Physics 364, Fall 2012, Lab #1

(resistors, voltage dividers, input/output resistance, lab equipment, and other basics)

start Friday, September 7 — finish Wednesday, September 12.

Course materials and schedule are at `positron.hep.upenn.edu/p364`

Jose will hand out breadboards and toolkits for you to use throughout the semester. You should take your own set of supplies to label with your name, in case you want to save your work between labs in the future. Be sure to pack up your lab supplies each day at the end of lab, so that your tools don't get lost when other courses use the lab space. You can work either alone or with a partner, as you prefer. Your write-up must be your own, and should indicate who your lab partner is, if any.

Lab Reports

The purpose of the lab report is twofold.

First, your report gives you credit for working through all the lab exercises — as this process (interacting with the components, the instruments, the instructors, and your classmates) is the primary way in which you will learn electronics this semester.

Second, you will develop the habit of keeping a running log of what you are doing in the lab. Keeping a notebook is an important part of doing original research, and can be helpful even if you are just sitting at home debugging the new video game you wrote last weekend or are in your parents' garage doing a difficult car repair. By explaining what you are doing and why to someone else (who usually turns out to be yourself long after you've forgotten the details of today's work), you clarify your reasoning and can work more systematically. And you will be surprised how often your old notebooks will contain valuable clues for reproducing today's work when you unexpectedly need to revisit them in a year's time.

The basic idea of a lab notebook is to explain what you are doing with enough detail that if you pick it up six months from now, it will be clear what you did and why you were doing it. Nothing elaborate is needed. (For one point of view on lab notebooks, see `en.wikipedia.org/wiki/Lab_notebook` .) While lab notebooks have traditionally been bound paper volumes, electronic documents have become popular, as they are easy to find, to search, and to share, and they avoid the hassle of carrying around a physical notebook. A "google docs" word processor document worked well for me (Bill) for several years. More recently, I have started using a wiki to document my own lab work. You can use a spiral notebook, a word processor, a wiki, or any similar means, as long as your notebook is readable, is reasonably neat, and adequately documents your lab work. You can even mix word processing with hand-written notes, e.g. by using your mobile phone camera to email images to yourself of your drawings or calculations, then pasting them in.

To get full credit on lab writeups, please take care to draw diagrams in your lab notebook that make it clear to Jose what circuit you are measuring and how you are measuring it.

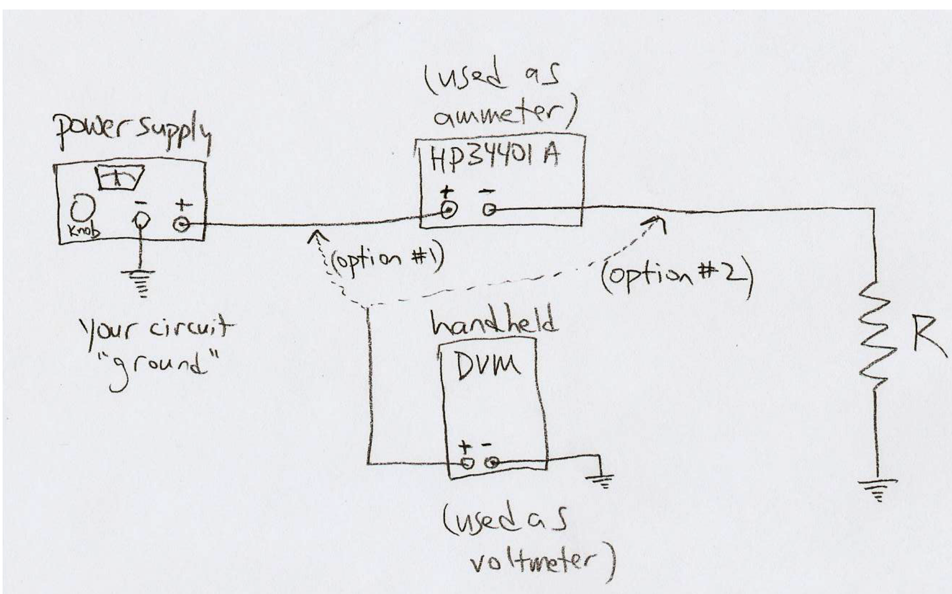
Four examples of OK lab notebook technique:
`positron.hep.upenn.edu/wja/P364_2012/lab_report_example1.pdf`
`positron.hep.upenn.edu/wja/P364_2012/lab_report_example2.pdf`
`positron.hep.upenn.edu/wja/P364_2012/lab_report_example3.pdf`
`positron.hep.upenn.edu/wja/P364_2012/lab_report_example4.pdf`

