

# **Project Based Engineering Instrumentation With CircuitPython**

A Brief Textbook Presented to the  
Student Body of the University of South Alabama

Last Update: June 30, 2022  
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# Manuscript Changes

1. Original tutorials in Google Docs created
2. Tutorials moved to LaTeX on this Github
3. December 21st, 2021 - Updated links for manuscript and hardware
4. Tutorials purchased by Tangibles that Teach and moved to url [https://tangibles-that-teach.gitbook.io/instrumentation-lab-manual/-MbMx70LQzRmEG\\_hS7Ld/](https://tangibles-that-teach.gitbook.io/instrumentation-lab-manual/-MbMx70LQzRmEG_hS7Ld/)
5. May 30th, 2022 - Tangibles that teach went out of business and chapter began the move to Github
6. June 28th, 2022 - Work began on a Chromebook. Unfortunately the Figures folder is not back up on Git. As such a main\_latest.pdf has been created that's the latest full version. The main.pdf is the version created by the Chromebook so it has new chapters but none of the older chapters. Figure files are now backup on Git but only figures from the 'Voltage Potentiometer' are currently there.

# Changes Needed

1. All chapters from TTT need to be moved here
2. More theory is needed in this book or direction to further reading for the students
3. The new kit has a CPB - Might need to add a chapter explaining the difference and maybe even having the students getting the bluetooth to work.
4. The Assignment section should be the same throughout by defining a macro in main.
5. The photo of the button lab could be better.
6. The circuit photo for the LSM6DS33 is not correct
7. Equations on thermistor need to be expanded
8. Equations relating voltage from protocol to Lux needs to be included
9. Example plots for light, sound, acceleration, etc needs to be expanded
10. Pendulum lab must be done in one of two ways. Either the pendulum is attached to a potentiometer or the CPX is mounted to the end of a string and data logged on board the CPX itself. The potentiometer is nice because you can record data with your laptop but the string idea is cool because you use the accelerometer. In either case you can make some really long pendulums
11. 3D printing a disc with holes on the outside to eventually mount to a shaft would be a really cool angular velocity sensor lab. Tangibles that teach could easily include a 3D printed disc that can mount to a pencil for ease of rotation. Could also include the CAD drawings so students can print more or even edit the design for better or worse performance.
12. Buying some load cells with the HMC converter and including them in the kit would add a whole lot different labs
13. Buying some magnetometers to measure magnetic field and do some sensor fusion would be neat. Could do roll, pitch and yaw calibration if we included a magnetometer.
14. Right now a lab just on roll and pitch estimation would be possible. Pendulum lab pretty much introduces them to this but could easily do an rc aircraft lab where they build an aircraft out of foam with an elevator and aileron so that the servos responds to roll and pitch change. There is a lab right now with just pitch but perhaps we could add roll to it.
15. Another cool project idea would be for the students to take temperature and light data on a cloudy day. Then have them infer if the amount of sunlight affected the temperature of the thermistor. They could plot the data with light on the x-axis and temperature on the y-axis and draw conclusions based on the plot they generate.
16. Could also have them take temperature and light data over the course of a whole day to plot sunrise and sunset and watch the ambient temperature rise and fall
17. For the aliasing lab, have the students sample as fast as possible and obtain the natural frequency of the system. Then have them sample at 1.0, 2.0 and 3.0 times the natural frequency they obtained. I originally picked 1,10 and 100 as arbitrary sampling frequencies and it would have been better to do 2,4 and 6.
18. On cool lab would be to take light data during sunset and watch light and temperature plummet.
19. Add this lab on frequency for notes

## Acknowledgements

The author, Dr. Carlos Montalvo would like to acknowledge a few key members who made this textbook possible. First and foremost I would like to thank Adafruit for their entire ecosystem of electronics, tutorials, blogs and forums. Much of what I have learned here to teach Instrumentation was from Adafruit and the Adafruit Learn system and specifically people like Lady Ada and John Park who have helped shape CircuitPython and the Circuit-Playground Express to what it is today. I would also like to thank Dr. Saami Yazdani for creating the blueprint for Instrumentation at my university by creating a laboratory environment for an otherwise totally theoretical course. His course was the foundation for this textbook and for that I thank him for showing the way. I'd like to also thank and acknowledge Tangibles that Teach for giving me the opportunity to morph this loose set of projects into a textbook that can be used for multiple universities and classrooms and of course help students learn and acquire knowledge through creating.

## About this textbook

This textbook has been designed with the student and faculty member in mind. First, this textbook goes hand in hand with Engineering Instrumentation taught at the undergraduate level at many universities. The course begins with simple plotting and moves into data analysis, calibration and more complex instrumentation techniques such as active filtering and aliasing. This course is designed to get students away from their pen and paper and build something that blinks and moves as well as learn to process real data that they themselves acquire. There is no theory in these projects. It is all applied using the project based learning method. Students will be tasked with downloading code, building circuitry, taking data all from the ground up. By the end of this course students will be well versed in the desktop version of Python while also the variant CircuitPython designed specifically for microelectronics from Adafruit. After this course students will be able to understand Instrumentation at the fundamental level as well as generate code that can be used in future projects and research to take and analyze data. Python is such a broad and useful language that it will be very beneficial for any undergraduate student to learn this language. To the professors using this textbook, 1 credit hour labs are often hard to work into a curriculum and “live” demonstrations in the classroom cost time and money that take away from other faculty duties. I’ve created this kit and textbook to be completely stand-alone. Students simply need to purchase the required materials and follow along with the lessons. These lessons can be picked apart and taught sequentially or individually on a schedule suited to the learning speed of the course. I hope whomever reads and learns from this textbook will walk away with an excitement to tinker, code and build future projects using microelectronics and programming.

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# 1 Measuring Voltage Across a Potentiometer

## 1.1 Parts List

1. Laptop
2. CPX/CPB
3. USB Cable
4. Potentiometer
5. Resistor (the Ohms depends on how large your potentiometer is)
6. Breadboard

## 1.2 Learning Objectives

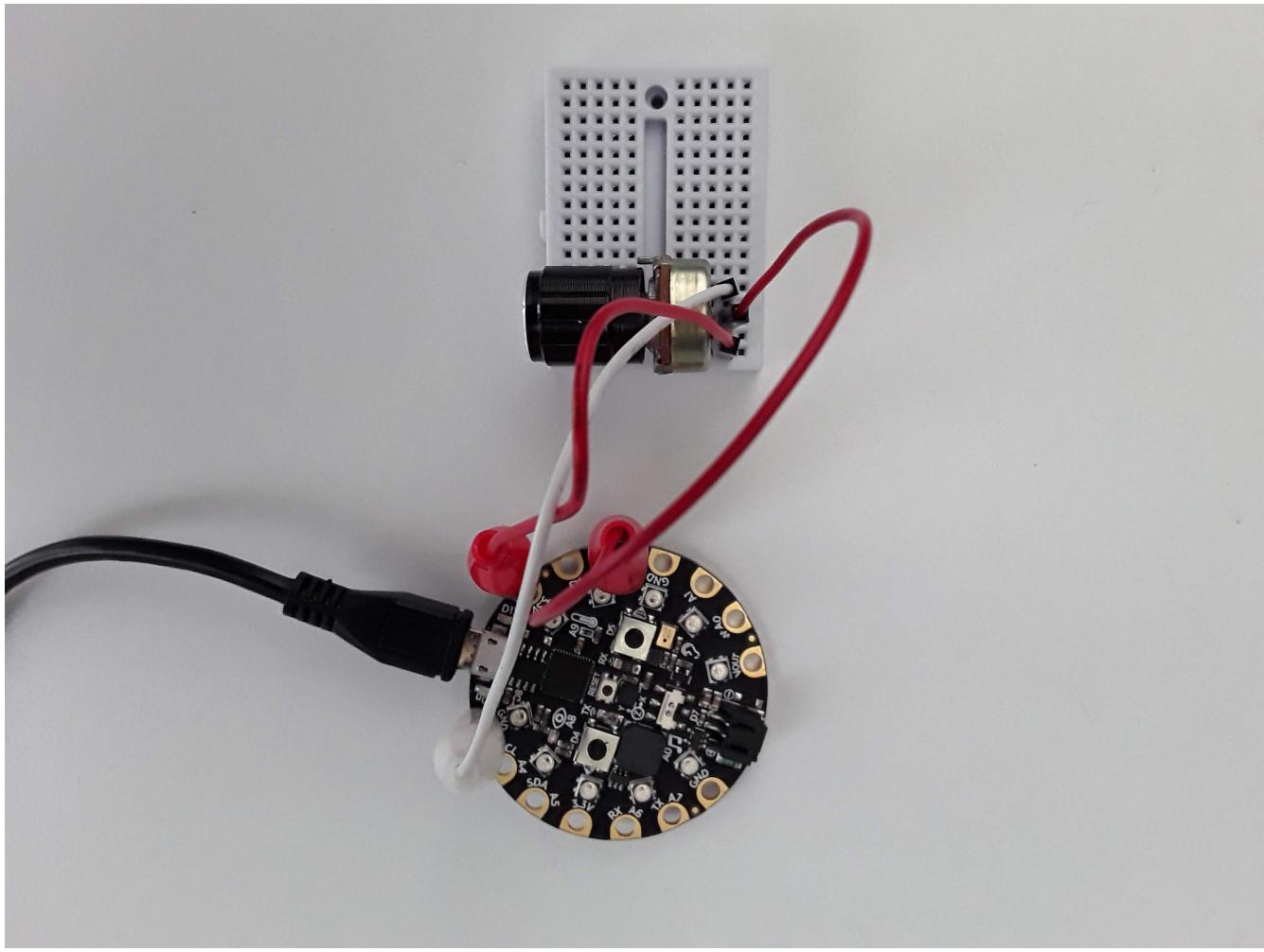
1. Understand voltage division of resistors in series
2. Measure an analog signal on the CircuitPlayground
3. Understand the binary measurement done by the analog to digital conversion (ADC)

## 1.3 Getting Started

At this point you've learned about analog to digital converters (ADC). It turns out that the CPX has 8 analog ports hooked up to a 3.3V logic 16 bit ADC. The input range on the ADC is 0 to 3.3V and the output range is 0 to 65536 which is  $2^{16}$  hence 16 bits. In order to get accustomed to the ADC on the CPX, we're going to do a simple example where we measure the voltage drop across a potentiometer. You can read about potentiometers online if you wish. Basically though, a potentiometer is a variable resistance resistor that changes resistance by turning a knob. The knob changes the connection point of a wire and thus the length of the wire. This in turn changes the resistance. Potentiometers come in all shapes and sizes. Here are some examples.

Here's my circuit all hooked up. Two legs are connected to 3.3V and GND while the middle leg of the potentiometer is connected to pin A2.

**CAUTION!!!:** Some potentiometers do not have enough resistance when turned all the way down. I suggest that you put a resistor in between the third leg and ground. Some experimenters have melted plastic or gotten really hot. One student even blew up a potentiometer.

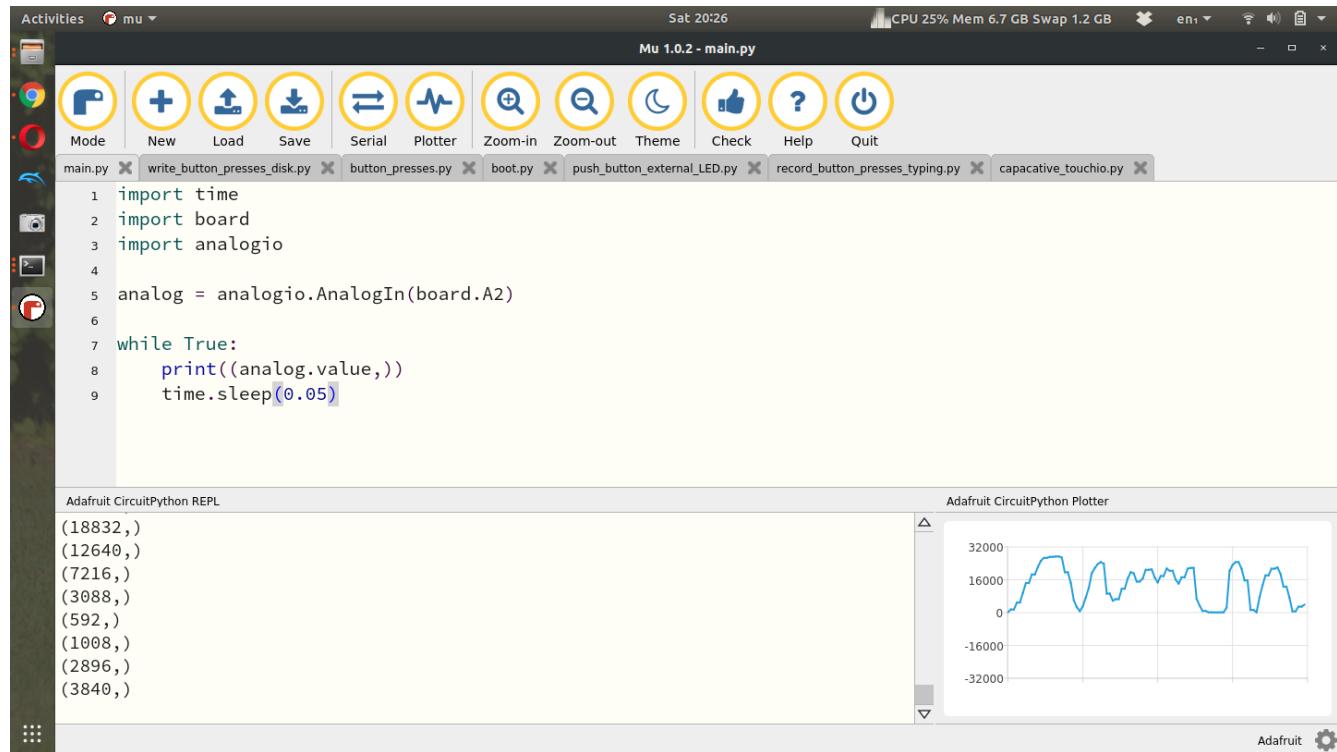


There is a relevant Adafruit Learn Tutorial to help with the *analogio* module but I'll explain the minimum required here to get some analog values plotted in *Plotter* and Python on your computer. First let's take a look at some simple example code to read an analog signal and plot it using the *Plotter*.

```
1 import time
2 import board
3 import analogio
4
5 analog = analogio.AnalogIn(board.A2)
6
7 while True:
8     print((analog.value,))
9     time.sleep(0.05)
```

In the example code above, lines 1-3 again import the necessary modules with *analogio* being the new module here. Line 5 creates the analog object by attaching pin A2 to the analog function. Lines 7-9 then simply read the analog value and print it to *Serial* and the *Plotter*. Running this code on my laptop and turning the knob on the potentiometer produces this output. My potentiometer has a very large knob on the front and is easy to turn. Some potentiometers have a small screw on top that you need to turn with a screwdriver. Turning the screw or the

knob results in chaning the resistance and therefore changing the voltage read by the CPX.



For this lab I want you to spin the potentiometer all the way to one side and then the other while recording time and the analog value. I then want you to plot the data with time on the x-axis and voltage on the y-axis. Remember to convert a digital output to voltage you just need to use the equation below where D is the raw value from the analog port. 3.3V is the range of the ADC and  $2^{16}$  is the maximum value the ADC can represent.

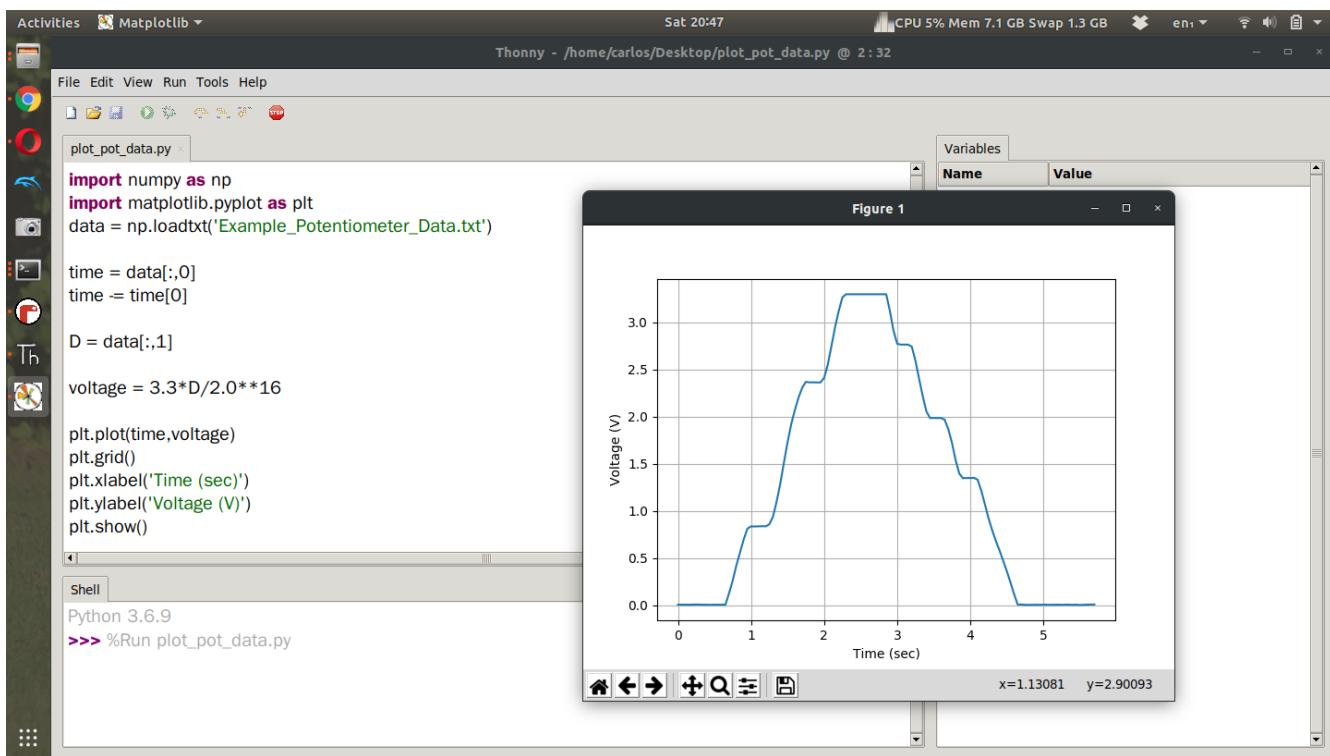
$$V = \frac{3.3D}{2^{16}} \quad (1)$$

After doing this experiment myself, this is the plot I obtain. The code is not provided as reading data and plotting has been discussed in a previous lab (See chapter ??). From the screenshot though you can see how I convert the digital output to an analog signal.

#### NOTE THAT ON LINE 6 IT READS

```
time -= time[0]
```

Notice the minus sign in front of the equal sign. That effects a lot.



Your assignment for this lab is to do the same as I've done above. Wire up the potentiometer, read the analog signal and plot it in Python on your desktop computer. I've made some youtube videos on first just creating the circuit and plotting the data and then another video where I write data to the CPX using method 3.

## 1.4 Assignment

Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Include a video of you wiggling the potentiometer and watching the digital signal in the Plotter in Mu go up and down (make sure your face is in the video at some point and you state your name) - 50%
2. Embed your plot of voltage vs time in a document and also include your code In Python both from the CPX and in Thonny or Spyder to plot - 50%

## 2 Wind Speed from Pitot Probe

### 2.1 Parts List

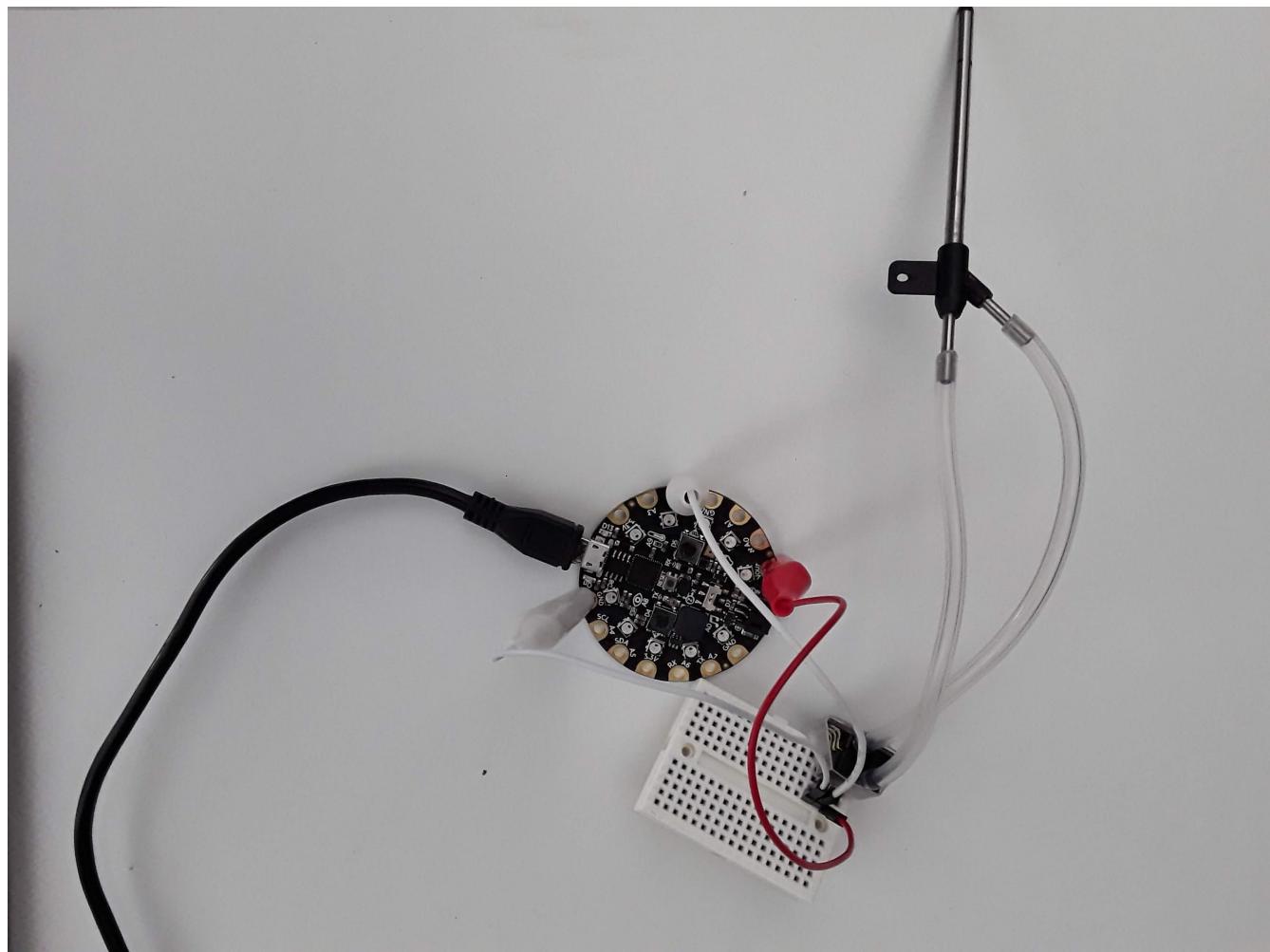
1. Laptop
2. CPX/CPB
3. USB Cable
4. Alligator Clips (x3)
5. Pitot Probe (Not included in kit at the moment so will need to buy this separately or borrow one)
6. Breadboard

### 2.2 Learning Objectives

1. Understand how pitot probes works
2. Understand the relationship between a voltage signal from a pitot probe to a pressure value
3. Understand the relationship between pressure and windspeed

### 2.3 Getting Started

Although a CPX has numerous sensors built in, you can easily augment the capabilities of the CPX using either I2C or just the ADC on board the CPX. In this lab, if you purchased a pitot probe you will be able to do this assignment. Since you don't need the pitot probe for very long you can always borrow one from some other team. Let's talk about the hardware and the wiring to get this to work.



