Lab 1: Instrumentation and Measurements

Prelab

Read the section *7.1.1 Lecture on Safety* in your textbook.

We will only be using line voltage in a few labs and we will review safety procedures when we do. There is no need to be scared of electricity, but you should have a healthy respect.

Read www.davidbridgen.com/earth.htm, www.amasci.com/amateur/whygnd.html, and section *2.10 Grounds* in your book.

List a few of the ways "ground" is used and the symbol for each.

The most common way we will encounter the word "ground" in this class is as a label for the reference potential, that is, the potential relative to which all our other voltage values are measured.

We will be using oscilloscopes in every lab and we should understand how our test equipment can affect the circuit that is being measured. Read section *7.5.6 Oscilloscope Probes* in your textbook.

What does it mean to compensate your probe? What does 10X mode do? What are the benefits of this mode?

Your textbook will be a useful reference during labs, be sure to bring it with you.

Part I: Learning to use the equipment

1.1 Digital Multimeter

You should have two multimeters at your desk. This will allow you to measure voltage and current at the same time. Turn on each multimeter and make a list of the measurements it is capable of performing. If there are any you don't recognize, look them up in the manual.

What is the maximum current that can be measured without blowing the fuse when using the black and leftmost red connections?

To test that the fuse is good in each meter, set one to the mA range and the other to measure resistance. Connect the probes together and you should read a very small resistance value if the fuse if good. If you read infinite resistance, then talk to your TA. Switch settings on the meters and test the other fuse.

The meter measures current by converting the voltage drop across that small resistor via Ohm's law. What resistance value did you measure? What maximum voltage could you apply to this resistor before the fuse would blow?

Never switch directly to current mode from voltage mode without disconnecting the multimeter!

1.2 DC Power Supply

You actually have two DC power supplies, one in the stack of equipment, and the other in the box your breadboard is glued to. The HP supply has one variable "rail" while the breadboard supply has one constant 5 volt rail and two variable "rails". A power rail is an independent voltage source.

Power on the HP power supply and the breadboard power supply. Use your multimeter to test the outputs of the breadboard supply and check the ranges for the variable rails. The HP supply has a built in voltmeter and ammeter which show the voltage being output and the current being drawn. Check what range of voltages you can obtain, note the switch which lets you change ranges.

The HP supply has three banana jacks (red, black and green). We will only be using the red and black ones. The green jack is grounded to earth through the third prong on the power cord. Without connecting to that jack we are using the supply in "floating" mode, i.e. not earth referenced.

The CC switch is very useful to keep from blowing things up. CC stands for "constant current", but it's often more useful to think of it as a "maximum current" setting. Hold this button down and use the current knob to set a max current of 100 mA.

1.3 The Breadboard

This will be where we build up all our circuits so you should make sure you clearly understand which holes are connected together. Figure 1 shows how the metal tabs are arranged beneath the surface.

Connect a banana to bnc adapter to your multimeter (tab side to the black port). Connect a minigrabber to this adapter and clip a short piece of wire into each grabber. Set the multimeter to continuity test mode and check several locations around the board to make sure you understand what is connected and what isn't.

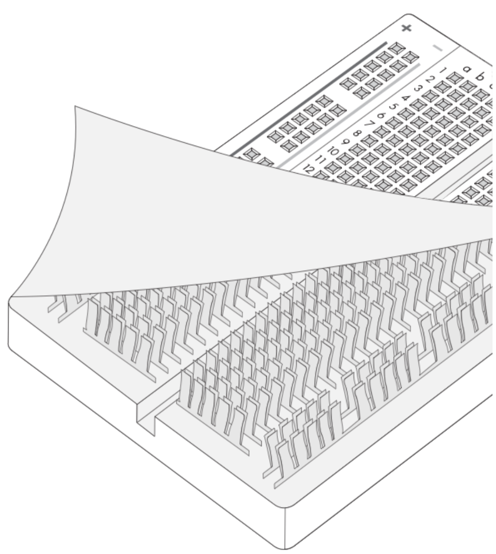

Figure 1: The internals of a solderless breadboard.
Source: http://kit.microview.io/breadboard

1.4 Testing with a simple circuit

Place a 220 Ω resistor on the breadboard and apply 5 volts across it using the HP power supply. What current do you expect to measure? Does that agree with the value displayed on the supply? Connect a multimeter in series and check that the current measured matches what you expect.