Part 1: using the multimeter

Pick out a range of resistors from the parts drawers: use values around 10 Ω, 1 kΩ, 100 kΩ, 1 MΩ. Measure each resistance with the multimeter.

Check the reading against the color codes on each resistor. (It's worth memorizing black(0), brown(1), R(2), O(3), Y(4), G(5), B(6), V(7), grey(8), white(9).)

(a) Most of the resistors we will use this term have a $\frac{1}{2}$-watt power rating. Calculate the largest voltage that you can safely apply to a 10 Ω resistor without exceeding the $\frac{1}{2}$ W power rating. Keep your answer in mind below. Also, since the power supply's maximum voltage is 25 V, calculate for your future reference the smallest $\frac{1}{2}$ W resistor that you can safely connect directly between +25 V and ground.



(b) Starting with the 1 kΩ and 100 kΩ resistors (where you should not find anything very surprising), use the circuit drawn above to measure I vs. V for a few points per resistor. Once you have measured the two medium-sized resistors, move on to the smallest and the largest resistors. For each resistance, try both options (indicated in the drawing) for the position of the voltmeter. If there is a difference (either in measured V or in measured I) between the two options, figure out why, and decide which answer should be closer to the truth. Hint: for the extreme cases, you need to consider the input resistance of the voltmeter and the series resistance of the ammeter.

(c) For the surprising cases, draw the circuit in a way that shows the resistances of the meters, so that the readings now make sense. (For instance, you might draw an ideal voltmeter in parallel with its input resistance, and you might draw an ideal ammeter in series with its "shunt resistance.")

(Keep your I-vs-V setup in place for the next part of the lab.)

(A copy of the specification for the HP 34401A meter can be found at `positron.hep.upenn.edu/wja/P364_2012/hp34401a_specs.pdf` .)

Part 2: mystery boxes

Now that you are set up to measure I vs. V, measure several points (just enough to see the shape of each curve) for the I-V curve for each of the two "mystery boxes" at the front of the room. Remember to try both positive and negative voltages, because not all devices' I-V curves are symmetric. You can safely apply up to 25 V to each box. Which one of the two boxes seems a bit unusual? Once you're done, you can look inside. Can you identify the contents?

Part 3: voltage divider

(a) Draw the schematic diagram for a voltage divider that will take $V_{\text{in}} = +3.0$ V as input and will provide $V_{\text{out}} = +2.0$ V as output, using one 1 kΩ and one 2 kΩ resistor. Now build it. Try to build your circuit on the breadboard, not in the air, and see if you can arrange your components to resemble (at least somewhat) the schematic diagram. (This may seem silly now, but starting out with good habits will help you when your circuits become more complicated later.) Supply +3.0 V to the divider's input. Measure V_{out}. So far so good?

(b) Measure V_{thev} and R_{thev} (the Thevenin equivalent voltage and resistance) for your voltage divider, where the two terminals referred to in Thevenin's theorem in this case are V_{out} and ground. Explain how you measured V_{thev} and R_{thev}. (Probably the easiest way to measure R_{thev} is to measure I_{SC} and to combine this result with V_{OC}.) How do your measured values compare with what you calculate by looking at the schematic?

