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The membrane as an RC circuit: A teaching method for undergraduate neuroscience students

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Abstract

Understanding the roles that current, resistance, and capacitance play in neuronal function are important, yet challenging concepts for undergraduate neuroscience students to grasp. Using simple labs and hands-on activities can improve understanding and reduce intimidation. Previously, the Resistance-Capacitance (RC) circuit has been used to create an equivalent model of the neuronal membrane. However, these electrical properties can still be difficult to understand and see in the lab. Here we describe an updated lab exercise where students build an equivalent RC circuit that utilizes a light emitting diode (LED). This allows for students to see the effects of capacitance and resistance within the circuit. Students gain experience with common electrical prototyping tools, such as a multimeter, and with collecting and plotting data. Through completing this classroom exercise, students also gain collaboration, manual dexterity, and problem-solving skills.

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THE MEMBRANE AS AN RC CIRCUIT: A TEACHING METHOD FOR

UNDERGRADUATE NEUROSCIENCE STUDENTS

By

Harlie Ann McKelvey

A Senior Thesis Submitted to the

Eastern Michigan University

Honors College

in Partial Fulfillment of the Requirements for Graduation

with Honors in Neuroscience

Approved at Ypsilanti, Michigan, on this date: April 28, 2021

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Table of Contents

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Understanding the roles that current, resistance, and capacitance play in neuronal function are important, yet challenging concepts for undergraduate neuroscience students to grasp. Using simple labs and hands-on activities can improve understanding and reduce intimidation. Previously, the Resistance-Capacitance (RC) circuit has been used to create an equivalent model of the neuronal membrane. However, these electrical properties can still be difficult to understand and see in the lab. Here we describe an updated lab exercise where students build an equivalent RC circuit that utilizes a light emitting diode (LED). This allows for students to see the effects of capacitance and resistance within the circuit. Students gain experience with common electrical prototyping tools, such as a multimeter, and with collecting and plotting data. Through completing this classroom exercise, students also gain collaboration, manual dexterity, and problem-solving skills.

Introduction

Background:

Learning neurophysiological concepts can put pressure on undergraduate students, as these concepts tend to be challenging and unfamiliar. However, intimidation can be reduced and understanding increased through the use of simple labs (Dagda *et al.* 2013; Lott *et al.* 2009). Hands-on models and activities allow students to visualize, manipulate, and conceptually grasp hard-to-understand concepts in a way that is more valuable than memorization (Keen-Reinhart *et al.* 2009). It is especially important to employ engaging material when teaching neuronal membrane properties because these concepts are fundamental to learning about future neuroscience topics (Cleland, 2002).

A common issue with most of the lab supplements that are available for teaching undergraduate neuroscience students is that they consist of expensive equipment and often take up more time than what is allotted for class (Kladt *et al.* 2010). More cost-effective and time sensitive lab exercises are necessary for the undergraduate neuroscience classroom in order to aid in learning and feasibility (Land *et al.* 2001). Therefore, we have developed a simple, inexpensive model that students are able to quickly and easily manipulate in order to visualize neuronal membrane properties.

Understanding the concepts of resistance and capacitance are critical to understanding how membranes use electrical potential and ion currents to effectively communicate within the cell. The membrane can be modeled by an equivalent circuit where capacitance and resistance are in parallel circuit (Hodgkin & Huxley 1952). In the neuronal membrane, ion channels act as variable resistors by controlling the flow of ions (Squire *et* *al*. 2008). When a cell is at rest, most ion channels are closed resulting in high resistance, as ions cannot flow across the membrane. In response to a stimulus, ion channels will open resulting in ion flow across the membrane and a decrease in membrane resistance. This is similar to if a weaker resistor is used within the RC circuit. Ohm's law, which states that conductance (I) is equal to volts (V) divided by resistance (R), can be used to calculate the current, in amperes flowing through the resistor which models the ion flow in a membrane. (Ohm, 1827).

