UTAH VALLEY UNIVERSITY

Physics 2215: Lab 3

Force, Data Analysis, and Sensor Calibration

Learning Objectives:

1. Learn how to calibrate and find the zero point of a sensor.
2. Learn about statistical analysis techniques such as standard deviation, percent error, and "goodness of fit" (the R-squared value), and how to mathematically model your data.
3. Distinguish between mass and weight.
4. Understand what a force is and get a qualitative sense for the Newton unit of force.

Introduction

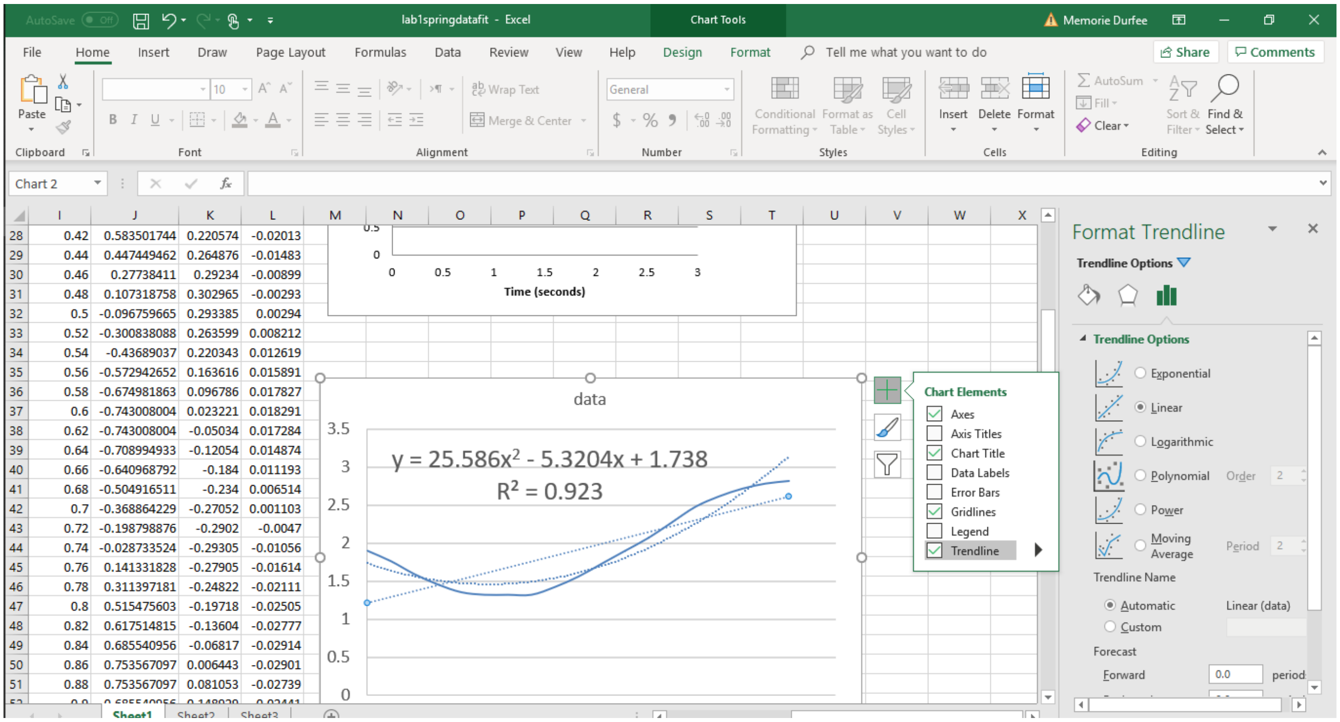
The terms "mass" and "weight" are often used interchangeably, but the two words don't have the same meaning. "Mass" is the amount of matter in a material, while "weight" is a measure of how the force of gravity acts upon that mass. For example, since the force of gravity on the moon is 1/6 of gravity on earth, a 1 kg mass on earth has a weight of 9.8 Newtons, where a 1 kg mass on the moon has a weight of about 1.6 Newtons!

