Lab 2: DC Circuits

▽ **I.** Before you come to lab...

 ▽ **A.** Read the following chapters from the text (Giancoli):

  ⊖ **1.** Chapter 25, sections 1, 2, 3, 5

  ⊖ **2.** Chapter 26, sections 1, 2, 4

 ⊖ **B.** Read through the entire lab, paying particular attention to the introduction and equipment list.

 ⊖ **C.** If you took PS2 or Physics 11a in the fall of 2006, then you have already been introduced to Logger Pro, the software used for data collection and analysis. If not, you should take some time to acquaint yourself with the software. Instructions for downloading the software and working through the tutorials can be found at:

   http://isites.harvard.edu/fs/docs/icb.topic109487.files/welcometolab.html

   If you don't have your own Mac or PC, you can use Logger Pro from any of the computers in the Science Center basement or in the lab itself.

 ⊖ **D.** Answer the questions at the end of this writeup and be prepared to turn them in at the beginning of lab. The assignment is a little bit more challenging than last time, so don't put it off until the last minute.

▽ **II.** Introduction

 ▽ **A.** Circuit basics

  ⊖ **1.** In this lab, you will be exploring the behavior of electrical components connected in circuits. The most basic thing to keep in mind is that nothing interesting will happen at all unless there is a *circuit*--that is, a closed loop where charge can flow.

  ▽ **2.** The two major concepts of circuits are current and voltage. Don't get them confused!

   ▽ **a.** *Current* (I) is the rate of flow of charge.

    ⊖ **(1)** It is measured in amperes (A), or amps for short. An amp is a coulomb per second. That is a very large current (remember how much charge 1 coulomb is!), so in practice we will often be dealing with milliamps (mA) and microamps (μA).

    ⊖ **(2)** In a simple circuit consisting of one loop, current flows continuously--every circuit element in the loop has the same current flowing "through" it.

    ⊖ **(3)** The preposition "through" is a very useful memory aid--if you think of current as something that goes through a circuit element, then it makes perfect sense that the same current also goes through the next element in the loop. It's only at junctions that current divides or combines.

   ▽ **b.** *Voltage* (ΔV or sometimes just V) is another name for potential difference, which is a quantity we have already encountered. Voltage is a measure of how much work it would take to move a charge from one place to another.

    ⊖ **(1)** It is measured in volts (also abbreviated V, which only adds to the confusion).

    ⊖ **(2)** Remember that potential is something which is a function of position. So a potential *difference* is something that depends on *two* positions, or two points on a circuit. So we will often speak in terms like "the voltage drop from A to B" or "the voltage across the resistor R"; these expressions mean "the potential at point A minus the potential at point B" and "the potential at one end of the resistor minus the potential at the other end."

    ⊖ **(3)** Voltages are considered to be "across" rather than "through" circuit elements. So if you have two resistors in a row, they do not, in general, have the same voltage across them. However, if you add up all of the changes in voltage as you go around a closed loop, you must get a total of zero when you return to your original position.

  ▽ **3.** Ohm's Law

   ⊖ **a.** In many circumstances, the current through and voltage across a circuit element are proportional to each other. That is, if you double the voltage, you would get twice the current.

   ⊖ **b.** The proportionality constant between ΔV and I is called the resistance, R. Then Ohm's Law can be stated as: $\Delta V = IR$.

This empirical fact is known as Ohm's Law.

**b.** The proportionality constant between ΔV and I is called the resistance, R. Then Ohm's Law can be stated as: ΔV = IR.

c. Resistance is measured in ohms (Ω). An ohm is a volt per ampere. Because amps are so large, resistances are often expressed in terms of kiloohms (kΩ) or megaohms (MΩ).

d. All real circuit elements have some resistance. However, when the circuit contains resistors or light bulbs, the comparatively small resistance of other circuit elements such as wires can often be neglected.

4. Series and parallel

a. Two or more devices which are in *series* are connected in the same loop. Therefore they have the same current passing through them (but not necessarily the same voltage).
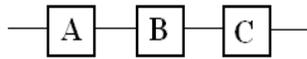
b. Two or more devices which are in *parallel* are connected independently between the same two points. Therefore they have equal voltages across them (but not necessarily the same current).
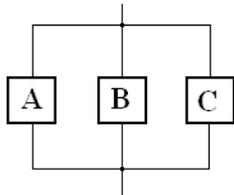

5. Power

a. The electrical power of a device is equal to the current through it multiplied by the voltage across it: P = I ΔV.

b. For resistive elements (resistors, light bulbs, heaters, etc.), the power is the rate at which electrical energy is being converted into heat or light. So we often talk about power "dissipated" in a resistor or bulb.

c. For a battery, P is the rate at which the battery is *supplying* electrical energy, which the rest of the circuit can use to do work. It is also the rate at which the chemical energy stored in the battery is being depleted.

