

RC Circuits – Charge Changing in Time

Observing the way capacitors in RC circuits charge and discharge.

January 19, 2014

Print Your Name

Print Your Partners' Names

Instructions

Before lab, read sections 0 and 1, the *Introduction* and the *Instructor Demonstration* (especially the captions to Figure 2 and Figure 3). Then answer the Pre-Lab Questions on the last page of this handout.

Hand in your answers to the pre-lab questions as you enter the general physics lab.

You will return this handout to the instructor at the end of the lab period.

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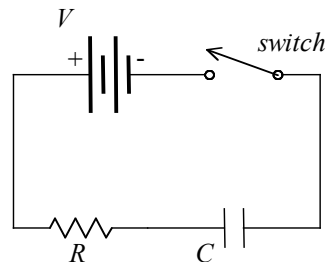
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0. Introduction

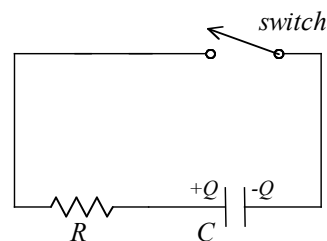
0.1 How capacitors are made

A capacitor is formed any time two conductors are separated by a non-conductor. You can think of capacitors as being two metal plates separated by air or vacuum. Many of the capacitors used in contemporary electronics are made with pairs of very large and very thin metal foils separated by a very thin layer of insulator (back in the early days of radio, paper was used for the insulator) rolled into a compact tube and sealed inside a plastic coat.

0.2 Charging and discharging a capacitor



(a) The capacitor will charge when the switch is closed.



(b) The capacitor will discharge when the switch is closed.

Figure 1 Circuits for charging, in (a), and discharging, in (b), a capacitor through a resistor.

When an uncharged capacitor and a resistor are initially connected in series to a voltage source, charge will flow in the circuit until the capacitor becomes fully charged, at which point the charge stored on its plates is $Q = CV$, where C is the capacitance (in Farads) of the capacitor, and V is the voltage. When the voltage source is removed and replaced by a simple piece of wire, the charge on the capacitor returns to zero; the capacitor discharges.

A charged capacitor has equal magnitude charges of opposite sign on its two plates. One way to introduce charge onto the plates of the capacitor, i.e., to charge it, is with a resistor and capacitor in series and connected to a voltage source through a switch.

Refer to Figure 1, part (a). An initially uncharged capacitor in an RC circuit in which the switch is open will remain uncharged. However, when the switch is closed, electrons from the negative terminal of the battery or power supply will move through the circuit and accumulate on the closest plate of the capacitor. This accumulation of negative charge on one plate will induce a positive charge on the other plate – essentially, the electrons on the opposite plate will be repelled and will move back to the positive terminal of the battery/power supply. All motion of electrons will stop when the charge on the plates becomes $Q = CV$.

Refer to Figure 1, part (b). Once a capacitor is charged, it can be discharged (i.e., the charge can be reduced to zero on its plates) after making two changes to the RC circuit in Figure 1, part (a). First, the voltage source (the battery or power supply) must be removed from the circuit. Second, the open circuit caused by the removal of the power supply must be closed with a wire. Once these changes are made and the switch is closed, the excess electrons from one plate of the capacitor will flow through the circuit until the deficit of electrons on the other plate is removed. The excess charge on the plates of the capacitor ($\pm Q$) will be zero when the capacitor is fully discharged, and no current will flow at that time.

0.3 Capacitor charge as a function of time

Suppose a capacitor C farads is given a charge Q_0 coulombs and then is made to discharge through a resistor R ohms. At time t seconds after the discharge begins, the charge Q remaining on the capacitor is given by the following formula.

$$Q = Q_0 e^{-\frac{t}{RC}}$$

In the above, e is a name for a mathematical constant, like π is a name for 3.14159.... The numerical value that e stands for is 2.7182818284..., so the above formula is essentially the same as the following.

$$Q = Q_0 \cdot 2.718^{-\left(\frac{t}{RC}\right)}$$

0.4 Example of capacitor **discharge** as a function of time

In this example, the capacitor is $C = 1000 \mu\text{F}$ (1000 microfarads), and the resistor is $10 \text{ k}\Omega$ (10 kilohms). At $t = 0$ seconds, the charge on the capacitor is $Q_0 = 0.24 \text{ C}$ (0.24 coulombs). Find the capacitor charge Q at $t = 3.0 \text{ s}$.