What is a force? ***A "force" is the thing that causes an object to change its velocity, or accelerate.*** Newton's First Law states: An object at rest tends to stay at rest unless acted upon by an external force. Newton's Second Law tells us: F = ma, or force = mass x acceleration. In other words, a force will cause a mass to accelerate. In this lab we will build and calibrate a load cell sensor that will enable us to measure force. However, since weight is also a force, we can measure the force of gravity acting on a mass and use the acceleration due to gravity to find the mass of an object.

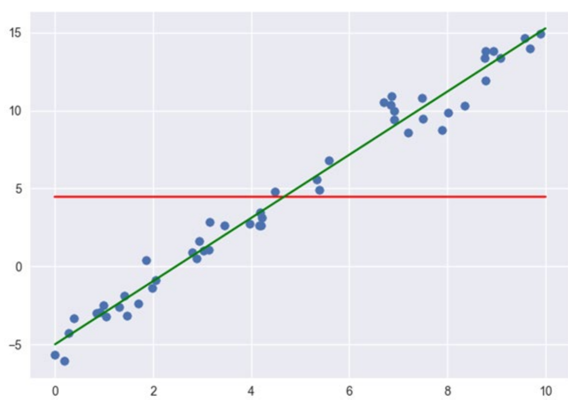
Last week we learned a little about data analysis. This week we will expand on that. We will use one or more of the data analysis techniques described below in this and all future labs. The type of data analysis you do generally depends on the type of data you have. Quite often we measure the same thing many times in order to make sure we measured it correctly. For these types of measurements it is useful to calculate the **average (or mean)** result, the **percent error**, and the **standard deviation** or degree of precision for our data. We covered averages/mean values, standard deviation, and percent error last week. This week we will learn about **mathematical modeling**, and **R-squared value or "goodness of fit"**.

By way of reminder, **percent error** is found by the following formula: **Percent error = |(predicted value – average value)/ predicted value| x 100%,** where the predicted value is obtained from the governing physics equations. Percent error indicates the size of the difference between the measured value and the accepted value (the theoretical predicted value.

Scientists also perform experiments where one of the properties of the system is changed **(the independent variable, or x-coordinate value)** in order to measure the effect on another property **(the**



dependent variable, or y-coordinate value). For this type of data it is common to make a plot of the data points on an x-y graph, and then **mathematically model** (find the 'trendline' or the equation of the line) of the line produced by connecting the data points, and then calculate the **R-squared value** for that model to see how well the model matches the data (or the theory). In this class we will do this using the 'trendline' feature in Excel, which will calculate an equation that best matches your data. The image below shows data plotted on an x-y graph, the equation of the line found using the trendline feature of Excel (I will describe how to do this later.) The image below also shows the R-squared value for the data.



R-squared value:

There are multiple definitions for the R-squared value, but the one we will use for this class is the one that is a measure of the "goodness of fit" of your data to the equation of the line (regression model) you are using to mathematically model your data. In the image below, the red line = mean or "baseline model", the green line = "regression model" (like a trendline), and the blue dots = actual data.

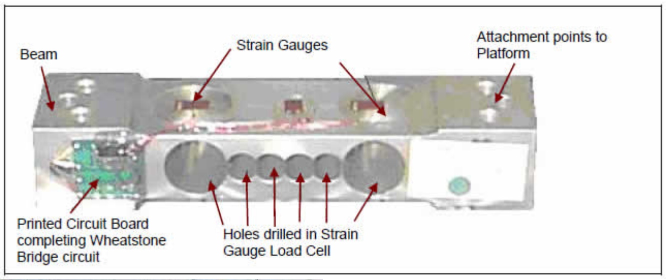
The R-squared value = 1 – SSR/SSB

$$\text{SSB} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad SSR = \sum_{i=1}^{n} (yi - \breve{y}_i)^2$$

Where: SSR = the sum of the squared differences from the regression model, and SSB = the sum of the squared differences from the baseline model.

You don't have to know how to calculate the R-squared value, Excel will do it for you. So what is all of this useful for? If the model perfectly matches the data then SSR/SSB is close to 0, and the R-squared value = 1, meaning a perfect fit for your model. If the SSR/SSB is close to 1, then the R-squared value is close to 0, and you now know that your model is really, really bad.

