# EXPERIMENT 1
## Ohm's Law

## Objectives

- Become familiar with the use of a digital voltmeter and a digital ammeter to measure DC voltage and current.
- Construct a circuit using resistors, wires and a breadboard from a circuit diagram.
- Construct series and parallel circuits.
- Test the validity of Ohm's law
- Reduce a complicated resistance circuit to a simple one-resistor equivalent circuit.

**Note:** If you are color blind or suspect that you are, you may find the color codes on the resistors difficult. Please consult your lab instructor for advice or help.

## Introduction

One of the fundamental laws describing how electrical circuits behave is Ohm's law. According to Ohm's law, there is a linear relationship between the voltage drop across a circuit element and the current flowing through it. Therefore the resistance R is viewed as a constant independent of the voltage and the current. In equation form, Ohm's law is:

$$V = I \times R \qquad (1)$$

Here,    V = voltage applied across the circuit and has SI units of volts (V)
       I = current flowing through the circuit and has SI units of amperes (A)
       R = resistance of the circuit and has SI units of ohms ($\Omega$)

Equation (1) implies that, for a resistor with constant resistance, the current flowing through it is proportional to the voltage across it. If the voltage is held constant, then the current is inversely proportional to the resistance. If the voltage polarity is reversed (that is, if applied voltage is negative instead of positive), the same current flows but in the opposite direction. If Ohm's law is valid, it can be used to define resistance as:
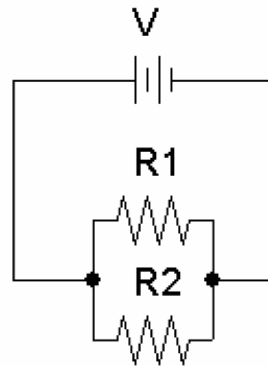
$$R = \frac{V}{I}$$

Where, R is a constant independent of V and I.

It is important to understand just what is meant by these quantities. The current (I) is a measure of how many electrons are flowing past a give point during a set amount of time. The current flows because of the electrical potential (V), sometimes referred to as the voltage applied to a circuit. In much the same way that a gravitational potential will cause mass to move, electrical potential will cause electrons to move. If you lift a book and release it from a height (high gravitational potential) it will fall downward (to a lower potential). The electrical potential works in a similar way. If we induce a large negative charge on one end of a wire and a large positive charge on the other, the electrons in the wire will flow because of the charge difference. The resistance of the circuit is just that; it is a measure of how difficult it is for the electrons to flow. This resistance is a property of the circuit itself, and just about any material has a resistance. Materials that have a low resistance are called conductors and materials that have a very high resistance are called insulators. Some materials have a moderate resistance and still allow some current to flow. These are the materials that we use to make resisters like the ones we will use in this experiment. In short, the electrical potential causes the current to flow and the resistance impedes that flow.

Two or more resistors can be connected together either in series or in parallel. Resistors in series means that the resistors are connected one after another (figure 1a). Resistors in parallel means resistors are connected side by side, parallel to one another (figure 1b).
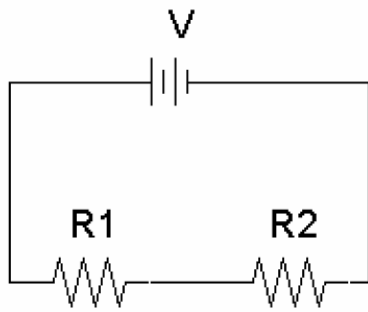


Figure 1a  series circuit                    Figure 1b  parallel circuit

Table 1 summarizes the equations and rules for two resistors in series and parallel circuits. The voltage from the power supply is $V_s$, the total current in the circuit is $I_s$ and the equivalent (total) resistance of the circuit is $R_s$ for the series circuit (and $R_p$ for the parallel circuit).

## Table 1
**Equations for two resistors in series and parallel circuits**

| Series | Parallel |
|---|---|
| $V_s = V_1 + V_2$ | $V_P = V_1 = V_2$ |
| $I_s = I_1 = I_2$ | $I_P = I_1 + I_2$ |
| $R_s = R_1 + R_2$ | $\dfrac{1}{R_p} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$ or $R_p = \dfrac{R_1 R_2}{R_1 + R_2}$ |

When two resistors ($R_1$ and $R_2$) are connected in series, the equivalent resistance $R_s$ is given by $R_s = R_1 + R_2$. Thus, the circuit in Figure 1a behaves (draws current from a given applied voltage) as if it contained a single resistor $R_s$.

When two resistors ($R_1$ and $R_2$) are connected in parallel, the equivalent resistance $R_p$ is given by:

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} \quad \text{or} \quad R_p = \frac{R_1 R_2}{R_1 + R_2} \tag{2}$$

Therefore, the circuit shown in Figure 1b behaves as if it contained a single resistor having a resistance of $R_p$.

Using these two relationships, a complex circuit can be redrawn as a circuit with a single resistor. You may wish to review the process of finding the equivalent resistance of circuits in your Physics textbook. Prove this relationship before you come to lab.

