Tier 1 Lab: EM1 - DC Circuits (Conner Chu and Faith Qiao)

Objectives

- Introduce students to ***circuit construction*** on a breadboard.
- Build and analyze various ***DC circuits***.
- Predict the currents in a complex circuit with multiple voltage sources.
- Apply the ***error analysis*** skills learnt in the intro labs to electrical measurements.

Overview

This experiment will give you an overview of the basics of circuit components and electrical measurement. It will first introduce the basics of measuring resistance, current and voltage. Using the iOLab and a DMM, you will explore Ohmic and non-Ohmic behaviors in resistors and LEDs. You will also learn about basic circuit components and practical circuit building on a breadboard. You will build resistors in series and in parallel in order to explore voltage and current division rules.

Online Lab Notebooks

Once again, you should record everything in ***lab notebooks***. When constructing our circuits, the circuit diagram should be drawn in the lab notebook and information/specs on all circuit elements used should be recorded. In addition, you should take a picture of every circuit you build to document the physical setup/wiring of the circuit. This picture should be included in the group submission.

All setups should be fully described/sketched in the lab notebooks. ***Circuit diagrams must be provided and labeled for all circuits you construct.*** *All procedures should be fully described in the lab notebooks.* *All data must be recorded in the lab notebook or in the iOLab repository.* *You must record your data as you take the data (not at the end of the lab period).*

What to Turn In

The **group as a whole** will submit a <u>single</u> copy of the lab worksheet pdf, with all measurements, calculations, error propagation derivations, graphs and question answers included. ***Clearly list the group members*** on the first page.

Each student is responsible for acquiring a full dataset for each circuit. *All* individual dataset recordings must be shared via the online repository. Include a picture of the dataset used in the analysis for each experiment and properly attribute.

All analysis work **must be equally** distributed in the group and properly attributed. The group, as a whole, decides which datasets each person will analyze.

Theory and background

Ohm's Law and Ohmic/Non-Ohmic Behavior

Ohm's law states that the current through a resistor is directly proportional to the voltage applied across it, and the proportionality constant R is defined as resistance:

$$R = V/I. \tag{1}$$

Materials and devices that follow Ohm's law are called ***Ohmic***, and common Ohmic components include metals and various fixed-value resistors.

In contrast, if the current through a device is *not* linear to applied voltage, it is called ***non-Ohmic***, or non-linear. There are many different reasons why a device can be non-Ohmic. For example, the thin filament of a light bulb is easily heated up to a high temperature, causing the resistance to increase. A semiconductor p-n diode has smaller resistance when it is positively biased by a battery, and larger resistance when the battery is flipped over. This is because with a positive bias, a vast number of carriers can flow through the p-n junction, while with a reverse bias, only a small number of carriers can flow through the p-n junction.

Resistors in Series and Parallel

The equivalent resistance for resistors wired in ***series*** (so that the resistors are constrained to carry the same current) is given by

$$R_{eq} = R_1 + R_2 + R_3 + \cdots. \tag{2}$$

The equivalent resistance for resistors wired in ***parallel*** (so that the resistors are constrained to have the same voltages) is given by

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \tag{3}$$

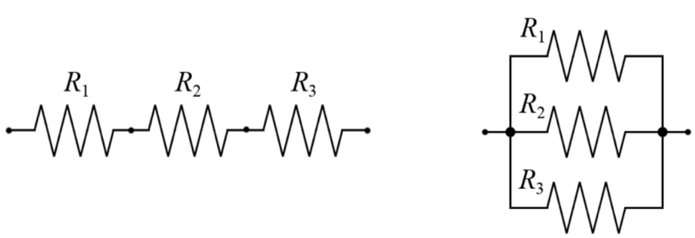


Figure 1. Left: Three resistors in series. Right: Three resistors in parallel.

Kirchhoff's Circuit Rules

One of the main tools of circuit analysis are the ***Kirchhoff Laws***:

- ***Junction Rule***: The sum of the currents entering a junction equals the sum of the currents leaving the junction. This can be represented as: $\sum I_{in} = \sum I_{out}$.
- ***Loop Rule***: The total voltage drop around any closed loop in a circuit is zero. This can be represented as: $\Delta V_{loop} = \sum(\Delta V_i) = 0$, where ΔV_i is the voltage drop across each element in the loop.

When using the junction and loop rules, the signs of each of your terms are crucial. You will need to keep track of your signs in both the theory and in practice in the lab!!

For the loop rule, if you are flowing *with* the current across the resistor, you get a voltage drop and if you are flowing *against* the current across the resistor, you get a voltage gain. If you go from the negative to positive terminal of a battery you get a voltage gain, and if you go from positive to negative, you get a voltage drop.

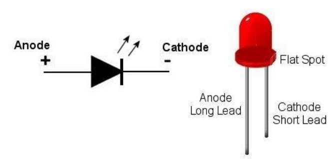
Equipment and Equipment Notes

Equipment List	
• **iOLab**	• **iOLab Software**
• **Fluke 179 Digital Multimeter (DMM)**	• **Banana-minigrabber leads**
• **iOLab Electronics Kit Circuit Components**	• **Breadboard**
• **4.5 V Battery Holder**	• **Three 1.5 V AAA Batteries**
• **Red & Green LEDs**	• **Jumper Wires (3)**
• **Jumper Wires (x3)** [pins at both ends]	
• **Hookup Leads** [pin at one end, alligator clamp at the other]	
• **Resistors (Kit):** 1 Ω (x3), 1 kΩ (x1), 4.7 kΩ (x2), 10 kΩ (x2)	

Battery Holder: The leads should already be twisted so all wires are tightly wound. If not, please twist. When using, be sure the switch is “ON”!

Jumper wires: Gently separate the wires if they are not already separate.

For LEDs: The longer lead is positive and should always be placed at the higher potential.



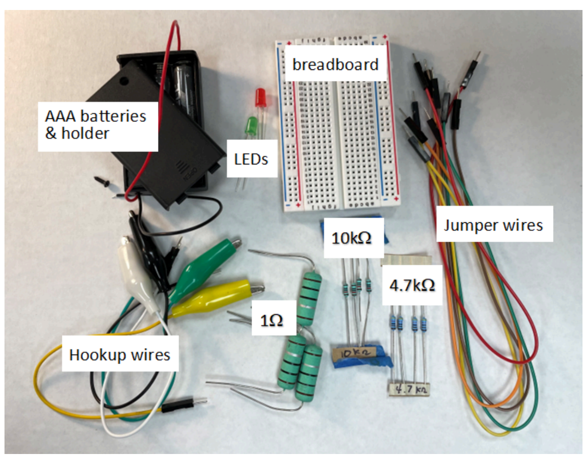
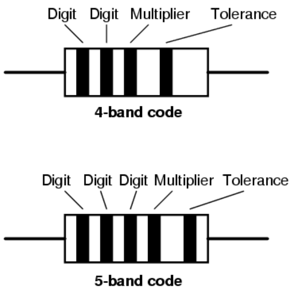


Figure 2. Some electrical components.

Resistors

Resistors typically come with a four- or five-band color code painted on them. This color code gives information about the resistance and tolerance of the resistor. The 10 colors (black, brown, red, orange, yellow, green, blue, violet, grey, white) each represent a digit (and can also represent an order-of-magnitude and a percentage). The band-structure is as follows:



Color	Digit	Multiplier/Unit		Tolerance (%)
Black	0	1.E+00	1 Ω	
Brown	1	1.E+01	10 Ω	1
Red	2	1.E+02	100 Ω	2
Orange	3	1.E+03	1 kΩ	
Yellow	4	1.E+04	10 kΩ	
Green	5	1.E+05	100 kΩ	0.5
Blue	6	1.E+06	1 MΩ	0.25
Violet	7	1.E+07	10 MΩ	0.1
Gray	8			
White	9			
Gold		1.E-01	0.1 Ω	5
Silver		1.E-02	0.01 Ω	10

Figure 3. Left: 4-band and 5-band resistor code locations. Right: Table showing the resistor color code.

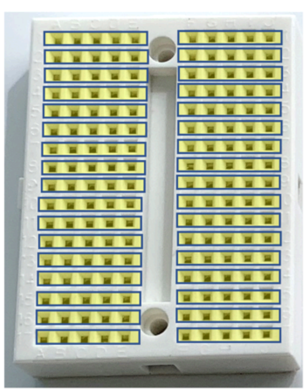
The tolerance in this case is mainly the uncertainty in the resistance from the manufacturing level. (Lower-tolerance resistors tend to cost a lot more!) All of the resistors we use in today's lab will have a tolerance of 10% (silver band), 5% (gold band), or 1% (brown band).

For example, the resistor  has a four-band code (green-blue-red-silver) so the first two bands give the two digits, the third band gives the multiplier, and the fourth, separated band gives the tolerance. This resistor would have a nominal resistance of $56{\times}10^2\,\Omega = 5.6\text{ k}\Omega$ with a tolerance of 10%.

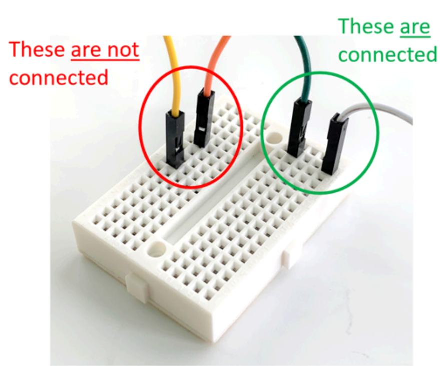
The Electronics kit resistor values and tolerances can be checked using the resistor code or a DMM (in class).

Breadboards

Breadboards can be a useful platform for simple prototypical circuit construction without needing many wires. The breadboard has metal strips on a bottom layer that electrically connects pins inserted into holes in the same row. Circuit elements can be plugged into the individual "holes"/terminals above these strips to connect to the corresponding terminal strip row or wires. As long as the two pins are within the same terminal strip, they are connected. Holes in different columns are not electrically connected.



The holes are electrically connected as shown in yellow



Examples

Figure 4. Left: A breadboard. Right: How to connect wires on a breadboard.

