**University of Utah**
**Electrical & Computer Engineering Department**
ECE 2210/2200 Lab 5
# Capacitors

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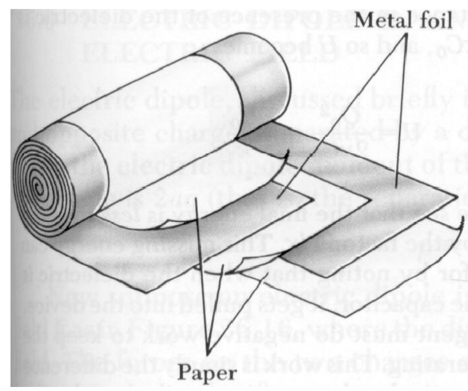
## Objectives
1.) Observe charging and discharging of a capacitor.
2.) Measure the time constant of an RC circuit.
3.) Observe and measure the frequency dependence of capacitor impedance.
4.) Observe the phase relationship of AC voltages and confirm KVL for these voltages.

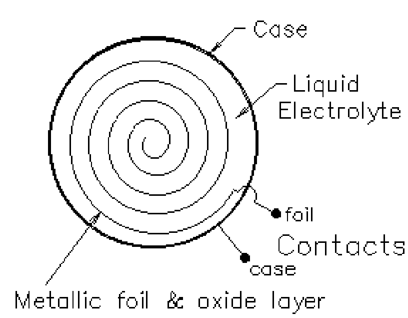
## Equipment and materials to be checked out from stockroom:
- ECE 2210 kit, optional, if available.
- Analog BK precision multimeter or similar.

## Parts to be supplied by the student:
These items may be bought from stockroom or may be in the ECE 2210 kit.
- 1 kΩ (brn,blk,red), and 100 kΩ (brn,blk,yel) resistors
- 0.1 µF (usually marked 104) and two 47 µF capacitors



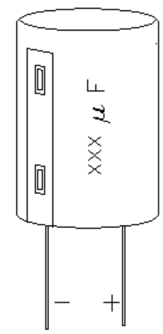

## Capacitors (General background information)
Capacitors with values less than 1 µF are usually constructed by layering sheets of metal foil and insulating material. Often these sandwiches are rolled into little cylinders or flattened cylinders. The metal foils are the plates of the capacitor and the insulator is the dielectric. The dielectric material determines the capacitor type (paper, mylar, ceramic, etc.). The value of a capacitor is proportional to the area of the plates and inversely proportional to the thickness of the dielectric material between them. In general, a capacitor with a larger capacitance value will be have to be physically larger as well. Capacitors come in many shapes and a huge range of sizes.

Many small capacitors are marked with numbers like 104K or 471M. The numbers are read like the bands on a resistor— two digits and a multiplier that indicate pico-farads (104 is 10 x $10^4$ pF = 0.1 µF or 471M is 47 x $10^1$ pF). Pico-farads are $10^{-12}$ farads or $10^{-6}$ µF. The letter indicates the part tolerance (how close should the actual value be to the marking), F = ±1%, G = ±2%, J = ±5%, K = ±10%, M = ±20%.



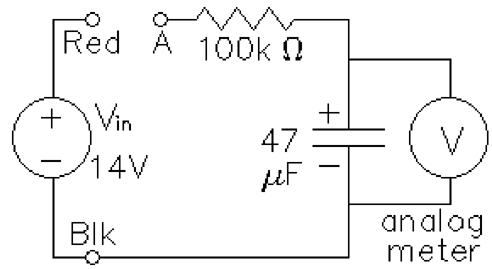

Capacitors with values greater than 1 µF are usually constructed by immersing a roll of metal foil in a conducting liquid (See top-view, at right). A conducting liquid is called an electrolyte and these type of capacitors are called electrolytic capacitors. The foil is one plate and the liquid is the other. The dielectric is a very thin layer of oxide formed on the foil. Because the oxide layer is so thin, electrolytic capacitors can have very large values in relatively small packages. Unfortunately, the oxide dielectric also gives them some other, less desirable, characteristics. Most electrolytic capacitors can only be charged in one polarity. Voltage of the wrong polarity can damage the oxide layer and sometimes even cause the capacitor to blow up. (I can personally vouch for this.) They are difficult to manufacture accurately and their actual value may differ from their claimed value by as much as a factor of two (-50%, +100%). The oxide is not the best of insulators so they can have significant leakage current. Finally, the oxide layer so thin that electrolytic capacitors have relatively low voltage ratings.

