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MEMS 411: Piston Pong

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Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
MEMS 411, Fall 2023

Piston Pong

This report documents the design process of our "Piston Pong" device. Our device was designed to be an educational demonstration of pneumatics and energy transformations using work and fluids models. The concept is that a bike pump will pump air into a holding container. After enough pressure is built up inside, the air will be released from the holding tank to a pneumatic cylinder. The cylinder will be released, hitting and launching a ball into the air. Additionally, force and pressure sensors would allow the energy to be calculated to fully understand the energy transformation. Our priorities for this design were safety, educational value, the ability to launch a ball, and pressure and force measurements. Throughout the design process, our goals and design were altered to best meet these priorities. Our final prototype was able to safely launch a ball while measuring the energy introduced to the system via the bike pump. While we have a functioning program and pressure sensor, we were not able to measure the pressure within the holding tank due to concerns about maintaining the airtight system.

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1 Introduction

We plan to create an interactive and educational display that shows children the conversion of different types of energy and the effect that air pressure converted to kinetic energy has on the height of a ping-pong ball. First, a crank will be turned or a handle will be pushed for the user to pump air into a holding tank. A readout will display the pressure in the tank and once the user has gotten the pressure to their desired amount they will press a button to release a piston that will be powered by the pressurized air and will hit a ping pong ball launching it up within a clear plastic tube so the viewer can see it. There will be a measurement scale placed near or within the tube so that a more exact height can be determined. The piston system and air tank will be hidden in the base of the device and the base will also include educational materials explaining the mechanisms contained within the system and the science behind them.

This device will be approximately three feet by five feet in size, cost around $400, and be designed as an educational and interactive museum exhibit for children ages 8-12. Using pressure measurements collected from a gauge connected to the air tank and information about the size and setup of the piston, we will be able to calculate the expected velocity of the platform launching the ball. Using this information, the distance that the platform pushes the ball, and the assumption that the tube is large enough to not impact the speed of the ball, we will be able to approximate a height that the ball should reach. This can be used as part of the information shared with the user as a demonstration of idealized calculations compared to the real-life experience of using the device.

2 Problem Understanding

2.1 Existing Devices

The following section contains devices with similar components or functions to our proposed design.

2.1.1 Existing Device #1: T-Shirt Launcher

Figure 1: Micro T-Shirt Launcher (Source: Amazon)

Link: https://www.amazon.com/Orginal-T-shirt-Launcher-Micro-Black/dp/B077KB8PDL/ref=sr_1_6?keywords=tshirt+launcher&qid=1694802116&sr=8-6
Description: The T-shirt launcher is a device commonly used at sporting functions to release T-shirts and other prizes into crowds. This device uses pneumatically generated forces to launch the prizes, similar to how our device will demonstrate physics by launching a ball. One important difference is that the T-shirt launcher utilizes carbon dioxide gas, while our pneumatic device will simply use air.

2.1.2 Existing Device #2: Lego Pneumatics Toy

Figure 2: ”Material Handler” Building Set (Source: Lego)

Link: https://www.lego.com/en-us/product/material-handler-42144
Description: The Rover FluorCam is a customizable fluorescence imaging system for physiological screening in greenhouses and large-scale fields. It is an automated system utilizing wheels that provide stability and maneuverability among the plants.

2.1.3 Existing Device #3: Airways Museum Exhibit

Figure 3: Kids playing with pneumatic airways at the Children's Museum of Phoenix (Source: Mindsplash.net)

Link: https://www.mindsplash.net/amazing-airways
Description: The Rover FluorCam is a customizable fluorescence imaging system for physiological screening in greenhouses and large-scale fields. It is an automated system utilizing wheels that provide stability and maneuverability among the plants.

2.2 Patents

2.2.1 Pneumatic launcher (US5660160A)

While this is an older patent, it applies well to the design we are taking on. It closely matches with the first existing device cited, the T-shirt cannon. The patent describes a very similar device that uses pneumatics to launch T-shirts and prizes into crowds at sporting events. While this particular patent has expired, it provides important insight into what areas of our design may be intellectually claimed.

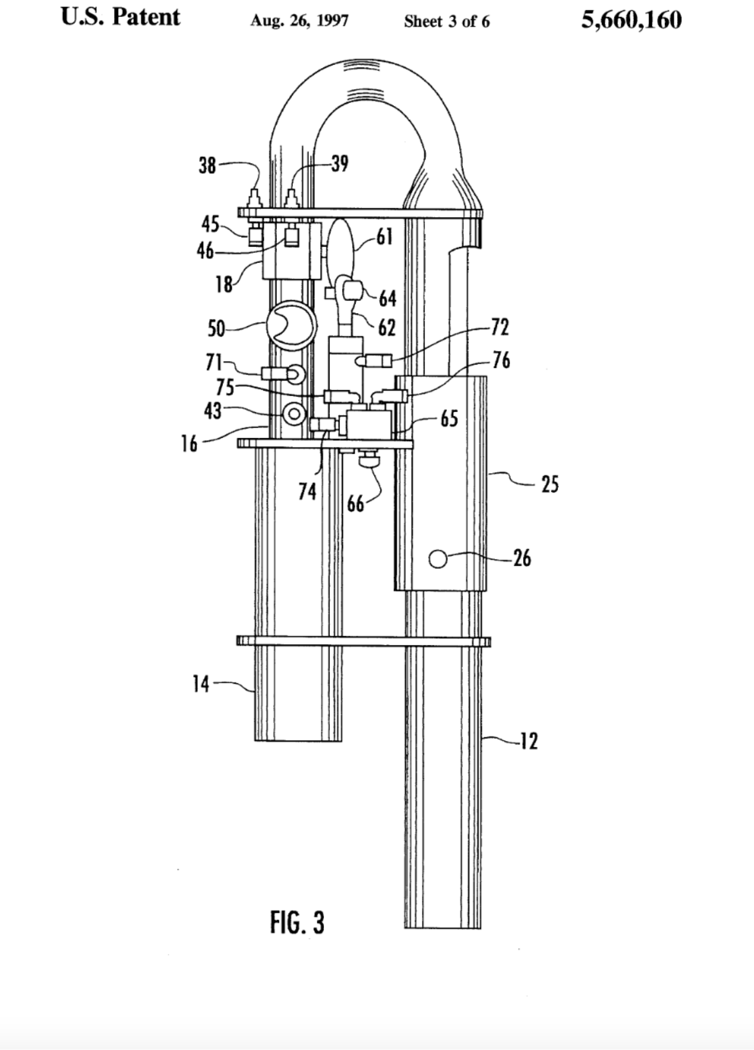


Figure 4: Structural diagram for pneumatic launcher patent

2.2.2 Bicycle pump (US20080038119A1)

This bicycle pump includes a pump, nozzle, and pressure gauge which is mounted on the body portion of the pump. There are also various sources of illumination attached to the pump allowing it to be operated in the dark and allowing the pressure gauge to be visible in such an application. The design also includes locations for the feet to be placed, stabilizing the pump with the user's body weight. This type of pump could be employed in our design as the mechanism for filling the compressed air reservoir and provide a method for measuring the pressure within the tank.

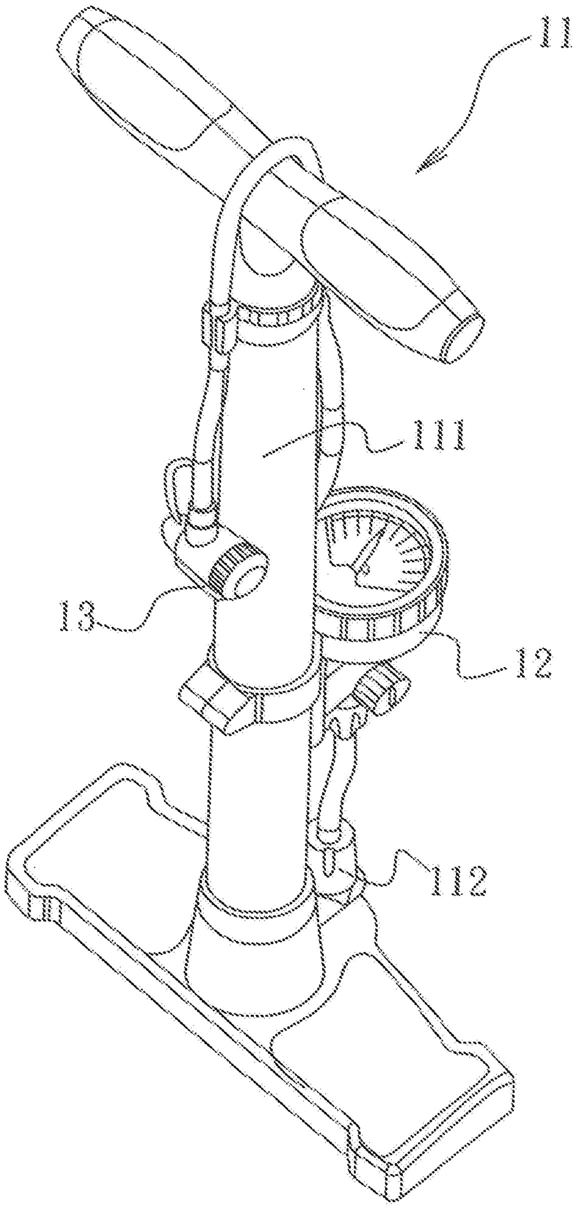


Figure 5: Patent Image for bicycle pump

2.3 Codes & Standards

2.3.1 Pneumatic fluid power (ISO 4414)

This international standard specifies general rules and safety requirements for pneumatic power systems. We are planning on the piston pong display being powered by a piston so this standard would be very applicable. It talks about principles that should be applied to avoid hazards. It talks about construction and modification which would be useful while designing our display.

2.3.2 Children's product safety standard (ASTM F963-17)

This standard addresses toy safety testing. Although our display is not technically a toy, a lot of these rules can be applied since it is made for children. It is specifically meant for children below 14 years of age which is our target audience. Sections 4.21, 8.13, and 8.14 specifically talk about projectile toys which is very applicable to the piston pong display.

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Jolley 110, Washington University in St. Louis, Danforth Campus
Date: September 8th, 2023
Setting: We talked to the customer about some ideas we had and made drawings on the board to help him visualize our ideas. The conversation took around an hour..

Interview Notes:
What size should the device be?

- It has to be easy to move from the basement up to wherever you are displaying it so cannot be too large or heavy. Five feet tall and 3 feet wide is around the biggest it should be.

What age range should we be targeting?

- It can be any range you want it to be. If they are younger then the educational side has to be simplified. If you target 8-13 year olds you can go into more detail on what is happening inside the piston pong device.

2.4.2 Interpreted User Needs

This section lists the most important user needs and their importance.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The piston pong display is safe for kids	5
2	The display is educational	4
3	The display is easy to transport	5
4	The display is easy to setup	3
5	The display is aesthetically pleasing	3
6	The display can be repeatedly used	5
7	The display demonstrates pneumatics in an easy-to-understand way.	3

2.5 Design Metrics

This section associates user needs with quantifiable metrics. These target specifications will be compared with the product to ensure all user needs are met acceptably.

