Experiment 3

Ohm's Law

3.1 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.

3.2 Introduction

In the US, most of us use electricity every day. That electricity is handled in circuits: a closed loop of conductors travelling from power plants to neighborhoods to households and back again. That closed loop, with all of its many parts, forms one huge electrical circuit. Today we'll use the 3 essential parts of a circuit – power supply (or battery), wires, and resistors. We'll learn how resistors affect the current of electrons that flows through them, and how connecting resistors in different ways changes their behavior.

3.3   Key Concepts

As always, you can find a summary on-line at HyperPhysics[1]. Look for keywords: electricity and magnetism, ohm's law, resistor, resistor combinations

To play with constructing circuits and actually see how the electrons flow through a circuit, check out the online simulation "Circuit Construction Kit"[2] from the University of Colorado.

3.4   Theory

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:

$$V = IR. \tag{3.1}$$

Here, V is the voltage applied across the circuit in volts (V), I is the current flowing through the circuit in units of amperes (A), and R is the resistance of the circuit with units of ohms (Ω).

Eq. 3.1 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 the 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:

$$R = \frac{V}{I}, \tag{3.2}$$

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 given point during a set amount of time. The current flows because of the

---

[1]http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html
[2]http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc

Last updated July 1, 2014

electric 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, the electric 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 electric potential works in a similar way; if one point of the circuit has a high electric potential, it means that it has a net positive charge and another point of the circuit with a low potential will have a net negative charge. Electrons in a wire will flow from low electric potential with its net negative charge to high electric potential with its net positive charge because unlike charges attract and like charges repel.[3]

As these electrons flow through the wire, they are scattered by atoms in the wire. The resistance of the circuit is just that; it is a measure of how difficult it is for the electrons to flow in the presence of such scattering. 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 electric potential causes the current to flow and the resistance impedes that flow.

Two or more resistors can be connected in series, connected one after another (Fig. 3.1(a)), or in parallel, typically shown connected so that they are parallel to one another (Fig. 3.1(b)). If the current can split (i.e. there is more than one way for the current to flow) and then rejoin, they are in parallel.

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 Fig. 3.1(a) behaves as if it contained a single resistor with resistance R_S — that is, it draws current from a given applied voltage like such a resistor. When those same resistors are connected in parallel instead, we use a different formula for finding the equivalent resistance. See Table 3.1 for all the necessary equations.

---

[3]Note that we say the current flows from high poential to low potential, but electrons flow from low to high. This is because current is defined as the flow of *positive* charges, and electrons are *negatively* charged. A negative charge flowing in one direction is like a positive charge flowing in the other. Yes, it's confusing, but we can't make the whole world start calling electrons positively charged, so we're stuck with it.
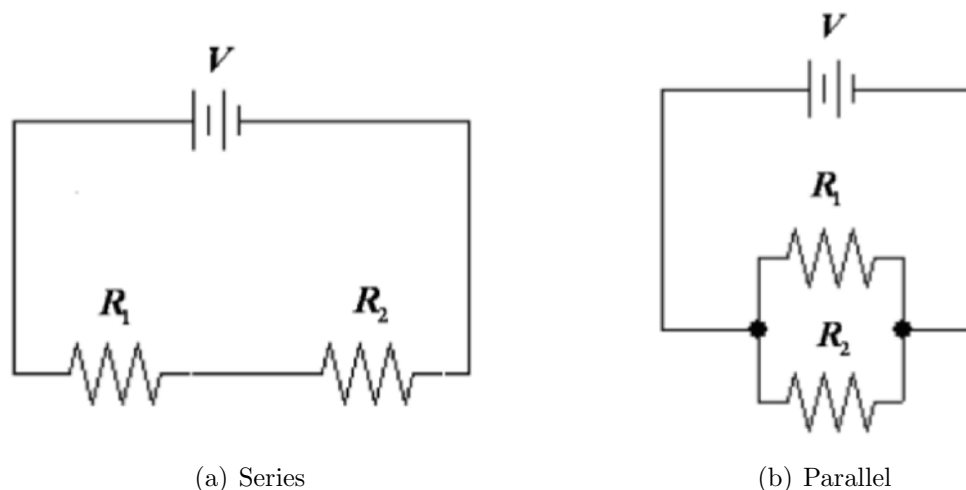
(a) Series   (b) Parallel

Figure 3.1: Schematics of circuits illustrating resistors connected in series and in parallel.

