SQUARE WHEELS DEMONSTRATION

A WORLD WITH SQUARE WHEELS

A world that values open-mindedness and abstract thinking, where creativity is widespread and math is approached with curiosity.

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1.1 Introduction

The objective of this section is to introduce our objective, which is to build a portable and interactive square wheels demonstration for students Zane Middle School.

1.2 Objective Statement

The objective of this project is to design and construct an interactive square wheels demonstration that stimulates an interest in mathematics in students and adults alike while challenging the definitive norm. This project will be based off the criteria created by the group subjected to the interests of the client, Zane Middle School.

1.3 Black Box Model

The black box model shown below in Figure 1 outlines the state of the world before and after the square wheels demonstration project is completed.

Input:
(A world where the wheel is defined as round)

- A world restricted through reinforcing normality.
- A world where math may be boring to the young growing mind.

Output:
(A world with square wheels)

- A world that values open-mindedness and abstract thinking, where creativity is widespread and math is approached with curiosity.

Figure 1.1: Black box model of the square wheels demonstration

2. Problem Analysis and Literature Review

2.1 Introduction to Problem Analysis

The preliminary analysis of the square wheel demonstration design will be discussed in this section of the document; the specific input/output variables and constraints, usage, and production volume of the design will be discussed below.

2.1.1 Specifications and Considerations

This section will discuss the guidelines and limitations of the square wheel demonstration design as determined by the criteria determined with the client, as seen in table 2.1 below.

Table 2.1.1: Criteria and Constraints

Criteria	**Constraint**
Storage	The demonstration must be made of materials that can withstand basement conditions, such as mold and water damage.
Size	The demonstration must be small enough to fit into a car and be transported with ease.
Safety	The completed project must be safe enough for children to use.
Portability	The demonstration must be easily moved from one location to another.
Sustainability	The project should be made from materials that are either up cycled, or considered environmentally friendly by legal standards to promote environmental consciousness.
Durability	Materials and assembly will need to be able with withstand daily usage from children and adults as well as indoor weathering and transportation conditions.

2.1.2 Usage

The design is projected to withstand usage of up to 50 daily cycles. It will be used by middle school students in a school setting as well as by users of all ages at the Discovery Museum and the Math Expo.

2.1.3 Production Volume

The design produced for this demonstration is meant for unique existence, it will be built with materials that can be easily found in any scrapyard or hardware store, and as such it will be easily reproducible. Additionally, instructions for smaller models made from household items will be displayed along with the demonstrations for users of all ages and capabilities to reproduce in their homes.

2.2 Literature Review

2.2.1 Introduction to Literature Review

The purpose of this literature review is to provide sufficient background information, which will provide a laid out foundation for the design process. The following topics will be discussed: history of wheels, geometry of square wheels, creativity, client criteria, models, materials, and sustainability.

2.2.2 History of the Wheel

The wheel is one of the most important mechanical inventions in the history of humankind. The definition of the word 'wheel', according to Webster's Dictionary, is "a circular frame of hard material that may be solid, partly solid, or spoked and that is capable of turning on an axle". This technology has been used for thousands of years by thousands of cultures. It is possible that the wheel was invented multiple times by different cultures who all shared similar needs. Pottery wheels and war chariots were in use in ancient Mesopotamia by 3000 BC. Pictures of wagons found on pottery in Eastern Europe also indicate the early use of wagon wheels in the same time period. The oldest evidence for the use of a wheel as a means of transportation is shown below.

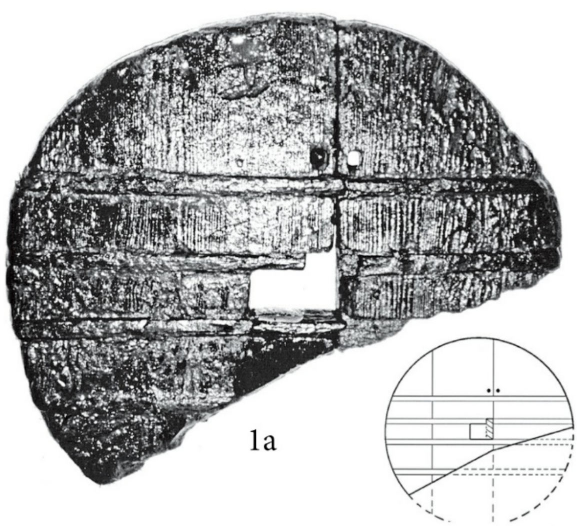


Figure 2.2.1: Earliest evidence for wheeled transport in central and Eastern Europe: 1a wooden wheel and axle from Staregmaine, Slovenia (c. 3500-3300 BC)

Some scientists believe that the creation of the wheel dates back even further. There is evidence of the use of cut trees made into logs to roll larger objects (Basalla, 2016). This was done by pushing the load on top of these cut tree trunks, which were laid on the floor in a row next to each other. As the heavy load was pushed, the cylindrical trunks would roll, and before the heavy load could fall off the other end of the lined up tree trunks, more trunks could be placed ahead to help push the load to further distances.

There is no evidence of the use of axels dating back before 3000 BC. Many of the oldest types of wheels were used for things such as pottery, farming, and transportation. There are Mesoamerican artifacts, such as small wooden vehicles that were fitted with axels to allow them to move, showing a working knowledge of the mechanical applications of the wheel (Basalla, 2016). There is no explanation on record for how this knowledge was used at the time, but it is known that it was available.

The precise cutting to fit a wheel on an axel was contributed by the metal tools during the Bronze Age. By this time in human history, people were already planting crops, herding domesticated animals, and living under a form of social hierarchy.

There is more than one type of wheel, and many improvements have been made since the "rolling log" concept. One of these improvements are the spokes on the wagons belonging to the families on the Oregon Trail. These spokes enable people to travel greater distances and support heavier loads than ever before. Nowadays, there are different types of tires for different occasions. Examples of these are: dirt tires, all weather tires, race tires, skateboard tires, etc. There is extensive research employing scientists and engineers to improve wheels and the roads that lay under them. This is important, as transport of materials is at an all-time high. Additionally, most goods today are made on conveyer belts that use wheels. The wheel now finds itself almost everywhere; cars, trains, planes, machines, bicycles, wagons, factories, farm equipment, and as shown in figure below, even on the moon.

