Solidworks Models: The final models are included in a seperate folder with some easy to open images. The curves are visual approximations, however, most of the dimensions are direct from the manufacturer. The gasket wasn't modeled. The 3D printed part is the same as the final one Bobby sent. The 45 degree angle cut of the 3D printed part isn't necessary should the hole for the acrylic tube be moved slightly further away from the short edge of the box. Ideally, one should use the black filament version of the one Bobby was using to keep reflections to a minimum. ABS is not recommended due to warping and worse tolerancing.

Breakout Boards: The final breakout boards, though slightly more expensive, had pads that better fit the LEDs and IR sensors. They were also smaller and had only 6 pins instead of the 8 from the Adafruit.

Measurement Routine: The turbidity sensor collects a total of six measurements: Sensor 1 dark, Sensor 2 dark, LED 1 transmission, LED 1 side scatter, LED 2 transmission, and LED 2 side scatter. The dark measurements are collected with both LEDs off to determine the amount of ambient light present to use as a baseline for the other measurements. In all of our code and documentation LEDs and Sensors are numbered so that LED 1 faces Sensor 1, and LED 2 faces Sensor 2. Therefore, the LED 1 transmission measurement is collected by Sensor 1 and its side scatter is collected by Sensor 2, and so on.

Since the sensors can output a maximum frequency of almost 600 kHz, but the ATmega329P microcontroller can only count edges on a signal up to 75 kHz (when it is clocked at 8 MHz), the SN74HC393N binary counter sits between the sensors and the microcontroller to effectively divide the incoming frequencies by 8. While this configuration allows the full range of the light sensors to be utilized, it also introduces a potential error since the microcontroller is only counting every eighth rising edge. This error is inversely proportional to the number of edges that are counted, so low frequencies are most affected. To address this, the functions controlling the measurement process make adjustments to try to receive at least 100 edges for each sample, which ensures an error of less than one percent.

For each measurement, the microcontroller first samples the sensor output for one second. If it receives 100 or more edges (corresponding to frequencies of 800 Hz and higher), it accepts this value. If it receives less than 100 edges, it determines the amount of time needed to receive 100 edges, with some additional headroom, and samples again for this extended amount of time. For example, if the microcontroller receives 37 pulses in one second, it will repeat for three seconds on the second pass. If less than three pulses are received in the first pass, the second pass is collected for the maximum length of two minutes. This will allow the microcontroller to detect frequencies as low as 5.87 Hz with a 1% error maximum error. As will be discussed below, this will correspond to a maximum expected collection time of about 8.5 minutes. If it is preferred to collect data more often, the maximum sampling time can be reduced at the expense of some precision. For example, if the maximum sampling time is reduced to one minute or 30 seconds, the minimum frequency detected at 1% error or less would be increased to 11.73 Hz or 27.47 Hz, respectively, with maximum expected collections times of about 4.5 minutes and 2.5 minutes, respectively.

Since the two dark measurements are the only ones that tend to be below the 800 Hz threshold, and are therefore the primary drivers of the collection length, they are not collected as often as the other four measurements in a cycle. The routine begins by collecting each of the two dark measurements, followed by five passes of the other four (two transmission and two side scatters), and then finishes with another collection of the two dark measurements. This means that there are a total of four dark measurements, which can take up to two minutes each depending on the amount of ambient light present, plus twenty transmission and side scatter measurements, which are very rarely longer than one second each. This results in the roughly 8.5 minute maximum collection time mentioned above. The six sets of measurements are then averaged so that only six values are reported to the data logger. The data logger computes the conversion to NTU and logs this value along with the six that were reported by the sensor.

Calibration Process: To calibrate the sensor, we collected measurements using six samples of varying turbidity - deionized water (treated as 0.0004 NTU for fit lines), 0.4 NTU, 4 NTU, 40 NTU, 400 NTU, and 4000 NTU. In the accompanying “Calibration” folder, we have provided the raw data from these measurements. The resulting best fit lines from our calibration process are listed below. Due to some saturation/non-linear behavior in our data, certain sections of the curves were not used to generate the fit lines. Since the side-scatter from LED 1 is fit from 0.0004 NTU to 400 NTU, this frequency value is used by the conversion function to determine what range of turbidity we are dealing with and therefore which formulas should be calculated and averaged to determine the NTU value.

LED 1 Side Scatter for < 4 NTU
NTU = 10^((freq-4884.51015963563)/(217.615730769231))

LED 1 Side Scatter for 4-400 NTU
NTU = (freq-4723.4758127632)/(112.799965681699)

LED 1 Transmission for > 400 NTU
NTU = exp((freq-905841.461548272)/(-108472.245937816))

LED 2 Side Scatter for 4-400 NTU
NTU = (freq-6696.20138888889)/(79.3873036786787)

LED 2 Transmission > 400 NTU
NTU = exp((freq-601607.276911029)/(-71291.2384864573))

Before applying these formulas, the dark measurement taken from the corresponding sensor is subtracted from the transmission or side scatter measurement. For example, if an LED 2 side scatter measurement is 10,160.00 Hz, and the Sensor 1 dark measurement is 73.85 Hz, then the difference, 10,086.15 Hz, is used in the NTU conversion formula. We determined that this is an accurate method for controlling for ambient light by measuring each calibration sample five times with regular lighting conditions and five times with an additional light shining into the turbidity sensor's tube. We found that the dark and transmission/side scatter measurements from collected from a light sensor would increase by the same number of hertz, with the difference between them remaining constant.

Possible Extension - LEDs Supplied by Current Sources: As Bobby has brought up, an alternative to our design with fixed resistors setting the current through the LEDs would be to implement a digitally or PWM controlled current source to drive the LEDs instead. This would allow the light intensities to be adjusted after a sensor is constructed, which would not only help with tuning an individual sensor to maximize its accuracy but would also be able to address variations from unit to unit due to the manufacturing process once the sensors are being produced in larger quantities. We did not get a chance to look into this alternative extensively during the semester and have not identified any specific hardware to implement, but if we were going to continue working on this project, this would be the next direction that we would explore.

Possible Extension - LEDs of Different Wavelengths: Since our design essentially collects redundant data from the two identical light sources, a possible extension would be to experiment with changing the wavelength of one of the LEDs. While researching the light sources recommended for measuring turbidity, we found that that the 860 nm wavelength that we implemented works best for the most common particle size of interest. By using a different wavelength with one of the LEDs, the sensor could measure the turbidity due to two different particle sizes in the water. We were not able to find any other wavelength recommendations, so we do not know if it would be most useful to increase or decrease the wavelength or by how much, but we believe that this is another possible area where the sensor's capability could be improved with some additional research.