Voltages across neuronal membranes are affected by capacitance. Capacitance is the ability a system has to store charge; this occurs when two components that are able to conduct electricity are separated by a non-conductor (ie. the phospholipid bilayer) (Monajjema, 2015). When applied, current will flow through resistors and to the capacitor. This allows us to observe tau in a biological setting (Squire *et al*., 2008). Tau (τ), or the time constant, is calculated as τ=RmCm, where Rm is membrane resistance and Cm is membrane capacitance (Byrne, 2020). It calculates the time it takes for a membrane to change potential. Importantly, τ is often empirically derived as the amount of time the membrane requires to reach 63% of a voltage (for examples see: Herness and Sun, 1995; Liu, Puche, and Shipley, 2016). It takes more time for a membrane to change potential when there is high resistance or high capacitance. This is because a high resistance will result in less current (i.e., ion flow), therefore causing the capacitor to take a longer time to build up its charge. With a higher capacitance, the capacitor then has the ability to hold a greater charge, causing it to take a longer time to build up its charge. An increase in either of these variables causes there to be a greater time constant and therefore a slower change in membrane potential (Byrne, 2020). Here, we use observation of LED brightness and decay over time to empirically derive the time constant at different resistance values within the RC circuit model to explore the variables impacting the time constant itself.

Past methods of using an RC Circuit as a model for the neuronal membrane have shown increases in student understanding of these concepts (Giglia, 2019; Dabrowski, 2013). Here we describe an updated method that uses an LED to visualize brightness and measure length of decay. The goal of this method is to allow students to better visualize the effects of voltage, resistance, and capacitance on membrane currents. Furthermore, students gain experience prototyping circuits using common electrical components and tools.

Learning objectives

Students should be able to:

1. Visualize capacitance and resistance by creating an RC circuit that utilizes an LED and mimics the electrical properties of a neuronal membrane.
2. Use Ohm's law, empirically derive a time constant with different resistor values, and apply these principles to the neuronal membrane
3. Develop experience with the use of common electrical tools and components, such as a multimeter and resistors.
4. Gain practice interpreting data and using it to plot graphs

Materials and Methods

Students may work in groups in order to reduce the amount of course materials needed and allow them to practice communication and collaboration skills. Each group should receive the following materials. Some of these materials are shown in figure 1.

Materials:

Half-size breadboard (10, $45.00; product # 64, adafruit.com)	**1000 µF Capacitor** (10, $3.32; product # 647-UKL1E101KPD1TA, mouser.com)
9 Volt battery (10, $6.36; product # BAT-40P, teachersource.com)	**3mm LED** (25, $4.50; product # 779, adafruit.com)
9 Volt battery clip (10, $4.90; product # 36-232-ND, digikey.com)	**2 Jumper cables** (20, $1.95; product # 1956, digikey.com)
1 kΩ resistor (10, $1.80; product # 660-CF1/4CT52R102J, mouser.com)	**Stopwatch** (ie. Phone app)
4.4 kΩ resistor (10, $1.90; product # 619-150-04720, mouser.com)	**Multimeter** (10, $79.50; product # DT830D, jameco.com)

Figure 1. Example of battery, battery clip, capacitor, LED, and resistor used in this lab exercise.

Procedure:

A worksheet (Appendix) can be provided to guide students through building the circuit. The circuit can then be manipulated to address learning objectives:

The neuronal membrane acts as a capacitor:

The circuit can first be built without the capacitor, and students can be instructed to disconnect the battery and observe what happens. Then, students can include the capacitor in the circuit. Once the battery is disconnected this time, they should observe that the LED slowly decays as opposed to immediately turning off. This shows the capacitors ability to store a charge, similar to the membrane's ability to do the same.

Ion channels act as resistors:

Build the circuit using the 1 kΩ resistor and then replace it with the 4.4 kΩ resistor. Students should observe and record the brightness of the LED and the time it takes to decay for each resistor. This allows them to understand how changing the resistance affects the conductance, as well as visualize how ion channels act as resistors by controlling the flow of ions within the membrane.

Why and how to use a multimeter:

Use a multimeter to measure the electrical components (resistor, capacitor, and battery) of this exercise and obtain their strength. Then, compare the actual measured values to the values listed on the equipment they are using. By looking at previous class data in Figure 2, it can be seen that the resistor values that the students measured using the multimeter closely match the listed values given.

Why and how to calculate Ohm's Law:

Students need to understand Ohm's law due to its importance in understanding how the variables of current, capacitance, and resistance are implicated in neurophysiology. Calculate current using Ohm's law in two different ways. LEDs consume voltage during light generation (i.e. the forward voltage; about 2.2V in the LEDs listed in the materials). Have students first calculate current by ignoring that LEDs use some voltage to generate electricity in order to relate more to the neuronal membrane. Then, have them take this into account and subtract the forward voltage to find the actual current in the circuit.

Observe Tau:

Through the measurement of LED decay time, tau can be experimentally derived based on observation. After completing the circuit, have students remove the battery wire to measure and record the time it takes for the LED to completely decay. This can be repeated with a different strength resistor in order to visualize the effect resistance has on the time constant. Previous class data that shows the dependance of decay time on resistor strength is shown in Figure 3. It shows that it takes more time for the LED to decay when resistance is increased.

