18-100: Intro to Electrical and Computer Engineering

LAB01: Circuits Lab

Writeup Due: Thursday, September 9th, 2020 at 10 PM

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How to submit labs:

Download from this file from *Canvas* and edit it with whatever PDF editor you're most comfortable with. Some recommendations from other students and courses that use Gradescope include:

pdfescape.com	A web-based PDF editor that works on most, if not all, devices.
Preview	Pre-installed default MacOS PDF Editor.
iAnnotate	A cross-platform editor for mobile devices (iOS/Android).

If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and mark the given box. ***Do NOT insert between pages.***

If you'd prefer not to edit a PDF, you can print the document, write your answers in neatly and scan it as a PDF. *(Note: We do not recommend this as unreadable lab reports will not be graded!).* Once you've completed the lab, upload and submit it to *Gradescope*.

Note that while you may work with other students on completing the lab, this writeup is to be completed alone. Do not exchange or copy measurements, plots, code, calculations, or answer in the lab writeup.

Your lab grade will consist of two components:

1. Answers to all lab questions in your lab handout. The questions consist of measurements taken during the lab activities, calculations on those measurements and questions on the lab material.
2. A demonstration of your working lab circuits and conceptual understanding of the material. These demos are scheduled on an individual basis with your group TA.

Question:	1	2	3	4	5	6	Total
Points:	3	10	9	11	9	8	50
Score:							

Lab Outline

The purpose of this lab is to help students become familiar with the lab equipment and measurements (specifically, the breadboard, multimeter and power supply) as well as give a practical understanding of Ohm's Law and LEDs in circuits (both skills that will be heavily used/tested in future labs).

1. Introduction
2. Ohm's Law and Resistor Fundamentals
3. Resistor Networks (Series/Parallel)
4. LED Analysis

Equipment Required

- Breadboard
- Adjustable Power Supply (ADALM2000 or Bench-top Supply)
- (Header Pin or Banana Plug) to Banana Plug Cables
- Digital Multimeter w/ Probes
- Wire Strippers
- Diagonal Cutters
- Needle-nose Pliers

Bill of Materials

1x 47Ω Resistor
3x 100Ω Resistors
2x 470Ω Resistors
1x 1kΩ Resistor
1x 4.7kΩ Resistor
1x 20kΩ Potentiometer (`B20K`)

5x Red LEDs
1x Blue LED
1x AA 1.5V Battery
1x LM317 Current Source
Jumper Wire

Introduction

Welcome to 18-100 labs! These assignments are meant to be the hands-on component to material covered in lecture. The labs are also a great opportunity to get familiar with some of the equipment you will use in future lab course and through your entire career as an electrical and/or computer engineer!

Each lab will come with a handout (a.k.a. what you're reading right now!) that contains the exercises that you are to complete each week. You will be asked to generate data from each experiment and draw conclusions from it. **Make sure to thoroughly read the handout before attempting the lab!**

Following the completion of the lab, you will submit a writeup to `Gradescope` (instructions are on the cover of every lab) and then complete a demonstration to a TA. These demonstrations consist of explaining your completed circuit and then answering a few high-level conceptual questions on the lab material. These questions are *not* meant to trick you and, if you completed the lab, you should not have to "study" for them. The circuits you will be asked to demo will be clearly marked in the lab packet with a message that looks similar to this:

> ⚠ **Do NOT take your circuit apart yet! You will need it for lab checkoff!**

These labs, writeups, and demonstrations are meant to be completed on your own. We want you to collaborate and discuss the labs with other students however, come time to submit/demo, **all work must be your own! Students found building other students' circuits, copying data, or plagiarizing answers to writeup questions will be found in violation of the course's policy on academic integrity (see the Syllabus for more information).**

With that said, we wish you the best on your future laboratory endeavors in 18-100! If you get stuck on any of the parts of the lab or don't feel you can finish the lab before the due date, reach out to your group TA; they're here to help!

1. Setup

Take a moment to ensure you have all the necessary equipment in your lab kit. A list of each component and where to find it in the lab kit can be found on *Canvas*.

Breadboard Setup

The breadboard is a prototyping device that consists of rows of 5 holes are connected by a metal strip underneath. In addition to these, the power rails (the leftmost and rightmost 2 columns) are connected across their entire length. In order to set up the breadboard, remove it from its packaging and install the terminal plugs. Then connect the +/- supply rails to eachother and then to the terminal plugs. In the end you're breadboard should look like this:

