Physics 310
Lab 2 – Circuit Transients and Oscilloscopes

Equipment: BK Precision 4003A function generator, Tektronix TDS 1001B oscilloscope, DMM, capacitance meter, BNC cable, BNC – alligator cable, BNC T connector, BNC – banana adapter, breadboards, wire packs, 6 banana cables, 2 alligator clips, decade resistor box, three 10k resistors, 0.01 µF capacitor, 100 Ω resistor, 7 mH inductor; O'scope user's manual, function generator's user's manual

General Lab Notebook instructions (from syllabus)

You should be sure to write down enough so that you can recall what you did several weeks later (it may come in handy when you're working on your final project.) The following information should be included:

1. Titles for labs and sections of labs.
2. Description of procedures followed (e.g. what was measured).
3. Well-labeled diagrams of circuits.
4. Record of observations and data (in tabular form when appropriate).
5. Analysis of data: computations and tables or graphs of results.
6. Comparison with theory: calculations and graphical or tabular comparison.
7. Answers to all questions.

General Procedures:
- Attach a BNC T connector to the output of the function generator. Connect one side of the T to Channel 1 of the oscilloscope using a BNC lead.
- Put a BNC to banana plug adapter on the other side of the T. Use banana leads to connect the black post of the adapter to the ground post on the breadboard and the red post of the adapter to another post on the breadboard. Use wires to connect the posts on the breadboard to two of the bus strips.
- Attach a BNC lead with alligator clips to Channel 2 of the oscilloscope. For the moment, connect the alligator clips to each other. This channel will eventually be used for looking at output signals from circuits.

2-1.   Using an Oscilloscope and a Function Generator
This section is about getting familiar with the new tools. Unless you're already familiar with oscilloscopes, these directions probably aren't sufficiently detailed – so explore and ask questions.
A. Getting a Good Signal Trace
1. Turn on the function generator. Set up the function generator to produce a 2-kHz sine wave with the amplitude set as large as possible. Make sure the amplitude and offset adjust knobs are pushed in (pulling out the amplitude knob reduces the amplitude of the output by a factor of ten – you don't want to do that just now.) This entails the following.
    (1) Turn the "Range" knob to "1kHz" and adjust the "Frequency" dial to about 2-kHz (to within a few percent.)
    (2) Turn the "Function" knob to point to the drawing of a sine wave.
    (3) Turn the "Amplitude" knob fully clock-wise.
2. Connect a BNC cable between the Function Generator's "MAIN" output and the Oscilloscope's "CH 1" input. Doing this *before* turning on the o'scope allows the o'scope's auto set-up to select reasonable display scales for you.
3. Turn on the oscilloscope. Almost every time you use an oscilloscope, you should begin by doing the following.

(1) Make sure Channel 1 is being displayed.

(2) Via the "Ch 1 Menu" (button above the Ch1 BNC cable connection), make sure it expects a "X1" probe (when you push the button, you should see "Probe X1 Voltage" on the right edge of the screen; if not, push the button just beside these words.)

(3) Then ground Channel 1's input by setting Channel 1's "coupling" to GND (done by pressing the button beside the screen where "Coupling" is reported), then using Channel 1's small "position" knob, adjust the vertical position until the trace for Channel 1 is in the center of the screen.

(4) Similarly, make sure Channel 2 expects a "X1" probe, then ground and center Channel 2's trace.

4. Select Channel 1 (press the "Ch 1 Menu" button again) and change the "Coupling" from "ground" to "DC" by pressing the button just by the display. (DC mode means the o'scope displays the signal just as it is, whereas AC mode subtracts off any constant off-sets.)

5. Rescale the image being displayed:

(1) Turn the large knob just above the Ch 1 input to change the vertical scale for displaying Channel 1 to 5 Volts/division (one grid square on the screen is 5 V tall) – there aren't any markings around the knob itself, but the scale is displayed in the lower left corner of the screen.

