Heavenly Bodies RSVP
Final Design Review

June 5, 2020

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PROJECT ATLAS

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Executive Summary

The purpose of the Heavenly Bodies RSVP project was to design and fabricate planet props, as well as a mechanism by which they could be raised and lowered in California Polytechnic State University's Pavilion theater. The project team was comprised of four fourth year mechanical engineering students: Allison Turnbaugh, Braden Lockwood, Jack Boulware, and Justin Spitzer. We conducted extensive research to determine the ideal solution for the design problem brought to us by our sponsor. In our analysis, we discovered that the most important aspects of our design were the absolute reliability of the system, fire retardant material selection, and the overall aesthetics of the planets. These criteria along with our past product research allowed us to design a product that aligned with the vision of our sponsor. The system of planets was planned for use by the Music Department for the 25th installment of their annual diverse transmedia series entitled RSVP XXV: Call and Response. Sponsored by Dr. Antonio Barata, the show's artistic director and producer, and professor in Cal Poly's Music Department, the project featured design considerations unique to the location and nature of the production. For instance, the project had a hard completion deadline set for May 17, 2020, as stage construction would have been completed in preparation for rehearsals the following week. We determined that approximately 20 planets would be manufactured by the end of the project as well as a system to deploy them. Our objective was to make these planets safe, quiet, aesthetically pleasing, lightweight, and suitably reliable for use in the play. Though our design was unique to the needs of our sponsor, research of patented mechanisms provided inspiration for a system to raise and lower the planets. This information was utilized during ideation, which resulted in the creation of a few viable solutions, discussed later in this document. Working with our sponsor and advisor, the team finalized and tested a design, then created a structural prototype. However, due to the outbreak of COVID-19, the team was forced to forgo construction of a final product, as the production was cancelled. In response, the team devoted its remaining time to creating a set of online instructions to assist others in building and implementing the developed system.

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1.0 Introduction

We are a team of four mechanical engineering students at California Polytechnic State University, San Luis Obispo. The team is comprised of Jack Boulware, Braden Lockwood, Justin Spitzer, and Allison Turnbaugh. Our objective was to help design a set of descending planets for the upcoming RSVP XXV: Call and Response production. Our sponsor, Dr. Antonio Barata, was the director of the production and wanted to ensure that his last RSVP production was one to remember, enlisting our services to realize his creative vision. He requested that we design a quiet, reliable, and safe system capable of raising and lowering spherical bodies from the ceiling of the Pavilion theatre. Our project not only benefited Dr. Barata, but also the performers and, the audience members, allowing the Mechanical Engineering Department to create stronger ties with the Music Department. The strict timeline of the project in conjunction with the magnitude and size of the system proved challenging as we were required to design, manufacture, and test a system in fewer than 20 weeks. This document outlines our research on the project, creation of concept designs based on this research, ideation, creation of a concept model, finalizing of the design and manufacturing of a structural prototype, as well as our detailed plan of action to ensure everything would be ready by the performance date. In addition, this report discusses the shift in our project deliverables as a response to the COVID-19 pandemic. This shift included a halt in manufacturing, cancelation of the production, and the creation of an online step-by-step guide for building our final design.

2.0 Background

After accepting the project, the team completed introductory work in clarifying the problem, researching possible solutions, and establishing communication with critical staff and faculty members, who were instrumental in discovering solutions to the presented problem. Through more communication with the theatre technicians, we have included more information regarding safety standards and a relevant product: a DMX winch. During our design process we tested possible methods of creating the planet models and determined the most reliable solution would be to utilize large exercise balls and create a suspension system for the balls which will not puncture them.

2.1 Information from Sponsor Interviews

In the earliest stage of the project, our team met with Dr. Barata to clarify the nature of the project itself. In the first weeks, the primary focus was gaining a better understanding of what Dr. Barata desired, in addition to learning considerations which were not evident beforehand. During this time, the team walked through the Pavilion black box theatre to gain first-hand experience of the space and its limitations. The Pavilion is a 72 ft by 42 ft theatre space on the far right of the main entrance to Harold Miossi Hall in Cal Poly's Performing Arts Center (PAC). Within the Pavilion, there is a structure that spans the width and length of the ceiling referred to as "the grid," to which all stage lights and speakers are mounted. The grid would support the planets; ideally planets will span the full length of the grid. Dr. Barata explained that the stage would be set against one wall of the theater; consequently, there may be space for a human to operate the planetary system behind the curtain.

In subsequent meetings with our sponsor, the team connected with Mr. Tim Seawell, Head Carpenter for the PAC, and Mr. Tom McPherron, its Technical Director. Mr. Seawell and Mr. McPherron were valuable resources concerning theater regulations, the Pavilion's technical specifics, and the finer points of theater tech. Meeting with Mr. Seawell and Mr. McPherron clarified several concerns the group had regarding what was possible in the theater space. For example, the team learned that aircraft cable is often used to support weight from the grid, as it is nearly invisible while holding items and has proved effective in the past. We were also made aware that the theatre department uses safety factors of approximately 7-9; this means the system needed to be able to hold 7-9 times the actual load of the planetary bodies. In addition, the maximum temperature recorded near stage lights attached to the grid is 150°F; our final design had to be able to withstand this temperature. Mr. Seawell and Mr. McPherron also recommended researching systems called a DMX winches. These are self-contained systems that can clip to the grid, using an internal motor to raise and lower objects individually.

Dr. Barata also introduced us to Clint Bryson, the Technical Director for Cal Poly Theatre and Dance. Mr. Bryson's knowledge of practical theatre manufacturing proved invaluable when deciding which types of pulleys to include in our design and how to manufacture the planetary bodies. After discussing our proposed design with Dr. Barata, he cautioned us about the feasibility of placing the heavenly bodies in certain locations due to the lighting equipment which would also hang from the grid. This meeting clarified that the planets were to cover only the 20ft x 35ft space which is to be designated as an open dance floor, providing an additional constraint for the project.

2.2 Product Research

We conducted introductory research into methods by which the planetary bodies could be manufactured, moved, and held. Though our team could not initially find exact matches for the desired system already available on the market, we researched designs which could prove essential to the project going into the ideation phase. After speaking with Mr. Seawell and Mr. McPherron, we researched DMX winches, which could constitute a more direct solution to the proposed problem.

Because our project was unique due to the needs of our sponsor, there was only one product on the market comparable to the mechanism we were designing. This mechanism, however, could not simply be copied due to a multitude of factors; as a result, other products were researched which proved useful in the construction of our project. Specifically, research was done on products that could be used to build planetary bodies as well as mechanisms capable of displacing them vertically in front of a live audience. Pulley systems and motors were investigated as a potential means of raising and lowering the heavenly bodies. Table 1 is a list of products cultivated by the team which were useful going into the design phase though it is by no means exhaustive.

Table 1. Relevant Products and their Characteristics

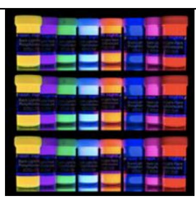
Related Product	Product Description
 ***Figure 1.*** *Beach Ball [1]*	Beach balls were researched for their potential use in the construction of large planetary bodies. They are lightweight and spherical, which were two of the most important design specifications for planet designs. It would have been necessary to coat the balls with a hardening agent that ensured the balls would not deform or 'pop' while in use.
 ***Figure 2.*** *Styrofoam Balls [2]*	Styrofoam balls were also researched for their potential use in the construction of small planetary bodies. Styrofoam is a very light-weight material and holds its shape better than inflatable alternatives. Unfortunately, the largest Styrofoam balls available on the market had a diameter of 1 foot, which is smaller than the group required for most planet props.
 ***Figure 3.*** *Strong Wire Rope [3]*	Strong wire rope was also an option for our design. It was important that the material used be strong enough to support the planets and durable enough to withstand wear and tear. However, it was also important for the wire to be as thin as possible, rendering it invisible to the audience.
 ***Figure 4.*** *Pulley [4]*	Pulleys were also considered to create our system. The system would require one pulley for every planet as well as extra pulleys to ensure wires can all connect back to a common mechanism (most likely a motor).
 ***Figure 5.*** *Electric Motor [5]*	A motor could help retract the wire and run the pulley system. Though Dr. Barata believed this action could be performed by a person, our team believed it will be more consistent and reliable to find a mechanical solution. A motor would have allowed us to lower the planets at a very consistent, steady speed.
 ***Figure 6.*** *Glow in the Dark Paint [6]*	Glow in the dark paint was considered to suit the project's aesthetic needs. It is important that the planets make a visual impact on the audience and glow in the dark paint would be an effective tool in achieving this. In addition, Dr. Barata has spoken about his desire to have some form of luminescence coming from the planets.
 ***Figure 7.*** *Phantom of the Opera Chandelier [7]*	The Phantom of the Opera Chandelier, manufactured by ZFX Flying Effects, is similar to what we planned on creating, in the sense that it is raises and lowers dramatically and safely. This system uses a 3 phase 208-240V motor to lift 500lbs at 4 ft/second and "crash" at 7ft/second. From this we had a good base point to try and find a viable motor to move our system.

Table 1. Relevant Products and their Characteristics

Related Product	Product Description
 ***Figure 8.*** *Wahlberg DMX Winch [8]*	The Wahlberg DMX Winch is a device designed to lift electrical stage items at loads of up to 22lbs. The winch can be controlled by 16-bit position down to the millimeter. The lowering and raising speed of the system varies from 2-11.8 in/s.
 ***Figure 9.*** *Exercise Ball [9]*	Exercise balls could serve as easy planet props, assuming there is no risk related to heat resistance. Because they can be ordered in a variety of sizes, they could be used to simulate many different planets, if a suitable way to hang them from the grid was devised.

2.3 Patent Research

All patent research was conducted through the Google Patent search engine, and although many patents were analyzed, the most relevant patents are listed in Table 2. Taking inspiration from this research, our team was able to generate design ideas while being careful not to violate any established patents. Patents related to theater tech were most useful to us as we considered designing around the theatre space. All other patents not directly related to the theatre space will be referenced, but not as heavily, as they deal with pulleys and items hanging above the ground.

Table 2. List of Relevant Patents and their Characteristics

Patent Name	Key Characteristics
Flexible Lightweight Overhead Storage Rack [10]	• Hanging Storage Device • Utilizes Pulley Systems • Holds items in positions high off the ground
Portable Game Hoist [11]	• Can be secured to rafters • Operates with a pulley and a crank • Moves objects up and down vertically
Compound winding apparatus and counterbalance system [12]	• Compound counterbalance system • Holds weight of window up • Allows for only vertical movement
Cable and pulley linkage for exercise machine [13]	• Multiple pulley system • Strategic weight distribution based on pulley placement • System that supports weight moving up and down consistently through multiple cycles
Apparatus for moving scenery [14]	• Operates in a theatrical setting • Utilizes a pulley system to raise or lower theatre scenery • Possible to pre-set heights that the scenery is lowered to and the speed that it is lowered at
Suspended theatre rise system [15]	• Operates in the theatrical space • Uses counterbalance to lower and raise weights

2.4 Safety Obligations

Considering that we designed and planned to construct a large-scale prop for a live theatrical show, there are very strict safety measures we needed to abide by. These safety measures consider heat resistance, fall protection, weight limitations, and electronic system verification. The most restrictive safety protocol specified that all materials and systems used in theatrical productions must be fire retardant [16,17]. Due to this strict constraint, we needed to ensure that all structures and materials constructed were fire retardant and could withstand the heat produced by the many theatre grade lights hung from the grid. This constraint also restricted which materials we could use for the project; for example, cardboard and nylon were prohibited materials [17]. In addition, to ensure that our planetary system would not fall we needed to account for how much weight the grid could support, and ensure the system was securely fastened. On "load-in" there would only be two technicians available to install our system, so we were required to design the system to be installed by two people. However, the system needed to be checked at least 30 days in advance to ensure it complied with all codes [18]. If we decided to utilize an electronic motor system to raise and lower the planets, the electronic system would need to be checked and validated by the head electrician at Cal Poly; this process could take up to a week.