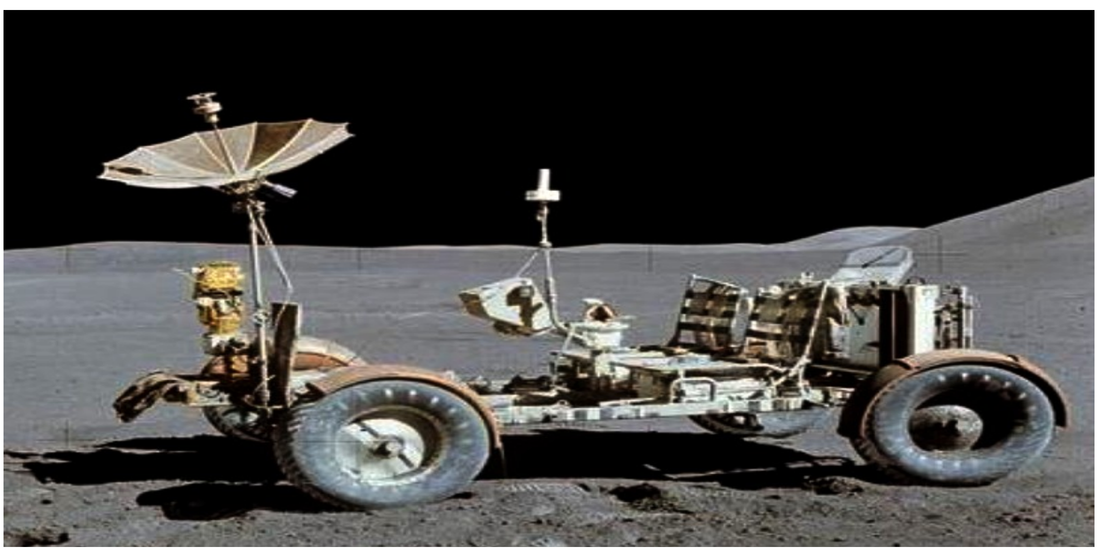


Figure 2.2.2: Apollo 15 Lunar Rover

(https://xenophilius.files.wordpress.com/2008/03/lunarrover.jpg)

2.2.3 Intro to Square Wheels

The performance of square wheels can be explained using mathematical concepts. Although a thorough explanation requires deep knowledge of mathematics, a simple model or demonstration can be explained using basic trigonometry and geometry. Additionally, square wheels provide a powerful display of creativity and innovative thought process.

2.2.4 Geometry of Square Wheels

The mathematical aspects of a square wheels model can be explained by using basic geometry and trigonometry. A square wheel on a flat surface would result in a very bumpy ride. One way to make the ride smoother would be to alter the shape of the road. A square wheel can roll smoothly, by requiring the axle to move in a straight line at a constant velocity, traveling over evenly spaced curves known as an inverted catenary (Peterson, 2004) as illustrated in figure below.

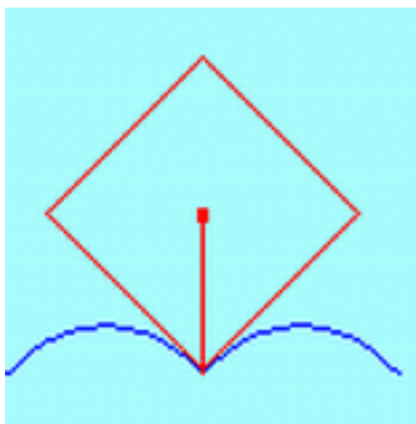


Figure 2.2.3: How a square wheel fits in between two catenary curves.
(http://cage.ugent.be/~hs/wheels/wheels.html)

A catenary is the curve that forms when a rope or chain is seen hanging loose between two supported positions, as pictured below. A catenary curve can be referred to as a parabola, but corresponds to the graph of a function called a hyperbolic cosine. The inverted catenary works well for a square wheel because, the catenary curve ends where the tangent is at a 45° angle. This means two catenaries together form a right angle, which is the same angle as the corner on the square. Additionally, the length of the curve can be made so that it is the same length as of one of the sides on the square tire, allowing the axle and center of the square tires to move in a straight line, much like a round wheel on a flat surface. Other polygons can be used as well, but the dimensions of the catenaries need to be adjusted accordingly. As sides are added to polygons, the length of the catenary would be reduced. Eventually, the more sides added to the polygon, the more it looks like a circle. The more the catenary is reduced, the more it looks like a straight line.

Figure 2.2.4: A catenary curve formed by a hanging chain supported by two posts. (https://upload.wikimedia.org/wikipedia/commons/0/04/Kette_Kettenkurve_Catenary_2008_PD.JPG)

A precise design allowing for exact assemblage can be accomplished by using mathematics. The width, height, and scale of the curve can all be determined using the equation below:

$$coshx = \frac{e^{x}+e^{-x}}{2} = \frac{e^{2x}+1}{2e^{x}} = \frac{1+e^{-2x}}{2e^{-x}}$$

2.2.5 Creativity

The invention of the wheel is seen as one of the turning points for the development of technology in human civilization. Square wheels remind people of all ages that there are many ways one can go about achieving revolutionary results. Creativity has been defined as ‘making something new’, ‘perceiving old things in new ways’, ‘finding new connections’, or ‘evoking pleasurable surprise’ (Maley, 2003), all of which can be experienced by exposure to the square wheel concept. The most important aspect of the square wheels demonstration is showing the user that there is more than just one right way to achieve a desired end result.

2.2.6 Materials: Plexiglas

Plexiglas, also known as Polymethylmethacrylate (PMMA), is a transparent plastic material often used in sheet form as a lightweight, shatter resistant, safer alternative to glass. This material is easy on handling and processing, as well as low cost. Plexiglas comes in two forms; modified and non-modified (Eplastics, 2016).

Non-modified PMMA will display brittle behavior when under an impact force, which is why the modified unit will hold more sufficient use for square wheels. Plexiglas comes in the options of various colors and designs, which would provide for an interactive and aesthetically pleasing project. PMMA, seen in Figure 6 below, will be considered as an advantageous material to the Square Wheels project with its durability and ease with which it can be decorated and made more interactive for the students at Zane Middle School. With a density of 1.18g/cm^3 (Eplastics), PMMA is one of the lighter materials available for the larger scale model.

