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# THE GEORGE WASHINGTON UNIVERSITY

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WASHINGTON, DC

**SCHOOL OF ENGINEERING AND APPLIED SCIENCE  
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING  
ECE 2110: CIRCUIT THEORY LABORATORY**

**Experiment #4:  
Voltage Division, Circuit Reduction, Ladders, and Bridges**

## **EQUIPMENT**

<b>Lab Equipment</b>	<b>Equipment Description</b>
(1) DC Power Supply	Supplied by the AD2
(1) Digital Multimeter (DMM)	Harbor Freight Model 63759 Handheld Digital Multimeter
(1) Breadboard	Prototype Breadboard
(1) Test Leads	Banana to Alligator Lead Set

Table 1 – Equipment List

## **COMPONENTS**

<b>Type</b>	<b>Value</b>	<b>Symbol Name</b>	<b>Multisim Part</b>	<b>Description</b>
Resistor	470 $\Omega$	R <sub>1</sub>	Basic/Resistor	---
Resistor	560 $\Omega$	R <sub>2</sub>	Basic/Resistor	---
Resistor	680 $\Omega$	R <sub>3</sub>	Basic/Resistor	---
Resistor	750 $\Omega$	R <sub>4</sub>	Basic/Resistor	---
Resistor	820 $\Omega$	R <sub>5</sub>	Basic/Resistor	---
Resistor	910 $\Omega$	R <sub>6</sub>	Basic/Resistor	---
Potentiometer	10k $\Omega$	R <sub>7</sub>	Basic/Resistor	---
LED Bar	Green	LEDs	LED/Bar_LED_Green_Ten	Bar of 10 Green LEDs

Table 2 – Component List

## **OBJECTIVES**

- To calculate and measure the total resistance in a series/parallel circuit
- To calculate and measure the total current in a series/parallel circuit for a given applied voltage
- To calculate the expected total power dissipated in a series/parallel circuit from nominal and measured values
- To calculate and measure the voltage drop across and the current through all components of a series/parallel circuit
- To calculate the power dissipated by each component of a series/parallel circuit from measured data
- Design, build and test a voltage ladder
- Use a Wheatstone Bridge circuit as a detector of unknown resistances

**INTRODUCTION**

**Voltage Division**

The voltage divider circuit is one of the most important and fundamental circuits that you will encounter in Circuit Theory. There are countless applications for voltage dividers, and you will find that throughout the semester, many calculations become simpler if you see the circuit as a basic voltage divider. A **voltage divider** is a linear circuit whose output voltage is some fraction of its input voltage. In other words, a voltage divider allows us to turn a large voltage into a smaller one. **Voltage division** refers to the splitting of a voltage among the components of the voltage divider.

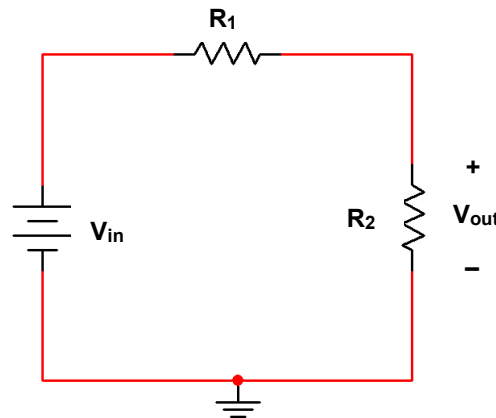


Figure 1 – Voltage Divider

$$V_{out} = \frac{R_2}{R_1 + R_2} \cdot V_{in}$$

Equation 1 – Voltage Divider Equation

**Potentiometer**

A **potentiometer** is a passive device that acts as a **variable resistor** or **voltage divider**. Potentiometers have three terminals and some type of rotary component that can be turned clockwise and counterclockwise to adjust the resistance. The resistance between the outer two terminals is constant and always equal to the nominal value of the potentiometer. The middle terminal is connected to the wiper shown in **Figure 4** that can be adjusted to change the resistance relationship between the two halves of the device. **Figure 2** shows the schematic symbol for a potentiometer, including the third middle terminal. Think of the potentiometer in **Figure 4** as two resistors connected in series with each other,  $R_1$  between terminals A and W,  $R_2$  between W and B, similar to the voltage divider of **Figure 1**. When the center dial is turned counterclockwise until it stops,  $R_1$  would be  $0\Omega$  and  $R_2$  would equal to the nominal value of the potentiometer. As the dial is turned clockwise,  $R_1$  increases and  $R_2$  decreases.



