`Ohm's Law III -- Resistors in Series and Parallel

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Objectives

The objectives of this experiment are: (1) to understand and use Ohm's Law, (2) to learn, understand, and use resistors connected in series and parallel, (3) to learn the basic concepts and relationships of current and voltage measurements in DC circuits containing resistors wired in series and parallel, (4) to learn the relationships of the total resistance of resistors connected in series and parallel, and (5) to learn to use ammeters, voltmeters, ohmmeters, and multimeters to properly measure voltages, currents, and resistances.

Introduction

Most common household electrical circuits are made of many devices connected in parallel. Each device is hooked to the power source in parallel with all the other devices, each connected to the same voltage source and availing itself of the same voltage. Each device has its own characteristic resistance, and therefore each draws from the source a different amount of current, depending on its resistive value. While the voltage being accessed is nearly the same for all devices, the amount of current drawn from the source increases as each device draws its respective current based on its resistance. As a result as more and more devices are connected in parallel, the total amount of current drawn from the source increases. It thus has the effect of causing the resistance to decrease with each additional resistance added. Additional devices added to a circuit, require additional current from the source until something is overloaded. More current is required beyond that which can be supplied by the source or carried by the conductors without burning up.

Series circuits are not as common, except for old time Christmas tree lights that are a challenge to fix when one unknown bulb has burned out and all the rest fail to work.

However, all wires that make connections and the connections themselves qualify as series resistance. Wires have resistance that depend on wire size, length, and type of material. Wires add series resistance to circuits, just as good and bad connections add also. In order to fully understand electrical circuits and their behavior, one must first understand Ohm's Law and the principles regarding resistors in series and parallel circuits.

Theory

Ohm's Law

Ohm's Law is the relationship between the current I flowing through a resistance R and the potential drop across it V. The current is directly proportional to the potential difference across the resistance and is inversely proportional to the resistance,

$$I = \frac{V}{R}. \qquad (1)$$

As an alternative, Ohm's Law may be stated as: The potential difference V across a resistance is directly proportional to the current I flowing through the resistance and the resistance R, or

$$V = I \times R. \qquad (2)$$

Ohm's Law can be rearranged to define the resistance R so that

$$R = \frac{V}{I}. \qquad (3)$$

If the potential difference across the resistance is measured in volts (V) and the current flowing through the resistance is measured in amperes (A), then the resistance values will be in units of ohms.

Resistors in Series

Figure 1 shows 3 resistors, R_1, R_2, and R_3, connected in series in a closed circuit powered by a single battery or Emf source. In this circuit the current supplied by the battery flows through each resistor, with the current in each resistor being the same. If the current supplied by the battery is I_T, the current in each resistor is I_1, I_2, and I_3, and they are all one and the same, then

$$I_T = I_1 = I_2 = I_3. \qquad (4)$$

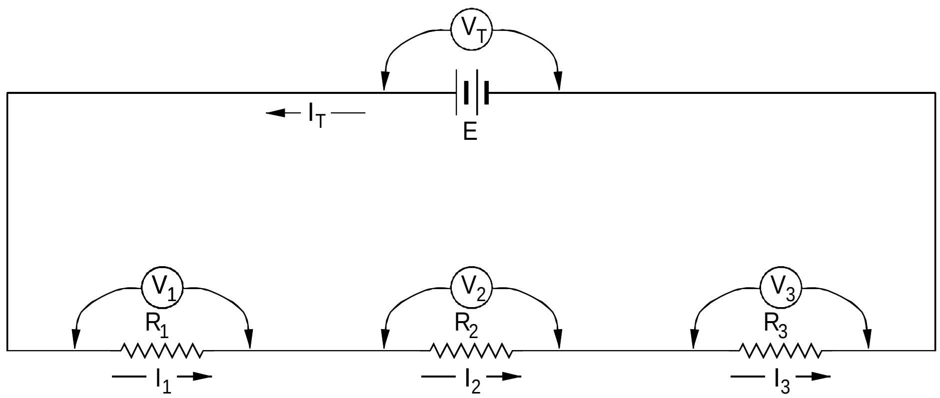


Figure 1. Three resistors R_1, R_2, and R_3 connected in series.

The voltage drop across the battery V_T will be the total sum of the individual drops across each of the 3 resistors, and

$$V_T = V_1 + V_2 + V_3 . \quad (5)$$

where V_1 is the potential difference across R_1, V_2 is the potential difference across R_2, and V_3 is the potential difference across R_3. From Equation 2,

$$V_T = I_T \times R_T , \quad (6)$$

$$V_1 = I_1 \times R_1 , \quad (7)$$

$$V_2 = I_2 \times R_2 , \quad (8)$$

and

$$V_3 = I_3 \times R_3 . \quad (9)$$

Substituting these equations into Equation 5 gives

$$I_T R_T = I_1 R_1 + I_2 R_2 + I_3 R_3 \quad (10)$$

and since $I_T = I_1 = I_2 = I_3$

$$R_T = R_1 + R_2 + R_3 . \quad (11)$$

Therefore, when resistors are connected in series, the total resistance is just the sum of the individual resistances. While this has been shown for 3 resistors, the total resistance of any number N ($N \geq 2$) of resistors connected in series, end to end, can be found using the same general procedure. Therefore for resistors connected in series