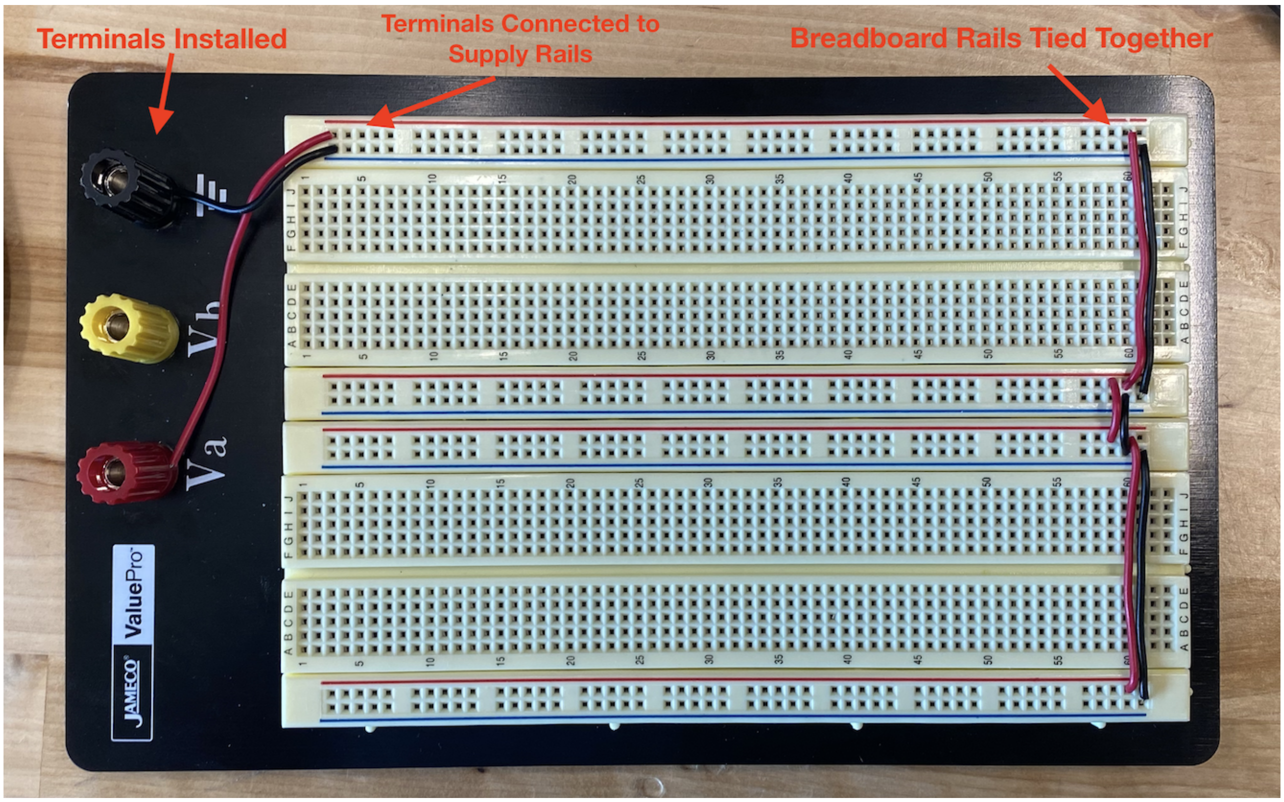


Figure 1: Breadboard setup complete

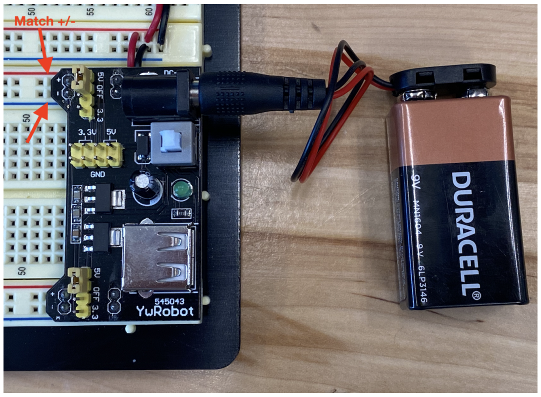
3 pts **1.1** Setup your breadboard as described above. Make sure to install the breadboard terminals, connect them to the breadboard rails using jumper wire, and tie all the breadboard rails together.[1]

If you need assistance setting up your breadboard, feel free to reach out to your group TA!

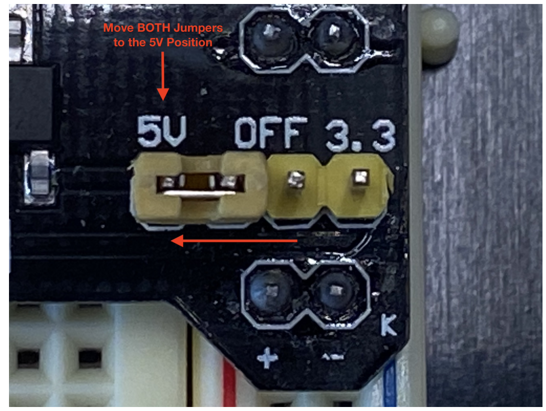
[1] That's right! A whole three points just for setting it up correctly!

Power Sources

There are two main branches of ways to supply power to your circuit: fixed and adjustable. In this course we provide one of each: an adjustable power supply that plugs into the terminals on your breadboard and a fixed 5V supply that is inserted directly into the breadboard power rails.



(a) Power Supply Installed



(b) Switch Jumpers to 5V!

Insert the prongs into the rails (the 2 columns on both sides of the breadboard marked with red and blue lines). It's a tight fit so don't be afraid to use a little force.

The breadboard power supply is useful when you simply need 5V (which we will in the upcoming labs). However, we will *not* be using it in this lab.

> ⚠ **Remove the breadboard power supply from your breadboard before continuing**

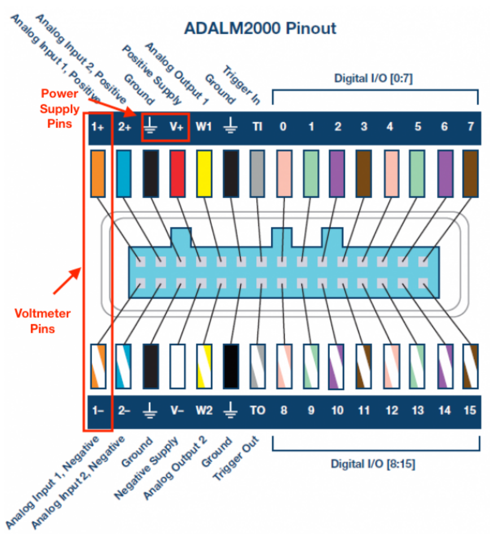
The adjustable supply included in the lab kit is a part of the ADALM2000 suite of hardware components. More information about the ADALM is on the next page.

