Educational Demo
Hyperboloid Hole in the Wall
Design Review 3 Report

University of Michigan: College of Engineering
MECHENG 450 - Senior Design

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Executive Summary

The motivation for our project is a lack of engaging and educational demos for young children to explain mathematical concepts. Our sponsor gave us the task of creating a scaled-up version of a demo often seen in science museums that shows how a straight rod that is angled and rotated about a center axis can fit through a curved hole and trace the shape of a hyperboloid of revolution. The purpose of the demo is to get children interested in math and science by interacting with this life sized demo with absurd proportions and shapes.

The user requirements for the demo encompass a few main priorities. First, the demo must be portable so that it can be moved to various schools. It should be able to be disassembled by one person in less than a half hour, and be able to be carried in two trips by one person to a car where it will fit, fully disassembled, in the trunk. We tied this to another engineering specification that the entire demo should weigh no more than 60 pounds. Second, the demo should target children ages 2-8, so we ensured that the demo was able to accommodate these children both in height and weight. Third, the demo should be both educational and fun. This was accomplished by portraying hyperboloids of 3 different aspect ratios. Finally, the demo must be stable and safe to operate.

Our chosen concept had two main components: a main module that included a base for the demo and spinning walls with hyperbolic cutouts, as well as a platform on which a child will lie as the walls spin around them. The walls are made of a PVC frame with interchangeable tarp inserts that show hyperboloids of different aspect ratios. These aspect ratios are matched with the angle of the platform, which is adjustable through a pin mechanism. We chose to have the walls rotate instead of the platform, which replaces the rod in the traditional demo, because of weight limitations. The rotation is powered by a motor that is housed in the base of the main demo. The motor is plugged into a wall socket and is controlled by both a master switch monitored by the supervisor of the demo as well as two buttons on the platform that allow the child to control when the demo rotates. The demo can be fully disassembled into pieces no longer than four feet long and can be put together using only pins and bolts; no tools are required.

The majority of the demo was made of wood, which was cut to size using appropriate saws. A few parts, including the main shaft, gears, motor mount, and the roller and bracket required for adjusting the angle of the platform were made of aluminum or steel, and were manufactured in the machine shop using the mill and/or lathe. The PVC frame was also cut using a saw and the appropriate adaptors that allow the frame to be screwed together were attached using glue.

We were able to complete manufacturing of our project on time. We conducted experiments to validate how our demo met the user requirements. We were able to meet the requirements of the demo being able to be disassembled, having educational and fun factors, and being stable. However, we were not able to meet our weight requirement, and we question that our demo is safe for younger children. There were a few aspects of our design that we would change in a second iteration of the project, including material choices for the platform and walls, and attachment methods for the legs. But, our sponsor is happy with the demo, and is pleased that it moves and is able to demonstrate the concepts he wishes to show.

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Problem Description and Background

Our sponsor has given us the task of creating an educational demo to show mathematical concepts that govern hyperboloids of revolution. He has requested we do this through creating a larger interactive model that shows how a hyperboloid of revolution is a curved surface made entirely of straight lines. This demo will be used both in science museums for small children to get them excited about math and in university classrooms for undergraduate math majors to help them visualize equations they are solving.

Currently there are some demonstrations of hyperboloids in museums (shown below in Figures 1 and 2), but these demonstrations are somewhat limited in user interaction or mathematical descriptions. There are also many papers written about the math behind hyperboloids and picturing their complex shapes, such as “Interactive visualization of hyperbolic geometry using the Weierstrass model” [1], but these descriptions are too mathematically dense for children to understand. Our task is to bridge the gap and make a demonstration that can be used by children and older students alike that is entertaining and stimulating while still being educational.

Our model will be an adaptation of small demonstrations shown in science museums, where a straight rod is angled and rotated through a hyperbolic hole, as seen below in Figure 1. The red rod revolves about the center axis, passing through the curved holes in the wall. The small plaque next to the demo in the figure reads: “It is an interesting fact that a moving straight line can describe the exact shape of a surface with compound curvature. This model is a demonstration of a line sweeping out the surface of a hyperboloid. The curved slot is a profile of the surface, called a hyperbola.” As our sponsor described it, the point of the demo is to get kids interested in a curious object that is curved but made of straight lines.

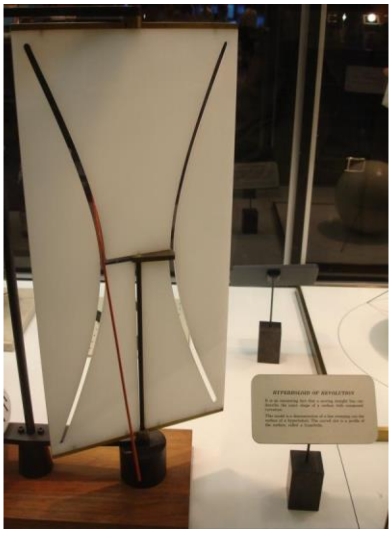

Figure 1: Demonstration on how a straight rod can be rotated to fit through a curved hole, outlining the surface of a hyperboloid of rotation. [2]

Figure 2: Elastic cords show how surface of hyperboloid of revolution changes as angle of straight lines changes. [3]

Our task is to scale up the wall to the order of six feet and replace the rod with a person, so that the demonstration can be more interactive and fun. This model, though it demonstrates basic mathematical facts about hyperboloids, is more focused on engaging small children rather than describing the exact equations behind the model.

In order to better demonstrate the mathematical concepts associated with a hyperboloid of revolution, our sponsor requested that the aspect ratio of the hyperbolic cutouts be adjustable. He suggested that we 3D print small hyperboloids that have the same aspect ratio as the large interchangeable walls so that children can see what the entire shape looks like. There should also be some sort of mathematical description of each hyperboloid, including relevant equations. The general equation we will be using for a hyperbolic surface is shown in Equation 1:

$$\frac{x^2}{a^2}+\frac{y^2}{a^2}-\frac{z^2}{c^2}=1 \qquad \text{Eq. 1}$$

In Equation 1, *x, y, z* are spatial coordinates of a Cartesian coordinate system, while *a* and *c* represent the axes and semi-axis of the surface, respectively. We will show how this general form changes with changing rod inclination angle [4]. Further equations can be found in detail in geometry and calculus textbooks such as *Geometry and the Imagination* [5].

The demonstrations that currently exist show some of the principles that govern hyperboloids of rotation, but do not directly incorporate the mathematical equations into the demos. Our design~~s~~ would build off of concepts of existing demos to create both fun and educational exhibits that could be used in a variety of settings and with a variety of audiences.

Because there were no patents or product descriptions for educational demos exactly like those our sponsor requested, we instead looked at various mechanisms to find benchmarks to compare our overall design to. Specifically, we looked at patents for rotating apparatuses that matched our initial thoughts for how we would construct the large model. These included “Collapsible revolving door having removable wings” [6] for the revolving mechanism. This assembly has wings that are attached to a center post by a bar connected to a frame and held in place by a spring mechanism that allows the wings to be collapsed.

We also looked at carousel and merry-go-round mechanisms that took different approaches to the problem of incorporating children into a rotating structure. For example, “Apparatus and method for a child’s suspended merry-go-round” [7] has a method of anchoring the frame to the ground and having the seats suspended from this anchored frame. “Rotary carousel apparatus and system” [8] has a stationary base with the central axis fixed relative to this base with rotating drive plates that allows items stored on various plates to be easily retrieved through accurate positioning of the mechanism. “Amusement Ride” [9] discusses vehicles that are constrained to an oscillating arm that is connected to a central driving element on the rotation axis. “Around the world rotary toy system” [10] includes a method for creating self-propelled rotary amusement devices. “Apparatus for children’s playground” [11] has one member for supporting a child and a second member that rotates around the first member when pushed by a second child, employing a track and rollers to guide the rotation of the second member.

User Requirements & Engineering Specifications

Our team met with our sponsor, Professor Martin Strauss, to conduct an interview to determine the user requirements for this project. Professor Strauss first provided information on the target audience and the goal of the project, which was to help children ages two to eight gain an interest in mathematics and have fun while using our educational demo. Next, Professor Strauss and our team discussed a general set up for the hyperboloid and settled on the idea for a large model that children can spin and interact with. The model must be sturdy enough to withstand children interacting with it. It should have a plaque on the side that gives a description of the math, as well as small handheld 3D printed hyperboloids of revolution. The last user requirement discussed was the ability to assemble and disassemble the large model. Professor Strauss gave us two main factors for this requirement. The model must be able to be set up or broken down by one person in a reasonable amount of time and the model must be light enough and small enough to be carried to a vehicle and placed in the trunk of a normal sized car.

Turning these user requirements into engineering specs, our group has decided that the most important choice to be made is the material. This material must be hard enough to resist scratches from children and strong enough to resist breaking. To evaluate the various potential materials, we plan on referencing different texts such as *Mechanical Behavior of Materials: Engineering methods for deformation, fracture, and fatigue* [13] and *Engineering Materials 1: An introduction to properties, applications, & design* [14] to weigh potential benefits and select the most appropriate material. Additionally, the material must be light enough to be carried by one person when broken down into pieces that can fit into a mid-sized sedan, which has a trunk volume of about 15 cubic feet. To meet the size dimensions, the walls must be broken down into pieces smaller than 3’ by 2.5’ by 2’. This is the maximum possible size, but our group would like the model to also fit into a compact sedan – 11-12 cubic feet – if possible [15].

The average weight that an adult female can carry with her arms at elbow height and partially extended is approximately 30 lbs [16]. Since our sponsor has indicated that he would be willing to make two trips in order to transport the disassembled educational demo, the weight of 30 lbs can be doubled to 60 lbs. An additional specification we want to achieve is to be able to break down or set up the model in approximately 30 minutes. Another requirement is to design the model so that the entire age range can use it. To do that, we need the hole for rotation to be able to fit a girl in the 95th percentile on height. The value for this is 54.5”, which is larger than the height for an eight-year-old boy [17]. Also, the material must be strong enough to support at least an 80 pound child. This is the 95th percentile for the weight of an eight-year-old girl as well, which is also greater than that of an eight-year-old boy [17][18]. We do however, want and expect the hole to be much larger and the material to be able to support a larger force with appropriate safety factors.

Aside from the user requirements we came up with from Professor Strauss, our group had other requirements we felt our stakeholders would find beneficial. These requirements focused on safety. Our group would like to place sensors in pinch points to stop the larger model if a user comes within a set distance of the proximity sensors [19]. We would like to set this distance to be one inch. The mechanism should have some sort of electronically triggered locking system if these sensors are activated. Also, we would like to have a way to control the rotation in order to make the model safe for all users. The speed of rotation should not surpass five revolutions per minute. In order to control the rotation, we will implement the use of a motor that will be activated by user actuators. We envision the user will have to have all buttons/sensors activated in order to start the motor. This increases the safety of the educational demo because it cannot be moving while a user is only half-on the platform, or if the user decides to flail his or her arms and legs while interacting with the demo. Through this, we will be implementing a control system to ensure this safety mechanism is functional. Lastly, our group would like to factor in safety requirements that could be related to our model like playground safety regulations [20].

Quality Function Deployment

Included in Table 1 is our Quality Function Deployment (QFD). Our team translated our user requirements into the design criteria, as seen on the left, and created the engineering parameters necessary to measure these criteria, as seen on the top. Our team then weighed the criteria and found each criterion's relevance to the engineering parameters using a scale of 9-3-1, with 9 being the most relevant. The total/normalized scores helped our team to find the most influential parameters, which aided our group in forming the engineering specifications. Indicated on each engineering parameter is whether it is beneficial for that parameter to be larger or smaller. If both options can be beneficial for different criteria, a negative value in the QFD expresses that for this criterion it will be beneficial for the parameter to be smaller.

Table 1: Quality Function Deployment

		Weight	Tensile Strength (+)	Fracture Strength (+)	Hardness (+)	Sensor Sensitivity to Movement (+)	Turning Radius (+)	Time delay on Sensors (-)	Oilled Bearings (+ or -)	Multi-colored (+)	Number of Parts (+)	Number of Parts (-)	Largest Dimension (-)	Second Largest Dimension (-)
Large Demo	Durability	7	9	9	6							5		
	Human Powered	4	7	7		9	3		8					
	Adjustable Size	8	8	8	2						1		1	1
	Light-weight	5	5	5	1								4	4
	Ability to Disassemble	7	6	6	3						9		7	7
Safety	Pinch Points	10				10	2	10						
	Soft Material	9	8	8	10									
	Controlled Rotation	6					4		5					
User Exper-ience	Fun to Use	6					6	8		5				
	Educa-tional	8				5	1	6						
	Concepts for Ages 2-8	8				3	1	4		6				
Total			350	350	247	245	187	315	139	78	71	70	77	77
Normalized			.16	.16	.11	.11	.08	.14	.06	.04	.03	.03	.03	.03

Concept Generation

To begin our concept generation, we first broke down our design using a function structure diagram (FSD), as seen below in Figure 3. The FSD demonstrates a flow of tasks necessary for ensuring the educational demo is ready for use. First, we will secure the central axis of the main module and attach the walls, performing safety checks to ensure stability.

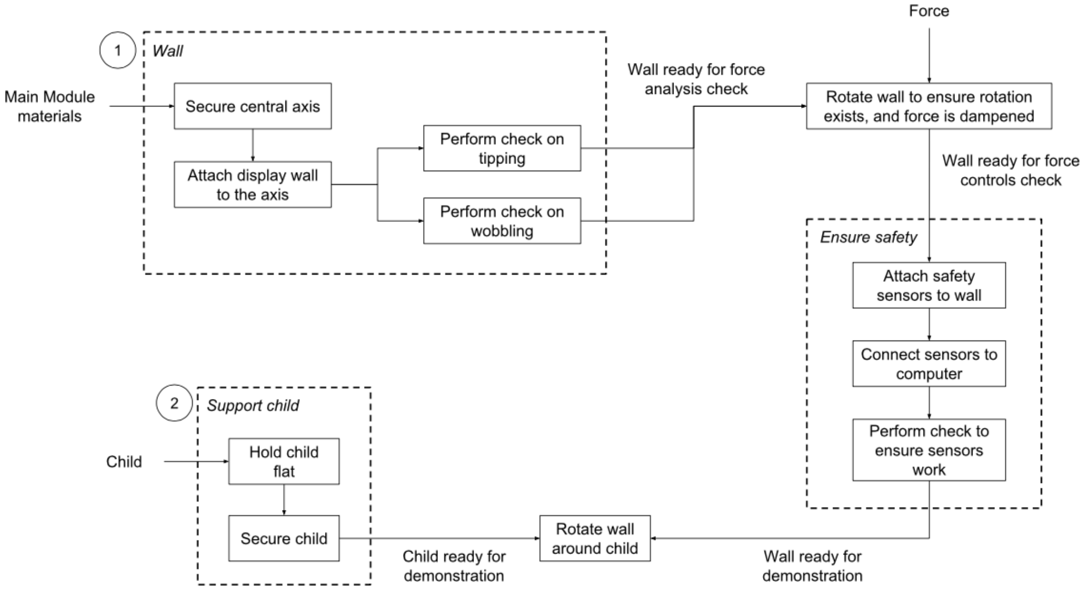

Figure 3: Function Structure Diagram

Once the assembly is determined stable, the main module is ready for the force analysis check. This check involves rotating the board to ensure it rotates with a desired speed, leading us to safety checks. To account for potential pinch points on the educational demo, we will attach sensors to the wall, connect them to the computer, and perform our own checks to ensure the sensors are indicating at the proper threshold. Once these checks are completed, the wall is ready for demonstration, and we will move onto supporting the child user. A child user will hold onto the platform, and be secured in place. Once the child is secure, he or she is ready for the demonstration to move through a hyperboloid hole in the wall.

From the FSD, we determined the four main areas of our design: the wall, base, power source, and platform features. The wall will show the hyperbolic cutout, demonstrating the mathematical concept. Because the wall will be tall and thin, the base will need to provide structural integrity to prevent the wall from tipping. The power source will determine how we will incorporate rotation into the demo. Finally, the platform features are important as the child user will need to be secured safely and comfortably.

Methods of Concept Generation

After meeting with our sponsor and hearing some of his initial thoughts for the design of the overall structure, we began our concept generation. We looked at various patents to get ideas for different aspects of the design. Namely, we looked to the patents we discussed previously for inspiration: collapsible revolving door [6], suspended merry-go-round [7], rotary carousel [8], and rotary toy system [10]. Afterwards, the entire team brainstormed how to generate rotation and adequately support a user, then individually developed component concepts. Using the four established main areas from the FSD, each member developed at least twenty component concepts to illustrate the different functions. The components were narrowed down to the top sixteen we felt best addressed each main area, and further combined into four functional full system solutions. Please refer to page 12 for our concept selection, and Appendix A on page 31 other concepts that were generated

Wall Concepts

Wall Concept 1: Each wall would be created from equally-sized boards made of a solid, sturdy material wall, attached together by hinges, as seen in Figure 4. The modularity of the walls allows it to be folded up into a smaller form to be easily stored and transported. However, these walls would not be as lightweight as wanted. In order to address the adjustable aspect ratio, multiple sets of these boards would need to be manufactured, which could cause a cost problem.

Wall Concept 2: Each wall would feature a slotted board where large sheets with the hyperboloid cutouts would slide into, as seen in Figure 5. This would allow us to demonstrate different aspect ratios, but would be harder to transport.

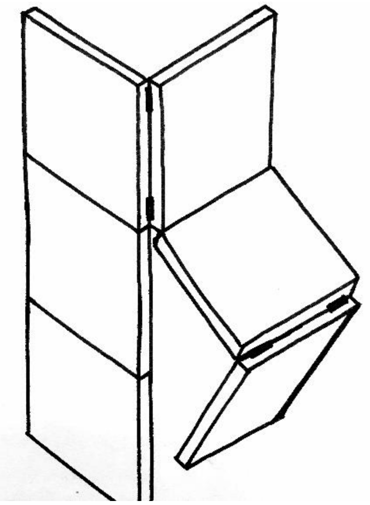

Figure 4: Wall Concept 1 – Solid, foldable walls.

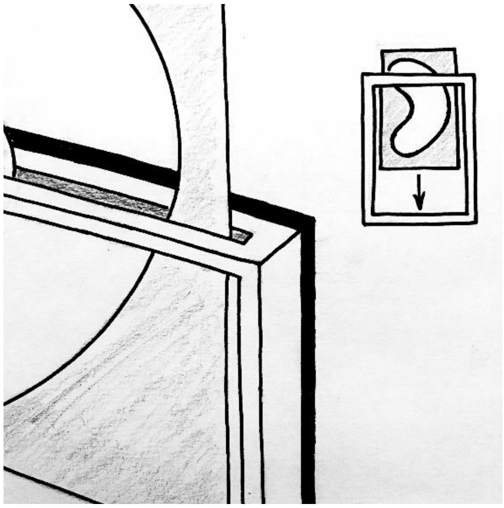

Figure 5: Wall Concept 2 – Interchangeable slide-in walls.

Wall Concept 3: Each wall frame will be constructed from plastic piping, as seen in Figure 6. A soft material, such as fabric, featuring the different hyperbolic cutouts will be attached to the frame by Velcro, or some other manner.

Wall Concept 4: Each wall will feature a formable mesh, as seen in Figure 7. The mesh can be pulled to demonstrate hyperboloids with different aspect ratios.

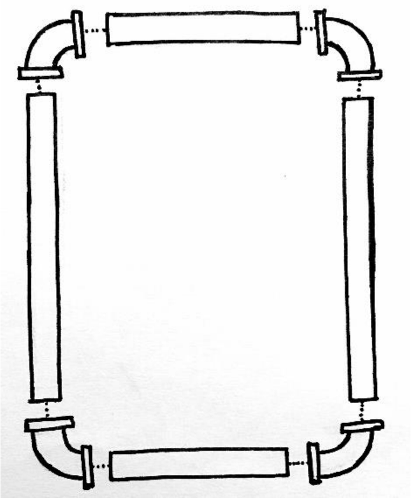

Figure 6: Wall Concept 3 –Wall frames made from piping, using soft inserts.

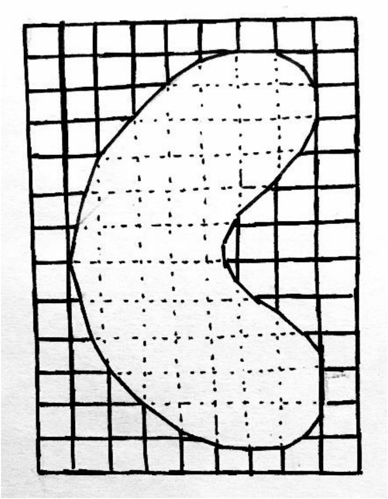

Figure 7: Wall Concept 4 – Formable mesh wall.

Base Concepts

<u>Base Concept 1:</u> A solid, conical base, as seen in Figure 8. This cannot be broken down to be smaller.

<u>Base Concept 2:</u> A cylindrical base with hinged, triangular feet. The hinges keep the base as one unit, but allows for easier transportation and storage. Slots are included in the feet so that a protective cover can be placed on top to prevent any tripping.