Table 2: Target Specifications

Metric Number	**Associated Needs**	**Metric**	**Units**	**Acceptable**	**Ideal**
1	1	Safety	FoS	2	1.5
2	2,7	Rating of ”educational” by parents and teachers	avg. score	8/10	9/10
3	3	Total Weight	lb	15	10
4	3	Total Volume	in^3	< 40	< 20
5	4	Rating of ease of setup by museum staff	avg.rating	3/5	4/5
6	5	Rating of Aesthetic status by audience focus group	avg. score	3/5	4/5
7	6	Display can be repeatedly used	Y/N	Y	Y

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

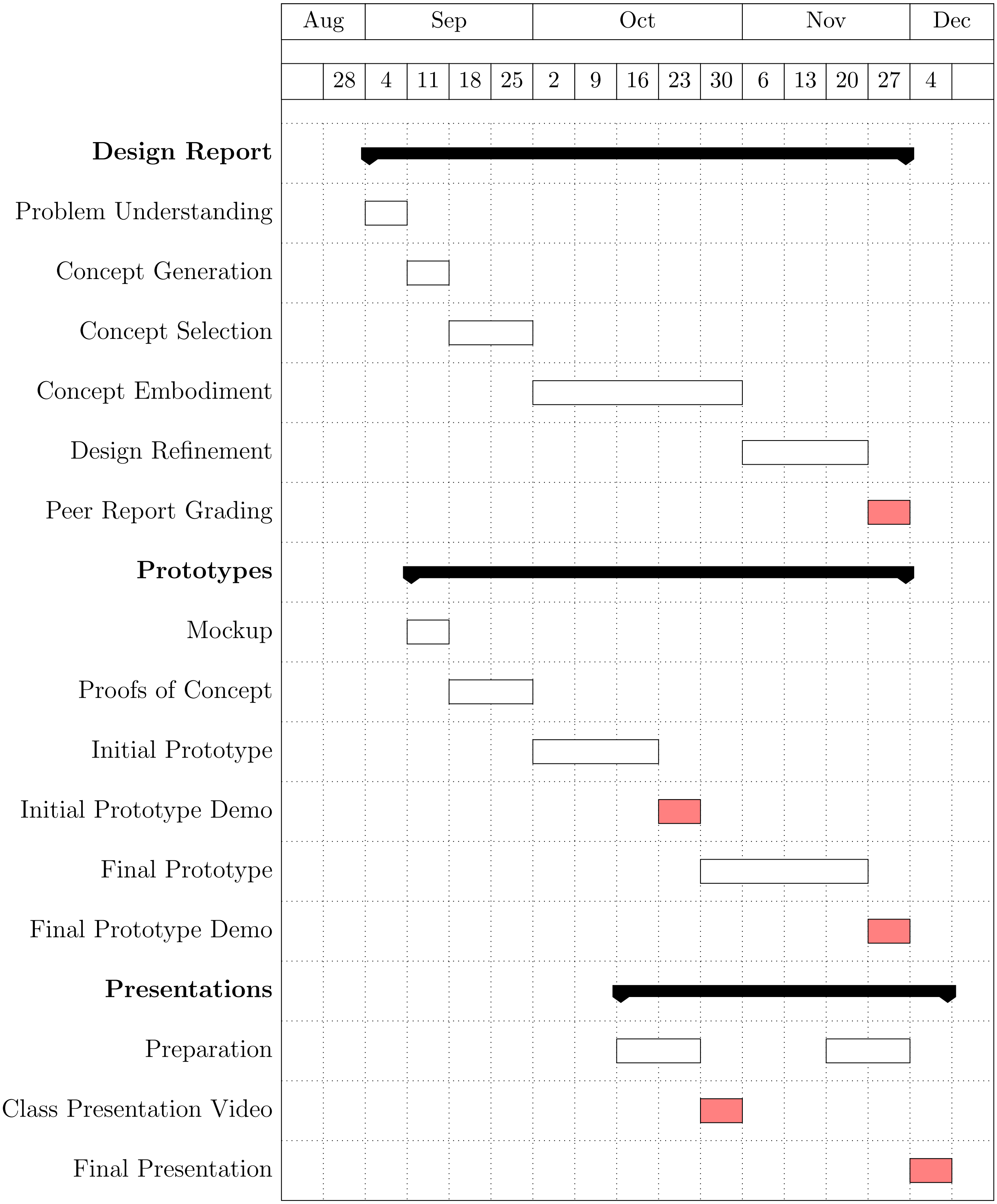


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

We built a prototype of the Piston Pong display using card stock to get a general idea of the shape and components. This can be seen in the images below.

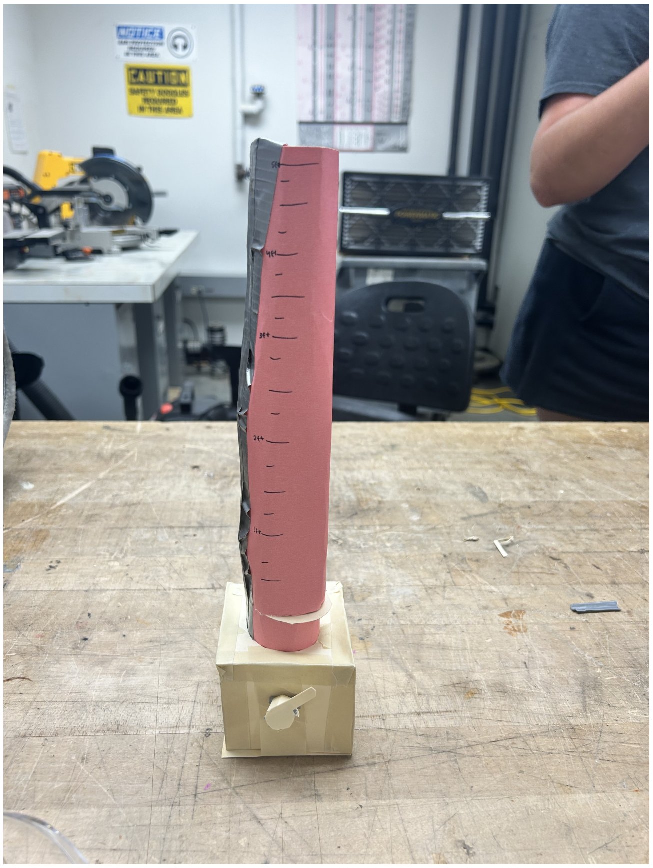


Figure 7: Side View of Prototype

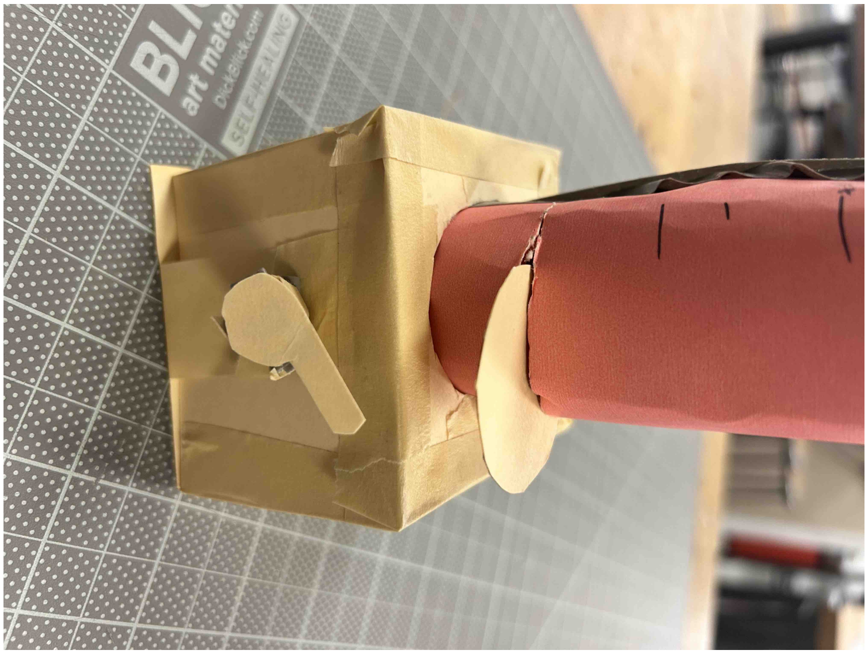


Figure 8: Detail Image of Prototype Base

Figure 9: Components of Prototype

We have a cylindrical tube made out of red card stock with a scale on the side so that the height of the ball inside can be determined. In our final design, we plan for this tube to be clear. There is a paper disk inserted into the tube that is standing for our mechanism to control the pneumatics and release the built-up air pressure to power a piston. The pump and holding tank will be stored inside the box under the tube which represents some form of display case. There is a Styrofoam ball that goes inside the tube standing in for a ball that will be used in future designs. This will ideally be scaled up to around 5 feet high in our final iteration.

3.2 Functional Decomposition

Figure 10 below shows the function tree for Piston Pong where the products are broken down into sub-functions and possible methods of achieving these functions. Our product has many sub-functions which may be components of the ones listed here or expanded upon in the future.

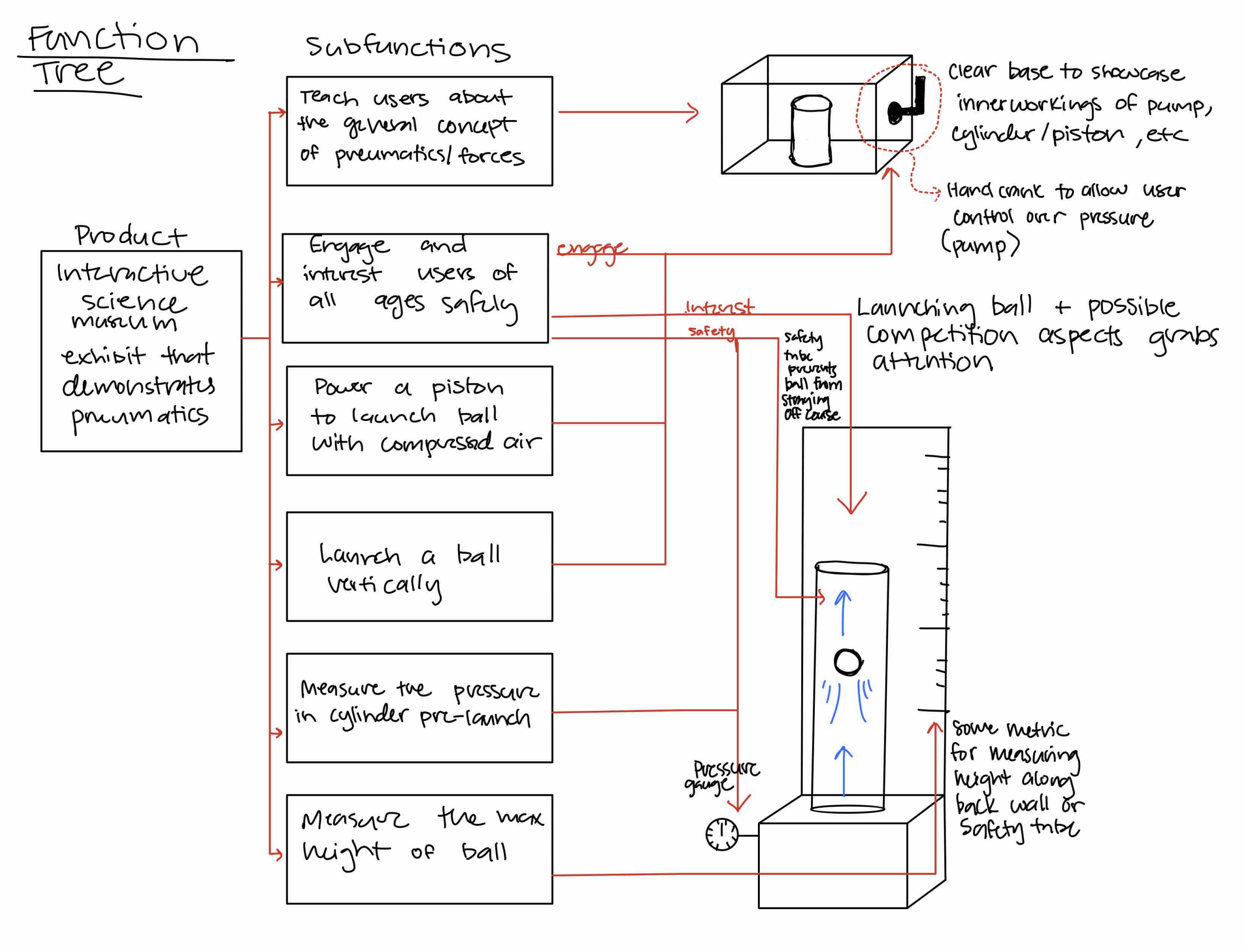


Figure 10: Function tree for Piston Pong, hand-drawn and scanned

3.3 Morphological Chart

Figure 11 below shows a morphology chart for our product. In this chart, each sub-function listed above is paired with several possible methods of achieving the sub-function. Of these possible solutions, concept ideas can be put together.