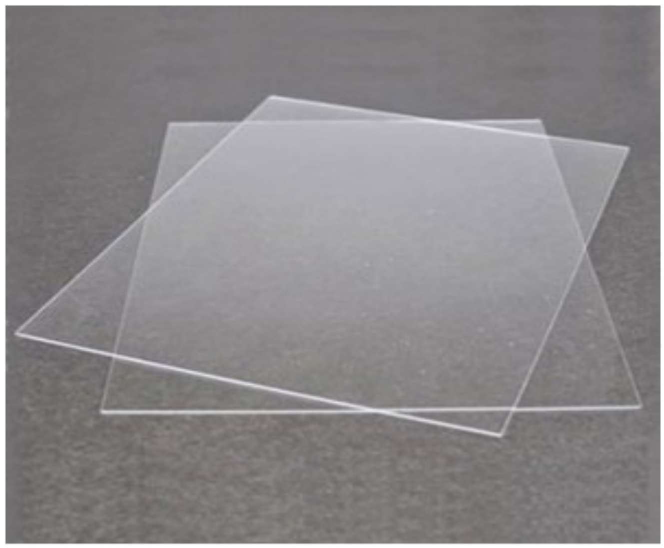


Figure 2.2.5: PMMA, the optimal form of Plexiglas considered for the square wheels demonstration. (http://www.eplastics.com/clear_plexiglass_sheet?gclid=CM_-6I74kcsCFQIcaQodPDQAIg)

2.2.7 Materials: Wood

Wood is a porous and fibrous structural tissue found in the stems and roots of trees and other woody plants (Wood, 2016). It is an organic material and a natural composite of cellulose fibers, which are strong in tension (Wood, 2016). It cannot only be used for just the wheels but also as a main foundation for the project piece itself. The risk of this material is the concern of how aged or used the wood is and if there has been any natural damage to it. Another thought of concern would be that although this material has the ability to be more cost effective and abundant in volume, there is the chance of this material splitting during the production process, transportation, and demonstration.

2.2.8 Cardboard

Cardboard, also can be represented as a heavy-duty paper of various strengths, ranging from a simple arrangement of a single thick sheet of paper to complex configurations featuring multiple corrugated and uncorrelated layers. Cardboard will strictly be used for a small – scale demonstration used to help the clients understand how and what was put into making the larger scale model. This material will be one of the lest cost effective materials put into the whole project due to the fact that is will be either donated of bought on an industrial scale.

2.2.9 Sustainability

Sustainability in design means we aim to use upcycled materials that have a low carbon footprint. Figure 7 above shows the carbon footprint of various materials considered for our final design. spending as little money as possible and re-using as many materials as we can for this project. This includes upcycling, which means taking an old object that is not being used and re-using it for a new purpose. Some materials may need to be bought because of certain safety issues, namely required strength to hold the forces exerted upon the demonstration. Most of the carbon footprint is due to CO_2 produced in the transportation of materials. (Shrink That Footprint, 2016). Aluminum and glass have to be extracted from raw materials with large machines before they are sent to factories for processing and being transported to the stores in which they are sold (Shrink That Footprint, 2016). For this reason, our goal is to use as many materials made locally as possible.

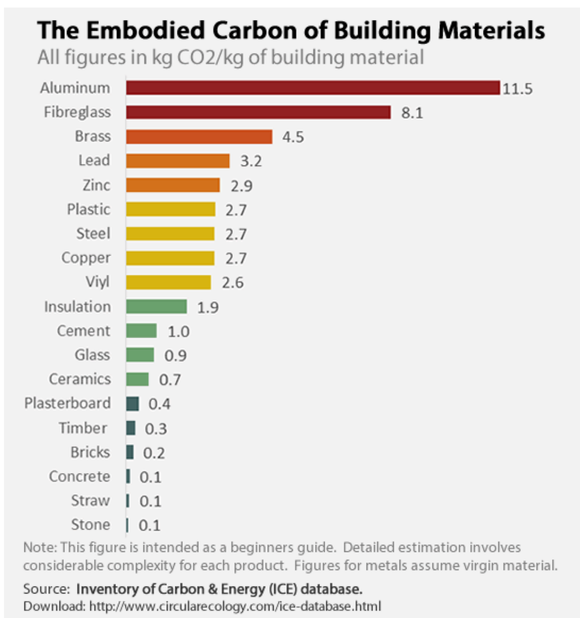


Figure 2.2.6: Carbon footprints of various materials.
(http://shrinkthatfootprint.com/beyond-efficiency-sustainable-home)

2.3 Client Criteria

2.3.1 Safety

Aspects of the design such as size, materials, and durability will need to be carefully evaluated to assure safety of the users. The safety of the user and spectators is the number one priority when designing the square wheel demonstration. The demonstration is going to be used by kids and adults alike, and as such will have a wide span of possible safety concerns.

Assuming the demonstration will involve a vehicle to be ridden by the user, the tricycle design as illustrated below would be safer than a bicycle design. The third wheel helps stabilize the vehicle, keeping the user safe. It would also allow users with no bicycle experience to ride the vehicle. A fourth wheel would increase safety but raise costs, design time and assembly time. The materials used in the design need to be sturdy enough to take the weight of a full-grown adult. This means that our design will need to be assembled by welding or screwed in correctly with proper bolts and connections that can withstand these forces. The machine needs to be very strong and child-proof, as it will be heavily used. The catenary-shaped track on which the vehicle will ride needs to be able to take the combined forces from the rider and bike plus any unexpected or unknown forces. This material needs to be sturdy and durable.

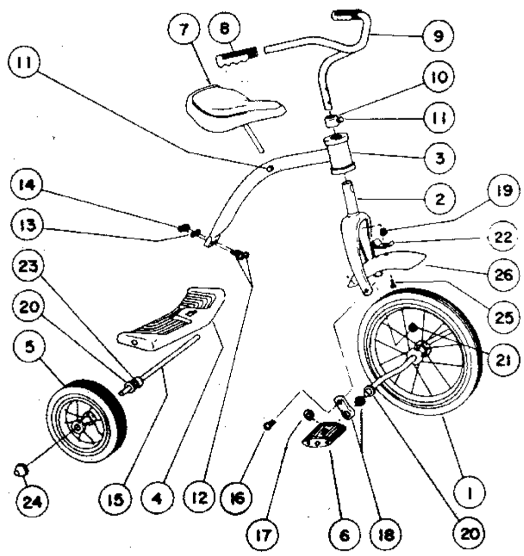


Figure 2.3.1: The components of a tricycle.
(http://www.searspartsdirect.com/modelpart/6702sr/0886/1303200/00040484/00001.html)

If the chosen design is a vehicle, tensile strength tests will need to be performed on both the individual components (frame, fork, pedals, wheels, track, and connections) as well as our final design. Strength must be tested in many different conditions with many different forces, using computer models as well as real world tests, as safety is integral to the successful completion of our design.

2.3.2 Durability

The durability of the demonstration is integral to the success of the project, which will be exhibited at the Humboldt County Math Expo as well as used at Zane Middle School. Children at Zane as well as the Math Expo will use the demonstration extensively.

2.3.3 Portability

As the demonstration will be transported between Zane Middle School and the Math Expo, it will need to be made highly mobile, meaning it will have to be lightweight and easily assembled with the use of tough and reliable materials.