## Experiment




Look at your two capacitors. Note that the 47 μF capacitor is larger than the 0.1 μF capacitor, but not 470 times larger. Also notice that the electrolytic capacitor has a voltage rating marked on the package and that one side has a whitish band that indicates polarity. Look for the polarity band, not the lead lengths. If you apply a voltage larger than the rating, or in the wrong polarity, you risk damaging the capacitor, quite possibly making it blow up. **DON'T DO THIS!**

### Charge and Discharge




Set the bench power supply's output to about 14 V. Wire the circuit shown at right using an analog multimeter (switched to 10 V DC range). Note that point A is NOT yet connected to the power supply. If the reading on the voltmeter isn't 0 V, short the capacitor leads together for a second and measure again. Now, while watching the voltmeter, connect point A to the power supply. Notice the rising voltage across the capacitor. Does the voltage seem to follow the expected charging curve for an RC circuit? Look at the curve on the next page. It changes quickly at first and ever more slowly as the capacitor approaches its final charge (voltage). Draw a rough sketch of the curve in your lab notebook and comment. Notice that the voltage only rises to about 10 V, not 14 V as you might expect. That's because the meter affects the circuit (see box at right).

**Meter Effects**

When switched to the 10 V DC setting, the BK meter is equivalent to 250 kΩ resistor hooked to the circuit. It is rated at 25 kΩ/V, to find its equivalent resistance you multiply the voltage setting by 25 kΩ/V (10V x 25 kΩ/V = 250 kΩ.

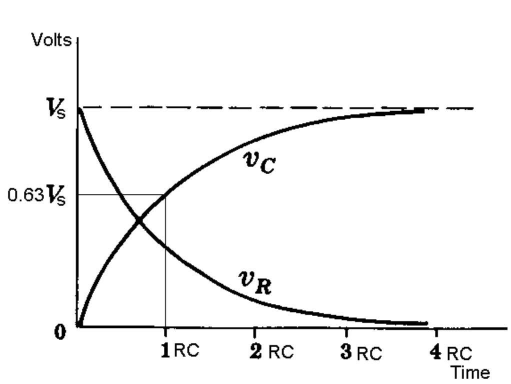

If you were to make a Thévenin equivalent circuit of the power supply, the 100 kΩ resistor, and the 250 kΩ internal resistance of the meter, it would look like a 10 V supply with a 71 kΩ resistor. Hence, the capacitor only charges to 10 V. If you change the range of the Simpson it will no longer look like a 250 kΩ resistor and the final capacitor voltage will be different.

Allow the capacitor to charge until the voltage across it changes very slowly and nearly equals 10 V. We'll call this fully charged, although in realty it will never quite reach 10 V. No exponential curve ever really reaches it final value.

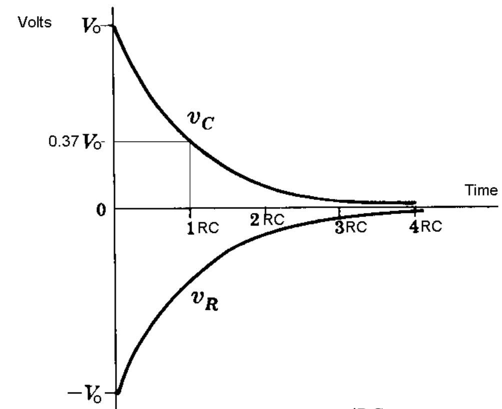
While watching the voltmeter, disconnect point A from the red connection of the power supply, allowing the capacitor to discharge though the meter. (Note: because the 100 kΩ is no longer part of this circuit, the discharge time will be longer than the charge time). Does the voltage seem to follow the expected discharge curve? Sketch the curve in your lab notebook and comment. You just made current flow through the meter, even though it was not connected to any power supply or battery. Where did the required energy come from?

**Measure time constant**

The charge and discharge equations and curves for an RC circuit are shown below.




Charge




$v_C(t) = V_o e^{-t/RC}$

Discharge

Where $v_C(t)$ is the capacitor voltage as a function of time, $V_S$ is the source voltage during charging (The Thévenin voltage for us), and $V_o$ is the initial voltage across the capacitor at the time that discharge begins.

For RC circuits the quantity $\tau = RC$ is defined as the "time constant". When $t = \tau = RC$ during charging $v_C(\tau) = 0.63\ V_{Th}$. When $t = \tau = RC$ during discharge $v_C(\tau) = 0.37\ V_o$. Calculating $\tau$ for the charging circuit: $\tau$ = 71 kΩ x 47μF = 3.4s. During discharge R is only the meter resistance. Calculating $\tau$ for the discharging circuit: $\tau$ = 250 kΩ x 47μF = 11.8s.