ADALM2000 Setup

The last bit of setup we will go over is the ADALM2000. The ADALM software-based power supply, voltmeter, oscilloscope, signal generator, spectrum analyzer, network analyzer, logic analyzer ... the list goes on. In each lab, we will ask you to use one or more of these features to analyzer the circuits you will build. For this lab, we will show you how to use the adjustable power supply and the voltmeter.

To use the ADALM2000, install its partner-software: Scopy. Installation instructions can be found here: https://wiki.analog.com/university/tools/m2k. **Note for macOS users: you do not need to install any additional drivers or software (just ignore that part of the guide)**

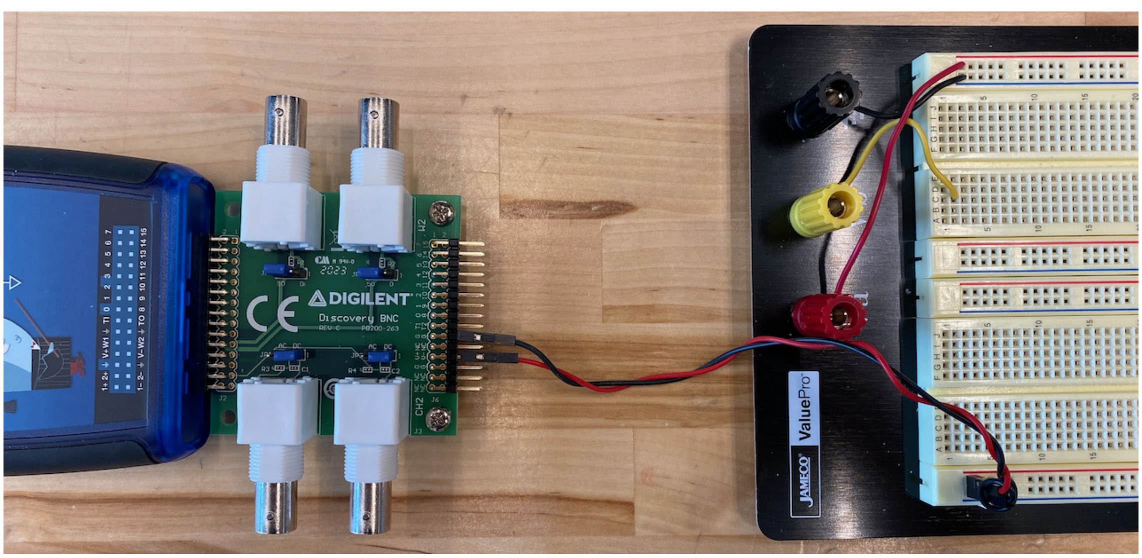
To interface your circuit with the ADALM, use the pins on the front of the unit. Their functions are labeled below:



(a) ADALM2000 Pinout

(b) Selecting Scopy Modules

To connect the ADALM to your breadboard rails, use the included (rainbow-colored) pre-formed jumper wires:



2. Resistance

In this section we'll take a look at resistors and their behavior in circuits.

1 pts

2.1 Using the tolerance band on the resistor, what are the minimum and maximum values each resistor can have to be within tolerance. Measure the actual resistance using your Digital Multimeter (DMM).

Resistor	**Minimum Value (Ω)**	**Measured Value (Ω)**	**Maximum Value (Ω)**
47Ω	44.25 ohms	46.60 ohms	48.95 ohms
100Ω	93.9 ohms	98.9 ohms	103.9 ohms
470Ω	445.5 ohms	469 ohms	492.5 ohms
$1k\Omega$	0.935 kOhms	0.985 kOhms	1.035 kOhms
$4.7k\Omega$	4.425 kOhms	4.66 kOhms	4.895 kOhms

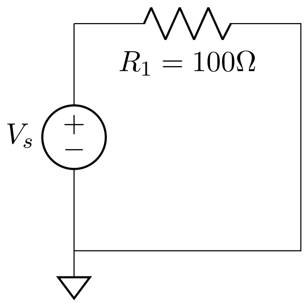
⚠ **Replace any resistors not within their tolerance value!**

1 pts

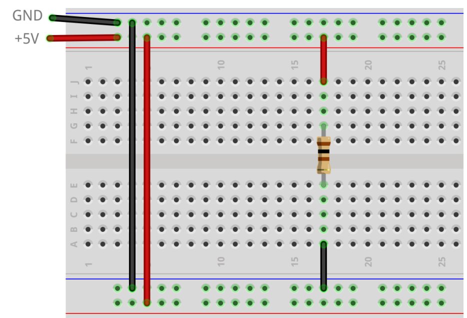
2.2 Do any of the measurements you took in 2.1 change if you flip the probes?

The measurements do not change when I flip the probes

Connect a 100Ω resistor to the breadboard by placing one of the leads in a row of five holes and the other lead in a separate row. Put the power supply on the breadboard, and set the rails to 5V. Connect each end of the resistor to a power rail, as shown in the diagram.