Although not all of the criteria for storage has been given, the team along with the client do agree that the model will be spending the majority of its time at Zane Middle School and will need to be kept in an area where it will not get withered due to weather conditions. It also has to be built in a way that if need be, can be folded or easily taken apart and reattached. As of this moment the main idea for storage of this square wheel model is the basement of the school. Although, this provides great space for the model this requires a limitation in weight. The model has to be of reasonable weight and finely detailed structure.

2.4 Model

2.4.1 Toilet Paper Tube Model

A model made using toilet paper tube, cardboard, and drinking straws will be displayed with our final design, along with instructions on how to build that model. The original instructions, described below, were taken from a book published by the Exploratorium Teacher Institute called "Square Wheels and other easy to build, hands-on science activities", written by Don Rathjen and Paul Doherty. The table below shows a list of required materials and their quantities.

Table 2.4.1: Materials required for construction of toilet paper tube model of square wheels demonstration

Material	Quantity
Hot glue gun	1
Glue stick	1
Toilet paper tube	20
Cardboard	4 in x 30 in
Ruler	1
Pushpin	1
Poster board	8 in x 10 in
Pencil or pen	1
Scissor	1
Drinking straw	1
Skewer	2
Paper clip	1
String	12 inches

Instructions for assembly:

1. Use the hot glue to attach toilet paper tubes to the poster board base
2. Cut squares of poster board measuring 2 inches by 2 inches

3. Draw a line connecting each corner of the square to the other diagonally across it – the center of the square will be found at the intersection of those lines.
4. Carefully poke a hole in the center of the square with the pushpin.
5. Cut a rectangle of poster board measuring 2 inches by 5 inches to be used as the cart body.
6. Cut the straw into two 2 inch pieces.
7. Hot glue one straw piece at each end of the cart body, 0.4 inches from the edge.
8. Cut skewer into two pieces 5 inches in length.
9. Carefully slide the skewer into the center of the square wheel until wheel is about 0.75 inches from the non-pointed end.
10. Slide the pointed end through the straw on the body of the cart and slide other square wheel onto skewer. Repeat for the other set of wheels.
11. Carefully poke a hole past the straw and close to the edge of the cart body, and then place a paper clip through the hole.
12. Attach the string to the paper clip, and your square wheeled cart is ready to be pulled.

3. Alternative Solutions

3.1 Introduction to Alternative Solutions

Our team relied on several brainstorming sessions to come up with alternative design possibilities. We developed a list of 14 possibilities, and after analyzing how each alternative fits in with the client and team criteria, we selected 8 options that exhibited the most favorable qualities for this project. Those options will be described below.

3.2 Brainstorming

To come up with the options outlines below, our team engaged in several brainstorming sessions. Many unstructured brainstorming sessions contributed to this documents, consisting of team discussion of ideas with no concern for constraints, time, or note keeping. Many of those ideas were later solidified and enhanced during our structured brainstorming session, which took place in a new and unfamiliar location to all team members in order to encourage a free-thinking environment for the brainstorming session seen in Appendix A.

3.3 Alternative Solutions

Our team, taking in considerations of the client and design constraints, selected the alternative solutions outlined below.

3.3.1 The Mono Wheel

The Mono Wheel is a simple design that has been used in the San Francisco Exploratorium. The design consists of one axle with two square wheels on it, and each side of the square will be as long as the catenary curves that is used to design the track. The idea is that when pulling the axle of the square tires collinear with the track, the tires will roll over the curves, and the path of the axle will also be linear. The figure below, illustrates the necessary dimensions needed and the appropriate ration of curve height, width, and length. The needed materials include wood, wood adhesive, screws, and PVC.

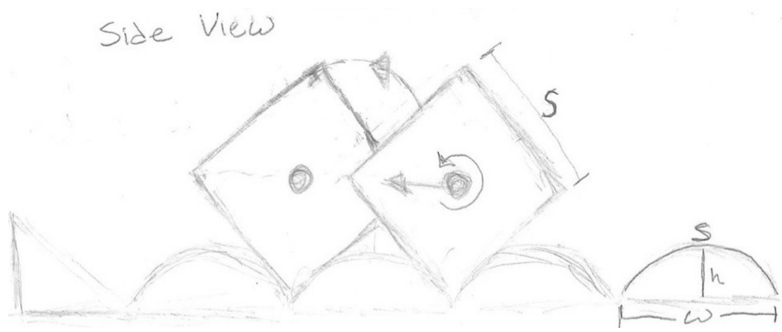


Figure 3.3.1: Side view of the Mono Wheel design by Andre Meza

3.3.2 Crank Model

The Crank Model will have two square wheels attached to a track made up of catenary curves. This design will have the same base structure as the Mono Wheel design, but there will be a crank handle attached to the bottom right of the base track as shown below in provided figure. Once the handle is cranked it will then cause the track to be put in motion. Demonstrating square wheels rotating on a moving surface. This design would be displayed on a small table where the handle can be accessible for both children and adult audience.

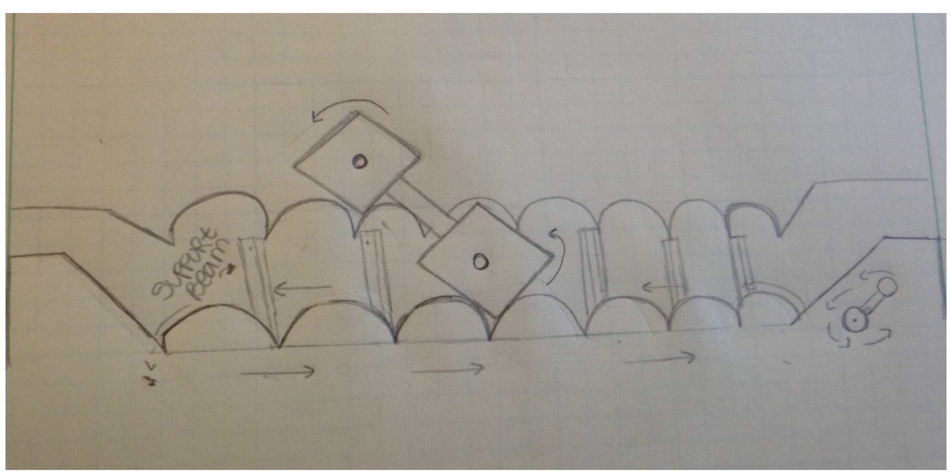


Figure 3.3.2: Crank Model design by Alyssa Sanchez

3.3.3 Ride – Able Tricycle Track

The Ride – Able square wheel track design would consist of two major components: a tricycle and a track. The tricycle would be constructed using sustainable upcycled materials such as wood. The pedals would be attacked to the front wheel eliminating the use of the sprocket and chain. The tricycle seat would be attacked to a frame that connects the front and rear wheels. By measuring the average leg length of the people using it, the pedals and seat would be placed at the correct distance from one another. This concept is illustrated in the figure below.

