ECE20007: Project 1: The Wheatstone Bridge

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ECE20007 Mini Projects

In ECE20007, there will be a series of two mini projects that will be completed to test your **individual skills and abilities** in electronics. **These labs will be individual.** You will still be in pairs with your lab partner at your bench, but you are expected to make the circuits and measurements yourself with your own lab kit. You can communicate with your lab partner, TAs, or other students, but you are expected to work out the math, do the experiments, and complete the report as an individual assignment.

You will have 2 weeks of lab time to work on the project and your report. The second week of lab time will also be open for making up a lab you may have missed in the prior weeks.

These labs will be written and submitted as a formal lab report, but you will not be required to setup the entire report for the first project, which you will just include your procedure and results. For the second project, you will be expected to include an introduction, theory, procedure, results, and a conclusion.

The projects will equate to 25% of your final grade, including the final project at the end of the semester. The mini projects will be 7.5% of your final grade, with the final project being 10%.

The main purpose of these projects is to get you thinking in a more experimental mindset, testing different ways of presenting data, and thoroughly explaining your process and results. As you move forward in science and engineering, effectively developing and explaining a project or product will become increasingly important, especially when justifying funding or employment. For the projects, the general expectations and best practices will be laid out in this document, but it will be up to you to determine a good process to complete the goals at hand. Below is the general outline for how the projects will work:

Before Lab, and Early Lab 1:

1. Complete the assigned reading for the project and watch any videos associated with the project. You may want to continue doing general research to get a better understanding on the concepts being used. Make sure to cite your sources.
2. Read through the tasks you will perform, along with effectively understanding what the end goal of the experiment is.
3. Develop a general schematic, along with general steps for how you will approach the tasks of the experiment. This can be changed once you talk with TAs in lab, but you should try to have a good plan ahead of time.

During Lab:

1. Work through your plan to complete the tasks.
2. Take thorough notes, measurements, screenshots, and pictures so that you will have enough information to work on your report after you are done.

After Lab:

1. Review your notes and measurements from lab, and verify you have enough data to justify your explanations and goals. If you do not, you may have to go back to lab to take more measurements.
2. Develop your lab report with the expected sections for that report. If you have at least a rough draft completed before the second lab session of the project, you are welcome to ask for feedback on your formatting, explanations, and your report in general prior to finishing and submitting.

General Information on a Wheatstone Bridge

A Wheatstone Bridge, or sometimes simply called a resistor bridge, has been at the core of simple and effective measurement devices for nearly two centuries. This circuit generally consists of two voltage dividers in parallel with a load attaching the V_{out}'s of the dividers.

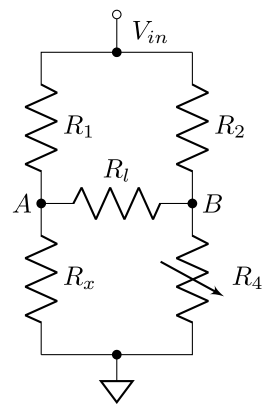

Figure 1: A standard Wheatstone Bridge. When doing research on the topic, you will likely see the bridge in a diamond pattern as well.

When using the bridge as a measuring device, a component with unknown resistance will be placed in location R_x, where R_4 will be a variable resistor. (The location of the unknown and variable resistors can of course be swapped, but they will generally stay on the bottom of the voltage dividers). The voltage at nodes A and B can be measured, and the user can then solve for R_x.

This is all good, but why bother making and using this circuit instead of just measuring the resistance of the unknown resistor with an Ohmmeter? The answer is precision. Older commercial measurement equipment, and even equipment today, is much better suited to measure voltages than resistance. This is a fun thought experiment as to why this is the situation, but taking a look at your personal or lab multimeter will verify this as well. The smallest range we can get on most commercial Ohmmeters is down to the 1Ω scale with maybe an extra decimal place or two of precision, where even an inexpensive voltmeter can usually get to the millivolt scale with at least two, maybe even three places after the decimal, or to about the tolerance of one microvolt. With this unit tolerance range between resistance and voltage apart by multiple orders of magnitude, we can get more precision on our resistor measurements by measuring voltages and then calculating resistance, and the Wheatstone bridge takes advantage of this realization.

The Math

Taking a look at Figure 1, determining the resistance of any of the resistors in the circuit is going to be rather tedious work. It is not impossible by any means, but since R_l is bridging the two voltage dividers (hence the name), and current can then flow between the two dividers, it makes the math quite annoying, even for experienced electrical engineers.

