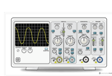
LAB 1: LINEAR CIRCUITS I

UC Berkeley Donald A. Glaser Instrumentation Laboratory

GENERAL GUIDELINES

- **You should complete the prelab questions before beginning benchwork.** Information required to answer the prelab questions can be found in the background material at the beginning of the lab, from lecture, in the stated references, and on the web.
- **Please ask questions of the GSIs or professor(s)** at any time during the course!
- Wikipedia has many useful and informative articles. You are strongly encouraged to use Wikipedia and other online resources to better understand any material.
-  **Problems with this icon need to be checked off by GSIs.**
-  **Problems with this icon indicate that you should take a picture of the circuit built for the problem and include it in your report. Include your student ID, with name clearly visible, in the photo.**
-  **Problems with this icon indicate that you should take a screenshot of the WaveForms oscilloscope.**
- **Important Safety Habits**
  - Before stopping for the day or taking a break, make sure you power down all equipment.
  - When possible, use the switches for the power supplies to power down the circuit when changing the wiring. It is easy to accidentally short wires and damage your equipment or electronic components.
  - Never place food or drink next to any apparatus. Accidental spills can damage or destroy the equipment and your experiment.

Check-off	**Instructor Name/Signature**	**Date**

Table 1. Check-off Table

1. LEARNING GOALS

(1) Become familiar with using a digital multimeter (DMM)

(2) Become familiar with the ADS (signal generator, voltage power supplies, oscilloscope, breadboard) and the WaveForms software

(3) Understand the all important concept of the voltage divider

(4) Understand Thévenin-equivalent voltage sources and Norton-equivalent current sources

(5) Understand and internalize the rule that output impedance of an earlier stage should be much greater than than the input impedance of a following stage so as to not load the previous stage.

(6) Power and RMS

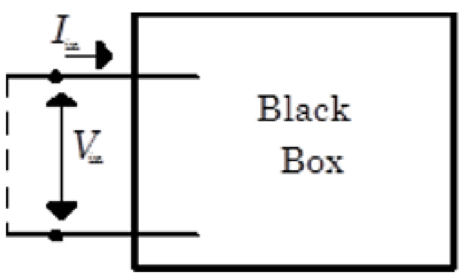
2. LAB BACKGROUND READING

"Student Manual for Art of Electronics" , Hayes & Horowitz	Chapter 1, p 1–31 and p 32–60
"The Art of Electronics", Horowitz & Hill, 3rd edition	Chapter 1.1–1.4, 1.7 and Appendixes A, B, C, D, skim H, and O.

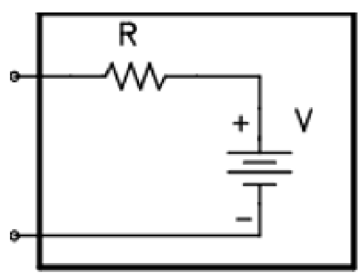
Table 2. Additional Background References

2.1. Thévenin equivalent circuits.

For some background and a proof, see this Wikipedia article or the first class uploaded to bCourses.



(a) A linear circuit black box of arbitrary complexity.



(b) The Thévenin equivalent circuit consisting of a voltage source in series with a resistor.

Figure 1. Any linear circuit of arbitrary complexity can be modeled with its Thévenin equivalent: an ideal voltage source with a resistor.

Perhaps the simplest general circuit is a black box containing some completely unknown and arbitrary internal circuitry that interacts with the outside world through only two external leads (or one port). (Fig. 1a). What can we deduce about the internal circuitry solely from measurements on the two leads? An equally interesting question is: what is the relationship between the current and the voltage across the external leads?

Thévenin's theorem states that if:

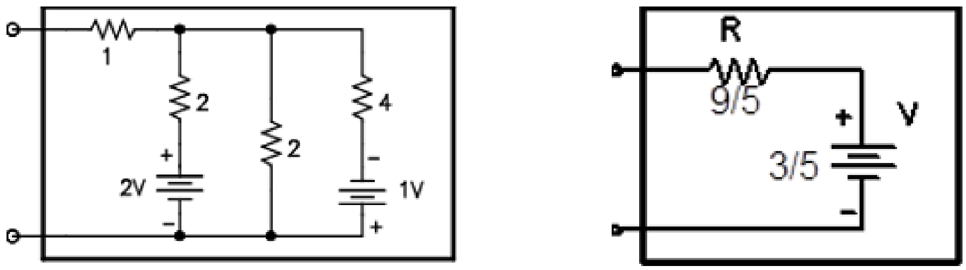
- all elements within the black box have linear relationships between current flowing through the element and the voltage across the element, i.e. $V_j = V_{jo} + I_j R_j$ where j indexes the element, V_j is the voltage across the j-th element, I_j is the current through the element, and V_{jo} and R_j are arbitrary constants)
- all elements within the black box are frequency independent (note: in lab 2, we will show that this constraint is superfluous and we can generalize these concepts to frequency dependent linear circuits with inductors and capacitors)

Then, the interaction of the black box with the environment (i.e. V_{in} and I_{in}) can be perfectly and precisely modeled by an ideal "Thévenin" voltage source, V_{th}, in series with a Thévenin resistance, R_{th} as shown in Fig. 1b. Equivalently, one can say that it is impossible to distinguish between the black box circuit (with all its potential complexities) and this Thévenin equivalent circuit with only external measurements.

How can we measure the model parameters V_{th} and R_{th}? Well, we have two unknown parameters, so we need two non-degenerate measurements. One simple and intuitive set of measurements is:

(1) Measure the "open circuit" voltage, V_{open}. "Open circuit" means that the external leads are disconnected from all loads (except the volt meter); i.e. no current flows in the leads. This measurement directly estimates $V_{\text{th}} = V_{\text{open}}$.

(2) Measure the "short circuit" current, I_{sc}. "Short circuit" means that the leads are connected together with a zero resistance wire; i.e. the leads are "shorted" and there is no voltage drop between the two leads. $R_{\text{th}} = V_{\text{th}}/I_{\text{sc}} = V_{\text{open}}/I_{\text{sc}}$



(a) A relatively complex circuit. (b) Its Thévenin equivalent voltage and resistance.

FIGURE 2. An example of a complicated linear circuit, and its Thévenin equivalent.

For example, the complicated circuit shown in Fig. 2a can be reduced to the Thévenin equivalent circuit in Fig. 2b by measuring the left circuit's open circuit voltage, which is $V_{\text{open}} = \frac{3}{5}$V and its short-circuit current, which is $I_{\text{sc}} = \frac{1}{3}$A. Thus, the circuit on the right must have an internal battery voltage of $\frac{3}{5}$V to match the left circuit, and a resistor of $R_{\text{th}} = V_{\text{open}}/I_{\text{sc}} = \frac{9}{5}\Omega$ to possess the same short circuit current.

Thévenin's theorem would be just a curiosity if it only worked for isolated black boxes. Its power lies in the fact that the Thévenin equivalent circuit behaves to the outside world exactly like the original circuit when inserted into any external circuit. For example, the currents and voltages across and through the external resistors R_1 and R_2 will be absolutely identical in both the original circuit and its Thévenin equivalent (Fig. 3).

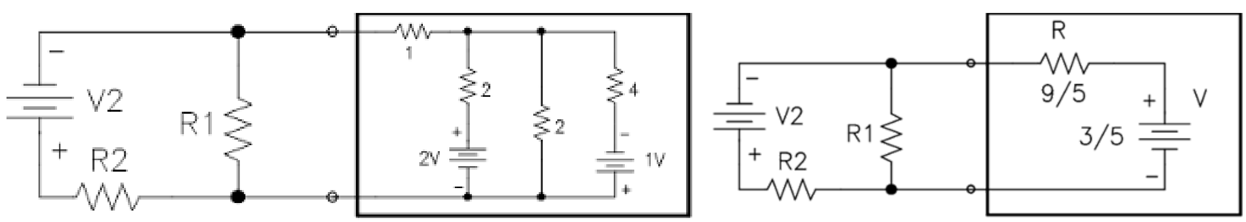


FIGURE 3. All currents and voltages outside of the box are absolutely identical for a circuit and its Thévenin equivalent.

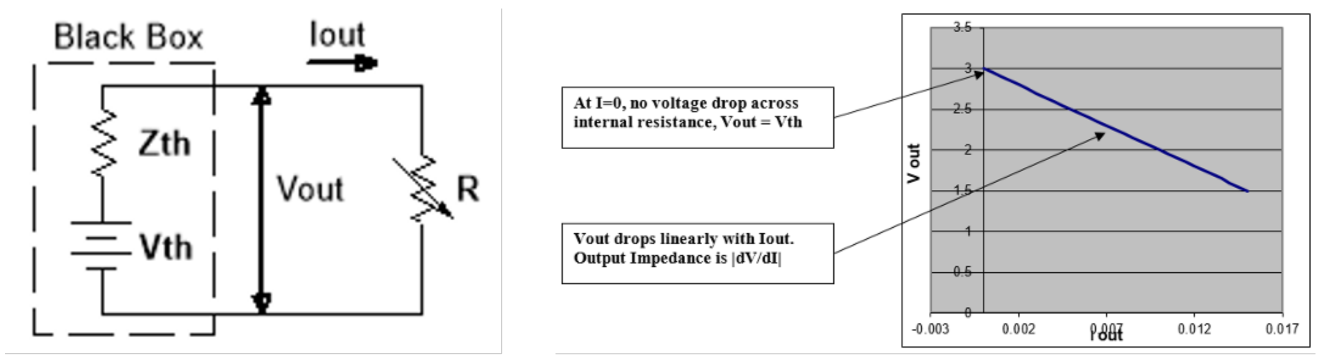
2.2. **Techniques to measure Thévenin equivalent parameters.** In practice, the "short circuit" measurement used above has at least two significant drawbacks. First, oscilloscopes (instruments that measure voltage) are pervasive in labs, while near-ideal current measurement devices are less common. Second, shorting many circuits, like power supplies, could draw excessive current and damage components. As such, a standard, easy way to measure current is to insert a sensing resistor, R, into the circuit as shown in Fig. 4a. With this measurement setup, $I_{\text{out}} = V_{\text{out}}/R$, and the Thévenin parameters can be estimated from this measurement pair:

(1) Open circuit measurement to find V_{th}: $V_{\text{th}} = V_{\text{open}} = V_{\text{out}}(R \to \infty)$.

(2) Measurement with finite R:

$$R_{\text{th}} = \frac{V_{\text{th}} - V_{\text{out}}}{I_{\text{out}}}$$
$$= R\frac{V_{\text{th}} - V_{\text{out}}}{V_{\text{out}}}$$

One subtlety here is how to choose R. If $R \gg R_{\text{th}}$, then your two measurements are nearly degenerate and $V_{\text{th}} - V_{\text{out}}$ is very noisy. On the other hand, if $R \ll R_{\text{th}}$, then V_{out} is close to zero and cannot be measured precisely. Thus, a good rule of thumb is to iterate so that $R \sim R_{\text{th}}$ to produce the most accurate results. To gain intuition about this



(a) A current sensing resistor, R can be used to measure I_{out} for estimation of Thévenin circuit parameters when V_{th} is non-zero.

(b) Graph of V_{out} vs I_{out}.

FIGURE 4. An alternative method of finding Thévenin equivalent parameters.

measurement, it's interesting to plot V_{out} vs I_{out} as one varies R over the entire range from $0 < R < \infty$ as shown in Fig. 4b. By Kirchoff's voltage law, $V_{\text{out}} = V_{\text{th}} - I_{\text{out}}R_{\text{th}}$. V_{th} is just the open circuit voltage ($I_{\text{out}} = 0$ or $R \to \infty$). $R_{\text{th}} = -\frac{\partial V_{\text{out}}}{\partial I_{\text{out}}}$ —it's just the negative of the slope!

