RC CIRCUIT

OBJECTIVES:

1) Observe the charge up and decay of the voltage on a capacitor.
2) Measure the time constant for the decay, $\tau = RC$.
3) Observe that the sum of the voltage on the resistor and the capacitor is always equal to the applied voltage.

APPARATUS:

Signal Generator
Oscilloscope
Resistors and Capacitors
Circuit Breadboard and Cable

INTRODUCTION

The Capacitor

A capacitor is a device that can store electrical charge. The simplest kind is a "parallel plate" capacitor that consists of two metal plates that are separated by an insulating material such as dry air, plastic or ceramic. Such a device is shown schematically below.

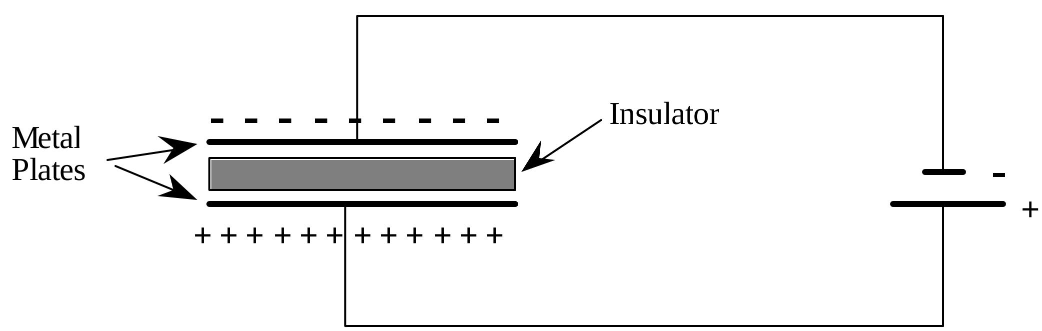


Figure 1. A simple capacitor circuit.

It is straightforward to see how it could store electrical energy. If we connect the two plates to each other with a battery in the circuit, as shown in the figure above, the battery will drive charge around the circuit as an electric current. But when the charges reach the plates they can't go any further because of the insulating gap; they collect on the plates, one plate becoming positively charged and the other negatively charged. The voltage across the plates due to the electric charges is opposite in sign to the voltage of the battery. As the charge on the plates builds up, this back-voltage increases, opposing the action of the battery. As a consequence, the current flowing in the circuit decays, falling to zero when the back-voltage is exactly equal and opposite to the battery voltage.

If we quickly remove the wires without touching the plates, the charge remains on the plates. Because the two plates have different charge, there is a net electric field between the two plates. Hence, there is a voltage difference between the plates. If, sometime later, we connect the plates again, this time with a light bulb in place of the battery, the plates will discharge: the electrons on the negatively charged plate will move around the circuit to the positive plate until all the charges are equalized. During this short discharge period a current is flowing and the bulb will light. The capacitor stored electrical energy from its original charge up by the battery until it could discharge through the light bulb. The speed with which the discharge (and conversely the charging process) can take place is limited by the resistance of the circuit connecting the plates and by the capacitance of the capacitor (a measure of its ability to hold charge). In this lab you will test the theory that models this behavior by measuring some discharge rates with an oscilloscope and comparing them to predictions of the theory.

RC circuit

An RC circuit is simply a circuit with a voltage source (battery) connected in series with a resistor and a capacitor.

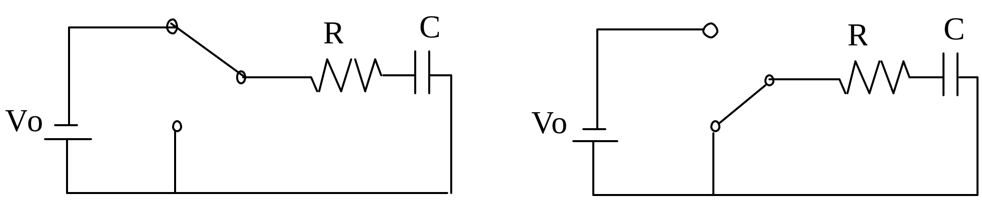


Figure 2. (a) Charging Figure 2. (b) Discharging

As with circuits made up simply of resistors, electrical currents can flow in this RC circuit, with one modification. A battery connected in series with a resistor will produce a constant current. The same battery in series with a capacitor will produce a time varying current, which decays gradually to zero. If the battery is removed and the circuit reconnected without the battery, a current will flow (for a short time) in the <u>opposite</u> <u>direction</u> as the capacitor "discharges". A measure of how long these transient currents last in a given circuit is given by the "time constant", τ.

