Physics 120A
D. R. Smith
Due: at start of section, week of April 12, 2004

Experiment #1: Measuring Current, Voltage and Resistance

Purpose:

This week, you will gain a working knowledge of the basic measurement equipment that we will use throughout the quarter. This equipment includes the oscilloscope and the digital multimeter. In electronics, the two fundamental parameters that characterize a circuit are the voltage and the current; in this lab, you will learn to make accurate measurements of these parameters, including static (DC) and time-varying (AC), taking into account the inherent limitations associated with electronics measurement.

Equipment:

This lab will require the following items:

- Oscilloscope
- Digital multimeter
- Appropriate clip-leads and banana cables
- Power supply
- Function generator
- Resistor “decade” box
- Three 1 kΩ resistors

INTRODUCTION

DC Voltage Measurements

In physics 120A we use the two most common electronics measurement instruments to measure *voltages*: the **digital multimeter** and the **oscilloscope**.

The heart of a digital multimeter is an ADC (**A**nalog-to-**D**igital **C**onverter). For the time being, let us consider the ADC as a "black box" whose input is a DC voltage between 0.0 V and 1.0 V and whose output is a number digitally encoded to drive an LCD (**L**iquid **C**rystal **D**isplay) display. The digitizing process takes a certain amount of time, so only DC or slowly varying voltages can be measured. Between the input terminals of the DMM and the input to the ADC we have an amplifier with 10 MΩ input impedance and adjustable gain. Together, these two items give us a device for measuring DC voltages over a wide range of values.

In an oscilloscope, the input voltage vertically deflects an electron beam on its way to a fluorescent screen. The amount of vertical deflection is proportional to the input voltage. If, additionally, we provide a horizontal deflection which is proportional to time, we can measure time-varying voltages. It is easy to move the beam of light electrons at high speed, so we can observe and measure voltages which vary rapidly with time.

AC Voltage Measurements

In AC mode, the oscilloscope and DMM have a capacitor between the input connector and the input circuit. Thus, any net DC offset of your input signal is blocked, and you *observe the AC component only*. This feature is useful only when a small AC signal is superimposed on a large DC offset.

In general, you are advised to avoid AC mode.

Electric power commonly available has a voltage (and hence current) which varies in time as

$$V(t) = V_0 \sin(2\pi ft) = V_0 \sin(\omega t)$$

where V_0 is the amplitude of the voltage and f is the frequency. In North America, $f=\omega/2\pi = 60$ Hz; in the rest of the world, f = 50 Hz. The AC voltage across a resistor R dissipates an *average power* $P = V_{rms}^2/R$, where

$$V_{rms}^2 = \frac{1}{\tau}\int_0^\tau dt V^2(t) = \frac{V_0^2}{2},$$

with t=1/f. The subscript "rms" indicates "root-mean square."

For the electrical power engineer or the electrician, a DMM which would calculate V_{rms} would be a great convenience. Your DMM, when in the **AC Volts** mode, does not do this. Your DMM measures the time average of the rectified (but *not* squared) AC component of the input signal, or

$$\overline{V}_r = \frac{1}{\tau}\int_0^\tau dt\left|V(t)\right| = \frac{2}{\pi}V_0.$$

Thus, for voltages that vary as $V(t) = V_0 \sin(\omega t)$, you can see mathematically that

$$V_{rms} = \frac{\pi}{\sqrt{8}}\overline{V}_r = 1.1\,\overline{V}_r.$$

The DMM measures $\overline{V}_r$, multiplies by 1.11, and displays an approximation to V_{rms}! Note that this rescaling factor, built in to your DMM, is *not* correct for other wave shapes, such as square or triangle waves.

Caution

When using instruments in the AC mode, be aware of the following two limitations:

- The input resistance of the front-end circuit of your oscilloscope is $Z_{in} = 1$ MΩ, and that of your DMM is, $Z_{in} = 10$ MΩ. At low enough frequency, the impedance of the DC blocking capacitor will be comparable to those resistances, so that only a fraction of your input signal will be measured by your instrument. Note that the 10x oscilloscope probes effectively increase the input resistance to the oscilloscope, to a value of 10 MΩ.

- Your DMM in AC mode is an “industrial” instrument, built to be accurate at around 60 Hz. At high enough frequency, the performance of the rectifying circuitry degrades, yielding an incorrect reading. In case of doubt, always check the reading against the oscilloscope display; the frequency dependence of the oscilloscope is superior to that of the DMM.