# Apparatus

### THE DC POWER SUPPLY

A DC power supply is used to provide varying voltage to a circuit. The power supply used in this lab is shown in Figure 2. The black and red connectors are the negative (-) and positive (+) output terminals respectively. The voltage knob controls the output voltage of the power supply and the current knob sets a *limiting* current. In this lab, **adjust the current control to its maximum setting (all the way clockwise) at all times.**

**Note:** Prior to making any change in the circuit, always turn the voltage knob to its minimum setting (all the way counterclockwise) and turn off the power supply! So the next time you turn on the power supply its output will be zero volts.
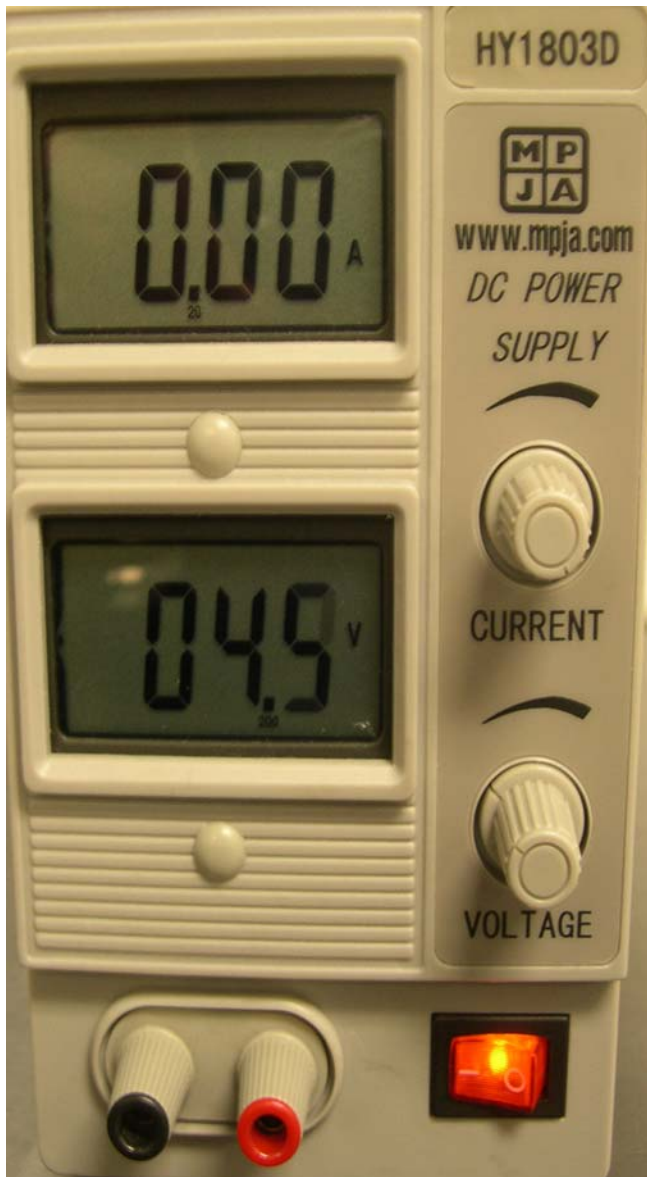
**Figure 2  DC Power Supply**



**Figure 3  Digital Multimeter**

## THE DIGITAL MULTIMETER

The digital multimeter is shown in Figure 3 above.  As its name suggests, a multimeter has multiple functions.  It can be used for several different purposes, two of which are a voltage measuring device (a voltmeter) and a current measuring device (an ammeter) will be used in this experiment.

To use the multimeter as a voltmeter, the dial selector is set to one of the positions labeled "V".  The probing cables are then connected to the plugs labeled "VΩ" and "COM".  There are two types of "V" settings.  The setting with the tilde (~) over it is used for measuring AC voltage.  The other type of "V" setting has two lines over the V –

one line is solid and the second line is dashed this indicates DC voltage.  AC is an abbreviation for alternating current.  An AC voltage is a voltage whose magnitude and polarity vary with time.  DC is an abbreviation for direct current.  A DC voltage is a *constant* voltage.  During this experiment, only the DC setting is used.  There are two DC voltage settings on the multimeter:  "V" and "300 mV".  When using the "300mV" setting, the output of the multimeter will be in millivolts.  Whether the multimeter is used to measure voltage (as a voltmeter) or current (as an ammeter), one cable is ALWAYS connected to the COM plug.  If the multimeter is used to measure current, the other lead is connected to either the 10A plug or the 300mA plug.