3.0 Objectives:

After gathering all the necessary background information on our project, we moved onto defining our problem and better understanding the specific requirements of the project. We also amended a few of our engineering specifications at the request of our sponsor and based on the limitations of our final design.

3.1 Problem Statement

Cal Poly RSVP needed a way to suspend, store and deploy numerous planetary bodies for a production, directed by Dr. Barata, because there was no system that could raise and lower the bodies to carry out Dr. Barata's vision. The mechanism designed needed to be safe, quiet, reliable, and complete by the day of load-in during the early weeks of May.

3.2 Customer Wants and Needs

Through discussion with our sponsor and staff working in the Performing Arts Center, we highlighted key considerations which were necessary during the design process. For instance, the method of propulsion needed to move the mass of approximately 20 'planets', the heavenly bodies had to be fire retardant to be allowed within the theater, and a silent mechanism was preferred to maximize the 'wow factor' experienced by the audience. While many of the desired qualities of the project, such as size or weight, could be represented empirically, some were more abstract. For instance, though Dr. Barata stressed how important it was to have a "completely reliable" system, it was difficult to quantify that desire. It is easy to understand what was required; there must be complete certainty that the system would work through the end of the production. All the necessary requirements set forth by our customers as well as the extra features desired can be seen in Table 3.

Table 3. Customer Wants and Needs

Wants	Needs
Aesthetically pleasing	Safe for operators & performers
Hidden from audience	Near-silent operation
Variable movements	Raise and lower on command
Smooth consistent movements	Fire Retardant
No interference with stage lighting	Spheres of varying sizes
Easy to install	Can be installed by two people

3.3 Boundary Diagram

To accurately define the scope of our project, we created a boundary diagram. A boundary diagram is used to see what is within our control and what is out of our control regarding the project. Everything within the dotted line of Figure 10 was within our control. The Pavilion grid was not within our control because we could not make alterations to it; however, the dotted line goes through it because we needed to attach our system to the grid. In addition, we included the seating arrangement in the boundary diagram because our design had to consider where the audience was in relation to the planets. For example, any planets hanging over the audience could not move too low, as they would have obstructed their view or collided with the audience.

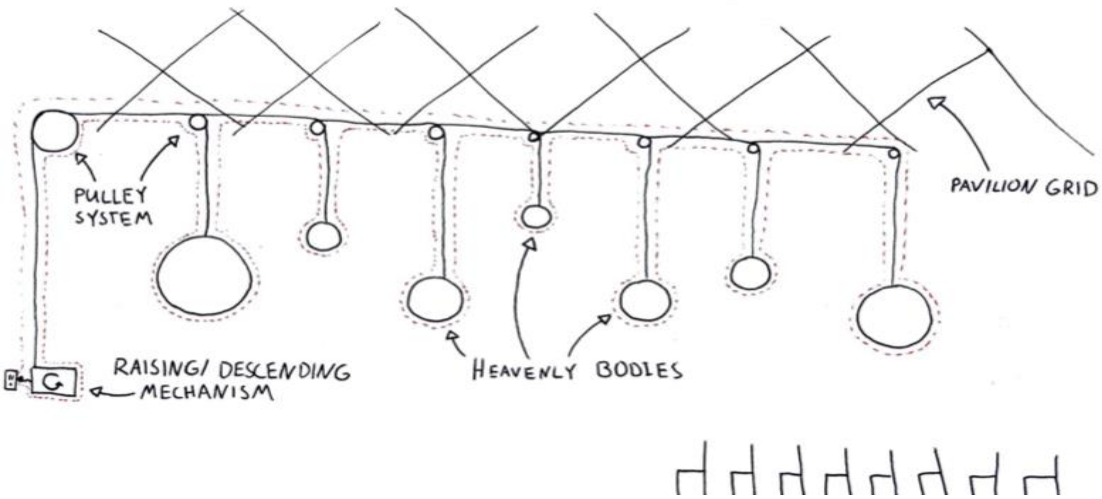


Figure 10. *Boundary Diagram*

3.4 Quality Function Deployment (QFD)

With past research completed the next step in our process was to complete a QFD, also known as a House of Quality graph. The purpose of the QFD was to ensure that the design chosen would most effectively fulfil the customer's desires. To do this, we set out to define who our customers were, their needs and wants, what solutions existed at the time, and how we could specify these quantities. All categories were evaluated with numerical values or symbols and used to determine what specifications were the most important to our design. Our analysis showed that heat resistance, consistent function, and aesthetics proved to be our most important design criteria. To see more, tour complete QFD can be found in Appendix A.

3.5 Engineering Specifications

To better understand and quantify the various engineering specifications required for this project, we developed Table 4, which details each of the engineering specifications. This table also includes the target values, tolerance, risk, and compliance for all the specifications. Compliance was assessed by analysis (A), testing (T), inspection (I) or a combination of the three.

Table 4. Engineering Specifications

Spec #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Production Cost	$3000	Max.	M	A
2	Total System Weight	50 lb	Max.	L	A, I
3	Individual Planet Weight	5 lb	Max.	L	A, T
4	Operating Volume	35 dB	± 5 dB	M	T, I
5	Operating Speed	8 ft/sec	± 1.5 ft/sec	H	A, T
6	Heat Resistance	150 °F	Min.	H	A, T

The requirements for cost operating volume and weight were established based on previous RSVP senior projects and the requirements for our specific project [19,20]. We concluded to aim for 35 dB operating volume, because 40 dB is comparable to a computer running or a babbling brook and 30 dB is comparable to a whisper; an operating speed within that range would be ideal [21]. However, an operating volume of 30 dB was not considered a minimum, because anything below 30 dB would not distract from the performance and was therefore an acceptable operating condition. Because we would need to fabricate around 20 planets of varying sizes, purchase ropes, pulleys, and potentially a motor, we anticipated cost to be approximately $3,000, including the cost for technicians to install the system. We aimed to minimize the weight of the planets and the overall system, such that it would only require two people to install and to ensure we would not overload the grid. We would test compliance for total system weight by first calculating the anticipated weight, which was compared to the weight of all individual components. We would also confirm that the system works ergonomically by testing if two people could lift the system. The same process was used to test the weight of the individual planets. The operating volume of the system in a quiet room would also be measured. Operating speed would be tested similarly, by measuring the speed of the rising and lowering planets. To test the heat resistance of the planets, we planned to conduct preliminary tests with a theatre light to determine which materials are the least effected by the heat. We anticipated that any feasible material which reaches a temperature above 150 °F would deform such that the overall aesthetic will be compromised.

3.5.1 High Risk Specifications:

Most of the engineering specifications were very achievable within our time frame. We considered operating speed and heat resistance high risk specifications because these two specifications would be the most difficult and time consuming to get right. To ensure the operating speed was accurate and reliable, we would simultaneously plan a hand operated system and an electrically operated system. This would allow us to fine tune an electrically operated system while ensuring we could still have a functioning system that was not dependent on a motor. To guarantee a fire-resistant planetary system, we set aside a portion of the budget to pay for fire-resistant material or products to make our material fire retardant. Because of the sizable amount of heat let off by the theatre lights and the proximity of planets to these lights, it was imperative that our planets were able to withstand this heat without any damage to the structure of the planets or their aesthetic. We planned on performing a variety of tests to see what materials can withstand this heat without any damage.

4.0 Concept Design

Using the information collected, the team set out to generate concepts that could be developed into a final product. In the following section we will detail the process we went through to obtain our final design as well as preliminary tests and current concerns.

4.1 Concept Development

Initially, we performed Functional Decomposition, which broke down the overall project into subsystems, known as functions, to brainstorm ideas based on these functions. We considered four functions: planet design, method of connection, method for vertical movement, and method of propulsion. By understanding what the system needed to do on a base level, this allowed us to generate ideas to fulfill these functions. With all functions listed out on a white board our team began brainstorming as many ideas as possible that could achieve the specific functions we created. All ideas generated through this brainstorming session are in Appendix B. After brainstorming ideas, our team generated more ideas by brainwriting and brain sketching. In these activities each team member wrote and drew specific ideas for each function in a logbook. In each session, five minutes were allotted to each team member to create ideas for the respective function. At the end of the five minutes, the books were passed to a new team member until all members had generated ideas for each function. To see all additional ideas generated from these exercises see Appendix B.

Once all initial ideas were generated, they were placed into a Pugh Matrix. The Pugh Matrix allowed the team to evaluate the ideas generated for each function against a specific baseline or datum concept. For example, our datum concept for propulsion of the planets is a motor. With reference to our datum, other ideas of propulsion were assessed such as: manual, drill power, counterweights, or gear trains. These ideas were assigned positive, neutral, or negative rankings relative to the datum for various criteria like noise level and cost. For a full listing of all Pugh Matrices see Appendix C.

From the Pugh Matrices the top three ideas for each function were placed in a Morph Matrix, its purpose is to take individual ideas and combine them into a fully functional system. Starting from the left side of Table 5 and moving to the right, lines are drawn to combine the function ideas into a system. Each system created contains one of idea from each of the functions in Table 5.

Table 5. Morph Matrix Options

Planet Design	Connections	Vertical Movement	Propulsion
Wire Frame	Loop	Wind Up Rod	Motor
Plastic Shell	Adhesive	Levers	Manual
Cross Plates	Bolts	Pulleys	Gear Train

4.2 Initial Top Concepts

After the completion of our Morph Matrix we were left with a total of six plausible systems to continue our design with. Each of the top function ideas listed in Table 5 are further explained in Tables 6-9.

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Table 6. Planet Design Ideas

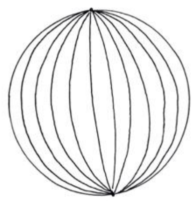
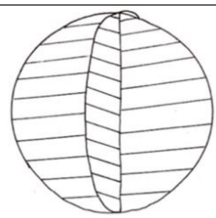
Ideas	Pictures	Description
Wire Frame	 ***Figure 11.*** *Sketch of Wire Frame Planet*	Thin metal wire will be formed into a spherical shape, which can be covered with fabric if desired.
Plastic Shell	 ***Figure 12.*** *Sketch of Plastic Shell Planet*	A plastic shell in the shape of a sphere will be purchased, then painted to resemble a heavenly body.
Cross Plates	 ***Figure 13.*** *Sketch of Cross Plate Planet*	Two flat circular plates with intersecting notches will be slotted together, which could also be covered for aesthetic purposes.

