ECE 110L Spring 2023

Laboratory 2:

Basic Electrical Measurements and Analog to Digital

Contents

Reminder on Prompts

Throughout this and future lab documents, there will be four different prompts to let you know specific work that needs to be done either for the pre-laboratory assignment, the in-laboratory assignment, or the post-laboratory assignment. The four prompts are as follows, with N representing a number to help make sure you see all the prompts:

- **Pre-lab Deliverable (N):** Work to be documented in the pre-laboratory assignment.
- **Checkpoint (N):** Work to be shown to a TA during the laboratory.
- **Discussion (N):** Questions to be discussed with your lab partner and then answered in the post-laboratory assignment if specified.
- **Deliverable (N):** Other items to be completed individually and then included in the post-laboratory assignment.

1 Abstract

In this laboratory exercise you will learn how to use a DC power supply as a voltage source and a digital multimeter to measure voltage, current, and resistance. You will build several resistive circuits and compare measured voltages and currents to their theoretical values. Throughout the semester, you will use the digital equipment to make measurements. You will be required to interpret these measurements, and your understanding of how the equipment works is critical to the interpretation process as well as your ability to debug problems with circuit construction.

2 Objectives

After performing this laboratory exercise, students should be able to:

1. Describe and use a potentiometer as a variable resistor in a circuit.
2. Simulate resistive circuits and take measurements in the simulation.
3. Build a resistive circuit on a solderless breadboard from a schematic.
4. Use a DC power supply as a voltage source.
5. Measure resistance, voltage, and current using a digital multimeter.

3 Background

As a part of this course, you will be learning how to build and analyze electric circuits. Building a circuit requires the ability to read a schematic and assemble and connect elements. Examples of circuit elements include resistors, capacitors, inductors, and sources. Analyzing a circuit involves solving the circuit for unknown voltages and currents. This process requires the ability to identify errors in equations and calculations in order to correct an erroneous solution. This process is called *troubleshooting*.

Effective troubleshooting is critical to successful circuit analysis. It is also critical to successful circuit construction. Once a circuit is built and energized, it is often the case that it fails to operate as expected - this is where the process of *troubleshooting* the circuit begins. Essential to the troubleshooting process is effective use of test instruments and correct measurement techniques. In this laboratory exercise you will learn how to make basic electrical measurements using the test instruments.

An electric circuit may be energized using a variety of different types of sources. In this lab, you will work with independent voltage sources in order to supply a constant voltage to your circuit. There are two common sources of constant voltage. One is a battery and the other is a DC power supply. A battery is a two terminal device that converts chemical energy into electrical energy producing a constant (DC) voltage. When a voltage source is connected to a circuit, current flows through the elements. The amount of current that flows through resistive elements depends on the voltage across that element and the element's resistance. Voltage, current, and resistance are basic electrical quantities that are used to characterize circuit elements.

3.1 Solderless Breadboard

A solderless breadboard is a device that will allow you to make quick, temporary electrical connections between elements. For more information on breadboards, see the EGRWiki page at https://egrwiki.com/wiki/ECE_110/Equipment/Breadboards.

3.2 Resistors

Most resistors we will use in lab have four colored bands to indicate their resistance. The meanings of the colors of each band are shown on the EGRWiki page at http://egrwiki.com/wiki/Resistor_Color_Codes.

3.3 DC Power Supply

Each lab group will have a triple-output power supply. Information about the specific power supply you are using is at the EGRWiki page at https://egrwiki.com/wiki/ECE_110/Equipment/Keysight_36311A.

3.4 Digital Multimeter

Each lab group will also have a digital multimeter for taking a variety of measurements. Information about the specific digital multimeter you are using is at the EGRWiki page at https://egrwiki.com/wiki/ECE_110/Equipment/Keysight_34460A.

3.5 Taking Measurements

There are three primary types of measurements you will take - elemental values (which must be taken *before* the elements are connected to a circuit), voltage measurements, and current measurements. The elemental and voltage measurements will be taken by placing the meter probes in parallel with the element while the current measurements will be taken in series with the element. For the latter, this generally means re-wiring the circuit to put the meter in series with other connections.

In Tinkercad, you can change the type of meter by clicking the appropriate letter on the right side of the meter to measure **A**mperage, **V**oltage, or **R**esistance. You can also click on the meter itself and change the mode in the infobox for the meter. Tinkercad's meters are *not* ideal - you will learn more about that later!