Solution First, note that the product $RC = 10$ seconds ($10 \times 10^3 \Omega \times 1000 \times 10^{-6} \text{ C}$), so $t/RC = 3/10 = 0.3$. If your calculator has an e^x function, use it to calculate $Q = 0.24 \times e^{-0.3}$.

Alternatively, you can use the “raise to a power” function y^x to compute $Q = 0.24 \times [2.718^{-0.3}]$.
Answer $Q = 0.18 \text{ C}$.

1. Activity #1: Instructor demonstration of charge stored in a capacitor

Abstract: Your lab instructor will use a charged capacitor to light a bulb, thereby demonstrating that a capacitor stores electrical energy.

Equipment: 12V, 200 mA light bulb [Radio Shack 1815]
78 mF electrolytic capacitor [sic: 78 *millifarads* = 78,000 μF]
Variable DC Power supply, 0 to 15 VDC, 0.1 A.
Voltmeter (3 digits, 20 V range)

1.1 The aim of this activity is to demonstrate to you the ability of a capacitor to store charge and provide a potential difference when completely charged. Your lab instructor will demonstrate this by first charging up a capacitor by connecting it across the terminals of a DC power supply. Once fully charged your lab instructor will then discharge the capacitor by connecting it across a light bulb.

1.2 In order to charge up the capacitor, connect the capacitor across the terminals of a DC power supply as shown in Figure 2.

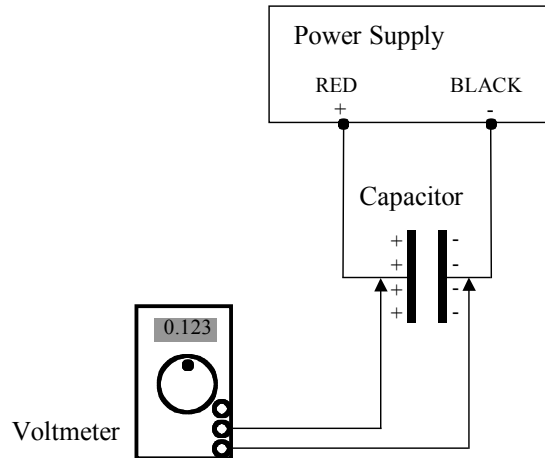


Figure 2: Charging a capacitor by connecting it across the terminals of a power supply. Electrons flow through the wire from the negative terminal of the power supply onto the capacitor plate on the right, making it negative. The negative charge drives electrons away from the capacitor plate on the left, making it positive. The electrons that were driven away from the left plate flow into the positive terminal of the power supply. The voltmeter does not do anything except watch the difference in voltage between the two capacitor plates.

1.3 Once fully charged, the capacitor is now disconnected from the terminals of the power supply and connected across a light bulb as shown in Figure 3.

1.4 Carefully observe what happens to the light bulb when it is connected across the terminals of the capacitor.

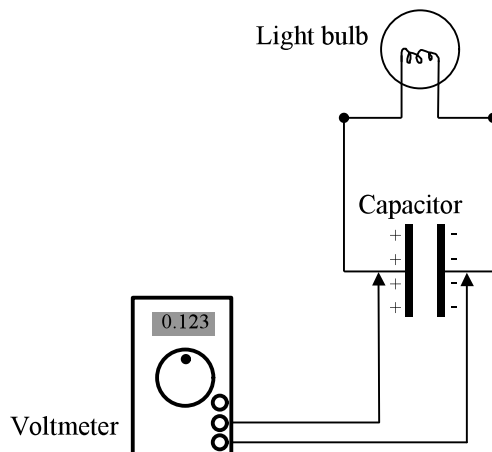


Figure 3: Discharging a capacitor through a light bulb. Electrons on the negative capacitor plate can move to the positive plate to which they are attracted by traveling through the light bulb. In passing through the light bulb, they make the bulb glow. As with the previous circuit, the voltmeter does not do anything except watch the difference in voltage between the two capacitor plates.

