Electromagnetism Labs with iOLab

for Phys 114/122

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Acknowledgment

The author acknowledges the amount of work and effort accomplished before him to the best of his knowledge.

The original contents, published as iOLab for Scientists and Engineers, have been developed by Tom Hemmick.

The template of the lab report has been inspired by the one that Prof. Frank Wolfs uses in the course Phys 141.

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Contents

Introduction

Inside the box

When you have obtained the iOLab device, you should find the following in the box:

- One device/remote and one dongle (Figure 1), and
- For Experiment 1, wire leads and breadboard,
- For Experiment 2, wire leads, breadboard, two 4.7 kOhm resistors, two 10 kOhm resistors, and three 1 Ohm resistors,
- For Experiment 3, wire leads, breadboard, two 4.7 kOhm resistors, one 10 kOhm resistors, three 1 Ohm resistors, three AAA batteries, and battery cage,
- For Experiment 4, three or four D batteries with appropriate battery cage, breadboard, two 0.5 Ohm resistors, 12 ft spool of wire, and wire leads,
- For Experiment 5, wire leads, breadboard, two 100 μF capacitors, two 56 μF capacitors, one 10 kOhm resistor.

Figure 1: The primary contents of the iOLab device. From left to right, the device/remote and the Dongle.

Driver and iOLab application

Please visit www.iolab.science to download the driver (Windows only) and the iOLab application (Windows and Mac). Follow the instructions for the installation.

Pairing

When you have downloaded the iOLab application, launch it. Insert the Dongle into the computer. While pressing on and holding the `+` button, power on the device. Hold until the bulb next to the `+` button lights up in triplets (three fast dots). Select `Remote 1` in the application, and it should automatically pair the remote.

Calibration

You must calibrate the device on every computer you use in correspondence with the iOLab device. In order to calibrate the device, make sure your device is turned on and the dongle is plugged into your computer. Click on the tools button in top right corner of the page (small gear icon). This will give you a dropdown menu.

One of the options in this menu is `Calibration`. You will then be able to click on either `Accel - magn - gyro` or `Force` under `Calibration`.

You will do two calibrations: one for the `Force` sensor and one for the `Accelerometer - Magnetometer - Gyroscope`. You will need to attach the eyebolt to the force probe in order to complete the calibration of the force probe.

Once you select a calibration, simply follow the directions given. The calibrations are a pretty quick process, but it is necessary to do in order to ensure you are getting accurate data. Once you are done with the calibration, make sure you hit the save button.

Taking data

Open the iOLab software. On the left hand side of the page, you will see a menu with all the possible sensors (with check boxes next to each). To take data, first make sure the dongle is plugged into the computer and the device is turned on. Then check the boxes of the sensors you would like to use. There are limitations, but you can use multiple sensors at the same time.

In this example, we will be using the sensors `Force` and `Accelerometer`. Watch this video to find out how to get started. You can try it out for yourself on the right hand side of this screen. The sensors have already been selected for you but you can control when you start and stop the recording, the smoothing, the y axis, and the zooming function. By selecting the `Remove` button above all the plots, this will clear the plots and allow you to retake the data if you would like to.

Analyzing the data

After you take the data, there is some analysis to do. Watch this video to see an example of analysis in action. The following are the instructions in words.

Looking at the software page where you took the data, there are three connected buttons that look like a bar graph, a magnifier, and two arrows orthogonal to each other. The "bar graph" is the analysis mode. The middle one is the zoom button. It has actually a dropdown menu: The first option allows you to choose a box section of the plot on which to zoom. The second option allows you to zoom horizontally only, and the last option allows you to zoom vertically only. To unzoom, simply click on the plot while in Zoom mode. The last button in this block of three allows you to move the position of the plot.

The analysis mode of the software allows you to highlight specific sections of the plots to analyze. When a section of the plot is highlighted, the following information will be given to you: μ, σ, a, and s:

- μ is the average value of the highlighted portion.
- σ is the uncertainty in the highlighted portion.
- a is the area under the curve.
- s is the slope of the highlighted section.

Saving data

All data that you take will be saved within the software. If you take data in the normal iOLab application, just click on the folder button and you will see all the data you have taken in the order you have taken it. The most recent data will be at the top of the list and each item in the list will be time stamped and marked by which sensors were used. However, keep in mind that any highlighting you do under analysis mode will not be saved.

If you take data within a lab manual, you will be able to access it by selecting the "Show reports" link underneath each lab manual title. Once you click on that link, your old reports will show up in a box. By clicking on the box of the report you want, you can open your lab manual with the data that you have taken. In addition, if you take data within the lab manual and you want to re-take the data, you can hit the remove button on top of the plot in order to erase the data and start fresh.

Error analysis

There are three major types of error that we deal with in science:

- Instrument precision
- Unknown error
- Known error

For the purposes of this lab, we will only be dealing with the first two types.

Instrument precision

Every time you use a measuring apparatus such as a ruler, there is a level of uncertainty associated with reading the value. Two people might not read the same exact value and you might not read the same value if you conducted the measurement multiple times. For errors like this, there is usually a known precision of that instrument. This is usually half the smallest divison of the instrument, or the smallest increment in which you can accurately read. For example, the smallest division on a ruler is 1 mm. Half of that is 0.5 mm. Therefore, the error in a measurement from a ruler would be ± 0.5 mm.

Unknown error

There are other errors that do not stem from the instrument itself, but in the way the experiment is conducted. In these cases, the error is not necessarily known, but it is possible to estimate them. To do that, you have to repeat the same experiment in the same conditions multiple times. You should find that the measured values are spread about a mean value, μ. The spread from the mean, σ, is called the standard deviation. This will be the range in which the "true value" is likely to lie, with the most probable value being the mean. Here are the formulae associated with the mean and the standard deviation:

$$\mu = \sum_i \frac{x_i}{N}$$

$$\sigma^2 = \sum_i \frac{(x_i - \mu)^2}{N-1}$$

where N is the number of trials and x_i is the value measured during that trial.

Note that for future labs, Δ will be used to denote the error in a quantity. For example, the error in x is Δx.

Compatibility

This manual is 100% self-contained that you can download (and even printout, and then you can use a QR code reader to access the links) and view all the original YouTube videos. The procedure is explained carefully step by step for each experiment, completing possible missing steps in the original one. You should be able to complete each experiment by following the steps written here and write a proper lab report.

If you really want, then you can always read the original manual that comes with the device. There is only one problem with the original manual: It does not tell you what to record or how to write your lab report. Eventually, you need to go over this manual, again.

Writing a lab report

There are certain data (graphs and tables) you will record and analyze by using the iOLab application. However, there is no lab report format offered with iOLab. Therefore, I want you to prepare a lab report by using the template in Figure 2.

In the title, please do not keep the "#" symbol. To illustrate, in your first lab report, if you take the course Phys 114, the title should look like

> Experiment 1: Breadboard
> Kagan Simsek
> Phys 114
> July 26, 2020

You may use a word processor, a spreadsheet application, a Mathematica notebook, LaTeX, or any other means to type it. Or, you may simply write it by hand (*and it is your responsibility for your handwriting to be legible*), scan the pages, and create a pdf.

Please, if you want to write the report by hand, do not submit a zip file containing lots of photos generically named like `IMG_2881.jpg`, `IMG_2882.jpg`, etc. It is very important for you to create a pdf out of your scanned image files.

For the submission of your lab report, I have prepared submission links at the end of each experiment (See here, here, here, here, and here). The lab reports that are not submitted in this way (with the correct subject of the email and the correct format for the file name of the lab report) are highly likely to get lost in my inbox, hence they will not be graded.

Experiment #: Title of the experiment
Student name
Phys 114 or Phys 122
Date

Abstract
Summarize your main results here. Be brief and concise.

I. THEORY
Include the motivation and objectives of the experiment. Describe the theory behind it. Mention the key formulae, explaining the meaning of the symbols used. One paragraph should be sufficient.

II. EXPERIMENT DETAILS
Briefly describe the apparatus you are using. Write down the procedure in your own words – do not copy from the manual coming with the iOLab. Describe the steps as if you are explaining to someone who will do it for the first time. If necessary, draw small figures, but you don't have be artistic.

III. DATA ANALYSIS AND RESULTS
Perform the **TASKS** here by using subheadings as in

Task 1 Do exactly what Task 1 tells you to do.

Task 2 Do exactly what Task 2 tells you to do.

While completing tasks, explain all the plots and the steps in your calculations. Sometimes, you will need to prepare tables. You can prepare them by using a spreadsheet application and copy it to your report. Do not forget the units.

IV. CONCLUSION AND DISCUSSION
Quote your final result(s) here and put a box around them or prepare a small table and put the final result(s) there. If you obtain more than one results for one variable (e.g. mass, the coefficient of friction, to name a few), it is this place to compare them. Discuss if your results agree with the theory.

Sometimes there will be tasks to complete specifically in the discussion section. Do them here, using task subheadings again.

Figure 2: The format of the lab report.

Experiment 1

Breadboard

This will be the easiest experiment of all the five; however, it is vitally important. In this course, many of the experiments will involve wiring electrical circuits and all such labs will use the breadboard as a central component.

1.1 Objectives

In this experiment, we are going to

- form a map of all connections across the breadboard, and
- mimic complex circuits by "hopping" a connection using multiple wires.

We will need the following materials:

- Wires
- Breadboard

1.2 Useful links

Here are some links that contain useful information about the theory behind this experiment and instructions on how to take and analyze data.

- Breadboard Intro
- Breadboard Hopping

1.3 Introduction

The modern (white plastic) breadboard was invented in 1971 by Ronald J. Portugal. Since that time, it has become a centerpiece in electrical design and prototyping. Figure 1.1 below shows a breadboard very much like the one you will use.

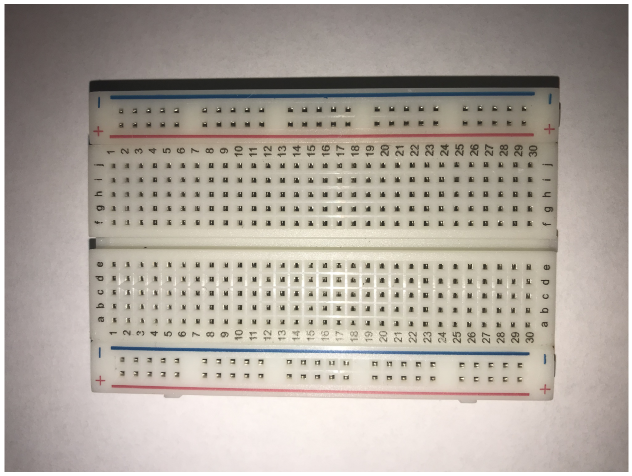


Figure 1.1: The breadboard.

The ends of wires, resistors, capacitors, inductors, motor leads, and many more devices can be plugged into the holes of the breadboard. Some of the holes are electrically connected and by choosing the right set of holes, every circuit you will require this semester can be created. The key to successful breadboard use is to have a thorough understanding of the pattern of connected holes. Today's lab will require you to deduce that pattern experimentally using the iOLab. For this lab, the only sensor that will need to be used in the iOLab software is the Analog 7 (A7) sensor.

1.4 Connection pattern

The first part of the experiment involves a quest to experimentally determine the pattern of connected holes. The breadboard has many holes and so an attempt to try every pairwise combination would be hideously lengthy. Instead of trying every pair of holes, you are asked to apply intelligence to the issue and try enough holes that the pattern of connections has become absolutely certain.

Launch the iOLab software, insert the dongle, power on the device, and pair it to the computer. Select the sensor A7 on the left-hand side. Take two wires (with both male ends).

You should see on the front face of your iOLab device on the right-hand side a column like

V0
3.3V
3.3V
D1
⋮
D6
A7
A8
A9

We are going to use the ports 3.3V (either of them will do) and A7. It is important to remark that

(1) the 3.3 V means that, when you build a closed circuit, the voltage provided will be 3.3 V, and

(2) when nothing is plugged into the iOLab device or the circuit is not closed, it measures 1.5 V at the A7 sensor, which is half of the battery voltage inside the device.

Connect one end of one wire to 3.3V and its other end to the hole with the coordinates a10 on the breadboard. Take the second wire and connect its ends to A7 on the device and the hole e10 on the breadboard. Click Record in the software.

Wait for one or two seconds, and remove the end of the wire at the hole e10 on the breadboard. Wait for another second, and then re-plug it into the hole e10. Remove it again from the hole e10 and insert it to the hole a15. Wait for one second or two. Finally, stop recording.

TASKS

(1) Include the screenshot of the voltage-time graph you have just obtain.

(2) What is the voltage value when you plug the wire into the hole e10?

(3) What is the voltage value when you remove the wire from the hole e10?

(4) What is the voltage value when you insert the wire to the hole a15?

(5) What can you say about the connection pattern? Is the pair a10-e10 connected together? Is the pair a10-a15 connected together? Why?

This should give you an idea about the connection pattern of the holes. When we have the connection pattern, this means we read the correct voltage value in the iOLab application. This should be a hint for you in Task (5) and in the upcoming tasks.

Let's determine the complete connection pattern for the whole breadboard. First, we are going to do the central region, from 1 to 30 and from a to j.

TASKS

(6) Prepare the following table:

Pairs	Voltage (V)	Pairs	Voltage (V)
a1-e1		g2-h1	
a1-c3		g2-i2	
a1-a5		g2-h3	
a6-e6		g7-h6	
a6-c8		g7-i7	
a6-a10		g7-h8	
a11-e11		g12-h11	
a11-c13		g12-i12	
a11-a15		g12-h13	
a16-e16		g17-h16	
a16-c18		g17-i17	
a16-a20		g17-h18	
a21-e21		g22-h21	
a21-c23		g22-i22	
a21-a25		g22-h23	
a26-e26		g27-h26	
a26-c28		g27-i27	
a26-a30		g27-h28	

Reset any previous runs in the software, then hit Record. Connect one wire between the hole a1 and the port 3.3V on the iOLab device, and the second wire between the hole e1 and the port A7. Read the voltage value in the graph in the software. Write it in the table. Repeat the procedure for all the pairs shown in the table.

(7) Within the central region (from 1 to 10 and from a to j), take five more arbitrary pairs that you believe will help you determine the connect pattern. Prepare a small table for these pairs and the voltage values just like the one above.

By now, you should have succesfully discovered the connection pattern of your breadboard by taking into account the remark about the voltage values above.

Next, let's do the red and blue lines, namely the + and - lines at the edges. We have 25 rows of + and 25 rows of - holes in each side. Since there are no labels now, it is impossible to prepare a table just like the one above and keep track of the holes that you are working on. You must work out these parts, as well, but you should try the holes that will give you some idea about the connection pattern.

Try out a couple of pairs of + and - holes in the left-hand side. Try also pairs like one from the + line and one from the central region. You don't need to record the voltage values now. Just convince yourself about the connection pattern.

Repeat a similar job for the holes in the + and - lines in the right-hand side and their combinations with the holes in the central region. Do as many takes as you need.

TASKS

(8) Take a photo of the breadboard. By using your smartphone's draw-on-image tools or by uploading the image to your computer and importing the image to PowerPoint or Keynote or other similar applications, draw the connection pattern on the breadboard. Include the figure with the connection pattern.

For instance, you should have an image as in Figure 1.2. Please note that this is not the correct pattern.

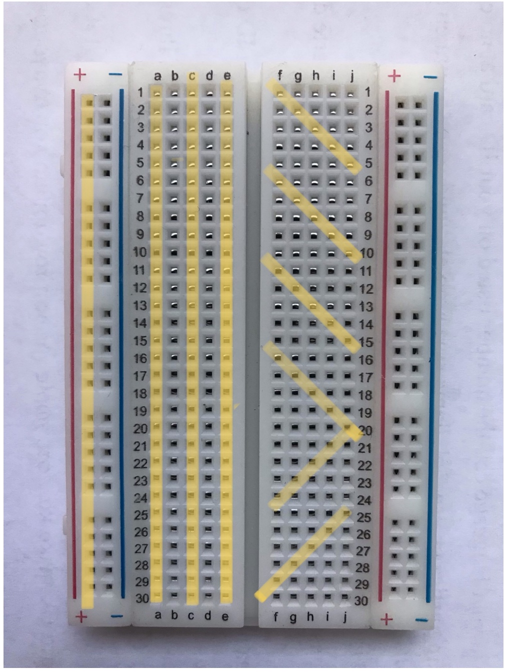


Figure 1.2: An example of the connection pattern on the breadboard. This is not the correct pattern — most or all the lines are wrong!

Also, since drawing all the lines may be complicated, you may want to draw some examples of your connection lines, provided that the pattern should be clear to somebody else than you, too.

