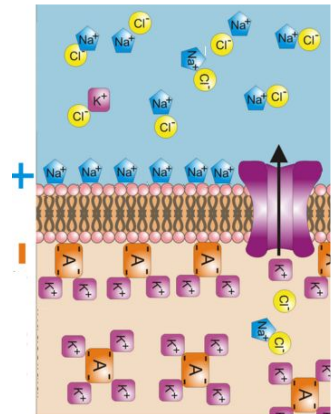
Lab 6: RC Circuits

1. Introduction



Resistor-Capacitor (or '*RC*') circuits are very common elements in everyday electronics. How do flashing lights work? These devices have time-dependent behavior of voltages and currents in their circuit elements. Having both electrical resistance and capacitance, cell membranes and neural action potentials can be modeled as *RC* circuits. Automated external defibrillators (AEDs) charge an *RC* circuit before delivering a shock via discharge to the patient. The goal of this lab is to help you visualize and understand how *RC* circuits work based on variations in voltage at characteristic timescales set by the choice of components. You will also see examples of how varying the capacitance can "tune" this timescale. For definitions and review of concepts related to this lab, see **Chapter 23.6-23.8** in the Knight textbook.

2. Experiment

Activity 1a - Capacitors in Series & Parallel

In this set of experiments, you will explore the effects of *capacitance* within circuits. Many common types of circuits contain multiple capacitors. In this case, we can simplify the circuit to predict its behavior, similar to how we did for multiple resistors in Lab 5. When capacitors are connected in series, the equivalent capacitance C_s is

$$\frac{1}{C_S} = \sum_j \frac{1}{C_j} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \qquad \text{(1a)}$$

You can convince yourself that this results in a C_S that is reduced relative to C_1, C_2, C_3, etc. For capacitors in parallel, the equivalent capacitance C_P is

$$C_P = \sum_j C_j = C_1 + C_2 + C_3 + \ldots \qquad \text{(2a)}$$

Locate your capacitor components labeled 'C4' and 'C5' and your resistors 'R2' and 'R3' in your circuits kit, and consider the circuit in Figure 1a. After studying the circuit schematic, try to predict how it lights the LED before building the circuit. In doing so, consider whether R2, R3, C4, and C5 are in series or in parallel with each other and with the LED D1. Based on what you have learned about how capacitors charge and discharge in circuits, what's happening to C4 when S2 is ON? For **deliverable 1**, take a picture of your assembled and working circuit and include a circuit diagram (keep S1 OFF for now). Note: you can reference basic circuit symbols in Knight Figure 23.2 or use the symbols already printed on your components. What is the total voltage being supplied to your circuit when S2 is closed? Is C4 in series or in parallel with the R3/LED sub-circuit? Explain your reasoning.

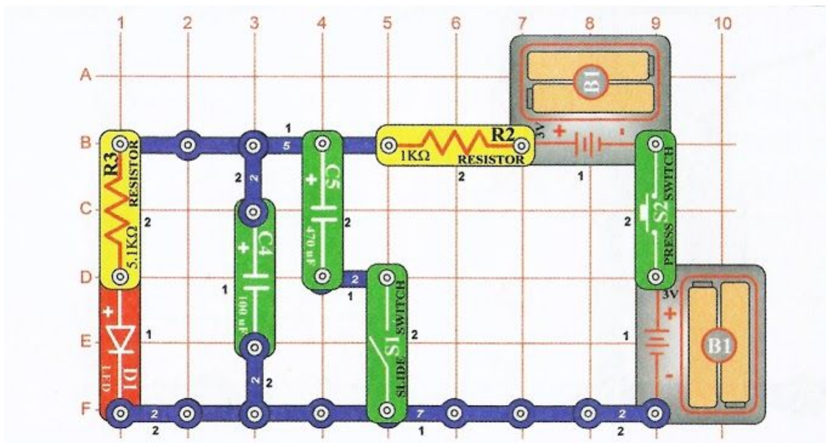


Figure 1a: *capacitor tester circuit with LED*

When S2 is ON, you should notice a brief delay before the red LED reaches full brightness, which is the result of C4 being charged by the batteries. What happens when you release S2? How is it possible that with S2 OFF (i.e., the batteries removed from the circuit) the LED can still be on for a short time? There is another (more noticeable) delay before the LED turns off completely as it discharges. What would happen if the capacitors were removed (try it)? For **deliverable 2**, take a picture of your new circuit without the capacitors and repeat your experiment turning S2 ON/OFF. Record any differences in the behavior of the LED and form a hypothesis about the role of C4 in controlling the behavior of your original circuit.

Now test your hypothesis by restoring your original circuit from Figure 1a, but this time set S1 to ON. What are you changing (if anything) by closing this switch? Repeat your experiment from before pressing/releasing S2 and observing the LED turn ON/OFF and record any differences in the behavior of the LED compared to your original circuit where you kept S1 OFF. For **deliverable 3**, summarize your observations and comment on any changes you observed. With S1 closed, has the overall capacitance of your circuit increased, decreased, or stayed the same? Check your prediction by also showing your calculations of the equivalent capacitance using Equations 1a or 2a (whichever is appropriate).

Consider the variation on the circuit for your first set of experiments in Figure 2a. How many capacitors are in the circuit if S1 is OFF? How many when S1 is ON? Are C4 and C5 in series or in parallel with each other? Assemble your circuit and test your understanding by noting how the LED operates with your S1 ON and OFF. For **deliverable 4**, include a picture and circuit diagram of this circuit, and show your calculations for the equivalent capacitance when S1 is ON. State whether C was larger or smaller when S1 was closed, and also show your calculations of the equivalent capacitance using Equations 1a or 2a (whichever is appropriate).

