Hydraulic Bridge Breaker
&
Force Measurement-Display System

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Abstract

For our popsicle stick bridge competition, our goal was to find an efficient way to crush popsicle stick bridges, measure and record the force applied to each of the bridges, and present the data in an accessible and understandable way. To do this, we used a hydraulic bridge crusher, load cells, and a Phidget™ board. The hydraulic bridge crusher was created and modified to apply force to our popsicle stick bridges. The four load cells attached to the Phidget™ board measured the force from the bridge breaker and sent it to a computer. Python code was written to record the data, convert the data to the correct units, plot the data, and display the graphs on a screen. Our final result was a hydraulic bridge-crushing system that could record total force, graph data, and display it in real-time. The construction of a cheap but effective bridge breaker is important as an engaging and interactive method to help teach students about physics and the application of physics, without spending excessive amounts of money on commercially available bridge breakers.

Introduction

The annual Thompson Rivers University (TRU) Popsicle Stick Bridge competition challenges students to design and build a popsicle stick bridge that can withstand large amounts of compressive and tensile force. The bridges must span a 50cm gap, and may use at most 100 unaltered popsicle sticks. They rest on 2 abutments beneath a hydraulic jack. The goal of the competition is to build a bridge that can withstand a large amount of force without breaking or snapping. Using button load sensors and the laws of physics, we were able to determine the external force applied on each bridge.

Our goal was to replicate the hydraulic jack and testing system used at the TRU competition at a lower cost, and at a higher replicability. Our design and components use the theory of static equilibrium and Ohm's law to determine the exact force

$$V = IR$$

Ohm's Law

applied to the top of each bridge. The bridge crusher we built uses four Phidget™ button load cells, two at each abutment, to measure the force applied to the popsicle stick bridges. As the hydraulic jack slowly increases the amount of force on the bridge, the force is transferred through the trusses of the bridge and pushes on each of the load cells. Based on the laws of static equilibrium, we know that the force of the hydraulic jack must be balanced, and that it will be equal to the sum of the forces at each point of contact on the abutments.

$$\Sigma F = 0$$

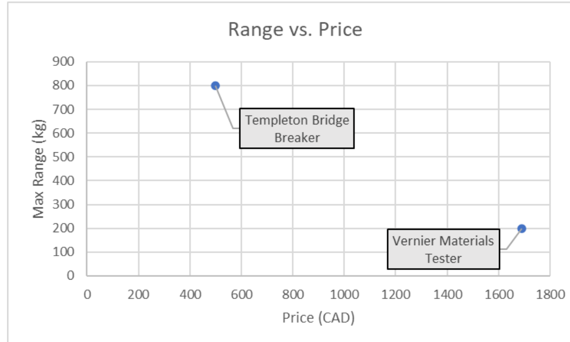
Sum of forces is equal to zero

Adding the total force of all 4 load cells allows us to determine the force the hydraulic jack is pressing down with. After determining a final force, our code projects the data to an easily accessible and understandable graphed format.

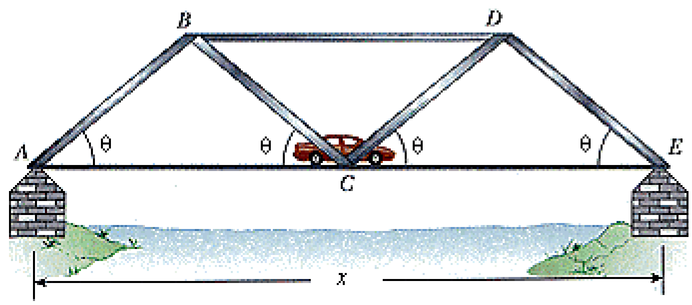
Our Phidget™ load cells use a Wheatstone bridge circuit. When compressed, the resistance of the resistors inside changes, thereby changing the voltage drop across them. (for further detail see section x sam and nathan) Using calibration techniques we were able to find a ratio of change in voltage to change in force. We then used this value as a constant to calculate the value of any given force placed on the load cell.

