PHYS 40C: Lab 6
Neuronal Circuitry
(Includes Pre-Lab Assignment)

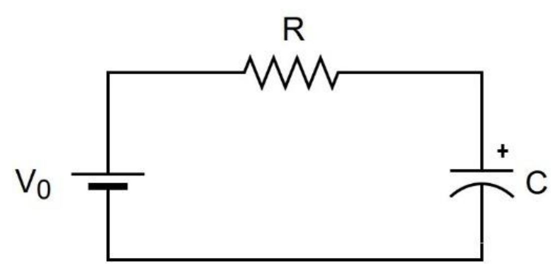
Objectives

These lab activities will focus on time-dependent RC (Resistor-Capacitor) circuits and how these circuits can be used to model neurons in the brain. You should read all the steps in each part before you start. Work in your assigned groups and maintain a collaborative and communicative team.

Introduction

In previous labs, we have discussed circuits with properties that did not change with time. We assumed that the voltage drop across components was constant in a given configuration. This week, we will be studying time-dependent RC (resistor-capacitor) circuits, and we will develop an understanding for how these circuits can be used to model the propagation of electrical impulses in neurons. We will be examining at the charging and discharging of a capacitor in an RC circuit and extrapolate this behavior to model what is going on inside your brain right now.

RC Circuit Background



Before we seek to understand neuronal impulses, we must first understand RC circuits. The voltage across the charging capacitor shown to the right with capacitance, C, is given as a function of time t, by:

$$V = V_0\left(1 - e^{-t/RC}\right) = V_0\left(1 - e^{-t/\tau}\right) \tag{1}$$

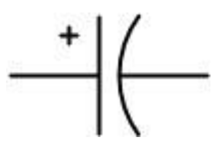
where R is value of the resistor and V_0 is the voltage placed in series with the capacitor. The product RC has units of time and is referred to as the time constant, τ, of the circuit. τ represents the amount of time it takes for the capacitor to charge to 63% of its final value.

The voltage across a discharging capacitor is given by:

$$V = V_0 e^{-t/RC} = V_0 e^{-t/\tau} \qquad (2)$$

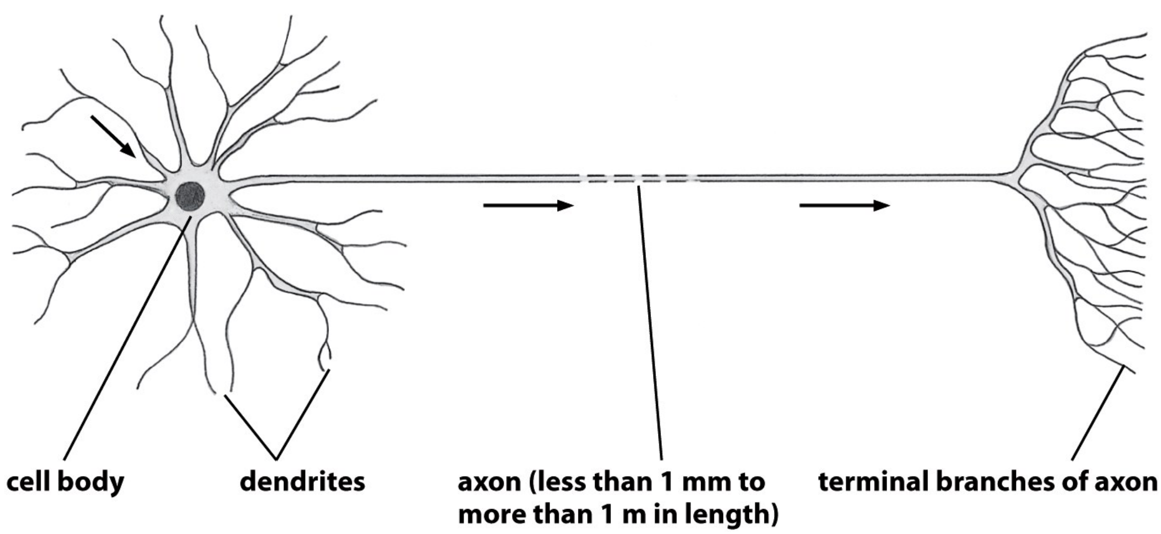
Where τ represents the amount of time it takes for the capacitor to discharge to 37% of its initial value. A good rule of thumb to use is that is takes about $5*\tau$ for a capacitor to look like it is either fully charged or discharged.