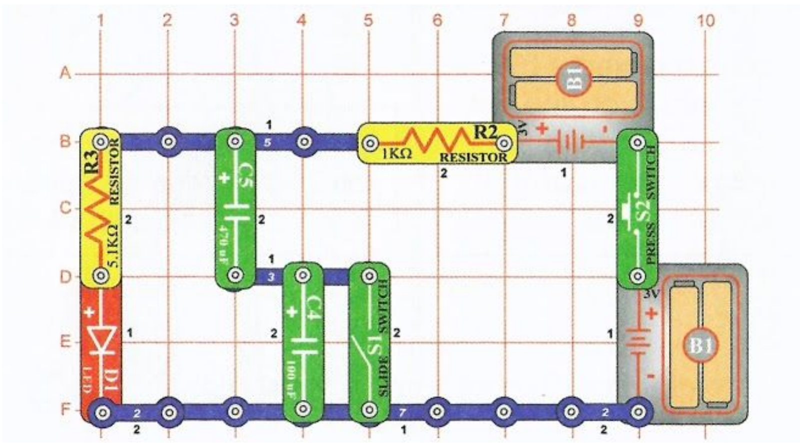


Figure 2a: *variation of capacitor test circuit with LED*

These experiments explored how capacitors add time lag within a circuit, and you learned different ways of combining the same electrical components to achieve different results. In Activity 2, you will perform more quantitative analyses of the time-dependent behavior of *RC* combinations within circuits.

Activity 1b - Capacitors in Series & Parallel

In this set of experiments, you will explore the effect of *capacitance* within circuits. Many common types of circuits contain multiple capacitors. In this case, we can simplify the circuit to predict its behavior, similar to how we did for multiple resistors in Lab 5. When capacitors are connected in series, the equivalent capacitance C_s is

$$\frac{1}{C_S} = \sum_j \frac{1}{C_j} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \qquad (1b)$$

You can convince yourself that this results in a C_S that is reduced relative to C_1, C_2, C_3, etc. For capacitors in parallel, the equivalent capacitance C_P is

$$C_P = \sum_j C_j = C_1 + C_2 + C_3 + \ldots \qquad (2b)$$

Navigate to the circuit construction kit simulation, and select the 'Lab' option to open a new workspace. This is a more advanced version of the circuits simulation you have used in previous labs, with a few added features. Keep 'Labels' and 'Values' checked in the options window at the upper right, and look over the simulation features to see if you recognize any of the components. Next, consider the capacitor circuit in Figure 1b. Study the circuit and try to predict how it works with the lightbulb before building and testing it. In doing so, consider whether the capacitors C1 & C2 are in series or in parallel with each other and with the lightbulb. Based on what you have learned about how capacitors charge and discharge in circuits, predict what's happening to the C1 component with capacitance C = 0.10 Farads (F) when S1 is first closed to complete the circuit? Will the lightbulb light? For **deliverable 1**, take a screenshot of your assembled circuit that shows it works (keep the other switch S2 open for now). Include a circuit diagram for this circuit using the voltage V and resistor values shown using proper symbols and orientation of the battery. Note: you can reference basic circuit symbols in Knight Figure 23.2. Is C1 in series or in parallel with the lightbulb?

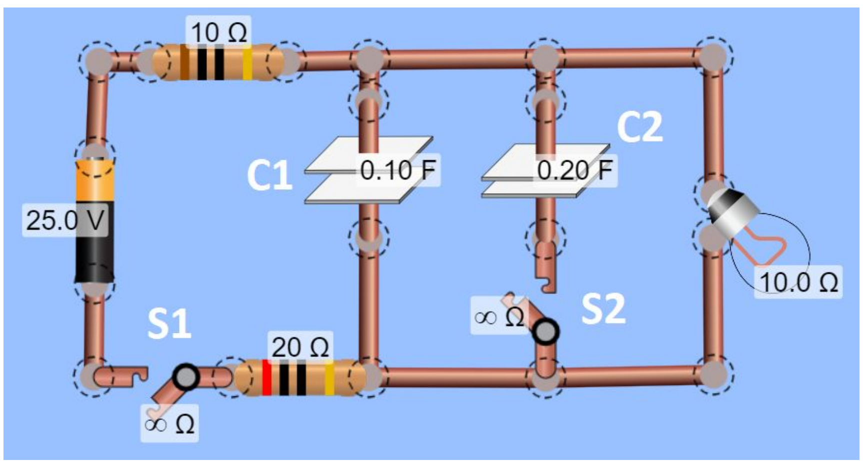


Figure 1b: *labeled capacitor tester circuit with lightbulb*

When S1 is closed, you should notice a brief delay before the lightbulb reaches full brightness, which is the result of C1 being charged by the battery. What happens when you open S1 after the lightbulb has reached maximum brightness? How is it possible that with S1 open (i.e., the battery removed from the circuit) the lightbulb can still be on? Note: you can also check 'Show Current' if you wish to see the flow of charges. You should observe a delay before the lightbulb turns off completely as C1 discharges. What would happen if C1 were removed as well (try it)? For **deliverable 2**, take a screenshot of your new circuit without the capacitors and repeat your experiment turning S1 ON/OFF. Record any differences in the behavior of the lightbulb and form a hypothesis about the role of C1 in your original circuit.

Now test your understanding by restoring your original circuit from Figure 1b, but this time with the other switch S2 closed. What are you changing (if anything) by having S2 ON? Repeat your experiment from before turning S1 ON/OFF and observing the lightbulb turn ON/OFF and record any differences in the behavior of the lightbulb compared to your original circuit where you kept S2 open. You may wish to open a second simulation window to enable a side-by-side comparison. For **deliverable 3**, summarize your observations and comment on any changes you observed. With S2 closed, has the overall capacitance of your circuit increased, decreased, or stayed the same? Check your prediction by also showing your calculations of the equivalent capacitance using Equations 1b or 2b (whichever is appropriate).