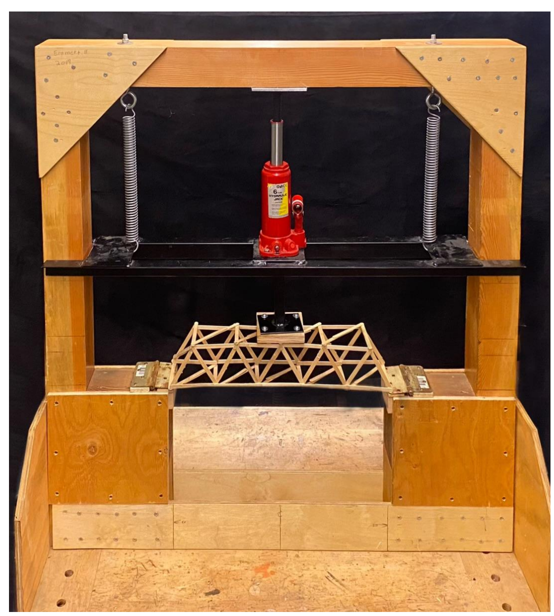
Although many companies sell various commercial bridge crushers online, the models are quite expensive and are unable to measure high force loads. The Vernier "Structures and Materials Tester" can be used to measure the amount of force applied to any object. At first glance, the tester may seem like a reliable design; however, it can only be used to measure values up to 100kg and costs $1690 CAD. In comparison, our design can measure up to 800kg (200kg per load cell) and costs ~$500 CAD. Just like the Vernier system, our system can be used to measure the force applied to almost any object.

With market prices being so high, our goal is to ensure that every school has access to their own bridge breaker, one that they can make themselves with low costs and minimal experience.



This device is not just a tool; it is an opportunity for education and learning. It offers a chance to put physical theories to practice while learning about coding and engineering.





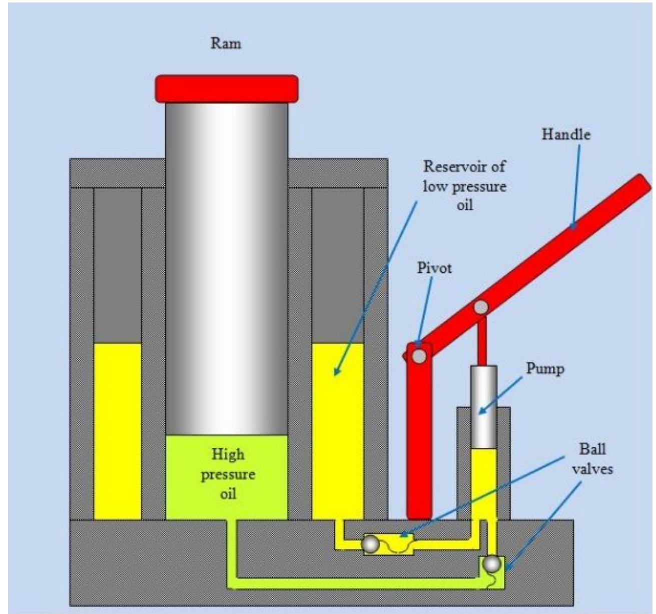
Frame Design

Overview

The bridge crusher is mainly made of wood and is equipped with a hydraulic pump rated for six tons. It exerts this force on a 10x10cm square plate which presses on the top of the bridge. The crusher is able to accommodate bridges with a minimum span of 50cm, and a maximum span of 90cm. Bridges can have a maximum height of 22cm from the abutment, and there is no minimum height for the bridge, as additional plates can be added to increase the travel distance of the piston. To measure the force exerted on the bridge, there are four load cells, two on each abutment. The load cells are able to measure a force of up to 200kg and so although the crusher can exert up to six tons of force on a bridge, it can only test bridges that can withstand 800kg or less. This is sufficient for almost any popsicle stick bridge competition.