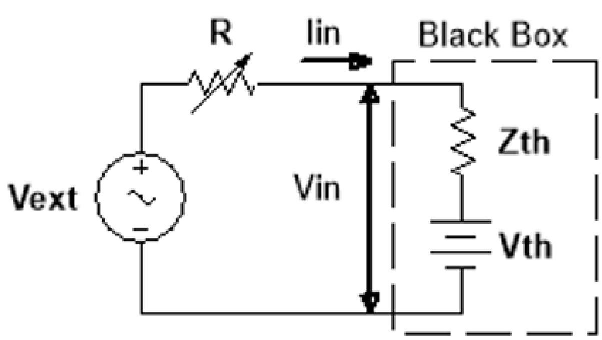


FIGURE 5. An external voltage source V_{ext} and current sensing resistor, R, can measure Thévenin parameters in all possible scenarios.

If $V_{\text{th}} = 0$, then the current through the external port will be 0 for all R; the second measurement in both of the above pairs will not determine R_{th}. In this case, one must measure the black box with an external voltage source, V_{ext}, as shown in Fig. 5. In this configuration, $R_{\text{th}} = \frac{\partial V_{\text{in}}}{\partial I_{\text{in}}}$.

2.3. **Calculating Thévenin equivalent parameters from a circuit diagram.** Given a single port circuit diagram, it is possible to determine the Thévenin circuit parameters by solving a set of linear equations formed by applying Kirchoff's laws. This is always tractable if a little tedious. One technique that is quite useful for calculating R_{th} is:

- replace all ideal voltage sources with short circuits (see P1.4)
- replace all current sources with open circuits (see P1.7)
- calculate the effective total resistance of this source-free circuit (by combining resistors using parallel and series rules or Kirchoff's laws). This is the Thévenin equivalent resistance.

This calculation technique fundamentally works due to the linear nature of the circuit (assumption 1). The currents on each and every element can be calculated for each and every voltage/current source separately and then added together.

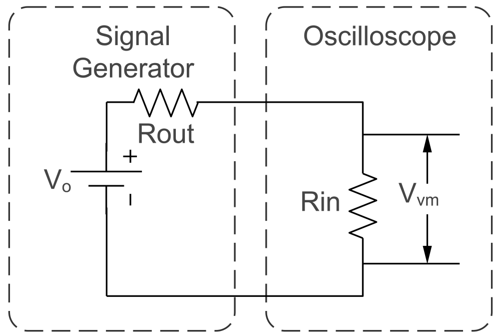
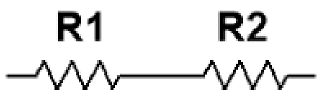


FIGURE 6. We can separately model a signal generator as a Thévenin equivalent output circuit and an oscilloscope as a Thévenin equivalent input circuit. Then, we can connect these two Thévenin models to understand the behavior of the signal generator connected to an oscilloscope!

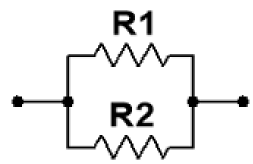
2.4. **Input and output impedance.** When the black box that we would like to model as a Thévenin equivalent circuit is connected to a circuit that is putting a signal **into** the black box, we call its Thévenin equivalent resistance an **input resistance,** R_{in}. Thus, we say an oscilloscope has an input resistance, or the input port of an amplifier has an input resistance (the oscilloscope in Fig. 6). By contrast, if the black box that we want to model is **outputting a signal** to a circuit, like a voltage power supply, a signal generator, or the output port of an amplifier, we call the Thévenin equivalent resistance an **output resistance** R_{out}. Using this nomenclature allows us to understand complex circuits by splitting them up into Thévenin equivalent circuits that interact with each other. For example, in Fig. 6, a Thévenin model of a signal generator is connected to a Thévenin model of an oscilloscope. Notice how the combination is simply a voltage divider! This is why voltage dividers are everywhere!

3. PRE-LAB QUESTIONS

P1.1) Using Ohm's Law ($V = IR$), derive expressions for the resistance of two resistors R_1 and R_2 in both series (Fig. 7a) and in parallel (Fig. 7b).



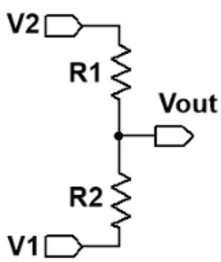
(a) Two resistors in series.



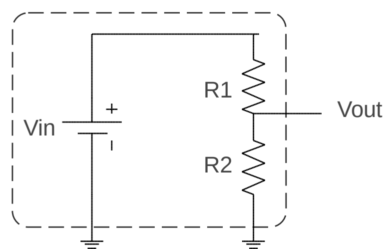
(b) Two resistors in parallel.

FIGURE 7. Resistor combinations.

P1.2) Find an expression for the voltage V_{out} relative to ground (as a function of V_1, V_2, R_1, R_2) in the resistor voltage divider of Fig. 8a. Note that neither V_1 nor V_2 are necessarily at ground. Simplify your solution to show that V_{out} is a weighted average of V_1 and V_2.



(a) Voltage divider between 2 non-zero voltages.



(b) Your standard run-of-the-mill voltage divider connected to ground.

FIGURE 8. Voltage divider setups.

P1.3) In this problem, we use the method for calculating Thévenin-equivalent circuits described in the lab background to the voltage divider in Fig. 8b. This is a really important problem, because voltage dividers are everywhere in circuits!

(a) What is the open circuit voltage V_{out} (voltage relative to ground when V_{out} is not connected to any external components)

(b) What is the shorted circuit current I_{sc} (current when V_{out} is shorted to ground)?

(c) Using your results from (a) and (b) calculate the Thévenin equivalent voltage V_{th} and resistance R_{th}.

(d) Calculate the Thevenin Equivalent resistance using the technique in Sec. 2.3. Confirm that it gives the same answer.

P1.4) **Voltage sources:** I have a voltage source with a Thévenin output impedance R_{out} of $50\,\Omega$ that is connected to a load resistance, R_{L}, as shown in Fig. 9.

(a) When $R_{\text{L}} \to \infty$, what is the voltage across the load resistor, V_{L}, in terms of V_0?

(b) When $R_{\text{L}} = 50\,\Omega$, what is V_{L}? What is the fractional change in V_{L} compared to its value in (i)?

(c) An ideal voltage source is one in which the voltage across the load is independent of R_{L}. What is the output impedance, R_{out}, of an ideal voltage source?

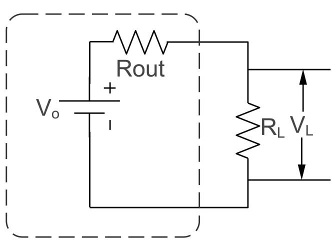


FIGURE 9. Thévenin-equivalent voltage source

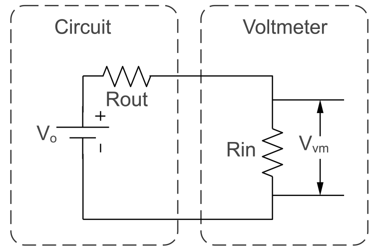


FIGURE 10. Model of a physical voltmeter with input impedance R_{in} attached to an arbitrary circuit.

P1.5) Ideal voltmeters: A physical voltmeter can be thought of as a Thévenin input impedance R_{in} across which a voltage V_{vm} is measured. In Fig. 10, we've connected this volt meter to a voltage source with an output impedance of R_{out}.

(a) If the input impedance of the voltmeter, $R_{\text{in}} = 1\,\text{M}\Omega$, and the output impedance of the voltage source, $R_{\text{out}} \to 0$ what is V_{vm} in terms of V_0?

(b) Now $R_{\text{out}} = 1\,\text{M}\Omega$. How much smaller is V_{vm} now compared to its value in (i)?

(c) An ideal voltmeter would measure the voltage that would exist if the voltmeter wasn't connected to the circuit. What is the impedance of an ideal voltmeter?

Notice what we've done in this problem. Both the voltage source and the voltage meter are being modeled by their black box Thévenin equivalents. The actual circuits are almost certainly way, way more complex than this! Then we put these two simple Thévenin circuits together and made a voltage divider, that we can trivially understand!

P1.6) Current meters: To measure the current flowing through a line, one can break the line and splice in a current meter. An ideal current meter measures the same current that would be flowing through circuit before the circuit was modified for measurement, while a bad current meter doesn't! In Fig. 11a, we break the line and splice in a resistor, R_{in}, and then measure the voltage across R_{in} with a voltmeter as shown in Fig. 11b. Basically, one can make a current meter out of voltage meter (beware: it may not be good current meter![1])

(a) What is the equation for the current I, in terms of R_{in}, R_1, and V_0?

(b) What is the input impedance, R_{in}, of an ideal current meter?

(a) Circuit whose current I we'd like to measure.

(b) A way, though almost certainly not the best way, to measure the current is to break the line and add R_{in}, then measure the voltage across R_{in} with a voltmeter.

FIGURE 11. Measuring currents with current meters.

[1] We'll show you how to make a near ideal current meter using an op-amp about half way through the course.

P1.7) Current source to voltage source transformations: A voltage source supplies a voltage to a circuit and an ideal voltage source supplies a fixed voltage, no matter how big or small the load resistance. Likewise, we can think about a "current source" which supplies a current to a circuit, and an ideal current source which supplies a fixed current to a circuit no matter how big or small the load resistance is. Just like we can simplify any linear circuit to Thévenin equivalent circuit with an effective Thévenin ideal voltage source, V_{th}, in series with a Thévenin resistance, R_{th} (Fig. 12a), we can simplify any linear circuit to a Norton equivalent circuit with an effective Norton ideal current source, I_{N}, in parallel with a Norton resistance, R_{N} (Fig. 12b). After thinking about this for a second, this means that you must be able to transform a voltage source into a current source.

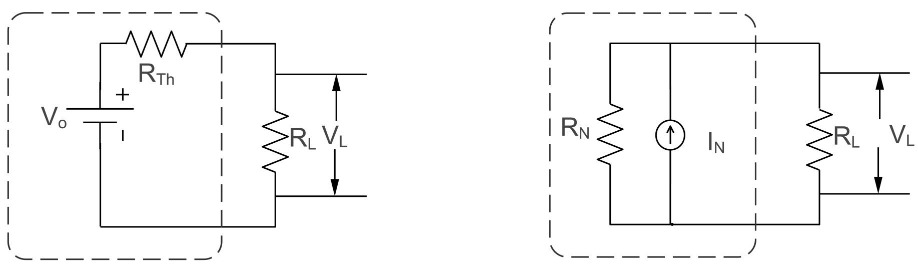
(a) What is the Norton resistance for an ideal current source (one that keeps its current fixed for all possible loads)?

(b) Find the transformation $R_{\text{N}}(V_{\text{th}}, R_{\text{th}})$ and $I_{\text{N}}(V_{\text{th}}, R_{\text{th}})$ such that current flowing through R_{L} is the same for Thévenin and Norton equivalent circuits. With this transformation, you can now think of any voltage source as a current source (though it may be far from ideal), and any current source as a voltage source (though it may be far from ideal)!

(c) What is the Thévenin impedance for an ideal current source (one that keeps its current fixed for all possible loads)?

(d) What is the Thévenin voltage for an ideal current source?

(e) In Sec. 2.3, we talked about a method for simply estimating the Thevenin equivalent resistance/Norton Equivalent resistance. Now that you've done this problem, explain why you replace ideal current sources with an open circuit.



(a) A Thévenin voltage source equivalent circuit. (b) A Norton current source equivalent circuit.

FIGURE 12. Thévenin to Norton equivalent circuit conversion.

P1.8) Any circuit composed solely of linear elements can be solved precisely, though doing the linear algebra by hand can be tedious. In Fig. 13 is a circuit with a few more elements.

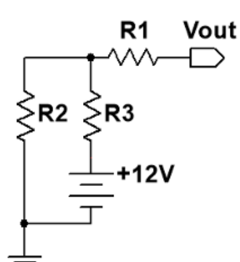


FIGURE 13. A slightly more complex linear circuit.