Next, consider the variation on the circuit for your first set of experiments in Figure 2b. How many capacitors are in the circuit if S2 is closed? How many when S2 is open? Are C1 & C2 in series or in parallel with each other? Build your circuit and test your understanding by noting how the lightbulb operates with your S2 ON/OFF. For **deliverable 4**, summarize your observations and comment on any changes you observed. With S2 closed, has the overall capacitance of your circuit increased, decreased, or stayed the same? Check your prediction by showing your calculations of the equivalent capacitance using Equations 1b or 2b (whichever is appropriate).

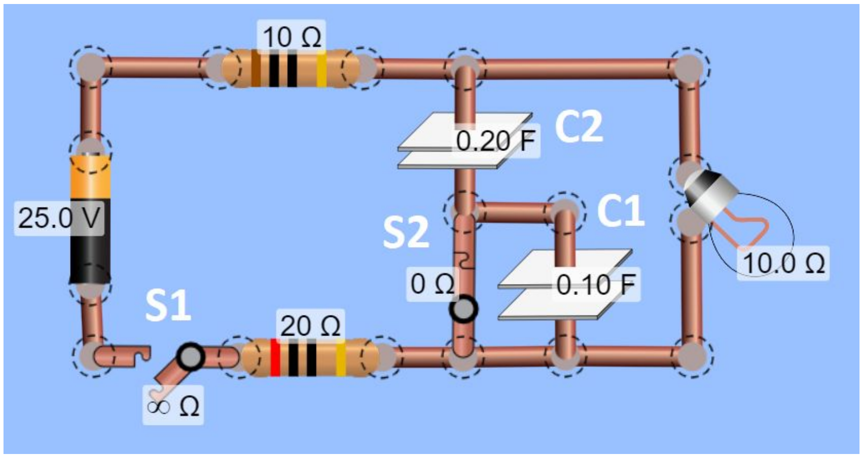
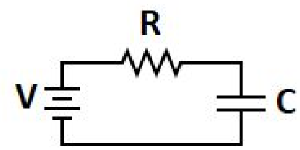


***Figure 2b:** variation of capacitor test circuit with lightbulb*

These experiments explored how capacitors add time lag within a circuit, and you learned different ways of combining the same electrical components to achieve different results. In Activity 2, you will perform more quantitative analyses of the time-dependent behavior of *RC* combinations within circuits.

Activity 2a - Measurements in RC Circuits

In this activity, you will analyze the *RC* circuit more quantitatively by measuring the voltage *V* vs. time *t* across a single capacitor circuit. You will also experiment with varying the capacitance to learn how this combines with resistance to affect the circuit response. Consider a simplified version of the *RC* circuit in the diagram, which contains a single resistor *R* and capacitor *C* and a voltage source *V*. If you recall your earlier experiments with your circuits in Activity 1a, you should have observed that adding capacitance $C \neq 0$ resulted in a time delay between removing the batteries from your circuit and the LED turning off. This was the result of a decaying voltage drop across one or more capacitors ΔV_C from energy previously stored in the capacitor(s). Both the current *I* and ΔV_C during discharging are exponentially decaying functions of time *t:*



$$I = I_0 e^{-t/\tau} \qquad (3a)$$

$$\Delta V_C = (\Delta V_{C,0}) e^{-t/\tau} \qquad (4a)$$

In the equations above, $\tau = RC$ and is the time constant of the circuit, I_0 is the initial (maximum) value of current when $t = 0$, and $\Delta V_{C,0}$ is the initial voltage drop across the capacitor at $t = 0$. During the initial charging process, the current still decreases according to Equation 3a as the capacitor has ΔV_C increasing from zero up to a maximum value $\Delta V_{C,max}$:

$$\Delta V_C = \Delta V_{C,max}(1 - e^{-t/\tau}) \qquad (5a)$$

For example graphs of these equations, refer to Chapter 23.7 of your textbook. Review the *RC* circuit in Figure 3a below. It consists of two battery packs B1 in series with a resistor R4 = 10 kΩ, a capacitor C5 = 470 μF, two switches S1 & S2, and a voltmeter configured to monitor ΔV_C. After studying and building this circuit, you can convince yourself that S1 allows you to add/remove the batteries from your circuit, while the momentary switch S2 effectively short-circuits the capacitor terminals permitting you to quickly discharge it safely without having to reconfigure your circuit. This will be your *RC* circuit #1 for your charging experiment. Keep S1 OFF while making the remaining connections, and set your voltmeter to read $\Delta V_C \cong 0$ V. If needed, briefly press S2 to get rid of any charge on C5 that is giving you $\Delta V_C \neq 0$ V.

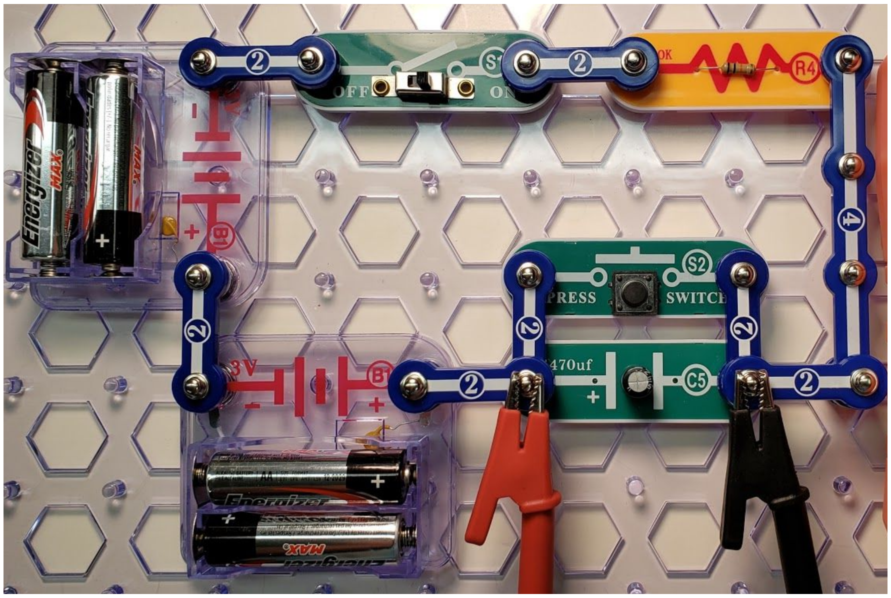


Figure 3a: *RC charging circuit #1*

Given your values for R and C, what do you expect the characteristic charging timescale to be for this circuit? With your voltmeter ON, what do you observe when you close S1? For **deliverable 5**, include a photo of your circuit that includes your voltmeter and report your approximate value of $\Delta V_{C,max}$.