(2) Turn the large knob labeled "Sec/Div" so the horizontal axis scales to 250 μs/division. Again, there are no markings around the dial, but the horizontal scale is displayed at the bottom center of the screen.

B. Investigating the Role of "Trigger"

1. Through the "Trigger Menu" (button below the knob, far right), set the trigger mode to "AUTO" and the source to Channel 1. It's probably already set this way, but it's good to see how you can control this.

(1) Note: "Trigger" controls exactly when the oscilloscope re-samples the signals and refreshes its screen. Like blinking while looking at a spinning fan, if you "sample" the fan's position in synch with its motion, then each snapshot looks the same, and the 'movie' of all your snapshots is steady; if you sample out of synch, then the movie of all your snapshots is all jittery.

Question: What happens when the trigger level is adjusted? (Hint: Notice the arrow pointing down from the top of the screen and the arrow pointing over from the right of the screen?)

Question: Set the horizontal trigger arrow a little below the signal's peak value; now, what happens when the slope selector for triggering is switched from "rising" to "falling" via the "trigger menu"? (Hint: Again, notice the signal where these two arrows point.)

Question: What happens to the image of the signal when the trigger source is set to Channel 2? Why? (the o'scope is taking an new snapshot when the channel 2 signal, which is just random noise, crosses that threshold set by the arrow on the right.)

C. Measuring the Signal's Amplitude and Frequency

1. Switch the trigger source back to Channel 1 and use the trace to determine the period and peak-to-peak voltage of the signal. There are three ways to do this, and for different purposes each has its own use for different purposes.

(1) Just 'reading it off the plot' - Note how many division (to the tenth of a division), then use that number and the scale to determine these values.

(2) Mark and measure with – Press the "cursor" button in the second row at the top, then with the buttons beside the screen you can select whether the "Type" should be horizontal lines to measure "Amplitude" or vertical lines to measure "Time." You can also select "Courser 1" or "Courser 2" should move when you turn the knob up right of the screen.

    (a) So, you can select Amplitude and then move Courser 1 to run along the top of the sine wave and Courser 2 to run through the middle of the screen – read off the wave's amplitude as ΔV.

    (b) You can select Time and then move the two Coursers to span one period and read that off as Δt.

    (c) When you're done, you can make the cursors go away by changing the "Type" to "off."

(3) Let the o'scope measure for you – Press the "Measure" button in the top row of buttons. The five text cells along the right of the screen display different measurements.

    (a) If one of them isn't already "Ch 1 Pk-Pk" (measures the signal's height, from deepest trough to highest peak), then press one of the buttons beside the cell and you'll get two cells of options – the "Source" which you can set to be "Ch 1" and the "Type" which you can set to be "Pk-Pk", that done, press the "measure" button again. Read off that full height, divide it by two, and you've got the amplitude of the wave.

    (b) Similarly, if one of them isn't already "Ch 1 Period", press the button by the cell you want to change, and then set the Source to be Ch1 and the Type to be Period; return to the regular display by hitting "measure" again. Read off the period.

Question: How do the values measured by the three methods compare with each other? Agree to within a few percent?

Question: How does the measured period compare to what you expect, based on the Function Generator's setting?

D. **Printing a Screen Shot**

1. Here's one more *very* useful operation – often you want to preserve in your notebook what's being displayed by the o'scope – you can copy it over by hand (but be *very* careful to include the scales and copy it accurately enough to preserve the signal's character) or you can just print it. To print,

(1) Just under the knob near the center top of the o'scope is a button with "Print" written on it and "Save" written above it. If the light by "Save" is green, then pressing the button will save the screen's image to a low-capacity thumb drive inserted into the USB Plug on the front of the o'scope. If the light by "Save" *isn't* green, here's how to get it turned on:

    (a) Press the "Utility" button, then by the screen press the button for "Options" and then the one for "Printer Setup"; finally, pressing either of the top two buttons by the screen will change the function of the button between printing the image (if a printer's connected), saving the image, and saving "all" (the image and data tables that could be transferred to something like Excel to reproduce the image and for analysis.) You're probably interested in just

saving the image, and you probably want it to be saved as a jpeg (bottom button by the screen.)