Table 7. Attachment Ideas

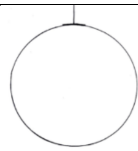
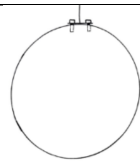
Ideas	Pictures	Description
Loop	 ***Figure 14.*** *Sketch of looped connection*	A loop on the end of our cable will be carabiner clipped onto the planet
Adhesive	 ***Figure 15.*** *Sketch of adhesive connection*	The end of our cable will be attached with a strong epoxy directly to the planet
Bolts	 ***Figure 16.*** *Sketch of bolted connection*	The cable with plate attachment will lower onto our planet and bolt through the plate into the planet

Table 8. Vertical Movement Ideas

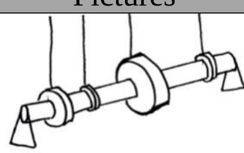
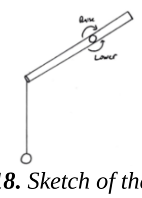
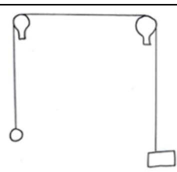
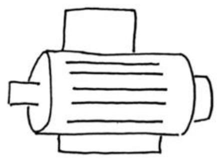
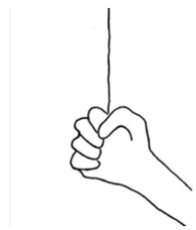
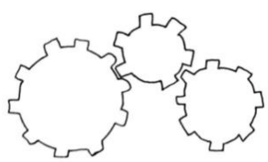
Ideas	Pictures	Description
Wind Up Rod	 ***Figure 17.*** *Sketch of the wind-up rod*	A shaft with various diameter circles welded on will allow cable to loop over diameters and allow for variable planet lowering speed
Levers	 ***Figure 18.*** *Sketch of the levers*	A “teeter-totter” design will have one shaft running along the grid with several supporting planks from which planets are suspended
Pulleys	 ***Figure 19.*** *Sketch of the pulleys*	A cable will loop over pulleys attached to the grid

Table 9. Propulsion Ideas

Ideas	Pictures	Description
Motor	 ***Figure 20.*** *Sketch of the motor that will attach to our shaft*	A motor purchased online will be used to rotate the shaft and lower the planets
Manual	 ***Figure 21.*** *Sketch of manually operating the mechanism*	A person standing with a rope will pull up and down on a cable to rotate a shaft in order to raise and lower the planets
Gear Train	 ***Figure 22.*** *Sketch of a gear train that will control our shaft*	A gear train will be used with a motor connected directly to the shaft allowing for variable control of the shaft

The ideas accumulated in Tables 6-9 were combined in a variety of ways to create fully functioning systems that meet all necessary function requirements. Our various system ideas are represented by the block diagrams of Figure 23- 28 and show the viable combinations that were revealed through ideation. Once all the systems were decided we analyzed the systems against our project criteria to determine which idea was the best.

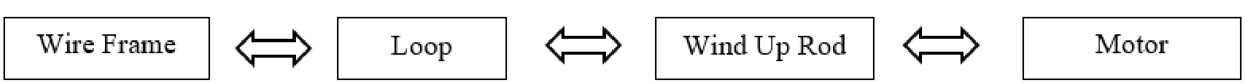


Figure 23. *System 1 Components and Connections*

This system will allow for an easily attached clip from the cable onto the wire frame of the planets. This will loop onto the wind-up rod which will be held on the grid and attach to a motor located behind the curtain that will wind and unwind the shaft.

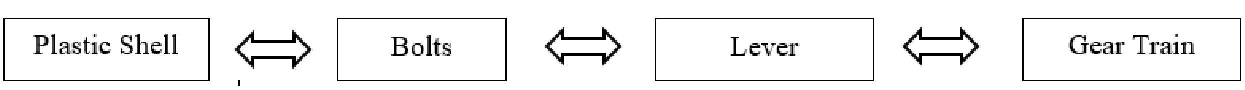


Figure 24. *System 2 Components and Connections*

System 2 allows for easy manufacturing of sphere shell and will allow for strong connection with the bolts. The lever design will allow for planets to rock up and down while having variable control from the gear train attached to the shaft.

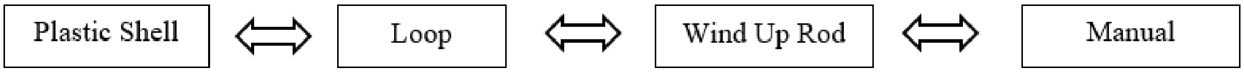


Figure 25. *System 3 Components and Connections*

Like System 2, System 3 gives easy access to planet manufacturing as well as a strong connection clipped on to the cable and a hook attached to the planet. This will all be connected to the multi diameter rod allowing for carriable speed control that will be operate manually which will reduce noise and cost.

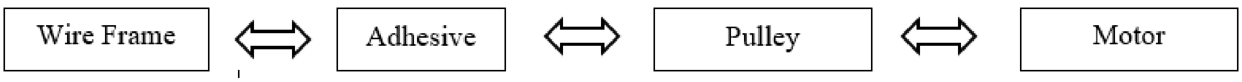


Figure 26. *System 4 Components and Connections*

Differing from the previous two ideas, this system uses lightweight wire frame and adhesive to avoid complications with other attachments. Pulleys are also used as they have proved efficient in prior theater productions as well as a motor to provide consistent power to the system.

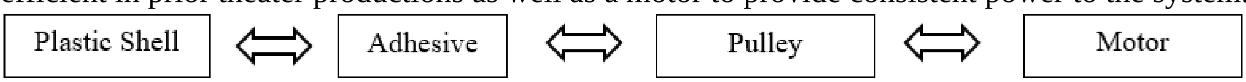


Figure 27. *System 5 Components and Connections*

This system is very similar to the system in Figure 26, the only difference is the planet material choice, this design allows for easier manufacturability.

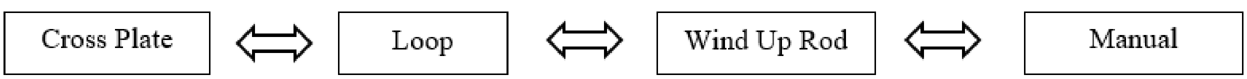


Figure 28. *System 6 Components and Connections*

This system is very similar to that of Figure 25, except the planet material has also changed. The benefit of this system is that it will be cheaper to create and be lighter in weight than the previous option.

A seventh fully functional system that already exists called a DMX winch (see Table 1 Figure 8.) was discovered in our design process and added as another possible option. This solution is the most high-tech and requires the least amount of construction materials. The system of powered winches would be able to lock into the grid and operate without any mechanism behind the stage. The winches can be programmed to move however we want them to move making this option very simple.

4.3 Concept Selection Process

Once our team had our full system ideas laid out it was time to further define what our final design would look like. In this step of our process we created a weighted decision matrix, a tool that allowed us to rank our systems on a scale from 1-5 as well as weight the criteria we define from 1-5. In this matrix we placed all the seven system items created before and lined up criteria from our House of Quality. As a team we went through each individual box and scored each system based on how well it fulfilled the criteria we set forth. After doing this for each system, we were left with a range of weighted scores that showed us the system best fit to solve our problem. The results for this test can be found in Appendix C and will be discussed further in section 4.4 Selected Concept.

4.4 Selected Concept

In the end, we decided to select the design featuring a rotating shaft of varying diameter controlled by a motor in conjunction with the planets being made of wire frame or a plastic shell. These planets will be connected to system via the loop method described previously. This concept will also utilize pulley to guide the planets to their predetermined drop location. The different diameters of the shaft will allow the planetary bodies to be lowered at different distances from the ground while still dropping at the same speed. In total, there will be four or five shafts each controlling approximately five planetary bodies. These shafts will be positioned at different locations to ensure that the heavenly bodies can cover the whole stage and part of the audience. Ideally, these shafts will be positioned behind the curtains as to hide the mechanism from the audience and add to the wonder and surprise when the planets eventually descend from the grid.

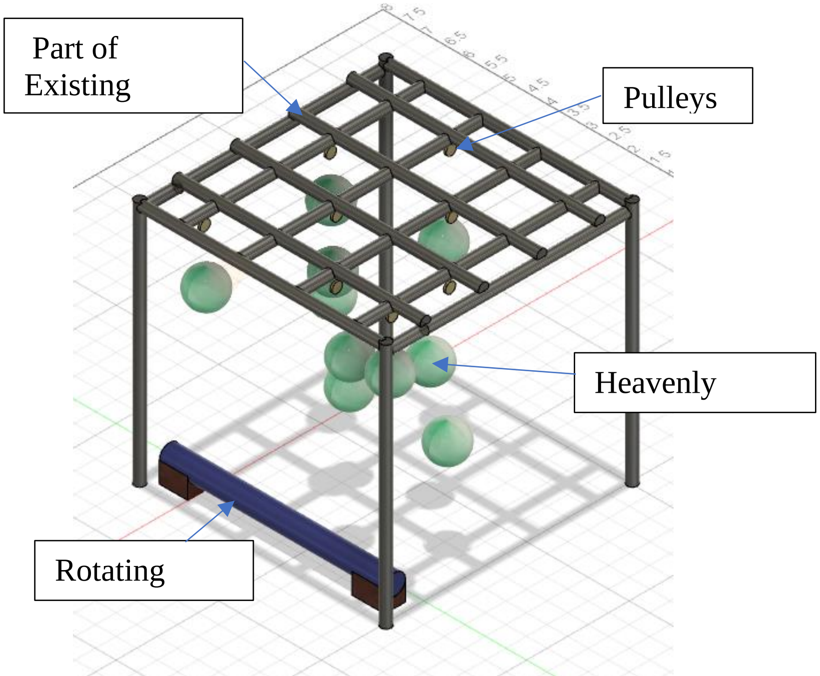


Figure 29. *Model of Chosen Concept*

Figure 29 shows the overall concept while not including the wire connecting the shaft to the planetary bodies. The wire was neglected for this 3D model for the sake of visual clarity.

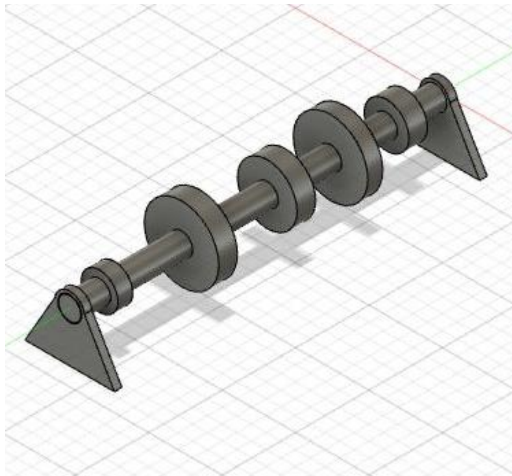


Figure 30. *Model of Rotating Shaft for Chosen Design*

Figure 30 shows a 3D model of our proposed rotating shaft. The overall length of the shaft had yet to be determined as was dependent on the space available behind the curtain and where the curtains were to be placed in relation to the stage, which had yet to be decided at that time. In addition, the radial size of the disks was decided based on future calculations of where each planet was to be placed and how far the planet would have descended.

Figure 31. *Concept Prototype*

Our concept prototype seen in Figure 31 illustrates how our proposed system worked to lower and raise the planetary bodies. The concept prototype is powered manually by twisting the handle attached to the shaft, whereas we planned to power the final model via motor. Within the prototype the cable ties take the place of the pulleys which would be attached to the grid to guide the planetary bodies to their designated position. This system validated our idea and encouraged us to continue pursuing this solution.

4.5 Preliminary Analysis

Preliminary analysis confirmed the feasibility of our design. The main concern with the rotating rod system was that the weight of the planets might apply an upward force on the bar that is too heavy for the motor to pull. There was also concern that the planets might displace the bar, pulling it into the air. To address these concerns, we concluded it was necessary to bolt the bar down to the same support structure that attaches to the grid. We also considered introducing a counterweight to help balance the pull on the bar. The easiest solution, however, was to minimize the weight of the planets to ensure that there are no complications raising and lowering them.

It was aesthetically important to ensure the planets could be deployed to varying heights. To ensure this variation is possible with our wind-up rod design we determined the necessary radius for different planetary heights. The radius was calculated by using the speed of the motor, the time of descent, and the descent distance. The speed of the motor and the time of descent were multiplied to calculate the total number of cycles. The number of cycles were then used to calculate the circumference of the rod that each planet is attached to. This calculation confirmed that a wide range of planetary heights could be achieved by modifying the radius a proportional amount. This calculation can be found in Appendix D.

4.6 Current Design Risks

As we developed our design, we took note of ways in which it could present a hazard to operators or the audience. Because of the relative mechanical simplicity of the system, the only risks of note are those that arise due to the mechanism itself; for example, there are no risks related to flammable gasses or hydraulics. However, there are several ways that the system may cause harm. These risks can be classified into three types – hazardous motion, falling objects, and misuse. The complete list of potential hazards can be found in Appendix E.