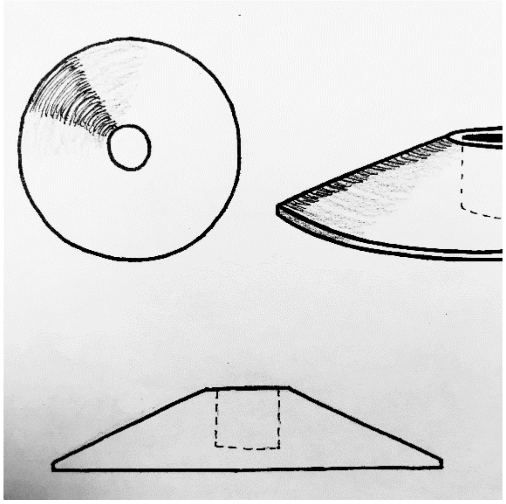

Figure 8: Base Concept 1 –Solid, conical base

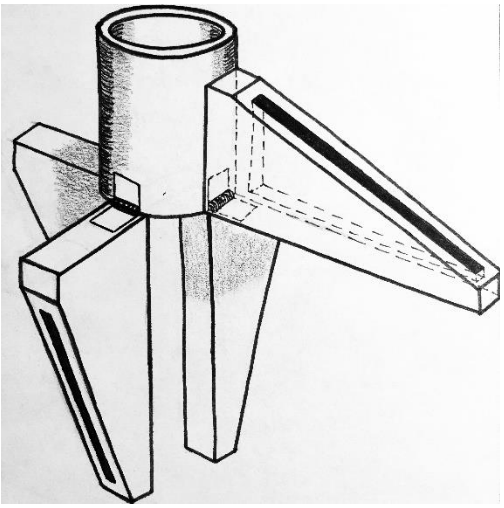

Figure 9: Base Concept 2 – Cylindrical base with hinged, triangular feet.

<u>Base Concept 3:</u> A cylindrical base with hinged, retractable feet as seen in Figure 10. The feet would feature a series of slotted rectangular blocks, so that each inner block could be pulled outward.

Base Concept 4: A cylindrical base with detachable, triangular feet, as seen in Figure 11. These allow the feet to be removed for easier storage and transportation. The feet will be secured to the base by some sort of pin or bolt. Similar to Base Concept 2, a slot is included in each foot to accommodate a protective cover.

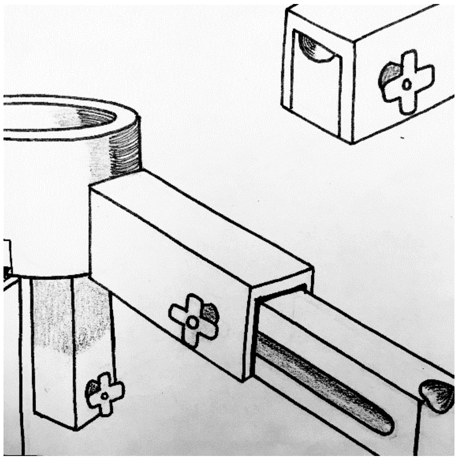

Figure 10: Base Concept 3 – Cylindrical base with hinged retractable feet.

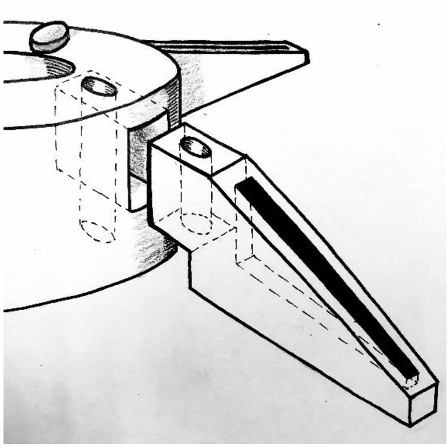

Figure 11: Wall Concept 4 – Cylindrical base with detachable, triangular feet.

Power Source Concepts

Power Source Concept 1: A second user will directly apply force to the wall, demonstrated in Figure 12, causing the wall to revolve around the first user on a stationary platform.

Power Source Concept 2: A second user will directly apply force to the platform where the first user will be secured, demonstrated in Figure 13, causing the platform to revolve around the wall on a track.

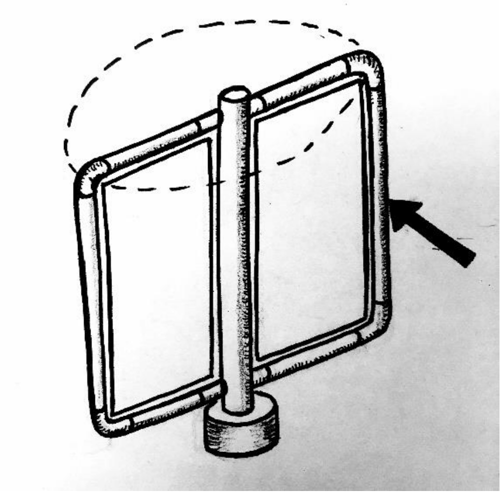

Figure 12: Power Source Concept 1 – Directly applied force to the wall, stationary platform.

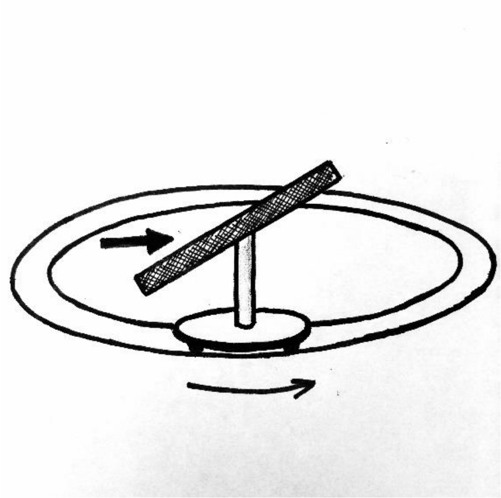

Figure 13: Power Source Concept 2 – Directly applied force to the platform, stationary wall.

Power Source Concept 3: A second user will turn a wheel rigidly attached to a shaft which is connected to the wall's central axis shaft by a belt, as seen in Figure 14. Both shafts will feature a base that allows for rotation. A cover, not pictured, will be made to protect the belt and ensure user safety.

Power Source Concept 4: A second user will turn a crank attached to a vertical belt that is attached to a horizontal shaft. The horizontal shaft, will run along the ground perpendicular to the wall's central axis shaft, will transmit the power from the crank by way of bevel gears. This can be seen in Figure 15. Again, some sort of cover, not pictured, will be made to protect the system.

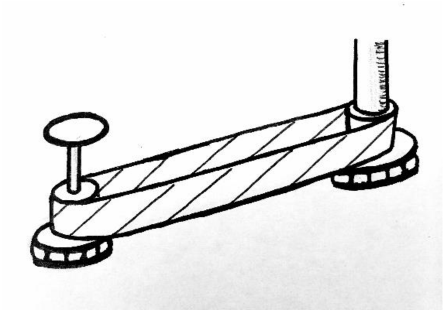

Figure 14: Power Source Concept 3 – Belt system transmission.

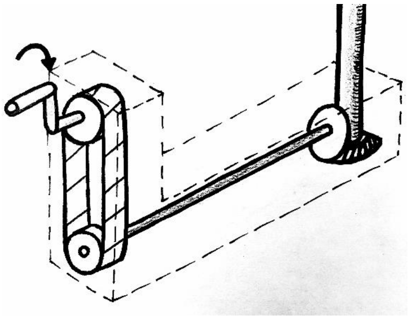

Figure 15: Power Source Concept 4 – Bevel gear and pulley system transmission.

Platform Features Concepts

Platform Features Concept 1: Attach a seatbelt to the platform to secure the user, as seen in Figure 16. For this, the child would be on their back on the platform, and the seatbelt would keep them from falling off.

Platform Features Concept 2: Attach two side handlebars to the platform to secure the user, as seen in Figure 17. The bars can be placed on either side of the platform, depending on how to user will be oriented – face up or face down.

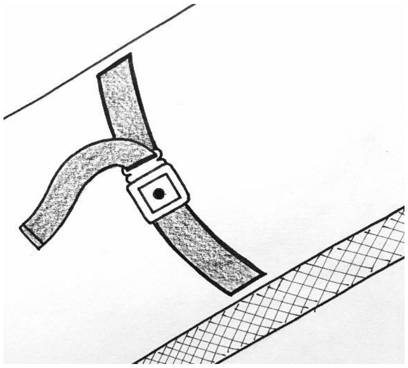

Figure 16: Platform Features Concept 1 – Seatbelt as a user restraint.

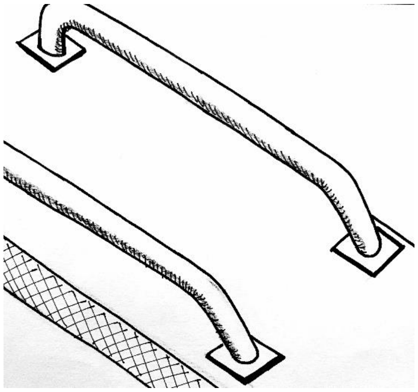

Figure 17: Platform Features Concept 2 – Side handlebars as a user restraint.

Platform Features Concept 3: Spaced foot cutouts would be placed at the bottom of the platform to accommodate users of varying height, as seen in Figure 18. The user will have to lie face down on the platform.

Platform Features Concept 4: A sliding step, as seen in Figure 19, will be incorporated to accommodate varying user heights. The step will slide along a slot that runs up and down the platform near the bottom.

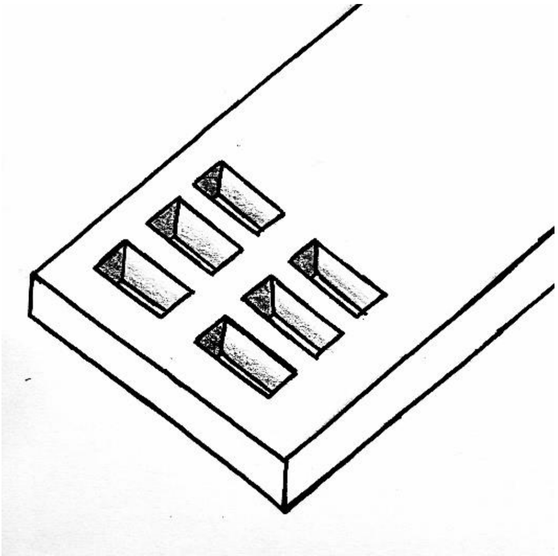

Figure 18: Platform Features Concept 3 – Foot cutouts at different heights.

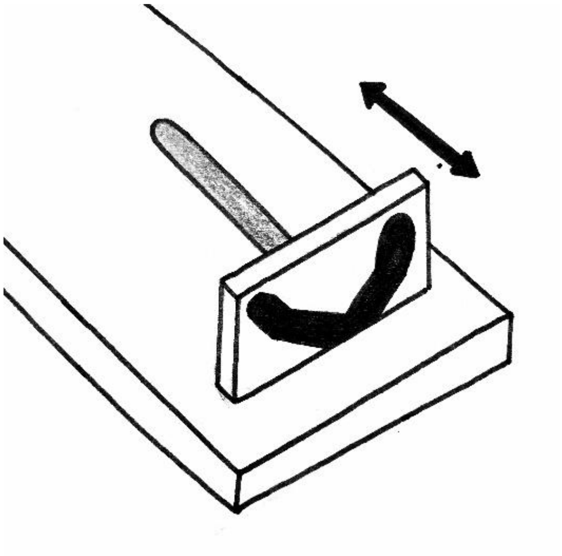

Figure 19: Platform Features Concept 4 – Sliding step for different user heights

Concept Selection

After generating our concepts, we then ranked them on various criteria to assess their ability to meet our user requirements and feasibility. These design evaluation criteria can be found in Table 2. Each concept was evaluated on how well it met the applicable criteria.

Within each of the four parts discussed in concept generation (wall, base, power source, and platform features) each criteria was given a different weight to reflect its relative importance to the function of that part. However, some criteria did not apply to the part, for example adjustability of the base. For these parts, the irrelevant criteria were not considered in the ranking. We then ranked each concept on a 1-3-5 scale for each criteria, where 1 is the lowest possible score and means that the concept poorly achieves the function, 3 means the concept sufficiently achieves the function, and 5 is the highest score and means that the concept excellently achieves the function.

Table 2: Design Evaluation Criteria and Justifications.

Design Evaluation Criteria	**Justifications**
Adjustability	-Target audience includes wide range of users aged 2-8 years old of different sizes and weights, design must accommodate them all. -Adjustable aspect ratio requested by sponsor.
Cost	Budget of $400.
Durability	Structure should withstand frequent use, including assembly and disassembly.
Ease of Assembly	-User requirement: demo is easily set up and broken down by one individual. -Engineering specification: demo should take no more than 30 minutes to assemble or disassemble.
Ease of Manufacturing	Limitations of course require that parts are manufactured in machine shop within the semester.
Ease of Use	Target age range of 2-8 year old children.
Feasibility	Design must be logical and as simple as possible.
Necessary Applied Force	User requirement: demo is powered by a child.
Safety	Target age range on 2-8 year old children.
Stability	-User requirement: Strong enough to handle children. -Engineering specification: Must support a weight of 80 pounds.
Weight	-User requirement: Able to be carried by one individual. -Engineering specification: Should not weigh more than 28.7 pounds.

Wall Concept Evaluation and Ranking

Our Pugh chart for the wall can be seen in Table 3. We gave adjustability the highest weight, 20%, because our sponsor requested that the aspect ratio of the hyperbolic cutout of the wall be adjustable to better show the mathematical concepts behind a hyperbola of revolution. Next, safety and stability were each given a weight of 15%. The walls are one of the key design features that contribute to safety - they are the largest part of the design and the one that the children have the most possibility to run into. Stability is also equally important because the walls are hanging off of the center axis, and could cause it to tip if they are not properly attached or balanced. Next, cost, ease of assembly, ease of manufacturing, and weight were each given a weight of 10%. Cost and weight are important again because the walls represent one of the largest pieces of our design and could take up a large piece of our budget or max weight requirement. Ease of assembly is important because it’s important that the walls can be put together quickly and efficiently by one person, per the user requirements. Ease of manufacturing ties back to our capability to manufacture these parts. Finally, durability and feasibility were each given a weight of 5%. The durability of the walls is less important than other parts of the design because these can easily be interchanged or reproduced, while something like the power source, for example, would be harder to reproduce. Feasibility was given a lower weight for the walls because it is such a critical part of the structure that we can afford to spend more time and effort on this aspect of the design.

Table 3: Pugh chart for ranking wall concepts.

Wall	**Weight**	**Folding Wall**	**Slide in Walls**	**Piping Frame**	**Formable Mesh**
Adjustability	20	1	5	5	5
Cost	10	1	1	3	3
Durability	5	5	1	3	3
Ease of Assembly	10	3	5	1	3
Ease of Manufacturing	10	1	5	5	1
Feasibility	5	1	3	5	1
Safety	15	1	3	5	5
Stability	15	5	1	3	3
	100	2.0	3.2	3.8	3.6

The four concepts we ranked were the folding wall, the slide in changeable walls, the piping frame, and the formable mesh, as described in concept generation.

The folding wall was given a score of 1 for adjustability, because this would be one piece that would not be interchangeable or adjustable. There would be one fixed aspect ratio, which does not meet our sponsor's request of an adjustable aspect ratio. It was given a score of 1 for cost, because the design would be made from a solid piece of plastic that would be expensive. The durability of this design was given a rank of 5, because a solid piece of plastic would be able to withstand constant use by young children. The ease of assembly was given a score of 3 because this design would neither be very difficult or very easy to put together. Ease of manufacturing and feasibility were each given scores of 1 because this piece is a very complex design and would be difficult to machine, and it is not entirely practical to have solid walls hinged and stay together while also easily breaking apart. The total weighted score for the folding wall was 2.0/5.0.

The slide in changeable walls were given a score of 5 for adjustability because it would be easy to change out the various panels to have a wall with a different aspect ratio by simply sliding the piece in. They were given a score of 1 for cost because it would be expensive to create several complete walls to create an interchangeable set, rather than one adjustable wall. They were given a score of 1 for durability because these walls would only be supported at the center axis and would not be made of a very hard material, so they would not be able to withstand much use. They were given a score of 5 for ease of assembly because, like adjustability, it would be very easy to slide the panels in. They were also given a score of 5 for ease of manufacturing because the design would not be very complex, just a panel with some sort of lip to hold them in place after being slid into slots in the center axis. They were given a score of 3 for feasibility because the design would make sense, though it is not the simplest design. They were also given a score of 3 for safety because the walls would be made of a softer material so they would not pose much of a hazard to small children running into them. They were given a score of 1 for stability because simply sliding the walls into the center axis does not give a very rigid attachment, and the structure could easily be tipped. Finally, the slide in walls were given a score of 3 for weight because they would be light compared to solid walls, but still would weight a substantial amount. The total weighted score for slide in changeable walls is 3.2/5.0.

The piping frame was given a score of 5 for adjustability because it would be very easy to attach a different insert with a hyperbolic cutout of a different aspect ratio to the Velcro patches around the edge of the frame. It was given a score of 3 for cost because it would be less costly to manufacture one frame and have multiple simple fabric inserts as opposed to multiple walls. It was given a score of 3 for durability because the frame would be fairly sturdy, while the fabric inserts might not be as durable. It was given a score of 1 for ease of assembly because the piping frame might be difficult to put together initially. It was given a score of 5 for ease of manufacturing because it would be very simple to cut the pieces of piping to size to create the frame. It was given a score of 5 for feasibility because this is a simple and practical design that could easily be accomplished in the time frame of the project. The piping frame was given a score of 5 for safety because the fabric inserts would be very soft if a child ran into them, and the piping frame could bend at the corners to prevent a hard impact. It was given a score of 3 for stability because these walls would not tip very easily, especially if they are secured through the center axis, but they do not provide much support for the structure. Finally, weight was given a score of 3 because this design would not be very heavy because the piping frame would be relatively light and the inserts would also be light. The total weighted score for the piping frame is 3.8/5.0.

The formable mesh walls were given a score of 5 for adjustability because it would be very simple to adjust the aspect ratio by simply pulling on the wire frame in the wall. The cost was given a score of 3 because it would be fairly expensive to find the correct material for this application, but only one wall would need to be made. The durability was given a score of 3 because the mesh would be able to withstand some impact without breaking. The ease of assembly was also given a score of 3 because it would be fairly simple to attach these walls to the center axis, but not as easy as simply sliding them in. Ease of manufacturing was given a score of 1 because it would be difficult to manufacture the wire frame so that it would make hyperbolic shapes of the correct aspect ratios. Feasibility was also given a score of 1 because the math behind this sort of design would be very complicated. Safety was given a score of 5 because the mesh would be very soft and would not pose a hazard to a child. Stability was given a score of 3 because these walls would offer some support to the overall design, but not as much as a solid wall. Finally, weight was given a 5 because this would be the lightest of the four wall design concepts. The total weighted score for the formable mesh walls is 3.6/5.0.

The piping frame had the highest weighted score of 3.8/5.0, and this was the concept that was chosen for our final design.

Base Concept Evaluation and Ranking

Our Pugh chart for base selection can be seen in Table 4. We gave safety and stability the highest weights of 20% each, because the base is the main part of the design that creates stability, which is tied into the safety of the overall design. Next, feasibility and weight were each given 15% because it is important that this critical part of our design is practical and because the base will most likely contribute the most to the overall weight of our design because it needs to provide enough support for the walls. Then, durability and ease of assembly were each given weights of 10% because the base needs to be able to withstand frequent use, but will not be subjected to as much battery as the walls, and it is alright if the base takes a bit longer to assemble because it is one of the more critical parts of the design and it is important that time is taken to ensure it is put together correctly. Finally, cost and ease of manufacturing were given weights of 5% each because the base is an important part of our design and we need to ensure that it is stable and secure, so the cost and manufacturing processes can be a little more involved in order to achieve this goal.

The four concepts we ranked were a solid base, hinged legs, slide in legs, and retractable legs, as discussed in concept generation.

Table 4: Pugh chart for ranking base concepts.

Base	**Weight**	**Solid Base**	**Hinged Legs**	**Slide in Legs**	**Retractable Legs**
Cost	5	1	5	5	3
Durability	10	5	5	3	1
Ease of Assembly	10	5	5	1	3
Ease of Manufacturing	5	3	5	1	1
Feasibility	15	5	5	5	1
Safety	20	3	3	3	1
Stability	20	5	3	3	1
Weight	15	1	3	3	5
	100	3.7	3.9	3.1	1.9

The solid base was given a score of 1 for cost, because it would be most expensive to create one solid piece from a large chunk of material. It was given a score of 5 for durability because with one piece, there would be no moving parts that could break. It was also given a score of 5 for ease of assembly because there would be nothing to put together - the piece would come fully assembled. For ease of manufacturing, the solid base was given a score of 3, because it would be slightly difficult to manufacture the solid piece and get the proper bearings in place in such a large part. It was given a score of 5 for feasibility, because this is a very practical solution that could easily be accomplished. It was given a score of 3 for safety because there would not be exposed parts to trip over. It was given a score of 5 for stability, because a solid base is the best way to produce a very stable mechanism. It was given a score of 1 for weight because one solid piece would have to weigh a lot to be stable. The total weighted score for the solid base is 3.7/5.0.

