SENIOR PROJECT
TEAM 45
FINAL DESIGN REVIEW

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Abstract

The purpose of this report is to document the Senior Project that has been laid out by Bellevue-Santa Fe Charter School, assigned to Team W45, or "Experiment 626." The school's SciTechatorium is a classroom of displays relating to STEM subjects and the challenge presented to the Cal Poly team of mechanical engineers was to design and build a new, exciting exhibit that would be added to the SciTechatorium. The display should be engaging to children, educational in demonstrating a STEM concept, and be durable enough to withstand excessive use by children. The Scope of Work summarized in Sections 1-3 presents the introduction to the project, background information gathered, and objectives of the final product. In the Preliminary Design Review, the team decided on showcasing earthquake concepts through a shake table, where students would create and then topple structures.

As the team moved into the Critical Design Review, several key decisions had been made. The team decided that the shake table would incorporate two degrees of freedom (DOFs), the vertical axis and the horizontal axis. These axes of motion are independent of one another, and in conjunction can produce a waveform of motion, which is more accurate to how actual earthquakes function than a single DOF shake table. The team had met some challenges due to the COVID-19 pandemic, namely in communicating with each other, securing funding, and sourcing parts. At the time of the CDR writing, the team planned to go ahead with the manufacturing of the verification prototype. At this stage, funding for a budget of $2000.00 was secured through both Bellevue-Santa Fe Charter School and Cal Poly.

Moving into Fall Quarter, the team divided the main portions of the work into two teams: Kellen Fujishin and Alysson Loo handled all documentation, visual exposition, and otherwise virtual deliverables, and Joshua Clemens and Samara Van Blaricom handled the physical manufacturing of the prototype. The original design changed very little, with the cams requiring slight modification and additional springs being added, and manufacturing was completed at the end of Week 10 after the Senior Project Expo. At the time of this writing, the completed project will be delivered to Bellevue-Santa Fe Charter School on December 3, 2020, which is the optimal time for both team and sponsor.

1.0 Introduction

Christian Strauli is the science teacher and the SciTechatorium Director at the Bellevue-Santa Fe Charter School. The SciTechatorium is a classroom dedicated to building interest among students aged 5-12 years of age in STEM subjects and has also received Cal Poly Senior Projects before. Students can visit the "SciTech" during their lunchtime, while interested parties outside of the school are able to take guided tours led by older students. Jennifer Crooks, along with other dedicated parent volunteers, supervise the SciTech when it is open to students.

The Cal Poly Experiment 626 Team was tasked with creating a new exhibit for the SciTech to further increase interest in STEM amongst students. The display should be physically interactive to increase engagement and demonstrate a STEM concept in a way that students have direct control over.

In the Preliminary Design Review, several concept choices were reduced to a single concept: earthquakes and their causes. To simulate an earthquake, the team decided on building a shake table, but specifics of the design remained unclear. The concept at that time was a simple one degree of freedom shake table, powered by an electric motor.

For the Critical Design Review, multiple decisions were made finalizing the design of the prototype as a two degree of freedom, manually powered shake table. A subsection was added to the Background that explains the new direction the team planned to take. The Objectives section was updated to accurately reflect the new design requirements. A section was added called Concept Design, which details the new preliminary design of the product. Lastly, the Project Management section of the report was updated with future milestones.

For this Final Design Review, sections were added detailing part procurement, assembly of the prototype, and subsequent testing. Final conclusions and next steps are also detailed, along with changes to the concept model presented in the CDR.

2.0 Background

2.1 Sponsor Interview

The team met with both Mr. Strauli and Ms. Crooks on their visit to the SciTech on January 16, 2020. Upon arrival, the team interviewed Mr. Strauli to get a better idea of his vision for the display. Mr. Strauli has the final say on displays for the SciTech, but funding for the project would have to be secured through the principal of Bellevue-Santa Fe. No particular STEM concept was preferred over another, so the design was largely open-ended. However, the STEM concept selected had to both appeal to and be understood by the age range of students visiting the SciTech, which is ages 5-12 years old. The team then transitioned to a tour of the SciTech, where the team met Ms. Crooks. Both Ms. Crooks and Mr. Strauli stressed the need for something physically interactive to maintain interest and emphasized that the display should be "unbreakable" to cope with the stress of being handled by children. The display should be able to fit through a standard door and should be no larger than a standard school table, roughly 3 feet by 6 feet. An additional desire for the display would be that it is easily transportable for use in schoolwide assemblies. A preferred quality of the display would be having a certain "wow" factor for a demonstration, as something that has the capability to amaze or arouse a sense of wonder would be helpful in generating interest. This "wow" factor includes bright colors, elements that light up or make sounds, and the STEM concept causing a drastic effect such as the Van de Graaff generator which can cause hair to stand on end. The team concluded the interview with a better understanding of the project, with a full list of customer requirements located in Appendix C.

2.2 Additional Interview Information

In addition to the two interviews conducted at the SciTech, the team also interviewed a docent named Alicia at the SLO Children's Museum, who generously provided a tour free of charge to the team. The first floor of the Children's Museum was largely STEM based, while the top two floors were more imaginative play oriented. When asked about which displays garner the most interest, Alicia stated that the displays that children can directly manipulate generate the most interest. Alicia also stated that children do not do well standing still and tend to have shorter attention spans, so movement combined with color, sounds, and buildable items tend to hold their interest for the longest duration. This gave the team an idea of aspects that could be incorporated into their final design aside from the core STEM concept to be displayed.

The team also met with two Liberal Studies students, Carrie Buckley and Celeste Elam, who are working with the SciTechatorium to better convey the STEM concepts that are being demonstrated in the displays to students. Ms. Buckley and Ms. Elam explained that they are using the Next Generation Science Standards (NGSS) to guide their process and encouraged the team to do the same. They also emphasized the desire for students to want to ask questions about concepts. The NGSS focuses more on the "how" rather than the "what" of a question, encouraging students to go more in depth with their knowledge and learning instead of regurgitating facts. As an example, Ms. Buckley said that an NGSS based curriculum would ask "How do metamorphic, igneous, and

sedimentary rocks form?” as opposed to “What are the differences between metamorphic, igneous, and sedimentary rocks?”

Ms. Buckley and Ms. Elam also brought up the concept of a display evolving with the students’ knowledge. Such a display would have elements that could be understood at one point in their education and have more complex concepts that would be understood later in their education to keep their engagement throughout their time at school. This meeting drove the educational poster creation, shown in Appendix M.

2.3 Product Information

Although there are many examples of science displays, there is not a consumer market for these displays as most, if not all, are custom, one-of-a-kind displays. The advantage of this is that there is a copious amount of inspiration, even just throughout California. The team researched five different locations, two in person, and three online through the organizations’ websites and exhibit information.

The first background came from the tour of the SciTechatorium to get an idea of what displays are already present and which appeal to the students most. The SciTech’s displays include a wind tunnel with a model plane wing, a Van de Graaff generator, live reptiles and arachnids, and a display of rocks and gems.

Locally, one of the San Luis Obispo Children’s Museum’s three floors is dedicated to STEM oriented displays, including a shake table, Mission to Mars exhibit, and kinetic sand. While appealing to children, the museum was somewhat limited in its scope to STEM related topics, so additional research was required.

The California Academy of Sciences, located in San Francisco, was another source of background on STEM displays through their website, containing both interactive and noninteractive displays. Displays such as the Discovery Tidepool provide physical interactions, whereas their planetarium is more of an educational show.

The Exploratorium in San Francisco also provided some background for the team’s research by way of their comprehensive list of exhibits online. Displays that were of interest were ferromagnetic sand, a vibrating rod that changes pitch based on the free length, and a pendulum that combines magnetism and mechanics.

Finally, the Discovery Cube in Orange County was the last location the team researched, again through their online exhibit guide. Some displays that piqued the team’s interest were the seismograph, the cloud ring, and the dinosaur quest.

Through most of the research, the displays were often interesting but lacked a full concept that was being demonstrated and thoroughly explained. This would help form the team’s objective by building on displays that had been researched and adding information on the concept to be displayed to give a clearer, more complete educational exhibit. Examples of STEM interactive science displays that the team will draw inspiration from is documented in Appendices A and B.

2.4 Additional Background

Due to the nature of the project, and the fact that the display will not be replicated, technical research and patent research are not applicable to the project. The project being aimed at a younger age group will also limit the complexity of a technical concept. Displayed poster text is all original work of the team.

2.5 PDR Updated Information

Since the creation of the Scope of Work, the team and Mr. Strauli have decided to pursue a shake table design. This direction was chosen after careful consideration of multiple design concepts. A shake table would provide adequate educational value and engagement for children of all age groups. The shake table from the San Luis Obispo Children's Museum and shake tables made for other Cal Poly senior projects would be used as references when creating the final design. This choice of direction has multiple implications for the objectives of the project, which is addressed in subsequent sections of this document.

2.6 CDR Updated Information

Since the PDR, the team has decided upon a finalized design of the shake table: the shake table will incorporate two degrees of freedom, with a vertical and horizontal component. This is different from most other shake tables, as vertical motion allows a waveform to be approximated, which is normally found on much more advanced shake tables. It will achieve this by using a camshaft with followers to produce the vertical motion and potential energy stored in springs to create the horizontal motion.

2.7 FDR Updated Information

Since the CDR, the team has created a verification prototype that meets all criteria and functions as designed. In addition, the expo poster was created for and showcased at the Senior Project Expo. Sections have been added to the report to reflect the creation of the prototype, including manufacture of custom parts, assembly, and testing. Finally, at the time of this writing, an educational poster focused on the science and causes of earthquakes has been created and revised by the sponsor to supplant the project and provide a more well-rounded experience. The project is to be delivered to the sponsor on December 3, 2020.

3.0 Objectives

The main objective of the project is to create a display that will fit through a standard door and on a standard classroom table (approximately 3 feet by 6 feet) that displays a STEM related concept. The display will be able to be physically interacted with by students aged 5-12 as part of the SciTech experience. The display should showcase a concept that is able to be understood by most of the students that interact with it, not simply be a fun activity with little to no educational value. The display should be extremely durable to allow long life without need for major upkeep and to withstand excessive use from the students. The display should give a complete picture of a STEM concept with a practical, interactive example along a brief theoretical explanation behind the concept to be displayed. These major specifications were weighted the highest in the QFD (Quality Function Deployment) in in Appendix E, which will drive the project prototype development.

In addition, it is desirable that the display have a certain “wow” factor so that it can be used in school-wide assembly demonstrations to further garner interest in STEM related topics and keep students coming back to the display rather than viewing it once and returning infrequently. It is desirable for the device to be portable, easy to clean, and handicap accessible. These were weighted slightly less than the primary objectives in the QFD.

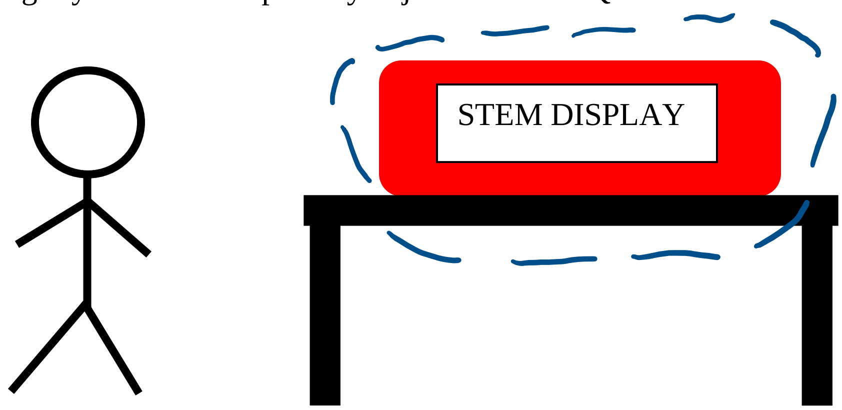

Figure 3-1. Boundary Diagram

The boundary diagram depicted in Figure 3-1 is a simple depiction of what is under the team’s control, and what is outside of the team’s control. The most important takeaway is that the team cannot predict or control what children do with the display. Excessive force, misuse, and mishandling are all possibilities. Though every scenario cannot be accounted for, by creating a robust display and minimizing breakable parts on the display, unpleasant situations can be mitigated.

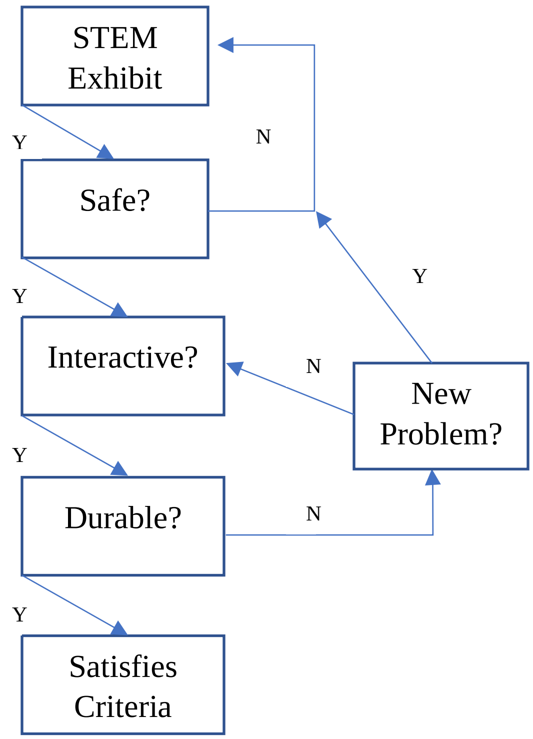

Figure 3-2. Design Process Flow Diagram

The flow diagram shown in Figure 3-2 details the sequence of events that must be satisfied so that all sponsor-designated design criteria were met. This diagram highlights how any initial idea must first revolve around the safety of the users, and then it must be engaging such that is receives adequate use. Finally, the amount of use it receives must be reflected in the durability of the design. If these three primary criteria are met, the client's fundamental needs will be satisfied. It is worth noting that this diagram does not encompass additional design criteria such as client/user wants and technical engineering design challenges.

The new design choice of a shake table has affected the current objectives of the project at the time of Preliminary Design. A shake table would fulfill the previous objectives already stated, but it also created more design challenges and goals to accomplish. The team still needed to finalize some of these objectives with Mr. Strauli, but most come naturally with the decision of making a shake table. Such objectives include making a shake table that shakes sufficiently enough to topple simple structures made of blocks. Another objective is making a table that does not shake so vigorously that it presents a danger to the users. Though these are helpful starting points, more objectives needed to be agreed upon with Mr. Strauli before progress is made.

At the time of the Critical Design Review, the objectives were built and have been finalized: to create an interactive, educational STEM display in the form of an earthquake simulator/shake table. Safety concerns have been outlined as making sure there are no pinch points or access to moving parts. An educational poster will be displayed alongside the table to provide a well-rounded experience.

4.0 Concept Design

4.1 STEM Concept Selection

Once the challenge and objectives of the project were understood, the next challenge was to determine which STEM concept would be displayed, and in what way it would be interactive. The process started with concept selection, and team member brainstormed which STEM concepts learned in elementary school would be easier to understand with a physical display. Ideas were also drawn from the NGSS (Next Generation Science Standards), which were suggested by Ms. Buckley and Ms. Elam. Ideas included magnetism, plate tectonics, electricity, structures, and light reactivity. This was narrowed down to magnetism, plate tectonics, and electricity as the final three selections for STEM concepts.

