

Oscilloscope Fundamentals and Joystick Interfacing

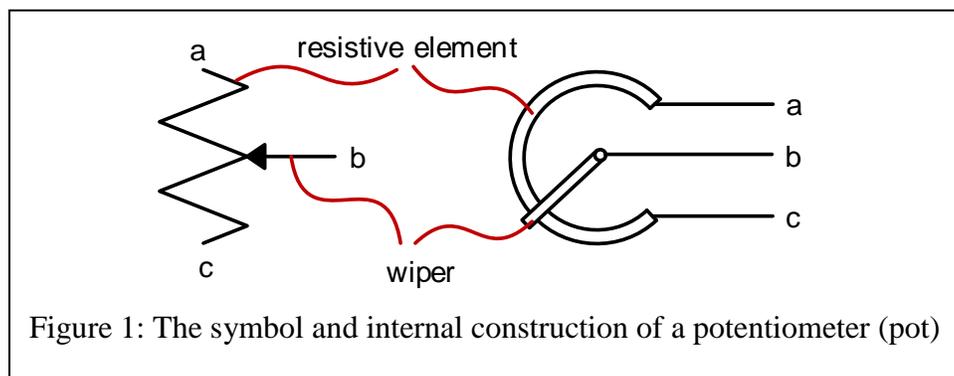
Objectives

- 1) Learn the fundamentals of how all oscilloscopes (analog and digital) work:
 - Vertical amplification subsystem (Volts/Division)
 - Horizontal sweep subsystem (Seconds/Div)
 - Triggering subsystem
- 2) Be able to measure a waveform using the triggered mode of oscilloscope operation
- 3) Be able to describe where to connect the scope's negative/ground lead.
- 4) Be able to describe how potentiometers work
- 5) Be able to describe how to design a variable voltage reference

Prelaboratory: Read this article about potentiometers and creating a voltage reference, skim the instructions for the lab, and answer the prelab questions. As always, prelab questions are to be done individually, and the lab is to be done with your lab partner.

Potentiometers

A potentiometer is a standard 2 lead resistor with a third lead attached which taps into the resistive element at a variable point: see Figure 1. The potentiometer's control can typically be twisted from about $\theta = 0^\circ$ to 270° . At $\theta = 0^\circ$, the center tap of an $100\text{k}\Omega$ potentiometer is taken at one extreme end of the resistor as shown in Figure 2a, leads a and b are shorted together, and both see $100\text{k}\Omega$ of resistance with respect to lead c. As the control is twisted, lead b separates from lead a, and sees an increase in resistance with respect to lead a and a decrease in resistance with respect to lead c. When the pot's control is twisted to the other extreme, lead b sees the full $100\text{k}\Omega$ with respect to lead a and zero resistance (a short) with respect to lead c. This can be used to construct a variable voltage reference as shown in Figure 3.



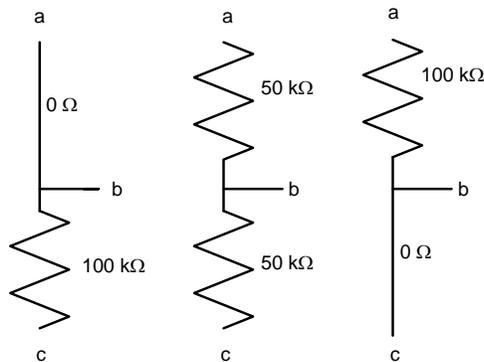


Figure 2: The equivalent circuit of a 100kΩ potentiometer (pot) when the control is fully twisted clockwise (left), is centered (middle), and is twisted fully counter-clockwise (right).

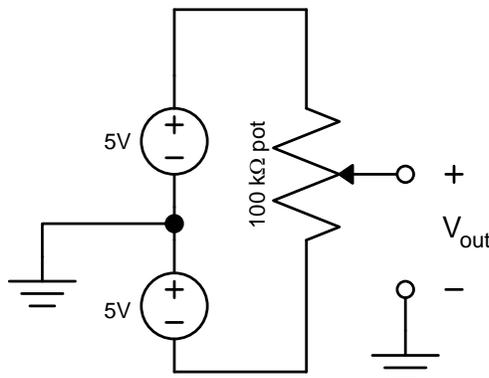


Figure 3. A simple variable voltage source. If you find the ground symbols confusing, connect the grounds with a wire and erase the ground symbols. Ground symbols are just shortcuts to say two things: “there’s an invisible wire that connects all these symbols” and “if you’re asked to measure a voltage at a **point**, measure it between that point and ground.”

