Measuring Electric Phenomena: the Ammeter and Voltmeter

1 Objectives

1. To understand the use and operation of the Ammeter and Voltmeter in a simple direct current circuit, and
2. To verify Ohm's Law for the resistor.

2 Introduction

The German physicist, Georg Ohm, was the first to explore the relationship between the current *through* an object compared to the voltage applied *across* that object. He published his results, *Die galvanische Kette, mathematisch bearbeitet*[1], in 1827. His results were not immediately accepted, because his methods were so revolutionary, and challenged the accepted requirements of scientific reasoning of his day; science is a human endeavor, and this result has a fascinating backstory that I urge you to investigate.

To investigate the properties of voltage and current, and the relationship between the two, we need tools and equipment to do it. We measure voltage with the *voltmeter*, and current with the ampmeter or *ammeter*. In a later lab, you will study the detailed properties of ideal meters, and contrast them with the real meters that we can actually build. In this lab, however, you will learn the proper use of these devices while investigating Ohm's Law.

3 Theory

Ohm showed that a *steady* current was caused by a *constant* voltage, and that were directly proportional to each other, and scaled with the length of the *resistive* element through which the current flowed. Today, we express this relationship mathematically as $V/I \propto 1$, where V is the voltage (measured in the SI system in *volts*, V) and I is the current (measured in *amperes*, A). We give the *constant of proportionality* the name *resistance*, and the symbol R

$$\frac{V}{I} = R \; ,$$

[1] The galvanic circuit investigated mathematically

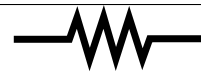
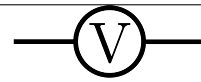
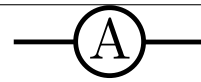
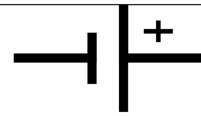
Resistor	
Voltmeter	
Ammeter	
DC Voltage source	

Table 1: The various schematic elements used in this lab.

Resistance is measured in *ohms*, with the symbol Ω.

In this lab, the resistance R will be constant for a given object. Later, we will investigate the limits of this relationship: under what conditions does it hold true, when does it fail, and how can we understand these properties as the results of microscopic physics.

Let's now introduce the voltmeter and the ammeter. A voltmeter is designed to measure the voltage *across* a portion of a circuit, while an ammeter is designed to measure the current *passing through* a particular point in the circuit. That is, the voltmeter stays *outside* the circuit, while the ammeter must be inserted *into* the circuit. While these devices have distinct properties and uses, the ammeter and voltmeter are such a basic part of the scientific measurement toolkit, that the are usually found integrated into a single device called the *multimeter*. There are many kinds of multimeters: desktop or handheld, analog or digital, manual or autoranging, low and high voltage, etc. Beware, however! Switching a multimeter from ammeter to voltmeter mode usually requires the inputs to be rewired; failing to do so can result in blown fuse, or damaging the device. And finally, for safety reasons, never use a multimeter for measurements in high voltage circuits, unless you have been specifically trained for that task! We won't be exposing you to such risks in this course.

In order to talk in more detail about these devices, we need a language describe the connections between them in a particular *electrical circuit* - the circuit diagram, or schematic. Schematics are a kind of descriptive map: they make explicit the wired connections between electrical devices in a circuit. They are, however, not a photograph. The connections between devices in a diagram do not indicate literal wires, but only the required relationships (ie "topological connections") between the devices; for practical reasons, there may be multiple ways to connect the devices, requiring more or fewer actual wire than shown in the diagram. There may also be multiple physical realizations, or *layouts*, of a given schematic, and there may be multiple equivalent schematics for a given layout.

The language of circuit schematics is highly evolved, and there are de facto standard representations of typical devices. Table 1 contains the common symbols used in this lab.

When learning to build or "wire" a circuit from a schematic, it is usually best to arrange your physical devices (resistors, power supplies, meters, etc.) in the same orientation as the devices on the schematic. Then, follow the "map" given by the schematic: pick one terminal on the first device, and locate all the terminals on other devices that are connected to that terminal all the schematic. Using one or more wires, reproduce those schematic connections

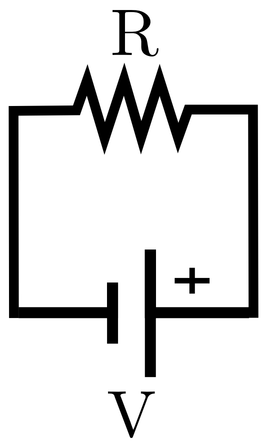


Figure 1: The simplest direct current circuit.

Figure 2: The direct current power supply.

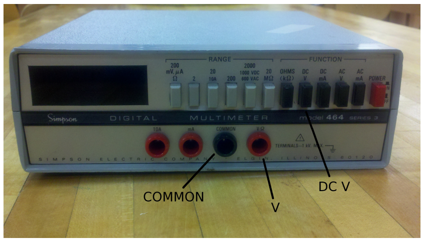
in the physical world. Repeat until you have "visited" all terminals on the schematic. Note that not all terminals may be labeled identically on the schematic and on the physical devices: they may be labeled same, differently, or perhaps not labeled at all! You will need to use your judgment, ask questions of your instructor, or simply try an experiment to figure things out on your own.