Hydraulics

Our bridge crusher utilizes a manual hydraulic bottle jack to break the bridge being tested. When the handle is pumped, low-pressure oil from the reservoir located in the jack is pushed into another reservoir under the ram, where pressure builds up. As more oil is pumped into the high-pressure reservoir, the ram is pushed further out towards the bridge, and more force is exerted once it makes contact with the bridge. To release the pressure behind the ram, the ball valves can be opened allowing the pressurized oil to flow back to the low-pressure reservoirs. Without pressurized oil behind it, the ram returns to its original



position due to gravity. Furthermore, in our case, there are tension springs that help bring the ram back to its original position once the pressure is released.

Materials and Cost

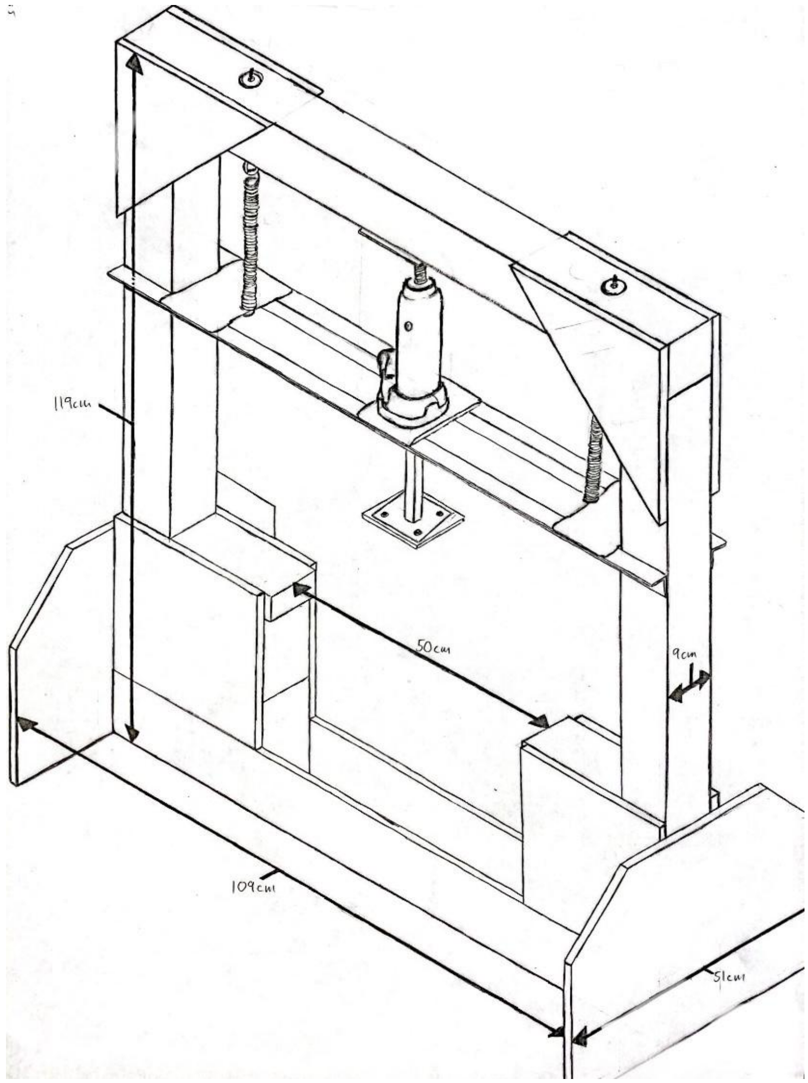
All together, the materials used to construct the bridge crusher cost roughly $500.

Hydraulic press - $50
Wood - $75
Springs, screws and metal - $50
Phidget™ sensor equipment - $325

Power tools, or handsaws, screwdrivers, and wrenches are also necessary for the construction process. We have not included these tools in the total estimated cost.