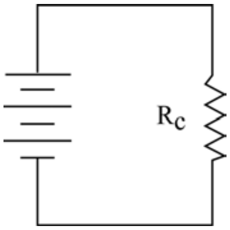
Current Measurements

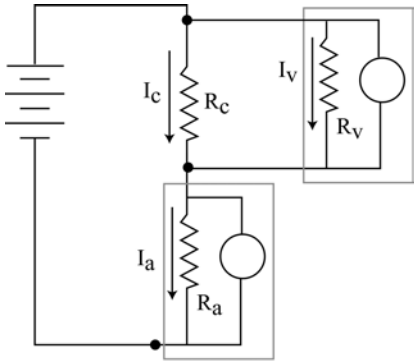
Given a sensitive voltmeter, a method of measuring the *current* flowing in some section of a circuit would be to break the circuit (cutting a wire, for example), insert a small precision resistor, and measure the voltage across the resistor. Of course, the value of the resistance added to the circuit should ideally be negligible in comparison to the other circuit elements, otherwise an error will be introduced.

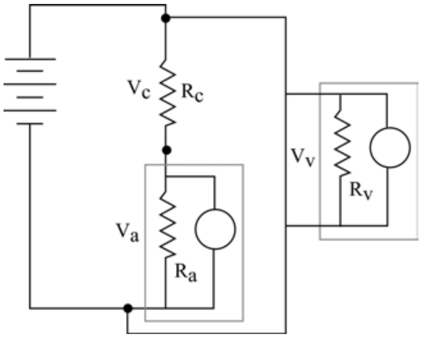
The instrument that measures current is called an **ammeter**, and its operation is exactly as described above; if you want to measure the current flowing at some point in a circuit, break the circuit and insert (in series) the ammeter. The current in your circuit will be unchanged by the presence of the ammeter only to the extent that the precision resistor internal to the ammeter is small compared with the total resistance R_c of your circuit.

Resistance Measurements

The resistance R_c of a conducting element is defined as the ratio between the voltage drop (ΔV) across the element and the current (I) through the element. In the simple circuit shown in Fig. 1a, presumably measuring the voltage across the resistor with the DMM to obtain ΔV, then breaking the circuit and inserting an ammeter to measure the current I should provide a reasonable measurement of $R_c=\Delta V/I$.







However, as shown in Fig. 1b, it must be kept in mind that the ammeter and the voltmeter have their own internal circuits that should be taken into account. The voltmeter effectively connects its (large) input resistance R_v in parallel with R_c, and the ammeter connects a (small) resistance R_a in series with R_c. When $R_c > R_v$, an error is introduced: the current measured by the ammeter will include the current I_v flowing through the voltmeter ($I_a=I_c+I_v$)! In this case, the circuit of Fig. 1c is more accurate. We will use the technique depicted in Fig. 1c in a later lab.

In setting up the experiments in this lab, and later analyzing the results in your lab write-up, make certain you have understood the impact of the measuring equipment on the measurement.

Voltage and Current Sources

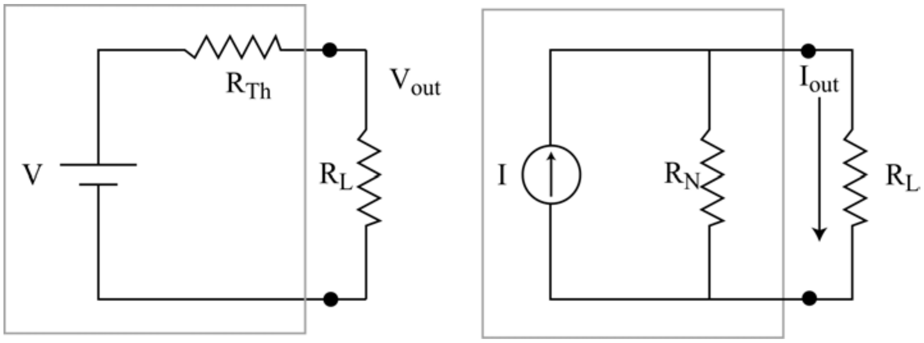
There are several classes of voltage and current sources.

- An **ideal voltage source** has an output voltage, which is independent of the current drawn by a load across its output.

- An **ideal current source** issues an output current which is independent of the voltage required across the load through which the current is drawn.

- A **Thévenin** voltage source is an ideal voltage source with a series resistor (Thévenin resistance R_{Th}). Here the output voltage decreases linearly with increasing output current. An ideal voltage sources has a zero Thévenin resistance.

- A **Norton** current source Fig. 2b is an ideal current source with a parallel resistor (Norton resistance R_N). Here the output current decreases linearly with increasing output voltage. An ideal current source has an infinite Norton resistance.



Your Instek power supply can be used as a regulated voltage source or as a regulated current source. The source remains "regulated" over a wide (but finite) range of load resistances. Within that range, the power supply acts like an ideal source by virtue of its regulation circuitry. Regulation is achieved by active feedback, a subject that you will study later in the course.