$$R_T = \sum_{i=1}^{N} R_i \,. \tag{12}$$

<u>Resistors in Parallel</u>

Resistors are connected in parallel when one end of each resistor is connected to a common point and each of their other ends is connected to another common point as shown in Figure 2. The current I_T that is supplied by the battery is divided into 3 separate currents, I_1, I_2, and I_3, each flowing through resistors R_1, R_2, and R_3 respectively. After flowing through the resistors, the 3 currents rejoin into a common current, I_T, or that current flowing back to the battery. The total current flowing in the circuit is the sum of the separate currents flowing through the resistors,

$$I_T = I_1 + I_2 + I_3 \,. \tag{13}$$

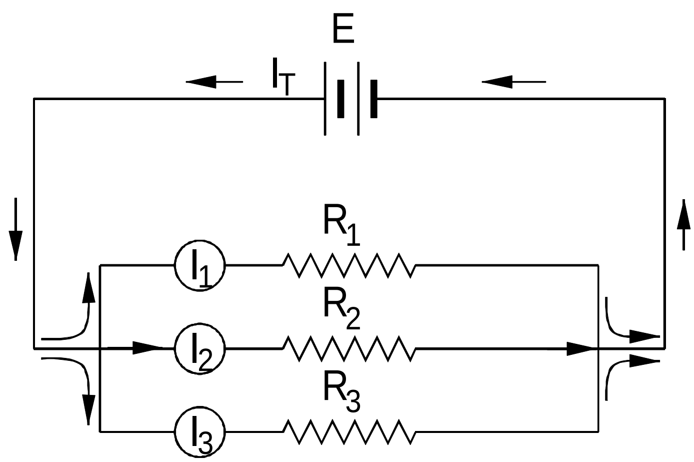


Figure 2. Three resistors R_1, R_2, and R_3 connected in parallel showing the flow of current.

From Equation 1 the total current is related to the total voltage and total resistance by

$$I_T = \frac{V_T}{R_T} \,. \tag{14}$$

and the current, potential difference, and resistance of each separate resistor is given by

$$I_1 = \frac{V_1}{R_1} \,, \tag{15}$$

$$I_2 = \frac{V_2}{R_2}, \tag{16}$$

and

$$I_3 = \frac{V_3}{R_3}. \tag{17}$$

Substituting these equations into Equation 13

$$\frac{V_T}{R_T} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}. \tag{18}$$

The voltage drops across the battery and resistors are all equal, and as illustrated in Figure 3,

$$V_T = V_1 = V_2 = V_3. \tag{19}$$

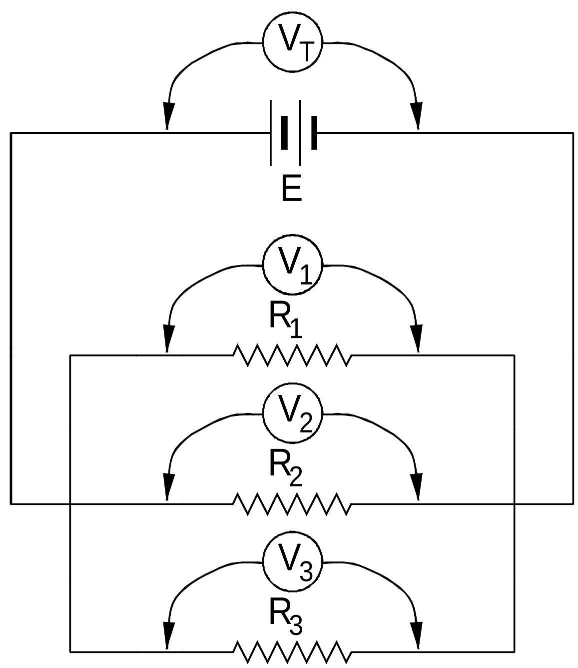


Figure 3. Three resistors R_1, R_2, and R_3 connected in parallel showing the potential differences all being equal.

Since all the potentials are equal Equation 18 reduces to

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \tag{20}$$

which is the equation for the total resistance of 3 resistors connected in parallel. As was the case for series resistors, the total resistance of any number N ($N \geq 2$) of resistors connected in parallel can be found using the same general procedure and will result in the relationship

$$\frac{1}{R_T} = \sum_{i=1}^{N} \frac{1}{R_i}. \tag{21}$$

In circuits with combinations of resistors in series and parallel, the total resistance can be found by breaking the circuit down into its simplest unit consisting of either resistor in series or parallel and then adding its total resistance back into the next simplest unit and finding its total resistance, and so on until the entire circuit has been reconstructed.