(a) Find its Thévenin equivalent circuit ($V_{\text{th}}, R_{\text{th}}$) using the method in P1.3. An alternative technique to calculate the Thévenin equivalent impedance is discussed in Sec. 2.3:

- Replace all ideal voltage sources in the system with short circuits
- Replace all ideal current sources in the system with open circuits
- Calculate the total resistance of the output port across the source free circuit. This is the Thévenin equivalent resistance. Does this match your measurement in part (a)?
- Look back at your answers to P1.7 and P1.4. Why does this work?

Show that the Thévenin resistance reduces to the expected simple answers when we take

(b) $R_2 \to \infty$

(c) $R_3 = 0$

P1.9) Before starting the lab, be sure to pick up a lab kit, unbox your ADS, and install the WaveForms software to control the ADS on your computer of choice. Instructions can be found in Appendix E.

4. LAB EXERCISES

Problem L1.1 - Component measurements with the Digital Measurement Meter (DMM).

(a) Get five $10\,\text{k}\Omega$ resistors from your resistor kit (see Appendix A). Always check the value of the resistor by reading its color code, given by the colored bands printed on the resistor. A given resistor will not always have precisely the specified value. The specified values, as opposed to the actual values, are often called the "nominal" values. With the DMM (see Appendix D for instructions on how to unbox and use the DMM for resistance measurements), measure and record the actual values of your five resistors.

The tolerance for most of the resistor values in the lab is $\pm 1\%$; this means that the measured value of the resistor should be within $\pm 1\%$ of its nominal value. *Your DMM likely comes with a specifications sheet showing the relative uncertainties for each resistance measurement range – use the specific datasheet for your DMM if available; more details can be found in Appendix D.6.* After accounting for measurement error of the DMM, are your resistor measurements consistent with the 1% resistor specifications?

(b) Repeat this exercise with five $10\,\text{nF}$ capacitors (see Appendix D.5). The capacitors are only accurate to $\pm 10\%$, so you may observe large variations and discrepancies.

Problem L1.2 - ADS Voltage Power Supply Measurements. If not already done, read the Appendix E to unbox and setup your ADS breadboard and gain familiarity with its operation. Turn on the fixed voltage power supplies ($\pm 12\,\text{V}$, $+5\,\text{V}$, $+3.3\,\text{V}$) by flipping the power supply switches on the breadboard that are shown in Fig. 24b. Verify that the green LEDs turn on to show that the power supply is working.

Use the DMM to measure the DC voltage for each of the fixed power supplies. *Your DMM likely comes with a specifications sheet showing the relative uncertainties for each voltage measurement range – use the specific datasheet for your DMM if available.* Record your results, and attach a voltage reading uncertainty to your results using the specifications of your DMM.

Problem L1.3 - ADS: Getting to know the signal generator and oscilloscope. In this preliminary exercise, you will become familiar with the ADS and the basic functions of the Wavegen and Scope instruments. Here you will be taking signals from the signal function generator and feeding them directly back into the oscilloscope. The signal function generator (also called the Wavegen) produces a voltage that changes as a function of time. The ADS signal function generator has the capability to produce many different types of functions including simple sine, triangle, and square waves. The oscilloscope makes a series of rapid voltage measurements and displays them live as a function of time on the screen of your computer.

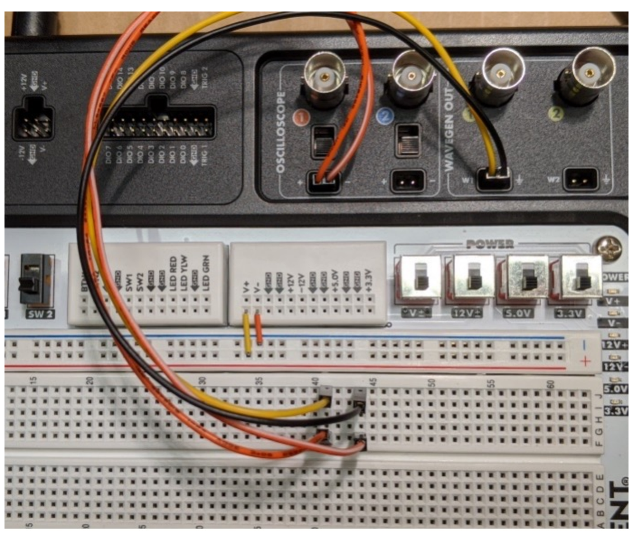


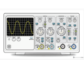
FIGURE 14. Direct connection of the ADS signal generator (W1) to the ADS oscilloscope (C1) with MTE cables.

As shown in Fig. 14:

- take out two sets of MTE cables: orange [O] + orange/white [W] MTE , yellow [Y] + black [B] MTE).
- Connect the YB MTE to channel 1 of Wavegen, with B connected to ground
- Connect the pin end of the YB MTE to 2 breadboard columns
- Connect the OW MTE to channel 1 of oscilloscope (O to + and W to -)
- Place the O pin on the same column as the Y pin to make an electrical connection
- Place the W pin on the same column as the B pin to make an electrical connection

You have now successfully made your first circuit! You've connected the ADS signal generator to the ADS oscilloscope!

- make a diagram of your electrical circuit in your notebook.
- In the WaveForms welcome menu, open the Wavegen instrument by clicking on the Wavegen button on the upper left. Leave all the settings as defaults and click the green Run arrow in the upper left to create the waveform. This will output a 1 kHz frequency, 1 V amplitude sine wave on Wavegen 1.
- Go back to the WaveForms welcome page and open the Scope instrument by clicking Scope. Leave all the settings as defaults and click on the green Run arrow to begin acquiring data. You should see several cycles of the sine wave displayed as a function of time for the orange C1 trace.
- Go back to the Wavegen instrument and vary the frequency of the waveform by changing the values, found in the boxes on the upper left side of the Instrument panel, and observe the changes on the Scope instrument. If you change the frequency by a large factor, you may see only a small portion of the wave or many cycles. In that case, you should adjust the Timebase of the Scope so that it displays several cycles of the wave. Experiment with changing the amplitude of the waveform.
- Open the Wavegen instrument and add a DC offset of +1 V to the waveform. You will now see the waveform on the Scope displaced by this offset. In the Scope panel, add an offset of −1 V to recenter the waveform back at zero volts.



- On the Wavegen GUI, change the type of function between sine, square, and triangle waves and observe the output.

Now that you have demonstrated the basic functionality of the Wavegen and Scope instruments, ideally you would spend some time understanding your ADS in greater depth. Digilent has created several tutorials specifically for this purpose (see Appendix E.7 for links).

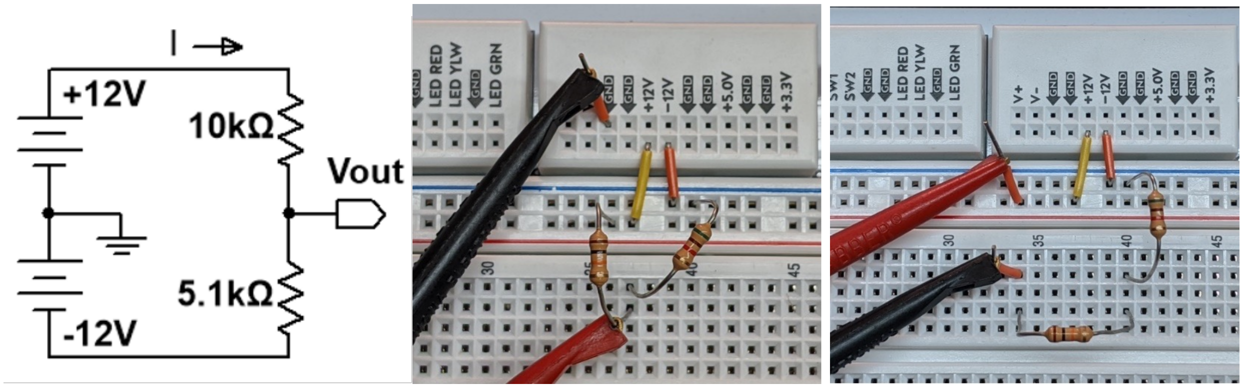
Problem L1.4 - Resistor Voltage Divider. Consider the voltage divider shown in Fig. 15a. Note that the ohm symbol (Ω) is often suppressed when showing resistor values in a circuit diagram, hence, a label "10k" means a resistor with value 10 kΩ, and "5.1k" means a resistor with value 5.1 kΩ. The resistor divider is connected across the +12 V and −12 V supplies.

(a) Calculate the voltage drop across each resistor, the voltage V_{out} relative to the circuit ground, and the current running through the circuit, I. (You've already done the math in Prelab 2 ... just plug and chug!)

(b) Get the 5.1 kΩ and 10 kΩ resistors necessary to build the divider from your resistor kit. Repeat the calculations from (a) using the actual measured resistances and power supply voltages measured with the DMM rather than the nominal resistances and voltages. Are the results different? For most applications, we do not care about small differences in resistor values from the nominal values and do not need to account for deviations at the 1% level.

(c) Now use the breadboard, the power supplies and the DMM to build the voltage divider in Fig. 15a with your measured resistors. A picture of the circuit with the DMM configured to measure V_{out} is shown in Fig. 15b.

(d) **Use the DMM to measure the voltage** across each of the two resistors. For this measurement, the red clip lead should be plugged into the V/Ω/Hz input and the dial should be set to an appropriate V (DC) setting, where DC is indicated by a solid bar over three dashes. Your circuit should look something like Fig. 15b.



(a) Circuit schematic.

(b) Circuit built on the ADS breadboard. The DMM is measuring V_{out} relative to ground.

(c) Measurement of current with the DMM.

FIGURE 15. A voltage divider.

(e) **Use the DMM to measure the current** through the resistors. To measure the current, break the circuit and insert the DMM as a current meter as in Fig. 15c. For this measurement, the red clip lead should be plugged into the µA/mA input and the dial should be set to mA. **After this measurement, be sure to return the DMM connections and settings for voltage measurement**.

(f) Use the measurements from parts (d) and (e) to determine a resistance value for each resistor. Do these values agree with your previous measurements within expected uncertainties?

Problem L1.5 - Voltage Divider: Power Calculations. Using the nominal resistor and voltage supply values for simplicity:

(a) Calculate how much power each resistor in the voltage divider from L1.4 dissipates.

(b) Calculate the minimum value of a single resistor that can be placed across the $+12\,\text{V}$ and $-12\,\text{V}$ power supply without exceeding the maximum $0.25\,\text{W}$ power dissipation allowed for your resistor. **Throughout the rest of this course, you will want to think carefully before inserting resistors of this value or lower in your circuits.**

(c) If you keep the ratio between the two resistors in the divider the same, while lowering the values, which resistor exceeds the maximum power rating first? What is the value of that resistor?

(d) When the condition in (c) is met, what is the total power dissipated by both resistors?

Problem L1.6 - AC Power Calculations. The amplitude of an AC signal can be characterized in different ways: by the peak voltage (or amplitude), the peak-to-peak voltage, or the root-mean-square (RMS) voltage. The RMS voltage is particularly useful for measuring the average power in an AC signal. The average power dissipated by a resistor with AC voltage across it is $P = V_{\text{RMS}}^2/R$. The AC power line voltage, $120\,\text{V}$ in the US, is an RMS voltage, not an amplitude or peak-to-peak voltage. The **RMS** voltage is calculated taking the square root of the mean of the square of the voltage:

$$V_{\text{RMS}} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} V(t)^2\,dt}$$

where T_1 and T_2 mark the beginning and end of one period of $V(t)$.

Derive the coefficients that convert between the amplitude, peak-to-peak voltage, and RMS voltage for

(a) sine waves

(b) triangular waves

(c) square waves

Construct a table showing your results.

Problem L1.7 - RMS Voltages: Measurements.

(a) Use the Wavegen to feed a 1 V amplitude 100 Hz sine wave into both the DMM and the scope. Set the DMM to measure AC Volts (the V∼ setting). **Record** the measured value.

