Ohm's law

I. OBJECTIVES

- Become familiar with the use of a digital voltmeter and a digital ammeter to measure DC voltage and current.
- Construct a series circuit using resistors, wires, and a breadboard.
- Test the validity of Ohm's law.

II. BACKGROUND

In the U.S., 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 will use the three essential parts of a circuit: power supply (or battery), wires, and resistors. We will learn how resistors affect the current of electrons that flows through them, and how connecting resistors in different ways changes their behavior.

A. Key concepts

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 is viewed as a constant independent of the voltage and the current. More explicitely,

$$V = iR\,, \qquad (1)$$

where 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). (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:

$$R = \frac{V}{i}\,, \qquad (2)$$

where R is a constant, independent of V and i.

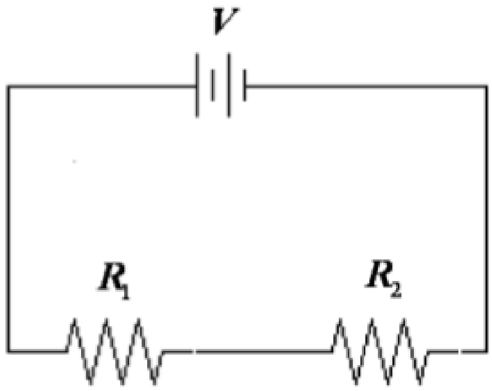

FIG. 1: Schematics of circuits illustrating resistors connected in series.

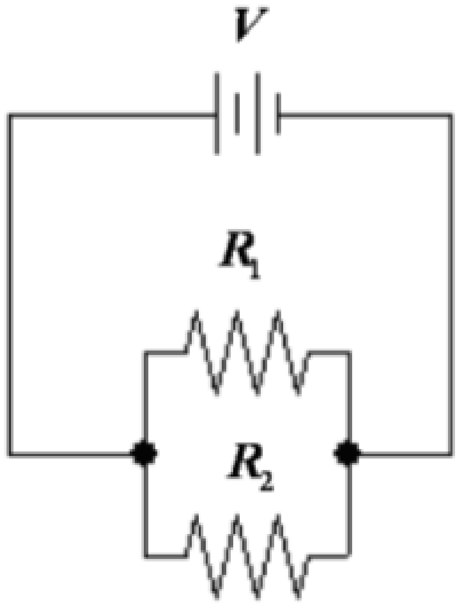

FIG. 2: Schematics of circuits illustrating resistors connected in parallel.

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 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.[1]

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 resistors 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 (that is connected one after another as shown in Fig. 1), or in parallel (that is the current can split: there is more than one way for the current to flow as shown in Fig. 2). When two resistors R_1 and R_2 are connected in series, the equivalent resistance $R_{\rm eq}$ is given by

$$R_{\rm eq} = R_1 + R_2 \,. \qquad (3)$$

Hence, the circuit behaves as if it contained a single resistor with resistance $R_{\rm eq}$ and it draws current from a given applied voltage like such a resistor. When those same resistors are connected in parallel instead, the equivalent resistance is related to R_1 and R_2 according to

$$\frac{1}{R_{\rm eq}} = \frac{1}{R_1} + \frac{1}{R_2} \,. \qquad (4)$$

B. Standard electronic symbols and resistor color codes

Standard electronic symbols are shown in Fig. 3. The positive side of a battery or power supply is indicated with the longer vertical line.

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 1 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%. In Fig. 4 we show an example together with a color code chart, from which one can tell the resistance of a resistor.

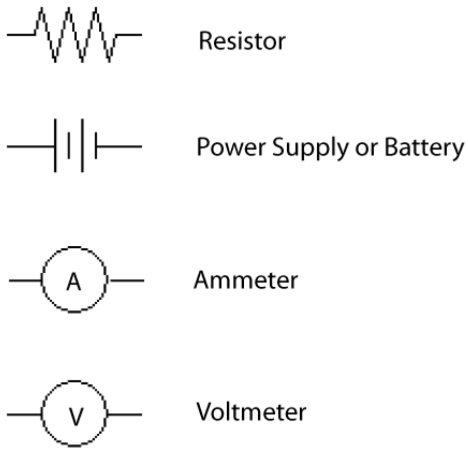

FIG. 3: Standard symbols.

C. 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. 5. 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.

D. The digital multimeter

The digital multimeter is shown in Fig. 5. As its name suggests, a multimeter has multiple functions. It can be used for several different purposes: *(i)* a voltage measuring device (a voltmeter), *(ii)* a current measuring device (an ammeter), and *(iii)* a resistance measuring device (an ohmmeter). We will use all these functions 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

[1] 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 is confusing, but we cannot make the whole world start calling electrons positively charged, so we are stuck with it.