Simple Resistor Circuit (Schematic)



Simple Resistor Circuit (Breadboard)

Figure 4: Measuring Voltage across Resistor

1 pts

2.3 What voltage is measured across the resistor?

Measured Value = 5.00 V

1 pts

2.4 Using Ohm's law, what should the current be flowing through the circuit? Show all work.

V=IR
I=V/R
I=5/100 = 5 A = 0.05 mA

R=100 ohms
V= 5V

$I =$ 5 A mA

Measure and record the current through the resistor using the multimeter. This involves physically breaking the circuit and connecting the meter in series as discussed in class. Before measuring current, verify that you've connected the multimeter correctly in series.

⚠ **Measuring current incorrectly can damage your multimeter!**
Always check your probes before powering on a circuit!

1 pts

2.5 What is the actual current flowing through the circuit?

Measured Value = 4.9 mA

1 pts

2.6 Using the measurements collected in 2.3 and 2.5, calculate the power consumed by the resistor

Power = I(V)
P=(0.049)(5.00)
P=0.245 W = 245.0 mW

$P =$ 245.0 mW

We're going to repeat the process of measuring current and voltage to fully characterize this resistor. With this data, we can construct an I-V curve (a.k.a. a current-vs-voltage graph).

3 pts

2.7 Measure the current/voltage through/across the 100Ω resistor and plot it in a chart. Use 1V step increments from -5V to 5V. Repeat this process for a 470Ω resistor and overlay the two curves. We've provided this spreadsheet to aid in the process: Google Sheets Template. Then insert a screenshot of your table and graphs here:

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

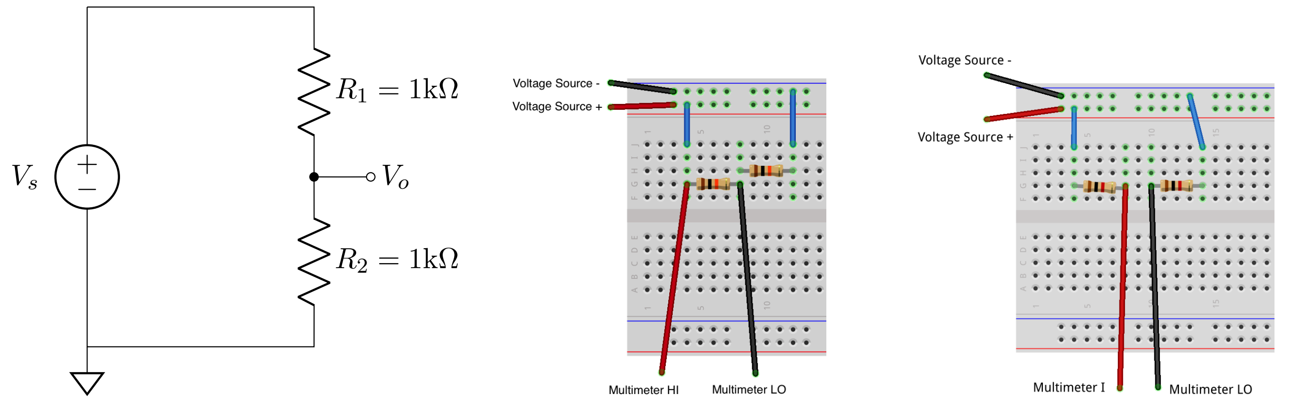
1 pts

2.8 Take note of the slopes of the best fit lines. How do they relate to the resistance of the resistors?

3. Resistor Networks

Series Resistors / Voltage Divider

Build the circuit shown below in Figure 5 which features a pair of 1kΩ resistors wired in series.



(a) Series Circuit (Schematic) (b) Series Voltage Measurement (c) Series Current Measurement

Figure 5: Measuring Series Resistors

1 pts **3.1** Calculate the equivalent resistance, R_{eq}, of the circuit as seen from the voltage source, V_s.

$R_{eq} =$ ____________ kΩ

1 pts **3.2** Measure the voltage across, and current through, each resistor in Figure 5. Use Figures (b) and (c) to aid in your measurement process. The voltage source $V_s = 5V$. R_1 and $R_2 = 1\text{k}\Omega$

$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

1 pts **3.3** Using Ohm's Law and KVL/KCL, what can one expect the voltage across, and current through, each resistor in Figure 5 to be? The voltage source $V_s = 5V$. R_1 and $R_2 = 1\text{k}\Omega$

$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

1 pts

3.4 Replace the resistor R_2 in Figure 5 with a 4.7kΩ resistor. Measure the voltage across, and current through, each resistor in Figure 5.

$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

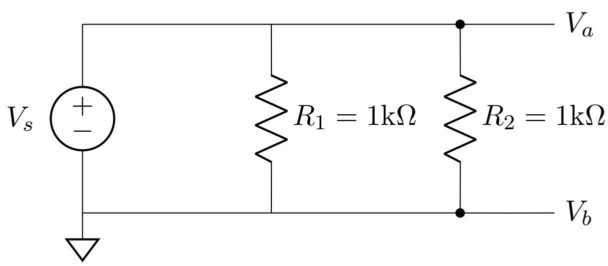
1 pts

3.5 Using Ohm's Law and KVL/KCL, what can one expect the voltage across, and current through, each resistor in Figure 5 to be? The voltage source $V_s = 5V$. $R_1 = 1\text{k}\Omega$ and $R_2 = 4.7\text{k}\Omega$

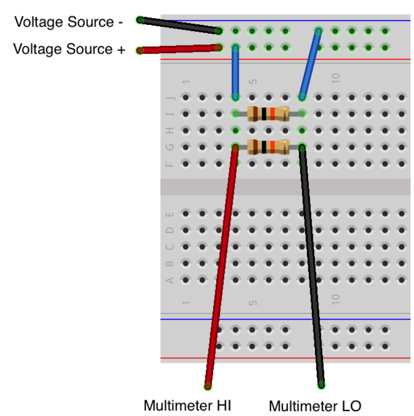
$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

Parallel Resistors / Current Divider

A similar experiment will be attempted with two resistors in parallel this time. Build the circuit shown in Figure 6 below. R_1,$R_2 = 1\text{k}\Omega$. Again $V_S = 5V$.