1.5 Hopping exercise

Once you are clear on the pattern of connections, you need to understand how knowledge of this pattern will allow you to realize a full electric circuit. In the case of a full electric circuit, you will be attaching batteries, resistors, capacitors, inductors, to one another by pushing the leads into a proper set of holes on the breadboard. Today, we are going to do something similar to that in idea but even simpler: We will put a set of several wires in a series to complete a circuit.

The structure of an "N hop" circuit can be defined as follows (it will be quite useful to take a pen and paper at this point and draw the connections to be described): Suppose you take a hole on the breadboard and connect it to the power supply (in our case, it is the 3.3V port on the device). Let's call this the hole x1. Then, suppose you find a hole that you know is connected to x1, say x2. Now suppose that you connect x2 to some other hole that is not connected to either of x1 and x2. Let's call this the hole x10. Suppose we know that x11 is in connection with x10. Now let's take a hole that we know is not connected to any of the aforementioned holes, say x20. Imagine a connection between x11 and x20. Repeat this fashion N times. If you connect the last hole to the port A7 on the device, you obtain an "N hop" circuit.

Let's make a more concrete example that will help you visualize the situation even better. We will start with a 2-hop circuit. Recall that we will be using the sensor Analog 7 throughout the remainder of the tasks.

TASKS

(9) Reset any previous runs in the software. Connect the hole a1 on the breadboard to the port 3.3V on the iOLab device. Connect also the hole j30 to the device at the port A7. Start recording data. Read the voltage in the graph.

(10) You will need four more holes on the breadboard, which we will call x, y, z, and t. Choose x in connection with a1 but not with j30, and t with j30 but not with a1. Now choose y and z such that the two are connected to each other but not to the points a1, j30, x, or t. Take two wires and connect x to y and z to t. Read the voltage in the graph again. What should be the voltage value when you make the connections correctly? Did you obtain it?

(11) Give an example to the set of points x, y, z, and t that will give you the proper voltage value on the screen.

Voilà! You have a 2-hop circuit. Imagine a frog hopping along these two new wires. This is why it is called a 2-hop circuit. In the next task, you are going to work out a 3-hop circuit.

TASKS

(12) Reset any previous runs and unplug everything. Connect a1 to 3.3V and j30 to A7, to begin with, and hit Record. Choose six points x, y, z, t, p, and q as follows: x should be in

connection only with a1, y and z should be connected to each other only, t and p should be connected to each other only, and q should be in connected with j30 only. Connect x to y, z to t, and p to q. What should be the correct voltage value? Did you obtain it?

(13) Give an example to the set of points x, y, z, t, p, and q that will give you the proper voltage value on the screen.

There you go! You have a 3-hop circuit now. By now, you should have understood the hopping because the next task is totally on you!

TASKS

(14) Reset any previous runs and unplug everything. Connect a1 to 3.3V and j30 to A7. On top of this, choose eight points x, y, z, t, p, q, r, and s in the spirit of the previous task. Build a 4-hop circuit. What should be the correct voltage value? Did you obtain it?

(15) Give an example to the ordered set of points x, y, z, t, p, q, r, and s that will give you the proper voltage value on the screen.

Now, let's do it hypothetically.

TASKS

(16) Suppose a1 is connected to 3.3V and j30 to A7 on the device. List 16 ordered holes on the breadboard that will form a proper 8-hop circuit.

Verifying and documenting the full set of "hop" exercises will complete your lab. There is no error analysis required.

1.6 Submitting lab report

In order not to experience any difficulties with the submission, please name your file as

`p114_exp1_lastname_firstname.pdf`

or

`p122_exp1_lastname_firstname.pdf`

minding the underscores and avoiding capital letters. Then, click here to submit your paper [1].

[1] If the link does not work, please send your pdf to `kagannsimsek@gmail.com` by typing the subject of the email exactly as Electromagnetism Experiment 1. You may leave the body of the email empty.

Experiment 2

Ohm's law

In this experiment, we will build circuits with resistors in both parallel and series configurations using both the iOLab device and our breadboard. In the process, by taking measurements of voltage and current, we will be able to compare the measured currents to those predicted by the Ohm Law and thereby verify the validty of the Ohm Law. In addition, we will be able to use similar measurements to verify the rules for adding resistors in parallel and series.

2.1 Objectives

In this experiment, we are going to

- learn how to build circuits using breadboards,
- build circuits with resistors in both parallel and series configurations,
- verify the Ohm Law, namely $V = IR$, and
- predict the currents in a complex resistor network.

We will need the following materials:

- Wires
- Breadboard
- Two 4.7 kΩ resistors
- Two 10 kΩ resistors
- Three 1 Ω resistors

2.2 Useful links

Here are some links that contain useful information about the theory behind this experiment and instructions on how to take and analyze data.

- Resistor Network
- Voltage Divider
- 10k
- 10k Parallel

2.3 Introduction

The iOLab device can be used to provide a potential difference for driving circuity. By connecting one side of the breadboard to the 3.3V port and the other side to the GND hole (front face, column on the left-hand side, any of the three), the potential difference across the entire circuit will be about 3.3 V.

Whenever there is a potential difference, there is a non-zero electric field. When a charged particle enters an electric field, this particle will experience an electric force. Negative charges (such as electrons) will move from low potential to high potential. The movement of these electrons create what we call current. It is the rate at which charge flows,

$$I = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{2.1}$$

Therefore, with the iOLab as the source of the potential difference, current will flow through the wires attached to it, as long as the circuit is complete.

In this experiment, we will also be using resistors in our circuits. Resistors will slow the rate at which charge flows. This can be analogous to water flowing through a pipe. With nothing blocking the pipe, water will simply be able to flow through the pipe without anything slowing it down. Now picture a pipe partially filled with gravel. The water flow will be slowed down in this instance. Something similar happens with electrical current through resistors.

Current, resistance, and potential difference are all related using the Ohm Law, which states

$$I = \frac{\Delta V}{R} \tag{2.2}$$

where I is the current (measured in Ampers, A), R is the resistance (measured in Ohms, Ω), and ΔV is the potential difference (measured in Volts, V). The Ohm Law states that by establishing a potential difference across an electrical device with resistance R, an electric field is created that will in turn cause a current. This can be written as $V = IR$.

In this experiment, we will be creating both series and parallel circuits. In a series circuit, resistors are aligned end to end, with only one path to take as in Figure 2.1.

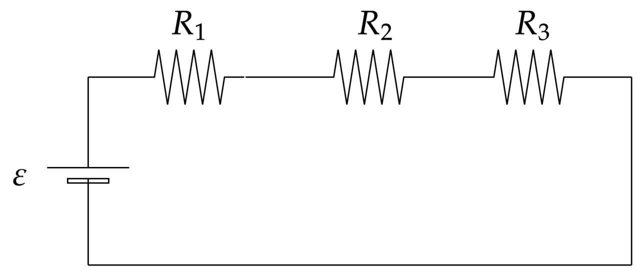


Figure 2.1: An example of a series circuit.

Since there is only one path for the current to take, the current through each of the resistors is the same. The potential difference across each resistor will depend on the value of the resistance. When there is more than one resistor connected in series, it is often important to find the total resistance of the circuit, or the *equivalent resistance*. In series circuits, we find the equivalent resistance using the following equation:

$$R_{\text{eq}} = R_1 + R_2 + R_3 + \cdots \tag{2.3}$$

TASKS

(1) Taking $R_1 = 150 \pm 15\ \Omega$, $R_2 = 470 \pm 47\ \Omega$, and $R_3 = 255 \pm 26\ \Omega$ in Figure 2.1, compute the *average* equivalent resistance and its uncertainty. You may want to read the last section in this manual for the complete set of formulae for the error analysis.

In a parallel circuit, resistors are aligned side-by-side at both ends, as pictured in Figure 2.2.

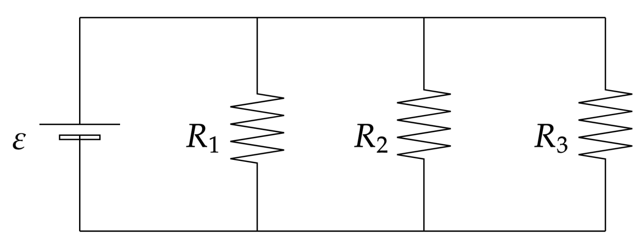


Figure 2.2: An example of a parallel circuit.

In this case, the current has more than one path to take. The potential difference across each "branch" or pathway are the same in parallel circuits. However, the current through each of these branches may be different. Since there is more than one path way for the current to take, parallel circuits actually reduce the total resistance of the circuit. To compute the equivalent resistance of a parallel circuit, we use the following equation:

$$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \tag{2.4}$$

TASKS

(2) Taking $R_1 = 150 \pm 15\ \Omega$, $R_2 = 470 \pm 47\ \Omega$, and $R_3 = 255 \pm 26\ \Omega$ in Figure 2.2, compute the *average* equivalent resistance and its uncertainty. You may want to read the last section in this manual for the complete set of formulae for the error analysis.

2.4 How to use a breadboard

One piece of equipment that you will use in this lab is the breadboard. The breadboard will be the critical component in many of this semester's labs and so we'll spend some time introducing it here. These boards require no soldering and allow you to build prototypes of any desired circuit, from the simplest to very complex ones.

When looking at a breadboard the first thing one notices is that it contains many holes. Every hole is actually an electrical contact connecting to a certain set of neighboring holes. Circuits are created by pushing leads into holes in an appropriate pattern so that all required contacts are made and no incorrect contacts are made. Therefore, the most critical information in using the breadboard is understanding which holes are connected. The breadboard that we are using contains 2 main "busses": Power Rails and Terminal Strips.

The power rails run vertically down the sides as shown in the figure below. Your breadboard has two power rails on the left and two power rails on the right. Each pair is labeled as "+" (red) or "-" (blue). There is actually nothing that forces you to use these contacts for power. However, experience shows that power and ground are the most common contacts in your final circuit and these rails provide many connected holes. Every hole on the power rail is connected. It is important to know that that pair of rails on the left is not connected to the pair of rails on the right. If you wish to have the same power voltages available on both sides, you will need to add your own jumper wires to accomplish this.

The next key components of the breadboard are the Terminal Strips. Terminal strip contacts run horizontally in groups of five. Looking closely at Figure 2.3, you can imagine that "a1 $\rightarrow$ e1" comprise a single terminal strip. Similarly "a2 $\rightarrow$ e2", "a3 $\rightarrow$ e3", etc. are additional terminal strips.

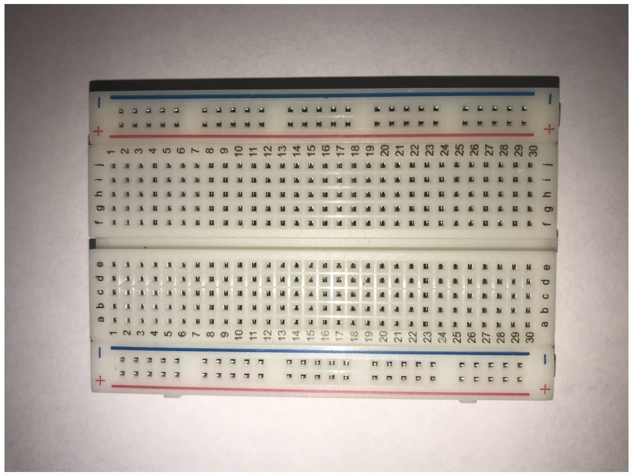


Figure 2.3: The breadboard, again. The "valley" that separates the central region into two is called the crevasse.

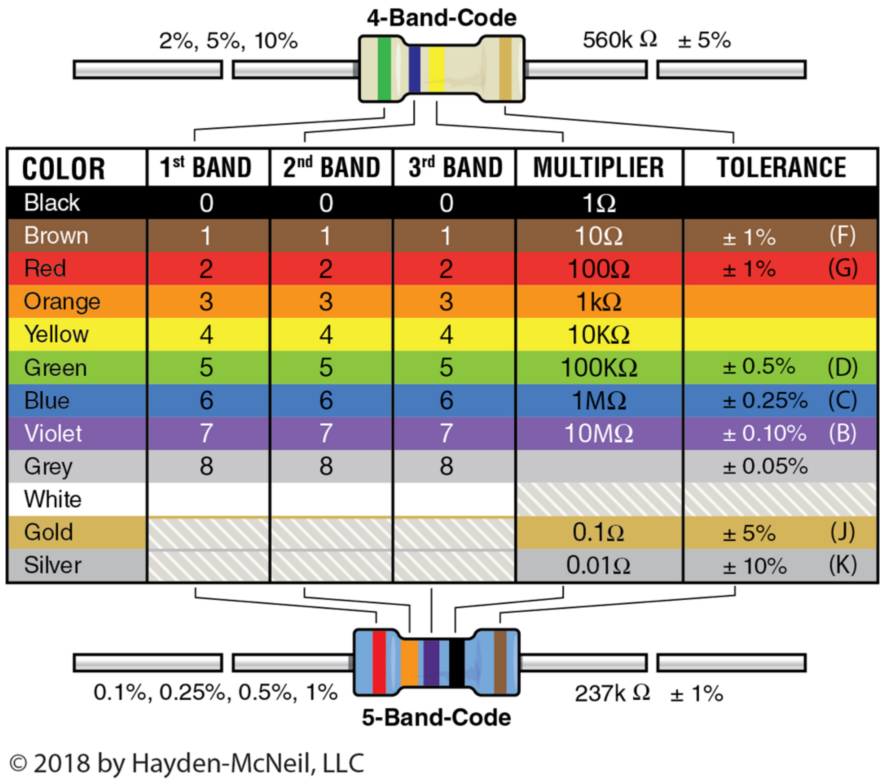
The breadboards are separated by a crevasse between columns e and f. Therefore, "f1 $\rightarrow$ j1" is a separate terminal strip from "a1 $\rightarrow$ e1". Your breadboard has a total of 30 rows and therefore 60 independent terminal strips.

2.5 How to distinguish one resistor from another

Among your supplies, you will need to find two 4.7 kΩ resistors, two 10 kΩ resistors, and three 1 Ω resistors. There is a color code on each resistor that will enable you to determine the resistance and tolerance of said resistors. Every color represents a different value, and each band stands for the digit multiplier, or tolerance. The number of color bands on a resistor can range from 3 to 6. Two of the resistors you have contain 4 bands while the last one has 3.

For a four-band resistor, the first two colors represent the first two digits. For example, if the first two colors were red, followed by green, this gives the number 25 (red = 2 and green = 5). The third band is the multiplier. If our multiplier is black, this is a multiplier of 1, meaning the resistor has a value of 25 Ω (take the multiplier and multiply it by the number given by the first two bands).

The last band is the tolerance of the resistor. Tolerance is the precision of the resistor and is given as a percentage. If the band is gold, those resistors have a 5 percent tolerance, so that means the actual value of the resistor could be 5% higher or 5% lower than value in question. If the resistor in question has 5 bands, the first three are the leading digits, where the 4th band is the multiplier and the 5th is the tolerance. For example, if we had a resistor of color code Red, Black, Black, Brown, Gold, this would leave two a value of 2000 Ω resistor with a 5% tolerance. See Figure 2.4 for a schematic on how to read the resistor codes.



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 1% (G)
Orange	3	3	3	1kΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	± 0.5% (D)
Blue	6	6	6	1MΩ	± 0.25% (C)
Violet	7	7	7	10MΩ	± 0.10% (B)
Grey	8	8	8		± 0.05%
White					
Gold				0.1Ω	± 5% (J)
Silver				0.01Ω	± 10% (K)

Figure 2.4: The color code for determining resistance. (C) 2018 by Hayden-McNeil, LLC.

TASKS

(3) Suppose we have three resistors containing 4 bands of colors given as

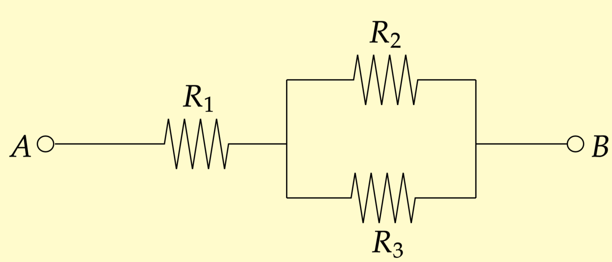
R_1 : orange, orange, orange, silver

R_2 : brown, black, red, silver

R_3 : green, violet, brown, silver

from left to right. Compute the resistance values and their uncertainties.

(4) Compute the equivalent resistance between the points A and B below with the obtained values of $R_1 \pm \Delta R_1$, $R_2 \pm \Delta R_2$, and $R_3 \pm \Delta R_3$.