(b) Open the ADS Voltmeter instrument window. This has similar, but slightly different functionality to the "Measurements" functionality of the Scope instrument. In the upper left of the Voltmeter panel, there is a sprocket symbol. Click on it and set the Update Rate to 1 s. Next to the sprocket, the frequency range 4 Hz to 2.048 kHz should be listed. This is the range over which the AC voltmeter (with this update rate) will produce accurate results. This value is fine for the 100 Hz frequency signal that we are currently inputting. When using the ADS AC voltmeter, you must adjust the Update rate so that the frequency of the signal you are trying to measure falls within the displayed range. Shorter update times will accommodate higher signal frequencies. **Record** the measured AC RMS on the ADS.

(c) Open the Scope instrument window. Configure the trace to show several periods of the signal waveform. A Vertical Range of 200 mV/div and horizontal Time Base of 5 ms/div should work well. On the top of the display there is a toolbar with a number of functions. Click on the button that says Measurements (roughly in the center of the bar). A window labeled "Measurements" will open on the right side of the display. Click on the green (+add) button and select Defined Measurement from the drop down window and then Channel 1, Vertical, and click ≥ to expand a list of measurable vertical axis (voltage) quantities. Click on AC RMS and then Add to begin making the measurement. **Compare** to the measured estimates from the DMM.

(d) Add the additional measurements of Peak2Peak voltage, and Amplitude. **Compare** results to your calculations in L1.6.

(e) Using a 1 V amplitude sine wave, vary the frequency of the signal between 10 Hz and 10 kHz as well. **Measure**, as a function of frequency, the RMS voltage of the signal using:

   (a) the DMM.

   (b) the ADS Voltmeter instrument, making sure that the update rate is set so that the signal frequency is within the specified range.

   (c) the ADS Measurements function in the Scope instrument, making sure the scope horizontal axis is adjusted so that several periods of the signal are displayed.

   Create a table with your results. For what values of frequency do the different measurements agree? The DMM is only specified to measure AC voltages in a frequency range (50-400 Hz) and should not be used outside this narrow range. The RMS measurements from the properly configured ADS Scope and Voltmeter should be accurate over a much broader range of frequency.

Problem L1.8 - Thévenin Analysis. Build the circuit that you analyzed in P1.8 with the resistor values shown in Fig. 16.

(a) Use the DMM to measure the open circuit voltage and short circuit current. From this, compute and sketch the Thévenin equivalent circuit. Compare your results with the general calculation you did for the prelab.

(b) Successively attach load resistors R_L of approximate value 330 Ω, 1 kΩ, 3 kΩ, 10 kΩ, 33 kΩ and 100 kΩ from the V_out terminal to ground and measure the output voltage (i.e. the voltage across R_L). Plot the inferred current $I_\mathrm{out} = V_\mathrm{out}/R_\mathrm{L}$ against the measured voltage V_out for each value of R_L. On the same graph, plot the output current predicted by the calculated Thévenin circuit you found in part (a) as a function of the output voltage for these load resistors. Does the Thévenin circuit model predict these voltages accurately?

(c) Remove the +12 V source from the circuit and replace it with a short circuit to ground (**do not short the power supply!**). Use the DMM to measure the resistance between the two terminals. Is it the same as the Thévenin resistance? This is the physical manifestation of the R_{th} calculation technique discussed in Sec. 2.3.

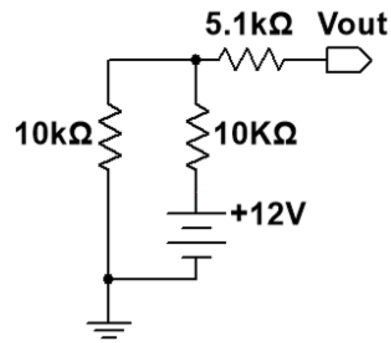


FIGURE 16. Diagram for the circuit studied in P1.8 with specific resistor values.

Problem L1.9 - Measuring Low Frequency Oscilloscope Input Impedance. Build the circuit in Fig. 5 with the scope being the "black box" and use it to measure the input impedance of the scope by connecting the scope to a voltage source through a known resistor R whose value can be varied. Set the Wavegen for a 100 Hz, 1 V amplitude sine wave. Repeat the measurement with several different resistors (for example 0 Ω (a short), 100 kΩ, 1 MΩ, 5.6 MΩ). Use the Scope Measurements function to determine the amplitude of the wave for each resistor value. Use the combination of the measurement of the short and each of the resistors to determine a value for the input impedance of the scope. It is worth mentioning that the output impedance of the Wavegen is not zero. However, its output impedance is so small ($\sim 50\,\Omega$) compared to input impedance of the scope that it can be neglected for this exercise. As we will see in the next lab, the input of the impedance of the scope is actually a function of frequency, and decreases significantly at higher frequencies.

Problem L1.10 - Measure Wavegen Output Impedance. Build the circuit in Fig. 4a, and use it to determine the output impedance of the signal generator.

(a) Set the Wavegen to produce a 1 V amplitude 1 kHz sine wave. Measure the open circuit voltage ($R \to \infty$) with the Scope Measurements function. Of course, you should measure a 1 V amplitude since you set V_{th}.

(b) Measure V_{out} (and thus I_{out}) for a variety of load resistances: 50 Ω, 100 Ω, and 1 kΩ. Determine a value of R_{out} from each measurement.

Problem L1.11 - Measure Power Supply Output Impedance. Calculate the minimum value of a load resistor, R_L, that can be placed across the +12 V power supply and ground under the conservative assumption that the power supply output impedance of the voltage supply is zero. Measure the change in output voltage of the +12 V supply with the resistor closest to this value (but not smaller!) as a load to place an upper limit on the output impedance of the power supply. The supply uses an active circuit to produce an extremely low output impedance.

Problem L1.12 - How does your DMM make a resistance measurement?. Using your ADS and the concepts of Thévenin equivalent circuits, figure out the effective circuit that the DMM uses to make a resistance measurement (i.e. the DMM circuit is the black box for which you are trying to find V_{th} and R_{th}). Draw the Thévenin equivalent circuit for this measurement. Note: each DMM resistance range will have a different R_{th} value. You should find the full Thévenin equivalent circuit (both voltage and resistance: V_{th}, R_{th}) for several resistance ranges, and make sure to choose several load resistors that match the range you are working with.

A. RESISTORS

FIGURE 17. Resistor kit.

FIGURE 18. Loreso capacitor kit.

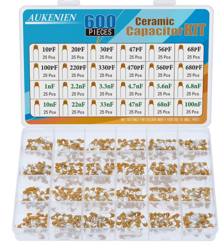


FIGURE 19. Aukenien capacitor kit.

The resistor kit is made up of 1/4W 1% tolerance resistors. It contains 25 resistors ranging from 0 Ω to 5.6 MΩ, and 50 resistors of 100 Ω, 220 Ω, 1 kΩ, and 10 kΩ. The full list of resistances can be found on the inside cover of the resistor kit, as shown in Fig. 17.

The quantity and range of values should be sufficient for the entire semester. However, you should be careful not to waste resistors. After you use a resistor on your breadboard, store it somewhere where it can be reused. If you throw away or lose resistors after using them, you may run out of some values. The color code for the resistors is on the box. Become familiar with it. It is a good idea to check each resistor with the DMM before placing it in the circuit.

B. CAPACITORS

The capacitor kit is made up of ceramic capacitors with 24 different values spanning the range 10 pF to 10 µF, with 25 capacitors for each capacitance value. You may have either a kit from Loreso (Fig. 18) or from Aukenien (Fig. 19). The full list of available capacitances are shown on either the inside cover (if you have a Aukenien kit) or both covers (if Loreso) of the storage box.

Unfortunately, the capacitors are not organized in the box in ascending capacitance. Use the label on the box lid to find the right bin. You should check the value printed on each capacitor. The values are in picofarads ($= 10^{-12}$ farads), with a two-digit number and exponent. In general, a code "*abc*" corresponds to a capacitance of $C = (10a + b) \times 10^c$ pF. For example, "470" $= 47 \times 10^0$ pF $= 47$ pF and "472" $= 47 \times 10^2$ pF $= 4.7$ nF. The tolerance of the values is $\sim$10%. If you need to know a precise value, you can measure the actual values with a DMM. If you need a capacitor value that is not supplied, you can synthesize it with series and parallel combinations. In any case, it is good practice to check the component values before putting them in your circuit. Be aware that the DMM cannot accurately measure capacitance below about 100 pF, so you will not be able to check very small capacitance values with the DMM. The capacitors have relatively short leads ($\sim$0.375"). They will typically span about two columns in your breadboard. If you need to span a wider range of columns with a capacitor, you will need to bend the leads appropriately, or add jumper wires. We have also supplied you with six 0.1 µF capacitors with longer leads. These will be useful later in the course for circuits involving operational amplifiers. They will also be used in Lab 2. Save them for these applications and do not use them for the Lab 1 and Lab 2 exercises unless specifically directed to do so.

C. WIRE JUMPER KIT

The included jumper wire kit (Fig. 20) contains a number of wires precut and bent to convenient sizes. These can be used to easily connect different sockets on the breadboard together to make a circuit. Please try to conserve and reuse these wires as much as possible. We have also included two spools of wire that can be used for longer jumpers or to replace lost or damaged wires. When you use these jumper wires, try to avoid bending them, and choose appropriately sized wires such that they lay flat on the breadboard. This will help immensely in keeping your breadboard organized and visible.

FIGURE 20. Wire jumper kit.

D. DIGITAL MULTIMETER (DMM)

D.1. **Unpacking.** The digital multimeter (DMM) which you have been supplied is the Centech 61593. It is an affordable meter with functionality similar to many more expensive models, and can be used to measure AC and DC voltages, AC and DC currents, resistance, capacitance, as well as measuring the frequency of an oscillating signal, voltage across a diode, and even temperature of the supplied thermocouple. A few key features will be described below, but you are encouraged to refer to the manual for detailed specifications and operating instructions. You should have received a physical paper copy of the manual with your DMM and a PDF is also posted on the bCourses site. We have included two sets of leads with the DMM: point probes and clip leads. The latter can be used to connect to components or short jumper wires that can be plugged into the breadboard as seen in Fig. 21b. You will nearly always find the clip leads more useful for this class. Normally, the meter range automatically adjusts to accommodate the magnitude of the signal being measured. However, you can manually adjust the range. The accuracy of the DMM depends on the size of the signal compared to the maximum signal that can be measured on the DMM range. The manual contains a detailed description of the maximum measurement error as a function of the particular type of measurement, scale of measurement range, and size of the signal. The batteries in the DMM will run out with use, so make it a point to turn off the DMM after making a measurement. The meter will enter a sleep mode after 30 minutes and you will need to push the "Hold" button to wake it up.

Before using the DMM, you will need to install the 9 V battery included in the box. To do this, you will need to remove the screw holding on the battery panel of the meter. The screw is located underneath the removable folding stand on the back of the DMM as shown in Fig. 21c. We have included a Phillips-head screwdriver in the parts kit for this purpose. If your DMM stops working at some point (most likely after you attempted a voltage measurement with the leads connected to the current measurement port), it's likely that you blew a fuse. Pull the back off the meter by unscrewing the 4 corner screws and look for the fuse (Fig. 21d) on the main PCB located below the lead ports. If broken, get a new fuse from a GSI or Win and then install.

D.2. **Voltage Measurement.** The red and black inputs on the DMM that indicate where to insert the test leads to make a voltage measurement; remember that red is positive and black is negative and hook up the test leads accordingly. You have several different voltage measuring options that are selected by the DMM dial: DC Volts, AC Volts, Temperature, AC Current, DC Current, Capacitance, Frequency, and Resistance. AC voltages are reported as Root Mean Square (RMS) voltages and not the amplitude of a sine or triangle wave. The AC voltage function is specified to meet the stated accuracy only over the narrow frequency range (40 Hz to 400 Hz). For this reason, the DMM is not useful for much beyond DC and 60 Hz signals.