(b) Once you've made your selection, you probably want to press "measure" so any measurements the scope is making get displayed alongside the plot (and so will be included in the saved image.)

(2) Once the file has been saved to the thumb drive, unplug it, and take it to the printer to print your image.

(a) To print the image using the printer in the lab room, plug your thumb drive into the USB slot on its front and then select the image from the menu displayed. Unfortunately, the thumbnail image that is displayed is simply the Tektronix logo, but the images are listed in the order that they were saved.

E. Investigating the Difference between AC & DC Modes

1. Switch the function generator to produce a square wave (this will avoid some distracting triggering effects.)
2. With Channel 1 of the oscilloscope in DC mode, pull out the offset adjustment knob on the function generator and turn it. Describe what happens to the signal. (Note: if the trace goes jittery, that's not what we're interested in, it's because the trigger arrow on the right of the screen no longer points at the signal, so you'll need to adjust its level by turning the "Trigger" knob.)
3. With the trace shifted so that it is off-center, switch the oscilloscope to AC mode and describe what happens to the trace. For that, you push the "CH 1 Mode" button and then change the Coupling to AC.

Question: Which mode (AC or DC) gives you the most complete information about the signal that the Function Generator is producing?

F. Making Grounding Mistakes

1. A DMM can be used to measure the AC voltage (the root mean square or rms value which will be discussed soon) between any two points in a circuit, but will not show what it looks like (for example, the phase shift of AC signals will be measured in the next lab). An oscilloscope measures the signal with respect to ground. Because of exactly how the o'scope does this, you need to be a little careful to make sure you're really measuring what you intend to be. This next experiment will drive the point home.

Pre-Lab
2. In 5Spice, build the following circuit.
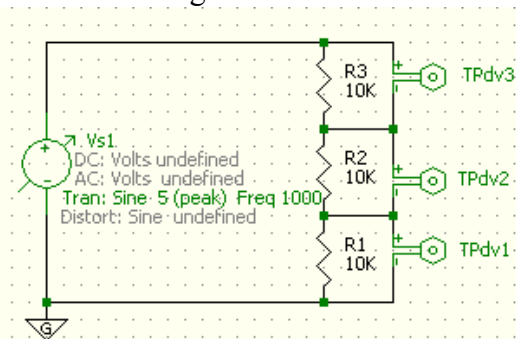
3. You'll plot the voltages across each resistor. This is a fairly trivial circuit, but that makes it a great one to use for learning the techniques.
   (1) Hit F8 to bring up the Analysis dialog box.
   (2) Under the Analysis tab,
      (a) go to the Select Analysis box and click on "Transient-New"
      (b) go to the Time box and select to run the simulation from 0 to 2.5m (short for milliseconds)
      (c) At the bottom left of the display, check the box for using Vs1 as the voltage source.
   (3) Under the Graph/Table tab,
      (a) select Plot1 to be TPdv1, and choose it to use the left axis, select Plot 2 to be TPdv2, and choose it to use the left axis too, and similarly select Plot 3 to be TPdv3 and choose it too to use the left axis.
      (b) In the Title box give the plot you'll make an appropriate name.
   (4) Bottom left, hit the "Apply and Run" button.
   (5) If any error messages appear, you'll need to address them, otherwise, you'll have a plot of the three traces (given the symmetry of the situation, they'll all be on top of each other.)
   (6) Print out the plot and tape it into your note book
      (a) If you' aren't using a color printer, you'll need to first select "Graph Print Settings" under the File menu and in there choose for graphs to print in black and white.
      (b)) If you aren't connected to a printer, right click on the plot and you'll get the option to "save image to file…" For that matter, you can save an image your circuit diagrams the same way.

