PRINCETON UNIVERSITY   **PHYSICS 104 LAB**
Physics Department   Week #3

EXPERIMENT III
RESISTORS, CAPACITORS, DC CIRCUITS, AND RC CIRCUITS

Introduction. Electronic circuits are important to nearly all science and technology, not to mention to your everyday life (just image living without television and computers). This lab is designed to help you understand two of the basic components of all electronic circuits, the resistor and the capacitor. You will also be exposed to "breadboarding": the practice of testing circuits by constructing trial versions on some sort of board or jig.

The following table shows the symbols used in schematic diagrams for these components, as well as those for voltmeters, ammeters, and ground.

Name	Symbol	Function
Resistors	—⌇⌇—	Impede the flow of charge through a circuit. Metal wires provide very little *resistance*, carbon or thin metal films can provide a lot of resistance.
Capacitors	⊣⊢	Store charge.
Battery	⊣|⊢	Charge (current) and potential difference are usually supplied by a battery or its electronic equivalent, a power supply. For DC (direct current) circuits these sources have a polarity. Be careful to observe the polarity, especially when connecting voltmeters and ammeters.
Voltmeters	—(V)—	Measure the potential difference (in Volts) between two points in a circuit or across a component, like a resistor. *Good voltmeters have a very large internal resistance, and are put in parallel with the circuit element across which you want to measure the voltage.*
Ammeters	—(A)—	Measure the current flowing through them. That means that you must break the circuit and insert the ammeter where you want to measure the current. *Good ammeters have a very small internal resistance and are placed in series with the element the current through which you want to measure.* **Use extreme caution when using the ammeter, if used improperly it will be damaged**.
Ground	⏚	Most circuits have a common or a ground conductor which acts as the zero reference for potential measurements (like the arbitrary choice of $r = \infty$ as the reference for gravitational potential energy). Usually the negative side of the power supply is connected to *ground;* this point may or may not be connected to the Earth.

Voltmeters, ammeters, and electrolytic capacitors have a specified polarity, indicating which lead is to be connected electrically closer to the positive end of the power supply. Electrolytic capacitors provide large capacitance in a very small space by using a special polarized dielectric. Such capacitors connected the wrong way will often explode, sometimes spewing pink smoke. *Get the polarity right before you put them into a circuit.* The breadboard (described on p. 5)

allows you to make electrical connections without soldering. Be careful when pushing wires into the sockets; don't force them or you will damage the clips in the breadboards.

Measurements. Construct the following circuits with resistors and the power supply on your breadboard. Measure the current through, and the voltage across, each circuit element. Unless otherwise noted, also calculate the voltages and currents by using the resistor color-code values (see below) and the power supply voltage that you measured with your voltmeter. Sketch the circuits in your notebook and show the values that you measure and that you calculate. Explain in your own words what is going on in the circuit. Use graphs and tables when appropriate. (Note: When you do need the actual tolerances, they are: $\pm$ 1% for resistors, and $\pm$ 0.3% for the multi-meter.)

Compared to Labs 1 and 2, the electric fields and voltages in Lab 3 are small, but the charges and currents are large. The underlying physical principles are the same.

1. Resistors in Series: A Voltage Divider. The circuit is shown in the schematic diagram on the right. Construct it using resistors of a few thousand Ohms (a few kΩ). Measure voltages across and currents through all components. Explain your results in your own words. Compare your measured values to those you calculate using circuit equations.
- Do the component tolerances explain the differences between your calculated and measured values?
- Why is the arrangement called a "Voltage Divider"?
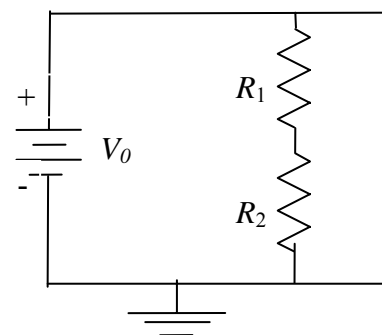
2. Unknown Resistor. There is an "unknown" resistor in your tray. Measure its resistance. Explain your method by drawing the circuit diagram of the set-up you used. Using the tolerances given above, assign a tolerance to the value you measured.