The time it takes for these transient currents to decay depends on the resistance and capacitance. The resistor resists the flow of current $\Rightarrow$ slows down the decay. The capacitance measures capacity to hold charge: like a bucket of water, a larger capacity container takes longer to empty than a smaller capacity container. Thus, the "time constant" of the circuit gets larger for larger R and C. In detail:

$$\tau \text{ (seconds)} = R(\text{Ohms}) \times C(\text{Farads})$$

Note that the current does not fall to zero at time τ; τ is the time it takes for the voltage of the discharging capacitor to drop to 37% its original value. It takes 5 to $6 \times \tau$ for the current to decay to 0 amps. Just as it takes time for the charged capacitor to discharge, it takes time to charge the capacitor. Due to the unavoidable presence of resistance in the circuit, the charge on the capacitor and its stored energy only approaches a final (steady-state) value after a period of several times the time constant of the circuit elements employed.

<u>What's going on in this RC Circuit</u>

1) Initially, the switch is open, and no current is flowing.
2) The switch is closed as in Figure 2. (a). The capacitor will charge up, its voltage will increase. During this time, a current will flow, producing a voltage across the resistor according to Ohm's Law, $V_R = IR$. As the capacitor is being charged up, the current will be decreasing, with a certain time constant τ, due the stored charge producing a voltage across the capacitor.
   For $\tau = RC$, the voltage across the resistor and the voltage across the capacitor when the capacitor is charging look like:

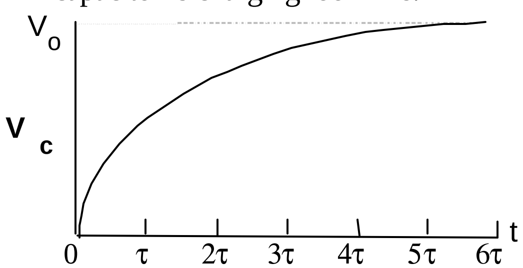


Figure 3. (a): Voltage across the capacitor V_c as a function of time. Time constant $\tau = RC$

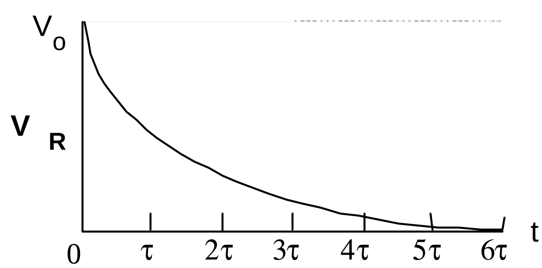


Figure 3. (b): Voltage across the resistor V_R as a function of time. Time constant $\tau = RC$

   Mathematically, V_C and V_R during the charge up time can be expressed as:

$$V_c(t) = V_0\left(1 - e^{\frac{-t}{RC}}\right) \qquad V_R(t) = V_0\, e^{\frac{-t}{RC}}$$

   The sum of these two voltages must equal the applied voltage, so $V_O=V_C(t)+V_R(t)$

3) If we flip the switch as shown in Figure 2(b), we will discharge the capacitor.

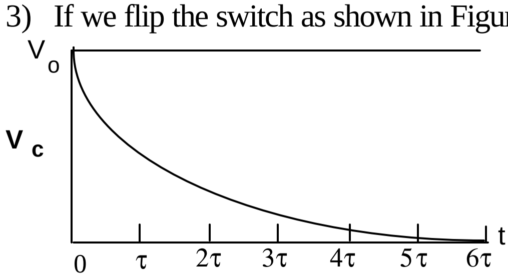
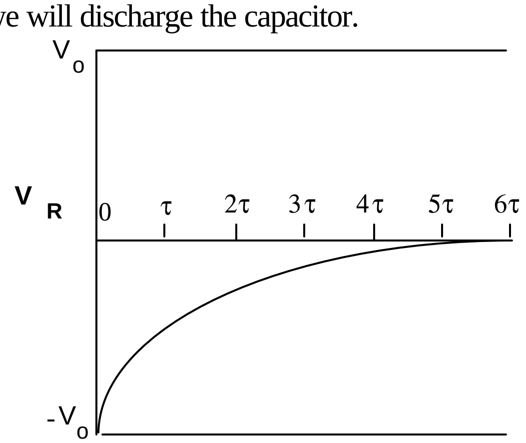


Figure 4. (a) Voltage across the capacitor V_c for the discharging capacitor. $\tau = RC$

Figure 4. (b) Voltage across the resistor V_R for the discharging capacitor. $\tau = RC$



The voltage of the resistor is exponentially increasing from $-V_o$ to zero. It is critical to remember that the total voltage between the capacitor and the resistor must add up to the applied voltage. If the circuit is disconnected from power supply, then the sum of the voltage must be zero.