Then, test each power rail of the breadboard power supply at 5 volts. Use one meter to check the voltage and the other to measure the current. If any values are off from what you expect, alert your TA, this could indicate faulty equipment.

Is the breadboard power supply floating with respect to earth? How can you test that?

1.5 Function generators and Oscilloscopes

You have two function generators which can output square, triangle/sawtooth, and sine waves with various amplitudes and frequencies. Turn on both function generators and your oscilloscope. Connect a coaxial cable with from the output of the black 2 MHz function generator (set to the 1k range) to the channel 1 input on the scope. Use the "AUTO SET" button on the scope to quickly get going.

Look at each type of signal and figure out what each of the controls on the function generator does. Four of the knobs can be pulled out for secondary functions which are labeled in yellow.

The TTL/CMOS knob controls the TTL/CMOS[1] output. Connect a second coax cable from this output to channel 2 of the scope. This will always output a square wave at whatever frequency the main output is set to. Let's see how how we can use this to make our lives easier.

The scope uses a "trigger level" to know when to restart it's sweep across the screen. This level was set to a sensible value for you when you used the "Auto" button. Find the trigger section on the scope controls and watch what happens as you move the level up or down. If you move it above or below the signal, then the scope doesn't know what to do and it starts displaying the signal somewhat haphazardly. There is a connector marked "Ext Trig" which we can use instead of setting the level. Set the level high enough that it is no longer triggering properly and then connect the TTL/CMOS output from the scope to this input. To tell the scope to use this signal, hit the trigger menu button and change the trigger source to external. Now it will trigger properly no matter what amplitude the signal is, which makes life much easier when we are dealing with signals of various amplitudes as we will be shortly.

The "VCF IN" connection is used to set the frequency via an external voltage. We will discuss this more in upcoming labs.

Sometimes certain ranges on a function generator will go bad. Set it to output a sine wave and test each range by looking at the output on your scope. If you see any distortions in the signal, alert your TA. We can use the scope to double check the frequency as well. Hit the "measure" button and set it to display frequency and Pk-Pk amplitude for channel 1. Check that the frequency displayed on the function generator and the frequency measured by the scope agree. (Note that the number on the generator updates each time the "Gate" light flashes.) Once you are satisfied that the 2 MHz generator is working properly, repeat the tests using the 5 MHz generator.

[1] TTL stands for transistor-transisotr-logic and CMOS stands for Complementary metal–oxide–semiconductor.

What are the range of frequencies and peak to peak amplitudes each are capable of outputting?

Part II: Identifying electrical components

There are an assortment of electrical components in the yellow tray on your desk, make a list of what each one is and the properties (value, uncertainty, pin out, etc...) which you are able to ascertain via the markings and numbers.

Looking up data sheets is an important part of working with electronics, so don't hesitate to Google part numbers such as "LM337 datasheet". Another very useful resource is the table of components at the front of your textbook.

Part III: Voltage divider circuits

3.1 DC divider

Build the circuit shown in figure 2. Calculate and then measure the following values. Organize your results in a well formatted table.

- Current through each resistor
- Voltage drop across each resistor
- Power dissipated in each resistor (calculate only)

Change R1 to 510 Ω and repeat the same calculations and measurements.

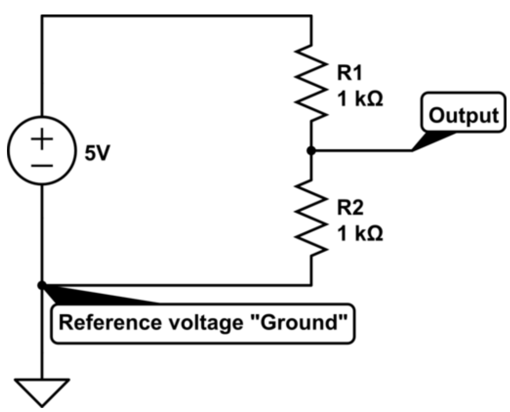

Figure 2: A voltage divider circuit

This is the simplest way to set an output voltage, however, what if you don't have exactly the right resistor values? Or what if you want to be able to adjust the voltage easily? That is what a potentiometer is for (commonly called a "pot").

A pot has three wires which correspond to the three voltage regions of the divider circuit. Figure 3 shows the internals of a potentiometer. The total resistance between the A and B pins is constant and this is the value the pot is labeled with.