Now we want to monitor the time-dependent charging behavior of your circuit so that we can experimentally test whether your real circuit obeys theory in Equation 5a. To do this part, you will record video of your charging process with your voltmeter readings visible. To begin, use your S2 switch to remove excess charge on C5, then position your camera to be able to record ΔV_C. Close S1 when your recording begins and create a video of your charging circuit for about 30 seconds. Analyze your video and use the timestamps to create a set of ΔV_C in Volts (V) vs. elapsed time t after closing S1 in seconds (s). Note that in Equation 5a, $\Delta V_C = 0$ corresponds to $Q_C = C\Delta V_C = 0$, so you want C5 to be as completely discharged as possible when $t = 0$. If you close S1 at some later time t' in the video, estimate and then subtract t' from all of your t values for the following analysis. For **deliverable 6**, include a data table of your ΔV_C vs. t values and make a plot in Google Sheets/Excel of your data with properly labeled axes. Calculate your expected value for $\tau = RC$ from your circuit components and overplot your theoretical curve using Equation 5a (see example plot in Figure 4a). Note that R should be in Ohms (Ω) and C should be in Farads (F) for your $\tau = RC$ to have units of seconds (s). For an example of how to overplot a theoretical curve using an equation with experimental measurements, review the video tutorial on the CCLE Lab Resources page. How well does Equation 5a describe the charging behavior of your circuit?

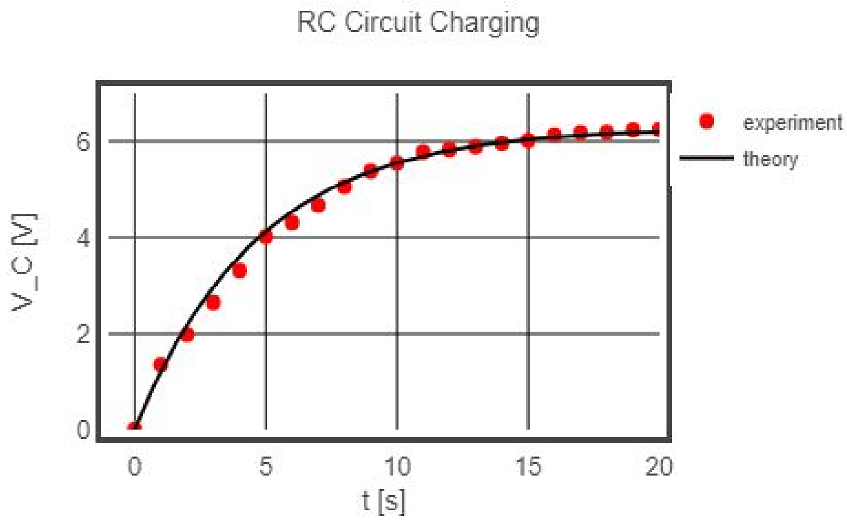


Figure 4a: *example data from charging capacitor voltage vs. time w/ overplot of Eq. 5a. Example Python code trinket to help you generate your own plot here.*

To evaluate Equation 4a for C5 discharging, you first need to charge it, then modify your circuit to remove the batteries and allow C5 to discharge back through R4. An example of a minimally modified circuit is shown in Figure 5a. In our example, the only modification was to move S1 to the new position shown while C5 was fully charged at $\Delta V_{C,0}$ = 6.35 V at t = 0 s.

Next, record a video of the discharging process, taking note of your value of $\Delta V_{C,0}$. From your video analysis, construct a table of ΔV_C vs. t values and make a plot of your experimental data. Use Equation 4a to overplot the theoretical ΔV_C vs. t curve (see the example in Figure 6a). For **deliverable 7**, include your data table and plot, as well as a picture of your discharge circuit with your voltmeter showing your value for $\Delta V_{C,0}$. For **deliverable 8**, add a best-fit exponential curve to your discharge plot and give a comparison of your best-fit parameters to your measured $\Delta V_{C,0}$ and your expected time constant τ = RC = R4*C5. Show your best-fit line in your new plot. Note: your best-fit exponential will likely be reported by Excel/Google Sheets as a function of the form Ae^{Bt}, where A represents the best-fit value for $\Delta V_{C,0}$ and the parameter B is the best-fit value for $-(RC)^{-1}$.