First, the motion of the mechanism could harm operators by pinching or drawing. As the shaft rotates, it could draw in and damage nearby objects such as the loose fabric of the curtain. In addition, the winding of the rope about the shaft presents a pinch point; an unwary operator could hurt themselves by getting fingers caught between the rope and the shaft. To prevent these kinds of hazards, the team plans on containing the shaft within a rigid box such that the rope can still be pulled around the shaft, but it is impossible to access the shaft itself without removing the box.

The most obvious risk associated with the design is that of the planets falling on the cast or audience. The simplest way to address this issue is to pinpoint all the ways the planets can become disconnected with the mechanism and design them so that failure is impossible. For example, we will ensure a factor of safety between 7-9, as suggested by Mr. Seawell, and Mr. McPherron, so that the rope holding the planets will not snap. In addition, the team is considering using a counterweight as a failsafe. In the current design, if the motor fails, then the planets will drop. By using a counterweight with more mass than the planets, if the motor fails, the planets will simply be pulled back to their positions at the top of the Pavilion. In addition, the use of a counterweight means that a lower torque output would be needed by the motor.

Finally, there will inevitably be ways that misuse of the system could cause harm. For example, if there is enough slack in the system, it will be possible for an operator to allow the planets to descend too far and hit audience members. Issues such as these will be addressed through design as much as possible, inevitably there will still be many ways the system can be misused. This risk will be mitigated by having a meeting with all cast members before the show and explaining operating process of the mechanism and how to operate it safely.

5.0 Final Design

Our product design went through many iterations in order to be certain that it would meet all the design specifications. Most of the adjustments made to the design were to simplify our assembly and prioritize the theatrical nature of our project. Our system was designed to make minimal noise and provide an aesthetic backdrop for a live performance. With our updated design, we would be able to successfully raise and lower 20 planets simultaneously and suspend them above the show during critical scenes set in space. The final design could be broken into three main sub-systems: the wind-up rod, pulley system, and planet assembly. This section of the report describes in detail each of the three main sub-systems of the final design.

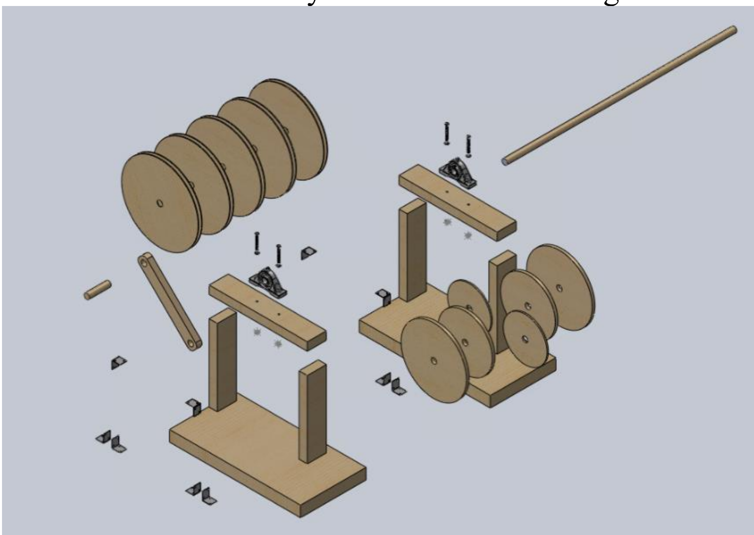


Figure 32. *Exploded View of Wind-Up Rod Assembly*

5.1 Wind-Up Rod Assembly

The first subsystem is the wind-up rod itself. The wind-up rod is responsible for supplying the necessary torque to raise and lower the planets. The rod is elevated to chair height using a wooden base which is comprised of two stands with a bearing attached to each. A wooden dowel locks into the bearings and rotates smoothly along the axis. Each stand is anchored to the floor with stage weights that rest on the base of the stand. This ensures that the upward forces caused by the planets does not flip over the wind-up rod. The design for the base stands for the wind-up rod can be seen in Figure 33. Since each planet is going to weigh an average of five pounds it is necessary that both stands can withstand an upward force of 25 pounds. Since each stage weight weighs 50 pounds this solution is sufficient to anchor the base down. The planets themselves are attached to the rod by a series of wooden discs glued down along the length of the rod. Above each disk there will be a hole built into the stand for the wire to feed through to ensure that the wire stays in place and coils properly. Each disc is comprised of three separate disks, one smaller disc sandwiched between two 14” discs. The middle disc has a variable diameter ranging from 8” to 12” as shown in Figure 34. This allows the planets to all descend at different rates. The planet will descend at a speed proportional to the circumference of the middle disc that the wire is attached to. Therefore, the planet attached to the 12” disc will descend at a rate of 1.5 times that of the planet attached to the 8” disc.

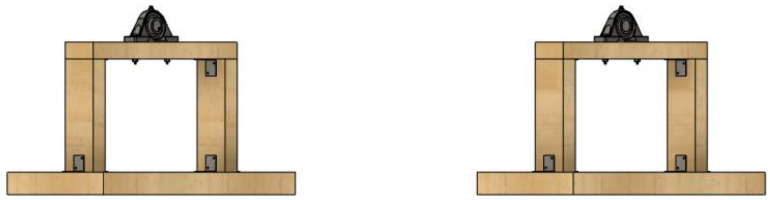


Figure 33. *Base Structure*

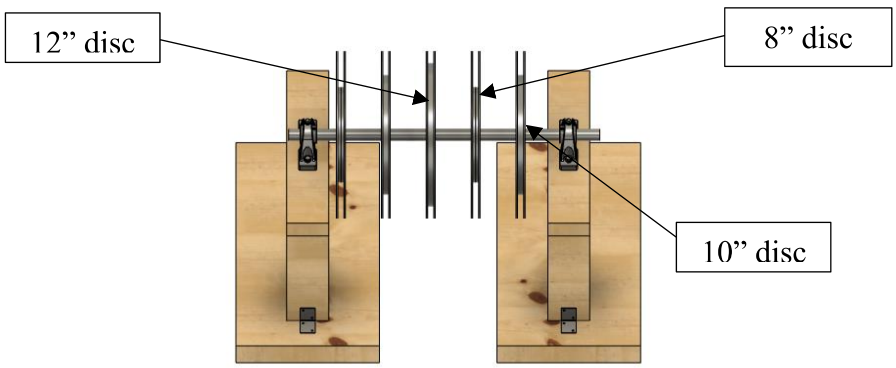


Figure 34. *Shaft System with Differing Diameters*

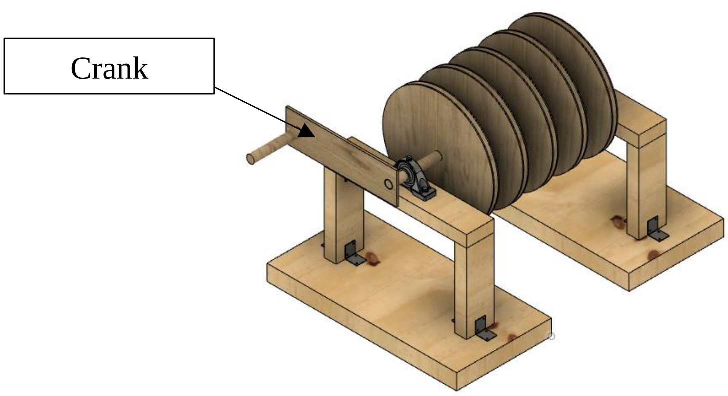


Figure 35. *Isometric view of Wind-Up Rod Assembly*

The main adjustment made to the wind-up rod since the preliminary design report was to remove the motor from the assembly. Figure 35 shows the design of the assembled wind-up rod with the crank handle. In its place, our group elected to go forward with manual cranks to simplify the design. This was done for numerous reasons, the sound created by the motors being one factor. Our group would like to ensure that our project could not draw any unnecessary attention away from the show due to excessive noise. Another factor that reinforced our decision to go with the manual option is reliability. The purpose of our design was simply to lower and raise 20 planets multiple times over three set performances. In these conditions, we believed that the manual crank option would result in a lower chance of showtime complications than a system of multiple motors. This is especially true considering how important the timing of the deployment is. It is easier to ensure that four people see a visual cue and begin cranking than it is to trigger four motors at the correct time and have them start simultaneously. The torque required to lower and raise the planets is applied to the dowel using a crank attached directly to the rod. The length of the crank is 1 foot. This length ensures that an average person will be able to supply enough torque to comfortably move the planets. Since each planet is attached to a disk with an average radius of 5 inches the overall torque applied by the planets is 125 in-lbs. Therefore, the person operating the crank only needs to supply 10 lbf of consistent force to the lever to move the planets.

5.2 Pulley System

The second subsystem that makes up our design is the pulley system. The pulley system includes the aircraft cable and the series of pulleys that guide the cable to its destination in the grid. Figure 36 shows the potential placement of the pulleys on the grid. As seen in Figure 37 there are many lighting obstructions that will require us to use multiple pulleys per planet. Figure 37 also showcases the "Dance Floor" which is the area where all the planets would have dropped. We would have used at least 40 pulleys which dangle just under the grid. The pulleys will loop over the grid and then be used to reduce friction when the wire is fed through them. One pulley per planet will be placed directly above the wind-up rod. The wire would go directly up from the discs to the first pulley and then spread out from there. Some of the planets would only require two pulleys and their wire would go directly to a pulley placed at their final location. Other planets would require one to two additional pulleys to get the wire to its ideal position in the grid while avoiding major obstacles or tangling with other lines.

