Laboratory 6: Oscilloscopes and Circuits

NE 401/550

**Pre-laboratory Questions:**

1. Read the laboratory assignment in its entirety before coming to lab.
2. Read the Wikipedia page on oscilloscope (<https://en.wikipedia.org/wiki/Oscilloscope>).
3. What is the purpose of AC coupling on an oscilloscope?
4. What is the most common use of an oscilloscope?
5. In a DMM, the resistance values will change as a function of the current magnitude being measured. Explain why this happens and if this could affect a measured value in a given experiment.
6. In class we analytically solved the differential equation describing a CR network.
   1. Graphically display via Mathematica how the input sinusoidal wave is modified at the output when modifying the input frequency. Plot the cases when the input frequency varies in decades from 103-107 Hz. Use a time constant of 10 µs, a peak-to-peak input amplitude of two volts, and a time domain covering at least four periods. Put the input and output on a single plot (5 plots total).
   2. determine the relative (fractional) attenuation of the amplitude as a function of the quotient of cutoff frequency to the input sine wave frequency (i.e., fcut / fsine). Do not forget to account for the 2π.
   3. Print out the Mathematica Notebook and turn in the solution with the rest of your prelab assignment.

**Equipment:**

Digital multimeter

E&J Instruments CADET analog/digital electronics trainer

Various Resistors and Capacitors

Oscilloscope

Small gauge wire

NIM bin with Tail pulse generator or standalone function generator

**USB Drive**

**Introduction:**

This course requires a working knowledge of a variety of electronic instruments. The purpose of this experiment is to gain experience with the use of an oscilloscope and some experimental experience with circuits. An oscilloscope is one of the most powerful inspection equipment in the laboratory. Oscilloscopes are able to capture and analyze various analog and digital signals, enabling the diagnostic analysis of various electronic system components and signals. In the nuclear instrumentation laboratory, the oscilloscope will provide the means to inspect the signal coming from the detector, preamplifier, amplifier, discriminator, and many other modules not covered in this class. Further, we will investigate the use of the digital multimeter (DMM) for investigating circuits.

***Oscilloscope***

In learning to use the oscilloscope, experience will also be gained with a function (or tail pulse) generator. The function generator can simulate both signals coming from a detector and from a preamplifier. The oscilloscope will be used to inspect the signals generated by the function generator. An image of an oscilloscope is provided below, and the discussion of its basic functions corresponding to each colored box overlaid on the image in Figure 1 is provided in the supplemental document to this laboratory discussed in-class.

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| Figure 1: Image of the oscilloscope used in the teaching laboratory. The colored boxes highlight important regions to get students acquainted with the basic functions of the oscilloscope, and are discussed in a supplementary document. |

***Digital Multimeter***

For any probe to make a measurement of a system, it must become part of that system, meaning that it will perturb the state of that system. This is the case when a circuit is probed by a digital multi-meter to determine the current or voltage flowing through a particular component in that system. In the case of current measurements, the resistance of the measurement circuit is set to a very small value in an attempt to minimize changes to the total circuit resistance. This is accomplished by measuring current in a circuit by adding the DMM in series, where the additional resistance added by the DMM should be very small compared to the total circuit resistance. The total circuit resistance for all components in the system is given in equation 1.

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Likewise, in the case of voltage, the resistance of the measurement circuit is set to a very large value to ensure that the equivalent resistance of the perturbed system is as close to the unperturbed state as possible, thereby maintaining the appropriate voltage drop across the circuit element of interest. This is accomplished by probing across the circuit element of interest. If the resistance of the DMM is much larger than the element being probed, then the equivalent resistance of the new component (i.e., the component resistance—RC—and the DMM resistance—RDMM—in parallel) is approximately equal to the resistance of the component. The governing equation for resistors in series is given in equation 2.

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| Figure 2: Color code band description of resistors. |

In the case of one circuit element and the DMM, equation 2 reduces to equation 3, which further reduces to RC as RDMM approaches infinity.

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Figure 2 is a guide in determining the resistance of a resistor. Note that students in previous years may place the wrong resistor in the wrong slot, so students should verify the resistance of chosen resistors using the color bands.

