Physics 364, Fall 2014, Lab #2 **Name:** ____________________

(meter imperfections; voltage dividers; Thevenin equivalents)

Wednesday, September 3 (section 401); Thursday, September 4 (section 402)

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

Work in pairs (if possible), but write up your own "report," by filling in your own answers to the questions as you work through the lab handout. We strongly encourage you to cooperate with your lab partner and other classmates in reasoning through through the lab questions, but you will turn in your own paper that reflects your thinking.

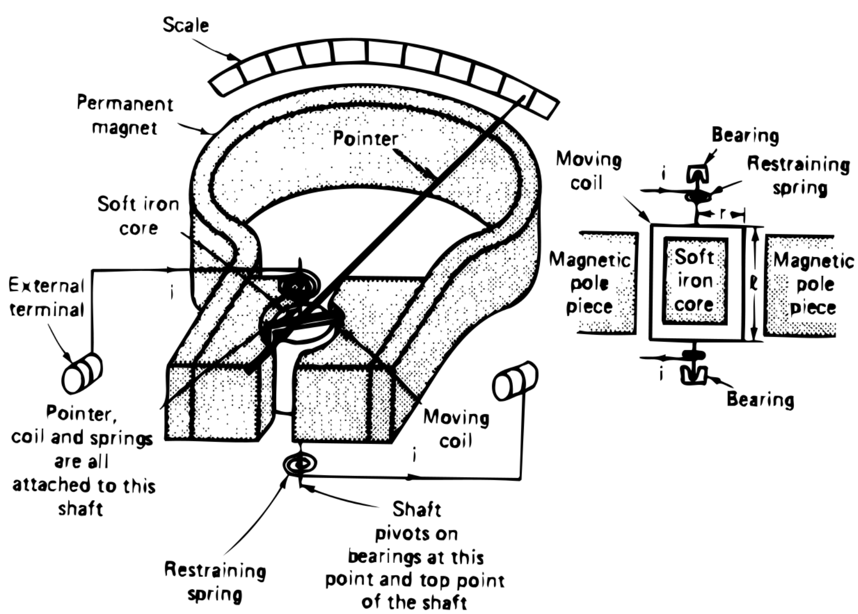
Don't waste time making your work look polished. Just write clearly enough that we can follow your reasoning. Most importantly, your written work should convince us that you thought about the questions asked in the lab assignment. Turn in your work at the end of class. If you need extra lab time to finish a given assignment, just let us know.

Part 1 **Start Time:** ____________

converting analog "meter movement" into home-made voltmeter & ammeter

In the reading assignment, you saw that two resistors wired in series form a *voltage divider,* while two resistors wired in parallel form a *current divider.* Let's apply this idea to build home-made versions of a voltmeter and a current meter ("ammeter").[1]

You will start with a bare-bones "meter movement" — a device that lets a current deflect a needle. This mechanism is basically a current-measuring device: the needle's deflection is proportional to the torque exerted on a coil of wire that sits in the field of a permanent magnet, and this torque is proportional to the current through the coil. Here's a sketch:



[1] Part 1 of this lab is borrowed from Lab 1L.2 of the Harvard course. I've copied most of their wording.

An analog "multimeter" or VOM (volt-ohm-milliammeter) is just such a meter movement, with switchable resistor networks attached. If you'd like to try out one of these old-fashioned analog meters, we have a bunch of them available in the back of the room. Just ask us, if you're interested. We will normally use digital voltmeters (DVMs) instead.

1.1. Internal resistance of the movement

You could design a voltmeter by simply assuming that the movement's R_{internal} is negligibly small. The resistance of this movement is pretty low — well under 1 kΩ. But let's be more careful. Let's first measure the internal resistance.

Measure R_{internal} any way you like. You could use the Amprobe DMM on its own, or you could use the lab power supply, some known resistors, and the lab's voltage or current meters. It's up to you. The meter movements are protected. Don't worry about burning out the movement, even if you make some mistakes. Even "pinning" the needle against the stop will not damage the device, though in general you should avoid doing this to analog meters. We have provided diodes that protect the movement against overdrive in both forward and reverse directions. You should *note,* as a result, that these diodes that protect the movement also make it behave very strangely if you overdrive it. (No doubt you can guess what device it behaves like.) So don't use data gathered while driving the movement beyond full scale.

In the space below, sketch the arrangement you use to measure R_{internal} (the meter movement's internal resistance). **Note your measured values** of R_{internal} and of $I_{\text{full-scale}}$ (the current flowing through the meter when it is deflected full-scale).