NOTE: The schematic representation of an electrolytic capacitor is shown alongside its real-life counterpart. Notice the minus sign on the actual electrolytic capacitor. This corresponds to the curved side of the schematic representation. In other words, this means that the electrolytic capacitor is polarized and that the orientation of the capacitor matters! Make sure to double check that your capacitor is facing the right way with respect to the direction of the current.



Electrical Building Blocks of the Brain

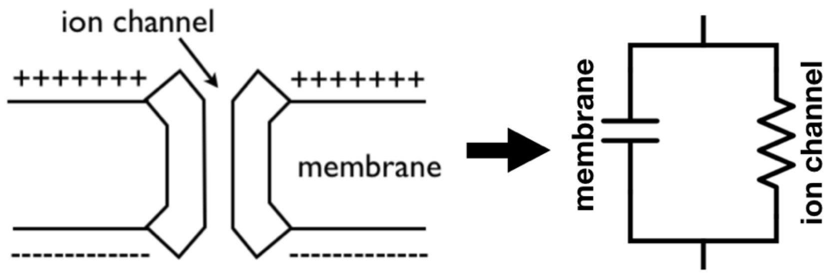
Neurons (pictured below) are cells with two main features that allow them to form complex networks with partner cells (in the brain) and to allow them to transmit information over relatively large distances. Dendrites and terminal branches allow nerve cells to communicate with vast networks of other nerve cells. Axons allow a single cell to transmit information over long distances.



Information is transmitted through neurons via electricity, similar to how computers transmit information. When a signal exists, it looks like a binary ‘ON’, and when it doesn’t, it looks like a binary ‘OFF’. We (society) know pretty well how to control electric potentials propagating through complex electric circuits, but how do biological systems transmit these electrical signals? We need to think about two things: how a potential difference can exist at a fixed location in a neuron, and how that potential can then propagate down the length of a neuron.

Electric Potential across Neuron Cell Membranes

We know that electrical current is generated when charges are separated and a potential difference is created between two points of a conducting material. It is easy to generate potential differences using batteries or power supplies, but we don’t have power supplies inside our brains. Recall the electrolytic mechanism in the “Electricity Generation” lab – that mechanism relied on the *transport of charged ions through diffusive processes*. That is the same mechanism utilized by neurons!



A neuron’s cell membrane contains ion channels which allow for the flow. These ion channels allow the cell membrane to control the diffusion of charged ions either into or out of the cell. When an electric impulse is excited, the ion channels are activated to *force the separation of differently charged ions across the cell membrane*. The cell membrane becomes a capacitor, and the ion channels function like resistors! This difference in ion concentration on the cell’s membrane is called an action potential (diagramed in the image above).