D.3. **Current Measurement.** Current measurements are made by breaking a circuit and inserting the DMM. Ideally, the DMM should be much lower impedance than the impedance of the circuit you are probing. There are two possible inputs for the positive lead when making current measurements labeled "20A max" and "mA". The input labeled "20A max" is only used for measuring currents larger than 200mA; this input will result in very poor resolution for the lower currents typically encountered in this lab.

(a) Centech 61593 DMM + probes + multi-function socket.

(b) Clip leads for the DMM.

(c) Unscrew the DMM battery panel to install the battery.

(d) Location of fuses below the battery.

FIGURE 21. The supplied DMM and accompanying components.

You must never exceed the maximum current of 200 mA DC or RMS on the "mA" input. If you do, it will destroy a fuse used to protect the meter that will need to be replaced. **Never** try to measure the current from the output of a power supply to ground. This will not only blow the fuse in the DMM, it may potentially damage the power supply. A common mistake is to leave the meter configured for a current measurement, forget about it, and then attempt to make a voltage measurement. This will end in tears - both yours and the GSIs. **Immediately** after making a current measurement (before you forget), put the red probe back in the voltage measuring position.

Once the correct input for the current has been selected, you can use the yellow button to select an AC or DC current measurement. The AC current function is only specified to meet the stated accuracy over a narrow range in frequency (40 Hz to 400 Hz).

D.4. **Resistance Measurement.** To make the measurement, hook up the red probe to the correct input along the bottom of the DMM for measuring resistance indicated by the Ω symbol and set the dial to the Ω symbol to select a resistance measurement. Be sure to **disconnect the electronic component** you wish to measure from any other circuit elements before making the resistance measurement. The DMM can measure impedances from about $0.5\,\Omega$ to $20\,\mathrm{M}\Omega$. During a measurement, be careful not to touch the component leads with your fingers as they are conductors and will typically contribute an impedance of $\sim 10\,\mathrm{k}\Omega$. When trying to measure low impedances, it is helpful to measure and subtract the impedance of the DMM / scope probes themselves, which is not be negligible. The DMM can also be configured to measure continuity and will make an audible beep if the impedance is less than $75\,\Omega$ between the two probes. This can be useful when you are tracing a low impedance circuit and don't want to look away to see what the meter is reading.

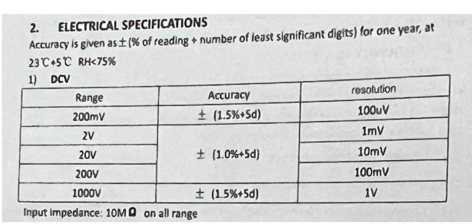
D.5. **Capacitance Measurement.** To measure capacitance on your DMM, use the scope probes with i) the negative (black) probe in the COM (ie, common) slot, and ii) the positive (red) probe into the slot with a capacitor symbol. Also, sometimes one must jiggle the capacitor a bit to get good continuity.

This DMM can measure capacitance values from about 20 nF up to 2 mF. The capacitance measurement option is selected by setting the dial to the capacitor symbol. Most of the capacitors that we supplied are unpolarized. This means that they do not care which capacitor lead is positive and which lead is negative. There are other types of capacitors, called electrolytic or tantalum capacitors, which are polarized. Polarized here means that the lead marked + must always be at a positive voltage with respect to the lead marked -. Note that sometimes, the polarity of only one lead is marked. **Failure to respect this polarity will destroy the capacitor and can lead to fires and/or small explosions**. Polarized capacitors generally have larger capacitance than unpolarized capacitors; we have given you several polarized electrolytic 47 µF capacitors like those shown in Fig. 22. For measurements of small capacitors, it may be necessary to subtract the background capacitance value before measuring. Measurements of capacitance smaller than ~ 100 pF with this DMM will be inaccurate, and you will be better off just using the nominal values.

D.6. **Measurement Uncertainty.** Measurements can suffer from both non-linearity and fundamental limitations of the noise and digitization of the signal. To capture both types of error, the accuracy of the meter is specified by uncertainty $= \pm(n \times \text{reading} + \text{m} \times \text{digits})$ where n is an uncertainty expressed in % and m is the uncertainty in the least significant digit displayed. The value of n represents the non-linearity in the measurement and overall gain errors, while the value of m represents the magnitude of uncertainty due to internal offsets, noise, and rounding errors.

FIGURE 22. An electrolytic capacitor.

Note briefly the distinction between "accuracy" and "precision." Accuracy refers to how close the measurement is the "true" value (for example, can I measure 1 V correctly, or am I measuring 2 V because my instrument is not properly calibrated, etc?). Precision refers to how many digits of uncertainty one can measure down to (for example, can your instrument resolve the difference between 1.001 V or 1.005 V?).



2. ELECTRICAL SPECIFICATIONS

Accuracy is given as ± (% of reading + number of least significant digits) for one year, at 23℃+5℃ RH<75%

1) DCV

Range	Accuracy	resolution
200mV	± (1.5%+5d)	100uV
2V	± (1.0%+5d)	1mV
20V		10mV
200V		100mV
1000V	± (1.5%+5d)	1V

Input impedance: 10MΩ on all range

FIGURE 23. Example of DMM electrical specifications for DC voltage readings.

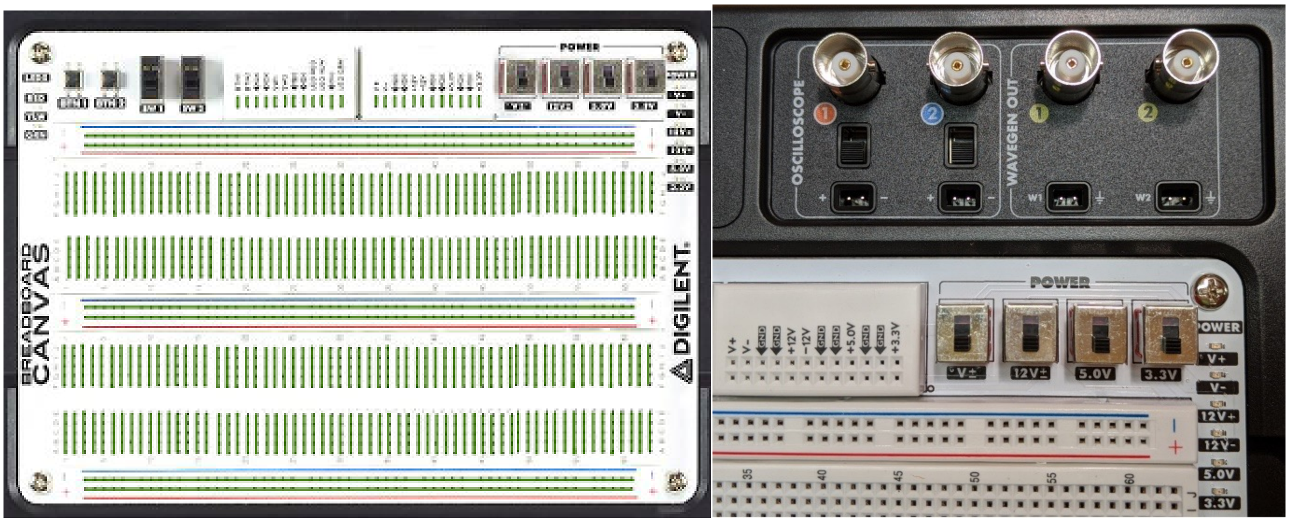
For a given DMM, the values of n and m vary between measurement functions and range. For example, for the 2 V range of the DMM spec sheet shown in Fig. 23, the DMM has an uncertainty of $\delta V = \pm(1.0\% \times \text{reading} + 5 \times \text{digits})$, referring to the least significant digit. If there are 4 digits in the voltmeter display, then on the 2 V range, the most significant digit represents integer multiples of 1 V and the *least significant digit* represents integer multiples of 1 mV (i.e. 0.001 V). This DMM uncertainty means that the range of measurement values expected for a "real" voltage of 1 V is actually $1\,\text{V} \pm (1.0\% \times 1\,\text{V} + 5 \times 0.001\,\text{V}) = 1 \pm (0.010\,\text{V} + 0.005\,\text{V}) = 1 \pm 0.015\,\text{V}$. That is, given the uncertainty of the 2 V range when using this specific DMM to measure 1 V, it can only measure 1 V to an accuracy of 15 mV.

On the 1000 V *scale*, the uncertainty is worse: $\pm(1.5\% \times \text{reading} + 5 \times \text{digits})$ where the most significant digit is now 1000 V and the least significant digit is 1 V. Repeating a measurement of a 1 V signal on the 1000 V scale leads to a range of expected values of $1000\,\text{V} \pm (1.5\% \times 1\,\text{V} + 5 \times 1\,\text{V}) = 1 \pm (15\,\text{V} + 5\,\text{V}) = 1\,\text{V} \pm 20\,\text{V}$. Obviously, the $\approx$1% uncertainty translates into less uncertainty in volts on the 2 V scale than on the 1000 V scale. In almost all circumstances, you should use the most sensitive scale that does not overflow, i.e., for which the signal is within bounds. Said another way, the fractional error is reduced when the signal is closer to the full range.

DC current, AC voltage, AC current, resistance, and capacitance error calculations are performed in a similar manner using the pertinent specifications, ranges, and input signal values. Consult the manual for the appropriate uncertainties for each function and range. In the non-remote version of the course students have access to a DMM that is nearly an order of magnitude more accurate than the one provided here.

E. DIGILENT ANALOG DISCOVERY STUDIO (ADS)

The Analog Discovery Studio (ADS) contains a dual channel oscilloscope, dual channel function generator, fixed and adjustable power supplies, and a breadboard. Basically it has everything you need to test analog circuits! Your home computer connects to the ADS with a USB cable and will control the unit and can be used to store configurations and any data that you gather. The technical specifications of the unit are given here. Please be aware that this unit costs $\sim$ \$500 and you will be required to return it in working order at the end of the semester. But you do get to keep your circuit components and DMM!



(a) ADS breadboard.

(b) Zoomed view into the upper right of the ADS: close up of oscilloscope inputs, Wavegen outputs, power supply switches, and power supply LED indicators.

FIGURE 24. The ADS components.

E.1. Unboxing the ADS.

Instructions for unboxing, getting set up, and downloading and installing the "WaveForms" software used to control the Analog Discovery Studio are here.

A few important instructions:

- A foam protector is placed underneath the breadboard canvas (i.e. the breadboard assembly) to protect the power access pins during shipping (note: since your boards have already been used by previous students, the foam protector may or may not be there). The canvas is held to the ADS by magnets and is **NOT** attached by screws. **Do not remove** the screws on the corners of the breadboard. Remove the canvas by lifting it straight up to remove the foam (Fig. 25). Place the canvas back down onto the ADS once the foam has been removed.

The WaveForms software is available here. Please install it on your home computer now. If you have trouble, please refer to the support information on the Digilent web site before asking the 111A staff for help. Not only will you likely get faster help, we can only provide limited support.

E.2. Powering up the ADS.

Please follow the set-up instructions carefully. For reasons that will become clear as this lab progresses, you will need to take care when constructing circuits to never connect the power supplies directly to the circuit ground, Wavegen output, or each other. This will lead to an overcurrent condition with the potential of damaging your test apparatus. Please proceed with caution.