(c) Now load the divider with a 100 kΩ resistor. Draw the new schematic. Measure V_{out}. Does the change (or perhaps lack of appreciable change) after vs. before adding the 100 kΩ load resistor make sense? (Do you remember the rule-of-thumb, from page 8 of my notes, for making sure that a circuit can drive a given load without drooping?)

(d) Now load the divider instead with a 3 kΩ resistor, and measure $V_{\rm out}$. Does the result make sense?

(e) What value for the load resistor would bring $V_{\rm out}$ down to half of its original (unloaded) value? (You shouldn't need to do any new calculations to figure this out. Make sure you can reason your way to the answer, instead of mindlessly calculating!) Now try it out to check your answer. (There is a standard resistor value only a few percent away from the answer I have in mind.)

(Don't discard your 1 kΩ and 2 kΩ resistors too soon, as you will need them again later in the lab.)

(f) Now draw, and then build, the Thevenin equivalent circuit for your voltage divider. With no load connected, what is $V_{\rm out}$? Try loading the equivalent circuit with 100 kΩ, then with 3 kΩ, and measure $V_{\rm out}$ in each case. In what sense is the Thevenin equivalent circuit equivalent to the original circuit? (Hint: one sense in which the original circuit and its Thevenin "equivalent" are *not* equivalent is the power internally dissipated, as you can easily convince yourself by considering the case in which no load resistor is present. What other important property *is* equivalent?)

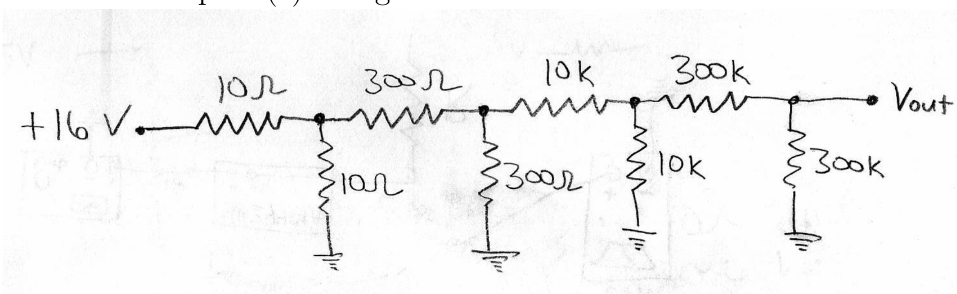
(g) Find two 10 MΩ resistors (ask Bill or Jose if you don't know where to find them). Use the ohmmeter to check that they are (within tolerance) really 10 MΩ. Now build a new voltage divider using these two 10 MΩ resistors, using $V_{\rm in} = 10$ V. Measure the current through the divider. How did you do it? Is the answer what you expect? Now use the benchtop HP multimeter (not the hand-held meter) to measure $V_{\rm out}$. Whoa! What do you read? Look up the HP34401 meter's input resistance. Draw the circuit that includes the meter's input resistance. Does the reading make sense now?

Part 4: voltage divider as load for voltage divider

(a) Re-build the original 1 kΩ:2 kΩ voltage divider from part 3a. Now build a second voltage divider using much larger resistors, like 100 kΩ:200 kΩ. Use $V_{\rm out1}$ from the first divider to supply $V_{\rm in2}$ for the second divider. Use $V_{\rm in1} = +9$ V from the power supply. Draw the circuit. What is the *input resistance* of the second divider? (In other words, what does the first divider "see" as the resistance of its load?) What do you expect for $V_{\rm out1}$ and $V_{\rm out2}$? (You can do this in your head.) Measure them!

(b) Now replace the 100 kΩ:200 kΩ divider with a second 1 kΩ:2 kΩ voltage divider. Draw and build the circuit. You should have two identical voltage dividers, with $V_{\rm out1}$ from the first feeding $V_{\rm in2}$ for the second. What is the input resistance of the second divider? Now what do you expect for $V_{\rm out1}$ and $V_{\rm out2}$? (Unlike part (a), you probably need a pencil for this one.) Measure them.