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%

FIG. 4: The upper panel shows the resistor color codes. The first digit of the resistance in the lower panel is a 4, the second digit is a 7 and the multiplier is a 3, so the resistance is $R = 47 \times 10^3\ \Omega$. 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 is given by: uncertainty = $R\times$ tolerance = $4.7\times10^4\Omega\times5/100 = 2.35\times10^3\Omega$.

FIG. 5: The DC power supply (left) and the digital multimeter (right).

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, we will only use the DC setting. 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 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 10 A plug or the 400 mA plug.

A voltmeter must be connected in parallel (across) to the circuit element of interest, as shown in Fig. 6. 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 10 A plug or the 400 mA plug. If you have a large amount of current (anything above 400 mA), you must connect the cable to the terminal marked 10 A. If you put it in the 400 mA terminal you could damage the multimeter. If you are unsure if you have too much current for the 400 mA plug, start with the 10 A plug. If you do not get any reading at all (that is 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. 6. 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. 6 (right) 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. 6 (left) 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.

An ohmmeter does not function with a circuit connected to a power supply. If you want to measure the resistance of a particular component, you must take it out of the circuit altogether and test it separately.

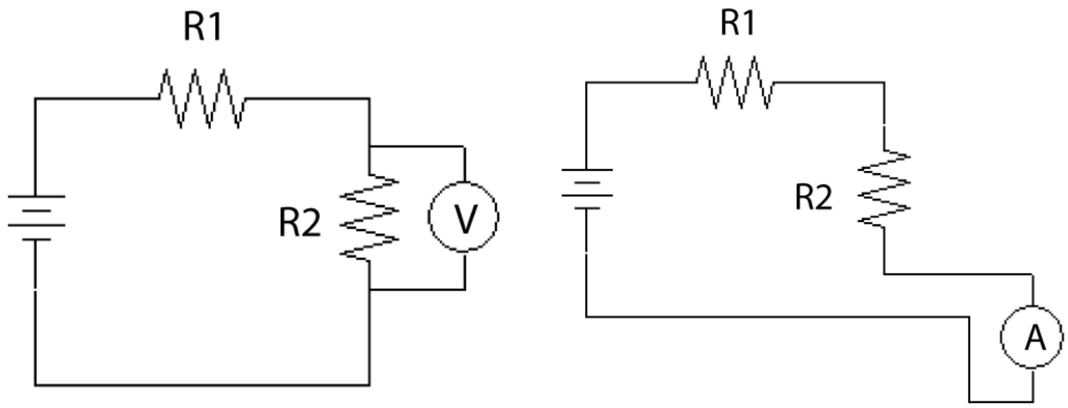

FIG. 6: Schematics of meters being connected in a circuit. Voltmeter connected in parallel (left) and ammeter conected in series (right).

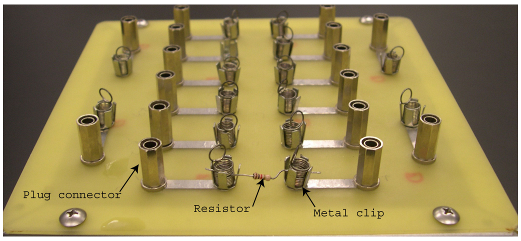

FIG. 7: The breadboard.

E. The breadboard

The breadboard is designed for quick construction of simple electronic circuits and is shown in Fig. 7. Electronic elements (e.g. resistors) are easily attached using the metal spring 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 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.

F. 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.[2] 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. 8.

G. 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 circuits 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. In Fig. 9 we 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.

[2] 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.

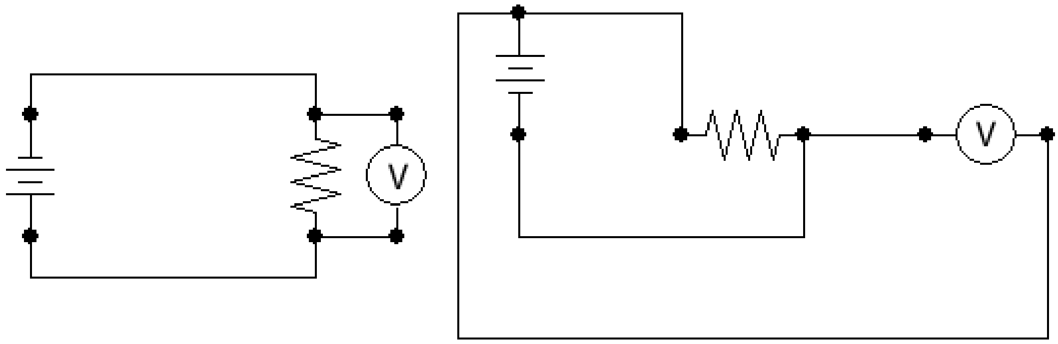

FIG. 8: These two circuits are equivalent. They have the same configuration of elements and will act in exactly the same manner.