2.6 Measuring the output voltage of the iOLab device

Although we are using the output port entitled 3.3V from the iOLab device, it is still important to measure this output voltage so we can continue on with the lab in the most accurate manner possible. The way we are going to accomplish this is by creating a voltage divider using two 10 kΩ resistors in series. By taking a measuring of the voltage after the first resistor but before the second resistor, we can determine the output voltage. By using two resistors of the same resistance, we know that the voltage drop across the first resistor will be half of the output voltage (The current in series is the same and the two resistors have the same value, so the voltage drop across each resistor will be the same. Since there are two resistors, this must be half the output voltage).

Take the two 10 kΩ resistors and three male-to-male wires. When you are ready, we are going to construct the circuit in Figure 2.5. The trick is to always start from the power supply, construct the subcircuits (namely, smaller, parallel, and perhaps more complicated parts, if any), then complete the circuit by wiring the *everything* in series, and finally connect the measurement devices[1].

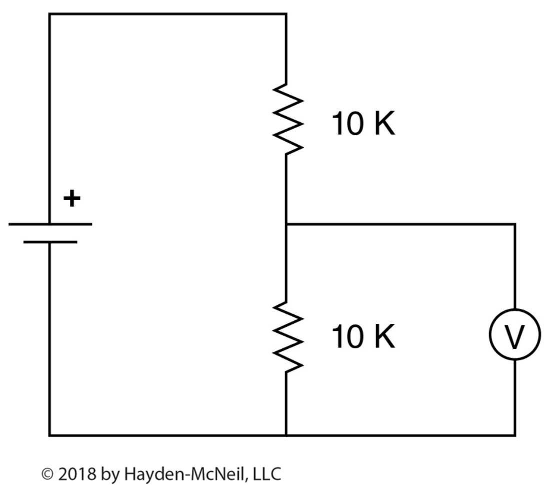


Figure 2.5: The first circuit. (C) 2018 by Hayden-McNeil, LLC.

(1) Connect one end of the first wire to the port 3.3V on the iOLab device.

(2) Connect the other end of the first wire to a hole in any hole in the "+" column (the positive trail) on the left-hand side (for convenience, you may choose it to be the one at the bottom).

(3) Connect one end of the first 10k resistor to any hole in the same positive trail in the previous step.

(4) Connect the other end of the first 10k resistor to any hole in the central region. For convenience, no matter which row you choose (from 1 to 30), you may want to connect it to a hole in the column a so that we have room in the columns b, c, d, and e.

[1]This is just a rule of thumb by experience. You may find any other method easier for your taste. You will have enough experience if you spare one day or two to understand the basics of the breadboard and the connections.

(5) Connect one end of the second 10k resistor in series to the first one; that is, connect it to any hole in the same row as the hole you pick in the previous step. For convenience, you may select the column e now to make room for an additional wire to be connected in between.

(6) Connect the other end of the second 10k resistor in any hole in the negative trail on the right-hand side of the breadboard.

(7) Connect one end of the second wire to any hole in the negative trail on the right-hand side of the breadboard. Imagine the invisible connections between the holes that you have discovered in the previous experiment.

(8) Connect the other end of the second wire to any of the GND ports on the iOLab device.

Now, the circuit is complete. We can connect the items that measures something now, namely the voltmeter, which is provided by the sensor A7: If you connect one end of the third wire to a common hole to the ones in steps (4) and (5) above, and if you connect its other end to the port A7 on the iOLab device, you can take measurements.

When you are ready, launch the application, power on the device, pair it to your computer, select the sensor Analog 7, and start recording data. After waiting for one second or two, stop recording. Select the analysis tool (the tool that is just above the graph you are looking at, that looks like a bar graph). By using this tool, you can read off the values on the graph: Having selected the analysis tool, click anywhere on the graph, hold it, and move the cursor to the left or right (depending on where you start highlighting). There will appear some quantities just below the graph, μ, σ, a, and s, which have been discussed in the section Introduction.

TASKS

(5) What is the voltage value? Include the screenshot of the highlighted graph.

When you are getting averages from the graph, you should never forget to include the uncertainty, as well.

TASKS

(6) Taking into account the two resistance values used in this circuit and the voltage value you have just obtain, and given the circuit in Figure 2.5, what is the voltage provided by the iOLab device? How do you compute it?

The voltage value you find in Task (7) will be used throughout the rest of this experiment.

2.7 Testing the Ohm law: 10 kΩ resistor

IN this part, we are going to test the Ohm Law, $V = IR$, by replacing a known voltage across a known resistor and measuring the induced current. The current measurement is a little tricky. An input pair on your iOLab device that you may not have used yet is the G+/G- ports, known as the High Gain sensor in the iOLab software. This circuit allows you to measure a small difference in potential between two points. This sensor will be used in all sequential measurements in this lab. There are a few caveats to this measurement. Although every exercice in this lab is designed to avoid trouble, you should nonetheless be aware of these if you design your own measurements:

- The measurement range of G+/G- is ± 1 mV.
- In addition to G+ and G- being within one millivolt of each other, each signal should be within 1 V of the iOLab ground.

Consider now the circuit shown in Figure 2.6. However, in order to simulate an ammeter, we need to insert a very small resistance, for which we have the 1 Ω resistors. Thus, indeed, we are connecting a 10 kΩ resistor and a 1 Ω resistor in series. Because 1 Ω is so small as compared to 10000 Ω, the error introduced by the measurement is negligible.

TASKS

(7) Compute the theoretically expected current.

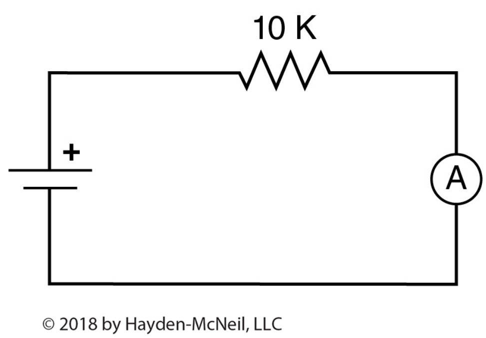


Figure 2.6: Testing the Ohm Law for 10 kΩ resistor. (C) 2018 by Hayden-McNeil, LLC.

Let's focus on the 1 Ω resistor. When we build the circuit, we are going to connect the G+ port to one end of this resistor, and the G- port to its other end. By using the G+/G- ports, we will measure some voltage. Since the resistance is 1 Ω, the current will be given by the voltage divided by 1, which is itself. Hence, whenever we want to measure the current in a branch, we can simply connect a 1 Ω resistor in series to that branch, connect its ends to the ports G+ and G-, and directly convert the apparent voltage value to current. Well, if that just sounds like ammeter with extra steps, it is.

Repeat the procedure by which you construct the two 10k resistors in series, but replace the second one by a 1 Ω resistor. Take two additional wires and connect the ends of the 1 Ω resistor to the ports G+ and G- (the G- wire should be connect to the end of the 1 Ω resistor that is along the negative train, as the sign suggests). Reset any previous runs on the software. Select only the High Gain sensor and start recording. Wait for one second or two.

TASKS

(8) By selecting the analysis tool, highlight the graph, obtain the average voltage value, and then compute the current value.

(9) Compare the experimental current value in the previous task to the theoretical one that you computed in Task (8) by computing the relative percent error.

Make sure that you understand how to connect resistor to the breadboard[2] and comprehend the function and usage of the 1 Ω resistor.

2.8 Two 10 kΩ resistors in series

Unplug everything, construct a circuit with two 10 kΩ resistors in series. Now we are going to measure the current in this circuit. By now, you should have understood the function of the 1 Ω resistor in construction an ammeter. Don't forget to connect the ends of the 1 Ω resistor to the ports G+/G-.

TASKS

(10) Take a photo of your circuit together with the iOLab device and include it in the report.

(11) By using the High Gain sensor, obtain the voltage value, hence the experimental value of the current.

(12) Compute the equivalent resistance.

(13) Compute the expected theoretical value of the current.

(14) Compare the experimental value of the current to the theoretical one by using the relative percent error.

If you don't have the device, please draw a breadboard and show the resistors and other connections (3.3V, GND, G+, and G-) on it. Pay attention to the holes that you draw. You don't have to be artistic but be very clear.

2.9 Two 4.7 kΩ resistors

Repeat the previous section for two 4.7k resistors in series.

TASKS

(15) Take a photo of your circuit together with the iOLab device and include it in the report.

(16) By using the High Gain sensor, obtain the voltage value, hence the experimental value of

[2] Be gentle, or you may hurt the little legs of the resistors.

the current.

(17) Compute the equivalent resistance.

(18) Compute the expected theoretical value of the current.

(19) Compare the experimental value of the current to the theoretical one by using the relative percent error.

2.10 Resistors in parallel

Repeat the previous section for two 10k resistors in parallel. Be careful with the fact that we are not interested in the current along each branch but we want the total current.

TASKS

(20) Take a photo of your circuit together with the iOLab device and include it in the report.

(21) By using the High Gain sensor, obtain the voltage value, hence the experimental value of the current.

(22) Compute the equivalent resistance.

(23) Compute the expected theoretical value of the current.

(24) Compare the experimental value of the current to the theoretical one by using the relative percent error.

2.11 Combination circuit

If you can do this without any problems, congratulations! You have mastered 50% of the electronics experiments that involves the breadboard. When you are ready, take a look at the circuit in Figure 2.7 and built it.

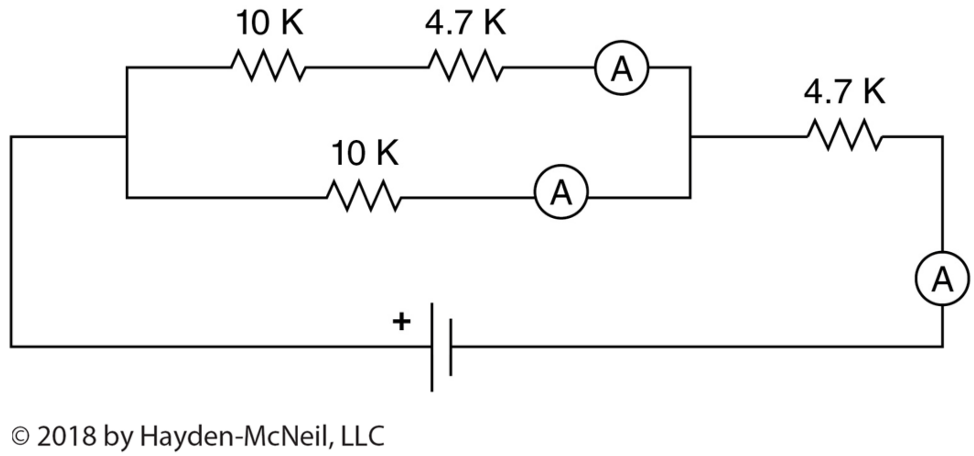


Figure 2.7: A network of resistors. (C) 2018 by Hayden-McNeil, LLC.

Even though you should have three 1 Ω resistors for all the three ammeters, you should not try to measure all the currents at once. Do it one by one.

TASKS

(25) Compute the equivalent resistance in Figure 2.7.

(26) Compute the theoretical current in the "top" branch in Figure 2.7.

(27) Compute the theoretical current in the "bottom" branch in Figure 2.7.

(28) Compute the theoretical current in the "vertical" branch in Figure 2.7.

(29) Measure the current in the "top" branch as described earlier. Include the screenshot of your highlighted graph. Compare the experimental value of the current to the theoretical one by means of relative percent error.

(30) Measure the current in the "bottom" branch as described earlier. Include the screenshot of your highlighted graph. Compare the experimental value of the current to the theoretical one by means of relative percent error.

(31) Measure the current in the "vertical" branch as described earlier. Include the screenshot of your highlighted graph. Compare the experimental value of the current to the theoretical one by means of relative percent error.

2.12 Submitting lab report

In order not to experience any difficulties with the submission, please name your file as

```
p114_exp2_lastname_firstname.pdf
```

or

`p122_exp2_lastname_firstname.pdf`

minding the underscores and avoiding capital letters. Then, click here to submit your paper [3].

[3] If the link does not work, please send your pdf to `kagannsimsek@gmail.com` by typing the subject of the email exactly as Electromagnetism Experiment 2. You may leave the body of the email empty.

Experiment 3

Kirchoff's laws

In the previous lab, we learned how to build circuits using the iOLab device as our voltage source. In this lab, we will be using two voltage sources: the iOLab device and AAA batteries. Due to the fact that we will be using more than one voltage source, it is easiest to use the Kirchoff Laws to analyze the circuit. By using the same trick as the last lab with the 1 Ohm resistors, we can measure the current through the circuit and verify the Kirchoff Laws.

3.1 Objectives

In this experiment, we are going to

- continue learning how to analyze circuits,
- build circuits with more than one voltage source,
- predict the currents in a complex circuit with multiple voltage sources, and
- verify the Kirchoff Laws.

We will need the following materials:

- Wires
- Breadboard
- Two 4.7 kΩ resistors
- Two 10 kΩ resistors
- Three 1 Ω resistors
- Three AAA batteries
- Battery cage

3.2 Useful links

Here are some links that contain useful information about the theory behind this experiment and instructions on how to take and analyze data.

- Kirchoff
- Kirchoff 2
- Measure IOLab Voltage
- Measure the Battery
- Building the Circuit
- Current Direction
- Measuring Currents

3.3 Introduction

As we learned in the last lab, current is the rate at which charge flows. From the law of conservation of charge, we know that charge cannot be created nor destroyed. However, charges can move and be transferred from one object to another. Due to the relationship between current and charge, the only way that we would be able to decrease the current through an ideal wire, would be to decrease the amount of charge, or decrease the velocity at which the charges flow. Due to the conservation of charge, we know that we cannot decrease the amount of charge, but is decreasing the velocity possible? If we use the pipe through which water flows as a comparison again, we know that the amount of water that flows into the pipe must be equal to the amount of water that flows out of the pipe. Therefore, the water is flowing out of the pipe at the same rate that it flows in. It is the same for a current-carrying wire. The rate at which charge flows in is equal to the rate at which charge flows out. Therefore, this leads to the law of conservation of current, which states that the current in a current-carrying wire is the same at all points.

This is easy to picture if there is only one path through which the current flows, but what happens if there are multiple paths as in Figure 3.1?

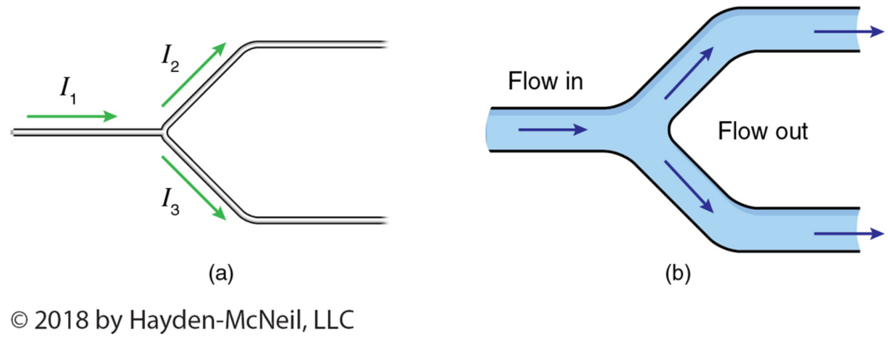


Figure 3.1: (C) 2018 by Hayden-McNeil, LLC

In this picture, the wire has branched into two separate paths. However, the general rule still applies: the current that flows in still must equal the current that flows out. In part (a) of Figure 3.1, this would mean that $I_1 = I_2 + I_3$. A more general way to write this is

$$\sum_{\text{in}} I_i = \sum_{\text{out}} I_i \tag{3.1}$$

This is formally known as the Kirchoff Junction Law, and states that the sum of the currents into a junction equals the sum of the currents coming out of that junction.

It is also important to note that in reality, it is the electrons that move and cause current. Due to the structure of the atom and the strong force, protons are locked into the nucleus. However, with the proper amount of energy, electrons can be transferred between atoms. Although it is known now that it is the electrons that move around the circuit, in the past it was believed that it was the positive charges that moved and caused current. Therefore, conventional current is defined as the movement of positive charges through the wires of a circuit. This movement of positive charges, however, has the same effect in the circuit as the movement of negative charges. Conventional current starts at the positive terminal of the battery and travels through the circuit to the negative terminal. Electron flow, on the other hand, starts at the negative terminal of the battery and travels through the circuit to the positive terminal. Therefore, when dealing with circuits, we deal with conventional current. However, it is really the electrons that move, and in the opposite direction as the coventional current. You will be dealing with conventional current in this lab, but it is important to know what is actually happening.