4. Construct the circuit shown below leaving the function generator connected to Channel 1 of the oscilloscope. Adjust the function generator so that it produces a 1-kHz sine wave with an amplitude of 5V (10 V peak-to-peak.)
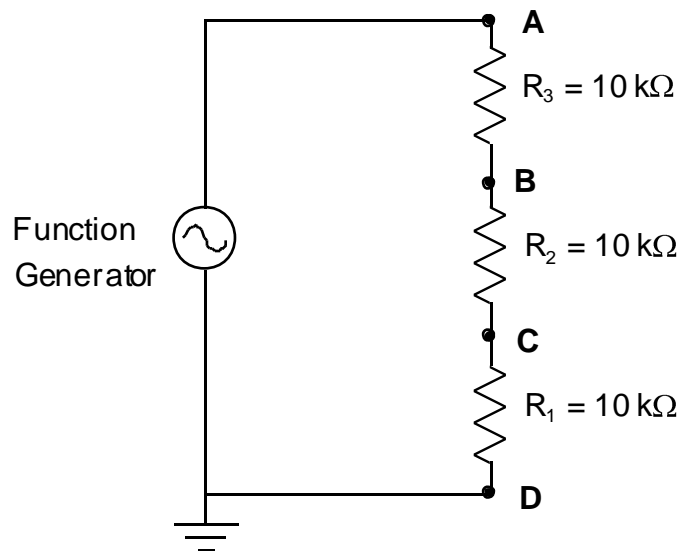
5. Calculate what the voltage amplitudes should be across each of the resistors; this should agree with the pre-lab plot you've printed.
6. Use Channel 2 of the oscilloscope to measure the voltages across R_1 by placing the black ground clip at point D and the red clip at point C. Measure the voltage across R_2

by placing the ground clip at point C and the other clip at point B. Measure the voltage across R_3 by placing the ground clip at point B and the other clip at point A.

Question: Why don't all of the voltages measured with the oscilloscope agree with the predicted values? Draw diagrams to explain the discrepant results with the oscilloscope. Great, now you'll be wise enough to avoid making this mistake on your own.

## 2-2.   RC Circuit Transient Behavior

Pre-Lab

A. In 5Spice, draw the following circuit. Note that the supply is set to generate a Square wave (though it isn't displayed here, the "offset" is set to be 2.5 V.)
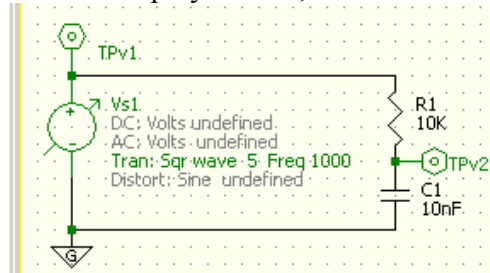

B. Now follow a similar process as in the previous pre-lab to plot both the voltage of the supply (that reported by TPv1) and the voltage across the capacitor (that reported by TPv2) but run it from 2m to 3m (again "m" is short for milliseconds.)

C. Print and tape in the plot of the supply and capacitor voltages.

D. Derive a relation between the time ($T_{1/2}$) it takes for the voltage to rise to half of its final value (or drop to half of its initial value) and the time constant (τ_{RC}). In the lab, you'll use this relation to experimentally determine the time constant.

