Final Design Report:
Written Tutorial on How to Build an Analog Scale

Team: Brandon Bonifacio, Zeneve Jacotin, Jordan Stone

December 2023

Introduction

In this report, the team details how to build an analog scale. Scales have seen much commercial use as a way for engineers to measure the mass of objects and people to keep track of their weight, among many other applications. An example digital scale is given in Figure 1. In this project, the team will construct an analog scale, which is different from the digital scale shown here because the signals within an analog circuit are continuous while the signals within a digital circuit are discrete. This allows analog circuits to have a theoretically infinite resolution, which could lead to a greater accuracy when measuring the weight of objects.

Figure 1: An example digital scale [1]. Scales are used for a plethora of applications, and their impact is widespread. This particular scale is used to keep track of a person's weight.

The analog scale detailed in this report will measure how many sets of 5 Jenga blocks have been placed on the scale through the use of LEDs, up to a total of 10 LEDs. So, if 0 Jenga blocks are on the analog scale described in this report, 0 LEDs will be on. The maximum number of LEDs that can be on in the system is 10 LEDs, which will happen when 10 sets of 5 Jenga blocks, or 50 Jenga blocks total, are on the scale. A table describing how many LEDs will turn on for a given number of Jenga blocks is detailed below.

# of Sets of 5 Jenga Blocks on the Analog Scale	# of Jenga Blocks Total on the Analog Scale	# of LEDs on
0	0	0
1	5	1
2	10	2

3	15	3
4	20	4
5	25	5
6	30	6
7	35	7
8	40	8
9	45	9
10	50	10

Table 1: Description of the behavior of the analog scale described in this report. For every 5 Jenga Blocks added to the scale, up to a maximum of 50 Jenga blocks, an additional LED will turn on.

There is also an accompanying video to show the primary components of the analog scale and give a video demonstration of the scale working [6].
https://www.youtube.com/watch?v=kMTFbr8YRqk

System Description
Our system works identically, in principle, to the system of a bathroom scale. Weight, as an input, is applied to the system, and the output of the system is a human-readable indication of how much weight has been applied to the system. For this system, the weight input is sets of 5 Jenga blocks that have been taped together. The human-readable output is the number of LED lights that have been turned on in this system, with the number of LED lights indicating the number of sets of 5 Jenga blocks that have been added to the scale.

For example, if no Jenga blocks are on the scale, then no LED lights will be on. If one set of 5 Jenga blocks is put on the scale, which is 5 Jenga blocks total, then 1 LED light will be on. If two sets, which is 10 Jenga blocks total, are on the scale, then 2 LED lights will be on. This pattern will continue until 10 sets of 5 Jenga blocks, or 50 Jenga blocks total, is on the scale, at which point all 10 LED lights will be on. This is the maximum number of LED lights that can be on, and adding more Jenga blocks will not turn on more lights. The total system of the Analog Scale is depicted in the block diagram below.