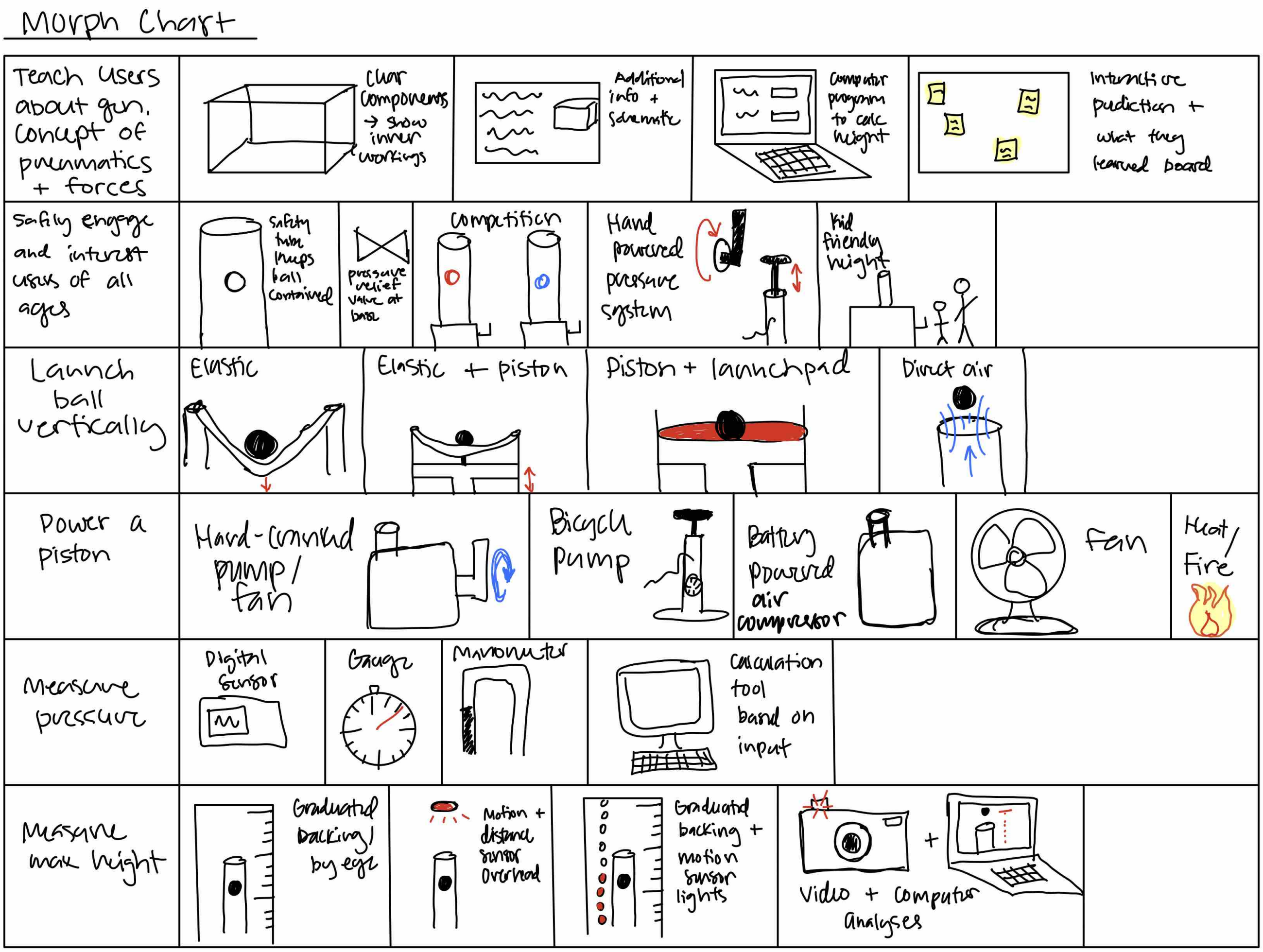


Figure 11: Morphological Chart for Piston Pong

3.4 Alternative Design Concepts

3.4.1 Concept #1: Piston and Lights

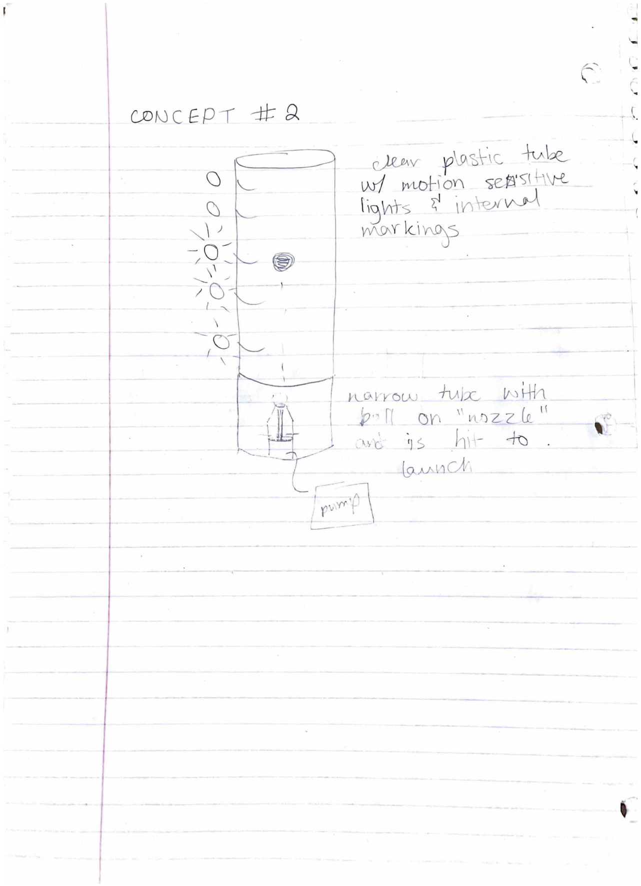


Figure 12: Sketches of Piston and Lights

Description: A platform held in place with pins is released and pressurized air from a pump pushes it up with a pin hitting the ball sitting on top of it. The ball is shot into a clear open-ended tube where a measurement scale in the side of the tube and motion-activated lights show the user how high the ball has gone.

3.4.2 Concept #2: Background Scale

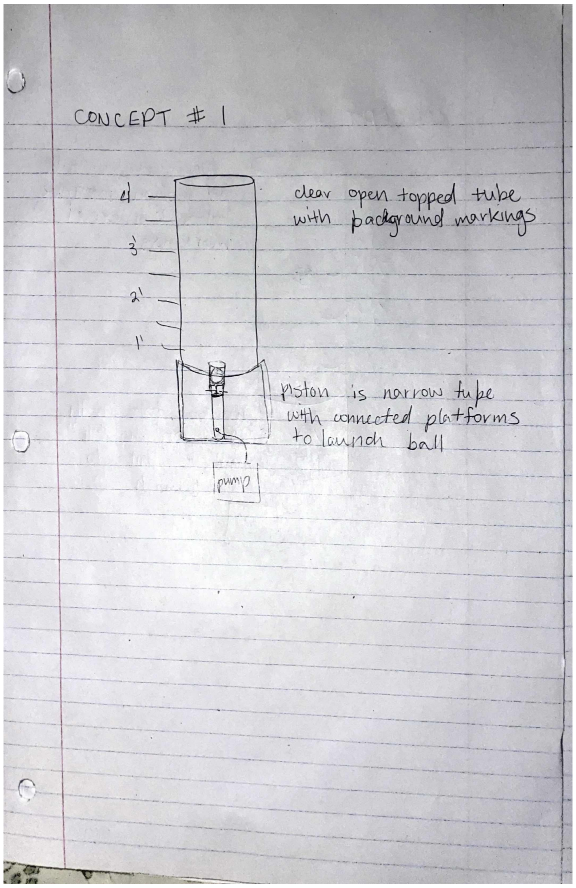


Figure 13: Sketches of Background Scale

Description: This concept utilizes two connected platforms with a ball sitting on top of the highest one. When pins are released, pressurized air shoots the two platforms up pushing the ball into an open-ended clear tube where there is a measurement scale on a backdrop so the viewer can see how high the ball has gone.

3.4.3 Concept #3: Engaging Launcher

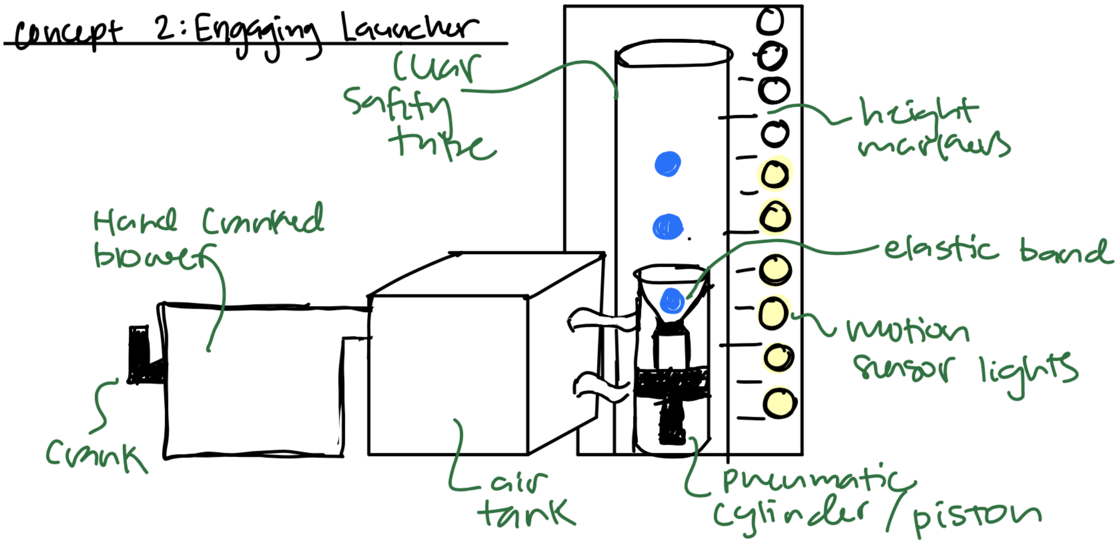


Figure 14: Sketches of Engaging Launcher concept

Description: This concept starts with a manually operated blower. As the crank turns, air is pressurized and stored in the air tank. The pneumatic cylinder pulls from this tank to power the piston. The tank includes a relief valve for the safety of the user and device. The piston pushes up, releasing the elastic band from tension and launching the ball. The ball is contained within a clear, plastic tube for safety. Motion sensor lights track the ball along a wall labeled with the height.