Prelab questions: (write the answers to each question on your individual prelabs; these will be graded in the first 5 minutes of the lab)

1. For the simple variable voltage source shown in Figure 3, what is V_{out} when the potentiometer (aka “pot”) is:
 - a. rotated all the way clockwise (as defined in Figure 2 and shown in Figure 1),
 - b. centered, and
 - c. rotated all the way counterclockwise? To analyze, replace the pot with equivalent model shown in Figure 2.
2. As you twist the pot clockwise, you smoothly decrease the top resistor from 100kΩ to 0 and increase the bottom resistor from 0 to 100kΩ, as shown in Figure 2, however their sum always remains 100 kΩ. What are the values of the top resistor and the bottom resistor to make the output of the circuit in Figure 3 equal to 2.5V? Hint 1: to analyze Figure 3, replace the pot with the two resistor model of Figure 2. Hint 2: the two resistors are not the same value.

3. As it stands, this is a poor voltage source because the output changes voltage if you place a load resistor on it. To prove this, connect the output of the circuit you designed in problem 2 to a $75\text{k}\Omega$ load (i.e. in Figure 3 connect a $75\text{k}\Omega$ between V_{out} and ground representing a load like a motor or light source). V_{out} will drop because the load forms a voltage divider with the potentiometer. What is the new V_{out} ?
4. To fix this problem, draw an opamp buffer circuit (the same thing as an amplifier with a gain of $\times 1$) between V_{out} from the potentiometer and the load resistor. Draw the entire circuit. (You may need to refer to your EE122 notes to draw the buffer.) Now adding or removing the $75\text{k}\Omega$ load resistor won't change the voltage at the output of the opamp. In fact, you can load the output of the opamp with anything and as long as it draws less than the maximum output current of the opamp (about 15mA for a common 741 opamp), V_{out} will remain unchanged.

Laboratory #2: Oscilloscopes

Probe fundamentals

There are two types of probes we use in the lab that have BNC connectors on them as shown to the right: these are coax cables and scope probes. Coax cables look like straight black cables that have a BNC connector on one end and red and black mini-grabbers on the other, shown to the right. Internally, they are simply wires connecting the outer shell of the BNC connector to the black minigrabber and the inner wire of the BNC to the red. Use them to connect any piece of lab equipment to each other or circuits EXCEPT the scopes.



Scope probes look as shown on the right. They may have grey or blue ends. Use them exclusively with the the oscilloscope (scope) inputs also called Channel 1 and Channel 2. They are not simple wires, but rather have circuitry embedded in the cube-like plastic attached to the BNC connector. Some probes have a slider that says x10, x1, and REF. Keep the slider on the x10 position at all times; this will use the circuitry to avoid distorting the waveform. Unfortunately, it will also cut the signal down to 1/10 of its former value, so the oscilloscope must “know” to show the signal as 10x higher than what it actually reads. Since this is the normal situation, the scope defaults to this setting when you reset it.



Oscilloscope fundamentals

The oscilloscope is a device that graphically displays voltage waveforms. In this lab, you will learn to use the standard triggered mode of scope operation. Although the specific keys this lab instructs you to use are specific to the Agilent digital oscilloscope we use in the lab, the core of the material is common to all types of oscilloscopes.

Turn on the scope (the white button in the lower left corner) and reset all the weird possible configurations by waiting for it to boot and then pressing the “Default Setup” button in the upper right. The yellow line is the voltage vs. time; it is flat at zero because nothing is connected. Attach a scope probe to Channel 1 (under the “1” key).

Press the tip of the probe against your finger; you will see a small signal. Turn the vertical gain knob (the large knob under the Vertical label over the “1”) counterclockwise while the probe is pressed against your finger; you will see a rough 60Hz waveform that has been coupled into your body by the AC power lines in the building. You are an antenna!

Frequency generator fundamentals

To use the oscilloscope that measures changing electrical signals, you must first understand how to generate changing electrical signals. Last semester in EE122 when the signals did not change in time it was easy; there was just one variable called voltage, and you set it from a DC Voltage power supply. (The phrase “DC Voltage” is a misnomer since DC stands for “Direct Current” and it is not a constant current supply but a constant voltage supply; this confusing terminology became fixed a century ago.) Now in EE223 we introduce voltages that changes with time; these are functions and exist in infinite varieties. Although we could generate them by making a rat constantly rotate the amplitude knob of a DC power supply, they have a hard time doing so at audio rates (20-20,000 times per second) and tend to get tired after a few hours. Instead, we rely on a function generator.