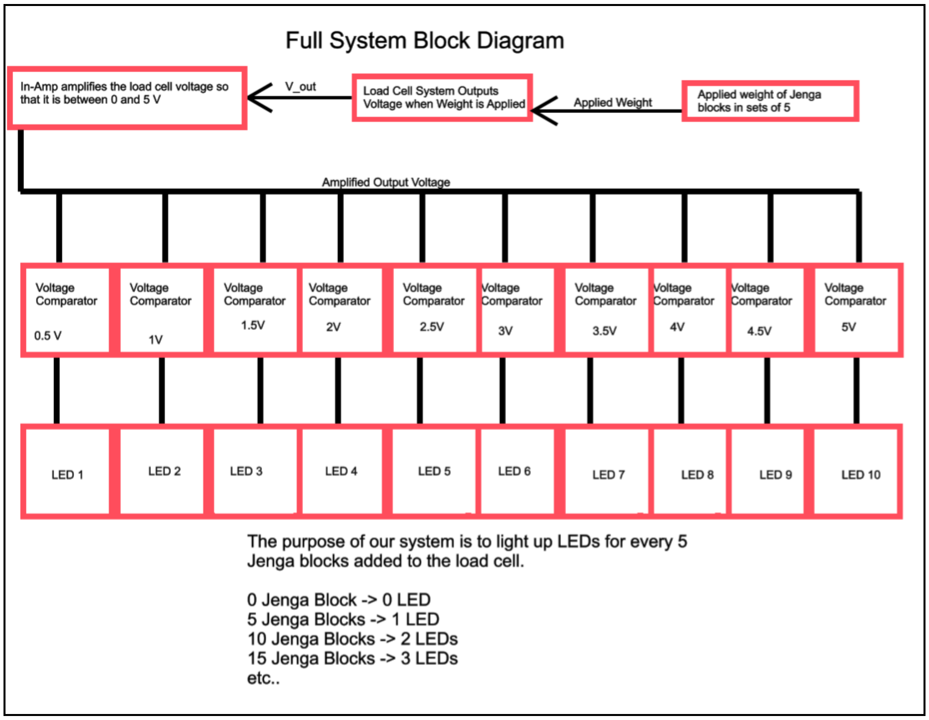


Figure 2: Full System Block Diagram.

In Figure 2, the input to the system takes the form of sets of 5 Jenga blocks, and the output to the system takes the form of LED lights turning on. For every 5 Jenga blocks added to the system, an additional LED light will turn on up to the maximum of 10 LED lights. 0 LED lights are on if 0 Jenga blocks are on the scale. As a note, the voltage thresholds at which the 10 LEDs turn on are example values, and the exact values are detailed later in this report.

There are two primary components to this system. The first is that of the load cell, which inputs the Jenga block weight and outputs a voltage on the scale of millivolts. A block diagram describing the load cell is given below.

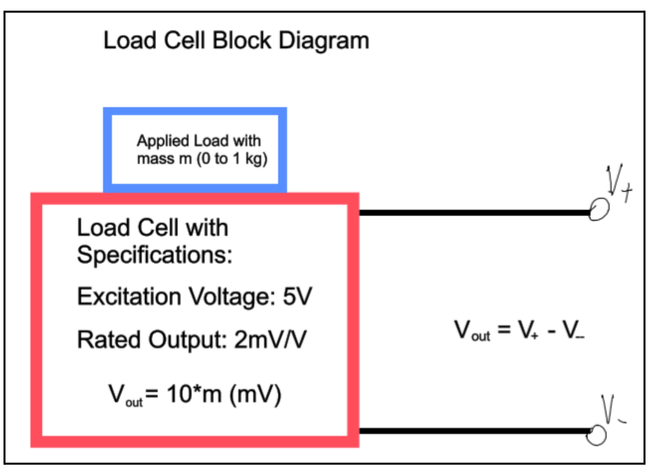


Figure 3: Load Cell Block Diagram.

In Figure 3, the input to the load cell is weight in the form of Jenga blocks, and the output of the system is a voltage difference on the scale of millivolts. Akin to Figure 2, the values given in this diagram are provided as an example and are not the exact values. The exact values are detailed later in this report.

The second primary component to this system is the analog circuit. The input to the analog circuit system is the voltage difference from the Load Cell, and the output of the analog circuit is the number of LEDs that are on. At the beginning of the analog circuit, the output voltage of the load cell is amplified and placed on a rail. Then, comparators in the form of MCP6002's are placed such that, when the rail voltage becomes greater than a particular LED's threshold voltage, the comparator will turn on the LED. Each LED's threshold voltage is described later in the report.

The entire circuit diagram for the analog scale is provided below as a simulation via Falstad, for which the link is provided here, https://tinyurl.com/yp9ydyvh. An image of the simulation is provided below.