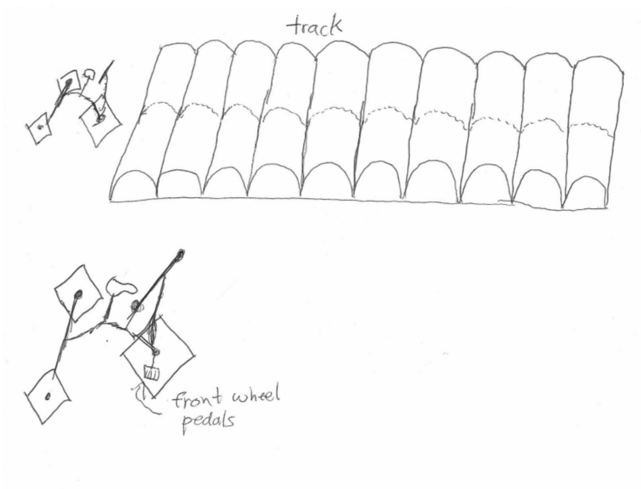


Figure 3.3.3: Ride – Able Tricycle Track design by Andrew Heise

3.3.4 The Cube Wheels

The Cube Wheels design involves the use of two cube wheels on a bicycle that would be places on a stationary catenary curve shaped track. It will consist of the exact same properties as the Ride – Able Tricycle Track design, but instead of thin squared wheels this design will have long thick cube wheels laying longitude as shown in the figured below.

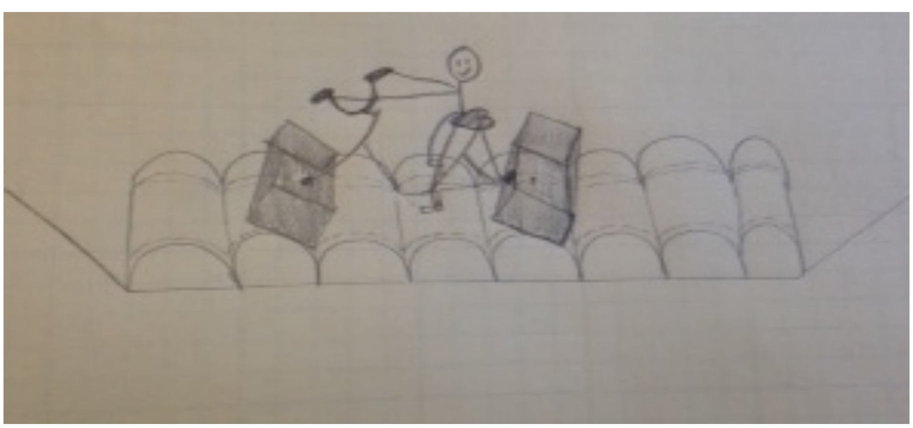


Figure 3.3.4: Cube Wheels Bicycle design by Alyssa Sanchez

3.3.5 Square Wheels Exercise Bike

The Square Wheels Exercise Bike design would be a contained system. Unlike the square wheels tricycle track where the tricycle moved on the track, the Square Wheels Exercise Bike would stay in a fixed position and the track would move underneath it, like an exercise bike at the gym. The goal for the design is that the square wheeled bike would physically move the track under it, making the track go around like a treadmill rotating. The bike would be fixed atop of a track that is then fixed to a main frame holding the system together. The track would need to be hovered slightly above ground, just enough to give the track clearance from the floor. There would be a metal frame, welded to hold all the components together. This is shown in the figure below.

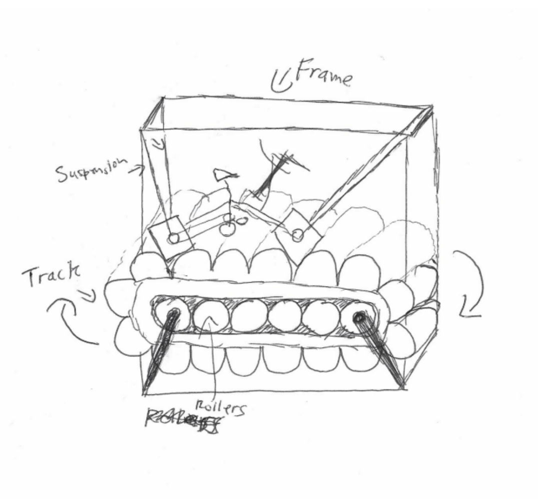


Figure 3.3.5: Square Wheels Exercise Bike design by Andrew Heise

3.3.6 The "Skuare" Board

The "Skuare" Board design involves a sit – down skateboard with square wheels on a catenary curve surface. The inspiration for this design is a mixture between a sled and a skateboard. The catenary surface would only be wide enough to fit a child and the skateboard. For safety purposes, the track would be contained by raised edges. Along the catenary surface there would be a separate flat track on which another child could walk alongside while pulling the skateboard, which would be attached to a rope. Another option for this design would be to have two ropes attached to the front center of the skateboard, which could then be pulled by two children walking along the side of the track. As illustrated in the figure shown below.

Figure 3.3.6: The “Skuare” Board design by Ana Zurawski

3.3.7 Square Drop Wheel Machine

The Square Drop Wheel Machine alternative is inspired by a pinball machine mechanism. The components of this design would be attached to a flat surface and operate like a vertical pinball machine. The user would drop a square wheel made of wood into the drop wheel machine, and gravity would be the main source of moving the square wheel to the bottom of the machine. The figure below illustrates how the square will move down the machine.