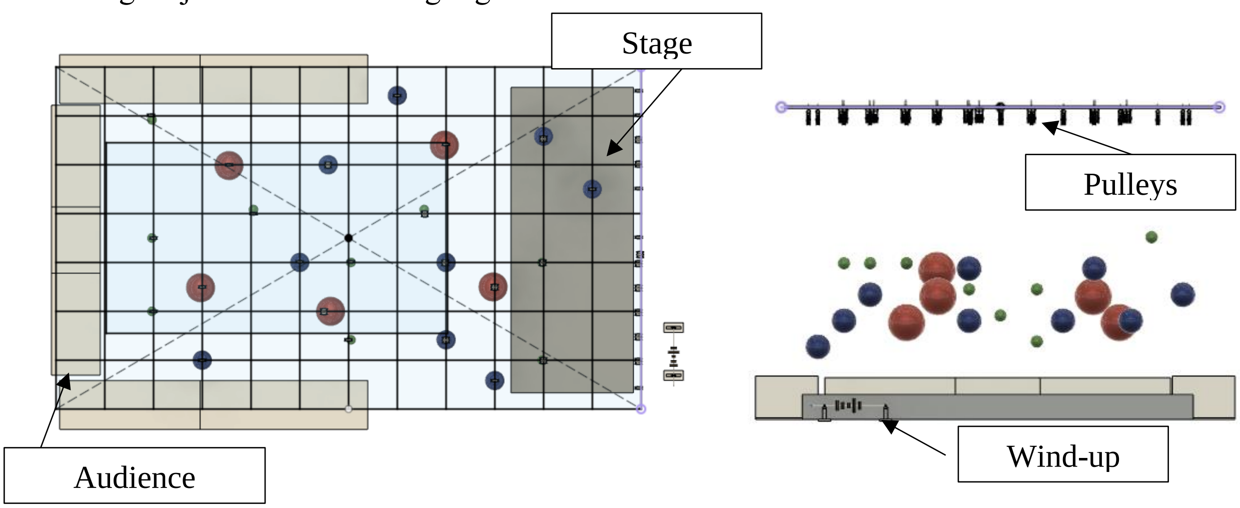


Figure 36. *Top View and Front View of Grid Layout*

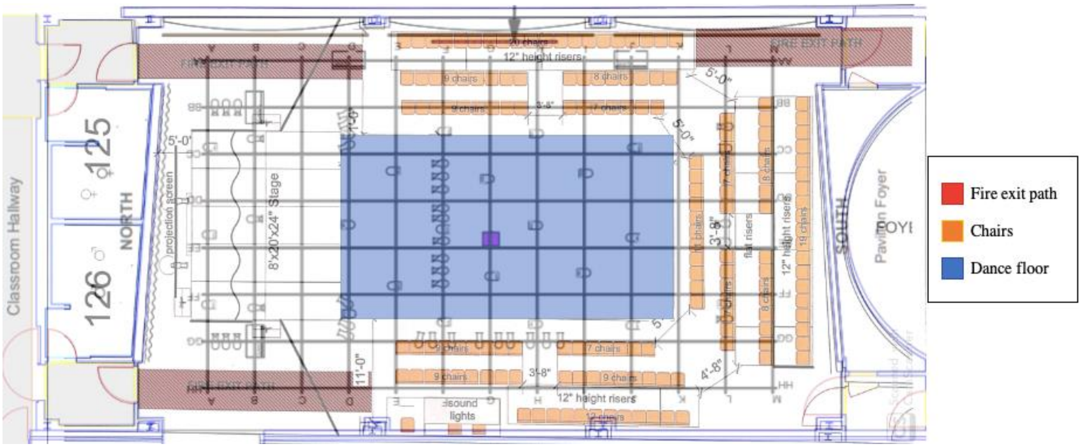


Figure 37. *Floor Plans with Lighting*

5.3 Planet Assembly

The last subsystem of our final design is the planet itself as well as the means of attaching the planet to the pulley system. The planet assembly underwent many alterations since the preliminary design report. The main adjustment was made to the planets themselves. Initially we had planned on using fiber glass resin to coat the outside of beach balls and create a spherical shell that we could use. After creating a prototype using this manufacturing process it became obvious that it was not realistic to create 20 planets using this method. The prototype was created by covering a beach ball with strips of resin-soaked sheets of fiber glass. The sheets were very difficult to position smoothly along a spherical surface. The ball also began deflating during the process. We concluded that it would be better to use pre-existing balls that were durable enough that we could suspend them over the performance. It was also important to keep the cost of the planets down so exercise balls were the perfect option. The material is thick enough that we were not concerned about props popping or melting under the heat of the light. The surface of the material is also very paintable; this was confirmed by a theater technician who had previously created a planet from an exercise ball. The smallest planet would have a diameter of 45 cm, the medium planet would have a diameter of 65 cm, and the largest planet would have a diameter of 85 cm. Each planet would be painted with a unique planetary design.

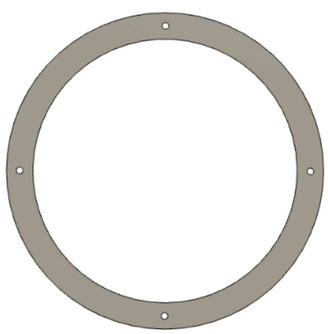


Figure 38. *Ring Base (4” outer diameter)*

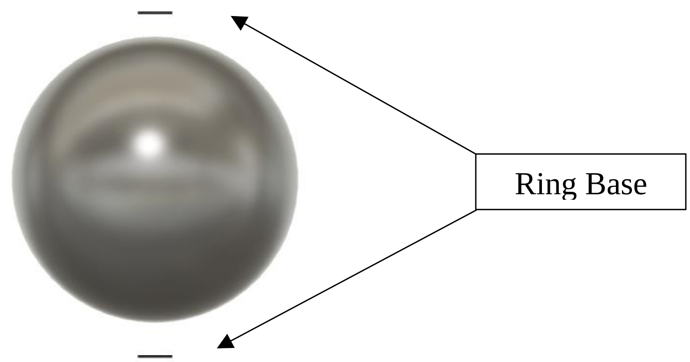


Figure 39. *Planet with Ring Bases*

The next major adjustment made to the design is the means of attaching the planets to the pulley system. To ensure that the planets are locked in place and cannot fall we added reinforcements to our previous design. Instead of simply attaching wire to the top on the planet, we decided to wrap each planet with four lines of fishing wire and attach them to rings placed on the top and bottom of the planet. By attaching the two rings to each other and pulling the wires taught, the planet would be supported and locked in place. One ring is pictured in Figure 38. The fishing line is strong enough to support the ball but thin enough that the audience would not be able to see how the ball is suspended. This is important to give off the impression that the planets would be floating in space. The four additional lines also helped minimize our safety concerns. The exercise balls would be supported using the two-disc system shown in Figure 39. The disc at the bottom of the ball is placed to support the ball and ensure the ball remains upright while suspended from the grid. The top disk held all the fishing line in place and helped attach the planet to the aircraft cable.

5.4 Safety and Maintenance

The planets would be suspended over performers' heads during the live show; accordingly, it was critical that safety concerns regarding the planets and the wind-up rod are minimal. The volume and weight of the exercise balls ensured that no one would be in critical danger. However, it was still crucial that we take every precaution to avoid having a planet fall loose from the grid. The fishing line holding the ring bases together was rated for eighty pounds which was believed to be sufficient, considering the exercise balls weigh under five pounds. Furthermore, the aircraft cable carrying the force of the planet through the pulleys was rated for over 200 lbs. After talking to the theater technicians, we were confident that neither the fishing line nor the aircraft cable were at risk of snapping. The only other safety concern that could result in a planet dropping on a performer was the crimps used to attach the aircraft cable to the planet. Under enough force it was possible for wire to squeeze through the crimp. We addressed this concern by tying knots at the end of the crimp so that there was no chance of the crimp coming undone. Based on our final design and the changes that were made since our preliminary design review, we updated our Design Hazard Checklist and our FMEA. These changes can be seen in Appendix E and Appendix F, respectively.

The maintenance of the wind-up rods was very simple because almost the entire design could be manufactured from wood. The base of the rod was made exclusively from 2x4s and a 2x12 sheet of wood with pillow block bearings bolted in to hold the axis steady. The rod itself was a wooden dowel, as were the discs used to wind the wire up. Wood is a very easy material to work with and easy to replace. If the wood in the base were to snap it would be very simple to unscrew the bolts, detach the broken wood, and screw in a new piece of wood. Similarly, if the dowel or disk were to fracture due to the torque we could easily remove and replace the parts.

5.5 Minor Adjustments to Design from CDR

After our Critical Design Review, we slightly altered the design to make the system more efficient. We added a guide to the top of the wind-up rod to better the alignment of discs to the pulley and ensure that there are no issues as we try to reel in or deploy the planets. Figure 40 shows the addition of the guide.

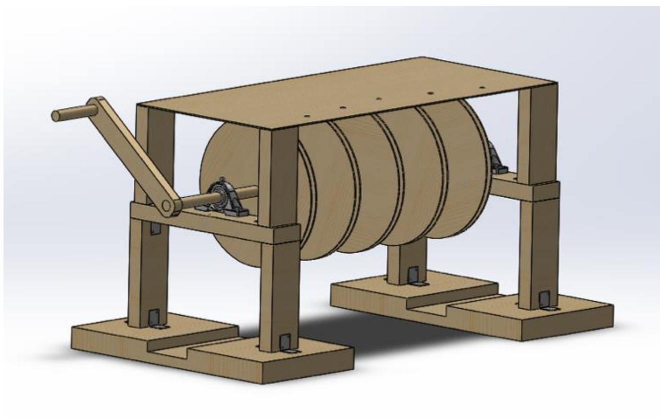


Figure 40. *Full Wind-Up Rod Assembly with Guide*

Another modification to our design was the design of the ring bases. This redesign consisted of increasing the width of the ring to decrease the chance of shear tear-out and creating two different designs for the top and bottom ring. The top ring design now consists of four groups of three holes to make it easier to incrementally tighten the rings against the exercise balls. Figure 41 shows the top ring design as three concentric discs corresponding to each of the three exercise ball sizes. The bottom disc design will stay consistent with the original disc design consisting of four $1/8^{in}$ holes spaced evenly around the disc. This is seen in Figure 42 as three concentric discs.

Figure 41. *Top Ring Disc Redesign*

***Figure 42**. Bottom Ring Redesign*

These CAD drawings will be turned into Adobe Illustrator files to laser cut the discs and utilize the material most efficiently.

6.0 Completed Manufacturing and Testing

Successfully manufacturing and installing our final design would have been the crux of the project. As such, the team chose to build one of the four wind-up rods and one planet as a verification prototype. By doing so, it was possible to get a more realistic picture of the size needs behind the curtain, efficacy of moving the planets by hand crank, and cost to manufacture the entire system. This process was comprised of procurement, manufacturing, and assembly. Though the team will not be able to fully manufacture and install the final design (attaching the final system to the Pavilion grid may only be done by licensed professionals, for example), it was unnecessary to outsource any portion of the prototype's manufacture. By building a full-scale, operational wind-up rod, we confirmed that our team of four could manufacture the entire system within our budget.

6.1 Procurement

The verification prototype is comprised of one wind-up rod, one planet, one planet connection, and two pulleys. Components required to construct these subsystems are listed in the indented Bill of Materials (iBOM) in Appendix G. The iBOM lists the necessary materials to construct the entire final design; to reproduce the prototype, it is unnecessary for any component to purchase more than one quarter of the listed quantity. It should also be noted that as only one planet was used in the prototype, only two 14" disks and one 12" disk are needed to construct the prototype wind-up rod, and one exercise ball is needed to build a planet. In addition, while aircraft cable will be used for the final product, the prototype planet was suspended from fishing wire; as a result, aircraft cable is unnecessary to build the verification prototype. All prototype components can be purchased from the four sources listed in the iBOM: Home Depot, Amazon, McMaster-Carr, and Woodpeckers Crafts. In addition, because of the simplicity of the design and low forces involved, it is relatively unnecessary to obtain parts from the same sources; disks could be cut from standard 4'x8' plywood instead of being purchased from Woodpeckers Crafts, for example.

Heavenly Bodies RSVP Prototype Bill of Materials (BOM)						
Part Number	Description	Qty	Cost	Ttl Cost	Source	More Info
111100	Wood 2x4	1	2.97	2.97	Home Depot	96 inch whitewood
111200	Wood 2x12	1	15.42	15.42	Home Depot	96 inch whitewood
111300	Angle Frame Anchor	12	0.68	8.16	Home Depot	item 23-4509
111400	Screws	1	7.98	7.98	Home Depot	72 Screws
111500	Pillow Block Bearing Set	1	15.75	15.75	Amazon	2 Pillow Blocks
111600	25 1/4-20 Hex Bolt	1	5.92	5.92	McMaster	PN # 92240A552
111700	100 Hex Nut	1	4.24	4.24	McMaster	PN # 91845A029
111800	25 Washer	2	9.60	19.20	McMaster	PN # 91525A416
112100	1in Diameter Wood Rod	1	3.98	3.98	Home Depot	48" long (6416U)
112210	10in Discs	2	5.50	11.00	Woodpeckers	1/2 in
112220	11in Discs	1	6.00	6.00	Woodpeckers	1/2 in
112230	12in Discs	1	5.50	5.50	Woodpeckers	1/2 in
112250	14in Discs	6	2.60	15.60	Woodpeckers	1/8 in
121000	Ring Base	2	0.00	0.00	custom	scrap wood
122000	"Godline" Fishing line	1	13.99	13.99	Amazon	150yd
132000	58-65 cm Exercise Ball	1	21.99	21.99	Amazon	
Total Parts		35		157.70		

Figure 43*: Prototype Simplified Bill of Materials*

6.2 Manufacturing

The only tools required to build the verification prototype are a drill with a ¼" drill bit, a Phillips-head driver bit, a router saw, a band or table saw, a crimping tool, and a pencil or other marking tool. First, the 2”x12” board is cut into 24” long sections, and two 18” long sections are cut from the 2”x4” board; the remainder is cut into 4 equal sections. In each 18” board, two ¼" holes are drilled at a distance of 2” from the center of the board, along its long axis. Then, using a router, a 6”x12”x½" cut is made perpendicular to the board’s long axis; this cut will allow a stage weight to slot into the prototype to ensure it stays in place. The crank handles will be made from 14” long 2”x4” sections with two 1” holes drilled 12” apart. Finally, a 1” circle is cut from the center of each disc and an 1/8” hole is drilled into the 14” discs so wire can be fed through once assembled.