(a) Parallel Circuit (Schematic)



(b) Voltage Measurement

Figure 6: Measuring Voltage across Parallel Resistors

1 pts

3.6 Calculate the equivalent resistance, R_{eq}, of the circuit as seen from the voltage source, V_s.

$R_{eq} =$ ____________ kΩ

1 pts

3.7 Measure the voltage across, and current through, each resistor in Figure 6. Use Figure (b) to aid in your measurement process. The voltage source $V_s = 5V$. R_1 and $R_2 = 1\text{k}\Omega$

$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

1 pts

3.8 Using Ohm's Law and KVL/KCL, what can one expect the voltage across, and current through, each resistor in Figure 6 to be? The voltage source $V_s = 5V$. R_1 and $R_2 = 1\text{k}\Omega$

$V_1 =$ ________ V $I_1 =$ ________ mA $V_2 =$ ________ V $I_2 =$ ________ mA

1 pts

3.9 What is the current one can expect to be delivered by the power supply (i.e. I_s)?

$I_s =$ ____________ mA

1 bonus

3.10 Based on your knowledge of resistors, why does adding resistances in parallel decreases the overall resistance, whereas adding resistances in series results in a greater overall resistance?

4. Where Ohm's Law Breaks Down

In this section, we'll look at LEDs and how semiconductor devices behave differently than 'ohmic' devices (a.k.a. resistors).

Create the following circuit (Figure 7) on your breadboard using a red LED. Note: the **longer** wire is the **anode** (**positive** end) and the **shorter** wire is the **cathode** (**negative** end).

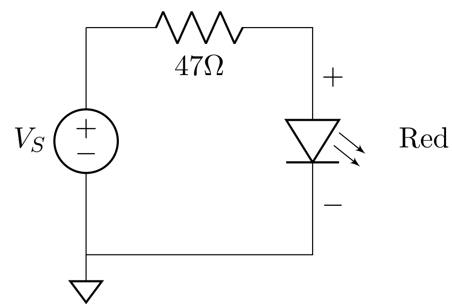


Figure 7: Single-LED Circuit
Hint: It should light up

3 pts

4.1 Once the LED lights up, flip the LED's direction. Does the LED continue to emit light? Why?

3 pts

4.2 Measure the Voltage across the LED and the current through it and generate an IV Curve as you sweep V_S from -5V to +5V (using the same sheet as in question 2.7). Repeat this process with a **blue** LED. Insert a screenshot of your table and graphs here:

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

3 pts

4.3 Using the I-V curves generated in Question 4.2, identify the turn-on voltage, V_f, for each LED.

$V_{f,red} =$ ____ V $V_{f,blue} =$ ____ V

2 pts

4.4 Locate the forward voltages in the datasheets for each of the LEDs (posted on *Canvas*). Are they close to the values you measured? Calculate the percent error of your measurement against the datasheet values for each:

% Error Red = ____ % % Error Blue = ____ %

5. Sources

Sources supply energy in electric circuits, either as a voltage or a current. The ADALM2000 power supply (pins V_+ and V_-) and batteries act as *voltage sources*. *Current sources* are also commonly used, but they are usually more complex than voltage sources. Connecting sources to resistances will *load* them, prompting the sources to deliver power. As the power delivered increases, we say that the load on the source has increased.

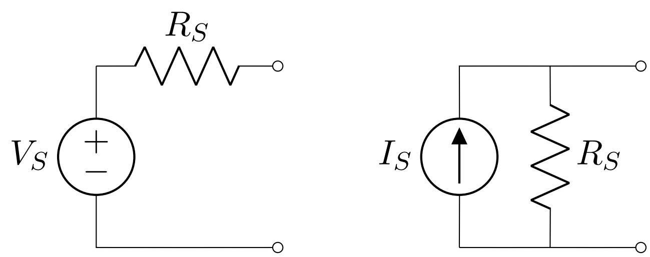


Figure 8: Realistic voltage and current sources.[2]

Our models for realistic sources add some source resistance R_S (sometimes called the internal resistance R_{int}) as shown in Figure 8 to account for the limits of the source to deliver power. In this exercise, we are going to measure the I-V characteristics of a realistic voltage source, the AA battery in your kit, and a realistic current source, built from a voltage regulator integrated circuit. You will use a 20k potentiometer as a variable resistor and use your multimeter(s) to measure current and voltage as the load varies.

[2]Note the resemblance between Thevenin and Norton equivalents.

Voltage Sources

Voltage sources supply electric potential to circuits, which is measured in Volts. An electric potential can do work on electric charges, meaning that they can accelerate electrons through conductors. An ideal source supplies the same voltage regardless of the load, but no source is truly ideal. A more realistic model of a voltage source looks like the *Thévenin equivalent* circuit: an ideal voltage source V_S in series with a source resistance R_S.