1.2. 10 V voltmeter

Show how to use the movement, plus whatever resistors are needed, to form a 10-volt full-scale voltmeter. (That just means that 10 V applied to the input of your circuit should deflect the needle fully.) Be sure to choose component values that are available in the lab. If you're not content with the values avaiable at your workbench, you can find a wider selection in the closet in the back of the room. **Draw your circuit.**

How large an effect does the movement's own internal resistance have on the accuracy of your voltmeter's readings? (How much would your meter's voltage readings change if this internal resistance were zero, or if it were doubled?) Is this comparable to, much smaller than, or much larger than the inaccuracy caused by available resistors (either the available values or the tolerance in their values)?

Does your voltmeter work as advertised? How did you check? What is the *input resistance,* R_{in}, of your complete voltmeter? (Compare this R_{in} with the 10 MΩ R_{in} of the Amprobe hand-held digital meter, when it is in voltage mode. For comparison, an old-fasioned analog VOM has $R_{\text{in}} = 200$ kΩ when set for 10 V full-scale.)

1.3. 10 mA current meter ("ammeter")

Show how to use the movement, plus whatever resistors are needed, to form a 10 mA-full-scale ammeter, and test your circuit. **Draw your circuit.**

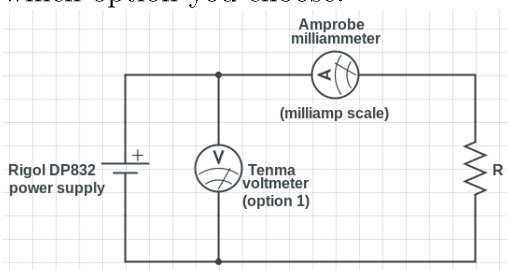
Does your current meter work as advertised? How did you check? What is the input resistance of your ammeter? (For comparison, your Amprobe meter's manual reports an input resistance of 10 Ω when measuring currents on the milliamp or microamp scale, and 0.035 Ω when measuring currents on the amp scale.)

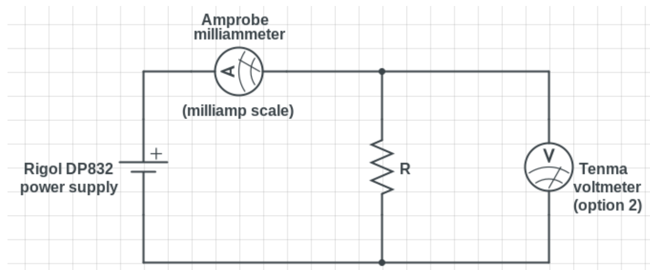
Part 2 **Start Time:** ______________

imperfections of real meters

Last week, you got used to measuring voltages and currents using the Amprobe hand-held digital multimeter (a.k.a. DMM or DVM) and the Tenma benchtop DMM. Meanwhile, you concluded after the first reading assignment that an ideal voltmeter should have $R_{\text{in}} = \infty$, while an ideal ammeter should have $R_{\text{in}} = 0\ \Omega$. Let's see under what circumstances the non-ideal nature of the lab's meters can be seen. (Most of the time, these meters can be treated as if they were ideal, but it is good to keep in mind under what circumstances you need to think more carefully.)

Start by measuring just one or at most two points (to keep this from getting boring) along the I-vs.-V curve of a 10 kΩ resistor. Use the Amprobe hand-held meter to measure currents, and the Tenma benchtop meter to measure voltages. As with the "mystery box" exercise from last time, there are two options for connecting the voltmeter. Try option 1 first, and then option 2, as illustrated below. For $R = 10$ kΩ, it shouldn't make a significant difference which option you choose.





Quickly jot down the current and voltage you measure for option 1 and for option 2. Choose a power-supply voltage that gives you a current of a milliamp or so.

Now replace the 10 kΩ resistor with $R = 1$ MΩ (be sure to measure its resistance with the ohmmeter first), and set the power supply for 30 V (which is as high as it goes). Again try options 1 and 2 for measuring the voltage. Does the presence of the voltmeter affect your current reading? (Remember that the digital voltmeter's R_{in} is 10 MΩ, and that the Amprobe current meter's R_{in} (when measuring mA or μA) is 10 Ω, according to the manufacturers' manuals.) In this case, which option is better suited to simultaneously measuring the voltage across the resistor and the current through the resistor, and why?

Now set the power supply down to zero volts, replace the resistor with $R = 10\ \Omega$, and then carefully dial the power supply up to 1 volt. (You want to keep the current well below the 400 mA limit of the amprobe meter in the milliamp range. You also want to stay below the $\frac{1}{4}$ watt power rating of the resistor. Remember that it is for the smallest resistor values that you have to be most careful about exceeding the resistors' power rating, since $P = V^2/R$.) Now can you explain the difference, if any, between options 1 and 2 for positioning the voltmeter? In this case, which option is better suited to simultaneously measuring the voltage across the resistor and the current through the resistor, and why?