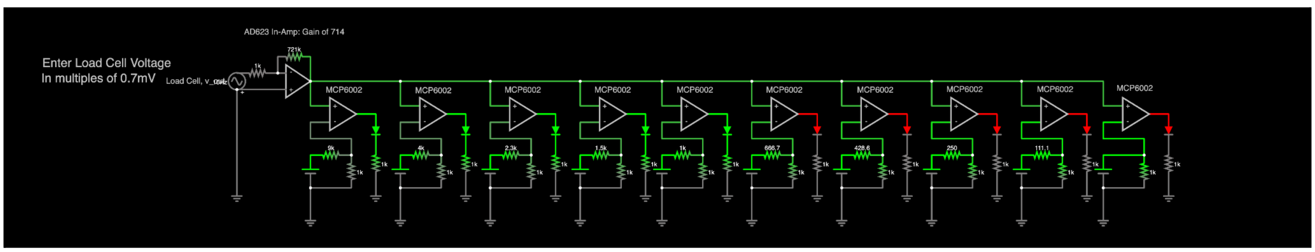


Figure 4: Circuit Diagram of the Analog Scale.

In Figure 4, the left side of the circuit is a simple representation of the load cell, outputting a varying voltage on the scale of millivolts to represent different weight being applied to the system. The rest of the circuit depicts the load cell voltage being amplified by the AD623 onto a rail, and then the LED lights turn on according to whether the rail voltage is greater than or less than each LED's threshold voltage. The threshold voltages are determined by a simple voltage divider, as described later in the report.

How to Build the Analog Scale

How to Build the Load Cell Platform

The purpose of the load cell platform is to effectively transfer the weight of the blocks to the load cell. The way a load cell works is that it uses strain gauges to measure the strain in a material caused by its deformation when a load is applied to it. The deformation in material happens in the weakened area of a load cell which can be seen as two intersecting circles in the top of Figure 5.

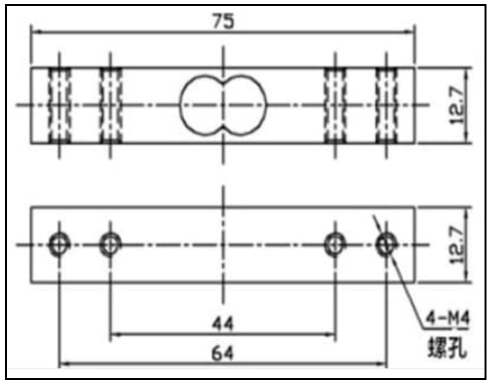


Figure 5: Mechanical drawing of load cell.

However, in order to make sure that the load cell gets an accurate reading of this force through the center of this beam, the load cell needs to be completely supported on one edge of it and the load needs to be applied on the other edge. It is important that the flats on the top and bottom of the load cell are not supporting the load because of this because any load applied to the flats will not be measured as it will not cause the weakened section of the load cell to displace. This means the strain gauge will not be able to read the information. The screw holes on both sides of the load cell help to mount platforms in a way that ensures the strain gauge deforms and the correct load is read.

To build the load cell platform, we consulted the diagram that is posted on the product page of the load cell as is seen in Figure 5. From this diagram we can see the dimensions of the holes, which are M4 and the distance they are apart from each other. Using this information, we can create an accurately sized model of the load cell in Solidworks. Now we use solidworks to design a flat sheet of material that will bear the load of the load cell platform.The flat sheet simply contains two screw holes to go into the load cell. Because this system is a cantilever beam, to prevent tipping the load cell during use, we'll make sure that the sides are mounted opposite of each other so that the center of mass is in the center. An image of how this was done can be seen in Figure 6. The flat sheet modeled in Solidworks can be exported as a DXF file and then cut on one of the laser cutters in the makerspace.