A rule of thumb for voltage sources (opposite for current sources) is that the *source resistance* (a.k.a. R_{thev}, a.k.a. "output resistance") of the driving circuit needs to be much smaller than the *input resistance* of the load, if you do not want the source voltage to "droop" or "sag" under the load. The advantage of following this rule of thumb is that it allows you to consider the parts of a complicated circuit individually. Alternatively, keeping in mind R_{thev} for the driving circuit and R_{in} for the load allows you quickly to calculate or to approximate the interactions between two adjacent stages of a circuit. Does this exercise make the rule of thumb clear to you? If so, then you should find part (c) straightforward.



(You don't need to build this!)

(c) Look at (but don't build) the circuit drawn above: what is V_{out}? (Do it in your head! If you can't, then you're not looking at it the right way yet.) Why would it be much more difficult (maybe even impossible) to do in your head if every resistor were 1 kΩ?

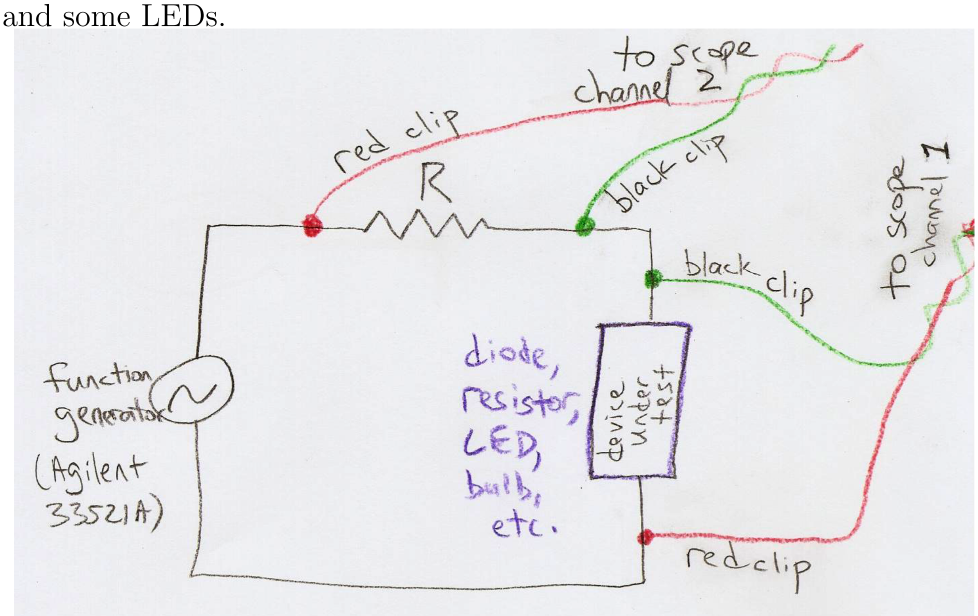
Part 5: oscilloscope and function generator

(a) Put your venerable 1 kΩ:2 kΩ voltage divider back together. Drive it with an 0.5 Hz, 10 V_{pp} ("volts peak-to-peak") sine wave from the Agilent 33521A function generator. Connect the oscilloscope to graph V_{in} vs. time on channel 1 and V_{out} vs. time on channel 2. Does the voltage divider behave as you expect for time-varying input? (Note: the amplitude displayed by the function generator may be wrong by a factor of two. If this irks you, we can show you how to put the function generator into "high Z" mode. Either way, the oscilloscope will show you the true amplitude. **Don't hesitate to ask for help if you find the oscilloscope or function generator confusing!**)

(b) Now replace the 2 kΩ resistor with a 1N4148 (or similar) diode. Sketch $V_{\text{in}}(t)$ and $V_{\text{out}}(t)$. You should see the diode *clamp* V_{out} at about 0.7 V. This feature is often used to protect sensitive circuits from excessive input voltage.