Equipment: Computer running Logger Pro and MS Excel
LABQUEST
Voltage Probe plugged into CH 1 of LABQUEST
Voltmeter (3 digits, 20 V or 30 V range)
Low-voltage power supply set for 5 volts; **Important: floating + and – outputs**
Banana-plug circuit board with 1000 μF & 500 μF capacitors and 2.2 $\text{k}\Omega$ resistor
Alligator clips, one pair, red and black
RC_Circuits.mbl (Logger Pro initialization file)

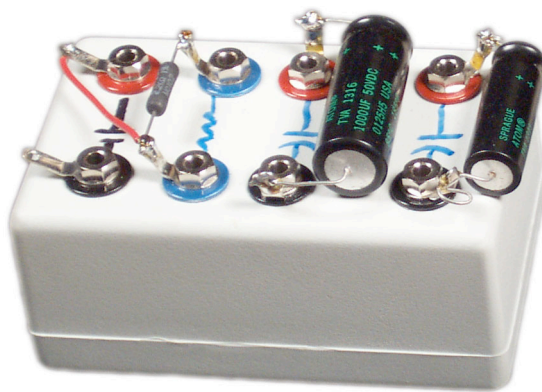


Figure 4 Banana-plug circuit board holding the resistor and the capacitors

2. Activity #2: Observing the discharge of a capacitor in an RC circuit

2.1 Your first job is to build an RC circuit - a series circuit incorporating a resistor, labeled by its resistance R , a capacitor, labeled by its capacitance C , and a switch S which will allow you to easily include or bypass a DC power supply in the circuit. You will operate your switch by changing the location of one end of a wire plug. Your data will be automatically recorded by Logger Pro using a voltage probe connected across the capacitor by clipping the probe's leads directly onto the lead wires of the capacitor.

2.1.1 See Figure 5 on page 9 for the diagram of the circuit you are to construct.

2.1.2 In this Activity, you are using the **1000 μF** capacitor. The capacitor connection with **the red identifier must be connected to the + side of the power supply**.

2.1.3 The switch is formed by a movable banana plug wire. One end of the wire stays fixed in the plug at the minus-side of the capacitor. The other end can connect to the minus-side of the power supply (when charging the capacitor), or directly to the resistor (via a simple wire connection), excluding the power supply from the circuit (for discharging the capacitor).

2.1.4 Before you proceed, have your instructor check your circuit and demonstrate how to switch from charging the capacitor to discharging the capacitor.

2.2 Connect the Voltage Probe to CH 1 on LABQUEST.

2.3 If necessary, turn on the interface and the computer.

2.4 Run Logger Pro 3, and load the file RC_Circuit.mbl. (If the *Sensor Confirmation* dialogue box appears, press the button).

2.5 Charge the capacitor as follows:

2.5.1 Adjust the voltage regulator knob on the power supply so that the max voltage across the terminals of the power supply is about 5.0V. Use the voltmeter to check the voltage.

2.5.2 Connect your switch so as to include the power supply in your circuit (see Figure 5 on page 9). Wait a minute or two, and then check that the capacitor is fully charged by clicking the Logger Pro **Collect** button. You should see a constant voltage of 5 Volts on the Logger Pro graph.

Q 1 Calculate the charge on the capacitor.

2.6 Record the voltage data for the discharging capacitor. In order to discharge the capacitor, the power supply must be removed from the circuit. This is accomplished as follows.

2.6.1 Refer to Figure 6 on page 10 for the circuit diagram showing the circuit after it has been modified to allow the capacitor to discharge.

2.6.2 Remove the switch's wire plug (free end) from the connector on the – side of the power supply (the banana plug where the black alligator clip is attached).

2.6.3 Start data collection using the **Collect** button on the screen.

2.6.4 As soon as the data collection trace becomes visible on the screen, plug the switch's wire plug into the connector (resistor side; see Figure 6 on page 10). Data will be recorded as the capacitor discharges, ending with zero voltage across the capacitor.

2.7 Save the graph you have just obtained in the following manner: From the tool bar, select **Experiment**, and then **Store Latest Run**. The graph just obtained will remain on your screen, but will appear lighter than it was.

Q 2 Describe in words the way in which voltage across the capacitor (and so also the charge on its plates) varies during the discharge process.