Sometimes you may want to connect two different rows of a breadboard together. Two different types of wires are supplied in the kit. A jumper wire with two long pointy ends (pins) allowing easy insertion into breadboard can be used. Or a hookup wire with a pin at one end and an alligator clip at the other end can be used.

Resistor leads can easily bend so insert them straight into the breadboard hole. Do not force them in.

Pre-Lab Preparation

Submit a single pdf for all 3 tasks:

TASKS 1-3: See prelab page on bCourses about measuring voltages. ***Submit a picture of your iOLab recording.***

Part 0: Using the Digital Multimeter

Measuring Resistance

Digital multimeters (DMMs) are one of the most used equipment in many modern research labs. They provide easy and accurate measurements of electrical quantities including DC and AC voltages, DC and AC currents, resistance, capacitance and more. In this section, we will explore some uses of DMMs.

Preparation: Select one resistor from the kit.

Now we will learn how to use the Fluke DMM to measure resistance.

Setup: Turn the dial of the Fluke 179 DMM to ***Ohmmeter mode*** (the 'Ω' symbol). Use the Auto Range feature. Insert the classroom black banana test lead into the COM (means common) input terminal on the DMM and insert the red banana test lead into Ω terminal. Connect the two mini-grabber test leads (red and black) across the ends of a resistor.

Measure: Now that we have the Fluke meter set up in "ohmmeter" mode, measure the resistance of one of the resistors you picked out using the mini grabbers.

10.02 ± 0.01 kOhm

Analysis: Perform an agreement test with the nominal value, obtained using the color code. Use 1% as the uncertainty in the nominal value for resistors of 1Ω or larger, 5% for the 0.5Ω resistors.

Analysis of Nominal Value starts here:

$$|\bar{A} - \bar{B}| < 2\left(\alpha_{\bar{A}} + \alpha_{\bar{B}}\right)$$

$$|10.02 - 10| < 2(0.01 + .01)$$

$$0.2 < 0.4$$

Our measured values agree with the nominal value.

Note: In practice, you'll always use the ohmmeter setting on your multimeter to measure resistance; the color code is provided so that you can determine resistance in the absence of other tools.

Part 1: Using the iOLab and DMM

The prelab provided an introduction to voltage measurements using the IOLab. The 3.3V IOLab output, a 1.5V AAA battery voltage, and the DAC output were measured with the IOLab A7 input.

In this section, a voltage divider is explored with both the IOLab and DMM. Finally, current is measured with both an IOLab "current meter" developed by pairing the IOLab G+G- inputs with a 1Ω resistor, and a DMM.

Experiment 1A: Resistors in Series/Voltage Divider

A ***voltage divider*** is a linear circuit that produces an output voltage (V_{out}) that is a fraction of its input voltage (V_{in}). Voltage dividers are one of the most widespread electronic circuit fragments and are useful for measuring a high voltage, or for creating reference voltage. To characterize a voltage divider, we can define its transfer ratio, $H \equiv V_{our}/V_{in}$. The smaller the transfer ratio is, the less voltage will be output (transferred).

The simplest voltage divider is a pair of resistors wired in series. By measuring the voltage after the first resistor, but before the second resistor, at V_{out}, and the circuit input voltage, V_{in}, we can determine the transfer ratio, H.

We will use two resistors of the same resistance and verify that the voltage drop across the first resistor will be half of the output voltage, or $H=0.5$.

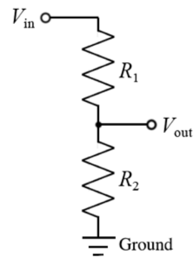


Figure 5. Experiment 1a voltage divider circuit. Vin is the DAC output, Ground is IOLab GND input

Using the IOLab to measure voltage

Setup: Connect two 10 kΩ resistors in series on the breadboard.

Connect the DAC voltage output to the "top" of the first resistor, using either the hookup wire's alligator clamp or a jumper wire pin. The "bottom" of second resistor should be connected to IOLab GND with a wire. Connect pin A7 on the iOLab device to the "top" of the first resistor to determine V_{in}. Connect pin A8 to the breadboard row that connects the two resistors, to determine V_{out}

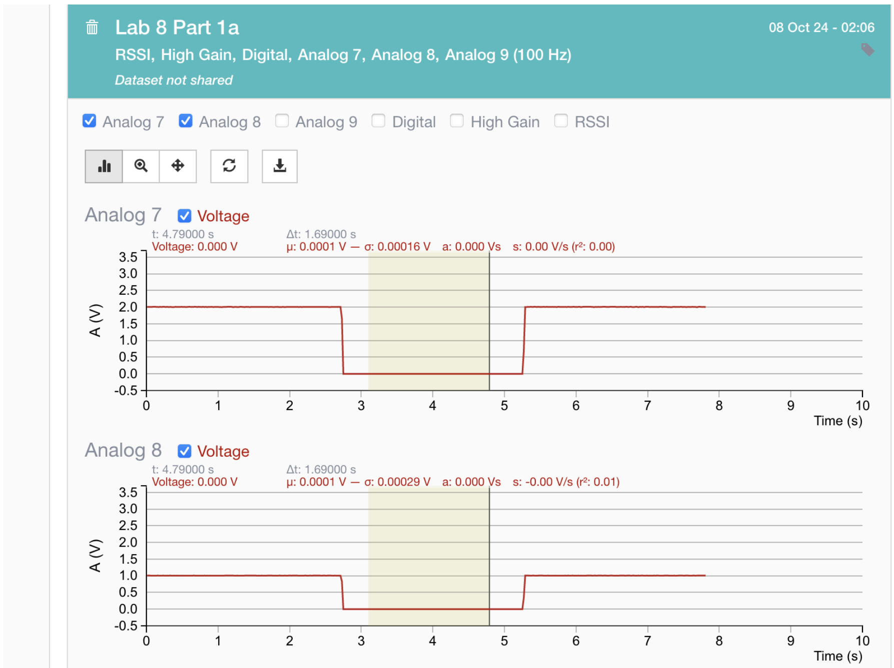
Set up the DAC by using the "Expert Mode/Output Configuration" menu item.

Two kOhm resistor values via DMM:

10.02 kOhm

10.05kOhm

Measure: Record sensors A7 and A8. Set the DAC to 2.0V using "Expert Mode", start the IOLab recording, then turn the DAC on and off.



Important Note: *If the A7 reads 1.8V after the IOLab is restarted, even though it's set to 2.0V, you've encountered a software bug! Set the DAC to 2.5 V then back to 2.0 V. If that fails, restart the IOLab software.*

Analysis: Determine the transfer ratio, *H*. Compare the experimental value to the theoretical value based on the nominal resistor values.

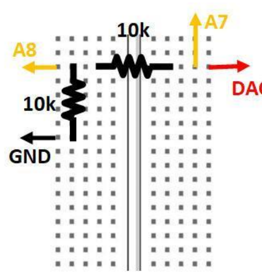


Figure 6. Breadboard layout, Experiment 1A

Error Propagation:

$$H = \frac{V_{out}}{V_{in}}$$

$$\alpha_H = \left[\left(\frac{\partial H}{\partial V_{out}} \alpha_{V_{out}} \right)^2 + \left(\frac{\partial H}{\partial V_{in}} \alpha_{V_{in}} \right)^2 \right]^{1/2}$$

$$\alpha_H = \left[\left(\frac{\alpha_{V_{out}}}{V_{in}} \right)^2 + \left(\frac{-V_{out}}{V_{in}^2} \alpha_{V_{in}} \right)^2 \right]^{1/2}$$

$H \equiv V_{out}/V_{in}$ = (1.0052 ± 0.0016) / (2.0071 ± 0.0031) = 0.5008 ± 0.0017 V

The expected value of the transfer ration falls within our experimental value for the transfer ratio!

Using the DMM to measure voltage

Voltage measurements are another common measurement performed using a DMM. In this section, the voltage output of the DAC will be measured.

Setup: turn the DMM dial to the DC voltage mode (labeled $\overline{V}$ on the Fluke, DCV). The DMM voltage mode uses the same terminals as the resistance mode, so you do not need to change the test lead connections. Using the Figure 6 layout, attach the DMM test leads to measure the DAC-GND voltage (you can attach the mini-grabber ends to the DAC and GND wires connected to the IOLab).

Measure: Turn on the DAC, record the DMM value including sign, then turn off the DAC.

Analysis: Compare the IOLab DAC output previously measured with A7 to the DMM voltage measurement. Do they agree?

DMM Measurement: 1.999 ± 0.001 V

A7 Output: 2.0071 ± 0.0031 V

Agreement Test:

$$|2.0071 - 1.999| < 2(0.0031 + 0.001)$$

$$0.001 < 2(0.0041)$$

$$0.001 < 0.0082$$

Thus, it is within the accepted value.

Experiment 1B: Measuring Current

Using the IOLab to measure current

The IOLab can only measure voltage, as opposed to the Fluke DMM, which can also measure current. We will use the same configuration as a DMM's to ascertain the current in a circuit, then compare the values of the two devices.

A DMM measures current in the following manner: the circuit is opened at the location where a current measurement is needed and the DMM inserted. Internally, the DMM measures the voltage drop across a low-value resistor placed directly in the circuit and calculates the current value.

When using the IOLab, we will be using a similar configuration, shown in Figure 6. We'll place a known voltage across a known 1 Ω resistor and use Ohm's Law V=IR to measure the induced current. In a circuit diagram, the symbol A with a circle around it indicates this configuration when using the IOLab as seen below.

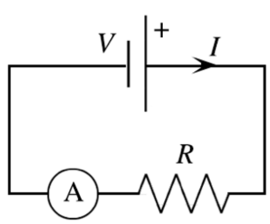


Figure 7. Circuit for Experiment 1b. V is DAC output, R= 10 kΩ, A defined as 1 Ω resistor measured with the G+G- inputs when using the IOLab

This setup works for this Lab's experiments because the 1 Ω resistor voltage drop is much less than the 10 kΩ voltage drop.