6.3 Assembly

Assembly of the prototype consists of assembly of the support structure, shaft, and planet connection. To begin assembly of the support structure, a short 2”x4” board is secured at a right angle to both ends of each 18” section with drilled holes using screws and angle brackets; only one angle bracket is necessary for each connection. Afterwards, the connected 2”x4” sections are centered on the cut 2”x”12 board, then attached, also with the angle brackets. In this case, an angle bracket is used on each side of each 2”x4” for added stability. It should also be ensured that the router cut is facing the “U” shape made by the 2”x4” boards. Each pillow block is then installed with the ¼" bolts, nuts, and washers on top of the long 2”x4” board using the pre-drilled holes. The disks are slid to the center of the 1” rod, then affixed there using wood glue; the 12” disk is to be placed between the 14” disks. Afterwards, the shaft is fed through the pillow blocks on each support structure, then fixed to their bearings by the set screws inside each pillow block. Figure 44 is an image of the structural prototype with three discs affixed to it.

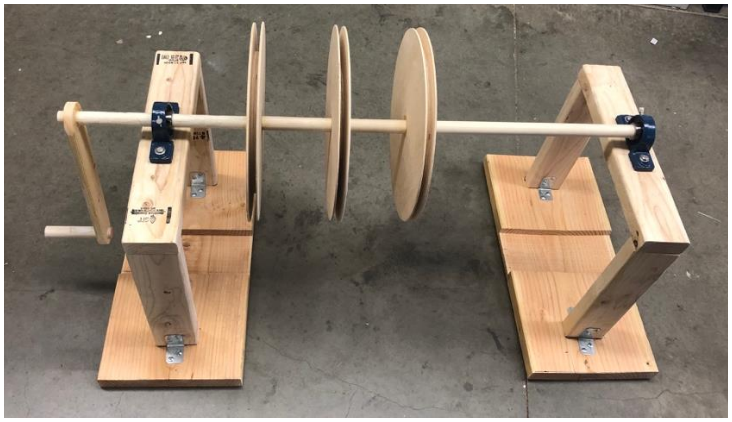


Figure 44. *Structural Prototype*

The planet connection is made by tying fishing wire to the top and bottom ring base at 90° intervals, preventing the exercise ball from falling out of the structure made by the wire, as seen in Figure 45. After the connection is made, the pulleys are attached to the ceiling of the room where the prototype is to be displayed. Note that depending on the circumstances, this can be done in different ways; for example, the pulleys could simply be zip-tied to a portion of the ceiling's support in many rooms. To complete the manufacture of the verification prototype, fishing wire is tied around the 12" disk, ran through both pulleys, and tied off to the planet connection.

Figure 45. *Planet Assembly Prototype*

6.4 Manufacturing Status due to COVID-19

Due to the outbreak of the new Coronavirus, all manufacturing operations for the planetary system built by our team were put on hold indefinitely. The following section will discuss all manufacturing completed as well as the manufacturing that remains unfinished for the Heavenly Bodies senior project.

6.4.1 Completed Manufacturing

Manufacturing successfully completed before the presentation of our critical design review was a fully functioning wind up rod system. This included the base support structure cuts of wood complete and assembled with bolts and pillow block bearings and the shaft glued together with the disks of varying diameter to support three separate planets. These two features were then assembled to create the finished wind up rod. Manufacturing also completed included the creation of the wooden disks used to hold the planet in place while hanging on string. These wooden disks were then assembled onto the planet to hold it while hanging in the air.

Once critical design review came to an end, and the functionality of our system was shown additional manufacturing was completed. This included the laser cutting of wood and acrylic to mass produce the rings to go around the top and bottom of each planet. The updated design of these rings is shown in Appendix J. The manufacturing of all the base support structures was completed for the additional three wind up rods. The pillow block bearings were also installed on each of the support structures.

At the time of the COVID-19 outbreak we had completed the frame for the first wind-up rod. The wind-up rod could functionally raise and lower planets, but we had yet to complete the full design. Our team had completed the cuts necessary to assemble the frames of the three other rods. These cuts included the base of all the wind-up rods as well as the segments of 2x4 required to assemble the frame. We had drilled together both sides of each frame and attached the pillow blocks, but we had yet to insert the rod itself and attach both sides of the frame together.

6.4.2 Incomplete Manufacturing

Although many of the structures were built for our wind-up rod to be functional for the date of the play, there were still steps of manufacturing that were not completed. All shaft assemblies had yet to be completed as well as the creation of the circular disks that would attach to the shaft to allow for varying motion of the planets during operation. As of our last in person meeting as a team, our plan was to use four disks per shaft meaning we would need to glue together a total of 13 more circular disks to complete manufacturing in that area. One of those disks would attach to the already built prototype and the other 12 would be split evenly to attach to a total of three more shafts.

Once this intermediate assembly step was complete the full wind-up rod assembly would be completed by mating the shaft with the disks and placing the shaft into the pillow block bearings. This would be done for each of the remaining wind-up rod assemblies.

An additional piece of manufacturing we were unable to complete was the clue. The clue is an important part of the final design because it helps ensure that the wire coming up from the different spools does not get crossed and tangled during the performance. Building a clue for the wind-up rod would require using a thin cut sheet of plywood and 2x4. The first cut on the plywood sheet would size it to be the same area as the base support structure. Various holes corresponding to the number of disks on the wind-up rod would be drilled to feed wire through them. The next cuts would be to create four smaller pieces of 2x4 capable of attaching the clue to the base support structure of the wind-up rod. These would be attached to the base support with angle frame anchors and to the plywood sheet with a screw through the small end of the 2x4. Once completed the wire can easily feed through the holes and branch off without becoming tangled.

Some simpler manufacturing that still had to be finished was painting the exercise balls to look like planets and fasten the exercise balls between the acrylic and wood rings. This would be done with fishing line by placing one ring on top and the other on the bottom then looping fishing line through the laser cut holes on the rings.

6.5 Testing Status due to COVID-19

Though the team was forced to cease physical work on the project before testing was complete, several important tests clarified issues that needed to be addressed, as well as certified the chosen design. The completed tests were those that pertained to the loading capability and smooth operation of the design. Fortunately, the results are useful regardless of whether the system is incorporated in a theater setting; they will also help those using the Instructable the team created.

The first test the team ran concerned the functional strength of the cable used to suspend the planets. This test was important to the team due to the inherent cost of stronger cable. Because projections indicated the team would need at least 2000 ft of cable, it was critical that the team find a cable that was strong enough to ensure safety, but as inexpensive as possible. To this end, the team mainly tested fishing line; a cable that would be cheap and invisible to the audience. The strength of the cable was tested by connecting it to weights of increasing size, then raising the weights by pulling the cable through a pulley system approximating the theater conditions. This test confirmed that fishing line would not be safe. In all tests, the fishing line underperformed relative to its stated rating. In the most extreme case, line rated for 70lbs failed to raise a 40lb load. This may in part be due to the testing procedure – because the team was considering using static "C" links (similar in form to carabiners) to cut down on cost, the cable was run in part through these links. It is likely that the fishing line did not perform as well as expected due to rubbing on the links.

6.5.1 Testing Plans Prior to COVID-19 Pandemic

As our design continues to develop testing to confirm the overall systems functionality will commence along with testing of subsystems and individual components. This section covers the initial plan for testing laid out by our team, previous testing completed, and information collected from these tests. All planned tests along with specification number can be found in Appendix H.

6.5.2 Preliminary Testing

One of the largest design challenges our group was facing was, how we were going to create our planets. With fear of a ball full of air possibly popping due to the heat put out by the lights, we investigated alternative methods of creating a planet. To make a planet that is very light weight our team tested the use of fiberglass resin along with fiberglass tape to mold a sphere to use as a planet.

In our manufacturing process of this fiberglass sphere, we used an inflatable beach ball to mold the fiberglass resin and tape around. Initially, this seemed like a very feasible idea; however, after testing our idea we found that the beach ball deflated during application of the fiberglass resin and tape over the top of the shell as shown in Figure 46. Other than the deflation of the beach ball, Figure 46 also shows how the fiberglass did not mold very well to the plastic the beach ball was made from. This method also requires the use of the fiberglass resin which was realized to be very toxic when smelled from a close distance, as well as cause us to waste multiple other materials that were coated in the fiberglass resin.

Figure 46. *Deflated Beachball with Fiberglass Tape*

Moving forward, this test taught us that the use of fiberglass resin was not feasible for our project. We believe this method could work; however, the benefit of extremely light planets does not outweigh the struggle it would be to consistently manufacture fiberglass planets.

6.5.3 Planned Testing

Planet weight was to be measured using the weight scale inside of the Bonderson High bay. All planet weights will be individually recorded to verify that estimated values used in hand calculations were an accurate representation of the loading. The goal is to verify all planets weights will be at a maximum five pounds. Planet weight remaining under five pounds will reduce the risk

The operating volume of the system would have been tested by measuring the decibel levels of the system using a phone app. To accomplish this, we will suspend 10 pulleys (the necessary number of pulleys for one wind-up rod and 5 planets) and string wire through each pulley. We will then run the system multiple times in a quiet room and measure the decibel level. The total decibel level for all four wind-up rods needs to be below 40 dB; therefore, if the single wind-up rod produces a decibel level less than 10 dB our system is verified.

The Operating speed test would require all the same materials that are necessary for Specification #5. In this test a timer will be used to record how long it takes to move the planets from the ceiling down to the floor. The current time set to move the planets is five seconds, as this would be enough time for the lights to go on and off in the play and have the planets reappear when the lights come back on. This test will be conducted around twenty times with the full system and data points will be recorded to analyze after.

The planets will experience heat from the stage lights during the performance; therefore, a Heat Resistance test would have been performed. To confirm that the planets would not pop, lights from the stage will be trained on the exercise ball planets. The goal of this test is to ensure the balls will not build excess internal pressure caused by heat and pop during the performance.

7.0 New Project Scope & Results

At the end of the winter quarter of 2020 Cal Poly's campus was closed due to the COVID-19 pandemic. Due to the pandemic and campus closure, Cal Poly's RSVP XXV: Call and Response production was canceled resulting in a shift in our project scope and the deliverables related to our project which is explained in the following sections.

7.1 Altered Problem Statement & Project Scope

Since the production was canceled there is no real need to finish construction of our planet moving system. However, we decided to broaden the scope of our project to extend beyond just Cal Poly's RSVP XXV performance which resulted in the following new problem statement.

Theatre productions may need a way to suspend, store and deploy numerous planetary bodies for a production, as there is currently no system that can raise and lower the bodies. The mechanism designed must be safe, quiet, reliable and can be completed in a timely fashion.

The broadened scope of the project led us to altering our objective from designing and building a fully functioning system, to creating some sort of guide to create the system. The details of this guide are explained in the next section.