1 pts

5.1 With your multimeter, measure the voltage across your AA Battery.

$V =$ [ ] V

Build the test circuit in Figure 9 to apply a variable load to the battery. Use the battery clip included in your lab kit to mount the battery to the breadboard. See Figure 10 for a suggested breadboard layout that demonstrates how to connect the potentiometer as a variable resistor (i.e. the third terminal is unused).

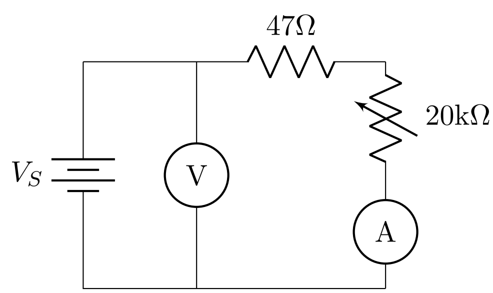


Figure 9: Variable load test circuit schematic

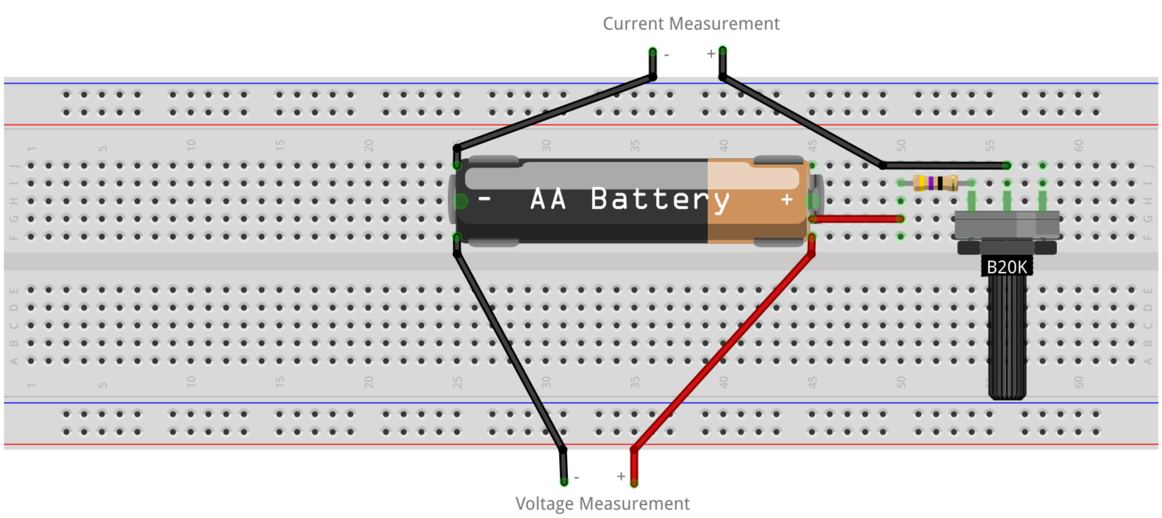


Figure 10: Variable load test circuit on the breadboard

3 pts

5.2 Create an IV curve for your AA Battery with a copy of this google sheet again. Paste your screenshot here:

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

1 bonus

5.3 What is the internal resistance of your AA battery? Please justify your answer based on the I-V curve you measured.

1 bonus

5.4 Why do you think we added a resistor in series with the potentiometer in this measurement circuit? Hint: Remove the potentiometer from the breadboard and measure its full range of resistance with your multimeter.

Current Sources

Current sources supply current, the flow of electric charge, which is measured in Amperes. An ideal source supplies the same current regardless of the load, but no source is truly ideal. A more realistic model of a current source looks like the *Norton equivalent* circuit: an ideal current source I_s in parallel with a source resistance R_s. You will use a voltage regulator (LM317), which can be configured to act as a constant current source.

The LM317 is an integrated circuit, which means that it consists of several different circuit elements built into a single piece of silicon. Information on the LM317 is provided in its *datasheet*, which we have provided on Canvas. You'll come across many datasheets in your circuit studies, so it's good to get used to seeing them and understanding what information they contain. Most interesting to you will be the *pinout*, which maps out the pins on the LM317: the INPUT, OUTPUT, and ADJUST pins. The operation of the LM317 is also outlined in Section 8, including how to use the chip as a current regulator. Don't worry if you cannot understand everything (or much at all) in the datasheet. There is enough information you *can* understand and use to build something useful, so focus on that.

Please build the circuit in Figure 11, which also indicates where to probe for current and voltage. We have also provided a suggested breadboard layout in Figure 12. *Notice that we have not specified what value to use for R.* We would like you to select an appropriate R from your kit to produce an **output current of 12.5 mA.**