In the previous labs, we also dealt with the electric potential. The electric potential deals with the amount of work needed to move a charge from point A to point B within an electric field, per unit charge. In other words, it is the potential energy possessed by a small charge, q, divided by the charge itself. When talking about electric potential, we often use the term potential difference, as charged particles will often move through a region of changing potential. Therefore, we will look at $\Delta V = V_f - V_i$, with V_f being the potential at the ending point and V_i being the potential at the starting point. Similar to the way that the amount of work done in moving a mass up a hill from point 1 to point 2 is independent of the path, the amount of work done in moving a charge from point 1 to point 2 (where the electric potential at point 2 is greater than the electric potential at point 1) is independent of the path. So what if the starting point is the same as the ending point, as in many circuits? Since the electric potential is the same at the starting and ending points, the potential difference around the loop, is 0 Volts. This is more formally known as the Kirchoff Loop Law, which states that the sum of all potential differences encountered while moving around a loop or closed path is zero. This can be represented as

$$\Delta V_{\text{loop}} = \sum_i (\Delta V)_i = 0 \tag{3.2}$$

With these two laws in mind, we will be able to theoertically find the current at three different locations in the specified circuit. We will then be able to build the circuit and test to see if our measurements match our theoretical expectations.

3.4 The circuit

Please see Figures 3.2 and 3.3 for the schematic and circuit diagram of the circuit you will be building.

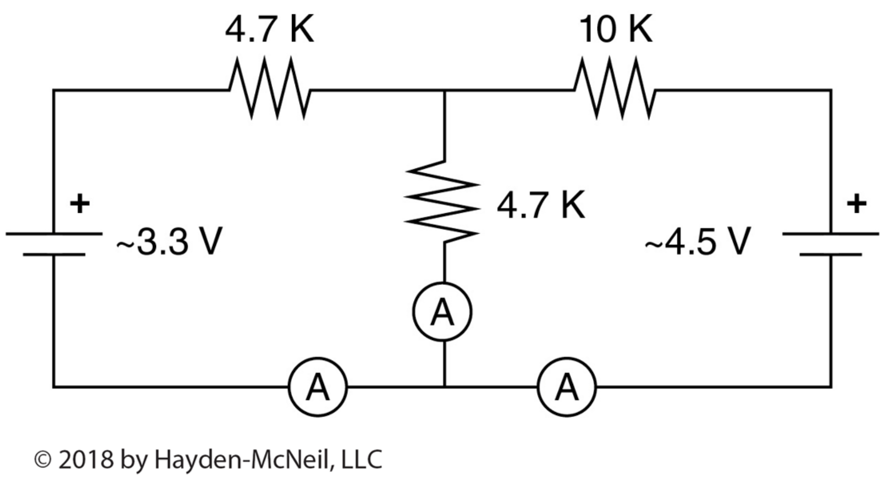


Figure 3.2: (C) 2018 by Hayden-McNeil, LLC

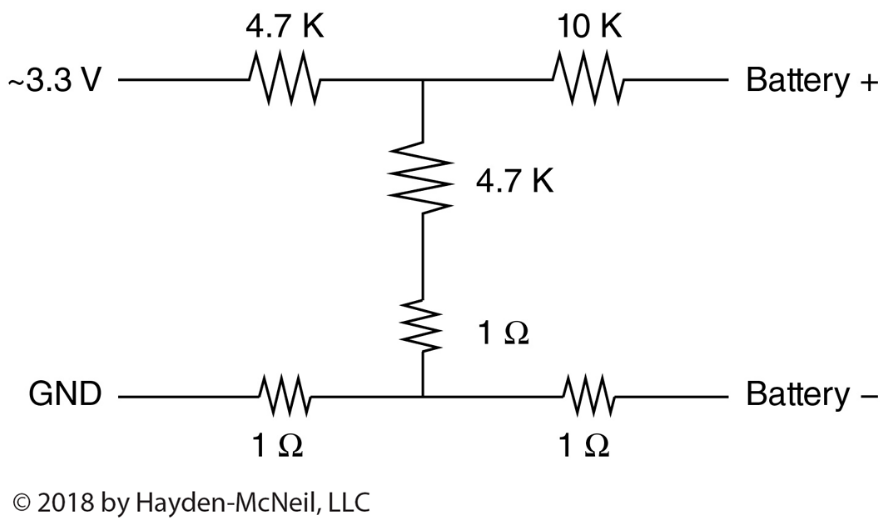


Figure 3.3: (C) 2018 by Hayden-McNeil, LLC

Everywhere there is a 1 Ohm resistor is where you will measure the current using the A7 sensor in the software. Remember that this is a voltage, but you are across a 1 Ohm resistor. You will then compare the measured values to the ones you calculated using the Kirchoff Loop Law and the Kirchoff Junction Law.

3.5 Measuring your supply voltages

Depending upon the state of the batteries in your iOLab device and the state of the batteries in your battery pack, the actual power supply voltages will differ from the expected values. Just as done in prior labs, you will be able to get the most accurate results by measuring the actual values and using these rather than the ideal ones.

There is one caveat. The iOLab analog inputs can only measure voltages in the range ±3 Volts. To compensate for this, we will use a voltage divider with equal resistors to measure half the supply voltage as shown in the videos below. This is the same procedure that was done in the previous lab, remember for this measurement to use the A7 sensor.

Be certain to include the results of both these measurements in your lab report, both as measured and doubled for use in further calculations.

When you are ready, take three wires and two 10k resistors.

(1) Connect the first wire between 3.3V on the iOLab device and anywhere along the positive trail on the left-hand side.

(2) Connect the second wire between GND on the iOLab device and anywhere along the negative trail on the right-hand side.

(3) Connect the first 10k resistor between anywhere on the positive line on the left-hand side and c5.

(4) Connect the second 10k resistor between e5 and anywhere on the negative line on the right-hand side.

(5) Connect the third wire between A7 on the iOLab device and d5.

We have just built a voltage divider. We are measuring the voltage across the second 10k resistor (because it is between the ground and the A7 sensor).

Launch the iOLab application, power on the iOLab device, pair it to your computer, select the sensor Analog 7, and start recording.

TASKS

(1) Wait for some time. Stop recording. Highlight the graph and record the voltage value. Include the screenshot of the graph with the highlight.

(2) Now that we know the voltage across one 10k resistor and we have two of them, what is the voltage provided by the iOLab device?

Now, we are going to do it for the batteries.

(1) Place the three AAA batteries into the appropriate cage.

(2) Remove the wire that goes between the breadboard and the 3.3V port on the device.

(3) Connect the red wire that comes out of the batteries to anywhere along the positive line on the left-hand side.

(4) Do not remove the wire that goes to the GND.

(5) Connect the black wire that comes out of the batteries to anywhere along the negative line on the right-hand side.

Reset any previous runs on the application. Select the sensor Analog 7. Start recording.

TASKS

(3) Wait for some time. Stop recording. Highlight the graph and record the voltage value. Include the screenshot of the graph with the highlight.

(4) Now that we know the voltage across one 10k resistor and we have two of them, what is the voltage provided by the batteries?

3.6 Build your circuit

Next we need to implement our circuit on the breadboard. We are using 1 Ohm resistors in every place at which we desire to measure current. Because 1 Ohm is such a small voltage, the presence of these resistors does not significantly affect our results.

To implement the circuit we will use both sets of power rails (one for the iOLab power and one for the battery back power) as well as multiple resistors. Figure 3.4 shows one possible way to wire the circuit. Because of the flexibilty of the breadboard, there are many ways to correctly wire the circuit. Experience shows, however, that choosing a neat placement of components that looks similar to the original circuit diagram is effective in reducing the probability of wiring errors.

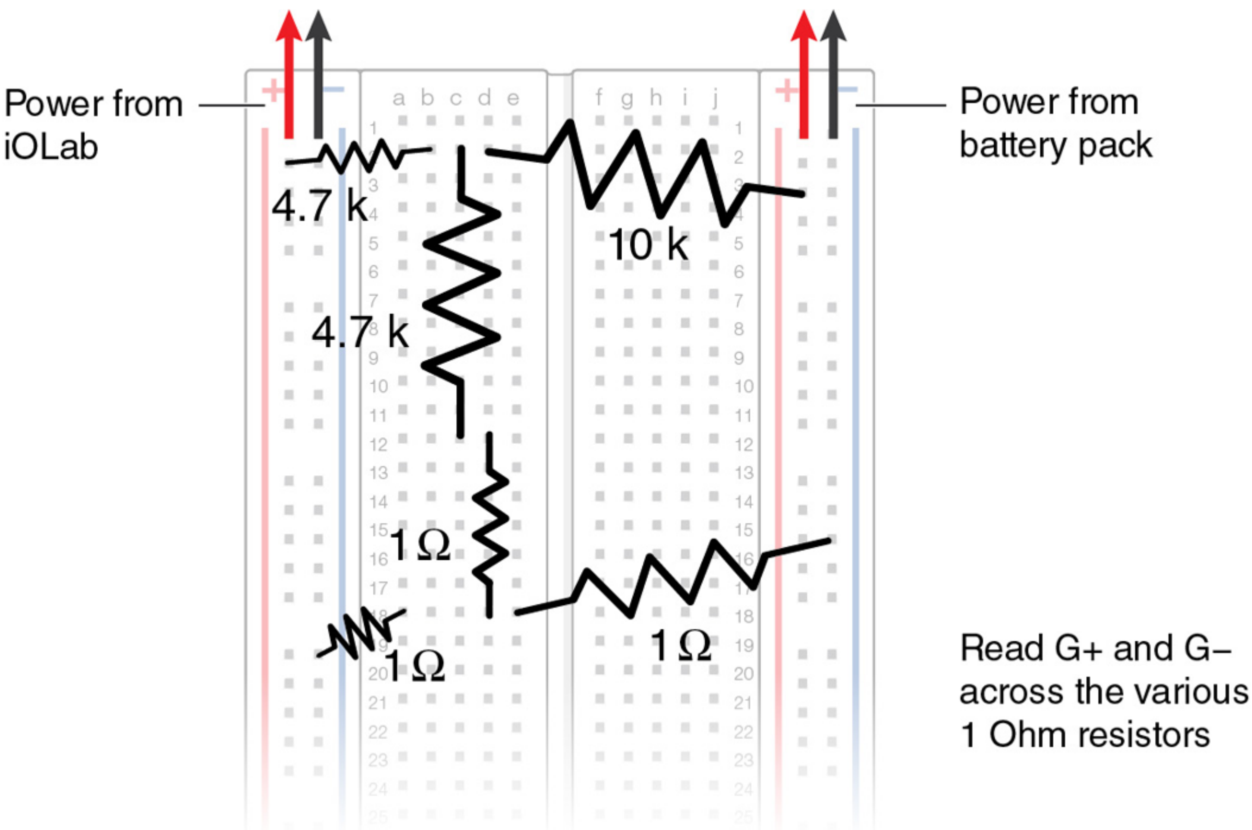


Figure 3.4: (C) 2018 by Hayden-McNeil, LLC

Now that your circuit is complete, you must perform a Kirchoff circuit analysis before proceeding to the next step. This analysis should predict for us both the magnitude and direction of the three currents that we will measure.

TASKS

(5) Find the theoretical direction and magnitude of the current read by the ammeter in the vertical branch in Figure 3.2.

(6) Find the theoretical direction and magnitude of the current read by the ammeter on the left-hand side in Figure 3.2.

(7) Find the theoretical direction and magnitude of the current read by the ammeter on the right-hand side in Figure 3.2.

Depending on how you proceed, you may not obtain the current values in this order. If you don't obtain the current values in this order, just solve the problem before Task 5 and quote the results in Tasks 5, 6, and 7.

3.7 Measure current directions

We will verify the Kirchoff calculation in two steps:

- Verify the direction that each current is flowing.
- Verify the value of each current.

We'll proceed first with the current direction by using the High Gain sensor. By placing the G- input to the iOLab at the junction point between the three 1 Ohm resistors, we have made it simple to measure all three currents by simply moving the G+ lead onto the other end of each resistor. Since we are only concerned with direction at this point, we shall:

- Predict whether each voltage measurement will be positive or negative.
- Check the prediction measurement.

Note that you will be assuming that the current is running in the direction from G+ to G-. Therefore, you should note which ways you hook up the high gain sensor. If you get a positive value, this means that this is actually the way that current is moving. If you get a negative value, it means that the current is flowing in the opposite direction. As a result, by determining if the current is positive or negative, you can determine the direction of the current.

Once you build the circuit given in Figure 3.4 and feel ready, take two wires.

(1) Connect one end of the first wire to G+ on the iOLab device.

(2) Connect the other end of the first wire between the 4.7k and the 1 Ohm resistors in the vertical branch. This point can be any of a12, b12, and e12 in Figure 3.4. Please select this point based on your connections on your breadboard.

(3) Connect one end of the second wire to G- on the iOLab device.

(4) Connect the other end of the second wire at the junction of the three 1 Ohm resistors. This point can be either of b18 and c18 in Figure 3.4. Please select this point based on your connection on your breadboard.

(5) Reset any previous runs on the software. Select only the High Gain sensor. Start recording, wait for some time, and stop recording.

TASKS

(8) Take a screenshot of the graph you have just obtained (no highlights, just the graph itself). Record the sign of the voltage, and deduce the sign of the current.

Now, remove the end of the G+ wire from the breadboard[1] and connect it to anywhere along the negative lines on the left-hand side. Reset the previous run on the software. Select the High Gain sensor, start recording data, wait for some time, and stop recording.

TASKS

(9) Take a screenshot of the graph you have just obtained (no highlights, just the graph itself). Record the sign of the voltage, and deduce the sign of the current.

Finally, remove the end of the G+ wire from the negative line you have just connected, and connect it to anywhere along the negative line in the left-hand side. Reset the previous run on the software. Select the High Gain sensor, start recording data, wait for some time, and stop recording.

TASKS

(10) Take a screenshot of the graph you have just obtained (no highlights, just the graph itself). Record the sign of the voltage, and deduce the sign of the current.

(11) Draw the circuit given in Figure 3.2 on a piece of paper and indicate the direction of the currents read in all the ammeters. You should be able to determine which current you analyzed in Tasks 8, 9, and 10. Take a photo of this figure and include it in this Task.

It is essential to remark that if you have a positive sign for the voltage measured at the High Gain sensor, then one should realize that the current goes from G+ to G-, and that if you have a negative sign for the voltage measured at the High Gain sensor, then the current goes from G- to G+.

3.8 Measure current values

The trick that we use to measure current with the High gain Sensor is a good one, but it is prone to subtle troubles. Because the voltages involved are so small, minute errors (such as the thermo-

[1]If you have copied the connections in Figure 3.4, then it was any of a12, b12, and e12.

electric effect) creep in and disturb the measurement. You will find that swapping the G+ and G- leads changes the result! Hey, what's 10 microVolts among friends? To minimize this error, we will

- Measure both the normal and swapped configuration of the High Gain leads.
- Measure the values multiple times (3x each way).
- Average the absolute values of the 6 measurements.

When you are ready, unplug the wires that goes to G+ and G- from your breadboard but the rest should stay as is. Prepare the following table:

Vertical branch		Left branch		Right branch	
Trial	Current (mA)	Trial	Current (mA)	Trial	Current (mA)
1		1		1	
2		2		2	
3		3		3	
4		4		4	
5		5		5	
6		6		6	

Here, Vertical branch refers to the ammeter in the vertical branch that contains the 4.7k resistor in Figure 3.2, Left branch refers to the ammeter in the horizontal branch in bottom left in Figure 3.2, and Right branch refers to the ammeter in the horizontal branch in bottom right in Figure 3.2.

For Task 12, you can continue recording until you obtain the last data (the 18th data). You don't have to include a screenshot of your graph. Also, during the measurement, you don't need to take average: Just hover your cursor along the constant voltage line and pick a value on that graph.

TASKS

(12) By using two wires and the High Gain sensor, measure the voltage across the 1 Ohm resistor in the vertical branch[a]. By taking its absolute value, deduce the current value and record it in as the current value for the first trial for the vertical branch in the table.
Change the *polarity*[b]. Measure the voltage again and deduce the magnitude of the current. Record this as the current value in the second trial for the vertical branch. Repeat this procedure two more time so that you have 6 trials.
Repeat the procedure for the 1 Ohm resistors in the left and right branches, as well. Fill the table.

[a] For instance, as in Figure 3.4, if the 1 Ohm resistor is connected between d12 and d18, connect G+ to d12 and G- to d18.

[b] For instance, as in Figure 3.4, if the 1 Ohm resistor is connected between d12 and d18, connect G+ to d18 and G- to d12.

3.9 Error analysis

Finally, now that you have recorded 6 values for each of the three currents, you will need to analyze the results.

