1 Your Breadboard

You'll be building all of your circuits on something called a breadboard. In the bad old days, people would just screw electronic components onto big wooden cutting boards.

Rotate your breadboard *sideways* so that the colored banana plugs are on the left and the stripes are horizontal. These stripes will become your power supplies (usually +15 V, +5 V, 0V ground, and -15 V).

In circuit diagrams, constant voltage supplies are drawn from the highest voltages at the top down to the lowest voltages at the bottom. Signals (information carried in changing voltages) flow from left to right through things like amplifiers and filters.

Color coding of wires is important. Unfortunately your wire kits make different colors different lengths. If at all possible, reserve the following wire colors:

- Black is 0 V "ground".
- Red is a positive power supply, for you probably +5 V.
- In this class, white will be negative power supply, usually -5 V.

It's incredibly difficult to debug a complex circuit when the layout and colors don't follow this convention. Help me help you—use short wires of meaningful colors. Also, don't use wires at all when you can reach with the component itself—resistors can go quite far.

2 Breadboard Connections

Your multimeter has a "continuity" setting that beeps when the wires touch. Find this setting. It often looks like a speaker or wifi symbol. You may need to hit a shift-type key. Make sure it beeps when you touch the wires together. Test the following things with the beeping continuity setting on your multimeter:

- Each little column of 5 holes in the main area is connected together.
- The "bus bars" are each a single row that's connected across. These are for constant power supplies and are not connected to each other.

3 Battery internal resistance, output impedance, input impedance

There are two things in this lab that people tend to struggle with for the next several weeks. The first is the dual concepts of **output impedance** and **input impedance**. Be sure you understand what these are and how to measure them by the time you finish this section, at least for the examples here. Summary:

- **Output impedance** is like the internal resistance of a battery

- **Input impedance** is just the resistance that a load like a lightbulb has when you plug it in.

Hook up one of the AAA batteries to the larger lightbulb to make sure it lights. It will be dim with only a single AAA battery, but that's ok.

- Measure the voltage *across* the battery with no light bulb. Draw a circuit for what you did with the battery and volt meter:
- Measure the voltage *across* the light bulb when it's turned on:
- This voltage should be less than the voltage across the battery with no load (no light-bulb) because the battery has some internal resistance. The goal of what follows is to measure the internal resistance of the battery.
- Instead of the lightbulb, whose resistance changes when the filament gets hot, use your 10Ω large gold-colored power resistor in your kits for the following tests. Remember, these values are only good to 1%, 5%, or 10% depending on how much money Harvey Mudd was willing to spend. Use your meter to measure its resistance more exactly:
- While measuring the voltage across the physical battery (with its internal resistance), connect and disconnect the 10Ω resistor. Record both voltages. Don't leave such low resistors connected for more than a few seconds so the battery doesn't drain.
- In the boxes below, draw a circuit diagram as follows (Don't bother drawing the volt meter.)
  - Model the battery in its dotted "black box" as two things: an ideal voltage source $V_{internal}$ and an internal resistance $R_{internal}$. This internal reistance is also known as the **output impedance**. (Impedance is a more general term than resistance, but when we are dealing only with a resistance, they are the same thing.) This is the output impedance because it's coming out of a box that provides a voltage.
  - If you measure the voltage across the physical battery with nothing connected, no current flow (only less than a micro amp through the meter), so the voltage across the internal resistance is basically zero and you are measuring $V_{internal}$.
  - The load black box is R_{load}, which will correspond to the load resistance or **input impedance** your fixed resistor, lightbulb, motor, speaker, etc. For now, this should be a single resistor with whatever value you measured your 10Ω gold resistor to be. This is the "input impedance" of the load because it's what you see looking *into* the second black box.
  - Remember, resistors have exactly 3 zigzag points on each side, no matter how big their resistance. I am not good at drawing them consistently on the board, so do what I say not what I do.
  - While measuring the voltage across the physical battery, connect and disconnect the 10Ω resistor and record the two voltage readings.

  – Use voltage-divider concepts and your two measurements to calculate your battery's internal resistance (its output impedance) and the latest value of $V_{internal}$.