Figure 2 – Potentiometer Symbol



Figure 3 – Potentiometer

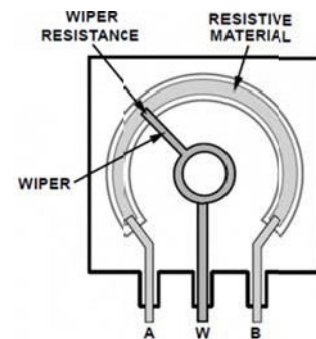


Figure 4 – Potentiometer Diagram

**Voltage Ladder**

A **voltage ladder** is a simple electrical circuit comprised of multiple resistors in series used to create multiple voltage points between 0V and the source voltage. Similar to a voltage divider, the source voltage is split across the resistors as determined by the ratio of the individual resistor to the entire equivalent resistance.

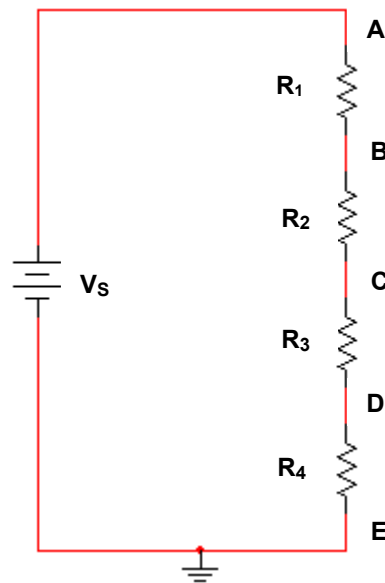


Figure 5 – Voltage Ladder

**Wheatstone Bridge**

A **Wheatstone Bridge** is an electrical bridge circuit used to determine an unknown resistance. The Wheatstone Bridge circuit consists of four resistances, three of which must be known and one that is unknown. By balancing the two legs of the bridge circuit and deriving the resistive relationship, the unknown resistance can be quickly determined. In **Figure 6**,  $R_x$  is the unknown resistance we are trying to find,  $R_3$  is a variable resistor such as a potentiometer that we can adjust, and  $R_1$  and  $R_2$  are known resistances.