**A voltmeter must be connected in parallel(across) to the circuit element of interest,** as shown in figure 4a.  Since the voltmeter measures potential difference between two points, it is easy to connect.  To measure the potential difference (voltage drop) across a resistor, use a cable to connect one plug of the voltmeter to the circuit before the resistor and a second cable to connect the other plug of the voltmeter after the resistor.  A voltmeter typically has a very large internal resistance; therefore the very little current will flow through the voltmeter.  Consequently, the current in the circuit will be approximately the same before and after the voltmeter is connected.
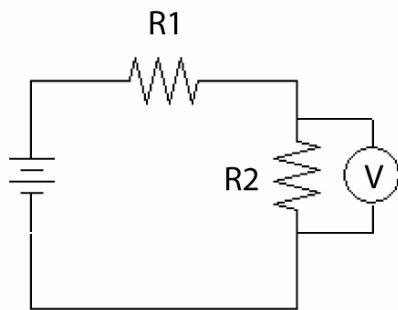


Figure 4a:  schematic of          Figure 4b: schematic of
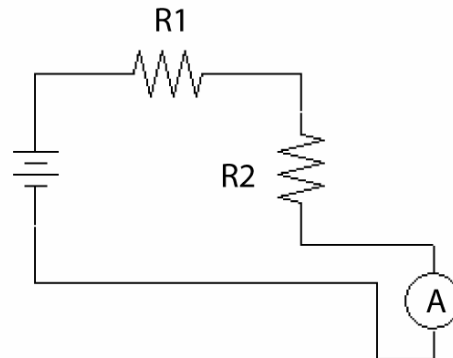a voltmeter in a circuit          an ammeter in a circuit

To use the multimeter as an ammeter, the dial selector is set to one of the positions labeled "A".  Similar to the voltmeter settings there are AC and DC settings.   Like the voltmeter, two cables must be connected to the ammeter.  One of your cables MUST be connected to the plug labeled "COM".  The second cable can be connected to one of two possible plugs – either the "10A" plug or the "300mA" plug.  If you have a large amount of current (anywhere close to 1A or higher), you **must** connect the cable to the terminal marked "10A".  If you put it in the "300mA" terminal you could damage the multimeter. If you are unsure if you have too much current for the 300 mA plug, start with the 10A plug.  If you do not get any reading at all (i.e. 0.00), you have a very small current and can then move the cable to the 300 mA plug.

**An ammeter must be connected in series with the circuit element of interest**, as shown in Figure 4b above. This means that unlike measuring voltage, if you want to measure current you must break the circuit and wire the ammeter in. All of the current must flow through the ammeter in order for it to be measured. If you use your finger to trace the path of a charge in Figure 4b after it leaves resistor R1 you will see that it must go through both the resistor R2 AND the ammeter. In contrast, tracing the path of a charge in Figure 4a you will see that it has two "parallel" paths through which it can go it will go through either R2 or the multimeter (do not connect an ammeter in this manner). An ammeter typically has a very small internal resistance. Therefore, the current in the circuit is approximately the same before and after the ammeter was connected.
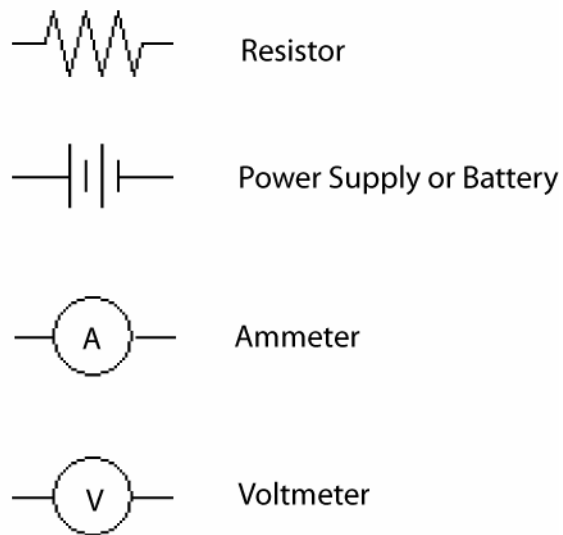