How the Force Sensor Works

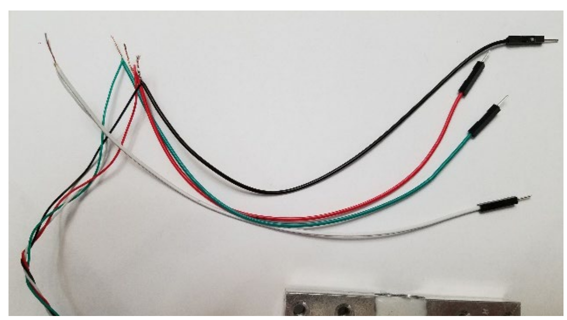


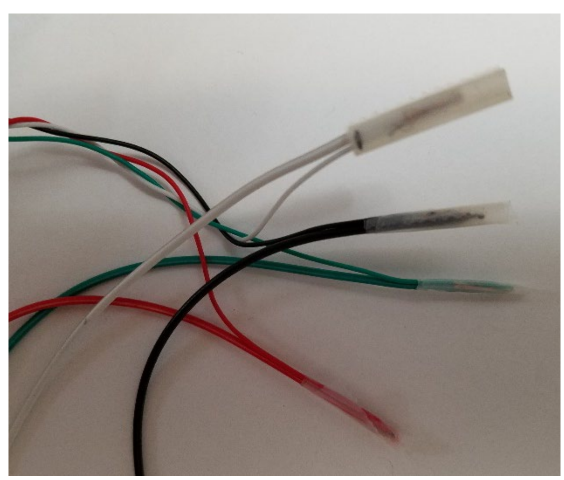
Our force sensor will consist of a load cell and an HX711 Amplifier and Analog to Digital Converter board. The load cell contains two strain gauges (shown to the left) glued to the bottom and top of a piece of metal with holes in it that allow it to bend slightly. When the metal bends, the resistance value for the strain gauges changes linearly. When a voltage is applied, these resistance changes produce tiny voltage changes. By measuring the change in the voltage drop across the strain gauges we can determine the force exerted on the end of the load cell. The HX711 board amplifies these voltages and converts it into a 24-bit digital signal allowing us to measure the applied force with 0.005 Newton precision (or 0.5 grams in weight).

Figure 1 A magnified image of a strain gauge.

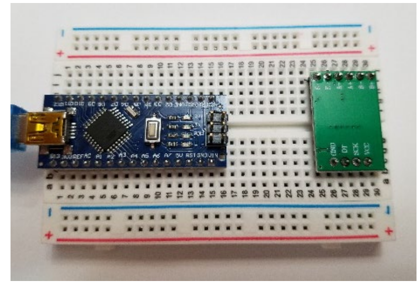
Building the Force Sensor Circuit

Before we start wiring the circuit together we need to prep the force sensor so that we have connectable ends. The wires that come with the force sensor are too fragile to use on their own, so first we have to splice some connector wires on so that we can plug the force sensor into our circuit. Watch the following 1 minute video to learn how to strip the wires: [How to strip small wires](). We need to remove the insulation from both the force sensor wires and 4 connector wires.