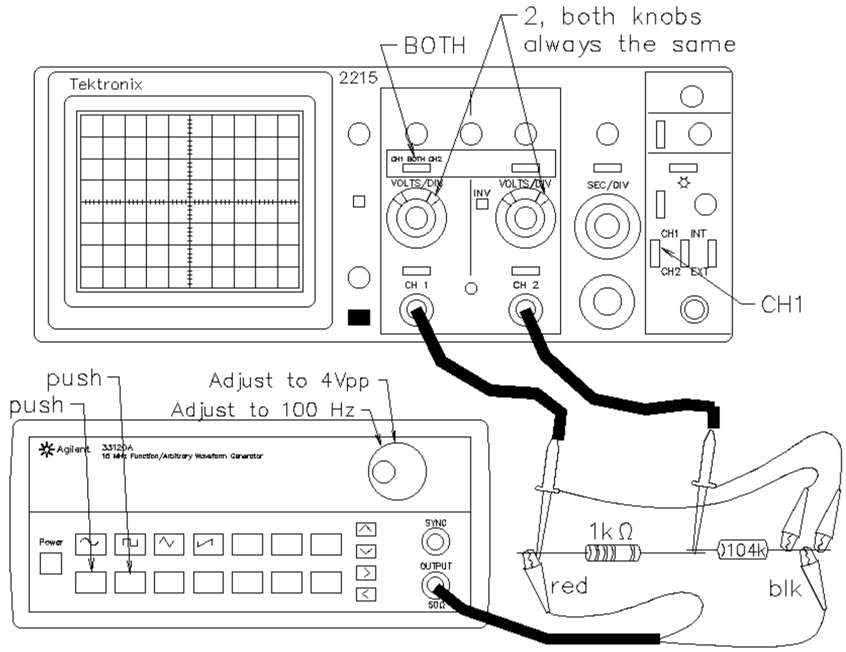
Repeat the charge and discharge procedure above, only now use a clock, watch, or stopwatch to try and measure the time it takes for the capacitor to charge to 63% of 10 V. Yeah, I know this is tricky and not likely to produce an accurate measurement, but for now, it's good enough. During discharge, measure the time it takes to discharge to 37% of the fully charged voltage. Compare your measured time constants to those calculated in the previous paragraph.

Quickly repeat this time constant measurement for two 47 μF capacitors in parallel and again for two 47 μF capacitors in series. Comment on series and parallel capacitors.

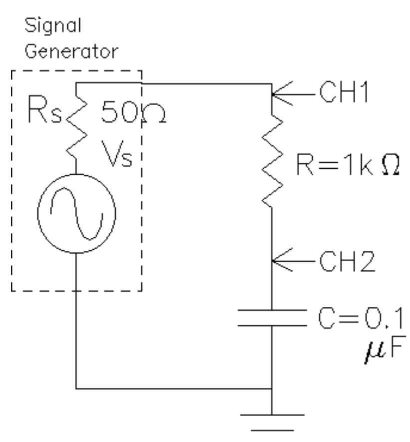
**RC Filter**

The previous sections you looked at the response of an RC circuit to a DC input voltage switched on and off. In this section you'll see how this circuit behaves when the input voltage is steady-state AC rather than DC. It turns out that the response of the circuit depends on the frequency of the AC input voltage. This type of circuit is commonly called a *filter*. It *passes* some frequencies and *filters out* other frequencies.

Set up the scope and circuit as shown on the next page. This is a voltage divider for AC voltages. Use an Agilent or HP 33120A function generator as the signal generator. (It's internal source resistance $R_S$ is shown on the schematic to remind you that it exists). Using the knob and arrow buttons, set the signal generator to 4 $V_{pp}$ (actual output will be double this, $8V_{pp}$) at about 100 Hz. (Because the scope screen is 8 divisions high, I will often specify signals like $8V_{pp}$ that will fill the screen.)



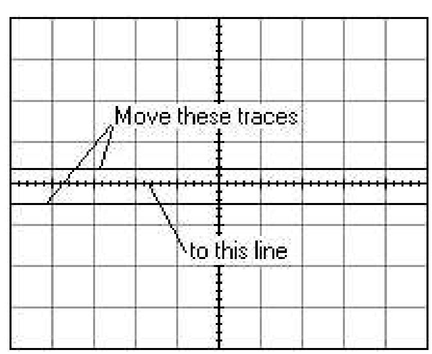

Measure the peak-to-peak voltage across the capacitor (CH2) at 100 Hz, 300 Hz, 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz. Make a graph in your notebook to plot these $V_{pp}$ measurements. If you divide your horizontal axis into 7 even divisions and label them with the 7 frequencies above, then you'll have a close approximation of a logarithmic scale for frequency. That's the way frequencies are normally plotted, on a log scale. Note: If you want to use log paper for your plot, or use a computer to make a log plot, that would be even better.