How to interpret and graph data:

Averages can be calculated from the data that the class collected in this lab exercise. These can then be used to graph the relationship between resistor strength and length of LED decay. Students can also graph the relationship between the measured and listed values of the resistors. Students should properly label all parts of the graph and include effective figure captions.

Previous class data is shown below:

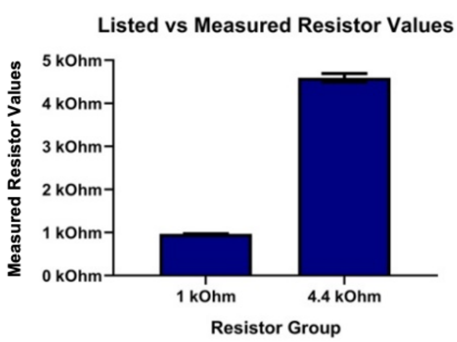

Figure 2. The relationship between the measured resistor values found using the multimeter (Y-axis) and the listed resistor values (X-axis). Students received experience with the multimeter.

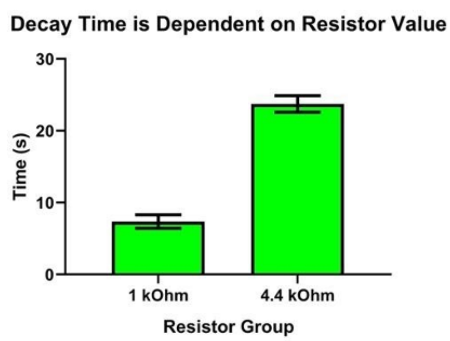

Figure 3. Observed LED decay time compared to resistor strength. The time it takes for LED brightness to decay (Y-axis) increases with increasing resistance (X-axis).

Possible discussion questions:

Why was the LED still able to generate light after the battery had been disconnected?

- The capacitor stored the charge, so even when the battery was disconnected there was still current moving through the circuit.

Looking at the observations, what was the difference between the 1KΩ resistor and the

4.4KΩ resistor?

- The student should note the difference in LED brightness and discuss that the reason for this difference is that a stronger resistor results in there being less current flowing through the circuit.

What was the difference in total LED decay time between the two resistor groups? What does this mean in terms of current flow?

- It is important that the student makes the correlation that with lower resistance, the current flows more quickly than it would if there was a higher resistance.

Discuss the time constant (Tau).

- The student should note that Tau is the time it takes for the membrane potential to reach 63% of the final value. It is an index of how fast the membrane will respond to a stimulus. It is calculated using τ=RmCm

Describe Ohm's law and use it to calculate the current that flowed through the LED for both of the resistor groups. First, do this while ignoring that the LED uses some voltage to generate the electricity and then take this into consideration and complete the calculation again.

- It is important that the student is able to show an understanding of what this calculation means and that they use the correct units.

Discussion

This paper describes a novel laboratory exercise that demonstrates the role of capacitance and resistance within a parallel circuit. With the use of this lab exercise, students are able to visualize capacitance and resistance within the context of the time constant (τ). The breadboard RC circuit represents the membrane of a neuron in a physical manner that supplements the teaching of Ohm's Law and neuronal membrane properties. Through the use of a light emitting diode (LED), students can see the effects of manipulating membrane properties because they are able to visualize the effect on the electricity generated.

The ability to relate current, resistance, and capacitance to a neuronal membrane is crucial to learning neuroscience (Dabrowski *et al.* 2013). This laboratory exercise provides students with a visual model that allows them to physically manipulate components of a neuronal membrane (ie. changing the strength of the resistor which affects conductance and removing the capacitor to visualize its role in storing charge). Giving students the ability to learn this way allows them to strengthen problem solving skills, interact with the material beyond simply memorization, and work with the concepts in a way that goes beyond a stand-alone lecture (Krontiris-Litowitz, 2003).

A variety of learning objectives can be met through the use of this lab. The students are able to work with one another towards a common goal allowing them to practice collaboration skills. Additionally, the students are able to improve manual dexterity by using small components to build the overall circuit. The lab exercise described also allows students to gain experience with common electrical tools such as a multimeter and gives them practice with interpreting and plotting data. These learning objectives are critical for undergraduate neuroscience students (Dabrowski *et al.* 2013).