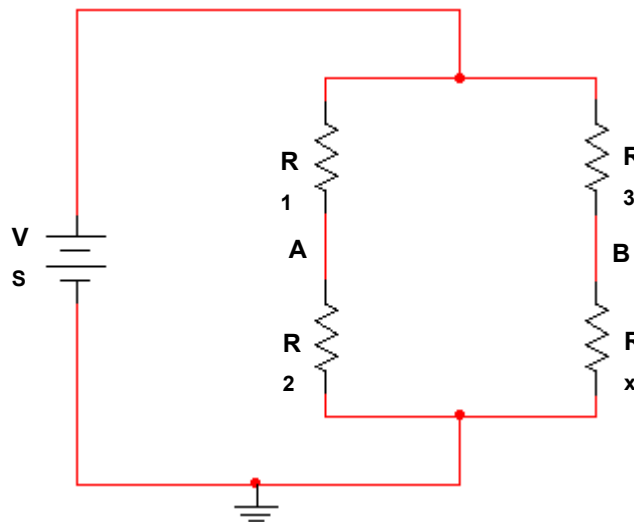


Figure 6 – Wheatstone Bridge

**PRELAB**

**Part I – Simplifying a Parallel Circuit**

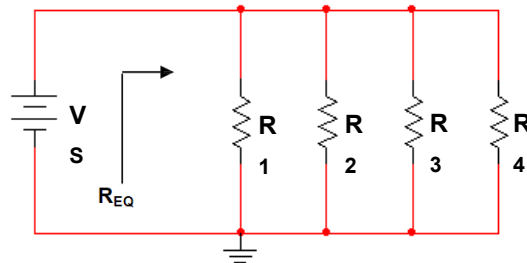


Figure P.1 – Parallel Circuit

1. **Simplify** the circuit in **Figure P.1** to find the voltage across, current through, and power dissipated by each resistor.
  - a. **Find** the equivalent resistance  $R_{EQ}$  from the perspective of the voltage source  $V_S$  in **Figure P.1**. Leave your answer in terms of  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$ . **Show all work**.
  - b. **Calculate** the actual equivalent resistance  $R_{EQ}$  using the resistor values given in **Table 2**.
  - c. **Calculate** the total current drawn by  $R_{EQ}$  and the total **power** dissipated by  $R_{EQ}$  assuming  $V_S = 5V$ .
  - d. **Calculate** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - e. **Record** all your results in **Table P.1**.
2. **Simulate** the circuit in **Figure P.1** in **Multisim**.
  - a. **Find** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - b. **Record** all values in **Table P.1**.
3. **Calculate** the **percent error** between your **calculated** and **simulated** results.
  - a. **Record** the error in **Table P.1**.

Electrical Quantity		Resistor				
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$
Voltage (V)	Calculated					
	Simulated					
	Percent Error					
Current (mA)	Calculated					
	Simulated					
	Percent Error					
Power (mW)	Calculated					
	Simulated					
	Percent Error					

Table P.1 – Prelab Data Table 1

**Part II – Simplifying a Series Circuit**

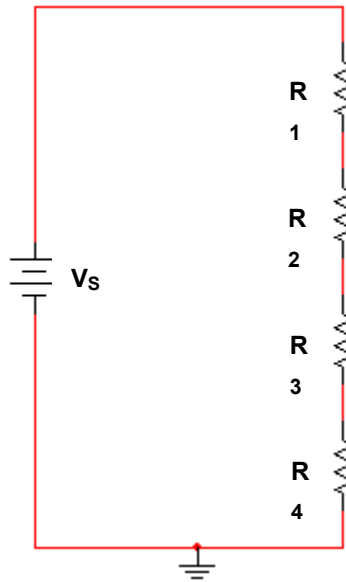


Figure P.2 – Series Circuit

1. **Simplify** the circuit in **Figure P.2** in order to find the voltage across, current through, and power dissipated by each resistor.
  - a. **Find** the equivalent resistance  $R_{EQ}$  from the perspective of the voltage source  $V_s$  in **Figure P.2**. Leave your answer in terms of  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$ . **Show all work**.
  - b. **Calculate** the actual equivalent resistance  $R_{EQ}$  using the resistor values given in **Table 2**.
  - c. **Calculate** the total **current** drawn by  $R_{EQ}$  and the total **power** dissipated by  $R_{EQ}$  assuming  $V_s = 5V$ .
  - d. **Calculate** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - e. **Record** all your results in **Table P.2**.
2. **Simulate** the circuit in **Figure P.2** in **Multisim**.
  - a. **Find** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - b. **Record** all values in **Table P.2**.
3. **Calculate** the **percent error** between your **calculated** and **simulated** results.
  - a. **Record** the error in **Table P.2**.

<b>Electrical Quantity</b>		<b>Resistor</b>				
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$
<b>Voltage (V)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Percent Error</b>					
<b>Current (mA)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Percent Error</b>					
<b>Power (mW)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Percent Error</b>					