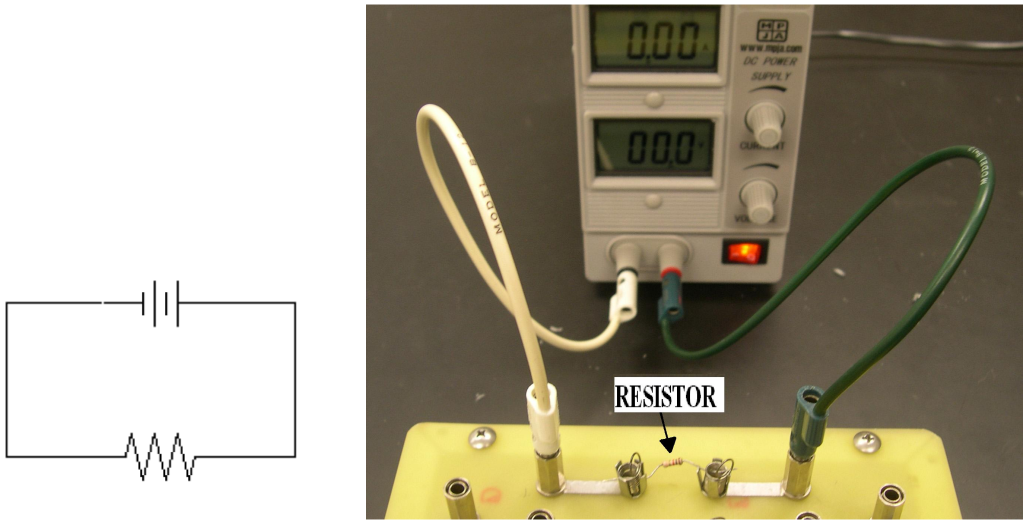

FIG. 9: Building a circuit that includes a power supply and resistor; schematic (left) and in practice (right).

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 400 mA or 10 A 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 400 mA 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), that is the place where the green wire was connected in Fig. 9. 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. In Fig. 10 we 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 will have to do this again if the multimeter turns off automatically. Note that the ammeter should display "DC" just to the right of the numbers and an "A" for ampers (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 V 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. 11. Never connect an ammeter in this fashion as it can damager the

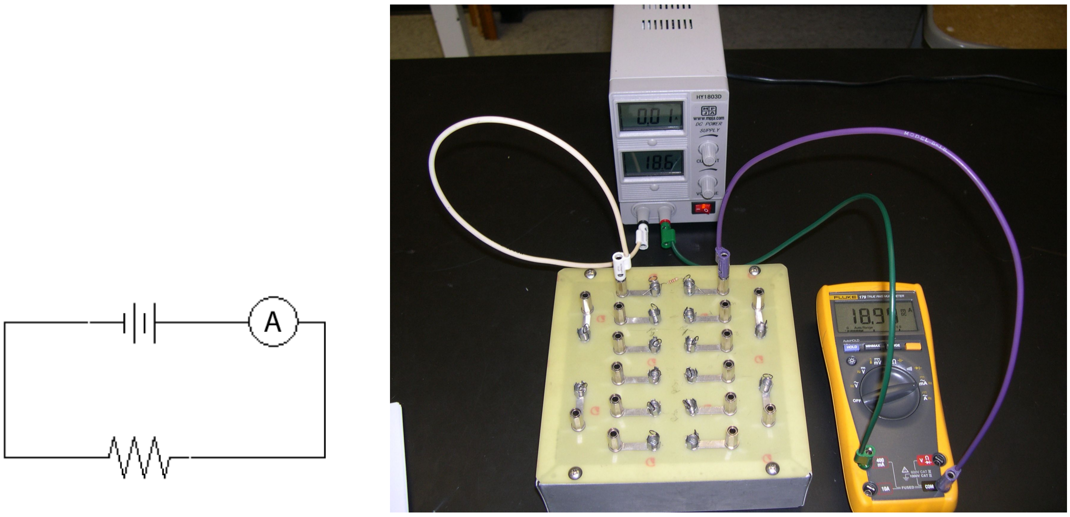

FIG. 10: Building a circuit that includes a power supply, ammeter, and resistor; schematic (left) and in practice (right).