7.2 Ideation and Analysis for New Scope

With our major deliverable for this project shifting from a physical system to a step-by-step instruction guide, we underwent some ideation to determine the direction for our instruction guide. While the overall manufacturing of our system is not very complicated, there are numerous steps and pieces to keep track of. As a team we wanted to create something akin to a LEGO Instruction Booklet because it is easy to follow and provides necessary visual cues throughout the process. There are several online platforms that specialize in clear step-by-step guides including WikiHow and Instructables. After looking into both websites, we decided to create our guide on Instructables because it has an easy to use interface and could get our guide out to the most people. Seeing as our design was finalized before the pandemic, there was no additional analysis that needed to be completed.

7.3 Instructables for Future Engineers/Theatre Productions

The Instructable guide is a compilation of our year working on this project and is meant to contain all the necessary information for anyone to create their very own moving solar system. All potential issues and safety requirements for proper use of the planet moving system will be articulated throughout the Instructable guide. This document can be found on Instructables.com and searching "Planet Prop Suspension System." In addition, the full Instructable document can be found in Appendix K.

8.0 Project Management

In order to ensure we complete this project in a timely manner and by the day of load-in we have planned out our analysis and design process up to the completion of this project, which is detailed in the following sections.

8.1 The Design Process

We initially set out to understand the problem that we would be facing and explore ideas that have solved similar issues in the past. We worked to define our customers and better understand the parameters that will be involved in our design, by interviewing potential customers and specifying requirements that must be met. The process we went through is a QFD which gives a structured approach to keeping your customers best interests in mind when designing, for results from this process refer to Appendix A. As we moved forward as a team, we brainstormed ideas and explored which one is the best option to solve our problem using past research. This consisted of concept model generation, prototyping and computer aided drafting (CAD). We presented our chosen idea at Preliminary Design Review and proceeded to construct a well generated structural prototype. The functionality of the prototype was displayed at the Critical Design Review. All feedback from the CDR will be taken into account as we move forward with the manufacturing, assembly, and testing of our design. At this point we will have a fully finished product ready to present in Final Design Review. Major deliverables will be found in Table 10. A projected timeline of all milestones and achievements within the project can be viewed in Appendix K.

Table 10. Intended Design Deliverables and Due Dates

Deliverables	Due Date
Concept Model Generation	10/28/19
Concept Prototype	11/14/19
Preliminary Design Review	11/15/19
Interim Design Review	1/16/19
Structural Prototype	1/31/19
Critical Design Review	2/4/19
Manufacturing & Test Review	3/12/19
System Ready for Theatre Performance	5/17/19
Final Design Review and EXPO	5/29/19

8.2 Plan up to Critical Design Review

To prepare for the Critical Design Review (CDR) we designed the final system and generated a plan for its manufacture. To begin, the team completed a Failure Modes and Effects Analysis (FMEA) to clarify the purpose of each subsystem of the overall design, how they can fail, and what the failure of a subsystem will cause. We then began designing the final system with these considerations in mind. Next, the team used a Design for Manufacturability Analysis (DFMA) to ensure that the system is designed in such a way that it can be manufactured and installed at minimal expense. With these tools, the team began detailed analysis of the system, paying attention to the calculations regarding rotation, pulley forces, stress distributions, and dynamic loading. These calculations informed us of the material and dimensions needed for each component of the system. After these analyses were completed, a detailed, final model of the system was constructed using CAD software; the model reflected the actual parts to be used as much as possible and demonstrated the functionality of the system. At the same time, the team generated a list of parts required to manufacture the project, found sources for the parts, and calculated the projected cost to construct the project. This work was used to create the CDR report, which shows the finalized budget and request the funds needed to begin manufacturing the project. For full details of this timeline reference Appendix K.

8.3 Plan Up to Final Design Review

As our project continues to develop, we look forward into the future at what is to come and the plan that we have as a team moving forward. With the CDR presentation finishing up on 2/6/20, our final design will be locked in place unless a major design flaw is found during construction. After constructing our structural prototype and demonstrating its function at CDR, we are confident that our current designs mechanics will work. With this said, problems may still arise logistically, such as pulley placement on the grid in the pavilion as to avoid interference with lighting set up. In the next few weeks, we will be reaching out to Tim, Tom and Clint the technicians in the theatre to inquire about the placement of lights in order to solidify our pulley placement.

Our next step is to reach out to Dr. Barata once more to confirm the funding he will be giving us for the rest of the project. Once this is done, we will work out the cost of paint and labor costs for our design. When all financial concerns are in order, we will begin to order the rest of our parts from the iBOM to construct the remainder of wind up rods. Once parts are received, the manufacturing process that was used to create our structural prototype will be used to develop three more wind up rods. We will be making a template to laser cut wood for our system to hold our planets in the next coming weeks as well. At the end of the quarter our Manufacturing and Test Plan will be reviewed to confirm that they are in fact completed and reasonable to complete.

Once the entire mechanical system has been assembled, the painting of the planets will begin. As the full system with all four wind up rods gets closer to being constructed, we will test the specifications we laid out in Appendix H until we can finally test specifications that rely on the final system to be built. These full system test will be occurring around the first two weeks of spring quarter. The full system will be complete and ready to go by the 17^{th} of May followed by EXPO on May 29^{th} and our Final Design Report on June 4^{th}. This is a brief look forward at what our team will be achieving in the coming months a more detailed look at the plan see Appendix K.

8.4 Plan Changes due to COVID-19

Due to our project objective changing because of Corona Virus, the play that this project was designed for did not happen and new deliverables were assessed. Moving forward the entire manufacturing and testing of the system will come to a stop as access to the machine shop in which we build is now closed. To compensate for this all current progress will be documented in the other sections of this report and on the website www.instructables.com. The mission on this page is to describe the general process of making a wind-up rod system to raise and lower any item of choosing. In addition to this, a virtual expo to showcase our current progress and progress made during our virtual spring quarter will still happen on the same date as planned.

8.5 Remaining Issues

Although many of our ideas were set in stone moving forward, some decisions were unmade and still needed further solidification. For example, during initial testing of our system with a very heavy object, the string we were using was much too thin. A much thicker diameter string, although more visible would most likely need to be used during actual production to ensure audience safety.

Another issue that was found during initial testing was the mechanism designed to hold the planets in place once the planets were deployed. The system we designed was a pin that would go through the rod and mount inside of the base support. This idea although easy to implement proved to be an ineffective way to hold the planets. The rotational moment experienced by the shaft was enough to bend the pin that we used to hold the planets. This would be unsafe and a redesign for that issue would be needed moving forward. In addition, the choice to use pulleys was still up in the air as we were unsure if pulleys or carabiners would provide less friction and easier use for the system.

Most of the problems addressed above pertained to the operation of the system; however, there were many other logistical concerns in the way leading up to the performance. Some of the minor concerns for our system was moving it over to the Performing Arts Center on the opposite end of our college campus. This issue could be easily resolved by moving the system in stages inside of a car. The biggest logistical concern however was the setting up of the system inside of the black box theater in the PAC Pavilion. Inside of the theater was a grid in which all the pulleys or carabiners would hang from with the aircraft cable running through them and down to the wind-up rod behind the curtain.

The major issue for our team and the theater technicians with this was finding a way to align the pulleys and aircraft cable in the already messily set up grid. The grid contains lights and other fixtures that prevent sending straight lines of cable from the front of the grid to the back. This makes for an immense challenge setting up the locations of where the planets will drop from and where we set the wind-up rods. Initially glancing at the grid, showed a few obvious paths for the line to run. On the downside, it was very difficult to find multiple paths that would allow for good placement of the planets. This challenge is very difficult but also causes financial issues as it does not give us a set number of pulleys or carabiners to buy.

These issues although all pressing would have been assessed and dealt with by show day.

9.0 Conclusions & Recommendations

The information contained in this document detailed the steps taken to create the Heavenly Bodies that were intended to appear in Cal Poly Music's RSVP production during the spring quarter of 2020. Through our analysis, we determined our top design focus needed to be making the bodies lightweight, fire retardant and hidden while in use. Our chosen design featured a rotating shaft of varying diameter to lower the planets to different heights. This design would have been powered by a hand crank, use pulleys to guide the planets, and employ a loop connection to attach the planets to the system. After completion of the initial design, our work over the past few months would have ensured completion of a system that would have been functional by May 17th. Due to the pandemic caused by COVID-19, the RSVP production was canceled, and our project became obsolete. This resulted in a broadening of our project scope and the creation of an Instructable guide so that anyone can create a planet suspension system. Our guide can be found in Appendix L or through Instructables.com by searching "Planet Prop Suspension System". This guide is intended to be a step-by-step walkthrough in creating the system designed for the RSVP production, but still allows for different uses and different space requirements. Overall, the RSVP Heavenly Bodies project focused a lot on creativity and project management. For future engineers, it is important to keep the larger picture in mind while creating a system of this size and magnitude.

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Appendix A: QFD: House of Quality

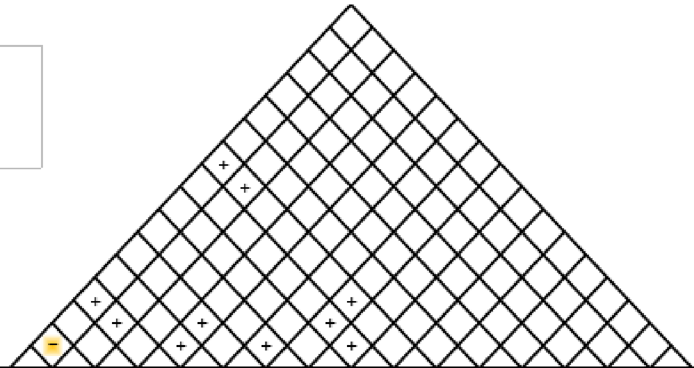
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: 42. PROJECT ATLAS (Heavenly Bodies RSVP)
Revision Date: 10/14/2019



Row #	Weight Chart	Relative Weight	Dr. Barata	Technicians/Operators	Actors	Audience	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	1 Overall weight	2 Planet Weight	3 Sound test	4 Cost	5 heat resistant	6 Surface Profile	7 Visual Test	8 Works Everytime	9 No collisions	10 Lowering Speed	11	12	13	14	15	16	Exercise Pulley Machine	Pulley (Snatch Block 9 ton)	Phantom of Opera Chandelier	Crane	Hydraulic scenery Raiser	Row #
	WHO: Customers							Direction of Improvement	▼	▼	▼	◇	▲	◇	▲	◇	◇	◇							NOW: Curr. Products					
1		13%	8	10	9	6	10	Safe	○	○			●				○								5	5	5	4	4	1
2		10%	7	3	6	9	10	Quiet			●							▽							4	4	5	1	4	2
3		14%	9	10	8	10	10	Reliable					▽			●	▽								4	4	5	4	3	3
4		7%	5	8	3	1	10	Lightweight	●	●															2	5	1	1	2	4
5		4%	8	3	1	1	10	Low Cost				●		▽											2	5	1	1	3	5
6		11%	7	9	7	4	10	Fire Retardent					●												5	5	5	5	5	6
7		11%	9	3	8	9	10	Aesthetic						○	●										2	2	5	1	2	7
8		9%	9	2	7	7	10	Spherical				▽		●											1	1	1	1	1	8
9		8%	7	3	3	9	10	Hidden							●		○								1	1	3	1	5	9
10		8%	10	7	3	2	10	Moves Vertically	▽	▽						○	●								5	5	4	5	5	10
11		5%	8	1	1	5	10	Smooth Movement									●	●												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	<= 50lb	< 1lb	< 35dB	< $3000	> 150 deg F	surface test	Visual survey	Pass 15 test runs	No collisions 9/10 runs	7 < x < 9 ft/s						
Max Relationship	9	9	9	9	9	9	9	9	9	9						
Technical Importance Rating	105.8	105.8	85.79	49.06	225.6	121.4	172.7	153.2	195.9	55.91	0	0	0	0	0	0
Relative Weight	8%	8%	7%	4%	18%	10%	14%	12%	15%	4%	0%	0%	0%	0%	0%	0%
Curr. Products: Exercise Pulley Machine	3	2	3	2	5	2	2	5	4	3						
Pulley (Snatch Block 9 ton)	3	5	5	5	5	3	2	5	4	3						
Phantom of Opera Chandelier	3	3	4	1	5	4	5	5	5	1						
Crane	1	1	1	1	5	2	1	5	5	2						
Hydraulic scenery Raiser	4	3	4	3	5	3	2	5	4	4						
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B: Ideation and Decision Phase

