PHY 112L Activity 4

Capacitance and the RC Time Constant

Name: _____ ID #:_____

Section: _____ Date: _____

Lab Partners: _____ TA initials: _____

Objectives

1. Introduce capacitance and RC time constants for charging and discharging capacitors
2. Experimentally determine the capacitance of different capacitor configurations
3. Experimentally determine the time constant of an RC circuit and compare to calculated values (lab report)

Materials & Resources

1. Computer with Data Studio, Pasco interface, and voltage sensor
2. Capacitance module, multimeter, and power supply

Introduction

Another commonly used electronic component is the capacitor. Capacitors have a different physical property than those of resistors. This property, called capacitance *C*, describes the capacitor's ability to store electrical charge. The SI unit of capacitance is the farad (F). Charge, capacitance and voltage are related by

$$Q = CV$$

This equation says that the amount of charge stored in a capacitor *Q* at any given time can be calculated by multiplying the capacitance *C* of the capacitor and the voltage difference *V* measured across it.

Like resistors, capacitors can be configured in parallel and series to form equivalent capacitances C_P and C_S, respectively. If two capacitors are connected in parallel, then

$$C_P = C_1 + C_2.$$

This is because the voltage on both capacitors is equal; only the charge differs according to the value of each capacitor. On the other hand, if the capacitors are connected in series, the charge on both capacitors is equal, but the voltage differs according to the value of each capacitor. In this case, the equivalent capacitance is given by

$$C_S = \frac{C_1 C_2}{C_1 + C_2}.$$

A circuit that contains both a resistor and a capacitor is called an *RC* circuit. Simple *RC* circuits can be used to illustrate the charging and discharging properties of a capacitor. When you apply a voltage across a capacitor, it will begin to store charge at a rate that depends on both the resistance *R* and the capacitance *C* of the circuit. Similarly, when the charged capacitor is configured to discharge, it will do so at the same rate because of this dependence on *R* and *C*.

The time in which the charging or discharging occurs can be extremely rapid in computers or other common devices, but here *R* and *C* are chosen to make charging and discharging easy to observe. The charging and discharging formulas are:

$$\text{Charging: } Q = Q_m\left(1 - e^{-\frac{t}{RC}}\right) \quad \text{and} \quad \text{Discharging: } Q = Q_o e^{-\frac{t}{RC}}$$

where Q_m is the maximum amount of charge that can be stored within the capacitor, *t* is the time elapsed since the voltage was turned on (for charging) or off (for discharging). Inside the exponential function, *RC* characterizes how fast the capacitor stores charge and is referred to as the circuit's time constant, $\boldsymbol{\tau = RC}$. This is how long it takes for the capacitor to charge to 63% of its maximum value Q_m or to discharge to 37% of the initial amount of charge Q_o. It is very <u>useful</u> to be able to control the timing of a circuit's charging and discharging by choosing different values for *R* and *C*!

1. *Measuring Capacitance and Equivalent Capacitance*

Procedure:

Section 1 - Capacitor 1 (C_1):

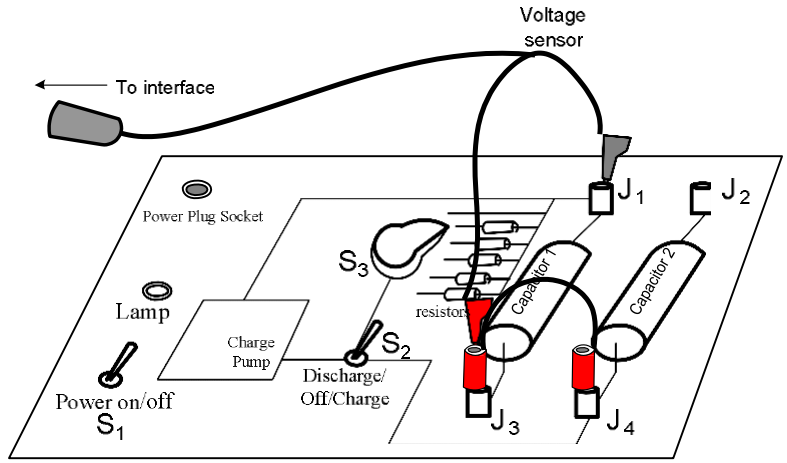

Figure 1

1) Start DataStudio, setup the voltage sensor on an open input port, and then display a voltage vs. time graph.
2) Connect the voltage sensor leads to the capacitance module as shown in Figure 1 (red to J_3, black to J_1, and jumper between J_3 and J_4). In this configuration, you will be measuring the voltage across C_1.
3) Connect the power adapter to the power plug socket.
4) Reset the capacitance module. This is done by changing S_1 to Off, S_2 to Discharge, and S_3 to R_0, where there is no resistor.