As you will determine experimentally, both your audio signal generator and your function generator do indeed behave like Thévenin voltage sources. You can determine the Thévenin resistance, according to the definition, as its open circuit output voltage divided by its short circuit current.

Resistance Measurements: Experiment

Set your DMM to the **Ω** mode.

With the DMM connected to a resistor, there are actually four resistances in series. Each of the two leads has a resistance, the DMM has an internal resistance, and the resistor being measured has some resistance. In addition, at every connecting point (or contact point) there can be a resistance that differs from the lead and other resistances in the problem. A poor contact will have a larger resistance.

1. What does the DMM read with nothing connected to the leads? This is what you will expect for an open circuit.

2. Connect together the two inputs of the DMM with the shortest available banana-banana lead. You have measured the sum of two contact resistances, the smallest resistance you ever expect to measure in this lab. Unplug and plug in the short lead several times and take a measurement. How repeatable are the contact resistances?

3. Connect together several lengths of coaxial cable (RG-58) and, at each end of this chain connect a BNC-banana adapter. Connect one adapter to the DMM and short out the adapter at the other end. You now have a measurement of the cable resistance. How does it compare with the manufacturer's specifications?

4. Connect two banana-banana leads to the DMM and hold the end of each of the leads in each of your hands. You have measured the resistance of your body, under the current conditions (humidity, perspiration, dirt, etc.) of your skin. As you can see, if you wish to measure a high resistance, do not touch the contacts with your hands.

5. Connect, using two short banana-banana leads, the DMM to your resistor box. Set the resistance of the box to a range of values, from the lowest to the highest, and, for each setting, record the reading on the DMM. After correcting for lead and contact resistances, what is the agreement between the box settings and the DMM readings? Analyze the differences in terms of possible sources of errors (box setting, changes in contact resistances, digitization error on the DMM, other errors).

DC Voltage Measurements: Experiment

Here we will compare the measurements using the DMM with those on the oscilloscope.

1. Set the DMM to the DC VOLTS mode. Set the oscilloscope trigger to AUTO.

2. Connect the output of the dual power supply to the DMM *and* to the oscilloscope.

3. Set the oscilloscope input to GROUND. Set the oscilloscope intensity and focus to get the sharpest trace. Using the vertical adjustment, locate the trace on a convenient grid line.

4. Enable the ΔV mode on the oscilloscope. Line up, as well as you can, the bottom reference line with the trace. Set the oscilloscope input to DC.

5. Set the output of the dual power supply to about 4 V. By changing the vertical scale of the oscilloscope, get the trace onto the screen. Line up, as well as you can, the top reference line with the trace. Record the DMM reading and the ΔV reading.

6. Estimate your oscilloscope measurement error by taking, **independently** for yourself and your partner, several measurements at this power supply voltage. How can you use these measurement errors to estimate the errors for future measurements?

7. Repeat the above measurements at about ten voltage values over the full range available. Analyze the agreement (or disagreement) between the DMM and oscilloscope measurements.

AC Voltage Measurements: Experiment

Using oscilloscope measurements in the DC mode, we now study oscilloscope performance in the AC mode and V_{rms} measurements on the DMM in the AC mode.

1. Set the DMM to the AC VOLTS mode.

2. Set the oscilloscope to the DC mode.

3. Set the function generator to the **sine wave** mode.

4. Connect the output of the function generator to the DMM and to channel 1 of the oscilloscope and set it to trigger on channel 1.

5. Adjust the **frequency** of the function generator to approximately 60 Hz.

6. Adjust the output **amplitude** of the function generator to approximately 0.5 V (1 V peak-to-peak).

7. Center, vertically, the trace on the screen.

8. Set the oscilloscope into the ΔV mode.

9. Using the ΔV reference lines measure and record the signal amplitude.

10. Record the DMM reading. Does it agree, within errors, with your prediction?

11. Should you use the scope calibration determined above for a DC voltage? Why? Why not?

12. Now set the function generator to the **square wave** mode and repeat the above measurements and analysis.

13. Set the function generator back to the **sine wave** mode.

14. Over the *full* available frequency range, measure at ten different frequencies:
    a. Signal amplitude on the oscilloscope in the DC mode.
    b. Signal amplitude on the oscilloscope in the AC mode.
    c. V_{rms} reading on the DMM in the AC mode.

15. Estimate the size of the AC mode coupling capacitors, both in the DMM and the oscilloscope.

16. Over which frequency range does the DMM, in the AC mode, give “good” measurements. Define “good.”

Thévenin Resistance Signal Source: Experiment

We wish to investigate whether our signal sources (audio oscillator and function generator) behave as Thévenin sources; and to the extent that they do, determine their Thévenin resistance (source resistance). Recall that in a Thévenin source the output voltage decreased linearly with increasing output current.