4.2 STEM Display Selection

From here, the decision process turned to determining the method of conveying the information through an interactive medium. The final three physical concepts were a railgun to show magnetism, a shake table to demonstrate plate tectonics, and using conductivity of the human body as a game to complete a circuit would show electricity. A full list of both concepts and physical ideas can be found in Appendix G.

4.3 Final Concept Selection

These three concepts and their theoretical displays were presented to Mr. Strauli via email, along with descriptions of their functions. Full communication can be found in Appendix G. While waiting for a reply, the team eliminated using electricity due to safety concerns with current entering the human body. Additionally, using Pugh Matrices such as the one presented in Appendix F showed each concept's potential strengths and weaknesses. Mr. Strauli's reply was heavily in favor of the shake table, and this finally led the group to select the shake table to be prototyped in the coming months.

4.4 Shake Table Concepts

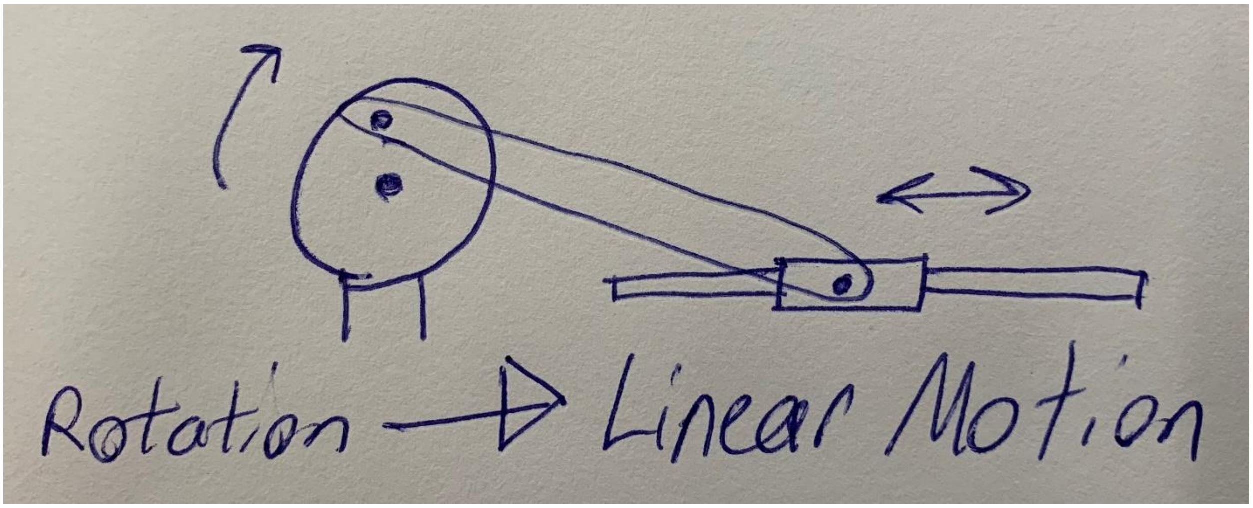

Figure 4-1. Conversion of Circular to Linear Motion

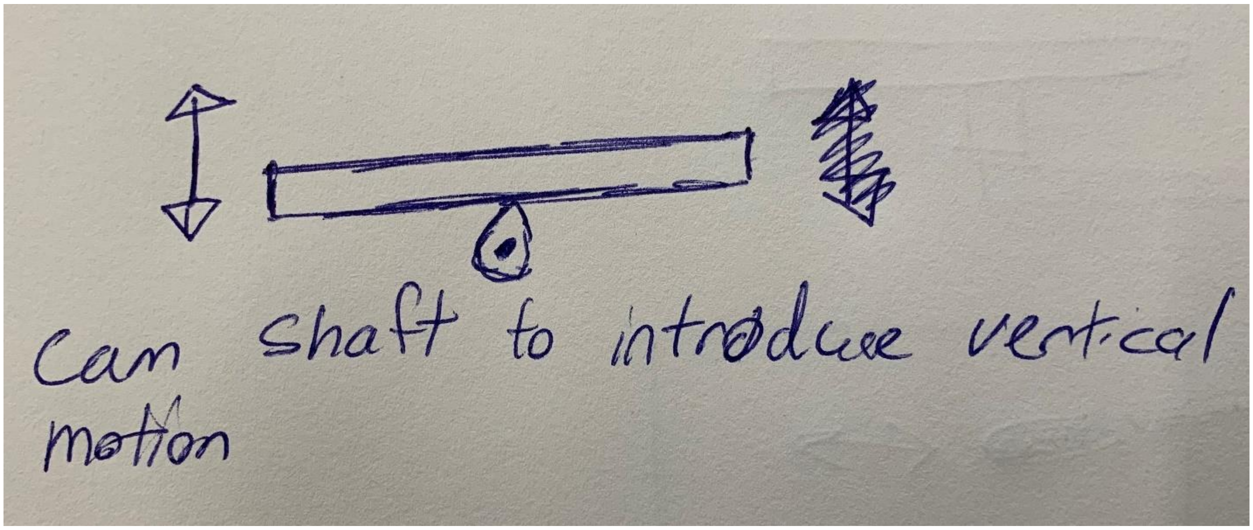

Figure 4-2. Usage of a Cam to Introduce Vertical Motion

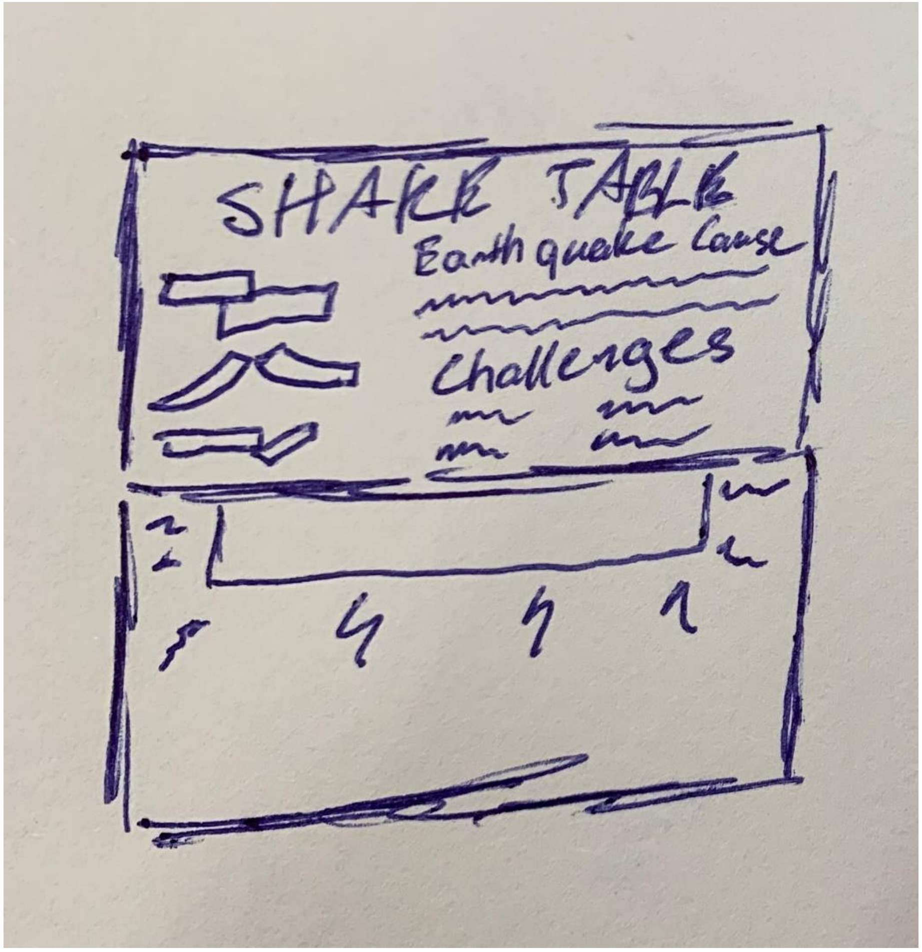

Figure 4-3. Poster Concept with Challenges

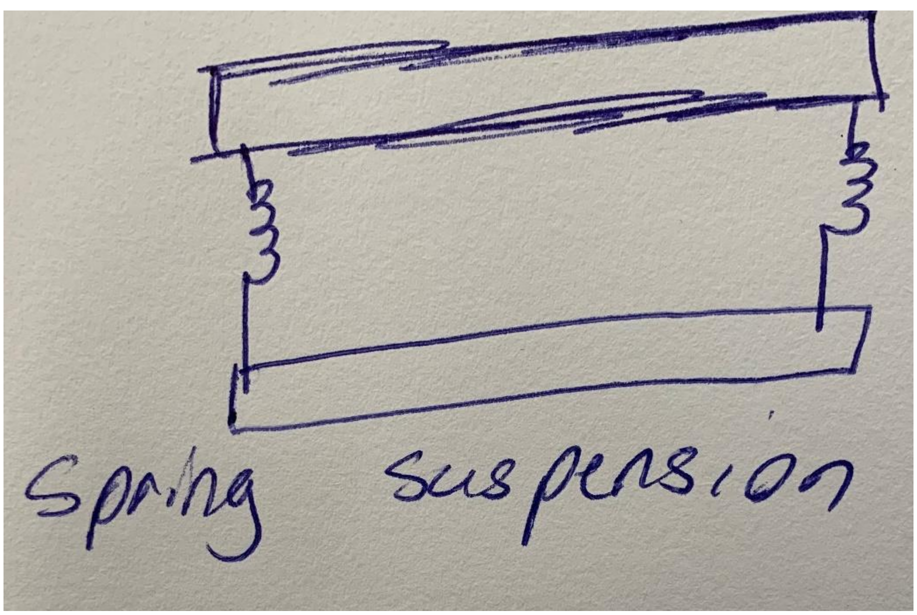

Figure 4-4. Suspension of Table using Springs

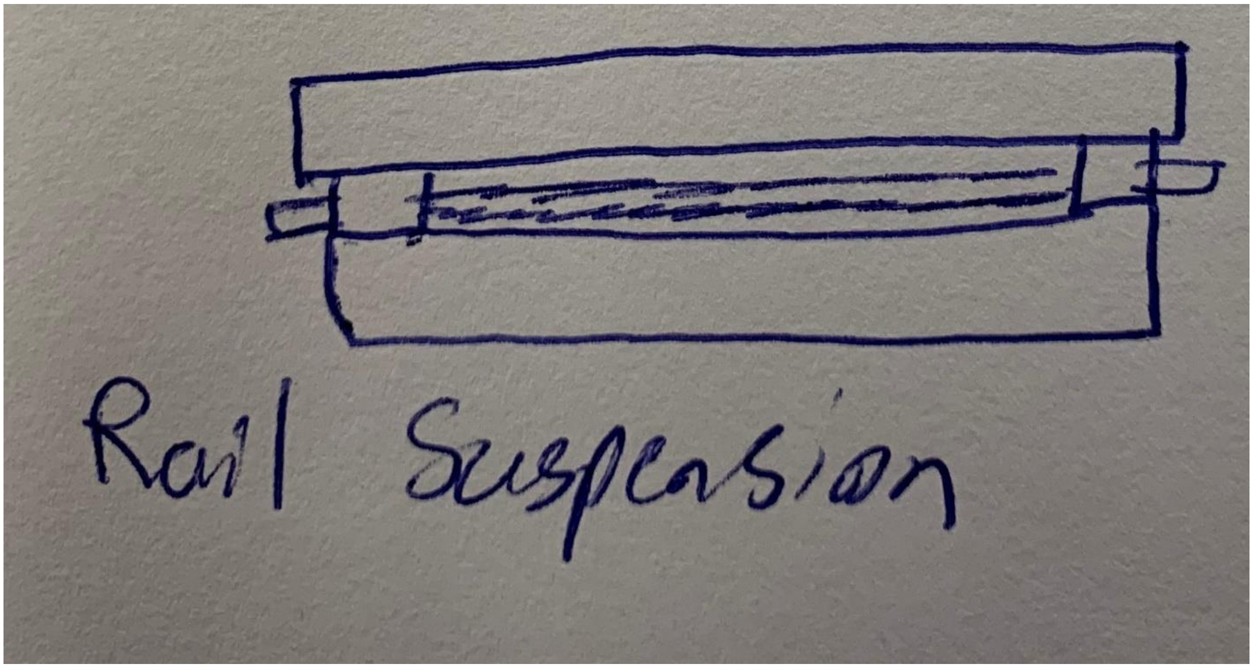

Figure 4-5. Suspension of Table using Rails

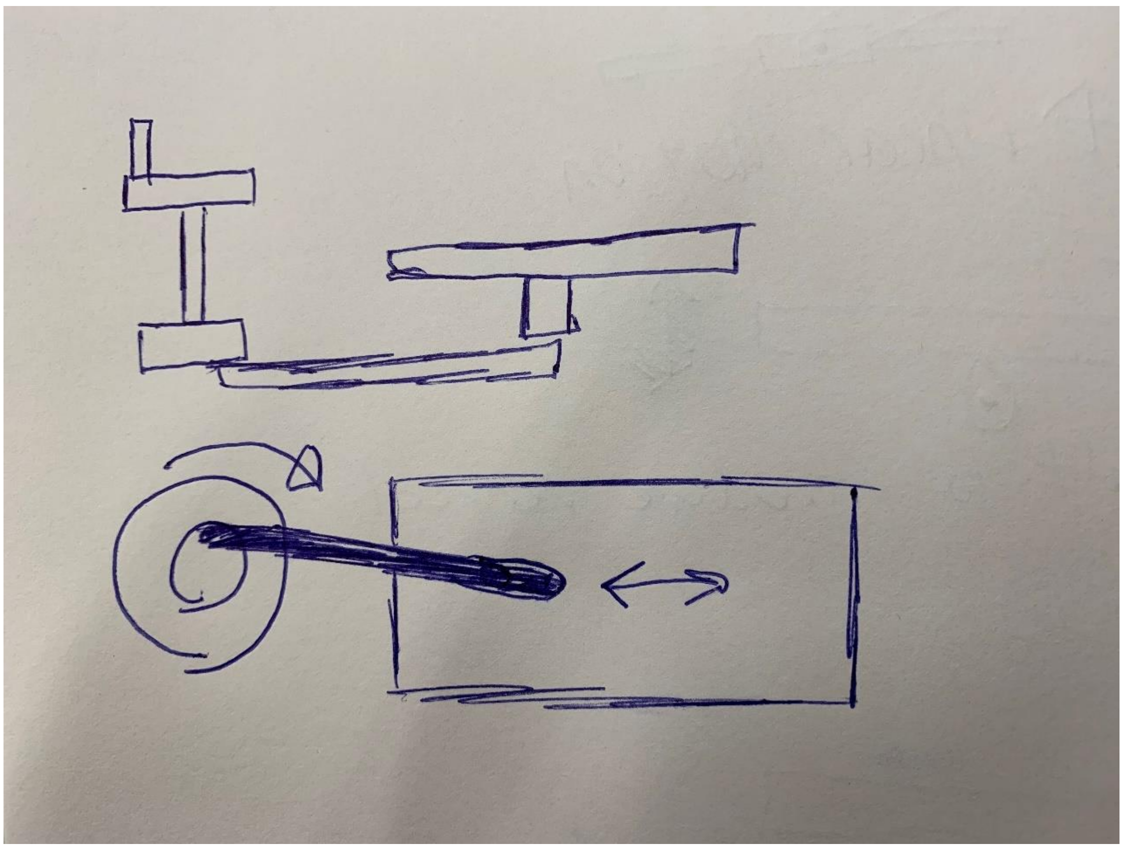

Figure 4-6. Hand Crank for Manual Power

4.5 Preliminary Decisions

Based on feedback from Mr. Strauli, the team made final decisions on degrees of freedom, final dimensions, and power source on Tuesday, February 25, 2020 during the sponsor meeting. This document was amended after the meeting.