4) If we now repeat this process and alternate the switch position every 6τ seconds, the voltages will look like:

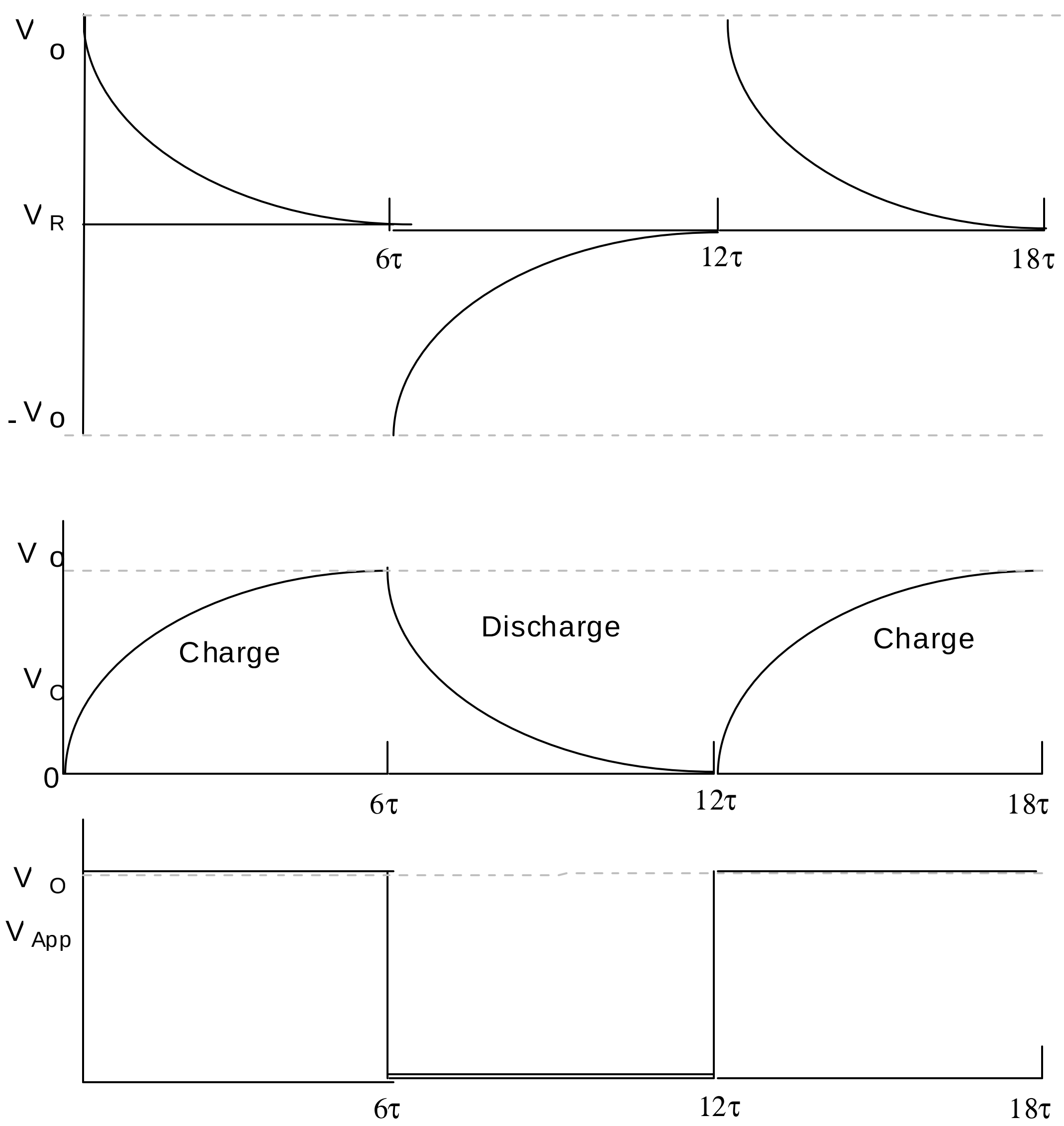


Figure 5. Repeated cycles between Figure 1. (a) and Figure 1. (b)

5) In this particular experiment, we are hooking up a wave generator to a RC circuit, which allows us to reverse the applied voltage. In effect, it will allow us to drive the circuit with V_0 and $-V_0$ as input voltage. The voltage as a function of time for both the resistor and the capacitor are shown below.