Table P.2 – Prelab Data Table 2

**Part III – Simplifying a Series-Parallel Circuit**

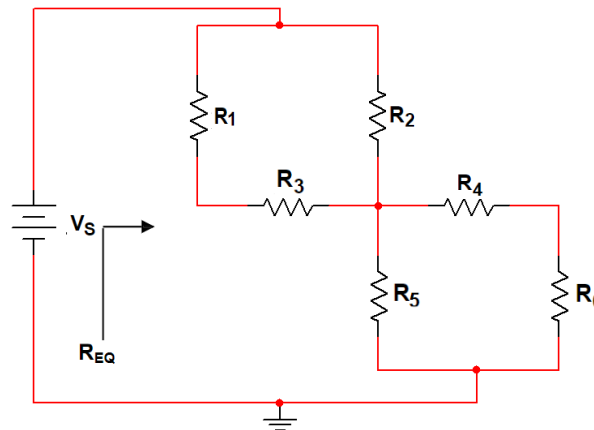


Figure P.3 – Series-Parallel Circuit

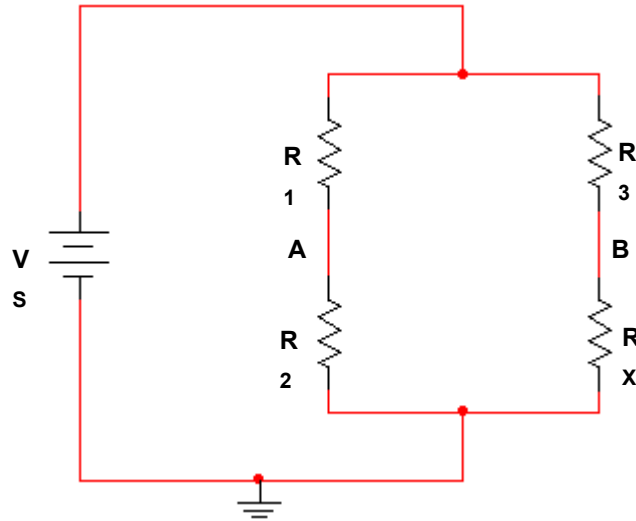
1. **Simplify** the circuit in **Figure P.3** in order to find the voltage across, current through, and power dissipated by each resistor
  - a. **Find** the equivalent resistance  $R_{EQ}$  from the perspective of the voltage source  $V_S$  in **Figure P.3**. Leave your answer in terms of  $R_1, R_2, R_3, R_4, R_5$  and  $R_6$ . **Show all work**.
  - b. **Calculate** the actual equivalent resistance  $R_{EQ}$  using the resistor values given in **Table 2**.
  - c. **Calculate** the total **current** drawn by  $R_{EQ}$  and the total **power** dissipated by  $R_{EQ}$  assuming  $V_S = 5V$ .
  - d. **Calculate** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - e. **Record** your results in **Table P.3**.
2. **Simulate** the circuit in **Figure P.3** in **Multisim**
  - a. **Find** the voltage drop across each resistor, the current through each resistor, and the power dissipated by each resistor.
  - b. **Record** all values in **Table P.3**.
3. **Calculate** the **percent error** between your **calculated** and **simulated** results.
  - a. **Record** the error in **Table P.3**.

<b>Electrical Quantity</b>		<b>Resistor</b>						
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$	$R_5$	$R_6$
<b>Voltage (V)</b>	<b>Calculated</b>							
	<b>Simulated</b>							
	<b>Percent Error</b>							
<b>Current (mA)</b>	<b>Calculated</b>							
	<b>Simulated</b>							
	<b>Percent Error</b>							
<b>Power (mW)</b>	<b>Calculated</b>							
	<b>Simulated</b>							
	<b>Percent Error</b>							

Table P.3 – Prelab Data Table 3

**Part IV – Wheatstone Bridge**

The circuit below in **Figure P.4** is a **Wheatstone Bridge**. As discussed in the **Introduction** to this lab, the purpose of the Wheatstone Bridge is to use three known resistors ( $R_1$ ,  $R_2$ , and  $R_3$ ) to find an unknown resistance  $R_x$ . We need to generate an algebraic expression for resistor  $R_x$  in terms of the known resistors. Use the following steps to solve the bridge circuit for  $R_x$ :



**Figure P.4 – Wheatstone Bridge Circuit**

1. **Solve** for  $V_A$  in terms of  $R_1$ ,  $R_2$ , and  $V_S$ . (*Hint:  $V_A$  is just the voltage across  $R_2$* )
2. **Solve** for  $V_B$  in terms of  $R_3$ ,  $R_x$ , and  $V_S$ . (*Hint:  $V_B$  is just the voltage across  $R_x$* )  
*Note: The bridge is said to be “balanced” when  $V_A = V_B$ .*
3. **Solve** for  $R_x$  by setting your equations for  $V_A$  and  $V_B$  equal to each other.  
*Note:  $V_S$  should drop out of the equation if you have done everything correctly.*