As a final set of experiments, students will investigate the high pass and low pass filter. Each filter does as its name suggests, where the high pass filter passes a high frequency, and a low pass filter passes a low frequency. Now, high and low are relative words, and a high pass filter could pass a frequency of 1 Hz or 1 GHz, depending on the circuit elements comprising the filter.

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| Figure 3: A high pass filter with input (E­in) and output (Eout) signals shown. |

A high pass filter is composed of a capacitor and resistor in parallel. A capacitor by itself theoretically passes any signal of any frequency instantaneously. The capacitor is in series with the input signal, but there is also a resistor in parallel to the input signal. This resistor “resists” any change that the capacitor wants to experience, and for frequencies much higher than the time constant of the CR network, the voltage will exist entirely across the resistor. Therefore, the output voltage measured (Eout) is completely passed. However, as the frequency is reduced, the RC time constant of the CR network starts bleeding the charge induced on the plates from the input signal (Ein), onto the capacitor thereby reducing the voltage across the resistor. An image of a high pass filter is provided in Figure 3.

The governing differential equation for the high pass filter is given in equation 4, where I have substituted V in for E, and τ is the time constant of the high pass filter (τ=RC). The reciprocal of the time constant is the cutoff frequency of the high pass filter, where the output signal amplitude is ~70% of the input amplitude (-3 dB). The solution to equation 4 is provided in equation 5 for a unit step voltage input. The solution to equation 4 will differ on the input signal provided to the CR (i.e., high pass filter) network.

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The low pass filter is the same as a high pass filter, except that we read out the voltage across the capacitor rather than the resistor. The equivalent circuit shown in Figure 4 is drawn in such a way as to point out that the resistor is effectively in series with the input signal and the capacitor is in parallel with the input signal. Hence, it is exactly the opposite of the high pass filter, commonly referred to as an RC network, and correspondingly behaves exactly opposite of the CR network. The governing equation for the low pass filter is provided in Figure 4, its mathematical description in equation 6, and its solution for a step input in equation 7.

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| Figure 4: A low pass filter with input (E­in) and output (Eout) signals shown. |

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**Experimental Procedure:**

**Reminder:** Always include box-diagrams, flow charts, tables, etc. in the lab notebook to illustrate how the experiment is conducted. All instruments should be listed and their setting recorded at each step of the experiment.

***Oscilloscope***

1. When you arrive to the laboratory, the NIM rack should be set up to connect a Berkeley Nucleonics tail pulse generator (various models available) and the oscilloscope. Note the model of the tail pulse generator in your laboratory notebook.
2. On the tail pulse generator, turn the amplitude knob all the way down to zero to set the output wave amplitude to zero.
3. If not already powered, power on the oscilloscope and NIM bin now.
4. Select a tail pulse output with a fast rise time (sub-microsecond) and a fall time of ~150 microseconds (document actual choice) and a frequency of ~1 kHz. Be sure to document these settings in the lab notebook.
5. Ensure that the tail pulse generator output pulse polarity is set to positive and connected to channel one on the oscilloscope.

The oscilloscope has several controls on its front panel. In this exercise, the student will be introduced to the basic functions of the oscilloscope.

*Basic controls to find a signal:*

1. On the oscilloscope, the channel number button just above the knob that is just above the BNC input connectors turns the channel on and off and also opens up options for the channel (see the red box in the provided figure of the oscilloscope). Press the channel button now until the on-screen options for channel one appear at the bottom of the screen.
2. Ensure that the coupling type to DC[[1]](#footnote-1) and the impedance to 1 MΩ for channel one (use buttons just below the green box).

*Horizontal control:*

1. Under the horizontal control column on the front panel of the oscilloscope, there is a position knob and a time division knob (see the blue box). The position knob controls the location that the trace will cross trigger level on the graticule, or graduated grid on the screen. The location can be seen by the yellow arrow at the top of the display. Move the positioner to move it left and right, and then to the center of the screen (see where the yellow arrow should appear by looking at the yellow box in the provided figure of the oscilloscope).
2. The time division knob controls the time division between abscissa grid lines on the display. You can see what the current time division is near the bottom of the display (see the green box in the provided figure of the oscilloscope). Twist the time division knob while looking at the display to verify where it is on the display. Then set the division per grid line to ~50 µs.