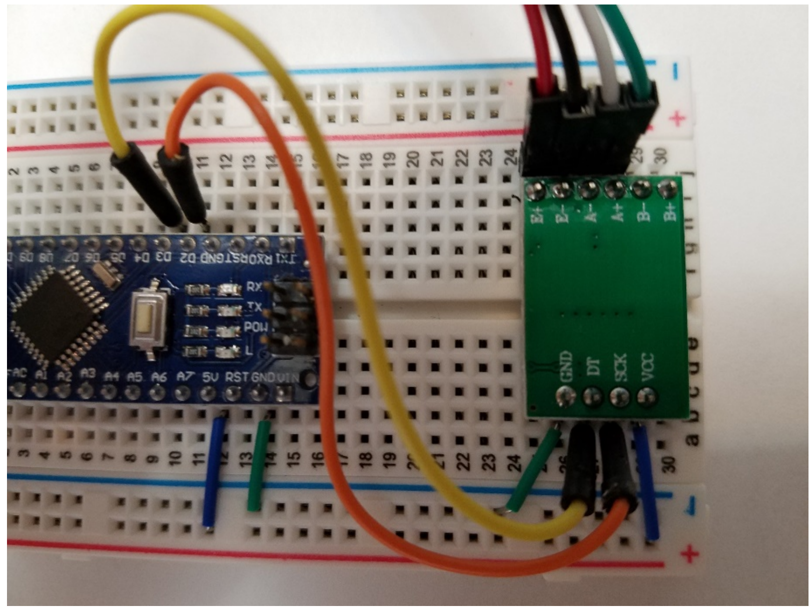




1. Select 4 wires that match the colors of the load cell wires (white, black, red, and green).
2. Clip off the female side of the connector wires (the end without the protruding pin) with scissors or wire clippers. **(We will only strip one side of the connector wires. Leave the male connector pin on the other side.)**
3. Using the technique shown in the video, strip the ends of both sets of wires by heating the bottom ½ inch of the wires with a lighter and then quickly stripping the insulation off with your finger nails (if you lick your fingers first you are less likely to burn yourself.) Do this for one end of the 4 force sensor wires, and one end of the 4 connector wires (8 wires total).

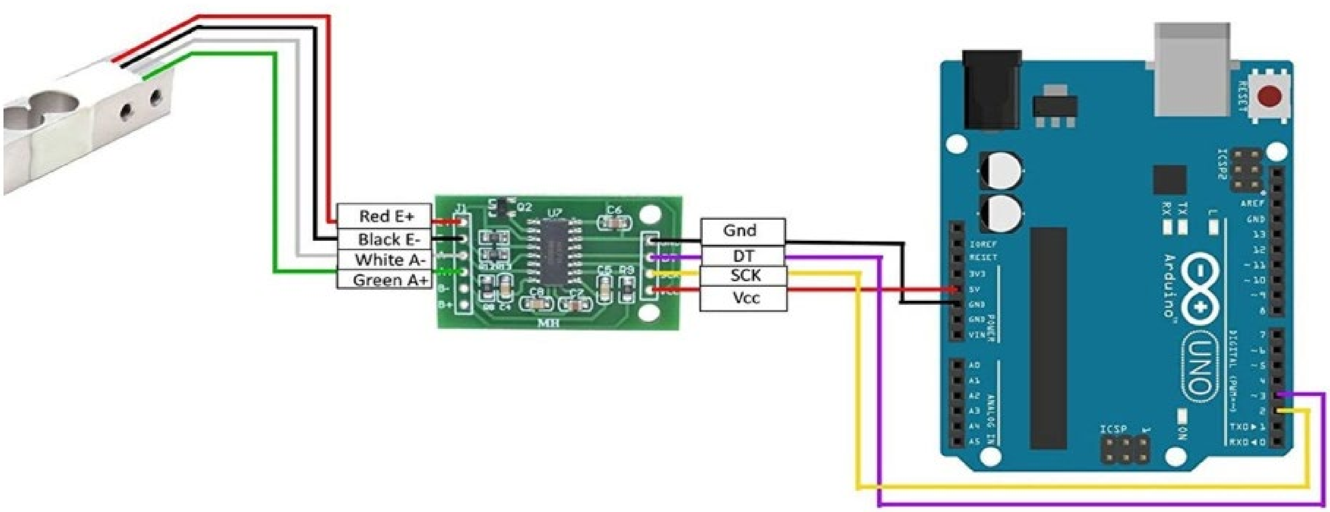


4. Lay the matching wires along side each other and twist together the exposed wire ends of the two wires (one connector wire and one load cell wire, white with white, red with red, etc.).
5. Fold just the exposed twisted ends down over the rest of the wire. Wrap the exposed wire junction with a piece of tape to insulate and strengthen it as shown in the image above.
6. Mount your HX711 in your breadboard as shown. Leave space on either side of the board for wires to be plugged in to the adjacent pinholes. MAKE SURE YOU LEAVE ONE OF YOUR PHOTOGATE CIRCUITS ON YOUR BREADBOARD FOR LATER USE *(even though the photogate circuit is not in the images shown).* Move the photogate components over a few rows in the breadboard if you need to make room.