**LAB**

**Part I – Parallel Circuit Measurements**

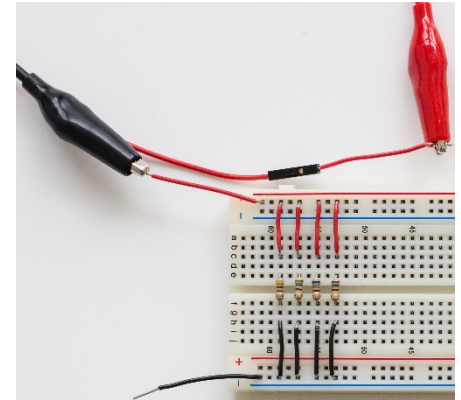
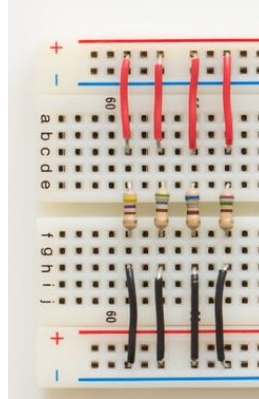
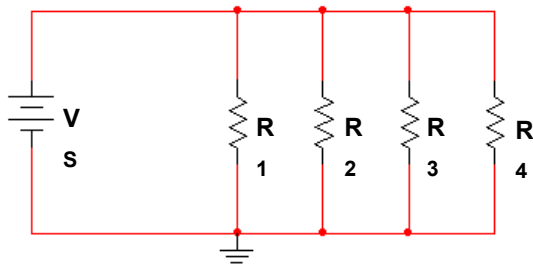


Figure 1.1 – Parallel Circuit

Figure 1.2 – Measuring Total Current

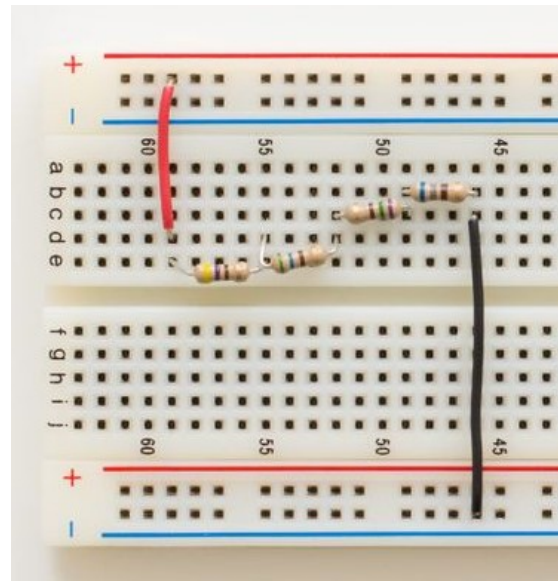
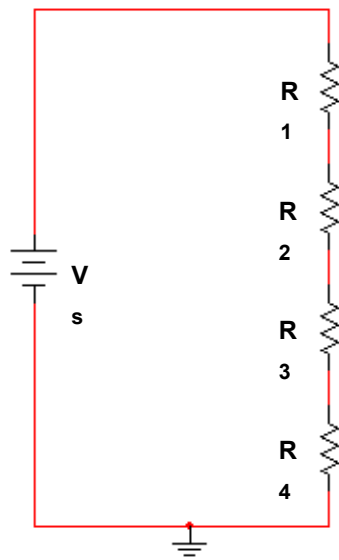
1. **Build** the circuit in **Figure 1.1** on a breadboard. **Before** connecting the AD2 to the circuit, use the DMM to **measure** the equivalent resistance  $R_{EQ}$  of the circuit.
2. **Connect** the AD2 ( $V_s = 5V$ ) to the circuit, turn on WaveForms, and click "Supplies".
3. **Click the play button** in WaveForms to turn on the voltage source.
4. **Measure the voltage across** each resistor and the **current through** each resistor with the DMM. **Note:** Remember that it is impossible to measure the current across a resistor. You must use the DMM differently when measuring current. You can check back to Lab 3 if you need a reminder.
5. **Measure the total current** supplied by the AD2. **MAKE SURE THE AD2 IS NOT SUPPLYING A VOLTAGE TO YOUR CIRCUIT FIRST.** To do this, **disconnect** the positive and ground wires from the resistors. Then take those wires and put them anywhere else on the breadboard, just **not on the same rail**. Set your DMM to measure **current**, connect the red lead to the positive terminal, the black lead to ground, and then turn on the power supply. **Figure 1.2** shows the result of this process.
6. **Calculate** the **power** dissipated by each resistor using the measured voltage and current.
7. **Record** all data in the **Measured** sections of **Table 1.1**.
8. **Compute** the **percent error** between your **calculated** and **measured** results and record it below.