4 Procedures

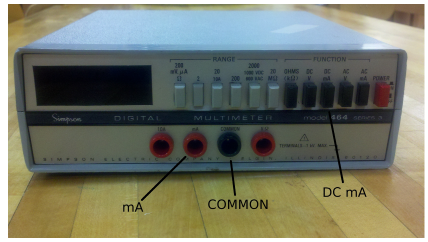
In this lab, we will investigate the relationship between current and voltage in the simplest possible circuit, consisting of a direct current voltage source and a single resistance (Figure 1). You should receive a power supply, two digital multimeters, and two decade resistance boxes. The wires you need are located on a rack in the back of the lab.

1. First, construct the circuit shown in Figure 1. For the resistor, use one of the two decade resistor boxes; set this to something between 100 Ω and 300 Ω. Turn the `Voltage` knob on the power supply (Figure 2) to its minimum setting (fully counter clockwise), and the`Current` limiter knob to its maximum setting (fully clockwise). Plug in and turn on the power supply.

FiXme: *Is this a good range of values?*



(a) Settings for voltmeter mode



(b) Settings for ammeter mode

Figure 3: The multimeter.

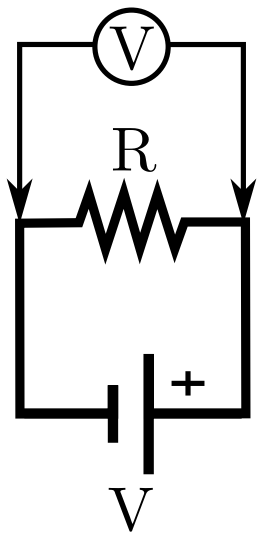


Figure 4: The simplest direct current circuit, with voltmeter installed.

2. Next, configure your first multimeter as a voltmeter: connect your test leads to the `COMMON` and `V` inputs, and select the `DCV` (Direct Current Voltage) Function; see Figure 3a. Plug in and turn on the multimeter.

3. We'll now get a feel for how the meter works. First, connect the test leads to opposite ends of the resistor - that is, *across*) the resistor (Figure 4). To make a measurement, you must select the correct `RANGE`; the meter will measure values from 0 V up to the value specified above the `RANGE` button: 2 V for the 2 button, 20 V for the 20 button, etc. For maximum precision, always choose the smallest `RANGE` value larger than the voltage you are measuring. When in doubt, start at the largest setting, and work you way down. What happens when you go to far?

   Now, raise the voltage on the power supply; If you have connected the circuit and meter correctly, you should see the voltage display on the power supply increase from zero, and the value on the multimeter should roughly match that on the supply. If not, you did something wrong and should "debug" your connections to make sure they are correct. What happens when you swap the leads connected to the resistor? Why?

   Turn the voltage down to zero before proceeding; unless our instructions say otherwise, you should always do this before changing the configuration of a circuit.

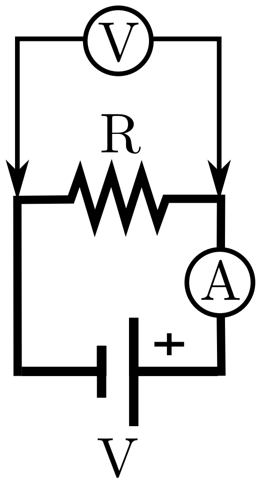


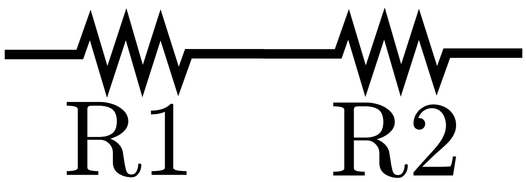
Figure 5: The direct current circuit with ammeter inserted.

4. Next, configure the second multimeter as an ammeter: connect your test leads to the `COMMON` and `mA` inputs, and select the `DCmA` (Direct Current milliAmps) Function; see Figure 3b. Again, you must choose an appropriate `RANGE`. You measure current *through* a device, which means you must insert the meter *into* the circuit: you must "cut" the circuit, and "splice" the meter into the "hole". In this case, you should insert the meter between the output of the power supply and the resistor. Make sure the voltmeter is still connected across the resistor. At this point, you should have recreated the circuit in Figure 5. Again, slowly raise the voltage output, and observe the changes in the voltage and current values as measured on the respective meters.