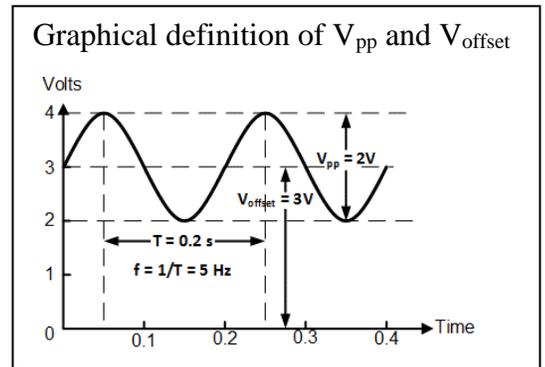
Two waveforms are the common:

- square waves which alternate between one constant voltage for one time period, then switch to a second voltage for a second time period, and
- sinusoids which smoothly vary between a low and high voltage according to the equation

$$v(t) = \frac{V_{pp}}{2} \cos(2 \pi f t) + V_{offset}$$

(think: why $\frac{V_{pp}}{2}$ and not V_{pp} ?)

See the box on the right for a graphical explanation:



We will use sinusoids exclusively in this lab. In the equation given, the voltage between the top and bottom peaks is V_{pp} (V_{pp} stands for $V_{peak-to-peak}$), and it oscillates between those extremes centered at an average of V_{offset} with a frequency of f , so that in 1 second there are f periods (i.e. cycles) of the sinusoid and each period occurs in $1/f$ seconds. Example: you could generate a waveform that smoothly varies between 2 and 10V seventeen times per second by setting $f=17$, $V_{pp} = 8$, and $V_{offset} = 6$. What setting would you use to make a waveform that varies between -1.5V and 3.5V with a period of 100us (not 100ms)?

frequency f	V_{pp}	V_{offset}

We are lucky enough to have a function generator built into our oscilloscope, but don't be confused: the function generator creates the signal and outputs it through the coax cable connector in the lower left called “Gen Out”; the oscilloscope measures the signal and inputs it from the two oscilloscope probe connectors on the lower right. One is an output, the other two are inputs.

Make a $f = 10\text{kHz}$ sinewave that oscillates between -1.5V and of 3.5V on the frequency generator of the Agilent 2012A scope. To do this,

- 1) Connect a standard black coax cable with red and black minigrabbers to the Gen Out coax connector, and connect its black ground lead to the same electrical point as the black ground leads of the scope cables (doing this by clipping them to wires on the breadboard is cleaner than trying to connect the alligator clips together) and connect the signal leads together (i.e. the bigger lead clip from the scope probe to the red clip from the frequency generator, again cleaner to do on a wire inserted into the breadboard).
- 2) Press the “Default Setup” button on the scope and then the “Factory Default” softkey (and confirm). This resets the myriad of configurations the previous students may have used to defaults.
- 3) Turn on the frequency generator (press the WaveGen key in the scope’s center).
- 4) Change the Frequency, Amplitude and Offset buttons to make it output the waveform described above. You can change the values by selecting the button below the property you want to change on the bottom left part of the screen and turning the  knob in the dark grey box under “Push to select.” You are still too far zoomed out to see anything, however.
- 5) Twist the vertical zoom (above the “1” key) until “1V/div” appears in the upper-left hand corner. Press in (do not twist) the Trigger Knob that says “press for 50%”. You should see about 10 cycles displayed on the screen.

Adjusting Basic Scope Controls

Imagine a perfect graph of a signal exists that you want to measure. The graph measures voltage on the vertical axis and time on the horizontal axis. If the signal is fast-changing (say, 10kHz like you just measured) and you observe it for one second, the plot would have 10,000 cycles and be very long. Imagine now the small rectangular window of the scope screen superimposed over the plot. That is what the oscilloscope displays. You need to be able to scale the idealized underlying plot to make it appear bigger or smaller so that it fits correctly on your small windowed screen, and you may need to translate it up/down or left/right as well. In this section you will learn to do just that.