Apparatus

The apparatus is shown in Figure 4 and consists of: (1) 2 Meterman Model 15XP digital multimeters, DMMs, (2) a prototype circuit board with banana jacks for wiring the circuits, (3) a Pasco model PI-9877 power supply, (4) stackable double banana plugs with resistors or shorting bars (jumper wires) mounted, and (5) assorted leads with banana plugs. These components have been chosen to minimize problems with improper use, while at the same time providing good results for analysis and learning the concepts.

The digital meter provides convenience and accuracy of readings consistent with modern instrumentation. The digital multimeters can read voltages, currents, and resistance, but have to be properly connected to the correct inputs. There are separate inputs for voltage and resistance measurements and for current measurements. The center switch can be adjusted for the specific function that is needed and/or the range of the chosen function.

The power supply can be adjusted to supply voltages of 0 to 18 volts, but the current that it can supply is limited to 1 ampere. The power supply has extra features not needed in this experiment and should be disregarded. The digital ammeter is fused with a 2 ampere fuse and should withstand the maximum current available from the power supply.

The prototype circuit board has an array of banana jacks conveniently laid out in a manner to wire and to help expedite the construction of the circuits to be studied. The array is constructed such that a minimum number of jumper plugs are needed. Resistors are supplied mounted to stackable double banana plugs that can installed at a desired position on the circuit board. Connections between banana jacks on the circuit board can be made either by using a stackable double banana plug with a jumper wire across its terminals or with a lead wire with a banana plug on each end.

Resistors are mounted on red stackable double banana plugs and are numbered 1, 2, and 3. Shorting bars or jumper wires are mounted on black stackable double banana plugs and can be used to make connections on the prototype circuit board. Additional lead wires with banana plugs are used to make connections to the meters and power supply.

Resistors are manufactured in many different materials, forms, shapes, values, power ratings, and tolerances. While some resistor values are labeled with text, common resistors are color coded with bands to indicate their ohmic values. The color-numeric key is given in Table 1. The first colored band represents the first digit of the value followed by a second band for second digit. A third band indicates the number of zeros following the second digit. The fourth band indicates the tolerance, the maximum percent difference the actual value may have from the indicated value. For example a resistor marked with a green band followed by violet, brown, and silver bands, indicates a value of 570 ±10% ohms. The code can be remembered as starting with black, no color or 0, followed by brown, a little color 1. The color brown is then followed by the colors of the rainbow, red, orange, yellow, green, blue, and violet for the numbers 2 through 7. Gray and white finish the code for the digits 8 and 9, with white being the extreme difference and opposite black.

Color Code		
Black	Bk	0
Brown	Br	1
Red	R	2
Orange	O	3
Yellow	Y	4
Green	Gn	5
Blue	Bl	6
Violet	V	7
Gray	Gy	8
White	W	9
Tolerance Code		
Gold	Gd	5%
Silver	S	10%
None	N	20%