B. Common circuit elements

1. Battery

a. A battery can be considered as a source of constant voltage. The voltage it supplies is also

called electromotive force, or emf, symbolized by $\mathcal{E}$. In circuit diagrams, a battery is represented by the following symbol:
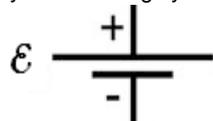
b. An ideal battery is just a voltage source; however, a real battery acts like an ideal battery in series with a small resistance, which is called the internal resistance of the battery.

c. The internal resistance of a battery is usually less than 1 Ω. However, for a "dead" battery the internal resistance goes way up.

2. Resistor

a. Resistors are just circuit elements that have resistance. They are indicated in circuit diagrams by the following symbol:

b. Resistors obey Ohm's Law, so the voltage across a resistor is always equal to the instantaneous current through it multiplied by its resistance.

c. Resistors connected in series add: Req = R1 + R2 + ...

d. Resistors connected in parallel add inversely: 1/Req = 1/R1 + 1/R2 + ...

e. The power delivered to a resistor can be calculated by $P = I \Delta V = I^2 R = \Delta V^2 / R$ (all equivalent due to Ohm's Law). This is the rate at which electrical energy is being converted to heat energy.

▼ **3.** Capacitor

a. Capacitors are circuit elements that store charge. They are represented by the following symbol:
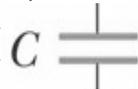
b. The voltage across a capacitor is equal to the charge stored on it divided by its capacitance, $\Delta V = Q/C$. Capacitance is measured in farads (F); 1 farad = 1 coulomb per volt.

c. To speak of the current "through" a capacitor is technically incorrect, as a capacitor consists of two non-touching conducting plates; however, everybody does it. What actually happens is that current deposits charge on one plate of the capacitor, and an equal current removes charge from the other plate at the same rate, so that the two plates always have equal and opposite charges. So it is actually quite convenient to think of it as being a single continuous current. Note that the current through a capacitor is the *rate of change* of the charge on the capacitor: $I = dQ/dt$.

d. Capacitors in parallel add: Ceq = C1 + C2 + ...

e. Capacitors in series add inversely: 1/Ceq = 1/C1 + 1/C2 + ...

f. Capacitors store energy, which means it takes energy to charge a capacitor. However, unlike with resistors, you can get the energy back and use it to do useful work (for instance, like melting a piano wire into a zillion glowing pieces). The energy stored in a capacitor is given by $U = 1/2\ C\Delta V^2 = 1/2\ Q^2/C = 1/2\ Q\Delta V$ (all equivalent). When a capacitor is charging, energy is being put into it; when discharging, energy is being taken out of it and can be used elsewhere. So the electrical power consumed by a capacitor can be positive or negative.

▼ **4.** Wire

a. A wire is the simplest possible circuit element. It is just a conductor which connects two points, so that they are maintained at the same potential. A wire is represented by a straight line on a circuit diagram.

b. A wire can be thought of as a resistor with a resistance of 0 ohms.

▼ **5.** Voltmeter

a. A voltmeter is a device used to measure the potential difference between two points in a circuit. Most commonly, it measures the voltage *across* a single circuit element, such as a resistor.

b. To measure a voltage, connect the voltmeter in *parallel* across the device you are interested in knowing the voltage across. (Remember, parallel devices share the same voltage difference.) Putting the voltmeter in series with your circuit will cause the circuit itself to be drastically altered, and will give you meaningless results.

c. A voltmeter basically acts like a very large resistor, usually on the order of megaohms. The larger the resistance, the less the voltmeter affects the circuit, because it is in parallel and parallel resistances add in *inverse*.

d. You will be using two different devices as voltmeters in this lab. Both the digital multimeter and

▼ **C.** RC circuits

1. Circuits containing a resistor and capacitor are called RC circuits. They were discussed at great length in lecture and in section 26-4 of the text. We will not go over all the details, but here are the

the differential voltage probe act like 10 MΩ resistors when placed in parallel with a circuit.