When the WaveForms software is installed and your computer is ready, plug in the power supply for the ADS and connect it via the supplied USB cable to your computer as in Fig. 26. Connect the ADS to your computer through

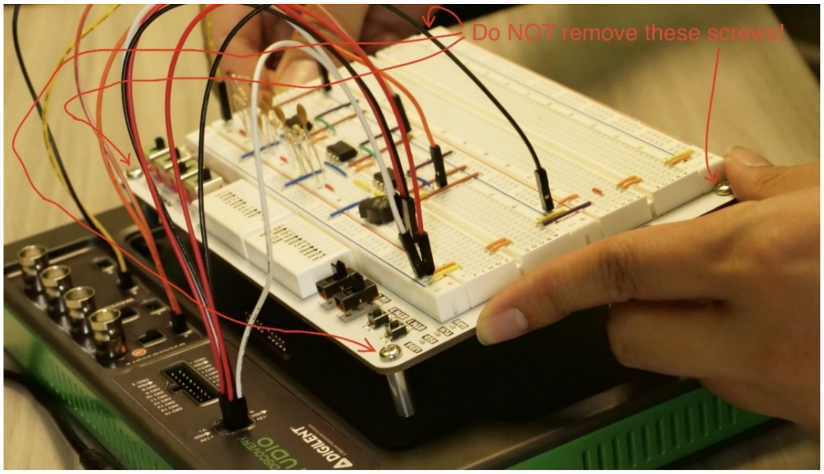


FIGURE 25. Breadboard insert being removed by hand from the base of the ADS unit.

the supplied USB-A to printer cable and turn it on! Launch the WaveForms software on your computer.

FIGURE 26. The ADS connected to power supply and to a computer.

E.3. **Breadboard.** Commercial electronic equipment is constructed on printed circuit boards (PCBs); "wires" are photo-etched onto a sheet of copper, and components are soldered into place. An example of a PCB, for use at CERN, and designed by an undergraduate student, is shown in Fig. 27. Unfortunately, we do not have time to teach you how to make PCBs in this class, but by the end of the class you will be in a position to learn how to design them! In the modern connected world, a couple-layer mid-sized PCB board can be ordered on the internet and shipped to you two weeks later for $30.

To save time, and allow us to reuse components, we will build our prototype circuits on solderless breadboards. A breadboard is an insulating board with a regular pattern of holes that can be used as sockets. The sockets are interconnected with hidden wires, and electronic component leads, or wires pushed into the socket holes will make contact with the interconnecting wires below. On the ADS breadboad (Fig. 24a), there are horizontal rows of sockets marked in red or blue that are all connected together. These are typically used to distribute power to all the components on the breadboard. Between the red and blue rows the sockets are connected together in vertical columns. When you start working with IC Dual Inline Package (DIP) devices, you will see why this is convenient configuration. Fig. 24b

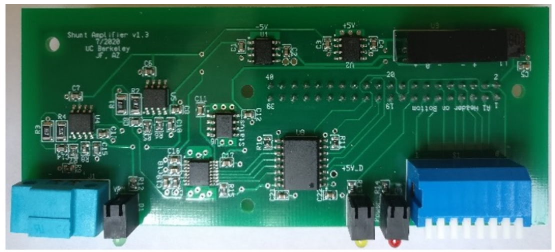


FIGURE 27. Unique PCB board made for for the ALPHA antihydrogen experiment at CERN.

shows a close up of the upper right portion of the breadboard. Here you can see inputs or the oscilloscope and outputs for the Wavegen. The switches below the scope inputs select either the MTE connectors or oscilloscope probes as the inputs. Always have the switches in the downward position; we will not be using oscilloscope probes this semester.

Breadboard best practices.

- Use 22-gauge solid (not stranded) wire to make connections. Wire gauges (thicknesses) are listed at here. Use the precut wire jumpers when possible, but for long wires (e.g. for an antenna) you can:
  (1) Cut interconnecting wires from the provided spool to the right length.
  (2) Strip $\sim$ 3/8" of insulation from each end. A video demonstrating the operation of the wire strippers is posted on bCourses: go to the 111A page $\rightarrow$ Media Gallery $\rightarrow$ Lab 1 $\rightarrow$ Stripping_MVI-0152. Note you must click on Lab 1 to see all five videos!
  (3) Poke the bare wires into the breadboard socket holes until they bottom out.

  Breadboards are delicate! Forcing wires or component leads into the board can damage the sockets or make a poor connection. Wires or leads that do not fit easily into the breadboards may be too thick.
- Use the buses (the long horizontal strips shown in Fig. 24a) for power and ground connections. A "bus" is jargon for a signal going to many places. Typical examples are power and ground connections. Good bus habits will save you lots of time and trouble with complicated circuits by making your circuit wiring more transparent and by removing unnecessary clutter.
- Build your circuits compactly. Long leads between components introduce stray capacitance and can result in oscillations or high frequency (e.g., radio frequency (RF)) pickup.
- For clarity, signals should flow from left to right; place input signals on the left side of the board, circuitry in the middle, and output signals on the right side. If you need more than one row, have your signals flow from top to bottom.

E.4. **Power Supplies.** The ADS has four fixed power supplies +12 V, −12 V, +5 V and +3.3 V. The ADS also has two adjustable power supplies, one (labeled V+) can be set between 1 and +5 V and the other (labeled V-) between -1 and −5 V. The voltage of the adjustable supplies is set with the Power Supplies panel in the WaveForms control software. All of the supplies are available from connections at the top of the breadboard (Fig. 24b) that are labeled for each of the supply voltages. The row of switches in the upper right corner is used to enable the breadboard power supplies. The switch labeled 12 V± enables both the +12 V and −12 V supplies and the switch labeled V± enables both the V+ and V- supplies. When any of the power supplies are enabled, the LEDs corresponding to those voltages will light. In Fig. 15b, the +12 V and −12 V switched supplies have been connected to the red and blue horizontal busses with short jumpers. The +12 V, −12 V, V+ and V- supplies are also available from the MTE cable in the upper left side of the ADS. However, these supplies are not controlled by the switches on the breadboard. It is convenient to be able to power down your circuits while leaving the main power and computer interface active when you are modifying the circuit, so you should use the switched supply outputs at the top of the breadboard for most applications.

The output impedance of all the power supplies is very low (50 mΩ) and they should never be connected to directly to ground with a wire or with the DMM configured for a current measurement, a Wavegen output, or another power supply.

E.5. **Commons and Grounds.** Recall that voltage is a measure of the potential difference between two points. Although we say "the voltage at point A", we really mean "the voltage at point A with respect to the local zero-potential reference point." The most useful zero-potential reference point is the earth itself — the "ground." A ground in any circuit is defined to be any wire, lead or bus somehow connected to the earth.

The utility company thoughtfully provides a wire connected to the earth in all three-pronged power outlets (Fig. 28), and that ground wire is often connected to a ground lead in electrical equipment. Thus, the potential of a point in a grounded circuit is the same as the potential difference between that point and the earth. Why do most electrical wall sockets have three leads? The utility company intends current to flow between the hot and neutral wires in the wall socket, the two rectangular slots. No current should flow in the ground wire. The utility company arranges its transformers so that the hot lead is approximately 120 V from the neutral, and the neutral is approximately at ground. But things are rarely perfect, and the neutral lead is often a few volts from ground. As for the ground lead itself (the horseshoe shaped hole), the utility company grounds the lead by actually attaching it to a long conducting rod stuck into the earth. Look for the ground wire the next time you walk by a transformer on a pole!

Other good grounds are available. Cold water pipes, for example, are well connected to the earth, and are often used as grounds. The utility company doesn't supply the ground as a courtesy for electronic circuits builders; they supply it for shock prevention. Electrical shocks occur when a sufficiently high voltage drives a sufficiently high current through the victim's body. Most dangerous are shocks in which currents travels through the victim's heart; only 50 mA can be lethal. Grounding the outer case of a piece of equipment greatly reduces the chance of shocks by shielding the user from any high internal voltages. It is difficult (but not impossible!) to get a serious shock with voltages less than about 50 V. While you should always think before touching a bare wire or component, shocks should not be a problem with any of the circuits in the 111A lab.

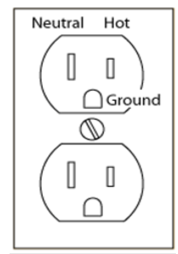


FIGURE 28. A wall outlet.

Caution: Standard electronic circuit construction always uses black for ground, red for power and other colors for signal leads. However, North American building wiring always uses white for neutral, BLACK FOR HOT (the dangerous lead), and green for ground. Do not attempt to use the ADS scope to look at any of the lines from the wall outlet or circuits directly connected to the wall outlet. This will destroy the ADS unit and expose you to potentially lethal voltages.

Despite the fact that the ADS analog input channels are fully differential, a GND connection to the circuit under test is required to provide a stable common mode voltage. The ADS's GND reference is connected to the USB GND of the cable. Depending on the PC powering scheme, and other PC connections (Ethernet, audio, etc. – which might also be grounded) the ADS GND reference might be connected to the whole GND system and ultimately to the power network protection (earth ground). To avoid damage to the ADS unit, any circuit under test cannot exceed the specified voltage limits of common mode ($|V_{\text{common}}| < 50\,\text{V}$) and differential ($|V_{\text{common}}| < 25\,\text{V}$). Be careful and check for any potential differences with the DMM before connecting the ADS to any external circuit. The grounds for the Wavegen outputs, power supplies, and BNC inputs to the scope are all connected together.

E.6. **Oscilloscope.** An oscilloscope is a device that displays a plot of signal voltage versus time.

Historically, an analog oscilloscope produced this image by having the voltage produce a B-field, which would bend the trajectory of e^- flying out of a cathode ray tube just like in the very first TVs.

By contrast, a modern digital oscilloscope does this in four steps:

(1) Digitization: The oscilloscope digitizes the data with an analog to digital converter (ADC). For our ADS, the ADC is 14 bit.

(2) Triggering: the oscilloscope decides what time period to store.

(3) Storage: The oscilloscope stores this digitized trace in either short term or long term memory storage.

(4) Plotting: The oscilloscope plots the data onto a screen.

Thus, in a very true sense, any laptop can be turned into a digital oscilloscope if you have an ADC card! In fact, most ADC cards that you buy have manufacturer-supplied software included to reproduce oscilloscope functionality to various degrees.

Oscilloscope control. The main WaveForms Welcome window shows all of the available instruments. Click on the Scope instrument to open the oscilloscope.

- Channel configuration and vertical controls: You can turn channels Channel 1 (C1) and Channel 2 (C2) on/off for viewing by checking the boxes on the right side of the scope screen which are color coded orange (C1) and blue (C2). In this box, you can click on the box labeled Range to adjust the vertical scale (volts/division). If the input signal is a 1 V amplitude sine wave (2 V peak to peak), setting the Range to 200 mV/div the signal would take up all ten divisions in the display. The Offset of the displayed signal can also be adjusted. By selecting an Offset of −1 V, the center of the scope display will now be 1 V rather than the default 0 V. The offset can be quickly adjusted by clicking and vertically dragging the triangular indicators for each of the channels on the left side of the display. This is a useful feature if the signal you are interested in is an AC signal with a large DC offset. You can offset the display and decrease the volts/division to create a high-resolution display of the AC signal. If you click the icon in the upper right of the box for each of the channels, there are additional configuration settings. The most useful setting is an Average control that allows you to average several traces together to increase the signal-to-noise of a properly triggered periodic signal.

  By making a selection from the Math menu in the Add Channel menu, you can create a new channel that is a mathematical function of C1 and C2. One simple and common function would be to calculate the difference between channels C1 and C2. You can configure this by selecting “Simple” from the math menu. A box labeled Math 1 will appear and you can set it for your desired function Math=C1-C2.

- Horizontal scaling and position controls: The horizontal scale of the display is set by adjusting the values in the Time box. The Base setting adjusts the time interval being displayed. There are 10 divisions, so a Base setting of 1 ms/div will display 10 ms of data. During this time, 1 kHz sine wave will make ten complete cycles. The center of the scan is determined by when the scan is triggered, which we will discuss in the next section. By entering a non-zero value in the Position window, the center of the display is shifted to center the scan on that time relative to the trigger. The triggering time of the scan is unaffected. This allows the user to more closely inspect what came before or after the event triggering a trace. The Position value can be quickly adjusted by clicking and horizontally dragging the triangular indicator at the top of the display.

- Triggering: Many signals of interest are repetitive. Traces of repetitive signals can be made to overlay and produce a quasi-static image. To make the trace repeat, the scope will need to be triggered so that it begins the scan at the same point in the waveform. The scope “Trigger” is one of the more subtle controls to understand.