Q 3 You already (in Q 1) calculated the initial charge on the capacitor plates. Now use Logger Pro's Analyze-Examine tool to find the voltage 3 seconds after the discharge began, and then use $Q = CV$ to calculate the charge on the capacitor plates 3 seconds after the discharge began.

3. Activity #3: Observing the charging of a capacitor in an RC circuit

3.1 Now you are to reverse the process and monitor a charging capacitor. The idea is to convert the circuit of Figure 6 back into the circuit of Figure 5 by moving exactly one connection. Proceed as follows, referring to Figure 5 on page 9.

3.1.1 Unplug the wire from the left end of the resistor.

3.1.2 Click the **Collect** button to start data collection.

3.1.3 As soon as the trace appears on the screen, plug the same wire plug into the banana plug socket that is connected to the minus side of the power supply.

3.1.4 New data will be collected while the previous run remains faintly visible on the screen.

3.2 Print a copy of the Logger Pro graph (containing two curves) for everyone in your group.

3.3 By hand, label the discharge graph **Discharge**, and label the charging graph **Charging**.

Q 4 Describe the graph of the data for charging a capacitor. How does this graph look similar to and different from the graph obtained when discharging the capacitor?

Q 5 When the capacitor is discharging (as it did in Activity #2), where does the charge on each plate of the capacitor “go”?

4. Activity #4: Discharging different capacitors through the same resistor

4.1 In this Activity, we will compare the discharge curve of a circuit with a 1000 μF capacitor to the discharge curve of the same circuit with a 500 μF capacitor.

4.2 Following the directions in Section 2.5.2 (and refer to Figure 5 on page 9), charge the 1000 μF capacitor again.

4.3 You will discharge the capacitor by switching out the power supply as in section 2.6 (refer to Figure 6 on page 10). However, with a view to comparing the two different capacitors, use the following procedure instead of the procedure in section 2.6.

4.3.1 When the capacitor is fully charged, you may unplug the switch's wire plug, holding it ready for the next step. It is best to have one person in charge of the wire plug.

4.3.2 It is also helpful to have a second person responsible for monitoring the data collection. Have this person start data collection by clicking on the **Collect** button. When the trace on the screen reaches the 5 seconds mark, this person should say “Now”, so that the first person – the one in charge of the wire plug - can close the switch by plugging the wire into the plug connected to the resistor. See Figure 6 on page 10.

4.3.3 Save the data from this run as you did in Section 2.7.

4.4 Modify the circuit so that the 500 μF capacitor will be charged and reconnect the leads of the Voltage Probe across the new capacitor, as in Figure 7 on page 11.

4.5 While referring to Figure 7 (page 11) and Figure 8 (page 12), repeat the procedures in Sections 4.2-4.3 with the 500 μF capacitor.

- 4.6 Print out copies of the graph (containing two curves) for everyone in your group.
- 4.7 By hand, label the curve for the $1000\ \mu\text{F}$ capacitor ***1000 μF*** , and label the curve for the $500\ \mu\text{F}$ capacitor ***500 μF*** .

Q 6 Compare the two curves on your graph.

Q 7 Use $Q = CV$ and the data on the graph to calculate the charges on the two capacitors at a time 3 seconds after the discharges began.

5. When you are done ...

- 5.1 Check that all questions are answered.
- 5.2 Attach your copies of your group's ***hand labeled*** graphs (see sections 3.2-3.3 and 4.6-4.7) to this document.
- 5.3 Hand in this document and the attached graphs.
- 5.4 Turn off the power supply, the voltmeter, and LABQUEST.