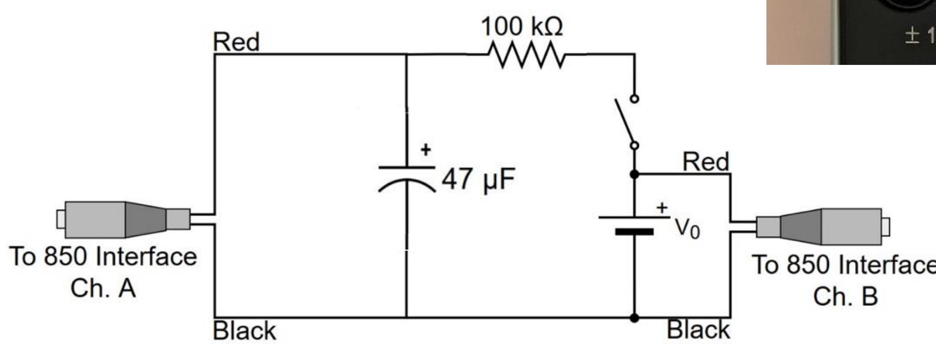
We can simulate this transfer of ions by creating a cell in which a voltage is generated through an electrolytic reaction between saltwater, a zinc anode, and a copper cathode. Although the chemistry we will employ is not the same as that which generate currents in the brain, our electrolytic cell is a simple and fun way to model the generation of neuronal electricity. This describes the potential at a fixed location in a neuron. You will not have time to explore how that potential can propagate down the length of a neuron, though you will be asked to think about it at the end of the lab.

1. Building an RC Circuit

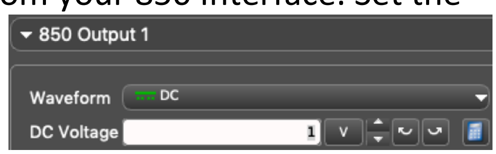
1.1: Open the *Capstone* template corresponding to this week's lab. You will see a Graph display which has already been configured for you.

1.2: Using the digital multimeter, measure and record the true resistance of the 100 kΩ resistor.

1.3: On your breadboard, construct the circuit below and have your TA double check it before connecting the power supply, which is part of the Pasco 850 box, as pictured to the right.



1.4: Refer to Eq. 1 and Eq. 2. Graph by hand the shape of the Voltage vs. Time curve for both charging and discharging of a capacitor in an RC circuit. Explain why the curves look the way they do. Numbers aren't exceedingly important here, just identify the correct curve. To charge the capacitor in your circuit, you will use voltage supplied from your 850 Interface. Set the "Signal Generator" to output 1 V DC. With this setting, what is the maximum voltage to which the capacitor can be charged?



1.5: Turn on the power supply, click "Record", and close the switch. The voltage across the charging capacitor (Voltage Sensor A) as well as the voltage across the power supply (Voltage Sensor B) should be shown on the graph.

- You may need a few attempts to get a clear trace of the charging behavior. To repeat your attempt, click "Stop" then open the switch. Wait about 30 seconds after opening the switch to ensure the capacitor has discharged fully before you start charging it again.

- Click “Stop” when you have a good trace. Does the trace match the curve you drew for capacitor charging behavior in part 1.4?

1.6: You can get a trace of the discharging behavior on the same graph as the charging behavior. To do this, click “Record” then close the switch. After you feel the capacitor is sufficiently charged, open the switch. After you have a nice trace of the discharging behavior, click “Stop.”

Analyze your Results:

1.7: Determine the time constant from the graph of the charging capacitor. To do this, use the data highlighter tool () to select the data points on the charging curve. Apply a user-defined fit to model Eq. 1: “A*(1-exp(-B*t-C))”. What is the time constant, τ? Take a snapshot () of your best-fit graph.

1.8: Is the time constant the same for both the charging and the discharging curves? How do you know? (You do not need to fit the discharge curve according to Eq. 2, but we know mathematically that **τ is the time it takes for the voltage to reach 63% of its maximum for the charge cycle, and τ is also the time it takes for the voltage to drop to 37% of its maximum for the discharge cycle**. Use the coordinate tool to help your estimates.)

1.9: What parameters of the RC circuit control the value of the time constant, τ? Based on the capacitance of your capacitor and the resistance of your resistor, what should the value of the time constant be? How does this value compare with your measured values from 1.7 and 1.8?