The pitot probe has two pressure taps that measure ambient pressure and stagnation pressure. These taps move through two silicon tubes to a pressure transducer that has a strain gauge in separating both pressures. When the pressure on one side of the transducer is larger than the other, it will flex the membrane and create strain. This strain runs through a wheatstone bridge with a voltage offset to the pin labeled analog. The transducer has 3 pins, +5V, GND and Analog. It is pretty straightforward how to wire this up but remember that +5V needs to go to VOUT, GND to GND and Analog to any analog pin. I chose pin A2. At that point it's very simple to just print the analog signal in bits to Serial. I've done this below. The code is the same analog code that we've used in the past.

```

1 import time
2 import board
3 import analogio
4
5 analog = analogio.AnalogIn(board.A2)
6
7 while True:
8     print((analog.value,))
9     time.sleep(0.05)

```

---

The goal of the experiment is to take pitot probe data for 15 seconds with no wind, then 15 seconds of data with a fan on and then 15 seconds of no wind data. You'll need to use one of the datalogging methods (See chapter ??) to log both time and pitot probe analog value. Once you have that data, import the data into Python on your desktop computer and convert the signal to windspeed. In order to convert the analog value to windspeed you need to first convert the analog value to voltage. Remember that the ADC on the CPX is going to convert the analog signal from the pitot probe to a digital output. So use this equation first to convert the analog signal (which I call D) to voltage. The 2 to the 16th power represents the 16 bit ADC.

$$V = \frac{3.3D}{2^{16}} \quad (2)$$

Before converting Voltage to windspeed we need to first subtract off the bias from the pitot probe. I explain this process in this accelerometer video. I've done this project before and have posted a video on Youtube about Converting Pitot Probe Data to Windspeed. *There is a typo in the video. V1 is supposed to have a sqrt()).* Once you have computed the bias you can compute the change in pressure using the equation below which converts the change in voltage to Pascals ( $V_b$  is the voltage bias you obtain when the wind is off). The data sheet states that the voltage is linearly proportional to pressure in Pascals which is nice.

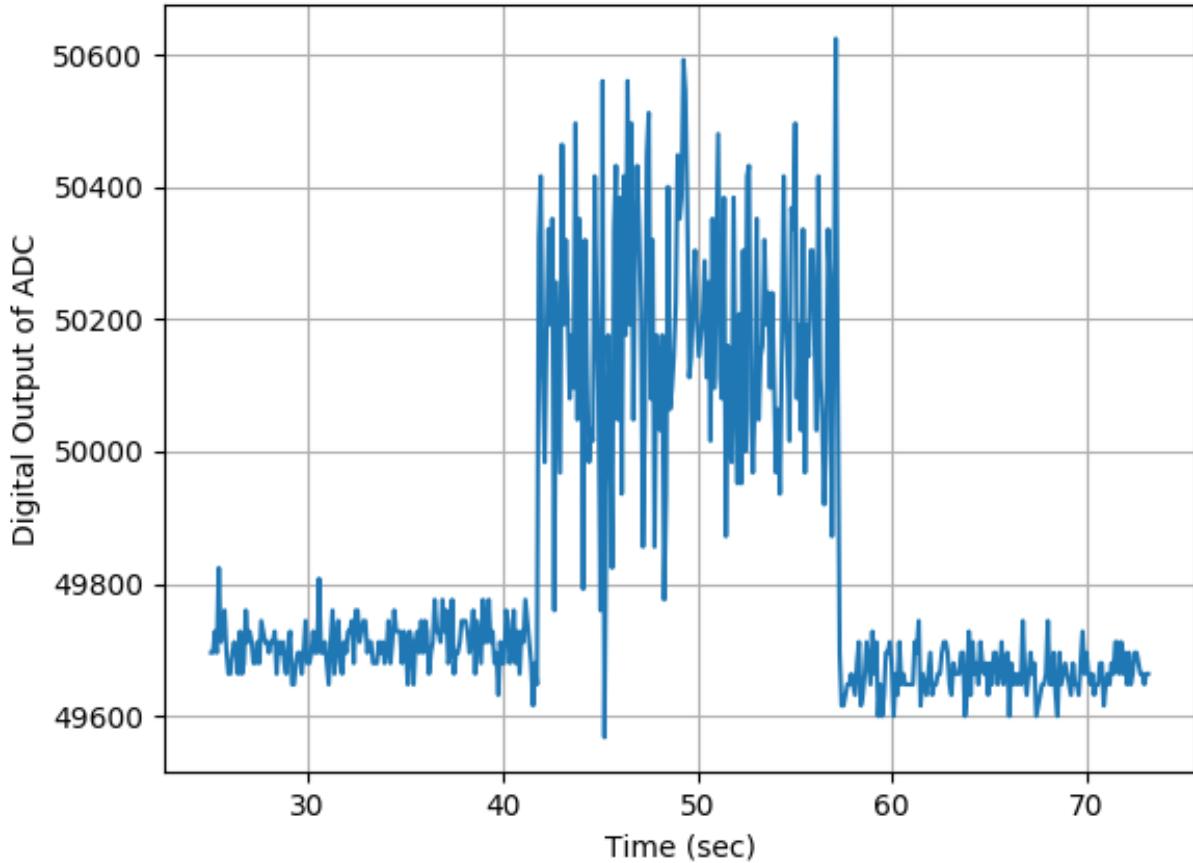
$$P = 1000(V - V_b) \quad (3)$$

Using pressure, the equation below can be used to compute windspeed, where U is the windspeed and the density at sea-level ( $\rho$ ) is 1.225  $kg/m^3$ .

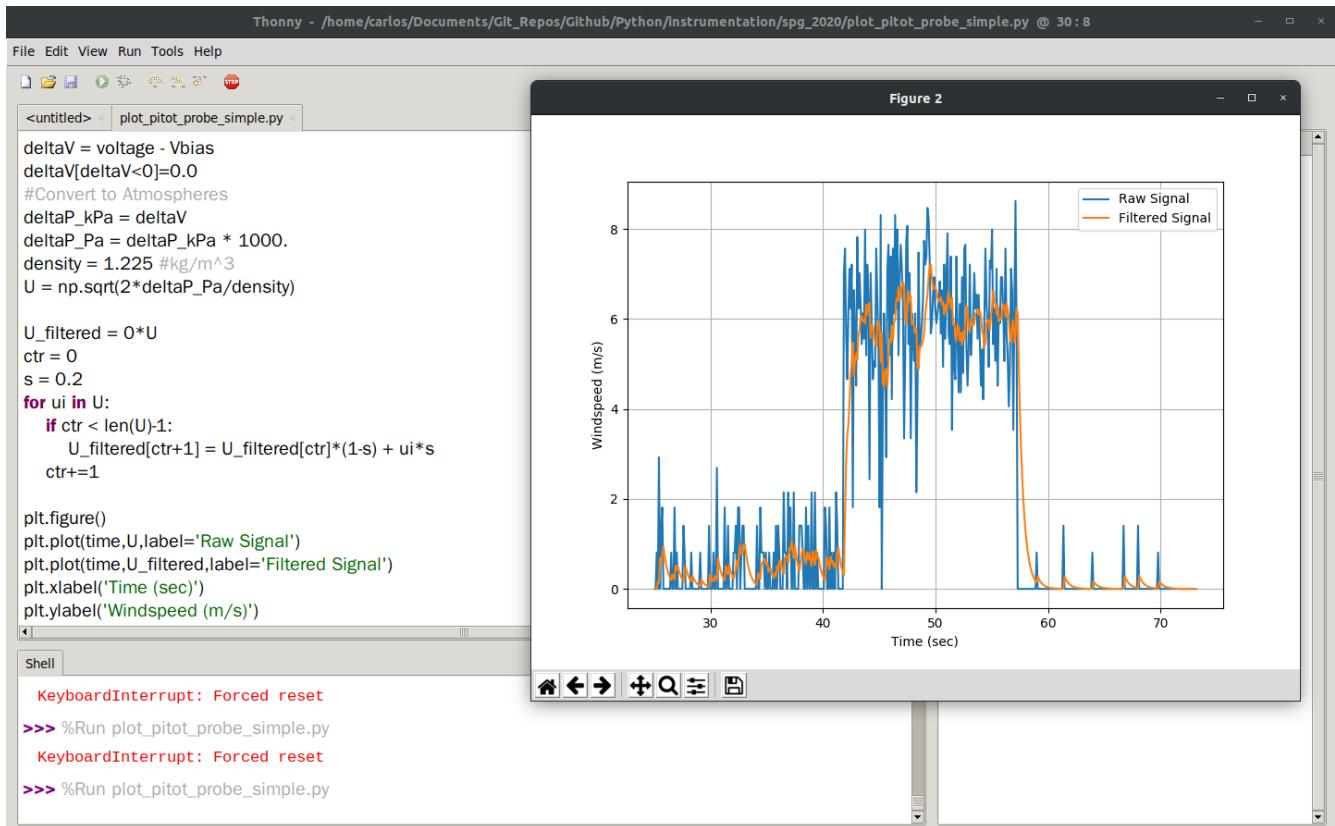
$$U = \sqrt{\frac{2P}{\rho}} \quad (4)$$

Using your data, create a plot of windspeed with time on the x-axis and windspeed on the y-axis. Some steps that might help you as you complete this project. First, have Mu plot the voltage coming from the pitot probe. If you've done everything right it will not be zero. The data sheet says there's an offset voltage of 2.5V so you will hopefully get something around 50,000 when you don't blow into the pitot probe. 50,000 multiplied by  $3.3/2^{16}$  is around 2.5V. Make a note of that average value you get so you can subtract it off later. Once you've verified you're reading the pitot probe correctly, blow into the pitot probe and using the Plotter or Serial, verify that the analog signal increases. If the signal decreases, it means the pressure taps on the pressure transducer are backwards and you need to flip them. Either that or just flip the sign in your plotting routine on your computer but flipping the tubes might be easier for you. Hopefully when you do this lab you will get some data that looks like this. In this

Figure you'll see that when the fan wasn't running the signal was something around 49,800 which is fine. It means your bias is around 2.5 volts. Every pitot probe and circuit will be different. You can then convert this signal to voltage then and then pressure and then finally wind speed.



The code to accomplish this is relatively simple and a portion of the code is shown below. You'll see that when I subtracted the bias from the voltage I also zeroed out any negative values. That is, any delta voltage less than zero was set to zero. A couple of things about this chart. The data from the pitot probe is super noisy which means attaching a complementary filter is probably a good idea provided you don't over filter the signal and run into aliasing issues. You can see that I implemented an offline complementary filter and plotted it in the orange line which helps the noise issue quite a bit. You'll also notice that the noise is about 2 m/s. It turns out that pitot probes are actually not very accurate lower than about 2 m/s. They would be great for an airplane or you driving down the highway but they wouldn't be very good to take wind data outside on a calm day.



## 2.4 Assignment

Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. If you borrowed a pitot probe return the pitot probe - Pass/Fail - If you don't return the pitot probe you receive a zero
2. Include a video of you taking data and explaining the circuit (make sure you are in the video) - 50%
3. Include a plot of the raw analog signal vs time just like I did above - 20%
4. Include a plot of windspeed vs time as I did above - 20%
5. Filter your signal using an offline complementary filter and include it in your plot like I did above - 10%

## 3 Circuit Playground (CPX/CPB) Modules

### 3.1 Parts List

1. Laptop
2. CPX/CPB
3. USB Cable

### 3.2 Learning Objectives

1. Understand the different sensors on the Circuitplayground
2. Learn the difference between high level and low level control
3. Get more practice plotting data from onboard sensors

### 3.3 Extra Help

If you need extra help on this assignment I have uploaded a youtube video where I read the temperature and accelerometer from the CircuitPlayground Bluefruit

### 3.4 Getting Started

The CPX has numerous built-in sensors. These include a light sensor, an IR sensor, an accelerometer, a microphone, a speaker, some neopixels, a temperature sensor and 8 analog inputs with ADCs and even I2C (pronounced I squared C - it's a kind of serial communication) that you can use to easily hook up more sensors to it. We're not going to utilize all of these sensors since that would be a rather large project. Instead we're going to learn how to use the temperature, light and sound sensors as well as the accelerometer. For each of these examples there is a relatively easy way to access the sensors using a built-in module called *adafruit\_circuitplayground.express* if you are using the CPX. If you are using the CPB you need to type *adafruit\_circuitplayground.bluefruit*. It's a very nice module because it imports everything on the board. The problem is you can run into module conflicts. This happens when two different modules try to access the same pins on the CP. Sometimes if you import *adafruit\_circuitplayground* you won't be able to import some other modules. **Note you might need to add the *adafruit\_circuitplayground* library to your lib/ folder on your CIRCUITPY drive.** Due to this module conflict issue, there are some low level control commands you can use to access each of the sensors on board. We're obviously going to learn the low level control method first and then I'll show you how to access the sensors using the *adafruit\_circuitplayground* module. **If you get a “currently in use” error it means you have a module conflict. Hence why I’m showing you the low level control method.**

### 3.5 Low Level Control

#### 3.5.1 Light

The light sensor on the CPX is just a simple photocell wired in series with a resistor. There is a lab on photocells (See chapter 7 if you'd like to do that lab first to learn about photocells. The GND leg of the photocell is connected to pin A8. You can check the pin by looking at the graphic of an eye on the CPX and taking a look at the digital pin next to it. We've already learned how to access analog pins (See chapter 1) in a previous lab so just use the code from that lab and change the pin to A8. Here's what my code looks like when I change the pin to A8. I also brought the Plotter up and moved my finger in front of the light to make sure the light was working. Verify that your CPX responds the same way before moving on.

The screenshot shows the Mu 1.0.2 IDE interface. At the top is a toolbar with icons for Mode, New, Load, Save, Serial, Plotter, Zoom-in, Zoom-out, Theme, Check, Help, and Quit. Below the toolbar is a code editor window titled "main.py" containing the following Python code:

```

1 import time
2 import board
3 import analogio
4
5 analog = analogio.AnalogIn(board.A8)
6
7 while True:
8     print((analog.value,))
9     time.sleep(0.05)

```

To the left of the code editor is the "Adafruit CircuitPython REPL" output window, which displays a series of tuples representing sensor values over time:

```

(832, )
(2016, )
(2848, )
(4608, )
(4832, )
(4736, )
(4784, )
(4816, )
(4800, )

```

To the right of the code editor is the "Adafruit CircuitPython Plotter" window, which displays a line graph of the analog signal. The y-axis ranges from -8000 to 8000, and the x-axis represents time. The plot shows a fluctuating signal with a periodic pattern.

### 3.5.2 Sound

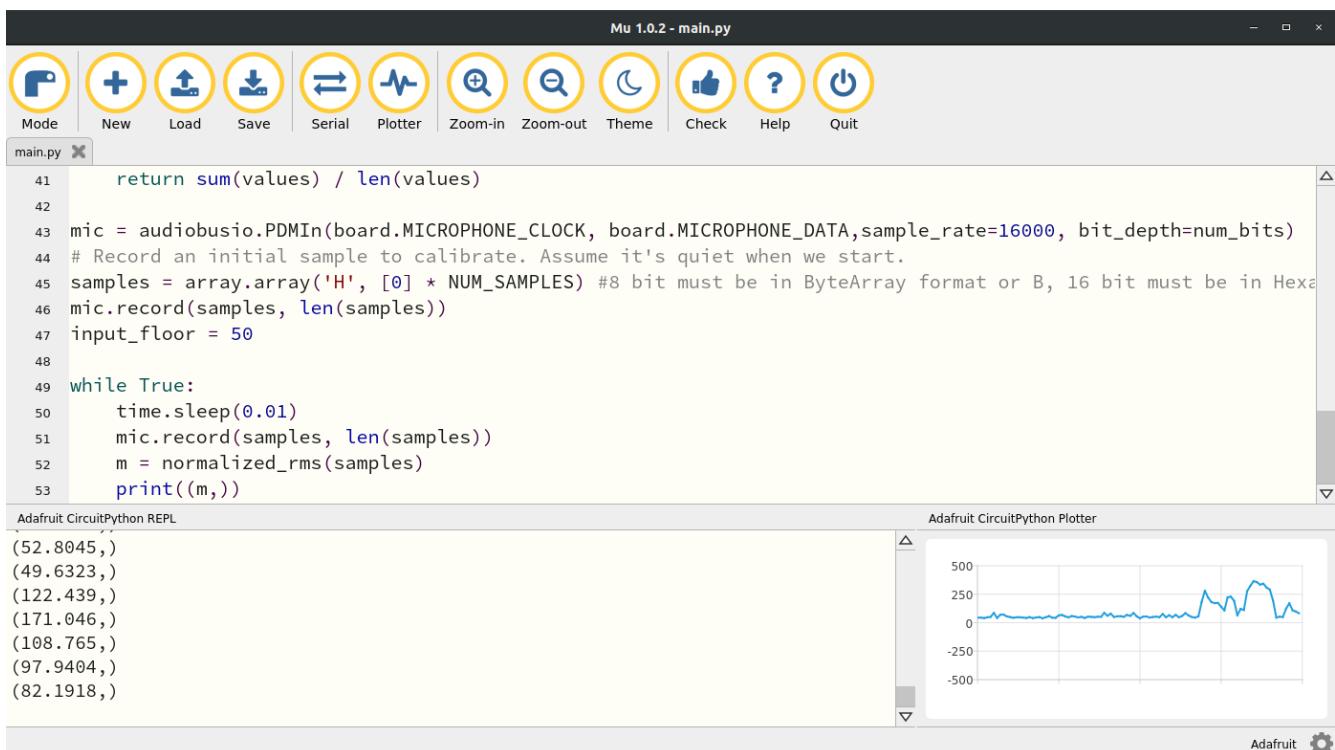
The sound sensor uses the audiobusio library and creates a mic object using the (Pulse Density Modulation) PDM library. You have to set the sample rate and the number of bits to use to capture the data. We're going to set the bits to 16 to utilize the whole spectrum and then set the sample rate to 16 kHz. It's not quite 44.1 kHz like most modern microphones but it will do. After creating the mic object we have to compute some root mean squared values and thus two functions are defined before the while true loop in the code. The code itself is shown below. The code starts on line 22 because the first 22 lines are copyright from Dan Halbert, Kattni Rembor, and Tony DiCola from Adafruit Industries. I have edited the code a bit to fit my needs and uploaded my version to Github. In the code line 23-27 import standard modules as well as some new ones. The array module is used to create array like matrices. The math module is used to compute functions like cos, sin, and sqrt. Then of course the audiobusio module is used to create the mic object on line 42. Notice the two functions defined on 33 and 39 which create a function for computing the mean and for computing the normalized root mean square value of the data stream. Basically what's going to happen is we're going to record 160 samples as defined on line 160. So on line 43 we create a hexadecimal array (hexadecimal: base 16 hence the num\_bits set to 16 on line 31) with 160 zeros. In the while true loop we're going to sleep for 0.01 seconds and then record some samples. Since we're sampling at 16 kHz the time it takes to record 160 samples is  $160/16000 = 16/1600 = 1/100 = 0.01$  seconds. Since we're taking 160 samples we need to compute some sort of average which is why the normalized root mean square value is computed on line 48.

```

22 # Circuit Playground Sound Meter
23 import array
24 import math
25 import audiobusio
26 import board
27 import time
28
29 # Number of samples to read at once.
30 NUM_SAMPLES = 160
31 num_bits = 16
32
33 def normalized_rms(values):
34     meanbuf = int(mean(values))
35     samples_sum = sum(float(sample - meanbuf) * (sample - meanbuf) for sample in values)
36     rms_mean = math.sqrt(samples_sum/len(values)) ##Notice that samples_sum = (sample-mean)**2
37     return rms_mean
38
39 def mean(values):
40     return sum(values) / len(values)
41
42 mic = audiobusio.PDMIn(board.MICROPHONE_CLOCK, board.MICROPHONE_DATA, sample_rate=16000, bit_depth=num_bits)
43 samples = array.array('H', [0] * NUM_SAMPLES)
44
45 while True:
46     time.sleep(0.01)
47     mic.record(samples, len(samples))
48     m = normalized_rms(samples)
49     print((m,))

```

When I run this code and talk normally into the microphone. I get this output in the Plotter. You'll notice that the data is pretty noisy in the beginning. It's possible we could increase the number of samples we take each loop by editing line 30 but that would slow down our code. So there's a tradeoff between filtering here and speed. That's something will investigate in some later labs.