The current measurement on an IOLab can be a little tricky. An input pair, the G+/G− sensor inputs, known as the High Gain sensor in the software, will be used. The High Gain sensor allows us to measure a small difference in potential between two points, without reference to ground. This sensor will be used in all sequential current measurements in this lab.

There are a few caveats to this measurement. Although every exercise in this lab is designed to avoid trouble, you should nonetheless be aware of these if you design your own electrical measurements for the Capstone project:

- The IOLab's A7-A9 or A1-A3 inputs are referenced to the internal IOLab ground, GND. The IOLab cannot be configured in the same manner as a DMM because the component could get shorted to GND. That's why we're using G+/G-, which are floating and therefore NOT referenced to GND!
- The G+/G- input cannot be zeroed! Any small offsets, if present, must be added (or subtracted) to the measured voltage.
- The measurement range of G+/G− is ~ ±1mV!!
- In addition to G+ and G− being within one millivolt of each other, each signal should be within 1 Volt of the iOLab ground.

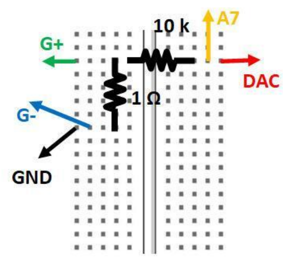
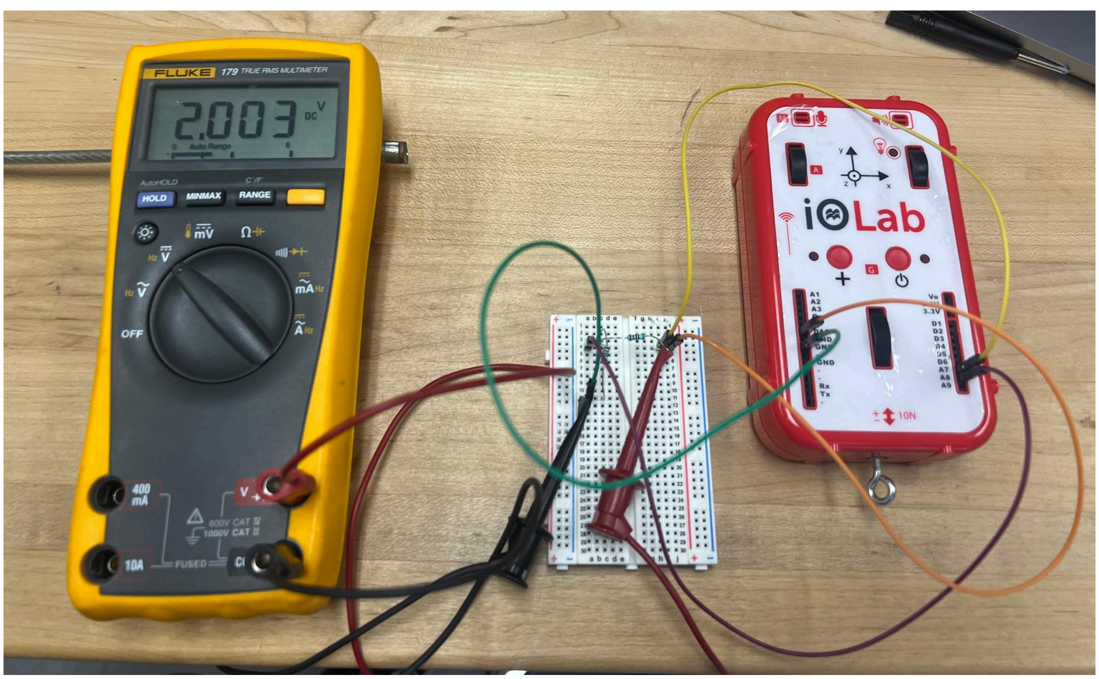
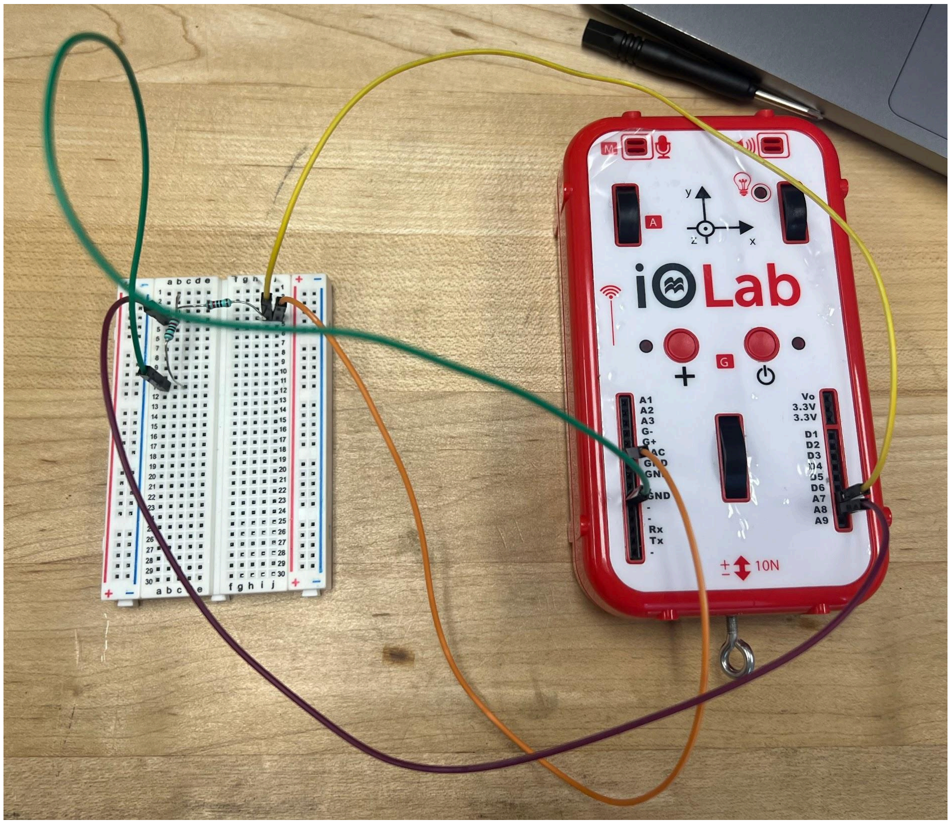


Figure 8. Experiment 1B breadboard layout. When using the DMM, reconfigure as discussed in text.

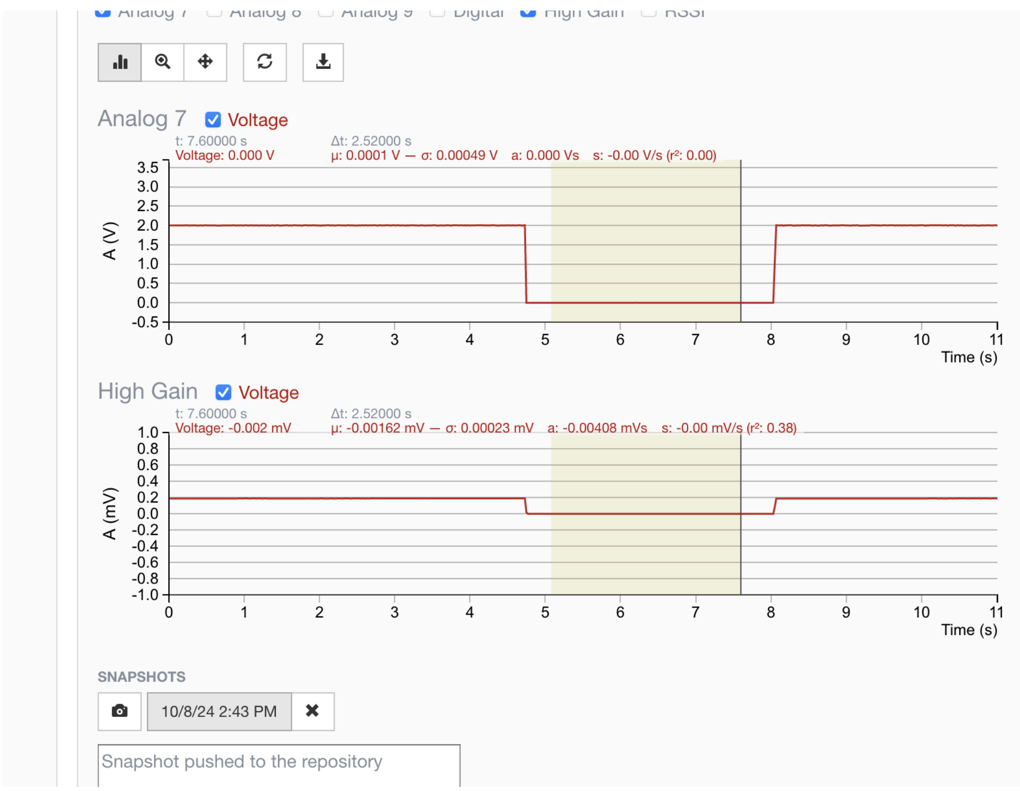
Setup: Remove the second 10 kΩ from the breadboard used in the Experiment 1A (Figure 6) and replace it with a 1 Ω resistor as shown on the breadboard in Figure 8. Then add the connections from the breadboard to the iOLab as shown on the circuit in Figure 8.





Even though we are showing the circuit diagram here and breadboard schematics here, you still need to draw one in your lab notebook and include in your lab submission. *Remember to take a picture of your circuit or to sketch the connections/how you actually wired the circuit in your lab notebook.*

Measure: Record the A7 and the High Gain sensor. Set the DAC to 2.0V, start the IOLab recording, then turn the DAC on and off.



Analysis (In-class self-check): Determine the current from the 1 Ω resistor voltage measurement. How does it compare to the predicted value?

Error Propagation:

$$I = \frac{V}{R}$$

$$\alpha_I = \left[\left(\frac{\partial I}{\partial V} \alpha_V \right)^2 + \left(\frac{\partial I}{\partial R} \alpha_R \right)^2 \right]^{1/2}$$

$$\alpha_I = \left[\left(\frac{\alpha_V}{R} \right)^2 + \left(\frac{-V}{R^2} \alpha_R \right)^2 \right]^{1/2}$$

V=IR

0.187mV = (I)(1.0 Ohm) →1.87 x 10^{-4} A = 0.187 ± 0.019 mA

Agreement Test:

$$|0.187 - 0.20| < 2(0.019 + 0.011)$$

$$|0.013| < 2(0.030)$$

$$0.013 < 0.060$$

It is within the accepted value.