Figure 5  Standard Symbols

## THE BREADBOARD

The breadboard is designed for quick construction of simple electronic circuits and is shown in Figure 6. Electronic elements (i.e. resistors) are easily attached using the metal clips in the middle of the breadboard. Each metal clip is electrically connected to a plug connector by a metallic strip. The resistance between the metal clip and the plug connector is negligible; therefore, you can assume these two points are at the same electrical potential (voltage). Circuits are constructed by connecting the electronic circuit elements and the power supply together using cables with banana plugs. The banana plugs fit securely into the plug connectors on the breadboard, the multimeter and the power supply.
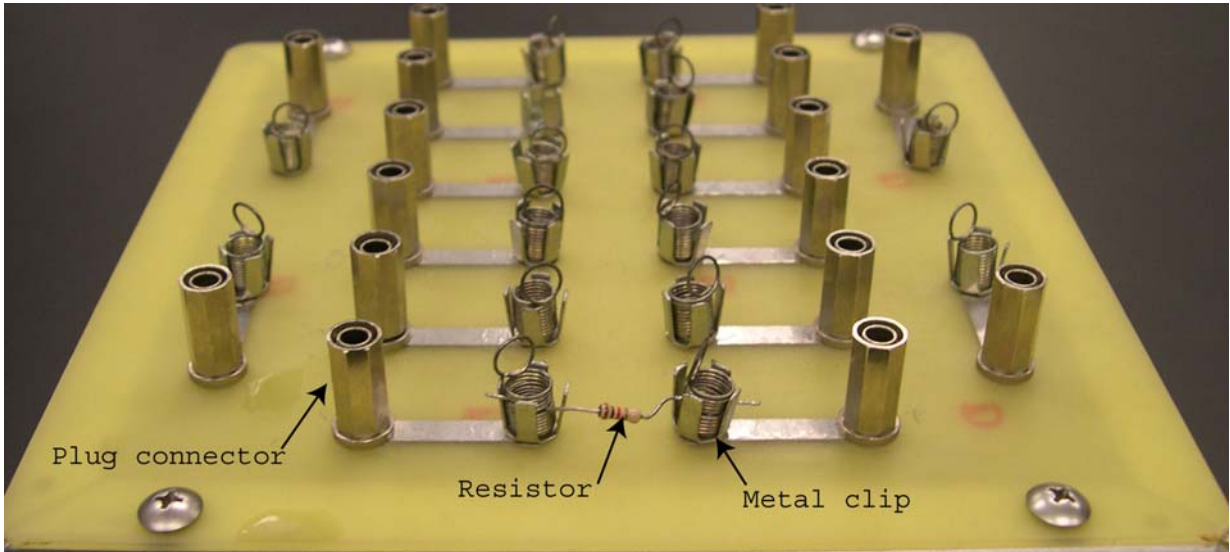
**Figure 6   Breadboard**

## WIRES

You will have to hook up wires to make the circuits described in the circuit diagrams. Each line without any circuit element should correspond to a wire in your circuit. A wire (or line in the diagram) represents a path where current can flow. A wire is a resistor with very low resistance. **All points on a wire/line have the same voltage.** Because of this, a circuit may be realized by several different arrangements of wire.

The two circuits in Figures 7 below are equivalent. The dots represent where the wires (banana plug cables) are connected to plug connectors on the breadboard, multimeter or power supply.
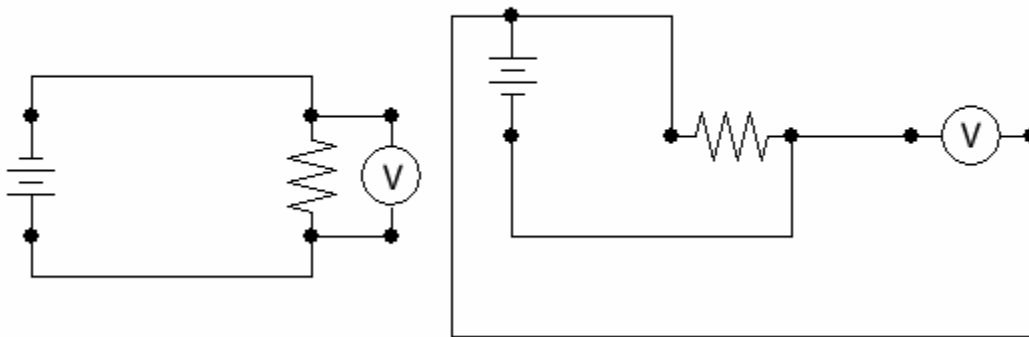


**Figure 7 Equivalent circuits**

# SUGGESTIONS FOR BUILDING CIRCUITS

The schematic representation of electronic circuits typically shows wires as straight lines and changes in the direction of the wires are indicated by abrupt bends in the wires. In practice, the flexible wires are not straight and as you might expect changes in direction are not abrupt 90 degree bends in the wires. Adding measuring devices (ammeters and/or voltmeters) to the circuit increases the circuit's complexity. The following steps will guide you through the construction of a simple circuit, including an ammeter and a voltmeter. To avoid confusion, all of the wires used in the following example have different colors. The figure in this guide show both the circuit represented schematically and how the circuit actually looks in practice.