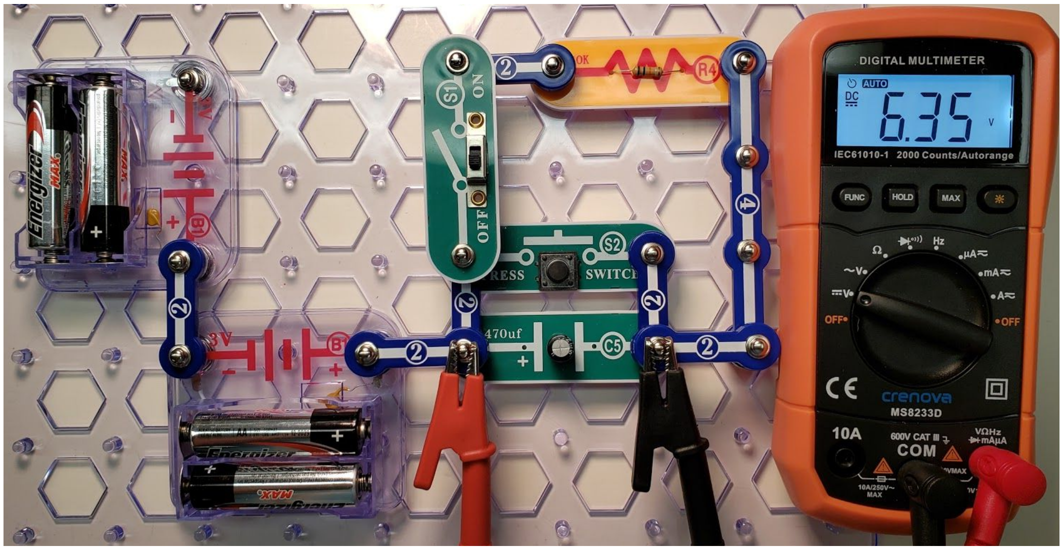


Figure 5a: *example modified RC circuit for discharge*

In our example discharge circuit from Figure 5a, our best-fit (blue curve) had A = 6.25 V and B = -0.189 s^{-1} giving an experimental time constant $\tau_{exp} = -B^{-1} = -(0.189)^{-1}$ = 5.291 s. This is a difference of ~10% from our theoretical RC value of 4.700 s and indicates that our real circuit was "slower" than theory would predict from RC values alone. Given that the manufacturer of our components reports a variance of ± 5 % in the reported R4 and C5 values, this is a reasonable result for our simple equipment.

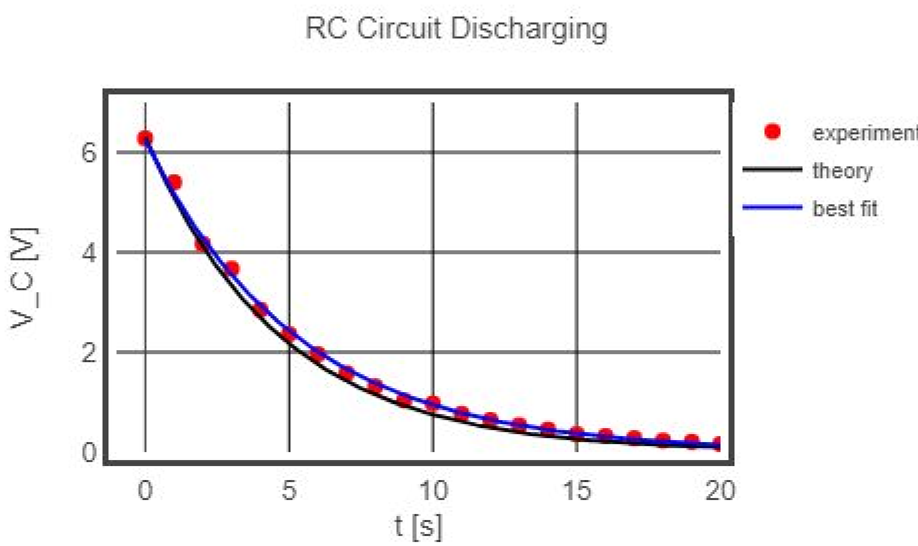
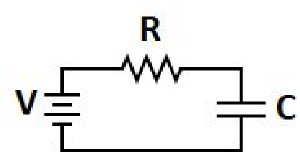


Figure 6a: *discharge data (red points) w/ Eq. 4a (theory; black curve) & best-fit (blue curve)*
Example Python code trinket to help you generate your own plot [here](#).

Given your experience with Activity 1a, how do you expect your charging/discharging behavior to change if you add another capacitor to your circuit? Add your C4 = 100 μF component to create a new *RC* circuit #2 that has C5 & C4 in parallel. What do you expect for the new value of total circuit capacitance *C′* and new time constant τ' = *RC′*? Build and test your new circuit and determine on your own how to switch between your charging circuit and your discharging circuits. Verify that your circuits work using your voltmeter to monitor the charge/discharge process. For **deliverable 9**, include a photo of your working charge & discharge circuits, and show your calculations for the new total equivalent capacitance *C′* and your new time constant τ'. For **deliverable 10**, make a new version of your discharging plot, similar Figure 6a, where you repeat your analysis using a best-fit line to your data for this new circuit. Evaluate and explain how well your *RC* circuit #2 experiment results match your expected time constant from your values of *R* and *C′*.

Activity 2b - Measurements in RC Circuits

In this activity, you will analyze the *RC* circuit more quantitatively by measuring the voltage *V* vs. time *t* across a single capacitor circuit. You will also experiment with varying the capacitance to see how this combines with resistance to affect the circuit response. Consider a simplified version of the *RC* circuit in the diagram, which contains a single resistor *R*, capacitor *C*, and a voltage source *V*. If you recall your earlier experiments with your circuits in Activity 1b, you should have observed that adding capacitance $C \neq 0$ resulted in a time delay between removing the battery from your circuit and the lightbulb turning fully off. This was the result of a decaying voltage drop across one or more capacitors ΔV_C from energy previously stored in the capacitor(s). Both the current *I* and ΔV_C during discharging are exponentially decaying functions of time *t:*



$$I = I_0 e^{-t/\tau} \qquad (3b)$$

$$\Delta V_C = (\Delta V_{C,0}) e^{-t/\tau} \qquad (4b)$$

In the equations above, τ = *RC* and is the time constant of the circuit, I_0 is the initial (maximum) value of current when *t* = 0, and $\Delta V_{C,0}$ is the initial voltage drop across the capacitor at *t* = 0. During the initial charging process, the current still decreases according to Equation 3b as the capacitor has ΔV_C increasing from zero up to a maximum value $\Delta V_{C,max}$:

$$\Delta V_C = \Delta V_{C,max}(1 - e^{-t/\tau}) \qquad (5b)$$

For example graphs of these equations, refer to Chapter 23.7 of your textbook. Review the *RC* circuit in Figure 3b below. It consists of a 30 V battery in series with a fixed resistor R = 25 Ω, a 10 Ω lightbulb, a capacitor C1 with C = 0.15 F, and two switches S1 & S2. Navigate back to the RC circuit construction kit simulation, and select 'Lab' to open a new workspace. In the upper right options window, keep only 'Labels' and 'Values' checked. After building this circuit, you can convince yourself that S1 allows you to add/remove the battery from your circuit, while the switch S2 provides another path for current permitting you to discharge C1 through the resistors without having to reconfigure your circuit. What potential problem do we create if *both* S1 & S2 are closed at the same time (try it!)? This will be your *RC* circuit #1 for your charging experiment. Keep S1 & S2 open for now, and add the voltmeter tool configured to monitor the potential difference (watch your polarity) across the capacitor, ΔV_C.

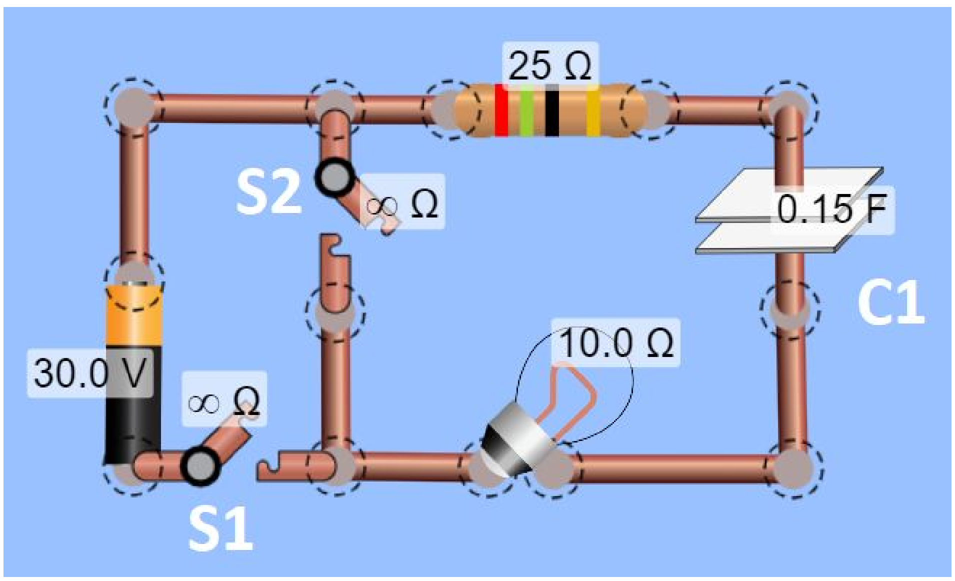


Figure 3b: *RC circuit #1*

Given your values for R and C, what do you expect the characteristic charging timescale to be for this circuit (Hint: both the fixed resistor and the light bulb contribute to the equivalent resistance R_{eq})? With your voltmeter added to your circuit, what do you observe happening to the charge distribution on C1 and the lightbulb brightness when you close S1? For **deliverable 5**, include a screenshot and a circuit diagram for this circuit that includes your voltmeter and report your approximate value of $\Delta V_{C,max}$ from Equation 5b, which represents the voltage reading across C1 at full charge Q_{max} = $C\Delta V_{C,max}$. If you want to repeat the charging process, select C1 in your circuit and click the discharge icon to the left of the slider adjustment for your C value to set Q = 0 again.

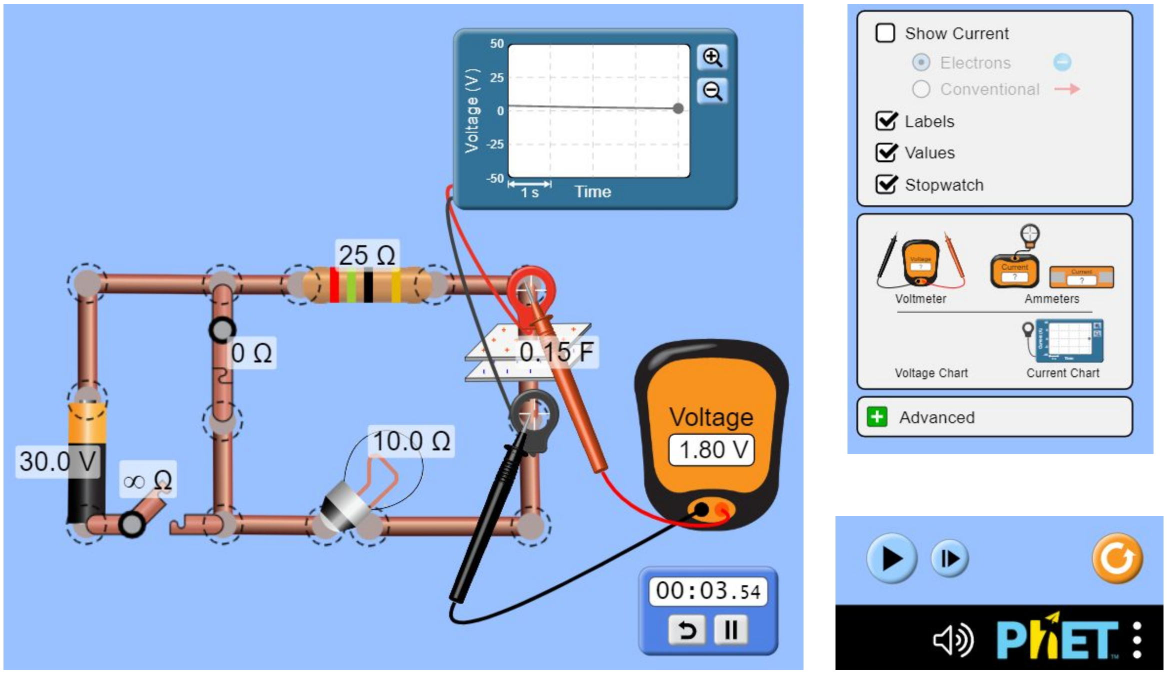


Figure 4b: *RC circuit #1 with voltmeters, stopwatch tool, and Δt controls (lower right)*