Using the DMM to measure current

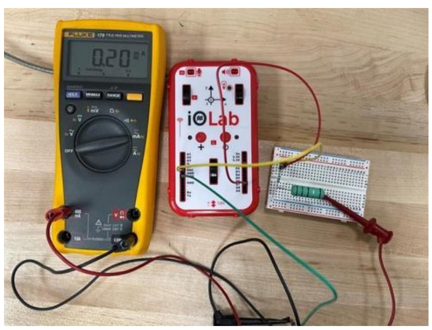


Figure 9. A DMM measures current in the following manner: the circuit is opened at the location where a current measurement is needed and the DMM inserted. It will be inserted between the 1 Ω resistor *and* GND.

Setup: Turn off the DAC. LEAVE the circuit components shown in Figure 5 in the breadboard.

Setup: Remove the G+/G- and GND leads from the breadboard.

Setup: On the DMM, *change the red test lead banana plug from the voltage/resistance input terminal to the current terminal* (use the 400mA setting). The black common lead banana plug stays in the same terminal.

Setup: Insert the DMM into the circuit: attach the DMM black test lead mini-grabber to the GND wire from the IOLab. Attach the DMM red mini-grabber to the 1 Ω component wire previously connected to the GND.

Measure: Select the DC current option (mA on switch and yellow button for DC) on the DMM, turn the DAC on, then measure the current.

We measured 0.20mA using the DMM.

Analysis (In-class self-check): Compare briefly the current measurement from the IOLab and DMM. Which one has higher sensitivity?

It appears as though the IOLab has a higher sensitivity because it went to a more precise decimal value.

Checkpoint 1

Call the instructor or GSI over to discuss your data at this point before moving on to Part 2. Explain your experimental procedure and how you are accounting for the G+G- offset.

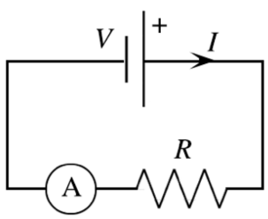
Part 2: Ohmic and Non-Ohmic Behavior

In this experiment, we will test the linear relationship $V = IR$ predicted by Ohm's law for a resistor and an LED. You need to measure voltage and current simultaneously. We will utilize everything we have learnt so far to build such a circuit.

Experiment 2A: Ohmic Behavior

The circuit for Experiment 2A is identical to the circuit for Experiment 1B. To verify Ohm's Law, the voltage applied across R is tuned over the desired range using the DAC output.

Setup: Build the circuit shown on the breadboard. Be sure to record the details of all circuit elements in your lab notebook, noting whether anything changed from Experiment 1B. Use the IOLab for the voltage measurements, and either the IOLab or DMM for the current measurements.



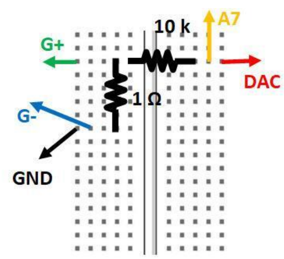


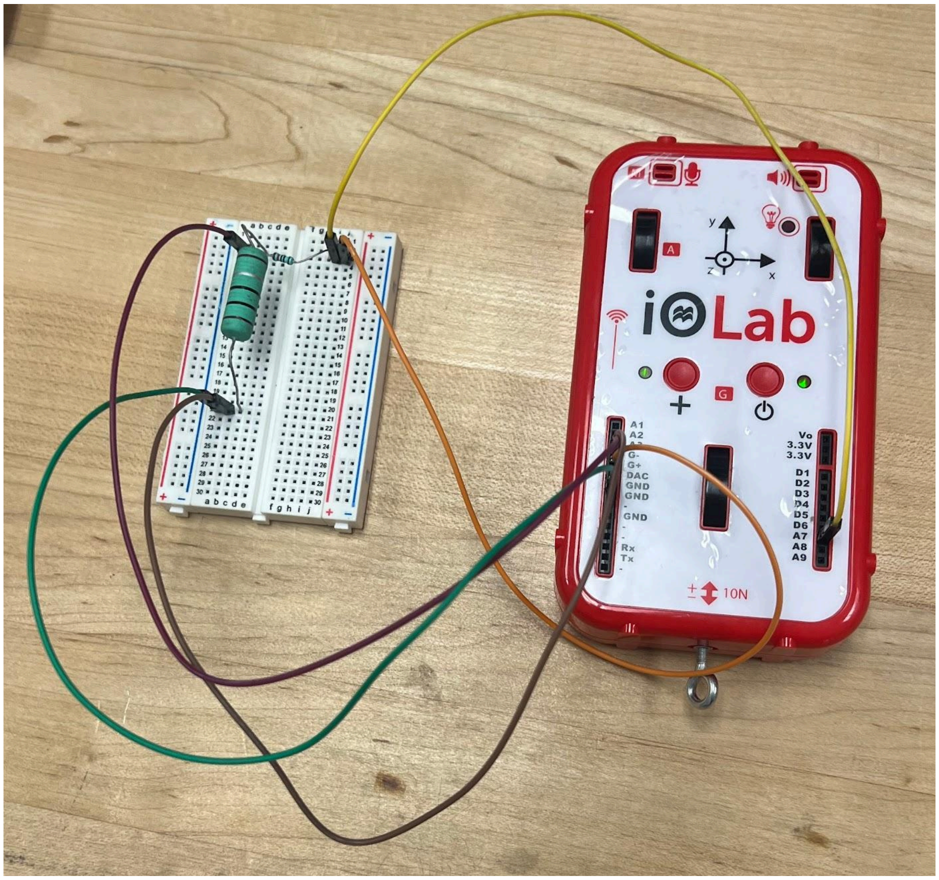
Figure 10. Experiment 2A circuit, Ohm's Law. Left: The abstract circuit diagram. Right: A breadboard diagram. V is the DAC output, R= 10 kΩ, A defined as 1 Ω resistor measured with the G+G- inputs, or the DMM current inputs inserted into the circuit.

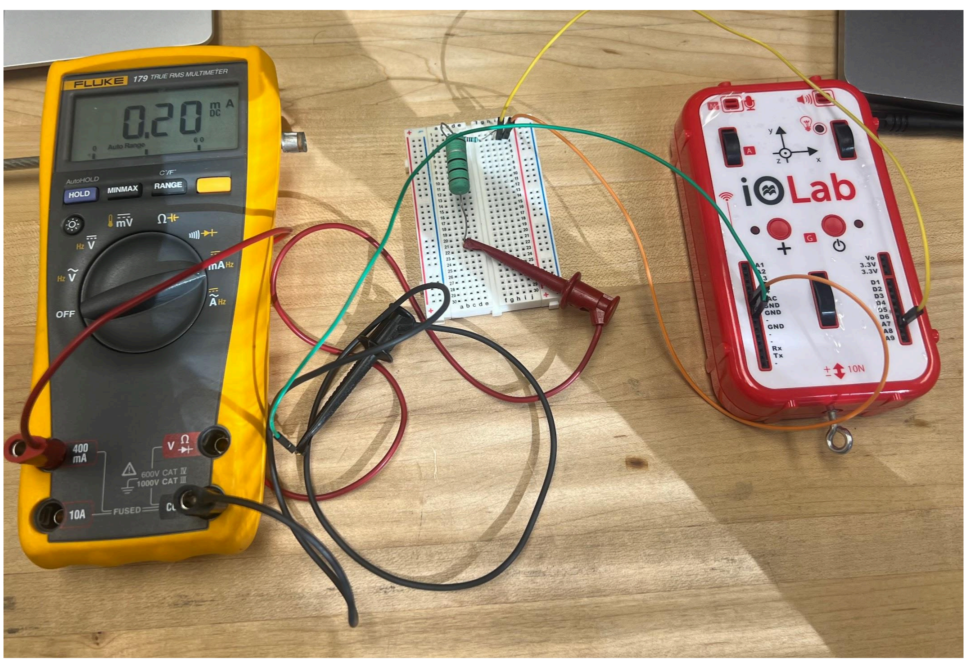
Measure: Before doing serious measurements, it is usually good practice to play with your setup to quickly check how well it works and what range of data it can provide. Change the DAC settings from the minimum to the maximum and observe the values.

Our DMM measured voltages for the resistors are the following: 1.1Ohm, 10.02kOhm.

Measure: Since we expect the I-V curve to be linear, select 10 points roughly evenly distributed in the attainable voltage range. Measure both the voltage and "current" and record your results (with any applicable errors or uncertainties) in a data table.

Analog 7 (V)	Error (V)	High Gain (mV)	Error High Gain (mV)
0.0001	0.0004	-0.00362	0.00018
0.3082	0.0013	0.02482	0.00022
0.6293	0.0017	0.05476	0.00022
1.0533	0.0023	0.09411	0.00019
1.3614	0.0031	0.12288	0.0002
1.6823	0.0037	0.15287	0.00018
2.3121	0.0048	0.21206	0.00018
2.6333	0.0041	0.24181	0.00019
2.9539	0.0061	0.27148	0.00017
3.2752	0.0059	0.30155	0.00021





Experiment 2B: Non-Ohmic Behavior

Certain devices such as LEDs do not follow Ohm's law for various reasons. A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. The color of the light is determined by the properties of the semiconductor. Because LEDs can draw substantial amounts of current, a 1.0 kΩ current limiting resistor is added to the circuit.