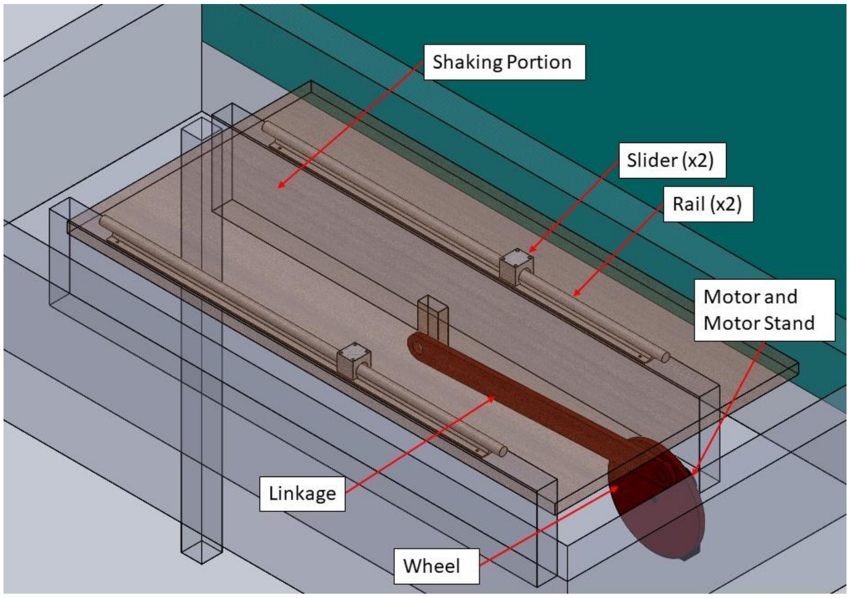

Figure 4-7. Labeled Isometric View of Shake Table and Shaking Mechanism

At the time, the team had temporarily decided on a single degree of freedom shake table powered by a DC motor, as seen in Figure 4-7.

4.6 Specification Requirements

As documented in the Scope of Work, while there are no technical specifications that this project should meet, both faculty and students that are intimately familiar with the SciTech are confident that the shake table will be engaging and educational, and Mr. Strauli sees the table as an anchor for a complete display on tectonic plates. With this feedback, the team is confident the design will be able to meet the original goal of an interactive, engaging, and educational STEM display.

4.7 Current Risks and Challenges

With a shake table comes moving parts, which presents a risk of getting fingers or hands caught in moving parts. Plans at the time were to ensure that all moving parts are covered and not able to be reached. In addition, a structure breaking may fly apart somewhat violently. To this point, the team first envisioned encasing the actual shaking portion of the table in an acrylic shell, specifically to prevent injury. A full list of potential hazards anticipated at the time can be found in Appendix H.

5.0 Final Design

5.1 Overview

After the sponsor meeting, the concept underwent a radical redesign by incorporating a second degree of freedom and would now be manually powered. The shake table is comprised of three main subassemblies: the frame, the vertical motion subassembly, and the horizontal motion subassembly. The frame houses the two motion generating subassemblies as shown in Figure 5-1, and either motion subassembly can be used independently of each other to produce horizontal or vertical motion of the main platform. Alternatively, a waveform motion can be created by using both motion subassemblies at the same time, which mimics an actual earthquake very accurately due to its similarity to actual seismic waves. The outside of the frame is completely encased in clear acrylic, so that students can safely view the internal mechanisms. A canvas cover (not pictured) prevents access to moving parts from the top.

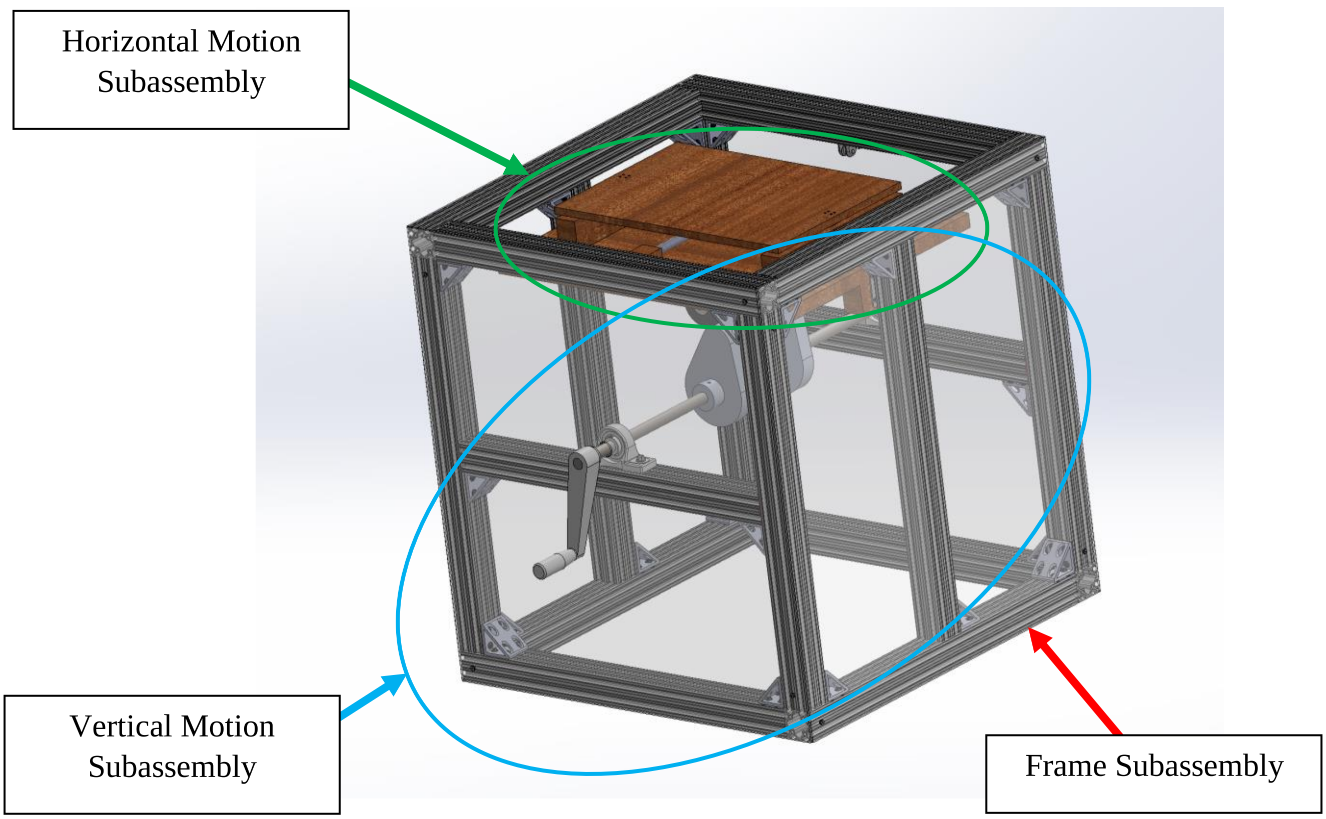

Figure 5-1. Labeled Isometric View of Shake Table and Subassemblies

5.2 Differences from Concept Design

Compared with the concept design outlined in the PDR, the final design is more complex and contains more interactive features. The final design is now completely manually powered, with no electrical components. This eliminates potential electrical safety issues and increases user

engagement. The addition of the second degree of freedom in the vertical axis is the most drastic design change.

5.3 Design Subassemblies

The frame is composed of square 2-inch cross-section beams of aluminum, held together by brackets to create a near cube structure with dimensions of 28 inches long by 28 inches wide by 30 inches tall to house the following subassemblies, seen in Figure 5-2. The high strength of aluminum combined with the minimal loading being put on the structure coupled with the high corrosion resistance of aluminum makes this an ideal material choice, given that the project will eventually be located near the ocean. All frame components were commercially purchased from 80/20.

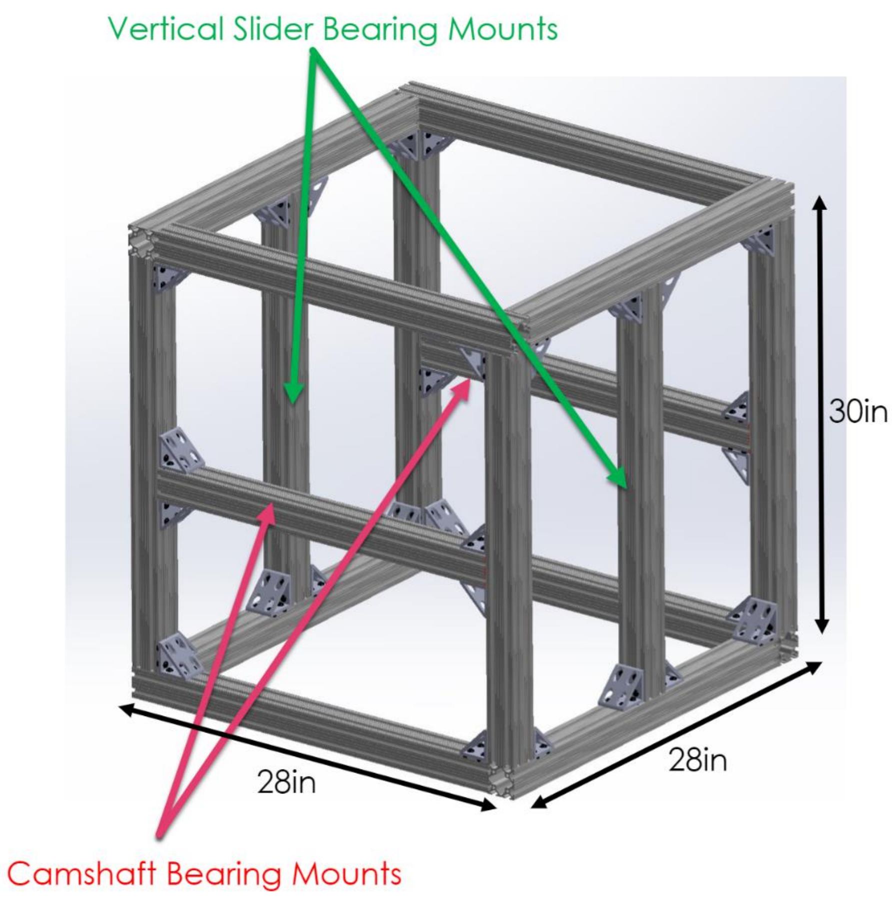

Figure 5-2. Labeled Isometric View of the Frame

The horizontal subassembly contains the main platform mounted on linear bearings coupled to a coil. The platform will be pulled to one side using a string and released to begin oscillating. The

springs and bearings were commercially purchased, while the platforms were made of wood and woodworked to specifications.

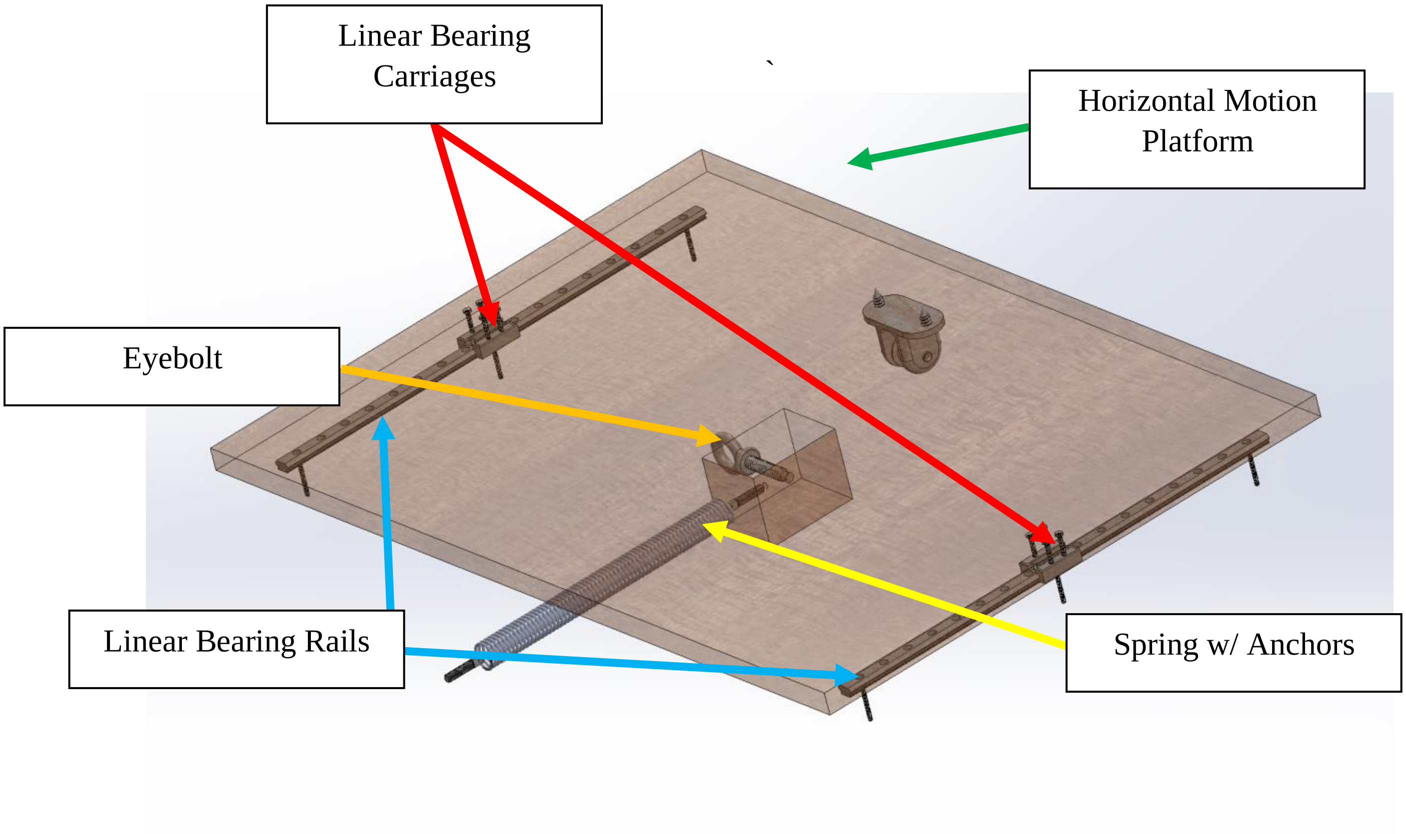

Figure 5-3. Horizontal Subassembly

The user will pull a cord that is run through two pulleys and attached to the platform of the horizontal subassembly to pull the platform to one side to begin oscillations. The string enters the casing through a drilled hole and one pulley attached to the frame converts the horizontal motion of the user pulling the string to vertical motion. A second pulley attached to the platform converts the vertical motion back to horizontal and allows the system to move vertically without pulling the string at an angle. The pulley attached to the platform of the horizontal subassembly ensures that the string remains horizontal. Finally, the string is attached to an eyelet hook that is screwed into the platform of the horizontal subassembly.