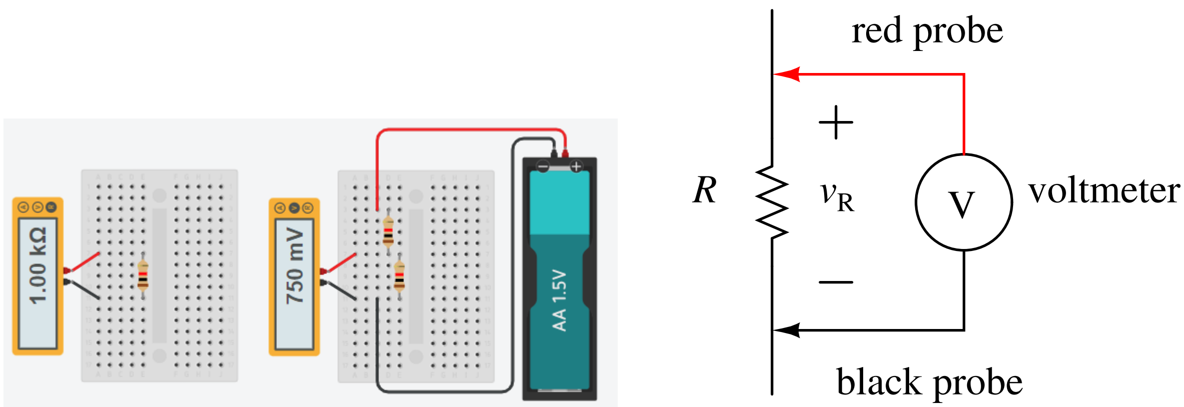

Figure 1. Measuring the resistance of a resistor with an ohmmeter ("R" mode in Tinkercad) or the voltage drop across a resistor with a voltmeter ("V" mode in Tinkercad). The resistor should not be connected to other circuit elements if you are measuring resistance. Note in both cases that the meter is in parallel with the branch (similar to series with the isolated element).

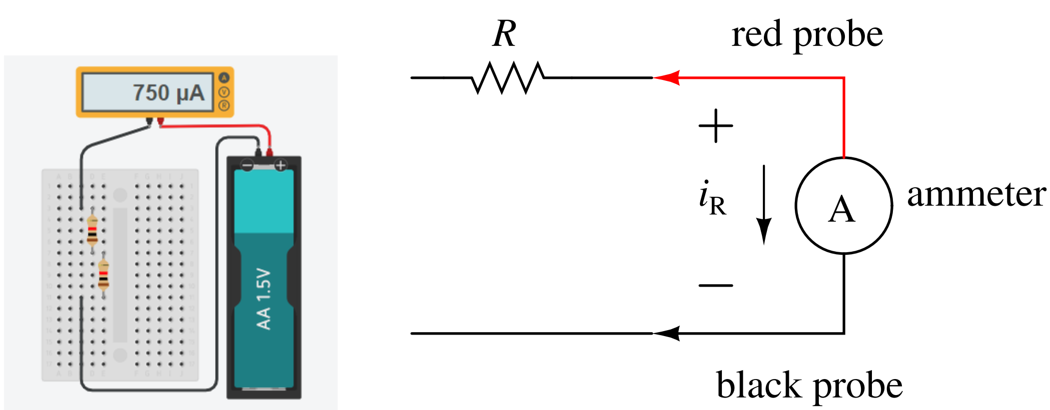

Figure 2. Measuring the current flowing through a branch with an ammeter. The ammeter measures the magnitude and direction of the current that enters the meter through the red probe and leaves through the black probe. Note that the meter is in "A" mode and is in series with the branch.

3.6 Potentiometer

A variable resistor is called a **potentiometer**. Unlike a resistor, which is a two-terminal device, a potentiometer has three terminals (see Figure 3). There are two types of potentiometers: *linear* and *rotary*. Both types use a movable **wiper** to vary the value of the resistance. The resistance between the outermost terminals of a potentiometer is fixed (e.g., 1 kΩ or 100 kΩ). As the slide or knob is moved, the point of contact between the wiper and the fixed resistor changes. This causes the value of the resistance between the wiper terminal and the outer terminals to change.

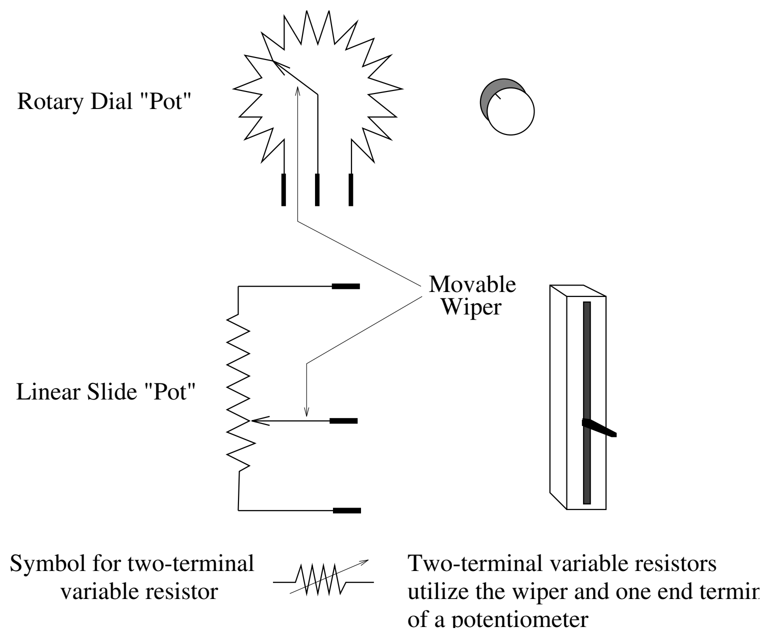

Figure 3. Rotary dial potentiometer, linear slide potentiometer, and symbol for variable resistor.