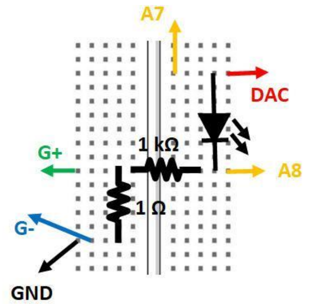
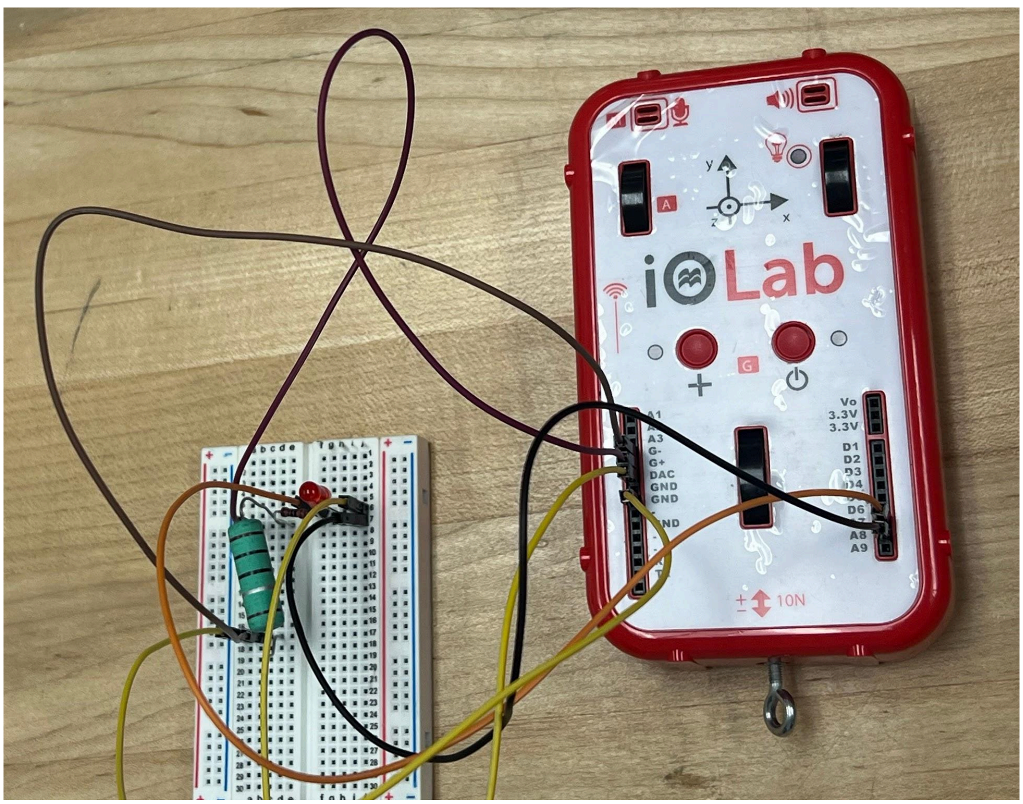
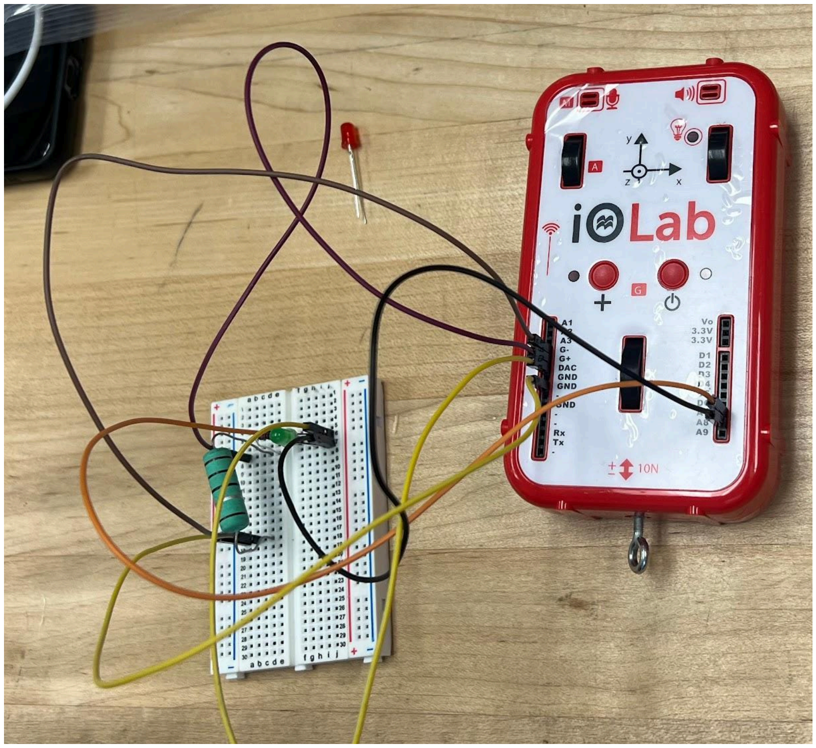


Figure 11. Experiment 2B circuit, Non-Ohmic Behavior of an LED.

Setup: Replace resistor *R* from the previous circuit with an LED followed in series by a 1.0 kΩ resistor and a 1.0 Ω resistor for the "ammeter". One group member should use a red LED, and one green, and the remaining group member can choose either one (if a 3-person group). Connect A7, A8, and G+ and G- (if using the IOLab for *I*) as shown in Figure 11.



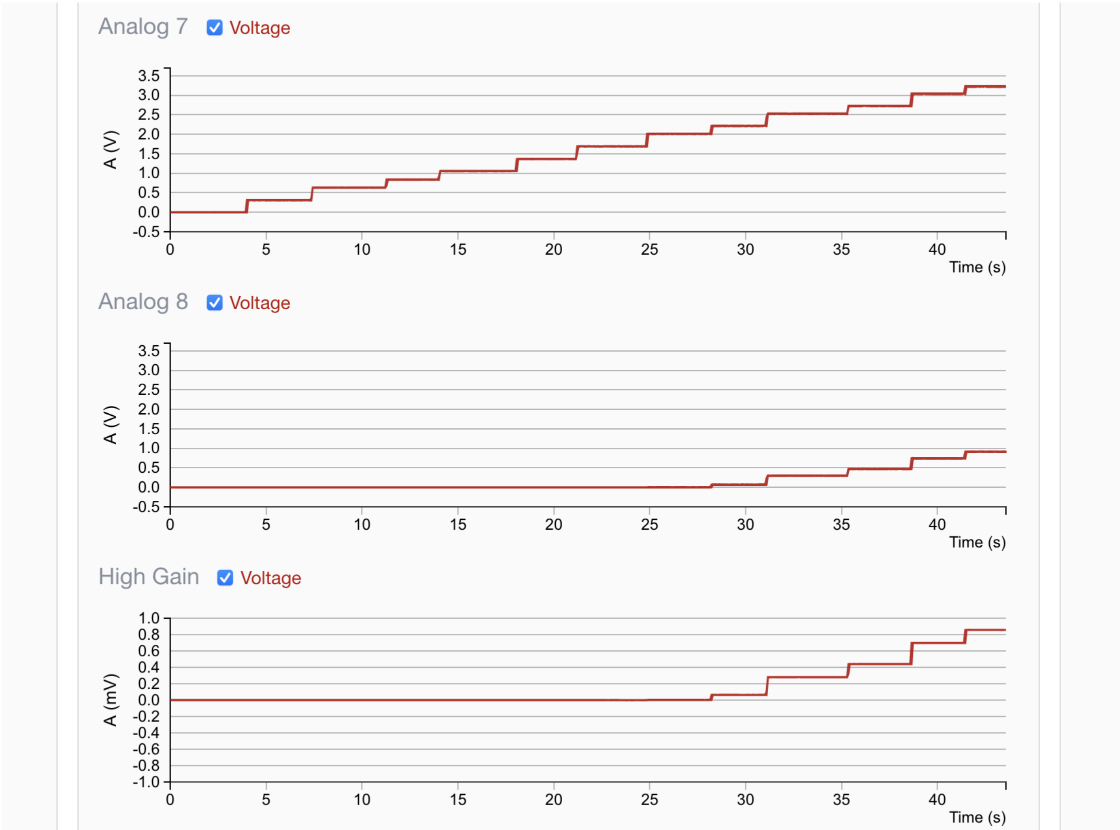


Our measured resistance values for each of our components are 0.997kOhm for the 1kOhm resistor, 1.740 mOhm for the red LED, and 5.66 mOhm for the green LED. We found that the green LED turns on at 2 volts and the red LED turns on at 1.7 volts.

Note: the longer LED lead should be placed at the higher potential!

Measure: Before doing serious measurements, play with your setup to quickly check how well it works and what range of data it can provide. Change the DAC settings from the minimum to the maximum and find the "reasonable" values.

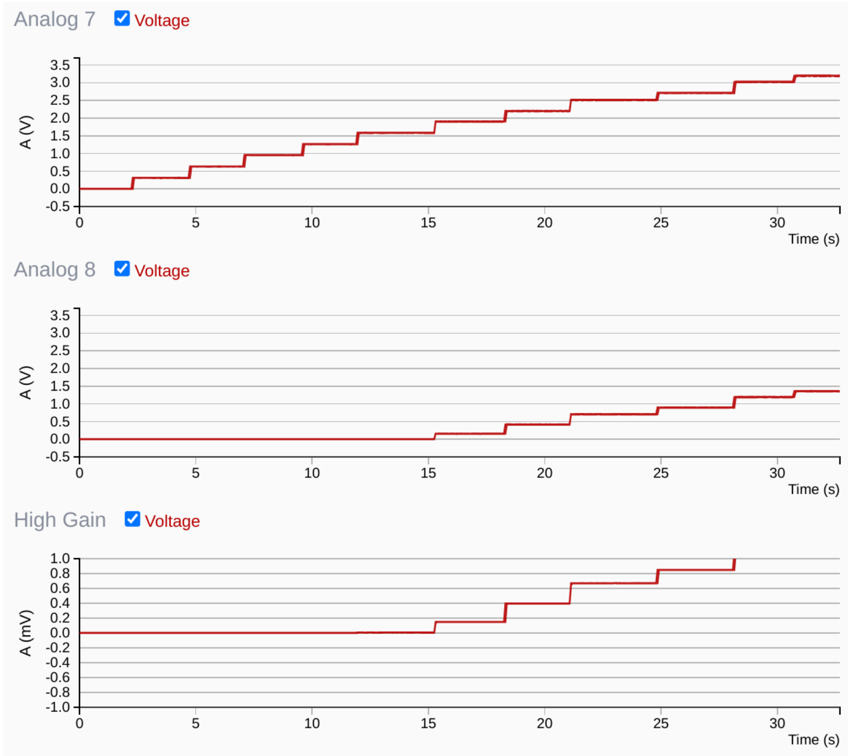
Green LED



Analog 7 (V)	Error 7 (V)	Analog 8 (V)	Error 8 (V)	High Gain (mV)	Error High Gain (mV)
0	0.00033	0	0	0.00014	0.00019
0.3093	0.0013	0	0.000082	0.00007	0.00012
0.6319	0.0013	0	0.000041	0.00004	0.00014
1.0571	0.0018	0	0	0.00024	0.00026
1.3671	0.0019	0	0	0.0002	0.00025
1.689	0.0026	0	0	-0.00085	0.0026
2.0113	0.0028	0.0025	0.0002	0.0015	0.000015
2.529	0.0037	0.3003	0.0023	0.28054	0.00022
3.0409	0.0058	0.7441	0.0035	0.69767	0.00019
3.2296	0.0067	0.9139	0.0041	0.8568	0.00019