Frame Construction

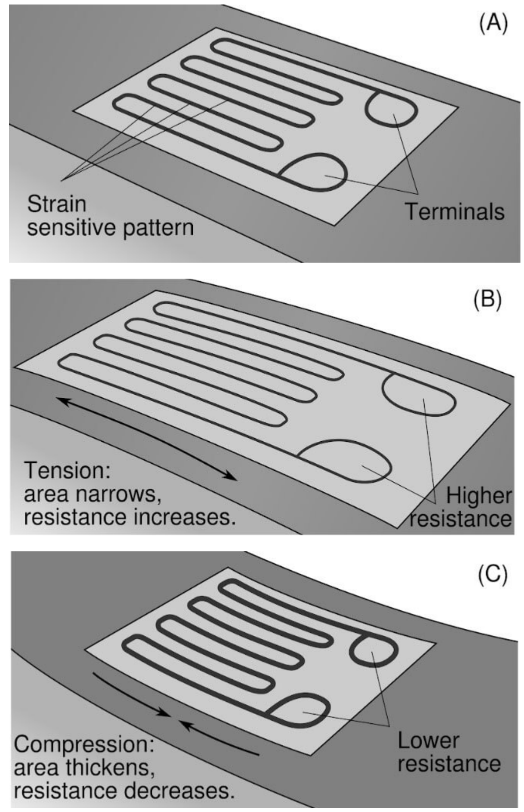
Our bridge crusher is constructed of 22 cuts of plywood and fir, 8 pieces of steel (2 angle braces, 5 plates and 1 square beam), 2 tension springs, 6 nuts, 4 bolts, and roughly 150 screws. It had to be built with strength in mind, as the bridge needs to break before the crusher does. In order to achieve maximum strength for cost, we selected un-knotted 4x4 fir beams for the main structure. The main rectangular structure was supported by triangular plywood gussets in the top corners to help strengthen the structure, as well as additional plywood supports for stability. In order to ensure that the ram travels directly downwards and does not sway, welded steel guides are present. These steel guides run along the outsides of the vertical fir beams. There is a steel plate at the point where the jack meets the horizontal fir beam. This is in order to expand the surface area and reduce the pressure on the beam from the jack. At the abutments, strength is also a concern, considering that they will be supporting the bridge under load. The abutments are made of solid blocks of 4x4 fir, leveled with each other in order to provide a stable platform for the bridges. These blocks have a massive amount of compressive strength. The gap in the middle has a span of 50cm to comply with the rules of the TRU competition.



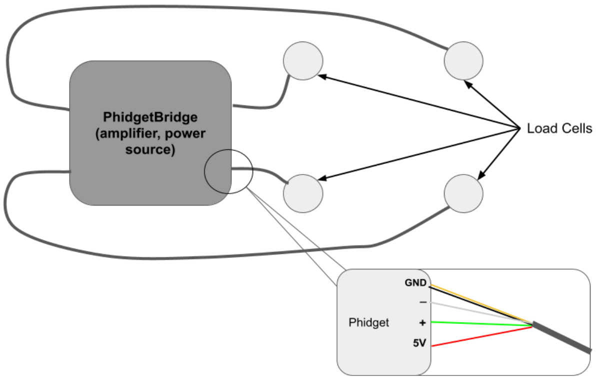
Circuit Design

Load Cell Operation

Strain (as well as stress) is the result of an external force being applied to a stationary object. Strain is how much a material deforms under an applied stress. The stress, in our case, is the force of compression on top of the small button on the load cell. Our load cell uses a strain gauge mechanism to calculate the compressive force. With the strain gauge model, the calculated force is dependent on the strain applied to the gauge. Strain on an object can be caused by either compression or tension, but our load cells only measure the force of compression. Every strain gauge has conductors in it that conduct current. When the conductor is compressed, or when weight is placed on the load cell, the diameter inside the conductor increases, while the total length decreases, subsequently decreasing resistance to allow for a higher voltage. This explains the higher voltage readings seen when the weight on the load cell is increased. The opposite of this is true when the conductor is stretched, or put under tension. The diameter inside the conductor decreases and the length increases, which in turn increases resistance. While there are other types of load cells such as pneumatic or hydraulic, the strain gauge model is the most common, and the best fit for this project. The other variants of load cells are used in much more specific scenarios, while the strain gauge model is best for the generated measurement of force and strain.