The hinged legs were given a score of 5 for cost, because it would not be very expensive to have legs, and the only necessary fasteners would be the hinges. It was given a score of 5 for durability because there would be no clipping parts that could break from use. It was given a score of 5 for ease of assembly because the only necessary step would be opening up the legs and placing the base on the ground to have the weight of the structure keep the legs in place; there would be no additional fasteners. It was given a score of 5 for ease of manufacturing because there would be no need to drill additional holes or slots for fasteners, only the attachment of the hinges. It was given a score of 5 for feasibility because it’s a very logical and straightforward design that could be accomplished in the time frame of the project. It was given a score of 3 for safety because the exposed legs could potentially be tripped over. It was given a score of 3 for stability because it would offer a stable base, but would be less stable than one solid piece. It was given a score of 3 for weight because it would be much lighter than one solid piece, but the individual legs would still need to be heavy enough to offer support. The total weighted score for hinged legs is 3.9/5.0, the highest overall, which was the concept chosen for our final design.

The slide in legs were given a score of 5 for cost, because it would not cost very much to drill the extra holes and cut the slots in the base. They were given a score of 3 for durability because they would have more moving parts that could be damaged by continuous use. They were given a score of 1 for ease of assembly because it would be difficult to put the parts together each time, and there would be a lot of parts that would need to line up precisely to fasten the legs in place. They were given a score of 1 for ease of manufacturing because there would need to be slots and keyholes in very precise places in order for the legs to be put together and support the weight of the structure. They were given a score of 5 for feasibility because they would be a practical solution for the design, and they could be created within the time frame of the project. They were given a score of 3 for safety because the exposed legs could be a tripping hazard. They were given a score of 3 for stability as well, because again they would offer a stable base, but not as stable as one solid piece. They were also given a score of 3 for weight because they would be much lighter than one solid piece, but the legs would need to be substantial to give support. The total weighted score for the slide in legs is 3.1/5.0.

The retractable legs were given a score of 3 for cost, because they would have more parts and be more expensive to purchase. They were given a score of 1 for durability because there would be many moving parts that could easily jam or break. They were given a score of 3 for ease of assembly because it would be simple to pull the legs to extend them. They were given a score of 1 for ease of manufacturing because it would be difficult to ensure that all the concentric cylinders were properly aligned and fit well enough together. They were given a score of 1 for feasibility because it is a very elaborate solution to the problem and is not practical. They were given a score of 1 for safety because the legs could potentially collapse and cause a safety hazard, as well as be tripped over. They were also given a score of 1 for stability because the potential for the legs to unintentionally collapse could cause the entire structure to tip over. They were given a score of 5 for weight because this would be a very lightweight and compact solution. The total weighted score for the retractable legs was 1.9/5.0.

Power Source Concept Evaluation and Ranking

Our Pugh chart for the power source selection can be seen in Table 5. We gave feasibility a weight of 20% because it was very important that the concept for the power source be practical Next, we gave durability and ease of use a weight of 15% each, because it is important that the power source be able to withstand constant use because it would be very difficult to replace, and because it must be easy to power the demo because of our target audience of 2-8 year old children. Next, we gave ease of assembly, ease of manufacturing, necessary applied force, and safety each a weight of 10%. It must be easy to assemble the power source, because a complicated gear train for example would take much longer than a half hour to assemble. It must be easy to manufacture because of the time constraints on our project. The power source must provide the necessary applied force to move the wall, because otherwise the demonstration would not work. Safety is also important because we don't want the child to get harmed while powering the demonstration. Finally, cost and weight were each given a weight of 5%. The cost is less important for this part of the structure because having the structure be human powered means that there will be no motor that we will have to purchase. The weight is also less important because this part of the structure is small, and will all in all contribute little to the overall weight of the structure.

Table 5: Pugh chart for ranking power source concepts.

Power Source	**Weight**	**Push on Wall**	**Moving Platform**	**Bevel Gears/crank**	**Belt**
Cost	5	5	1	3	3
Durability	15	1	1	3	5
Ease of Assembly	10	5	1	3	3
Ease of Manufacturing	10	5	1	3	3
Ease of Use	15	3	1	5	5
Feasibility	20	3	1	3	5
Necessary Applied Force	10	1	1	5	5
Safety	10	1	1	5	5
Weight	5	5	3	3	3
	100	2.9	1.1	3.7	4.4

The four concepts we ranked were the two types of directly applied force - child pushing on the wall and the moving platform - and the two types of transmission - a bevel gears/crank system and a belt system. These four concepts are discussed in the concept generation.

Pushing on the wall was given a score of 5 for cost, because it would require no additional parts to be purchased or added to the design. It was given a score of 1 for durability because continuous pushing on the wall could damage the wall and lead to failure. It was given a score of 5 for ease of assembly and ease of manufacturing because there would be no extra parts to assemble or manufacture. It was given a score of 3 for ease of use, because it might be difficult for a young child to produce enough force to move the wall and because they might have to push at an awkward angle. It was given a score of 3 for feasibility because even though it is a simple and logical solution, it might fail in its execution. It was given a score of 1 for necessary applied force again because young children might not be able to exert enough force to move the wall. It was given a score of 1 for safety because it could be dangerous having a child simply push on the wall and it could be difficult to have some sort of limit on how quickly they could push the wall. It was given a score of 5 for weight because there would be no added parts to increase the weight. The total weighted score for the power source of pushing on the wall is 2.9/5.0.

The moving platform was given a score of 1 for cost, durability, ease of assembly, ease of manufacturing, ease of use, feasibility, necessary applied force, and safety. It would be an expensive design because it would require adding a track and a new support system for the platform. It would not be durable because these added parts, especially the track and wheels system could easily break. It would be difficult to assemble the track and align the platform with the track. This would also be a very difficult part to manufacture. It would be difficult to use because the child pushing on the platform to move it would have to weave in and out of the stationary walls, and it would be difficult for them to find a place on the platform to push. It is not a very feasible design because of all the complicated design factors it would require. It would be difficult to provide the necessary applied force because the child would have to push up to 80 pounds (the maximum allowed weight of the child on the platform). It would also be very unsafe to have the child in motion on the platform, and there would be many pinch points, especially between the wheels and the track. Finally, the moving platform was given a score of 3 for weight because the track would add a significant amount of weight to the overall weight of the structure, but could potentially be made from lightweight material. The total weighted score for the moving platform is 1.1/5.0.

The bevel gears and crank transmission was given a score of 3 for cost because it would be relatively expensive to purchase the necessary shafts and gears, but there would be less parts total compared to the track required for moving the platform. It was given a score of 3 for durability because there would be less moving parts and they would be protected by some sort of barrier, so they would be less exposed and less easily broken. They were given a score of 3 for ease of assembly and ease of manufacturing because it would be fairly easy to put these parts together, and the manufacturing would not be that difficult because the gears and shafts could be ordered from stock. However, it would be difficult to properly align the bevel gears. It was given a score of 5 for ease of use, because the child would only have to turn a crank. It was given a score of 3 for feasibility because it is a logical solution to the problem, though perhaps not the most simple. It was given a score of 5 for necessary applied force because through the proper gear reduction, it could be very easy to turn the crank and produce enough torque to spin the center axis. It was given a score of 5 for safety because these parts would be encased so they would not pose any pinching hazards, and neither child would be in motion. It was given a score of 3 for weight because it would add some parts to the overall design, but not very large or heavy parts. The total weighted score for the bevel gears and crank transmission is 3.7/5.0.

The belt transmission was given a score of 3 for cost because it would be relatively expensive to purchase the correct belt, but the number of necessary parts and materials would be low. The durability was given a score of 5 because there would not be many moving parts to break and they would be encased in a protective barrier. It was given a score of 3 for ease of assembly and ease of manufacturing because the limited number of moving parts could relatively easily be put together, and it would be fairly easy to manufacture the transmission because most parts would be ordered to our specifications. It was given a score of 5 for ease of use because all the child would have to do to turn the center axis would be to turn a wheel. It was given a score of 5 for feasibility because this is a very practical design for remote turning of the walls that requires limited parts. It was given a score of 5 for necessary applied force because through the proper reduction the child could very easily turn the center axis by turning the wheel. It was also given a score of 5 for safety because the parts would be encased to prevent a pinching hazard and neither child would be in motion. It was given a score of 3 for weight because there would be some added parts to the design, but they would be small and lightweight. The total weighted score for the belt transmission system is 4.4/5.0.

The belt transmission system had the highest total weighted score of the four concepts, and was the concept chosen for our final design.

Platform Features Concept Evaluation and Ranking

Our Pugh chart for selection the platform features can be seen in Table 6. Adjustability was given a weight of 20% because it is important that children from the entire target age range of 2-8 years old can be situated in the platform. Next, ease of use was given a weight of 15% because it's important that all children can easily get on the platform to situate themselves. Next, cost, durability, ease of manufacturing, and feasibility were all given a weight of 10% each. Cost is important because these are additional features that are not critical to the function of the design, and should therefore not contribute much to the total cost of the structure. Durability is important because children will be directly touching these parts of the structure the most and they should withstand continued use. Ease of manufacturing is important again because these features are not critical to the design, and we should not dedicated too much time towards these features. Feasibility is important because these features need to be practical in order to make them worthwhile to include. Finally, ease of assembly and weight were each given a weight of 5%. These features will be built into the design and will not need much time to assemble each time the structure is put together, so the ease of this assembly is not critical. The weight of these features is also minimal.

Table 6: Pugh chart for ranking platform features concepts.

Platform Features	**Weight**	**Seat Belt**	**Handles**	**Cutout Steps**	**Sliding Step**
Adjustability	20	3	5	5	5
Cost	10	5	5	5	3
Durability	10	1	5	5	3
Ease of Assembly	5	3	5	5	3
Ease of Manufacturing	10	5	5	3	1
Ease of Use	15	3	5	5	3

Feasibility	10	5	5	5	3
Safety	15	3	3	5	3
Weight	5	5	5	5	3
	100	3.5	4.7	4.8	3.2

The four concepts we ranked can again be broken up into two types: restraint and step concepts. The two restraint concepts, seat belt and handles, are on the left, while the two step concepts, cutout steps and a sliding step, are on the right. These concepts are discussed in concept generation.

The seat belt was given a score of 3 for adjustability, because it would be able to extend, but the main clasp would have to be fixed. It was given a score of 5 for cost because it would be fairly inexpensive to purchase. It was given a score of 1 for durability because it would be a fabric which children would grab onto, dirty, and potentially tear. It was given a score of 3 for ease of assembly because it may need to be snapped into place each time the demo is assembled, which would be easy but would take some time. It was given a score of 5 for ease of manufacturing because the only extra step would be drilling holes for the attachment of the seat belt to the platform. It was given a score of 3 for ease of use because most children would be able to buckle themselves in, but younger children might need assistance. It was given a score of 5 for feasibility because this is a very straightforward and simple solution. It was given a score of 3 for safety because while the seat belt would keep the child secure on the platform, it poses a hazard if the child slips out the bottom of the platform or if they get caught in the seat belt and cannot get themselves loose. The straps could pose a choking hazard. Finally, it was given a score of 5 for weight because it would be a very lightweight part. The total weighted score of the seatbelt is 3.5/5.0.

The handles were given a score of 5 for adjustability, cost, durability, ease of assembly, ease of manufacturing, ease of use, feasibility, and weight. The handles allow the child to hold on wherever is comfortable for them, allowing them to adjust the feature to fit themselves without moving any parts. The cost of two handles would be very inexpensive. They would be durable because they would be made out of metal or plastic that would not break or bend through consistent use. There would be no necessary assembly for the handles, because they would be screwed in during the manufacturing process. They would be very easy to manufacture because the only additional step would be drilling holes in the platform, and the placement of these holes would not be critical. They would be easy to use because the child would simply need to grab onto the handles and they wouldn’t have to buckle themselves into anything. This is a very feasible solution because there is not much that can go wrong with the execution and use of this concept. They would be very lightweight as well. The handles were given a score of 3 for safety because they depend on the child holding themselves to the platform. If the child lets go, either purposefully or accidentally, or is knocked off, there is nothing keeping them in place. The total weighted score of the handles is 4.7/5.0.

The cutout steps were given a score of 5 for adjustability, cost, durability, ease of assembly, ease of use, feasibility, safety, and weight. They would be easy to adjust because steps of various height would be built in, and there would be nothing to change from user to user, the child would simply climb up to whichever step is most comfortable. They would be inexpensive because it requires no extra purchases. They would be durable because there are no moving parts that could break. They would be easy to assemble because there would be nothing to put together - the platform would come with the steps cutout. They would be easy for the child to use because they simply have to climb up and put their feet in the most comfortable cutout. This is a very feasible solution because it is very simple and requires no extra parts. It is safe because there are no moving or protruding parts that could break and cause the child to fall. The cutout steps would actually reduce the weight of the overall structure by removing material from the platform for the steps. The cutout steps were given a score of 3 for ease of manufacturing because it might be slightly difficult to machine slots out of the large platform. The total weighted score for the cutout steps is 4.8/5.0.

The sliding step was given a score of 5 for adjustability because the step would be able to be fixed at any desired height. It was given a score of 3 for cost, durability, ease of assembly, ease of use, feasibility, safety, and weight. It would require purchasing extra parts, which would slightly increase the cost of the structure. There would be extra moving parts, which would not be very durable, especially because the weight of a child would be resting on these moving parts. It could be difficult to assemble, because the step would have to be inserted into the platform each time. It would be relatively easy to use, but it would need to be adjusted each time, and the child would have to step off of the platform in order for the step to be adjusted. It is a logical idea, but it may be hard to implement, which decreases its feasibility. The potential for the step to break makes it unsafe. Finally, adding an extra piece would slightly increase the weight of the structure, but not significantly. The sliding step was given a score of 1 for ease of manufacturing, because it would be difficult to create a step that would lock at any desired position. The total weighted score for the sliding step is 3.2/5.0.

Because the two types of concepts were different and could be implemented together, we chose the best concept from each type. The handles were the highest scoring restraint concept, with a score of 4.7/5.0, and the cutout steps were the highest scoring step concept, with a score of 4.8/5.0. These were the two platform features chosen for our final design.

Complete Design Ranking and Final Design Selection

After looking at each of the four main parts of the overall design individually, we also looked at complete designs to look at how different concepts would work together to ensure that we not only chose the best concepts, but the concepts that would work the best together for the structure as a whole. The four designs we chose were as follows.

Design #1 had solid folding walls that were moved by a child pushing directly on the wall, a solid base, a sliding step, and handlebars. The solid walls would be most able to withstand a child pushing directly on the wall, and would also require a solid base in order to support the additional weight of a solid wall. The platform, because it is stationary, would also have a solid base.

Design #2 had slide in changeable walls, slide in legs, a moving platform, cutout steps, and a seat belt. The slide in changeable walls have the same idea behind them as the slide in legs, and make sense to be in the same overall design. The moving platform goes well with this concept because not moving the slide in walls will increase their stability and durability. With the moving platform, it would be good to have some sort of seat belt to ensure the child stays in place and does not wobble or fall.

Design #3 had formable mesh walls, retractable legs, a bevel gear/crank transmission system, a sliding step, and a seatbelt. The formable mesh walls and the retractable legs are both the lightest options, and make sense to be in the same design, because this is the only type of walls that the retractable legs would easily be able to support. The bevel gear/crank transmission system will also work well with the retractable legs because the horizontal shaft will easily be able to access the center rod to provide the rotation.

Design #4 (our final design) had a piping frame, hinged legs, a belt transmission system, cutout steps, and handlebars. The piping frame and hinged legs make sense together, because the hinged legs will easily be able to support the weight of the lighter piping frame. The belt transmission system also makes sense with the piping frame, because this sort of design would have to be moved by a transmission rather than being directly pushed. The cutout steps and handlebars also make sense together because a child would have to lay on their stomach in order to use both.

We ranked each of the designs in a Pugh chart based on their components, as seen in Table 7. Each component was given a different weight based on its overall importance to the design. The walls and base were each given a weight of 30%. The walls are important because they are the part of the demo that shows the math, which is the main point of the demonstration. The base is important because it provides the main support for the structure. The structure would not be able to function without a stable base. The power source was given a weight of 25% because moving the walls is also a key part of the function of the demo that give another physical demonstration of the math. Finally, the platform features were given a weight of 15% because they are important to situate the child in the demo and ensure their safety.

Table 7: Pugh for ranking entire design concepts.

Final Design	**Weight**	**Design #1**	**Design #2**	**Design #3**	**Design #4**
Walls	30	2.0	3.2	3.6	3.8
Base	30	3.7	3.1	1.9	3.9
Power Source	25	2.9	1.1	3.7	4.4
Platform Features	15	3.95	4.15	3.35	4.75
	100	3.0275	2.7875	3.0775	4.1225

The values for each component of each design come from their total weighted score in the Pugh chart for each individual part. For example, the walls for Design #1 are the solid walls, so the value of 2.0 for the walls of Design #1 comes from the total weighted score of the solid walls. The values for the platform features are calculated slightly differently, because each design has two platform features, one restraint feature and one step feature. The value for the platform features is an average of the two platform features in the design, one of each type. For example, Design #2 has cutout steps and a seatbelt, so the value for platform features for Design #2 is the average of 4.8 and 3.5, or 4.15.

From this Pugh chart, we can see that Design #4 has the highest score of 4.1225. This was selected as our final design, as seen in Figure 20 on page 23. As previously discussed, our final design has a piping frame with replaceable inserts of different aspect ratios. The base has hinged legs. The power source is a belt system. The platform features are handles and cutout steps. We also decided that because the platform is stationary, it will have the same base structure as the main base for the center axis.

Additional Concepts

After determining the components that addressed the four main areas of our design, as a team we developed a few other component concepts we felt completed our system. These ideas did not fit into any particular function or part of the overall mechanism, and were mostly unique ideas with no similarities to other concepts. These components were integrated into our final design in Figure 20.

With an adjustable aspect ratio, the angle of the platform must be adjustable to ensure that the platform fits correctly through the hyperbolic cutout in the wall. This ties back to the math behind the shape. The only concept we generated to make the angle of the platform adjustable was a pin system, as seen in the final concept. The pin could be removed, the angle of the platform adjusted, a hole lined up with the hole in the supporting rod of the platform, and the pin re-inserted. This would ensure that the platform was kept at the correct angle during use, but would also be easily adjusted.

For supporting the platform, all of our concepts used a ground support rather than a horizontal rod connecting the platform to the center axis. This was mostly a physical restraint, because of weight considerations and moments induced on the base.

We also had the idea to have a covering over the base, especially for the leg concepts. This would prevent children from tripping over the exposed legs and would provide a solid surface.

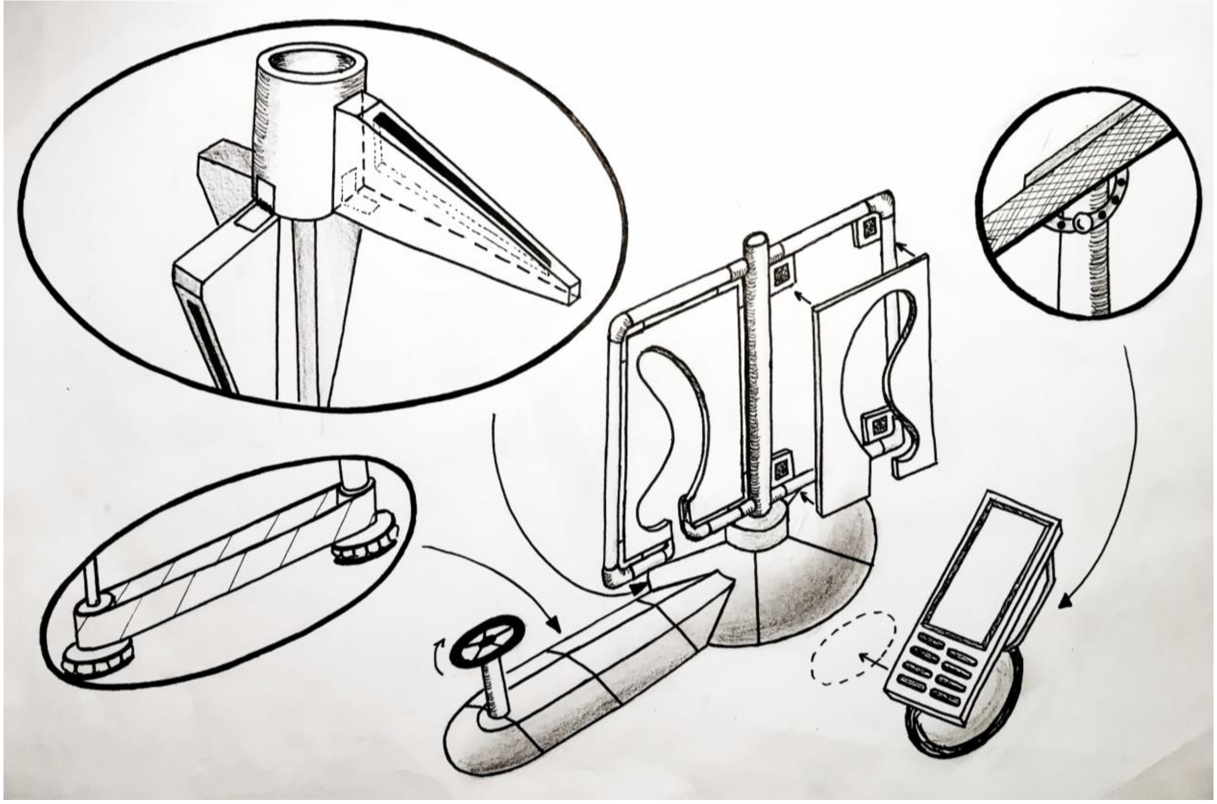

Figure 20: Final Design.