Get a 10k potentiometer and check that the resistance between the left and right pins is always 10kΩ. Then connect one multimeter between the left pin and the center pin, and connect the second multimeter between the right pin and the center pin. Watch what happens to the resistance values as you turn the knob. Do they always sum to 10k?

Now connect 5 volts across the outer two pins and measure the output voltage on the center pin (with respect to the lower voltage side). What range of voltages do you get on the output wire?

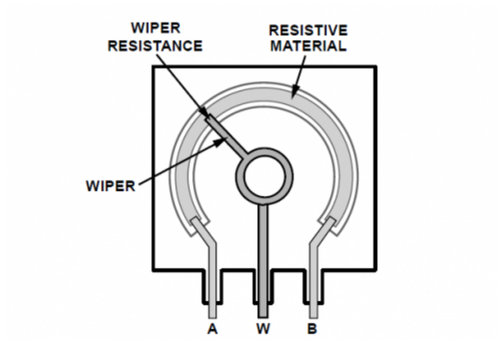

Figure 3: Internal diagram of a potentiometer

3.2 AC divider

We can use a voltage divider to attenuate an alternating voltage just like we did for a constant voltage. Build the circuit in figure 4. Connect the scope probes as shown. Note: never connect to probe ground clips to different voltage regions! Usually you should only use one of the ground clips to be safe. Adjust the scope so that both channels have the same volts/div and use the peak to peak voltage measurement of channel 1 to set the input amplitude to 5 volts.

Measure both the period and output Vpp using the cursors and using the measure menu. Both methods of measurement will be useful in future labs.

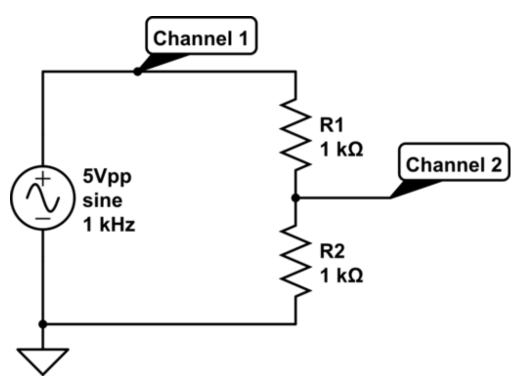

Figure 4: Voltage divider circuit with an alternating voltage source.

Part IV: Are your results meaningful

4.1 Theory

4.1.1 Why do we care?

The result of an experiment is almost, if not entirely, meaningless without an understanding of the uncertainty associated with that value. If I tell you that I measured two objects to be 3.2 meters and 3.25 meters in length then you might think those objects are very similar in size. But if then I tell you that my measuring was done in a manner that gave each value an uncertainty of ± 3 meters, you would realize you can assume no such thing.

Note: Remember that in the context of statistics "uncertainty" and "error" are exactly the same thing. A "statistical error" is NOT a mistake.

You should be familiar with the terms "relative" and "absolute" uncertainty. The absolute uncertainty is simply the plus or minus range, like the example above. Relative uncertainty is the absolute uncertainty divided by the value. So if the absolute is $\pm\Delta x$ then the relative is $\Delta x/x$. To get the percent, just multiply this by 100%. Relative uncertainty is often useful when dealing with number ranges outside of our intuitive experience. For example, let's say I measured the distance to the moon with an absolute uncertainty of ± 3000 km. Is that good or not? It turns out that would be about a 0.7% error.

There is another value often used and that is the "percent difference" or "percent change" between two values. This should not be confused with percent uncertainty and ought to be used with caution. Again, think about the first example which would have a percent difference of $|3.2 - 3.25|/3.2 * 100 =$ 1.6% which seems very small, but we know that number is irrelevant since our absolute uncertainty is so large. One place where percent difference (or percent change) is useful is when reporting stock market changes. Saying the DOW was down 13 points doesn't mean much if you don't know the starting value. However if I say the DOW dropped 5% then you would know that was a fairly significant drop. This works well since stock market prices have no uncertainty. In general we would only want to use percent difference when the absolute uncertainty is much smaller than the difference between the two numbers.

4.1.2 Assumptions

You've all had it beaten into you that "everything has uncertainty," but figuring out how to account for that uncertainty in real life can get tricky. We're going to cover just the most basic knowledge you need to effectively produce an answer at the end of a experiment which has the appropriate error bars. In the vein of simplification we are going to make two assumptions which will serve us well in most cases. (If you want to know why these are helpful, go read a statistics book.)