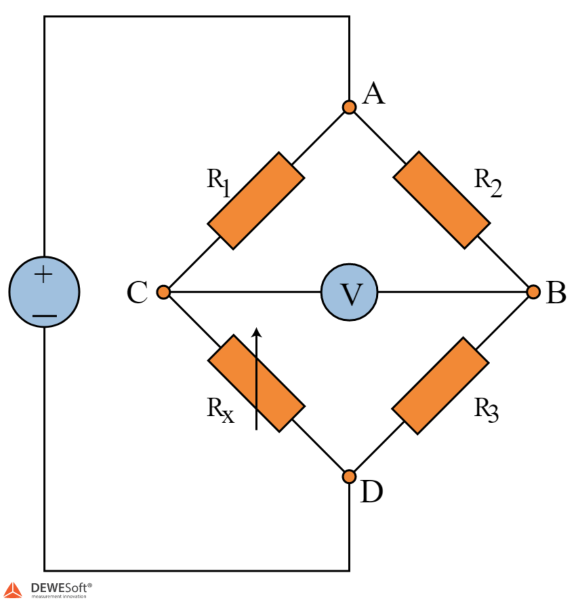


In most modern load cells, there are four strain gauges per one load cell. This is for maximum accuracy in the readings. Within the load cells, the gauges are attached to an electrical conductor that deforms when weight is applied to it. The key difference between load cells and the strain gauges themselves is that load cells are considerably more sensitive than the gauges. This is because load cells require a very small change in resistance to give readings.



Load Signal

Load signals are incredibly minute because of the minimal change in physical deformation. As the load cells are already quite small, the strain ends up being quite small as well; having multiple load cells involved makes that strain even smaller as it is now being distributed among them. To measure the small changes in resistance, four strain gauges are placed in a circuit. This circuit is known as a wheatstone bridge. The wheatstone bridge configuration consists of the four strain gauges arranged in

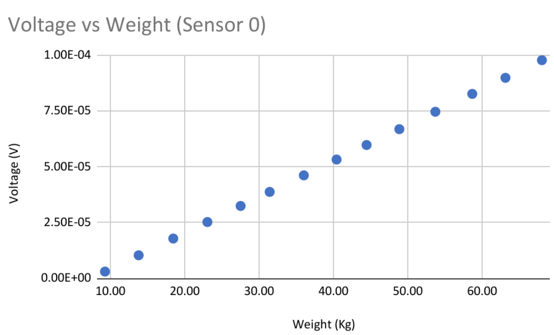


a diamond shape. When no force is acting on the system, the voltage measured at the two middle points of the bridge will be zero, as the bridge is balanced. When a force begins acting on any of the strain gauges, the resistance changes in the respective gauge. This results in an unbalanced wheatstone bridge, and therefore, an output voltage no longer equal to zero. These changes are miniscule, so different load cells use different strategies to convert the resistance and voltage changes to readable data. Phidget™ uses the addition of an amplifier to make the load signals more readable. This amplifier is crucial for data collection and is a part of the bridge itself. The amplifier is a high-resolution analog-to-digital converter. It works by converting the original signal of mV (millivolts) to mA (milliamperes), a significantly more readable value. The one issue with implementing the amplifier is that it may lead to unwanted noise in the signal. However, this is fixed by a process called signal conditioning. Signal conditioning is a circuit that manipulates a signal to prepare it for the next stage of processing. Effectively, this means that the data is being corrected so it can be accurately measured and shown. In this case, the signal conditioning filters out the excess noise so that only the original data is measured.

Sensor Calibration

As voltage (measured in V), and force (usually measured in N), have different units, you must convert the voltage readings from the load cells into corresponding weight values. This requires a process called *calibration.*

The load cells are designed to send voltage signals that are directly proportional to the force that is being applied to them. In other words, doubling the amount of force should double the amount of voltage that the cell reads; graphing the voltage/weight relationship would result in a linear function. By calibrating the cells, we can make sure that the readings are, in fact, proportional to the amount of force being applied to them, or linear.