1. Set your audio oscillator and your function generator to the **sine wave** mode.
2. Set the frequency to about 60 Hz. Your earlier measurements should have determined that, at that frequency, the DMM performed well.
3. We will now connect a variable load (i.e. our resistance box) across one of the two signal sources. Before we do this, we remember that the power dissipated in a resistor R, when we apply a voltage V across it is $P = V^2/R$.
4. What is the power rating of the resistors in the box? Check the manufacturer's specifications or ask your TA.
5. Set the box to a relatively low resistance, about 10 Ω.
6. Now set the signal amplitude to a safe level, let's say 1/2 of the maximum safe voltage.
7. Measure and record this signal voltage when the resistance box is disconnected.
8. Now connect the R_{box} and connect your DMM across it.
9. For increasing resistance values, measure and record the voltage across the resistance box. Make sure that at least one of your measurements yields a voltage less than half the open circuit voltage. Why? Determine your measurement errors.
10. Plot your measurements and do a straight line fit.
11. Considering your measurement errors, how well do your results agree with the straight line hypothesis?
12. What is your best estimate of the Thévenin resistance? How well does it agree with the manufacturer's specifications?
13. Repeat the above measurements and analysis with the other signal source.

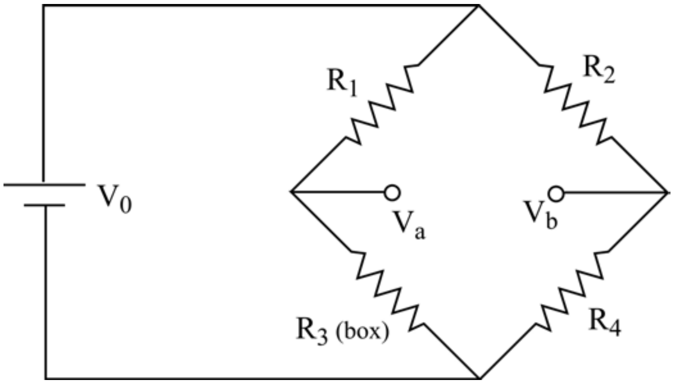
You will need your results in future experiments when the signal sources are used.

The DC Bridge Circuit

Bridge circuits provide a sensitive means of comparing electrical signals or components. They were first developed by Wheatstone to compare resistances.

In Fortney, p.12, a bridge circuit is analyzed, using the branch method. The Thévenin analysis of the same circuit (Fortney, p. 18) allows us to study the effect of the finite input resistance of the **null detector** (our DMM, or oscilloscope). In this experiment we will:

Set up a DC Wheatstone bridge to study the measurement of resistances and the resolution of these measurements.



DC Wheatstone Bridge: Theory

The analysis in Fortney, p.18 considers the Wheatstone bridge as a voltage supply (terminals **a** and **b**, with a Thevenin voltage V_{Th} and a Thévenin resistance R_{Th}.

$$V_{Th} = V_{ab,open} = V_0\left(\frac{R_3}{R_1 + R_3} - \frac{R_4}{R_2 + R_4}\right)$$

$$R_{Th} = \frac{R_1 R_3}{R_1 + R_3} + \frac{R_2 R_4}{R_2 + R_4}$$

If we choose all resistances to be 1 kΩ, then R_{Th} = 1 kΩ; thus, if V_{ab} is measured with a DMM (input resistance = 10 MΩ), our measurement will be erroneously low by only 0.01 %.

To *balance the bridge* means to adjust R_3, the decade resistor box, so that V_{ab} = 0 V. Under this condition

$$R_1 = R_3 + \frac{R_2}{R_4}$$

DC Wheatstone Bridge: Experiment

1. Select three 1 kΩ resistors (check the color code).
2. Measure and record their resistance, using the DMM.
3. Warm one resistor with your fingers, while measuring. Does the resistance measurement change noticeably?

4. Using your “proto” board, set up a bridge as shown in the figure above.
5. Set the DC power supply to 1 V and connect it to the bridge.
6. Connect the decade resistor box as shown and the DMM between points **a** and **b**.
7. Increase the sensitivity of the DMM until you get a non-zero reading.
8. Change the setting of the decade resistor box (Rbox) to reduce to zero the reading on the DMM.
9. Repeat the previous two steps until the bridge is balanced with the DMM on its most sensitive scale.
10. How well does this setting agree with above balance condition?

Do NOT dismantle this circuit when you are done: you’ll need it for the experiments next week!