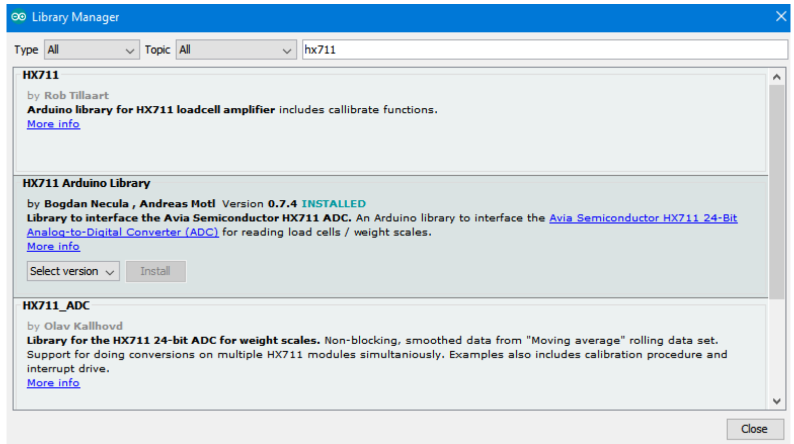


7. Connect the force sensor to the Nano as shown in the image above and in the circuit diagram below. (The Arduino in the circuit diagram is an Uno, but the connections are the same as on the Nano).

HX711	GND	DT	SCK	VCC	E+	E-	A-	A+
Connect To	Nano GND	Nano D3	Nano D2	Nano 5V	Red Load Cell	Black Load Cell	White Load Cell	Green Load Cell

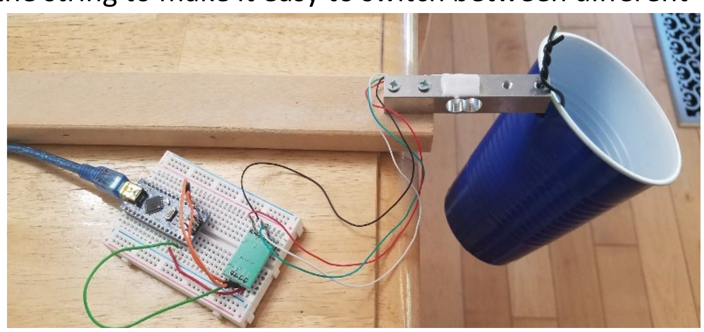


8. Download the program named “Lab3LoadCellTest.ino” from Canvas.
9. Create a directory with the same name in your ‘Arduino’ folder in the ‘Documents’ folder on your computer, and place the program file in it.
10. You will need to install the “HX711.h” library into the Arduino IDE. Libraries are chunks of pre-made code that extend the functionality of your program. Add this library to the Arduino IDE by selecting the menu ‘Tools’, then ‘Manage Libraries’. A window should open up that looks like the image to the left. Enter “HX711” in the search bar. Select the HX711 Arduino Library by Bogdan Necula and Andreas Motl.



11. Now you are ready to upload the “Lab3LoadCellTest.ino” program to your Nano. Open the Serial Monitor. It should be reading out a steady stream of 6 or 7 digit numbers.

We will be hanging different masses from our force sensor to calibrate it. To hang the masses we need a connection point. If you are doing this experiment at home you may want to attach a plastic cup to the outer hole of your sensor as shown, making sure the connecting wire or string hangs over the end of the sensor, not the side. If you are doing this experiment in the lab, you should tie a string from the bolt on the bottom of the sensor. Make a loop in the string to make it easy to switch between different

masses. Your assembled sensor should look like one of the images above.

Once your sensor is prepped and you are displaying an output of numbers in the Serial Monitor window, you can play with your force sensor. Position your sensor so that the end of it is hanging over the edge of a table. Place a weight on the wooden mount to keep it from falling. Now look at the numbers displayed on the Serial Monitor. When you push down on the end of the force sensor does the reading go up? When you push up on it does the reading decrease, or even go negative? What does it mean? It means that the sensor output changes with the applied force. To understand how it changes we will need to calibrate our sensor.

Calibrating the Force Sensor

Calibrating is done by recording the output of the sensor when we apply a known force. **If you are doing the experiment at home you will use pennies as your masses. In the lab we will use calibrated masses. These instructions will refer to both, but you only need use the method easiest for you.**

We will calibrate your force sensor by either adding small masses (pennies) to the cup, or hanging the calibrated masses from the loop attached to the bolt, and plotting the change in the sensor output for each quantity of mass.

Pennies manufactured before 1982 weigh 3.11 grams. Pennies made after 1982 weigh 2.50 grams. If you have other coins you wish to use, you can look up their masses online.