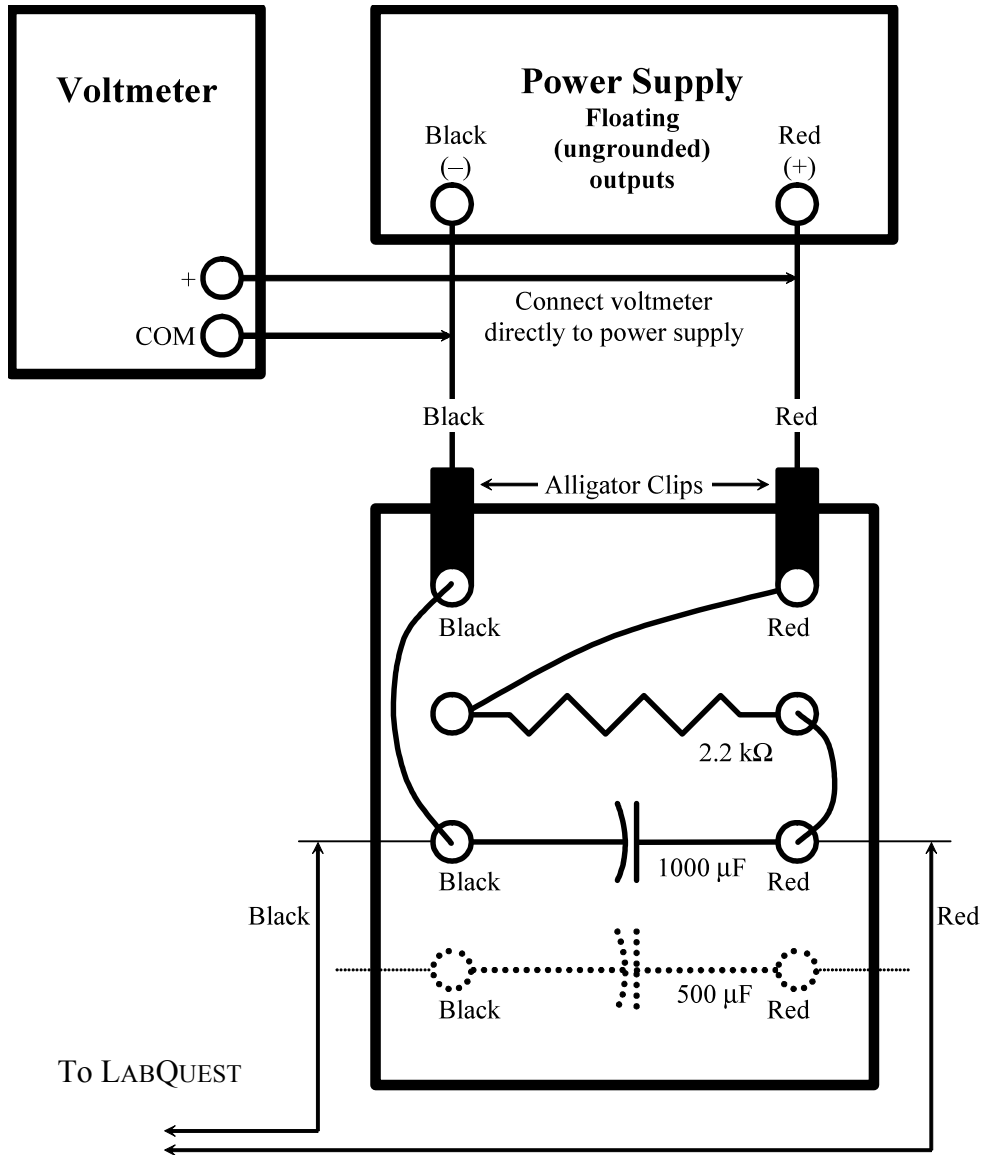


Figure 5 Circuit diagram for charging the 1000 μF capacitor through resistor R .