3.4.4 Concept #4: Bike Pump Powered

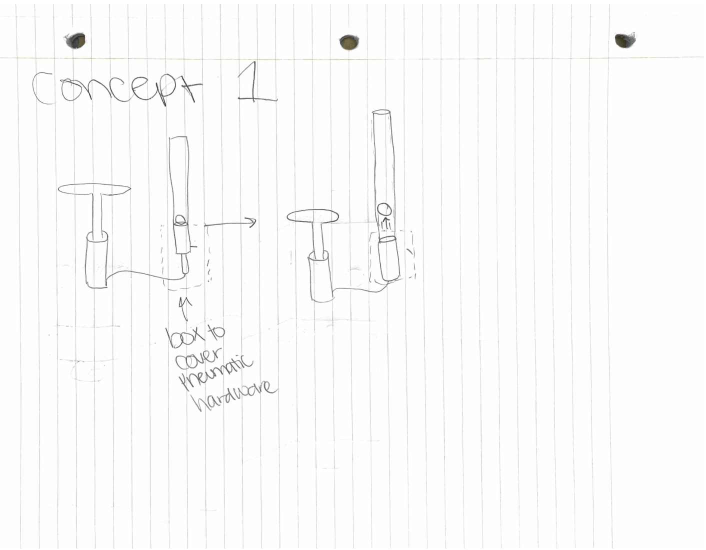


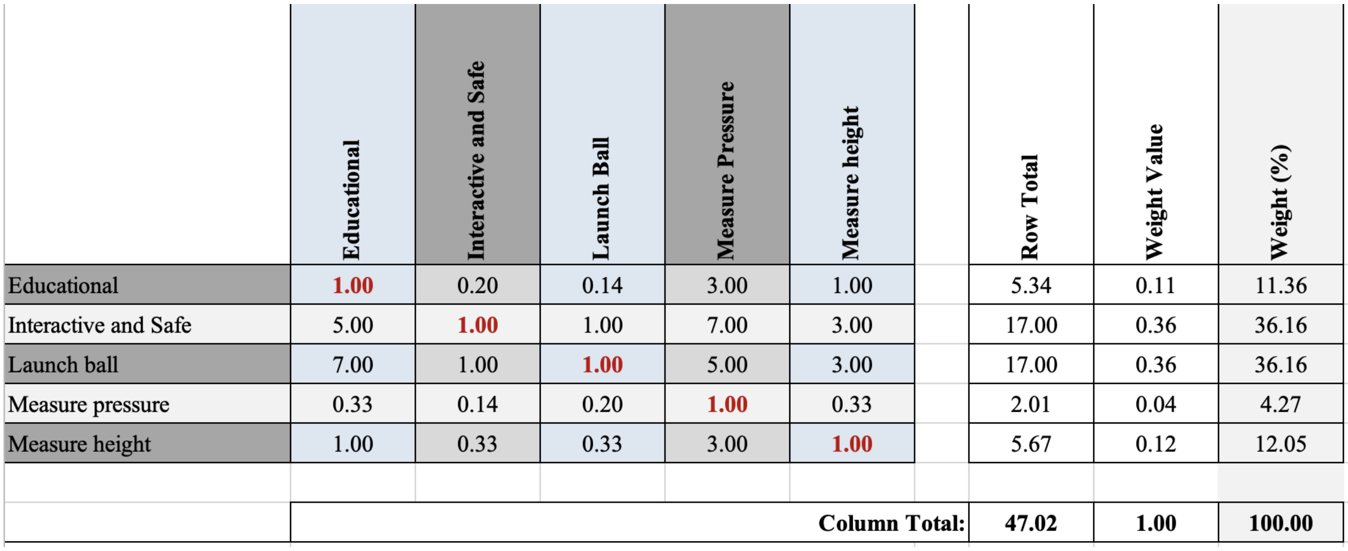
Figure 15: Sketches of a bike pump-powered concept

Description: This concept utilizes a bike pump to power our device. The pump is used until a desired pressure is reached then released to shoot a ball into a clear open-ended tube. The pneumatic hardware is contained for safety and aesthetics in the base of the device.

4 Concept Selection

4.1 Selection Criteria

The selection criteria are weighted based on comparing importance of the criteria.

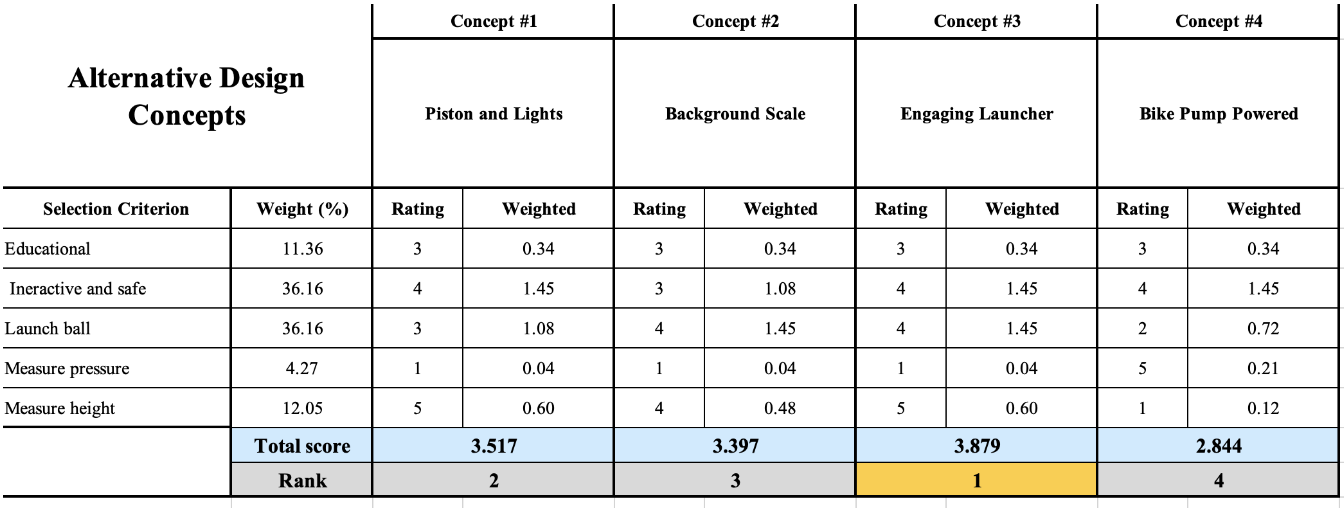


	Educational	Interactive and Safe	Launch Ball	Measure Pressure	Measure height	Row Total	Weight Value	Weight (%)
Educational	1.00	0.20	0.14	3.00	1.00	5.34	0.11	11.36
Interactive and Safe	5.00	1.00	1.00	7.00	3.00	17.00	0.36	36.16
Launch ball	7.00	1.00	1.00	5.00	3.00	17.00	0.36	36.16
Measure pressure	0.33	0.14	0.20	1.00	0.33	2.01	0.04	4.27
Measure height	1.00	0.33	0.33	3.00	1.00	5.67	0.12	12.05
					Column Total:	**47.02**	**1.00**	**100.00**

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Using the weights from the Analytic Hierarchy Process in Fig. 16, the following evaluation of the four concept ideas was generated.



Alternative Design Concepts		**Concept #1**		**Concept #2**		**Concept #3**		**Concept #4**	
		Piston and Lights		**Background Scale**		**Engaging Launcher**		**Bike Pump Powered**	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Educational	11.36	3	0.34	3	0.34	3	0.34	3	0.34
Ineractive and safe	36.16	4	1.45	3	1.08	4	1.45	4	1.45
Launch ball	36.16	3	1.08	4	1.45	4	1.45	2	0.72
Measure pressure	4.27	1	0.04	1	0.04	1	0.04	5	0.21
Measure height	12.05	5	0.60	4	0.48	5	0.60	1	0.12
	Total score	**3.517**		**3.397**		**3.879**		**2.844**	
	Rank	**2**		**3**		**1**		**4**	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

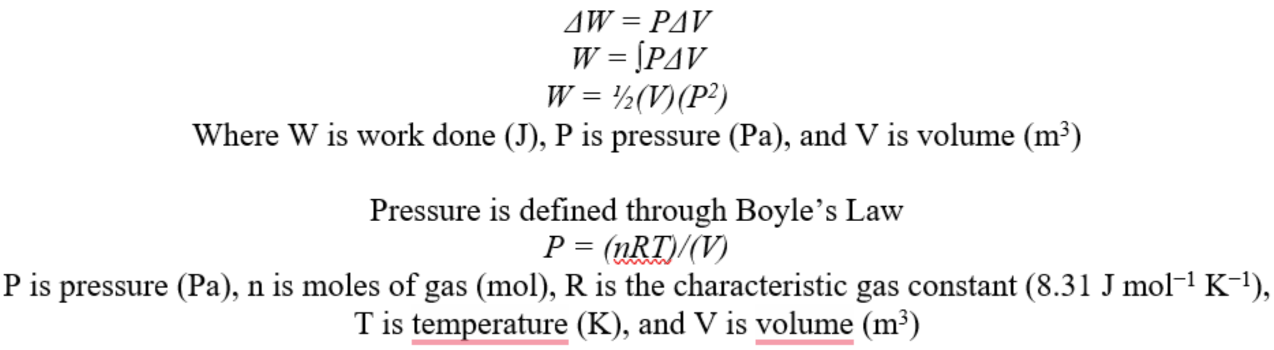
4.3 Evaluation Results

The Engaging Launcher was the top-rated concept. It was given a 3 for its educational value because of the visual, hands-on demonstration of a daunting physical concept. It was given a 4 for being interactive and safe due to features such as the height lights, safety tube, and pressure gauge. It was also given a 4 for its ability to launch the ball since this design utilizes an elastic band to assist a cylinder/piston system in launching the ball. It was only given a 1 for measuring pressure since there is no system for this function currently indicated in the design. Finally, it received a 5 rating for measuring height since it includes both the motion sensor lights and a scale to measure the maximum height reached by the ball.

Since all of the devices were given the same ranking for educational value, this criteria did not have much say in the concept selection despite the 11.36% weight given to this criteria. What really set this concept apart was the high ratings on the ability to launch the ball and for being interactive and safe since the Analytic Hierarchy Process gave these two criteria the most weight.

4.4 Engineering Models/Relationships

Conservation of Energy: The law of conservation of energy states that the total energy of an isolated system remains constant. This system is isolated as all the components that do work and experience shifts in energy from one to another are considered to be within the same system. In relating the conservation of energy to this system, the work done to compress the air into the tank is equal to the potential energy of the air inside the tank due to the law of conservation of energy. The work done by the user with a bicycle pump can be determined through equations seen in Fig. 18.



$$\Delta W = P\Delta V$$

$$W = \int P\Delta V$$

$$W = \tfrac{1}{2}(V)(P^2)$$

Where W is work done (J), P is pressure (Pa), and V is volume (m^3)

Pressure is defined through Boyle's Law

$$P = (nRT)/(V)$$

P is pressure (Pa), n is moles of gas (mol), R is the characteristic gas constant (8.31 J mol^{-1} K^{-1}), T is temperature (K), and V is volume (m^3)

Figure 18: Equations used in determining potential energy of the pressurized air.

In this case, we will have sensors to determine the pressure in the pneumatic chamber, meaning we will be able to calculate the initial energy that contributes to the energy of the ball launch. Seeing as the point of the demonstration is to see how high the ball goes, with the information given we will be able to calculate an estimate of how high the ball will go using the kinetic energy equation shown in Eq. 1. and the potential energy equation shown in Eq 2.

$$KE = \frac{1}{2}mv^2 \tag{1}$$

$$PE = mgh \tag{2}$$

By equating these different energy equations at different points in the system's operation, the height of the ball can estimated and measured to compare the values.

We will also utilize Bernoulli's Equation as a model for our design. Bernoulli's equation is given below as

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{3}$$

P_1 is the known pressure in the tank, ρ is the known density of air, v_1 is the known velocity of air exiting the tank, P_2 is the known pressure in the tube, h_1 and h_2 are the known heights at the measurements of interest in the tank and tube respectively, and v_2 is the unknown velocity through the tube.