	A	B	C	D	E	F	G	H	I
1		zero weight	3.14 g	6.29 g	33.24 grams	79.64 grams	138.34 grams	Load Cell Output	Weight in grams
2		182231	183745	184894	196117	215431	239840	182072.08	0
3		182137	183694	184864	196030	215437	239836	183620.69	3.14
4		182152	183671	184923	196028	215420	239793	184910.92	6.29
5		182113	183669	184906	196075	215474	239810	196013.15	33.24
6		182055	183704	184920	196042	215449	239824	215442.31	79.64
7		182063	183614	184896	196010	215409	239795	239840.42	138.34
8		182056	183588	184913	195984	215462	239826		
9		182053	183559	184929	196013	215428	239850		
10		182057	183557	184914	195990	215453	239835		
11		182033	183533	184924	195935	215469	239886		
12		182016	183602	184935	195996	215460	239835		
13		181974	183533	184903	195981	215399	239900		
14		181997	183600	184921	195970	215459	239895		
15	**Average**	**182072.0769**	**183620.6923**	**184910.9231**	**196013.1538**	**215442.3077**	**239840.4167**		
16	**Std Dev**	**69.93146828**	**69.38105483**	**18.75038461**	**47.11660386**	**23.62690774**	**34.75039199**		
17				This calibration was for a 5 kg load cell.					
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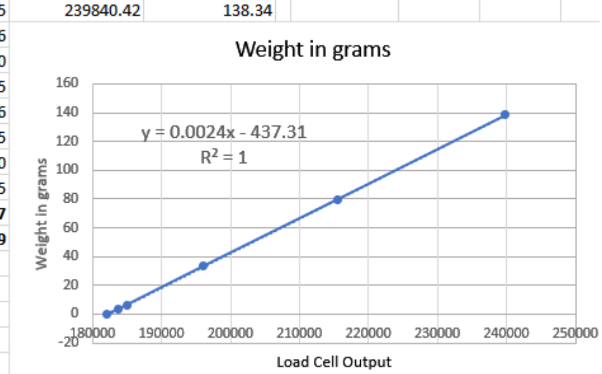
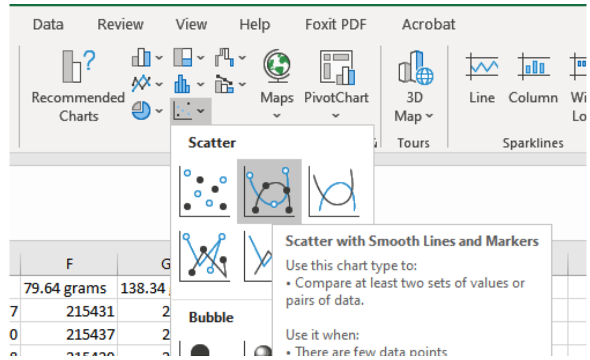


Your force sensor will output a reading every second into the Serial Monitor. Open an Excel file and create a spread sheet similar to the one shown above.

1. Hang a mass from force sensor (you can pick your own mass values for your calibration), stabilize it so that it isn't swinging, then wait for at least 10 additional force sensor readings (after stabilizing the mass) to accumulate on the Serial Monitor. **MAKE SURE YOU ARE NOT TOUCHING THE TABLE WHILE YOU MAKE MEASUREMENTS!!!**
2. Unplug the Nano from the computer to freeze the output on the Serial Monitor. Copy and paste at least 10 values for the output from the serial monitor into each column of your spreadsheet.
3. At the bottom of each column of output data calculate the average (=@AVERAGE(datarange)) and standard deviation (=STDEV(datarange)) for each column. If the standard deviation for any column of data is greater than 100 you should retake the data for that mass value. The standard deviation for my data ranged from 18.75 to 69.93.
4. Repeat steps 1 through 3 for at least 5 different masses.
5. Create two additional columns where you will place the average value of the sensor output next to the corresponding weight for each of the five masses (as shown in the example table above).