TASKS

(13) Compute the average and the uncertainty of the six current measurements for the vertical branch. Compare it to the theoretically expected current value by using relative percent error.

(14) Compute the average and the uncertainty of the six current measurements for the left branch. Compare it to the theoretically expected current value by using relative percent error.

(15) Compute the average and the uncertainty of the six current measurements for the right branch. Compare it to the theoretically expected current value by using relative percent error.

3.10 Submitting lab report

In order not to experience any difficulties with the submission, please name your file as

`p114_exp3_lastname_firstname.pdf`

or

`p122_exp3_lastname_firstname.pdf`

minding the underscores and avoiding capital letters. Then, click here to submit your paper [2].

[2] If the link does not work, please send your pdf to `kagannsimsek@gmail.com` by typing the subject of the email exactly as Electromagnetism Experiment 3. You may leave the body of the email empty.

Experiment 4

Magnetic field

In this experiment, we will be measuring the magnetic field created by a current flowing through a long straight wire. We will use iOLab's 3-axis magnetometer along with the wheel to measure the magnetic field as a function of position near to a wire carrying a large current. Analysis of the data will only verify the result from the Ampere Law, but also confirm the shape of the magnetic field as being comprised of concentric circles surrounding the wire.

4.1 Objectives

In this experiment, we are going to

- learn to measure magnetic field strength and direction,
- understand how to derive the field of a wire using the Ampere law,
- verify the shape of the magnetic field around a wire (circles), and
- verify that the magnitude of the field falls off as $1/r$.

We will need the following materials:

- Three or four D batteries with appropriate battery cage
- Breadboard
- Two 0.5 Ω resistors
- Two 10 kΩ resistors
- 12 ft spool of wire
- Wire leads

4.2 Useful links

Here are some links that contain useful information about the theory behind this experiment and instructions on how to take and analyze data.

- Long wire
- Magnetic field calibration
- Magnetic field setup
- Magnetic field data taking

4.3 Introduction

In this experiment, we will be measuring the magnetic field due to a large current flowing through a straight wire. Despite using currents of typically 2 A (depending upon the freshness of your batteries), the magnetic fields will be rather small and we will need to take care with the calibration of our device and control for stray fields like the magnetic field of the Earth.

4.3.1 Ampere law

For a collection of currents that exhibits sufficient symmetry, the Ampere law provides the simplest means by which to calculate the magnet's field. The Ampere law states that

$$\oint \vec{B} \cdot \mathrm{d}\vec{L} = \mu_0 I_{\mathrm{in}} \tag{4.1}$$

Simple solutions exist when the magnetic field is uniform along some closed path. Consider Figure 4.1.

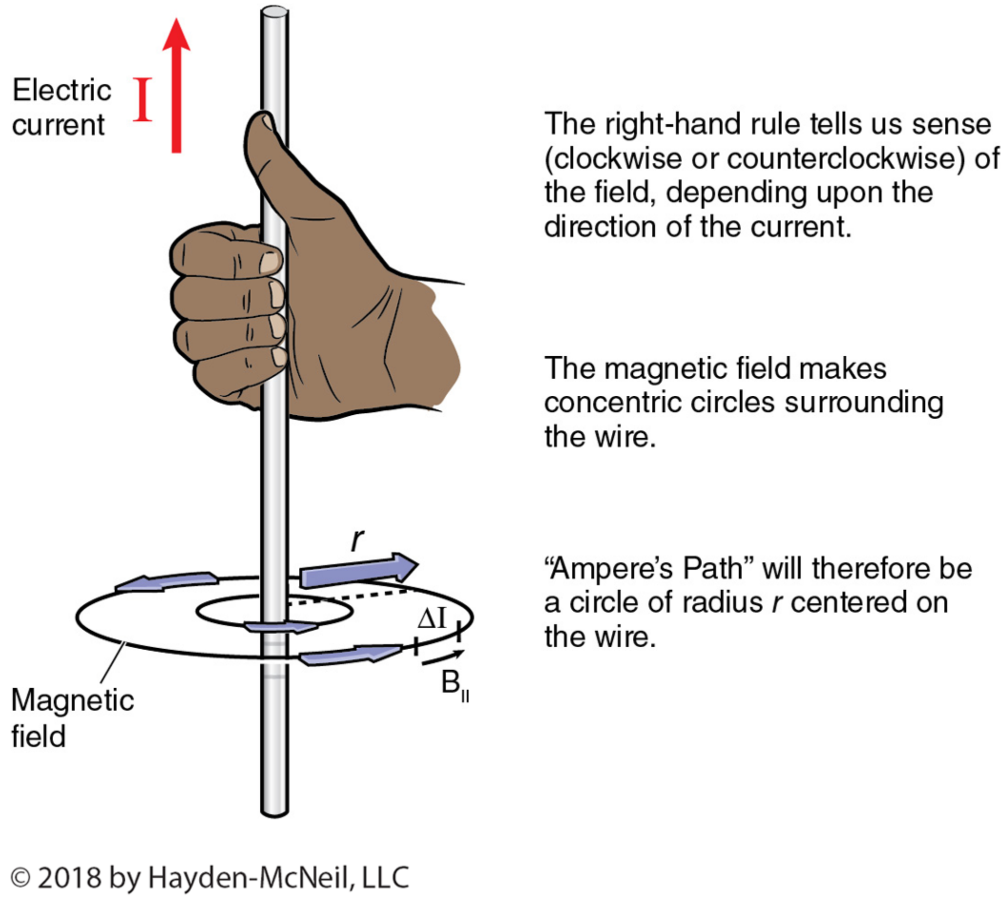


Figure 4.1: Moving charges create magnetic field. (C) 2018 by Hayden-McNeil, LLC

Here the field lines make circles centered on the wire and define that we should "walk" a circular Ampere path. Along this path, B is both constant and parallel to $\mathrm{d}L$. Thus,

$$\oint B \, \mathrm{d}L = \mu_0 I_{\text{in}} \tag{4.2}$$

$$B \oint \mathrm{d}L = \mu_0 I_{\text{in}} \tag{4.3}$$

$$BL = \mu_0 I_{\text{in}} \tag{4.4}$$

where $L = 2\pi r$ and $I_{\text{in}} = I$. Hence,

$$B = \frac{\mu_0 I}{2\pi r} \tag{4.5}$$

In this experiment, we are going to verify this formula.

4.3.2 The measurement

The iOLab device contains a magnetometer in its upper left corner. We will use three D cells and two high-power 0.5 Ohm resistors to establish a large enough current to detect the magnetic field. We will then "roll" the iOLab magnetometer through the field. Consider Figure 4.2.

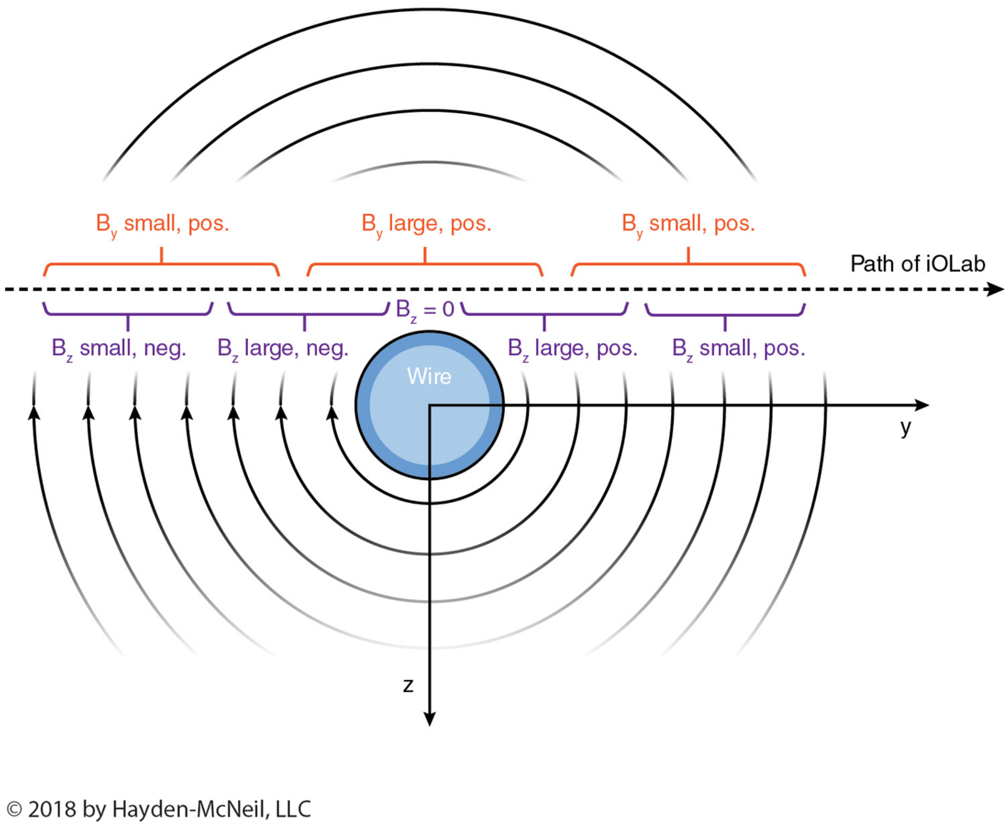


Figure 4.2: The magnetic field components measured by the iOLab device. (C) 2018 by Hayden-McNeil, LLC.

The blue circle indicates a wire that carries current into the screen or into the paper. As a result, the field lines make concentric clockwise circles. The iOLab will be placed with the wheels facing the floor and rolling along the direction indicated by the dashed black arrow. As a result, the iOLab coordinate system (indicated on the front face) will match the axes shown: positive z is downward and positive y is to the right.

Because the magnetometer is inside the iOLab, it will pass 1 cm above the wire itself. Now, follow the field lines carefully. As indicated in red, the y component of the field is always positive and is at its largest when the magnetometer is closest to the wire, i.e. directly above it.

The purple markings in the figure indicate what one might expect for the z component of the magnetic field. Everywhere to the left of the wire, the lines point up. Everywhere to the right of the wire, the lines point down. Thus, the z component of the magnetic field should be expected to "flip sign" as the iOLab crosses $y = 0$. Furthermore, just prior to flipping sign, the z component will peak due to the close proximity of the wire. Both of these behaviors are summarized in Figure 4.3. Be certain that

- you understand why these components behave as indicated, and

- you are able to deduce the direction of the current using either the B_z or B_y measurement.

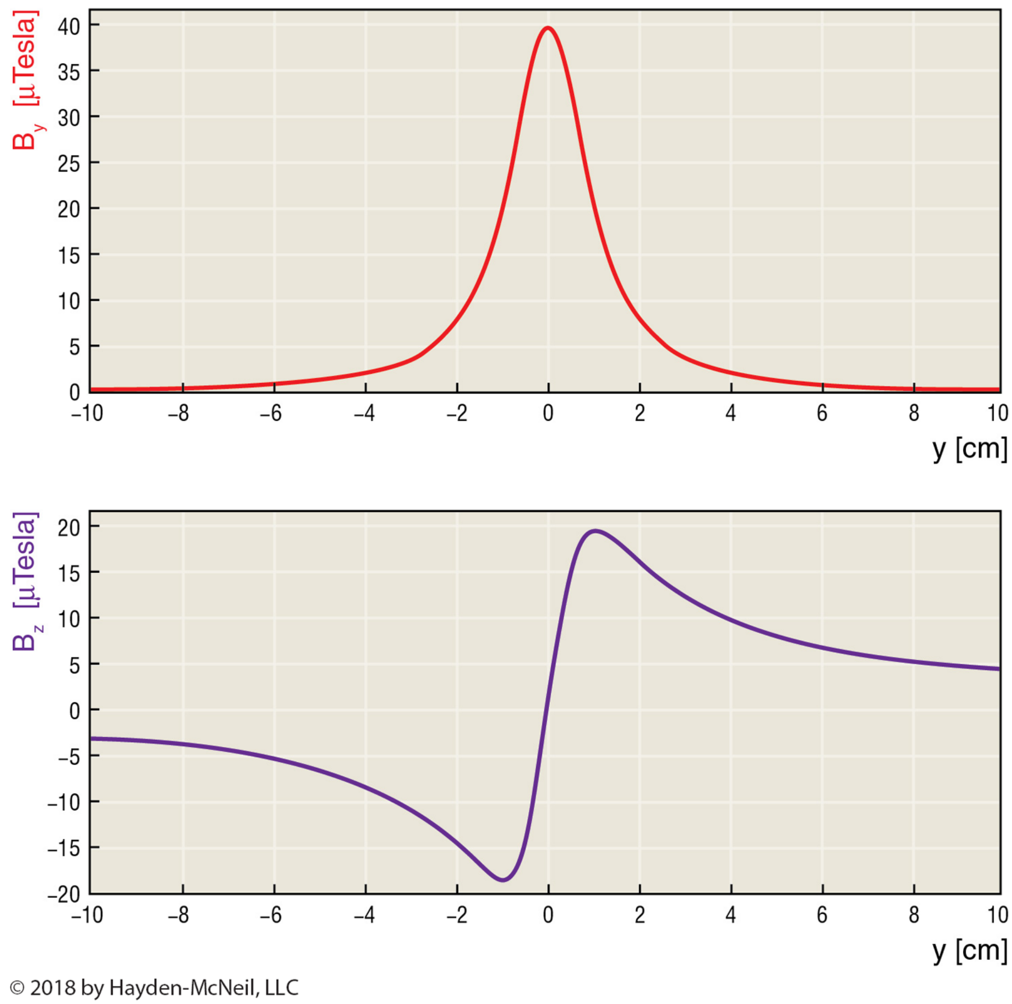


Figure 4.3: The measurement of the y and z components of the magnetic field. (C) 2018 by Hayden-McNeil, LLC.

4.3.3 Digging deeper

Curves like the red and purple lines above are representative of the data you will collect and will qualitatively demonstrate that the field lines make circles around the wire. As the last measurement, we will use our data to make a more profound conclusion about the rate at which the field falls with r. Consider for a moment Figure 4.4.

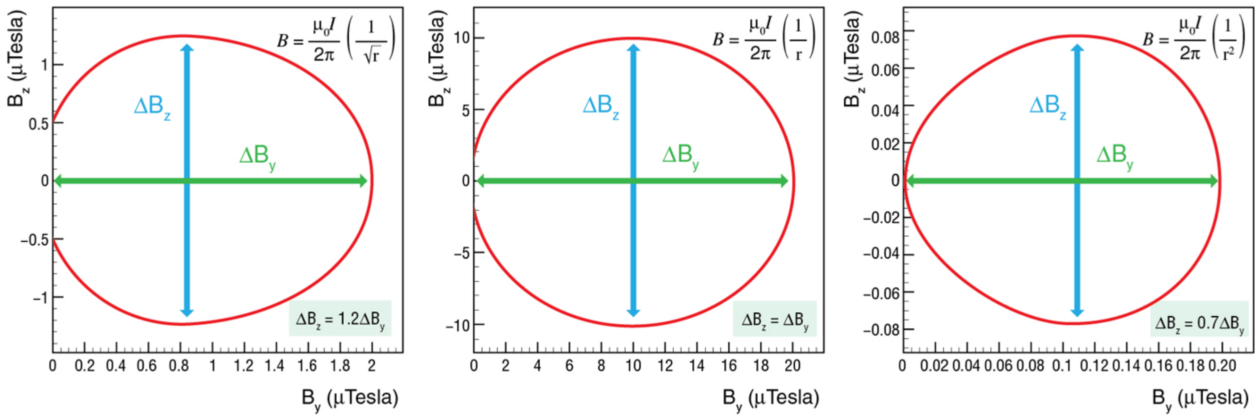


Figure 4.4: Parametric plots for B_z vs. B_y. (C) 2018 by Hayden-McNeil, LLC.

The center plot represents a correct calculation of B_z vs. B_y since it uses the correct formula for the magnetic field (a $1/r$ dependence). Notice that this plot makes a perfect circle with the width matching exactly the height. The other two plots are not circles since they assume different r-dependencies of the fall off of the magnetic field. Please note that these two formulae are very bad since they do not even have correct units. Nonetheless, we can see that the shape of the plot does indicate the correct "power of r" that the field formula follows. You will measure exactly this correlation and compare your results to these figures to see whether the iOLab measurement can indeed prove the $1/r$ result from the Ampere law.

4.4 Calibration

The magnetic field probe is very sensitive and measures quite small magnetic fields. This also means that the measurements can easily be disturbed by stray fields in the local environment. For this reason, we are going to both calibrate the sensor and verify the accuracy of the calibration prior to making our measurements. Be certain to find a good space for performing your measurement on a non-magnetic table, far from any high current devices, and also far from field sources like the neodymium magnets from your lab kit. Once you have selected a good place for making the measurements, follow the instructions in the video below to both calibrate and verify your device. To get to the calibration, when in the iOLab software, click the settings button on the top tool bar, select calibration and then from the drop down menu, select the `Accel-magn-gyro` option (Figure 4.5).