- 1) Set the function generator to a 100Hz sinewave at $2V_{pp}$ with no DC offset. If you ever lose the ability to change the waveform’s properties, just hit the Wave Gen button again. The scope may look screwed up (we say it has “lost the trigger lock”); you’ll fix this in a moment.
- 2) Increase the Horizontal zoom (the knob under the “Horizontal” label) until it is 10ms/div (read it out in the upper right corner of the display). You should now see a (possibly jittery) signal.
- 3) There are four things you can do to change the way the waveform is graphed in this mode: you can stretch it horizontally, translate it horizontally, stretch it vertically, or translate it vertically. Experiment with the Vertical Gain knob (the large one above the “1” button), the Vertical Offset knob (the small one below the “1” button), the Horizontal knob (the large one underneath the “Horizontal” label) and the Horizontal Offset knob (the smaller one to the right of the Horizontal knob). Write in the table below which of the 4 actions above map to each of the 4 knobs.

Horizontal		Vertical	
Zoom in/out	Translate left/right	Zoom in/out	Translate up/down

Briefly turn the Vertical Gain knob of channel 1 clockwise and observe that you can easily saturate the scope display – do not leave it there as it can damage the scope. The waveform should always remain in the display area. Turn it counterclockwise and observe how the scope “loses its lock” on the waveform, and the waveform starts to jitter horizontally. More on this later. For now, leave the vertical gain on 1V/div. The scope has a grid pattern overlaid on it; this means each of the major horizontal lines are spaced at 1Volt per division. Be able to read the voltage of the waveform using the grid division lines.

Turn the Horizontal knob and note how you can stretch the waveform. If you choose a 1 ms/div setting the 100 Hz waveform (that takes 10ms to complete one cycle) looks expanded. How far can you zoom in? If you choose a 100ms/div setting, the 100 Hz waveform looks compressed. Leave it at 5ms/div.

*Remember; the scope controls don't change the actual signal; your function generator does that. The scope controls only change your **view** of the signal.*

Using the Scope in Triggered Mode

Go back to our idealized model: that a perfect voltage vs. time plot exists on paper and that the scope window is a small rectangular overlay over that very long true plot. You now know how to scale the underlying true plot in size and translate it around so the scope window can examine different parts of it. But *which* particular small window are you observing? You could take a snapshot in time by pressing the big green Run/Stop button in the upper right, which will freeze the display. The normal “triggered” mode does something far smarter however...it takes repeated snapshots automatically. It snaps a picture, then centers that picture on the display so that the signal is just rising past some threshold (by default 0V) in the center of the display. Look at the display now: you'll notice that at the very center of the screen, directly under the orange triangle on top, the sine wave is rising above the 0V threshold. The scope then takes another snapshot a few milliseconds later and centers that picture in the same way. If the signal isn't changing it will look like a still picture, even though it may be redrawing at the same spot 100 cycles every second, as in our current case.

1. You need to know this because you need to understand why this sometimes fails. With the same setup as previously described (function generator at $V_{pp}=2V$, $V_{offset}=0V$, $f=100Hz$, and scope at 1V/division vertical gain and 5ms/division horizontal sweep speed), change the vertical sensitivity to 10V/division. The signal will just wiggle; it is not tall enough for the scope to be able to tell where it crosses zero, so the scope gives up and just overlays every picture it takes at a random horizontal location, giving the appearance of jitter. Turn the vertical gain back to 1V/division. At what setting of the Vertical Gain knob does the trigger fail to lock? _____

2. The trigger can also fail to lock if the waveform has a DC offset. Dial in a 2V offset to the signal in the generator. Now the signal never passes through 0V so the oscilloscope never triggers. You can make the scope trigger by changing its trigger level from 0V to something else. Twist the Trigger Level knob (a new one we haven't yet used) until the threshold rises enough into the signal that the trigger locks. For what range of voltages will the trigger lock?

Lowest: _____ Highest: _____

Remember: although you could also get it to lock by changing the V_{offset} of the function generator, in practice you will be measuring some signal you have no control over so this won't be an option. Instead, if the scope image jitters wildly on the screen, you must change the Trigger Level knob until its horizontal line intersects with the trace you want to measure; then it will "lock" into place and draw without jittering.