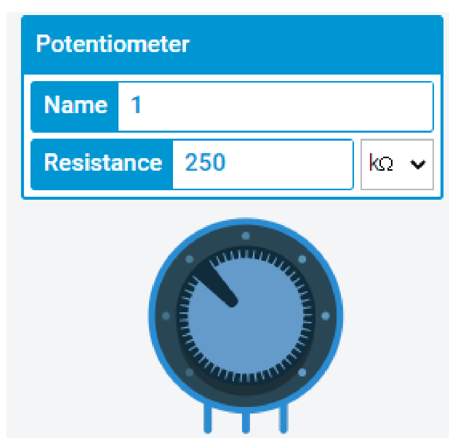

Figure 4. Rotary dial potentiometer in Tinkercad, showing information box. The pins in the model exactly match the pins in the rotary dial potentiometer above.

3.7 More Information on Voltages and Currents

Depending on context, electric circuits may utilize voltages on the order of a μV (10^{-6} V) to a MV (10^6 V). An electroencephalograph (EEG) is a biomedical instrument that measures voltages across different points of the scalp. These voltages are on the order of a μV and are commonly called brainwaves. Other applications require far greater voltages, like delivering electricity to homes. A typical high voltage power transmission line operates at voltages in the range of 300,000 V - 1 MV.

Depending on context, electric circuits may utilize currents on the order of a fA (10^{-15} A) to tens of kA. The currents in some tiny integrated circuits are on the order of a fA, while the current in a typical lightning bolt is typically around 30,000 A.

The amount of current a wire or cable can carry safely is called its **ampacity**. The maximum current a wire or cable can carry before it burns is called its **fusing current**. For example the ampacity of 24 AWG wire used to make connections on a breadboard is 3.5 A. A large high-voltage transmission line cable consists of 75 aluminum conductors. Each conductor has an ampacity of 125 A for a total cable ampacity of 9,375 A!

4 Pre-Laboratory Exercises

The pre-laboratory exercises and several of the laboratory exercises use the same circuit. You will get simulated values before lab so you can troubleshoot your own circuit in lab.

4.1 Kirchhoff's Laws: Voltage Measurements in Tinkercad

For this pre-laboratory exercise, you will use Tinkercad to build the circuit shown here:

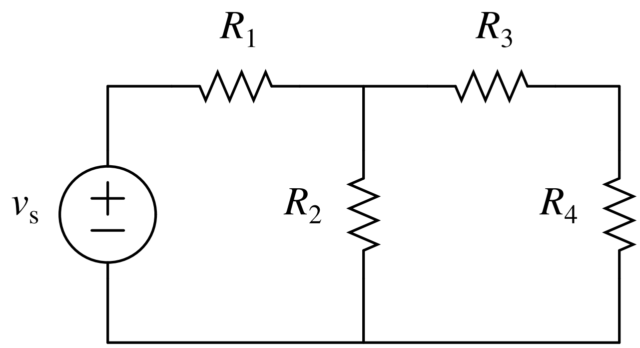

Figure 5. Circuit with five elements, three essential branches, four nodes, two essential nodes, two meshes, and three loops.

To do so, you will choose four (4) different resistors between 43 Ω and 10 kΩ for resistors R_1 through R_4. Then, you will measure the voltage across each resistor using a multimeter set to voltage mode.

1. To begin in Tinkercad, add the following Components to a new project circuit:
   - Breadboard—choose Breadboard Small so you have some common high and ground rails.
   - Power Supply—set the Voltage to 2 V (the current limit can stay at the default "5 A").
   - (4) Multimeters—leave these in Voltage mode for this exercise.
   - (4) Resistors—Set each resistor to a different value chosen from the following list:

     43 Ω   100 Ω   220 Ω   470 Ω   1 kΩ   2 kΩ   4.7 kΩ   10 kΩ

     You are limited to these resistors because these are the values of resistors we will provide for you in lab when you build your actual circuit. Your model should initially resemble Figure 6 below.