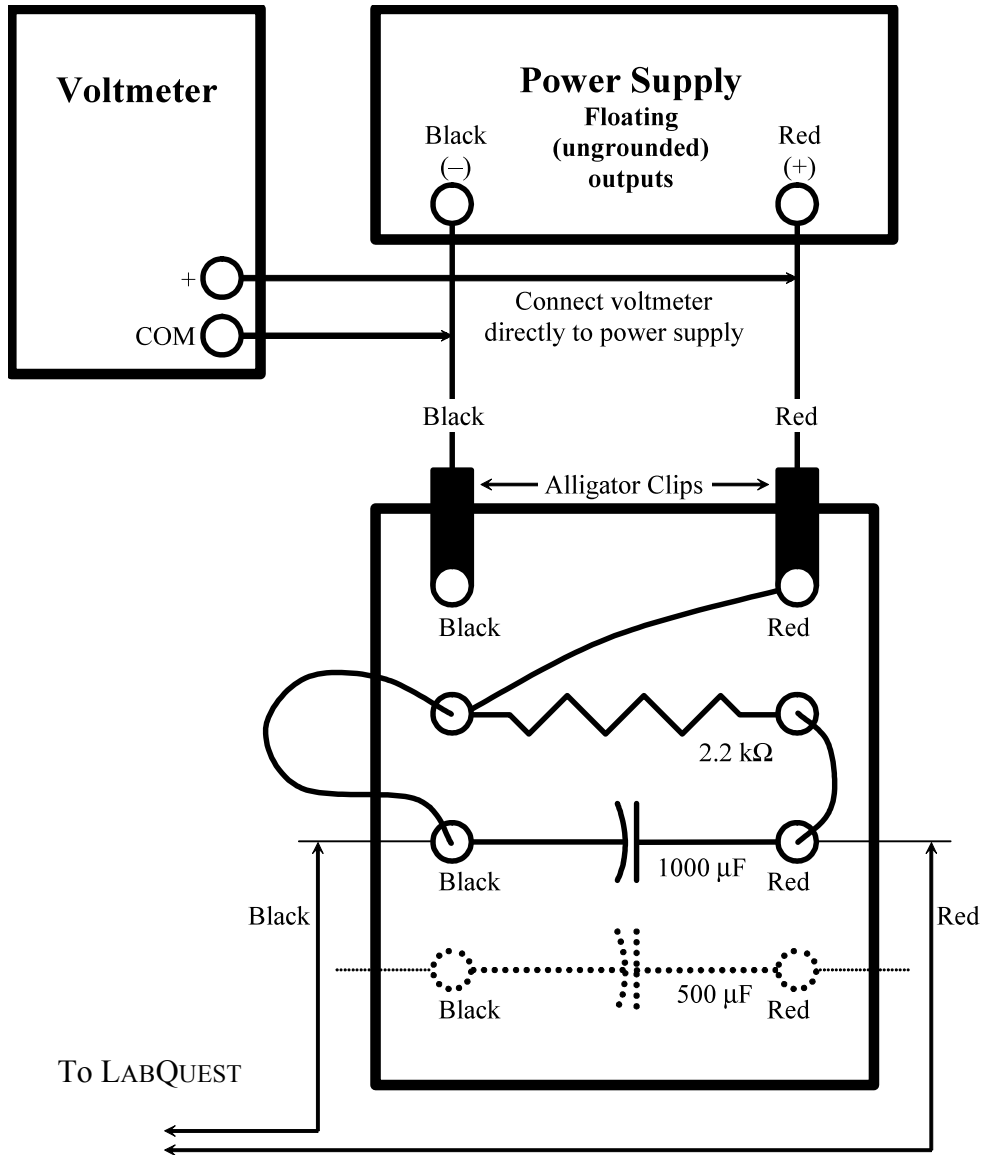


Figure 6 Circuit diagram for discharging the $1000\ \mu\text{F}$ capacitor through resistor R . Current must always flow in a closed loop, and the only closed loop in the circuit is through the resistor and back to the capacitor.