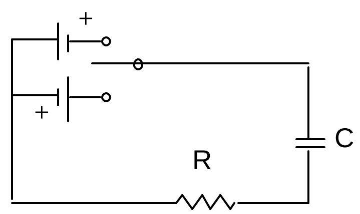
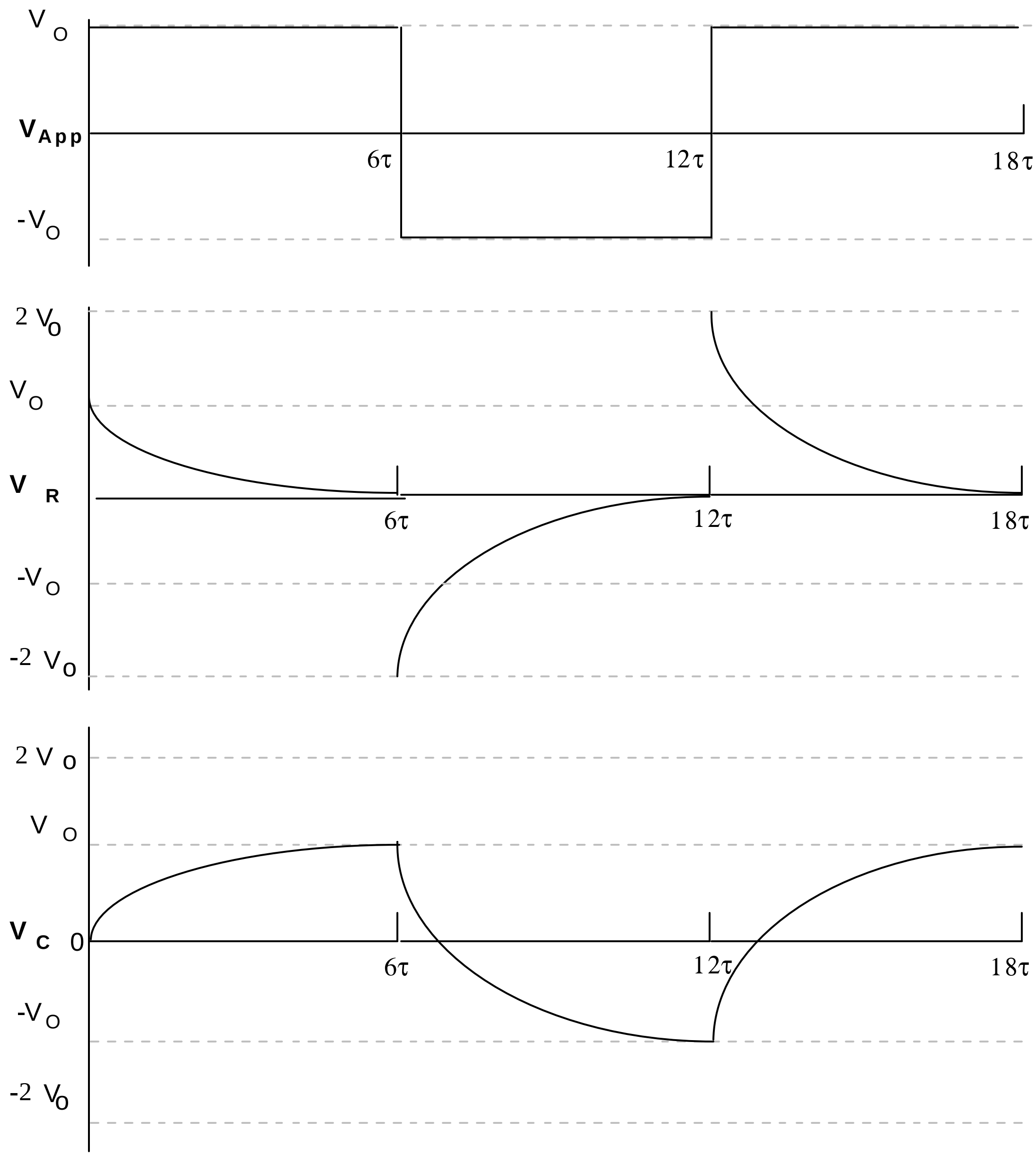