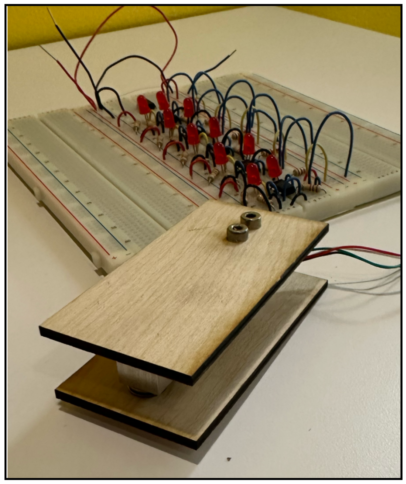


Figure 6: Image of the load cell with platforms attached.

How to Build the Circuit

To build the circuit, we first simulated its functionality in Falstad. We knew that we wanted ten increments, and thus needed 10 op-amps in total. Each op-amp would require its own voltage divider to control the threshold voltage for turning on its respective LED. The output from the load cell is a very low voltage, so we knew to use an instrumentation amplifier to make it a more useful measurement. This schematic is demonstrated in the below image from Falstad.

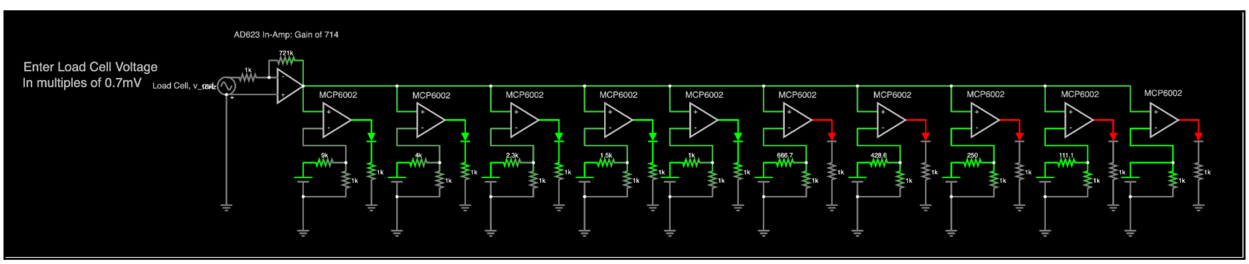
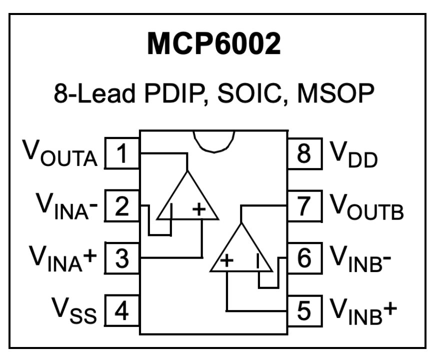


Figure 7. Falstad Circuit Schematic.

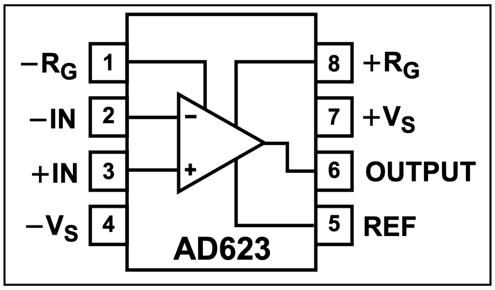
The schematic in Figure 7 was then breadboarded. Here are the steps required to build the circuit:



1. Place each op-amp on the board. Only 5 MCP6002s are needed because there are two op-amps in each chip.
    a. Pin 1 to cathode of LEDx
    b. Pin 2 to LEDx_threshold_voltage_output (from voltage divider, where x is the current LED circuit that is being built)
    c. Pin 3 to output (Pin 6) from AD623 (see Step 2)
    d. Pin 4 to GND
    e. Pin 5 to output from AD623 (used a rail for easy access that was not being used for power or GND)

f. Pin 6 to LEDx+1_threshold_voltage_output (from voltage divider, where x is the current LED circuit that is being built)
g. Pin 7 to cathode of LEDx+1
h. Pin 8 to 5V