We will have a holding tank for the pressurized air in our design and will need to know what the velocity of air is in the tube that will be holding the ball. As mentioned above, we need to determine the velocity of the ball as it exits the tube to estimate how high the ball will go. This is determined by the speed at which the piston launches it and is in turn determined by how fast air is passing through the tube. We will be able to place pressure sensors on both the holding tank and the tube with the ball allowing for that measurement. However while size constraints allow us to measure the velocity exiting the tank, they will prevent us from measuring the velocity within the tube. Using the known heights of each measurement point in each device and the data collected from them, we can calculate v_2 which is the velocity in the tube.

The last model used is Newton's Second Law. This can be represented by the equation below

$$f = m * a \tag{4}$$

Where f is the force applied (on the ball in this case), a is the acceleration of the ball, and m is the mass. We want the ball to easily pop up without having to apply a lot of force because the display is meant for kids. This means we want it to have a high acceleration. Rearranging the equation we can see that $a = \frac{f}{m}$. This shows that making the mass of the ball smaller would mean less force would need to be applied. On the other hand, we do not want the ball to be too easy to accelerate because then it would go too high up. We can estimate the force our piston is going to apply when a child is using the system and pick a ball with a mass that would be appropriate.

5 Concept Embodiment

5.1 Initial Embodiment

The basic components of our mechanical structure were modeled in SOLIDWORKS. Three drawings of the model are included in Figures 19, 20, and 21 below. The electronic details are not included as there was no benefit to modeling these in CAD. The housing is also not included since its purpose is to conceal the inner workings.

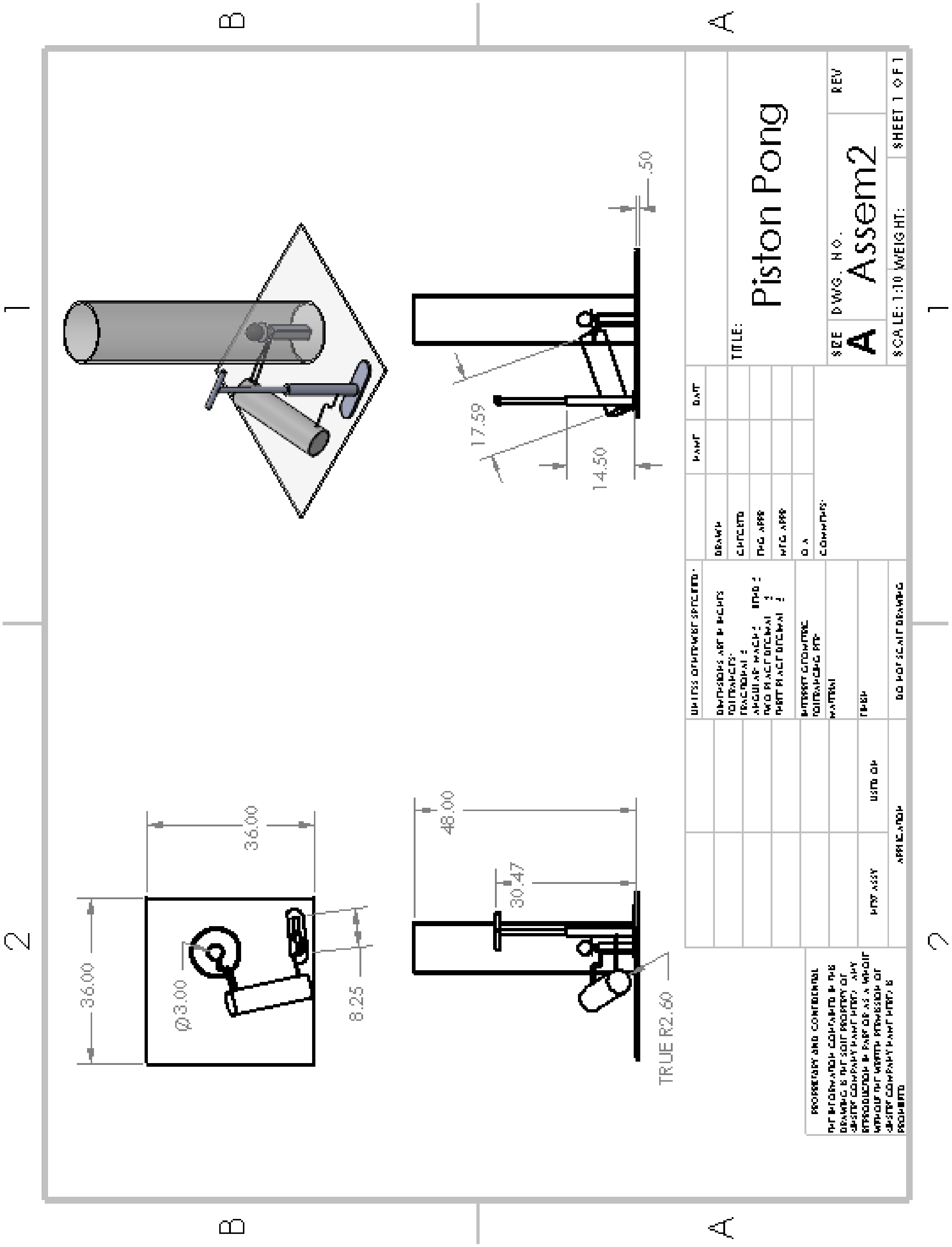


Figure 19: Assembled projected views with overall dimensions

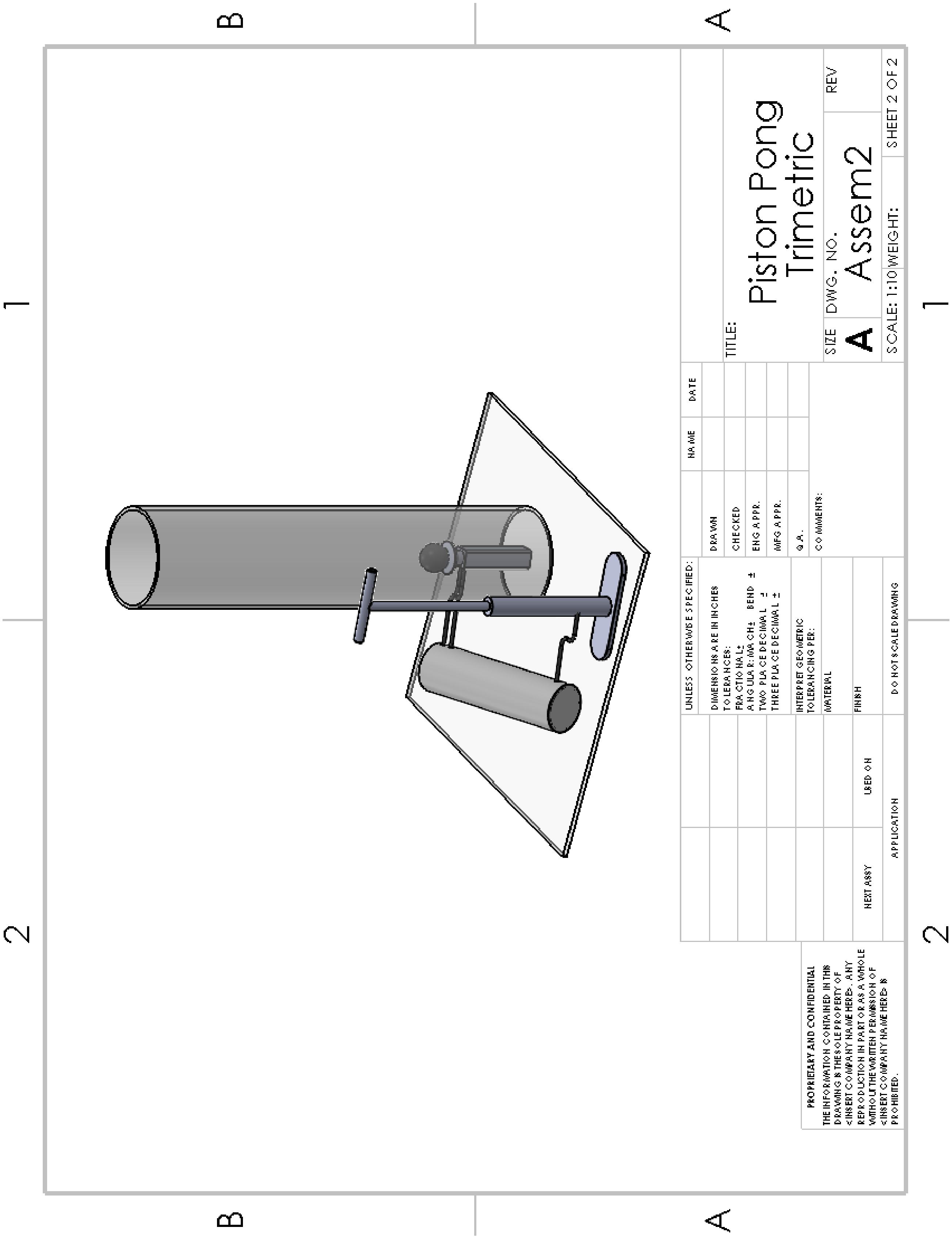
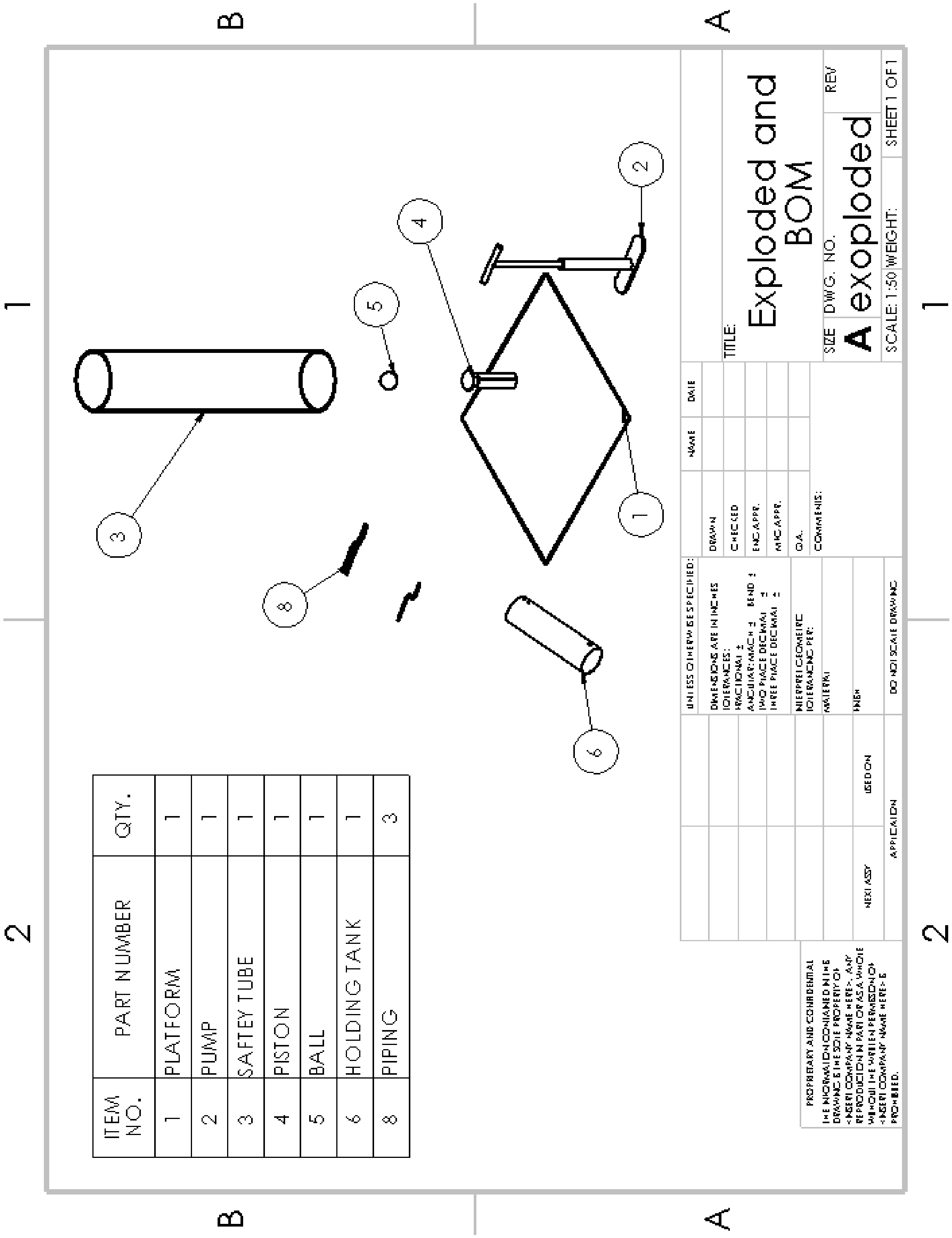


Figure 20: Assembled alternate view



ITEM NO.	PART NUMBER	QTY.
1	PLATFORM	1
2	PUMP	1
3	SAFTEY TUBE	1
4	PISTON	1
5	BALL	1
6	HOLDING TANK	1
8	PIPING	3

Figure 21: Exploded view with callout to BOM

5.2 Prototype Performance Goals

The goals we set for our prototype were to measure the amount of work done when the bike pump is pressed down, measure the amount of work done in the increase of pressure in the storage cylinder, and to trigger the piston to shoot the ball after a specified amount of time.