Key Design Drivers and Challenges

After selecting a final design from the different concepts we developed, we verified that this final design meets the engineering specifications we determined from the user requirements. This verification comes in the form of key design drivers (Table 8) that address the various specifications.

The engineering specification requiring that the educational demo support a weight of 80 lbs, and that it must be large enough for a 54.5” individual are encapsulated in the design drivers that the Educational Demo must target the appropriate user age range and be stable. If our final product lacks these traits, then Prof. Strauss will not be able to use the demo for his specified age range, and it may present certain safety issues related to tipping. We will have to determine the demo’s center of mass, and the required forces and torques to be input to the demo to ensure that users in the target age range can operate the demo safely and efficiently. To achieve these goals, we will need to analyze the strength of the demo, namely the shape of the platform and the materials we choose for the platform. The material and size of the platform must not yield under the load of the target user age range.

The safety specifications - pinch points less than one inch and rotation no greater than six rpm - are captured in the design driver stating that the educational demo must be safe to operate. If the demo is unsafe to operate, severe injury may ensue due to the demo’s moving parts. To ensure safety we will insert IR proximity sensors near potential pinch points on the demo. We predict that a sufficient threshold proximity is one inch, and we can verify this threshold or change it based on testing on a physical prototype of the demo. Regarding controlled rotation, we predict a safe operating speed of six rpm could be controlled by adding more weight to the demo to dampen the applied force. However, a challenge with adding more weight is that we have a maximum weight requirement discussed previously of 28.7 lbs. Through our engineering analysis we will determine if there are other methods for controlling the rotational rate of the demo and an optimum weight that will not exceed our weight specification to ensure we meet the safety specifications.

The transportability of the educational demo, another design driver, supports the engineering specification that the demo weigh less than 28.7 lbs and be contained within a volume of 3 ft by 2.5 ft by 2 ft when disassembled. For this to be met, the assembly must be disassembled into multiple parts and be lightweight, thus easy to carry. If we fail to achieve this specification, it will be cumbersome for a single individual (namely Professor Strauss) to transport the demo from his car to the demonstration site, and it may be difficult for the demo to fit in his car. We will need to consider the spatial dimensions and weights of the disassembled components in order to achieve this engineering specification. There is the potential to run into cost difficulties because materials tend to be more expensive as specific strength (strength per weight) increases, and our budget is currently limited to $400. It could be challenging to design a strong structure for the demo while also maintaining a lightweight design.

An important design specification is to be able to assemble and disassemble the educational demo in no more than 30 minutes. The design driver supporting this specification is that the demo must be easy to assemble and disassemble, for if the demo is not and requires too much time and effort (e.g. greater than 30 minutes), then this will deter Professor Strauss from wanting to bring the demo to classrooms and museums to demonstrate the mathematical concepts to children that he wishes to convey. To ensure ease of assembly and disassembly, we must measure forces required for putting together and taking apart the various components of the demo, and measure the time it takes to assemble and disassemble the demo. The more complex the design and the more parts required for the complete assembly, the more time it will take to assemble and disassemble. Therefore, a foreseeable challenge is to design an optimal number of parts that provides the functionality the demo requires and does not make the assembly and disassembly take too long. We will analyze all functions of our design to ensure that our final design concept is in fact our simplest competent model.

Two user requirements that were difficult to quantify into engineering specifications were the requirement that the educational demo be “educational” by teaching the desired mathematical concepts and “fun” by being interactive and aesthetically interesting to the target age range. If the educational demo is not educational, then Professor Strauss would not want to use our final product. If the educational demo is not fun, then users in the target age range (or of any age) may not want to use the demo. Though these requirements may be difficult to gauge numerically, we can do research on the level of mathematics that is comprehensible to and what colors and/or textures are attractive to the target age range. We can validate these design drivers with focus groups of teachers and children in the target age range.

Table 8: Key Design Drivers

Driver ID (Educational Demo Must…)	Description	Importance	Design Driver Analysis	Validation
Target appropriate user age range	Educational Demo must support the weight and accommodate the height of a user between the ages of 2 and 8	If a user between the ages of 2 and 8 is not supported by and/or does not fit into the demo, then the sponsor will not use the demo for his desired target audience	Determining forces and moments applied by users; choose appropriate materials with desired strength, hardness properties;	Test of physical prototype
Be stable	Educational Demo must remain upright to function properly and maintain a safe user environment	If the demo were not supported well, or otherwise become unstable, then the demo would tip, creating safety issues for users	Determining center of mass, and moments/forces acting on the demo, to ensure appropriate support by the base	Test of physical prototype; apply loads
Be safe to operate	Educational demo must not cause any user injury under normal operating conditions	If the demo were unsafe to a user, then we would be unable to use the demo to educate about the desired mathematical concepts	IR proximity sensors at potential pinch points; damping to ensure controlled rotation	Testing of physics prototype with sensors attached
Be transportable	Educational demo must be light enough for an individual to carry, and compact enough to be placed in the trunk of a "regular car"	If the demo were too heavy, then a single individual would be unable to carry it, and would need help to transport it; if the demo were too large, it would not fit into a "regular car" and our sponsor would have to rent a larger vehicle.	Measure the volume/maximum dimensions when disassembled; weigh the assembly;	Ensuring the sponsor can lift the demo and fit it into his car
Be easy to assemble and disassemble	Educational demo must be easy to assemble and disassemble, and if done by a single	If the demo were to be difficult to assemble or disassemble, then it could deter Prof.	Measure force required to secure components; measure time to assemble and	Create instructions manual for assembling and disassembling, and collect a focus

	individual must take less than 30 minutes	Strauss from wanting to use the demo	disassemble	group, and observe as they assemble and disassemble the demo
Be easy to assemble and disassemble	Educational demo must be easy to assemble and disassemble, and if done by a single individual must take less than 30 minutes	If the demo were to be difficult to assemble or disassemble, then it could deter Prof. Strauss from wanting to use the demo	Measure force required to secure components; measure time to assemble and disassemble	Create instructions manual for assembling and disassembling, and collect a focus group, and observe as they assemble and disassemble the demo
Have an educational factor	Educational demo must be educational. It must demonstrate the mathematical concepts at an appropriate age-level for the target users	If the educational demo were not educational, then it would simply be a demo. Also, the sponsor would not be able to convey the math associated with the project to the target users	Match mathematical concepts with what the target users are learning in school	Collect focus group of users within target age range; use focus group of teachers for target age range;
Have a fun factor	Educational demo must be interactive, colorful, capture the attention of target users	If it is not fun, the users will not have a positive learning experience with the demo	Research fun colors, textures; ones that are agreeable with children	Focus group target users

Chosen Design Mockup

After comparing our chosen concept to our key design drivers, we constructed a mockup. This mockup was made using materials supplied in the assembly room, along with materials brought from home. The materials used were wood, paper, foam, Styrofoam, and cardboard, as seen in Figures 21 through 23. While constructing our mockup, we discovered a few potential complications to keep in mind as we finalize the specifics of our design.

The first complication we discovered is that the distance between the base of the center axis and the base of the platform is shorter than we anticipated and the legs of each may not fit in the space. A potential idea to resolve this issue is making the walls wider and increasing the distance between the center axis and the holes on the inserts.

The second complication we discovered through making the mockup is that the insert is not well supported in the middle and is loose and doesn't stay in place when the structure is rotated. We will need to take this into consideration when choosing the material for the inserts. A potential idea to resolve this issue would be to add a horizontal beam at the midpoint of the frame to support the cutout, as seen in Figure 23.

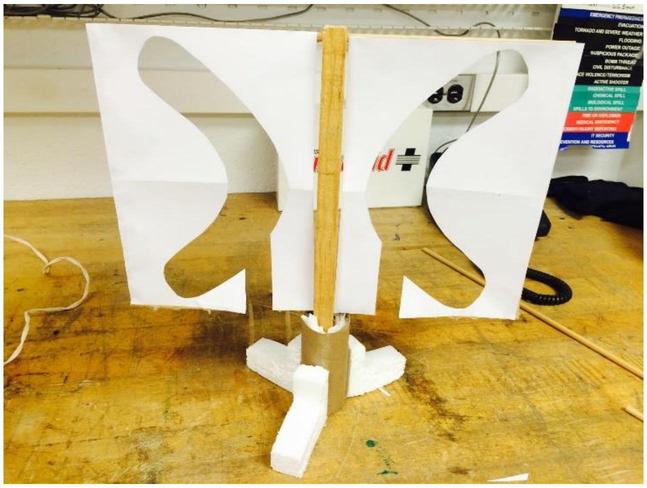

Figure 21: Mockup of wall

Figure 22: Mockup of platform

Figure 23: Mockup wall and platform together

Concept Description

Our final concept can be seen as a whole in Figure 24. The main module consists of a center axis supported by a base with hinged legs, as well as a piping frame and fabric wall inserts. The platform has a supporting axis, a base with hinged legs, and the seat for the child.

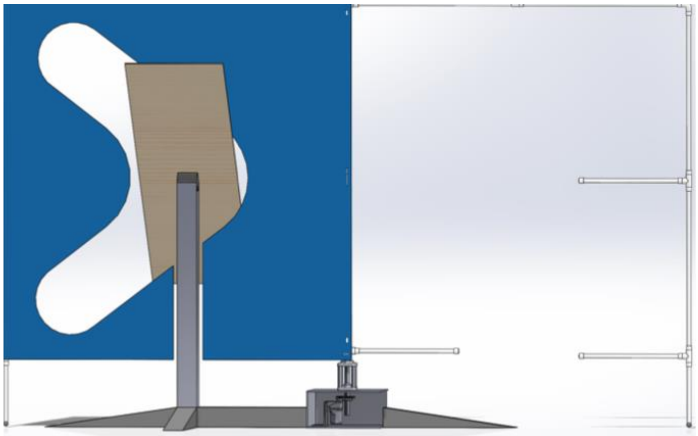

Figure 24: Final Concept as a Whole

The base and center axis of the main module can be seen in cross section in Figure 25. The base consists of two parts - a bearing housing and a motor housing. An aluminum shaft is inserted into the PVC cross at the bottom of the center axis and held in place with a pin. The aluminum shaft is press fit into the bearings. The bearing housing is two concentric locking flange bearings that are separated by spacers. Having two bearings will also prevent wobbling of the structure. The bearings are held together by shoulder bolts that go through each bearing housing and through the top of the motor housing to keep the entire base of the main module together and aligned. Inside the motor housing is the motor, which is held in place by an angle bracket screwed to the bottom plate. The pinion on the motor meshes with a gear mounted on the aluminum shaft using a key.

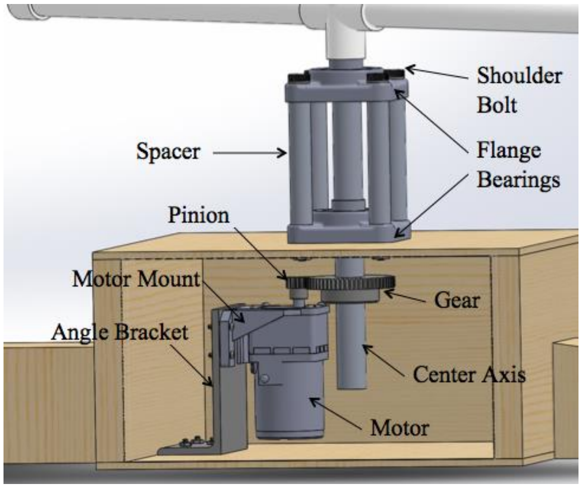

Figure 25: Cross Sectional View of Base and Center Axis

The legs are attached by hinges to the bottom of the cylindrical housing of the base. There is a cutout on the bottom of the cylinder and legs that allow the hinge to fold and sit in this gap when fully unfolded, preventing the weight of the structure from sitting on the hinge (Figure 26). There will be three legs on the base. They will be trapezoidal in shape and made from wood.

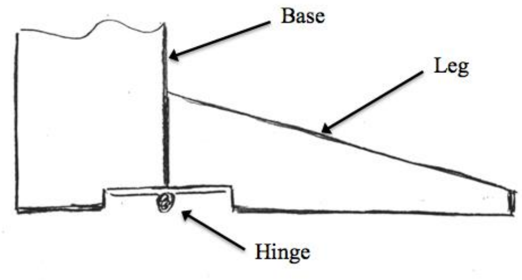

Figure 26: Hinge Attachment of Legs to Cylindrical Housing of Base

The center axis is made of three pieces. A 1 inch aluminum shaft will be fixed in the housing of the base and two more pieces will be attached on top of this through a pin and couples. Attached to the center axis is the piping frame. The piping frame is also made of PVC piping with a diameter of ½ inch. The frame is attached at the top of the center axis by a ¾ inch three way T attachment and at the bottom by a ¾ inch four way attachment, as seen in Figure 27. We will use 1 to ¾ inch and ½ to ¾ inch adaptors from the PVC piping of the center axis and the frame, respectively, to the attachments. This allows us to increase the diameter of the center axis to allow for greater stability, as well as decrease the diameter of the frame to make it lighter and more easily supported. Because we will have two walls, the piping frame extends on both sides of the center axis. This balances the center module. There will be couples halfway along the top of the frame to attach two sections of pipe together. This will allow us to break down the the frame into smaller pieces. At the corners of the frames are ½ inch 90 degree elbows. There is ½ inch three way T attachment halfway down the exterior edge of the frame that has a ½ inch pipe coming into the area of the wall. The purpose of this pipe is to provide extra support for the wall insert and to ensure that it keeps its shape and does not flap as the wall rotates. We will also include extensions of the piping frame at each bottom corner with castor wheels in order to provide another point of support for the frame to prevent sagging as well as to aid the rotation. At each end of the PVC piping not connected to a joint or another section of piping there will be an appropriately sized cap. The sections of piping frame are connected to each other and to the joints through threaded adaptors. We will attach the adaptors to the pipe by cleaning and priming the adaptor and pipe and gluing them together. Then, the frame will be assembled by screwing the adaptor end of the pipe into the joints.

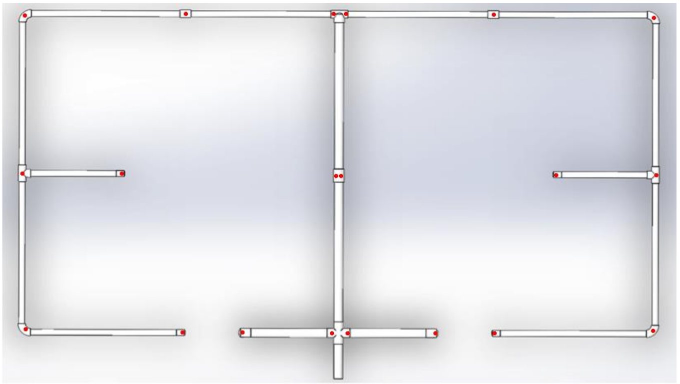

Figure 27: Frame, Center Axis Piping Shape, Attachments; Red Dots indicate Velcro Location

The wall inserts are made from tarp with a hyperbolic cutout. The inserts will be attached to the frame by velcro. There will be 10 points of attachment around each insert, 3 on the top, 3 on each side, 3 on the bottom, and 1 at the tip of the supporting pipe, as indicated by the red dots in Figure 27. We will have three inserts of different colors with aspect ratios of .5, 1, and 1.5.

The platform consists of the seat for the child, the supporting rod, base, and legs. The platform is a solid piece made of high-density polyethylene (HDPE) with an adjustable step made of wood. The platform can be seen below in Figure 28.

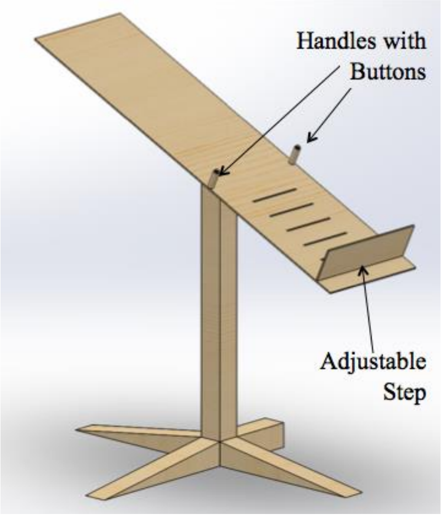

Figure 28: Platform

The step will be adjusted on a slide. There will also be handles attached on the sides of the platform that will have buttons. The user will be required to press these buttons in order to run the motor that spins the wall. The supporting rod of the platform is a 4 in by 4 in piece of Yellow Pine wood, which fits into a base with a rectangular cutout to support it and prevent rotation. Similar to the base of the main module, there will be three hinged legs attached to the base of the platform. The angle of the platform will be adjustable in order to correspond with the inserts of varying aspect ratios. This will be accomplished by having the platform mounted on a cylinder that fits into a hollow cylinder mounted on the platform's supporting rod and rotates within it. Then, a pin can be inserted through a bracket on the side to hold the cylinder - and thus the platform) at the correct angle. This can be seen in Figure 29.

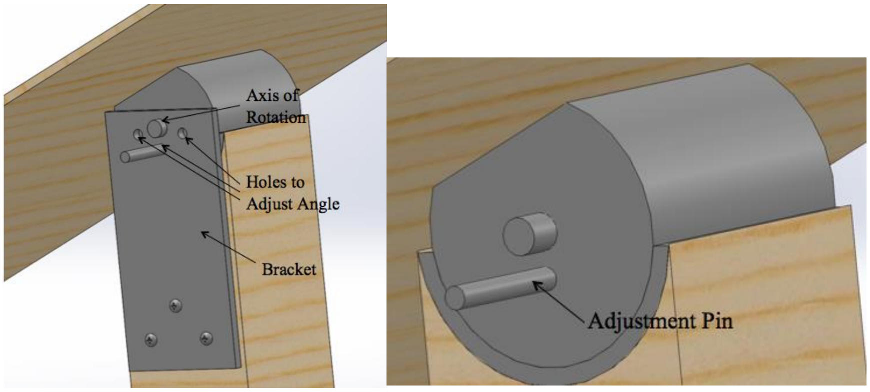

Figure 29: Mechanism for Angle Adjustment of Platform

Between the platform and the main module, there will be a connecting rod that serves three purposes. The first is to offer more support to the platform so that it does not tip when a child climbs on it. It will act as a fourth leg for the platform and the main module. The second purpose is to ensure that the platform will be the correct distance from the center axis of the main module. This is important to make sure that the platform will be able to fit through the hyperbolic cutout properly. The third purpose is to hold any wiring that will need to be fed from the buttons on the platform to the main base. This will prevent any loose wiring that could be a hazard.

Engineering Analysis

As discussed in Key Design Drivers and Challenges in Table 8, our design drivers are that the demo must be stable, be safe to operate, be transportable, be easy to assemble and disassemble, target the appropriate age range, and have an educational and a fun factor. We used engineering fundamentals and principles of various scientific fields to evaluate and analyze our design based on aspects of these design drivers.

Be Stable

Stability can be evaluated by looking at solid mechanics to determine the center of mass of the main module and platform to prevent tipping. We did this analysis through theoretical modeling, which is an appropriate choice because it is not feasible to do any physical testing of a full scale model. We also did theoretical modeling to ensure that our material choices were appropriate and that our demo would not fail.

Tipping: In order to determine the required length of the legs of the main module so that the demo would not tip, we did a force and moment analysis. We analyzed what we determined to be the 'worst case' scenario: a child hanging from the top corner of the frame. Our free body diagram can be seen in Figure 30.

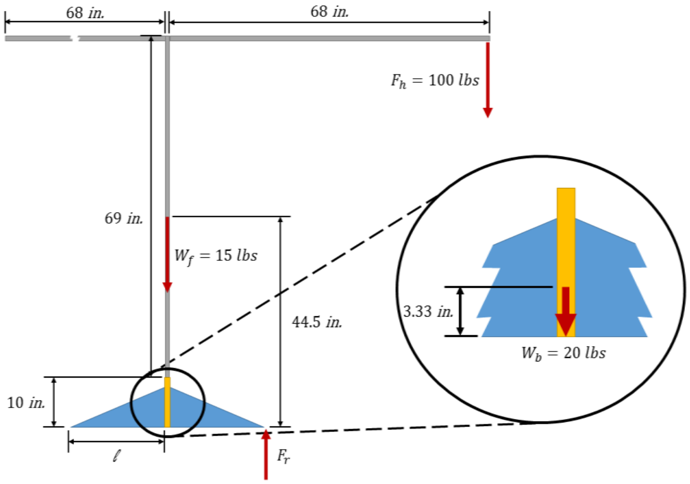

Figure 30: Free Body Diagram of Tipping Analysis

F_h is the hanging force, which we determined to be 100 pounds, or the weight of an 8 year old child with a 1.25 safety factor. F_r is the reaction force between the ground and the leg. We estimated the weight of the frame (W_f) to be 15 pounds and the weight of the base (W_b) to be 20 pounds for the purposes of this calculation. These are purposely slight overestimates, because calculation of stability does not need to be very detailed. Rather, it would be better to have a more rough calculation with appropriate overestimates to build in extra safety factors in our calculation. We calculated the center of mass of the frame and base separately. Their locations, as seen on the free body diagram, are ½ the way up the frame (44.5 in from the ground) and ⅓ the way up the base (3.33 in from the ground), respectively. Other dimensions of the frame are pictured on the free body diagram, with l representing the length of the leg necessary to prevent tipping.

$$\Sigma F_y = 0 \qquad \text{Eq. 2}$$
$$\Sigma M_o = 0 \qquad \text{Eq. 3}$$

Summing the forces in the vertical direction and moments about point O, as seen in Equations 2 and 3, we found that the legs must reach 29 inches from the center of the module, so subtracting the 2 inch radius of the center axis and housing, this means that the legs must be 27 inches long each. This seems functional and would be proportional. We are confident in this analysis and have not overlooked any technical issues. The analysis for tipping is complete and no further calculations are necessary.