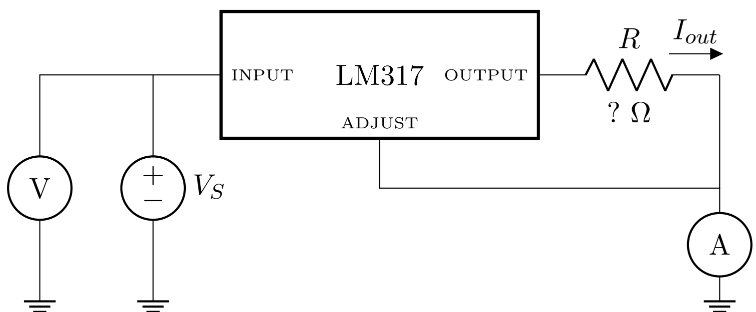


Figure 11: Current source test circuit schematic

1 pts

5.5 With your multimeter, measure the current flowing through your circuit.

$I =$ mA

1 pts

5.6 What value resistance did you choose for R and why?

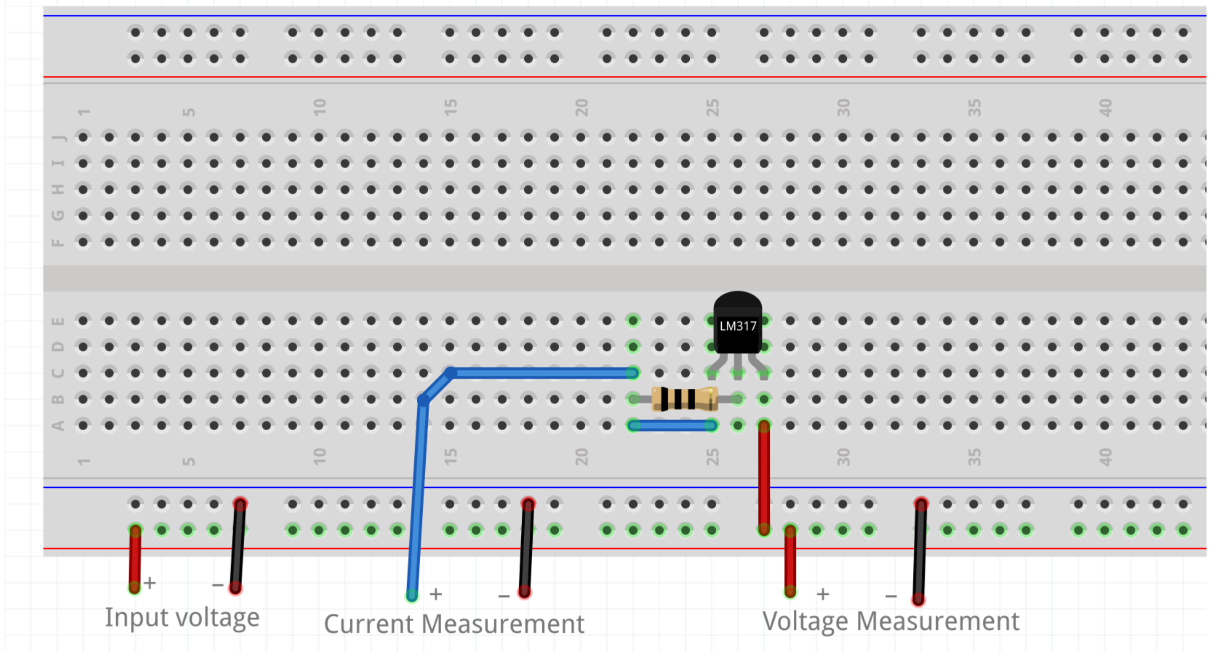


Figure 12: Current source test circuit on the breadboard. Notice that this resistor has a value of 0 Ω. It is acting as a placeholder for the R that you will select.

3 pts

5.7 Create an IV curve for your current source with a copy of this same google sheet from before. Sweep through values of V_S from 0V to 5V to do so. Paste your screenshot here:

`Paste Screenshot Here`

☐ I have appended the screenshot to the back of my lab writeup

1 bonus

5.8 Please describe any interesting features about your I-V curve (i.e. any deviation from the an ideal current source). Then, explain why you see this behavior, using information from the LM317 datasheet to support your answer.

6. Putting It All Together

Assemble the following circuit (Figure 13) on your breadboard.

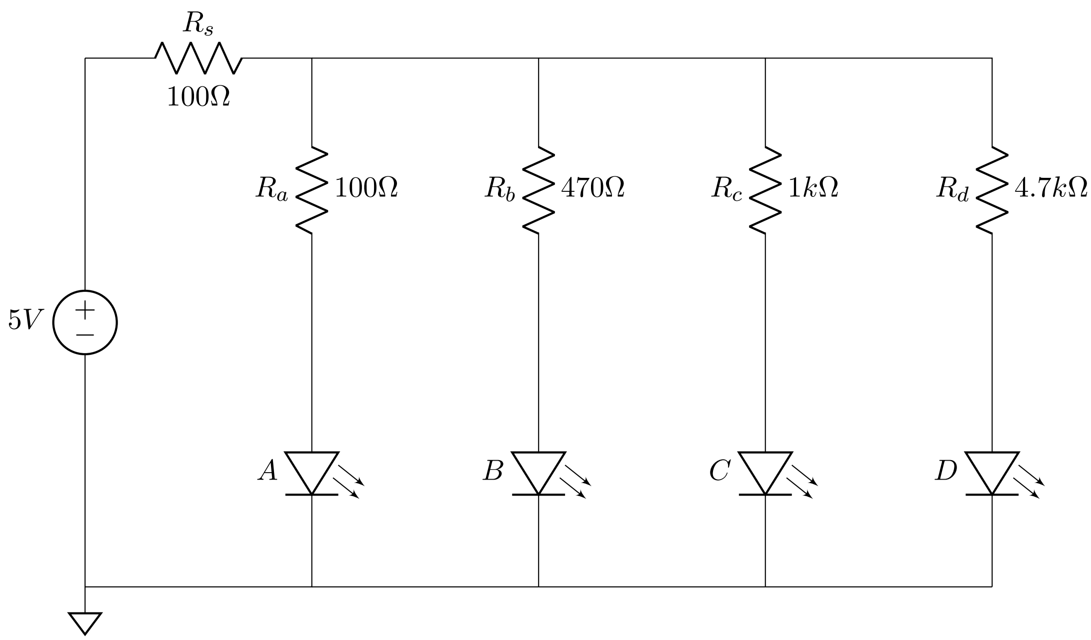


Figure 13: 4-LED Circuit

The figure below (Figure 14) shows the circuit connections on the breadboard. Refer to the diagram if you have difficulties wiring up the circuit.