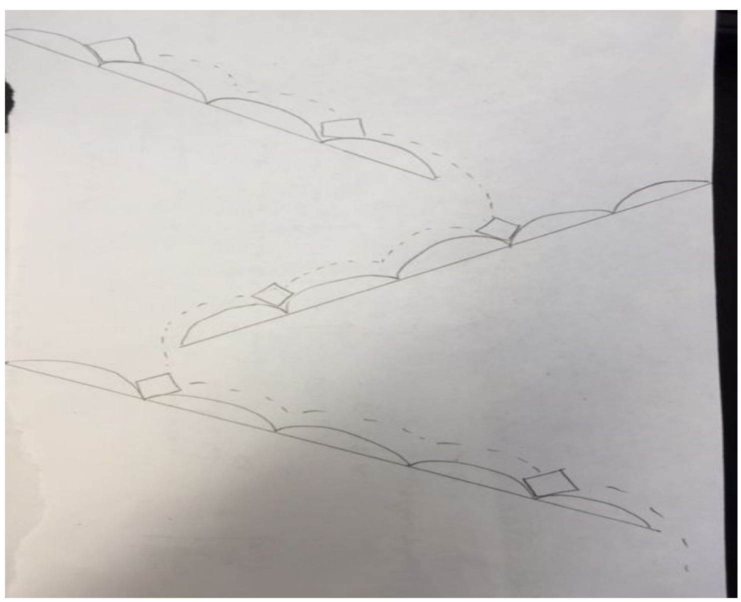


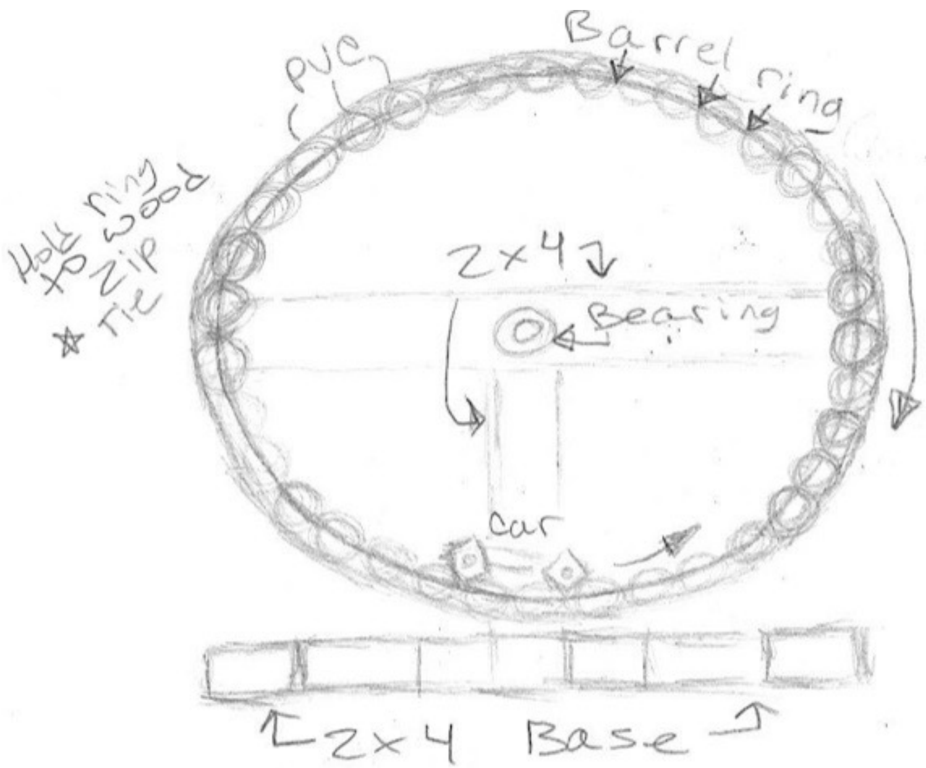
Figure 3.3.7: Square Drop Wheel Machine design by Ana Zurawski

3.3.8 The Squared Hamster Wheel

The Squared Hamster Wheel design is a circular rotating wheel similar to that of a hamster wheel. The inside of the wheel will consist of several catenary curves

Figure 3.3.8: The Squared Hamster Wheel design by Andre Meza

making up the track. Inside of the wheel will be a small stationary toy car with square wheels. To demonstrate the motion of square wheels the user will spin the wheel causing it to rotate around the car.



4 Decision Process

4.1 Introduction

Section 4 of this document outlines the process used to evaluate the alternative solutions described in section 3. A decision-making method called the Delphi Matrix will be used to select the final design, and its application will be explained in Section 4.4 below.

4.2 Criteria

This is the set criterion by which the available alternatives will be judged.

- Safety: the most important criteria is safety of the children who will be interacting with the demonstration. The finished project should be made safe for a wide age range.
- Durability: the demonstration should be able to withstand conditions inside of a middle school classroom environment, and should ultimately require little to no maintenance.

- Portability: the final design should be easy to transport, with the required size set by the client.
- Construction time: the final design must be built and assembled in time for presentation set in the final week of the Spring 2016 semester.
- Cost: The cost will not exceed $300.

Table 4.2.1: Table of Criteria Weights

Criteria	
List	**Weight**
Safety	**10**
Durability	**10**
Portability	**9**
Construction Time	**7**
Sustainability	**6**

4.3 Solutions

The following list is comprised of the alternative solutions listed in Section III. More details on each design can be found starting on page 12 of this document.

- Mono-Wheel
- Crank Model
- Ride-able Tricycle Track
- The Cube Wheels
- Square Wheels Exercise Bike
- The "Skuare" Board
- The Square Drop Wheel Machine

4.4 Decision Process

The Delphi method was developed as a tool to aid decision making by mathematically finding the best alternative given a set of criteria. After assigning each criterion a weight between 1 and 10 (from least to most important, as shown in Table below), those weights are multiplied against the graded range that each alternative scored for each individual criterion. After those values are multiplied, they are added up for each individual option to yield a final number. For example, safety is the most important criterion and as such was rated 10; the overall safety grade for the design was rated a 6, therefore the total number representing the safety for that design is 60. The design with the highest final number is the preferred alternative considering the criteria and how each alternative is rated.

Table 4.4.1: Delphi Matrix used for the decision making process

Criteria		Solutions						
List	Weight	Dropwheel	Skateboard	Cube Bike	Tricycle	Exercise Bike	Monowheel	Hamster Wheel
Safety	10	10 / 100	5 / 50	4 / 40	7.5 / 75	4 / 40	10 / 100	9 / 90
Durability	9	6.5 / 58.5	5 / 45	4 / 36	4 / 36	4 / 36	10 / 90	3 / 27
Portability	9	10 / 90	6 / 54	1 / 9	4 / 36	2 / 18	10 / 90	7 / 63
Construction Time	7	2 / 14	1 / 7	2 / 14	3 / 21	2 / 14	9 / 63	2 / 14
Sustainability	6	7 / 42	7 / 42	3 / 18	6 / 36	7 / 42	7 / 42	7 / 42
	Total	304.5	198	117	204	150	385	236

4.5 Final Decision

The Mono-Wheel best met the set criteria scoring the highest rating on the Delphi Matrix. The design is affordable, and it is possible to find recycled materials for construction needs. The time needed for construction is based on availability of the students on the Alpha Team. It is designed to be the desired size, and it can be transported in a pickup truck. It is durable enough to maintain functionality and durability at the hands of middle school children. The design also scored a high safety rating, the most important criteria.