### 3.5.3 Temperature

The temperature sensor is actually a thermistor. A thermistor is basically a thermometer resistor which means the resistance depends on temperature. This means that you can read the analog signal coming from the thermistor just by reading the analog signal from pin A9. If you look for the thermometer symbol on the CPX you'll see pin A9. Therefore, it is possible to just use the analogio library and just read in the analog voltage but in order to convert to celsius and then fahrenheit you need to use some heat transfer equations to convert the analog signal to celsius. Thankfully the folks at Adafruit have done it again with an *adafruit\_thermistor* module. If you head over to their github on this module you'll see the relevant conversion under the definition temperature which at the time of this writing is on line 86. The Adafruit Learn system also does a bit of work to explain the conversion from voltage to temperature. For now though we will just appreciate the simplicity of the code below which is also on my Github.

```

1 import time
2 import board
3 import adafruit_thermistor
4
5 #Temperature Sensor is also analog but there is a better way to do it since voltage to temperature
6 #Is nonlinear and depends on series resistors and b_coefficient (some heat transfer values)
7 #thermistor = AnalogIn(board.A9) ##If you want analog
8 thermistor = adafruit_thermistor.Thermistor(board.A9, 10000, 10000, 25, 3950)
9
10 while True:
11     temp = thermistor.temperature
12     #temp = thermistor.value #if you want analog
13     print((temp,))
14     time.sleep(0.5)

```

As always lines 1-3 import the relevant modules and then line 8 create the thermistor object. You'll notice the

input arguments are the pin which is A9 as well as the resistor values which are in series with the thermistor. These resistors are soldered to the PCB so they are fixed at 10 kOhms. The 25 is for the nominal resistance temperature in celsius of the thermistor and 3950 is the b coefficient which is a heat transfer property. Running this code and then placing my finger on the A9 symbol causes the temperature to rise just a bit. You'll notice the temperature rise quite quickly when I place my finger on the sensor but when I remove the sensor it takes some time before the sensor cools off. This has to do with the dynamic response of the sensor. We'll discuss this in some future labs on dynamic measurements. For now you can move on to the accelerometer.

```

Mu 1.0.2 - record_temperature_thermistor.py
Mode New Load Save Serial Plotter Zoom-in Zoom-out Theme Check Help Quit
main.py record_sound_simple.py record_temperature_thermistor.py
2 import board
3 import adafruit_thermistor
4
5 #Temperature Sensor is also analog but there is a better way to do it since voltage to temperature
Adafruit CircuitPython REPL
(29.0464,)
(29.0236,)
(29.0236,)
(29.0009,)
(29.0236,)
(28.9553,)
(29.0464,)
(29.0236,)
(29.0464,)
(29.0009,)
(28.9553,)
(29.0009,)
(29.0009,)
(28.978,)
(28.978,)
(29.0009,)
(28.9553,)

Adafruit CircuitPython Plotter
Adafruit

```

### 3.5.4 Accelerometer

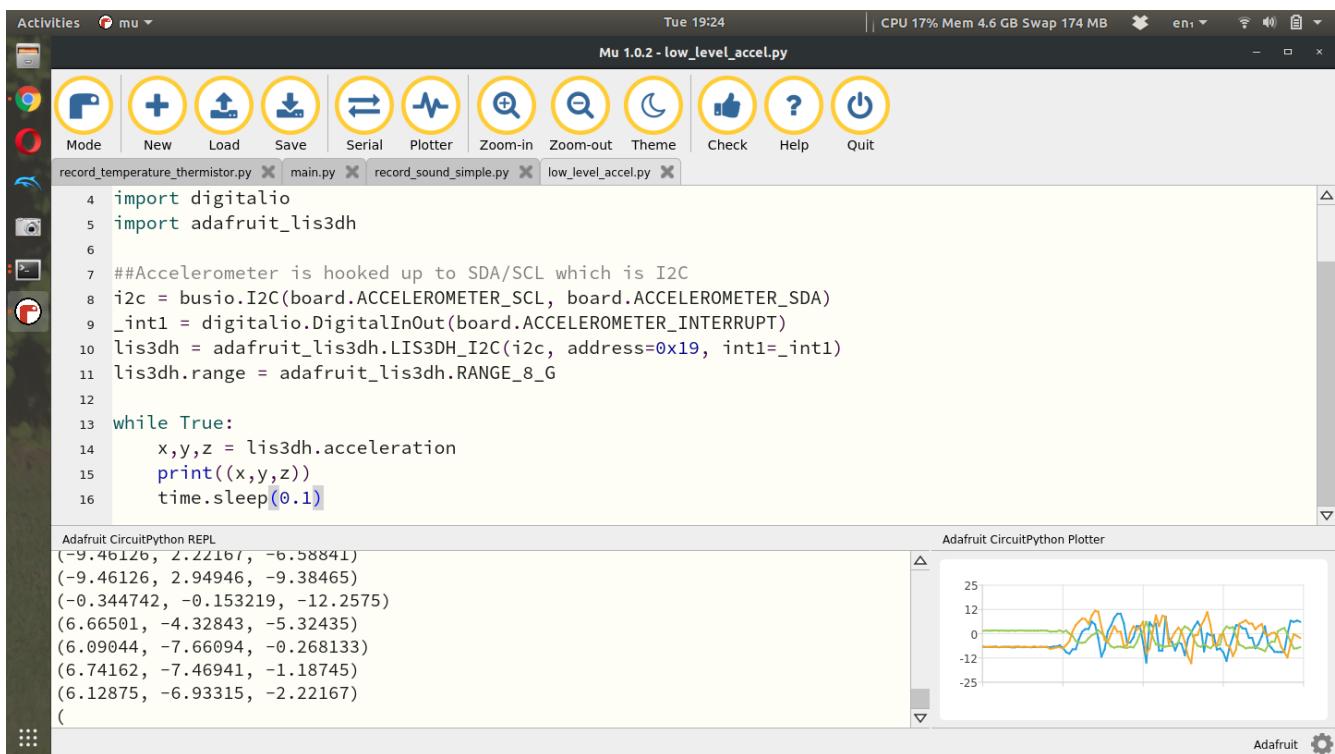
The accelerometer is a 3-axis sensor. As such it is going to spit out not just 1 value but 3 values. Accelerations in x,y and z or North, East, Down or Forward, Side to Side, Up and Down. Since it's reading 3 values we can't just read 3 analog signals (we can but the accelerometer chip design didn't want to do that) so instead we're going to use the I2C (I like indigo and square C. So I squared C. Not 12C or one two C. It's I squared C) functionality. I2C is a type of serial communication that allows computers to send strings rather than numbers. It's a much more complex form of communication but since it's standard we can just use the busio module which contains the I2C protocol.

```

1 import time
2 import board
3 import busio
4 import digitalio
5 import adafruit_lis3dh
6
7 ##Accelerometer is hooked up to SDA/SCL which is I2C
8 i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
9 _int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
10 lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
11 lis3dh.range = adafruit_lis3dh.RANGE_8_G
12
13 while True:
14     x,y,z = lis3dh.acceleration
15     print((x,y,z))
16     time.sleep(0.1)

```

In this code we see a lot more imports than normal. In addition to the standard time, board and digitalio modules we need the busio module and the *adafruit\_lis3dh*. You might think that LIS3DH is a very weird name for an accelerometer but it's actually the name of the chip on your CPX. The chip itself is very standard and is well documented on multiple websites. Here's one from ST. You can also buy the chip on a breakout board from Adafruit and then of course the Adafruit Learn site has plenty of tutorials on reading Accelerometer data in CircuitPython. As always I've learned what I can from the relevant tutorials and created my own simple version to read the accelerometer data and posted it to Github. I digress, lines 8-11 of the code do a lot. It first uses the SCL and SDA pins to set up an I2C object which establishes serial communication to the accelerometer. Line 9 creates an interrupt which is beyond the scope of this course. Finally, line 10 creates the actual accelerometer object by sending it the I2C pins, the hexadecimal address in the I2C protocol and finally the interrupt pin. Line 11 then sets the range. Line 14 in the while loop is where the x,y and z values of the accelerometer are read and then promptly printed to Serial on line 15. If I run this code and shake the sensor a bit I can get all the values to vary. If you put the CPX on a flat surface, the Z axis will measure something close to 9.81. The units of the accelerometer are clearly in  $m/s^2$ .



### 3.6 High Level Control

Alright so we've learned the hard way for all the sensors using low level control of the various sensors. Let's now import the simple `adafruit_circuitplayground.express` module. The Adafruit Learn site offers pretty much every example code snippet you'd ever need for all the different push buttons and sensors on the CPX. Head over there if you ever need something outside of the scope of this text. As I said before, the main module you need to import is done by adding the following to the top of your code

```
from adafruit_circuitplayground.express import cpx
```

**Note that you need to change that line to `adafruit_circuitplayground.bluefruit import cpb`. Then everywhere you see `cpx` you replace with `cpb`.** This will import the `cpx` module into your working code. From here the commands to read different things are relatively simple. Here are the commands for all the various sensors

```
light = cpx.light

x,y,z = cpx.acceleration

temperature = cpx.temperature
```

There unfortunately is no simple module for the sound sensor. You'll still need to use the low level control no matter what. According to Adafruit though, if you get the Circuit Playground Bluefruit there is a simple way to read the sound level. Implementing the various sensors into a while loop on my CPX looks like this.

```

from adafruit_circuitplayground.express import cpx
import time

while True:
    t = time.monotonic()
    light = cpx.light
    temp = cpx.temperature
    x,y,z = cpx.acceleration
    print(cpx.light,cpx.temperature,x,y,z)
    time.sleep(0.1)

```

Adafruit CircuitPython REPL

```

4 28.2297 -4.36673 -0.57457 8.61855
3 28.1846 -4.40504 -0.612875 8.42703
4 28.2072 -4.32843 -0.612875 8.35042
4 28.2072 -4.44334 -0.612875 8.46534
4 28.2297 -4.48165 -0.57457 8.54194
4 28.2072 -4.36673 -0.65118 8.46534
4 28.1846 -4.36673 -0.727789 8.69516
4

```

I left out the sound sensor stuff just because it kind of messes with the simplicity of the code above. The `adafruit_circuitplayground.express` module outputs just as before except for the light sensor. In the low level control we simply computed the voltage across the photocell but the `adafruit_circuitplayground.express` module outputs data in Lux.

### 3.7 Assignment

Using either **low or high level control** take at least 60 seconds of data for each of the sensors above. Make sure log time and the raw sensor value at 1Hz or faster. To make the project more challenging, try and log all sensor data all at once. Import the data onto your desktop and make 4 plots total with time on the x-axis and the sensor data on the y-axis.

Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Using the Plotter in Mu, take a video of you plotting light, sound, temperature and acceleration one at a time while varying light, sound, temperature and acceleration individually and watching the plot change in Mu (be sure to be in the video and introduce yourself) - 30%
2. Copy and paste your CPX code that you used to log data for each of the sensors - 20%
3. Copy and paste your Python desktop code that you used to plot data for each of the 4 sensors - 20%
4. Include 4 plots with time on the x-axis and sensor data on the y-axis (No screenshots) - 30%

## 4 Bluetooth on the CircuitPlayground Bluefruit (CPB Only)

### 4.1 Parts List

1. Smart Phone
2. Adafruit BLE Connect App (Play Store/App Store)
3. CircuitPlayground Bluefruit
4. USB Cable
5. Laptop

### 4.2 Learning Objectives

1. Understand the bluetooth module on the CircuitPlayground Bluefruit
2. Learn how to send data via the Bluefruit to your smart phone
3. Understand how to plot data sent via UART

### 4.3 Extra Help

You might find plotting data via bluetooth to be rather difficult and it was pretty difficult for me until I learned that you can export data as a txt file rather than a csv file. Before I learned how to do that I put together a 4 part series describing everything in this module. Worst case you can just watch the third video in the series. The video is 30 minutes but the first 8 minutes goes through setting up the bluetooth module and the rest of the video is just on plotting the exported csv data which took me some time. Note that exporting data as a txt file is the preferred method as parsing the file is way easier.

### 4.4 Getting Started

In this module we're going to go over how to get the bluetooth module on the Circuitplayground Bluefruit (CPB). There is a lot you can do with bluetooth but the bottom line is that you can send data from your phone to your CPB and you can also send data to your smart phone. All code required for this module is on my Github.

First we're going to run the bluetooth\_uart\_send.py script which sends data to your smart phone via something called UART which is a type of serial communication. It's beyond the scope of this lesson but serial is digital as opposed to analog like we will do in future videos.

```

4 import board
5 import time
6 import analogio
7 import adafruit_thermistor
8 from adafruit_ble import BLERadio
9 from adafruit_ble.advertising.standard import ProvideServicesAdvertisement
10 from adafruit_ble.services.nordic import UARTService
11 import adafruit_lis3dh
12 import busio
13 import digitalio
14 import math
15
16 #####Setup blue tooth
17 ble = BLERadio()
18 uart_server = UARTService()
19 advertisement = ProvideServicesAdvertisement(uart_server)
20 print('Bluetooth Setup')
21
22 ##Setup thermistor
23 thermistor = adafruit_thermistor.Thermistor(board.TEMPERATURE, 10000, 10000, 25, 3950)
24 print('Thermistor and Light Sensor Setup')
25
26 ##Accelerometer is hooked up to SDA/SCL which is I2C or just some kind of protocol
27 i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
28 _int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
29 lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
30 lis3dh.range = adafruit_lis3dh.RANGE_8_G
31 print('Accelerometer Setup')

```

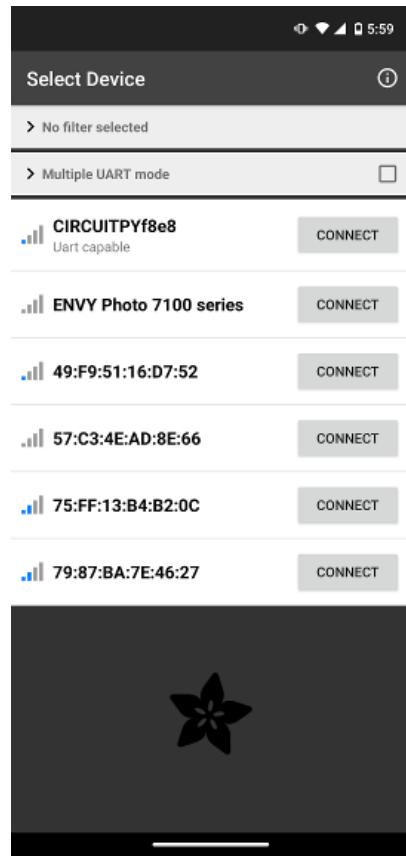
Lines 4-14 import a ton of modules. You'll recognize many of them like analogio, thermistor, and lis3dh but the new ones are the ones that say ble. These are the bluetooth modules required for the CPB. Lines 22-24 setup the thermistor and lines 26-31 setup the accelerometer as we've done in another lesson. Lines 16-20 kick off the BLERadio object and the UARTService() to send data. That's the only required setup for this lesson. **Note:** The image below is from an old version o the code. On line 35 a new line of code has been added print('Look for',ble.name). ble.name is the name of your CPB which is unique to your device.

```

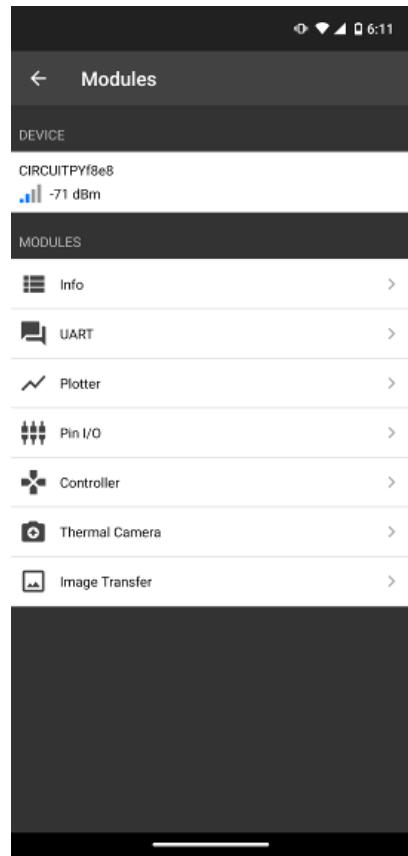
33 while True:
34     # Advertise when not connected.
35     print('Not connected')
36     ble.start_advertising(advertisement)
37     ##Keep looping until connection established
38     while not ble.connected:
39         pass
40     #Stop advertising once connected
41     print('Connected')
42     ble.stop_advertising()
43
44     ##Once connected
45     while ble.connected:
46         #Time =
47         t = time.monotonic()
48         #Print thermistor to serial
49         T = thermistor.temperature
50         #Accelerometer
51         x,y,z = lis3dh.acceleration
52
53         #Print to STDOUT
54         print((t,x,y,z,T))
55
56         #And send them over uart (which is basically serial) but this is _server
57         uart_server.write('{},{},{}\n'.format(x,y,z))
58
59         #Sleep for 5Hz
60         time.sleep(0.2)# Write your code here :-)

```

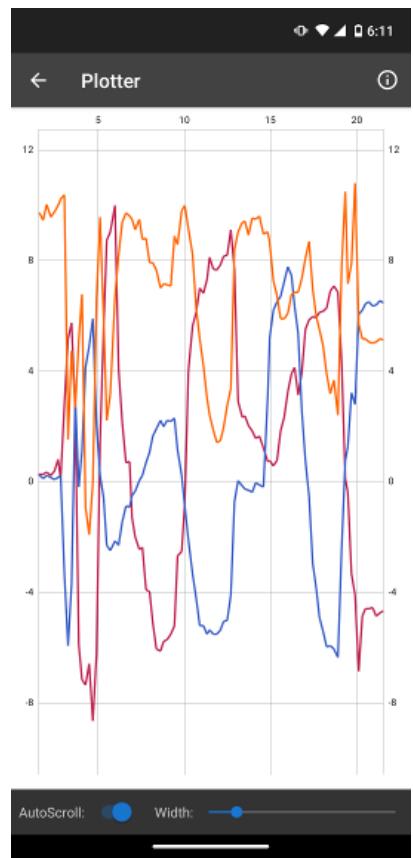
The code above is the infinite while loop which actually contains 2 while loops. Lines 33-42 check to see if bluetooth is connected. If bluetooth is not connected it will start advertising to any devices that are listening. It will then enter a while loop from 38-39 until bluetooth is connected. Once bluetooth is connected it will enter into the second while loop from line 45-60. In those lines 47-54 is responsible for taking all the necessary measurements and printing them to the serial monitor in Mu. Line 57 send the data over bluetooth using the UART server. You'll notice in this case I'm sending x,y,z by using the format variable an the 3 empty brackets. If you want to send more data you need to add more empty brackets and more variables to the format function. When you first save this script your CPB will not be connected and enter into an infinite while loop where it waits for your smart phone to connect. If you open your smart phone and open the Bluefruit Connect App the following screen will pop up.



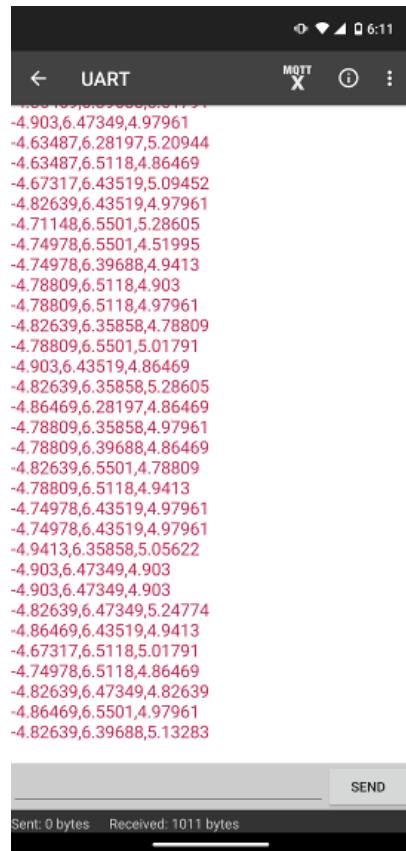
In this case there are numerous different bluetooth modules can be seen but the one you need to click is the one that says CIRCUITPYf8e8. You will have a different code after CIRCUITPY and you can figure out what your 4 digit code is by making sure you have the *print('Look for',ble.name)* in your code. Once you do that the CPB will begin sending x,y,z accelerometer data to the smart phone.



There are numerous items you can click. The Controller is very fun for creating a remote control robot but we're only going to go over the UART and Plotter tabs. If you click the plotter tab you will be greeted with a live screen of the data being sent.



In the photo above you can see three data streams that is coming directly from the CPB. This is great for live demonstrations and for debugging if you need to see data from an experiment and you don't have access to a laptop with Mu. If you hit the back arrow and then click UART you will see the raw data come in as text.