3. Resistors in Parallel: a Current Divider. The schematic on the right shows a parallel circuit that can be called a "current divider". Construct it using resistors of a few kΩ. You may use resistors of the same value or of different values. Again, measure the voltages across and currents through each circuit element and compare them to values you calculate using circuit equations.
- How close are the measured values to the calculated values?
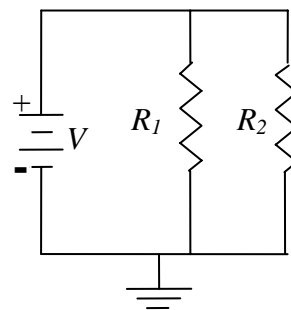
4. Capacitor Discharge. The schematic on the next page shows a circuit that lets you see how a capacitor and a resistor can be used to mark time. This is a more controlled version of the measurement you made last week when you used the electrometer as a capacitor (which was also the voltmeter) and a very large resistance to ground. When the switch is closed, some of the current from the power supply charges capacitor C. Then, when the switch is opened the capacitor discharges through resistor R. As discussed in Lab 2, you should observe an exponential decay of the voltage, $V(t) = V_0\,e^{-t/RC}$, with *time constant RC* (in seconds) that you should deduce.

To follow the discharge on the voltmeter, the time constant should be large. Use a large resistor, $10^6\Omega$ (1 MΩ) and a very large capacitor, 22×10^{-6}F (or 22μF). This is an **electrolytic** capacitor, **so make sure that you connect the + side of the power supply to the + side of the capacitor.**
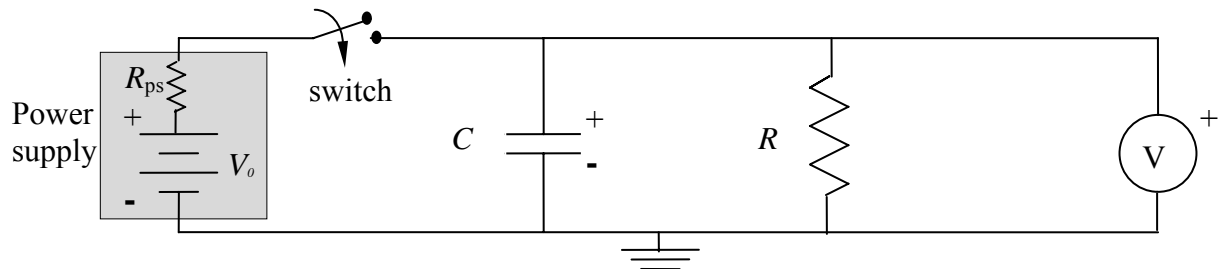
Measure the voltage across the capacitor as a function of time after the switch is opened. (Note: It is not enough merely to switch off the power supply, because the power supply then remains as an element in the circuit.)

- Make a plot of $\ln(V/V_0)$ vs. t or (V/V_0) vs. t, using semi-log paper.
- Estimate your errors and show them as error bars in the plot. Draw a "best fit" straight line.
- Deduce a value (and uncertainty) for the time constant, based on the slope of the line. One way to estimate the uncertainty is to plot the line with the largest slope that is just barely acceptable according to the error bars, and the line with the smallest slope that is just barely acceptable according to your error bars (refer to p. 4 of the Lab 1 manual), in addition to the "best fit" line.
- Does the time constant equal the product RC of the values of the resistance and capacitance? Electrolytic capacitors typically have $\pm 20\%$ tolerances.

5. Capacitors in Parallel. The figure below shows a scheme for measuring the capacity of an unknown capacitance. Use a 1μF capacitor for the known capacitor (C). Make sure that the unknown capacitor (X) is fully discharged before you start; you should do this by touching a wire simultaneously to both of the capacitor legs ("shorting" the capacitor). It is not sufficient to use your fingers to short the capacitor; the time constant $R_{you}C$ is too long. Connect the switch to the power supply so as to charge the known capacitor, and read the voltage on the voltmeter. This is the voltage to which the known capacitor is charged up. Then connect the switch to capacitor X, so as to place it in parallel with capacitor C, which causes the two capacitors to share the charge that was initially on capacitor C. Quickly read the voltage again. Deduce the capacity of X (in μF) via an appropriate application of the general rule that $Q = CV$.
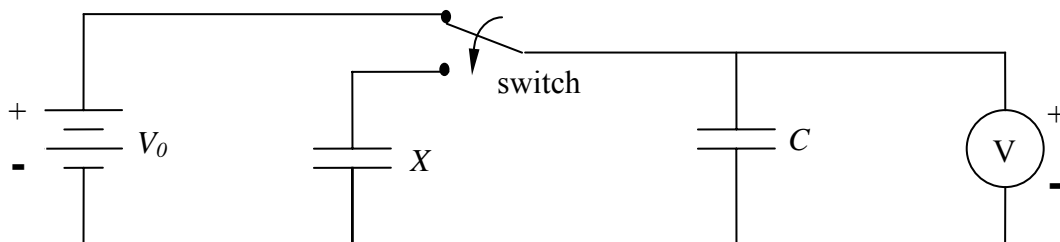

The voltmeter has a large but finite internal resistance. As a consequence the voltmeter discharges the capacitors slowly, which will cause an uncertainty in your determination of capacitance X if you wait too long to read the voltmeter. Deduce the value of the internal resistance of the voltmeter by observing the time dependence of the voltage across capacitors C and X.