5 Design Specifications

5.1 Introduction

This section describes in detail the components of our final design, costs, assembly and storage.

5.2 Description of Solution

5.2.1 The Wheel

The wheeled component in this project consists of two square wheels and an axle. The wheels are 8- inches on each side (as requested by the client), and the thickness is ¾ inches. In the center of these square wheels is a wooden axel with a plastic PVC pipe incasing the axel. This allows the axel to spin freely as the user rolls the wheels along the catenary shaped track. The wheels and axel mechanism are bound together using 3-inch wood screws.

5.2.2 The Track

The track is made from cedar lumber purchased at the local lumberyard. The track system for the wheels to roll over consists of 2 parallel tracks (one for each wheel), a guiding track on the inside of the wheels to keep the wheels on the track, a base board to attach all components together, and wooden cross members for support (like train tracks). The dimensions of the catenaries were printed on a piece of paper and traced onto the cedar wood before cutting it. The 45-degree angles were traced using a protractor and rulers. We used 3-inch screws to join everything together. The finished design is coated with paint so it is resistant to weathering and mold. The criterion to fit the demonstration on top of a 5-foot table was requested by the client. The overall design is about 30 to 40 pounds and requires that two people carry it.

5.2.3 The Geometry

The mathematical aspects of this square wheel presentation may be explained by using basic geometry and trigonometry. A square wheel on a flat surface would result in a very bumpy ride. One way to make the ride smoother would be to alter the shape of the road. A square wheel can roll smoothly if it travels over evenly spaced bumps of just the right shape, called an inverted catenary. A catenary is the curve that is formed when a rope or chain is seen hanging loose between two supported positions. It looks like a parabola but it corresponds to the graph of a function called the hyperbolic cosine. If you flip it upside down, you have an inverted catenary.

The inverted catenary works well for a square wheel because the catenary ends where the tangent is at a 45° angle. This means two catenaries together form a right angle, which is the same angle as the corner on the square. Additionally, the length of the curve can be made so that it is the same as the length of one of the sides of the square tire, allowing the axle and center of the square tires to move in a straight line, much like a round wheel on a flat surface. Other polygons can be used as well, but the dimensions of the catenaries need to be adjusted accordingly. As sides are added to polygons, the length of the catenary would be reduced. Eventually, the more sides added to the polygon, the more it looks like a circle. The more the length of the catenary is reduced, the more it looks like a straight line.

5.3 The Materials and Design Costs

Materials and design costs were aimed to keep at a minimum without sacrificing quality or safety. Most items were donated and upcycled but certain parts of the project needed to be straight and we couldn’t sacrifice quality so we purchased the parts needed such as, lumber and paint shown in table below.

Table 5.3.1: Materials and Costs

Materials and Costs	
Items	**Costs (in Dollars)**
2"x12'x20' Cedar Board	$50.00
Axle	Donated
Bearings	Donated
Box of 3" Screws	Donated
Box of 1 3/4" Screws	Donated
Paint	$15.00
Projected Total $	65.00

5.4 Design Costs (Time in Hours)

The majority of the design time was spent on the literature review and alternative solutions, followed by the building time, brainstorming, problem analysis, and specifications, as illustrated in figure below.

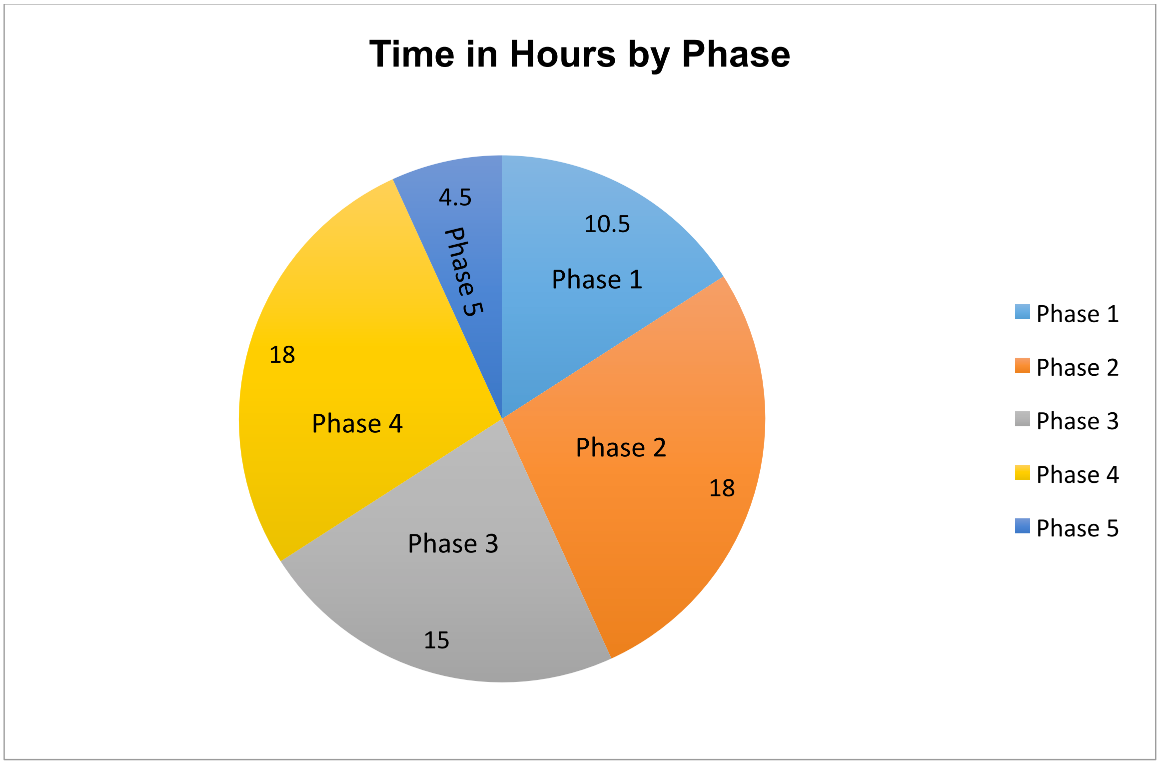


Figure 5.4.1: Time spent on each phase of design in hours

5.5 Maintenance Costs

Little or no maintenance is required when using this square wheels design. However, the team will provide an extra axel for the client, in case one breaks, as well as leftover spray paint. The track will need to get dusted and cleaned whenever dirty, and the paint may need to be reapplied from time to time. The design is robust and should not need much extra or unique care.