Again here you can see the 3 data streams separated by commas. The very neat thing with the UART tab is that you can click the three vertical dots in the upper right hand corner and click export to TXT. The easiest thing for me was to export the data to google drive and then download the data to my computer. Before I downloaded the data though I went back and changed the following line of code

```
uart_server.write('{}, {}, {} \n'.format(x, y, z))
to
uart_server.write('{}, {}, {}, {}, {}, {} \n'.format(t, x, y, z, T))
```

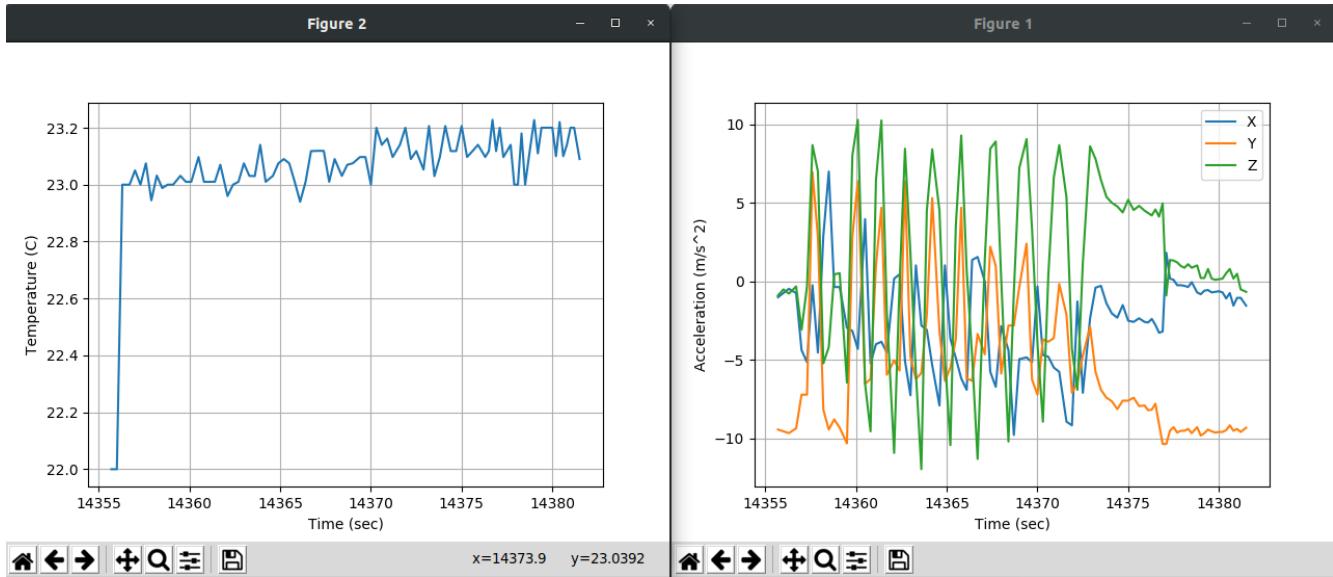
In this case I added more empty brackets and also added the time and the temperature. When I opened the UART tab I was greeted with 6 data streams separated by commas. Once I downloaded the TXT file to my computer and opened it the data file looked like this.

2653.33	8.23551	-5.7074	9.61448	26.6599
2653.68	7.08637	-4.0986	7.04806	26.7489
2653.99	6.12875	-4.0603	7.27789	26.7043
2654.3	6.01384	-4.02199	6.85654	26.7043
2654.61	6.85654	-4.40504	6.93315	26.7043
2654.91	7.00976	-4.17521	6.35858	26.7267
2655.22	7.12467	-4.32843	5.63079	26.6152
2655.53	6.62671	-4.51995	5.24774	26.7267
2655.84	6.77993	-4.21351	5.7074	26.6152
2656.15	6.24366	-4.29012	5.7074	26.682
2656.45	6.32027	-4.44334	5.97553	26.7267
2656.76	7.08637	-4.29012	6.47349	26.7712
2657.07	7.27789	-4.40504	6.05214	26.7712
2657.43	7.08637	-4.36673	5.93723	26.7712

If you export the file as a CSV the data file will look completely different and it's much more complicated to plot. If you export the data as a TXT file you just need to use the np.loadtxt command to read in the data. Note you might have commas in your data file. If there are commas just use the CTRL+H command and replace all commas with spaces or use the np.loadtxt('file.txt',delimiter=',') command. Here's a simple piece of code to plot temperature and the accel data. I have not uploaded this code to Github simply because the code is very simple to create on your own.

```
import numpy as np
import matplotlib.pyplot as plt
data = np.loadtxt('CPB_Datalog.txt')
t = data[:,0]
x = data[:,1]
y = data[:,2]
z = data[:,3]
T = data[:,4]
plt.plot(t,x,label='x')
plt.plot(t,y,label='y')
plt.plot(t,z,label='z')
plt.grid()
plt.xlabel('Time (sec)')
plt.ylabel('Accel (m/s^2)')
plt.legend()
plt.figure()
plt.plot(t,T)
plt.grid()
plt.xlabel('Time (sec)')
plt.ylabel('Temp (C)')
plt.legend()
plt.show()
```

The code reads in the data with the np.loadtxt command and then extracts each column. Once that's done the code plots all the data. In my case this was the result.



## 4.5 Assignment

Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. First get the bluetooth code on your CPB and connect your smart phone to it and video tape yourself connecting the CPB to your smart phone (20%)
2. Take a screenshot of the Plotter on your phone (15%)
3. Take a screenshot of the UART raw data on your phone (15%)
4. Export time, accelerometer and temperature data to a TXT file and plot it on your computer. Include your raw data in an appendix (20%)
5. Include two plots: one of temperature and the other of acceleration like the lesson did above (30%)

## 5 Integrating Acceleration

### 5.1 Parts List

1. CPX/CPB
2. USB Cable
3. Laptop
4. Some sort of temporary adhesive
5. Automobile

### 5.2 Learning Objectives

1. Taking acceleration data
2. Numerical Integration
3. Data is not perfect

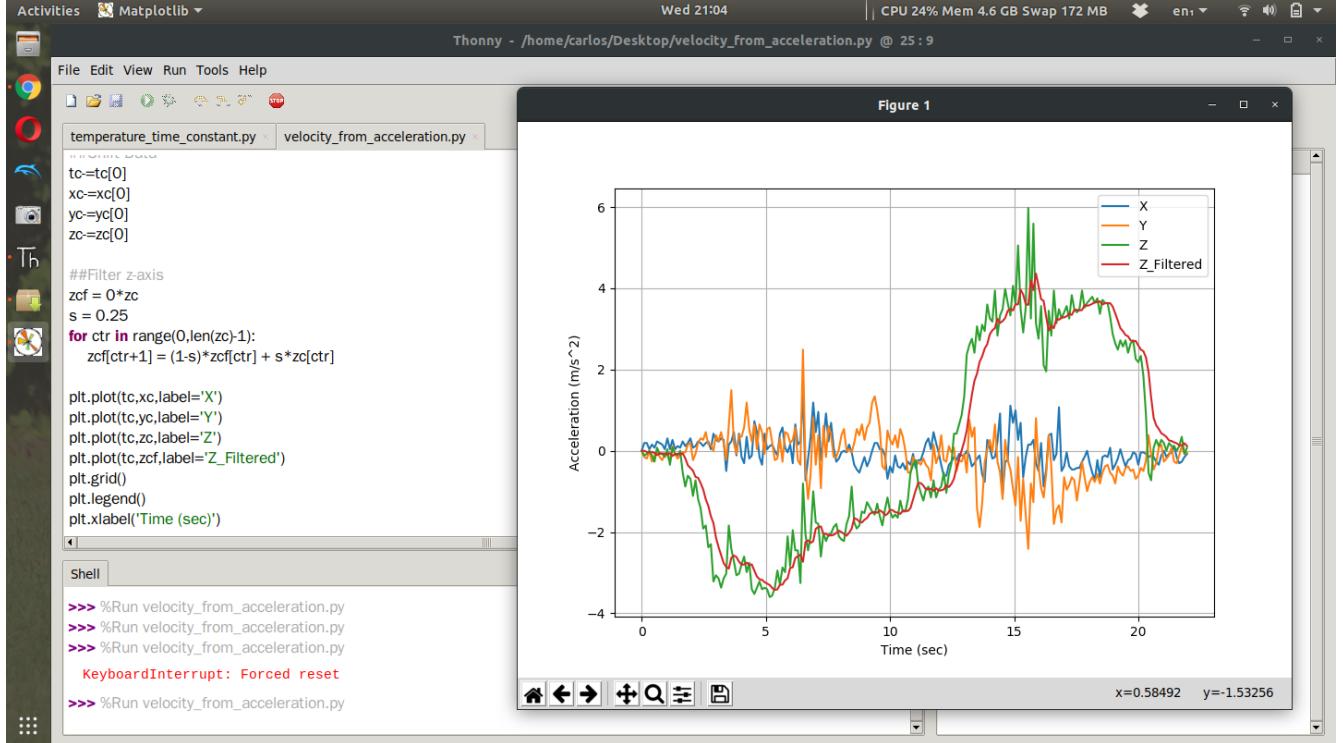
### 5.3 Getting Started

The code for this lab is to have the CPX log acceleration. So when you're done with this lab you will hopefully have a data file with 4 columns of data: time, acceleration x, acceleration y, acceleration z. The code I'm using is the same as the lab on accelerometers (See chapter 3.5.4). I'm using method 1 for datalogging so I'm just having it print to Serial (See chapter ??).

```
1 import time
2 import board
3 import busio
4 import digitalio
5 import adafruit_lis3dh
6
7 ##Accelerometer is hooked up to SDA/SCL which is I2C
8 i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
9 _int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
10 lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
11 lis3dh.range = adafruit_lis3dh.RANGE_8_G
12
13 while True:
14     x,y,z = lis3dh.acceleration
15     print((x,y,z))
16     time.sleep(0.1)
```

The code on Github has a sleep of 0.1 seconds but make sure to have the CPX take data as fast as possible. A sleep of 0.01 is probably good. You will probably get a lot of data points for this experiment. Once your code is working, place the CPX on your dashboard with one of the axes of the accelerometer pointing towards the nose of your car. Try and place the CPX on as flat a surface as possible. You can use 3M tape or duct tape or hot glue. Just make sure you don't damage your car and make sure the CPX is well anchored to the dashboard. This way when the car accelerates, the CPX will measure that acceleration. Note, if you'd like to do this with a bike or some other motor vehicle that is just fine. Just make sure to take pictures and videos when you do the experiment. I suggest you do this in a parking lot for safety reasons. I am not responsible for any damage done to your vehicle or anyone else because you are doing this project. Once you have the CPX anchored, accelerate your vehicle to 20 mph (or however fast you are comfortable driving) and then slam on the brakes. Once your data is logged, plot your acceleration in Python on your desktop computer. After doing the experiment myself, this is what my acceleration plot looks like. I had to clip the time series to only include the part from where I accelerated and decelerated quickly. I also subtracted the first data point from each accelerometer axis to zero it out and subtract

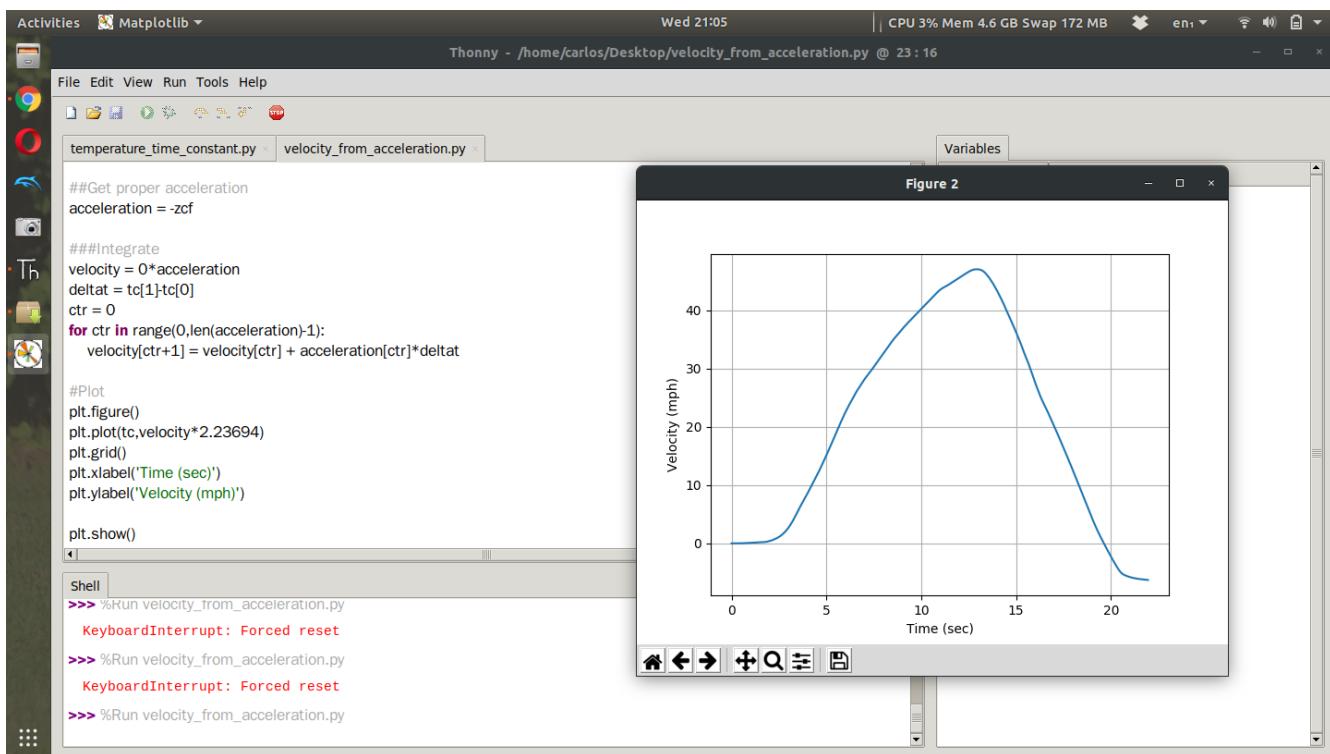
off the bias. Since I took some data for a bit before I started moving I could have averaged the first few data points to obtain the bias. I've done this in a Youtube video if you're unsure what I mean. Instead just to get something working properly I went ahead and just used the first data point.



It's clear from the plots that the z axis was oriented towards the nose of the car. In this case I am going to have to flip the z-axis since the beginning is acceleration and the end is deceleration. I also through the acceleration in the z-axis through a complementary filter with a filter value of 0.25. I think it makes the acceleration profile a bit less jumpy. I then used a Reimann sum and integrated the acceleration data points to get velocity. The equation itself looks like this:

$$V_i = \sum_{n=0}^i (a_i - a_0)\Delta t \quad (5)$$

This of course assumes the initial velocity is zero. Notice that I take the individual acceleration points and subtract off the bias. Computing that summation by hand is pretty trivial but getting the code to work is another story. For a Reimann sum we're going to use a for loop where we loop through all the data points. The good news is that the time between data points is the same so we can just treat that as a constant. Once you have acceleration integrated you can plot velocity. This is what mine looks like after I did the experiment. According to my plot I accelerated to about 45 mph. I guess I can't lie in this instance. I said to accelerate to 20 mph but I really wanted to see a large change in acceleration so I punched it. Notice though that at the end of the time series the velocity is negative. This is because as time goes on you are integrating error and the error just gets worse.



This is why speedometers are used. They are just much more accurate than integrating acceleration which is prone to bias and drift. This code has a lot of conditioners so this example is posted on my Github to help with your project. **Note, that code has a bias filter, truncation filter and complementary filter before I integrate. That code may not work for you and you may need to tune the filters for your specific data set.** For example, notice that I clip the data to only take data after 248 s. If you didn't take more than 248 seconds of data, your code will throw an error because there isn't any data past that. Make sure to understand what each filter does and think about how it applies to your data set.

## 5.4 Assignment

Upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Record yourself in your vehicle explaining how you mounted your CPX to your vehicle in some way. Explain how you plan on taking data and what speed you plan to accelerate to. - 25%
2. Plot your accelerometer data and apply whatever signal conditioners are necessary to make it look obvious as to when you accelerated and decelerated as I did. Include the plot in your submission. Include a small paragraph explaining what signal conditioners you applied. - 25%
3. Integrate acceleration and plot velocity as a function of time. Comment on whether or not the maximum velocity is the same as what you did in your actual car - 25%
4. Integrate the velocity and compute position. Plot your position as a function of time and include that in your report. Although you didn't measure how far you went, comment on the accuracy of the plot and whether or not you think you traveled that far. - 25%

## 6 Inertial Measurement Unit - Accelerometer, Rate Gyro, Magnetometer

### 6.1 Parts List

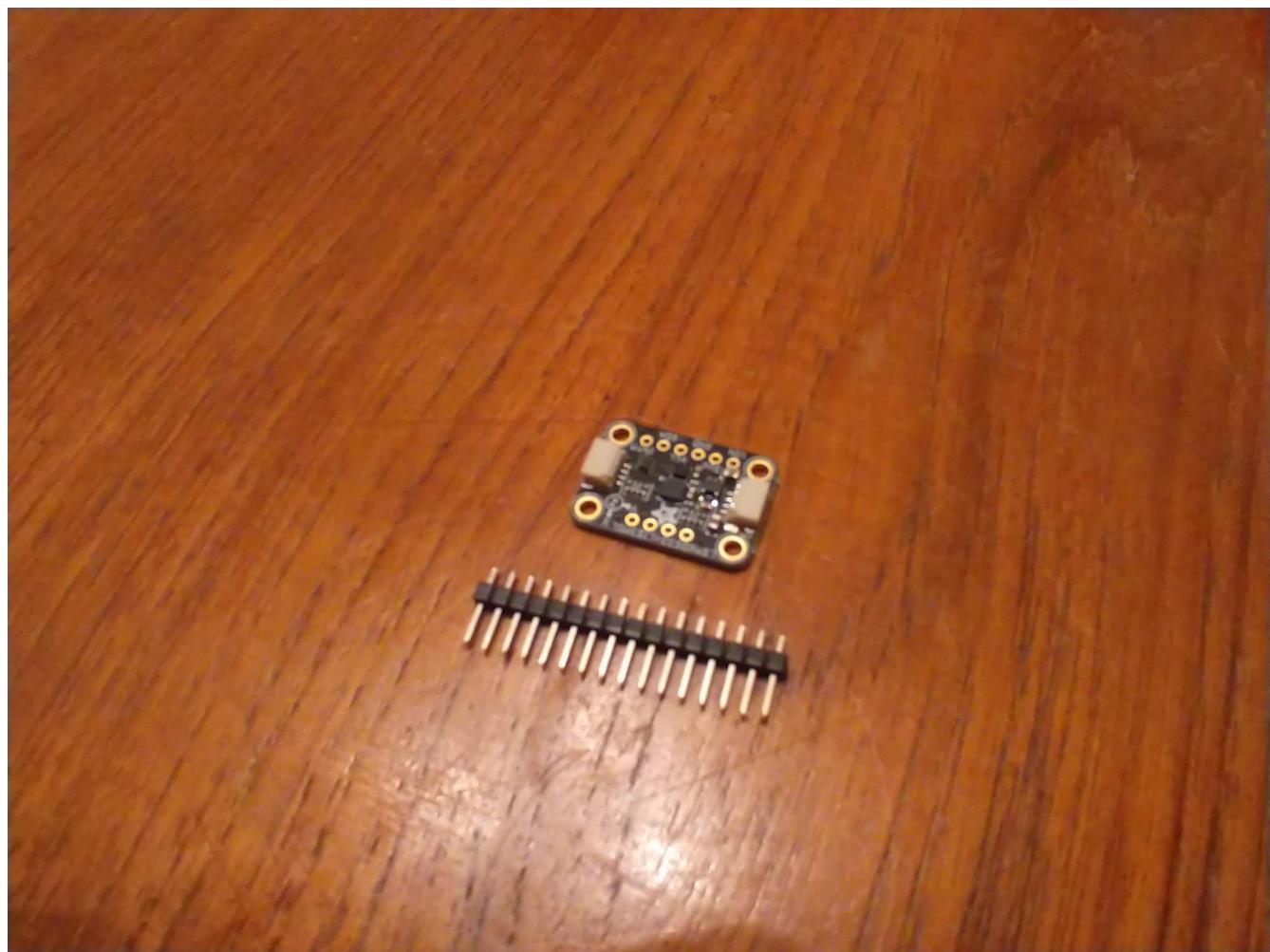
1. Laptop
2. CPX/CPB
3. USB Cable
4. LSM6DS33+LIS3MDL (Not included in kit. Note that other Inertial Measurement or "DOF" Sensors will work for this lab you will just have to change the code to accommodate the change in hardware)
5. Alligator Clips (x4)
6. Bread Board
7. Soldering iron

### 6.2 Learning Objectives

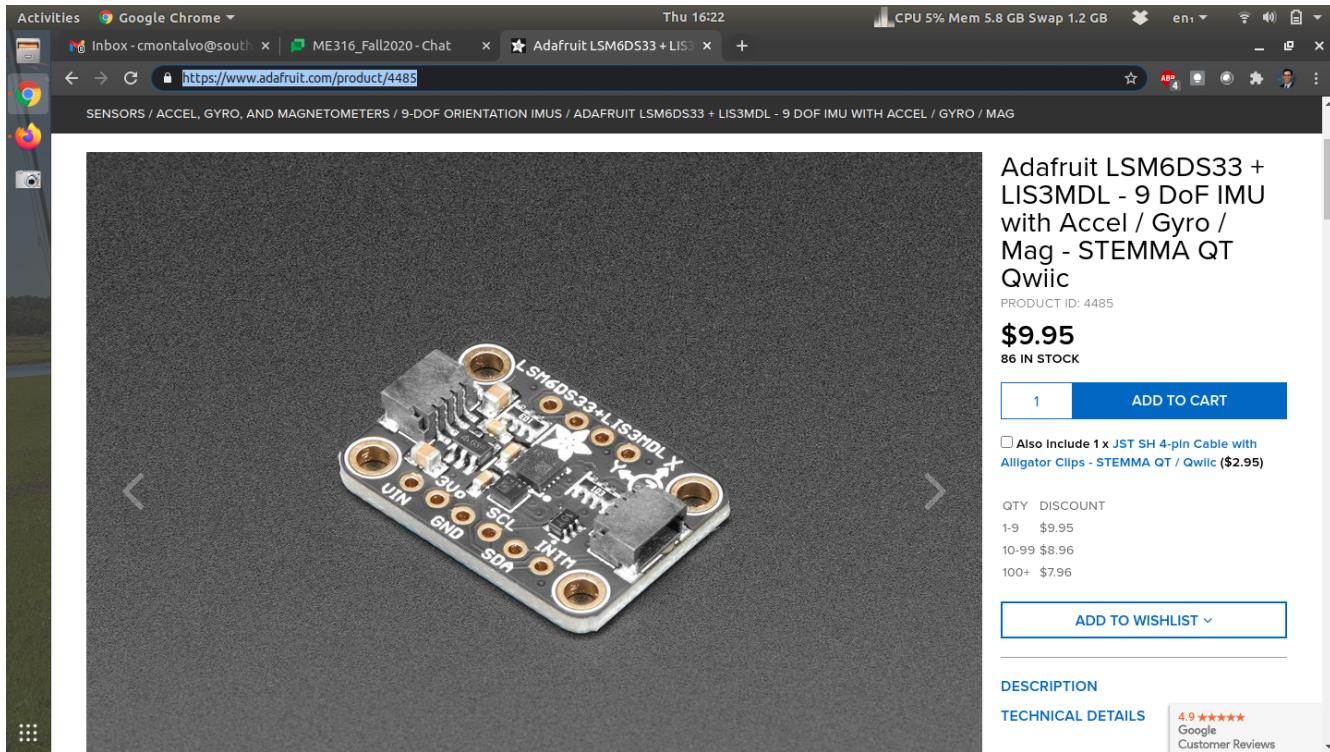
1. See and understand the concept of soldering
2. Understand the I2C protocol at a high level
3. Learn the components of an IMU (Accelerometer, Rate Gyro, Magnetometer)
4. Read IMU data and plot