*Vertical control:*

1. Likewise, the volts per division knob above any channel BNC connection controls the volts per ordinate division of the graduated grid on the display (see the green box). Twist the knob to locate where the indicator is on the display. Once found, set the division per grid line to 100 mV.
2. The position knob above the channel number controls the ordinate location of the trace on the graticule and its setting can be seen on the left side of the display via an arrow. Move the arrow to the ordinate center of the display. The channel trace should be on the arrow and now centered on the display, since there is no input signal on the channel (no DC offset present). If a slight voltage offset (~10 mV) is present, this is okay and the student may move on to the next step.
3. Under the trigger control column on the front panel of the oscilloscope controls how the oscilloscope looks for signals (see to the right of the blue box). This operation is like a discriminator, where only traces that pass the trigger threshold are shown on the display. Press the menu button and look for the various functions that pop up either on the screen. There will be options for channel number and slope type. The channel number controls the input that the trigger will look for. If this is not set to channel one, then the signal will not be properly displayed for this laboratory. The slope is very important, as it controls when the oscilloscope will trigger. For a positive slope, the signal must pass from below to above the trigger threshold to be displayed, and the opposite goes for the negative trigger. The level knob is the threshold for which the output signal will be displayed. When actively turned, the trigger line (threshold value) will show up on the screen.

*Find a Signal:*

Now that an introduction to the basic operations of the oscilloscope, students will now experiment with finding and displaying a pulse using an oscilloscope.

1. Have the GTA come over and provide a positive polarity, 100 mV, input from the tail pulse generator to channel one on the oscilloscope via the variable amplitude adjustment knob using the same settings in step 4. Also ensure that the GTA sets the time division to 100 nanoseconds (ns) and a voltage division of 5 V.
   1. Note: Watch the GTA during this process to gain exposure on how to control the tail pulse generator and the oscilloscope.
2. Ensure that the run/stop button is glowing green, which means that the oscilloscope is actively searching for traces.
3. Find the signal.
   1. Hint: Both the vertical and horizontal control knobs will be needed to find the signal. Also, the trigger for the oscilloscope should be set to positive slope and its threshold should be varied to find the input signal.
4. Ensure that only two cycles are displayed on the screen and that the amplitude of the pulse is ~25% across the screen. Make note of the trigger settings and other observations in the laboratory notebook.
5. Next, change the trigger slope from positive to negative.Note the observed effect in changing the slope in the laboratory notebook. Further consider the effect of what the observed pulse on the screen would look like if (or is) the trigger is off the observable screen and how this would look to the unseasoned student (**Hint:** it would look like there is no signal and the system is not functioning properly, but it is user error).

*Impedance:*

1. Reset the trigger slope to positive.
2. The impedance setting controls the effective resistance the signal sees across the oscilloscope. Note that the impedance of channel one should be set to 1 MΩ from step 7. The screen displayed should be the same as that shown in step 16.
3. One of the other settings is 50 Ω. Switch the setting to 50 Ω. In the laboratory notebook, note the observed effect, changing the ordinate scale and trigger setting as necessary to display the input pulse.
4. When finished, return the oscilloscope impedance to 1 MΩ and restore the ordinate and abscissa settings to the 1 MΩ values in the “find a signal” procedural section.

Students have now been introduced to the necessary basic functions of the oscilloscope available in the teaching laboratory. Refer to this document and the laboratory notebook for future reference. Students should also note that there are many, many more functions available, including saving traces, conducting measurements (e.g., frequency, rise/fall times), and more. Mastering the use of an oscilloscope takes consistent use and practice, and students are encouraged to experiment, as able, with the tools of the laboratory through the remainder of the semester.

***Using a Digital Multi-Meter:***

**Note:** that students in previous years may place the wrong resistor in the wrong slot, so students should verify the resistance of chosen resistors using the color bands.

This experiment will utilize the breadboard as discussed in-class. The breadboard is an array of perforated holes that are electrically connected in such a way to allow the construction of multi-component circuits, as discussed in-class. An image of the analog and digital training system, with the breadboard within the center of the device, is provided in Figure 5.