3. Channel Coupling. Sometimes you'll have a small sinusoid on a big DC offset voltage. If you zoom out enough to see it, it will look like a flat line. Then if you zoom in enough to see the sinusoid and get a trigger lock, the large offset will cause the signal to go upwards, off the window and you see nothing. If that happens, you can put a small DC filter in series with your signal to remove the DC offset. It just effectively puts a capacitor in series with your input signal, changing it by removing the DC offset. This is called the "AC" signal, instead of the usual see-everything-mode called "DC". Try it now:

1. Restore the trigger level to 0V (you'll lose your trigger lock when you do this).

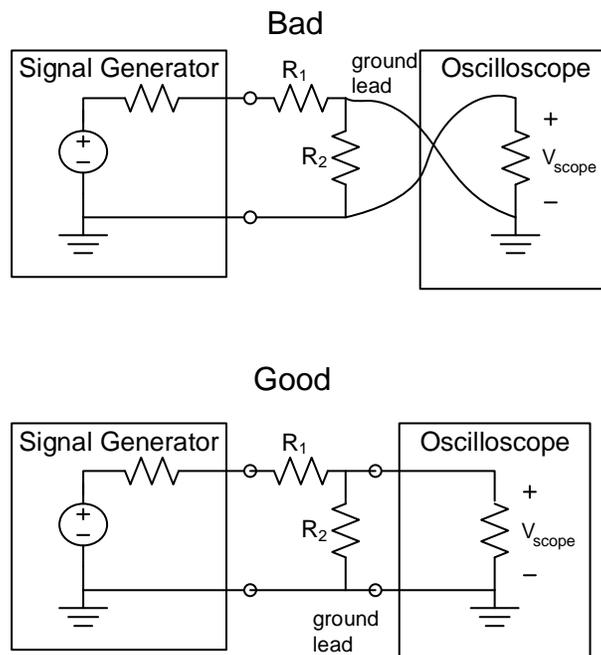
2. Press the "1" key, and then the "Coupling" menu item. Choose "AC".

You'll see the signal drop down as if it had no DC offset, and the trigger will lock again. The signal in the external coax cable still has the DC offset; the scope is just removing it. Don't keep it in this mode since now you are no longer seeing the true signal and if you forget to change it back it could cause the next student to get confused; return it to "DC" coupling which just means the scope does not alter the incoming waveform in any way.

Scope Ground Lead

The scope probe has two leads; the positive lead and the ground lead. The positive lead is electrically connected to a very large resistance of about $10\text{M}\Omega$ inside the scope. This is large enough that the scope draws very little current and therefore provides very little loading to circuits that have resistances of less than about $1\text{M}\Omega$ (and nearly all of yours, at the undergraduate level, fit into this category). The ground lead however is electrically connected to the ground power terminal leading into the scope. This is at the exact same potential as the ground terminal that appears on your CADET II power supply or the signal generators (they are electrically connected through the wires that power both instruments). This means that while you may place the positive scope probe anywhere you desire to measure voltage, **you must connect the ground lead of the scope probe to your circuit's ground**. Say this out loud until you believe it. If you connect the scope ground lead anywhere else (say, to the output of your complex circuit) and you have done the equivalent of shorting that terminal to ground. If you make this mistake you will have shorted the output to ground and the scope will read exactly 0V (plus perhaps damage the circuit you are measuring if the circuit wasn't designed to be connected to ground). The moral of the story: **ALWAYS CONNECT THE SCOPE GROUND LEAD TO GROUND**. This is totally different than the battery-powered DMM, whose negative lead can be placed anywhere.

This raises the good question: how do you measure the voltage across a component in a circuit if neither end of the component is grounded? The next laboratory will answer that question.



The above diagram summarizes this information. A student wishes to use the scope to measure the voltage across R_2 in a R_1, R_2 voltage divider circuit. In the top panel, (s)he places the scope ground lead at a point in the circuit that wasn't previously grounded. While that would work with a DMM, the scope's internal ground just grounded that top node. Since the bottom of R_2 is already grounded, now there's 0V at the top and bottom of R_2 , and the scope reads nothing. The bottom panel shows the correct way to measure the voltage across R_2 .

Numerical Measurements

1. Voltage Measurements: Set the function generator to deliver a squarewave that alternates between $\pm 1\text{V}$ at 2kHz with no offset, and change the Horizontal knob on the scope so you get about 4 periods of the waveform on the display with the Vertical Gain knob set so it mostly fills the screen without running off the top (aka *saturating*). Look at the middle of the scope under the Measure section and press the “Meas” softkey. Look on the bottom of the screen. Change the measurement type to V_{pp} (Voltage peak-to-peak) and then select the “add measurement” button. It will vary (“jitter”) a little. What range of V_{pp} voltages do you measure? Only measure to 3 significant digits.

V_{pp} lowest _____ V_{pp} highest _____.

2. Time/Frequency Measurements: Now measure the actual frequency. By default it is shown on the right side of the screen. What is the range?

f lowest _____ f highest _____.