Electrical Quantity		Resistor				
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$
Voltage (V)	Calculated					
	Simulated					
	Measured					
Current (mA)	Calculated					
	Simulated					
	Measured					
Power (mW)	Calculated					
	Simulated					
	Measured					
Percent Error (%)	Voltage					
	Current					
	Power					

Table 1.1 – Parallel Circuit Data



**Part II – Series Circuit Measurements**



**Figure 2.1 – Series Circuit**

1. **Build** the circuit in **Figure 2.1**. **Before** connecting the AD2 to the circuit, use the DMM to **measure** the equivalent resistance  $R_{EQ}$  of the circuit.
2. **Connect** the AD2 ( $V_s = 5V$ ) to the circuit. **Ensure** WaveForms is still open on your computer.
3. **Click the play button** in WaveForms to turn on the voltage source.
4. **Measure** the **voltage across** each resistor and the **current through** each resistor with the DMM.
5. **Measure** the **total current** supplied by the AD2.
6. **Calculate** the **power** dissipated by each resistor using the measured voltage and current.
7. **Record** all data in the **Measured** sections of **Table 2.1**.
8. **Compute** the **percent error** between your **calculated** and **measured** results and record it below.

<b>Electrical Quantity</b>		<b>Resistor</b>				
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$
<b>Voltage (V)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Measured</b>					
<b>Current (mA)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Measured</b>					
<b>Power (mW)</b>	<b>Calculated</b>					
	<b>Simulated</b>					
	<b>Measured</b>					
<b>Percent Error (%)</b>	<b>Voltage</b>					
	<b>Current</b>					
	<b>Power</b>					

**Table 2.1 – Series Circuit Data**

**Part III – Series-Parallel Circuit Measurements**

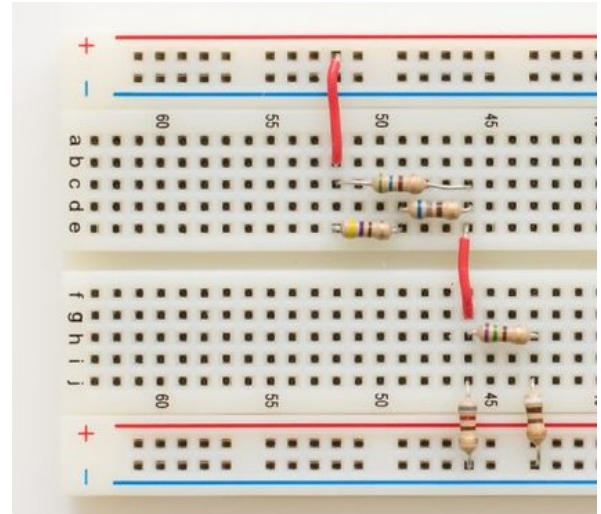
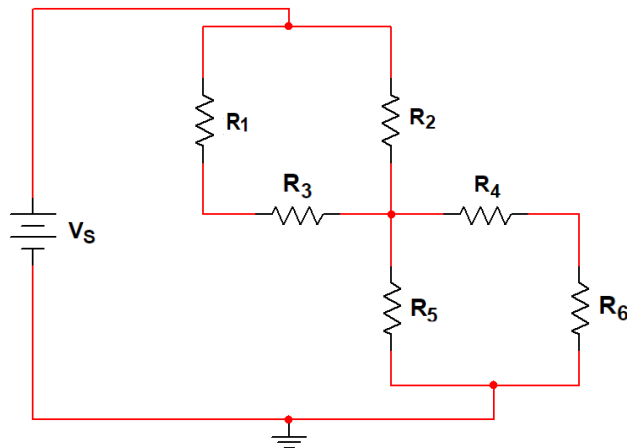


Figure 3.1 – Series-Parallel Circuit

1. **Build** the circuit in **Figure 3.1**. **Before** connecting the power supply to the circuit, use the DMM to **measure** the equivalent resistance  $R_{EQ}$  of the circuit.
2. **Connect** the power supply ( $V_S = 5V$ ) to the circuit.
3. **Measure** the **voltage across** each resistor and the **current through** each resistor with the DMM.
4. **Measure** the **total current** supplied by the power supply.
5. **Calculate** the **power** dissipated by each resistor using the measured voltage and current.
6. **Record** all data in the **Measured** sections of **Table 3.1**.
7. **Compute** the **percent error** between your **calculated** and **measured** results and record it below.