Measure: Since we expect the I-V curve to be non-linear, select 10 "reasonable" points in the DAC voltage range and repeat the Ohm's law experiment. Measure both the voltage and current and record your results (with any applicable errors or uncertainties) in a data table.

Red LED



Analog 7 (V)	Error 7 (V)	Analog 8 (V)	Error 8 (V)	High Gain (mV)	Error High Gain (V)
0.0001	0.00037	0	0	0.00145	0.00019
0.3095	0.0014	0	0	0.00007	0.00125
0.6318	0.0018	0	0.000095	0.00004	0.00135
0.9544	0.0021	0	0	0.00138	0.00021
1.2641	0.0025	0	0	0.00131	0.0002
1.9021	0.004	0.1553	0.0021	0.147875	0.0002
2.5134	0.0053	0.7051	0.0036	0.66993	0.00019
2.7128	0.0054	0.8938	0.0039	0.84904	0.00022
3.0245	0.0059	1.192	0.0049	1.07012	0.000018
3.197	0.0065	1.3579	0.0044	1.07041	0.00017

Checkpoint 2

Call the instructor or GSI over to discuss your data at this point before moving on to Part 3. Explain your experimental procedure and how you are accounting for the G+G- offset, if any.

Analysis (Outside of Class) - Ohmic and Non-Ohmic Behavior

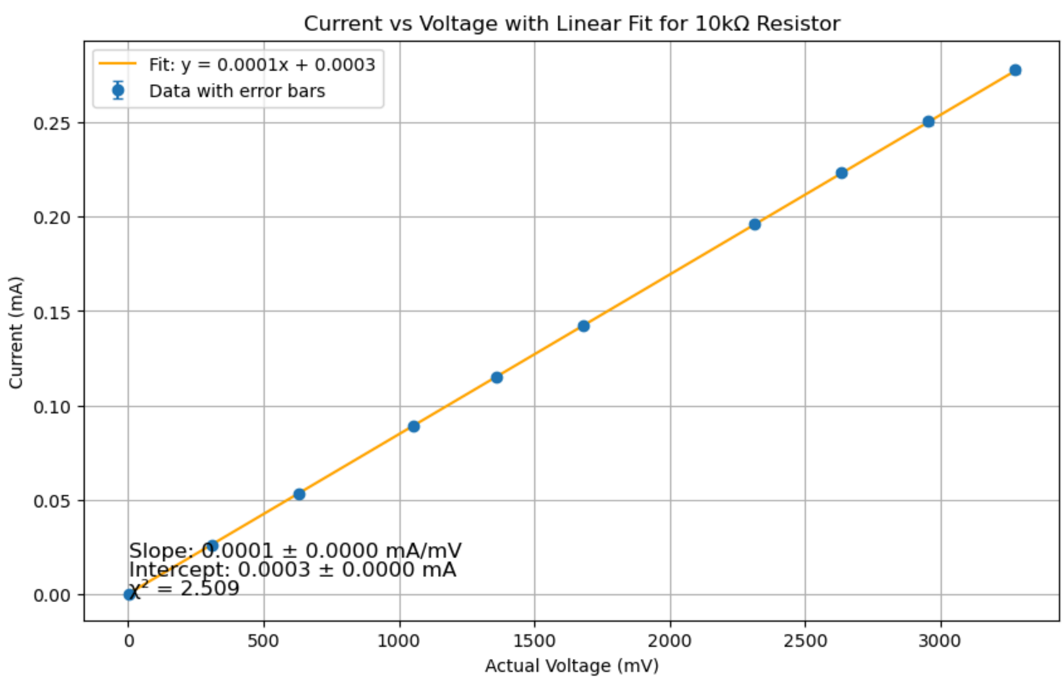
Our aim is to quantify the Ohmic and non-Ohmic behavior of the resistor and LED components.

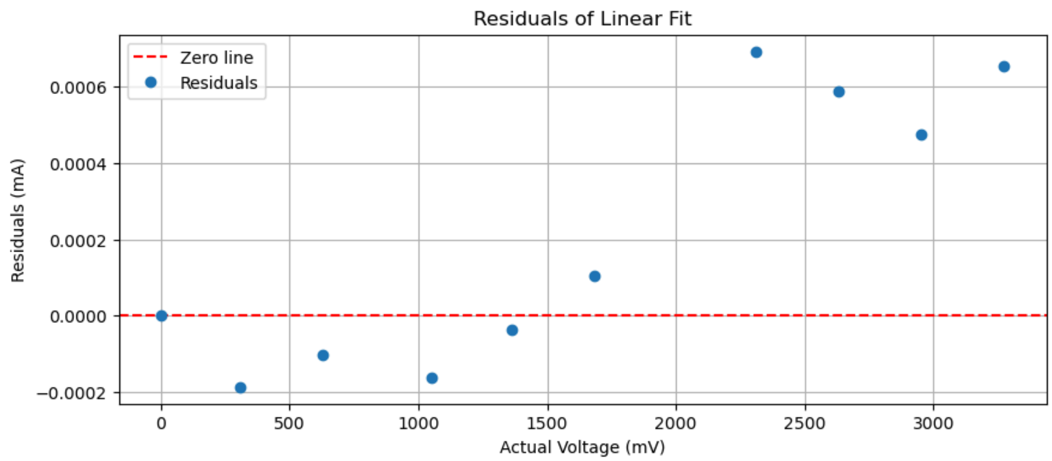
- For the resistor: Calculate the actual voltage across the resistor, 10 kΩ, subtracting off the 1 Ω resistor voltage if needed. Calculate the current using the 1 Ω voltage and correct for the G+G- offset (systematic error). Using either Python or Excel, plot the current and voltage data, placing the current measurements on the *y*-axis.

Voltage across 10 kOhm = A7 - High Gain

Current of 1 Ohm = Adjusted high gain / 1.1 ohm

Analog 7 (V)	Error (V)	High Gain (mV)	Error (V)	Voltage 10kOhm	Current 1Ohm (mA)
0.0001	0.0004	-0.00362	0.00018	0.00372	0.00035
0.3082	0.0013	0.02482	0.00022	0.28338	0.02620
0.6293	0.0017	0.05476	0.00022	0.57454	0.05342
1.0533	0.0023	0.09411	0.00019	0.95919	0.08919
1.3614	0.0031	0.12288	0.0002	1.23852	0.11535
1.6823	0.0037	0.15287	0.00018	1.52943	0.14261
2.3121	0.0048	0.21206	0.00018	2.10004	0.19642
2.6333	0.0041	0.24181	0.00019	2.39149	0.22346
2.9539	0.0061	0.27148	0.00017	2.68242	0.25044
3.2752	0.0059	0.30155	0.00021	2.97365	0.27777





- For the LED: Calculate the actual voltage across the LED. Calculate the current using the 1 Ω voltage and correct for the G+G- offset (systematic error). Using either Python or Excel, plot the current and component voltage data, placing the current measurements on the *y*-axis.

  Voltage across LED = A7 - A8

  Current of 1 ohm = Adjusted high gain / 1.1 ohm

Red LED

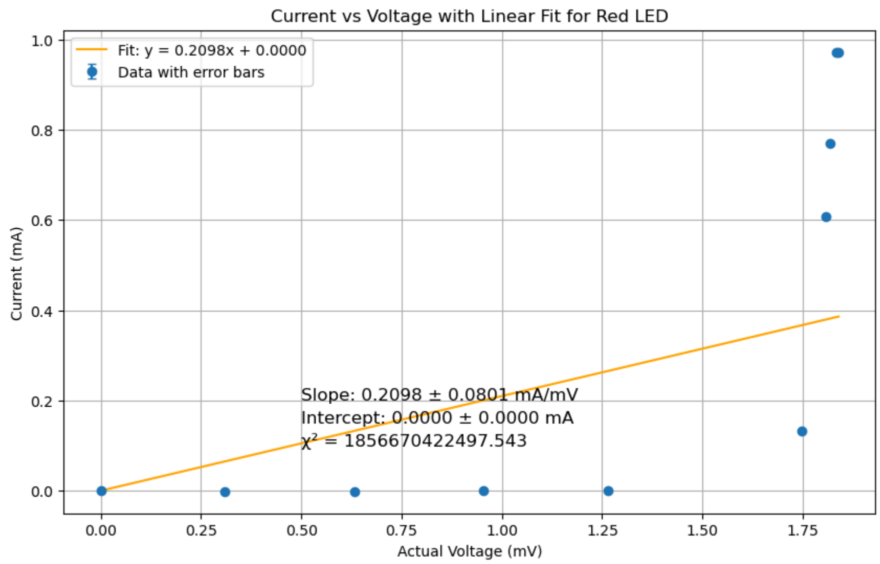
Analog 7 (V)	Error 7 (V)	Analog 8 (V)	Error 8 (V)	High Gain (mV)	Error High Gain (V)	Red LED Voltage	Current 1Ohm (mA)
0.0001	0.00037	0	0	0.00145	0.00019	0.0001	0.00003
0.3095	0.0014	0	0	0.00007	0.00125	0.3095	-0.00123
0.6318	0.0018	0	0.000095	0.00004	0.00135	0.6318	-0.00125
0.9544	0.0021	0	0	0.00138	0.00021	0.9544	-0.00004
1.2641	0.0025	0	0	0.00131	0.0002	1.2641	-0.00010
1.9021	0.004	0.1553	0.0021	0.147875	0.0002	1.7468	0.13314
2.5134	0.0053	0.7051	0.0036	0.66993	0.00019	1.8083	0.60774
2.7128	0.0054	0.8938	0.0039	0.84904	0.00022	1.819	0.77056
3.0245	0.0059	1.192	0.0049	1.07012	0.000018	1.8325	0.97155
3.197	0.0065	1.3579	0.0044	1.07041	0.00017	1.8391	0.97181