Table 1

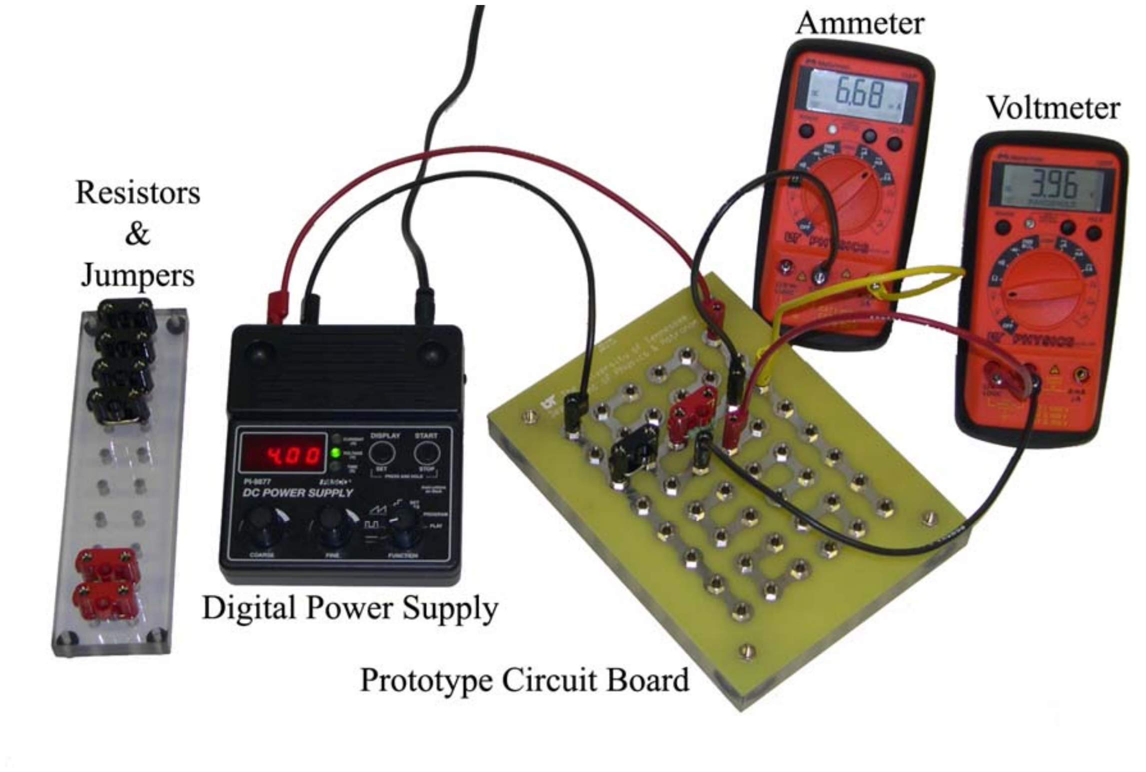


Figure 4. Apparatus for Ohms Law experiment to study resistors in series and parallel.

Procedure

Ideally, when ammeters and voltmeters are placed in a circuit, their placement does not perturb the circuit, so as to change the current and voltage values associated with each component that existed before their placement. In practice this always occurs, however, the changes can be minimized with the use of high impedance digital voltmeters and low impedance current devices. The Meterman15XP Digital Multimeter meets these conditions rather well, but there will be some slight changes in the values measured and the values that existed before their placement. It should be noted that the values read by the meter are the correct values for the measurement being taken. The actual values just change back to their unperturbed values when the meters are taken out of the circuit.

In this experiment, the effects of introducing an ammeter or voltmeter into a circuit will be neglected. As a result, values that are measured may not produce results that are in exact agreement with the theory that is being tested. However, the deviations of the measured values with the theoretical predictions will be very small. The emphasis of this experiment is to learn the concepts of DC circuits, Ohm's Law, and the addition of resistors in series and parallel. The effects of the ammeters and voltmeters on the circuit is studied in the preceding experiment.

Procedure

CAUTION! – Do not turn on the power supply until you are ready to make measurements, and when you are finished making measurement, turn the power supply output voltage to zero and then turn the power off until the next measurements are made.

<u>The Ohmmeter</u>

1. An Excel data sheet should be constructed as shown in Figure 5 to enter your data and to plot and analyze your results. Rename the Sheet 1 worksheet, Parallel Resistors by right clicking on the Sheet 1 tab at the bottom of the workbook and choosing rename in the pop up menu. Type in the new name in the highlighted tab.

	A	B	C	D	E	F	G	H	I	J
1										
2		Band #1	Value	Band #2	Value	Band #3	Value	Band #4	Value	Tolerance
3	Resistor #1									
4	Resistor #2									
5	Resistor #3									
6										
7		Ohmmeter values			Slope Values			% Differenc	nverse Slop	Inverse Sum
8	Resistor #1	R_1=		Ohms	R_1=		Ohms			
9	Resistor #2	R_2=		Ohms	R_2=		Ohms			
10	Resistor #3	R_3=		Ohms	R_3=		Ohms			
11	Measured Parallel Resistors	R_T=		Ohms	R_T=		Ohms			
12	Calculated Parallel Resistors	R_T=		Ohms	R_T=		Ohms			
13	Difference									
14										
15	Resistor #1		Resistor #2		Resistor #3		Parallel Resistors			
16	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current		
17	0									
18	1									
19	2									
	---	---	---	---	---	---	---	---		
34	---	---	---	---	---	---	---	---		
35	18									
36										
37		Resistors in Parallel								
38		Current	5 Volts	10 Volts	15 Volts					
39	Total	I_T								
40	Resistor #1	I_1								
41	Resistor #2	I_2								
42	Resistor #3	I_3								
43	Sum $I_1+I_2+I_3$									
44	Difference Total & Su									
45										
46										
47	Power Suppl	V_T								
48	Resistor #1	V_1								
49	Resistor #2	V_2								
50	Resistor #3	V_3								
51										

Figure 5. Example of Excel spreadsheet for recording and reporting data.

2. For each of the three resistors supplied, read and record the color coded bands with the numeric code and their values including the tolerances.

3. The Meterman 15XP digital multimeter can be used as an ohmmeter to directly measure resistance. Plug each of the 3 resistors provided you into the red **ΩV** and black **COM** input banana jacks. Adjust the function switch on the meter to read ohms by setting the switch to the **Ω** position. If necessary push the Range button to maximize the number of significant digits for your reading.

4. Record your values for your 3 resistors in the Excel data sheet. Save your data sheet frequently, particularly after a series of measurements have been added. This will prevent accidental loses of data.

5. Compare the ohmmeter values with the color coded values.

<u>Ohms Law—Single Resistor</u>

1. Wire the power supply, ammeter, voltmeter, and resistor #1 according to the following schematic diagram using the prototype circuit board and components as shown in Figures 4 and 6 . The Figure 6 shows the placement of the ammeter, A, the voltmeter, V, the resistor R_1, and the jumper wire J. Figure 4 is a photo of the setup.