Fortunately, there are a few actions to take that will make the bridge easier to diagnose. The first way is to make the load resistor as large as possible; in fact, we can just replace it with a voltmeter, which ideally would have infinite resistance, but likely is around $1M\Omega$. This allows us to minimize the current flow between the two voltage dividers, and gives us a measuring device. We can now measure the voltage difference between the two voltage dividers, and then solve for R_x using our voltage divider equations.

$$V_A - V_B = V_{in} * \left(\frac{R_x}{R_1 + R_x} - \frac{R_4}{R_2 + R_4} \right) \tag{1}$$

Again, solving for R_x is not impossible here, but the algebra will get messy pretty quickly. This situation will work in a pinch, especially if you have equation-solving software at your disposal, or are using the bridge in conjunction with a microprocessor to monitor the bridge, but we can make this better yet. If R_4 is a variable resistor, like a rheostat, or a resistor box (also called a decade resistance box) that can clearly state what the resistance is at that time, we can tune the bridge so that V_A and V_B are the same (or very close), so that $V_A - V_B = 0V$.

$$V_A - V_B = 0V, \quad \frac{R_x}{R_1 + R_x} = \frac{R_4}{R_2 + R_4} \tag{2}$$

When $V_A - V_B = 0V$, the voltage variables reduce to 0, and we are left with a simple mater of ratios between our four resistors. R_x can be efficiently solved for, and we are able to make a few rules about how to approach this scenario. $V_A - V_B = 0V$ when:

- $R_1 : R_2 = R_x : R_4$
- $R_1 : R_x = R_2 : R_4$

When this scenario occurs, we say that the bridge is **balanced** since the output voltages are the same on both sides. Note that the input voltage is irrelevant in the calculations, so as long as your resistors can handle the current from V_{in}, you will technically be fine; however, adjusting your V_{in} might allow for better precision when measuring the difference between V_A and V_B.

Using the Wheatstone Bridge to Measure an Unknown Resistor

Between the two ratios above, we can determine different ways of balancing the bridge. The simplest approach would be to make $R_1 = R_2$. This will often work when you know the general range for your unknown resistor. If it is the same range as your variable resistor in R_4, you can then just adjust your variable resistor until $V_A - V_B = 0V$, and you don't need to do any additional math because you will have the same voltage divider on both sides. If $R_1 = R_2$, $V_A - V_B = 0V$, then $R_x = R_4$. However, if you do not know the range of your unknown resistor, it will likely be better for you to choose R_1 and R_2 at a known ratio that works well for your variable resistor. You would want to be able to get a large range of voltages from your variable resistor side of the bridge, ideally all the way from 0V to V_{in}, as this will allow you to get whatever voltage you would need to match your unknown, but as you increase range, you decrease precision, so finding a good middle-ground between range and precision will need to be found, generally around 50%-75% of the range of the variable resistor.

At this time, it is worth noting that we are not measuring at a common ground, we are measuring voltage across two arbitrary points (A and B) in a circuit. This is fine as long as we know what the voltage difference means in this case. Recall from Lab 1 that a voltmeter does not care what it is attached to, it will always take V_-, usually the black input, and subtract it from V_+, usually the red input. When this type of measurement is taken, it is called a **floating point measurement** or **differential measurement** since we are not using a common ground that we can treat as $0V$, instead, we are looking at voltages that can be almost anything. From this point on, we will be assuming that V_A is attached to V_+ and V_B is attached to V_- to keep signs consistent.

As you adjust your variable resistor, the voltage difference between V_A and V_B will hopefully move closer and closer to $0V$. If the voltage difference is positive, you then know that $V_A > V_B$, so increasing the resistance of the variable resistor will increase the voltage at V_B, bringing V_A and V_B closer together. If the voltage output is negative, $V_A < V_B$, so decreasing the resistance of the variable resistor will decrease the voltage at V_B. Once V_A is as close as possible to V_B, R_x can be calculated using the other known resistor values.

Limitations of the Wheatstone Bridge

While Wheatstone bridges can be very precise, they do have their limitations. If the bridge is setup properly, it can be used to measure very small resistances, even less than 1Ω. That said, as the resistance you are trying to measure decreases, the proper creation of the bridge becomes critical. If you are trying to measure a component with a very small resistance, the resistance of the wires in the circuit need to be included in your calculations, which adds complexity, and can decrease precision. On the other side, if the resistances in the bridge are too large, the bridge can become insensitive to small changes in resistance. This becomes a larger issue if you are using the bridge to monitor a sensor, such as a thermistor or a light-dependent-resistor.

An interesting scenario of a Wheatstone bridge is that we are taking an experimental measurement to define a set value. This is fine as long as we know our tolerances and the error in our system. The closer we can get to a balanced bridge, the better we will be, but there will still be error there. Make sure to keep this in mind when measuring and calculating.