2. Place the AD623 on the board.
    a. Pin 1 to Pin 8 with 33Ω resistor
        i. A resistor of 33Ω allowed the output voltage of the in-amp to be about 3V with 50 Jenga blocks. The load cell's zero point was not actually zero, so we had to add a bias voltage (2V) to the in-amp to force its zero point to be zero.



    b. Pin 2 to load cell output (white)
    c. Pin 3 to load cell output (teal)
    d. Pin 4 to GND
    e. Pin 5 to 2V bias voltage
    f. Pin 6 to positive terminal of op-amps (Pins 3 and 5 on each MCP6002)
    g. Pin 7 to 5V
    h. Pin 8 to Pin 1 with 33Ω resistor
3. Add each op-amp's voltage divider
    a. Pin 3 (and Pin 6, but separate voltage divider) on each op-amp was connected to the node between the voltage divider resistors.
    b. 5V voltage source → variable resistor → (Pin 3/6) → 1kΩ → GND

Once all steps have been completed, the circuit should look like Figure 8, with yellow wires as placeholders for each of the variable resistors from the voltage dividers:

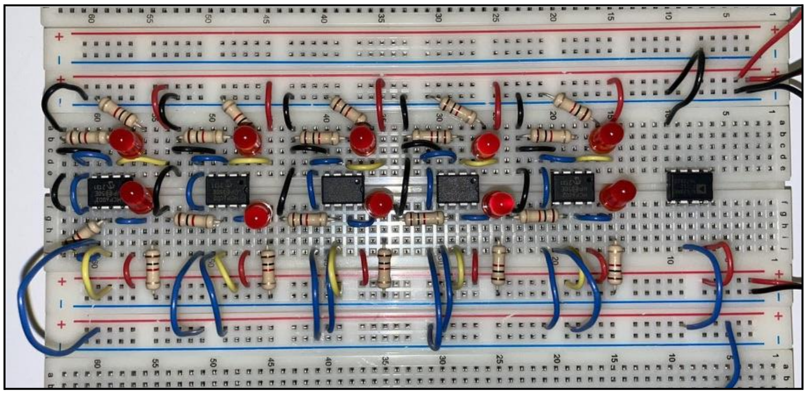


Figure 8. Breadboarded circuit, with placeholder wires (yellow).

The next step is to place each of the variable resistors (8kΩ, 4.3kΩ, 3.8kΩ, 2.7kΩ, 2.2kΩ, 1.6kΩ, 1.2kΩ, 1kΩ, 800Ω, 560Ω) in place of the yellow wires. These resistor values were chosen experimentally, but initially were based on calculations. After trying out our calculated resistances, we adjusted them to achieve the desired effect at the prescribed load. This adjustment was necessary for several reasons. The first of these is the inherent error within the resistors, which meant that some 560Ω were actually 555Ω, for example. This meant that we had to try a couple different resistors until we found one that worked. Another reason why the resistors needed to be adjusted, especially the 33Ω resistor, was that the output gain of the load cell needed to be experimentally determined because this information was not provided with the load cell. This meant that the exact gain required in order to transfer the output voltage of the load cell, which was on the scale of milliVolts, into the rail voltage connected to the LED comparators, which was on the scale of Volts, needed to be experimentally determined by attaching different resistors to the AD623. As the team discovered, for this brand of load cell, a 33Ω resistor was appropriate and allowed the team to generate a rail voltage versus Jenga block linear fit given in Figure 9.