Unfortunately, every sensor has its own calibration value. This means that applying 100N of force on one cell may produce a larger change in voltage than that same force applied on another cell. Additionally, each cell has a different initialization voltage - the voltage value read when there is no weight on the cell. Calibrating the sensors eliminates both of these issues, by converting the voltage readings of the cells into useful and meaningful measurements of weight that are consistent as the weight increases.

Because of the linear relationship between voltage and weight, measuring how the voltage of the cells change with changes in weight will produce a conversion value that can be used to convert between the two. First, determine what is called the zero-level offset, which is the voltage reading of a sensor with no load/weight. Then, add a load to the cell, and record how much the voltage reading changes. This can be done as many times as necessary in order to get the most accurate trend line, the slope of which models how the sensor readings change with weight. The formula below shows how to find the slope, or calibration value for a given sensor:

$$M_{cal} = \frac{1}{N} \sum_{i=0}^{N} \frac{V_{i+1} - V_i}{F_{i+1} - F_i}$$

The slope, M_{cal}, is our calibration value, N is the number of data points chosen, V is the voltage reading, and F is the force reading. Breaking the formula into components reveals change in voltage (rise) over the change in weight (run) for every data point, and averaging all the calculated values to find an appropriate slope. Averaging these values is useful, because it reduces error in our data pool, by data points that deviate from the mean. Once this calculated value has been found, it can be plugged into the following formula, which returns a weight value, F.

$$F = \frac{V_i - V_0}{M_{cal}}$$

Here, V_i is the current reading, and V_0 is the zero-level offset.

To actually get these numbers, we placed a wooden board over four sensors placed near the corners of the crusher abutments (see below):

We wanted to include the board in our zero-level offset, so we used both Python and the Phidget™ Control Panel to collect the voltage measurements with 'no weight'. We then added weight in 10lb increments (as those were the weights we could access), up to 150lbs - every time, we used Microsoft Excel to record the voltage readings for every sensor, in a format similar to the table below. To simplify, you first note your weight and then the voltage reading from the sensor and compare them.

Voltage	Weight in Kg	Calculated weight in kg
3.10E-06	9.07	9.29
1.04E-05	13.6	14.0
1.79E-05	18.1	40.4

It is important to note that the zero-level offset should be recalculated every day, in order to achieve the most accurate readings from the load cells. We found some small optimization techniques to improve the quality of the data. We had a python project that would total the values of one sensor and average them to give us a number that ignores fluctuation. This would increase the speed of testing and reduce human error.