- Now you're done with the 10Ω resistor, but hopefully you now know the ideal internal voltage of the battery and its internal resistance, which you'll use below.

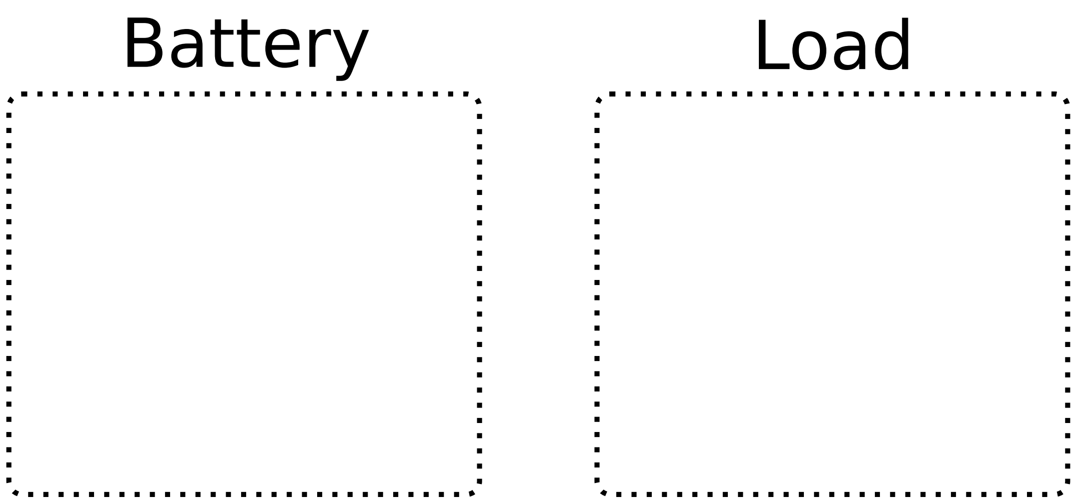
- Measure the resistance of the motor with the ohm meter. It should be very low when the motor isn't being run because it acts just like the long wire that it is.

- Plug and unplug the motor while measuring the voltage across the physical battery, which when plugged in, should be the same as the voltage across the motor. Use your knowledge of the battery's internal resistance and voltage-divider concept to answer the following:

- What is the motor's load resistance when it is allowed to run freely?

- What is the motor's load resistance when you stop it with your fingers (don't do this for long)?

- Do the same for the big light bulb: What is the light bulb's resisance when you measure it with the ohm meter when "off" as compared to its load resistance as calculated through the voltage divider equation when "on"?



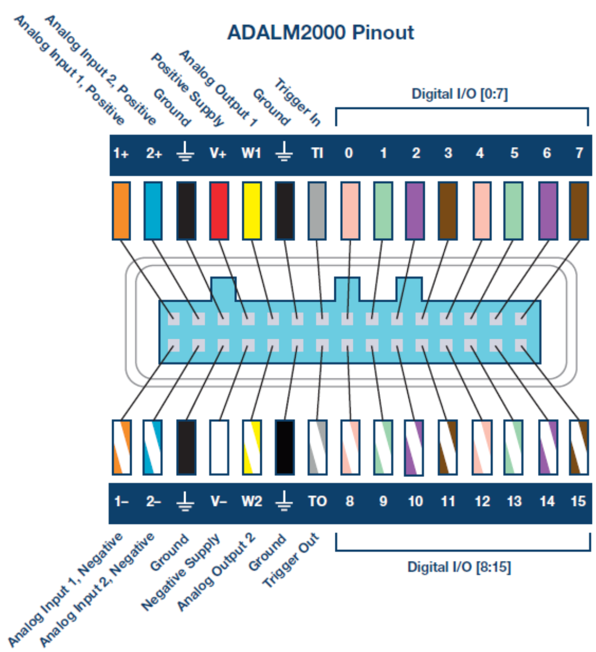
4 Scopy and the ADALM2000 ("M2k")

Follow the instructions on `https://wiki.analog.com/university/tools/adalm2000/users` to install the drivers—under "Quick Start"—note Mac users do NOT need to install HoRNDIS and Windows users run the .exe and need to reboot after. Install the Scopy software (some of you did this earlier). Upgrade the firmware by following the directions *very* carefully: download m2k-fw-v0.25.zip, unzip it, copy the m2k.frm file onto what looks like a hard drive, then "eject" but do *not* actually unplug until rapid blinking stops after an entire minute or so.