5.3 Proofs-of-Concept

Creating our prototype helped us figure out which of our goals were too ambitious and needed editing. We planned for many different measurements and calculations to be done using the sensors and Polulu board we have but as we began to develop the prototype realized that some goals were harder than expected. We also realized that we did not have the equipment we needed. To power our solenoid valve, we needed a 9V battery but only had 5V provided by the Polulu board through the laptop so we had to purchase more materials to work towards that goal. We realized the design we had talked about would not allow for work measurements because it is an isochoric system in which by definition no work is done if the pressure is increased. Overall, making a prototype helped us think more critically about what is and isn't possible for us to do in the given time frame.

5.4 Design Changes

The selected concept had multiple significant differences from the initial prototype. Most notably, the method of building up air pressure is different from the original concept. In the initial prototype, air will be compressed using a bike pump rather than a hand crank as seen in the concept. This method is easier to implement in the prototype. In addition to this difference, a different holding tank will be incorporated into the design, instead made out of PVC as it is once again easier to implement in the prototype. Additionally, some components will be added to the prototype that are not shown in the concept sketch, such as housing that will enclose the entire system except for the bike pump handle and the clear safety tube where the ball will be launched. In addition to a housing, release buttons, pressure sensors, force sensors, and ultrasonic sensors were added to the prototype that was not originally specified in the concept sketch.

6 Design Refinement

6.1 Model-Based Design Decisions

One model-based design decision made was the choice of ball we were going to launch. Given the scale of our project, our most feasible options included a tennis ball, wiffle ball, golf ball, ping pong ball, baseball, and pool ball. The relationship between the ball's acceleration and weight was determined using Newton's 2nd Law of Motion (Eq. 4). For the purposes of this design, air friction is neglected. This law was used only to develop a relative relationship to use in choosing an appropriate ball for the design, as seen in Figure 22.

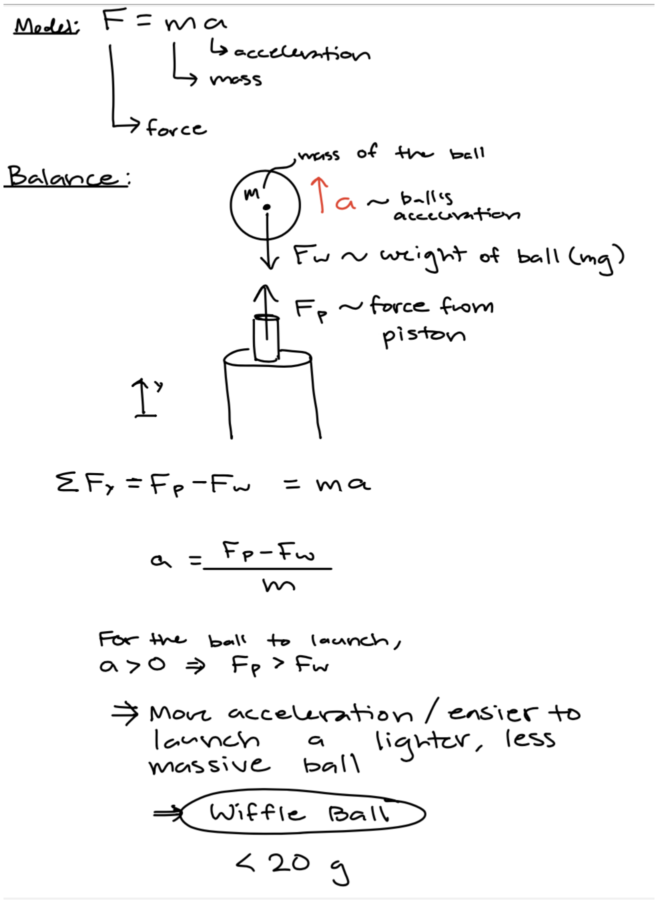


Figure 22: Free body diagram and mathematic analysis of the piston-ball system.

Given the demonstrated relationship, we opted for a lighter ball to decrease the force necessary to launch the ball. The wiffle ball and ping pong ball were the lightest of the options. We opted for the wiffle ball because it is sturdier and easier to work with the larger diameter.

From here, we could make design decisions about the piston size for the device. One model for using pistons within larger systems is described in Equation 5 below,

$$F = P * A \tag{5}$$

where F is the force exerted by the piston, P is the pressure input to the piston, and a is the bore area of the piston ([1]). The bore area is the circular area of the inner cylinder's cross-section, calculated with the inner diameter of the cylinder. The pressure range can be approximated since a bike pump is being used and these pumps are generally used for a small range of tire pressures ([2]). Given that we need more than 20 grams of force to accelerate the ball (see Fig. 22) and we can expect our bike pump system to exert at least 50 psi, we calculated an appropriate bore size for the piston in Figure 23.

$$F_p = P\overset{\text{bore area}}{A} > 20\ \text{g} \approx 0.04409\ \text{lbs}$$

$$\overset{\text{pressure}}{P} \geq 50\ \text{psi} \qquad (\text{increasing pressure} \Rightarrow \text{minimum area decreases})$$

$$A > \frac{F_P}{P} = \frac{0.04409\ \cancel{\text{lbs}}}{50\ \cancel{\text{lbs}}/\text{in}^2} = 0.0008818\ \text{in}^2$$

$$A = \frac{\pi D^2}{4} \qquad (D \sim \text{bore diameter})$$

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(0.0008818\ \text{in}^2)}{\pi}} = 0.0335\ \text{in}$$

↳ minimum bore diameter

Available bore sizes

10 mm $\simeq$ 0.39"

16 mm $\approx$ 0.63"

25 mm $\approx$ 0.98"

32 mm $\approx$ 1.25"

$$\left.\begin{aligned} F_p &\propto a \\ F_p &\propto A \end{aligned}\right\} a \propto A$$

↳ greater bore ⇒ greater acceleration

Figure 23: Choosing a cylinder/piston size based on a model of piston force.

It turned out that most bore sizes were larger than the minimum for accelerating the ball. Given that the acceleration and area are both proportional to the force of the piston, the two are also proportional to each other. Therefore, a larger bore diameter should produce a larger acceleration, so we opted for the larger, 1.25" bore size.

6.2 Design for Saftey

Every device or system can fail in some way, and failure can result in damage to people and/or property. The following section identifies potential hazards associated with the device and prioritizes the risks relative to each other.

6.2.1 Risk #1: Ball Escapes from Tube

Description: This risk occurs if the ball launched in the device escapes from the housing. This might occur if the user builds up more air pressure than accounted for.

Severity: The severity of this risk is marginal. While this failure includes flying projectiles, the projectile will most likely not be moving quickly enough to cause severe harm to anyone.

Probability: The probability of this failure occurring is occasional. It is dependent on how much work the user does on the system, though the length of the tube used should be sufficient in most situations.

Mitigating Steps: To prevent this risk from happening, a top can be added to the tube so that even in extreme situations the ball cannot escape.

6.2.2 Risk #2: Pressure Device Failure

Description: This failure occurs if the apparatus holding the pressurized air fails. while this could include air leaking from the tank, the failure mode focused on here is an explosion of the pressure tank.

Severity: This failure is of catastrophic severity. The failure could cause injury from both the failed device itself and potential shrapnel it accelerates and expels.

Probability: The probability of this risk happening is seldom. The more likely mode of failure is an air leakage, not an explosion of the device. The user would have to build up a large amount of air in the pipe for this to occur.

Mitigating Steps: To decrease the likelihood of this risk, the pipe will be completely contained in a flexible enclosure of some kind. This will hopefully negate the risk and also minimize damage if it does occur.

6.2.3 Risk #3: Bike Pump Screw Failure

Description: This failure can occur if the fasteners keeping the bike pump secured to the base fail in some way, most likely ductile failure. This might be more likely in extreme temperatures.

Severity: This risk is of marginal severity. While the force exerted on the bike pump may cause it to launch up and away from the base, the housing will limit it from going too far.

Probability: The probability of this risk is unlikely. The fasteners used are rated for much higher stresses than the ones the device will be subjected to.

Mitigating Steps: More fasteners can be added to decrease the likelihood of this risk even more.

6.2.4 Risk #4: Housing Fastener Failure

Description: This failure can occur if the housing, made of a large storage tub, comes apart during use of the device. This can expose electrical and choking hazards.

Severity: This failure is of critical severity. A failure of the housing fasteners is dangerous and potentially harmful as there is nothing to limit its range of motion, and a lack of cover on the interior workings presents risks related to them including electrical and choking hazards.

Probability: The probability of this risk occurring is seldom, meaning it is possible but not likely. The current design of the housing should be sufficient for the use of the device.

Mitigating Steps: To mitigate the risks associated with this failure, failsafes will be built into the latching system of the device. This will make the fastening mechanism stronger by building in contingency aspects into the design.

6.2.5 Risk #5: Bike Pump Failure

Description: This failure is defined by a malfunctioning bike pump. This most likely means that air will escape out of the bike pump and not travel throughout the rest of the system.