1. **Start by building the circuit without any meters**. Where two lines meet, you will need two wires. Although it may seem efficient to initially construct the circuit with the meters included, experience has shown that this method often leads to wiring errors. Figures 8a (schematically) and 8b (in practice) below show a simple circuit with a power supply and a single resistor. The green wire is connected to the positive terminal of the power supply and the white wire is connected to the negative terminal.
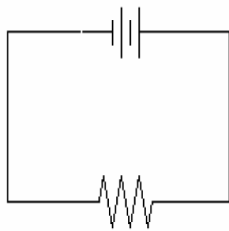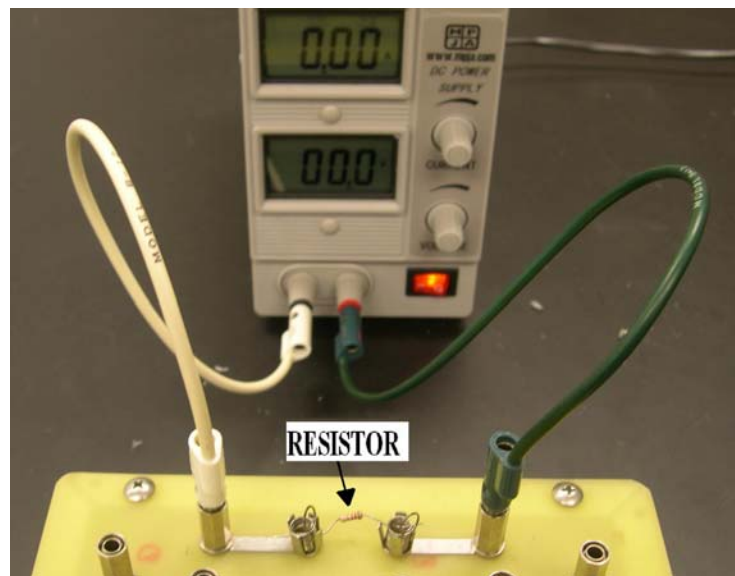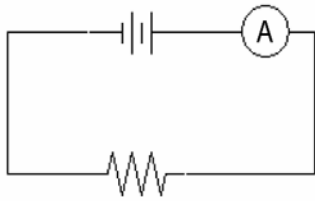


**Figure 8a Circuit schematic**          **Figure 8b Wired circuit**

2. **Include an ammeter in the circuit to measure current.** Attach a single wire to the "COM" input of your ammeter in this example, this is the purple wire. Identify the element in your circuit through which the desired current is flowing (in this case the resistor). Unplug wire (or wires) leading into one end of that element and plug all of them into either the 300mA or 10A input of your ammeter, depending of the size of the current you are measuring. In this example, there is only one wire leading to the resistor (the green wire) and we are using the 300mA setting of the ammeter. Plug the free end of the purple wire into the plug on the breadboard where you removed the circuit's wire (or wires) – i.e. the place where the green wire was connected in Figure 8b. You have now forced all of the current carried by the wire (or wires) to go through the ammeter in addition to the circuit element of interest. The ammeter is now properly connected in series with the resistor. Figures 9a (schematically) and 9b (in practice) below show our simple circuit with a power supply, a single resistor and an ammeter.
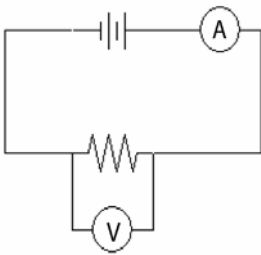


**Figure 9a Circuit schematic with ammeter**
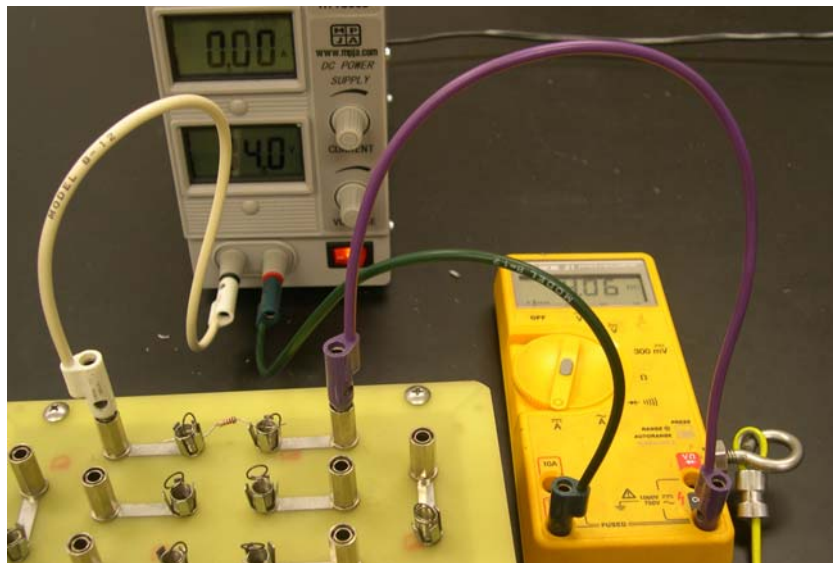
**Figure 9b Wired circuit with ammeter**

3. Attach two wires to the voltmeter inputs. In the example below the red wire is connected to the "VΩ" input and the black wire is connected to the "COM" input of the voltmeter. Attach the free end of each wire across the points whose voltage you would like to measure – in this case the red wire is connected to the right of the resistor and the black wire is connected to the left of the resistor. The voltmeter is now properly connected in parallel with the resistor – NEVER CONNECT AN AMMETER IN THIS FASHION.