E. Construct the following circuit.
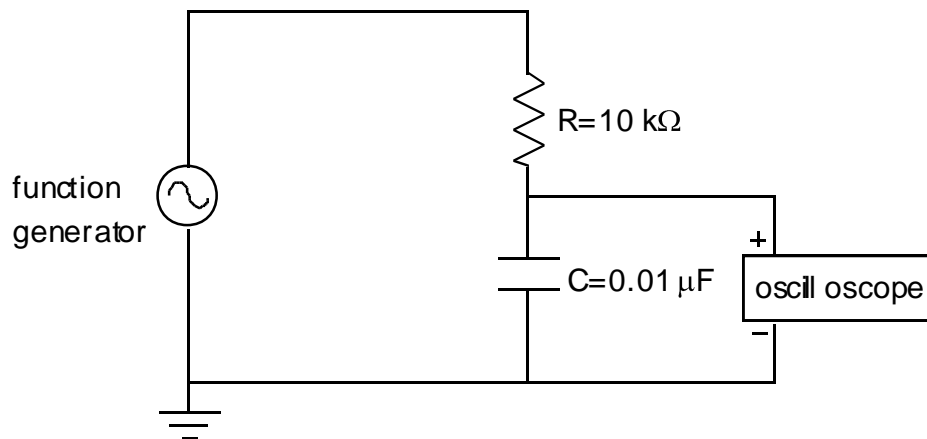
F. The following is a more common representation of the same circuit that just shows where a signal will be input (V_{in}) and where the voltage will be measured (V_{out}).
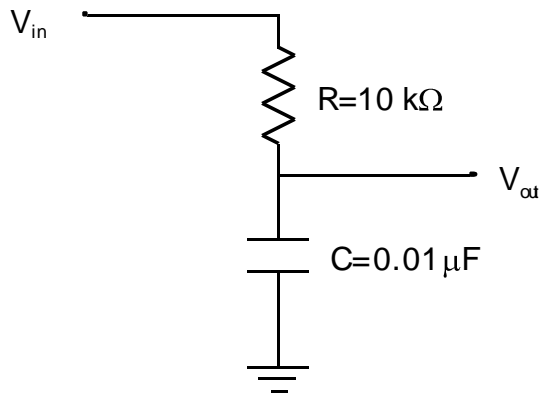
G. Use the offset adjustment of the function generator to produce a *square* wave that toggles between zero and 5 V with a frequency of 1 kHz. Carefully draw or print out the curves for charging and discharging of the capacitor. (Hint: It helps to adjust vertical and horizontal scales so one cycle fills the oscilloscope's screen.) Note: if you draw, don't forget to mark and label your axes including units and scale.

H. Now experimentally determine the time constant, τ_{RC}. To do this, firist determine the value of $t_{1/2}$ from the oscilloscope (the o'scope's cursor, that you learned about on pages 2 and 3, can be handy), and then use the relation between $t_{1/2}$ and τ_{RC} that you derived in the pre-lab to now determine τ_{RC}.

Question: How does this experimentally determined value of τ_{RC} compare with what you'd theoretically expect, given the *measured* values of resistance and capacitance?

## 2-3 Differentiator

A. Construct the following circuit.
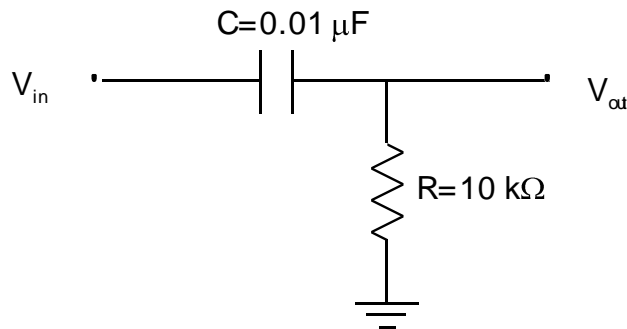
B. Drive it with a *triangle* wave with a frequency about 100 Hz. Sketch the output.

Question: Is the output around RC times the derivative of the input?   Recall, it's an approximation that this is a perfect differentiator, so you'll see a significant % difference, but they should be in the same ball park?

Question: What happens to the output's amplitude as the period of the input is decreased?