Series	Parallel
$V_S = V_1 + V_2$	$V_P = V_1 = V_2$
$I_S = I_1 = I_2$	$I_P = I_1 + I_2$
$R_S = R_1 + R_2$	$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$ or $R_P = \frac{R_1 R_2}{R_1 + R_2}$

Table 3.1: Equations for two resistors in series and parallel.

Using these 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.

3.5   In today's lab

Today we'll become accustomed to some standard electrical equipment: we'll figure out how to use the circuit boards, resistors, and wires to create series and parallel circuits. Then we'll learn how to measure the current through a wire, as well as the voltage between two points in a circuit. Finally, we'll verify that the equations that are presented in the theory section are actually correct.

3.6   Equipment

- DC Power Supply (Fig. 3.2)

- 2 digital multimeters (Fig. 3.3)

- breadboard (Fig. 3.6)

- several banana-to-banana wires

Safety Tips

- When plugging or unplugging wires, first **turn off all electronics that are connected** or will become connected to the circuit.

- 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.

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 Fig. 3.2. The black and red connectors are the negative (−) and positive (+) output terminals, respectively. The voltage knob controls the power supply's output voltage. The current knob sets a limiting current. **Here, 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.

The Digital Multimeter

The digital multimeter is shown in Fig. 3.3. 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). We will use these functions in this experiment.
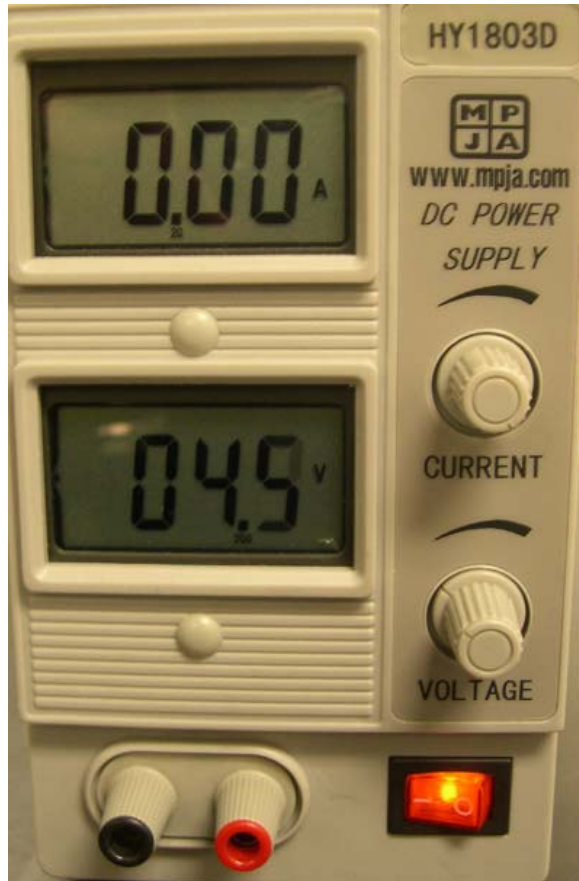
Figure 3.2: DC power supply