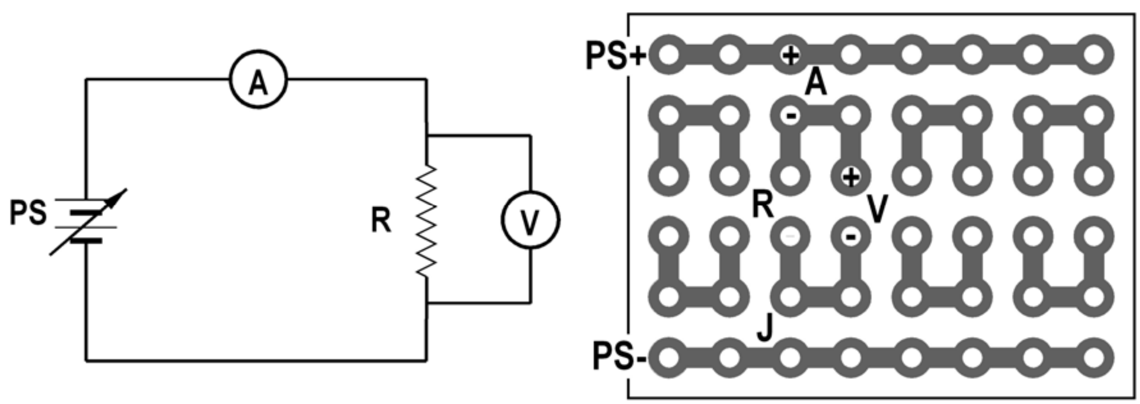


Figure 6. Schematic diagram and construction aids for wiring circuit to measure current and voltage for a single resistor.

2. Plug in the power supply and adjust the voltmeter to read DC volts, $\overline{V}$. Adjust the ammeter to read DC milliamps, $\overline{mA}$. Make sure the **FUNCTION** switch of the Pasco PI-9877 power supply is in the DC voltage output position, ⎓ . Turn on the power supply with the **OFF-ON** slide switch located at the right side of the power supply. The default setup of the power supply allows the voltage to be changed in 1 volt increments by adjusting the **COARSE** knob. Smaller increments may be made with the **FINE** adjustment control knob.

3. Measure the current flowing through the resistor as a function of the applied voltage by increasing the voltage in one volt increments from approximately 0 to 18 volts. Record both the voltage and the current in milliamperes (1 ampere = 1000 milliamperes) as measured by the power supply voltmeter and the digital ammeter. After recording your data in the Excel spreadsheet, return the power supply output to 0 volts. Use a second column to convert your measurements from milliamperes to amperes.

4. Make an Excel chart, Chart 1, of voltage versus current for your measurement to investigate the validity of Ohm's Law as given by Equation (2).

    - From the main menu bar, choose Insert, then Chart . . . from the pull down menu to produce the chart wizard. Choose XY (Scatter) from the standard types and points only (the default choice) from Chart sub-types options.
    - After clicking on Next, click on the Series tab for the step 2 menu. Click on Add and type "Resistor #1" in the name box. In the x values box, click on the arrow in the right side of the box and this will produce a menu box that can be filled in by taking your mouse and selecting the current in amperes data corresponding to the 0 to 18 volt data.
    - Once you have selected that data, the range of cells should appear in the pop-up window. If this range is acceptable, click on the arrow box at the end of the window and this will return to the step 2 pop up window. Repeat this for the y values box to select the corresponding voltage values and choose Next.
    - The step 3 pop up window allows you customize the graph. In step 3 under the Titles tab, enter "Ohm's Law" in the Chart title box, "Current (milliamperes)" for the Value (X) axis box, and "Voltage (Volts)" for the Value (Y) axis box.
    - You can customize the rest of the graph by choosing the other tabs and selecting the options.
    - Once step 3 is completed, click on the Next button and the step 4 pop up window allows you to choose the location.
    - Choose the "As object in: Sheet 1" option and then click on the Finish button. You can always relocate the graph to a separate sheet by right clicking on the graph and choosing Location from the pop-up menu.

5. According to Ohm's Law the voltage drop across a resistor is directly proportional to current flowing through it and the constant of proportionality is the resistance R, or V=RI (or most familiarly, V=IR). Right click on one of the data points in your graph and select Add Trendline from the pop-up menu. Select the linear analysis type and under the Options tab select the Display Equation on chart option and then OK.

6. For pure resistance, the data should be a straight line and the slope is equal to the value of the resistance. In SI units the resistance is in ohms if the voltage and current are measured in volts and amperes.

7. Record your value for this resistance as computed from the slope and compare it to the value measured with the ohmmeter.