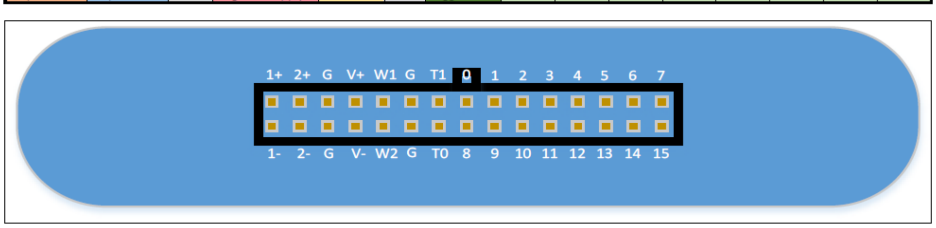
Finally, open the "Power Supply" and "Voltmeter" tutorials. When you plug in the bundle of cables, you probably have to push harder than you think—you shouldn't see any metal. To get wires to your breadboard, open the smaller bag of rainbow-colored wires that come with black and silver pins attached, peal off wires of the appropriate color, plug one end into the M2k's holes, and plug the other end into your breadboard. Specifically,

- Output +5V (red wire) and -5V (white wire). All voltages are with respect to ground (any of the black wires). Don't try to connect wires in mid-air because the oxide on the wires will always lead to an intermittent connection—always plug wires into the breadboard. Feel free to peal apart the colored wires with the nice pins. Measure the two voltages on your multimeter. Change the voltages and watch the readings change. A mouse's scroll wheel makes changing these values more pleasant. Can you change the positive voltage independent of the negative voltage?

- Now measure the voltages with the M2k device itself. Analog input 1 is measured between the orange wire and the orange wire with the white stripe. The orange wire is like the red wire on your multimeter, while the orange-with-white-stripe is like the black wire on your multimeter, which is almost always connected to ground. Analog input 2 is blue and the ground connection is blue-with-white-stripe right below it. Note that a "real" oscilloscope *forces* you to measure voltages with respect to a single, common, universal ground. This is both for safety and for noise-reduction reasons.



Scope Ch 1 +	Scope Ch 2 +	GND	Positive Supply	AWG Ch1	GND	Trigger In 1	DIO 0	DIO 1	DIO 2	DIO 3	DIO 4	DIO 5	DIO 6	DIO 7
Scope Ch1 -	Scope Ch2 -	GND	Negative Supply	AWG Ch2	GND	Trigger In 0	DIO 8	DIO 9	DIO 10	DIO 11	DIO 12	DIO 13	DIO 14	DIO 15



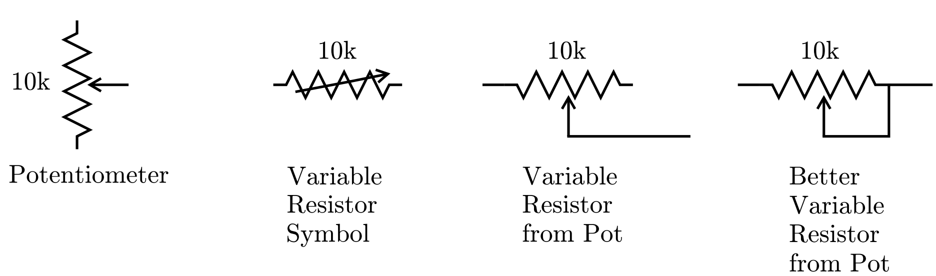
5 Potentiometers and Variable Resistors

The second thing that people ask me over and over again for the first few weeks is how to use a potentiometer: the three-terminal variable resistor with the knob. You'll build one out of pencil markings and if you don't fully understand what's going on and how to use one of these things by the end of this section, make sure you ask me.