1. All input variables are *independent*.
2. All uncertainties follow a Gaussian distribution.

4.1.3 Where does uncertainty come from?

Often one of the first quantitative things students learn about uncertainty is the idea of analog and digital precision, often stated as

1. Digital uncertainty is ± 1 in the smallest digit.
2. Analog uncertainty is ± 0.5 of the smallest division.

These rules are mostly useless. The first thing one should realize about these rules is that they are a MINIMUM level of uncertainty. A digital display is *incapable* of displaying a number with any greater precision, this is the *resolution* of the display.[2] HOWEVER, there are many things that can increase this uncertainty! So, what are these things?

One reason that the uncertainty would be higher than this minimum level is how the instrument is being used or what is being measured. Imagine measuring the radius of a soccer ball by using a meter stick and trying to line up the markings by eye. This would clearly have a vastly larger uncertainty than $\pm 0.5mm$. A more subtle example might be using a vernier scale caliper to measure a rough surface where the unevenness of the surface is on the order of (or larger than) the uncertainty of the caliper.

There are a whole host of ways uncertainty can creep into our measurements (such as analog to digital conversion, temperature dependence, component specs, etc). Fortunately, much of the time we don't have to worry about those details because instruments such as these always have manuals with uncertainty specs which we can use. The answer to the question "what is the uncertainty of my measurement?" will nearly always be "**READ THE MANUAL**."

Think of the uncertainty as the range of numbers that you are sure the "true" value falls between.

Examples

- In one experiment I was measuring the change in pressure of a chamber with a mercury barometer by measuring the height of the column of mercury with a meter stick. We know from our analog uncertainty rule that the minimum uncertainty would be $\pm 0.5mm$. However, the vacuum was changing fairly rapidly and so I had to estimate where the top of the column was while it was moving. For the uncertainty, I looked at it and determined what two points I was *sure* the height of the mercury column was between and I decided I was confident that at a given time point the height was in a range of about $4mm$, or an uncertainty of $\pm 2mm$.
- Something many of you have experienced in lab is having the value your multimeter displays fluctuate over time. So in this case I would base my uncertainty on the range of variation. Let's say after looking at the readout for long enough to get a good sense of the fluctuations, the lowest number you have seen is 1.382 Amps and the highest is 1.397 Amps, then a good approximation of the uncertainty would be $(1.397 - 1.281)/2 = \pm .008$ Amps

Caveat: There may be multiple sources of uncertainty and one must always use largest. So say your multimeter was fluctuating as in the example above, but from looking at the manual you have

[2] Often DMMs and the like will be specified as being $3\frac{1}{2}$ digits or similar, don't confuse this with with the resolution. For more info see www.edn.com/electronics-news/4389451/What-s-a-half-digit-anyway

determined that the measurement uncertainty is $\pm.01 Amps$, then that would override the $\pm.008$ Amps.

4.1.4 The Math

Now we know how to determine the uncertainty of a measurement, but how do we translate those into uncertainties for our final calculated value? This is where *propagation of uncertainty* comes into play. The most general equation for uncertainty propagation is the total partial differential with respect to all variables which contain uncertainty. So for a value F which is a function of multiple variables, $F = f(x \pm \Delta x, y \pm \Delta y, z \pm \Delta z, \ldots)$, then the uncertainty of F is given by:

$$(\Delta F)^2 = \left(\frac{\partial F}{\partial x}\right)^2 (\Delta x)^2 + \left(\frac{\partial F}{\partial y}\right)^2 (\Delta y)^2 + \left(\frac{\partial F}{\partial z}\right)^2 (\Delta z)^2 + \ldots \tag{4.1}$$

This allows us to propagate uncertainty through any differentiable equation. It simplifies down for basic arithmetic operations to a few equations you may be more familiar with.

For addition and subtraction

$$F(x, y) = (x \pm \Delta x) \pm (y \pm \Delta y) \qquad \Delta F = \sqrt{(\Delta x)^2 + (\Delta y)^2} \tag{4.2}$$

For multiplication and division

$$F(x, y) = (x \pm \Delta x) \times (y \pm \Delta y)^{\pm 1} \qquad \Delta F = F \times \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2} \tag{4.3}$$

For exponents (with uncertainty in the base)

$$F(x) = (x \pm \Delta x)^n \qquad \Delta F = F \times n \times \left(\frac{\Delta x}{x}\right) \tag{4.4}$$

4.2 Application

Question 1

In your lab report derive the formula for multiplicative uncertainty (4.3) (ΔF when $F = x \times y$) using the general uncertainty equation (4.1).