  The triggering menus are in a toolbar just above the display. The scope can be set to trigger just once (Single) and display the data, or to trigger repeatedly (Run) and update the trace continuously. Usually we will want to trigger repeatedly, so we will click the Run button.

  There are three options for the triggering. Selecting None will start the data acquisition at a random time. In this configuration, a repeated waveform will jump around in phase and appear jumbled on the screen. This setting is rarely useful for repetitive waveforms.

  When the trigger is set to Normal the scope will, for a repetitive signal, attempt to find the same “place” in the signal for every scan across the screen. The Source control determines what channel signal will be used for the triggering. It can be set to either channel of the oscilloscope, either channel of the Wavegen, or to dedicated triggering inputs. In the simplest case, we set the scope to trigger on the scope channel with the signal we are interested in. The Level control selects the trigger voltage. When the selected input reaches this value, the scope will trigger. It is good practice to set this to a level where the signal is changing rapidly, that way the signal will pass through the trigger level quickly and will be less effected by noise. For a sine or square wave centered around 0 V, the signal is changing most rapidly as it passes through 0 V. The trigger level is indicated by the triangular indicator on the right side of the display and can be adjusted by clicking and dragging that indicator. With the Condition configuration, the scope can be configured to trigger only when the signal is increasing (Rising) or decreasing (Falling) in time. Without this, there is an ambiguity where to start the scan as a periodic signal will cross the trigger threshold twice per period. When the scope is set to trigger on either Rising or Falling, a high signal to noise periodic signal will produce the same trace with every trigger and will appear to be fixed on the screen. The horizontal position of the trigger will be marked by the triangle symbol at the top of the display. By default, this will be at the center of the screen. However, it can be moved with the Position control.

When the trigger is set to Auto, the scope will trigger in the Normal mode if the triggering conditions are met. If the triggering conditions are not met, the scope will trigger randomly as in the None mode. This Auto option makes it easy to get a quick look at the signal while adjusting the trigger levels.

- Making Measurements: The digital oscilloscope is capable of performing mathematical operations on a trace or series of traces to make measurements of an input signal such as frequency or amplitude. You can configure the scope to perform a measurement by clicking the Measurements button at the top of the scope controls. From there, select Add, Defined Measurement, Channel, and Vertical or Horizontal. If you select Vertical, you will be presented with a list of measured quantities including Average, Amplitude, Peak2Peak, and RMS. These results are calculated from all the values in the trace and are generally much more accurate than trying to guess the values from looking at the trace. However, sometimes a measurement is nonsense; you should always make sure that the measurement makes sense by confirming it on the trace. For instance, one thing that users commonly wish to measure is the peak to peak amplitude (Peak2Peak). This measurement is often confounded by noise. The Amplitude measurement uses an algorithm that is less sensitive to noise, and twice the Amplitude is often more a more accurate measurement of the peak to peak amplitude than the Peak2Peak measurement.

  One of the more powerful functions, which we will use in the second lab, is the "FFT" which performs a fast Fourier Transform on the trace data and displays signal components as a function of frequency. This is particularly useful for identifying and measuring weak signals in the presence of noise or other strong signals.

Oscilloscope Measurement Accuracy. The ADS scope is a digital scope in which the incoming signal is converted into a digital representation before being processed or displayed. The analog to digital converter (ADC) for the scope function has a resolution of 14 bits: which means that it can digitize a voltage range into 2^{14} bins. The user has the freedom to choose the size of this voltage range by setting the maximum input voltage, V_{ref}. A voltage V in the range of $|V| < V_{\text{ref}}$ will be digitized in discrete steps of $\Delta V = (2V_{\text{ref}})/2^{14}$, while those outside of this range will be saturated. Thus, one can have a large V_{ref} with large digitization voltage error, ΔV, or a small V_{ref} with small ΔV. Thus, one should choose the digitized range to match the range of expected voltage signals.

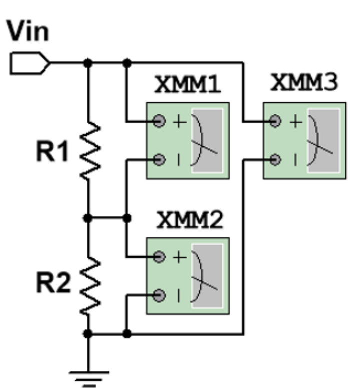
For the ADS, the value of V_{ref} is implicitly chosen (in what is truthfully a non-optimum way) by setting the vertical scale on the oscilloscope plot:

- When the vertical scale $= 0.5\,\text{V/div}$ is chosen, there are 10 divisions on the screen spanning $\pm 2.5\,\text{V}$, and $V_{\text{ref}} \sim 2.6\,\text{V}$,slightly beyond the maximum displayed range. $\Delta V = 0.32\,\text{mV}$.
- When the vertical scale $< 0.5\,\text{V/div}$ is chosen, V_{ref} remains $\sim 2.6\,\text{V}$ with a corresponding $\Delta V = 0.32\,\text{mV}$.
- When the vertical scale $> 0.5\,\text{V/div}$ is chosen, V_{ref} is $\sim 26\,\text{V}$ with a corresponding $\Delta V = 3.2\,\text{mV}$ (the signal is attenuated by a factor 10 before digitization).

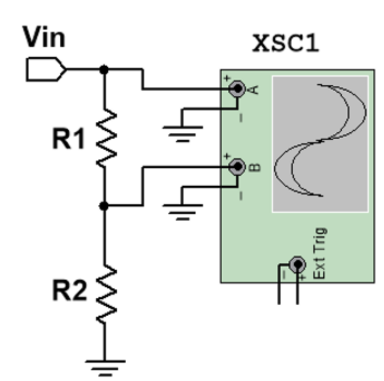
In determining the resolution, the offset matters as well and the ADS will default to coarse resolution if $5 \times (\text{volts/div}) + |\text{offset}| > 2.6\,\text{V}$. In practice, noise, offsets, and non-linearities in the scope amplifiers and ADC will generally degrade the accuracy below the limit from the digitization. The absolute accuracy depends on the volts/div scale being used for a measurement. For scales $\leq 0.5\,\text{V/div}$, the accuracy is specified as $\Delta V = \pm 0.5\% \times \text{signal} \pm 10\,\text{mV}$, where $\pm 0.5\%$ signal represents non-linearity in the ADC converter and $\pm 10\,\text{mV}$ comes from a constant offset in the input stage (which can in principle be zeroed). The measurement of a sine wave amplitude is insensitive to this later offset. For AC measurements, the accuracy is limited by non-linearity for large signals and by noise (RMS $\sim 0.3\,\text{mV}$, which is close to the resolution) for small signals. For repetitive signals, the noise can be averaged down over several scope scans. For scales $\geq 1\,\text{V/div}$, the signal is attenuated before digitization and the noise and input offset of the scope amplifiers are larger by a factor of 10 compared to the incoming voltage. Thus, the accuracy is specified as $\Delta V = \pm 0.5\%$ signal $\pm$ $100\,\text{mV}$. The accuracy of a large amplitude AC measurement is unchanged, but the noise increases (RMS $\approx 3\,\text{mV}$). With the ADS and laboratory oscilloscopes as well, we should use the smallest value of volts/div that can capture the signal in order to maximize the signal-to-noise.

Oscilloscope Inputs and Grounding. There are two ways to input signals to the oscilloscope: the MTE and Bayonet Neill–Concelman (BNC) connectors. The BNC connectors are the silver cylinders in the upper right of Fig. 24b. These are primarily used with scope probes and will not be used in this class. The other input to the scope is through the "MTE" connectors (Fig. 14) which are a pair of wires with a plug on one end and pins for the breadboard on the other. This is the how we get signals out of the Wavegen to the breadboard and into the Scope from the breadboard. The input to the scope ADC is differential; the voltage displayed is the voltage difference between the positive and negative inputs. The wires from the MTE connector preserve this fully differential input and are labeled as (+) or (-) to denote polarity. These inputs can be configured in the same way as for a voltage measurement with the DMM. These wires can be connected to any place in the circuit so long as neither of the voltages exceeds ±50 V relative to the ADS ground and the difference between the (+) and (-) inputs does not exceed ±25 V. If you switch the (+) and (-) inputs, the voltage will simply switch sign. Fig. 29a shows the possible configurations for a differential voltage measurement. In this figure, XMM1, XMM2 and XMM3 represent differential voltage measurements that could be a differential voltage measurement or one of the scope channels when using the MTE connector. In this configuration, it is possible to measure the voltage across both R_1 and R_2 directly with a single channel.

However, with the Bayonet Neill–Concelman (BNC) input to the scope, the outer connector (shield) of the cable is automatically connected to the ground of the power supplies which is connected to the USB ground. When using the BNC input, the outer connector must never be connected to anything other than ground, and especially not any of the fixed or adjustable power supply outputs. Fig. 29b shows the only two direct measurements of the voltage divider that can be made with the BNC inputs. With the BNC input, it is not possible to directly measure the voltage across R_1. However, you can use the "Math" function in the oscilloscope instrument to compute the voltage difference between the C1 and C2 inputs, (VC1−VC2) to determine the voltage across R_1. If the voltages on C1 and C2 are large, then it requires that the scope channels be set to a larger and potentially less accurate input scale. As we will see in Lab 2, there are good reasons to use the BNC inputs (and scope probes) for high frequency signals and high impedance circuits. However, we will generally be working at frequencies low enough that scope probes are not required, and no scope probes are provided in the ADS kit. There are switches above the scope MTE connections, that select between the BNC and MTE inputs. These should always be in the "down" position to select the MTE inputs.



(a) Possible voltage measurements when using a differential voltage measurement device (XMM) like the ADS oscilloscope when using MTE connectors.



(b) When using the ADS oscilloscope with BNC connectors, the - channel is directly connected to ADS ground. Thus, measurement of the voltage across R_1 requires 2 channels.

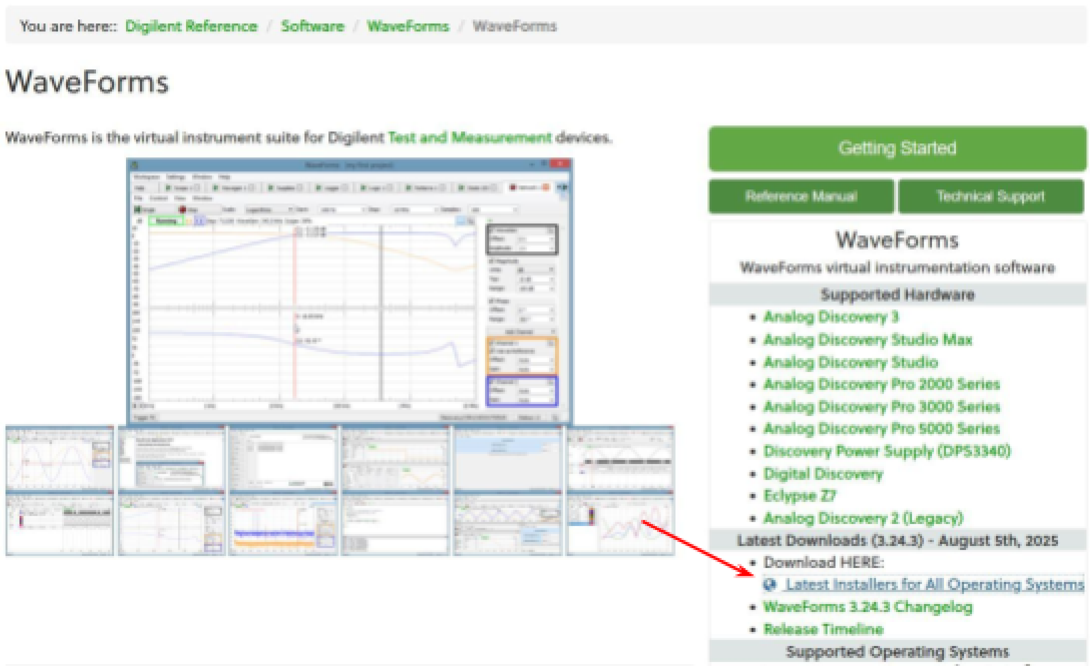
FIGURE 29. Measuring voltages with MTE and BNC connectors.