Figure 6. Repeated cycles of alternating power supplies. Time constant τ = RC



Kirchoff's voltage law for AC circuits

In the Ohm's Law, Part B, experiment, we saw that 'voltage drops' across the circuit elements added up to the voltage applied to the circuit. If you choose a particular path to loop around the circuit and count the voltage as positive if it increases in that direction and negative if it decreases, this would be the same as saying that the sum of these voltages is zero around a loop. This same law applies instantaneously, at each individual time, in a time-varying circuit such as the RC circuit. Looking at figure 6, you can see that at each instant, $V_c + V_R = V_{app}$. We will also demonstrate this in our circuit by measuring V_c ,V_R and V_{app} at various times.

Partners ____________________________ Name___________________________

____________________________ Section_________________________

PROCEDURE:

You will make the measurements using the Phillips digital oscilloscopes. Channel A will be used to measure the voltage drop across the resistor as a function of time and Channel B the voltage drop across the capacitor.

1. Set up the signal generator and the scope: Connect the "output" on the signal generator (SG) to the A-Channel of the oscilloscope. Set the frequency on the SG to 1800Hz, square wave with the "amplitude" set to under halfway. Display Channel A (toggle the A/B button until just A is displayed). Set the time base (TB) to .1 ms/cm and set the voltage sensitivity to 0.5V/cm on both Channel A and B.

Adjust the vertical position of the trace using the Y POS knob so that the trace appears mid screen. To check that this adjustment is accurate, press the GND button for A CHANNEL. The signal is replaced by a horizontal lne, which can be positioned accurately in the middle of the screen. The signal is recovered by pressing GND again. This adjustment can be made at any time you are displaying a signal and you may find it useful when you are lining up traces on Channels A and B later in the experiment.

Adjust the amplitude of the signal from the SG until it is 2V peak-to-peak (two divisions above zero and two divisions below zero on the scope). *Sketch* the input signal below.

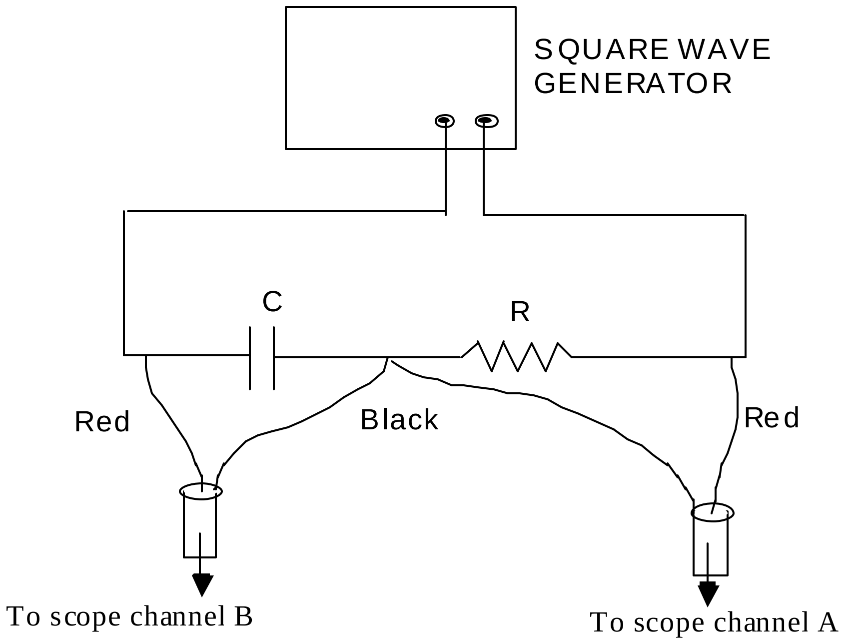


Figure 7. RC Circuit Diagram

2. Disconnect the SG from the scope and proceed to connect up the circuit shown in Figure 7. Make sure that the black leads and the red leads of the banana jack connector are connected in the same way as in the diagram or the oscilloscope will not display the signal. The two black leads must be connected to the same voltage, because they are both connected to ground at the scope. You should see a rising/falling wave form with about one full cycle visible on the screen. Channel A is the voltage across the resistor produced by the square-wave, which you displayed previously. You will measure the time constant of this signal.