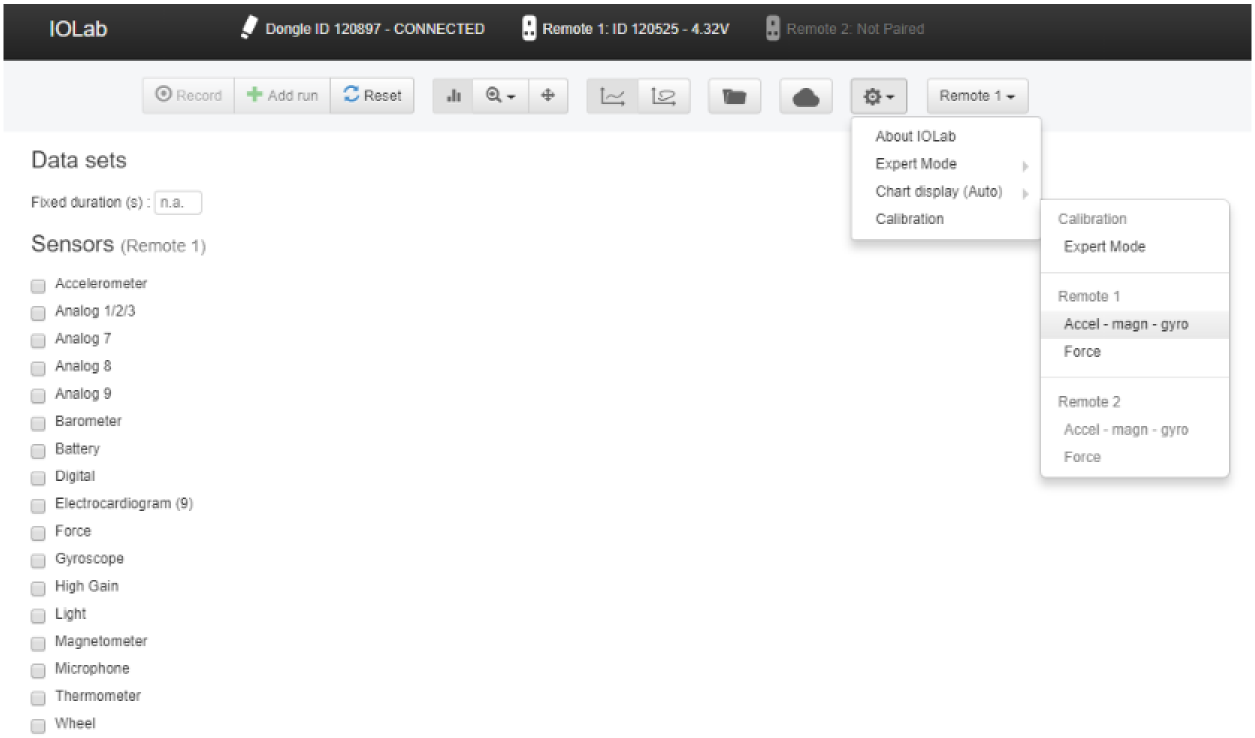


Figure 4.5: Calibration menu in the iOLab software.

After the calibration is completed, we have to test it. Select the Magnetometer sensor from the left, and deselect Bz above the graph that has just appeared. Put the device on a piece of paper on a table with the wheels pointing toward the ceiling, hit record, and then rotate the device about its center of mass (the point G on the front face) six times (Figure 4.6). You will see very roughly sine-like waves in the graph. Stop recording.

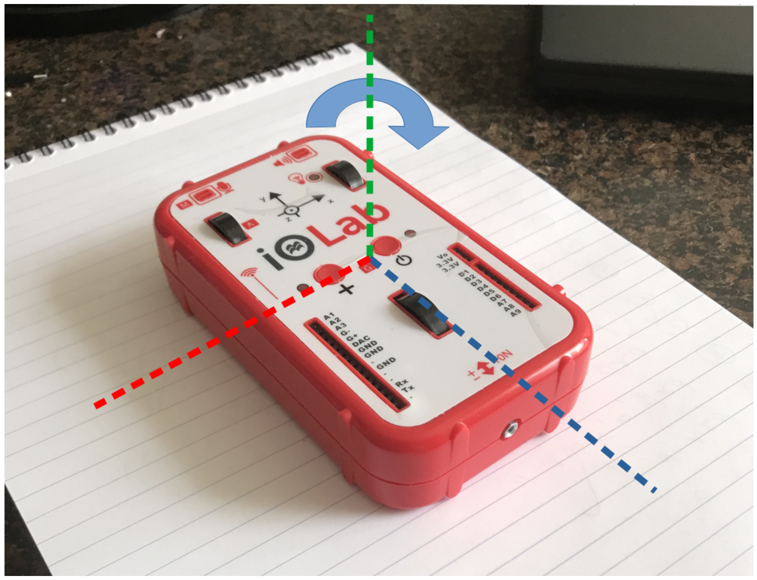


Figure 4.6: Rotate the device about the vertical axis passing through its center of mass.

We are going to switch to the parametric mode now. Click on the button that looks like a closed curve in an xy plane (See the top panel: From left to right, Record, Add run, Reset, Analysis tool (bar-chart like button), Zoom (magnifier), Browse mode (two arrows at right angle to each other), Chart mode (wavy line), and then Parametric mode).

After switching to the parametric mode, select the analysis tool and highlight all the data – be advised, you can highlight the data at the bottom, namely the rough wavy line.

Then click on the Settings button, located just below the bottom left corner of the graph (a box with an arrow, pointing in the "north-eastern" direction). You will see a row that looks like Magnetometer, Norm, Magnetometer, Norm, and so on. Change the first Norm to By and the second Norm to Bx.

TASKS

(1) Take a screenshot of the graph.

By just looking at the graph, the greatest diameter in the horizontal direction seems to be equal to the greatest diameter in the vertical direction, so we have a circle (it does not look like a circle due to the aspect ratio). If you are not satisfies with the shape you obtain, please re-calibrate your device; otherwise, move to Task 2.

TASKS

(2) Compute the ratio of the greatest diameter in the horizontal to the greatest diameter in the vertical by measuring it in anyway you like (holding a ruler at the your screen, or using a screenruler application).

This will be your reliability factor.

TASKS

(3) Compute the absolute value of the difference between this factor and 1. This number will be your first global uncertainty.

Now, we are going to repeat it for the pair of By and Bz. You will repeat the same procedure, but with the exception that you will now put the device on its side (so that the front face will look ahead, and you will see the back of the device, and the y axis of the device points to the left and the x axis points downward). Rotate the device 6 times in the plane of the table again on its side about an axis normal to the table, passing through the center of mass (Figure 4.7). Also, when you are in the parametric mode, change the first Norm to By and the second Norm to Bz in the Settings window.

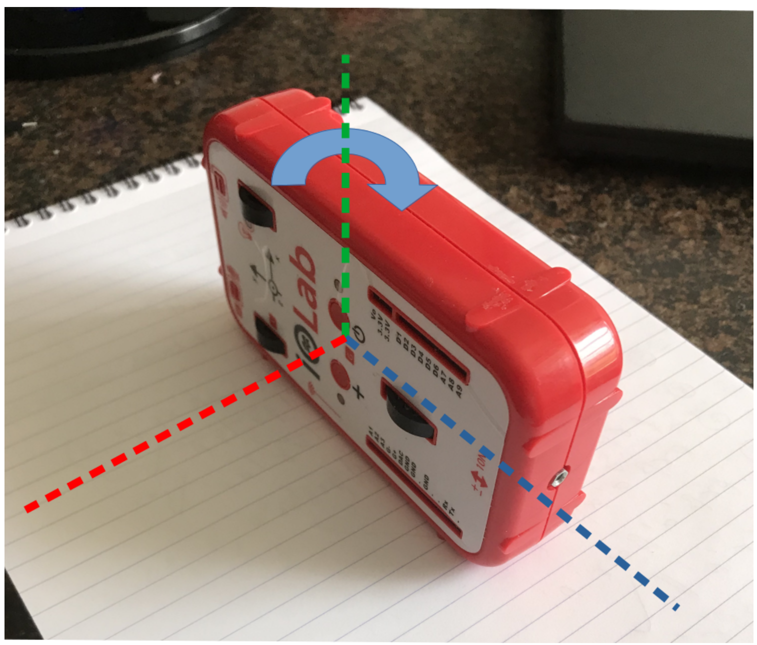


Figure 4.7: Rotate the device on its side about the vertical axis passing through its center of mass.

TASKS

(4) Take a screenshot of the graph.

(5) Compute the ratio of the greatest diameter in the horizontal to the greatest diameter in the vertical by measuring it in anyway you like (holding a ruler at the your screen, or using a screenruler application).

(6) Compute the absolute value of the difference between this factor and 1. This will be your second global uncertainty.

(7) Compute the average of the two global uncertainties. By multiplying the result by 100, treat this number as a global tolerance (or error percentage) of your data.

4.5 Experimental setup

The schematic for the circuit to be used is indicated in Figure 4.8.

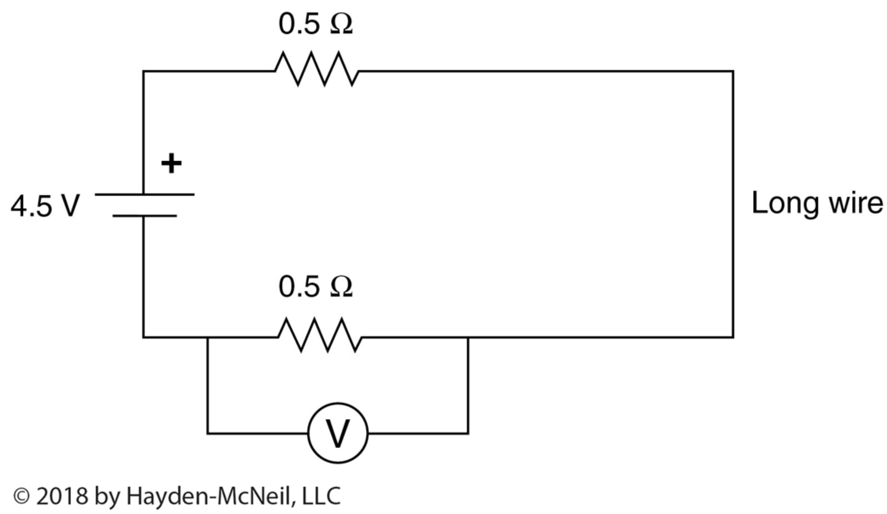


Figure 4.8: (C) 2018 by Hayden-McNeil, LLC.

Here, the 4.5 V source is the pack of three D batteries. We will limit and measure the current in the circuit using the two 0.5 Ohm high-power resistors. Be certain that you are using the correct resistors since low-power resistors will become extremely hot and may smoke with this much current running through them. Expect to have over 2 A of current in your circuit when the batteries are fresh.

Because we are drawing a large current from the batteries, they will not last for a long time. Be certain that the long wire is unplugged when you are not using the circuit.

Before starting to take data, we are going to remove the effects of all the external magnetic sources (including the one due to the Earth) by aligning the device in the direction of the Earth's magnetic field.

(1) Take a piece of paper and put the iOLab device on it on a flat table. Note that you will need a lot of space to do this experiment, so arrange your desk accordingly. You may also do it on the floor.

(2) Mark the location of the magnetometer (denoted by the point M in the top left corner on the front face of the device) on the paper (Figure 4.9).

(3) Put the iOLab device away from the paper.

(4) Draw a line that is parallel to the short side of the paper and that goes through the point which shows the location of the magnetometer (Figure 4.10).

(5) Put the device on the line again so that the line goes through the magnetometer (Figure 4.11).

(6) Launch the software, power on your device, pair it to your computer, select the sensor Magnetometer on the left, deselect Bx and Bz, and hit Record.

(7) On the graph you may see a nonzero value. Now, rotate the paper (but try not to move the device) in clockwise or counterclockwise direction until the By value becomes exactly zero (up to really minor errors).

(8) When you obtain $B_y = 0$ to a really good approximation, stop recording. Now do not touch or remove the paper. We will use this direction in a second.

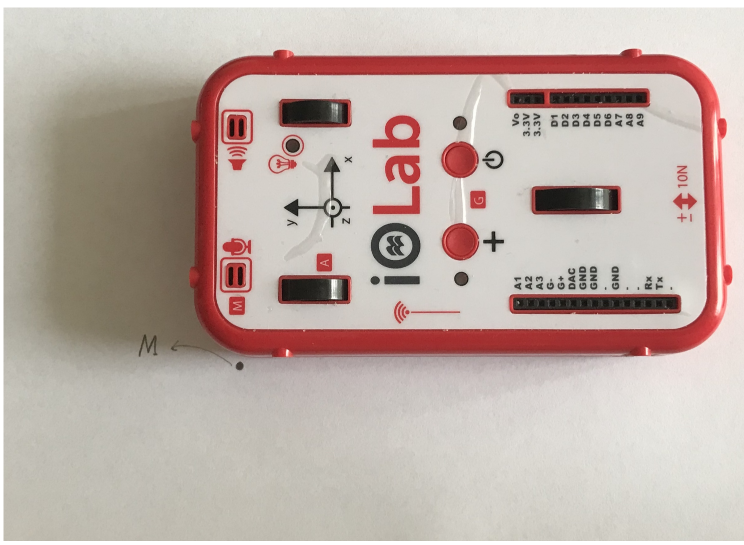


Figure 4.9: Mark the location of the magnetometer on the paper.

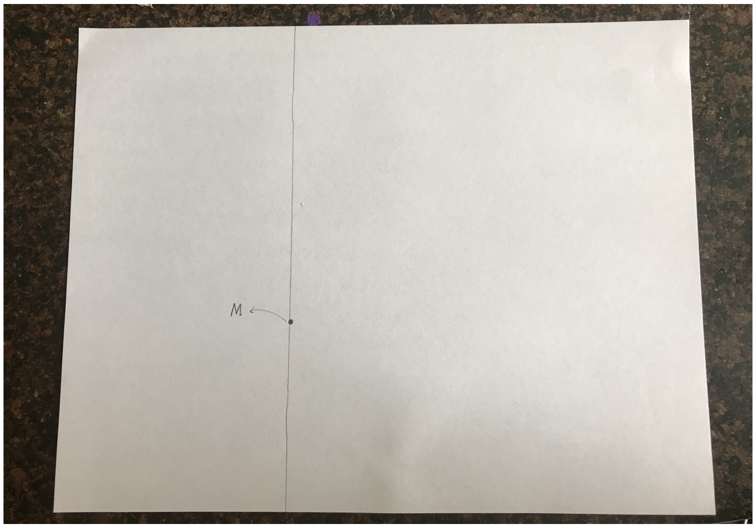


Figure 4.10: Draw a line parallel to the short side and that goes through point M in Figure 4.9.

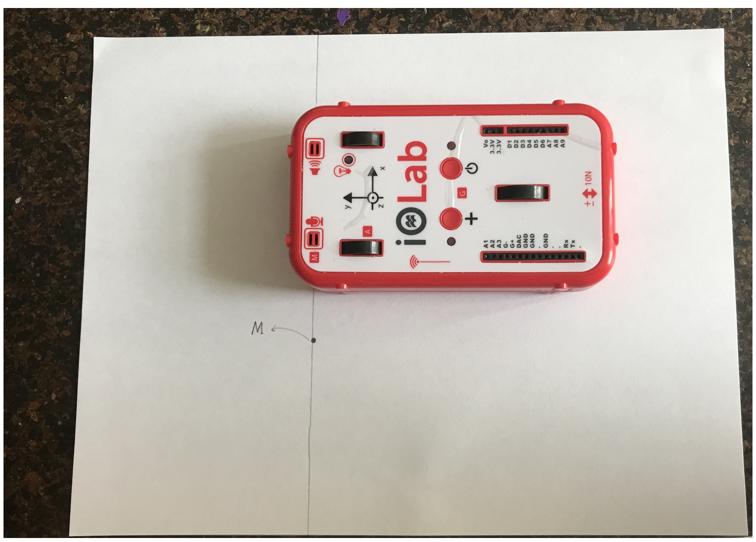


Figure 4.11: Put the device back on the line so that the magnetometer lies on the line.

TASKS

(8) Take a screenshot of the graph you have just obtained.

Now, let us construct the circuit.

(1) First, we need to make sure that we keep the iOLab device aligned in the direction that gives $B_y = 0$. Tape the paper at the top right and bottom right corners as in Figure 4.11.