### 6.3 Getting Started

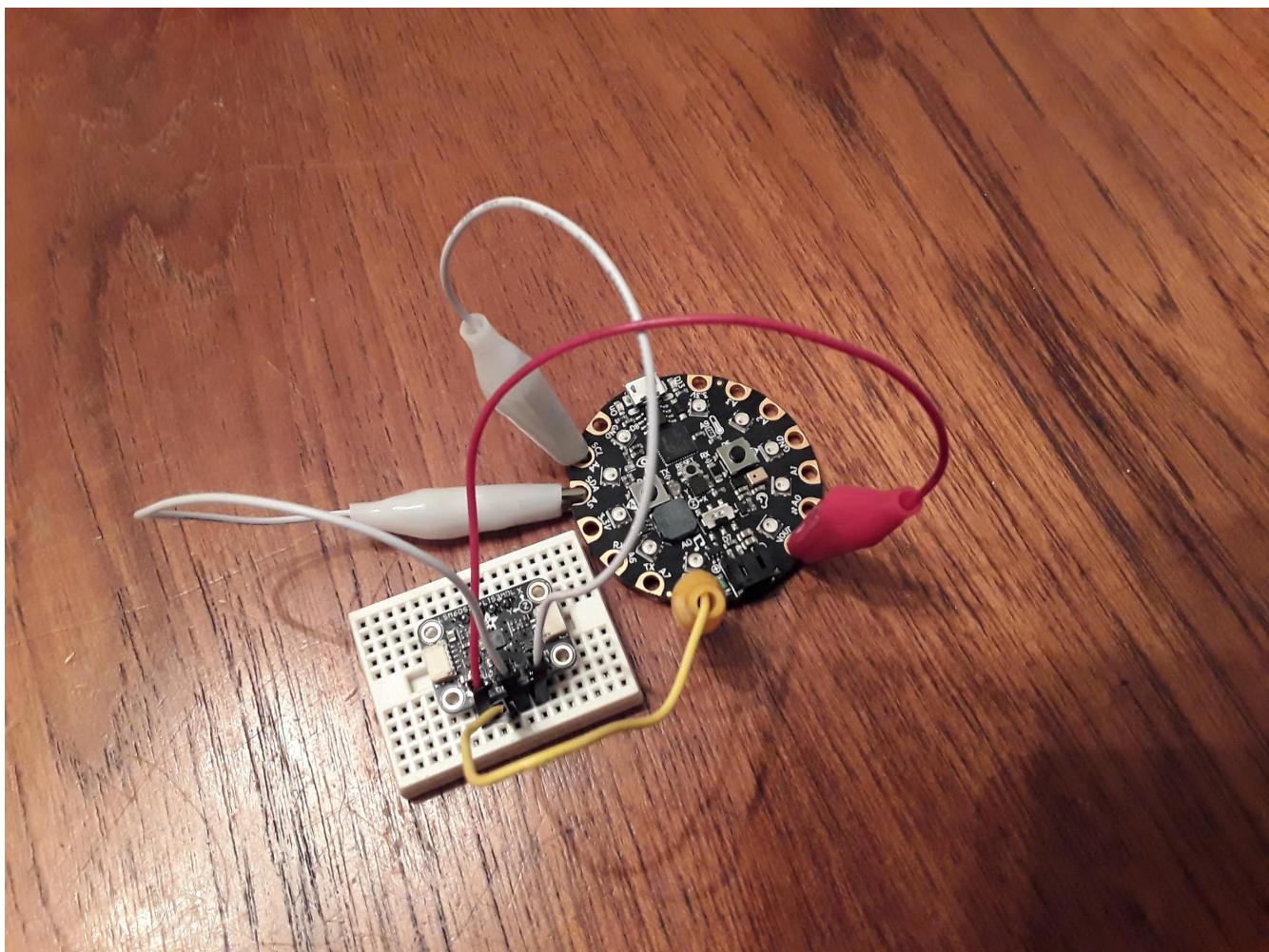
In this lab we're going to use this an external sensor to measure angular velocity and the magnetic field of the surrounding environment.



The sensor above is the LSM6DS33+LIS3MDL. You basically have 2 separate microchips in one. The first (LSM6DS33) is a 3-axis accelerometer and 3-axis rate gyro. The first measures acceleration and the second measures angular velocity. The LIS3MDL is a 3-axis magnetometer which measures magnetic fields. The three of these sensors put together (accelerometer, rate gyro, magnetometer) is called an IMU (Inertial Measurement Unit). It's actually possible to measure roll and pitch of an airplane and heading using the magnetometer. Combining the angular velocity of the rate gyro can create a complete attitude estimation algorithm for spacecraft. This sensor does not come standard in the current iteration of the kit. You can purchase one on Adafruit for only \$10 at the time of this writing. The interesting thing about this device is that you can actually purchase the LSM6DS33 and LIS3MDL separately but this breakout board has both chips on board. The goal of this lab is not necessarily to use this specific sensor but to understand IMUs and I2C protocol. Most if not all breakout boards on the Adafruit website use I2C communication. You'll know if the breakout board uses I2C if you find SDA/SCL pins on the board. It will also say it in the quick description of the sensor.



When you open the packaging of this breakout board you'll notice that the header pins are missing. First you'll need to cut a row of 4 and 6 for the top and bottom side of the board and solder the header pins to sensor. If you're taking my class you can stop by my lab one day and I'll solder this for you or teach everyone about soldering during a lecture session of class. If you are taking this class elsewhere you have two options: try and find someone who can solder this real quick (only takes about 5 minutes) or buy your own soldering iron and try to solder yourself. Once the device is soldered you can "plug" it into a breadboard. Then, using 4 alligator clips you need VOUT (5V) to run to (VIN), GND to GND and then SDA to SDA and SCL to SCL.



Believe it or not the photo above was actually wired wrong. I had SDA to SCL and SCL to SDA. You need to make sure you have the proper wires going to the correct pins or it won't work. SDA and SCL are 2 pins for something called I2C (pronounced I squared C) where I is I as in "I am a billy goat" or "I like to code". I2C is beyond the scope of this project but just know it's a type of serial communication that uses hexadecimal addresses.

Once you have the circuit wired and soldered it's time to work on software. First want to make sure you have your Circuit Python UF2 up to date. In this example I'm using the 6.X version. Once I updated my UF2 I also updated my Circuit Python Libraries. The Circuit Python Libraries download as a zip file. You need to unzip the folder and go into the lib folder and grab the following python modules.

1. adafruit\_bus\_device
2. adafruit\_register
3. lis3mdl
4. lsm6ds33

There will be folders for some and just floating .mpy files for others which are python modules that you can import just like time, board and busio as we've done in the past. Put those files into your lib folder on your CIRCUITPY drive. If the lib folder doesn't exist you just need to make one. Once you have the necessary modules you can run some example code. The Adafruit Learn page has a tutorial for the LSM6DS33. The problem with the tutorial is that it seems like it was written for the Raspberry or some other microcontroller. As such I had to find some example code on Adafruit's Github. After following both tutorials I was able to make my own script and upload it to my Github.

---

```

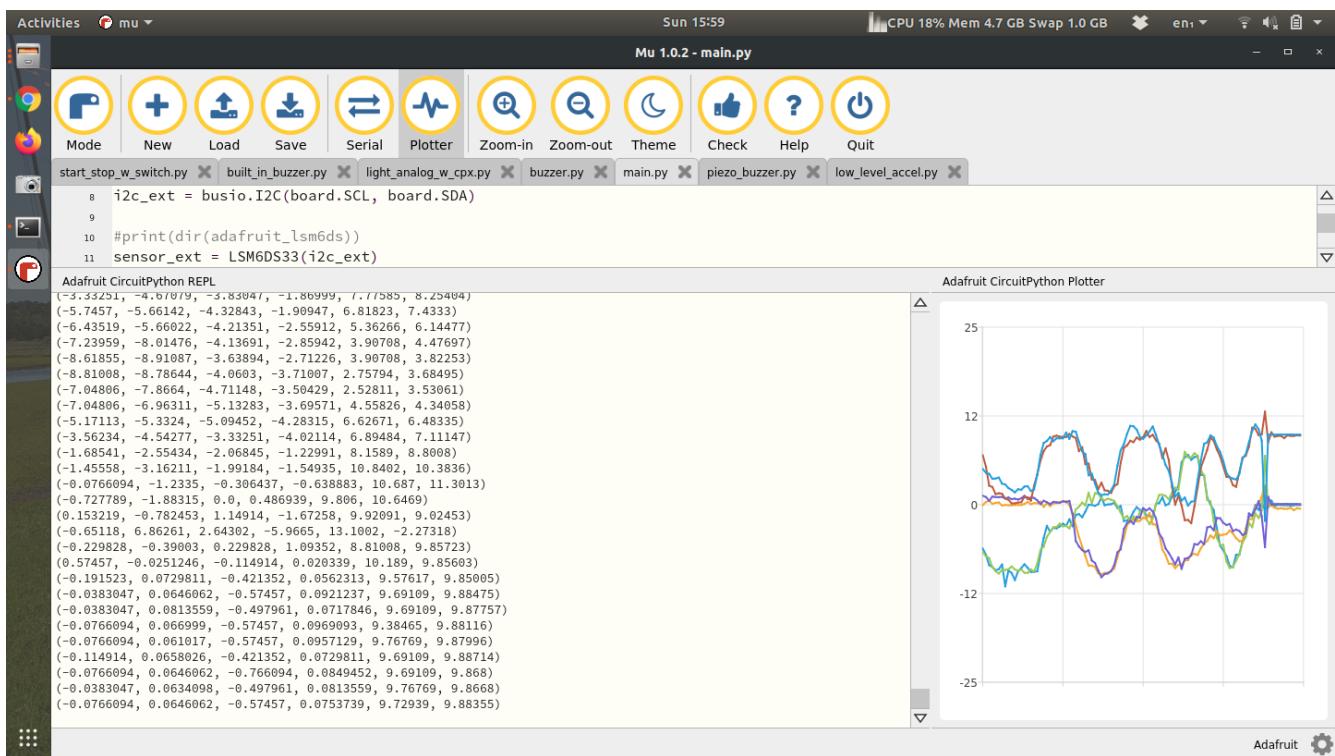
1 import time
2 import board
3 import busio
4 import digitalio
5 import adafruit_lis3dh
6 from adafruit_lsm6ds.lsm6ds33 import LSM6DS33
7
8 i2c_ext = busio.I2C(board.SCL, board.SDA)
9
10 #print(dir(adafruit_lsm6ds))
11 sensor_ext = LSM6DS33(i2c_ext)
12
13 ##Accelerometer is hooked up to SDA/SCL which is I2C
14 i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
15 _int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
16 lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
17 lis3dh.range = adafruit_lis3dh.RANGE_8_G
18
19 while True:
20     #x,y,z = lis3dh.acceleration
21     #xe,ye,ze = sensor_ext.acceleration
22     gx,gy,gz = sensor_ext.gyro
23     #print((x,xe,y,ye,z,ze))
24     print((gx,gy,gz))
25     time.sleep(0.1)

```

---

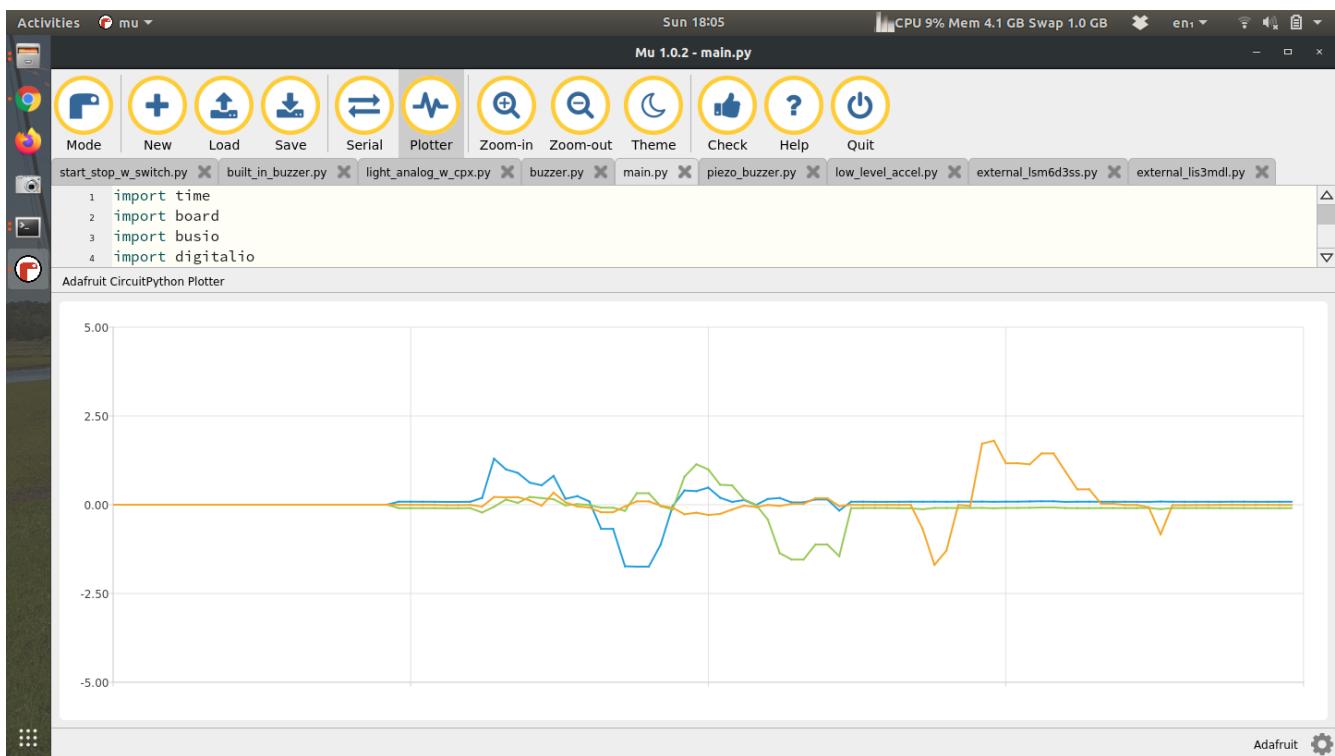
In the code above lines 1-6 import all the modules with line 5 importing the accelerometer on board the CPX and line 6 importing the external sensor wired up to SDA and SCL. Line 8 creates an I2C object using the SDA and SCL pins from the alligator clips and line 11 creates the sensor object. I also include lines 14-17 to include the onboard accelerometer. Notice I can access both sensors no problem. In the while loop line 20 checks the accelerometer on the CPX, line 21 checks the accelerometer on the breakout board and line 22 checks the angular velocity on the breakout board. Lines 23 and 24 print to serial and output to the plotter. Note that some lines are commented out because I wanted to try one thing at a time.

With both accelerometers printing to the Plotter I could move the CPX and the breakout board in unison and get the following output.



Notice that there are 6 numbers printed and 6 lines on the plotter. Both the CPX and the breakout board have little XYZ cartesian coordinate systems. I had to line them up properly before I started moving them. My suggestion would be for you to get some hot glue or 3M tape and place both breakout board and CPX on some sort of hard material like plywood, masonite, or even a cutting board. Anything to keep everything together.

Once you've done this, try uncommenting the line of code that prints the angular velocity. When I do that and move the breakout board around I can measure the angular velocity of each axis. The units are in radians per second but it's pretty obvious just from the magnitude of the graph.



The final part is to get the LIS3MDL (magnetometer) to work. The starting point for me was the Adafruit Learn page, along with the simple example from Adafruit's Github. After that I was able to create my own code. The only difference in your code is that the address will be 0x1c instead of 0x1e.

```

1 import time
2 import board
3 import busio
4 import digitalio
5 #import adafruit_lis3dh
6 #from adafruit_lsm6ds.lsm6ds33 import LSM6DS33
7 import adafruit_lis3mdl
8
9 i2c_ext = busio.I2C(board.SCL, board.SDA)
10
11 #print(dir(adafruit_lsm6ds))
12 #sensor_ext = LSM6DS33(i2c_ext,address=0x6a)
13 mag = adafruit_lis3mdl.LIS3MDL(i2c_ext,address=0x1e)
14
15 ##Accelerometer is hooked up to SDA/SCL which is I2C
16 #i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
17 #_int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
18 #lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
19 #lis3dh.range = adafruit_lis3dh.RANGE_8_G
20
21 while True:
22     #x,y,z = lis3dh.acceleration
23     #xe,ye,ze = sensor_ext.acceleration
24     #gx,gy,gz = sensor_ext.gyro
25     bx,by,bz = mag.magnetic
26     #print((x,y,z))
27     #print((x,xe,y,ye,z,ze))
28     #print((xe,ye,ze))
29     #print((gx,gy,gz))
30     print((bx,by,bz))
31     time.sleep(1.0)

```

---

The code is almost identical to the code before except all the LIS3DH and LSM6DS33 code is commented out. Instead I have code to grab the magnetometer (LIS3MDL) at address 0x1E. Line 25 then calls the magnetometer and prints it.

## 6.4 Assignment

Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Include a video of you reading both accelerometers and generating a plot like I did. Plotter is fine for this portion - 10%
2. Include a video of you getting the magnetometer to work and plotting the data in the plotter as you move the magnetometer. - 10%

3. Create a pendulum for your “cutting board” circuit and swing the pendulum. Include a video describing your pendulum - 20%
4. While swinging the pendulum record the accelerometer on the CPX and the breakout board as well as the angular velocity. Plot the angle (theta) using both accelerometers. You will have 2 lines since there are two accelerometers. Also plot the angular velocity of the pendulum. Plot these in Python - 20%
5. Take the two theta values and use the finite difference method to take a derivative and get the angular velocity. Plot the derivative of theta alongside the angular velocity and comment on the similarities and differences. - 20%
6. Finally, take the angular velocity and integrate using a Riemann sum to get theta from integration and plot it alongside your two other values of theta from the accelerometers. Comment on the similarities and differences - 20%

# 7 Histograms and Normal Distribution of Photocell Readings

## 7.1 Parts List

1. Laptop
2. CPX/CPB
3. USB Cable
4. Photocell
5. Resistor (10 kOhm)
6. Alligator Clips (x3)
7. Breadboard

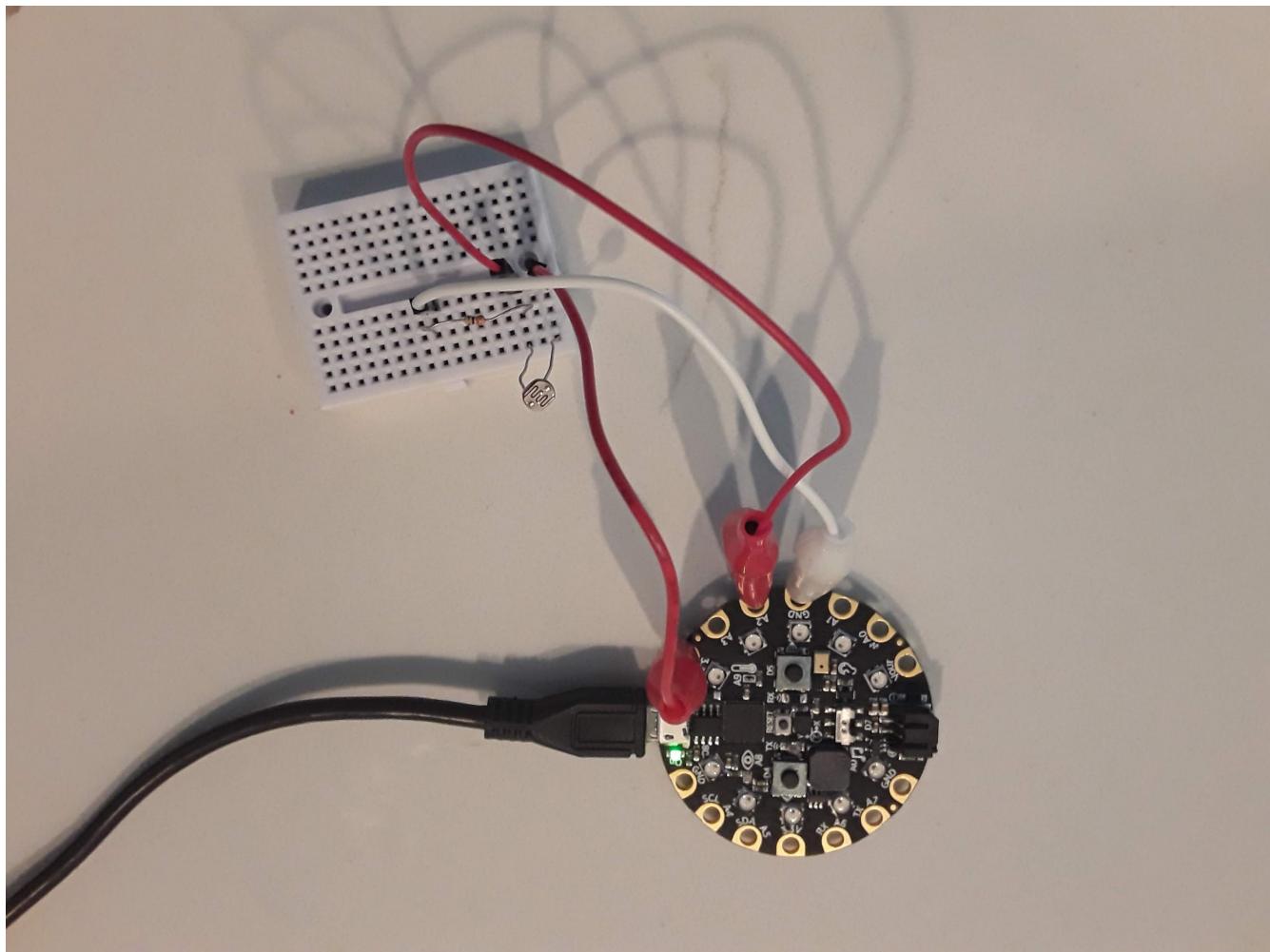
## 7.2 Learning Objectives

1. Understand how a photocell responds to light level by measuring the voltage across the photocell in different light conditions
2. Learn how to create histograms of a noisy data signal
3. Understand mean and standard deviation and how that applies to Normal distributions.