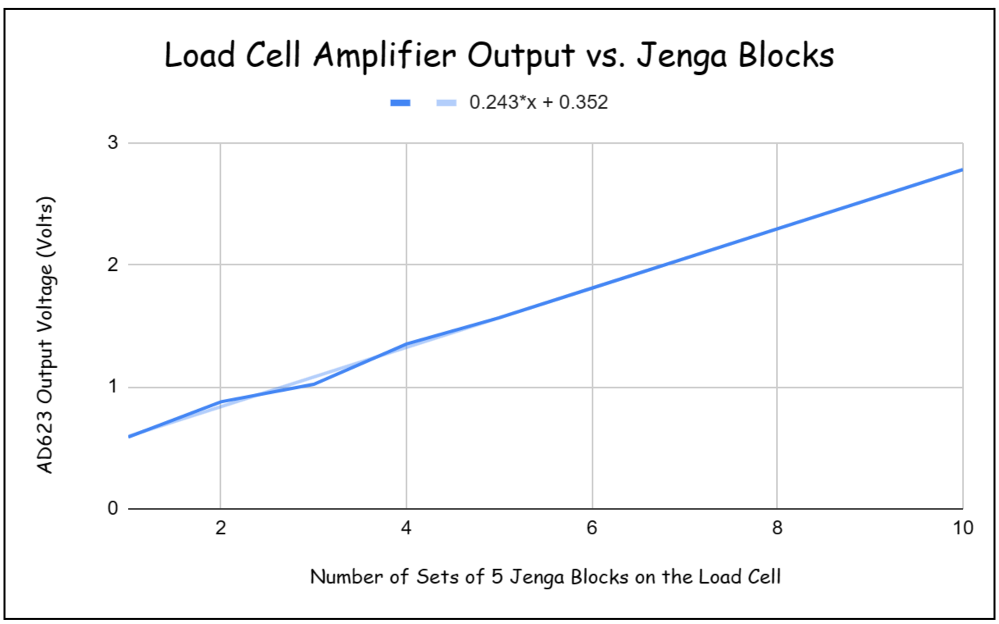


Figure 9: AD623 output voltage versus the number of Jenga blocks on the scale for a 33Ω resistor.

From this linear fit with the 33Ω resistor, the resistor values for each of the LED voltage dividers can be determined as shown in Table 2.

# of Sets of 5 Jenga Blocks on the Analog Scale	Threshold Voltage Required (V)	Approximate Resistor Value Required (Ω)
1	0.59	8000
2	0.88	4300
3	1.02	3800
4	1.35	2700
5	1.57	2200
6	1.81	1600
7	2.05	1200
8	2.23	1000
9	2.54	800
10	2.78	560

Table 2: Threshold voltage and approximate resistor value for each LED system. The resistor values were chosen to both satisfy the threshold voltage and also to be easy to source from the Engineering stockroom.

Component List:

- 1 1kg load cell [2]
- 1 AD623 (Instrumentation amplifier) [4][5]
- 5 MCP6002 (Operational amplifier) [3][5]
- 10 LEDs [5]
- 20 1kΩ resistors [5]
- 1 of each of the following resistors: 8kΩ, 4.3kΩ, 3.8kΩ, 2.7kΩ, 2.2kΩ, 1.6kΩ, 1.2kΩ, 1kΩ, 800Ω, 560Ω, 33Ω [5]
- 2 Breadboards [5]
- Multiple wires [5]