Now we want to monitor the time-dependent charging behavior of your circuit so that we can experimentally test whether it obeys Equation 5b. To do this part, you will need to record voltmeter measurements of ΔV_C as a function of time t, so check 'Stopwatch' to add the timer tool to your workspace (see Figure 4b). To begin, have S1 & S2 open, discharge C1, and press the play button on the stopwatch tool to enable recording t in seconds (s). After closing S1 (your lightbulb will light), nothing will happen yet because in this mode the simulation is programmed to wait for your prompts to advance time in the circuit. The two play controls (see lower-right insert in Figure 4b) advance t continuously (▶) or by intervales of $\Delta t = 0.1$ s (|▶) at a time. The voltmeter readings will update automatically, allowing you to take data for the charging process (you should practice this process several times to make sure everything is working as you expect). To start a new charging run, open S1, pause/reset the stopwatch tool, then use the discharge function to reset C1.

Record your ΔV_C in Volts (V) vs. elapsed time t in seconds (s) for 20 seconds in intervals $\Delta t \cong 1$ s. Note that in Equation 5b, $\Delta V_C = 0$ only when $t = 0$, so your first data point is just (0 V, 0 s). For **deliverable 6**, include a data table of your ΔV_C vs. t values and make a plot in Google Sheets/Excel of your data with properly labeled axes. Calculate your theoretical value for $\tau = RC$ using your circuit components and overplot your theoretical curve using Equation 5b (see example plot in Figure 5b). Note that R should be in Ohms (Ω) and C should be in Farads (F) for your $\tau = RC$ to have units of seconds (s). For an example of how to overplot a theoretical curve using an equation along with experimental data, review the video tutorial on the CCLE Lab Resources page. From your plot results, how well does Equation 5b describe the charging behavior of your circuit?

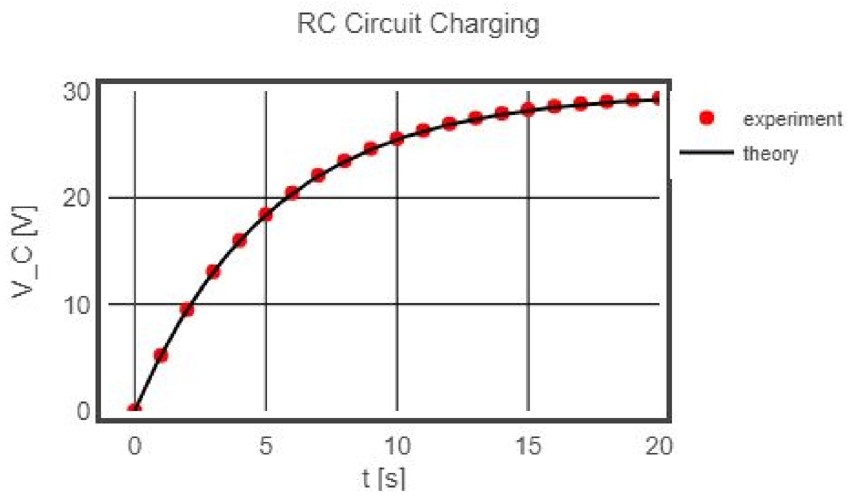


Figure 5b: *example data from charging capacitor voltage vs. time w/ overplot of Eq. 5b*
Example Python code trinket to help you generate your own plot here.

To evaluate Equation 4b for the capacitor discharging, you first need to charge your capacitor, then configure your circuit to remove the battery from your circuit and allow C1 to discharge through the same resistor(s) using the proper settings for S1 & S2. When C1 is fully charged, use this voltage reading as your value of $\Delta V_{C,0}$ at t = 0 s for the discharge process.

Next, reset your stopwatch tool and follow your procedure from earlier to construct a table of ΔV_C vs. t values over at least 20 s using the same approximate time intervals $\Delta t \cong 1$ s and make a plot of your experimental data. For **deliverable 7**, include your data table and plot, as well as a screenshot of your circuit configured for discharge and your voltmeter showing your value for $\Delta V_{C,0}$. For **deliverable 8**, compute a best-fit exponential curve to your data and give a comparison of your best-fit parameters to your measured $\Delta V_{C,0}$ and your expected time constant $\tau = RC$. Show your calculations for τ and display your best-fit line in your plot. Note: your best-fit exponential will likely be reported by Excel/Google Sheets as a function of the form Ae^{Bt}, where A represents the best-fit value for $\Delta V_{C,0}$ and the parameter B is the best-fit value for $-(RC)^{-1}$.