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| https://ctemedia.s3.amazonaws.com/gs/images/product_galleries/97/1-PB-503_main_72dpi.jpg |
| Figure 5: Global Specialties analog and digital training system in the teaching laboratory. |

*Measuring current:*

1. Power on the breadboard.
2. Measure the voltage from the constant 5 V line on the breadboard circuit from the red banana connectors at the top right of the board using the DMM. Record the determined value and assumed uncertainty in the laboratory notebook.
3. Find a 10 MΩ resistor and measure its actual resistance with the DMM. Note that the resistor should not be touched, but on the table during the measurement to avoid the parallel circuit created with your own body (that is right, your body conducts electricity). Note its value in your laboratory notebook.
   1. **Note:** If no 10 MΩ resistor is available, this is completely acceptable. Just find a large resistance resistor in the available stock for the experiment.
4. Build the circuit in Figure 6 using the quantified ~10 MΩ resistor and using the common voltage bars as discussed in-class. Incorporation of the DMM may be made using wires and wrapping the wires around the DMM probes.

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| Figure 6: Circuit for the current measurement experiment. |

1. Once the circuit is constructed, use the voltage drop measured on the DMM to calculate its internal resistance. This may be done by noting that the voltage drop across the ~10 MΩ resistor is the difference between the source and that measured across the DMM.
   1. **Hint:** Ensure that the probes of the DMM are plugged into the right ports for DC voltage measurements and that the turn knob is set to take DC voltage measurements (not AC voltage).
   2. **Hint:** Take the ratio of Ohm’s law for the resistor and the DMM to find the internal resistance of the DMM
2. Provide the answer, showing all calculation steps, in the laboratory notebook with uncertainty.

*Measuring voltage:*

1. Inspect the circuit shown in Figure 7, find the resistors needed, and measure their resistances with the DMM. Follow the same protocol as before. Note their actual values in your laboratory notebook
2. Construct the circuit. Note the switch (a wire on the breadboard here) shown in the circuit diagram. Be sure to change the DMM to measure DC and not AC current to get the right answer.
3. Measure the current through the DMM with and without the 10 Ω resistor in parallel to the DMM. Note the value in your laboratory notebook with uncertainty.
4. Use the difference in current measured () to calculate the internal resistance of the DMM using the equation . Note that the sum of the two currents in this equation should equal the current through the DMM without the 10 Ω resistor in parallel to the DMM (i.e., conserve charge).
5. Provide the answer, showing all calculation steps, in the laboratory notebook with uncertainty.

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| Figure 7: Circuit for the voltage measurement experiment. |

***Filtering transient voltage signals:***

In the final two experiments, students will investigate the effect of low-pass and high-pass filters on different types of transient voltage pulses.

*The High Pass Filter:*

A high pass filter is a circuit element that passes high frequencies but not low frequencies. It is often known as a differentiator or CR network. Figure 3 shows the circuit schematic.

1. Construct the high pass filter circuit with a time constant of 10 µs (time constant = τ = RC). Use the DMM to verify the values of the resistor and capacitor used, if possible. Document the specifics with uncertainty in the laboratory notebook.
2. Using a tail pulse or square wave input (see Berkeley Nucleonics modules, E&J Breadboards, or standalone units) with a fast rise time of nominally 1 ns (may be a few ns based upon function generator used) and a long decay time (or width for a square wave) of 1 ms. Verify the pulse properties through inspection with the oscilloscope. **Save the trace on a USB drive directly from the oscilloscope in .CSV format.**
   1. **Note:** Use the single button on the very right side of the oscilloscope to capture a single trace once your trigger settings are good. This will ensure you are saving the trace frozen on the screen. Also keep this in mind for all subsequent trace saves.
3. Now unplug the BNC from the oscilloscope and connect to BNC connector 1 on the breadboard. This input should be connected to Ein­of the high pass filter via jumper wires. The output of the RC network should be sent through BNC connector 2 and then into the oscilloscope with an impedance of 1 MΩ. Inspect the signal and comment on the results compared to the input waveform in the laboratory notebook. **Save the trace on a USB drive directly from the oscilloscope in .CSV format.**
4. Now generate a sine wave with a peak-to-peak amplitude of 2 volts. Investigate the input shape on the oscilloscope, and document observations in the laboratory notebook.
5. Investigate the sine wave after passing through the high pass filter for frequencies of 103-107 Hz (in decades) that will quantitatively depict the appropriate behavior of the CR network (high pass filter). Briefly discuss findings in the laboratory notebook (look at amplitude). **Save the traces on a USB drive directly from the oscilloscope in .CSV format.**

***The Low Pass Filter:***

A low pass filter is a circuit element that passes low frequencies but not high frequencies. It is often known as an integrator or RC network. Figure 4 shows the circuit schematic.

