.00 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Point A ( V_A = 1.50 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point B ( V_B = (0.5) V_A = 0.75 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Record your best estimate of \( T_{1/2} \) for this experiment. Explain why you feel this is the best value.

6. In words, describe how the potential changes in time as the charges originally stored in the capacitor flowed through the resistor. At what value did it start? How did it change in time?

7. Look at the neuron pulse pictured on page 1 of this lab. Make a sketch of this pulse in your logbook. Which part of this pulse have you been modeling? Explain.

8. In words, describe what \( T_{1/2} \) represents in terms of the neuron pulse and the transmission of a nerve signal.
Application #2 - Developing Mathematical Models of Your Data

Review the information on Creating an Exponential Decay Model (Appendix B3). Answer the following questions to assist in creating a mathematical model for your data set.

9. By measuring $T_{1/2}$ for your data, you have assumed that the measured voltages are changing exponentially as a function of time. Does this seem to be a reasonable assumption? Explain why you do or do not think the data for the discharging capacitor is exponential using the general properties of exponential functions.

10. If the data for the discharging capacitor is exponential, then it should obey a relationship with the form: $y(x) = A_0 e^{-bx}$.
   - What does the variable $y$ represent for this system?
   - What does the variable $x$ represent for this system?
   - What does the quantity $A_0$ represent for this system?
   - What are the units of $y$, $x$, $A_0$, and $b$?
   - Rewrite this general equation ($y(x) = A_0 e^{-bx}$) using variables and names appropriate for the system you have been studying (namely RC circuits).

The half-life time, $T_{1/2}$, is defined as the time it takes the potential difference across the plates of the capacitor to decrease by 50%. Using this fact and the general equation you wrote in the previous question, you can derive an algebraic expression for $T_{1/2}$ as follows:

\[
V(T_{1/2}) = \frac{1}{2} V(t = 0) = \frac{1}{2} V_0 \\
V(T_{1/2}) = V_0 e^{-bT_{1/2}} \\
\Rightarrow V_0 e^{-bT_{1/2}} = \frac{1}{2} V_0 \\
\Rightarrow e^{-bT_{1/2}} = \frac{1}{2} \\
\Rightarrow T_{1/2} = \frac{\ln 2}{b}
\]

11. According to circuit theory, $b = \frac{1}{RC}$. Use the algebraic expression for $T_{1/2}$ and your values of $R$ and $C$ for the circuit and calculate a predicted half-life time for your circuit. How does this compare to the value you measured experimentally?
You can use the tools of DataStudio to create a mathematical model of the actual data. To do this, follow the procedure outlined below. Begin with your data set from Experiment #2.

Creating an Exponential Model of the Actual Data

• Use the zoom select tool to display the relevant data.

• Highlight a small region of the relevant data with the mouse. Select a group of data near to the Y axis.

• Select "Natural Exponent" from the Curve Fit menu.

• A box should appear on your graph giving the parameters of the software’s fit to your data.

• Double-click on the "Natural Exponent Fit" parameter box.

• This will give you information about what each of the parameters means for the model.

• DataStudio will give you a model in the generic form:

\[ Ae^{-Ct} + B \]

• Print a copy of the graph showing the selected data and the Exponential Fit parameters. Place it in your logbook.

12. Using the variables and units you identified in question 11 and the information from DataStudio, write out the mathematical model representing your data set on the printout.
Application #3 - Comparing Models for Different R and C Values

Using the white boards in the room, share your data with the class by completing the following data table. Record your data as well as the data of the other groups in your logbook in a similar table.

Summary Data Table:

<table>
<thead>
<tr>
<th>Group</th>
<th>R₁</th>
<th>C₁</th>
<th>T₁/₂</th>
<th>Mathematical Model</th>
</tr>
</thead>
</table>

13. (a) How did changing the resistance seem to affect the half-life time?
   (b) How did changing the capacitance seem to affect the half-life time?

14. (a) Did changing the amount of resistance significantly change the value of $A₀$ in the models? Explain why or why not. If it did change, why do you think it changed?
   (b) Did changing the amount of resistance significantly change the value of $b$ in the models? Explain why or why not. If it did change, why do you think it changed?

15. (a) Did changing the amount of capacitance significantly change the value of $A₀$ in the models? Explain why or why not. If it did change, why do you think it changed?
   (b) Did changing the amount of capacitance significantly change the value of $b$ in the models? Explain why or why not. If it did change, why do you think it changed?

16. In today’s experiments, the class examined the effect of changing the total resistance in the circuit. Can you think of a way that different resistances might come into play when transmitting nerve signals within the human body? Explain your ideas.

17. In today’s experiments, the class examined the effect of changing the total capacitance in the circuit. Can you think of a way that different capacitances might come into play when transmitting nerve signals within the human body? Explain your ideas.

End of Lab Cleanup

- Turn off the multimeter.
- Unplug all banana leads.

References