Figure 3.3: Digital multimeter

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, to indicate 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 "mV". When using the "mV" setting, the output of the multimeter will be in millivolts. Whether the multimeter is used to measure voltage (as a
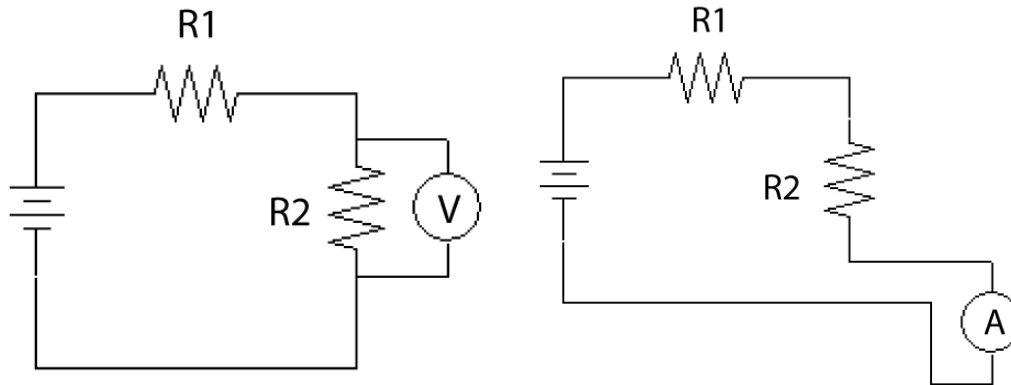
(a) Voltmeter connected in parallel   (b) Ammeter connected in series

Figure 3.4: Schematics of meters being connected in a circuit.

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 400mA plug.

A voltmeter must be connected in parallel (across) to the circuit element of interest, as shown in Fig. 3.4(a). 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 two cables to connect the plugs of the voltmeter to the circuit across the resistor (one cable before the resistor and a second cable after the resistor). A voltmeter typically has a very large internal resistance; therefore very little current will flow through it. Consequently, the current in the circuit will be approximately the same before and after the voltmeter is connected.

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 "400mA" plug. If you have a large amount of current (anything above 400 mA), you **must** connect the cable to the terminal marked "10A". If you put it in the "400mA" terminal you could damage the multimeter. If you are unsure if you have too much current for the 400 mA plug, start with the 10A plug. If you do not get any reading at
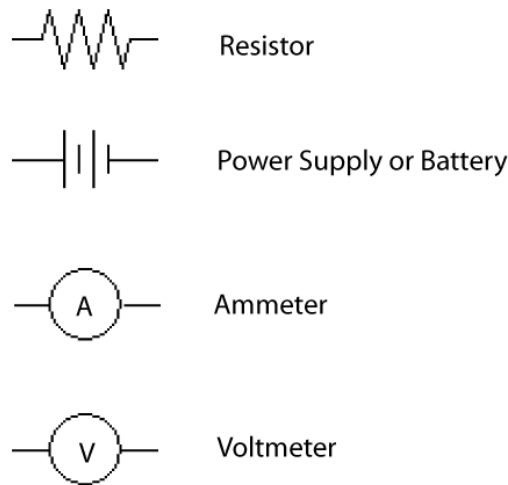
Figure 3.5: Standard symbols

all (i.e. 0.00), you have a very small current and can then move the cable to the 400 mA plug.

An ammeter must be connected in series with the circuit element of interest, as shown in Fig. 3.4(b). 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 Fig. 3.4(b) after it leaves the power supply, you will see that it must go through both the resistor **and** the ammeter. In contrast, tracing the path of a charge in Fig. 3.4(a) you will see that it has two "parallel" paths through which it can go (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 is connected.

Standard electronic symbols are shown in Fig. 3.5. The positive side of a battery or power supply is indicated with the longer vertical line.