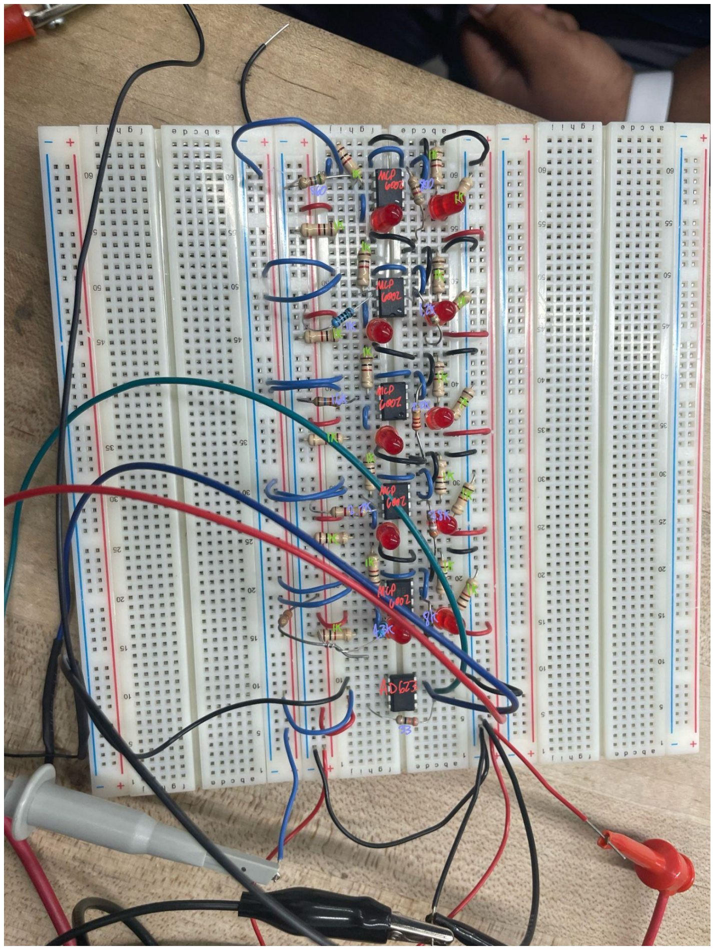


Figure 10: Labeled circuit with all the components fully installed.

Conclusion

Overall, the analog scale worked as the team had planned it to. As shown in the video [6], the number of LEDs turned on correlated exactly to the number of sets of 5 Jenga blocks on the scale. The only small discrepancy from this would be when some LEDs would flicker when a Jenga block was first placed on the scale, but this is to be completely expected because when a mass is first added to a scale, the weight of the object as measured by the scale temporarily increases because the scale has to stop the downward momentum of the object. This is akin to stepping on your bathroom scale. When first stepping on a bathroom scale, the weight at first is different from the actual weight, and you must wait a few seconds for the weight to come to equilibrium. This is the exact behavior seen in our system, which is to be completely expected.

Reflecting on the system as a whole, the team did not make any updates to the system from the beginning of the project to the end. The only part of the system that could be considered different is the resistor values used in each LED voltage divider system and the AD623 gain, but the team knew going into the project that these resistor values would need to be determined experimentally because the exact specifications regarding the load cell were not known. In other words, the output voltage for a given input weight for the load cell was not specified, so the team understood that the output voltage for the load cell would need to be experimentally determined in the lab. So, once this was experimentally determined in the lab, the team needed to analytically and experimentally determine the values of the resistors using this new information. However, as discussed before, this experimental process was planned beforehand.

Lessons Learned

The primary lesson learned in this lab was the importance of experimentation and iterative development. As described earlier, many components of the system such as the load cell specifications or the resistor values needed to be experimentally determined for several reasons. Furthermore, the team did not make the circuit perfect on the first try, and it took several iterations of debugging to remove the bugs.

The team also learned other lessons in this lab, such as the importance of sourcing your materials early, the importance of planning ahead and looking for possible roadblocks in circuit design, and the importance of making clean circuits for easy debugging, such as color-coding the wires.

Works Cited:

[1] Example digital scale. Amazon.com: Eat Smart Precision Plus Digital Bathroom Scale with Ultra-Wide Platform, 440 lb Capacity, Bath Scale for Body Weight, Grey : Office Products

[2] The load cell used in this project. WWZMDiB 1KG/5KG/10KG/20KG Load Cell Amplifier+HX711 24-Bit ADC Weighing Sensor Module Used to Measure Force, Pressure, Displacement, Strain, Torque, Acceleration. (10KG): Amazon.com: Industrial & Scientific

[3] MCP6002 datasheet. MCP6001/1R/1U/2/4 - 1 MHz, Low-Power Op Amp (microchip.com)

[4] AD623 datasheet. AD623 (Rev. G) (analog.com)

[5] Many of the circuit supplies were sourced from the Engineering Stockroom and the Analog Lab, including the op-amps and in-amps.

[6] Video tutorial supplementing this report https://www.youtube.com/watch?v=kMTFbr8YRqk