3. Custom measurements: Measure the risetime of the squarewave, defined as the time to rise from 10% to 90% of the waveform. Ideally this should be 0. Press the “Type:” button on the bottom of the screen and select “Rise Time” using the  button, and then “Add Measurement”. Record this value below.

risetime _____

It’s not very precise, is it? That’s because it can’t do much better than you can from looking at the scope trace, and the trace makes it look like it rises pretty much instantaneously. To be able to see it more accurately, zoom all the way in using the Horizontal knob until you see the non-vertical slope of the rising edge. Notice that the risetime measurement is now precise. What is it?

risetime _____

If you zoom out a bit so you see the area just after the trace rises, you may be lucky enough to notice a tiny ripple in the waveform after it rises. You are now zoomed in so far that you are seeing nanosecond artifacts (that is, characteristics of the waveform that last only a billionth of a second!). These ripples are caused by relativistic effects, and you could measure the speed of light in the cables by dividing twice the cable length by the time period of the ripples. (You’d find that, confined to the cables, the signal travels roughly half the speed of light in a vacuum).

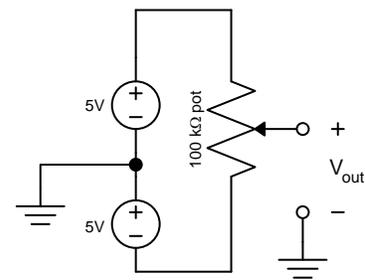
Turn the Wave Gen button off; you are done with the in-lab portion of the assignment.

Discussion Questions

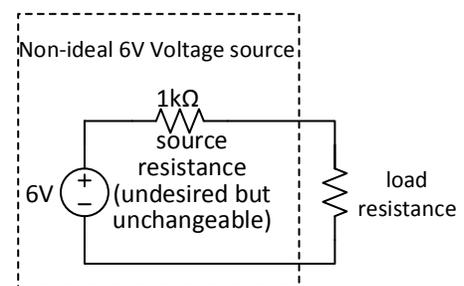
For this laboratory, no procedure is required, since that is provided in this lengthy lab packet itself. Instead, turn in this lab packet with the fill-in-the-blanks completed. Go back and examine the learning objectives. We concentrated primarily on objectives 1 and 2 since these are the most complex, but all 5 objectives are important to understand.

1. A friend is tempted to check her house current by plugging in her scope into an electrical plug. One side of a two prong outlet is called “neutral” and is set to the same ground potential as the scope’s ground lead; the other is “hot” and is the one that oscillates at $\pm 120V_{\text{rms}}$ relative to ground (we will explain in detail what V_{rms} is later in the course; for now it is one of several ways to describe the amplitude of an AC voltage).
 - a. If she hooks the scope’s ground lead to the electrical outlet’s neutral wire and the scope’s probe to the outlet’s hot wire, what should she see?
 - b. How about if she reverses the leads?

2. The most common type of potentiometer has a linear taper, which means the resistance between lead b with respect to leads a and c in Figure 1 changes in a linear manner with θ (the angular position of the control). Given a $100k\Omega$ linear taper potentiometer connected to $+5V$ and $-5V$ as shown to the right, graph the relationship of V_{out} with respect to θ (i.e. graph V_{out} as the potentiometer is rotated). A neatly-labeled hand-drawn sketch is fine, or you can use your EE120 skills and graph it in Matlab.



3. An ideal voltage source has zero internal resistance. The general rule for a good voltage source is that its internal resistance should be no more than about $1/10$ of the resistance of whatever load it powers. To see why this is true, see the example schematic below, similar to the one you made in the lab. The internal resistance of the poor $6V$ voltage source (which has an undesired but unremovable $1k\Omega$ equivalent resistance) would appear in series with the load resistance forming a voltage divider. If the load resistance was $1M\Omega$, almost all the $6V$ would appear across it. But if the load resistance was only 500Ω , only $6V * (500 / (500 + 1000)) = 2V$ would appear across the load! A good voltage source would have a low source resistance so the output would always appear the same.



- a. Now consider the (different) circuit above you analyzed above for Problem 2 with the potentiometer. What is the Thevenin equivalent of that circuit as seen by V_{out} when the potentiometer is rotated fully clockwise?
- b. Same question as above, but analyze for when the potentiometer is centered. (Hint: it is not $100k\Omega$ or $50k\Omega$ for either case. Instead, draw the equivalent circuit replacing the potentiometer with two resistors as shown in the **prelab** circuit of Figure 2).