Question 2

a. If you have a very noisy sine wave on your oscilloscope and you want to know the peak to peak voltage with uncertainty, how would you use the measurement cursors to determine reasonable values? (I recommend drawing a picture as part of your answer.)

b. What settings could you change on the oscilloscope to clean up the signal?

Question 3

Build the circuit in figure 5. We are going to find the equivalent resistance using three methods and compare the results. Show a representative subset of your work. Be sure to propagate the uncertainties through any calculations you do.

a. Calculate the equivalent resistance and uncertainty based on the color band codes (factory specified value and uncertainty).

b. Calculate the equivalent resistance and uncertainty based on the resistance value and uncertainty obtained from measuring each resistor with your multimeter. Note the uncertainty of the your meter.)

c. Calculate the equivalent resistance and uncertainty using Ohms law, $R = V/I$, by measuring the voltage drop and current through the resistor network at 5V, 9V and 12V. What are the uncertainties in your voltage and current measurements? Find the average equivalent resistance (don't forget to propagate uncertainty through the average equation).

You should have three resistance values with associated uncertainties ("error bars"), be sure to display them in a cleanly formatted table in your lab report. Are these values consistent with each other, how do you know?

In part (c) you did a simple average of the values, how might you use a graph instead? How would you account for (propagate) the measurement uncertainties?

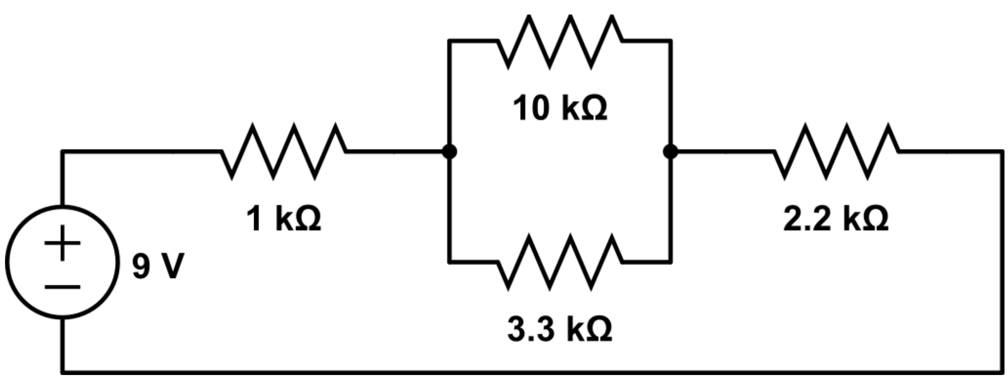

Figure 5

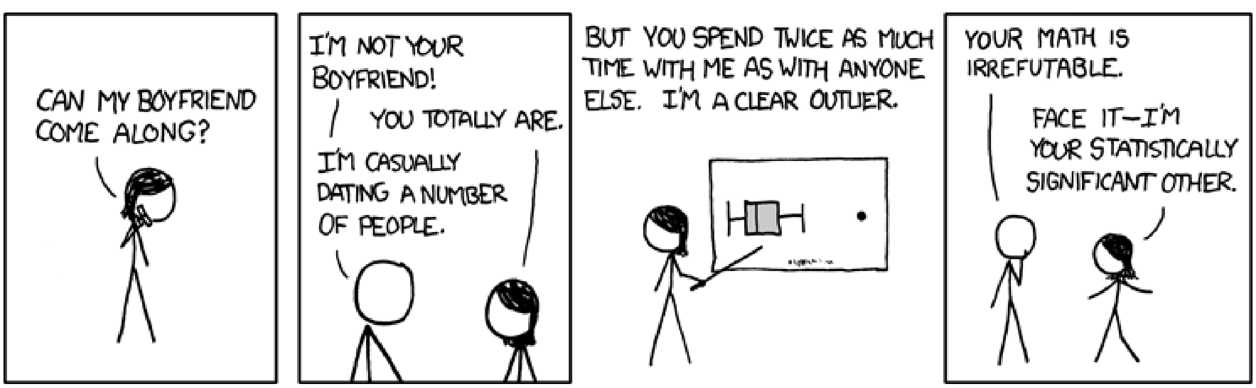

Figure 6: https://xkcd.com/539/