Electrical Quantity		Resistor						
		$R_{EQ}$	$R_1$	$R_2$	$R_3$	$R_4$	$R_5$	$R_6$
Voltage (V)	Calculated							
	Simulated							
	Measured							
Current (mA)	Calculated							
	Simulated							
	Measured							
Power (mW)	Calculated							
	Simulated							
	Measured							
Percent Error (%)	Voltage							
	Current							
	Power							

Table 3.1 – Series-Parallel Circuit Data

**Part IV – Design, Build, and Test a Voltage Ladder**

In this part of the lab, you are asked to design a **voltage ladder** using the concept of **Voltage Division**.

**Design Specifications:**

- $P_{total}$ :  $\leq 86mW$
- $V_S$ :  $5V \pm 5\%$
- $V_{AB}$ :  $1.724V \pm 5\%$
- $V_{BC}$ :  $0.345V \pm 5\%$
- $V_{CD}$ :  $1.724V \pm 5\%$
- $V_{DE}$ :  $1.207V \pm 5\%$

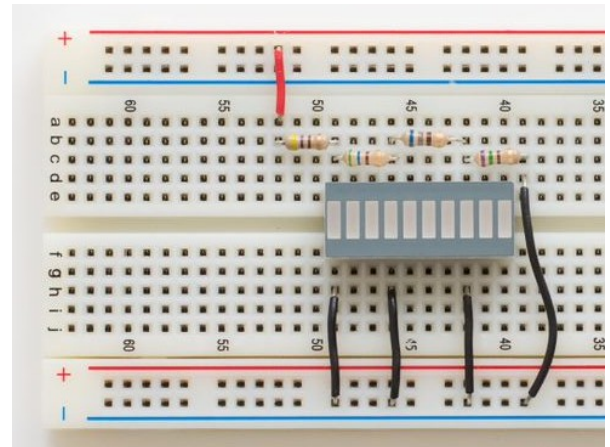
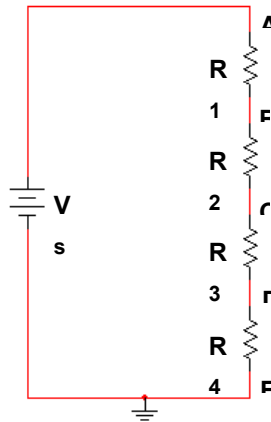


Figure 4.1 – Voltage Ladder

1. Using the circuit in **Figure 4.1**, find the appropriate values for  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  to build a voltage ladder that meets the **Design Specifications**. (*Hint: A good first step would be to examine the relationship between  $V_S$ ,  $P_{total}$ , and total current.*)  
**Note:**  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are for you to calculate. Do **not** use the values from **Table 2** that were used in earlier parts of this lab.
2. **After** designing the voltage ladder, **build** it on a breadboard.
3. **Turn on** the Power Supply in WaveForms.
4. **Measure** the **voltage** drop across each resistor and **compare** it to the value in the specifications.
  - a. **Record** your results in **Table 4.1**.
5. **Connect** the circuit to your green LED bar from points B, C, and D. **Wire** from nodes B, C, and D to the positive side (anode) of three individual LEDs in the bar. The positive side of the bar has the bar's serial code on it.
6. **Connect** the negative side (cathode) of the LEDs directly to ground. Vary the supply voltage from 0V to 5V (feel free to experiment).

**Question: What happens to the intensity of the LEDs as you vary the supply voltage? Do you notice a pattern?**

Quantity	Specified	Measured	Percent Error (%)
$P_{total}$			
$V_S$			
$V_{AB}$			
$V_{BC}$			
$V_{CD}$			
$V_{DE}$			

Table 4.1 – Voltage Ladder Data

**Part V – Wheatstone Bridge**

In this part of the lab, the GTA will assign you a value resistor  $R_x$ . You must build and use a Wheatstone Bridge to verify the value of its resistance.