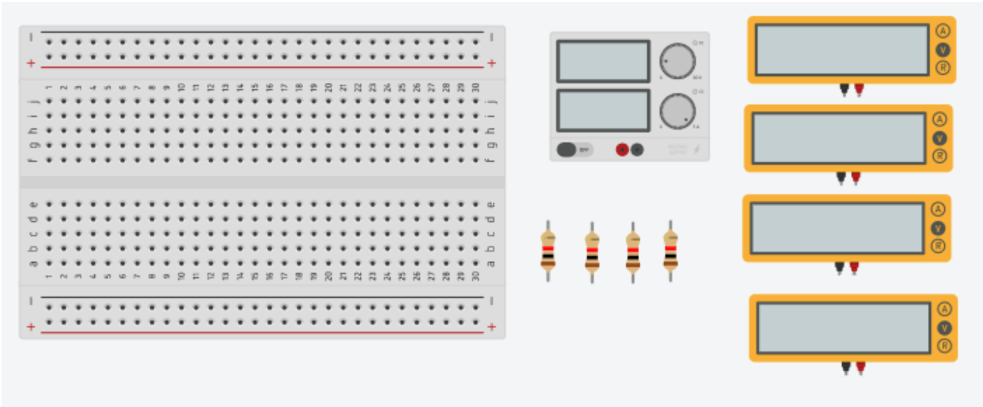

Figure 6. Tinkercad model with required elements. Note that unlike in this picture, you should have four *different* resistor values chosen from the table above.

2. Build a model of the circuit shown in Fig. 5.
3. Place multimeter wires to measure the voltage across each of the 4 resistors in the circuit. In the lab, you will only be using one multimeter; in Tinkercad, you can use four meters to get all the voltages at once. Measure the voltage drops going from left to right or from top to bottom, as appropriate. This will require some creative wiring and/or rotating the multimeters. Unfortunately, there is no way to flip the multimeter probes.
4. Ensure the power supply is set to 2V.
5. Simulate the circuit.
6. Record the voltages measured across each resistor. Record also the total current through the circuit as indicated on the power supply.
7. Take a screenshot of your project as it is running and then save this project.

Pre-lab Deliverable (1): Include a screenshot of your running simulation in your pre-lab assignment.

Note: If you would like to check your work, the calculations for the individual voltage drops are available at EGRWiki on the page of equivalent resistance examples, https://egrwiki.com/wiki/Examples/Req. You are not explicitly required to check your Tinkercad values for the pre-lab, though you will need to calculate values for the lab assignment.

4.2 Kirchhoff's Laws: Current Measurement in Tinkercad

In Section 6.5 Kirchhoff's Laws, you will use the same circuit from Fig. 5, except this time you will measure *current* through four resistive elements. For this pre-laboratory exercise, you will use Tinkercad and the same circuit you constructed in the above pre-laboratory exercise 4.1. Since measuring current requires placing the multimeter in series with the branch whose current you are measuring, you will be doing some significant re-wiring in your model.

1. In Tinkercad, copy your previous circuit for measuring voltages into a new project. You can do this by going to your Tinkercad dashboard, hovering over the project you want to copy, and clicking the gear icon that appears at top right. One of the options will be to **Duplicate** your project. Do that, then click **Tinker This** on the duplicated project.

2. In the new project, set the multimeters to **Amperage** mode. Remember, in order to measure current, you will need to 'break' the circuit connections between resistors (and power or ground) in order to place the multimeter's wires *in series* with each of the four(4) resistors. In the Tinkercad model, all you need to do to measure current is change the meter's mode and the wiring. With your actual meters, you will also need to change which *terminals* are used on the meter.

3. Re-wire the multimeter connections so you are measuring the current *through* each resistor. **You will need to delete and re-route some of the wires in your original and may need to move resistors!** Measure the current as it goes from left to right or from top to bottom through the resistor as appropriate - that is, your voltage measurements from the first circuit and your current measurements from this part will follow the passive sign convention. *Hint:* based on how this circuit is built and on the directions of your measurements, all the voltages and currents will be measured as positive. Use the same four (4) resistors values between 43 Ω and 10 kΩ that you used in the previous pre-laboratory exercise.

4. Confirm that the power supply is still set to provide 2 V.

5. Simulate the circuit.

6. Record the current through each resistor. Record also the total current through the circuit as indicated on the power supply. This value should match the value you found when you were measuring voltage drops since the circuit itself has not changed.

7. Take a screenshot of your project as it is running and then save this project.

Pre-lab Deliverable (2): Include a screenshot of your running simulation in your pre-lab assignment.

Note: If you would like to check your work, you can use the voltage calculations from the previous section and simply divide by your resistances. Again, you are not explicitly required to check your Tinkercad values for the pre-lab, though you will need to calculate values for the lab assignment.

4.3 Blinking a Light with Arduino

Create a new project in Tinkercad. From the **Starters** drop-down near the top right of the page, select **Arduino**. Among the various starters is the "Blink" starter. Drag that into your project and Tinkercad will add an Arduino Uno, a 220 Ω resistor, a red LED, and a few wires. The resistor is connected between pin 13 and the long leg of the LED; the short leg of the LED is connected to ground. Given that, if pin 13 is set to high (5 V), current will flow through that pin, through the resistor, through the LED, and back to ground. The resistor ensures that there is not too much current through the LED.