Yield Analysis: We performed a yield analysis on the center axis, made of 1 inch PVC pipe, to determine if it would fail when subjected to a 100 lbf (444.8 N) load, as seen in the free body diagram in Figure 31.

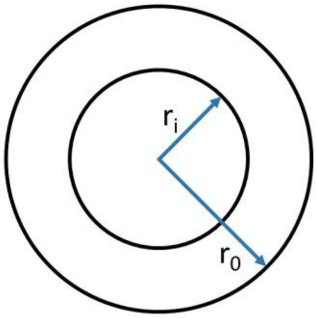

Figure 31: Free Body Diagram

Because we are analyzing a pipe, the cross section is an annulus. The outer diameter,Do, of the 1 inch PVC is 1.315 in, or 33.40 mm, giving an outer radius, r_o, of 16.70 mm. The inner diameter, Di, is 1.003 in, or 26.24 mm, giving an inner radius, r_i, of 13.12 mm. The thickness of the pipe, t, can then be calculated as 3.58 mm.

We first checked to see if a thin wall approximation was appropriate using Equation 4. The wall thickness was more than one-tenth of the outer radius, so the thin wall approximation was not valid.

$$\frac{t}{r_0} < 0.1 \qquad \text{Eq. 4}$$

Failure Due to Normal Stress: The normal stress (n) can be calculated from Equation 5

$$n = \frac{F}{A} \qquad \text{Eq. 5}$$

where F is the applied force and A is the cross sectional area. The cross sectional area of an annulus can be calculated from Equation 6 as

$$A = r_0^2 - r_i^2 \qquad \text{Eq. 6}$$

We can then use Equation 5 to calculate the normal stress at 1.326 MPa, which is less than the ultimate yield strength, σ_u, of PVC, which is 52 MPa. Therefore, the pipe will not fail due to the normal stress.

Failure Due to Bending Stress: The bending stress in the pipe (σ) can be calculated from Equation 7

$$\sigma = -\frac{My}{I} \qquad \text{Eq. 7}$$

where M is the applied moment, y is the distance from the neutral axis of the cross section to the point of application of the moment (in this case r_o), and I is the moment of inertia of the cross section. The applied moment M can be calculated as seen in Equation 8 from the applied force F and the lever arm distance d, which is 64 inches or 1625.6 mm.

$$M = Fd \qquad \text{Eq. 8}$$

The moment of inertia of an annulus can be found using Equation 9.

$$I = \frac{\pi}{4}(r_0^4 - r_i^4) \qquad \text{Eq. 9}$$

We can then use Equation 7 to calculate the bending stress as 319.31 MPa, which exceeds the ultimate tensile strength of PVC pipe, indicating that the pipe would fail due to bending stress when subjected to this load.

To remedy this, we have decided to add an extra support on the bottom corner of each wall, as seen below in Figure 32. These will be castor wheels that will provide more support against a load applied on the top corner. They will also prevent sagging of the frame and will aid in the rotation of the walls.

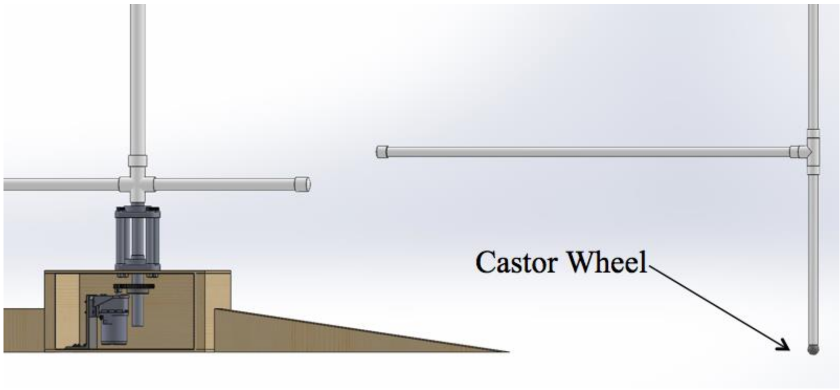

Figure 32: Castor Wheels to Provide Support Against Yielding

Fracture Analysis: We performed a fracture analysis of the hole for the pin that will connect the aluminum rod in the base to the PVC cross of the frame. A free body diagram can be seen in Figure 33.

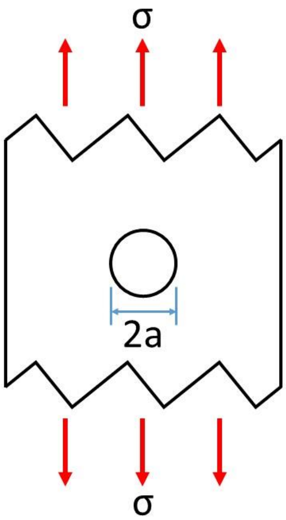

Figure 33: Free Body Diagram of Fracture Analysis

We did this by looking at the stress concentration factor, K_I, as seen in Equation 10

$$K_I = \sigma\sqrt{\pi a} \qquad \text{Eq. 10}$$

where σ is the fracture stress and a is the hole radius, in this case 0.125 in. We assumed the hole to be a circular hole in an infinite plate, giving a stress concentration factor of K_I=3. With an applied force of 100 lbf (444.8 N), we can find a stress of 319.3 MPa, which exceeds the fracture stress of PVC of 30 MPa. Because the fracture stress σ=30 MPa is less than the ultimate tensile stress u=52 MPa, the PVC will fail due to brittle fracture before it yields.

Again, we believe that adding the additional supports of the castor wheels will provide more support and lower the stress experienced at the hole - preventing it from failing in this mode.

Buckling Analysis: We performed a buckling analysis on the main axis and on the supporting rod of the platform. Both the main axis of the walls and the platform support can be approximated as a vertical column with one end fixed and the other end free to move (Figure 34). The vertical force on the top of the column required to cause buckling, Fc can be found from Equation 11 [21]:

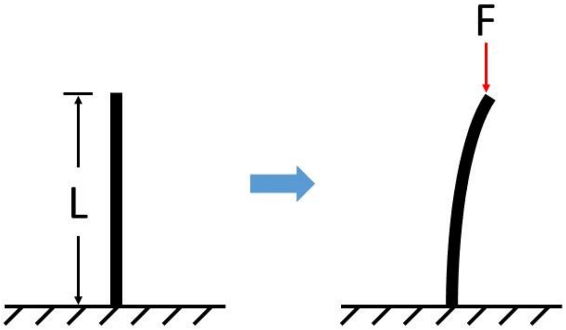

Figure 34: Free Body Diagram of Buckling of Center Column

$$F_c = \frac{\pi^2 EI}{(kL)^2} \qquad \text{Eq. 11}$$

where E is the Young's modulus, I is the moment of inertia as found from Equation 9, k is a geometric factor determined by the support conditions of the column, and L is the length of the center axis. For the case where the column has a fixed bottom and a top that is free to move, the geometric factor is 2.0. Then, we can evaluate *Fc*. Values for the main axis and the platform can be found in Table 9. From our buckling analysis, we determined that it is unlikely that the platform will buckle because the force required is significantly greater than any force a user in the target age range could exert. We also determined that the rotating walls could potentially buckle if a user in the target age range were to pull down on the walls from the top. We do not expect this to occur, however, because the educational demo will be supervised by our sponsor and/or a parent or guardian of the users. Therefore, neither column should buckle under standard operating conditions.

Table 9: Buckling analysis for PVC Main Axis and Yellow Pine Platform. We do not expect either to buckle under standard operating conditions.

Component	Young's Modulus (E, GPa)	Second Moment of Area (I, x10^3 mm^4)	Length (L, mm)	Force (F, N)
PVC, Main Axis	3.0 [22]	37.8	1830	83.7
Yellow Pine, Platform	6.0 [23]	5570	1240	53200

Bearing Analysis: We conducted an analysis of expected lifetime to determine the bearing size needed for the educational demo. The C10 rating of a bearing is a measure of the load carrying capacity. It is measured in Newtons and can be found in Equation 12, where F_D is the desired applied force in Newtons, L_D is the desired lifetime of the bearing in hours, L_R is the rated lifetime (assumed to be 10^6 hours since it is otherwise unstated in the bearing specifications), and a is a “shape” factor determined by the type of bearing. Since we decided that tapered roller bearings would theoretically be able to carry the loads in the demo, we used a = 10/3 [24].

$$C_{10} = F_D \left(\frac{L_D}{L_R}\right)^{\frac{1}{a}} \qquad \text{Eq. 12}$$

Under standard operating conditions, the weight the bearings would be carrying should weigh about 71.2 N, and we approximated that Professor Strauss would use the educational demo for at most 8 hours per week for 10 years, leading to a total of 4160 hours. These values give a C10 rating of 13.7 N, which, according to Table 11-3 in Shigley’s Mechanical Engineering Design, 9th Edition [24], would allow for any size bearing to support the loads and endure the lifetime we expect, since to design a strong enough shaft, one must select a bearing with a C10 rating greater than or equal to the C10 rating calculated with Eq. 12. This justifies our use of any size of bearing diameter that best fits our design.

Be Safe to Operate

Motor Selection: The safety of the demo can be evaluated by controlling the rotation of the demo, which we will accomplish by using a motor to power the rotation of the center axis. We performed theoretical modeling to get an initial idea of how much torque our demo requires, and used this to select a motor. We began our motor selection by doing a rough required torque calculation. Because of the design of the housing for the base of the main module, we had to select the gear to be affixed to the center axis first. The gear has to be large enough that the bore of the gear would fit over the 1 inch PVC pipe, which has an actual external diameter of 1.315 inches. The gear also has to be small enough that it fits inside of the housing, a dimension determined by the bearings. We selected a machinable gear that we could mill to a bore size of 1.315 inches and has an external diameter of 2.67 inches, which fits within the external diameter of the bearing (2.6875 inches). Then, using the pitch radius of this gear and the weight of the frame, we can determine the minimum torque that is required to rotate the module. With a pitch radius of 1.25 inches and a weight of 11.6 pounds, this torque is 14.5 in-lbs, or 1.6 Nm (Eq. 13).

$$T=Fd \qquad \text{Eq. 13}$$

In Eq. 13, T represents the torque caused by the applied force, F, at a distance, d, from the chosen pivot point.

Using this torque, we selected a motor with an appropriate range. We will be using the 2IK6UA-5A Induction Gear Motor. This motor has a rated torque of 1.59 lb-in. Other motor parameters are the power (6 W) and frequency, f, (60 Hz), and it has 4 windings, p. This motor also contains a gear box giving a reduction of 5:1. Given this information, we can determine the synchronous speed, n_s, of the motor using Equation 14.

$$n_s=2*60*f_p \qquad \text{Eq. 14}$$

Using Eq. 14, we determine the synchronous speed of the motor without the gearbox to be 1800 RPM. Given the 5:1 gear reduction attached to the motor, the synchronous speed comes out to be 360 RPM. The operating speed needs to be less than the synchronous speed, otherwise the motor will not generate any torque. We can also determine the slip, *s*, of our motor by measuring the operating speed and comparing that to the synchronous speed, using Eq. 15.

$$s=(n_s-n_{rns})/n_s \qquad \text{Eq. 15}$$

In Eq. 15, n_{rns} represents the operating or rotor speed of the shaft under loading. Given that there will only be 12 volts sent to the motor, lower than the rated 110 volts, we expect the operating speed to be about 40 RPM, given our desired wall rotating speed of 6-10 RPM and our further transmission reduction of 4:1. Therefore, we predict the slip to be 0.889, and will validate this during testing. The rotation of 40 RPM will translate to a torque of approximately 15 in-lb, or 1.69 Nm, which will be sufficient for our application.

Be Transportable

The transportability of the demo can be evaluated by ensuring that the total weight of the demo does not exceed the weight limit of 60 pounds and that it breaks down to fit in the back of a car. Although we would like the assembly to fit solely in the trunk - 3 ft by 2.5 ft by 2.5 ft, we can fold down the back seats for additional room. We analyzed our design on these aspects using theoretical modeling. We plan on doing more empirical testing of these requirements as we build our final design.

Weight: As we created our bill of materials, we calculated the total weight of the frame by summing the weights of each individual component, including the pipe, elbows, couples, crosses, tees, and adaptors. These specifications were provided on the Home Depot website for each part. We also accounted for the weight of the tarp insert, subtracting the weight of the hyperbolic cutout of the hole. The total weight of the frame was calculated to be 11.6 pounds. We will continue to calculate the weight of the platform and base as we finalize decisions on material selection.

Volume: The largest portion of the volume will be the frame. Broken down, this frame will include 14 pipes that are all 33 inches or less. This will result in a volume no more than 33 inches long and 4 inches tall and wide since the pipes can be stacked 4 by 4 and the widest pipe is 1 inch in diameter. The largest single piece will be the platform that the user will lay on. This platform is expected to be 6 feet tall which is too large to fit in the trunk. We will continue to look for ways to break up the platform into smaller pieces. We will continue to do empirical testing on parts of the design as we begin the building process.

Be Easy to Assemble and Disassemble

The ease of assembly and disassembly of the demo was evaluated through mockup construction. This is an appropriate mode of analysis because it is difficult to quantify the ease of a task. The only way we will get an approximation of how easy it is to assemble or disassemble the structure will be to construct a model. We measured the amount of time and the effort it took to construct a mockup of the demo, taking into consideration both the physical exertion required to assemble the parts as well as the number of parts that needed to be assembled.

Mockup Construction: In our original design, rather than having the threaded attachments, we intended to use slip fittings that would allow the user to press the pipe into each attachment to assemble and disassemble the frame. Using 2 ft pieces of 1 inch PVC pipe and slip fittings, we assembled a rough full size frame. Though the pieces were not precisely the right length, they provided a good estimate of how our design would work full scale.

From this mode of analysis, we learned a few things. First, the PVC was more difficult to assemble than we had thought. It took a significant amount of strength to connect the pipe to the joint, even only pushing the pipe in part of the way rather than fully inserting it. It was even more difficult to disassemble the frame and pull the pieces apart. We determined that this would not be suitable to meet the user requirement that the demo should be able to be disassembled in 30 minutes by one person.

Second, when the frame was assembled, the top rod was heavily cantilevered and the weight of the side pulled the corner of the frame down significantly so that it sagged a few inches, as seen below in Figure 35. We determined that this was because the pipes were not fully inserted into the joints and were not properly supported. However, it is not possible to press the pipes all the way into the joints and then easily remove them, as previously discussed.

Figure 35: Mockup Construction Shows Sagging Corner of Frame

To remedy this, we had the idea to use screw fittings rather than the smooth slip fittings. We will use adaptors that have a slip fit on one end which we will glue to the pipe. The other end of the adaptor will be screwed into threaded joints. This has two benefits. First, the joints will be much more secure because the pipes will be properly attached, fully inserted into the joint, and glued into place. This will prevent the excessive cantilever and sagging of the corner of the frame. Second, it will be much easier to assemble and disassemble the structure, because rather than having to push or pull on the piping with a great force, the user will simply have to screw or unscrew the pipe from the fitting. This will be a much more functional and reliable design. We plan on continuing to do mockup construction as we finalize our design and begin to build our final prototype to continue refining and optimizing our design.

Target Appropriate Age Range and Have an Educational and a Fun Factor

Finally, the educational and fun factors will be determined using empirical testing. We will consult local teachers for students in the target age range to determine that the mathematical concepts we are presenting, and the way in which we are presenting them, are appropriate for their students. To determine the fun factor of the educational demo, we will use a focus group of children in the target age range, and have them interact with the educational demo. We will survey them afterwards, and determine if they think it is a fun, interactive way of learning.

FMEA/Risk Analysis

In order to analyze the risk of failure of our design, we performed a risk analysis and FMEA in order to see what parts of our design could fail and lead to dangerous situations. This is especially important for our design because of our young target audience and our focus on safety. Our FMEA can be found in Table 10.

Table 10: FMEA

Item	Function	Potential Failure Mode	Potential Effects of Failure	Severity of Effect	Potential Causes of Failure	Occurs w/in year	Current Design Controls	Detection	RPN	Recommended Action
Base	Support Platform	Tips over	Break a bone or get bruised	9	Lack of proper support	2	Legs to support and prevent tipping	2	36	Do force analysis on center of mass of base and tipping point due to moment applied by child
Legs	Support main module	Child trips over legs	Child hits head, gets bruised or cut	5	Exposed legs	5	Give legs finish that makes them stand out/ noticeable	2	50	Read about ergonomical covers to prevent tripping
Platform	Adjust angle of Platform	Pin not inserted correctly - child falls	Break a bone or get bruised	8	Pin security not checked before use	2	N/A	3	48	Have detailed instructions/supervision
		Falls flat and slams	Child is frightened or pinches finger	5	Wear of material	4	N/A	3	60	Have detailed instructions/supervision

Wall Inserts	Rotates	May hit child in the head	Disoriented and distressed child	2	Incorrect usage	7	Design of platform and actuators on platform handles	4	56	Cut power when actuators not activated
				5	Platform not in correct location	2	Platform will be attached to main module at a fixed distance	3	30	Ensure platform is fixed at proper distance from main module to prevent it from contacting the inserts
Wall Frame	Supports Inserts	Piping falls apart	Child hits head, gets bruised or cut	5	Insufficient attachments between pipes	4	Piping is designed to not come loose	3	60	Do calculations on shrinking/expansion of pipes due to temperature
		Pull on frame and tip main module	Break a bone or get bruised	8	Lack of proper support	2	Legs to prevent tipping	3	48	Do force analysis on center of mass of base and tipping point due to moment applied

The two aspects of our design with the highest risk are the adjustability of the platform and the piping frame of the wall, each with a risk priority number of 60. For the platform adjustability, the mode of failure would be that while the angle of the platform is being adjusted if the user is not properly holding the platform in place while changing the pin, the platform could fall flat quickly and slam. This could frighten a child, and the user could also pinch their finger. This mode of failure is likely, and has serious impact. Our existing control method to prevent this hazard is to build in enough friction in the adjustment of the platform so that it stays in place unless a force is applied. For the piping frame of the wall, the mode of failure would be that if the frame is pulled on, the piping could fall apart and fall on a child. This could bruise or cut a child, and potentially hit them in the head. This mode of failure is likely and also has serious impact. Our current plan is to do calculations to ensure that the pipes do not shrink or expand due to temperature swings and ensure that there is a tight fit between connecting pieces so that they do not come apart easily.

Potential design changes that we could implement to reduce the risk of our design include having buttons on the platform that the user is required to depress with their hands and feet in order to run the motor that moves the walls, thus preventing them from flailing their arms and getting hit by the moving wall. In order to prevent tipping of the platform, we plan on connecting the base of the platform to the base of the main module through a connecting leg. This will not only provide more stability, but also has the added bonus of ensuring that the platform will be set up the correct distance away from the center axis each time, making assembly easier. In addition, any wiring from the buttons on the platform to the motor can be fed through this attachment, preventing loose wires that would pose another hazard. In order to prevent tripping, we plan on building a covering for the legs and filing the edges of the legs.

After adding these changes to our design, the overall risk will be at an “acceptable” level. Though some hazards are not entirely avoidable, we have minimized the potential impact that failure would have. Keeping with safety regulations of playgrounds and children’s museums, such as the Ann Arbor Hands On Museum, we also plan to pick materials that can be easily cleaned with bleach between uses. This will ensure minimum transfer of pathogens from one user to the next.

Current Challenges

While performing engineering analysis and finalizing our concept design, we found two aspects of our design that may cause difficulties in the future. The first difficulty is that the motor will need to be mounted to a rounded surface on the outside of the cylindrical casing while keeping the gears the appropriate distance from each other so they mesh properly. The second difficulty, discovered during the mockup construction, was that the joints on the frame were flimsy and difficult to secure together. In order to fix this we will be gluing the PVC pipes into threaded adaptors so that the joints can be screwed together instead of simply pressed in. This will only be successful if we can clean the ends of the pipes and correctly glue them into the adaptors without any bending or slipping.

After analyzing our design, there are still a few unresolved components. The biggest unknown revolves around the electrical engineering that will need to be done. The wiring needs to be covered for safety and easily connected every time the model is assembled. To do this, we need to find a way to run the wiring through a connecting leg from the base of the main module to the base of the platform. From the base, the wiring can be run up the supporting rod of the platform and into the handles. Once the wiring is connected, we will need to figure out how to program the motor so it only runs when both buttons on the handles are pushed in and there is no person or object in contact with the wall or near a proximity sensor. Another unknown factor is if we will be able to make carrying case for the disassembled demo so it can easily be transported. This will depend on how easy the parts are to carry on their own and how easy a case would be to construct.

One problem we anticipate is calculating the correct interference between the bearings/gear and the outer casing and shaft to achieve a successful light press fit. To address this problem, we will speak with professionals in the machine shop who will be able to help us machine the casing and shaft to the proper sizes. Once these fits are figured out, the next problem will be putting the parts together in the correct order. To address this problem, we can build the model in CAD first in order to find the correct order of assembly.