All the above experiments and write-ups should be completed before proceeding.

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Optional Experiments. If you are already acquainted with DC circuits, the measurements suggested in the previous pages may have gone quickly. Here are some additional experiments that you can do if you have time. Be sure to write up your earlier work before starting on these extra experiments.

6. Loops. Ph104 Learning Guide 3, Problem IX involves two loops. A similar circuit is shown below. In order to use available lab components, we have multiplied the resistances of Prob. IX by 10^3 and divided the voltages by 2. This causes the currents in your experiment to be smaller by a factor of 1/2000 than the values in the LG problem. Construct the circuit and measure the three currents I_1, I_2, I_3, including their signs. Measure the potential difference between points b and c. As always, **be cautious** when changing between current and voltage measurements. Don't "blow out" a meter!
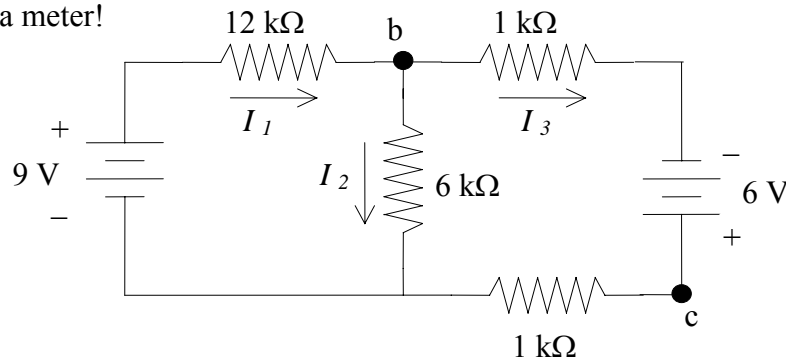
7. Resistor Cube. Twelve identical resistors are connected together to form a cube. Each resistor R is an edge of a cube. Measure the resistance of the network between two adjacent corners of the cube (such as between points 1 and 2), either directly with your multimeter used as an ohm-meter, or by measuring the currents in one of the leads when a power supply of known voltage is connected to those leads. Also measure the resistance of the cube when the leads are connected to points 1 and 3, and to points 1 and 7.

Calculation of the resistance in these three cases is challenging.

Perhaps the easiest calculation is when the leads are connected to points 1 and 7.   Then the current that flows into point 1 splits in 3 equal parts, going to points 2, 4 and 5. And, these 3 currents are also equal to the 3 currents that flow into point 7. Further, the current that flows into point 4 splits evenly at it goes to points 3 and 8, *etc*.   So, by summing the voltage drops along, say, the path 1-4-3-7 you can find $V_{tot} = I\,R_{eff}$. Or, note that $V_2 = V_4 = V_5$ and $V_3 = V_6 = V_8$, $\Rightarrow$ resistors 1-2, 1-4 and 1-5 are in parallel, as are 2-3, 2-6, 3-4, 4-8, 5-6 and 5-8, and also 3-7, 6-7 and 7-8, $\Rightarrow$ series circuit with $R/3$, $R/6$, and $R/3$.
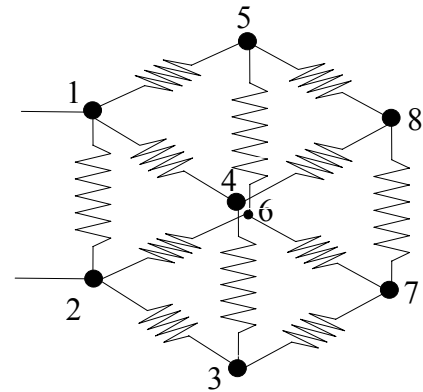

If the leads are connected to points 1 and 3, note that $V_2 = V_4 = V/2 = V_6 = V_8$. Thus, resistors 1-2 and 1-4 are in parallel and can be replaced by a single resistor of value $R/2$. Likewise, 2-3 and 3-4 merge into one with $R/2$, 5-6 and 5-8 merge into one with $R/2$, and 6-7 and 7-8 merge into one with $R/2$. Now it is "straightforward" to finish the analysis.