Experiment 1: Finding the Resistivity of a Resistive Wire

The first experiment you will be performing in this project is determining the resistance of Ni-Chrome wire, a resistive wire that is used in foam cutters and electronic lighters, as a function of the wire's length, meaning that your result will have a unit of $\Omega/meter$. The wire that is being used is 80% Nickel, a good conductor of heat and electricity, and 20% chromium, which helps prevent corrosion from heat at the cost of increased resistance. This wire is made with a lot of precision, and the resistance can often be found on datasheets to 4 or more significant figures. Your primary task for this experiment is to verify that the resistance per set length of the wire holds for a variety of lengths of the wire to as high of precision as you can comfortably measure.

Tips:

- Before starting with the unknown resistor (your Ni-Chrome wire), it might be worth your time to "calibrate" your bridge with a known resistor value, such as one in your kit. This will allow you to determine a good range and ratio for R_1 and R_2.
- Understand the constraints on your system. Using the decade resistor box provided as your variable resistor, what limitations will this provide to the experiment? How will this be a hindrance? How can you use this to your advantage?
- The datasheets of the wire are publicly available, and by searching online for "Ni-Chrome 80" (80% nickel) wire will likely give you a good idea about what ranges you will be working with.
- There is no required way to present your data, but it does need to be presented. Think of ways to present your data effectively. You will need to take multiple measurements at multiple lengths, and showing the error with your data will be important. Remember to **justify** the validity of your data, along with determining if it shows what you want it to show or not.

Experiment 2: Using a Wheatstone Bridge to Make a 3-State Circuit with Sensors

As mentioned multiple times throughout this document, a Wheatstone bridge is just two voltage dividers coupled together in some fashion. We know from previous labs that voltage dividers allow for quick work and analysis of sensors, and we can use them to trigger other components when certain conditions are met. Now that we essentially have two voltage dividers, we can now monitor two sensors, which means we have 3 states that we can use. Using two light-dependent-resistors (LDR) in your Wheatstone bridge, design and build a system that will drive the voltage difference across A and B to V_{in} if it is bright around the sensors, or $-V_{in}$ if it is dark. The voltage difference across A and B to V_{in} should be $0V$ for ambient brightness. This setting is used as a comparator, a device that compares two values and gives a definitive toggle when certain thresholds are met. Similar systems are used when setting up solar panel arrays to adjust to the highest concentration of sunlight.

Tips:

- Instead of using set resistors for pairs of your LDRs, it might be worth using potentiometers as Rheostats instead. This will allow you to fine tune each side of the bridge and adjust for different thresholds. As you learned from the previous labs, the potentiometers that are in your kit might be a bit unforgiving if you are trying to make a precise resistance change. Are there other types of potentiometers out there that might be more helpful? Where might you be able to get these?
- There are multiple ways to approach this experiment, but some methods might work better than others. Think back to Lab 2 with voltage division, and how you determined your resistor pair, and the location of each resistor. If your goal is to have a max difference across your bridge at certain states, how will your resistor pairs be setup? What does it mean to have a max difference across your bridge? Run through some scenarios about how the range will change in different configurations of the bridge.
- If you would prefer a more visual representation of the voltage changing direction rather than the multimeter saying a positive or negative voltage, try using LEDs, a diode that only emits light when current flows in the right direction, and will light up when enough voltage (and current) goes through it. Feel free to ask your TAs about this.

- Where else would a setup like this be useful?

Bonus Experiment (+10%): Making Another Useful Circuit with a Wheatstone Bridge

Design and build another useful sensor circuit using a Wheatstone bridge. Validate and justify your results in your report. Explain the usefulness and potential applications of the circuit. Since the previous tasks involved a light sensor and an unknown resistor, other applications should be explored to get credit.

Tips:

- A Wheatstone Bridge can be made from any four resistors, regardless of the type of resistors. All four resistors can be variable if you want them to.
- This is a great time for you to explore different sensors that might be out there. Feel free to stop by the ECE shop to see what sensors are at your disposal. You also have other sensors in your lab kit.
- When using sensors in a Wheatstone Bridge, you don't need to have a 3-state system, you don't even need to have one state. One side of the bridge can be a threshold, or a value to meet, and when the resistive sensor meets that threshold, something can happen.
- If you want even more precision from the bridge, there are modifications you can make to allow for accurate measurements below 1Ω without having to worry about the resistance of the wire as much. Another circuit that might be worth researching is called a Kelvin Bridge.

Follow-up Questions

As a guide, here are some questions that will be worth discussing in your results and discussion section of your lab report. The answers to these questions are likely to be a little subjective. That is why it is a discussion. Just make sure to justify why you think what you think.

- Did the results match what you expected? Why or why not?
- How could the experiment be improved? What went well, what did not go well?
- Is the precision of a Wheatstone bridge worth the extra work than just using an ohmmeter?
- Why use a Wheatstone bridge over just a single voltage divider?