Discussion/Design Critique

Though we were able to validate our design to meet most of our engineering specifications and user requirements, there were a few aspects of our design that we would recommend to change for future iterations of the project. Monetary and temporal limitations prevented us from making these changes during the course of our project. There were four major redesigns that we considered.

Redesign #1: Change wall material to reduce deflection and make hyperboloid cutouts more rigid. Our design used a rigid frame with a tarp insert, however, we had issues with the tarp flapping as it rotated. We considered using a solid piece of foam or plastic as the wall. This would eliminate the need for a frame and would give a sturdier wall. Calculations for using a solid wall would include looking at the deflection of the end of the wall, given by Equation 16

$$\partial = FL^3/(3EI) \qquad \text{Eq. 16}$$

where F is the force that can be determined by the approximate weight of the wall, assuming similar dimensions to our current design, L is the length of the wall, E is the Young's modulus, and I is the second moment of inertia. A comparison of a light foam (polystyrene) and HDPE to the PVC frame that we used can be seen in Table 11.

Table 11: Comparison of end deflection of various materials for wall choices, showing that any material choice gives a sturdier wall than our current design.

	Young's modulus (GPa)	Weight, F (N)	End Deflection, ∂ (mm)
Light Foam (polystyrene)	3[25]	50	8.74×10^{-4}
HDPE	0.8[25]	50	3.28×10^{-3}
PVC	2.4	0.1	127

The end deflection of either of these materials would be much less, giving a much sturdier design. However, some issues could arise with disassembling these walls and fitting them into a trunk to meet the transportability requirement. Additionally, some of these materials are expensive and might not fit into the budget.

Another idea for making the walls more sturdy is reinforcing the tarp and hyperboloid cutout with wire, and supporting it from the top with the PVC frame but not the sides or bottom. This would reduce the weight of the frame and the end deflection. The wire support could either just be horizontal, which would allow the insert to be rolled to transport, or could be a mesh, with both horizontal and vertical wires with strategic gaps to allow for folding.

Redesign #2: Addition of railings, mounting steps, handles, and cushions to the platform. Although our design included an adjustable step on the platform and buttons in an effort to make the demo both adjustable and safe, extra safety features can always be added for additional precautions, as well as other ergonomic features. Railings would ensure that young users would not roll off the platform. This was an expressed concern of people with young children who saw our demo at Design Expo. Mounting steps would help shorter users to get onto the platform, and would also prevent fracture of the platform if the user put all of their weight on one part of the platform while trying to get onto the platform. A few children who walked by the demo during Design Expo asked how they would get on the demo, and expressed that steps would be helpful. Handles would allow users to more easily be able to hold onto and press the buttons, and would also provide a something to grab onto while the demo is in motion. A cushion would make the platform more comfortable for the user, because a flat wooden platform is not very inviting.

Redesign #3: Slide in legs rather than hinges. Though using hinges to attach the legs reduced the number of tools required for assembly and the total number of parts of the demo, it made the base module too bulky, heavy, and cumbersome for one individual to carry for longer distances. Our recommendation would be to design a slide in and pin system for attaching the legs so they could be fully removed from the base in order to reduce the weight that would need to be carried per trip and help maximize space usage.

Redesign #4: Change material from wood to plastic. Wood is a dense and heavy material, which is good for stability, but a "thick" plastic may still be strong but also light, which would make the demo more easily transported. For example, HDPE has a density of 970 kg/m^3. In addition, using plastic rather than wood would give the demo a more polished look, would help it to last longer, and would be safer because there would be no risk of wood splinters.

We had a few additional recommendations for the project. We believe that our work on the project was a very good first step to creating a life-sized educational demo, however, it was the first iteration of the project. Another semester is required for the design to be refined, and new perspectives along with the lessons that we learned through this first iteration will be helpful to create a final educational demo.

In addition to our four major redesigns, we would recommend trying to create a carrying case to transport the disassembled pieces of the demo. This could perhaps be incorporated into the design as part of the base. Additional advice includes trying to be more vigilant in material selection, such as finding wood without knots in it and using stronger pins to connect the PVC cross to the aluminum axis rather than small bolts. This is a critical part of the design as it transfers the load from the motor. In addition, a stronger motor could be helpful, especially if using a solid piece of material for the walls would significantly increase their weight.

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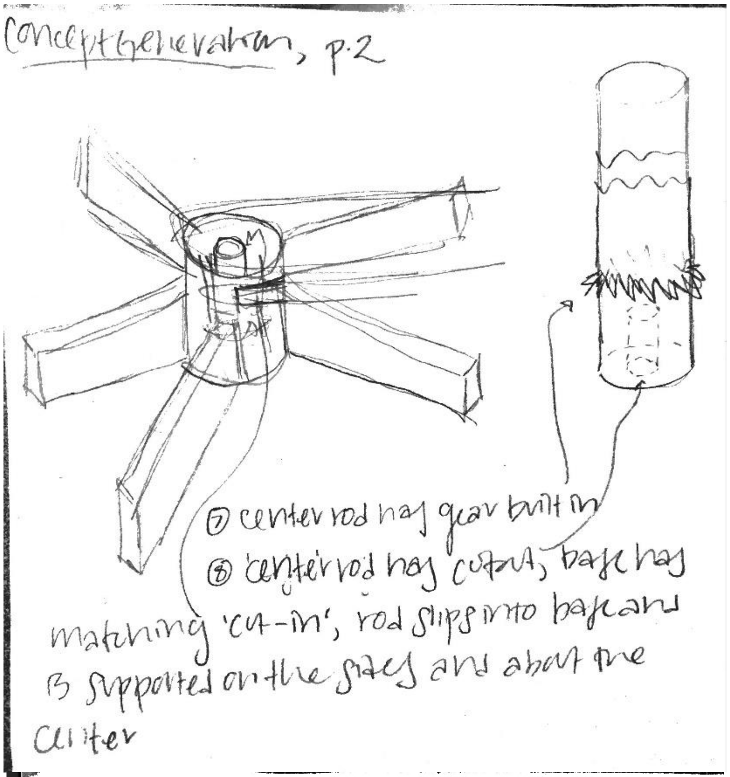
Appendix A: Extended Concept Generation



Concept generation, p.2

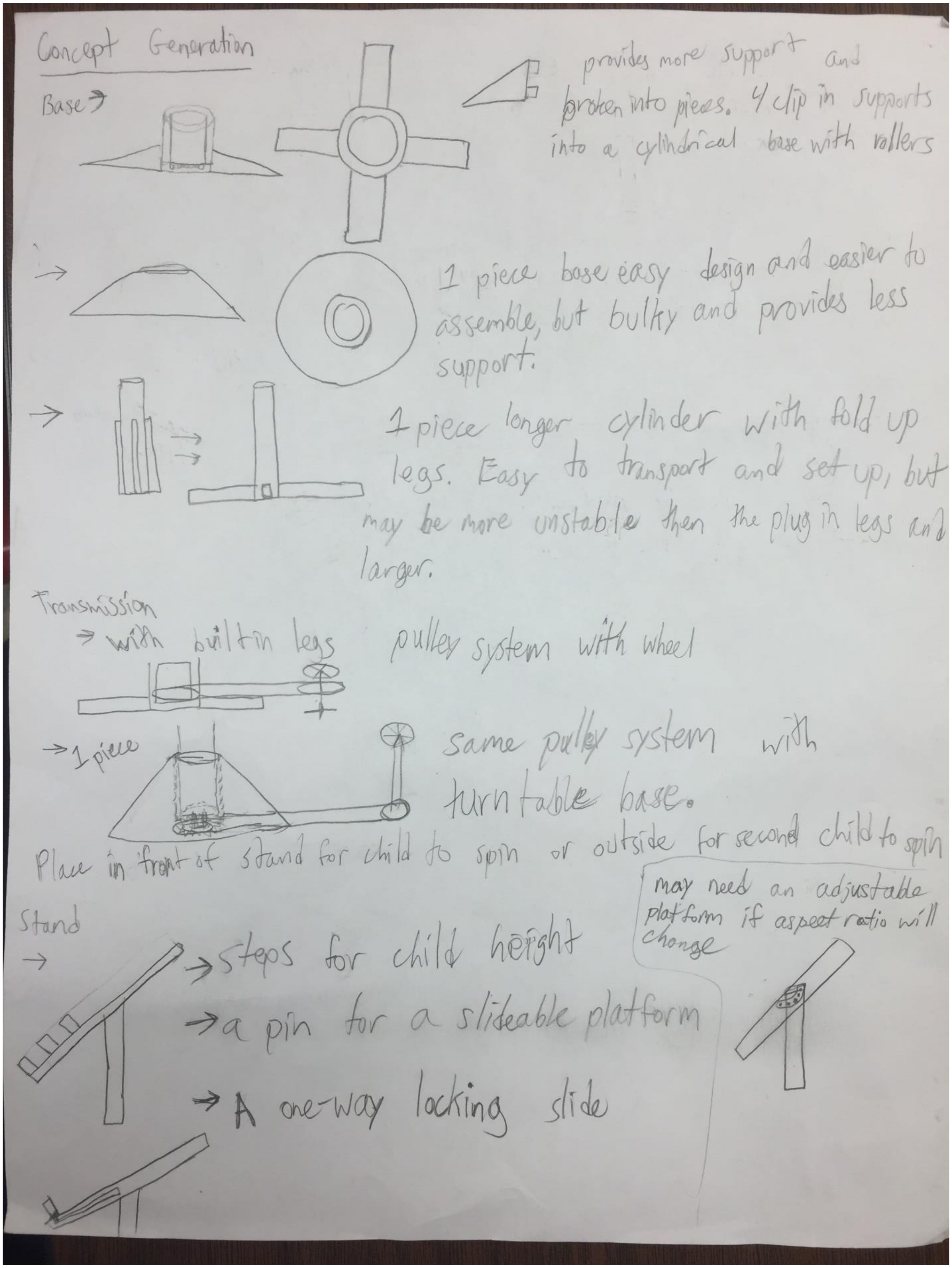
⑦ center rod has gear built in

⑧ center rod has cutout, base has matching 'cut-in', rod slips into base and is supported on the sides and about the center

Idea #1
- folding wall ← heavy, not changeable
- slide into column ← harder to assemble
- kid pushes wall.

Idea #2
- solid base ← heavy
- seatbelts to strap in ← safety hazard
- person turning track ←

Idea #3
- detachable legs ← harder to assemble
- curved seat
- bevel gear → crank



Concept Generation

Base →

provides more support and broken into pieces. 4 clip in supports into a cylindrical base with rollers

→ 1 piece base easy design and easier to assemble, but bulky and provides less support.

→ 1 piece longer cylinder with fold up legs. Easy to transport and set up, but may be more unstable then the plug in legs and larger.

Transmission

→ with built in legs

pulley system with wheel

→ 1 piece

same pulley system with turntable base.

Place in front of stand for child to spin or outside for second child to spin

Stand

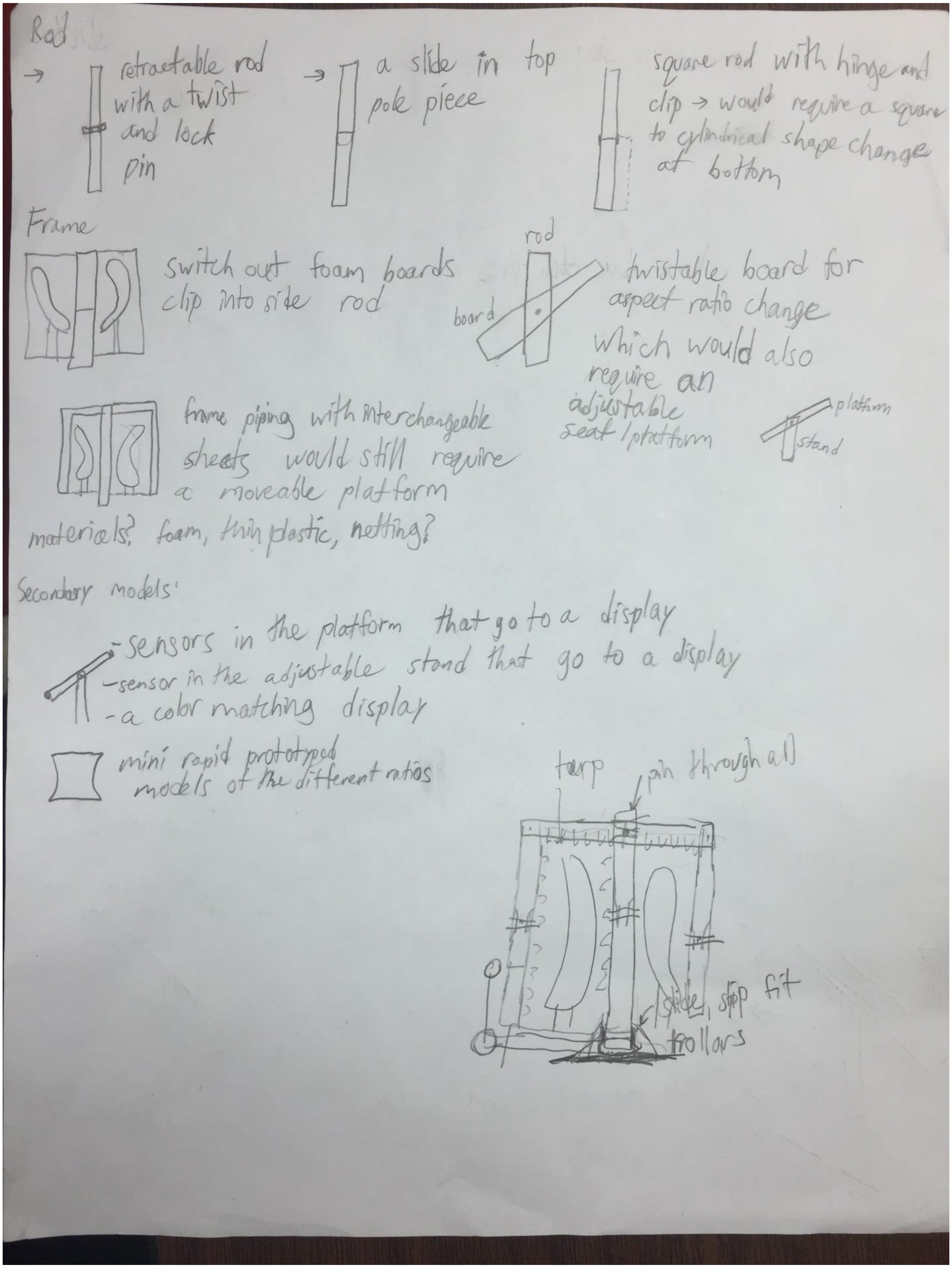
→

→ steps for child height

→ a pin for a slideable platform

→ A one-way locking slide

may need an adjustable platform if aspect ratio will change



Rod

→ retractable rod with a twist and lock pin

→ a slide in top pole piece

square rod with hinge and clip → would require a square to cylindrical shape change at bottom

Frame

switch out foam boards clip into side rod

twistable board for aspect ratio change which would also require an adjustable seat/platform

frame piping with interchangeable sheets would still require a moveable platform

materials? foam, thin plastic, netting?

Secondary models:

- sensors in the platform that go to a display
- sensor in the adjustable stand that go to a display
- a color matching display

mini rapid prototyped models of the different ratios

Appendix B: CAD

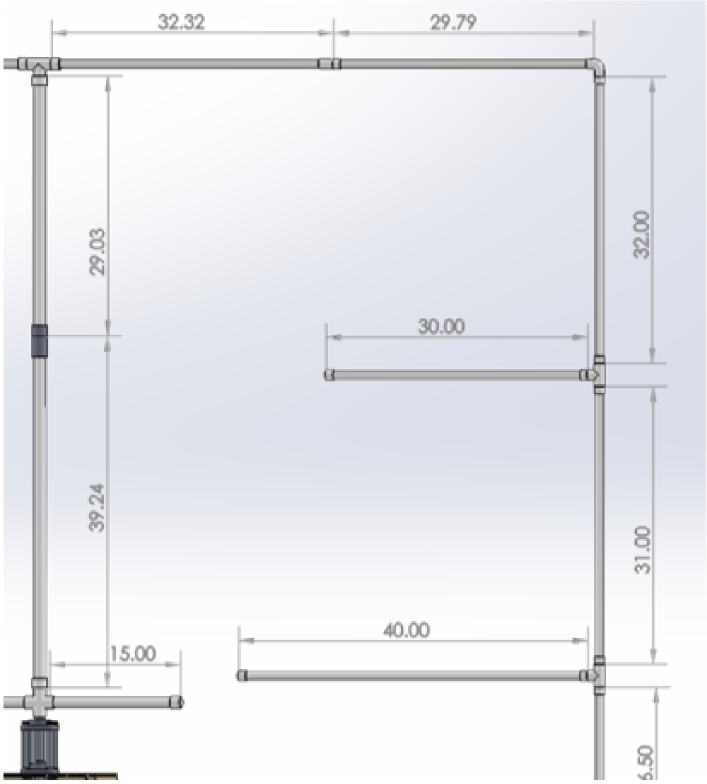


Figure 36: Dimensioned View of PVC Wall Frame

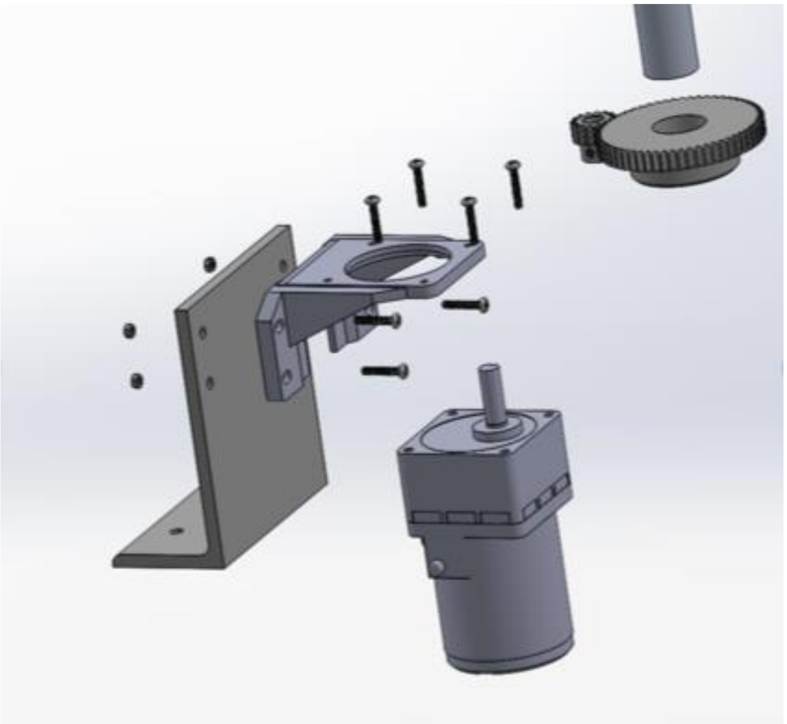


Figure 37: Exploded View of Motor Assembly

Appendix C: Engineering Drawings and Manufacturing Plans

Initial Manufacturing Plan

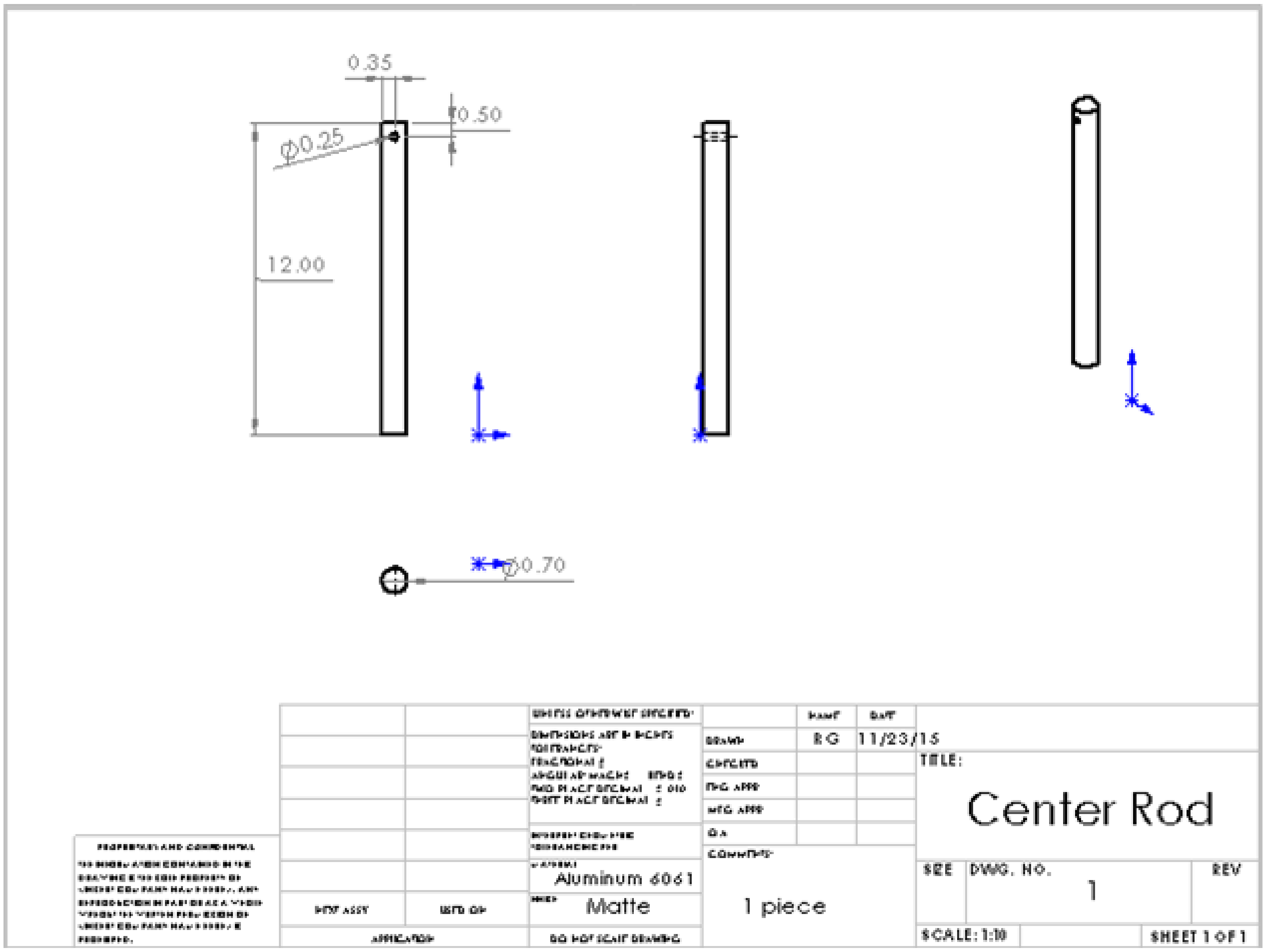
Frame: In order to make the pipes for the frame, we will be cutting the pipes to the appropriate lengths. Since the pipes are too long to fit in a band saw, we intend to use hand saws to cut to size. Since there are serious safety concerns associated with using hand saws, we will be filing safety plans to ensure proper and safe use of the equipment. The benefit to this method of manufacturing is that is it relatively simple, however the results may not be precise since we will not be using precision tools.