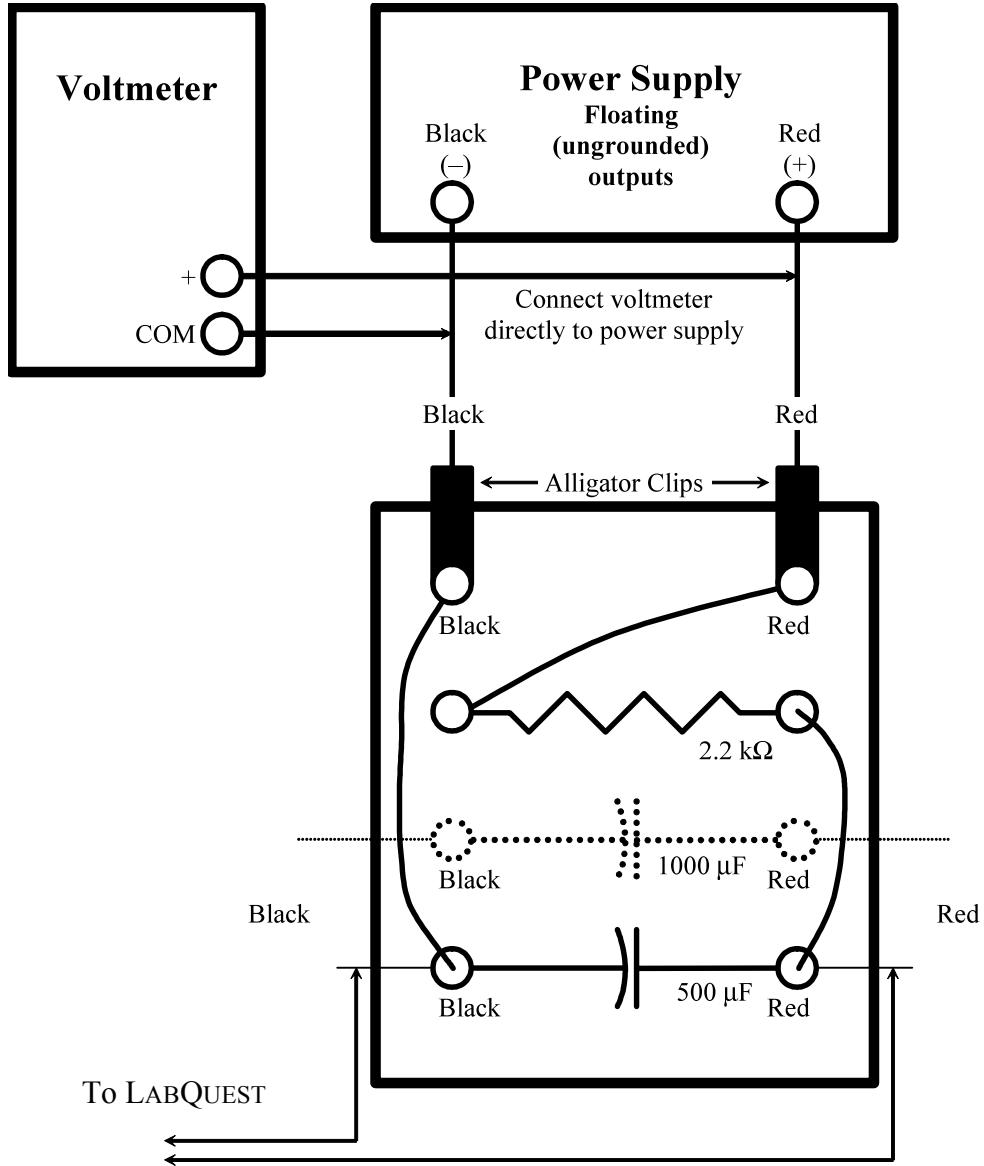


Figure 7 Circuit diagram for charging the 500 μF capacitor.