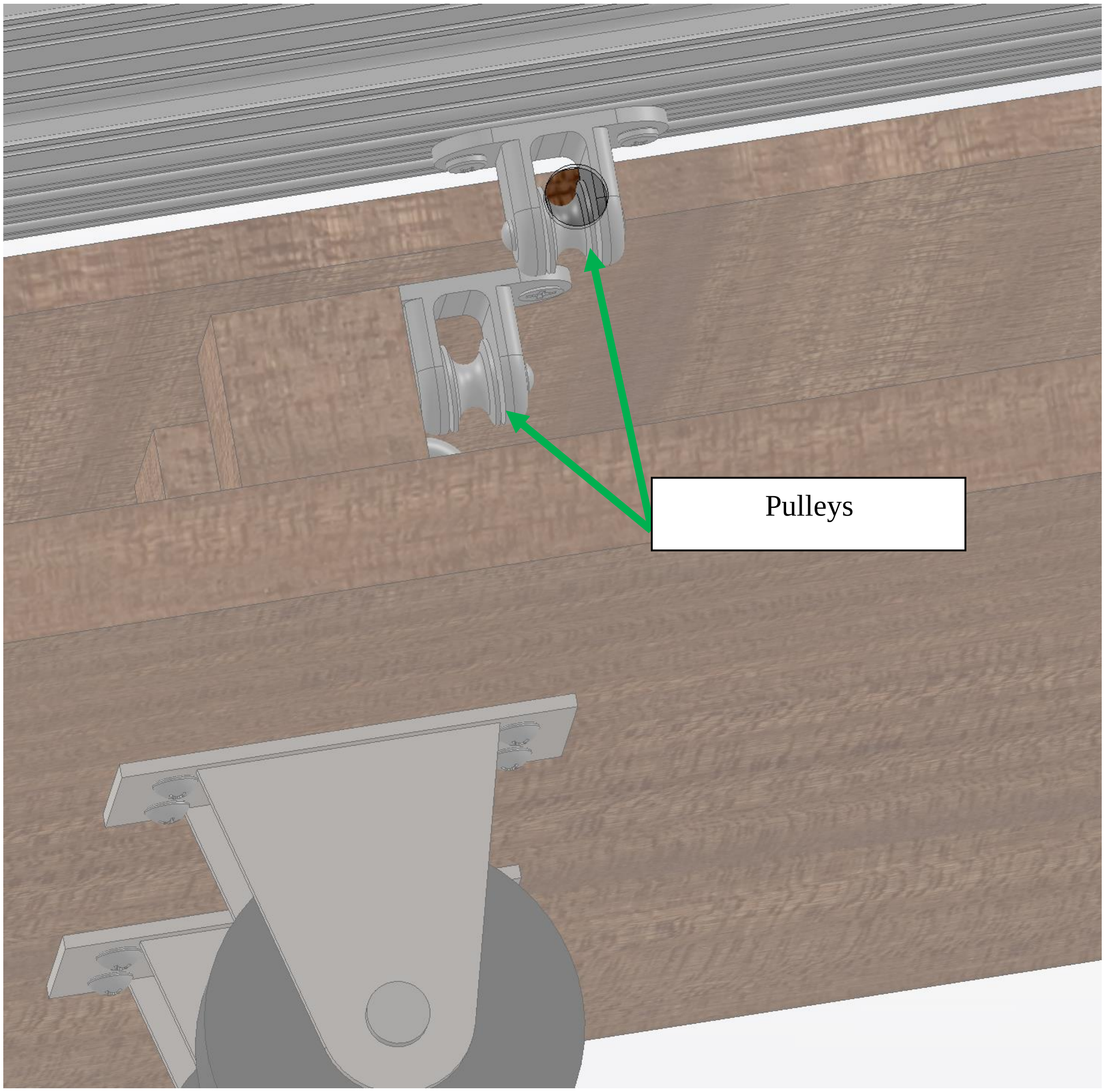

Figure 5-4. Pulley System

The vertical subassembly consists of a camshaft connected to a crank and two cams, whose followers are attached to the platform that mounts the horizontal subassembly, which is mounted on two vertical linear slider bearings, constraining its motion. The two cams distribute the weight of the vertical and horizontal subassemblies, and the structures built on top and provide stability to reduce tipping. The bearings, crank, and camshaft were purchased, and the cams were manufactured to the team's design specifications (see Section 6.2 for more details).

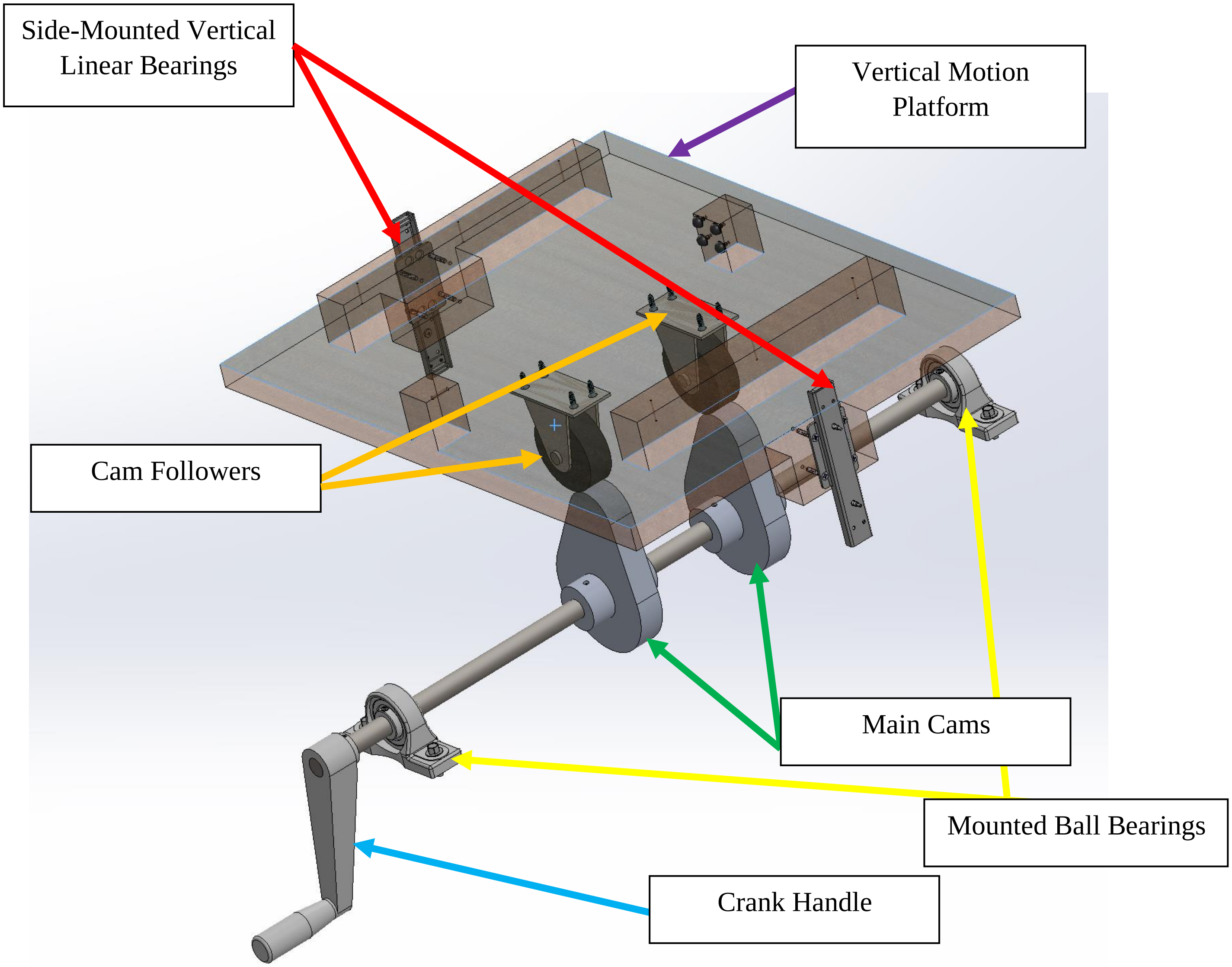

Figure 5-5. Vertical Subassembly

5.4 Specifications and Safety

Though the team does not have any technical specifications to meet, the overall goal is to provide something interactive and educational for the students using the project. With the inclusion of the vertical motion, the team believes that the educational aspect has been bolstered significantly because the table can be used as both a structural engineering challenge and a true seismic wave simulator. This increases its adaptability depending on curriculum and its variability will keep children interested in it for a longer period.

The primary audience for this device is children, so safety is paramount. The acrylic encasing eliminates much of the risk, and the small form factor and lightweight building blocks makes tipping a minimal issue. The main safety concern lies in potential pinch points from the horizontal subassembly oscillations. To reduce the risk of hazards, stopping blocks will be installed to make it so there is always clearance between the platform and the frame, eliminating a pinch point. In addition to this, the room that the shake table will be in is monitored by parent volunteers and older students, which will also help mitigate the risk.

5.5 Changes After CDR

Overall, very few changes were made after the submittal of the CDR. The exception to this is that the cams had to be modified in order to create smooth vertical motion. This reduced the vertical displacement from 1.5 inches to approximately 1.25 inches, but resulted in much smoother vertical motion. This is detailed more in Sections 6.2 and 7.3. The horizontal subassembly was also slightly modified with the addition of another spring on the opposite side of the central block.

6.0 Manufacturing Plan

6.1 Purchased Parts

All frame parts were sourced from 80/20, and there was not any machining needed to be done. The acrylic casing was custom ordered from TAP Plastics. For the horizontal subassembly, the coil springs and bearings were commercially purchased, while the platforms were woodworked from plywood and a 2 inch by 4 inch by 96 inch piece of whitewood stud. The vertical subassembly bearings, cranks, and cam followers were commercially purchased. Most commercial parts were purchased from McMaster-Carr, with fasteners purchased from Home Depot and Miner's Ace Hardware.

6.2 Manufactured Parts

The cams were manufactured from aluminum. Due to the relative simplicity of these components, the team initially believed that CNC machining would be the easiest way to manufacture the cams. Example CNC code shown below shows the initial data behind manufacturing the cams using CNC machining.

After consultation with the shop technicians, waterjet cutting was used to cut the original cam profile. Following profile creation, the round collars containing the set screws were welded to the cam profile. After testing failed to produce vertical motion without using excessive force on the crankshaft, the cams were shortened to be closer to a round profile, with the final design being shown in Drawing 17A. Unfortunately, waterjet cutting could not be used on the profiles because of the welded collars, so excess material was removed with a bandsaw and the profiles were sanded to complete the new profile. A comparison can be found in Figures 6-2 and 6-3.

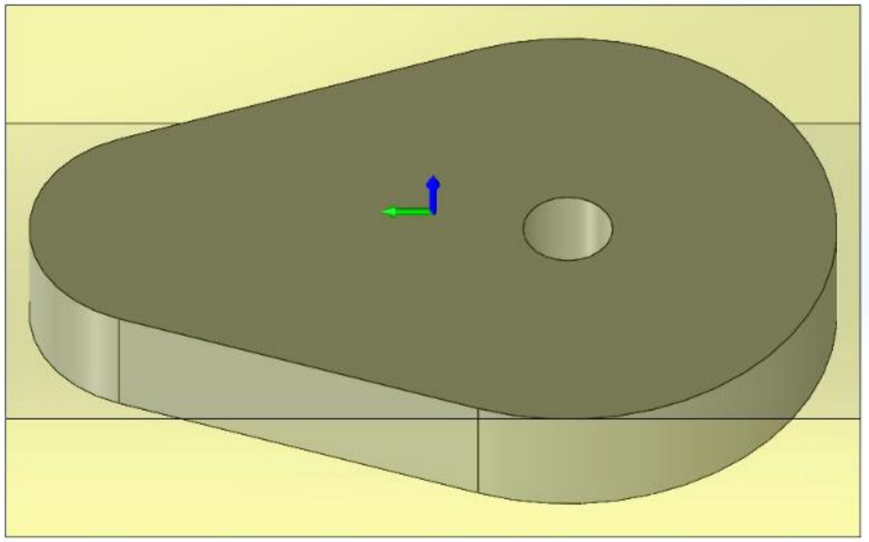

Figure 6-1: This image shows the rectangular stock that the cams can be machined from, with additional stock added to each face to allow for a uniform surface finish across the entire part's profile. The origin for the work coordinate system lies at the center of the stock's top face. The stock has dimensions of 7.15" L x 4.9" W x 1.4" H.

G&M Example Code for Cam CNC Machining Process

```
%
O00007 (CAM profile without collars)
(Using high feed G1 F500. instead of G0.)
(T1 D=2. CR=0. - ZMIN=-0.2 - face mill)
(T3 D=0.5 CR=0. - ZMIN=-1.78 - flat end mill)
(T4 D=0.75 CR=0. TAPER=118deg - ZMIN=-1.2 - drill)
(T19 D=0.5 CR=0. TAPER=45deg - ZMIN=-0.28 - chamfer mill)
N10 G90 G94 G17
N15 G20
N20 G53 G0 Z0.

(Adaptive2)
N25 T3 M6
N30 S3000 M3
N35 G54
N40 M11
N45 G0 A0.
N50 M10
N55 M8
N60 G0 X-2.7188 Y3.7342
N65 G43 Z0.6 H3
N70 T1
N75 G0 Z0.2
N80 Z-0.2937
N85 G1 Z-0.3437 F15.
….
N40425 Y2.6558 Z-1.73


(Face3)
N40450 M1
N40455 T1 M6
N40460 S6500 M3
N40465 G54
N40470 M11
N40475 G0 A0.
N40480 M10
N40485 M8
N40490 G0 X-3.75 Y2.7655
N40495 G43 Z0.6 H1
N40500 T4
N40505 G0 Z0.2
N40510 G1 Z0. F65.
N40515 G18 G2 X-3.55 Z-0.2 I0.2 K0.
N40520 G1 X-2.45
N40525 X2.45
N40530 G17 G2 Y0.975 I0. J-0.8952
N40535 G1 X-2.45
N40540 G3 Y-0.8155 I0. J-0.8952
N40545 G1 X2.45
N40550 G2 Y-2.606 I0. J-0.8952
N40555 G1 X-2.45
N40560 G18 G3 X-2.65 Z0. I0. K0.2
N40565 G0 Z0.6
N40570 M9
N40575 M5
N40580 G53 G0 Z0.

(0.75in Drill)
N40585 M1
N40590 T4 M6
N40595 S1530 M3
N40600 G54
N40605 M11
N40610 G0 A0.
N40615 M10
N40620 M8
N40625 G17
N40630 G0 X0. Y-1.125
N40635 G43 Z0.6 H4
N40640 T19
N40645 G0 Z0.2
N40650 G98 G81 X0. Y-1.125 Z-1.2 R0. F29.
N40655 G80
N40660 G0 Z0.6
N40665 M9
N40670 M5
N40675 G53 G0 Z0.

(2D Chamfer1)
N40680 M1
N40685 T19 M6
N40690 S5000 M3
N40695 G54
```

```
N40700 M11
N40705 G0 A0.
N40710 M10
N40715 M8
N40720 G0 X0. Y3.4967
N40725 G43 Z0.6 H19
N40730 T3
N40735 G0 Z0.2
N40740 G1 Z0.08 F20.
N40745 Z-0.28
N40750 Y3.4468
N40755 G2 X1.1283 Y2.6489 I0. J-1.1968
F40.
N40760 G1 X2.189 Y-0.3511
N40765 G2 X-2.189 I-2.189 J-0.7739
N40770 G1 X-1.1283 Y2.6489
N40775 G2 X0. Y3.4468 I1.1283 J-0.3989
N40780 G1 Y3.4967
N40785 G0 Z0.6

N40790 M5
N40795 M9
N40800 G53 G0 Z0.
N40805 M11
N40810 G0 A0.
N40815 M10
N40820 X0.
N40825 G53 G0 Y0.
N40830 M30

%
```

Figure 6-2: Original Cam Design

Figure 6-3: Modified Cam Design, with Shorter Profile

6.3 Bill of Materials

All of the information for purchased and manufactured parts is summarized and tabulated in the indented bill of materials (iBoM), including details such as procurement vendor, corresponding part numbers, quantity, and with direct links to the vendor's website where the item can be viewed for further specification information. This also encompasses a cost breakdown since the iBoM breaks each subassembly and primary assembly into cascading levels which allows the cost of each subassembly and its respective components to be viewed independent of other subassemblies. The iBoM is shown below in an abridged format, with the full version with budget and pricing in Appendix K.