Thought Experiment: Explain what is physically happening to the charge in the RC circuit during charging and discharging cycles (*i.e.* Why does the capacitor charge/discharge quickly at first but slows down with more time? Where is the charge going?). In the “DC Electrical Circuits” lab, we used the analogy of water flowing through a pipe to visualize Ohm’s law – can you extend that analogy to the RC circuit?

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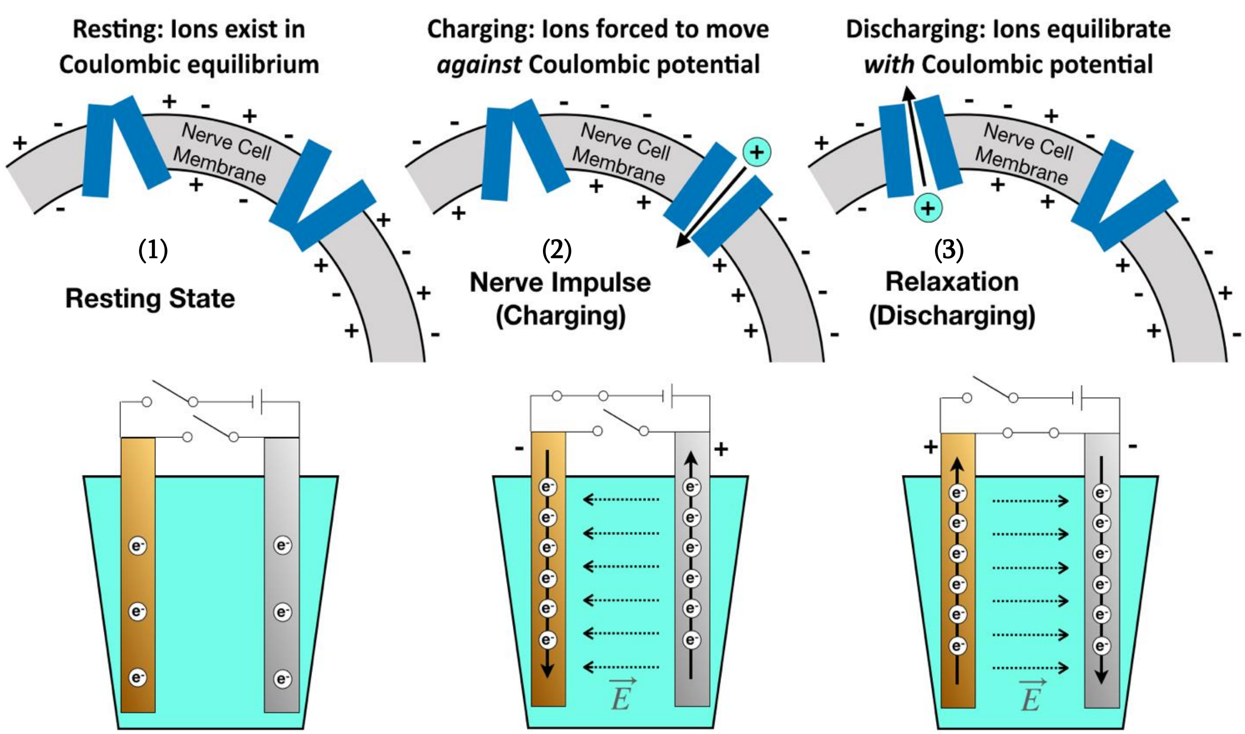
2. Opening and Closing Ion Channels