(2) Take the long red wire and put it under the paper such that it is right beneath the line on the paper. To do so, you may want to get rid of the cylinder on which the red wire is wound.

(3) Tape the red wire onto the table so that it is always aligned with the line on the paper.

(4) Tape the other two corners of the paper now onto the table.

(5) Put three D batteries into the battery cage.

(6) Connect the red wire that comes out of the battery cage to anywhere in the left positive line on the breadboard.

(7) Connect the black wire that comes out of the battery cage to anywhere in the right negative line on the breadboard.

(8) Connect one 0.5 Ohm high-power resistor between anywhere in the left positive line and a24 (but you may choose a more suitable spot if you have mastered the breadboard).

(9) Connect the other 0.5 Ohm high-power resistor between anywhere in the right negative line and j18 (again, you may choose it to be a more comfortable hole if you have mastered the breadbboard).

(10) Connect one end of the long red wire to e24.

(11) Connect the other end of the long red wire to f18. Please make sure you understand that the current will flow from e24 to f18. Following this line, indicate the direction of the current on the paper next to the line.

Note that you may not want to keep the long red wire connected for too long because it will drain your batteries really fast. Therefore, do not connect the long red wire until you start taking data and also remove the long red wire once you are done taking data!

4.6 Taking the data

After you take data, to reach the parametric plot mode, you must press the button , which can be found along the top of the iOLab software screen. Once you click this button, you will see two plots. You will have to use the top plot for y vs. B_y (you must change the magnetometer to B_y instead of norm) and for y vs. B_z (you must change the magnetometer to B_z in this case). Use the bottom plot for B_y vs. B_z (again, you must change these from norm).

You will need to take two sets of data. In the first step, you will use the A7 input of the iOLab to measure the current flowing through your circuit. Record the voltage across the 0.5 Ohm resistor.

In the second measurement, you will "roll" the iOLab device across the wire (using a few sheets of paper to make the trip "smooth") and record using both the Magnetometer and Wheel sensors. A few passes with the iOLab over the wire should acquire all the data you need to complete the full analysis of the lab.

When you are ready, we are going to start with measuring the current.

(1) If you connected the long red wire before this point (which you shouldn't until we start taking data), remove them.

(2) Connect one wire from the jumper kit between GND on the iOLab and anywhere in the right negative line on the breadboard.

(3) Connect another wire from the jumper kit between A7 on the iOLab and h18 (following the earlier prescription for reference).

(4) Reset any previous runs in the software, select the Analog 7 sensor only, and hit Record.

(5) Connect the long red wire to the points earlier (namely, e24 and f18) to complete the circuit.

(6) Wait for a short time (say 2 seconds) and stop recording and immediately remove the long red wire out of the breadboard.

(7) By using the analysis tool, highlight the graph.

TASKS

(9) Take a screenshot of the highlighted graph. Record the average voltage. Compute the current by using the Ohm law. (*Hint: You know the resistance.*)

Having obtained the current, let us start the most important part of the experiment.

(1) Do you recall our paper taped onto the table? Put your iOLab device on its wheels and place it on the paper such that its back end is on the back end of the paper, perfectly parallel.

(2) Reset any previous runs on the software. Select the Magnetometer and Wheel. When you select the Wheel sensor, there will appear some sub-sensors. Select only Position.

(3) Hit Record.

(4) Move the iOLab device nicely and slowly to the other end of the paper. Make sure that the short side of the device remains parallel to the short side of the paper at all times.

(5) Move the iOLab back to its starting position. This will complete one cycle. Repeat the cycle one more time.

(6) Stop recording.

(7) Switch to the parametric plot mode (as explained at the beginning of this section).

(8) Once you are in the parametric mode, click on the Settings button (the box with an arrow in the just below the bottom left corner of the graph). Chance Norm to By. Highlight the data in the figure below.

TASKS

(10) Take a screenshot of the highlighted graph. Record the coordinates of the peak point, namely the position and the magnetic field, by hovering the cursor on the peak point.

(11) Compute the theoretically expected value of the magnetic field by using Equation (4.5) by taking $r = 1$ cm.

We are not done yet. Now, click on the Settings button and change By to Bz. Highlight the figure below again.

TASKS

(12) Take a screenshot of the graph. Record the position of the point of symmetry.

Remark that when the iOLab device is just above the wire, the magnetic field will be zero. When you are just before and just after the wire, you will get a magnetic-field reading from the wire. Remark also that the asymptotic value of B_z is not zero, but rather the magnetic field of the Earth.

One last thing to do, and we are done: Deselect the Wheel sensor on the left and you should see the graph of Magnetometer vs. Magnetometer on the screen. Switch to the parametric mode again. Highlight the data that looks like Batman. Click on the Settings button, change the first Norm to By and the second Norm to Bz.

TASKS

(13) Take a screenshot of the graph.

(14) Measure the greatest diameter along the horizontal by putting a ruler on the screen or use a screen-ruler application. Please do not record any length value! Convert your measurement to a magnetic field value by scaling it to the horizontal axis. This will give you ΔB_y.

(15) Measure the greatest diameter along the vertical as described in the previous task. This will give you ΔB_z.

(16) Compute the ratio $\Delta B_z / \Delta B_y$.

Most probably, you will not get exact 1.00 for this ratio. That is totally okay.

TASKS

(17) Subtract your value from 1.0 and take the absolute value of the result, and multiply it by 100.

This value will represent your percent error for the deviation from the "inverse r" law (See Equation (4.5)).

You have two numbers that represents an error: One from Task 7, which is a global (or instrument) error, the other from Task 16, which represent measurement errors. You are encouraged to come up with a unique number that will represent the total percent uncertainty in your experiment.

4.7 Submitting lab report

In order not to experience any difficulties with the submission, please name your file as

`p114_exp4_lastname_firstname.pdf`

or

`p122_exp4_lastname_firstname.pdf`

minding the underscores and avoiding capital letters. Then, click here to submit your paper [1].

[1] If the link does not work, please send your pdf to `kagannsimsek@gmail.com` by typing the subject of the email exactly as Electromagnetism Experiment 4. You may leave the body of the email empty.

Experiment 5

RLC circuits

The RLC circuits plays a central role in nearly all wireless communications applications. In our modern society, we have filled the air with many sources of information carries by EM waves, including but not limited to radio, television, cellular phone, and wireless internet. Even your iOLab device itself uses EM waves to communicate its measurements to your computer. As such, a simple antenna, will be bombarded by all these communications and must necessarily list to only one. The RLC circuit exhibits a resonance condition when the impedance of the inductor matches that of the capacitor:

$$\omega L = \frac{1}{\omega C} \tag{5.1}$$

yielding

$$\omega = \frac{1}{\sqrt{LC}} \tag{5.2}$$

or

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5.3}$$

In this lab, we will be using the audio jack of your computer or similar device (e.g. a cell phone) as a source of variable frequency to drive "ear buds". The iOLab will pick up the output of the ear buds using the microphone probe. By intercepting the signal and filtering it with an inductor and capacitor, we will be able to show the effect of a resonant circuit and check that the frequency of the resonance changes in the expected manner when varying the values of L and C.

5.1 Objectives

In this experiment, we are going to

- understand how a resonant circuit works, and
- verify the dependence of the resonant frequency on L and C.

We will need the following materials:

- 3.5 mm audio extension cable
- Two 3.5 mm audio jack adapters
- Breadboard
- Hook up wires
- One 100 mH inductor
- Two 0.47 μF capacitors
- One 0.22 μF capacitors
- Ear buds, headphones, or other audio listening device — the listening device must be provided by the student.

5.2 Useful links

Here are some links that contain useful information about the theory behind this experiment and instructions on how to take and analyze data.

- LRC Derivation
- RC Circuit
- RL Filter
- RL Phase
- Setup
- FFT
- Data-taking

5.3 Introduction

This experiment will involve the study of AC circuit theory. AC circuits have similarities and differences to DC circuits. Both deal with relationships between voltages and currents. Both have laws for which voltage is proportional to current. For DC circuits containing resistors,

$$V = IR \tag{5.4}$$

and for AC circuits,

$$V = IZ \tag{5.5}$$

where Z is the impedance of the circuit element.

The aspects that distinguish AC from DC circuits include all of the following:

- The voltages and currents in an AC circuit oscillate both positive and negative. Therefore, we quantify their strength using either RMS or PEAK values.
- The voltages and currents in an AC circuit do not all peak at the same time. Voltages on resistors peak at the same time the current peaks; however, voltages on inductors peak before the current does and voltages on capacitors peak after the current does. Therefore, every voltage, current, and impedance in an AC circuit has its own unique phase.
- Passive devices, like resistors, have an impedance that does not vary with frequency. Active devices like inductors and capacitors have impedances that depend upon frequency.
- We can correctly account for the difficult math of summing sine waves with varying amplitudes and phases, by performing vector sums of impedances where the magnitude of the vector is the reactance of the device and the direction of the vector is the phase of the impedance.

The following table summarizes how we deal with R, L, and C using vector or "phasor" math:

Device	Reactance	Arrow
Resistor	R	$\rightarrow$
Inductor	ωL	$\uparrow$
Capacitor	$\frac{1}{\omega C}$	$\downarrow$

Using the rules of the table above, we can use vector addition to find the total impedance of a series circuit containing a resistor, R, inductor, L, and capacitor, C. The result is shown in Figure 5.1.

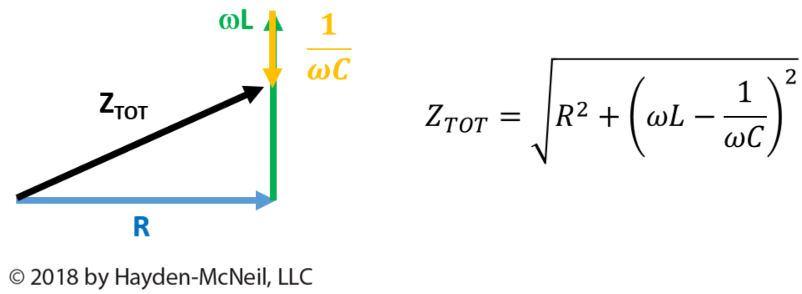


Figure 5.1: The total impedance for an *RLC* circuit in series. (C) 2018 by Hayden-McNeil, LLC

Because the impedance of the inductor and capacitor depends upon ω, the amount of current through the circuit varies with frequency. The largest current happens when the impedance of the inductor and capacitor exactly cancel, which occurs when

$$\omega L = \frac{1}{\omega C} \tag{5.6}$$

and hence

$$\omega = \frac{1}{\sqrt{LC}} \tag{5.7}$$

or

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5.8}$$

In this experiment, we will intercept the signal from the audio jack of your computer (or cell phone) onto our breadboard. This will allow us to insert an inductor and capacitor in series with the headphones (which play the role of R). The result will be a "loudest" frequency that we will observe using the microphone.

5.4 Audio setup

To study an AC circuit, we require an AC source. The trick that we will be using is to tie into the audio output of your PC, cell phone, or other device as a means of generating a variable AC source. To do this without damaging your earbuds or other audio equipment, we will be using a pair of audio jacks that plug directly into our breadboard.

There are many connections that must all be correct for the circuit to perform as desired. Fortunately, since we are using an audio source, you will be able to hear whether the connections are good by attempting to listen through the earbuds. The steps required include the following:

- Making all connections.
- Listening to an audio source and verifying that it plays through both channels.

- Determining the "wiring pattern" of the breadboard jacks:
  * Where is the left channel source?
  * Where is the right channel source?
  * Where is the common return connection?
- Disabling one channel so that the other channel is the only source of sound for the next part of the lab.

When you feel ready, take the two 3.5-mm audio jack adapters and the breadboard.

(1) You will notice that there are three leads at the bottom of each adapter. Connect them on the breadboard to the points indicated in Figure 5.2.

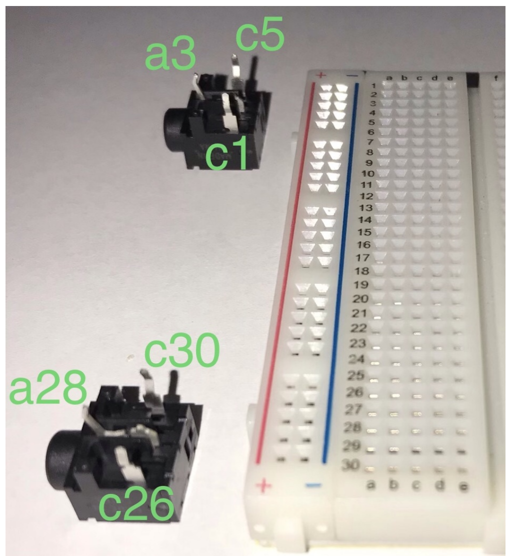


Figure 5.2: Connection points of the two audio jack adapters.

(2) Take your earbuds[1] and plug it into the adapter at the top of the breadboard, namely the one connected at (c1, a3, c5). Be careful not to break the leads of the adapter.

(3) Take the 3.5-mm audio jack cable and plug its one end to the other adapter on the breadboard. Be careful not to break the leads of the adapter.

(4) Plug the other end of the audio jack cable to your computer (or to your phone).

(5) Connect a wire from the jumper kit between e1 and e26 on the breadboard.

(6) Connect a wire from the jumper kit between e3 and e28 on the breadboard.

(7) Connect a wire from the jumper kit between e5 and e30 on the breadboard.

[1]Clearly, it has to have a 3.5-mm end. The iPhone earbuds with the Thunderbolt connection will be useless here.

(8) Put on the earbuds. On your computer, open this link (or on your phone, scan the code). Let it play until the end of Task 3.

If you are hearing the sound from both speakers, i.e. the right and left channels of your earbuds, proceed to the first task. If not, please check your connections.

TASKS

(1) Remove the end of the wire that goes into e26 (but do not touch the end at e1). Explain in a sentence what happened. Connect the wire back.

(2) Remove the end of the wire that goes into e28 (but do not touch the end at e3). Explain in a sentence what happened. Connect the wire back.

(3) Remove the end of the wire that goes into e30 (but do not touch the end at e5). Explain in a sentence what happened. Connect the wire back.

(4) By using your observation in Tasks 1-3, determine the left-channel source, the right-channel source, and the common return connection of the audio jack adapters connect at (c26, a28, c30).

Your answer to Task 4 can be in the form "e26 is common return, e28 is right channel, and e30 is left channel" (which is wrong!) or "top is common return, middle is right channel, and bottom is left channel" (which is wrong again!). The latter is more convenient because it is coordinate-independent on the breadboard — as long as the adapter *looks to the left*, it does not matter where we connect it[2].

It is quite essential for you not to make a change on any of the connections!

5.5 AC circuit setup

The circuit that we shall study is diagrammed in Figure 5.3.

[2]To make it more clear, *top* in our case corresponds to the lead of the adapter connected in the same row as e1 or e26, *middle* e3 or e28, and *bottom* e5 or e30.

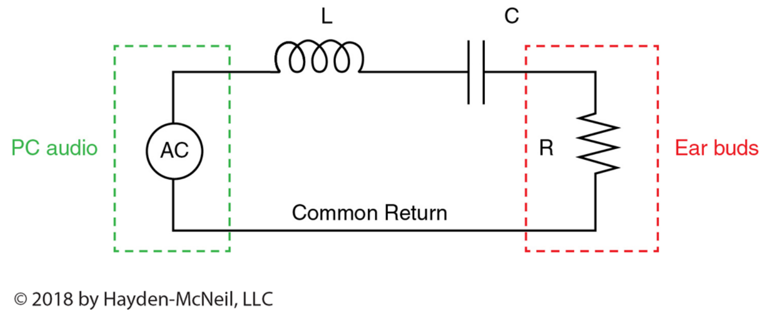


Figure 5.3: The circuit to be built in this experiment. (C) 2018 by Hayden-McNeil, LLC

In the place of an AC source, we will be using the audio output of your PC. In the place of the resistor, we will be using earbuds or headphones. Nonetheless, this is a standard AC resonant circuit for which we expect to have a resonant frequency of

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5.9}$$

At resonance, the impedance of the circuit is minimum and the current through the circuit is maximum. As a result, we will hear the "loudest" response when the frequency of the AC source hits the resonant value. To accomplish this trick, we will use a website to make a programmable frequency that will sweep from below resonance to above resonance. The microphone probe and sensor will allow us to spot the moment when the circuit is at resonance and using the FFT function in the iOLab software, we will measure the resonant frequency.