Gear: We will need to increase the bore size of the gear so that it will fit onto the aluminum shaft. To do this, we will fix the gear to a mill, and use a 1-5/16 inches endmill at a speed of 300 RPM. Then, to fix the gear to the PVC shaft, we will be machining a keyway into the gear. Endmill to fit the key dimensions. The benefits to this manufacturing method are that it is flexible and we can achieve tight tolerances and deliver high quality results.

Shaft: To ensure the gear remains in place, we will be machining a keyseat in the aluminum shaft to match the keyway in the gear. Endmill an appropriate sized slot into the shaft to match the dimensions of the key and keyway in the gear. This manufacturing method is precise and will allow us to achieve tight tolerances.

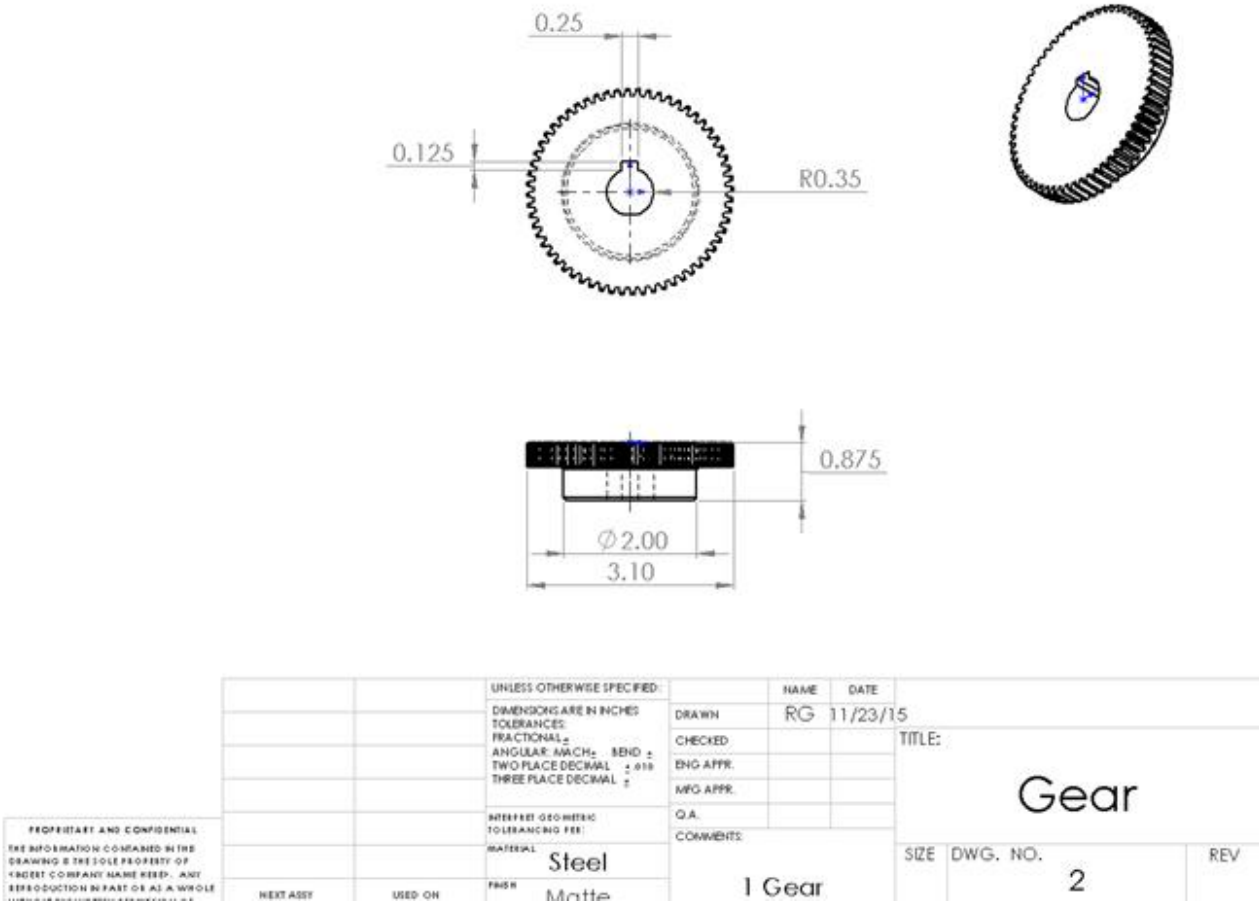
The two tapered roller bearings will be press fit to the main shaft of the educational demo. First, we will press fit one tapered roller bearing to the marked height. After fitting the first tapered roller bearing, slide the gear onto the shaft, and insert the key into the keyway and keyseat to keep the gear in place. Then, press fit the second tapered roller bearing to the marked height. A potential difficulty with this method is that it will be difficult to get the exact location of the bearings to match, which is supercritical for this application. Therefore, we will have to be extra careful in manufacturing this part, and/or find an alternate method of manufacturing.

We will be assembling the base of the shaft with the tapered roller bearings, gear, shoulder, and bearing housing as a sub-assembly, prior to delivering the final prototype to Professor Strauss. Therefore, he will not have to worry about light press fits with the bearings, making his assembly easier.



Part Number	1					
Part Name	Center Rod					
Team	27					
Raw Material Stock	Aluminum 6061, 1" OD, 1' L					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tools**	**Speed (RPM)**	**Notes**
1	Fix to lathe	Lathe	Spindle with 3-jaw chuck			
2	Install cutting tool	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale		
3	Find X,Z datum lines	Lathe	Spindle with 3-jaw chuck			

4	Bring 1" diameter down to .7" for half of the rod in passes of .05"	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale	300 or less	Use oil
5	Turn part around, so unfinished end is exposed, fix to lathe	Lathe	Spindle with 3-jaw chuck			
6	Find X,Z datum lines	Lathe	Spindle with 3-jaw chuck			
7	Bring 1" diameter down to .7" for half of the rod in passes of .05"	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale	300 or less	Use oil
8	Remove part from lathe					
9	File sharp edges			File		
10	Fix to mill					
11	Install edgefinder, find X and Y datum lines	Mill	Toe clamps	Edgefinder, drill chuck	1000	
12	Remove edgefinder, insert drill chuck and center drill specified locations on drawings	Mill	Toe clamps	Center drill, drill chuck	Check Cutting Speed Chart	
13	Drill 1/4" through holes at specified locations on drawings	Mill	Toe clamps	1/4" drillbit, drill chuck	Check Cutting Speed Chart	
14	Remove from mill and deburr			Deburrer		



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±.010
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Steel
FINISH Matte
NEXT ASSY
USED ON
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE

	NAME	DATE
DRAWN	RG	11/23/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

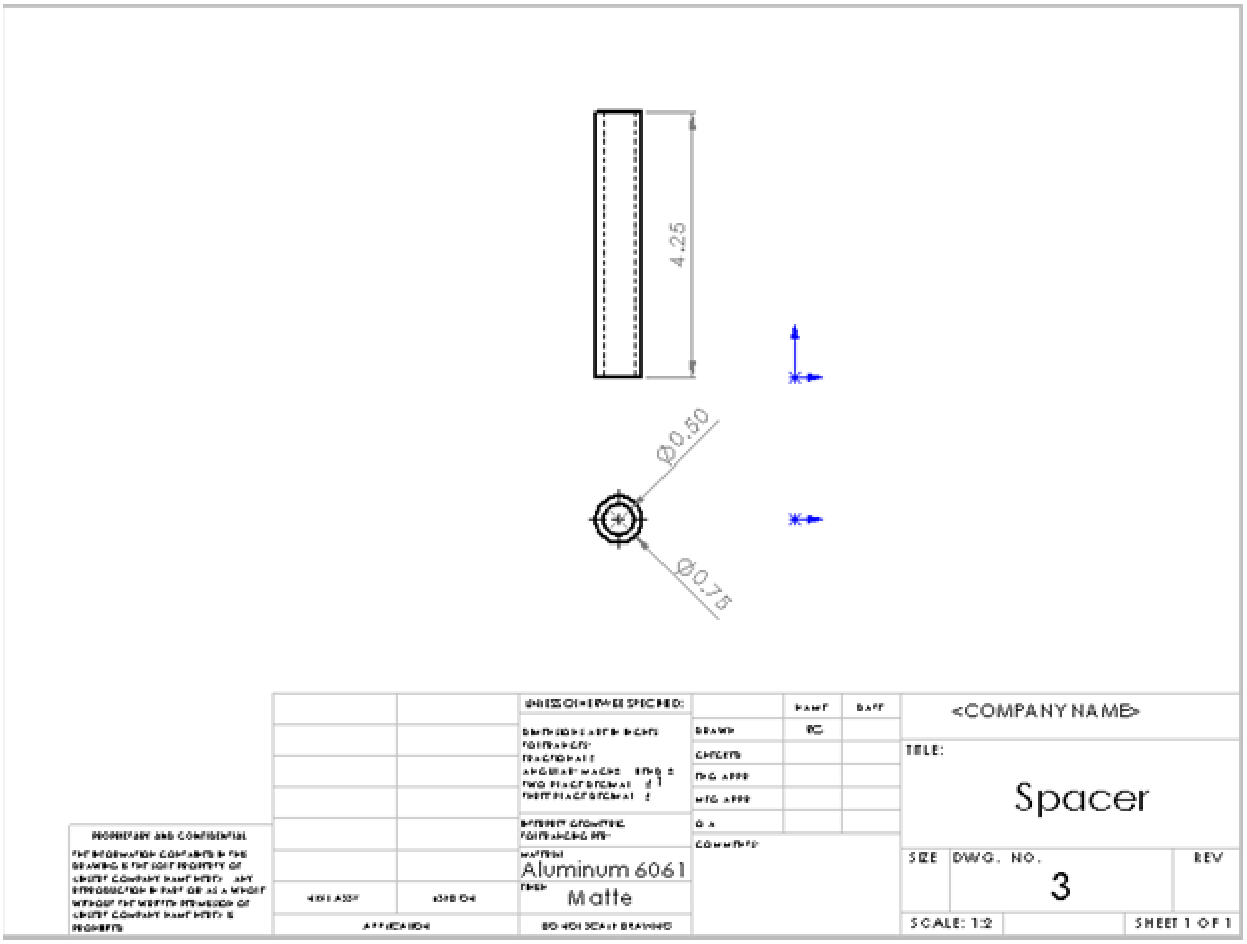
COMMENTS: 1 Gear

TITLE: Gear

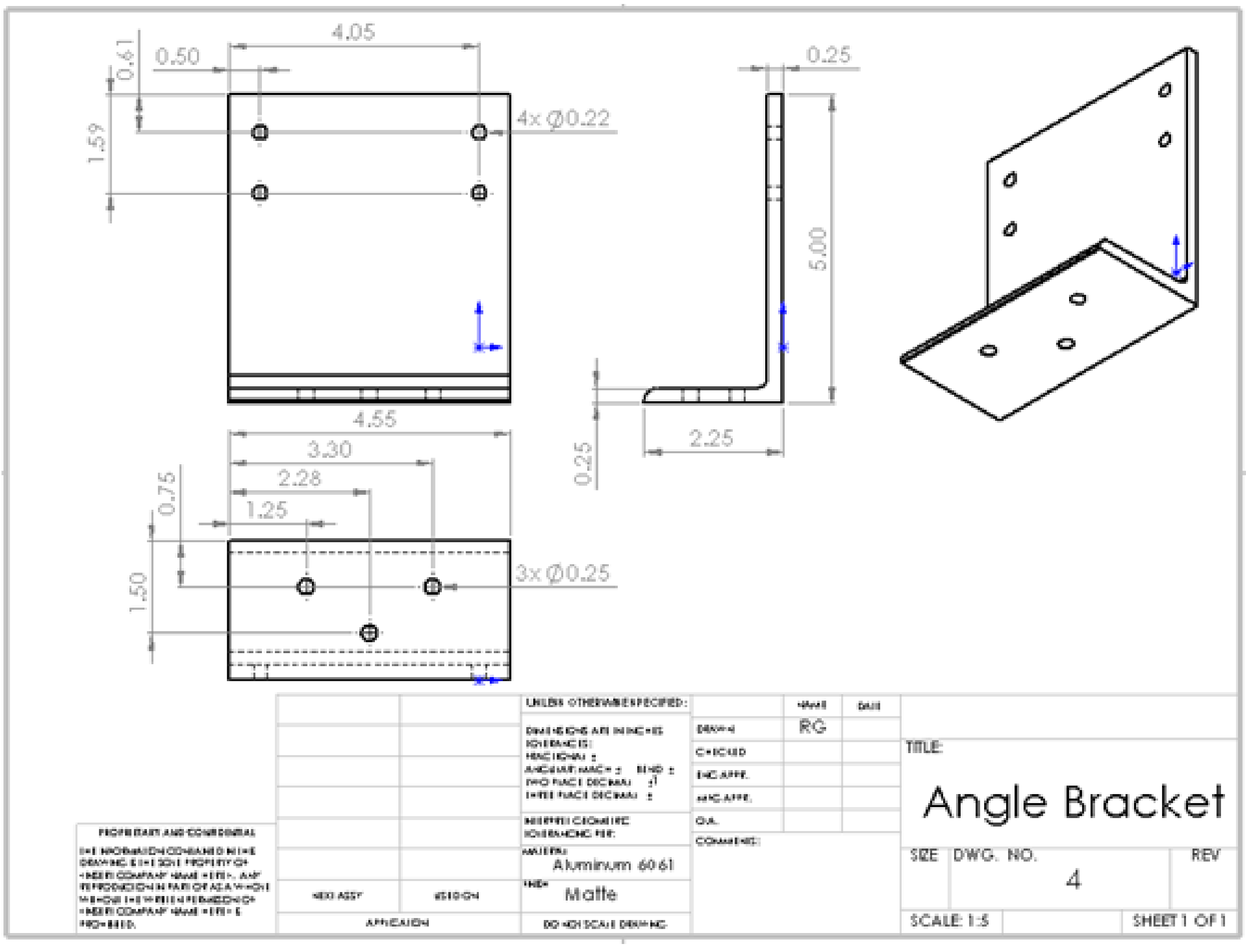
SIZE DWG. NO. 2 REV

Part Number	2					
Part Name	Gear					
Team	27					
Raw Material Stock	Steel Gear 3.1" OD, 3/8" ID					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tools**	**Speed (RPM)**	**Notes**
1	Fix to lathe	Lathe	Spindle with 3-jaw chuck			
2	Find X,Z datum lines	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale		
3	Install 45/64" drill bit	Lathe	Spindle with 3-jaw chuck	45/64" drill bit		

4	Drill 45/64" hole through center of piece	Lathe	Spindle with 3-jaw chuck	45/64" drill bit		
5	Remove from lathe and deburr			Deburring Tool		
6	Fix gear to mill with vise and scrap piece of wood/metal	Mill	Vise			Scrap wood/metal
7	Find datum, center of gear hole with dial indicator	Mill	Vise	Dial indicator		
8	Insert 1/64" endmill	Mill	Vise			
9	Mill keyway to depth of .125" in passes of .001"	Mill	Vise	Drill chuck, 1/64" endmill		
10	Remove gear from mill	Mill	Vise			
11	Deburr			Deburring tool		

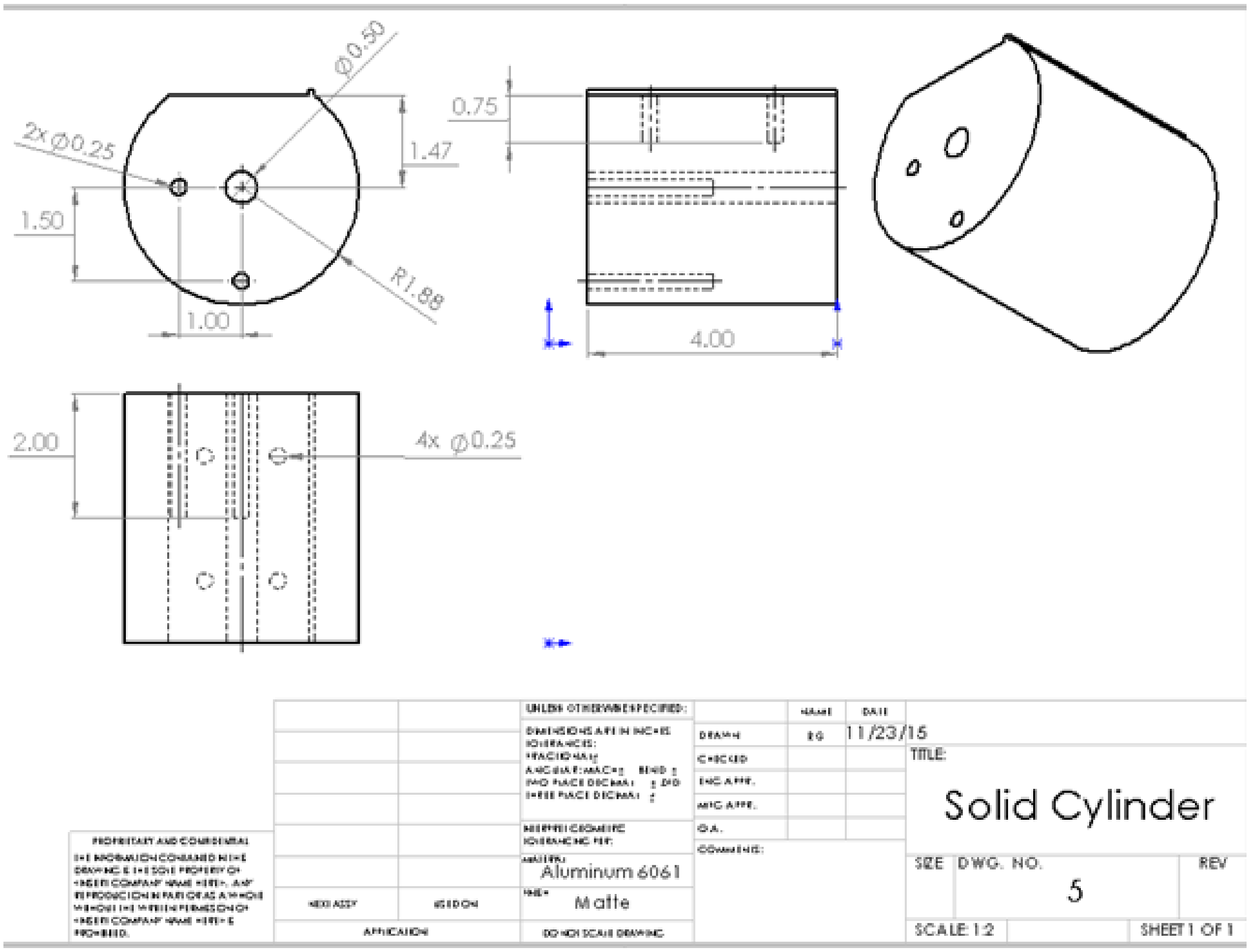


Part Number	3					
Part Name	Spacers					
Team	27					
Raw Material Stock	6061 Aluminum Tube					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tools**	**Speed (RPM)**	**Notes**
1	Roughly mark/score the tube stock at 4.5" intervals			Sharpie 12-inch scale/ruler		
2	Cut tube at marks	Bandsaw		Wood block(s)	[Chart]	
3	File cut ends			File		
4	Fix to lathe	Lathe	Spindle with 3-jaw chuck			
5	Install cutting tool	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale		
6	Find X,Z datum lines	Lathe	Spindle with 3-jaw chuck			
7	Lathe one end of the tube just enough to leave a smooth face	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale	300 or less	
8	Turn part around, so unfinished end is exposed, fix to lathe	Lathe	Spindle with 3-jaw chuck			
9	Find X,Z datum lines	Lathe	Spindle with 3-jaw chuck			
10	Lathe tube to length of 1.5 in in 0.05" passes	Lathe	Spindle with 3-jaw chuck	Cutting tool, scale		
11	Remove piece from lathe					
12	Measure tube with a scale/caliper			6-inch scale or Dial caliper	300 or less	