6. Insert a graph into Excel showing the linear relationship between the output of the load cell and the weight by highlighting the cells containing the data in Excel, clicking on 'Insert', clicking on the scatter chart icon, and then selecting the type of scatter plot you want. (I like connecting lines with dots, you can do it how you like.) **Make sure you put a copy of your graph and data tables in your lab report!**



Click on the graph that appears. In the top left of the graph there will be a small green plus sign. Click on that, then click on 'trendline', the arrow next to 'Trendline', then 'more options'. In the 'Format Trendline' dialog window that appears (shown on page 2), scroll all the way to the bottom to click the radio buttons that tell Excel to display the equation of the line on the chart and display the R-squared value. **(If you have trouble finding the menu options for the Trendline, use the search bar in Excel to search for 'Trendline').**

You now have an equation that tells you how the output of the force sensor relates to the mass placed in the cup. The x-value in your equation is the sensor output, and the y-value is the mass of the weights.

Normally the independent variable is on the x axis and the dependent variable is on the y axis. For the calibration graph shown they are reversed. This is so that I can easily determine an unknown weight by inputting the force cell output as the x value in my calibration equation!

Question 1) Describe in your own words the purpose of this experiment.

Question 2) Why do we need a calibration table for our force sensor?

Question 3) What is the 'Trendline' equation for your force sensor?

Question 4) What is the R-squared value for your data?

Question 5) Why did we use both the standard deviation and the R-squared value in analyzing our output data? (Hint: What is each analysis technique useful for?)

Question 6) What does the R-squared value for your modeling equation tell you about how well your data fits the trendline equation?

Question 7) What property is the independent variable, and what property is the dependent variable for your data?

Question 8) Again write down the equation of the line given by 'trendline', but instead of the x and y given use labels that indicate what property those variables represent. This will be the calibration equation for calculating mass (in grams) from the sensor output.

Question 9) What is the relationship between the mass in the cup and the force applied to the sensor?

We used mass to calibrate our sensor, but we want a force sensor, not a mass sensor. Create two more columns. In one put a copy of the average output values as before. Next to it place the force of gravity due to each mass by converting the mass into kilograms and multiplying by the acceleration due to gravity. Graph this data, and display the 'trendline' as before.

You now have a second calibration equation that enables you to calculate the force applied (in Newtons) based on sensor output. **Make sure you save both the Newton and the mass/gram calibration graphs for your force sensor, because you will need them for force sensor calibration for future labs.**

Question 10) Write down the new 'Trendline' calibration equation you just obtained that calculates the force from the sensor output.

But there is more! Notice we didn't measure the 'zero' value, meaning sensor output without any mass hanging from the sensor. In addition, the calibration equation you have now corresponds with when either a string or plastic cup is hanging from your sensor. That additional weight will affect the reading of your force sensor. You might not use a cup, or you might use a different weight string next time we use the force sensor, so we need a calibration equation that corresponds with no mass attached to the sensor. However the equation we just obtained can still help us. We now know the slope of the sensor's response (remember our 'Trendline' equation is of the form y = mx + b, or the slope-intercept equation of the line). We know the value of m, but what we don't know is the y-intercept value, the sensor output for zero force.

Find the y-intercept value for your sensor by removing the cup and recording and averaging the sensor output as before with nothing touching the end of the sensor. In my calibration equation for my sensor (yours will likely be different) the force (y-value) = 0.0024x – 437.31. I can now "zero" my sensor by recalculating the y-intercept value. With zero applied force, y = 0 = 0.0024 (times) (sensor output for zero force) – (y-intercept value), so the y-intercept value = (0.0024) times (sensor output for zero force).

Question 11) Re-write your newly 'zeroed' calibration equation for calculating the applied force, with the new y-intercept value, and insert it into your lab report. Is it different?

Question 12) Why is it important to 'zero' and calibrate your sensors? What type of error do we get when we fail to calibrate or zero our instruments?

Remember in future experiments that each time you use the force sensor you will need to 'zero' the calibration by adjusting the b value of your calibration equation such that the sensor output with no applied force reads as 0 Newtons in the read out. We will learn more about this next time.

Finishing Up

To complete your lab report, include a picture of your experimental setup, answers to all of the Questions, a snapshot of the Excel spreadsheet showing your data, and the two graphs showing sensor output as a function of force and of mass. Finish up with a Summary or Conclusion statement telling me what you learned. **Next week: We will be studying Friction and Hooke's Law. You will use your force sensor, so keep the circuit intact!**