The Breadboard

The breadboard is designed for quick construction of simple electronic circuits and is shown in Figure 3.6. Electronic elements (e.g. resistors) are
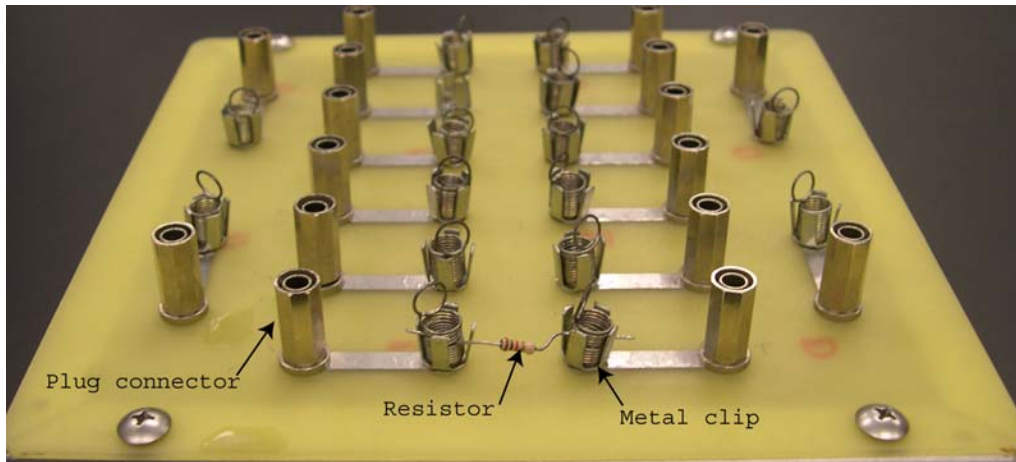
Figure 3.6: Breadboard

easily attached using the metal spring clips in the middle of the bread-board. 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 that these two points are at the same electrical potential (voltage) and the same point in a circuit. 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.

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.[4] **All points on a wire/line have the same voltage.** Because of this, a circuit may be realized by several different arrangements of wire. For example, see Fig. 3.7.

---

[4]A wire is actually a resistor with very low resistance compared to the resistors we typically use in class. Therefore, we can usually neglect (ignore) any resistance that it has. On the other hand, this resistance is a big factor in long-distance electrical transmission lines, since there is so much wire involved.
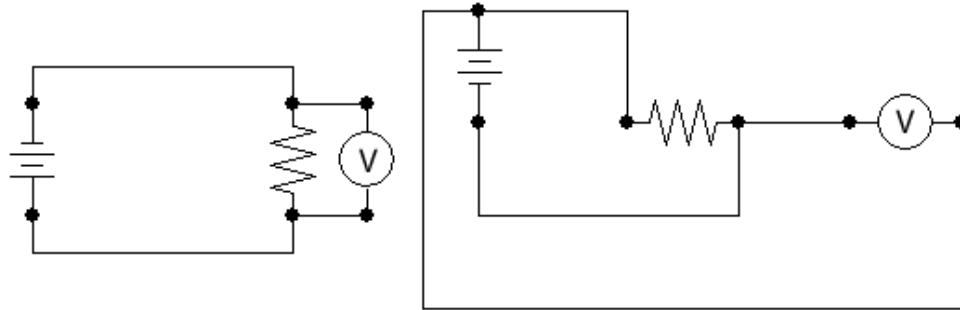
Figure 3.7: These two circuits are equivalent — they have the same configuration of elements and will act in exactly the same manner.

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 (e.g. ammeters, voltmeters) to the circuit increases the circuit's complexity. The following steps will guide you through the construction of a simple circuit that includes an ammeter and a voltmeter. To avoid confusion, all of the wires used in the following example have different colors. The figures 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. Figs. 3.8(a) (schematically) and 3.8(b) (in practice) 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.
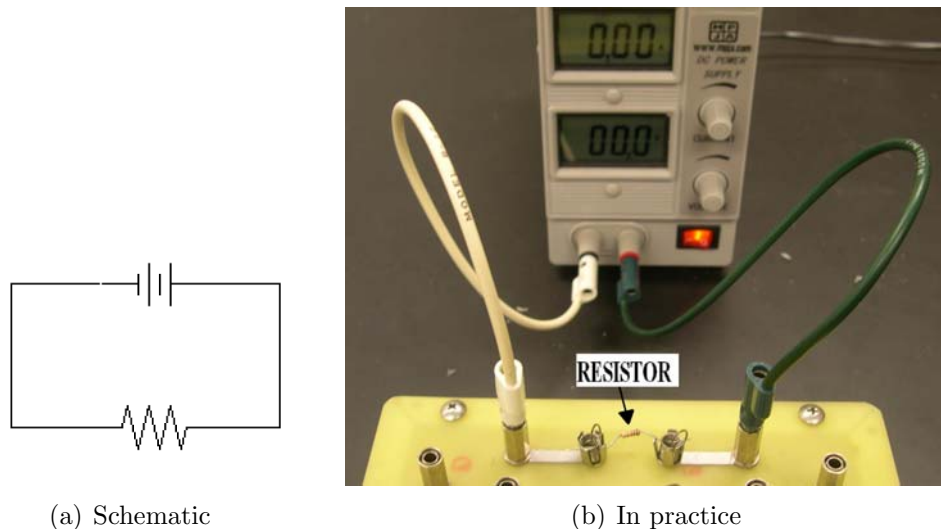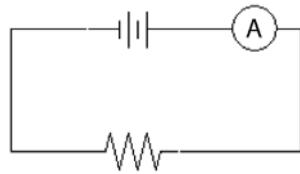
(a) Schematic   (b) In practice