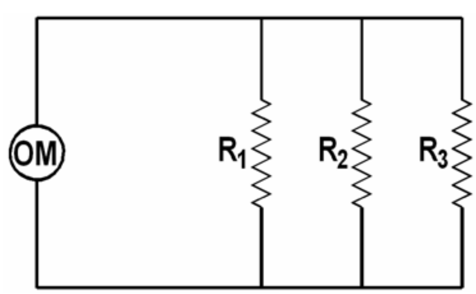
8. Replace resistor #1 with #2 and repeat the measurements recording your data in the spreadsheet.

9. Add this data to your graph by selecting the graph with a right click. Under the main menu bar, select Chart and then Source Data . . . from the pull down menu. Choose the Series tab from the pop-up window and click on Add to add a second set of data. Type "Resistor #2" in the name box and select the new x and y values from your data as you did in Step 4 above.

10. Add a trendline and find the slope of this graph as in Step 5 above.

11. Compute the resistance from the slope and record your value for the resistor #2. Compare your value with the ohmmeter value.

12. Replace resistor #2 with resistor #3 and repeat steps 8-11.



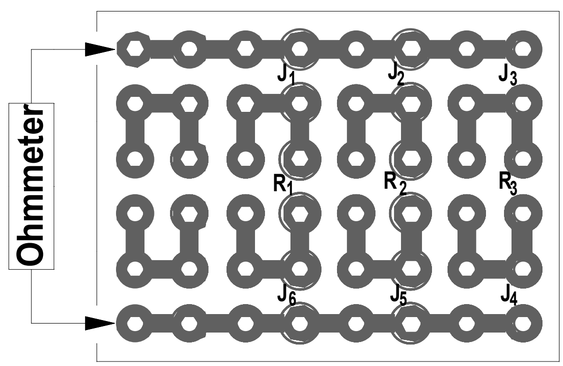


Figure 7. Schematic and wiring aid for measuring resistance of 3 resistors in parallel with an ohmmeter.

<u>Resistors in Parallel</u>

1. Connect only the jumpers and resistor #'s 1, 2, and 3 in parallel as shown in the schematic and wiring diagrams of Figure 7. Connect the ohmmeter as shown to measure the total resistance of the 3 resistors connected in parallel. Record this value in your spreadsheet. Note the value as compared to the values of the single resistors and the sum of the 3 resistors.

2. Use your 3 resistor values from your ohmmeter measurements and Equation (20) to calculate the total resistance of your 3 resistors connected in parallel. Enter your result in your spreadsheet and compare it with the measured value. Compute the percent difference between the measured and calculated values.

3. Connect the power supply, ammeter, and voltmeter to the 3 resistors in parallel as shown in the schematic and wiring diagrams of Figure 8. Notice the position of the ammeter and the positions of the jumpers.

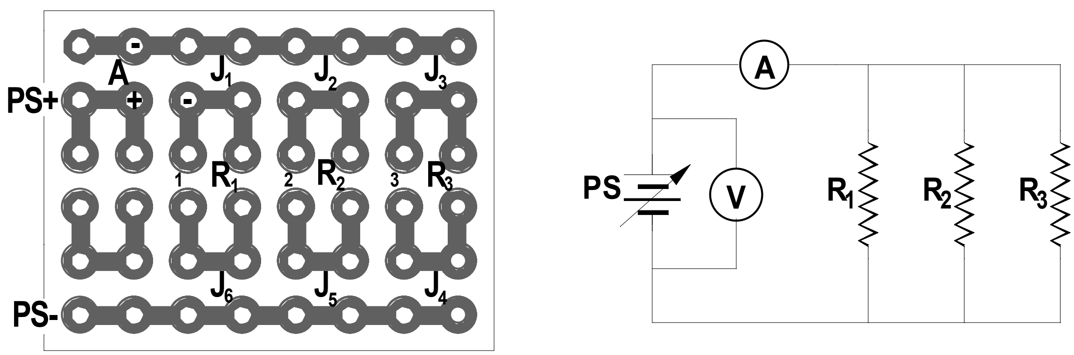


Figure 8. Wiring aid and schematic for measuring current versus voltage for 3 resistors in parallel.

4. Measure the current flowing to these three resistors as a function of input voltage from the power supply. Make the measurements for 0 to 18 volts in 1 volt increments and record this data in your spreadsheet.

5. Add this data to your graph plotting voltage V versus current I. Label this fourth series as "Resistors in Parallel."

6. Add a trendline and find the slope and total resistance of these 3 resistors in parallel.

7. Record the value in your spreadsheet and compare this result with the value determined with the ohmmeter.

8. Use your 3 resistor values from your 3 slope measurements and Equation (20) to calculate the total resistance of your 3 resistors connected in parallel. Enter your result in your spreadsheet and compare it with the measured value of slope. Compute the percent difference between the measured and calculated values.

9. Make a new chart, Chart 2, of the 4 data sets for the 3 resistors and the parallel combination, but instead of plotting voltage versus current, plot current versus voltage. This will test Ohm's Law in the form $I = \frac{1}{R}V$. The current is directly proportional to the applied voltage and as such should also give linear, straight line graphs. However, the slopes should give the inverse of resistance, $\frac{1}{R}$.