In your simulation, click the **code** button and then change the edit mode to **Text** using the edit mode drop down box at the top left of the editing window. This will change the blocks to Arduino code. Run the simulation, then make sure you understand generally what each line of code does and why some code is in the setup function and other code is in the loop function. As the simulation is running, change the resistor value to 220 pΩ - a pico-ohm is 10^{-12} Ω meaning the resistance is now exceedingly small. You should see a warning icon next to your LED. If you hover over the icon, you will see that Tinkercad is alerting you to a potential problem with your circuit involving the amount of current you are driving through the LED. Go ahead and change the resistance back to 220 Ω and the warning icon should go away. Give this project a meaningful name and save it. While there is no deliverable for this part, you will be using similar code and a similar circuit in lab and are thus expected to be familiar with this simulation.

4.4 Taking and Displaying Voltage Measurements with Arduino

Create a new project in Tinkercad. From the **Starters** dropdown near the top right of the page, select **Arduino**. Among the various starters is the "Read Analog Voltage" starter. Drag that into your project and Tinkercad will add an Arduino Uno, a 250 kΩ potentiometer, and three wires. The red (5 V) and black (GND) wires are connected across the entire resistance of the potentiometer, whereas the green (A0) wire is connected to the wiper. Analog pin A0 is thus measuring the voltage drop between the green and black wire. Assuming α is some value between 0 and 1 representing the experimental proportion of the selected resistance to the total resistance R:

- R is the resistance measured between the red and black wires
- αR is the resistance measured between the green and black wires
- $(1-\alpha)R$ is the resistance measured between the red and green wires

Using voltage division, this means that the voltage drop measured between the green and black wires is given by:

$$v_{\text{gk}} = v_{\text{s}}\frac{\alpha R}{R} = \alpha v_{\text{s}}$$

Note that α increases as you turn the knob clockwise. In the starter, the potentiometer is rotated such that the terminals are pointing up. If the dial is turned fully counterclockwise, the arrow should be pointing at about 1 o'clock and the resistance between the green (middle) and black (right) wires will (ideally) be 0. If the dial is turned fully clockwise, the arrow should be pointing at about 11 o'clock and the resistance between the green and black wires will be the full resistance of the potentiometer.

In your simulation, click the **code** button and then change the edit mode to **Text** using the edit mode drop down box at the top left of the editing window. This will change the blocks to Arduino code. Run the simulation, make the Serial Monitor viewable, and look at what happens to the voltage measured on the green wire as you move the wiper on the potentiometer. It should range from 0 V to 5 V. Make sure you understand what each line of code does and why some code is in the setup function and other code is in the loop function. Give this project a meaningful name and save it. While there is no deliverable for this part, you will be using similar code and a similar circuit in lab and are thus expected to be familiar with this simulation.

5 Pre-Laboratory Assignment

The documentation for the pre-lab involves submitting a single PDF file. Your document must include your name, NetID, and the Duke Honor Code statement: "I have adhered to the Duke Community Standard in completing this assignment" at the top. **EACH INDIVIDUAL** should submit their own assignment. Your document should also include:

1. A screenshot of your completed Tinkercad simulation measuring the resistor voltages, and
2. A screenshot of your completed Tinkercad simulation measuring the resistor currents.

This file should be uploaded to the ECE 110L Laboratory **Gradescope** site by the assignment deadline. Each student must submit their own **INDIVIDUAL** assignment.

6 Experimental Exercises

Be sure to take notes and record all necessary data and the answers to all questions found in the lab manual.

6.1 Equipment

1. Keysight E36311A DC power supply
2. Keysight 34460A digital multimeter
3. Jameco solderless breadboard
4. (1) 100 Ω resistor and (5) 1 kΩ resistors
5. (4) more resistors (values between 43 Ω - 1 kΩ, inclusive - same values as pre-lab assignment.)
6. (1) 10 kΩ potentiometer
7. Serial cable
8. 9-VDC wall-plug transformer
9. 22 AWG (American Wire Gauge) connecting wire

6.2 DC Measurements

1. Set the DC power supply to provide 3 V as shown on the digital display on the power supply front panel. (**See important note below**)
2. Set the multimeter to measure DC voltage, making sure the leads are plugged into the correct pair of jacks to measure voltage.
3. Measure the voltage produced by the DC power supply using the multimeter.
4. Set the DC power supply to 0 V.
5. Set the **current limit** to 50 mA.
6. Connect a 100 Ω resistor to the power supply. The easiest way to do this is to place the ends of the resistor in two different rows of a breadboard.
7. Connect the multimeter across the resistor and set it to measure DC voltage.
8. Starting from 0 V, increase the voltage (slowly) across the resistor.