Figure 3.8: Building a circuit that includes a power supply and resistor.

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 the wire (or wires) leading into one end of that element and plug all of them into either the 400mA or 10A input of your ammeter, depending on 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 400mA 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 Fig. 3.8(b). 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. Figs. 3.9(a) (schematically) and 3.9(b) (in practice) show our simple circuit with a power supply, a single resistor, and an ammeter. Turn the dial to read mA or A. **By default, it is set to read AC current.** We have DC current, so press the yellow button to change the mode to DC. You'll have to do this again if the multimeter turns off automatically. Note that the ammeter should
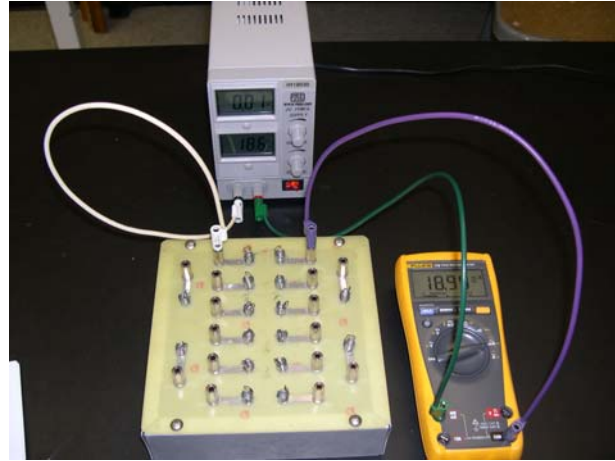
(a) Schematic (b) In practice

Figure 3.9: Building a circuit that includes a power supply, ammeter, and resistor.

display "DC" just to the right of the numbers and an "A" for Amps (the unit for current).

3. **Include a voltmeter in the circuit to measure voltage.** 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 circuit element 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, as seen in Fig. 3.10. **Never connect an ammeter in this fashion as it can damager the meter**.

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
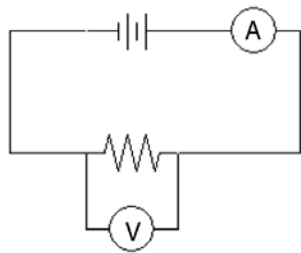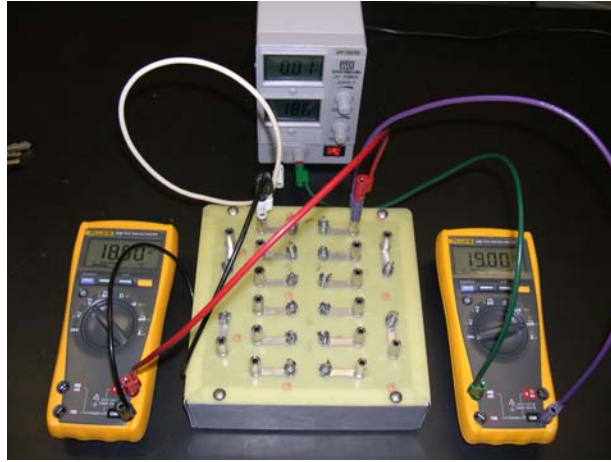
(a) Schematic   (b) In practice

Figure 3.10: Building a circuit that includes a power supply, voltmeter, resistor, and ammeter.