   Note: when resetting the capacitor, it must discharge for several seconds in order to remove <u>all</u> of the stored charge.
5) Select R_1 on S_3 and Charging on S_2, and then click "Start" in DataStudio, and <u>then</u> flip S_1 to On.
6) As the capacitor charges, the voltage will eventually approach a maximum value. Stop data collection when it reaches this point and reset the capacitance module as in step 4 above.
7) Select the range on the line that appears *linear (a straight line)* by highlighting it as shown in Figure 2, then select "Linear Fit" from the "Fit" menu. Record your results for slope *m* in column 1 of the table to the right, and then print this graph.

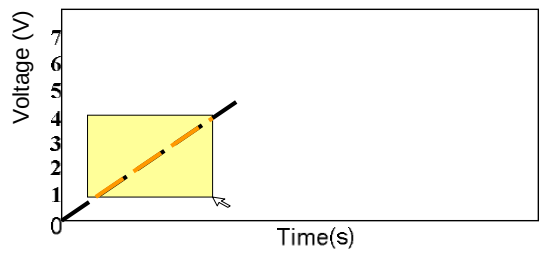

Figure 2

This graph is a plot of voltage vs. time. In order to calculate C_1, the *charge* and *voltage* are needed. The charge pump for the capacitance module delivers a steady current of 1.0 x 10^{-3} A. Thus, the equations $I = {}^{\Delta Q}/_{\Delta t}$ and $Q = CV$ can be used to interpret the slope *m* like this:

$$m = \frac{\Delta V}{\Delta t} = \frac{\Delta V}{\Delta Q} I = \frac{I}{C}.$$

So, capacitance equals current divided by the slope of the measured voltage vs. time plot, or simply $C = {}^{I}/_{m}$.

	Slope from graph (*m*)	Capacitance in (F) C = I / m (where I = $1x10^{-3}$ A)
C_1		
C_2		
C_{EP}		
C_{ES}		

Questions:

1) Briefly describe the voltage vs. time graph of an RC circuit when the charge stored on C is approaching…

   a) its maximum?

   b) zero?

2) Why is the slope of the voltage vs. time graph in Figure 2 a straight line instead of curved like an exponential?

Section 2 – Capacitor 2 (C_2):

8) Delete your data for C_1 by selecting "Experiment" and then "Delete ALL Data Runs."
9) Connect the voltage sensor across C_2 (red plug to J_4, black plug to J_2, jumper across J_1 and J_2). In this configuration, you will be measuring the voltage across C_2.
10) Repeat steps 4 – 7 above to find the capacitance of C_2.

Section 3 –Capacitors in Parallel (C_{EP}):

11) Modify the connections to the capacitance module as follows:

    Leave the jumper across J_1 and J_2 in place, and reconnect a jumper across J_3 and J_4 as in Part 1 above. Also, connect the voltage sensor across C_1 as described in Part 1. *Note, since the capacitors are now connected in parallel, the voltage measured here is the voltage across* <u>*both*</u> *capacitors in* <u>*parallel*</u>.
12) Delete your data for C_2 and repeat steps 4 – 7 above to find the capacitance of C_1 and C_2 in parallel, C_{EP}.

Section 4 –Capacitors in Series (C_{ES}):

13) Modify the connections to the capacitance module as follows:

    Remove the voltage sensor from the circuit and disconnect all jumpers. Connect the red plug of the voltage sensor to J_4 and the black plug to J_1, then connect a jumper across J_2 and J_3. *Note, the capacitors are now connected in series, and the voltage is measured across* <u>*both*</u> *capacitors in* <u>*series*</u>.
14) Delete your data for C_{EP} and repeat steps 4 – 7 above to find the capacitance of C_1 and C_2 in series, C_{ES}.
15) Using the equivalence formulas and the values measured for C_1 and C_2 above, calculate C_P and C_S; record below.

C_P: _____ = _____ ( ) C_S: _____ = _____ ( )

16) Calculate percent differences for both the parallel and series capacitor configurations; record your results below.

$$\%\ \text{difference (parallel)} = \frac{|C_{EP}-C_P|}{\frac{1}{2}(C_{EP}+C_P)} \times 100 = \_\_\_\_\_ = \_\_\_\_\_\ \%$$

$$\%\ \text{difference (series)} = \frac{|C_{ES}-C_S|}{\frac{1}{2}(C_{ES}+C_S)} \times 100 = \_\_\_\_\_ = \_\_\_\_\_\ \%$$

<u>Questions</u>:

1) Why must C discharge completely between different measurements of C_X? How can this be verified experimentally?

2) How would your measured values for C_S change if there was an initial charge on C_1 or C_2? What about for C_P?

3) Is your calculated value for C_P higher or lower than your measured value C_{EP}? What about your C_S and C_{ES}?

4) What quantity represents the uncertainty in the above method for measuring values for C_X?