This exercise provides a simple, inexpensive (~$15 per station) model to visualize neuronal properties. Due to the low cost, the exercises can be incorporated into biology and neuroscience courses at nearly any educational institution. Further, the simplicity of the exercises means that it can be used effectively with students at nearly any level.

Student Outcomes:

This lab has been successfully implemented in three different teaching formats and can be easily modified for other formats as well. These formats were: a face-to-face small-sized lab (10 students) with one instructor, a face-to-face medium-sized (12 students) lab with multiple instructors, and an online medium-sized lab (11 students). In the face-to-face labs, students worked in pairs and triplets. In both of these labs, all pairs and triplets successfully built their circuits with the exception of one pair or triplet in each section. That is, 8 out of 10 circuits were successfully built. In the online lab students first built their circuits alone, and then again as part of a group lesson using video chat (i.e., Zoom). When working alone students often built the circuit incorrectly with 4 out of 11 students 'burning out' the LED (lack of series connection with the resistor). However, when the students built the circuit as part of the online group lesson, all circuits were built successfully (11 out of 11). Additionally, in the online groups the circuits were built in less than 20 minutes making them more time efficient than the students working together in pairs and triplets who typically needed 30 minutes to complete the exercise.

This exercise can be altered to emphasize different learning objectives and course goals. Implementing this lab exercise into your classroom can be an easy, affordable, and effective way to teach the electrical components of the neuronal membrane to undergraduate students.

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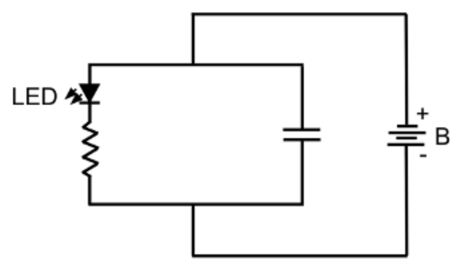
Appendix

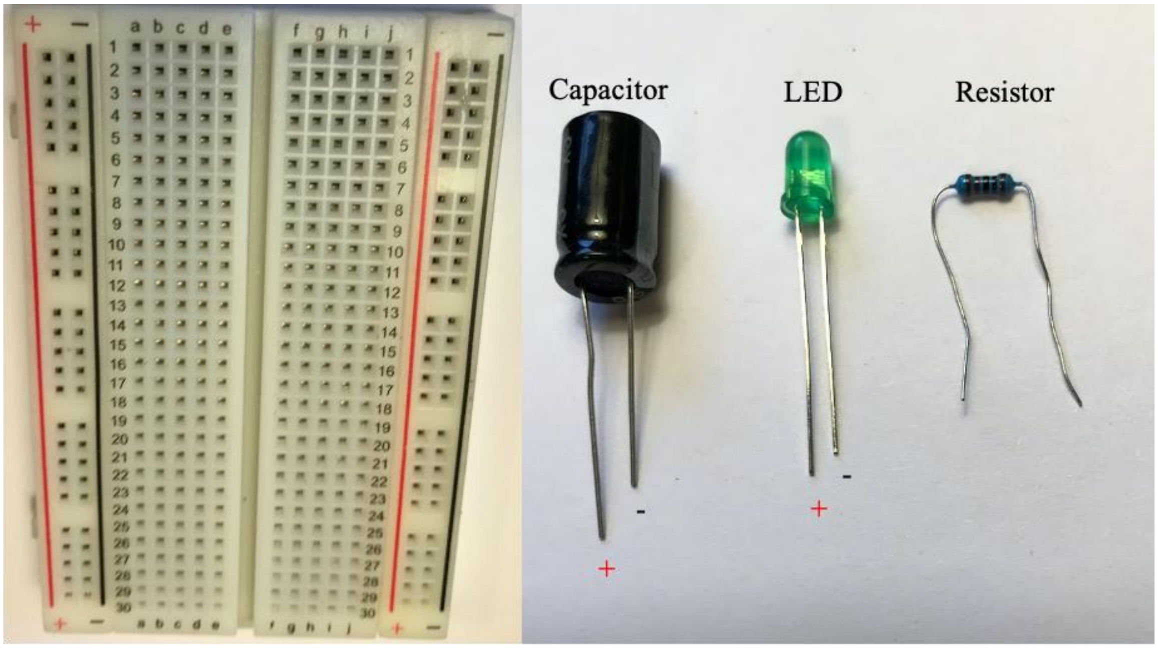
Example Lab

This lab demonstrates capacitance and Ohms law within the equivalent membrane circuit. This is an electrical model of a biological membrane with a resistor and a capacitor in parallel (see Appendix Figure 1 below). Note that a charge can travel from the battery to either the capacitor or the resistor—this is the definition of a parallel circuit.