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 fourth band is absent, it means the tolerance is 20%. Table 3.2 is a color code chart, from which one can tell the resistance of a resistor.

Example

Suppose the color code on a resistor is yellow, violet, orange and gold like the resistor depicted in Fig. 3.11. 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. From 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).

Table 3.2: Resistor color codes

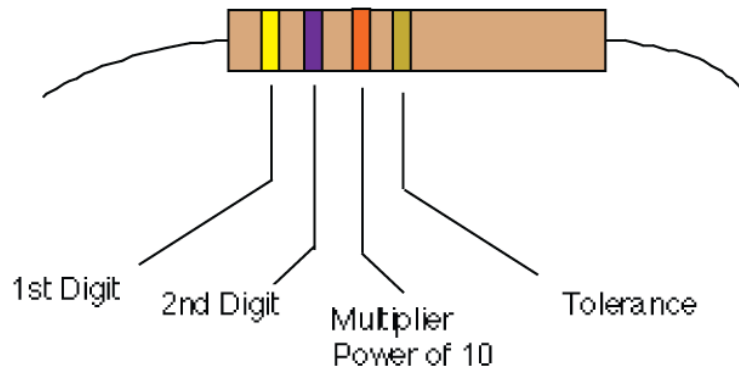| Color	1st digit	2nd digit	Power of 10	Tolerance
black	0	0	0	-
brown	1	1	1	-
red	2	2	2	-
orange	3	3	3	-
yellow	4	4	4	-
green	5	5	5	-
blue	6	6	6	-
violet	7	7	7	-
gray	8	8	8	-
white	9	9	9	-
gold	-	-	-	5%
silver	-	-	-	10%
none	-	-	-	20%

Figure 3.11: Example resistor.

So, the resistance is

$$(\text{first digit})(\text{second digit}) \times 10^{\text{multiplier}} \; \Omega$$

$$\begin{array}{ccc} 4 & 7 & \times\,10^{\;3} \quad \Omega \end{array} \qquad (3.3)$$

$$47 \times 10^3 \; \Omega$$

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

$$\delta R = R \times \text{tolerance} = 47\,000 \; \Omega \times \frac{5}{100} = 2\,350 \; \Omega \qquad (3.4)$$

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

Different classes of errors

Manufacturer's tolerance

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

$$R = R_{\text{nominal}} \pm \delta R = 100 \pm 5 \; \Omega \qquad (3.5)$$

This means that the company certifies the true resistance R lies between 95 and 105 Ω, or put another way, $95 \leq R \leq 105 \; \Omega$. 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.

Reading a digital meter

Suppose you measure the voltage across a resistor using a digital multimeter. The display says 7.45 V and doesn't change as you 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 half of that is 0.005 V. 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 of the voltage is between 7.445 and 7.454 V, the voltmeter rounds it to 7.45 V. Thus the average value and its uncertainty can be written as 7.45 ± 0.005 V. When you record this, be sure to write 7.45 V, not 7.450 V. Writing 7.450 V implies that the uncertainty is 0.0005 V.

Note that in the previous example we assumed that the meter reading was steady. If instead, the meter reading is fluctuating, then the situation is different. For this case, you need to estimate the range over which the display is fluctuating and then estimate the average value. For example, 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.

Combining uncertainties

Information on combining uncertainties is contained in Appendix A. 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".

Note!

You will be asked about the consistency of results, or to compare values. Whenever this is asked, it is meant to be a quantitative answer. See Appendix A for the instructions on determining consistency.

3.7   Procedure

- The units of all quantities must be specified, i.e. Ω = Ohms, V = Volts and A = Amps.

- For unit abbreviations, the prefix "k" means "kilo" = 10^3 and "m" means "milli"= 10^{-3}

- Set the **current** control knob to its maximum setting at all times (full clockwise position).