Neuronal Circuitry

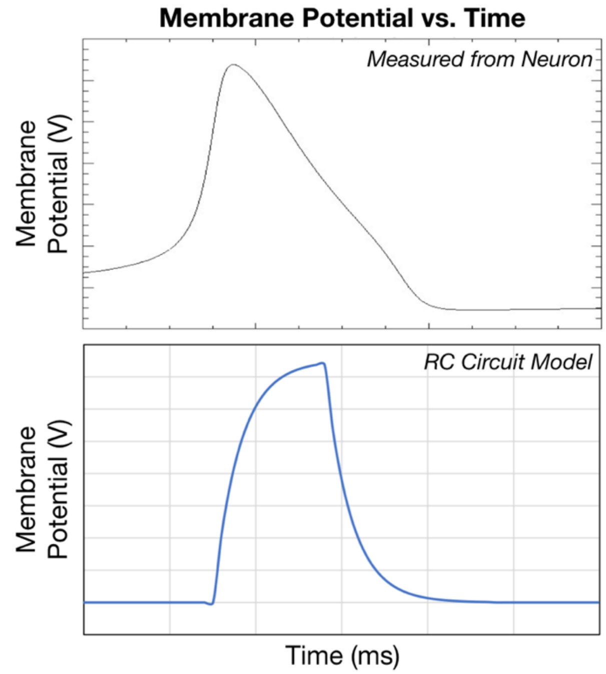
Now that you know, generally, how to control the charging and discharging of a capacitor in an RC circuit, you will attempt to transfer that knowledge to the membrane-capacitance model for the neuron, which was discussed on p. 3.
In our model of the neuron, we can establish a potential difference in a neuron cell membrane (like in a capacitor) by controlling the distribution of charges on either side of the capacitor. The charges in this system are ions – so we need to figure out how to control the separation of different-charged ions.

Recall from the electricity generation lab that this is the same physical phenomenon that drives electrolytic cells. The analogy is diagramed below.

(1) During a “resting” state when the neuron is not in use, the charges exist in equilibrium on either side of the membrane, *i.e.* there is no potential difference.
(2) When a neuron is excited, the membrane capacitor “charges” and different charged ions are pushed to opposite sides of the membrane, building up a potential.

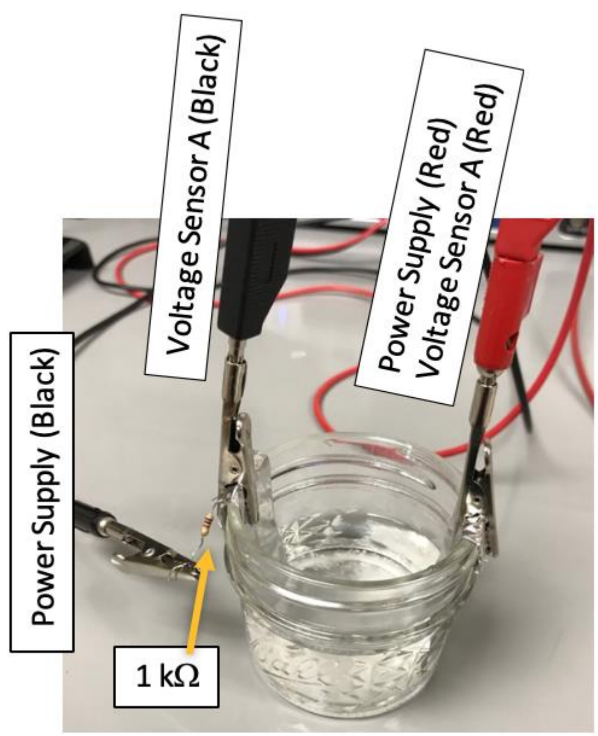


(3) When the potential reaches some threshold value, it will “relax” and discharge the accumulated electric potential.



Note that this analogy is a little bit different than the electrolytic cell you worked with in the "Electricity Generation" lab. There, your cell functioned as a power source – it generated its own potential. In this system, the electrolytic cell will function as a capacitor – it requires a power source to charge it, and it can exhaust the accumulated potential later.
In this experiment, from the physics perspective, your goal is to figure out how to model the membrane potential vs. time from a single location in a neuron (shown in the upper graph at right). Using an RC circuit with a homemade electrolytic capacitor, you can generate voltage vs. time potential that resembles the neuron signal (shown in the lower graph at right) – *i.e.* your goal is to show that an RC circuit can be used to approximate a firing neuron!