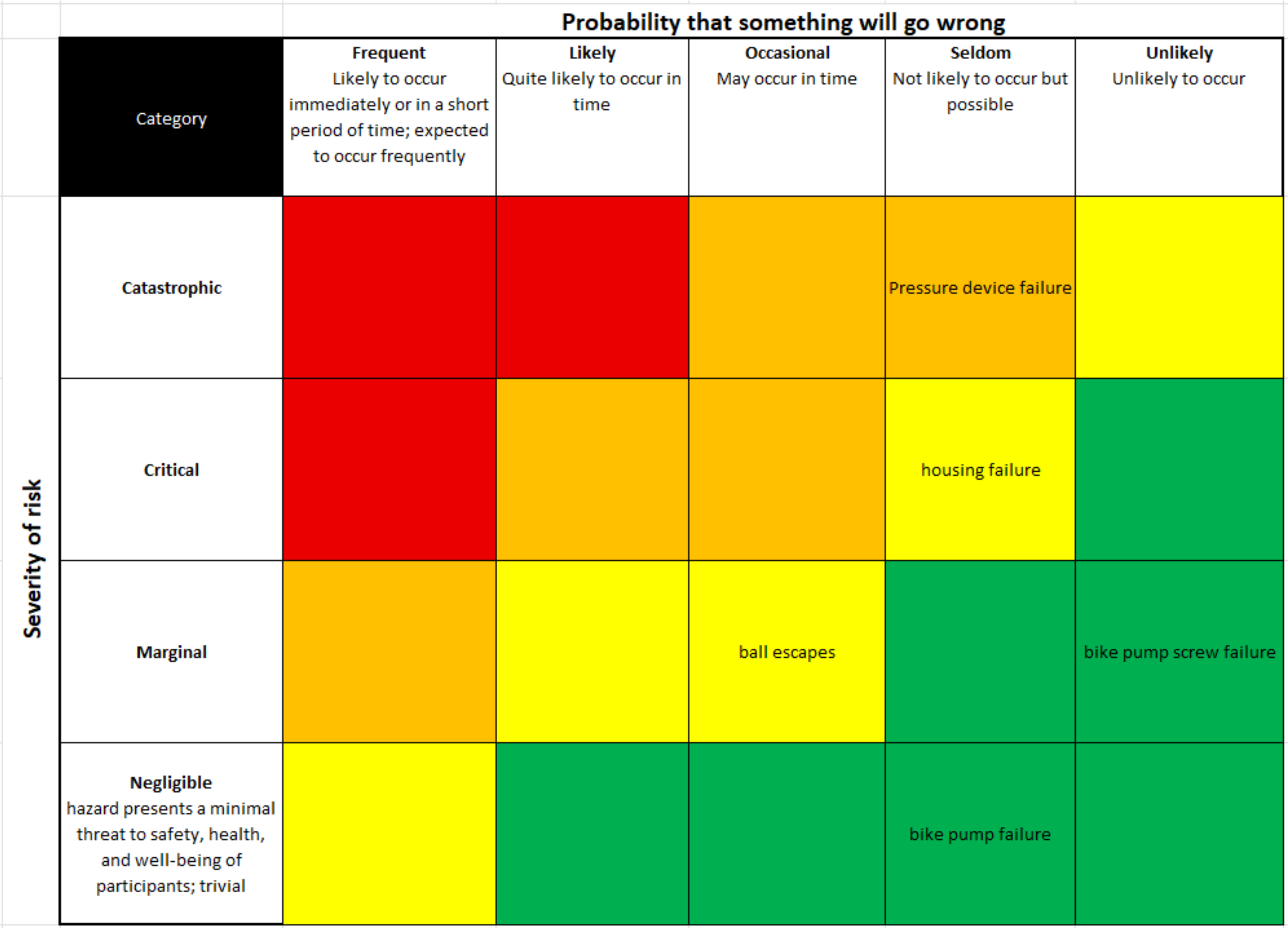
Severity: This failure is of negligible severity. An air leakage is threatening to the operation of the device, but not to users.

Probability: The probability of this failure occurring is seldom. In initial testing, this was not one of the problems encountered.

Mitigating Steps: In order to mitigate this risk, sealants will be used around the interfaces where air can possibly escape. This includes gaskets and tapes.

6.2.6 Heat Map

The heat map below takes each risk and categorizes it according to its probability of occurrence. The formatting helps to visualize the most important risks in terms of design.



		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**	🟥	🟥	🟧	🟧 Pressure device failure	🟨
	Critical	🟥	🟧	🟧	🟨 housing failure	🟩
	Marginal	🟧	🟨	🟨 ball escapes	🟩	🟩 bike pump screw failure
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨	🟩	🟩	🟩 bike pump failure	🟩

Figure 24: A visual analysis of each risk and their probabilities.

6.2.7 Risk Prioritization

The heat map helps to visualize and prioritize each risk. Based on the heat map, it is clear which risks should be given precedence and attention to. The most significant risk based on the heat map is a potential failure off the air pressure holding tank. This leads it to be prioritized first. The next two risks ranked with equal significance based on the heat map is a housing failure and a possible eruption of the ball from the device. Based on this, the housing latch failure is the second priority as the potential danger is higher. That leaves an escape of the projectile as the third priority. The last two risks are also weighted equally based on the heat map. Using the same reasoning as for risks #2 and #3, the bike pump screw failure would be ranked #4 as it is of higher severity, leaving a failure of the bike pump to be the 5th priority.

6.3 Design for Manufacturing

Number of Components: 27 (excluding threaded fasteners, electronics, and tape)
Number of threaded fasteners: 17
List of Theoretically Necessary Components:
- Bike pump
- Stand for the bike pump

- Bike pump nozzle
- Tubing
- Holding Tank
- Solenoid (or other type of valve)
- Button to control Solenoid
- Piston
- Ball
- Arduino hooked up to force sensors

Our goal when designing the bike pump-to-piston system was to have as few components as possible to eliminate resistance and leaking. We went through many different iterations of design and settled on one that we think uses the lowest possible number of components while still performing all of the functions we want it to. For display purposes, we have everything inside a storage box and stacked on pieces of wood. This was cobbled together sort of haphazardly and could have been designed better to have fewer components. We added multiple parts later on as an afterthought so we could rebuild with less pieces. Overall, however, the actual system has as few parts as possible currently.

6.4 Design for Usability

Vision Impairment: The main area where vision impairments such as color blindness would be an issue in our device is the buttons that are used to control the system. We currently have one green button and one blue button that will be labeled and referred to by both their color and labeled name to allow those with color blindness to use the device successfully. For our final prototype, we will likely not have any text and will rely on a verbal description and verbal instructions for use. Still, if we can produce text for the prototype it should be large and clear so that those with vision impairment can see it as clearly as possible. Although we currently are relying solely on verbal instructions and planning to shift to written it would be good to include an option for recorded verbal instructions that the user can activate if they wish.

Hearing Impairment: Our device does not currently have any sound components to it aside from the verbal explanations and user instructions we have been providing in demonstrations like the Prototype Expo. For a final device, we would have both written and recorded verbal instructions to allow users with hearing impairments to be able to use the device successfully.

Physical Impairment: Our device is currently not user-friendly for those with physical impairments because pressure is created through manual pumping of a bicycle pump. To allow those with physical impairments to utilize our device we would add an air compressor and a button that provides users with the option to power the device through the air compressor rather than the pump. Our buttons are also quite small and might be difficult to press for certain users which could be adjusted to larger buttons that are easier to press.

Control Impairment: Our device does not take very long to use and if an addition of the air compressor is made, the usage time would be reduced even further. The device is also very interactive which ideally should reduce the issues for those with distraction control impairments. For those with other control impairments, the ability to use the air compressor to pressurize the device rather than the bicycle pump should hopefully alleviate some of the issues that would arise for their use of the device.

6.5 Design Considerations

Table 3: Factors considered for design solution

Design Factor	**Applicable**	**Not Applicable**
Public Health		X
Safety	X	
Welfare	X	
Global		X
Cultural	X	
Societal	X	
Environmental	X	
Economic	X	

Table 4: Contexts considered for ethical judgments

Situation	**Applicable**	**Not Applicable**
Global context		X
Economic context	X	
Environmental context	X	
Societal context	X	