## 7.3 Getting Started

This lab is going to be similar to the potentiometer lab (See chapter 1). We are going to use a photocell though to vary the resistance instead of a potentiometer. Photocells are cool because they change their resistance solely based on the light intensity hitting the sensor rather than twisting a knob like the potentiometer.

Wiring a photocell is similar to a potentiometer except that you need to add a resistor in series with the photocell. There is a relevant Adafruit Tutorial on Photocells and the code required to measure the voltage if you'd like to read more about it. The lab this week requires you to do the same as the potentiometer lab. I'd like you to wire up the circuit, take data at the low and high value of the photocell by covering the sensor with your finger and then shining a light on it and plotting the entire data set in Python on your desktop computer. The wiring diagram is shown below. Have an alligator clip connected to 3.3V on the CPX and have it connected to either end of the photocell. Then place a resistor in series with the photocell and route the free end of the resistor to GND.



Then take another alligator clip from pin A2 and plug it into the same row on the breadboard as the resistor and photocell. Once you have the circuit wired properly you can use the same code as the potentiometer lab. The example screenshot below shows the analog signal below showing a high spike where I placed a flashlight over the photocell and then a low spot where I covered the photocell with my finger. Remember that you can use any Analog pin on the CPX provided you change line 5 to the same pin.

```

import time
import board
import analogio

analog = analogio.AnalogIn(board.A2)

while True:
    print(analog.value)
    time.sleep(0.05)

```

Adafruit CircuitPython REPL

```
(8304, )
(8336, )
(8272, )
(8288, )
(8352, )
(8336, )
(8336, )
(8336, )
(8320, )
```

Adafruit CircuitPython Plotter

Once you've gotten some example data you can plot the result in Python as you did for the potentiometer lab. Here's what your plot may look like.

```

import numpy as np
import matplotlib.pyplot as plt

data = np.loadtxt('Example_Light_Data.txt')

time = data[:,0]
light_digital = data[:,1]
voltage = 3.3*light_digital/2.0**16

plt.plot(time,voltage)
plt.xlabel('Time (sec)')
plt.ylabel('Voltage (V)')
plt.grid()
plt.show()

```

Figure 1

Voltage (V)

Time (sec)

Shell

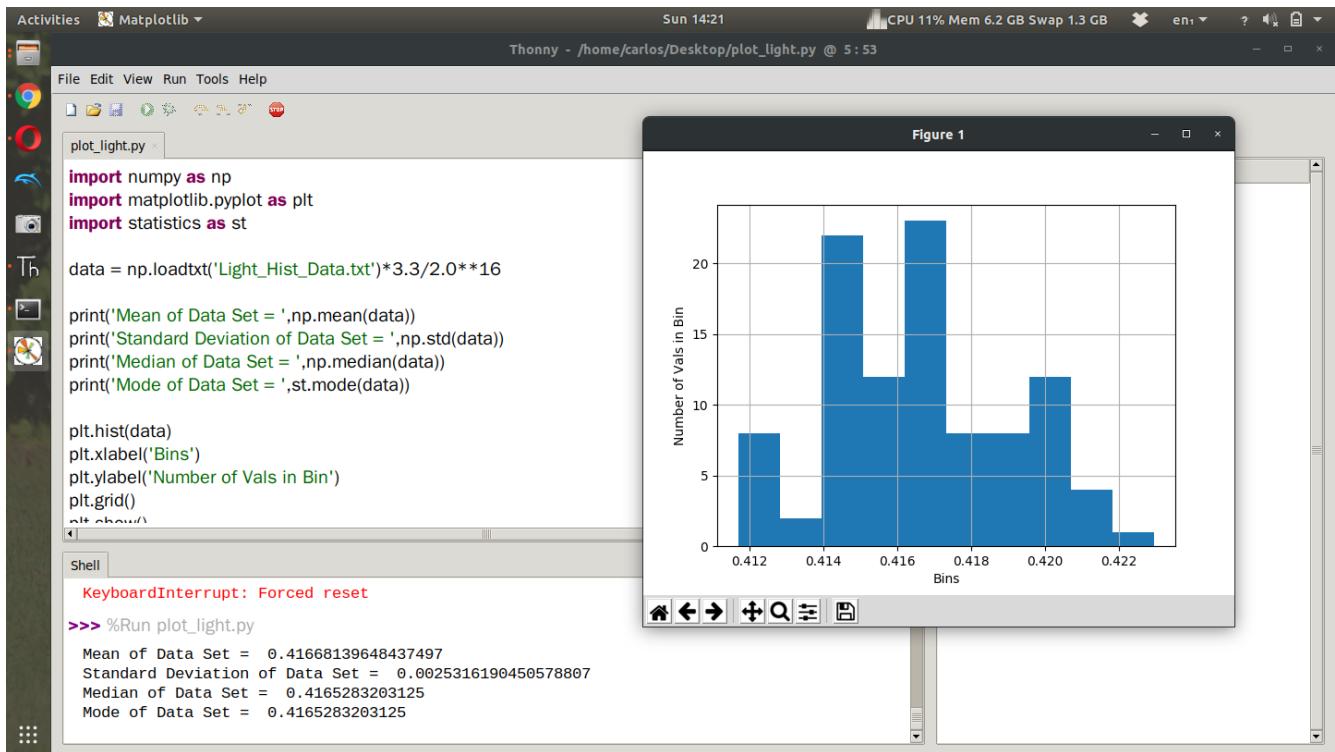
```

>>> run plot_light.py
>>> %Run plot_light.py
>>> %Run plot_light.py
>>> %Run plot_light.py
KeyboardInterrupt: Forced reset
>>> %Run plot_light.py

```

If you noticed the data you obtained even when the light source was constant was quite noisy. What I'd like you to do for part 2 of this lab is take 100 data points with the photocell with as constant of a light source as possible. Do this for three different light ranges. Low Light, ambient light and then a flashlight. With the three

different data streams, create a histogram of the data with appropriate labels and compute the mean, median, and standard deviation of the data stream. Creating a histogram in Python is fairly simple and I have a Youtube Video to supplement this tutorial. I also have another video where I get mean and median values for accelerometer data. Still, here is my example code showing code to get mean, median, and standard deviation as well as create the histogram. Notice in my code I imported the statistics module to compute the mode. Although it worked in my code, it's not typical to compute the mode of a continuous variable because often times you will not ever get the same value twice. Still, feel free to compute the mode if you so desire.



Again make sure to convert to voltage before you plot that way you can see what the noise level is in volts. Notice that I import the data and convert to voltage all in one line. However, note that my text file only has 1 column of data. It's possible your data has time in the first column and light value in the second column at which point you will need to extract the second column first and then convert to voltage. If you have two columns of data you'll need to add a few things. First, don't convert to voltage when you import the data.

```
data = np.loadtxt('Light_Hist_Data.txt')
```

Then extract the second column (assuming your photocell readings are in that column)

```
second_column = data[:,1]
```

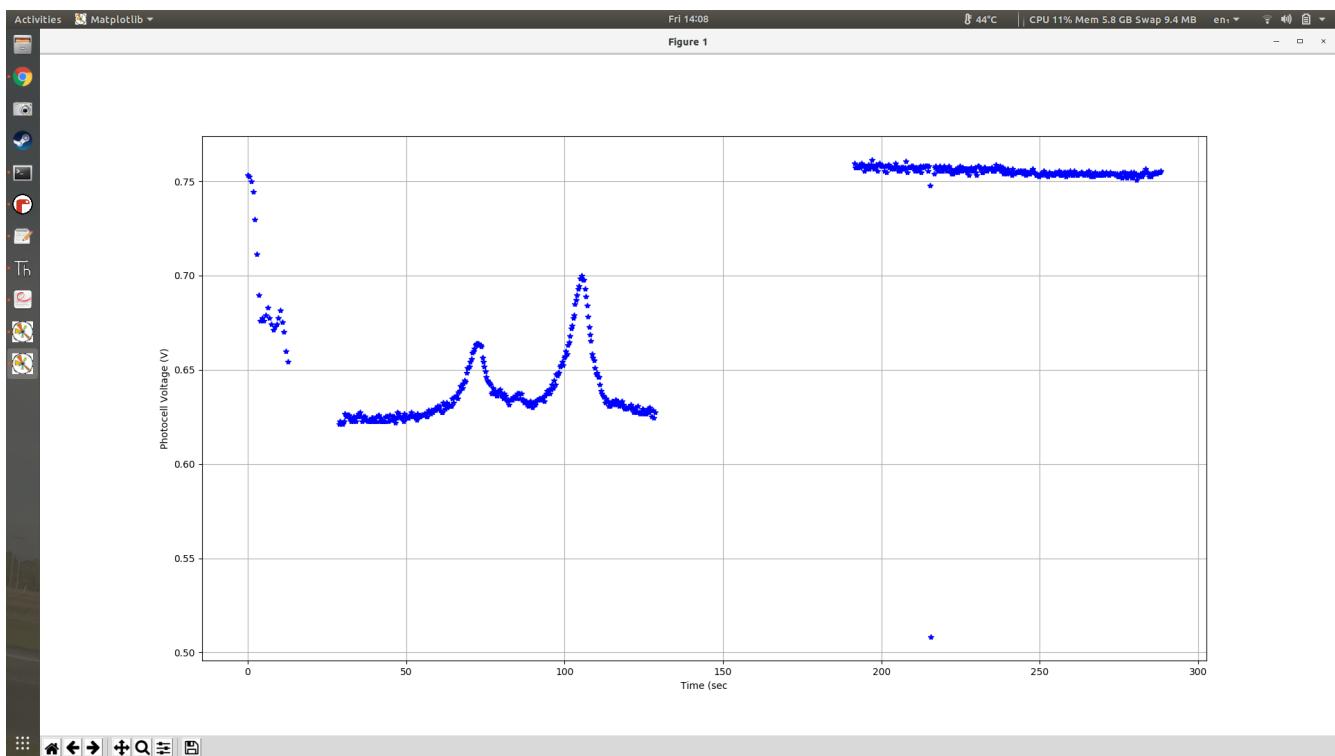
Finally convert to voltage

```
voltage = second_column*3.3/2.0**16
```

Then replace data in the rest of your code with voltage. Remember to remove `st.mode` since it does not work all of the time for continuous data sets.

## 7.4 Throwing Out Outliers

When I ran this experiment for a second time my CPX started and stopped 3 separate times. You'll see in the time series plot below that the voltage dipped in the first set and the second data set had some weird bumps probably from me changing tabs on my chrome tab. The photocell was close to my computer so that effected it. Thankfully the 3rd data set looked pretty good.



The only problem with the 3rd data set is that I put my hand over it for testing purposes. Because of that I had to remove those outliers. To do that I computed the current mean and standard deviation and then threw out all data points that were 3 standard deviations away from the mean. The code looks like this.

```
##COMPUTE CURRENT MEAN AND DEV

mean = np.mean(voltage)

dev = np.std(voltage)

print(mean,dev)

time = time[voltage > mean - 3*dev]

voltage = voltage[voltage > mean - 3*dev]

time = time[voltage < mean + 3*dev]

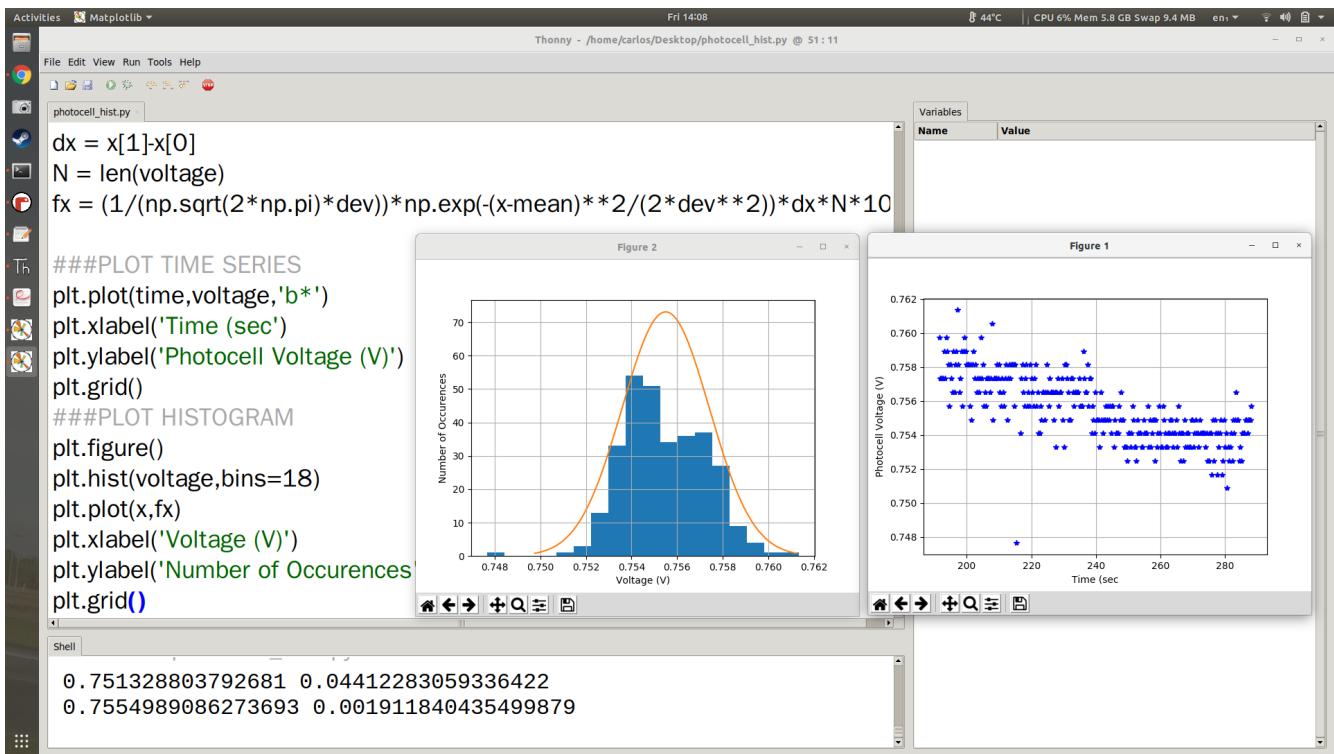
voltage = voltage[voltage < mean + 3*dev]

###COMPUTE NEW MEAN,STD

mean = np.mean(voltage)

dev = np.std(voltage) print(mean,dev)
```

Once I did all that clean up I was able to get a nice time series plot of my data.



## 7.5 Normal Distribution

I also was able to plot the Normal Gaussian Distribution on top of the histogram. You can see that in the left plot in orange. The code to do that is shown below where the 72 in the plot is the "height" of the histogram. Note that your histogram will have a different height and you will need to get that specifically from your plot.

###COMPUTE THE NORMAL DISTRIBUTION

```

x = np.linspace(-3*s+mu,3*s+mu,100)

pdf = 1.0/(s*np.sqrt(2*np.pi))*np.exp((-x-mu)**2/(2.0*s**2)) * (s*np.sqrt(2*np.pi)) * 72

```

The equations above make a time series from  $\pm 3$  standard deviations from the mean and then plot the PDF of a normal Gaussian distribution. The only extra thing you have to do is multiply by  $(s*\sqrt{2\pi}) * 72$  which first causes the height of the PDF to be 1 and then multiply by 72 which again is the height of the histogram which will be different for your system.

## 7.6 Assignment

Turning in this assignment Once you've done that upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

### 7.6.1 Part 1

1. Include a video of you varying light conditions and watching the digital signal in the Plotter in Mu go up and down (make sure your face is in the video at some point and you state your name) - 50%
2. Include your Python code in the appendix along with your data plotted in a Figure. Make sure to plot the voltage and not the digital output - 50%

### **7.6.2 Part 2**

1. Include a video of your circuit and explain how you captured the data to store on your computer (make sure your face is in the video at some point and you state your name) - 25%
2. Include the mean, median, and standard deviation of all light levels in volts - 25%
3. Include 3 histogram plots of low light, ambient light and high light levels. On top of the histogram I want you to plot the normal Gaussian distribution to see how close your histogram is to a Gaussian distribution - 50%

## 8 Pulse Width Modulation (PWM) and Servo Calibration ( $\text{pulse} = f(\text{angle})$ )

### 8.1 Parts List

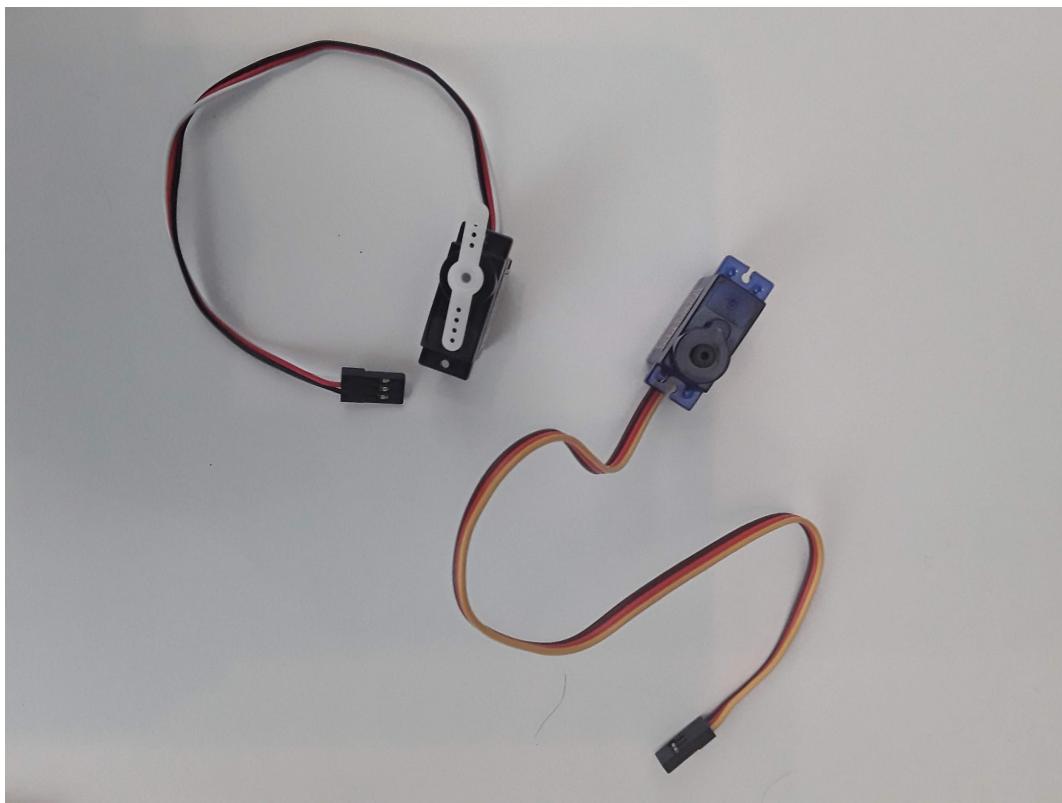
1. CPX/CPB
2. USB Cable
3. Laptop
4. protractor or piece of paper
5. servo
6. Alligator clips (x3)

### 8.2 Learning Objectives

1. Understand what a PWM signal is and how it affects a servo
2. Understand the inner workings of a servo and how to make it move
3. Practice first order regression and calibration techniques

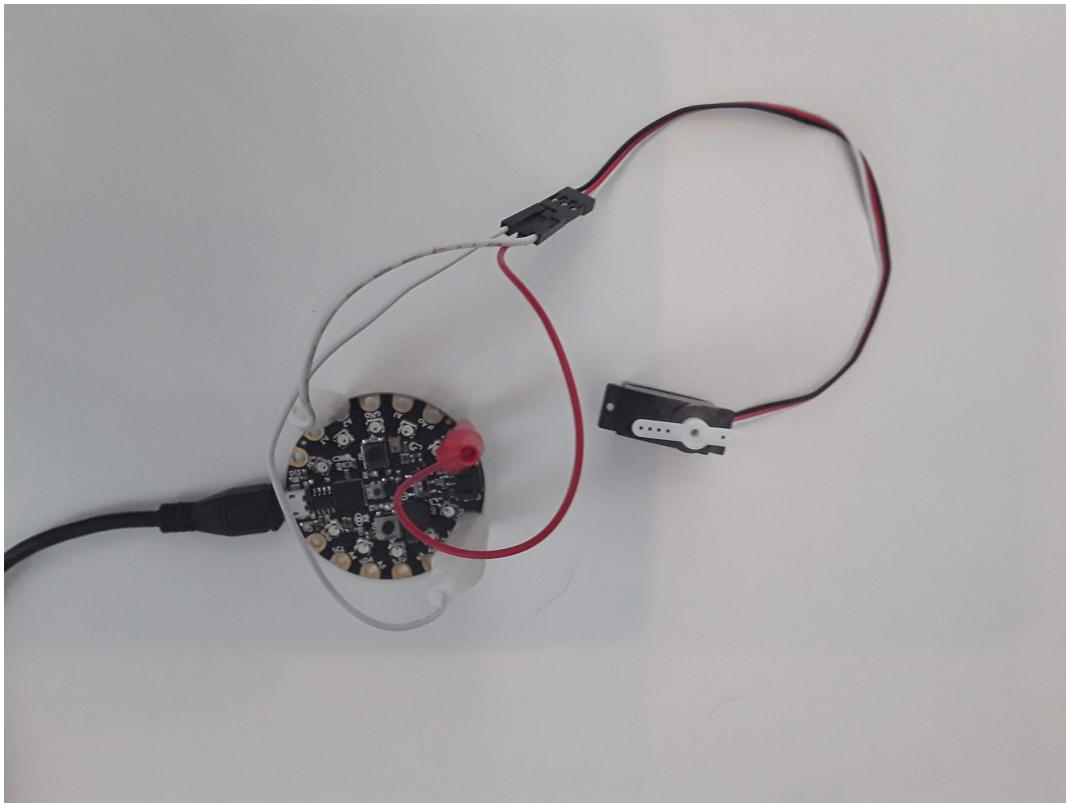
### 8.3 Getting Started

For this lab we are going to learn how to drive a servo. Servos accept what are called PWM signals which are basically square waves of varying frequency. The servo itself has a microprocessor on board that turns a DC motor based on the incoming PWM frequency which is typically called a duty cycle. The DC motor runs through some gear to rotate a shaft. Because of this rotation, you can make a number of things move! Servos are used for all sorts of things, opening doors, deflecting control surfaces on RC aircraft and many more! The neat thing about PWM signals is that they can not only move servos but they can also drive speed controllers to turn 3 phase motors and even change the light intensity of LEDs. Servos typically come in two different color schemes as shown below.