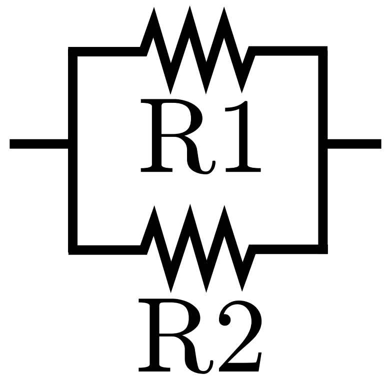
5. We are ready to repeat Ohm's measurements! Vary the voltage in small steps (say, ten steps from 0 V to 10 V), and record both the voltage and the corresponding current. Don't forget the units! Quickly plot your data, I vs V: if Ohm was right, this should be linear. Is it? What is the slope? How is this related to R? You will do this again more carefully in your Post-Lab exercises, but it's always a good idea to make "quick and dirty" plots while taking data to help get a feel for what the data may be telling you. Repeat the measurements; are your results consistent? Select a different resistance value, and repeat your measurements.

6. Next, we will use the multimeter in `Resistance` mode to confirm our results. In this mode, the multimeter performs the same experiment we just did in large: it applies a known voltage, measures the demand current, and deduces the resistance from these two values. Completely disconnect the circuit. Connect test leads to the `COMMON` and Ω inputs, select the `OHMS` Function, and an appropriate value for the `RANGE`. Connect the leads to opposite sides of the resistor, and record the value. Does the value you measured with the above procedure agree with the value the meter measures directly?

7. Imagine now that you are the power supply. When you look out from your terminals, all you see is one wire heading out to the left, and one wire heading out to the right; you can't actually tell what's connected to the wires! All you can do is measure the



(a) The series combination.



(b) The parallel combination.

Figure 6: Series and parallel resistance combinations.

resistance of the circuit that you are "driving".[2] In other words, to a DC power supply, the whole collection of devices connected to the terminals looks like a single resistor; you must be able to predict the effective resistance that a collection of devices in a circuit presents to the power supply. In particular, realize that an ammeter or voltmeter look *just like any other resistor* to the power supply! It should be obvious that we want to design these meters so that they have a minimal impact on the circuit: you don't want to change the behavior of the circuit when you connect the meter! This implies different requirements on an ammeter and a voltmeter. Let's explore what happens when you connect multiple resistors in circuit in two different ways. We'll study this in much more detail in a later lab; here, we'll explore the implications for the design of the meters.

(a) Configure one of your multimeters to measure resistance. Set *both* of you decade resistance boxes to the same value; measure and record both values. Are they identical? Why or why not?

(b) Next, wire the circuit shown in Figure 6a. This is known as the *series* combination of circuit elements: the tail of the first element is connected to the head of the second element. Measure the resistance of this combination. How does it compare to the individual resistances? Double one of the resistances, and perform the measurement again. How does it compare?

(c) Reset both resistors to the same value, and wire the circuit shown in Figure 6b. This is the *parallel* combination: the heads and tails of the resistors are tied together. Measure the resistance. How does it compare to the individual resistances? Double one of the resistances, and measure again. How does it compare this time?

(d) You always connect a voltmeter *in parallel* with the element you are measuring across, and you connect an ammeter *in series* with the element you are measuring

[2] We'll have a lot more to say about this point of view later in the semester, when we talk about not only resistors, but capacitors, inductors, diodes, etc.

the current through. Ideally, what would the resistance of the ammeter be so as not to change the behavior of the circuit? The voltmeter? Why?

Make sure you clean up your work space, and return every item to the condition and location you originally found them in!

Pre-Lab Questions

On a separate sheet of letter-sized paper, please answer the following questions in a neat and organized manner.

1. What do you use a voltmeter for?
2. How about an ammeter?
3. If you double the resistance in a circuit while keeping the current unchanged, what happens to the voltage? What if, instead, you keep the voltage unchanged?
4. Sketch the relationship between voltage and current implied by Ohm's Law.
5. You are told that a certain voltage will be between $3\,\mathrm{V}$ and $5\,\mathrm{V}$, and are given a non-autoranging voltmeter. If the range selectors are labeled $200\,\mathrm{mV}$, $2\,\mathrm{V}$, and $20\,\mathrm{V}$, which range do you select and why?

Post-Lab Questions

1. Prepare a neatly organized tabulation of your recorded data. Make sure to label your data, and include units where appropriate.

2. Plot all of your data sets on a single graph, preferably by computer. Ff Ohm was right, this should be linear. Is it? Does your data support or refute Ohm's Law? Why or why not? How do you determine the value of the resistance from your plot? Does it agree with the values you measured directly with the multimeter? Why or why not?

3. In Step 7a of the procedure, you separately measure the values of two "identical" resistors. Were they identical? Why or why not?

4. When you combine resistors in series and parallel (as you did in Steps 7b and 7c of the procedure), the resistance of the combination can be predicted if you know the individual resistances. Can you make an educated guess as to the correct formulae for these combinations?

5. Ideally, what would the resistance of the ammeter be so as not to change the behavior of the circuit? The voltmeter? Why?

6. Imagine you have a circuit consisting or two resistors and one power supply. How many different ways are there to connect these elements into a circuit? Draw schematics for all the possible inequivalent circuits. Make sure to label the components. For one of these circuits, draw a new diagram showing how you would connect a multimeter to measure the voltage across the power supply, and another to show how you would measure the voltage across one of the resistors.

7. Discuss briefly whether you have met the objectives of the lab exercises.