Part 3: voltage divider **Start Time:** ______________

3.1 Draw the schematic diagram for a voltage divider that will take $V_{\mathrm{in}} = +3.0$ V as input and will provide $V_{\mathrm{out}} = +2.0$ V as output, using two resistors whose values add up to 3 kΩ.

Now build your circuit on the breadboard. As you did last week, try to arrange your components to resemble (at least somewhat) the schematic diagram. Supply +3.0 V to the divider's input. Measure V_{out}. So far so good?

3.2 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_{thev}. A second method, which you should try as well, is to replace the power supply with a short circuit (a wire) and then to measure the resistance between V_{out} and ground with the ohmmeter.) How do your measured values compare with what you calculate by looking at your schematic diagram?

3.3 Now load the divider with a 100 kΩ resistor. Draw the new schematic diagram. 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 the last page of my notes, for making sure that an upstream voltage source can drive a given downstream load without drooping?)

3.4 Now load the divider instead with a 2 kΩ resistor, and measure V_{out}. Does the result make sense?

3.5 What value for the load resistor would bring V_{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, stored in the back room, only a few percent away from the answer I have in mind.)

(Set your 1 kΩ *and* 2 kΩ *resistors aside; you'll need them again for Part 4.)*

3.6 Now draw, and then build, the Thevenin equivalent circuit for your voltage divider. With no load connected, what is V_{out}? Try loading the equivalent circuit with 100 kΩ, then with 2 kΩ, and measure V_{out} in each case. In what sense is the Thevenin equivalent circuit equivalent to the original circuit? In other words, what key properties of the original and Thevenin-equivalent circuits are equivalent? (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.)

3.7 Find two 10 MΩ resistors (ask us 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 $V_{\text{in}} = 10$ V. Measure the current through the divider. How did you do it? Is the answer what you expect? Now use the multimeter to measure V_{out}. Whoa! What do you read? Draw the circuit that includes the meter's input resistance. Using your diagram, are you able to explain the meter's reading now?

Part 4 **Start Time:** ______________

voltage divider as load for voltage divider

4.1 Re-build the original (1 kΩ):(2 kΩ) voltage divider from part 3.1. Now attach to it a second voltage divider formed using much larger resistors, like (100 kΩ):(200 kΩ). Use V_{out1} from the first divider to supply V_{in2} for the second divider. Use $V_{\text{in1}} = +9$ V from the power supply. Draw the circuit.

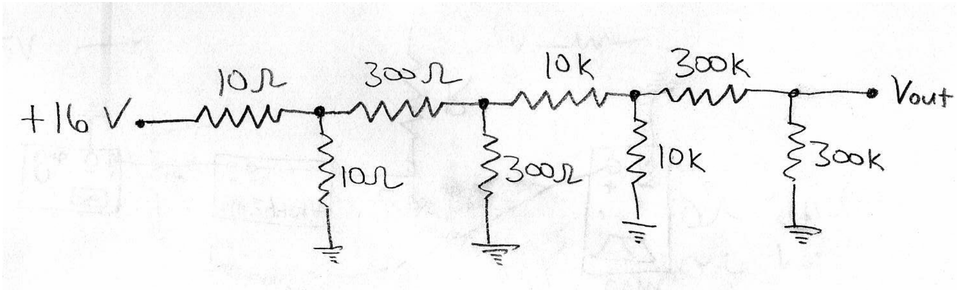
Remember that in part 3.2 you measured R_{thevenin} (a.k.a. the "source resistance," a.k.a. the "output resistance") for the first divider and in part 3.6 you drew a schematic diagram for the first divider's Thevenin equivalent circuit. Keep these in mind here.

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_{out1} and V_{out2}? (You can do this in your head.) Now measure V_{out1} and V_{out2} to check your prediction.

4.2 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_{out1} from the first feeding V_{in2} for the second. What is the input resistance of the second divider? Now what do you expect for V_{out1} and V_{out2}? (Unlike part 4.1, you probably need a pencil for this one.) Measure them and compare with the results you expect.

4.3 In making your voltage measurements in parts 4.1 and 4.2, you probably neglected the finite $R_{\text{in}} = 10\ \text{M}\Omega$ of the voltmeter. Explain why it made sense, in these measurements, to treat the meter as if its R_{in} were effectively infinite (i.e. to neglect it), as we normally do.

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 want the source voltage to be relatively unaffected by the presence of 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 4.4 straightforward.



(You don't need to build this!)

4.4 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 to do this calculation in your head if every resistor were 1 kΩ?