   Important Note: Again, be careful with the DC power supply leads. **Avoid letting them touch at all times**. When the power supply leads touch, a short circuit is formed, which can cause serious damage to the power supply. *Consider what would happen if you shorted the wall socket or a car battery!* Short circuits can be dangerous - even deadly - and so special care must be taken to avoid them.

Discussion (1): At approximately what voltage do you expect to observe a change from CV (Constant Voltage) to CC (Constant Current) on the DC power supply front panel display? If the change from CV to CC occurs at a voltage different from what you expected, explain why.

Discussion (2): What is the "resolution" of a digital display? Compare the resolution of the digital display on the front panel of the DC power supply to the display on the front panel of the multimeter.

6.3 Resistance Measurement

1. Select five 1 kΩ resistors (color coded brown-black-red-gold).
2. Place the resistors in the breadboard at your laboratory station. Be sure the leads for each are in completely different rows and that nothing else is connected to any of those rows.
3. Set the multimeter to measure resistance. To do this, press the button labeled Ω **2W**. Determine and record the measured value of each of the resistors. The words "actual," "measured," and "nominal" have different meanings when used accurately. They may not be used interchangeably.

   - The **actual** value is the true (deterministic, yet unknown) value, which is not the same as the **measured** value.
   - The **measured** value is the **actual** value plus measurement noise, bias due to internal resistance of the meter, etc.
   - The **nominal** value is the expected value (labeled on the element). The nominal values for electrical elements are generally given with some sort of **tolerance** - the manufacturer is telling you that the actual value of the element may fall in a certain range around the nominal value.

   The difference between the actual and measured value may best be described by some lines from a poem in the column **The story of Schroedinger's cat (an epic poem)**[1] by Cecil Adams:

   > *We may not know much, but one thing's fo' sho':*
   > *There's things in the cosmos that we cannot know.*
   > *Shine light on electrons — you'll cause them to swerve.*
   > ***The act of observing disturbs the observed...***

   Although the poem (and post) are primarily about quantum mechanics, the same applies to just about any measurement - the measurement device itself likely impacts the quantity that it is measuring.

   Discussion (3): What is the percent difference between the measured value of the resistor and the nominal value of 1 kΩ for each of the resistors? (Percent difference, recall, is calculated as [Measured - Nominal] / Nominal x 100%.). Are all the measured values within the tolerance specified by the fourth band on the resistor?

[1] CW: language. https://www.straightdope.com/21341296/the-story-of-schroedinger-s-cat-an-epic-poem

6.4 Current, Voltage and Ohm's Law

1. Make sure the middle (green) output of the power supply is off, then assemble the circuit in Figure 7 using one of the (nominally 1 kΩ) resistors as measured in Experiment 6.3 above.

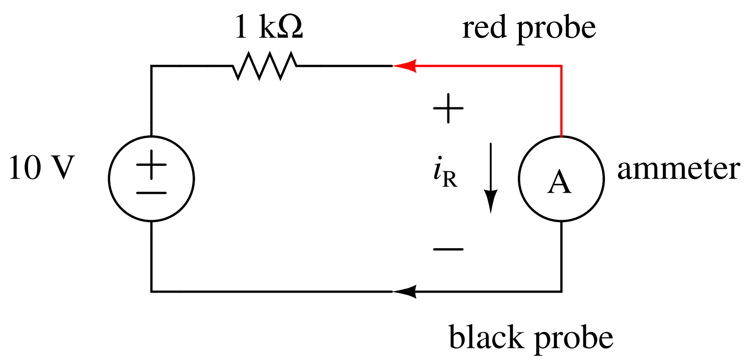

Figure 7. Circuit illustrating the measurement of current.

2. Set the multimeter to measure DC current, and make sure that the leads are in the correct jacks in the front panel of the multimeter to measure current.

3. Once you have assembled the circuit and connected the multimeter properly, turn the middle (green) output on with the voltage set to 10 V.

4. Measure the current flowing through the resistor. **Remember: An ammeter measures the current flow from the red probe to the black probe within the meter.**

   Checkpoint (1): Show this circuit to your TA so they can confirm your meter is measuring an appropriate value.

   Discussion (4): Does this value agree with Ohm's Law ($i = \frac{v}{R}$)?

5. Turn the output of the power supply off, then reconfigure the circuit to measure the current flowing through the resistor in the opposite direction. This is done by reversing the leads of the ammeter. Once your circuit is re-wired, turn on the output from the power supply.

   Discussion (5): Does this value agree with Ohm's Law ($i = \frac{v}{R}$)?

6. Calculate the percentage error between the theoretical current flowing through the resistor and the measured currents in either direction.

   Discussion (6): Does your experimental data agree with theory? What might be potential sources of error.

6.5 Kirchhoff's Laws

1. Obtain four resistors with the same nominal values as those you selected in the pre-lab. Your goal is to replicate the circuit you wired in Tinkercad on your physical breadboard.