10. Add trendlines to the 4 plots of current versus voltage and record your values of $\frac{1}{R}$ in your spreadsheet. Compare the sum of the values of $\frac{1}{R}$ for the 3 resistors ($\frac{1}{R_1}$, $\frac{1}{R_2}$, and $\frac{1}{R_3}$) with the value for the combination ($\frac{1}{R_T}$). Do your results agree with Equation (20)?

11. Derivation of Equation (20) was based on Equation (13). Verify Equation (13) by measuring the total current and the currents flowing through each resistor. To do this, wire the power supply, ammeter, and resistors in parallel as shown in Figure 8. Set the power supply at 5 volts and measure the total current, I_T, flowing to the 3 resistors. Record your results in your spreadsheet.

12. Interchange the ammeter with Jumper #1, J_1, and read and record the current, I_1, flowing in resistor #1.

13. Replace Jumper #1 and repeat this for Jumper #'s 2 and 3. Record the currents flowing in resistor #'s 2 and 3, I_2 and I_3.

14. Repeat steps 11-13 with the power supply adjusted to 10 and 15 volts.

15. In each case compare the sum of the individual currents, $I_1+I_2+I_3$, with the total current I_T.

16. What is the percent difference and explain why there is a slight difference.

17. Adjust the power supply to15 volts and place the voltmeter at positions 1, 2, and 3 across resistor #'s 1, 2, and 3. Read and record the voltages at these 3 positions, V_1, V_2, and V_3.

18. Compare these values with the power supply, V_T, value and explain any differences that may be observed.

Resistors in Series

1. To save time and effort, use the copy and paste commands to select and copy all the active cells in the Parallel Resistors worksheet into Sheet 2. Then use the Paste Special command to paste the same column widths also. Rename Sheet 2 "Resistors in Series." The single resistor data does not change.

   Note: *An easy way to accomplish this task is to Right Click on the Worksheet tab at the bottom and to select the Move or Copy* **. . .** *option from the pop-up menu. Then check the Create a copy option box and then click on OK. You can Right Click on the new worksheet tab to rename it.*

2. Replace the "Parallel" labels with "Series."

3. Connect only the jumpers and resistor #'s 1, 2, and 3 in series as shown in the schematic and wiring diagrams of Figure 9. Connect the ohmmeter as shown to measure the total resistance of the 3 resistors connected in series. Record this value in your spreadsheet. Note the value as compared to the values of the single resistors and the sum of the 3 resistors.

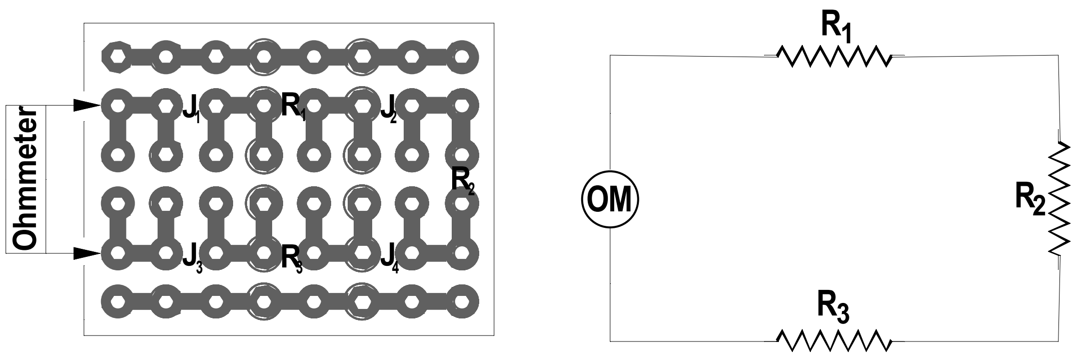


Figure 9. Wiring aid diagram and schematic for measuring the resistance of 3 resistors in series with the ohmmeter.

4. Use your 3 resistor values from your ohmmeter measurements and Equation (11) to calculate the total resistance of your 3 resistors connected in series. Enter your result in your spreadsheet and compare it with the measured value. Compute the percent difference between the measured and calculated values.

5. Connect the power supply, ammeter, and voltmeter to the 3 resistors in series as shown in the schematic and wiring diagrams of Figure 10. Notice the position of the ammeter and the positions of the jumpers.

6. Clear the current column under Series Resistors in your spreadsheet and measure the current flowing to these three resistors as a function of input voltage from the

power supply. Make the measurements for 0 to 18 volts in 1 volt increments and record this new data in your spreadsheet.

7. Add this data to your Chart 1 graph plotting voltage V versus current I. Label this fifth series as "Resistors in Series."