▼ **C.** RC circuits

⊖ **1.** Circuits containing a resistor and capacitor are called RC circuits. They were discussed at great length in lecture and in section 26-4 of the text. We will not go over all the details, but here are the most important results.

⊖ **2.** RC circuits have a time dependence--that is, they are not static circuits. The main behavior is that they asymptotically approach a steady-state limit in which all voltages remain constant and all currents go to zero. (Remember, a non-zero capacitor current means that the charge--and therefore the voltage--on the capacitor is *changing*.)

⊖ **3.** The difference between any voltage and its final steady-state value decreases exponentially with time; that is, it is proportional to $\exp(-t/\tau)$, where τ (the greek letter tau) is called the *time constant*. In a circuit with capacitance C and resistance R, the numerical value of τ is equal to R times C. If R is in ohms and C in farads, then the product RC has units of seconds. ($1\ \Omega = 1$ V/A; 1 F $= 1$ C/V; so $1\ \Omega \cdot$ F $= 1$ C/A $= 1$ s.)

⊖ **4.** The fact that all currents go to zero in the final steady state makes it easy to determine the final values of all of the voltages. Resistors cannot have a voltage across them without a current, so resistor voltages must be zero.

▼ **III.** Materials

▼ **A.** Digital multimeter

⊖ **1.** The multimeter is the tool you will be using to measure voltages. There are several settings on the dial; the one you will be using is the setting that says V with a pair of straight lines (not V with a wavy line, which is used to measure oscillating voltages).

⊖ **2.** Depending on the model of multimeter, you may also have to set the range of the instrument. You should always use the lowest (most sensitive) setting which is still larger than the voltage you are measuring. In this lab, the 2-volt setting should be suitable for your purposes.

⊖ **3.** The multimeter probes must both be in contact with something in order to get a reading. The digital readout will indicate *the voltage of the red probe minus the voltage of the black probe*.

⊖ **4.** This is a general convention for electric components: red terminals and leads are considered "positive" and black ones "negative." For a meter, nothing bad will happen if you reverse the two-- you will just get a negative reading if you put the red probe at a lower voltage than the black probe.

▼ **B.** RC circuit board

⊖ **1.** This is a board wired with the following circuit:
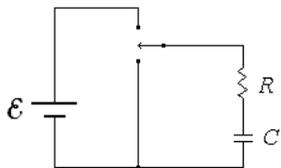
⊖ **2.** When the switch is in the up position, the battery is included in the circuit to charge the capacitor. When the switch is in the down position, the capacitor discharges through the resistor. When the switch is in between, no current flows and any charge on the capacitor remains there.

⊖ **3.** The values of the components on the board are:

R = 30 kΩ

C = 1 μF

The battery is a standard 1.5-volt AA cell battery.

▼ **C.** LabPro interface with differential voltage probe

⊖ **1.** The differential voltage probe is basically just a voltmeter. Like the multimeter, it measures the potential at the red probe minus the potential at the black probe.

⊖ **2.** However, the Logger Pro software allows you to collect voltage data automatically. In particular, you can ask it to measure the voltage every few milliseconds and then display the voltage as a

▼ **D.** Selection of resistors

function of time. This capability will enable you to study RC circuits, where the voltages are changing in time.

▼ **D.** Selection of resistors

⊖ **1.** The resistance of a resistor is indicated by the set of four colored stripes on the resistor. The first two bands taken together indicate the first two digits of the resistance, the third band is the multiplier (power of ten), and the fourth band is the tolerance.

Color Coding for Resistors			
Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
Colorless			20%

⊖ **2.** So for example, the following resistor has a resistance of 26 (red-blue) times 10^5 (green), within a tolerance of 5% (gold). So its resistance is 2.6 MΩ, give or take 5%.

⊖ **3.** If you are not sure which end to start from, most resistors have a gold or silver band as their fourth band to indicate tolerance.

▼ **IV.** Procedure

▼ **A.** Before you begin...

⊖ **1.** Take a picture of yourselves using Photo Booth. Drag the photo into the space below:

⊖ **2.** Tell us your names!

▼ **B.** Charging and discharging of a capacitor

⊖ **1.** Open the Logger Pro file Lab2.cmbl. The file has been set up for you so that you should be ready to collect data. When you click on the [▶] Collect button, it will collect data for 5 seconds and

⊖ **2.** Familiarize yourselves with the RC circuit board. Make sure you know which switch position does what (and which component is the resistor and which is the capacitor!). Note that if you charge the capacitor, *it remains charged*, even after you disconnect the battery, until you allow it to discharge.

then automatically stop. Do not press the stop button while it is collecting.