**Figure 10a Circuit schematic with ammeter and voltmeter**
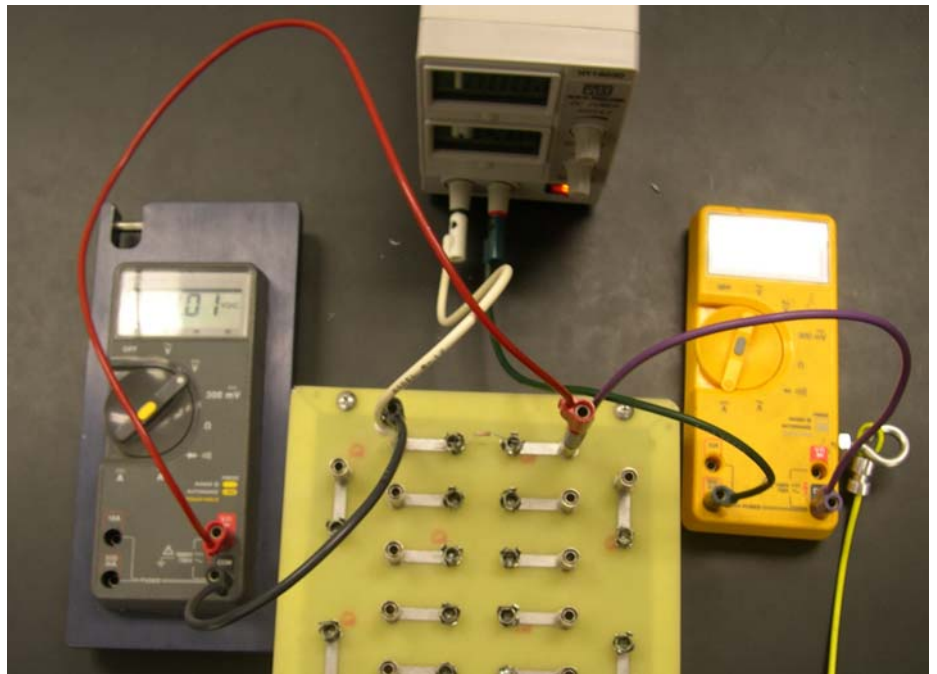
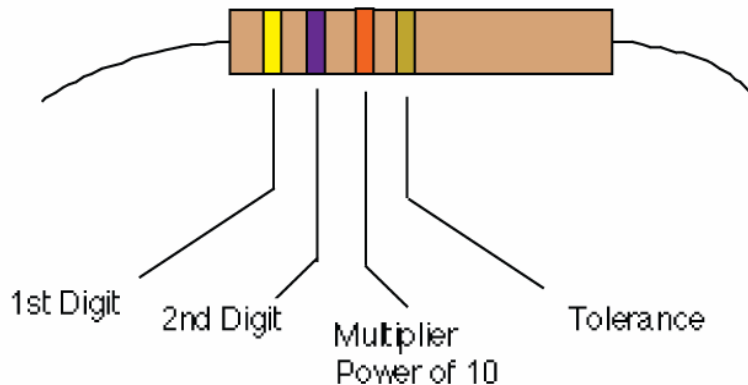**Figure 10b Wired circuit with ammeter and voltmeter**

Once you have constructed a circuit, no matter how complicated, you can use steps two and three to measure the current flowing through a given element in the circuit and the voltage across that circuit element.

# RESISTOR COLOR CODES

Most resistors are coded with color bands around one end of the resistor body. Using the resistor color code system is similar to using scientific notation. Scientific notation uses a number between 0 and 9.9 multiplied by some power of ten. The resistor color code system uses a number between 01 and 99 multiplied by some power of ten. These color bands tell the value of the resistance. Starting from the end, the first band represents the first digit of the resistance value and the second band the second digit. The third band represents the power of ten multiplying the first two digits. The fourth band represents the tolerance. If the forth band is absent, it means the tolerance is 20%. The following is a color code chart, from which one can tell the resistance of a resistor:

## Table 2  Resistor Color Codes

| Color | 1st Digit | 2nd Digit | Power of 10 | Multiplier | Tolerance |
|-------|-----------|-----------|-------------|------------|-----------|
| Black | 0 | 0 | 0 | 1 | - |
| Brown | 1 | 1 | 1 | 10 | - |
| Red | 2 | 2 | 2 | 100 | - |
| Orange | 3 | 3 | 3 | 1,000 | - |
| Yellow | 4 | 4 | 4 | 10,000 | - |
| Green | 5 | 5 | 5 | 100,000 | - |
| Blue | 6 | 6 | 6 | 1,000,000 | - |
| Violet | 7 | 7 | 7 | 10,000,000 | - |
| Gray | 8 | 8 | 8 | 100,000,000 | - |
| White | 9 | 9 | 9 | 1,000,000,000 | - |
| Gold | - | - | | | 5% |
| Silver | - | - | | | 10% |
| None | - | - | | | 20% |



1st Digit   2nd Digit   Multiplier Power of 10   Tolerance

**Figure 11  Resistor**

## EXAMPLE:

Suppose the color code on a resistor is yellow, violet, orange and gold like the resistor depicted above in Figure 11. What is its resistance and what is the uncertainty of this resistance?