Santa Fe Bellevue Charter School Shake Table

Indented Bill of Material (iBOM)

Santa Fe Bellevue Charter School Shake Table
Indented Bill of Material (iBOM)

M Level	Indented Parts Name Assembly Breakdown	Revision	Part Number	Qty.
1	**Frame**			
1A	2" X 2" T-Slotted Profile Length 1	A	2020	14
1A	2" X 2" T-Slotted Profile Length 2	A	2020	2
1B	**Hardware**			
1B	10 Series 8 Hole - Inside Corner Bracket	A	4138	24
1B	1/4-20 x .500" Button Head Cap Screw	A	3061	0
1B	1/4-20 Slide-in Economy T-Nut - Centered Thread	A	3382	0
1B	Bolt Assembly	A	3393	192
2	**Vertical Motion Subassembly**			
2A	Rotary Shaft	B	5947K52	1
2B	**Main Shaft Subassembly**			
2B	Mounted Acetal Ball Bearing	B	6357K43	2
2B	External Hex Flange Hex-Head Self-Drilling Screws	C	838472	4
2B	Main shaft Cam	B	N/a	2
2B	Cam Follower (Caster Wheel)	C	2407T64	2
2B	Crank Handle with Revolving Grip	A	6473K55	1
2B	Internal Hex Stainless-Steel Socket Set Screw	C	812198	2
2B	Stainless Steel Recessed Hex Socket Cap Screw	C	812138	1
2B	Phillips Flat Head Zinc Plated Wood Screw	C	809021	2
2C	**Vertical Slider Subassembly**			
2C	Side-Mount Ball Bearing Carriage	C	6004K13	2
2C	24.8 mm Wide Rail for Side-Mount Ball Bearing Carriage	C	6004K87-6004K61	2
2C	Phillips Pan-Head Self-Drilling Screws	C	4112	1
2C	Phillips Pan Head Zinc Plated Machine Screw	C	802788	3
3	**Horizontal Motion Subassembly**			
3A	Anodized Aluminum Guide Rail	A	9829K11	2
3A	Aluminum Sleeve Bearing Carriage	A	9829K1	2
3A	Phillips Flat-Head Machine Screws	C	13658	4
3A	Phillips Pan-Head Machine Screws	C	5318	2
3A	Corrosion-Resistant Extension Spring Stud Anchor	C	95907A110	2
3A	Music-Wire Steel Extension Springs with Hook Ends	C	9432K73	1
3A	Threaded-Stud Bumper	C	9541K8	1
3A	Fiberglass Routing Eyebolt	C	30295T22	1
3A	Mounted Pulley for Rope-for Horizontal Pull	C	3071T7	2
3A	Phillips Flat Head Zinc Plated Wood Screw	C	809011	1
3A	(Phillips Pan-Head Self-Drilling Screws, for reference only)	C	4112	0
3A	Braided Nylon Plastic Rope Pull Cord	C	2677T5	1
4	**Casing Subassembly**			
4A	Acrylic Frame Casing	C	508	4
4A	(Phillips Pan-Head Self-Drilling Screws, for reference only)	C	4112	0
5	**Lumber**			
5A	Sande Plywood	C	103078	2
5A	Premium Kiln-Dried Whitewood Stud	C	161640	1
5A	Phillips Flat Head Brass Wood Screw	C	809721	2
5A	Phillips Flat Head Zinc Plated Wood Screw	C	801862	1
5A	Wood Glue	C	62050	1

Figure 6-4: Abridged Indented Bill of Materials

6.4 Part Procurement

All sourced parts were successfully picked up or shipped from vendors. Specifically, the acrylic panels were picked up directly from TAP Plastics in San Jose, CA, all McMaster-Carr parts were picked up directly from McMaster-Carr in Santa Fe Springs, CA, while all other parts were purchased online or locally at Miner's Ace Hardware in San Luis Obispo, CA.

6.5 Assembly

The frame was assembled first, using directions from 80/20 and based on Drawings 7 and 8. The vertical motion platform, which supports the horizontal motion subassembly, was assembled from components outlined in Drawings 9-11. Likewise, the horizontal motion platform was assembled from components outlined in Drawings 13 and 14. The cams, made according to Drawing 17, were mounted to the shaft using set screws and the shaft was installed into the bearings using set screws, shown in Drawing 3.

To start the process of mating the vertical motion subassembly to the frame, the ball bearings with the shaft were bolted to the frame, shown in Drawing 1. Caster wheels were used as cam followers and attached to the underside of the vertical shaking platform, shown in Drawing 3. To finish the vertical motion subassembly, the vertical shaking platform was fastened to the frame using vertical linear bearings, shown in Drawings 1 and 3.

The horizontal shaking mechanism was assembled top-down, starting with the horizontal shaking platform being bolted to the linear bearing carriages, which was then slid on the rails, shown in Drawings 5 and 6. Also shown in Drawing 6, the spring was connected to two anchors, one on each end. An eyebolt was attached to the base of the horizontal motion platform to then be tied to the nylon pull cord. After preliminary testing, it was determined that a single spring would not provide the desired oscillatory motion. Incidentally, another spring was added on the opposite side of the central block on the underside of the platform and the bumpers in Drawing 5 were removed. The drawings were not updated to show these changes as the modifications occurred during manufacturing.

Finally, casing panels, shown in Drawing 17, were attached to the outside of the frame for safety, shown in Drawing 1. The front and back panels are identical, and the left and right panels have holes for the crankshaft and pull cord, respectively.

Limitations in CAD prevented the team from showing two components. First, a 2-foot nylon pull cord was attached to the eyebolt and fed through two pulleys shown in Drawings 1 and 3 and eventually fed outside through a hole in the casing, which is depicted in Drawing 15. In addition, a canvas cover was fixed to the top for safety to prevent children's hand from accessing moving parts from the top.

Wooden blocks for building structures were generously fabricated by project advisor Lee McFarland, with magnets being placed into the blocks to provide some adhesion between blocks.

Some more general details regarding the assembly process can be found in the detail drawings attachments appended to this document. These provide insight into how each component was used and fastened during assembly.

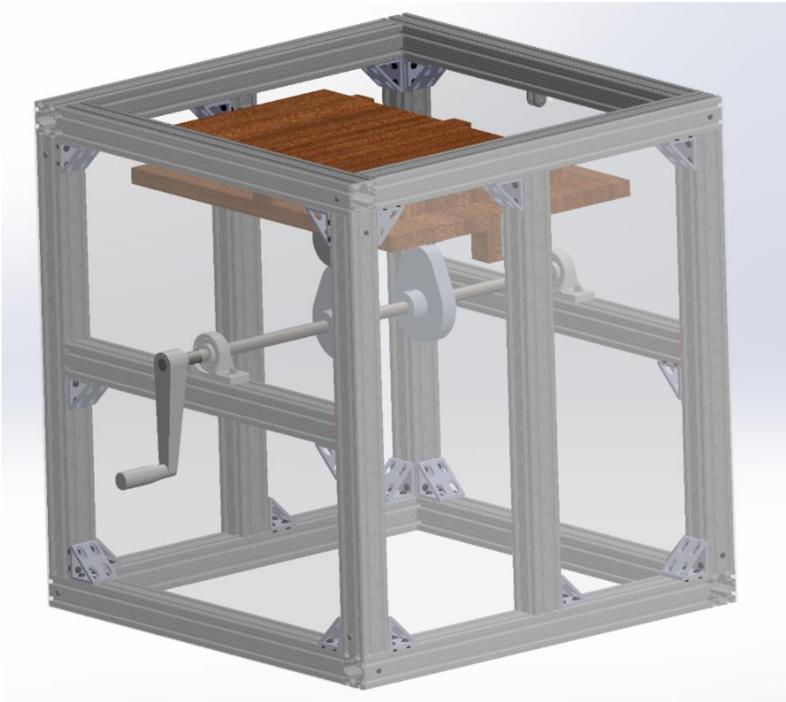

Figure 6-5: Final Concept Model with Modified Cam Design

Figure 6-6: Final Manufactured Prototype

7.0 Design Verification Plan

7.1 Specifications

While the project assigned to the team does not have any technical specifications, the key goal of the project was to provide an interactive and educational STEM oriented display, with an emphasis on safety. The display is very interactive, as the user can decide which motion to use, how much motion will be imputed, and how their structure will be built. This allows for endless combinations of scenarios to perform, which will hopefully keep children coming back to the display. Acrylic and canvas barriers prevent moving parts from being accessed. Educationally, the display accurately shows the motion of an earthquake as a wave, which is far more accurate than the preliminary single DOF concept. Aside from this, children being able to repeatedly test structure designs introduces them to the scientific method of hypothesizing, testing, and evaluation. In addition, the team's meeting with the Liberal Studies students gave better insight as to what should be displayed.

7.2 Simulated Testing

Ultimately, time will tell whether the display is successful or not, as it is truly up to the children interacting with the display. Ideally, the team would like to have a trial run at the school, but with the ongoing pandemic, this is not currently feasible.

The FEA simulation on the load-bearing shaft shows both stress and deflection, both critical design factors. The parameters of the test were 35 pounds acting on both cams, which is an extreme loading case. Figures 7-1 and 7-2 show the stress and deflection distributions, respectively.

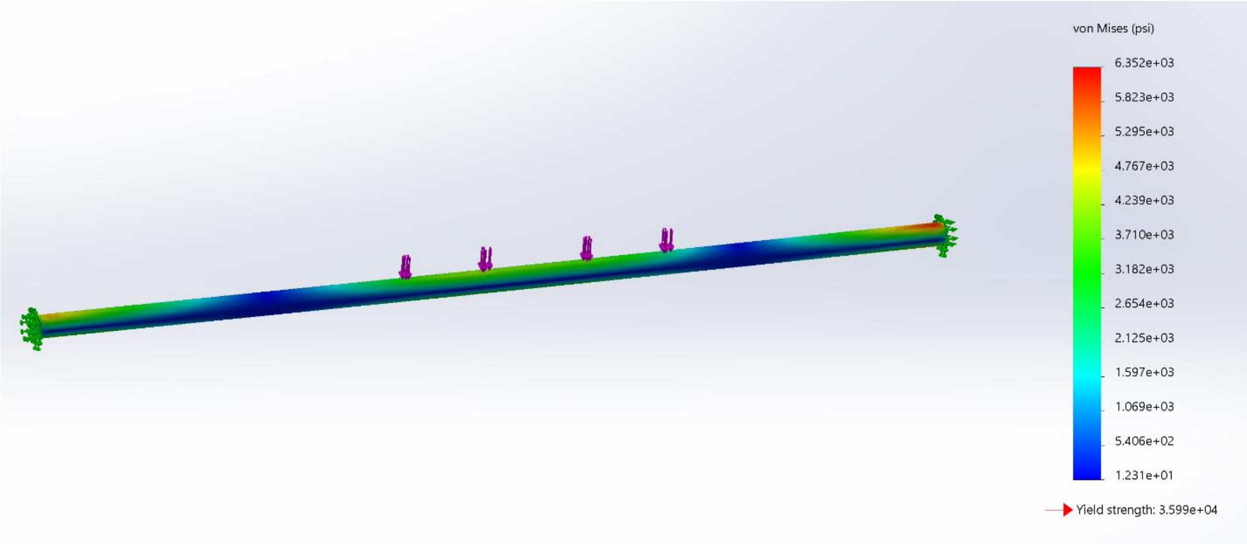

Figure 7-1. Stress distribution on the load-bearing shaft. Total factor of safety is 5.5

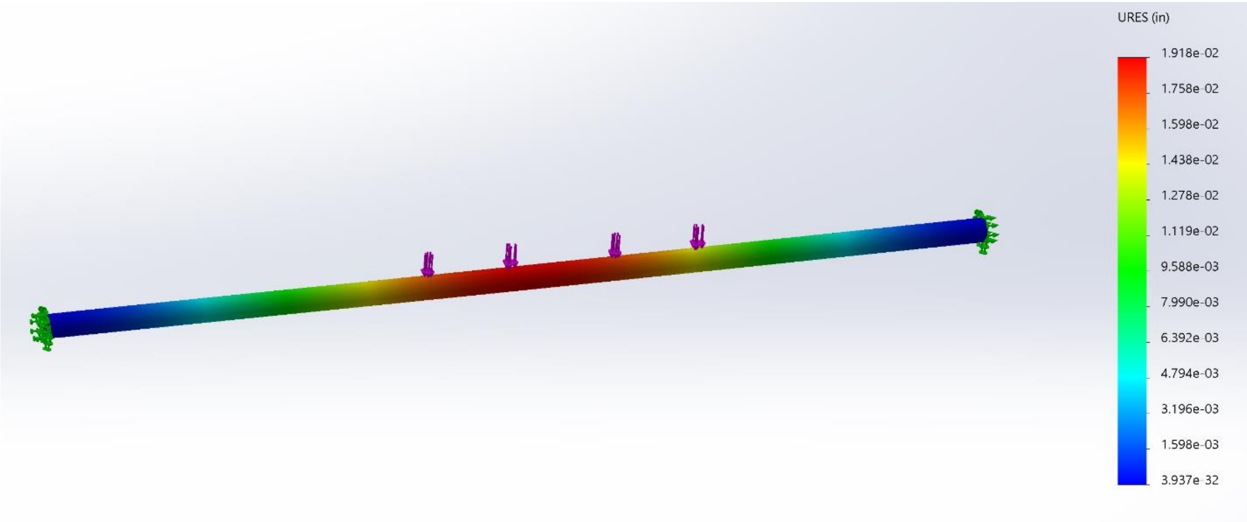

Figure 7-2. Deformation on the load-bearing shaft. Maximum deflection of 0.02in

In addition, the team investigated how to test springs virtually, using MATLAB to run simulations of oscillations based on different masses and spring constant values. Though showing initial promise, the team eventually decided to purchase a relatively stiff spring and would repurchase if testing resulted in the need for a different spring. Thankfully, the purchased spring was sufficient for the needs of the shake table.

7.3 Testing Overview

Testing was done on a qualitative basis, as the display's goals are not able to be truly measured. Ideally, the team would have performed tests with a target audience of children in the specified age range, but this was not possible due to COVID-19. However, the team is confident that the display will be interactive and fun to use, while the educational side has been coordinated with Mr. Strauli.

On the mechanical side, several tests were performed to ensure that the prototype would hold up under normal use for an extended time, as well as function as intended. Throughout these tests, an emphasis was placed on safety due to the primary users being students, who may or may not understand the risks of rotating and moving parts.

7.4 Tests and Results

Frame Stress Test – Using body weight, the aluminum frame can easily support up to 100+ pounds of weight being placed on it. This was not anticipated as a potential failure point but was nonetheless reassuring to the team.

Vertical Motion Test with Original Cams – The crank handle was rotated to simulate the vertical motion of the shaking platform. The cams stayed securely fastened to the shaft, but the main result was that the long, skinny cams were too different from a round profile to easily turn. The excessive force needed to turn the camshaft necessitated the modification of the cam profile (see Section 6.2 for more information).