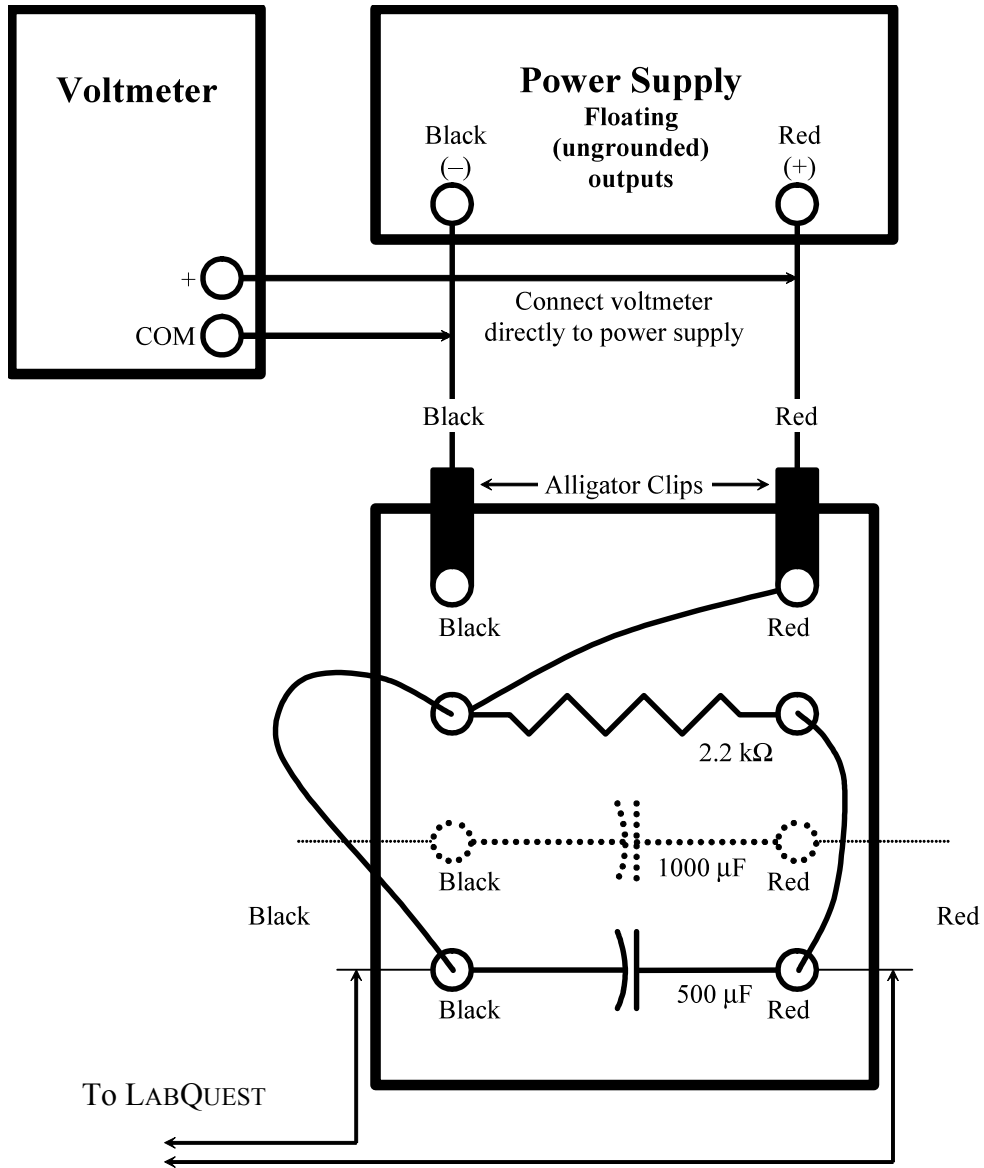


Figure 8 Circuit diagram for discharging the $500 \mu\text{F}$ capacitor through the resistor R .

Pre-Lab Questions

Print Your Name

Read the *Introduction* to this handout, and answer the following questions before you come to General Physics Lab. Write your answers directly on this page. When you enter the lab, tear off this page and hand it in.

1. A $220\ \mu\text{F}$ capacitor is charged through a $6.8\ \text{k}\Omega$ resistor by a $9\ \text{V}$ battery. Calculate the amount of charge on each plate of the capacitor when it is fully charged. Show your calculation.
2. For this question, refer to the *Ohm's Law and Electric Circuits* lab handout to see how an ammeter is included in a circuit. Then, redraw Figure 1, part (a), but with an ammeter in series with the resistor and the capacitor, so that the current flowing in the loop must pass through the ammeter.
3. Refer to the circuit you drew in answer to question 2, immediately above. When the switch is closed, the ammeter will show that current flows for a brief time. Does this mean that electrons are flowing through the layer of insulator between the capacitor plates? If you think the answer is Yes, you must explain what makes it possible for the electrons to get through the insulator. If you think the answer is No, you must explain what really is happening.
4. Refer to Figure 5 on page 9. Describe how the electrons move from the negative terminal of the power supply to the positive terminal. Name, *in order*, each circuit component the electrons pass through. For an example, see the caption to Figure 2. Recall that current always flows in closed loops.

5. Refer to Figure 6 on page 10. Describe how the electrons move through the circuit as the capacitor discharges. Name, *in order*, each circuit component the electrons pass through. For an example, see the caption to Figure 3. Recall that current always flows in closed loops.
6. A $1000\ \mu\text{F}$ capacitor discharges through a $2200\ \Omega$ resistor. Assume the capacitor initially held $5.0\ \text{mC}$ ($5\ \text{millicoulombs}$, or $0.005\ \text{C}$) of charge. Calculate the amount of charge on the capacitor at $t = 1\ \text{s}$, $2\ \text{s}$, $3\ \text{s}$, $4\ \text{s}$, and $5\ \text{s}$. Graph the initial charge and the calculated charges on the graph below. Show all calculation in the space under the graph.