2-4.   Integrator

A. Construct the following circuit.

$$R = 10\ k\Omega$$

V_{in} V_{out}

$$C = 0.01\ \mu F$$
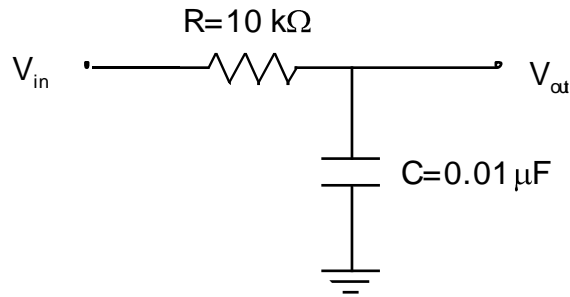
B. Drive it with a square wave of frequency around 10 kHz. Be sure the function generator's "offset" is off / knob's pushed in. Sketch the output.

Question: Is the output around the 1/(RC) times the integral of the input? Again, it's an approximation that this is an ideal integrator, so you'll get a significant percent difference, but they should be the right ball park.

Question: What happens to the output's amplitude as the period of the input is increased?

2-5. **Function Generator Output Resistance** – Most function generators have an output resistance that limits the current.

A. Construct the circuit shown below where R_{out} is internal to the function generator.
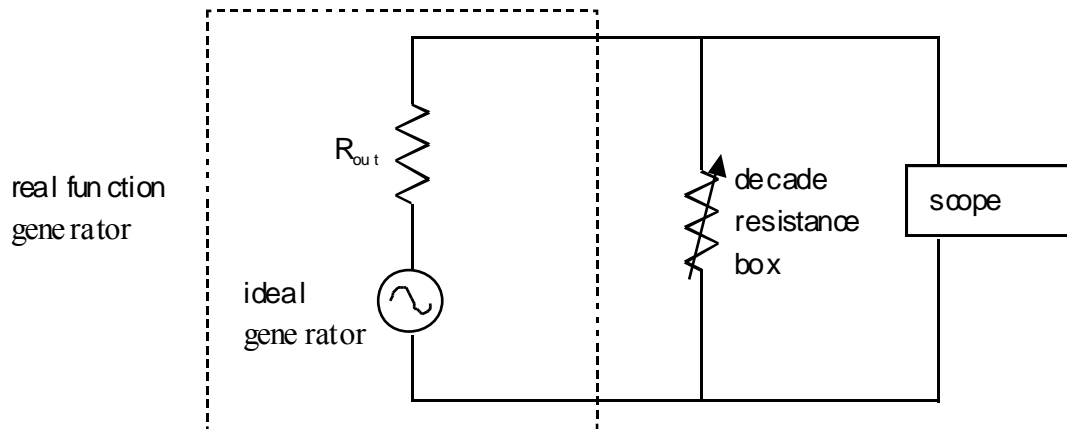
B. Set the decade resistor box to 100 kΩ and adjust the function generator until the signal on the oscilloscope is 1 V with a frequency of about 1 KHz. Reduce the resistance of the box until the voltage read on the oscilloscope is 0.5 V.

C. Don't worry about the input resistance of the oscilloscope. Assume that R_{out} is relatively small so that in the first case almost all the voltage drop is across the much larger 100-kΩ resistance. In the second case, there are equal voltage drops across R_{out} and the decade resistance box. Use this information to determine R_{out}. (Hint: You should be able to do this without any difficult calculation!)

Question: How does the measured output resistance compare to the value given in the manual for the function generator?

If time permits:

2-6. **RLC Circuit Transient Behavior ("Ringing")** – Loops in circuits and bad connections can introduce unwanted inductances and capacitances. These are usually noticed because of the ringing (or damped oscillations) that occurs when the voltage is switched suddenly. See Appendix B-2 for a description of this behavior.