5.6 Instructions for Implementation and Use of Model

Step 1: **Build wheel and axel**: Make two 8-inch squares out of wood (use a board that is between 3/4" and 1" thick). Attach 12" wooden dowel perpendicular to the wood but perfectly in the center of the square to act as an axel. Next, attach to one of the squares with a 3" screw. Slip PVC pipe (at least 1" in length) over the dowel, make sure there is room between wooden dowel and the PVC pipe so wooden axel can rotate within the PVC pipe Lastly attach second 8" square with a screw to the other end of that mechanism. Shown in figure below.

Figure 5.6.1: Wooden Dowel inside PVC Pipe attached to squares with screws

Step 2: **Trace out track**: Use geometry section to calculate the height, length, and thickness of catenaries. Once you know the size of wheel, you can determine the size of catenaries and start building the track. Print and cut out catenary shape on computer. Once the catenaries (or arc) is cut out you can start tracing it on to the 2″x 12″x 4.5′. Measure a straight line 5″ from the bottom of the wood (this 5″ line the where all the angles and arcs sit on top). Next draw a 45-degree line from on the top corners through the 5″ line. Once your line is straight you can start tracing around the piece of paper with your arcs on it. Start the arcs at the point where your 45-degree line intersects with the 5″ line you made to insure everything is straight. After you made your desired number of arcs draw another 45-degree line, opposite from the first one that was made. Repeat this whole process on a second piece of wood, as demonstrated below.

Figure 5.6.2: Traced out and cut track, bottom on left and top on right

Step 3: **Cut out Track:** Use a jig saw to take of any extra pieces of wood to make sanding the arcs easier. Use an orbital sander to sand and cut out arcs as pictured below. We found out it is easier to sand it into perfection as opposed to cutting it because a sander is more lenient towards mistakes and a sander will make the curves smooth, which will make the wheels roll easier. Make sure to get as close to the traced line as possible without sanding over the line. Once both pieces of track are cut out you are ready to put everything together.

Figure 5.6.3: Orbital Sander, sanding slowly towards lines

Step 4: **Cut out guide track**: Cut out two pieces of wood or material ½ thick to use as guides for your wheel to roll next to. These pieces are going to be ½ inch higher than your catenaries.

Step 5: **Assemble Track**: Using another 2″x 12″x 4.5′ for your baseboard, sandwich the guide track in between the baseboard and outer track. Do this for the other side as well. Afterwards, use a big clamp to clamp everything together. Proceed to drill 3″ screws into all tracks, eventually screwing together all wooden pieces, as shown in figure below.

Step 6: **Attach Support Pieces**: Cut out 6-12″ pieces of wood to screw in between the tracks adding further stabilization and durability.

Step 7: **Finishing and Paint**: Once everything is attached together, you can sand out any imperfections or sharp edges so nobody gets splintered or cut. Next, paint track and wheels however way you want. The paint will add years to the project, also cover any imperfections.

Figure 5.6.4: Inside track sandwiched between baseboards and outside track, screwed in with 3- inch screws

5.7 Assembly and Storage

There is only one loose piece with Square wheels and that is the axel. The track weighs approximately 30 pounds but it is long, and requires two people to carry it when moving or transporting. Keep in a dry place to reduce the chance of mold. Keep on level ground and not tilted up to store because tilt will eventually warp the wood and the square wheels will no longer run smoothly.

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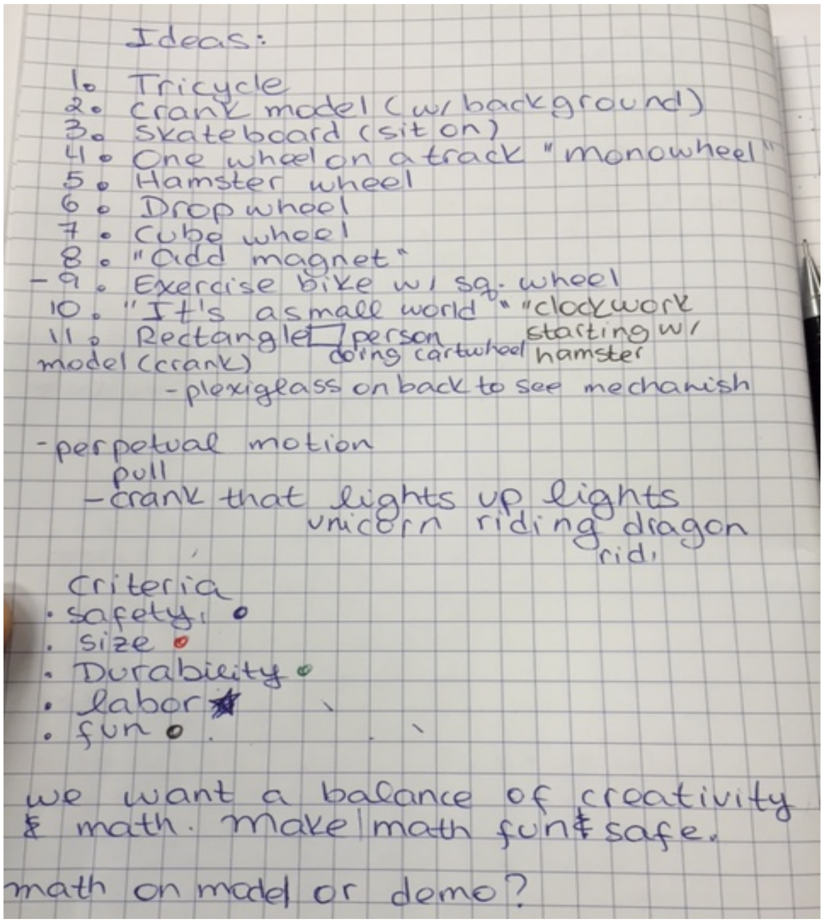
7. Appendices

Appendix A: Brainstorming Session



Ideas:

1. Tricycle
2. Crank model (w/ background)
3. Skateboard (sit on)
4. One wheel on a track "monowheel"
5. Hamster wheel
6. Drop wheel
7. Cube wheel
8. "Add magnet"
- 9. Exercise bike w/ sq. wheel
10. "It's a small world" "clockwork
11. Rectangle person doing cartwheel starting w/ hamster
model (crank)
- plexiglass on back to see mechanish

- perpetual motion
pull
- crank that lights up lights
unicorn riding dragon
ridi

Criteria
- safety
- size
- Durability
- labor
- fun

we want a balance of creativity & math. make math fun & safe.

math on model or demo?

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Signed by each team member:

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