Appendix Figure 1. Diagram of the parallel circuit used in this lab. The zig-zag line represents the resistor, the two straight lines represent the capacitor, and the 'B' represents the battery.

If the membrane is in a voltage field, then some charges will collect on the capacitor and some will flow through the resistor. With a real cell, the phospholipid bilayer acts as a capacitor as it separates and stores charge. The ion channels act as resistors as they modulate the current that flow through them. Capacitors store charges very quickly—a process usually too fast to see by the unaided eye. Likewise, the nearly instantaneous currents through the resistors cannot be seen. This lab will use a light emitting diode (LED) to physically visualize the current flowing through the circuit, and the effect of capacitance on this current.



Appendix Figure 2. Image of the half-size breadboard (left), the capacitor, LED, and resistor (right) used in this lab exercise. The longer end of the capacitor and the LED is the positive side, while the shorter end is the negative side.

In direct current, power (electricity from the battery) flows from the positive end (**red**) to the negative end (**black**). A closed (working) circuit allows current to flow from + to -. LEDs and capacitors (above right) have positive and negative ends (aka polarity) and each end needs to connect to the correct side (pole) of the battery (i.e. + to + and - to -). Resistors and wires are not polar and can be connected to either pole. Circuit components are connected on breadboards (above left) which have two sets of columns. Each set of five columns (A to E; F to J) is separated by a 'gutter' from the other set of columns. Columns are connected in the same row (i.e. A1-B1…E1 connect to each other) but not across rows (i.e. A1 does not connect with A2) or across the gutter.

Follow the instructions below to complete the lab and answer the questions as you go:

1.Use the multimeter to measure the electrical values of the battery (9V), both resistors (1kOhm, 4.4kOhms), and the capacitor (1000 microfarad, 25 volts). Record

the measured and listed values.

2. Connect the LED and resistor to the breadboard in series (do so in this order):

- Jumper: E1 to F1
- Light: LED (+) in I1; LED (-) in I5
- Resistor: E5 to F5
- Power: Battery (+) in A1; Battery (-) in A5.

<u>Checkpoint:</u>

Did your circuit smoke or pop? If yes, then disconnect and start over

Did your LED glow?

- If not, take everything out and start over (the LED may be flipped).
- If yes, observe the LED from the side. Remove the (+) battery wire and then re-insert it. Repeat. (keep in mind that the current must move through the LED and then the resistor—i.e. a series circuit)

<u>**Question 1:** What happened when you did this?</u>

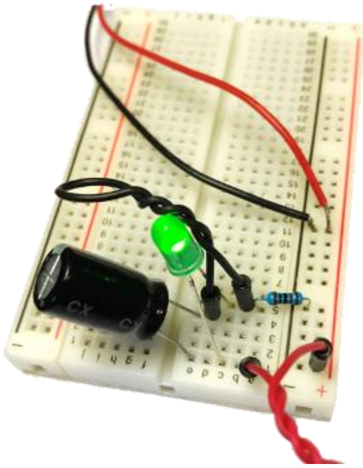
Keep the circuit together and start step #3.

3. Connect the Capacitor in parallel with the resistor (do so in this order):

- Capacitor: Cap (+) in J1; Cap (–) in J4
  - Observe the LED from the side
- Jumper: H4 to B5

<u>**Question 2:** Did anything happen when you connected the jumper to B5?</u>

Note at Step 3 your circuit should look like this:



Appendix Figure 3. Image of the RC circuit complete with connected battery, capacitor, LED, resistor, and jumper cables

Do the following:

Now, while observing the LED from the side remove the (+) battery wire and observe. Then, replace it.

Question 3: What happened when you removed the (+) battery wire? What happened after you replaced it?

- Remove the battery wire and measure the amount of time it takes for the LED to fully decay. Repeat for 3 measurements and record these measurements.
- Change your view of the LED so that you view it from above. Measure the amount of time it takes for the LED to fully decay once again. Repeat this for 3 measurements and record these measurements.

4.Write a brief report detailing your findings. Answer all the underlined questions from above. Include pictures of the circuit you built in steps #1 and #2.

Be sure to answer the following:

Specific for #1: If the resistor is 4.4kΩ, then how much current runs through the LED?

Specific for #2: Report the average total time to decay for the two observation conditions. Based on these observed averages what is the time constant in each observation condition?