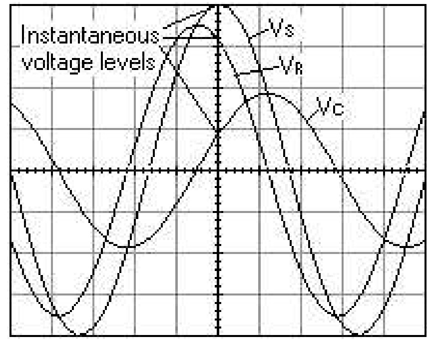



The calculations necessary to determine the theoretical capacitor and resistor voltages are shown in the appendix.
Look at the resistor and capacitor peak-to-peak voltages at 3kHz. How can they add up to more than the peak-to-peak source voltage? Is this a violation of Kirchoff's voltage law? Plot the theoretical values (found in the appendix) on the plot you made above. Compare the two lines.

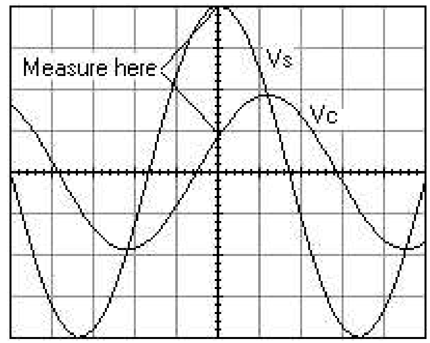
**Observe the phase relationship of AC voltages and confirm KVL for these voltages**

Set your signal generator back to 3 kHz. Switch each of the AC GND DC switches to GND and use the vertical position knobs to adjust both horizontal traces to center of the screen. Right along the center horizontal grid line. This "zeroes" the scope. Switch the AC GND DC switches back to AC. Do the two waveforms peak at the same instant in time? If not, then you really can't add the peak-to-peak voltages. You *cannot* add the peaks if they don't happen at the same time! You can, however, add the instantaneous voltage levels and we will try to do that next.



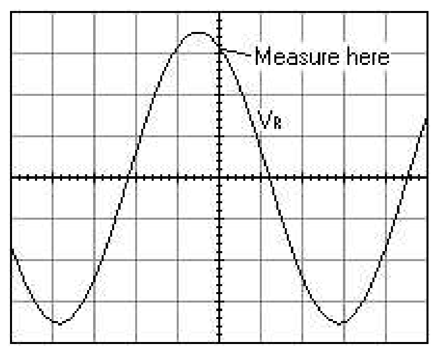



If you could look at all three voltages on the scope screen at the same time you'd see that at any instant in time, $v_R + v_C = v_S$. Unfortunately, the scope can't display three traces at a time, in fact we'll need both channels just to measure $v_R$ alone.




Ok, listen up. This is a very tricky measurement and you will have to be careful and pay attention. Both channels of the scope *must* be set at the same VOLTS/DIV setting. Measure the instantaneous voltage level of each trace where it crosses the center vertical line. That is, count the divisions between the center horizontal grid line (set to represent GND a minute ago) and the point where the trace crosses the vertical line. Multiply that number by the VOLTS/DIV setting. (Remember, if the trace is *under* the center horizontal grid line, then it's a *negative* voltage.) Now you have two numbers, one for the input voltage (the larger trace) and one for the capacitor voltage.

The next step is to find the instantaneous resistor voltage at this same time. The scope *is able* to measure the voltage between the two inputs to give you the resistor voltage, but it's not easy. Switch the ADD ALT CHOP switch to ADD. This adds the two input signals. Now switch the INVERT switch in. This changes the add to subtract. However, because not all scopes are calibrated perfectly, we have to do one more thing. Switch each of the AC GND DC switches to GND and use one of the vertical position knobs to the adjust horizontal trace to center of the screen. This "zeroes" the scope in this deferential mode. Switch the AC GND DC switches back to AC.




Now if you did all that just right, you can measure the instantaneous level of the resistor voltage. Take this measurement at the point where the trace crosses the vertical line— just like you did for the other two. Does the input voltage equal the sum of the capacitor and resistor voltages? If it does, very good— you did everything right! If not, you did something wrong. If you have no idea what went wrong, ask your TA for help, otherwise, try again on your own.

Once you have one good set of measurements, repeat the procedure for one other position on the waveforms. Hint: change the position of the trace with the horizontal position knob and make the same measurements again in the reverse order. Be sure to "zero" the scope after you switch the ADD ALT CHOP switch back to CHOP, and the INVERT switch back out.

**Conclude** Check-off as usual. Write a conclusion in your notebook. Make sure that you touch on each of the subjects in your objectives.