E.7. **ADS Getting Started & Tutorials.** **We highly recommend the Digilent Getting started guide, which has clear instructions for *installing the Waveforms software.*** Supplemental instructions to install *Waveforms* below.

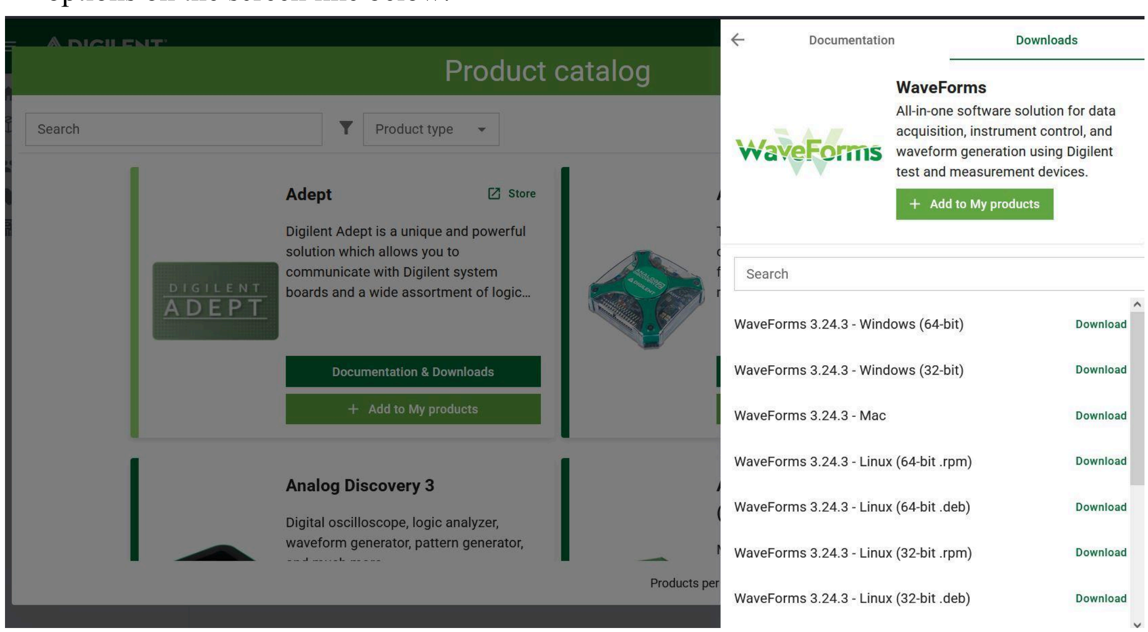
Digilent has also provided a series of tutorials for the various instruments (here) that will give you a more complete understanding of the equipment and its capabilities. At this point, you should work through tutorials for the following instruments: Power Supplies, Oscilloscope, Wave(form) Generator, and Spectrum Analyzer.

Installing Waveforms - Supplemental instructions

1. Go to the [WaveForms website]() and click ‘Latest Installers for All Operating Systems’.



2. Make an account with Digilent. We recommend registering using your Berkeley email account. Once you have created an account and logged in, you should see a list of download options on the screen like below:

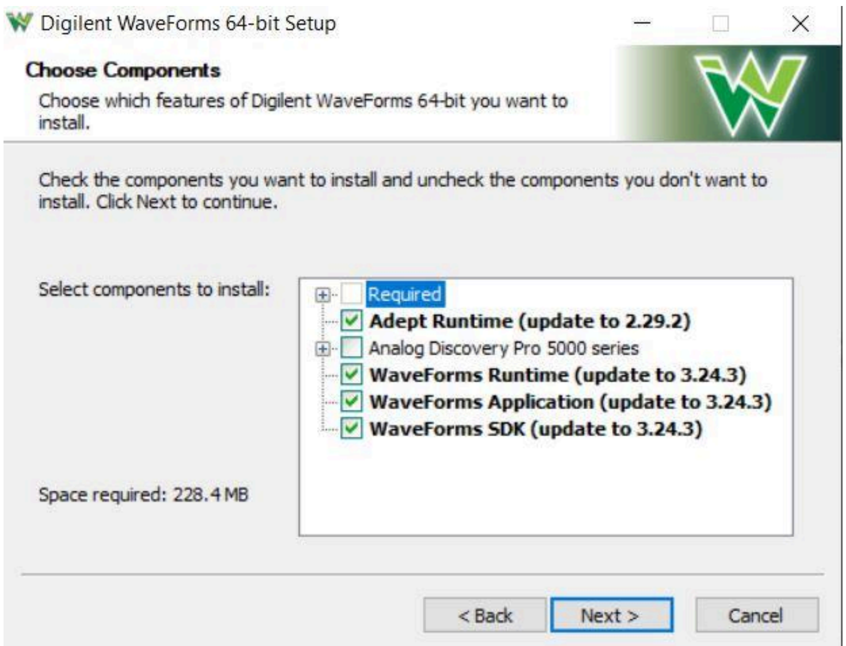


3. Select the version for the operating system for your computer and click ‘Download’. Then proceed to the section of this guide appropriate for the operating system your computer uses.

Supplemental instructions written by Auden Young, and last updated 8/28/25.

Windows

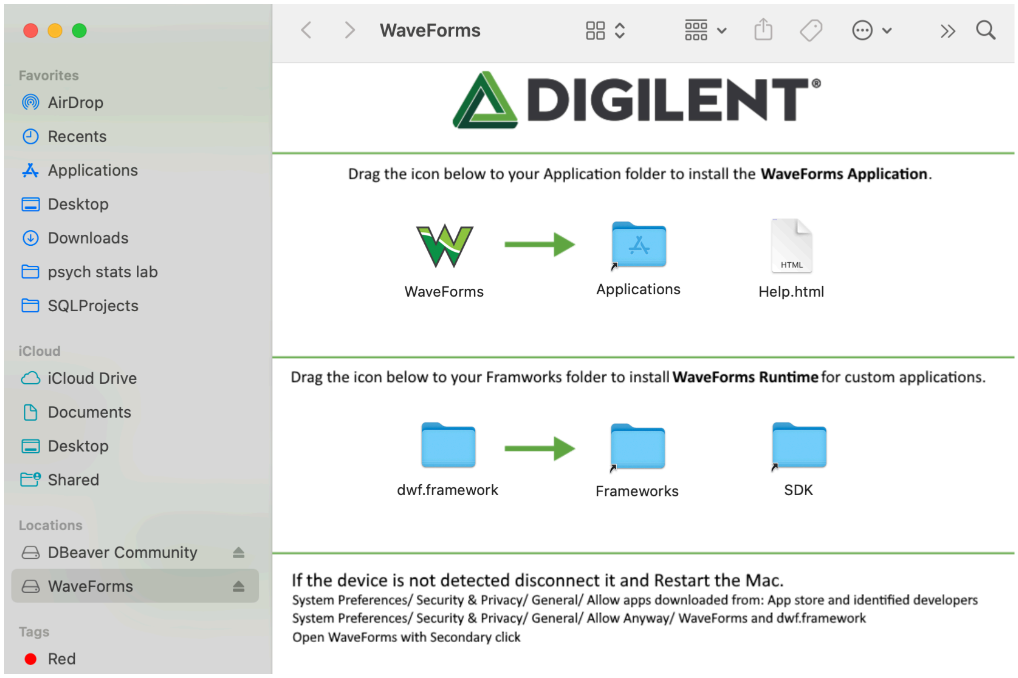
Click the .exe file that has downloaded and follow the prompts. The main thing to make sure of is that all of the options as in the window below are checked to be installed (Adept Runtime, WaveForms Runtime, WaveForms Application, and WaveForms SDK - this last will become important for Lab 10, so make sure you install it!).



After completing the Setup Wizard, WaveForms should run successfully.

Mac / iOS

PLEASE carefully follow all the steps in this section, or you will need to reinstall WaveForms for Lab 10. Click the .dmg file that you downloaded. You will see a screen like the one below:

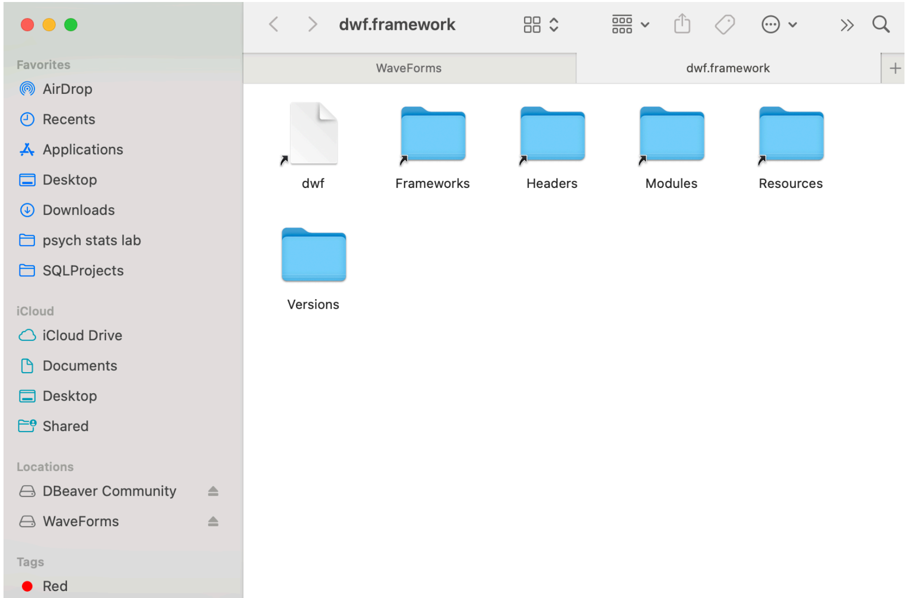


- It is very important that you drag both WaveForms to the Applications folder AND the ‘dwf.framework’ folder to the ‘Frameworks’ folder. It likely will not let you drag it, so you’ll have to manually copy it. (If you think it has been dragged into the ‘Frameworks’ folder successfully, right click to open the ‘Frameworks’ folder in a new tab and double check ‘dwf.framework’ is present.)

- Right click on the ‘Frameworks’ folder and click ‘Open in new tab’; do similarly for the ‘dwf.framework’ folder.

- Highlight all of the contents of ‘dwf.frameworks’ and copy, then paste into the ‘Frameworks’ folder. You will likely need to use your password to allow this.

- Create a subfolder in the ‘Frameworks’ folder called ‘dwf.frameworks’ and drag the contents you copied over into this subfolder. There should be a file called ‘dwf’, as well as folders called ‘Frameworks’, ‘Headers’, ‘Modules’, ‘Resources’, and ‘Versions’ - the contents are shown below:



Once you have moved the ‘dwf.frameworks’ folder into your ‘Frameworks’ folder and dragged the ‘WaveForms’ application into the ‘Applications’ folder, you have completed installation.

Linux

The lab staff will be less familiar with Linux-affiliated bugs that may arise, especially as Linux distributions and individual installations may vary greatly. However, it is possible (as far as we know) to do Physics 111A using the Waveforms software on a Linux machine.

- Navigate to the folder you have downloaded the file to on the command line. If you download the .rpm file, you should be able to run (replacing `mypackage` with the full filename):

```
sudo rpm -U mypackage.rpm
```

- If you download the .deb file, you should be able to run (again, replacing `mypackage` with the full filename):

```
sudo apt install ./mypackage.deb
```

Again, running the Waveforms software with an arbitrary distribution of Linux may be trickier with issues that we cannot easily support. If you use a Linux machine and have issues, it may behoove you to partner with someone who uses Windows or iOS.

Supplemental instructions written by Auden Young, and last updated 8/28/25.