2. Familiarize yourselves with the RC circuit board. Make sure you know which switch position does what (and which component is the resistor and which is the capacitor!). Note that if you charge the capacitor, *it remains charged*, even after you disconnect the battery, until you allow it to discharge.

3. Start with the capacitor fully discharged. Connect the clip leads of the differential voltage probe across the capacitor and click on Collect. When you see the message "Waiting for data," throw the switch into the charging position.

4. What results do you see? Is it what you expected? Try zooming in on the interesting regions of the graph. The easiest way to do this is by clicking and dragging to define a rectangle that you want to zoom in on, and then clicking on the ⊕ zoom in button.

    a. Try to determine the time constant of the circuit based on your graph by fitting the appropriate function to it. (You will need to select only the region you want to fit; do this by clicking and dragging on the graph to define the time interval you are interested in.) When you have done so, paste a copy of your graph here:

    b. What is the time constant? What is the uncertainty in your determination of the time constant? Is your measurement consistent with the stated component values for R and C?

5. When you have finished your analysis of the charging capacitor, store the data you have collected by pressing apple-L in Logger Pro. This will enable you to collect more data without clobbering your existing data. The old data is now in a data set named Run 1; new collected data goes into the data set named Latest. If you like, you can hide Run 1 so that it won't be cluttering your screen for the next part.

6. With the capacitor fully charged, press collect and then when it says "Waiting for data," throw the switch to the discharging position.

    a. You might notice a weird behavior here: when the capacitor is charged and the switch is in the neutral (neither charging nor discharging) position, the capacitor voltage seems to very slowly decrease over time. This is because of the voltmeter itself--remember, it acts like a 10 MΩ resistor connected across the capacitor. So even when the rest of the circuit is disconnected, the capacitor can discharge through this large resistor. What is the time constant for this discharging?

    b. To minimize any error caused by this slow discharge, keep the switch in the charging position until you are ready to throw it into the discharging position. It's okay if the voltage goes down a little bit before the discharging begins; the only difference is that it is as if the initial charge on the capacitor were somewhat lower.

7. As you did before, try to fit an appropriate function to the discharging curve.

    a. Paste your graph here:

    b. What is the time constant? Is it the same as it was for charging?

8. Store your data run for the discharging capacitor (it will be named Run 2) and save your Logger Pro file.

C. Black box exercises

  1. General instructions

    a. In this part of the lab, you will attempt to determine the contents of a black box containing electrical components. You will do so not by opening the box and looking inside, but by connecting various circuits to the exposed terminals of the box and performing intelligently-designed experiments.

    b.

      (1) A 1.5-volt battery

      (2) A selection of resistors of different values

        A digital voltmeter

b. The tools you will be allowed to use to investigate the behavior of the box are:

- **(1)** A 1.5-volt battery
- **(2)** A selection of resistors of different values
- **(3)** A digital voltmeter
- **(4)** LabPro interface with differential voltage probe and the Logger Pro software

c. Note that the only measurements you will be able to make are *voltage* measurements. You cannot make direct measurements of current, resistance, or capacitance. However, if you are clever, you can figure everything out this way. For instance, if you measure the voltage across a known resistor, you can calculate the current through it using Ohm's Law.

d. You may connect these components to the black box in any configuration you like. However, we recommend the following:

Circuit 1   Circuit 2   Circuit 3

$\mathcal{E}$ R $\mathcal{E}$ R
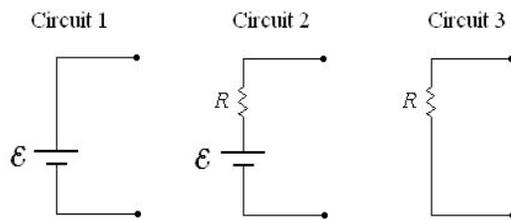
(Note that circuit 3 won't be very interesting unless the black box itself contains a voltage source or an already-charged capacitor.)

e. For any circuit you choose to connect, you will also have to decide which voltages to measure. You may use the voltmeter, the differential voltage probe, or both to make voltage measurements.

f. These experiments are designed to be challenging but fun. If you get stuck or find yourselves going around in circles, please don't hesitate to ask a TF for help! Your lab TFs are smart people who are experienced at working with circuits. They can provide you with useful hints.

g. Good luck and have fun!