On a piece of paper (the side of this page if you printed it out), in pencil (because graphite conducts), fill in a 1 cm wide vertical strip about 10 cm long. If you are off by a a factor of 2 in either dimension, it'll work *just fine*. Pencil it in a few times in different directions to get it nice uniform and shiny.

- Measure the resistance from the top to the bottom.
- Slide one of the probes around and see that the resistance increases linearly with distance. (Analog meters were much nicer for this. Grump Grump.) You have made a variable resistor!
- If you fix one connection at the bottom, note that the resistance gets bigger as you slide the other connection up.
- If you fix one connection at the top, note that the resistance gets bigger as you slide the other connection down.
- If you applied 1V across it, what would the current be? (Keep in mind that in this course, 1 mA is a reasonable current. Above 10 mA is high. 1μA is low.)
- Apply 1V from bottom to top. You may want to tape wires down, hold them both with one hand, or ask someone to help you. While you are applying 1V across the whole resistor, measure the voltage from the bottom to a point in the middle that you slide around. You just made a potentiometer! This will require coordination of many fingers and might be easier to do by putting your M2k wires into the breadboard and bringing more flexible wires from the breadboard to your pencil marking.

A potentiometer ("pot") is a 3-terminal device (top, bottom, and wiper) that can turn an input (voltage/signal) into a variably-attenuated version of that input. Think of this like a volume knob that can turn down a signal from its input level down to zero. A diagram of a potentiometer and its use as a variable resistor is shown below. It contains a resistive carbon strip with a fixed connection at the top, a fixed connection at the bottom, and a sliding connection that sweeps from one end to the other (first picture). You can use all three terminals to make a voltage divider, but by ignoring one of the ends or by shorting one of the ends to the middle, you can make a 2-terminal variable resistor:



- Repeat the measurements you did above with your 10kΩ potentiometer (probably the one with the orange knob). What does the 10k refer to? Can you find some reference to 10k printed on it? Find which terminal does what using a multimeter. Plug the pot into your breadboard so that you can access all three terminals.

- Repeat this measurement with a commercial 100k knob potentiometer (probably yellow knob).

- If you want a variable resistor that goes from 0 to 100k when you turn the knob "up," which two terminals would you use?

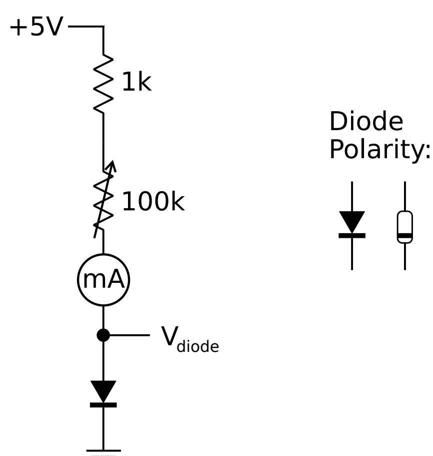
- If you want a variable resistor that goes from 100k down to 0 when you turn the knob "up," (maybe because you want to let through more and more current to a motor as you to turn it up), which two terminals would you use?

- When you use any of these pots as a variable resistor, it is good practice to tie the unused end to the wiper as shown above on the right. This is done for two reasons:

  1. So the unused end doesn't pick up interference like an antenna when it's flapping around in the breeze (electrically).
  2. So that when dirt inevitably gets under the wiper and it disconnects, the resistance doesn't become infinite. What does it become instead?

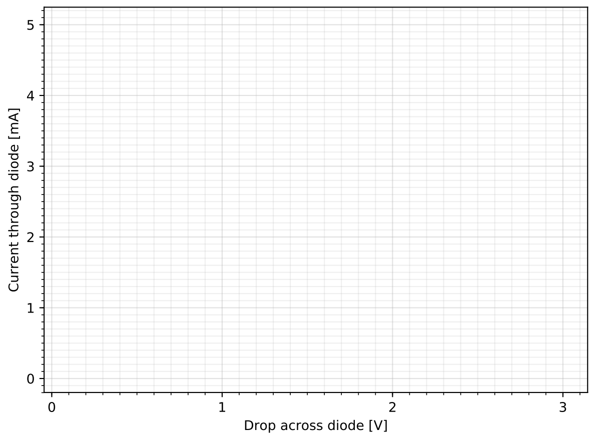
6 Diodes and Light-Emitting Diodes (LEDs)