Error

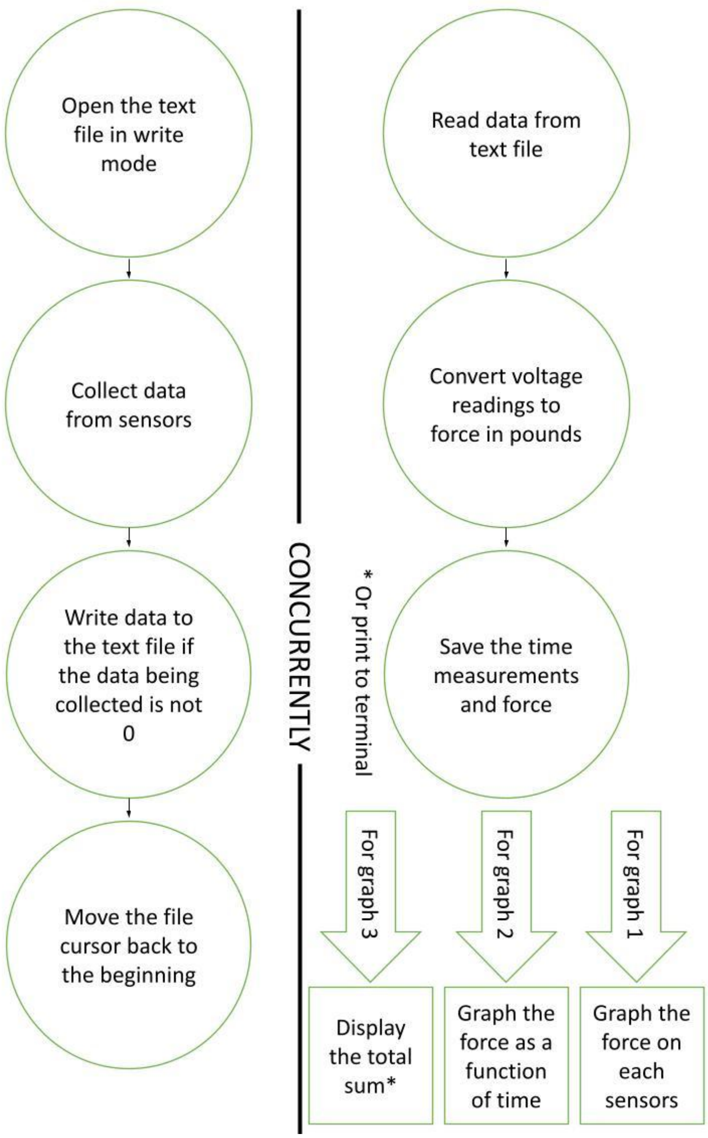
Error in our calibration is incredibly important as it affects the presentation of our final measurements. In total we could measure around ± 1 kg in our final readings.

The specification for the load cell[1] states that it would have a non linearity of 0.4 kg and a cell repeatability of 0.2 kg. Nonlinearity is how much the weights differ from a linear slope and cell repeatability is how much the cell changes by measuring on different days. There are a few places this sort of error is coming from. Our system of measurement used a board to place the sensors on and inconsistency in the boards placement would change the voltage readings. We limited this by measuring the board and keeping it exactly the same for every measurement taken. The most likely error in our system is in the wiring, something that is difficult to control. When building a similar system one must be very precise with the wiring and maintaining the continuity and consistency of all four sensors.

1 https://www.phidgets.com/?tier=3&catid=9&pcid=7&prodid=228

System Programming

In order to convert our Phidget™ cell readings into the proper measurements that we need, and convert our readings into live-updated graphs, we wrote code that allowed us to store data and graph it, before writing over the old data with new values.



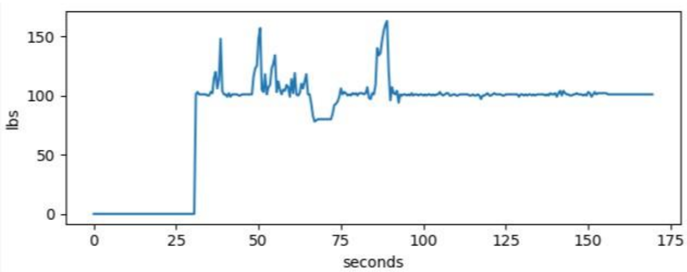
Flow chart of the two pseudo-codes running simultaneously.

Data-gathering pseudocode

```
setting up (is done once)

    open a text file in write mode
to allow the
    data to be overwritten

collecting data (to be looped)

    collect data from each sensors
    multiply the data from each
sensors by
    10 million to be easily read

    write the data to the text file

    move the writing cursor back to
the
    beginning of the text file so
that the
    previous data can be overwritten
```

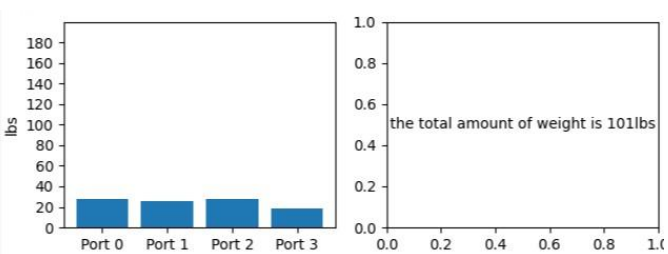
Graphing pseudocode

```
 setting up (is done once)

      create 2 different empty
graphs

  graphing (to be looped)

      collect data from text files

      convert the voltage reading to
force;
      remember to increase the
conversion
      factor by 10 million if the
original
      voltage level was multiply by
a factor of
      10 million

      clear your first graph*

      using your 1st graph, create a
time/force
      graph using the data that has
been
      Collected
```