Similarly, the case where the leads are connected to points 1 and 2 can be analyzed by noting that $V_3 = V_6$ and $V_4 = V_5$. Hence, resistors 1-4 and 1-5 merge into one with $R/2$, as do 3-4 and 5-6, 5-8 and 4-8, 2-3 and 2-6, and 3-7 and 6-7. It's now "easy" to complete the calculation.

The Breadboard

A breadboard allows convenient plug-in of electronic components and quick circuit assembly. In order to use the breadboard you must understand how its holes are connected internally.

The breadboard has a rectangular field of square holes, as shown in the photo below. Wires or leads from electronic components plug into these holes, and each hole is designed to hold one wire or lead firmly. The holes are metal-lined, and connected together in groups, so inserting a lead into a hole means connecting that lead to a set of holes.
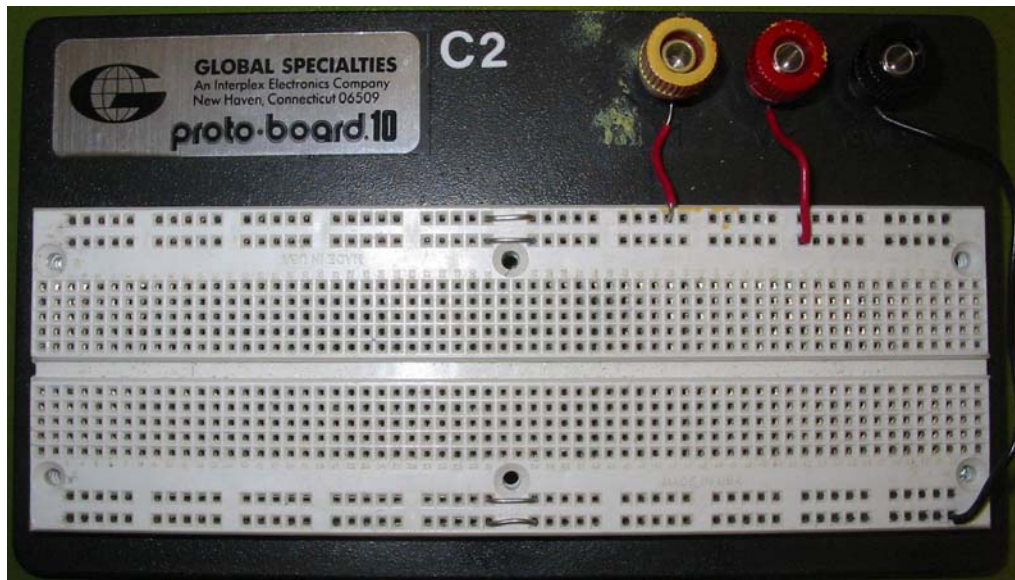
Circuit components can be quickly connected together electrically by pushing their leads into adjacent holes of a connected set.   The connections are on the bottom of the board, as shown in the photo below:

Thus, the entire top row of holes is interconnected, as are the other 3 horizontal rows as well. Similarly, each vertical group of 5 holes is connected together.
The 3 binding posts in the upper right can be used to establish a ground and two voltages along 3 of the horizontal rows, using jumper wires as shown in the upper photo.

Resistor Color Code

Most resistors are not marked with a printed number but have a series of colored bands that indicate their value. The resistors you will be using throughout the semester are **metal-film** resistors. On metal-film resistors the first 4 bands, starting with the band nearest one end, indicate the value. The first three bands indicate the value of the resistor, as digits, and the fourth band indicates the value as a multiplier. Such resistors have a tolerance of $\pm$ 1%, which means that a particular resistor's value should be within 1% of the value indicated on its label.

Lower precision resistors common in electronics are *carbon resistors*. In these resistors there are four bands indicating the value of the resistor and its tolerance. The first 3 bands indicate the nominal value; the first two indicate the value, as digits, and the third as multiplier. The fourth band on carbon resistors indicates the tolerance; $\pm$ 10% for a silver band, and $\pm$ 5% for a gold band.