Part Number	4					
Part Name	Angle Bracket					
Team	27					
Raw Material Stock	Aluminum 6061-T6 6"x6"x5" 1/2" thick stock					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tools**	**Speed (RPM)**	**Notes**
1	Roughly mark/score the stock at 2.25" on one side			Sharpie 12-inch scale/ruler		
2	Cut stock at mark	Bandsaw		Wood block(s)	[Chart]	
3	File cut ends			File		
4	Fix to mill	Mill	Toe			Mount on

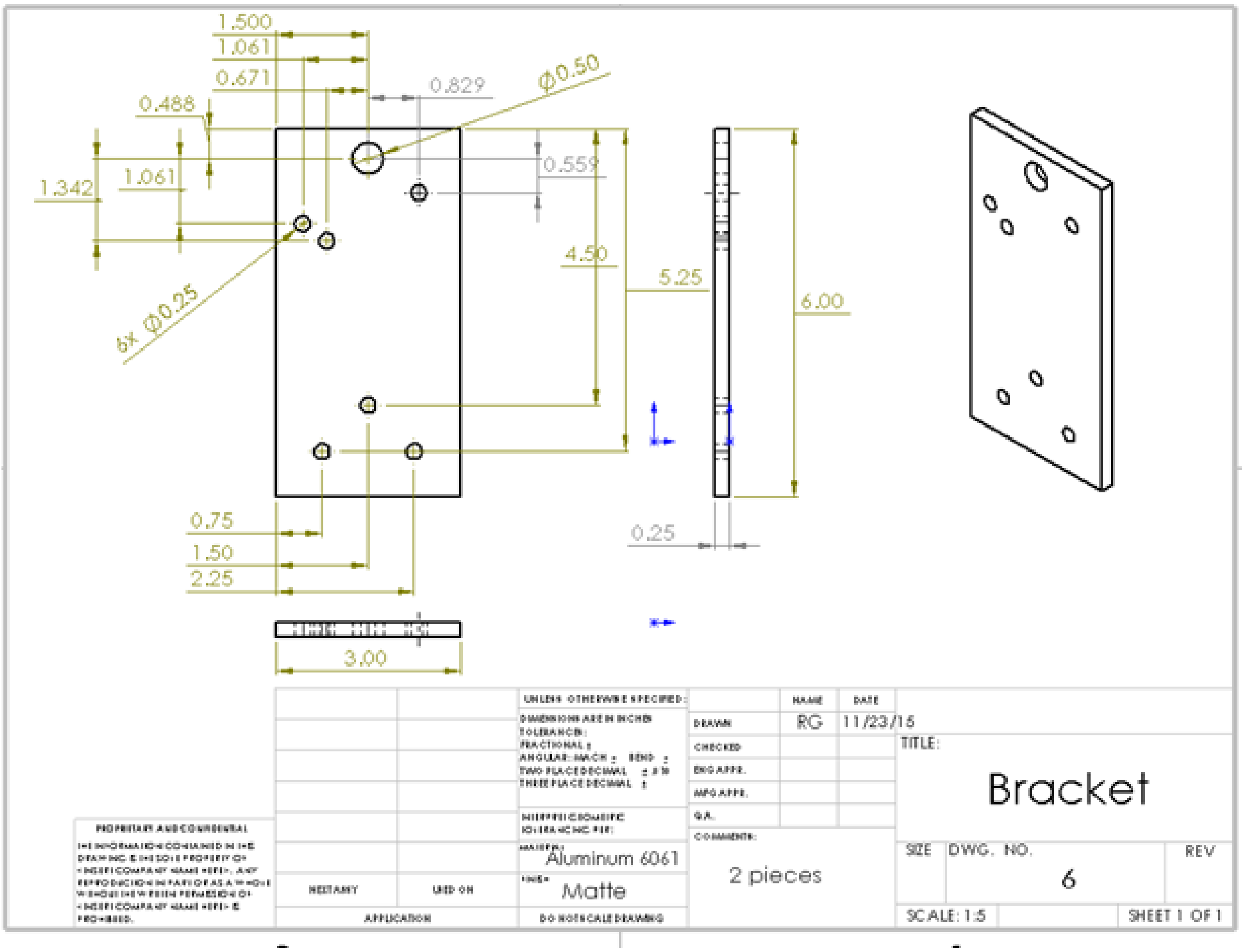
			clamps			sacrificial piece of material (wood) to make thru holes
5	Install edgefinder, find X and Y datum lines	Mill	Toe clamps	Edgefinder, drill chuck	1000	
6	Remove edgefinder, insert drill chuck and center drill specified locations on drawings	Mill	Toe clamps	Center drill, drill chuck	Check Cutting Speed Chart	
7	Drill 1/4" through holes at specified locations on drawings	Mill	Toe clamps	1/4" drillbit, drill chuck	Check Cutting Speed Chart	
8	Flip piece and fix to mill	Mill	Toe clamps			
9	Install edgefinder, find X and Y datum lines	Mill	Toe clamps	Edgefinder, drill chuck	1000	
10	Remove edgefinder, insert drill chuck and center drill specified locations on drawings	Mill	Toe clamps	Center drill, drill chuck	Check Cutting Speed Chart	
11	Drill .22" through holes at specified locations on drawings	Mill	Toe clamps	.22" drillbit, drill chuck	Check Cutting Speed Chart	
12	Remove from mill and deburr			Deburrer		



Part Number	5					
Part Name	Solid Cylinder					
Team	27					
Raw Material Stock	Aluminum 6061, 3-3/4" OD, 4" L					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tools**	**Speed (RPM)**	**Notes**
1	Fix to lathe	Lathe	Spindle with 3-jaw chuck			
2	Find X,Z datum lines	Lathe	Spindle with 3-jaw	Cutting tool, scale		

			chuck			
3	Install .5" drill bit	Lathe	Spindle with 3-jaw chuck			
4	Drill .5" hole through center of piece	Lathe	Spindle with 3-jaw chuck			
5	Remove from lathe and deburr			Deburring Tool		
6	Fix to mill	Mill	Vise			Mount on sacrificial piece of material (wood) to make thru holes
7	Install edgefinder, find X and Y datum lines	Mill	Vise	Edgefinder, drill chuck	1000	
8	Remove edgefinder, insert endmill	Mill	Vise	1/2" end mill, drill chuck	Check Cutting Speed Chart	
9	Mill top down .64" to create a flat surface in passes of .1"	Mill	Vise	1/2" end mill	Check Cutting Speed Chart	
10	Remove endmill, insert 1/4" drill bit	Mill	Vise	1/4" drill bit		
11	Drill 4 1/4" holes at specified locations to depth of .75"	Mill	Vise	1/4" drill bit	Check Cutting Speed Chart	
1	Remove piece from mill, rotate, and reaffix					
2	Find datum, center of gear hole with dial indicator	Mill	Vise	Dial indicator		
13	Remove dial indicator, insert drill chuck and center drill. Make center holes at specified locations:1.5" to the left of the center, and 1.5" to the bottom of the center	Mill	Vise	Center drill, drill chuck	Check Cutting Speed Chart	
14	Drill .25" holes to depth of 2"	Mill	Vise	1/4" drillbit,	Check	

	at 1.5" to the left of the center and 1.5" to the bottom of the center			drill chuck	Cutting Speed Chart	
15	Remove piece from mill					
16	File sharp edges			File		



Part Number	6					
Part Name	Platform Bracket					
Team	27					
Raw Material Stock	12" x 1/4" x 3" 6061 extruded aluminum					

Step #	Process Description	Machine	Fixtures	Tools	Speed (RPM)	Notes
1	Roughly mark/score the stock at 6" intervals			Sharpie 12-inch scale/ruler		
2	Cut stock at mark	Bandsaw		Wood block(s)	300	
3	File cut ends			File		
4	Fix to mill	Mill	Vise			Mount on sacrificial piece of material (wood) to make thru holes
5	Install edgefinder, find X and Y datum lines	Mill	Vise	Edgefinder, drill chuck	1000	
6	Remove edgefinder and insert .5" drill bit	Mill	Vise	Drill chuck and .5" bit	350	
7	Drill .5" hole at the specified location on the drawing	Mill	Vise	Drill chuck and .5" bit	350	
8	Remove .5" drill bit and insert .25" drill bit	Mill	Vise			
9	Drill 6 - .25" holes at the specified locations on the drawing	Mill	Vise	Drill chuck and .25" bit	800	
10	File sharp edges			File		

Appendix D: Bill of Materials

The bill of materials (BOM) for our project can be found in Table 12. We have tabulated most of the components we expect to purchase, including quantity, price per unit, part number and supplier. We have a total cost of $671.92, which is greater than the provided budget of $400, however, our sponsor has indicated that he will cover the difference, since the additional costs are necessary for completing the project. We have also indicated relevant manufacturing and assembly processes for each material.

Table 12: Bill of Materials

BILL OF MATERIALS: ME450 TEAM 27				**TOTAL COST**	**$671.92**					
CATEGORY	**PART**	**DESCRIPTION**	**QTY**	**PRICE/UNIT**	**TOTAL COST**	**PART NUMBER**	**COMPANY**	**SUPPLIER**	**STORE/ONLINE**	**HAVE?**
Wall	1/2" PVC Pipe	1/2" ID 10ft long	4	$1.66	$6.66	100113200	Charlotte	Home Depot	Store Purchase	YES
	1" PVC Pipe	1" ID 10ft long	1	$2.62	$2.62	202280936	Charlotte	Home Depot	Store Purchase	YES
	3/4" PVC Pipe	3/4" ID 10ft long	1	$3.06	$3.06	202280935	JM Eagle	Home Depot	Store Purchase	YES
	1/2" PVC Elbow FPT	-	2	$0.78	$1.57	PVC023020600	Charlotte	Home Depot	Store Purchase	YES
	3/4" PVC Cross	-	1	$2.63	$2.63	PVC024100600	Charlotte	Home Depot	Store Purchase	YES
	1/2" PVC Tee FPT	-	4	$1.77	$7.08	PVC024020600	Charlotte	Home Depot	Store Purchase	YES
	3/4" PVC Tee FPT	-	1	$2.40	$2.40	PVC024020800	Charlotte	Home Depot	Store Purchase	YES
	1/2" PVC Adaptor MPT	-	18	$0.40	$7.25	PVC021090600	Charlotte	Home Depot	Store Purchase	YES
	1/2" PVC	-	2	$0.68	$1.36	C435-005	Dura	Home Depot	Store Purchase	YES

	Adaptor FPT									
	3/4" to 1/2" Adaptor MPT	-	2	$1.04	$2.08	C436-074	Dura	Home Depot	Store Purchase	YES
	1" PVC Adaptor MPT	-	1	$0.78	$0.78	C436-010	Dura	Home Depot	Store Purchase	YES
	1" PVC Adaptor FPT	-	1	$0.86	$0.86	PVC021011000	Charlotte	Home Depot	Store Purchase	YES
	1" to 3/4" Adaptor MPT	-	2	$1.40	$2.80	PVC021100700	Charlotte	Home Depot	Store Purchase	YES
	1/2" PVC Socket Cap	-	6	$0.40	$2.42	PVC021160600	Charlotte	Home Depot	Store Purchase	YES
	3/4" PVC Socket Cap	-	2	$0.45	$0.89	100345011	Dura	Home Depot	Store Purchase	YES
	Blue Medium Duty Tarp	9' x 12'	3	$9.51	$28.52	203730907	HDX	Home Depot	Store Purchase	YES
	PVC Glue	-	1	$10.58	$10.58	204867549	PipeWeld	Home Depot	Store Purchase	YES
	Velcro	15'x3/4"	1	$15.89	$15.89	3458457	Velcro	Amazon	Online Purchase	YES
	Caster Wheels	2 wheels	2	$4.74	$9.48	-	Shepherd	Home Depot	Store Purchase	YES
Base	Bearings	1" Concentric Locking Flange	2	$14.95	$35	UEF205-16	Browning	The Big Bearing Store	Online Purchase	YES
	Aluminum Rod	6061, 1" OD, 1' L	1	$7.80	$7.80	8974K13	-	McMaster-Carr	Online Purchase	YES
	Aluminum Tube	6061, .75" OD, .5" ID, 3' L	1	$13.71	$13.71	9056K33	-	McMaster-Carr	Online Purchase	YES

	Machinable Metal Gear	Shaft 1-5/16", 2.67" OD	1	$48.19	$48.19	**6325K73**	Martin	McMaster-Carr	Online Purchase	YES
	Pinion	Shaft 3/8"	1	$28.64	$28.64	6867K27	Martin	McMaster-Carr	Online Purchase	YES
	Legs	4"x4"x8' Pine	3	$12.57	$37.71	205220341	-	Home Depot	Store Purchase	YES
	Plexiglass	18"x24"x.093" Acrylic Glass	2	$5.07	$10.13	202038047	Optix	Home Depot	Store Purchase	YES
	Motor	Induction Motor	1	$131.44	$131.44	2ik6ua-5a	Oriental Motors	Oriental Motors	Online Purchase	YES
	Angle Bracket	6"x6"x5" 1/2" thick	1	$14.50	$14.50	61a.5x6	-	Speedy Metals	Online Purchase	YES
	Base Walls	2"x8"x8"	2	$6.84	$13.67	-	-	Home Depot	Store Purchase	YES
	Bottom and Top	2' x 4' Plywood	1	$11.08	$11.08	-	-	Home Depot	Store Purchase	YES
	Hex Bolts	3/8 - 16 thread	4	$2.24	$8.95	-	-	Home Depot	Store Purchase	YES
	Hex Nuts	16 thread	8	$0.12	$0.93	-	-	Home Depot	Store Purchase	YES
	Hex Bolts	5/16 - 1/2 long	4	$1.09	$4.37	-	-	Home Depot	Store Purchase	YES
	Washers	1/2"	2	$0.39	$0.78	-	-	Home Depot	Store Purchase	YES
	Clamp Collar	-	1	$6.36	$6.36	2C-093	Climax Metal	Amazon	Online Purchase	YES
Platform	Platform	Plywood	2	$15.56	$31.12	-	-	Home Depot	Store Purchase	YES
	Outer Pipe	4" OD x 3.750" ID x .125" Wall x 4" long 6061-T6 Aluminum Tube	1	$23.12	$23.12	t61r4x.125	-	Speedy Metals	Online Purchase	YES
	Inner Pipe	3-3/4" x 4" long Rd 6061-T6511 Aluminum	1	$24.08	$24.08	61r3.75	-	Speedy Metals	Online Purchase	YES
	Bracket	12" x 1/4" x	1	$5.67	$5.67	61f.25x3	-	Speedy	Online	YES

		3" 6061 extruded aluminum						Metals	Purchase	
	Pin	Zinc Rod 1/4"	1	$4	$4	-	-	Home Depot	Store Purchase	YES
	Buttons	-	2	$14.30	$28.60	-	-	Digikey	Online Purchase	YES
	Support Bracket	A33 Angle	8	$2.72	$21.79	-	-	Home Depot	Store Purchase	YES
Miscellaneous	Wiring	-	1	Free From shop	$0	-	-	Mechatronics Room	Store Purchase	YES
	12 Volt Adapter	-	1	Free	$0	-	-	Mechatronics Room	Store Purchase	YES
	Switch	DC 12V Delay Timer Switch Adjustable Module	1	$5.89	$5.89	NE555	Ximco	Amazon	Online Purchase	YES
	Coarse Drywall Screws	1-1/4"	1	$4.63	$4.63	-	-	Home Depot	Store Purchase	YES
	Coarse Drywall Screws	3"	1	$4.63	$4.63	-	-	Home Depot	Store Purchase	YES
	Toggle Switch	-	1	$0.72	$0.72	-	-	Home Depot	Store Purchase	YES
	Switch Box	-	1	$2.81	$2.81	-	-	Home Depot	Store Purchase	YES
	Wall Plate	-	1	$0.29	$0.29	-	-	Home Depot	Store Purchase	YES
	Square Hinge	-	2	$2.73	$5.47	-	-	Home Depot	Store Purchase	YES
	T-Hinge	-	7	$3.89	$27.23	-	-	Home Depot	Store Purchase	YES

Appendix E: Validation Protocol Expectations

We must conduct validation tests in order to verify whether our prototype meets the design drivers we derived from our user requirements and engineering specifications. We can verify that we have met our design drivers both with inspection and through experiment. A summary of the design drivers and the respective validation protocols can be found in Table 13.

Table 13: Verification Protocol for Each of Our Design Drivers

Design Driver	**Validation Protocol**	**Equipment**
Target appropriate user age range	Apply load to the assembled platform	Sand bags or weights
Be stable	Inspection of built prototype; simple wiggle test	N/A
Be safe to operate	Run prototype under standard operating conditions, measure speed/slip	Stopwatch
Be transportable	Disassemble, bring to sponsor's car; weigh subcomponents	Sponsor's trunk; scales
Be easy to assemble and disassemble	Measure time it takes to dis/assemble; create assembly manual	Stopwatch/timer
Have an educational factor	Tactile and visual aids	N/A
Have a fun factor	Have user/focus group interact with the demo	N/A

For examining whether we have met our target age range for users, with respect to the strength of the platform, we will apply weight in the form of weights or sandbags to simulate the weight of a 95th percentile 8-year-old, the greatest weight of a child user we expect to be using the demo. We will have to weigh the mass we will be adding, and make sure it is equal to the weight of the user and distributed in the way that body mass is typically distributed. According to our calculations, the platform should withstand loads significantly larger than we expect (on the order of 100 times great). Since it would be impractical to apply loads 100 times greater than the maximum expected weight of a user, we will use a safety factor of 2 to account for potential variations in weight and material properties and material imperfections.

Since safety is so critical for our prototype given the target user (children ages 2 to 8), we will be conducting experiments to ensure the educational demo is safe to operate and stable. Determining whether the prototype is safe to operate will require us to run the demo as if a user was using it. We will need to measure the speed at which the walls are turning, since we have specified they should rotate between 6 and 10 RPM. Given the speed at which the walls will be turning, we will not require high-tech equipment, so we will simply need a stopwatch and be able to count the number of rotations in the measured amount of time. We can measure the speed multiple times to ensure we are getting consistent results, which we should because the motor should only spin at a single speed as specified by the power supply and transmission. However, if there is inconsistency in the results, as long as all measured speeds are within the range specified, we will pass that validation test. We can also take our measured rotating speed and use it to measure the slip of the induction motor to validate whether our prototype is performing as we expected. Regarding stability, we will be inspecting the stability, watching the demo to make sure it does not tip or otherwise fail under standard operating conditions. We measured a rotational speed of 9.5 RPM, which is within our range of acceptable rotational speeds. The slip corresponding to 9.5 RPM of the demo is (from Eq. 15) 0.894, which is similar to the theoretical slip for 10 RPM of 0.889.

We must also test whether the educational demo is transportable, defined as being able to be carried by our sponsor and be able to fit into his car. This validation test will be conducted by inspection, whether the demo can fit into the trunk of his car, and whether we have met our weight requirement, defined as approximately 30 pounds per trip, and we would hope that it takes 2 trips, giving the weight requirement of 60 pounds. Something we will be keeping in mind is that weight alone is not the only consideration for ease of transport, since the ergonomics of the shapes and weight distribution of the subcomponents must be considered, as well. We can determine the weight of all the subcomponents by weighing them on a scale.

The educational demo must also be easy to assemble and disassemble and each must take no longer than 30 minutes for a single person. To validate this design driver, we will be creating a user manual, a step-by-step guide to assist our sponsor with assembly and disassembly. This user manual will ensure that he can easily learn the assembly process. We will also be using a timer to time how long it takes one of our team members to assemble and disassemble the demo, to determine if we meet the 30-minute specification. Also, the ease with which our sponsor will be able to assemble and disassemble the demo will increase with the amount of times he uses the demo, and he has expressed he is not worried about the time it takes to assemble and disassemble.

Since our prototype is for an educational demo that is meant to be interactive, it must be both educational and fun. To verify and ensure the demo is educational, we will accompany the demo with tactile and visual aids to go along with the mathematical concepts addressed with the demo. Our sponsor has experience with these educational demos and will be providing us with the accompanying lessons. Regarding the fun factor of the demo, we must first validate the safety of the demo so we can then feel safe in having a user use it. Once we validate the safety, we can conduct a focus group of children in the target age range to determine how fun it is. Though, given the timeframe of the course, we may not be able to conduct this part of the validation. However, this would involve surveying users before and after they interact with the demo, asking them questions in such a way to determine what features they liked and whether or not they felt they learned something from it.

Authors

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Julia is studying Mechanical Engineering at the University of Michigan. On campus, she is the Treasurer for the Society of Women Engineers. In the past, she conducted research in the Design Heuristics lab, and served as a mentor for the Michigan Research Community and the Center for Engineering Diversity and Outreach. Julia has worked at Ford as a Program Management intern, as well as being a Product Engineering intern at Nexteer Automotive. After graduation, she is planning to pursue a career in the automotive field.

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