2. *RC Circuit Time Constant (Lab Report)*

Procedure: *(The connections for the capacitors in series will be reused here; connection changes are not needed.)*

1) Delete your data for C_{ES} by selecting "Experiment" and then "Delete ALL Data Runs."
2) Reset the capacitance module and then begin charging the series combination of C_1 and C_2 again by repeating steps 4 and 5 from Part 1 above.
3) Allow the capacitor to charge until the voltage vs. time graph flattens out at its maximum value V_{max}. This may take several seconds; be sure the voltage is flat before proceeding.
4) Turn S_2 to Discharge and allow the capacitor to discharge until the voltage has fallen to zero again. Then stop data collection and reset the capacitance module.
5) Use the Smart Tool in DataStudio to find the corner at the peak of the discharge curve as shown in Figure 3. This will give the precise time that the discharge began T_o as well as the maximum voltage for this capacitor V_{max} in the form (T_o , V_{max}). Record your measured values for T_o and V_{max} in the space below.

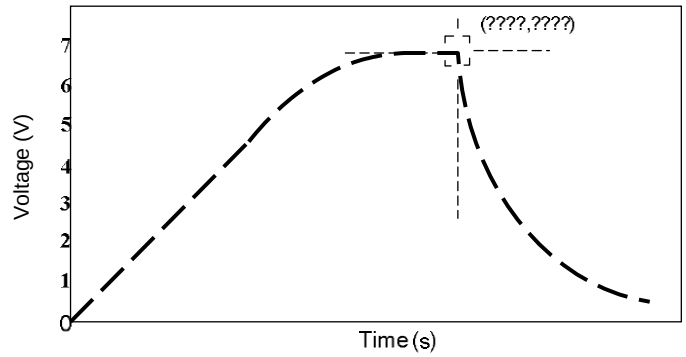

Figure 3

T_o = _____ ( ) V_{max} = _____ ( )

6) When the voltage across a discharging capacitor has fallen to 37% of its maximum value, one time constant is said to have passed. Calculate 37% of the maximum voltage V_{37} and locate this point on the curve as in Figure 4. Record your results below.

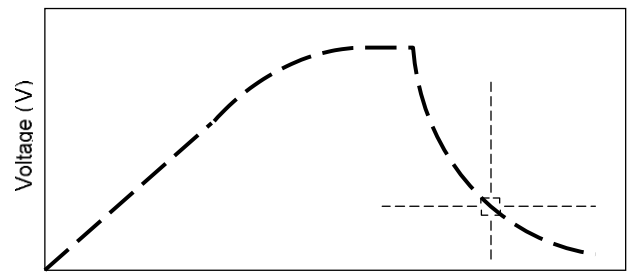

Figure 4

T_{37} = _____ ( ) V_{37} = _____ ( )

7) Use the Smart Tool to locate V_{37} on the discharge curve as accurately as possible, as shown in Figure 4, and then record the time at this point T_{37} in the space above.
8) Calculate and record the time constant τ_E using T_o and T_{37}.

$\tau_E = T_{37} - T_o$ = _____ = _____ ( )

9) Turn the multimeter to resistance mode, and then measure the resistance of R_1 as shown in Figure 5 record below.

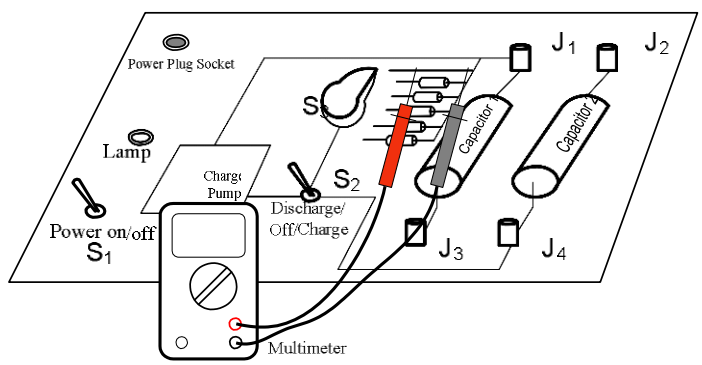

Figure 5

R_1 = _____ ( ) τ_C = _____ ( )

10) Calculate the time constant $\tau_C = R_1 C_{ES}$ using R_1 measured here and C_{ES} measured in Section 4 above and record your result above. Calculate the percent difference below.

$$\%\ \text{difference} = \frac{|\tau_E - \tau_C|}{\frac{1}{2}(\tau_E + \tau_C)} \times 100 = \_\_\_\_\_ = \_\_\_\_\_\ \%$$

Questions:

1) Which value for time constant is higher, τ_E or τ_C? Briefly explain why below.

2) How would your measured values for τ above change if R_2, which has a higher resistance than R_1, is used instead?