2. Resistor network black box

a. This box is the one with three terminals, labeled A, B and C. It contains three resistors of unknown resistances, arranged in an unknown fashion. Your task is to determine the layout of the resistors inside the box, and determine the values of the three resistances.

b. Record here which measurements you made. Be specific: for example, you could say, "we connected circuit 1 between terminals A and C and measured the voltage across AB" or "we connected circuit 2 with R = 1 kΩ between A and B and measured the voltage across R." Note that there are several different measurements you could make for each circuit. If you use circuit 2 or 3, be sure to specify which resistor value you used for R.

- **(1)**
- **(2)**
- **(3)**

c. What are the resistor values? How are they arranged? How did you determine them?

d. Is your solution unique? That is, is there another possible arrangement that would produce the same results for all of the measurements you made? (This part is hard, so don't spend too much time on it if you can't figure it out.)

3. RC black box

a. This box contains a resistor and capacitor in series, connected between the two terminals of the box. There are only two terminals. Your task is to determine the values of the R and C inside the box.

b. It's not as easy as it sounds. In particular, you may be stymied by the fact that you cannot measure the voltage across just the capacitor--only the capacitor and resistor taken together.

c. Remember that if you charge the capacitor and then disconnect the circuit, the capacitor will stay charged. To discharge it, short the two terminals of the box together briefly using a wire.

You will have to think of a creative way around this.

c. Remember that if you charge the capacitor and then disconnect the circuit, the capacitor will stay charged. To discharge it, short the two terminals of the box together briefly using a wire.

d. Record here which measurements you made. Also be sure to paste any graphs which are relevant to your calculations.

(1)

(2)

(3)

e. What is the value of R?

What is the value of C?

How did you determine them?

4. Voltage source black box

a. This part is slightly different. The third black box contains a "battery" which consists of a voltage source and a small-but-not-tiny "internal resistance." The battery is oriented so that terminal A is at a higher potential than terminal B. Your task is to determine the value of both the emf E and the internal resistance r.

b. Because the box already contains a battery, we ask you not to use circuit 1 or circuit 2. You can do everything using circuit 3. However, you will need to use several different resistors in order to determine E and r. (See pre-lab question B, below.)

c. Record your measurements here:

(1)

(2)

(3)

(4)

(5)

d. The analysis for this part is actually rather subtle and may take you somewhat longer than the amount of time you have in the lab. So the determination of E and r is actually a take-home activity that will be submitted with your homework next week. If you finish it while you are still in lab, so much the better. If not, finish it up at home--just be sure you have collected all the necessary data while you are here in lab.

e. The analysis involves a determination of whether your data fits an equation with unknown parameters, and then calculating what those unknown parameters might be.

(1) The equation is derived in pre-lab question B; fitting your data to it is another matter altogether.

(2) Hint: you want to rewrite the equation so that it is the equation of a straight line. You will not be able to do this if you stick to R and V as your independent and dependent variables, but look what happens if you take the reciprocal of your equation.

(3) The great part about fitting data to a straight line is that it's easy to see whether it fits. Not only that, fitting data to a line gives you two independent parameters: the slope and the intercept. Your equation has two unknowns: E and r. Hmm...

(4) You can use the data analysis features of Logger Pro to help you on this part. Just turn to page 2 of the file Lab2.cmbl and enter your data there.

f. If you finish while you are still in the lab, put your results along with any graphs you used here:

(1) E =

(2) r =

(3)

V. Conclusion

A. You've reached the end of the lab. Congratulations!

B. Save your work in this file and in Logger Pro.

C. Submit the electronic copy of your lab report as you did for Lab 1. The instructions for doing so are on a laminated sheet by each computer. There are two differences this time:

1.

2. After you create the folder Lab2 in your Sites folder. copy the Logger Pro file Lab2.cmbl into the Lab2 folder. Then go ahead with the Export to HTML from NoteBook. That way, both your NoteBook file and your Logger Pro data will be on the server; if you need to work on the last part

1. Obviously, this lab report should go in a folder called Lab2, not Lab1.

2. After you create the folder Lab2 in your Sites folder. copy the Logger Pro file Lab2.cmbl into the Lab2 folder. Then go ahead with the Export to HTML from NoteBook. That way, both your NoteBook file and your Logger Pro data will be on the server; if you need to work on the last part later in the week, you'll be able to download everything yourself.

▼ **VI.** Pre-lab assignment.

Answer the following questions on a separate sheet of paper *before* coming to lab. Remember to write your name and lab time on the sheet.