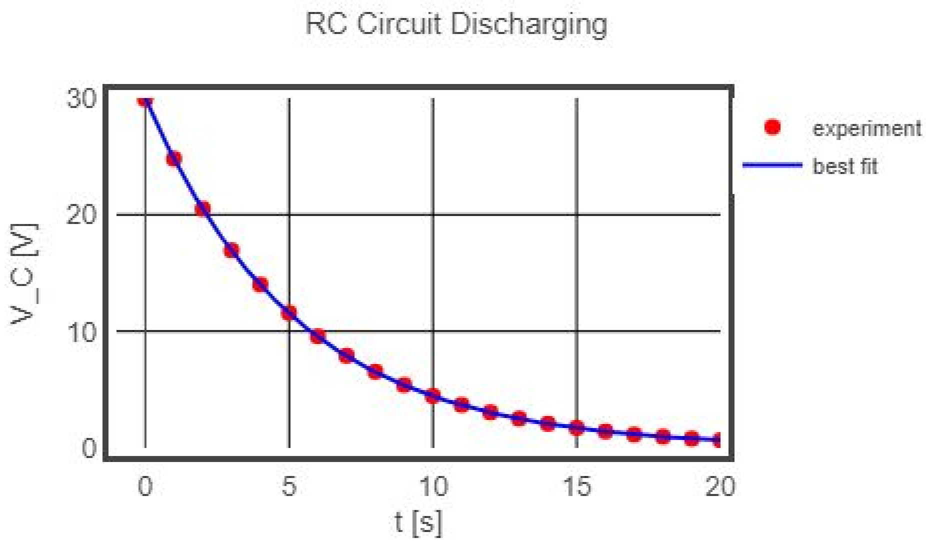


Figure 6b: *ex. discharge data (red points) & best-fit exponential (blue curve)*
Example Python code trinket to help you generate your own plot [here](#).

In our example discharge circuit from Figure 4b, our best-fit line had A = 30.0 V and B = -0.191 s^{-1} giving an experimental time constant $\tau_{exp} = -B^{-1} = -(0.191)^{-1} = 5.24$ s. This is a difference of ~0.3% from our theoretical *RC* value of 5.25 s and indicates that our simulation operates very closely to the ideal behavior predicted by Equation 4b.

Given your experience with Activity 1b, how do you expect your charging/discharging behavior to change if you add another capacitor to your circuit? Add another capacitor C2 = 0.10 F to create a new *RC* circuit #2 that has C1 & C2 in parallel. What do you expect for the new value of total circuit capacitance C' and new time constant $\tau' = RC'$? Test your new circuit and determine on your own how to switch between your charging circuit and your discharging circuits. Verify that your circuits work using your voltmeter and your lightbulb to monitor the charge/discharge process. For **deliverable 9**, include screenshots of your working circuits configured for charge & discharge, and show your calculations for the total equivalent capacitance C' and your new time constant τ'. For **deliverable 10**, make a new version of your discharging plot, similar Figure 6b, where you repeat your analysis using a best-fit line to your data for this new circuit. Evaluate and explain how well your *RC* circuit #2 experiment results match your expected time constant from your values of R and C'.

3. Deliverables

For full credit please include the following in your lab report. Follow the template provided on the Weebly Lab 6 page and include one deliverable per Google Slide in the order that they are presented for your set of activities below. Always label your images.

1. A picture and circuit diagram of your working circuit based on Figure 1a. Find the total voltage supplied to your circuit and state whether C4 is in series/parallel with the R3+LED sub-circuit and explain your reasoning.
2. A picture of your new circuit without capacitors; repeat your experiment turning S2 ON/OFF. Record changes in the LED operation; form a hypothesis about the role of C4 in your original circuit.
3. Summarize your observations after repeating the above experiments with S1 closed; has the overall capacitance of your circuit increased, decreased, or stayed the same? Show your calculations of equivalent capacitance.
4. A picture and diagram of your Figure 2a circuit; show calculations of equivalent capacitance with S1 ON. Was C was larger/smaller with S1 ON?
5. A picture of your RC charging circuit #1 that includes your voltmeter; give your approximate value of $\Delta V_{C,max}$.
6. Table and plot of ΔV_C vs. t values for charging circuit. Calculate your expected value for $\tau = RC$ and overplot your theoretical curve using Equation 5a.
7. Table and plot of ΔV_C vs. t values for discharging circuit. Overplot the theoretical ΔV_C vs. t curve using Equation 4a. A picture of your discharge circuit with your voltmeter showing your value for $\Delta V_{C,0}$.
8. Discharge plot from above with best-fit exponential curve added; compare your best-fit parameters to your measured $\Delta V_{C,0}$ and your expected time constant τ.
9. Pictures of your working charge & discharge circuits with C4 added; calculations for the new total equivalent capacitance C' and your new time constant τ'.
10. New discharging plot and repeated analysis using new best-fit line. Evaluate and explain how well your *RC* circuit #2 experiment results match your τ'.

1. A screenshot and circuit diagram of your working circuit similar to Figure 1b. Is C1 in series or in parallel with the light bulb? Explain your reasoning.

2. A screenshot of your new circuit without capacitors and repeat your experiment turning S1 ON/OFF. Record any differences in the behavior of the lightbulb and form a hypothesis about the role of C1 in your original circuit.
3. Summarize your observations after the above experiments with S2 closed. Has the overall capacitance of your circuit increased, decreased, or stayed the same? Show your calculations of equivalent capacitance.
4. Summarize your observations of your Figure 2b circuit. With S2 closed, has the overall capacitance increased, decreased, or stayed the same? Show your calculations of the equivalent capacitance.
5. A screenshot and circuit diagram for RC charging circuit #1 with your voltmeter and report your approximate value of $\Delta V_{C,max}$ from Equation 5b.
6. A data table and plot of your ΔV_C vs. t values. Calculate your theoretical $\tau = RC$ using your components and overplot your theoretical curve using Equation 5b.
7. A data table and plot, as well as a screenshot of your circuit configured for discharge and your voltmeter showing your value for $\Delta V_{C,0}$.
8. Plot with best-fit exponential curve to your data and give a comparison of your best-fit parameters to your $\Delta V_{C,0}$ and your $\tau = RC$. Show your calculations for τ.
9. Screenshots of RC circuit #2 configured for charge & discharge, and show your calculations for the total equivalent capacitance C' and your new time constant τ'.
10. New discharging plot and repeat analysis using new best-fit line. Evaluate and explain how well your RC circuit #2 data results match your expected $\tau' = RC'$.