Circuit with one resistor

1. **Construct the circuit shown in Fig. 3.12.** Refer to the Suggestions section above. Choose a resistor that has a resistance of at least 1000 Ω, so that we can neglect the ~ 6 Ω internal resistance of the ammeter. Choose a voltage setting on the power supply, and read off the voltage and current from the meters. Then use Ohm's Law (Eq. 3.1) to experimentally[5] determine the resistance. Record your measurements in Data Table 1 in your Excel spreadsheet. Refer to Eq. A.2 (included at the end of this write-up) to calculate the uncertainty in your experimentally determined resistance. Compare your measured value (Ohm's Law value) with the nominal value given by the color code (see Question 1).

---

[5]Here "experimentally" means that we are performing an experiment to measure the resistance, not that the method is "experimental" and thus not well-tested yet.
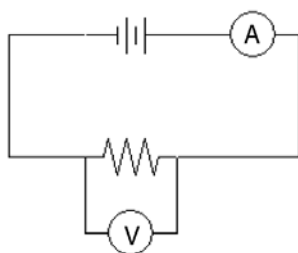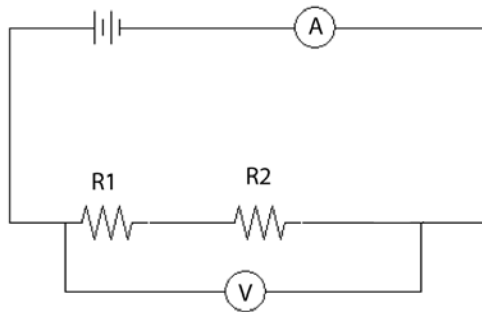

Figure 3.12: Schematic for Step 1

Figure 3.13: Schematic for 2 resistors connected in series.

2. **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 five 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 (make the electricity flow in the opposite direction through the circuit). You do this by switching the wires connecting your circuit to the power supply. Again, gradually increase the supply voltage. For five 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 2, 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. Compare this to your value for the resistance determined by Ohm's Law (see Question 2).

Two resistors connected in series

3. **Construct the circuit shown in Fig. 3.13.** 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 measured voltage and current in Data Table 3.
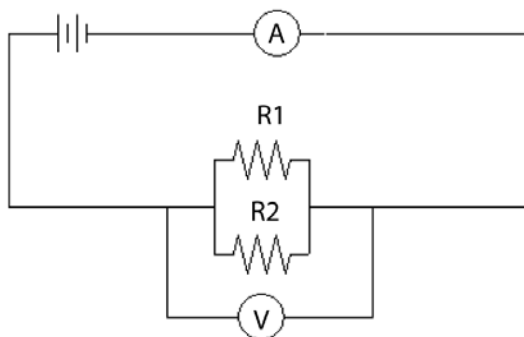
Last updated July 1, 2014

Figure 3.14: Schematic for 2 resistors connected in parallel.

Two resistors connected in parallel

4. **Construct the circuit shown in Fig. 3.14.** 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 measured voltage and current in Data Table 4. For two resistors wired in parallel, the uncertainty of the equivalent resistance is given by Eq. 3.6.

$$|\delta R_{\mathrm{P}}| = R_{\mathrm{P}}^2 \left(\left| \frac{\delta R_1}{R_1^2} \right| + \left| \frac{\delta R_2}{R_2^2} \right| \right) \tag{3.6}$$

5. **Make sure to answer questions 1-7.**

3.8 Questions

1. Discuss the consistency of the resistance found using the color codes and the measured resistance that was found using Ohm's Law.

2.   a) Does the resistance found from the slope agree with the resistance found using a single application of Ohm's Law (Eq. 3.1)?

   b) Explain which method is better.

3. Discuss the consistency of your nominal and measured effective resistance for two resistors connected in series.

4. Discuss the consistency of your nominal and measured effective resistance for two resistors connected in parallel.

5. Use your data from Data Table 1 to answer this question. What would happen if the ammeter (resistance $= 6\ \Omega$) 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.**

6. Use your data from Data Table 1 to answer this question. What would happen if the voltmeter (resistance $= 10$ M$\Omega = 10^7$ 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?