▼ **A.** Consider the resistor network shown below.

$$1200\ \Omega$$

A MWB C
$$1200\ \Omega$$
$$1200\ \Omega$$
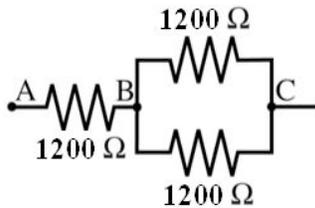
An external voltage of 9.0 V is applied from A to C. Calculate:

1. the current through each resistor

2. the voltage drop across each resistor

3. the power consumption of each resistor

▼ **B.** Answer the following questions about the circuit diagrammed below.

Ideal Voltage Source → $\mathcal{E}$

Internal Resistance → r

Real Voltage Source

R
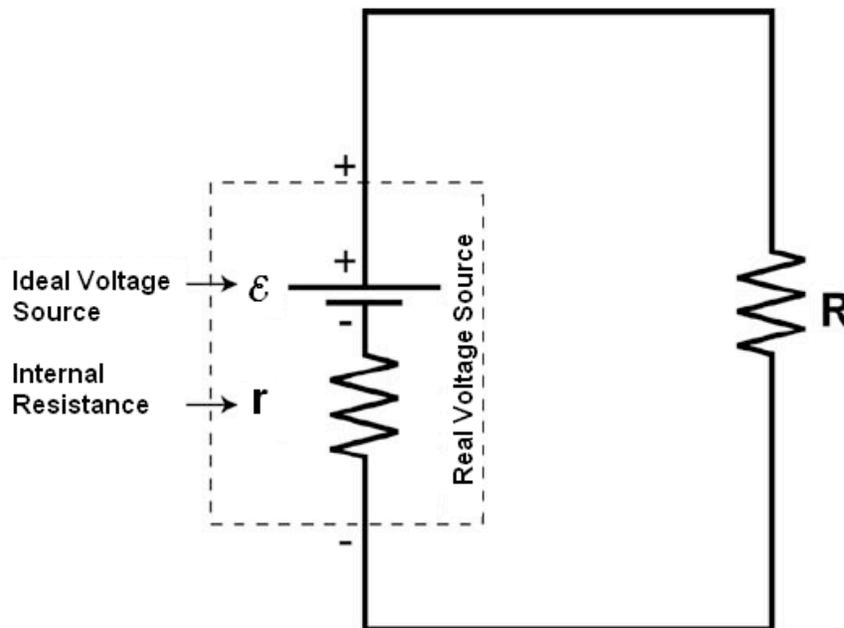
1.
Calculate the voltage drop across the resistor R, in terms of $\mathcal{E}$, r, and R.

2.
Suppose you could choose which value of R to put in your circuit. For what value(s) of R would the voltage drop across R be maximized? Minimized?

3.
Suppose you are asked to experimentally determine the unknown values of $\mathcal{E}$ and r by measuring the voltage drop across R for different values of R. How many different R values would you need to

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use to determine both $\mathcal{E}$ and r? Would it improve your results to take more data points than this?

▼ **C.**

Consider a capacitor which initially has stored charge Q. It is then connected in the circuit diagrammed below. At time t = 0, the switch S is closed and the capacitor begins to discharge. Answer the following questions.
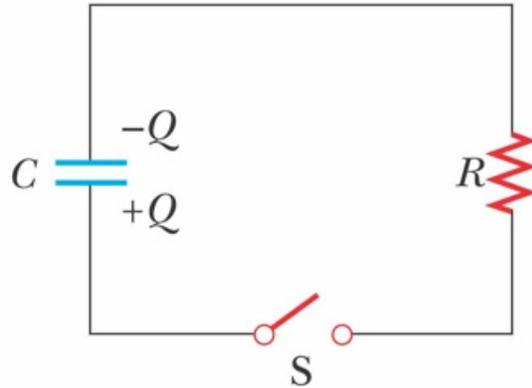
▼ **1.** What is the voltage drop across the capacitor...
  ⊖ **a.** before the switch is closed?
  ⊖ **b.** immediately after the switch is closed?
  ⊖ **c.** a long time after the switch is closed?
▼ **2.** What is the voltage drop across the resistor...
  ⊖ **a.** before the switch is closed?
  ⊖ **b.** immediately after the switch is closed?
  ⊖ **c.** a long time after the switch is closed?
▼ **3.** Suppose you added a resistor of resistance 2R in series with the existing resistor. How would the following quantities be different?
  ⊖ **a.** the final voltage across the capacitor
  ⊖ **b.** the time constant