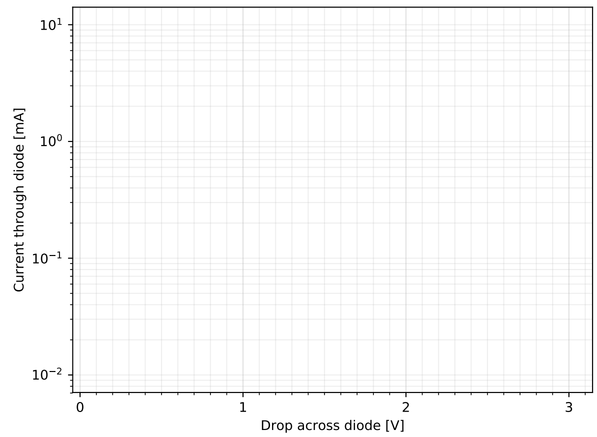
Build the following circuit using a 1N914 (black) or 1N5242 (blue) silicon diode. Hook up the 100k potentiometer as a variable resistor as you learned above. Use the multimeter to measure current and the M2k device to measure V_{diode}.



Diode part numbers often start with 1N and transistors often start with 2N. The 1k resistor limits the current to safe values even when the 100k variable resistor is turned down to 0 Ω. This makes the total resistance go from 1k to 101k as you turn the knob. As you'll see in a few minutes, an *enormous* amount of current would flow if you didn't have *some* resistance in the circuit.

Sweep the 100k pot back and forth to get a feel for the behavior. Make a plot of this behavior on both a linear and log-linear (or semi-log) form. You don't need more than a few points, but get a feel for the shape of the curve. Then turn the power supply voltage down to zero and plot a few more points as you do so.





Turn the power supply back up. What happens if you reverse the diode? How much current goes through a reversed diode? Why does that automatically give you the voltage that you see?

How would you summarize the V vs I behavior of a diode?

What would happen if you did put 5V directly across the diode (**don't try it!**)? What power would that correspond to? Keep in mind that 1/4 Watt is the maximum of these small components before they get hot to the touch. Much beyond that and they burn out.

Do the same for a red LED, a blue LED, and the 1N34A Germanium diode if your kit has one (take-home kits don't). Sketch and label each of their curves on the same plots. By eye, is the amount of LED light linear in voltage or current? 1 mA will be our standard design current, so the voltage at this current will be the voltage drop that we'll use when we design circuits with diodes (and transistors). Write this voltage down to one decimal place. This number should be good to 10%, even for a order-of-magnitude differences in current as long as the diode is "on".

Quantum Physics: Red light has a wavelength around 650 nm and blue light around 450 nm. Use the speed of light (3×10^8 m/s) and Plank's constant (4×10^{-15} eV·s) to convert these wavelengths into electron volts (eV). This is the minimum energy that an electron in the semiconductor looses when it falls from a high-energy state to a low-energy state and emits a photon. (It can loose a little extra energy to heat.) The numbers you get should look like they are in the same ballpark. What color photons does a silicon diode emit?

7 Numbers to Remember

- 1 mA is a typical current to design for (within a factor of few).

- 1.2-1.5 V is a AA and AAA battery. 5 to 15 V are typical power supply voltages.
- 0.6 V drop across a typical silicon diode when it's "on".
- 1/4 W is the maximum power for our breadboard components.
  - What current does this correspond to at 15 V?
  - What is the smallest resistor that won't exceed this current?
- 10k is a typical resistor value

8 Cleaning Up

- Multimeter: Move the plug from the current input back to the voltage input of the multimeter so you don't accidentally blow a fuse when you accidentally measure the "current across the power supply" next time when you meant to measure the voltage.
- Leave the potentiometer knobs in the center of their range so you don't accidentally short anything with a really low resistance if you plug them into a circuit next time.