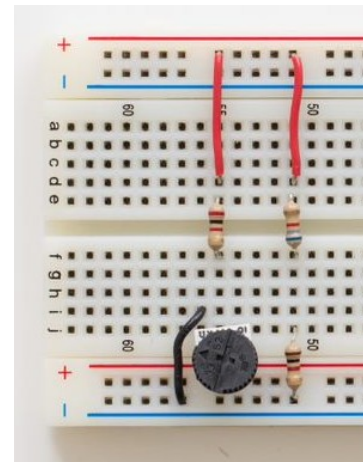
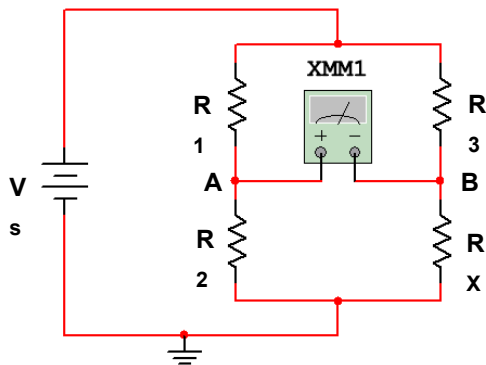


Figure 5.1 – Wheatstone Bridge

1. **Build** the Wheatstone Bridge in **Figure 5.1**. You will need the following components:
  - $R_1 = 2k\Omega$ ,  $R_3 = 5.1k\Omega$ ,  $R_2 = 10k\Omega$  potentiometer
  - DMM to measure voltage drop between nodes A and B ( $V_{AB}$ )
2. **After** you have completed the setup, **connect a 5V** supply for  $V_s$  from the AD2.
3. **Record** the initial (unbalanced) value of  $V_{AB}$  in **Table 5.1**.
4. **Adjust** the potentiometer until the bridge is balanced. (*Hint: Refer to Part IV of the Prelab to recall what balanced means for a Wheatstone bridge circuit.*)
  - a. **Record**  $V_{AB}$  once the bridge is balanced in **Table 5.1**.
5. **Remove** the potentiometer from the circuit without adjusting it and use the DMM to measure its actual resistance.
  - a. **Record** the value of  $R_2$  in **Table 5.1**.
6. **Measure** the exact resistances of  $R_1$  and  $R_3$  with the DMM.
7. **Use** the **measured values** for  $R_1$ ,  $R_2$ , and  $R_3$  and the expression you derived in **Part IV** of the **Prelab** to **calculate** the resistance of  $R_x$ . **Show your calculations.**
8. **Remove**  $R_x$  from the circuit and use the DMM to measure its exact resistance.
9. **Compare** your calculated and measured results for the resistance of  $R_x$  by **calculating** the percent error.

Quantity	Measured	Calculated	Percent Error (%)
$R_x$			
$V_{AB}$ (unbalanced)		n/a	
$V_{AB}$ (balanced)			
$R_1$			
$R_2$			
$R_3$			

Table 5.1 – Wheatstone Bridge Data

## **POST-LAB ANALYSIS**

*For part 1 of the lab:* Compare and contrast the calculated results from your prelab, to your Multisim simulations and finally to the DC measurements made in the lab itself. Show the percentage error in each case. Explain the differences between the calculated, measured, and simulated results then include a discussion on the reason for the discrepancies. Also explain the concept of tolerance in all the devices and equipment and how to compensate for the problem of inaccurate measurements.

*For part 2 of the lab:* Make sure to answer all questions asked in tandem with the lab instructions. Now that you have designed and observed the behavior of a voltage ladder / LED bar combination in detail, can you think of any applications for such a circuit? Name one or two possibilities in your report.

*For part 3 of the Lab:* Why does the bridge have to be 'balanced' in order to calculate the value of  $R_2$ ? Does your calculated value for  $R_2$  (from step 3 c) match your measured value of  $R_2$  (from step 3 d), what is the % error? Research and explain several uses of the Wheatstonebridge.