Vertical Motion Test with Redesigned Cams – This test produced smoother produce vertical motion that was easy to produce and did not risk breaking the table's components. A tradeoff of modifying the cams was a decreased vertical displacement from 1.5 inches to 1.25 inches.

Horizontal Motion Test – The pull cord was pulled to one side and then released. The resulting motion was oscillatory but damped out fast due to the stiffness of the spring. Instead of redesigning the table, the operating instructions of the table were modified to state that instead of pulling the cord once, the pull cord will be pulled repeatedly to create horizontal motion. While a greater period of oscillatory motion would have been preferable, the team deemed the motion produced with repeated pulls sufficient for the applications needed. The resulting modified instructions are also more engaging for the user as they pull the cord repeatedly as opposed to once.

8.0 Project Management

The project's development follows a progression of design, build, and testing. At this time, the team has decided on a final design and has sourced most of the final assembly parts, barring parts like springs that should be interacted with before firmly deciding on a purchasable part.

Table 8-1. Major Deliverables with Associated Due Dates

Quarter	Deliverable	Date
Winter	Scope of Work	February 2, 2020
	Preliminary Design Review	March 2, 2020
Spring	Interim Design Review	April 23, 2020
	Critical Design Review	May 14, 2020
	Manufacturing/Test Review	June 4, 2020
Fall	Project Manufacturing/Assembly	September 28, 2020- November 20, 2020
	Confirmation Prototype Review	October 20, 2020
	Senior Project Expo	November 27, 2020 *Updated: November 20, 2020*
	Project Delivery	December 3, 2020

Table 8-1 shows the major milestones of the project through its entirety. The team formulated concepts and preliminary prototypes before finalizing their decision on a two degree-of-freedom shake table. From there, the team transitioned into the design phase through Spring Quarter. It should be noted that this quarter presented unique challenges in being completely virtual. Finally, in Fall Quarter, the team executed their design in the form of the final verification prototype.

To ensure the team stayed on track through the end of the project, a Gantt chart, which is documented in Appendix D, was created to show the timeline of tasks and the order of task completion. While not a final, inflexible plan, the Gantt chart provided an excellent framework to ensure that tasks are divided equally and deadlines are met.

With the more fluid nature of Fall Quarter, and the academic calendar being modified as well as deadlines, the Gantt chart provided a framework but task completion was largely based on weekly goals as opposed to an overall plan. As the primary deliverables such as the prototype, FDR, and expo poster were all to be completed by the end of the quarter, this effectively created one large deadline, which was easy to keep track of.

9.0 Conclusions

9.1 Project Conclusions

The team was well-prepared to undertake the challenge presented by the Bellevue-Santa Fe Charter School. The goal was to create a unique display that allows a STEM concept to be presented with both a theoretical and a practical, interactive approach in the spirit of Learn by Doing. The team unanimously feels that they have accomplished this goal and more, as they have delivered both an interactive activity that shows the concept of earthquakes as well as displaying the theory and science behind the featured concept.

On the interactive side of the display, the concept of earthquakes is clearly the focus of the activity. Children can build their structure and choose what combination of motion will bring it crashing down, and then repeat the process again. While this shows the destructive capabilities of earthquakes on a much smaller scale, it also ties into the scientific method and iterative design. Being able to see which motion is more destructive, or what combination of block placements results in a stronger structure and then implementing changes to their experiment also gives a lesson in engineering and finding a better solution to a problem.

As far as safety is concerned, the team believes that it has done its utmost to reduce risk to a manageable level, as all moving parts are covered by rigid acrylic on the sides of the frame. The canvas covering the top of the shake table mitigates the risk from accessing moving parts from the top. The team believes that with the monitoring by a parent or older student docent, risk is greatly reduced and the display does not pose a threat of harming students.

Educationally, the posters that accompany the table show the causes of earthquakes, focusing on the "how" of earthquakes and how this relates to building structures meant for the real world. Additionally, the poster shows how and why earthquakes are important to California as a whole and may explain to a child why such an emphasis is placed on earthquake preparation at home or why the school occasionally has earthquake drills.

The project was given a ballpark budget of $2000, $500 of which was graciously supplied by Cal Poly. The team overperformed and came in with a budget of approximately $1418. The team considers this an additional success, as operating within budget is crucial to successful engineering projects.

9.2 Process and Team Conclusions

Concerning the project process, the team went through a very iterative design process, improving on each design as the project progressed. What was conceived as a single degree of freedom, motor-powered shake table turned into a manually operated two degree of freedom shake table,

with many design choices and changes between the two. The project evolution was something that all team members agree was one of the most rewarding aspects of the project.

The team also overcame numerous hurdles associated with the COVID-19 pandemic, completing the entire design phase of the project virtually. The team split into two two-person teams to accomplish both manufacturing and documentation of the project in Fall Quarter. This "divide and conquer" strategy worked exceptionally well, as multiple facets of the quarter could be tackled simultaneously, the key to success being constant and clear communication between the two smaller teams. The team believes that this added challenge helped them grow as engineers, as working with unexpected variables and adapting when necessary is a trait of a good engineer.

Though the team views the project as a success, there are a small number of tasks that would have been done differently, especially in different circumstances. The main differences are that the team would have liked to build a functional concept prototype and buy certain parts in person rather than online. The concept prototype would have revealed design flaws early in the process that were instead discovered during manufacturing, namely the cam shape and the rails aiding in the horizontal subassembly motion. The team would have easily been able to see that the original cam shape would not work and could have changed the design before water jetting to avoid having to bandsaw the cams by hand. The team would also have been able to see that it would be better for the horizontal subassembly platform to rest on at least two carriages per rail instead of one. Several concepts could not be tested physically until parts were acquired, and had these concepts not worked, it is likely the project would have been significantly delayed. One key example is testing springs; the team would have preferred physically going to a hardware store and testing many different springs to find an optimal arrangement. As stated before, testing with a focus group of children would also have been a top priority had it not been for the pandemic.

Finally, several factors were crucial internally to the team's success. There was no infighting amongst group members, and the team members were friends as well as teammates. This is not to say there were not disagreements; especially in deciding on a final concept for the display, the team had several disagreements that were settled and solved amicably, with all team members being focused on the same vision of the project. Being dedicated to the project as well as communicating clearly, especially virtually, paved the way to a successful project.

9.3 Next Steps

At the time of this writing, the pandemic prevents the display from being enthusiastically received by children in the SciTech. However, the team knows this will not always be the case, and enthusiastically looks forward to the day when it will have its first real field test. The Operations Manual in Appendix L contains all necessary information and warnings to promote safe and effective operation of the shake table. The team recommends an older student docent or parent volunteer monitor students using the shake table.

The team sincerely hopes that the project will inspire the engineers and seismologists of tomorrow, promote a love for STEM topics at Bellevue-Santa Fe Charter School, and encourage Bellevue-Santa-Fe Charter School to turn to Cal Poly for more additions to the SciTechatorium.

References

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Appendix A: Similar Products

Location	SciTechatorium	SLO Children's Museum	California Academy of Sciences	Exploratorium	Discovery Cube Orange County
Displays	Wind Tunnel, Euler's Disk, Van de Graaff Generator	Shake Table, Shadow Wall, Mission to Mars, Kinetic Sand	Planetarium, Curiosity Grove, Discovery Tidepool, Color of Life	Ferromagnetic Sand, Pitch Slider, Strange Attraction	Seismograph, Water Gallery, Cloud Ring, Dino Quest

Appendix B: Examples of Other Products

Figure B-1: Shake Table at the SLO Children's Museum

Figure B-2: Discovery Tidepool at the California Academy of Science

Figure B-3: Ferromagnetic Sand at the Exploratorium

Appendix C: Full Customer Requirements

- Interactive (able to be physically manipulated by students)
- Age appropriate for ages 5-12
- Safe for handling by children
- Able to fit through a standard door with a width of 32 in
- Able to fit on a standard table of 3ft x 6ft
- Portable, able to be moved from room to room
- Possess a certain "wow" factor to captivate students at a school assembly
- "Unbreakable," meaning that the display should be able to withstand constant use from students without need of constant maintenance and upkeep
- Demonstrate a STEM concept that is understandable for ages 5-12
- Secondary requirements: easy to clean and handicap accessible

Appendix D: Gantt Chart

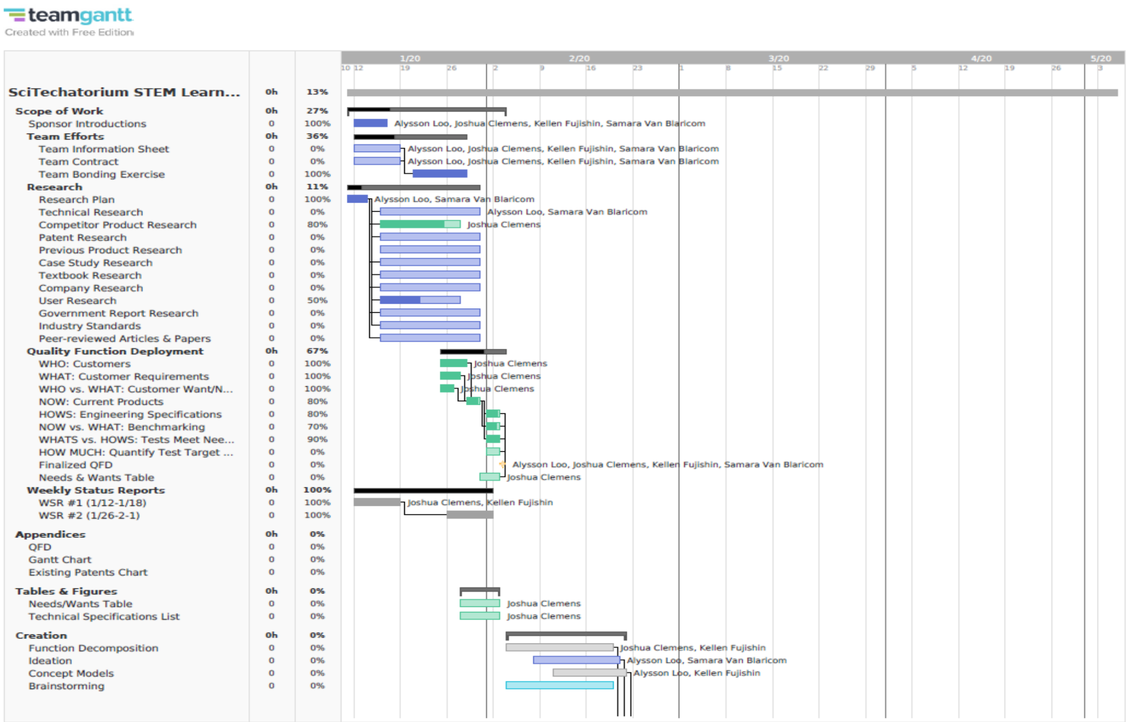


Figure D-1: Immediate timeline concerning Scope of Work objectives

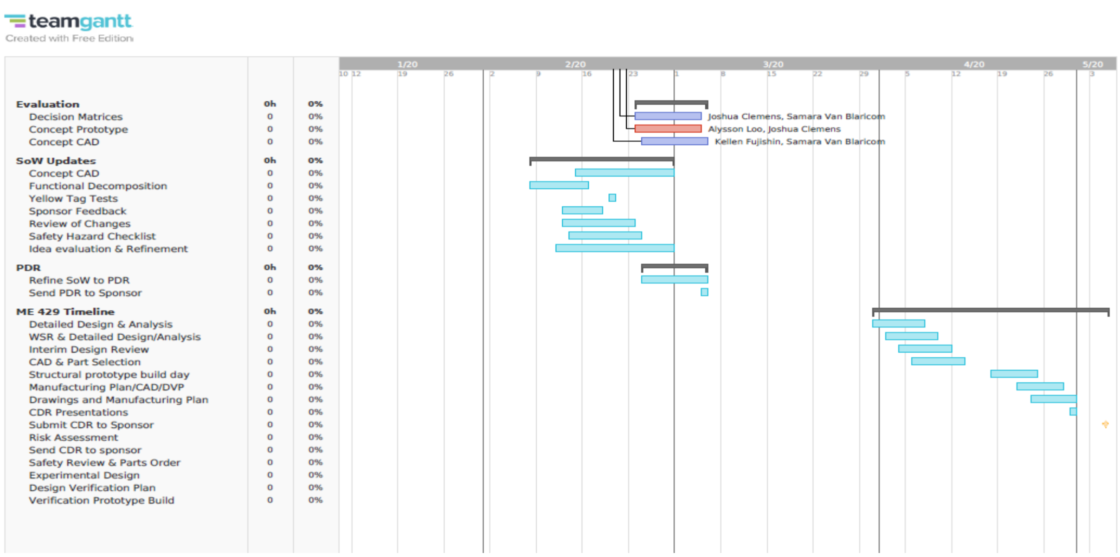


Figure D-2: Long-term timeline including creation and evaluation phases of design

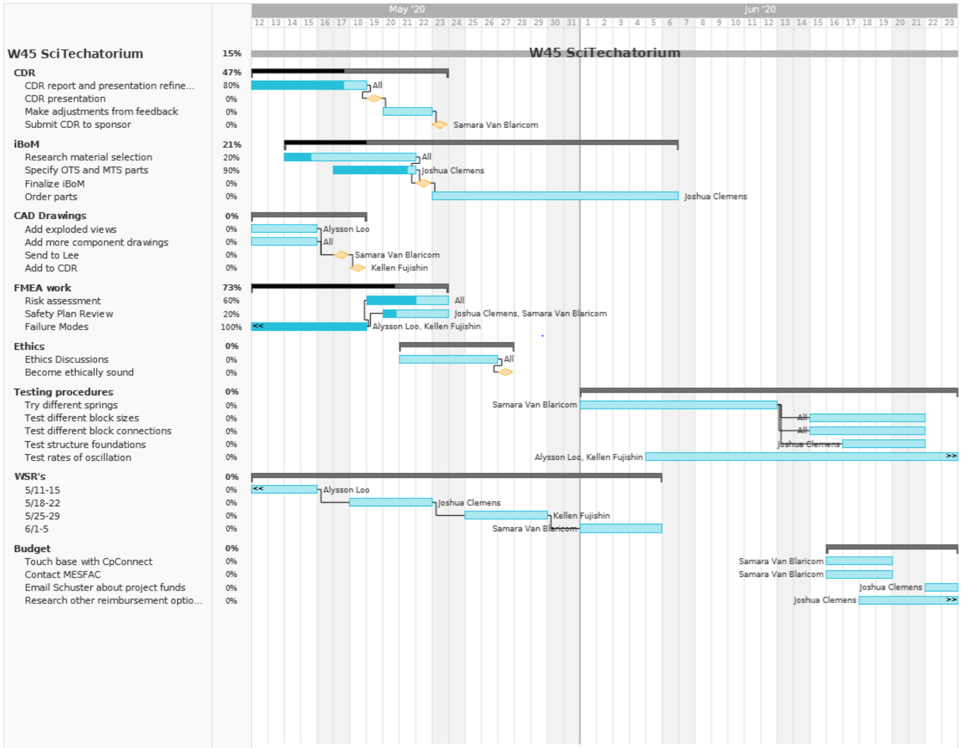


Figure D-3: Gantt Chart revision which attempts to account for the impacts of coronavirus on the project timeline. This portion of the Gantt chart extents the timeline to the end of Spring term, ending at the beginning of July 2020.