2. Assign each resistor a unique symbol (R_1, R_2, R_3, R_4) *based on how you assembled your circuit in the pre-lab* and use the multimeter as an ohmmeter to measure/record the value of each resistor. Be sure to measure these resistances *before* assembling your circuit!

   Deliverable (1): List the nominal and measured resistor values in your lab assignment. Use labels R_1 through R_4 as used in Figure 5 and be sure to include units.

3. Build the circuit shown in Figure 5. Use the DC power supply as the voltage source, v_s.

4. Set the DC power supply to 2 V output.

5. Using the multimeter configured to measure voltage, measure the voltage across every element in the circuit and record these voltages noting **both the value and polarity** of each measured voltage. Measure the voltage drops from left to right or from top to bottom across each resistor.

   Remember the following: A voltmeter is a device for measuring voltage. It measures the voltage **drop** from the red to the black probes. The voltmeter is placed in **parallel** with the circuit element whose voltage is to be measured (See Figure 1). Recall that two elements are in parallel when they share the same pair of nodes and hence share the same voltage.

   Deliverable (2): List the individual voltage drops in your lab assignment. Use labels v_1 through v_4 (for the voltage drops across R_1 through R_4, respectively) and be sure to include units.

6. Based on the voltage measurements performed above, verify that the circuit obeys Kirchhoff's Voltage Law (KVL) by applying KVL around all three loops in the circuit and substituting in your measured voltage drops. Save your measured values because you will need them for the assignment.

   Checkpoint (2): Show the TA your voltage measurements and how you verified KVL.

   Deliverable (3): Include the three KVL calculations in your lab assignment.

7. Turn off the output from the DC power supply, then reconfigure the multimeter to measure current.

8. Measure each current in the circuit. **This part will take some work and you must make sure to turn your voltage output off whenever you are re-configuring the circuit!** Measure the current flowing from left to right or from top to bottom in each resistor.

   Remember the following: An ammeter is a device for measuring current. It measures the current flowing from the red probe to the black probe **within the meter**. The ammeter is placed in **series** with the circuit element whose current is to be measured (See Figure 2). Recall that two elements are in series when they share the same current. *Hint:* carefully consider the connections you need to break and re-make to measure the current through each resistor.

Checkpoint (3): Explain to the TA how you are going to measure the current through R_1 and then the current through R_2

Deliverable (4): List the individual resistor currents in your lab assignment. Use labels i_1 through i_4 (for the currents through R_1 through R_4, respectively) and be sure to include units.

9. Based on the current measurements performed above, analytically verify that the circuit obeys Kirchhoff's Current Law (KCL) by applying KCL at each node. Save your measured values because you will need them for the assignment.

   Checkpoint (4): Show the TA your current measurements and how you verified KCL.

   Deliverable (5): Include the four KCL calculations in your lab assignment.

Note: You are now done with the DC power supply for this lab! Turn off the power supply and unplug the leads. You can use the Bot Shield for the remaining exercises.

7 Exploration - Converting an Analog Input to a Digital Output

Many sensors produce analog output signals. If you are to use these signals to control the behavior of the ’bot, these analog values will need to be translated into a digital signal. Depending on the need, this ‘analog-to-digital’ conversion can be done in a number of ways. In some cases, the range of possible input values needs to be translated into a range of digital values. In other cases, such as the situation you are going to explore next, it is sufficient to map the analog signal into a simple ‘HIGH’ or ‘LOW’ value.

In this exercise, you are going to build a system which turns an LED on or off depending on the value of an input voltage. This voltage, which will be measured across a potentiometer, will vary as the knob of the potentiometer is turned. There are two different circuits for this exploration. The “input” circuit consists of a potentiometer with a voltage drop across the outer terminals provided by the 5 V and GND terminals on the CX-Bot. The CX-Bot will also take a voltage measurement at the wiper of the potentiometer; as seen in the pre-laboratory exercises, that voltage will change as the position of the potentiometer knob changes.

The “output” circuit consists of an LED in series with a 220 Ω resistor. The output circuit will be energized by an output pin on the CX-Bot. Depending on the value the CX-Bot measures from the input pin, your code will decide whether to have the output pin high (5 V) or low (0 V). For this circuit, 5 V will be sufficient to turn the LED on.