We haven't really discussed diodes yet, except very briefly on page 4 of my week 1 notes, so you're entitled to find them mysterious. For the moment, we'll look at a diode simply as a device with an interesting (and non-linear) I-V curve: for $V < 0$

(called "reverse"), the current is negligible, and for $V > 0$ (called "forward" voltage for a diode), the current increases exponentially with voltage. Typically the current reaches an "appreciable" value (many milliamps) around the point where $V \approx 0.7$ V, so we very loosely say that the diode behaves like a very small resistance for $V > 0.7$ V, like an open circuit for $V < 0$, and somewhere in-between for $0 < V < 0.7$ V. Light-emitting diodes glow, usually monochromatically, as electrons and holes recombine—making the on/off transition more tangible. We'll use the scope and function generator below to trace out the I-V curves of several devices, including a diode and some LEDs.



(c) The most common use of an oscilloscope is to graph one or more voltages as a function of time: $V_1(t)$, $V_2(t)$, etc. — normally the horizontal axis represents time. But we're now going to put the scope into XY mode, so that we see V_2 vs. V_1 — the horizontal axis will be V_1, and the vertical axis will be V_2. Using this feature will let the scope and function generator trace out several I-V curves for us, far less tediously than measuring them point-by-point. Your set-up should look like the above diagram. We want to measure I vs. V for the *device under test*, which initially will be the diode from part (b). Scope channel 2 will show the voltage drop across resistor R (initially use 1 kΩ). Since the current through R equals the current through the diode (the scope's input resistance is 1 MΩ, so it will draw negligible current), we can look at channel 2 and infer the diode current $I = V_2/R$. Scope channel 1 will show (minus) the voltage drop across the diode.[1] Remarkably, you can fix this sign annoyance by telling the scope to "invert" the channel 1 signal! If all goes well (you will almost certainly need help making this work), you should see the scope trace out $R \times I_{\mathrm{diode}}$ vs. V_{diode} on the screen, with zero current for $V_{\mathrm{diode}} < 0$ and an exponentially increasing

[1]Unfortunately, the black clip for each scope input is wired to Earth ground, so we are forced to connect channel 1 upside-down, as shown in the diagram. Does that make sense? The function generator doesn't have this problem — the outer shield on its signal cable is "floating" (not held at any fixed potential w.r.t. Earth ground).

current for $V_{\mathrm{diode}} > 0$. Sketch the curve in your notebook.

(d) Now replace the 1N4148 diode with a red LED. The curve should look similar, though perhaps shifted to the right a bit w.r.t. the ordinary diode. Next try a blue LED. The curve should shift farther to the right. Expressed in electron-volts, what are the energies of red and blue photons? (Hint: $\lambda_{\mathrm{red}} \approx 630$ nm, and $\lambda_{\mathrm{blue}} \approx 470$ nm.) The forward voltages for the red and blue diodes should be close to the corresponding photon energies (in eV).

(e) Now replace the LED with a flashlight bulb, and replace the 1 kΩ resistor with approximately 10 Ω, so that you get enough current flowing to see the bulb light up. (It's a 1 W bulb, roughly.) Watch the bulb turn on and off as the scope traces out the $I(V)$ curve. Note that the bulb doesn't care about the sign of V, unlike the diode. Note also that the bulb is non-linear. Can you see that the resistance of the tungsten filament increases as the bulb heats up? There is also an interesting hysteresis that you might see, depending on the frequency that you set with the function generator: the bulb takes a while to heat up or cool down as the applied voltage changes.

(f) Finally, replace the flashlight bulb with a boring resistor (around 1 kΩ), and check that you get the straight-line $V(I)$ curve that you expect from Ohm's law.

If you have extra time, continue to tinker with the function generator and oscilloscope, to get to know their features. Ask for help about anything you find interesting or puzzling. For the rest of the course, the oscilloscope will be your means of seeing what is happening inside your circuits. Work with it until you are comfortable (or out of time).