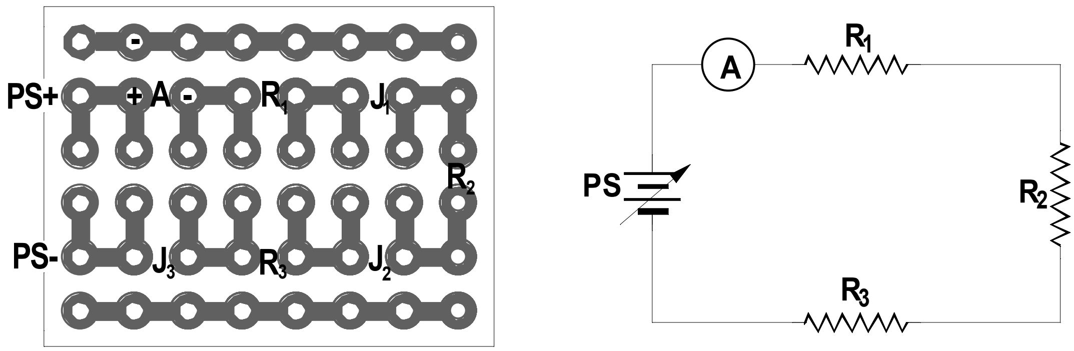


Figure 10. Wiring aid and schematic diagrams for measuring the current versus voltage of 3 resistors in series.

8. Add a trendline and find the slope and total resistance of these 3 resistors in series.

9. Record the value in your spreadsheet and compare this result with the value determined with the ohmmeter.

10. Use your 3 resistor values from your 3 slope measurements and Equation (11) to calculate the total resistance of your 3 resistors connected in series. Enter your result in your spreadsheet and compare it with the measured value of slope. Compute the percent difference between the measured and calculated values.

11. Derivation of Equation (11) was based on Equation (5), that the total voltage, V_T across resistors in series is equal to the sum of the individual voltage drops across each resistor. Verify Equation (5) by measuring the total voltage, V_T, and the voltages across each resistor, V_1, V_2, and V_3. To do this, wire the power supply, voltmeter, and resistors in series as shown in Figure 11. Begin with the voltmeter inserted at the V_T position. Set the power supply at 5 volts and measure the total voltage, V_T, across the 3 resistors. Record your result after modifying your "Series Resistor" worksheet as copied from the "Parallel Resistor" worksheet to reflect the measurement of voltages. See Figure 12.

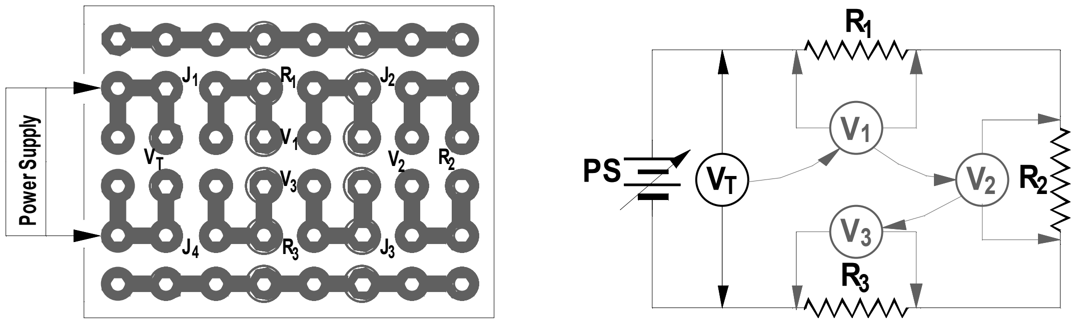


Figure 11. Wiring aid and schematic diagrams for measuring voltages across resistors in series and separately.

12. Remove the voltmeter and place it across resistor #1 at position V_1. Read and record the voltage, V_1, across resistor #1.

Resistors in Series				
	Voltage	**5 Volts**	**10 Volts**	**15 Volts**
Total	V_T			
Resistor #1	V_1			
Resistor #2	V_2			
Resistor #3	V_3			
Sum V_1+V_2+V_3				
% Difference Total & Sum				

Figure 12. Worksheet modification

13. Transfer the voltmeter to read the voltage drop across resistor #'s 2 and 3.

14. Repeat steps 9-11 with the power supply adjusted to 10 and 15 volts. In each case compare the sum of the individual voltages, $V_1+V_2+V_3$, with the total voltage, V_T.

15. Is there a difference? If so, how much of a difference and explain.

16. Derivation of Equation (11) was also based on the current flowing through each resistor being the same. Remove jumper, J_1, and replace it with the ammeter. Read and record the total current, I_T. Repeat this step for jumpers J_2, J_3, and J_4 to measure the currents I_1, I_2, and I_3 flowing in other parts of the circuit.

17. Compare the results to see if there are any differences. Explain any differences that are observed.

Questions

1. Draw a clear, schematic diagram for the circuit shown in the photo in Figure 12.

Figure 12

2. Draw a clear, schematic diagram for the circuit shown in the photo in Figure 13.
3. Draw a clear, schematic diagram for the circuit shown in the photo in Figure 14.
4.