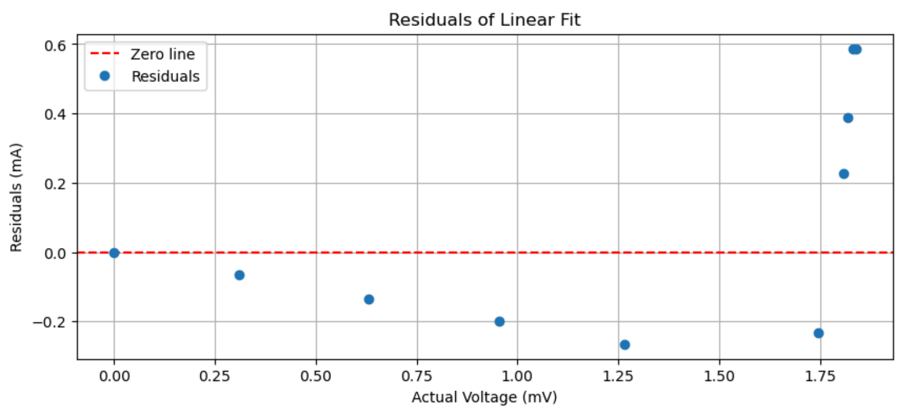
Green LED

Analog 7 (V)	Error 7 (V)	Analog 8 (V)	Error 8 (V)	High Gain (mV)	Error High Gain (mV)	Green LED Voltage	Current 1Ohm (mA)
0	0.00033	0	0	0.00014	0.00019	0	0.00003
0.3093	0.0013	0	0.000082	0.00007	0.00012	0.3093	-0.00004
0.6319	0.0013	0	0.000041	0.00004	0.00014	0.6319	-0.00006
1.0571	0.0018	0	0	0.00024	0.00026	1.0571	0.00012
1.3671	0.0019	0	0	0.0002	0.00025	1.3671	0.00008
1.689	0.0026	0	0	-0.00085	0.0026	1.689	-0.00087
2.0113	0.0028	0.0025	0.0002	0.0015	0.000015	2.0088	0.00126
2.529	0.0037	0.3003	0.0023	0.28054	0.00022	2.2287	0.25494
3.0409	0.0058	0.7441	0.0035	0.69767	0.00019	2.2968	0.63415
3.2296	0.0067	0.9139	0.0041	0.8568	0.00019	2.3157	0.77881

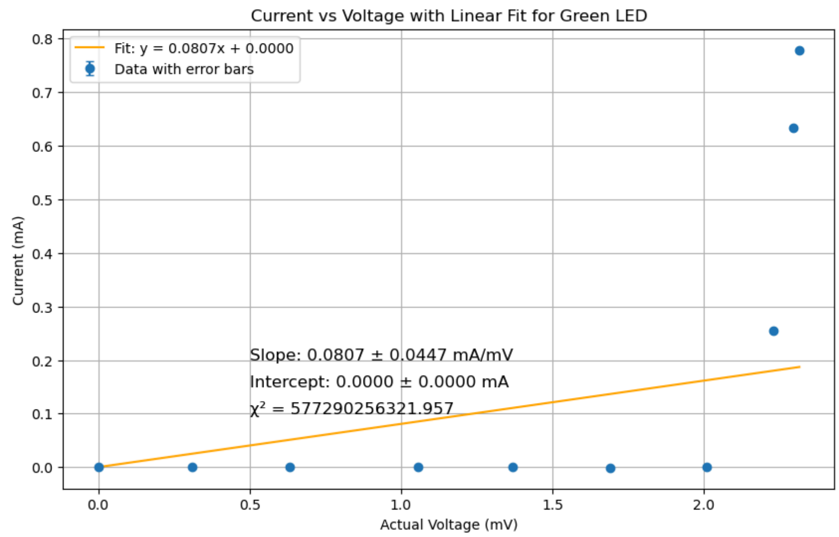
- For both the resistor and the LED: Perform a linear fit on the curves and add the fit curve to your plot. Include a plot of the residuals for each fit.
  - Make sure to label your plot fully. It should have a descriptive title, axis labels with units, the equation of the line-of-best-fit, the values of the slope and intercept with errors, and the value of $\tilde{\chi}^2$.

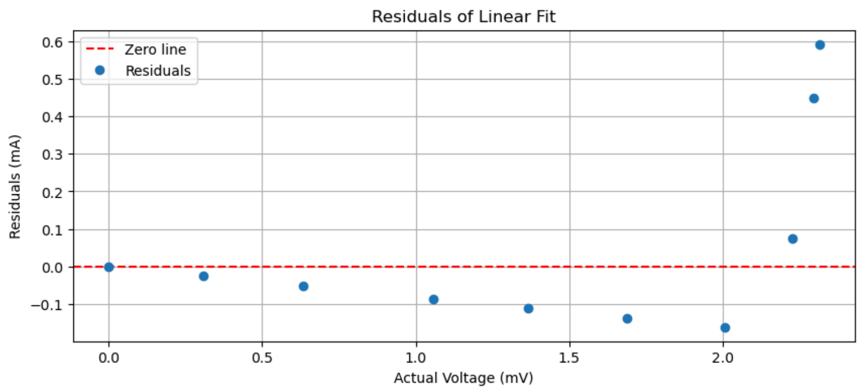
Red LED





Green LED





- For the resistor: Determine the resistance R with error from your fit. Use an agreement test to compare the fit value of resistance with the nominal value.

Resistance from fit is: 11832.37 ± 13.04 ohms

Comparison:

|11832.37 - 10000| = 1832.37 > 2|13.04 + 100|, thus it is not within the accepted values of our nominal value.

- For each LEDs: Is the linear fit good compared with the resistor? Does the LED obey Ohm's law? Calculate a best fit value of $R \pm \alpha_R$ and interpret the results.

<u>Red LED</u>:

We can see from the graphs above that the red LED generally does not obey Ohm's law, especially as the voltage applied to the system increases. Our best fit value for the red LED was 4.76 ± 1.82 ohm, which is inaccurate compared to the measured DMM value of 1.740mOhm.

<u>Green LED</u>:

Similarly, we can see from the graphs above that the green LED generally does not obey Ohm's law, especially as the voltage applied to the system increases. Our best fit value for the green LED was 12.38 ± 6.86 ohm, which is inaccurate compared to the measured DMM value of 5.66mOhm.

- Briefly, why are the green and red LED I-V curves slightly different?

The rapid growth of current through the red LED begins at a lower voltage than the green LED. This likely relates to the excitation energy level involved in emitting the specific wavelengths of light.

At last, you have all your results! Now it's time to determine whether or not your data matches the theory. Then we will determine whether or not your measured value of the resistance can meaningfully be said to agree with the accepted value.

- Determine whether or not your reduced chi-squared is too big, too small, or acceptable.

For the 10kOhm resistor, we have 8 degrees of freedom, implying that our reduced chi-squared value is likely acceptable. However, it is clear that the reduced chi-squared values are way too large for the LED experiments.

- Interpret these results! Based on your value of $\tilde{\chi}^2$, what can you conclude about your experimental results and whether or not your data matches the theory. If your value of $\tilde{\chi}^2$ is too big or too small, why do you think this might have happened?

Since our reduced chi-squared value is acceptable for the 10kOhm resistor, we can conclude that our experimental results for the calculated resistance matches theory. On the other hand, as expected, our reduced chi-squared values are large for the LED experiments which matches with theory in that LEDs do not follow a linear relationship between current and voltage.

Part 3: Kirchhoff's Laws

In Physics 5B, you learned to evaluate resistor networks using Kirchhoff's laws and the rules of series and parallel circuits. In this experiment, we will construct a circuit and compare the results to theoretical predictions! You can use either the IOLab, the DMM, or a combination for this section.