The value of the resistance can be found from the first three colors. Form the table above, the first digit is 4 (corresponding to the yellow band), the second digit is a 7 (corresponding to the violet band) and the power of 10 multiplier is 3 (corresponding to the orange band).

So, the resistance is:



The fourth color is used to calculate the uncertainty in the resistance. The tolerance of this resistor is 5% (corresponding to the gold band). So, the uncertainty of the resistor is:

$$\delta R = R \times tolerance = 47{,}000\,\Omega \times \frac{5}{100} = 2{,}350\,\Omega$$

The resistance of this particular resistor is $47{,}000 \pm 2{,}000\ \Omega$ or $47 \pm 2\ k\Omega$. Because the tolerance is only given to one significant figure, the uncertainty can only be known to one significant figure.


## DIFFERENT CLASSES OF ERRORS

### 1. Manufacturer's tolerance

Suppose I purchase a nominally 100 $\Omega$ resistor from a manufacturer. It has a gold band on it which signifies a 5% tolerance. What does this mean? The tolerance means $\delta R/R = 0.05 = 5\%$, that is, the fractional uncertainty. Thus, $\delta R = R \times 0.05 = 5\Omega$. We write this as

$$R = R_{nominal} \pm \delta R = 100 \pm 5\ \Omega.$$

It says that the company certifies that the true resistance R lies between 95 and 105$\Omega$. That is, $95 \le R \le 105\Omega$. The company tests all of its resistors and if they fall outside of the tolerance limits the resistors are discarded. If your resistor is measured to be outside of the limits, either (a) the manufacturer made a mistake (b) you made a mistake or (c)

the manufacturer shipped the correct value but something happened to the resistor that caused its value to change.

**2. Reading a digital meter.**

Suppose I measure the voltage across a resistor using digital multimeter. The display says 7.45 V and doesn't change as I watch it. The general rule is that the uncertainty is half of the value of the least significant digit. This value is 0.01 V so that half of it is 0.005. Here's why. The meter can only display two digits to the right of the decimal so it must round off additional digits. So if the true value is 7.454 or 7.445 V, these values, or anything in between, will get rounded to 7.45. Thus the average value and its uncertainty can be written as 7.45 ± 0.005.

When you record this in your notebook, be sure to write 7.45 V. Not 7.450 V. Writing 7.450 suggests that the uncertainty is 0.0005.

Note that in this example we assumed that the meter reading is <u>steady</u>. If instead, the meter reading is fluctuating, then the situation is different. Now, you need to estimate the range over which the display is fluctuating, then estimate the average value. If the display is fluctuating between 5.4 and 5.8 V, you would record your reading as 5.6 ± 0.2 V. The uncertainty due to the noisy reading is much larger than your ability to read the last digit on the display, so you record the larger error.

**3. Combining uncertainties.**

Information on combining uncertainties is contained in Appendix B. As was done in Physics 251, KaleidaGraph can give you the uncertainty in the slope of a graph by choosing "Curve fit", then "General fit" and finally "fit1".

**Procedure**

- The units of all quantities must be specified, i.e. $\Omega$ = Ohms, V = Volts and A = Amps.
- $K = 10^3$   $m = 10^{-3}$
- Set the current control knob to its maximum setting at all times (full clockwise position).

1. Construct the circuit shown below and measure the resistance of the resistor. Compare your result with the value of the resistor given by its color code. The ammeter has an internal resistance of about 6 $\Omega$; therefore the resistance of your resistor should be at least 1000 $\Omega$. Record your measurements in Data table 1 in your Excel spreadsheet.
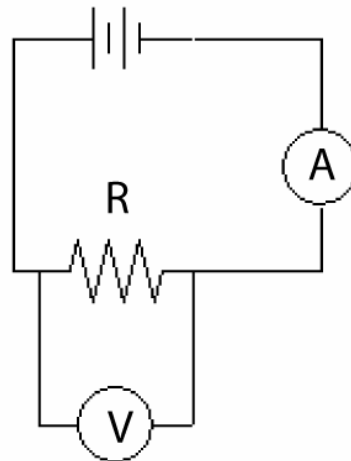


Use $\delta R = R\left(\dfrac{\delta V}{V} + \dfrac{\delta I}{I}\right)$ to calculate the uncertainty in the resistance found using Ohm's Law.

*Graphical test of Ohm's law for a constant resistor.* Use the same circuit as in step 1. Begin with a very small positive voltage and gradually increase the voltage. For several settings throughout the range, record both the voltage reading from the voltmeter and the current reading from the ammeter in the top half of Data Table 2. Decrease the supply voltage to its minimum value and change the polarity of the voltage. You do this by switching the wires connecting your circuit to the power supply. Again, gradually increase the supply voltage. For several of settings throughout the range, record voltage and current measurements in the bottom half of Data Table 2.  Using all of the data in Data Table, plot V (vertical axis) vs. I (horizontal axis). Have Kaleidagraph fit your data

with a best fit line, display the equation of the best fit line and the uncertainties in the slope and intercept (don't forget to briefly comment on your graph). Record the slope and its uncertainty in your spreadsheet.