When you feel good, proceed with the next task:

TASKS

(5) Prepare a table as follows:

Inductor	Capacitor configuration	f_{theo} (Hz)	f_{exp} (Hz)
100 mH	One 0.47 μF		
100 mH	One 0.22 μF		
100 mH	Two 0.47 μF in parallel		
100 mH	One 0.47 μF and 0.22 μF in parallel		

Compute the theoretical frequencies for the given capacitor configurations and record them in the table.

At this point, you may want to recall that

$$f = \frac{1}{2\pi\sqrt{LC_{\text{eq}}}} \tag{5.10}$$

where C_{eq} is the equivalent capacitance for the circuit. For a single capacitor, it is clearly C but for two capacitors in parallel, it is given by

$$C_{\text{eq}} = C_1 + C_2 \tag{5.11}$$

Get ready to build the circuit in Figure 5.3. You should have kept the circuit you built for Tasks 1-4 as is, if you didn't already. The following procedure will be based on that circuit.

(1) Remove the end of the wire at e26 and connect it to j7 (so that you have a wire between e1 and j7).

(2) Now you have a vacancy at e26. Connect a wire from the jumper kit between e26 and f22.

(3) Remove the wire that is connected between e5 and e30.

(4) Take the 100 mH inductor and connect it between f7 and j20.

(5) Take one of the 0.47 μF capacitors and connect it between h20 and h22. Those capacitors have rather short legs, so pay attention not to spread them.

(6) Go to the website

onlinetonegenerator.com/frequency-sweep-generator.html

(7) You will see a table in a gray box. Set all the variables exactly as in Figure 5.4.

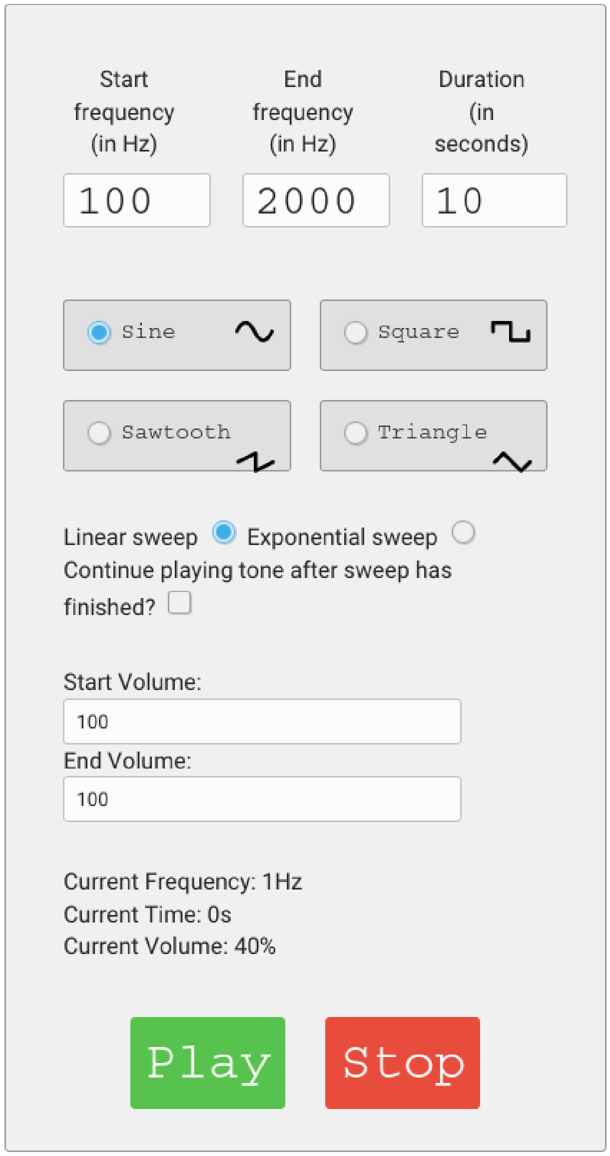


Figure 5.4: Variables for the frequency sweep generator.

(8) Open the iOLab software, select the sensor Microphone, and start recording.

(9) Take the earbud (there should be sound coming from only one of the earbuds!) and put its speaker onto the microphone sensor on the iOLab device (next to the magnetometer sensor that we used in the previous experiment,)[3].

(10) Go to the web browser again and hit Play.

(11) Wait for 10 s and stop recording data on the iOLab software.

[3] A word of caution is needed here: The iPhone earbuds are not working in this experiment.

TASKS

(6) Identify the peak point. Open the Settings window (by clicking on the box with an arrow on it on the bottom left corner of the graph). Choose the FFT option 256. Click on the peak and you will see a new mini graph just below the original one. By hovering the cursor in this small graph, read the frequency of the resonance. Record it in the table.

Now, replace the 0.47 μF capacitor with a 0.22 μF capacitor (for future reference, please make sure that the 0.22 μF capacitor is connected between h20 and h22). Reset any previous runs on the software, select the Microphone sensor again, start recording. Do not forget to put the speaker/earbud on the microphone sensor on the iOLab device. Open the web browser again, hit Play, wait for 10 s (for the sound to finish), and then stop recording.

TASKS

(7) Repeat Task 6.

Now you know how to repeat this procedure of data-taking. We have two more configurations to go.

TASKS

(8) Repeat Task 7 for the configuration of two 0.47 μF capacitors in parallel: Remove the previously connected 0.22 μF capacitor, connect one 0.47 μF between h20 and h22 and connect the other 0.47 μF between g20 and g22.

(9) Repeat Task 8 for the configuration of one 0.47 μF and one 0.22 μF in parallel: Remove the previously connected 0.47 μF between g20 and g22, and connect one 0.22 μF between g20 and g22.

By now, you should have four values of theoretical frequency and four values of experimental frequency.

TASKS

(10) Plot f_{theo} vs. f_{exp}. Insert a linear trendline with forcing intercept at 0. Show the trendline equation. By subtracting the slope from 1, taking absolute value, and multiplying with 100, obtain the percent error for this experiment.

5.6 Submitting lab report

In order not to experience any difficulties with the submission, please name your file as

`p114_exp5_lastname_firstname.pdf`

or

`p122_exp5_lastname_firstname.pdf`

minding the underscores and avoiding capital letters. Then, click here to submit your paper [4].

[4]If the link does not work, please send your pdf to `kagannsimsek@gmail.com` by typing the subject of the email exactly as Electromagnetism Experiment 5. You may leave the body of the email empty.

Formulae for error analysis

Each measurement comes with an error whose source may be the instrument itself or totally unknown. Technically speaking, the measured value is called the average and the error is referred to as the uncertainty in (or the standard deviation of) that measurement. Letting x denote the measured quantity, we write it as

$$x = x_{\text{av}} \pm \Delta x \tag{5.12}$$

It is important to note that the plus/minus sign is nothing more than a symbol since we make the fundamental assumption that the standard deviation is always a positive quantity. This will allow us to play with it freely. This means we can treat the minus/plus sign to be the same thing as the original uncertainty, and as usual. However, in all the cases, we will favor the argument that whenever we perform an operation on quantities with errors in them, the error in the next step should never be smaller due to error propagation.

Now take two quantities that contain errors, say $x = x_{\text{av}} \pm \Delta x$ and $y = y_{\text{av}} \pm \Delta y$. Let's us derive the uncertainty in the most basic calculations. Let's start with the arithmetics.

Let z defined by the linear sum of the two quantities x and y. Then,

$$\begin{aligned} z &= z_{\text{av}} \pm \Delta z \\ &= x + y \\ &= x_{\text{av}} \pm \Delta x + y_{\text{av}} \pm \Delta y \\ &= (x_{\text{av}} + y_{\text{av}}) \pm (\Delta x + \Delta y) \end{aligned} \tag{5.13}$$

and hence, using a more suggestive notation,

$$\boxed{\begin{aligned} (x + y)_{\text{av}} &= x_{\text{av}} + y_{\text{av}} \qquad (5.14) \\ \Delta(x + y) &= \Delta x + \Delta y \qquad (5.15) \end{aligned}}$$

Next, let z defined by the difference in the two quantities x and y. Then,

$$\begin{aligned} z &= z_{\text{av}} \pm \Delta z \\ &= x - y \end{aligned}$$

$$
\begin{aligned}
&= x_{\text{av}} \pm \Delta x - y_{\text{av}} \mp \Delta y \\
&= (x_{\text{av}} - y_{\text{av}}) \pm (\Delta x + \Delta y) \qquad (5.16)
\end{aligned}
$$

where in the last step, we have used the property that the minus/plus sign is completely equivalent to the plus/minus and the fact that the error should always accumulate or increase. Hence,

$$
\boxed{
\begin{aligned}
&(x-y)_{\text{av}} = x_{\text{av}} - y_{\text{av}} \\
&\Delta(x-y) = \Delta x + \Delta y
\end{aligned}
}
\qquad
\begin{aligned}
(5.17)\\
(5.18)
\end{aligned}
$$

Next, let z defined by the multiplication of the two quantities x and y. Then,

$$
\begin{aligned}
z &= z_{\text{av}} \pm \Delta z \\
&= xy \\
&= (x_{\text{av}} \pm \Delta x)(y_{\text{av}} \pm \Delta y) \\
&= x_{\text{av}} y_{\text{av}} \pm x_{\text{av}} \Delta y \pm y_{\text{av}} \Delta x + \Delta x \Delta y \\
&= x_{\text{av}} y_{\text{av}} \pm x_{\text{av}} y_{\text{av}} \left(\frac{\Delta x}{x_{\text{av}}} + \frac{\Delta y}{y_{\text{av}}} + \frac{\Delta x}{x_{\text{av}}} \frac{\Delta y}{y_{\text{av}}} \right) \\
&= x_{\text{av}} y_{\text{av}} \pm x_{\text{av}} y_{\text{av}} \left(\frac{\Delta x}{x_{\text{av}}} + \frac{\Delta y}{y_{\text{av}}} \right) \qquad (5.19)
\end{aligned}
$$

where we have ignored the term proportional to the product $\Delta x \Delta y$. We can justify this if we take into account the fact that uncertainties should be much smaller than averages. For instance, an acceptable percentage of error is around 5% in engineering and much less than 1% in optics. Thus, the first and second terms in the parentheses in Equation (5.19) are around, say, 1 to 5% but the last term is around 0.01 to 0.25% generally in the aforementioned fields. This is why the last term in the parentheses can be safely ignored.

There is one final word of caution here: Even if we assume that the standard deviation is always positive, the values x_{av} and y_{av} may not. It is okay if both x_{av} and y_{av} are positive or negative; it is problematic only when they have the opposite signs, which would decrease the error. Thus, we need to introduce absolute value just to be sure. Hence,

$$
\boxed{
\begin{aligned}
&(xy)_{\text{av}} = x_{\text{av}} y_{\text{av}} \\
&\Delta(xy) = |x_{\text{av}} y_{\text{av}}| \left(\left| \frac{\Delta x}{x_{\text{av}}} \right| + \left| \frac{\Delta y}{y_{\text{av}}} \right| \right)
\end{aligned}
}
\qquad
\begin{aligned}
(5.20)\\
(5.21)
\end{aligned}
$$

Next, let z be defined as the ratio of the two quantities x and y. Then,

$$
z = z_{\text{av}} \pm \Delta z = \frac{x_{\text{av}} \pm \Delta x}{y_{\text{av}} \pm \Delta y} \qquad (5.22)
$$

It would be much easier if the term in the denominator had been in the numerator as a factor multiplying the first term. There is a nice trick for that, and it employs the binomial approximation[5].

[5] If you know what a Taylor series is, then you can perform the explicit derivation by keeping the first-order terms only. Or else, stick to this "trick."

For a real number a such that $|a| \ll 1$, we have

$$(1+a)^{-1} \approx 1 - a \tag{5.23}$$

Then,

$$\frac{1}{y_{\mathrm{av}} \pm \Delta_y} = \frac{1}{y_{\mathrm{av}}\left(1 \pm \frac{\Delta y}{y_{\mathrm{av}}}\right)} = \frac{1}{y_{\mathrm{av}}} \frac{1}{1 \pm \frac{\Delta y}{y_{\mathrm{av}}}} \tag{5.24}$$

The second factor here meets the properties as a above: $\Delta y/y$ is a real number with magnitude much less than 1. So, we can use the aforementioned trick to write

$$\frac{1}{y_{\mathrm{av}} \pm \Delta y} = \frac{1}{y_{\mathrm{av}}}\left(1 \mp \frac{\Delta y}{y_{\mathrm{av}}}\right) = \frac{1}{y_{\mathrm{av}}}\left(1 \pm \frac{\Delta y}{y_{\mathrm{av}}}\right) \tag{5.25}$$

where in the final step we have used the fact that the minus/plus sign is completely equivalent to the plus/minus. Inserting this into Equation (5.22), we obtain

$$\begin{aligned}
z_{\mathrm{av}} \pm \Delta z &= (x_{\mathrm{av}} \pm \Delta x)\frac{1}{y_{\mathrm{av}}}\left(1 \pm \frac{\Delta y}{y_{\mathrm{av}}}\right) \\
&= x_{\mathrm{av}}\left(1 \pm \frac{\Delta x}{x_{\mathrm{av}}}\right)\frac{1}{y_{\mathrm{av}}}\left(1 \pm \frac{\Delta y}{y_{\mathrm{av}}}\right) \\
&= \frac{x_{\mathrm{av}}}{y_{\mathrm{av}}}\left(1 \pm \frac{\Delta x}{x_{\mathrm{av}}} \pm \frac{\Delta y}{y_{\mathrm{av}}} + \frac{\Delta x}{x_{\mathrm{av}}}\frac{\Delta y}{y_{\mathrm{av}}}\right) \\
&= \frac{x_{\mathrm{av}}}{y_{\mathrm{av}}}\left(1 \pm \frac{\Delta x}{x_{\mathrm{av}}} \pm \frac{\Delta y}{y_{\mathrm{av}}}\right) \\
&= \frac{x_{\mathrm{av}}}{y_{\mathrm{av}}} \pm \frac{x_{\mathrm{av}}}{y_{\mathrm{av}}}\left(\frac{\Delta x}{x_{\mathrm{av}}} + \frac{\Delta y}{y_{\mathrm{av}}}\right)
\end{aligned} \tag{5.26}$$

where we have ignored the last term in the parentheses in the penultimate step and by now, you should know why. Finally, inserting the useful absolute values, we get

$$\boxed{\begin{aligned}
\left(\frac{x}{y}\right)_{\mathrm{av}} &= \frac{x_{\mathrm{av}}}{y_{\mathrm{av}}} && (5.27)\\
\Delta\left(\frac{x}{y}\right) &= \left|\frac{x_{\mathrm{av}}}{y_{\mathrm{av}}}\right|\left(\left|\frac{\Delta x}{x_{\mathrm{av}}}\right| + \left|\frac{\Delta y}{y_{\mathrm{av}}}\right|\right) && (5.28)
\end{aligned}}$$

Next, let's do the square[6] Suppose z is defined by taking the square of x. By using Equations (5.20) and (5.21) (and I leave the tiny step of simplification to you), we get

$$\boxed{\begin{aligned}
(x^2)_{\mathrm{av}} &= x_{\mathrm{av}}^2 && (5.29)\\
\Delta(x^2) &= |2x_{\mathrm{av}}\Delta x| && (5.30)
\end{aligned}}$$

Finally, let's do the square root and complete this chapter. Suppose z is given by the square root of x:

$$z = z_{\mathrm{av}} \pm \Delta z = \sqrt{x_{\mathrm{av}} \pm \Delta x} \tag{5.31}$$

[6] I don't think you may ever encounter or need this in your labs, but for the third power, once you know z^2, you can obtain it by multiplying z by z^2, so the procedure is quite straightforward.

We are going to use the binomial approximation again. Let me quote the most general trick:

$$(1+a)^n \approx 1 + na \tag{5.32}$$

for any real number a such that $|a| \ll 1$. Then, it is obvious that

$$\begin{aligned}\sqrt{x_{\rm av} \pm \Delta x} &= (x_{\rm av} \pm \Delta x)^{1/2} \\ &= x_{\rm av}^{1/2}\left(1 \pm \frac{\Delta x}{x_{\rm av}}\right)^{1/2} \\ &\approx \sqrt{x_{\rm av}}\left(1 \pm \frac{\Delta x}{2x_{\rm av}}\right) \\ &= \sqrt{x_{\rm av}} \pm \frac{\Delta x}{2\sqrt{x_{\rm av}}}\end{aligned} \tag{5.33}$$

By taking the absolute values, we finally get

$$\boxed{\begin{aligned}(\sqrt{x})_{\rm av} &= \sqrt{x_{\rm av}} \qquad (5.34) \\ \Delta(\sqrt{x}) &= \frac{|\Delta x|}{2\sqrt{|x_{\rm av}|}} \qquad (5.35)\end{aligned}}$$