Appendix E: Quality Function Deployment

Correlations	
Positive	+
Negative	–
No Correlation	

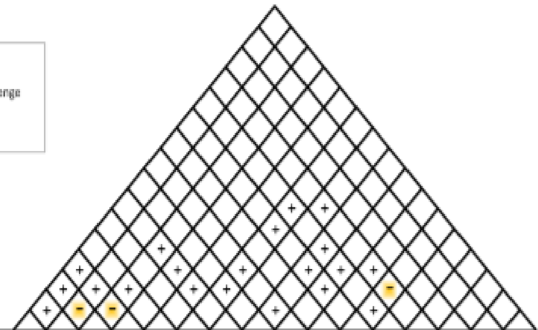
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: SciTechatorium STEM Design Challenge

Revision Date: 01/23/2020



WHO: Customers / NOW: Curr. Products

Row #	Weight Chart	Relative Weight	Students	Teachers	Parent Volunteers		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) \ HOW: Engineering Specifications (Tests)	Fit through door?	Fits on a table?	STOP: Hammer Time	Lightweight	Removable Parts?	Effect Timing/Duration	Cycles Until Failure	Competitive Aspect	Time for use (for kids)	Coaligns with Curriculum	Makes Noise	Lights up	Time of use (for school)				SciTechatorium	Discovery Cube	Exploratorium	CA Academy of Sciences	SLO Children's Museum	Row #
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
								Direction of Improvement	▼	▼	▲	▼	▼	▲	▲	◇	◇	▲	◇	▲	▲									
1		3%	1	7	2		5	Degree of Portability	●	●		●									○				3	0	0	0	0	1
2		8%	9	7	5		3	Module Count	○	○								●							2	5	4	5	3	2
3		9%	9	8	8		9	Interactive						▽		●	▽		○						3	5	5	2	4	3
4		5%	4	9	2		9	Durable			●	○	▽		●						●				3	4	4	5	2	4
5		10%	9	9	9		9	Safe For Children			○	▽	●		○	▽			○						5	5	5	2	4	5
6		6%	7	4	4		3	Multi-subject										●							3	5	5	5	4	6
7		4%	1	8	4		5	Low maintenance	▽				●		●						●				2	3	4	1	4	7
8		4%	5	3	3		5	Presentable		○				○					○	○	●				3	5	5	5	3	8
9		6%	2	8	6		7	Dimension Requirement	●	●		○													2	5	4	5	3	9
10		4%	2	4	6		4	Handicap Accessible		●		▽							○	○					3	5	5	3	3	10
11		7%	9	5	5		8	Engaging (Pizzazz Factor)					○	●		●	●		●	●	○				3	5	5	5	3	11
12		9%	8	8	8		7	Age Group Relevant						○		●	○	●	○	○	○				5	4	3	1	4	12
13		6%	6	5	6		8	1st-6th grade STEM topic						▽				●			●				4	2	3	1	3	13
14		5%	2	8	5		6	Explainability						○			▽	●			○				4	3	3	1	3	14
15		8%	8	6	7		6	Model Simplicity						○			▽	●			○				3	2	3	1	3	15
16		5%	2	6	7		4	Easy to Clean					●												3	4	4	5	4	16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	3' x 6.5' ('w' by 'h')	3' x 3' ('l' by 'w')	Withstand 20lb IF	Under 60 lbs	<5 components	>2 seconds	> 5500+ cycles	Game?	<1 minute	Y or N	< 70 dB	<12 lumens & colorful				
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9			
Technical Importance Rating	108.8	155.8	76.53	77.24	204	156.7	116.7	235.1	112.2	372.1	172.5	115.4	277	0	0	0
Relative Weight	5%	7%	4%	4%	9%	7%	5%	11%	5%	17%	8%	5%	13%	0%	0%	0%
Curr. Products: SciTechatorium	5	5	3	4	3	3	4	2	2	5	4	3				
Discovery Cube	2	2	5	1	5	5	5	5	4	3	4	4				
Exploratorium	2	2	5	1	4	4	4	4	3	3	3	3				
CA Academy of Sciences	1	1	5	0	3	4	5	2	2	1	5	4				
SLO Children's Museum	3	3	2	4	3	3	3	1	2	4	3	3				
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix F: Decision Matrices

Criteria	Baseline	Alternatives: Shake Table	Electric Game	Railgun	Magnetic Sand	Shadow Wall	Totals	Rank
Safety	0	0	–	–	+	+	0	6
Wow factor	0	+	+	+	–	–	1	5
Educational value	0	+	+	0	0	0	2	1
Relevence to curriculum	0	+	0	–	–	–	-2	9
Portability	0	0	–	+	+	–	0	6
Multiple Grade Understanding	0	+	0	–	+	0	1	3
Ease of explainability	0	+	0	–	+	0	1	3
All age appropriate	0	+	+	0	–	–	0	6
Low maintenance	0	–	0	+	+	+	2	2
	Totals	5	1	-1	2	-2		
	Rank	1	3	4	2	5		

Figure F-1. Pugh Matrix Comparing Characteristics of Different Concepts

Morphological Matrix for Shake Table				
Attributes:	Educational	Safe	Engaging	Durable
1	Teaches earthquake magnitudes	Completely enclosed	Lights up when activated	Coated with a durable material
2	Teaches torque transmission	Made of soft materials	Able to be manually cranked	Made with hard materials
3	Teaches structure stability	Made to shake softly	Made into a game or competition	Has a small number of moving parts

Ideas generated from Morphological Matrix	
1	A shake table that teaches earthquake magnitudes, is made of soft materials, is made into a competition, and has a small number of moving parts (1,2,3,3)
2	A shake table that teaches structure stability, is made to shake softly, is able to be manually cranked, and is coated in a durable material (3,3,2,1)
3	A shake table that teaches torque transmission, is completely enclosed, lights up when activated, and is made with hard materials (2,1,1,2)
4	A shake table that teaches structure stablility, is made of soft materials, is made into a game or competition, and has a small number of moving parts (3,2,3,3)
5	A shake table that teaches earthquake magnitudes, is made to shake softly, is able to be manually cranked, and is made with hard materials (1,3,2,2)

Figure F-2: Weighted Decision Morphological Matrix

Appendix G: Sponsor Feedback & Updates

Initial design proposals presented to the sponsor are detailed in the following email thread.

Hey there Christian,

After giving it much thought and conducting thorough research, our team has managed to narrow our scope to three potential project ideas that we hope you find interesting, engaging, and educational for the students. I'll list them below along with their descriptions and let us know what you think. If none of them encompass the finished project you had in mind, please don't hesitate to let us know and we'll continue to generate more design ideas to run by you.

1. Shake Table

   For this display, students would be able to build structures (out of wooden blocks or maybe plastic pieces such as Duplos) and see if it can withstand an earthquake, which would be simulated by using a shake table. The shake table itself would take input from the students turning a handle, so students would be able to make the table shake at an intensity of their choosing. The table could also be connected to a seismograph, so students have a visual record of the "earthquake" intensity. This display could also lend itself to a competitive aspect by seeing which students can build the tallest building that does not fall over during an earthquake of a certain intensity.

2. Interactive Circuit Loop Game

   This design would entail a simple controller circuit where a closed switch configuration forces an input to an interactive game that engages children to work together in order to achieve a common goal/objective/victory condition. More specifically, students complete the circuit by creating a connection between an anode and a cathode that allows a (very) small amount of current to flow due to a voltage differential. This can be done in a variety of ways, but the most engaging and interactive method is for students to grab the terminals themselves and use themselves as a high-impedance 'short circuit' that closes the current loop. This allows lots of experimental opportunity for students to find new and creative ways to play an interactive game by completing the circuit. For example, the interactive game might require a character to jump or duck certain obstacles and the only way for students to initiate these actions is to complete the right circuit by grabbing the proper anode cathode combination. They can work together or introduce a competitive aspect to the game, but either way promotes collaboration and interaction between students which is a key component to keeping them engaged and interested. There is also a great deal of learning potential in this project since it touches on a lot of different educational concepts,

3. Electrical accelerator game:

   This game would utilize the Lorentz force to accelerate a ball through a magnetic field. This creates an opportunity for a multitude of games the kids could play while also learning how magnetic fields and electrical currents affect physical objects. They could try to hit a specific goal with the ball or it could be a competitive game between two children. See the link below for the basic scientific principles and a simple design of the concept.

http://sciphile.org/lessons/classroom-rail-gun

We look forward to hearing back from you, all feedback is greatly appreciated! Furthermore, to keep you in the loop, you can expect a Scope of Work document from us by next Monday morning 02/03/20 which will help detail the direction our project is headed and what path we are going to commit to. Take care, and we'll be in touch.

Best,

CPSPT45

The project sponsor, Mr. Strauli, replied with the following feedback.

Hey all

Thanks for the email. I like all three of these ideas.

The shake table I have seen done before at other children's museums (there is one here in SLO at the Children's Museum similar to your concept). This is not necessarily a bad thing and it is a concept that would certainly be fully understandable to elementary students. Not too mention they would love making 'earthquakes'.

The interactive circuit loop game sounds pretty cool, I have never seen anything like that before. So when they complete the circuit with their hands they would feel a small shock? Is that what I understand? And then doing so would manipulate some simple video game... do I have that right? Essentially they are 'pressing buttons' on a controller by completing different circuits? This sounds pretty neat and I like the depth that sounds like it might be there, with the different combinations of anodes and cathodes. Is there an example of this that you could point me to so I could get more of an idea of exactly what it would look like/ work like?

I have had students try to make rail guns as science projects, and I think this may be coloring my perspective on this one because I keep picturing the junky one that a 6th grader made which barely worked (I mean the fact that it worked at all is pretty cool, he was a 6th grader). I am familiar with this concept, and the link you sent shed some more light on it. Of the three, I think I am less excited about this one, although I could be won over.

So I am not really sure if I am supposed to pick one of these three for you, I just thought I would give you my first impressions. I think they all sound super cool and we would be excited to have any of the three in the museum. Maybe try to give me a little context for the second one and I will ask my principal and some of my colleagues for their input on which sounds most intriguing to them.

Thanks for all your thoughtful work.

Christian

To further narrow down a finalized project direction, Mr. Strauli collaborated with fellow staff and colleagues to determine what project best suited the needs of the students, teachers, and the curriculum that is presented. The response of that collaboration is shown in the email below.

Hey all

I apologize for the delay in responding about preference regarding your three ideas. I threw it out to the rest of my staff, my principal and assorted students with a deep love for the place and the overwhelming majority were into the shake table idea. So there is that, for what it is worth. I agree that display could be a great addition and anchor a larger section dedicated to plate tectonics (which doesn't currently get much attention in the museum).

I glanced through this document that is attached (scope of work). It seems to be a review of what you have done to date, plus broad outline of what you intend to complete. Seems to be accurate to me.

Let me know if there is anything else you need from me at the moment. Thanks for all your hard work.

Christian

The team used this information along with additional research to confirm what project design would be pursued. This led to the development of the shake table design. Details are shown in the response below.

Christian,

No worries at all, we understand how busy your work keeps you. We're very glad to hear that you and the rest of your staff are enthusiastic about the shake table idea because after some more consideration, our team also feels that the shake table is the best design to pursue so that is most likely the path we intend to commit to. We'll be in touch about further developments and specifics regarding this decision.

Furthermore, the Scope of Work will continue to be revised as we work through various design challenge criteria and we'll be sure to keep you updated on that as well.

Finally, at the current moment the team and I agree that the project is well on track towards maintaining a punctual timeline. Soon however, we'd love to set up a second meeting in person just to briefly present to you some of the upcoming project developments. Let is know if you'd be okay with this and we can set up a date and time that is mutually convenient. Thanks for everything Christian, and thank your staff on our behalf for the feedback they provided about our design proposals. We look forward to speaking again soon.

Best,

CPSPT45

Appendix H: Project Ideation List

- Circuit Maker
  - Use the human body to complete a circuit to engage in a mechanical subsystem interactive game (treadmill with obstacles)
- Rail Gun
  - Use Lorentz force to accelerate a projectile towards a target
- Eddy Current Display
  - Present magnetic flux in the form of a magnetic field interacting with a conductive material to form an electric field that produces a back EMF
- Gear Mesh System
  - Present gear ratios & how this can serve as a torque amplification/delivery system
- Photo-sensitive Paper
  - Paper coated in light sensitive chemical that creates images by distinguishing between areas that did or didn’t experience photon collision.
- Shake Table
  - Use a motor or crank to create oscillatory motion
- Wind Tunnel
  - Demonstrate the concept of lift and its relevance to Bernoulli’s principle
- Pulley-belt System
  - Another method of introducing torque transmission/amplification to students
- Bernoulli Ball
  - Pose an experiment that discusses the fluid dynamics associated with a stream of fluid
- Foucault Pendulum
- Wave Generator Pool
- Magnetic Sand
- Shadow Wall

Appendix I: Design Hazard Checklist and Risk Assessment

Y	N	
Y		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	N	2. Can any part of the design undergo high accelerations/decelerations?
	N	3. Will the system have any large moving masses or large forces?
Y		4. Will the system produce a projectile?
	N	5. Would it be possible for the system to fall under gravity creating injury?
	N	6. Will a user be exposed to overhanging weights as part of the design?
	N	7. Will the system have any sharp edges?
	N	8. Will any part of the electrical systems not be grounded?
	N	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	N	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	N	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	N	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	N	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	N	14. Can the system generate high levels of noise?
	N	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
Y		16. Is it possible for the system to be used in an unsafe manner?
	N	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Risk Assessment

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Moving mechanism to produce a shaking effect	All moving parts will be shielded and not accessible unless panels are removed.	April 2020 (Planned Fabrication)	
Structures falling apart may produce projectiles	Either limit the shaking or enclose the shaking surface in a clear, polycarbonate casing. Ideally, a switch will be installed so that the table will not function without the case on	April 2020 (Planned Fabrication)	
While it is possible to use the shake table in an unsafe manner, all variables cannot be accounted for	With all moving parts covered as well as the shaking surface while in motion, the team believes that inherent risks will be mitigated.	April 2020 (Planned Fabrication)	

Updated Risk Assessment – Final Prototype

Description of Hazard	Corrective Action Taken	Planned Date	Actual Date
Moving mechanism to produce a shaking effect	All moving parts covered in polycarbonate, as well as a flexible canvas barrier installed on the top	October 2020	October 14, 2020
Structures falling apart may produce projectiles	Upon testing, all blocks reliably fall on the top platform or on the canvas. No corrective action needed.	October 2020	NA
Tipping Hazard	The table was designed to be only 30 inches tall, presenting a minimal tipping hazard.	October 2020	September 28, 2020

Appendix J: Report Edit Log

Report Edit Log

Team: Experiment 626

Edits for Report: (Check box)	PDR	
	CDR	
	FDR	X

Report Section #	Source of recommended edit (Sponsor, Advisor, Team, Reviewer)	Brief description of edit
1	Advisor	Updated for final documentation
5	Advisor	Added documentation on cam design changes following the CDR
6	Advisor	Added section detailing part procurement and building of the prototype
7	Advisor	Added testing and results section
8	Advisor	Updated to reflect completed tasks during Fall Quarter
9	Advisor	Conclusions heavily updated to reflect the entirety of the project

Note: ONLY edits to sections in previous report are listed.