2.1: Make the electrolytic capacitor. Inside the closed jar are 50 mL of distilled water with 2.5 g of borax ($Na_2[B_4O_5(OH)_4]$), a commonly used cleaning detergent – this will serve as the electrolyte. Remove the lid and insert the two foil electrodes over the lip of the jar and clamp them in place with alligator clip as shown below. Construct the circuit shown with your electrolytic cell as the capacitor (make sure to note the resistor value). Switch to the second tab in the *Capstone* template.



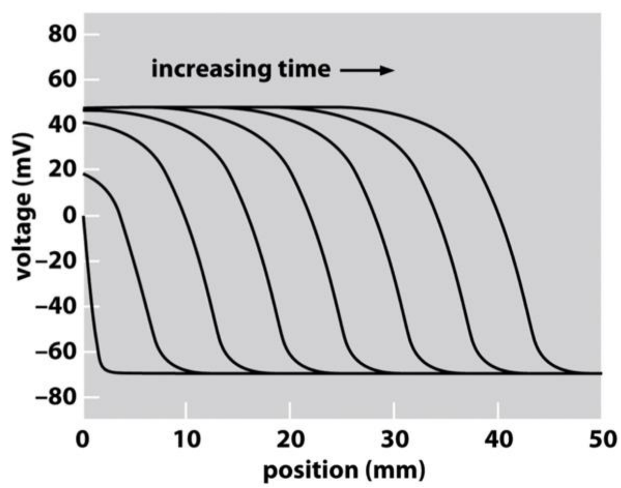
2.2: Acquire a trace of the charging and discharging curve for this circuit like you did in Part 1 (you may have to play with the scale on the x-axis). Does the behavior look like it did for the RC circuit in Part 1? *i.e.* Is the electrolytic cell a good capacitor?

2.3: When you are happy with the trace, repeat step 1.6 to measure the time constant of this RC circuit, and take a snapshot of the trace. Calculate the capacitance of your electrolytic capacitor using the time constant and the resistance of your resistor.

2.4: You have constructed a "membrane capacitor" circuit that functions in an analogous way to a neuron, but now you need to make the parameters of the circuit similar to those for a real neuron. In a real neuron, the time constant of charge/discharge (τ) is ~1.5 ms, and the peak voltage (V_0) is ~110 mV. What resistance value and power supply voltage do you need to use in your circuit to match the values for a real neuron?

2.5: Reconfigure your circuit according to your answer to 2.4. There are extra resistors available on the shared equipment bench – you may need to put multiple resistors together in series or parallel to get the right value.

2.6: Acquire a trace of the charging and discharging curve for this circuit. Take a snapshot of the trace, then open the journal ( ) and print the three snapshots you have collected. On the printed plots, label the charging voltages (V_0) and the time constants (τ).



Congratulations! You have just constructed something that works like a synthetic neuron! As mentioned in the introduction, however, this is only part of the functionality of a neuron. Your RC circuit behaves like a single point on the neuron. In a real neuron, the potential that you simulated needs to travel down the length of the cell membrane (*i.e.* it needs to exhibit position-dependent behavior as well as time-dependent behavior). You can think of this like a wave pulse propagating down some medium, as shown in the plot below.

Thought Experiment: Think about how the neuron membrane-capacitor works – via the motion of charged ions from inside-to-outside and outside-to-inside the cell (see p. 6). Describe phenomenologically (don't worry about the math) how you think the membrane potential can be made to propagate down the length of a neuron. Draw some diagrams to aid your description.

Pre-Lab Assignment (1 point)

1. Graph by hand the voltage vs. time behavior you expect to observe for a charging and discharging capacitor in an RC circuit with a time constant of 1.89 s and $V_0 = 6$ V.

2. If the resistance value in this RC circuit is 100 kΩ, what is the capacitance value in the circuit?