Colors	as digit	as multiplier
black	0	x 1 = 10^0
brown	1	x 10 = 10^1
red	2	x 100 = 10^2
orange	3	x 1000 (1k) = 10^3
yellow	4	x 10k = 10^4
green	5	x 100k = 10^5
blue	6	x 1000k (1M) = 10^6
violet	7	
gray	8	
white	9	

Example for ordinary resistors :   green, brown, red is 5100 ohms.
Example for metal-film resistors: brown, black, black, red is 10K ohms.
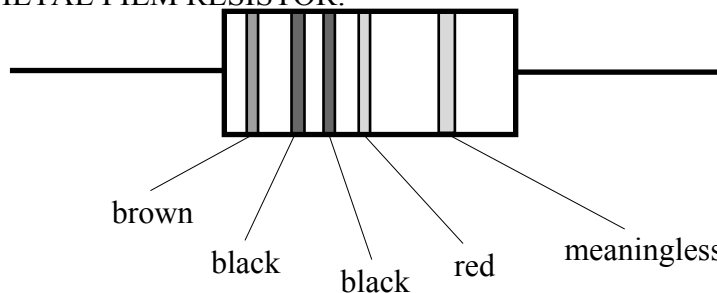
Manufacturer indicators of tolerance:

No band	$\pm$ 20%
Silver band	$\pm$ 10%
Gold band	$\pm$ 5 %
metal film resistors	$\pm$ 1 %

EXAMPLE OF METAL FILM RESISTOR:

brown
black
black
red
meaningless

VALUE : 1 0 0 x 10^2 = 10,000 ohms or 10 kilo ohms (usually written "10 kΩ").

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Name:_____   **Date/Time of Lab:**_____

EXPERIMENT III   PRELAB PROBLEM SET

1. This problem is an exercise in wiring breadboards. You are given a schematic diagram and a drawing of a portion of a breadboard. "Make" the circuits as you would in the lab by drawing the circuit components on the breadboards. Draw the circuit components as you would make the circuits in the lab, do not draw them like the schematic. Use the circuit elements as drawn below; use straight lines for wires; Ⓐ and Ⓥ for voltmeters and ammeters; and ⓟⓢ for power supplies.

The breadboard interconnections are shown in the breadboard drawing. The squares that have lines going through them are electrically connected together. Remember that you can only put one wire in each square as you would on the real breadboard. The component values in each circuit are not important.
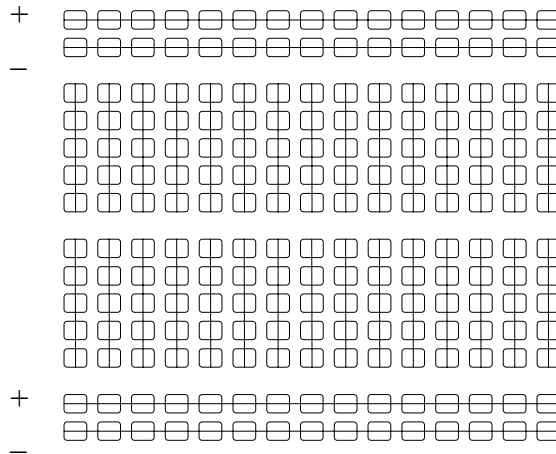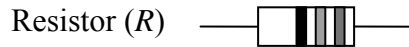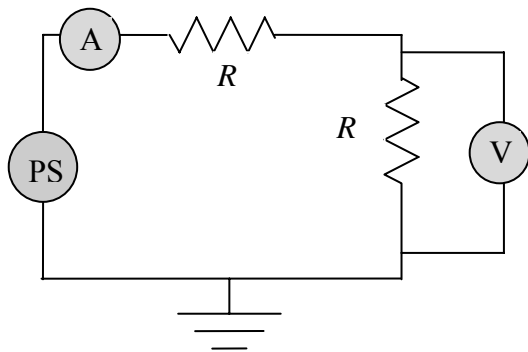
2. Given an ammeter, a voltmeter, a battery and an unknown resistor, draw the schematic of a circuit you would use to measure the resistance of the unknown resistor. What is the resistance, in terms of the measurements?

Refer to p. 1 of the writeup for the symbols you need to draw the circuit.

3. Confirm the statement that "the unit of the product RC is seconds", where R is a resistance and C is a capacitance. Note the definition of 1 Farad as one Coulomb per Volt, and consider resistance as defined by Ohm's Law.

4. The timescales of RC are often quite short, which is why we will use the unusually large 22 µF capacitor in this lab. A more "typical" capacitor (used later this semester in the amplifier and AM radio labs) has $C = 0.01$ µF. What is the "RC-time" for this capacitor when it is discharged across a 30 kΩ resistor?