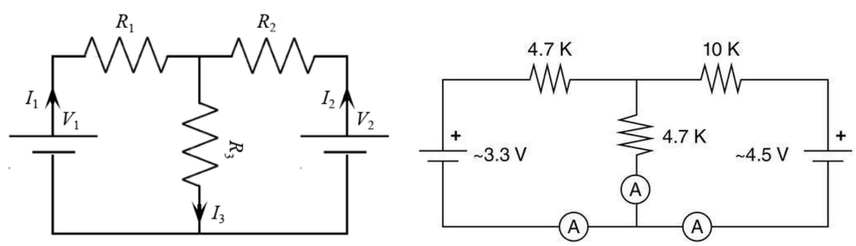
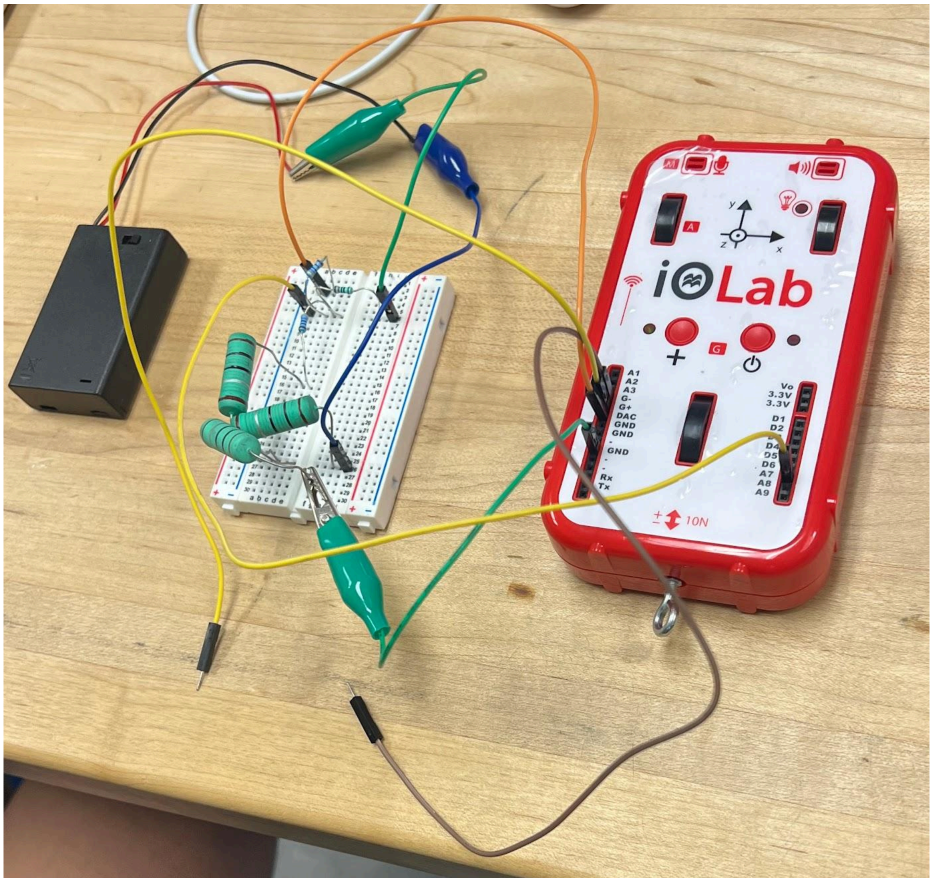


Figure 12. Kirchhoff's Law Circuit. Left: Abstract circuit diagram for Part 3. Right: Circuit diagram showing resistor and voltage values along with placement of ammeters.

Equipment: This circuit uses the IOLab DAC output for V_1, three AAA batteries in the battery holder for V_2, three resistors, R_1 = 4.7 kΩ, R_2 =10 kΩ , and R_3 = 4.7 kΩ and three 1.0 Ω resistors for the IOLab "ammeters".

Our three 1.0 Ohm resistors measured 1.1ohm, 1.2ohm, and 1.1ohm with the DMM. Resistor 1 was registered as 4.715 kOhm and resistor 3 was registered as 4.711 kOhm, and resistor 2 as 10.02 kOhm.

Setup: The A7 input can only measure input voltages *less than* 3.3 V. Measure each battery using the Prelab Task 2 procedure, using the A1 and GND inputs or the DMM voltage inputs.



Setup: Now, construct the circuit on the breadboard shown in the figures. Due to the flexibility of the breadboard, there are many possible layouts of the circuit. Experience shows, however, that choosing a neat placement of components that looks similar to the original circuit diagram can be effective in reducing the probability of wiring errors. If the resistors are larger than those shown in the figure, the breadboard layout must be modified.

Measure: Record the High Gain sensor, and the A7 as needed Set the DAC to 3.3V using "Expert Mode", start the IOLab recording, turn on the 4.5V battery holder, then turn the DAC on.

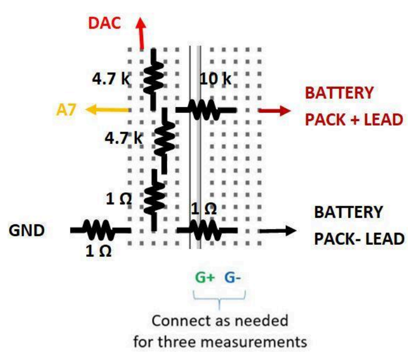
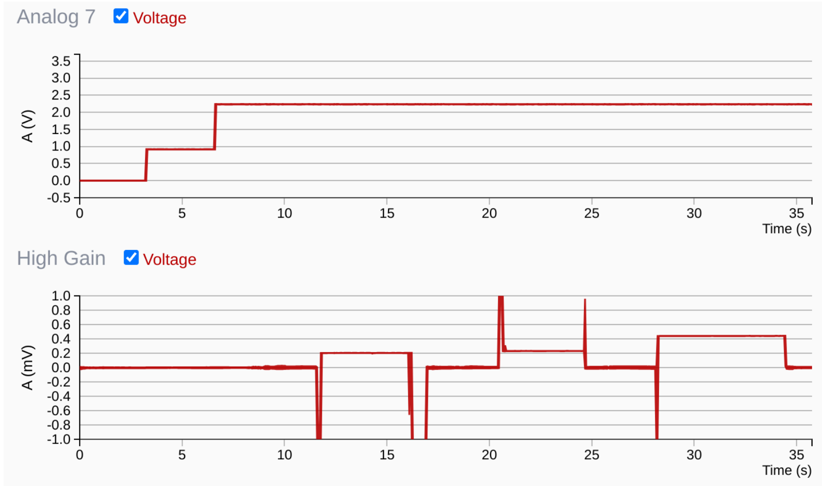


Figure 13. Breadboard diagram of Kirchoff's Law Circuit.



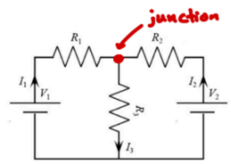
Measure: Move the G+G- leads to different 1.0 Ω resistors to measure all three currents I_1, I_2, and I_3. You will be assuming the current runs in the direction from G+ to G−. Therefore, note which ways you hook up the high gain sensor. If you get a positive value, this means that this is actually the way that current is moving. If you get a negative value, it means that the current is flowing in the opposite direction. As a result, by determining if the current is positive or negative, you can determine the direction of the current.

Measure: Record A7 as needed, with the DAC and battery holder on.

The first flat line section corresponds to the left resistor connected to ground, the second flat line section corresponds to the right resistor connected to ground, and the third flat line section corresponds to the middle resistor connected to R3.

Analysis: Solve for the expected currents and voltages of the circuit, in terms of I_1, I_2, I_3, V_{R1}, V_{R2}, V_{R3}, V_1, and V_2.

1. Identify a junction and write down the junction rule equation.
2. Identify all three loops and write down the loop rule equations for each of them. Be sure you understand/can explain the sign of each term.
3. Solve for the three currents I_1, I_2, and I_3 and the three voltages V_{R1}, V_{R2}, V_{R3}.



1. $I_1 + I_2 = I_3$
2. $V_1 - I_1R_1 - I_3R_3 = 0$

   $V_2 - I_2R_2 - I_3R_3 = 0$

   $V_1 - I_1R_1 + I_2R_2 - V_2 = 0$
3. $V_1 = I_1R_1 + I_3R_3 \qquad V_2 = I_2R_2 + I_3R_3$

$$V_2 = (I_1 + I_2)R_3 + I_2R_2$$
$$= I_1R_3 + I_2R_3 + I_2R_2$$
$$= I_1R_3 + I_2(R_3 + R_2)$$
$$\underline{V_2 = I_1R_3 + I_2(R_3 + R_2)}$$

$$V_1 = I_1R_1 + I_2R_2$$
$$V_2 = I_1R_3 + I_2(R_3 + R_2)$$
$$I_1 = \frac{V_1 - I_2R_2}{R_1}$$

$$V_2 = \left(\frac{V_1 - I_2R_2}{R_1}\right)R_3 + I_2(R_3 + R_2)$$

$$V_2 = \frac{V_1R_3 - I_2R_2R_3}{R_1} + I_2(R_3 + R_2)$$

$$V_2 = \frac{R_3V_1}{R_1} + I_2\left(R_3 + R_2 - \frac{R_3R_2}{R_1}\right)$$

$$I_2 = \frac{V_2 - \frac{R_3V_1}{R_1}}{(R_3 + R_2) - \frac{R_3R_2}{R_1}} = 0.159\,mA \Rightarrow V_{R_2} = 1.59V$$

$$I_1 = \frac{V_1 - I_2R_2}{R_1} = 0.255\,mA \Rightarrow V_{R_1} = 1.199V$$

$$I_3 = I_1 + I_2 = 0.414\,mA \Rightarrow V_{R_3} = 1.946V$$

Analysis: Verify Kirchhoff's junction rule equation for the junction.

1 Ohm Resistor:	Left Resistor Connected to Ground	Middle Resistor Connected to R3	Right Resistor Connected to Ground
High Gain:	0.20315 ± 0.00053 mV	0.23081 ± 0.00039 mV	0.44032 ± 0.00042 mV
Current:	0.18468 ± 0.00190 mA	0.20983 ± 0.00212 mA	0.40029 ± 0.00402 mA

Error Propagation:

$$V = IR$$

$$\alpha_V = \left[\left(\frac{\partial V}{\partial I} \alpha_I \right)^2 + \left(\frac{\partial V}{\partial R} \alpha_R \right)^2 \right]^{1/2}$$

$$\alpha_V = \left[(R\alpha_I)^2 + (I\alpha_R)^2 \right]^{1/2}$$

Resistor:	R1	R2	R3
Voltage:	0.86800 ± 0.01245 V	1.8814 ± 0.02666 V	2.0983 ± 0.02982 V

Analysis: How do the current and voltage measurements compare with your predictions? Explain.

The expected current and voltage of the left 1 ohm resistor connected to ground does not fall within the range of the experimentally derived quantity. The expected current and voltage of the middle 1 ohm resistor connected to R3 does not fall within the range of the experimentally derived quantity. The expected current and voltage of the right 1 ohm resistor connected to ground does not fall within the range of the experimentally derived quantity. However, more holistically, our current and voltage measurements do seem fairly reasonable according to theory.

Checkpoint 3

Call the instructor or GSI over to discuss your data at this point before cleaning up. ***Return all the resistors to their packages – they'll be used in future labs!***