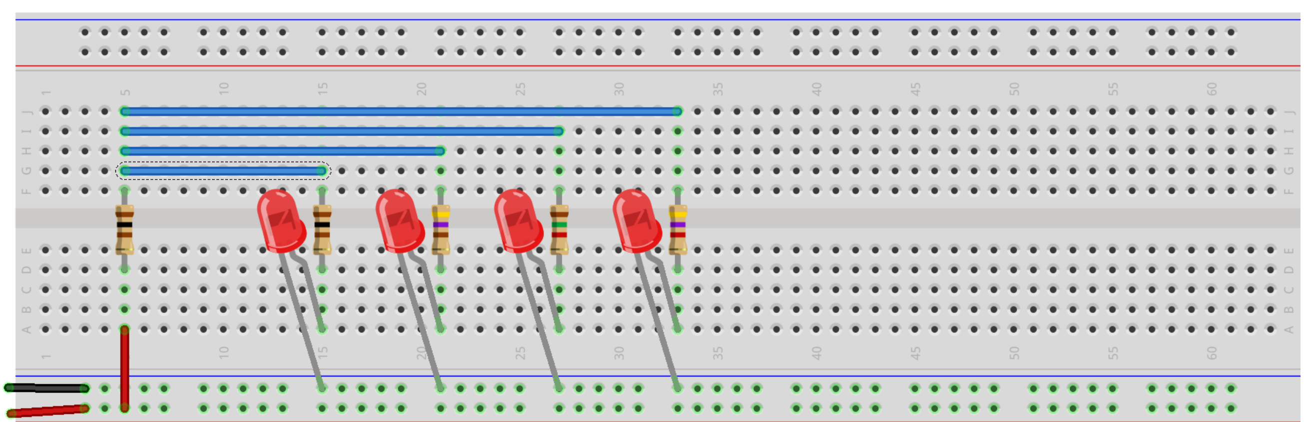


Figure 14: LED circuit breadboard diagram

1 pts

6.1 Observe the light intensity of each LED and provide a ranking from the least bright to the brightest (e.g. $B < A < D < C$).

1 pts

6.2 Measure the voltages across the 100Ω, 470Ω, 1.5kΩ, and 4.7kΩ resistors ($R_a - R_d$) as well as the voltage across each of the LEDs. Sum them together.

Branch	**Resistor Voltage** (V_{Rx})	**LED Voltage** (V_{Dx})	**Total Voltage** (V_x)
A			
B			
C			
D			

1 pts

6.3 What do you observe about the voltages of the LEDs?

1 pts

6.4 Measure the current through R_s (I_S) and the currents through LED A, B, C, and D (I_A, I_B, I_C, I_D). Remember that current is measured in series!

Quantity	**Measured Current (mA)**
I_S	
I_A	
I_B	
I_C	
I_D	

1 pts

6.5 What relationship do you hypothesize about the current through R_s (I_S), and the LED currents (I_a, I_b, I_c, I_d)? Write down the hypothesis and prove that it holds (roughly) with empirical data.

3 pts

6.6 Be prepared to demonstrate your working circuit to a TA.

⚠ **Do NOT take your circuit apart yet! You will need it for lab checkoff!**

1 bonus

6.7 Assume all the resistances in the 4-LED Circuit were the same and we were just trying to drive the 4 LEDs with the same current. See the figure below for a better idea:

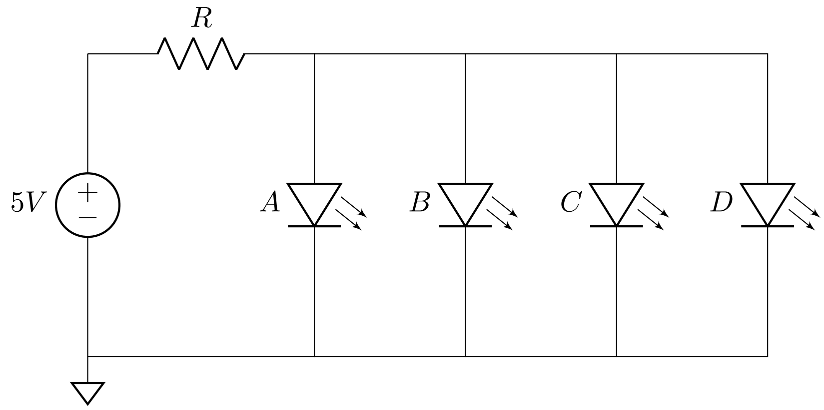


Figure 15: Modified 4-LED Circuit

Why might we not want to do this (use a single resistor and put all the LEDs in parallel)? *(Hint: think about what kinds of deviations in manufacturing can affect circuit behavior)*