3. Setting the Trigger
   By toggling TRIG COUPL, set the trigger to DC (the DC will appear next to where P-P appears in the center of the liquid crystal display). Make sure the trigger is triggering on the signal from the channel A (see A just above P-P or DC on the LCD). Set the TRIG LEVEL knob to mid-point.

   Q: Compare Channel A and Channel B with figure 6 for V_C and V_R. Sketch them in the space below.

4. Measuring the time constant of the signal
   The time constant is the time that it takes for the voltage across the resistor, V_R as shown by Channel A to fall to 37% of its peak value. You will measure this using the cursors. Find the value of R and its uncertainty from the color code and record it below. The capacitor is marked in μF ($\mu = 10^{-6}$) and its uncertainty is 10%.

   a) Place the Oscilloscope in "Digital Memory" mode and change the time base to 50 μsec / cm.
   b) Obtain the writing at the base of the main screen by pressing any of the soft-keys.
   c) Select CURSORS.
   d) Select MODE.
   e) Make sure that V-CURS and T-CURS are both on. Press RETURN.
   f) Select V-CTL.
   g) Move the cursors until the top cursor is at the top of the wave and the bottom cursor is at the bottom of the wave. Select RETURN then MODE.
   h) Toggle V/RATIO to V and then to RATIO. At the top of the screen you should be able to read: $\Delta V = 100\%$. Return to the V-CTL menu.
   i) You can now move the top cursor down until ΔV reads 37%. Where this cursor crosses the trace, the voltage has dropped to 37% of the initial value.
   j) Measure the time from where the signal starts to drop off to this point by using the T-cursors. This is the time-constant (τ_R). Record the results in the table below, with your estimate of the uncertainties.

k) Display Channel B on the screen in place of Channel A. Select .5V / cm sensitivity for the B Channel and center the trace on the screen. Measure the time-constant of this trace (τ_C) and its uncertainty.

R = ________________ ± ________________

C = ________________ ± ________________

RC = ________________ ± ________________

τ_R = ________________ ± ________________

τ_C = ________________ ± ________________

Q: Is RC compatible with τ_R within errors?

Q: Is τ_R compatible with τ_C within errors?

5. Next we examine the decay curve, $V_R = V_0\, e^{-t\,/\,\tau}$, in more detail by measuring the voltage across the resistor (Channel A) at several times.

a) Solve for V / V_0 and evaluate it at the values of t / τ suggested.

b) Using τ_R (the value you measured) for τ find the times t which will give the suggested t / τ and enter them in the table. Hint: $t = \tau\left(\frac{t}{t}\right)$

c) Measure V / V_0 at these times and enter them in the table. You may want to change the time base to 20 µsec / cm.

t / τ	V / V_0 (predicted)	t	V / V_0 (measured)	Measured / Predicted
0.000				
0.500				
1.000				
1.500				
2.000				
3.000				

Q: Comment on how closely the measured and theoretical values match. What is the typical difference of the ratio (in %) from what you expect (1.00) ?

6. Kirchoff's Voltage law for time-dependent circuits by analog addition of V_R and V_C.

   You can demonstrate the above mentioned relationship directly on the scope by doing the following:

   a) Change the time base to 100 μsec / cm and be sure both channels have a sensitivity of .5V / cm.
   b) Display both A and B channels on the scope.
   c) Put the scope into analog mode.
   d) Center the traces by grounding them.
   e) Toggle the ADD/INVERT button. When "INV" appears on the LCD the B Channel is inverted on the screen. Keep toggling until both "ADD" and "INV" appear on the LCD. On the screen you will see the A signal, the inverted B signal, and finally their sum, which is none other than $(V_A - V_B)$.

   Q: Does it look at all similar to V_{input} of part 1? Sketch below the trace representing V_A - V_B.

   Q: What do you discover about the relationship between V_{input} and $(V_A - V_B)$?

   Q: Why did you invert V_B? (Hint: Look at the circuit diagram of figure 7).

7. Measure the time constant of the unknown RC circuit. *Hint: you will get better measurements using the voltage across the resistor. (Check the diagrams on pages 4 and 5 to see what this would look like)*

   Box Label: ____________ τ = ________±________