As you can see, servos have 3 pins - the brown or black wire is GND, the red wire needs to go to a 5V signal so for the CPX it needs to go to the VOUT pin and the yellow or white wire is the signal wire which need to go to

an analog port on the CPX that supports PWM signals. Which ones support PWM signals? Adafruit Learn has a great description of which pins support PWM signals but as a quick check you can use the following analog pins: A1, A2, A3, A6 and A7. In my circuit I just picked pin A2 since I've been using it so much in the past.



**Very important:** It is recommended to power a servo through an external power supply instead of the CPX. Servos can draw a lot of current and the CPX although it supports 5V can only provide so much power ( $P$ ). Remember that  $P = VI$  so if  $P$  is low it means current is low. If the servo pulls more current than the CPX can provide the CPX will “brown out” which means it will go into a safe-mode setting. If you have the AA power supply you may consider doing that. For small servos you hopefully won't have any issues.

As I said before, a servo takes in a square wave. The square wave has a duty cycle in units of microseconds. If you send a roughly 500 us square wave to a servo it will rotate all the way to the left. If you send a roughly 2500 us signal to the servo, it will turn all the way to the right. The code to send PWM signals has been thoroughly explained in the Adafruit Learn system. I also have a simple servo.py script on Github. In this code as usual the top 3 lines are used to import the necessary modules. The pulseio module is used here to create a servo object on line 6 by connecting to pin A2. Make sure to change the pin to whatever pin you have the signal wire hooked up to. Lines 9-12 create a function that pulse in milliseconds and compute the duty cycle of PWM signal. Lines 16-19 then kick off an infinite while loop where a 800 us signal is sent to the servo and then a 2000 us signal is sent using a for loop which starts on line 16. You'll see servo command on line 18 which is responsible for sending the microsecond signal to the servo. The function servo.duty\_cycle converts the pulse in milliseconds to a duty cycle. The value is then passed to the attribute of the servo object servo.duty\_cycle. If you put this code on the CPX and run the code you will hopefully see your servo turning left and right in 1 second intervals. I did this project myself and posted a YouTube video about it.

Besides making the servo move back and forth I'd like you to vary the pulses on line 16 **SLOWLY** until the servo can't move any farther. This line of code is a for loop which loops through the array currently showing [0.8,2.0]. If you change that array to [0.9,1.2,1.5,1.8] the servo will move to a pulse in milliseconds of 0.9, 1.2, 1.5 and then 1.8. The for loop is a great way to loop through multiple commands. Using this array, determine the minimum pulse you can send to the servo and the maximum pulse you can send to the servo. If the servo makes a funny noise it means you sent a signal outside the bounds so try a different signal. Hence the need for moving the pulse signal slowly. If you change the array to just 1 number [0.8] the servo will just move to 1 angle and stay there

forever. **NOTE THAT IN CIRCUITPYTHON VERSION 7.0.0 YOU HAVE TO USE THE PWMIO LIBRARY INSTEAD OF THE PULSEIO LIBRARY.**

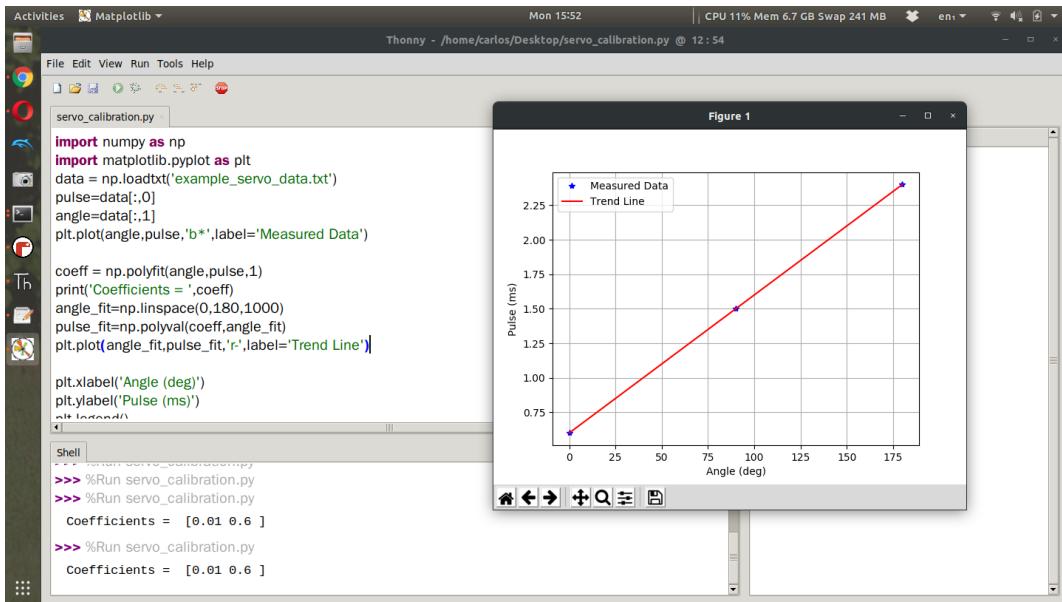
```
1 import time
2 import board
3 import pulseio
4
5 # Initialize PWM output for the servo (on pin A2):
6 servo = pulseio.PWMOut(board.A2, frequency=50)
7
8 # Create a function to simplify setting PWM duty cycle for the servo:
9 def servo_duty_cycle(pulse_ms, frequency=50):
10     period_ms = 1.0 / frequency * 1000.0
11     duty_cycle = int(pulse_ms / (period_ms / 65535.0))
12     return duty_cycle
13
14 # Main loop will run forever moving between 1.0 and 2.0 mS long pulses:
15 while True:
16     for pulse_ms in [0.8, 2.0]:
17         print('Milli Second Pulse = ', pulse_ms)
18         servo.duty_cycle = servo_duty_cycle(pulse_ms)
19         time.sleep(1.0)
```

---

If you notice, sending a pulse signal in microseconds moved the servo to a specific angle. Thing is I would like to be able to move the servo to a specific angle rather than having to just guess and check like we did in the last lab. So what we're going to do is start at the minimum pulse signal you computed in the last project and then change the servo pulse in equal increments until we reach the maximum servo pulse signal. When I did this lab I found that 0.6 ms was just about the smallest I could get the servo to move. We're going to call this 0 degrees. My maximum pulse signal ended up being about 2.4 ms. So I want you to test 10 different points between your specific maximum and minimum value which will hopefully be different for all of you. Everytime you test a pulse I want to measure the angle the servo makes with the minimum value being 0 degrees. Create a table of data with two columns. In the first column put pulse in milliseconds and in the second column put angle of servo in degrees. Use a protractor to measure the angle. If you don't have a protractor make one or you can download a picture and hold your servo up to the screen. I did this project with just 3 data points and here are my data points. Again you need to have around 10 data points

Pulse (ms)	Angle (Degrees)
0.6	0
1.5	90
2.4	180

Take your table of data and put it into a spreadsheet and save the data as a CSV or simply put your data into a text file. Since I only had 3 data points I just put them into a text file. Plot the data in Python on your desktop computer with servo angle on the x-axis and duty cycle on the y axis. Using the data, determine if the data set is linear, quadratic or cubic. Fit a trend line to the data and plot your trend line on top of the data. If you need help with trend lines in Python you can watch this video I posted on Youtube. I also made a helpful python script with some fictitious data on Github that fits the data with linear and quadratic fits. Here is my data plotted alongside the trendline in Python. I sort of made up the data and made it perfect on purpose so my trendline is perfect. Yours will not be so perfect.



You'll notice that I first import the data from the text file using the `np.loadtxt` function and then I use the `polyfit` and `polyval` functions to create the trendline. The `polyfit` function requires you to give it the X and Y axes and the order of the trendline which since the trend line is linear I sent it a 1 but you could easily do 2 for quadratic or 3 for cubic. I then print the coefficients which are [0.01 0.6]. This means my trend line looks like this.

$$Pulse = 0.6 + 0.01 * Angle \quad (6)$$

Where Pulse is in ms and Angle is in degrees. Now you have an equation where you can use angle in degrees to compute the pulse in milliseconds. In the code I've posted I then use `np.linspace` to create 1000 data points from 0 to 180 degrees and then use the `polyval` function to compute the pulse for all 1000 angles I created using the `linspace` command. I finally plot the trend line in red and use the remaining part of the script to create labels and legends. Once you have this plot write down your coefficients and create an equation like I did above. Again your numbers won't be so neat. Once you have this equation, return to Mu and create a function using the `def` keyword that takes in an angle as an input and then returns a pulse signal in milli seconds. It will look sometime like this

```
def angle2pulse(angle):
    return 0.6 + 0.01*angle
```

**Note: Functions in python must be after all your imports but before your while loop. If you put this function inside your while loop the code will not work.** Using that equation, modify your `servo.py` script to have the servo move through the following angles, 0, 45, 90, 135 (your servo may not travel to 180 degrees). Verify that your equation is working correctly by placing your protractor below the servo. Much of the code required for this project is not included because it is left as an exercise for the student.

## 8.4 Assignment

Upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

### 8.4.1 Part 1

- Send a video of your servo moving back and forth (make sure your face is in the video and make sure you introduce yourself) - 50%
- Experimentally determine the minimum and maximum values of the servo and report the 2 PWM signals in milliSeconds. Give at least 2 decimal points in your calculation - 50%

#### **8.4.2 Part 2**

1. Submit a video of you explaining how you took data (make sure you are in the video and you introduce yourself) - 25%
2. Include a Figure of your your data plotted in Python with your trend line on top - 25%
3. Submit your regression equation as I did above - 25%
4. Submit a video of your servo moving through 0,45,90,135 using the output from your regression equation. - 25%

## 9 Feedback Control with a Servo and Accelerometer

### 9.1 Parts List

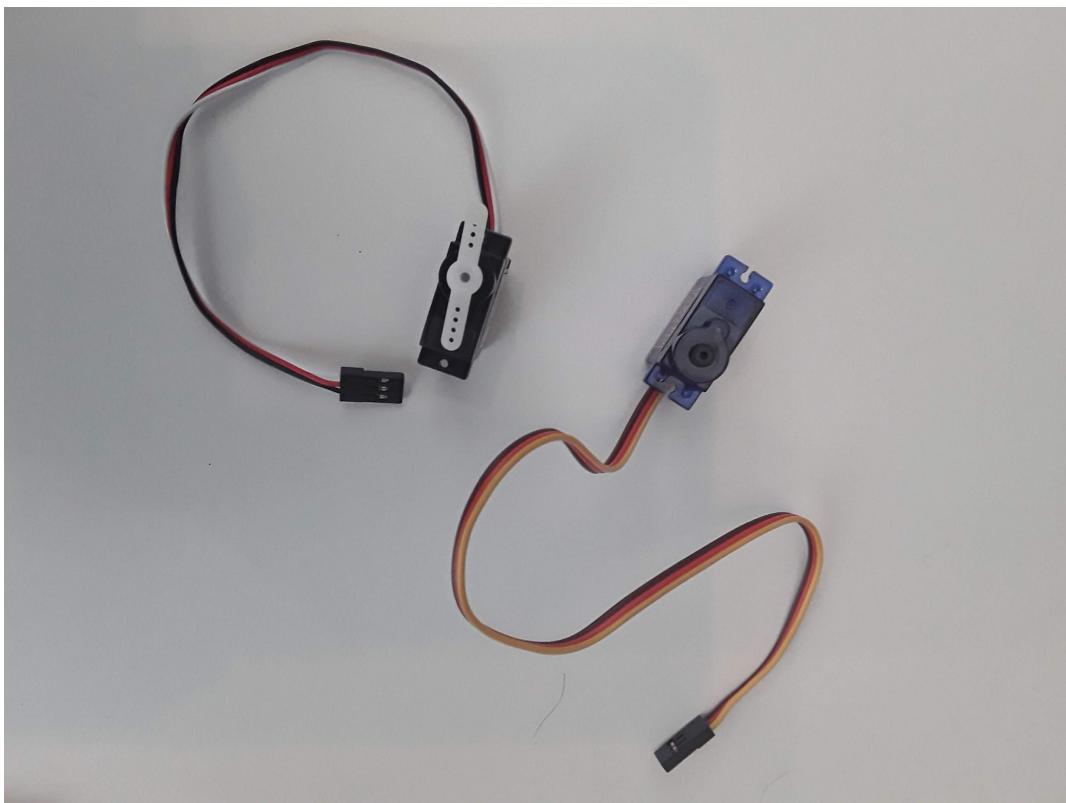
1. CPX/CPB
2. USB Cable
3. Laptop
4. servo
5. Alligator clips (x3)

### 9.2 Learning Objectives

1. Understand how to compute roll and pitch from an accelerometer
2. Learn the fundamental concepts of feedback control
3. Learn how to Combine two codes (servo code and accelerometer code into one)

### 9.3 Getting Started

Feedback control can be its own course or multiple courses but can be broken down into a few simple steps. The goal of feedback control is to drive the “state” of a “system” to a desired “command” by sending a “control” signal to the “system”. I explain this in much more detail in a controls overview Youtube video. For this lab we are going to make the bare bones circuitry required for pitch angle control of an airplane. The “system” then is the aircraft. The “state” is the “pitch” angle (measured by the CPX), the “command” is the desired pitch angle (programmed by you the pilot in command) and the “control” signal is the elevator command (actuated by a servo). I’m using the same circuit I created in the other servo projects (See chapter 8). Here’s the circuit for simple reference. Remember the servo has 3 pins - the brown or black wire is GND, the red wire needs to go to a 5V signal so for the CPX it needs to go to the VOUT pin and the yellow or white wire is the signal wire which need to go to an analog port on the CPX that supports PWM signals.



The elevator on an airplane is a control surface responsible for pitching the aircraft up and down. For this example we are going to assume that the desired pitch angle is 0. This means our “error” signal is going to be 0

minus the pitch angle. Our “control” signal will be the angle of the elevator. As I said, we are going to use a servo to control the elevator so this just means we need a way to relate our “error” signal to servo pulse width. There are a few steps here before we can move on. First, we need to relate our “error” signal to the “control” signal which will be the elevator pitch angle. I’ve made a table below to explain what I mean.

Pitch (deg)	Error (deg)	Elevator (deg)
-90	90	+90
0	0	-90
+90	-90	-90

This table basically says that if the aircraft is level with a pitch angle of zero I want the elevator to be zero as well. If the aircraft pitches down, I want the elevator to pitch up and counteract that rotation. Using these three data points I can create a simple equation to relate elevator angle to pitch angle.

$$\delta_e = -\theta \quad (7)$$

Now that we have the elevator pitch angle we need to relate this to the servo angle. Servo can only move from 0 to 180 degrees which means we can’t have the servo go negative. Thus we need to offset the elevator angle to the servo angle. Again we can make a table here.

Elevator (deg)	Servo (deg)
-90	0
0	90
+90	180

This also results in a simple equation to relate servo angle to elevator angle.

$$s = \delta_e + 90 \quad (8)$$

Finally, we can then use our calibration coefficients (See chapter 8) to relate servo angle to pulse width. When I calibrated my servo I obtained the following equation where P is the pulse and s is the servo angle.

$$Pulse = 0.6 + 0.01 * Angle \quad (9)$$

With these 3 equations I can now program my servo to respond to changes in the pitch angle of the CPX. I did forget one minor detail and that is measuring the pitch angle itself. This is similar to measuring the angle of a pendulum (See chapter 10). I’m going to rotate the CPX in the X/Z plane which can be done by rotating the USB cable where it plugs into the CPX. In this case we can ignore the Y axis data. If you print the raw accelerometer data, you’ll notice that when you place the CPX directly onto a flat surface, the x and y axes read a value around 0, while the z axis reads around gravity. If you then rotate the sensor clockwise 90 degrees, the x axis is reading about gravity while the z axis is now zero. This means we can form a triangle and get the angle using these two axes using the equation below which gives angle in degrees.

$$\theta = \tan^{-1}(x/y) \frac{180}{\pi} \quad (10)$$

On the CPX specifically we want to import the math module and use the atan2 function. With this equation I can finally put it all together. Here is my code which again is also online on Github.

```

1 import time
2 import board
3 import busio
4 import math
5 import digitalio
6 import adafruit_lis3dh
7 import pulseio
8
9 # Create a function to simplify setting PWM duty cycle for the servo:
10 def servo_duty_cycle(pulse_ms, frequency=50):
11     period_ms = 1.0 / frequency * 1000.0
12     duty_cycle = int(pulse_ms / (period_ms / 65535.0))
13     return duty_cycle
14
15 # Initialize PWM output for the servo (on pin A2):
16 servo = pulseio.PWMOut(board.A2, frequency=50)
17
18 ##Accelerometer is hooked up to SDA/SCL which is I2C
19 i2c = busio.I2C(board.ACCELEROMETER_SCL, board.ACCELEROMETER_SDA)
20 _int1 = digitalio.DigitalInOut(board.ACCELEROMETER_INTERRUPT)
21 lis3dh = adafruit_lis3dh.LIS3DH_I2C(i2c, address=0x19, int1=_int1)
22 lis3dh.range = adafruit_lis3dh.RANGE_8_G

```

The first 22 lines here will hopefully seem familiar. Line 1-7 are import commands of all the various modules needed. Lines 10-13 create the definition that converts pulse width to duty cycle. Line 16 creates the servo and lines 19-22 create the accelerometer. Hopefully this is a good example of combining different codes together to get a more complex piece of software. Lines 24-45 include a very long while loop. I will try and go through each line. Line 26 grabs the accelerometer data on the CPX. Line 28 uses the x and z axis accelerometer data and converts the values to pitch angle using the atan2 function in the math module which was imported on line 4. Line 30 computes the elevator pitch angle and line 32 computes the servo deflection angle. Line 34-37 is a type of signal conditioner called a saturation filter. Basically, I don't want the servo to break because I tried to make the servo rotate more than 180 degrees or less than 0 degrees. So I created two if statements that restrict the servo to be within these two values. If the servo angle is less than 0 as stated on line 34, the servo angle is set to 0 on line 35. If the servo angle is greater than 180 as stated in line 36 the servo angle is set to 180.

```

24  while True:
25      #Get Accelerometer
26      x,y,z = lis3dh.acceleration
27      #Get theta
28      theta = math.atan2(x,z)*180/3.141592654
29      #Get elevator angle
30      de = -theta
31      #Get servo angle
32      s = de + 90.0
33      #Saturation Filter
34      if s < 0:
35          s = 0.
36      if s > 180:
37          s = 180.
38      #Get pulse width
39      pulse_ms = 0.6 + 0.01*s
40      #Get duty cycle
41      duty_cycle = servo_duty_cycle(pulse_ms)
42      #Actuate Servo
43      servo.duty_cycle = duty_cycle
44      print(theta,de,s,pulse_ms)
45      time.sleep(0.1)

```

Line 39 uses the calibration equation from the previous experiment to convert servo angle to pulse width. You'll need to replace these numbers with your servo since all servos are different. Line 41 uses the definition created on lines 10-13 to convert pulse width to duty cycle. Line 43 makes the servo move. Line 44 prints everything to Serial for debugging purposes and line 45 pauses the script for 0.1 seconds which helps with some twitchiness in the servo. When I did this I didn't have to program a complementary filter so I guess the servo may have it's own low pass filter. Either way this circuit is ready to be placed on an aircraft. Whether or not it is effective is a completely different story. I'll leave that discussion to your controls professor. Note you can also include the angular rate sensor and use that as derivative gain as well.

## 9.4 Assignment

Upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Explain your circuit and what wires go where - 10%
2. Explain your code. Specifically discuss any changes you have to make from my code to get it to work on your circuit. At a minimum you will need to change line 39. What I mean by that is that I want you to use your linear regression model from a previous lab so that it better controls the angle of your servo. You may also have to change the saturation filter. - 20%
3. Show your servo moving as you rotate the CPX. Rotate the CPX positive and verify that the servo moves negative. - 50%
4. Verify that your saturation filter works correctly by rotating your CPX past 90 degrees - 20%
5. Again make sure that your face is in the video at some point and you introduce yourself.