7 Final Prototype

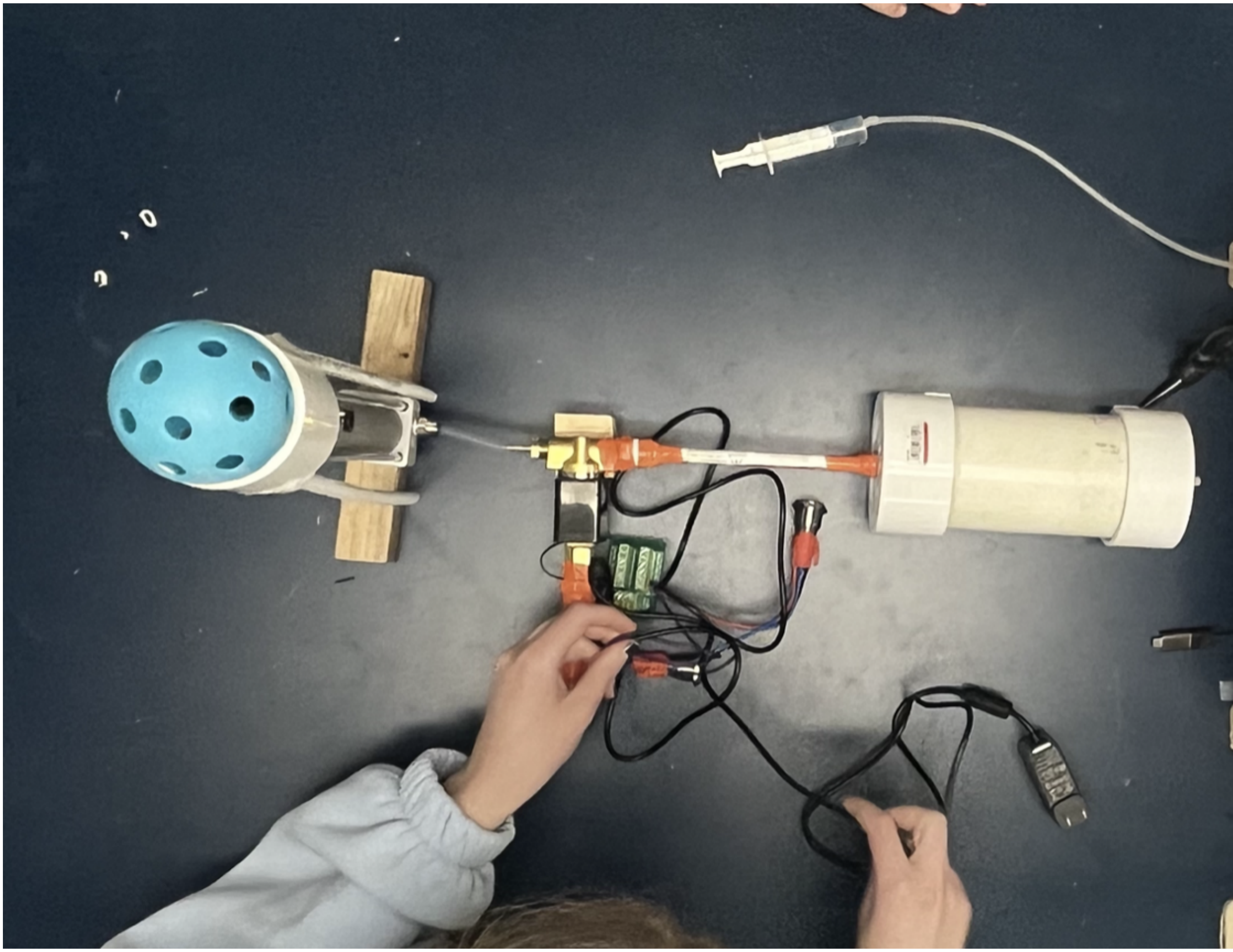


Figure 25: Final Prototype Overhead

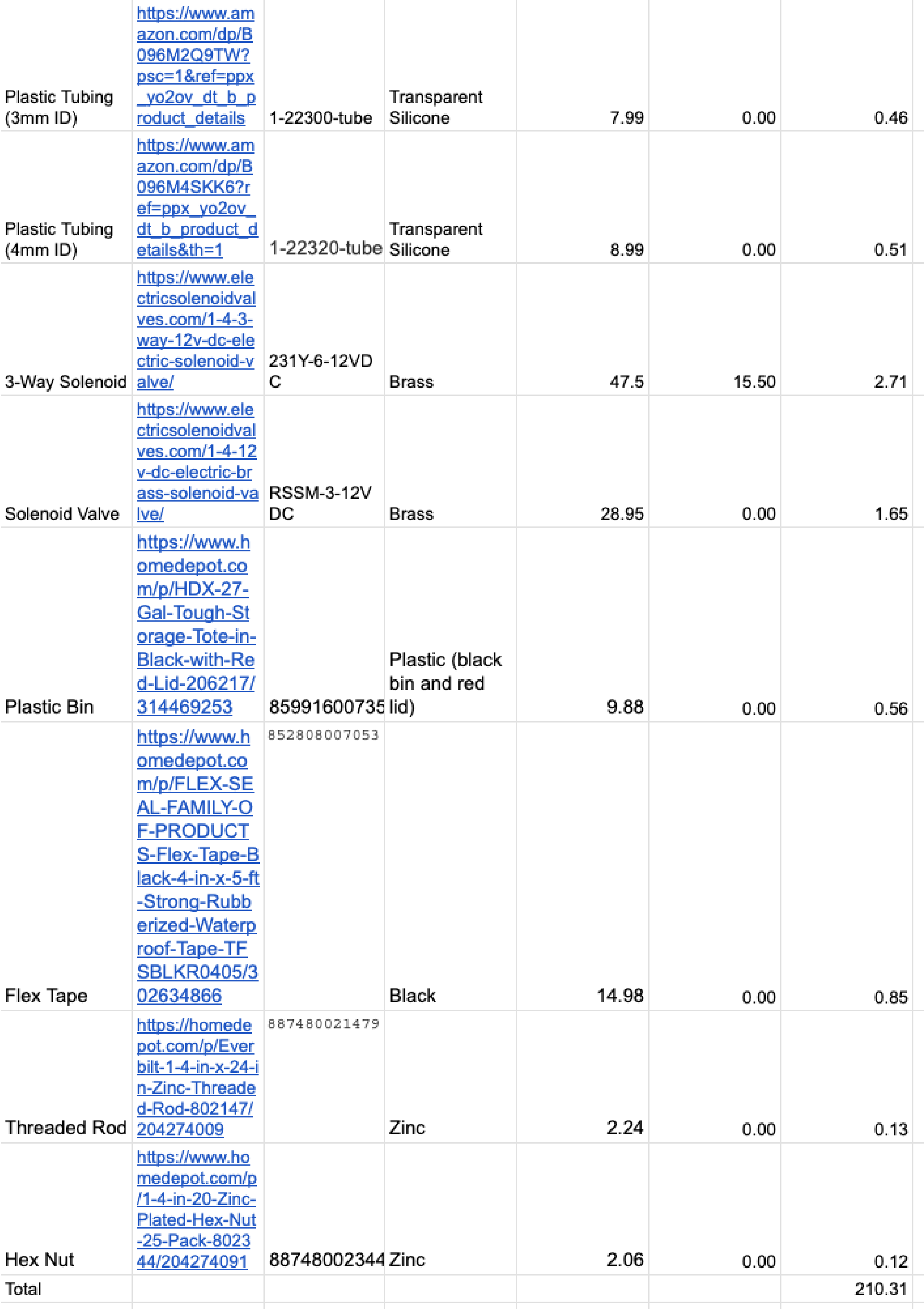
As we worked on the project, we had to change our goals to be more reasonable. The first two are the same - measure the mechanical work put into the system and measure the change in energy in the tank. The third however, we changed to be that the piston is released with a button. The first and last goal were both achieved. We had force sensors under the bike pump and an ultrasonic sensor on the handle and paired with Arduino code, we got the computer to display a value for work. The piston also released with a button. The second goal, however, we got close but could not fully implement it. We had a lot of issues with making the system airtight so wanted to try to to have as few connections as possible. Once we got it working we were worried about drilling another hole to put in the sensor. We also realized that the sensor we had only went up to 30 psi but we estimated that we we had around 60 psi in the tank right before release. With more time, we think we would have been able to achieve this goal but for now we have a syringe hooked up to the pressure sensor to demonstrate what could happen. Although our project did not come out exactly as we had imagined, we managed to implement almost all of the desired functions.

Bibliography

[1] Natasha Parks. *How to Calculate Piston Force*. 2018. URL: https://sciencing.com/size-pneumatic-cylinder-5115743.html.

[2] Spokester.com. *Bike Tire Pressure – Quick Guide to the right PSI for Bike Tires*. URL: https://spokester.com/blogs/news/bike-tire-pressure-quick-guide-to-the-right-psi-for-bike-tires.

A Parts List



Plastic Tubing (3mm ID)	https://www.amazon.com/dp/B096M2Q9TW?psc=1&ref=ppx_yo2ov_dt_b_product_details	1-22300-tube	Transparent Silicone	7.99	0.00	0.46
Plastic Tubing (4mm ID)	https://www.amazon.com/dp/B096M4SKK6?ref=ppx_yo2ov_dt_b_product_details&th=1	1-22320-tube	Transparent Silicone	8.99	0.00	0.51
3-Way Solenoid	https://www.electricsolenoidvalves.com/1-4-3-way-12v-dc-electric-solenoid-valve/	231Y-6-12VDC	Brass	47.5	15.50	2.71
Solenoid Valve	https://www.electricsolenoidvalves.com/1-4-12v-dc-electric-brass-solenoid-valve/	RSSM-3-12V DC	Brass	28.95	0.00	1.65
Plastic Bin	https://www.homedepot.com/p/HDX-27-Gal-Tough-Storage-Tote-in-Black-with-Red-Lid-206217/314469253	85991600735	Plastic (black bin and red lid)	9.88	0.00	0.56
Flex Tape	https://www.homedepot.com/p/FLEX-SEAL-FAMILY-OF-PRODUCTS-Flex-Tape-Black-4-in-x-5-ft-Strong-Rubberized-Waterproof-Tape-TFSBLKR0405/302634866	852808007053	Black	14.98	0.00	0.85
Threaded Rod	https://homedepot.com/p/Everbilt-1-4-in-x-24-in-Zinc-Threaded-Rod-802147/204274009	887480021479	Zinc	2.24	0.00	0.13
Hex Nut	https://www.homedepot.com/p/1-4-in-20-Zinc-Plated-Hex-Nut-25-Pack-802344/204274091	88748002344	Zinc	2.06	0.00	0.12
Total						210.31

B Arduino Code

```
  // Constants
const long msSample = 50;                  // [ms] time period between samples ...
    (50 ms = 20 frames/sec)
const float dtSample = msSample / 1000.0;  // [s] time period between samples
const float K = 0.3;                        // filter parameter
                                            // 0.1 ¬ average over 10 samples
                                            // 0.5 ¬ average over about 2 samples
// Position
float xNow;
float xPrev;
float xRaw;

// Time
long tNow;             // [ms] time instant now
long tPrev;            // [ms] time instant of previous sample

// Numbers
int k = 0;     // counter variable



//PRESSURE SENSOR
float pressPa;
float pressPrev;
float pressMin;
float pressMax;
float pressFinal;
float pressMinFinal=20;
float pressMaxFinal = 0;
float dVol;
float pressWork;

//WORK CALC VARIABLES
float pressChange;
float volChange;
float specHeat;

//ULTRASONIC SENSOR
const int pingPin = 5; // Trigger Pin of Ultrasonic Sensor, white on sensor
const int echoPin = 6; // Echo Pin of Ultrasonic Sensor, blue on sensor
long duration;
float dPrev;
float dNow;
float dDiff;
float dMax;
float dHighest;

//FORCE SENSORS
#include "HX711.h" //This library can be obtained here ...
    http://librarymanager/All#Avia_HX711

```

```
float calibration_factor = -7050; //This value is obtained using the ...
    SparkFun_HX711_Calibration sketch

#define LOADCELL_DOUT_PIN  9
#define LOADCELL_SCK_PIN  8

HX711 scale;



#include <Wire.h>
#include "Adafruit_MPRLS.h"

// You dont *need* a reset and EOC pin for most uses, so we set to -1 and don't ...
    connect
#define RESET_PIN  -1  // set to any GPIO pin # to hard-reset on begin()
#define EOC_PIN    -1  // set to any GPIO pin to read end-of-conversion by pin
Adafruit_MPRLS mpr = Adafruit_MPRLS(RESET_PIN, EOC_PIN);




void wait_for_sample() {
  for (;;) {
    tNow = millis();
    if (tNow - tPrev ≥ msSample) { break; }
  }
  tPrev = millis();
}


void setup() {
  xNow = 0.1;
  tPrev = millis();

  //Pressure Sensor
  Serial.begin(115200);
  Serial.println("MPRLS Simple Test");
  if (! mpr.begin()) {
    Serial.println("Failed to communicate with MPRLS sensor, check wiring?");
    while (1) {
      delay(10);
    }
  }
  Serial.println("Found MPRLS sensor");

  pinMode(pingPin, OUTPUT);
  pinMode(echoPin, INPUT);
  digitalWrite(pingPin, LOW);
  Serial.begin(9600);

//force sensor
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  scale.set_scale(calibration_factor); //This value is obtained by using the ...
      SparkFun_HX711_Calibration sketch
```

```
  scale.tare();  //Assuming there is no weight on the scale at start up, reset ...
      the scale to 0

}


void loop() {
  xPrev = xNow;
  xRaw = xNow + 0.05;


  // First-order filter
  xNow = K*xRaw + (1-K)*xPrev;

  //Pressure Sensor
  pressPrev = pressPa;
  float pressure_hPa = mpr.readPressure();
  pressPa = pressure_hPa / 68.947572932;
  if(pressMax-pressPa>.3){
    pressMaxFinal = pressMax;
  }
  if(pressPa>pressPrev){
   pressMax = pressPa;
  }
  if(pressPa-pressPrev<0){
    pressMin = pressPa;
  }
  if(pressPa-pressPrev>.3){
    pressMinFinal = pressMin;
  }

  specHeat = 1.401;
  //work = (p2v2-p1v1)/(specificheatratio - 1)

  pressWork = (0.001*pressMaxFinal-0.006*pressMinFinal)/(specHeat-1);
  digitalWrite(pingPin, HIGH);



  //force sensor
  //if current force > previous force start recording
  //    add each measurment to array
  //    if current force < 0
  //        break


  // starting position is 2 cm
  //ULTRASONIC SENSOR
  delayMicroseconds(10);
  digitalWrite(pingPin, LOW);
  duration = pulseIn(echoPin, HIGH);
  //Serial.print(duration / 29 / 2);
  //Serial.println(" cm");
  dPrev = dNow;
  dNow = duration / 29 / 2;
  dDiff = dNow-2; //starting position is 2cm up
```

```

  if(-dNow+dPrev>0.3){
   dMax = dNow;
    if(dNow == 2){
      k=k+1;
    }
  }


  Serial.print("Pressure (PSI): "); Serial.println(pressure_hPa / 68.947572932);
  //Serial.print("pressWork: "); Serial.println(pressWork);
  Serial.print("current height: "); Serial.println(dNow);
  Serial.print("pushes: "); Serial.println(k);

  wait_for_sample();
}

/*
 * if ultra senses movement and force sensors sense force (have to make sure ...
    platform to stand on is not connected to force sensors)
 * when start loop own time dependnecy until hit certain threshold call it 20s
 *
 *
 * pneumatic
 * take initial reading for minimum
 * continuously override for maximum
 * when pressure drops a certain amount stop cycle and begin new cycle
 * create minimum difference from current to maximum
 *
 */


 /*
  * long term
  * doesnt get stuck with like kid messes around with it
  *
  */

  //Serial.print("Pressure (hPa): "); Serial.println(pressure_hPa);

  //Serial.print("pressMax: "); Serial.println(pressMax);
  //Serial.print("pressMin: "); Serial.println(pressMin);
  //Serial.print("pressMinFinal: "); Serial.println(pressMinFinal);
  //Serial.print("pressMaxFinal: "); Serial.println(pressMaxFinal);

  //Serial.println(xNow);
```