1. Construct the low pass filter circuit using the same components used for the CR network.
2. Using a tail pulse or square wave input (see Berkeley Nucleonics modules, E&J Breadboards, or standalone units) with a fast rise time of nominally 1 ns (may be a few ns based upon function generator used) and a long decay time (or width for a square wave) of 1 ms. Verify that the pulse properties are the same as before through inspection with the oscilloscope
3. Now unplug the BNC from the oscilloscope and connect to the BNC connector 1 on the breadboard. This input should be connected to Ein­of the low pass filter via jumper wires. The output of the RC network should be sent through BNC connector 2 and then into the oscilloscope with an impedance of 1 MΩ. Inspect the signal and comment on the results compared to the input waveform in the laboratory notebook. **Save the trace on a USB drive directly from the oscilloscope in .CSV format.**
4. Now generate a sine wave with a peak-to-peak amplitude of 2 volts. Investigate the input shape on the oscilloscope, and document observations in the laboratory notebook.
5. Investigate the sine wave after passing through the low pass filter for frequencies of 103-107 Hz (in decades) that will quantitatively depict the appropriate behavior of the RC network (low pass filter). Briefly discuss findings in the laboratory notebook (look at amplitude). **Save the traces on a USB drive directly from the oscilloscope in .CSV format.**

**Post-laboratory Questions:**

***Guidelines:***

1. All post-laboratory calculations will be conducted in a single Mathematica notebook, unless otherwise noted.
2. All figures and tables should be properly formatted, as previously shown. This includes font, axes labels, plot point size (that do not overwhelm error bars, if applicable), plot title, error bars (if applicable), and differentiating between different curves on the same plot (e.g., solid vs. dashed and red vs. blue).
3. When reporting answers, carry the appropriate number of significant figures in a cell formatted for text input.
4. Properly add comments in the Mathematica Notebook to assist in grading.
5. When commenting on results, format the cell as text and not code.

***Analysis for the high pass filter:***

1. Plot the input and output for the square wave investigation on the same plot.
2. In a text-style cell, quantify what effect the filter had in (1) and if it is what you expected.
3. From the traces collected for the square wave input (csv format), measure the time constant of the network from the collected data and compare to its actual value. Consider equation 5 for this process.
4. Plot the sine wave results (simulated input and measured output on the same plot) on separate plots at each frequency (5 plots total).
5. For the sine wave, determine the relative (fractional) attenuation of the amplitude as a function of the quotient of cutoff frequency to the input sine wave frequency (i.e., fcut / fsine). Do not forget to account for the 2π.
6. In a text-style cell, compare the results in (5) to the analytical solution from the prelab and quantify any discrepancies and where they may have come from.

***Analysis for the low pass filter:***

1. Plot the input and output for the square wave investigation on the same plot.
2. In a text-style cell, quantify what effect the filter had in (1) and if it is what you expected.
3. From the traces collected for the square wave input (csv format), measure the time constant of the network from the collected data and compare to its actual value. Consider equation 5 for this process.
4. For the sine wave, determine the relative (fractional) attenuation of the amplitude as a function of the quotient of cutoff frequency to the input sine wave frequency (i.e., fcut / fsine). Do not forget to account for the 2π.
5. In a text-style cell, compare the results in (4) to the analytical solution from the prelab and quantify any discrepancies and where they may have come from.

1. There are three different options, AC, DC, and ground. With AC coupling, any DC component of the input signal is blocked by a capacitor. Since the objective is to observe a true representation of all voltage waveforms encountered in this course, DC coupling will always be used. The input coupling switch has a third position labeled “ground.” In this position, the input signal is disconnected, and the oscilloscope’s input circuitry is connected to ground instead. This is used in conjunction with the vertical position control to assign the zero volt reference potential to a particular horizontal gridline of the graticule. [↑](#footnote-ref-1)