# 10 Natural Frequency and Damping of a Second Order System and Issues with Aliasing

## 10.1 Parts List

1. Laptop
2. CPX/CPB
3. USB Cable
4. Some sort of oscillating system like a swinging pendulum or vibrating ruler

## 10.2 Learning Objectives

1. Learn the basic form of a second order system
2. Understand the difference between underdamped, critically damped, and overdamped
3. Understand natural frequency and damping ratio
4. Applied Estimation of a Second Order system
5. Understand the pitfalls of aliasing

## 10.3 Getting Started

A second order system undergoing free motion will have dynamics that look like this

$$\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2 \quad (11)$$

In this case, the solution to the above equation can be solved using standard second order differential equation techniques to obtain the solution below.

$$\theta(t) = \theta_0 e^{-\sigma t} \cos(\omega_d t) \quad (12)$$

$$\omega_n = \sqrt{\sigma^2 + \omega_d^2} \quad (13)$$

$$\zeta = \frac{\sigma}{\omega_n} \quad (14)$$

Looking at the equations you can see that if you the time series of the oscillations are known, the damping constant and damped natural frequency can be obtained. These two values can be combined to obtain the natural frequency. The damping ratio can also be computed. So let's get some data.

## 10.4 Oscillatory Ideas

What I'd like you to do for this lab is to find some sort of parameter that varies in some sort of sinusoidal way. I've come up with a few ideas below. You may pick anyone you want although some are easier than others.

1. Drive over a speed bump - If you drive over a speed bump slowly and place your CPX on the dashboard your car will hopefully vibrate for a few seconds after you drive over it. Your acceleration will look somewhat like a sine wave.
2. Build a photo interrupter for a bike tire or a swinging pendulum - Photointerrupters only work if you sample quickly enough to see the object rotate. If you place a photo interrupter on your bike tire you can use the photocell on the CPX to measure angular velocity. If you don't sample the photocell quickly enough you won't be able to detect the spokes flying by. You can also do this with a swinging pendulum by swinging a pendulum in front of the CPX.
3. Vibrate a ruler - If you place a ruler on the edge of a desk and deflect it, it will vibrate. If you place the CPX on the ruler you'll be able to measure the vibration of the ruler.
4. Attach CPX to a spring or a weight to the end of rubber bands - Take the CPX and attach it to a weight of some kind and attach the weight to a spring or a set of rubber bands. This is a mass spring damper simple and will vibrate at the natural frequency of square root of stiffness divided by mass. I chose to do this example.
5. Build a Pendulum: If you decide to build a pendulum, you need to hang a weight on the CPX or attach the CPX to something heavy. This will make the ratio between cable to end mass much smaller and thus better for data and fitting. An example includes duct taping your CPX to a water bottle or something. It would also be better to use a string and mount the CPX to the string with an external battery pack and have the CPX log data internally. This way most of the mass would be concentrated at the tip of the pendulum. Another idea is to take a paper towel cardboard tube and tape the cpx inside it with the cable running through it. Then duct a large weight on the end of the paper towel tube and then hinge the top of the tube by skewering a screwdriver through it. This will allow the tube to swing like a pendulum rather than the string.

There are most likely many other options so try and get creative and find something oscillatory or dynamic in some way. Try to find something that changes relatively quickly. The temperature outside changes in a sinusoidal fashion but it's so slow it would take you days to do this experiment.

## 10.5 Pendulum Example

In this example I'm going to swing a pendulum in the X/Y plane of the accelerometer sensor so that I can ignore the Z axis data. I'm going to get the actual angle of the pendulum but if you're building something else you can ignore this part. You'll notice that when you point the CPX directly at you with the cable pointing up the x axis reads around 0 and the y axis reads around gravity. If you then rotate the sensor so that the cable is coming out of the left side of the CPX, the x axis is reading about gravity while the y axis is zero. This means we can form a triangle and get the angle using these two axes using the equation below which gives angle in degrees.

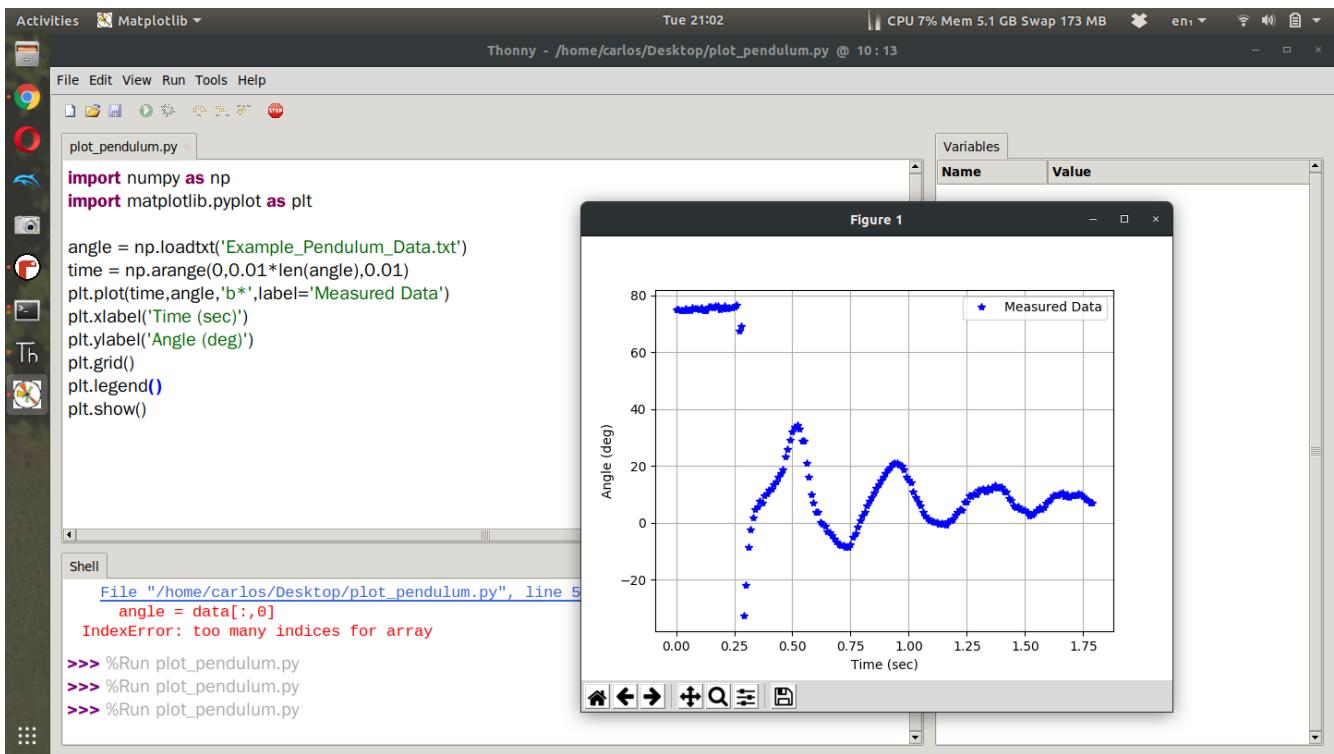
$$\theta = \tan^{-1}(x/y) \frac{180}{\pi} \quad (15)$$

On the CPX specifically we want to import the math module and use the atan2 function. When I swing the pendulum then this is the result I get from Plotter in Mu.

```
1 from adafruit_circuitplayground.express import cpx
2 import math
3 import time
4
5 while True:
6     t = time.monotonic()
7     x,y,z = cpx.acceleration
8     theta = math.atan2(x,y)*180/3.14159
9     print((theta,))
10    time.sleep(0.01)
```

The screenshot shows the Mu 1.0.2 IDE interface. At the top, there's a toolbar with icons for Mode (yellow), New, Load, Save, Serial, Plotter, Zoom-in, Zoom-out, Theme, Check, Help, and Quit. Below the toolbar is a tab bar with five tabs: record\_temperature\_thermistor.py, main.py, record\_sound\_simple.py, and low\_level\_accel.py. The main area contains the Python code provided above. At the bottom, there are two panes: the Adafruit CircuitPython REPL on the left showing a list of tuples representing sensor data, and the Adafruit CircuitPython Plotter on the right showing a line graph of the data over time.

If I then bring this into Python I get the following plot below. In my data set I only logged the angle. Since the time step between each point was 0.01 seconds I was able to just create a time series. It's pretty clear that there is some nonlinearity in the data so I chose to start the data at 0.5 seconds. Another thing I noticed was that the angle settled out to around 8 degrees so I chose to subtract off that bias from the angle data.



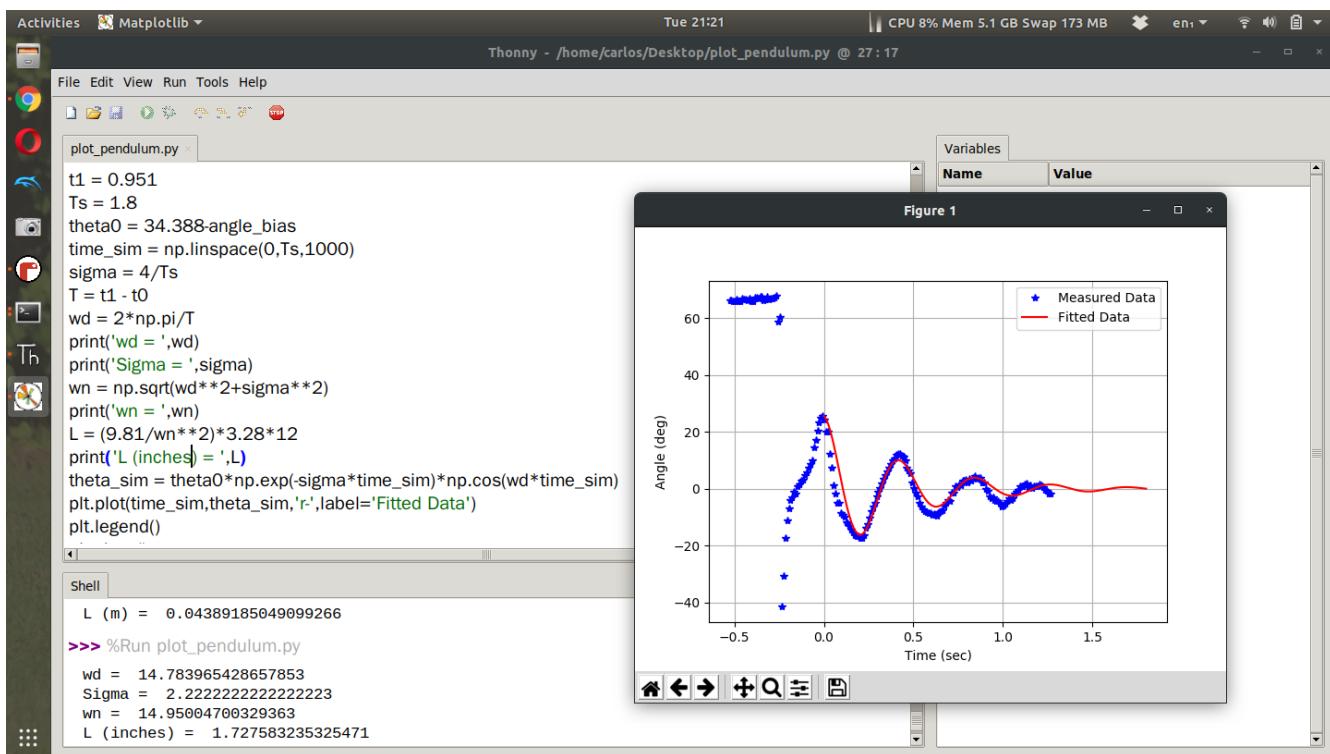
After trimming the data and removing some bias it was time to get my damping constant and damped natural frequency. There are a few equations that can help you obtain these parameters. First, the settling time is the length of time it takes for the oscillations to settle. The settling time can be used to find the damping constant. This is equal to:

$$\sigma = \frac{4}{T_s} \quad (16)$$

For my data set the settling time was about 1.25 seconds which gave a damping constant of 3.2. Once I had the damping constant I could obtain the damped natural frequency. This was done by measuring the distance between two peaks in the data set. There is a peak at around 0.5 seconds and another at around 0.95 seconds. I can use this to compute a period T. Period can be computed to angular frequency using the equation below.

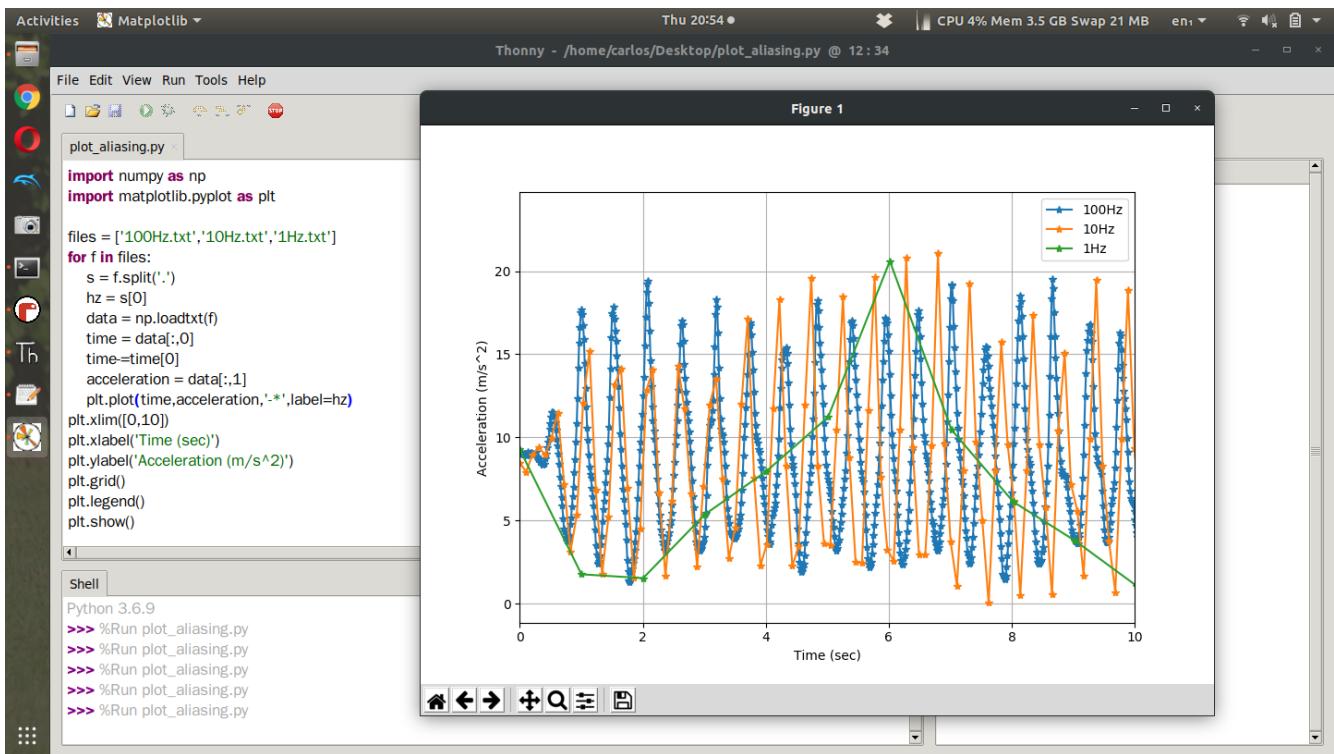
$$\omega_d = \frac{2\pi}{T} \quad (17)$$

Using the period in my wave form I obtained a damped natural frequency of about 14.8 rad/s. Using these values I can plot the simulated data on top of the measured data noting that my initial angle was about 35 degrees minus the bias of 8 degrees. When I first plotted the data I noticed that my fit wasn't entirely perfect. My period was correct but my damping rate was too high. I realized it was because my settling time was too big. I increased the settling time to 1.8 seconds and got this plot here. You can see that my fitted data lined up almost perfectly with my measured data.

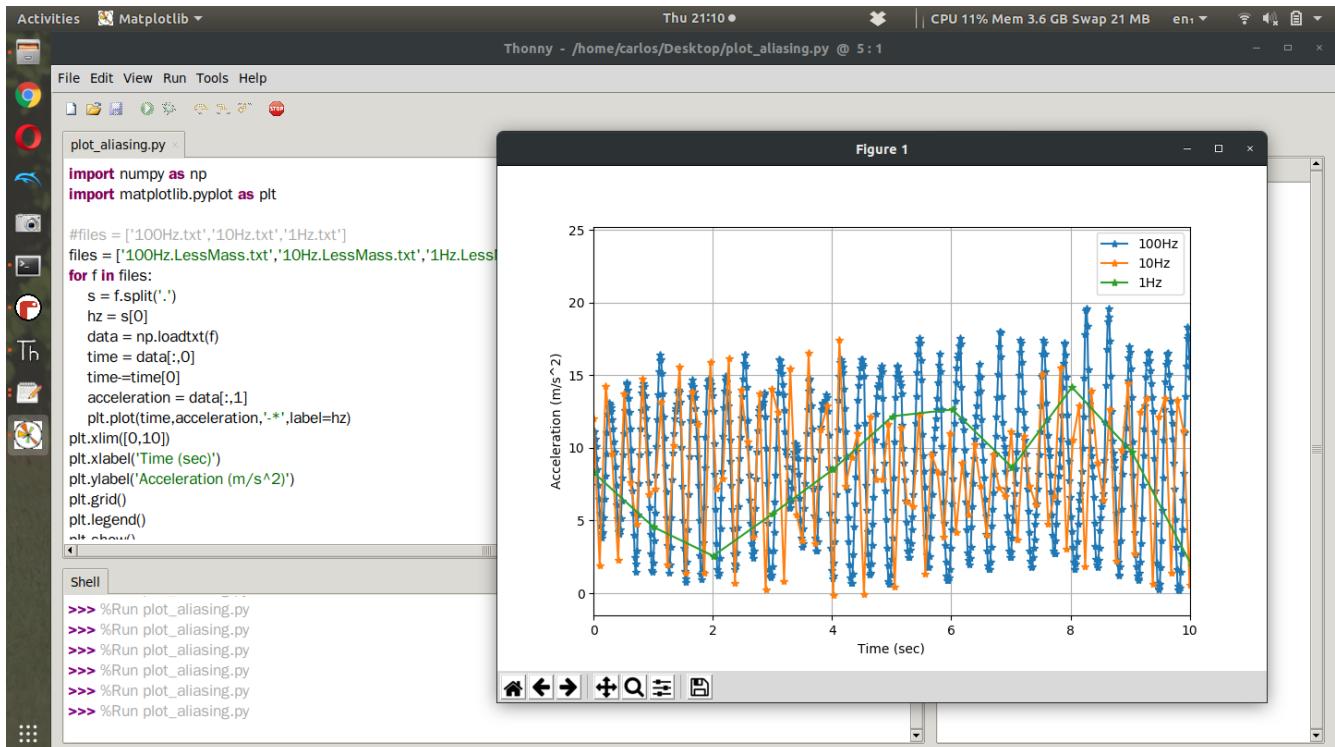


## 10.6 Aliasing

For the second part of this lab you need to vary the frequency somehow. In this case I changed the length of the pendulum which changed the natural frequency. I then proceeded to measure the angle as it oscillated at its natural frequency. I repeated this at sampling frequencies of 1, 10 and 100 Hz. The way I changed the sampling frequency was by changing the `time.sleep` value in the while True loop. The accelerometer code I used can be found on Github. After I finished the experiment I had 3 data files that I plotted on top of each other. This what I got with the longest string. It's easy to see in the photo that sampling at 1 Hz was way too slow to capture the natural oscillations of the water bottle. However, 100 Hz and even 10 Hz was plenty fast to sample the oscillations. According to the recorded data there was above 19 cycles in 9 seconds which is about 2 Hz. In this case, as long as we sample at 4 Hz the signal will be captured properly which is why 10 Hz and 100 Hz is able to capture the signal correctly.



Once you sample your waveform at 3 different sampling rates I want you to change something about your setup. For example, you can drive slower or faster over the speedbump, you can change the length of your pendulum or the length of your ruler that you're vibrating. I elected to shrink the length of the pendulum. This raised the natural frequency of the system by enough to change the results as shown in the figure below.



In this case you can see that there were 33 cycles in 10 seconds which is 3.3 Hz. The Nyquist criteria states that

I need to sample at 6.6 Hz. The Nyquist criteria is very specific though in that if you sample at twice the frequency, you will just obtain the correct frequency. This does not mean that you will capture every data point properly. Hence in the chart above, the blue line at 100 Hz is perfect, the green line at 1 Hz is too slow (less than 6.6 Hz) and the orange line at 10 Hz captures the frequency correctly but between 5 and 8 seconds does not adequately capture the waveform.

## 10.7 Assignment

Upload a PDF with all of the photos and text below included. My recommendation is for you to create a Word document and insert all the photos and text into the document. Then export the Word document to a PDF. For videos I suggest uploading the videos to Google Drive, turn on link sharing and include a link in your PDF.

1. Include a video of you explaining your experiment. What state are you measuring? What is varying? Show the system varying and explain the code you are using to capture the data. Use the Plotter in Mu to show the system varying. (Make sure you introduce yourself in the video and that you show your face at some point) Explain what you changed about the system to change the natural frequency. I changed the length of my pendulum which changed the natural frequency. What did you change? - 20%
2. Take data at 3 different frequencies and two different configurations (a total of 6 data sets). Include two plots as I did above with appropriate labels and legends - 20%
3. Explain the results of your experiment in 1 or 2 paragraphs. Did you encounter any aliasing? Did the amount of aliasing change when you changed the parameters of your system? Why or why not? - 20%
4. Plot your measured data in Python for your lowest frequency and highest sampling rate and attach a well formatted figure. Include a plot of your fitted data alongside your measured data. Do they match? Why or why not? Write a paragraph explaining your result - 20%
5. Estimate your damping constant, damped natural frequency, damping ratio, and natural frequency. State these values explicitly in the submission. Given the frequency you computed, comment on the frequency you would need to completely avoid aliasing and if the CPX is capable of doing that. - 20%