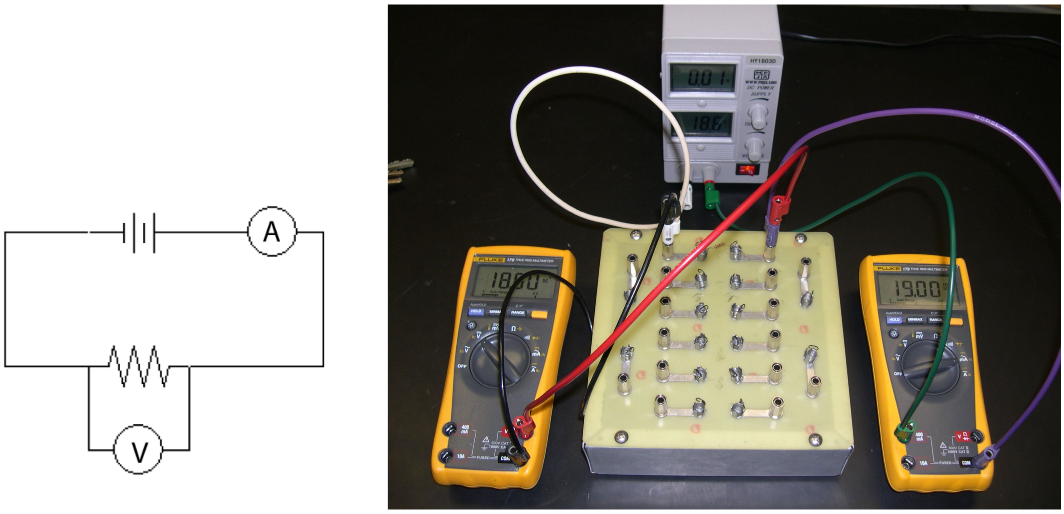

FIG. 11: Building a circuit that includes a power supply, voltmeter, resistor, and ammeter; schematic (left) and in practice (right).

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.

H. Safety tips

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

III. MATERIALS

- DC power supply; see Fig. 5.
- Two digital multimeters; see Fig. 5.
- Breadboard; see Fig. 7.
- Several banana-tobanana wires.

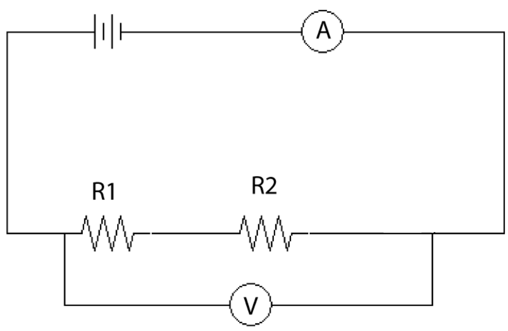

FIG. 12: Schematic for two resistors connected in series.

TABLE I: Measured voltage, current, and resistance.

Voltage (V)	Current (A)	$R = V/i$ (Ω)
0.20		
0.78		
1.36		
1.94		
2.52		
3.10		
3.68		
4.26		
4.84		
5.42		
6.00		

IV. ASSEMBLY AND OPERATION

1. Wire up the circuit shown in Fig. 11. Have your instructor check the connections before you plug in the power supply. If it is ok, turn it on, and vary the voltage by turning the "DC offset" knob. Note the changes in the voltmeter and ammeter readings. Vary the voltage in ten steps, from a low of about 0.2 V to the maximum possible (about 6 V). Record the voltage and current in Table I, and compute the resistance R from the ratio. Determine the average value of the resistance.

2. Disconnect the circuit. Use the ohmmeter function of the multimeter to make a direct reding of the resistance used in part 1, $R_1 =$_____ Ω. Compare this with the resistance measured in part 1. Compare the results with the value from the color code in the resistor and verify your results are within errors. Choose another resistor on the board and measure its resistance, $R_2 =$_____ Ω.

3. Consider the series circuit shown in Fig. 1. Use Ohm's law in the form $i = V/R$ to predict the current in this circuit, if the power supply is set to 5 V. (Remember, resistors in series add.)

4. Wire up the circuit shown in Fig. 12 and have your instructor check the connections. Adjust the power supply so that the voltmeter reads 5 V. How does the current compare with what you predicted in part 3?

5. Remove the voltmeter connections. Connect the voltmeter across R_1 and record the reading, $V_1 =$_____ V. Now, connect the voltmeter across R_2 and record the reading, $V_2 =$_____ V. What is the relation between V_1, V_2, and the power supply voltage of 5 V? Use Ohm's law in the form $V = iR$ to explain this result.