   A.   Construct the following circuit. Calculate its expected natural oscillation frequency,
   $f_0 = \dfrac{1}{2\pi}\sqrt{\dfrac{1}{LC} - \dfrac{R_{total}^2}{4L^2}}$. Note that total resistance (R_{total}) of the circuit includes the inductor's resistance and internal resistance of function generator.
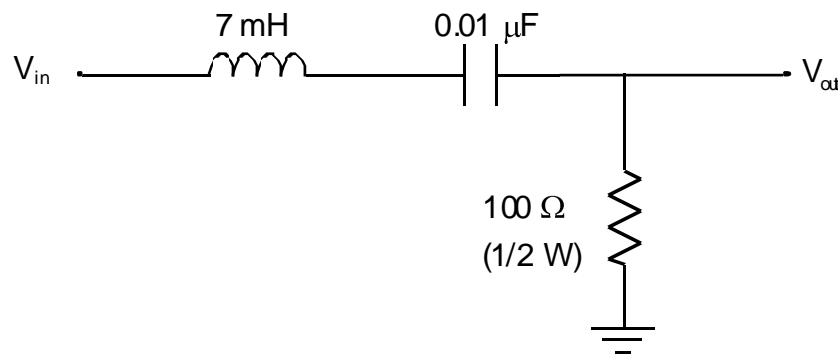
   B.   Drive the circuit with a square wave that has a frequency of about 1/10 of the natural frequency. Adjust the oscilloscope so that you can see the exponentially decaying oscillation of the output. Use this to determine the frequency of the ringing (the inverse of the time for one oscillation) and the time constant for the decrease in the amplitude of the ringing.

   Question: How do the expected and measured values of the natural frequency compare?

   Question: Is the time constant for the "decay" of the ringing signal ($2L/R_{total}$) as theoretically predicted? Be sure to include the inductor's resistance and internal resistance of function generator in the total resistance (R_{total}) of the circuit.

2-7.   Input and Output Resistances
A.   Oscilloscope Input Resistance
   1. Construct the circuit shown below and adjust the function generator to produce a 1-V signal with a frequency of about 1 KHz.
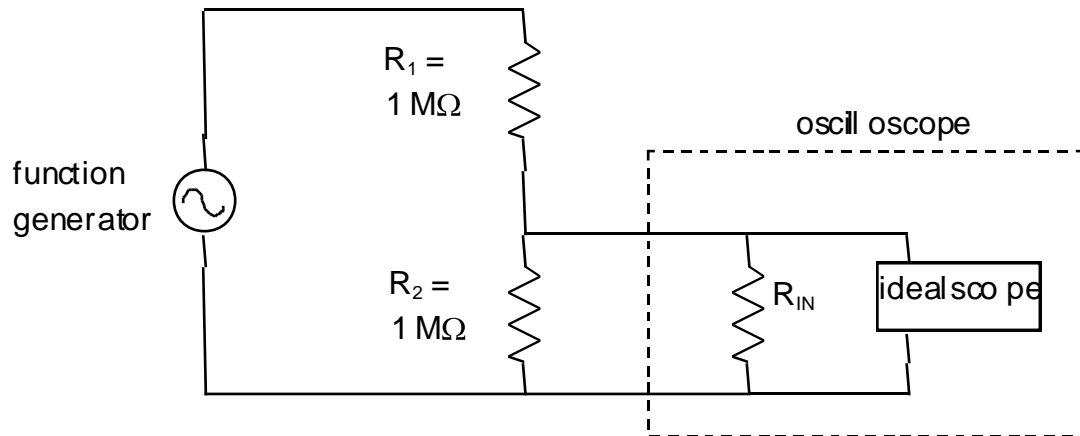
   2. Measure the voltage across R_2 with the oscilloscope. Using the above circuit diagram as a model for the oscilloscope, determine its input resistance (R_{in}) as you'd determined that of the multimeter in the previous lab.

Question: How does the measured input resistance compare to the value given in the manual for the oscilloscope?

Lab 2 Supplement: Capacitors

The reverse side has a table listing some of the properties of different types of capacitors. Two critical properties to determine are:
- the polarity (which terminal should be kept at higher voltage), if a capacitor is polarized,
- the maximum voltage rating.