1. Place a 10 kΩ potentiometer on the CX-Bot breadboard, being careful to position it so that each pin is in a different row.
2. Connect the wiper (middle) terminal of the potentiometer to P4 of the microcontroller. In your program, P4 will be treated as an input pin.
3. Connect one of the remaining terminals of the potentiometer to power (5 V) and the other to ground (GND) on the CX-Bot shield.
4. Elsewhere on the CX-Bot breadboard, build a series combination of an LED and a 220 Ω resistor, with the cathode (shorter, lower voltage) lead of the LED at the same node as one end of the resistor.
5. Connect the free end of the resistor to ground—the easiest way to do this is to connect a wire from the resistor to the same part of the breadboard as the potentiometer’s ground connection.
6. Connect P2 of the microcontroller to the anode (longer, higher voltage) lead of the LED. In your program, P2 will be treated as an output pin.
7. Write a sketch that turns the LED on and off depending on the voltage measured on P4 (which in turn depends on the setting of the potentiometer). You will first need to declare that P4 is an input pin and P2 is an output pin by typing (not copying and pasting) the following code at the beginning of your program (after the header information):

```
void setup(){
    pinMode(4, INPUT);
    pinMode(2, OUTPUT);
    digitalWrite(2, LOW);
}

void loop(){

}
```

Note that the above declarations mean you can use the code

```
digitalRead(4)
```

to examine the value of pin 4 and

```
digitalWrite(2, LOW)
digitalWrite(2, HIGH)
```

to set the value at pin 2. Since your program should continually monitor the voltage at pin 4 and adjust the output at P2 accordingly, those directives should be in the loop.

You will first want to examine how the CX-Bot interprets different voltages on P4. Write code in the loop that continuously monitors and displays the value of P4 to the Serial Monitor. Remember that you will need to initialize the Serial Monitor first! Look at previous code you have written (in lab or in Tinkercad) to help with this. You may also want to use the multimeter (as a voltmeter) to measure the analog voltage at P4 and compare that to the digital readings from the CX-Bot.

Once you have a good understanding of how the CX-Bot interprets analog voltages on a digital pin, you should write code that turns the light on for "high" voltages at P4 and off for "low" voltages at P4. Information in how to write an `if` statement in a sketch is available at https://www.arduino.cc/reference/en/language/structure/control-structure/if/

Checkpoint (5): Run your program and verify with the TA that the LED turns on and off as you vary the position of the potentiometer. How does the brightness of the light vary with the potentiometer knob position?

Discussion (7): What is the threshold analog voltage between a digital **HIGH** input and a digital **LOW** input for the micro-controller?

Deliverable (6): Include your code in your lab assignment.

8 Assignment

The assignment for this laboratory involves submitting a single PDF file. Your document must include your name, NetID, and the Duke Honor Code statement: "I have adhered to the Duke Community Standard in completing this assignment" at the top. **EACH INDIVIDUAL** should submit their own assignment. Your document should also address the following:

1. Suppose you set the **voltage of the DC power supply** to 5 V under open circuit conditions (it is connected to nothing). You then connect it to a circuit and the voltage provided by the power supply drops to 3 V. Describe what (probably) happened? Use a schematic to aid your explanation.

2. **Voltage Data Table for Experimental Exercise 6.5**
   Create a formatted table that contains the following information for each resistor in Figure 5:

   - The theoretical voltage drop across the resistor using the *nominal* values for all the resistors.
   - The theoretical voltage drop across the resistor using the *measured* values for all the resistors.
   - The simulated voltage drop across the resistor measured in Tinkercad.
   - The experimental voltage drop across the resistor measured using the multimeter.

   You can use the calculations at https://egrwiki.com/wiki/Examples/Req#Simple_Example for the theoretical values; just plug in your nominal and measured resistance values. Discuss any variation in your values for each resistor and potential sources for those variations.

3. **Current Data Table for Experimental Exercise 6.5**
   Create a formatted table that contains the following information for each resistor in Figure 6.5:

   - The theoretical current through the resistor using the *nominal* values for all the resistors.
   - The theoretical current through the resistor using the *measured* values for all the resistors.
   - The simulated current through the resistor measured in Tinkercad.
   - The experimental current through the resistor measured using the multimeter.

   You can use the calculations at https://egrwiki.com/wiki/Examples/Req#Simple_Example for the theoretical values; just use the voltages found above and divide by the appropriate resistance. Discuss any variation in your values for each resistor and potential sources for those variations.

4. **KVL verification**
   Using KVL for each of the two meshes, compare and contrast the results you get substituting in each of the four sets of voltage values. *Hint:* the theoretical voltage drops using the nominal values of the resistors should result in the total voltage drop across any closed loop in your circuit being zero!

   Do the magnitudes of any of the parameters, v, i, or R seem to affect the measured error?

5. **KCL verification**
   Using KCL for the top supernode only (i.e. the top of R_2), compare and contrast the results you get substituting in each of the four sets of voltage values. *Hint:* the theoretical currents using the nominal values of the resistors should result in the total current leaving any node/supernode/junction in your circuit being zero!

   Do the magnitudes of any of the parameters, v, i, or R seem to affect the measured error?

6. Include your code for turning an LED on or off based on a digital reading from the potentiometer wiper. State the approximate voltage threshold between "High" and "Low" for the digital input pin.

This file should be uploaded to the ECE 110L Laboratory **Gradescope** site by the assignment deadline. Each student must submit their own **INDIVIDUAL** assignment.