2. *Two resistors connected in series.* Construct the circuit shown below. Use two different resistors having resistances of approximately 1 KΩ and 2 KΩ. Set the power supply voltage to the middle of its range and record your data in Data Table 3.
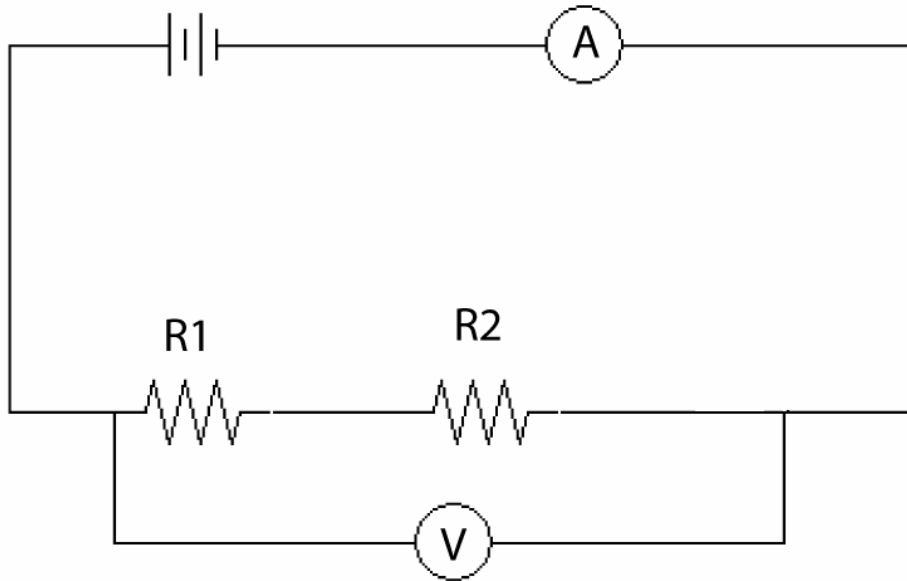
3. *Two resistors connected in parallel.* Construct the circuit shown below. Use two different resistors having resistances of approximately 1 KΩ and 2 KΩ. . Set the power supply voltage to the middle of its range and record your data in Data Table 4. For two resistors wired in parallel, the uncertainty of the equivalent resistance is given by:

$$\left|\delta R_P\right| = R_P^2 \left( \left|\frac{\delta R1}{R1^2}\right| + \left|\frac{\delta R2}{R2^2}\right| \right)$$
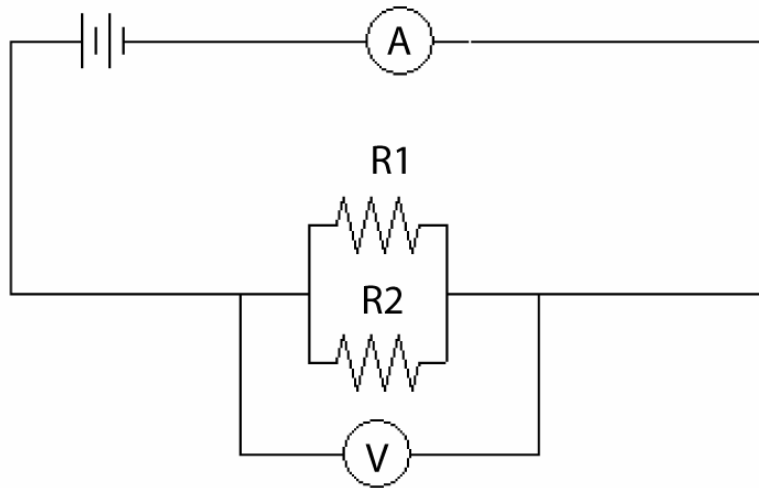


**QUESTIONS**
Part 1:

1. Discuss the consistency of the resistance found using the color codes and the measured resistance/calculated using Ohm's Law.
2. Does the resistance found from the slope agree with the resistance found using R = V/I?
3. Explain which method is better.

Part 2:

4. Discuss the consistency of your nominal and measured effective resistance.

Part 3:

5. Discuss the consistency of your nominal and measured effective resistance.

Additional questions:

6. Use your data from Data Table 1 to answer this question. What would happen if the ammeter (resistance = 6 Ω) was mistakenly connected in parallel with the resistor? Specifically, calculate the effective resistance of a parallel connection of the ammeter and the resistor. What current flows from the power supply if the circuit is connected in this fashion? **Never connect an ammeter in this way, it can damage the meter.**
7. Use your data from Data Table 1 to answer this question. What would happen if the voltmeter (resistance = 10 MΩ = $10^7$ Ω) was mistakenly connected in series with the resistor? Specifically, calculate the effective series resistance of the voltmeter and the resistor. What current flows from the power supply if the circuit is connected in this fashion?