If a capacitor is connected backwards or its maximum voltage is exceeded, it may explode!

Reading values off of capacitors can be tricky because their, "markings have been designed by an international committee to be nearly unintelligible," (Horowitz & Hill) so here are some hints. The only commonly-used units on capacitors are:

microfarads: $1 \ \mu F = 10^{-6} \ F$

picofarads: $1 \ pF = 10^{-12} \ F$

Therefore, you should get in the habit of <u>not</u> using "mF" or "nF". Also, note that a microfarad is a <u>million</u> picofarads, not a thousand.

Some of the tolerance codes for capacitors are:

<u>Code</u>	<u>Tolerance</u>	
Z	+80%, -20%	usually appears on large filter capacitors where minimum value is most important
M	±20%	
K	±10%	
J	±5%	

The following are the types of capacitors that you will see in lab this semester:
1. **Electrolytic**: These are often cylinders. They have large capacitances and are frequently used as filters in power supplies. These are usually easy to read, but "MF" is sometimes used for "microfarad". A "+" will mark the terminal that should be kept at higher voltage or a "-" the one to be kept at lower voltage.
2. **Ceramic**: These are usually orange or yellow discs. Ignore the markings that are obviously not capacitance values. For the remaining markings, you can often ignore the tolerance marking and use common sense to determine the capacitance. For example, ".02M" and "560M" mean ".02 μF" and "560 pF" with 20% tolerances. Sometimes a slightly confusing scientific notation is used where "103" means "10 x $10^{-3} \ \mu F$" (notice the minus sign in the exponential).
3. **Mylar**: These yellow cylinders are usually clearly labeled, except that but "MF" is "microfarad". The black band on one end is not important since these are not polarized.
4. **Tantalum**: The ones that you will use look like small beads. The biggest difficulty is reading the small lettering. The polarity may be indicated with a "+" or "-", or the longer leg will be the positive one.

Caution: A charged capacitor can store quite a bit of energy and is a shock hazard, so it is a good idea to make sure the charge has drained off of a capacitor before handling it. This can be done by connecting a small resistor across the capacitor.

Type	Capacitance Range	Maximum Voltage	Accuracy	Temperature Stability	Leakage	Comments
Mica	1pF-0.01μF	100-600	Good		Good	Excellent; good at RF
Tubular ceramic	0.5pF-100pF	100-600		Selectable		Several tempcos (including zero)
Ceramic	10pF-1μF	50-30,000	Poor	Poor	Moderate	Small, inexpensive, very popular
Polyester(Mylar)	0.001μF-50μF	50-600	Good	Poor	Good	Inexpensive, good, popular
Polystyrene	10pF-2.7μF	100-600	Excellent	Good	Excellent	High quality, large; signal filters
Polycarbonate	100pF-30μF	50-800	Excellent	Excellent	Good	High quality, small
Polypropylene	100pF-50μF	100-800	Excellent	Good	Excellent	High quality, low dielectric absorption
Teflon	1000pF-2μF	50-200	Excellent	Best	Best	High quality, lowest dielectric absorption
Glass	10pF-1000pF	100-600	Good		Excellent	Long-term stability
Porcelain	100pF-0.1μF	50-400	Good	Good	Good	Good long-term stability
Tantalum	0.1μF-500μF	6-100	Poor	Poor		High capacitance; polarized, small; low inductance
Electrolytic	0.1μF-1.6F	3-600	Terrible	Ghastly	Awful	Power-supply filters; polarized; short life
Double layer	0.1-10F	1.5-6	Good	Poor	Good	Memory backup; high series resistance
Oil	0.1μF-20μF	200-10,000			Good	High-voltage filters; large long life
Vacuum	1pF-5000pF	2000-36,000			Excellent	Transmitters

Table taken from p.22 of Horowitz & Hill's The Art of Electronics, 2nd Ed. Cambridge University Press, 1991.