Line graph measuring the total force over time

```
        clear your second graph*

        graph the amount of force
that is being
        applied to each sensors in a
bar graph

        display the total amount of
force that is
        being applied right now**
```



Bar graph measuring the force exerted on each sensor and annotated graph used to display total weight in pounds.

*: *The live updating graph is much like an old projector in that the previous image must be cleared before new images are projected, just like the initial values from the sensors must be replaced by the new values in order to update the graph.*

**: *This step is dependent on the library or graphing program being used. A simple but crude solution that is common across all programming languages is printing the sum to the terminal.*

This code was developed in the Visual Studios Code IDE. If your graphing library/program supports graph annotation then you can:

```
setting up

      create a third graph

graphing

      annotate the graph with the
sum

      clear the graph
```

Results

The pseudo-code written above is meant to:

1. Collect data from the load cells and convert it into force.
2. Create a moving graph that displays the sum of the force overtime.
3. Create a moving graph that displays the force on each individual load cell.
4. Display the total amount of force being applied to all the load cells at that moment.

Accessing the Code

- This code was written using the provided Phidget™ code (Phidget Sample Code)
- Select your chosen language.
- Select Phidget™ Bridge 4-input as your chosen device.
- Select all 4 channels for your bridge input.
- The downloadable code will be generated in the box below.

Conclusion

Currently, the system is capable of crushing most types of bridges and displaying their maximum load on live updating graphs, which can be projected onto a large screen for viewing. Were we to continue, our next steps would include making a more versatile bridge crusher, better minimizing the calibration error, and live updating the data to a website.

Our current bridge breaker requires a block to be placed between it and any low-slung bridge to crush it. It also can only measure bridges that sit atop the testing surface. This prevents our system from measuring the force applied on bridges- like an arch bridge- that would also rest on the sides of the testing surface. Making the height of the testing platform adjustable would easily allow for the system to test bridges that have low-slung trusses. By adding additional load cells on the sides of the testing surface, our system would be able to measure bridges that use arch abutments. However, the Phidget™ board is a 4-input system; we would need to buy a larger Phidget™ board to use four additional load cells. Another solution would be to look into measuring the pressure of the jack used to generate the force, but this wouldn't tell us how the force is distributed along the bridge's base, preventing us from measuring any torsion present on the bridges.

To increasingly minimize the calibration error within the system, we would increase the quality of the setup. By choosing higher durability wires to connect the load cells to the Phidget board, the wires would have a lower tendency to break, maximizing the consistency of our data. The weights used for calibration are old and worn, meaning that the real weight would not be equal to the expected weight, increasing our error margin. We could fix this problem by purchasing new weights or weighing them on a highly accurate and precise scale.

Additionally, we could improve the bridge breaker by including an output that displays a live-updating feed of pressure readouts. Future iterations of the bridge breaker would ideally include live updating data on an easily accessible website, but this would require extensive troubleshooting to get past the internet limitations within the school.

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Appendices

- **Online link to the project code:** https://github.com/DuctTape123/electronic-weight-code-package
- **Video of the system functioning:** https://youtu.be/v1auc_Tz2LI
- **Phidget™ sample code:** https://www.Phidget™s.com/?view=code_samples
- **Python Code for collecting voltage values (calibrating): https://drive.google.com/file/d/1r-oYR9CSWP9s6F2sllfzWO_-ht_Qov5N/view?usp=sharing**

Data from calibration https://docs.google.com/spreadsheets/d/1yixBhGKaWCarlWuQjWY8SmoBzp2c8Jnd/edit?usp=sharing&ouid=111749163128018617694&rtpof=true&sd=true