Appendix K: Full iBoM and Budget

Santa Fe Bellevue Charter School Shake Table
Indented Bill of Material (iBOM)

BOM Level	Indented Parts Name Assembly Breakdown	Revision	Part Number	Qty.	Unit of Measure	Procurement Type	Procurement Supplier	Price per Unit	Total Part Cost	Notes	Purpose	Hole Type for Fasteners
1	**Frame**											
1A	2" X 2" T-Slotted Profile Length 1	A	2020	14	26"	OTS	80/20	$16.87	$236.18		Outside of frame and vertical support beams	
1A	2" X 2" T-Slotted Profile Length 2	A	2020	2	24"	OTS	80/20	$15.73	$31.46		Horizontal support beams	
1B	**Hardware**											
1B	10 Series 8 Hole - Inside Corner Bracket	A	4138	24	Ea.	OTS	80/20	$7.45	$178.80	10 Series 8 Hole	Attach two beams at right angle	
1B	1/4-20 x .500" Button Head Cap Screw	A	3061	0	Incl.	OTS	80/20	$0.00	$0.00		Part of bolt assembly	
1B	1/4-20 Slide-in Economy T-Nut - Centered Thread	A	3382	0	Incl.	OTS	80/20	$0.00	$0.00		Part of bolt assembly	
1B	Bolt Assembly	A	3393	192	Ea.	OTS	80/20	$0.40	$76.80	Black Zinc	Attach bracket to beams	
2	**Vertical Motion Subassembly**											
2A	Rotary Shaft	B	5947K52	1	Ea.	OTS	McMaster-Carr	$47.10	$47.10	Chrome plated 1045 Carbon Steel, 3/4" Diameter, 36" Long	Rotating shaft for cams	
2B	**Main Shaft Subassembly**											
2B	Mounted Acetal Ball Bearing	B	6357K43	2	Ea.	OTS	McMaster-Carr	$48.87	$97.74	for 3/4" Shaft Diameter	Allow shaft to rotate and provide a mounting area	
2B	External Hex Flange Hex-Head Self-Drilling Screws	C	838472	4	Ea.	OTS	Home Depot	$0.77	$3.08	5/16 in. x 1 in. External Hex Flange Hex-Head Self-Drilling Screws	Attach bearings to frame	None
2B	Main shaft Cam	B	N/a	2	Ea.	MTS		$0.00	$0.00		Provide vertical motion, bear weight	
2B	Cam Follower (Caster Wheel)	C	2407T64	2	Ea.	OTS	McMaster-Carr	$7.65	$15.30	Rigid with 3" Diameter 75D Durometer Rubber Wheel (270 lb rating)	Translate cam motion to platforms	
2B	Crank Handle with Revolving Grip	A	6473K55	1	Ea.	OTS	McMaster-Carr	$25.78	$25.78	1/2" Diameter Unthreaded Through Hole, Stainless Steel	Method to turn shaft	
2B	Internal Hex Stainless-Steel Socket Set Screw	C	812198	2	Ea.	OTS	Home Depot	$1.17	$2.34	1/4 in.-20 tpi x 3/8 in. Internal Hex Stainless-Steel Socket Set Screw (2-Pi	Attach cams to shaft	Tapped Hole
2B	Stainless Steel Recessed Hex Socket Cap Screw	C	812138	1	Ea.	OTS	Home Depot	$1.10	$1.10	# 10-32 x 3/16 in. Stainless Steel Recessed Hex Socket Cap Screw (2-Pack	Attach handle to shaft	Tapped Hole
2B	Phillips Flat Head Zinc Plated Wood Screw	C	809021	2	Ea.	OTS	Home Depot	$1.18	$2.36	#10 x 3/4 in. Phillips Round Head Zinc Plated Wood Screw (6-Pack)	Attach caster wheels to platform	13/64 Pilot Hole
2C	**Vertical Slider Subassembly**											
2C	Side-Mount Ball Bearing Carriage	C	6004K13	2	Ea.	OTS	McMaster-Carr	$33.33	$66.66	for 24.8 mm Wide Rail	Provide/maintain smooth vertical motion	
2C	24.8 mm Wide Rail for Side-Mount Ball Bearing Carriage	C	6004K87-6004K61	2	160mm	OTS	McMaster-Carr	$22.40	$44.80	24.8 mm Wide Rail for Side-Mount Ball Bearing Carriage	Rail for carriage	
2C	Phillips Pan-Head Self-Drilling Screws	C	4112	1	Ea.	OTS	Home Depot	$7.23	$7.23	#8 1/2 in. Phillips Pan-Head Self-Drilling Screws (25-Pack) (4/25 used fron	Attach rails to frame (2 screws/rail)	None
2C	Phillips Pan Head Zinc Plated Machine Screw	C	802788	3	Ea.	OTS	Home Depot	$1.18	$3.54	M4-0.7 x 25 mm Phillips Pan Head Zinc Plated Machine Screw (3-Pack)	Attach carriages to platform	Tapped Hole
3	**Horizontal Motion Subassembly**											
3A	Anodized Aluminum Guide Rail	A	9829K11	2	260 mm	OTS	McMaster-Carr	$44.36	$88.72	7 mm Wide Guide Rail for 17 mm Wide Aluminum Sleeve Bearing Carriag	Rail for carriage	
3A	Aluminum Sleeve Bearing Carriage	A	9829K1	2	Ea.	OTS	McMaster-Carr	$21.32	$42.64	for 7 mm Wide Rail, 17 mm Wide	Provide/maintain smooth horizontal motion	
3A	Phillips Flat-Head Machine Screws	C	13658	4	Ea.	OTS	Home Depot	$0.58	$2.32	M2-0.4 x 14 mm. Phillips Flat-Head Machine Screws (2-Pack)	Attach carriages to platform	Tapped Hole
3A	Phillips Pan-Head Machine Screws	C	5318	2	Ea.	OTS	Home Depot	$0.68	$1.36	M2-0.4 x 20 mm. Phillips Pan-Head Machine Screws (3-Pack)	Attach rails to platform	Tapped Hole
3A	Corrosion-Resistant Extension Spring Stud Anchor	C	95907A110	2	Ea.	OTS	McMaster-Carr	$6.27	$12.54	8-36 Thread Size	Attach spring to platform	Tapped Hole
3A	Music-Wire Steel Extension Springs with Hook Ends	C	9432K73	1	Ea.	OTS	McMaster-Carr	$14.36	$14.36	Zinc-Plated, 4.5" Long, 0.5" OD (Pack of 6)	Provide horizontal motion	
3A	Threaded-Stud Bumper	C	9541K8	1	Ea.	OTS	McMaster-Carr	$6.64	$6.64	SBR Rubber, 6-32 Thread Size, 1/4" Thread Length, 7/16" OD (Pack of 25)	Prevent spring from over extending, minimize pinch points by maintaining 2.5" of clearance when platform is closest to frame	
3A	Fiberglass Routing Eyebolt	C	30295T22	1	Ea.	OTS	McMaster-Carr	$5.66	$5.66	with Shoulder-Not for Lifting, 1/4"-20 Size x 1" Long Thread	Attach rope to platform	Tapped Hole
3A	Mounted Pulley for Rope-for Horizontal Pull	C	3071T7	2	Ea.	OTS	McMaster-Carr	$8.97	$17.94	Steel, for 1/4" Diameter, 7/8" Wide, 11/16" OD	Pulley system to keep rope horizontal	
3A	Phillips Flat Head Zinc Plated Wood Screw	C	809011	1	Ea.	OTS	Home Depot	$1.18	$1.18	#10 x 1/2 in. Phillips Flat Head Zinc Plated Wood Screw (12-Pack)	Attach pulley to platform	13/64 Pilot Hole
3A	(Phillips Pan-Head Self-Drilling Screws, for reference only)	C	4112	0	Ea.	OTS	Home Depot	$7.23	$0.00	#8 1/2 in. Phillips Pan-Head Self-Drilling Screws (25-Pack) (2/25 used fron	Attach pulley to frame	None
3A	Braided Nylon Plastic Rope Pull Cord	C	2677T5	1	2 ft	OTS	McMaster-Carr	$11.87	$11.87	1/4" Diameter, 2' Long	Rope to initiate horizontal motion	
4	**Casing Subassembly**											
4A	Acrylic Frame Casing	C	508	4	28"x30"	MTS	TAP Plastics	$29.75	$119.00	28 in x 30 in x 0.118 in (1/8 in nominal) Acrylic	Cover open sides of table	
4A	(Phillips Pan-Head Self-Drilling Screws, for reference only)	C	4112	0	Ea.	OTS	Home Depot	$7.23	$0.00	#8 1/2 in. Phillips Pan-Head Self-Drilling Screws (25-Pack) (16/25 used fro	Attach covers to frame (4 screws/cover)	None
5	**Lumber**											
5A	Sande Plywood	C	103078	2	1/2"x2'x4'	OTS	Home Depot	$17.97	$35.94	(Common: 1/2 in. x 2 ft. x 4 ft.; Actual: 0.472 in. x 23.75 in. x 47.75 in.)	Main horizontal and vertical platforms	
5A	Premium Kiln-Dried Whitewood Stud	C	161640	1	2"x4"x96"	OTS	Home Depot	$3.22	$3.22	2 in. x 4 in. x 96 in. Premium Kiln-Dried Whitewood Stud (Actual: 1.5 in x	All other necessary pieces for the platforms	
5A	Phillips Flat Head Brass Wood Screw	C	809721	2	Ea.	OTS	Home Depot	$1.18	$2.36	#8 x 1-1/2 in. Phillips Flat Head Brass Wood Screw (2-Pack)	Attach piece cut from the 2"x4" to the main horizontal platform	11/64 Pilot Hole
5A	Phillips Flat Head Zinc Plated Wood Screw	C	801862	1	Ea.	OTS	Home Depot	$6.25	$6.25	#8 x 2 in. Phillips Flat Head Zinc Plated Wood Screw (50-Pack)	Attach all pieces cut from the 2"x4" to the main vertical platform	11/64 Pilot Hole
5A	Wood Glue	C	62050	1	18 fl. oz.	OTS	Home Depot	$7.28	$7.28	18 fl. oz. Wood Glue	Adhering pieces of wood together	
6	**Canvas**											
6A		C							$0.00			
6A		C							$0.00			
7	**Total Cost**											
7A	**Subtotal**											
7A	80/20								$523.24			
7A	McMaster-Carr								$497.75			
7A	Home Depot								$79.56			
7A	TAP Plastics								$119.00			
7A	All								$1,219.55			
7B	**Taxes**											
7B	80/20								$45.14	From 80/20 checkout		
7B	McMaster-Carr								$42.31	Estimated using an 8.5% tax rate		
7B	Home Depot								$6.76	Estimated using an 8.5% tax rate		
7B	TAP Plastics								$0.00			
7C	**Shipping**											
7C	80/20								$99.26			
7C	McMaster-Carr								$0.00	We won't be able to find this out until we place an order, but we may be able to pick it up in LA		
7C	Home Depot								$0.00	Pickup in store		
7C	TAP Plastics								$0.00	$14.25 if we order online, nothing if we pickup		
7D	**Total**											
7D	80/20								$667.64			
7D	McMaster-Carr								$540.06			
7D	Home Depot								$86.32			
7D	TAP Plastics								$119.00			
7D	All								$1,413.02			

Appendix L: Operations Manual

Shake Table Operation Manual

Note to Operator: This manual includes all safe operation instructions and procedures. Please read this document in its entirety, including all safety warnings, before operation of the shake table. **This shake table is only to be operated in the presence of an adult or student docent in the SciTechtorium.**

Safety Checks:

1. Verify that the shake table is on a level surface where it will not move during use.
2. Ensure that all acrylic panels are securely attached to the outer frame of the shake table. All panels should not wobble or move.
3. Remove any structures or blocks from table surface and canvas.
4. Check the canvas under the main shake platform for rips or tears and that it is securely fastened to the frame and main shake platform.
5. Gently rotate the crank handle. Operation should be smooth, without the need to use excessive force to turn the crank handle.
6. Ensure that the pull cord is properly nested in its pulleys. Gently pull on the cord to ensure smooth motion.

WARNING: If the shake table does not pass any one of these checks, notify an adult IMMEDIATELY.

Instructions for Usage:

The shake table is designed to allow motion of the main shake platform (where the structure is built) in two directions: side-to-side (horizontal), and up-and-down (vertical). The pull cord controls the side-to-side motion, and the crank handle controls the up-and-down. Both directions of motion can be used together or on their own. **With the exception of the pull cord and crank, do not touch any part of the shake table while in use**. Anyone observing the shake table should be behind the operator, **do not** stand at the sides of the shake table.

1. Build a structure on the main shake platform using the wooden blocks provided. The structure can be simple or elaborate.
2. To initiate horizontal motion, pull the cord away from the shake table, then release. Repeat as necessary to continue the motion of the platform.
    - **a.** **Caution: Do not release the cord if anyone is standing between the cord and shake table.**
    - **b.** The horizontal motion will stop on its own. **Do not stop the motion manually by grabbing the platform or grabbing the cord.**

3. To initiate vertical motion, rotate the crank handle either clockwise or counterclockwise at desired speed.
    a. **Caution: Persons not operating the vertical motion of the shake table should stand clear of the operator while the handle is being rotated to avoid impacts with the operator's arms/elbows.**
    b. To stop vertical motion, stop rotating the handle.
4. Rebuild another structure or clean up blocks that may have fallen and store in designated space.

WARNING – Excessive Force: Pulling the cord roughly or rotating the crank handle as fast as possible may decrease the lifespan of the table.

WARNING – Flying Blocks: Operator should have full attention on the structure and its parts. Operating the shake table with excessive force can cause blocks to be thrown off the platform, possible causing injury.

WARNING – Structure Weight: Do not place anything besides blocks on the platform. Excessive weight will damage the internal mechanisms.

WARNING – Pinch Points, Rotating Parts: All hands, loose clothing, long pieces of jewelry, and hair SHOULD NOT be in contact with any part of the structure, shaking platform, pull cord, or shaft. This can result in injury.

WARNING – Structure: Do not touch the structure while the platform is in motion. Do not attempt to build a structure while the platform is in motion.

Maintenance:

All blocks should be removed from the shake table after use. Use disinfectant wipes to periodically disinfect blocks and frequently touched surfaces of the shake table to lower the chance of illness spread, especially amongst students. No mechanisms require lubrication but may require occasional dusting to prevent buildup of debris. A compressed air can is the easiest and safest way to do this: remove the canvas safety cover when the shake table is not in use and clear any debris using compressed air. Operate the compressed air can following manufacturer's instructions and safety guidelines. All debris will fall to the bottom, where it can be swept up and disposed of after moving the shake table out of the way.

The shake table should be kept indoors to prevent corrosion due Bellevue-Santa Fe Charter School's proximity to the ocean.

Replacing Parts:

All parts, excluding the cams attached to the shaft, are commercial and can be easily replaced. Remove the broken part and determine which part it is from the attached part list and drawings of the shake table. The vendor will be listed as well as a part number to ensure easy replacement.

Troubleshooting:

If you are a student, do not attempt to fix the problem yourself. Find an adult to help you!

1. Horizontal or vertical motion is not working: Remove canvas cover and check for debris. Clear any debris in the path of the motion. Reassemble the canvas cover. If motion still does not occur, check all parts related to the motion path, specifically the rails that the platforms ride on. If any parts are warped or otherwise broken, replace the parts.
2. Pull cord is moving, but the top platform will not move: The pull cord has snapped or come untied from the platform. Reattach or replace the cord.
3. Shaft is moving freely, but the vertical motion is not consistent or not occurring at all: The cams on the shaft may have come loose. Tighten down the screws holding the cams to the shaft and reattempt to create vertical motion.

Appendix M: Educational Poster