To begin the ideation process, the team broke down the function of the system to be designed into three crucial parts: providing a force to move the planets, controlling the planet's movement, and ensuring the mechanism is silent. Then the team generated the following ideas for each purpose:

Table 11. Ideas for moving the planets

Moving the planets:	
• Wind string holding the planets around a rotating pipe • Connect the planets to levers • Display the planets as holographs; move the projected planets • use a counterweight to offset the weight of the planets • Attach bungee cords to planets, then release them and let them drop due to gravity • Use a bicycle to generate torque to raise and lower planets • Use hydraulic pistons to move planets • Use pneumatic pistons to move planets • Use a gas engine to pull ropes attached to planets • Use an electric motor to pull ropes attached to planets	• Use a 'marionette' system to maneuver the planets • Use spring power to store energy to move the planets • Incorporate a gear train into the system to move all planets at once • Use a pulley system to pull the planets up and down • place fans underneath the planets to blow them up or down • Use a ratchet system to hold the planets at a fixed position • Use cam shafts to change rotation from a power source to linear motion in the planets • Use magnetic force to keep the planets attached to the grid

Table 12. Ideas for controlling planetary movement

Controlling planetary movement:	
• Several stagehands memorize queues and lower planets by hand • Use a table of levers and switches to control motors • Control motors wirelessly via electronic signaling • Sync the planets' movements to music for easy descent/ascent queues • Mark the planets' movements on the script, and use it as a guide during performance • Sync descent/ascent to timers which will indicate when to rise/fall	• Group planets together for simpler control • Use several motors, and control them independently to move planets accordingly • Use springs of differing stiffness to control how far the planets can ascend/descend • Hire professionals to control when the planets move • Give the actors or stage director an actuator button to control when the planets move • Use gear trains to control all plants simultaneously from a single motor

Table 13. Ideas for making a quiet system

Making a quiet system:	
• Use a white noise machine to mask the sound of the system • Build a soundproof case for motors or other loud components • "Silent Disco" performance – audience members wear headphones which block out outside noise, but allow them to hear performers wearing microphones • Minimize the number of motors or other loud components used • Only use components which produce a manageable noise level • Ensure any pulleys have minimal friction to cut down on squeaking noise • Project the planets as holograms – no noise will be produced	• Use helical gears instead of spur gears • Use high-quality ball bearings wherever possible to reduce squeaking • Generate an anti-noise signal to cancel out the noise generated • Heavily lubricate all moving parts • Use minimal machinery and as few moving parts as possible • Keep planets lightweight to cut down on noise from pulleys or motors • Only use the system while other loud noises are present, like music

Appendix C: Decision Matrices

C.1 Pugh Matrices

Below are the Pugh Matrices that the team used to compare ideas for solving similar problems. For example, Figure 31 uses the idea of connecting the planets to the system via hooks as a baseline, then uses several criteria to compare the utility of other connection ideas.

Pugh Matrix - *A Decision Matrix*

:Problem/Situation CONNECTING THE SYSTEM TO THE SPHERES

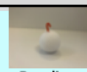
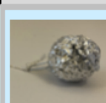
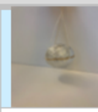
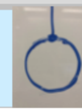
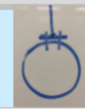
	Criteria	 Baseline (Hook)	Alternatives 1 	2 	3 	4 	5	Totals	Rank
1	LIGHTWEIGHT	0	0	−	+	−		-1	8
2	AESTHETICS	0	0	−	+	0		0	6
3	FIRE RETARDENT	0	0	0	0	+		1	2
4	RELIABILITY	0	+	+	0	+		3	1
5	COST	0	0	−	−	−		-3	9
6	MANUFACTURABILITY	0	+	−	+	−		0	7
7								0	
8								0	
9								0	
		Totals	2	-3	2	-1			
		Rank	1	4	2	3			

Figure 47. *Pugh matrix determining the connection between the spheres and system*

Pugh Matrix - *A Decision Matrix*

:Problem/Situation PICKING THE PLANET MATERIALS

	Criteria	Baseline (Styrofoam Ball)	Alternatives 1 PLASTIC SHELL	2 HOLLOWED OUT STYROFOAM	3 WIRE FRAME	4 INFLATABLE	5 CROSS PLATES	Totals	Rank
1	LIGHTWEIGHT	0	+	+	+	+	−	3	2
2	AESTHETICS	0	+	−	−	0	−	-2	9
3	FIRE RETARDENT	0	−	0	+	−	0	-1	7
4	RELIABILITY	0	−	−	+	−	+	-1	8
5	COST	0	+	0	+	+	+	4	1
6	MANUFACTURABILITY	0	0	−	+	+	+	2	3
7								0	
8								0	
9								0	
		Totals	1	-2	4	1	1		
		Rank	2	5	1	2	2		

Figure 48. *Pugh matrix used to determine planet material.*

Pugh Matrix - *A Decision Matrix*

:Problem/Situation MOVING THE SPHERES

	Criteria	Baseline (Pulley + Rope)	Alternatives 1: TEETER TOTTER	2: MARIONETTE	3: WIND-UP ROD	4: LEVERS WITH ATTACHED PLANETS	5	Totals	Rank
1	LIGHTWEIGHT	0	–	–	–	–		-4	8
2	ATTACHABILITY	0	–	–	–	–		-4	8
3	FIRE RETARDENT	0	0	0	0	+		1	1
4	RELIABILITY/STURDY	0	0	–	+	–		-1	5
5	COST	0	–	+	0	–		-1	5
6	MANUFACTURABILITY	0	–	–	+	+		0	3
7	SILENT	0	0	0	–	–		-2	7
8	FLEXIBILITY	0	–	–	+	+		0	3
9								0	
		Totals	-5	-4	0	-2			
		Rank	4	3	1	2			

Figure 49. *Pugh matrix used to determine the mechanism for raising and lowering the spheres.*

Pugh Matrix - *A Decision Matrix*

:Problem/Situation PROPULSION METHOD

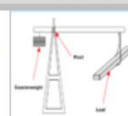
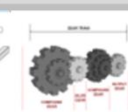
	Criteria		Alternatives 1: 	2: 	3: 	4: 	5	Totals	Rank
1	CONSISTENCY	0	–	0	–	0		-2	7
2	FIRE RETARDANT	0	+	0	+	0		2	1
3	POWER	0	–	–	–	0		-3	8
4	SILENT/UNNOTICABLE	0	+	–	+	0		1	2
5	COST	0	+	+	0	–		1	2
6	MANUFACTURABILITY	0	0	–	–	–		-3	8
7								0	
8								0	
9								0	
		Totals	1	-2	-1	-2			
		Rank	1	4	2	3			

Figure 50. *Pugh matrix used to determine methods of propulsion for the planets.*

C.2 Weighted Decision Matrix

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8	Criteria 9	Criteria 10	
CRITERIA DESCRIPTION	SAFE	QUIET	RELIABLE	LIGHTWEIGHT	LOW COST	FIRE RETARDENT	FEASIBILITY	HIDDEN	SMOOTH MOVEMENT/ FUNCTION	LOW RISK	
	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8	Criteria 9	Criteria 10	WEIGHTED SCORE
WEIGHT	5	5	5	2	4	5	4	3	4	5	42
	12%	12%	12%	5%	10%	12%	10%	7%	10%	12%	88%
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	Criteria 5 SCORES	Criteria 6 SCORES	Criteria 7 SCORES	Criteria 8 SCORES	Criteria 10 SCORES	Criteria 9 SCORES	
Wire Frame Planet - Looped - Wind Up Rod - Motor	5	3	5	3	2	4	3	4	5	5	168
Plastic Shell Planet - Bolts - Lever - Gear Train	4	3	3	3	3	4	2	2	3	5	139
Plastic Shell Planet - Loop - Wind Up Rod - Manual	5	4	4	3	4	4	4	4	2	4	163
Wire Frame Planet - Adhesive - Lever - Motor	4	3	4	2	3	3	2	2	3	5	137
Plastic Shell - Adhesive - Pulley - Motor	5	3	4	4	3	3	2	3	3	5	149
Cross Plate - Loop - Wind Up Rod - Manual	5	3	4	3	2	4	3	4	3	5	155
DMX Winch System	5	4	5	4	1	5	4	5	5	1	163

Appendix D: Hand Calculations

These hand calculations represent the analysis preformed to valid our theory that utilizing different diameter disks will drop the planets to different heights at the same rate.

VARIABLE RADIUS CALCULATION

MOTOR: 30 HZ

Planet 1 Drop Distance: 5 meters

Planet 2 Drop Distance: 7 meters

Planet 3 Drop Distance: 9 meters

Planet 4 Drop Distance: 10 meters

Drop Time: 3 seconds

Radius Calculation

- $(30 \text{ cycles}/s)(3 \text{ seconds}) = 90 \text{ cycles}$

Planet 1: 5 meters/90 cycles = $0.0\overline{555}$ meters circumference

Planet 2: 7 meters/90 cycles = $0.0\overline{777}$ meters circumference

Planet 3: 9 meters/90 cycles = 0.1 meter circumference

Planet 4: 10 meters/90 cycles = $0.\overline{111}$ meter circumference

↳ $C = 2\pi r \rightarrow r = C/2\pi$

Planet 1 Radius: 0.884 cm

Planet 2 Radius: 1.238 cm

Planet 3 Radius: 1.592 cm

Planet 4 Radius: 1.768 cm

Appendix E: Design Hazard Checklist

Below is the checklist the team used to determine whether the current iteration of the design would create any unnecessarily hazardous conditions. In addition, for any hazards that have been identified, the team created a potential solution to mitigate that risk, as well as when that solution could be implemented.

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

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Though it will be spun at low speeds, the wind-up rod has pinch points where the wire connects to the rod.	Design the rod such that people cannot reach the pinch points; operate at low enough speeds that pinching is not a particularly dangerous hazard.	5/16/2020	N/A (Due to COVID-19)
If cables/connections fail, planets could fall on the audience or cast.	Ensure the strength of the cable reflects a high factor of safety when choosing material and test the strength of any connections to ensure their reliability.	2/13/2020	2/20/2020
If stagehands lose control of the wind-up rods, planets will drop as far as they can, possibly harming any underneath/the stagehands.	Design the hand crank to be as light and small as possible, in case a person is struck by it. Only allow the planets to descend to a safe distance.	5/16/2020	N/A (Due to COVID-19)
Stagehands may have to use an unreasonable amount of strength to move the planets upward.	Ensure that planets are not too heavy, and the wind-up rod cranks are long enough that minimal torque is required to move the planets.	5/16/2020	2/28/2020

Design Failure Mode and Effects Analysis

Product: ______________________________ Prepared by: ______________________________

Team: ______________________________

Appendix F: Design Failure Mode and Effects Analysis

Date: ________________ (orig)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality	Action Results: RPN
Wind Up Rod / Convert Motor Torque to Tension in Wire	Rod Breaks	a) wires become slack and planets fall b) no planets for the produciton c) Barata is dissatisfied	8 7 5	1) Heavy Item is Dropped on Rod 2) Tension of chords yields bar	1) Move All Heavy Items Awayy from Rod during operation 2) Calculate Loads Bar will experience add factor of safety	1	Hang weights on the rod and spin it at performance speed to ensure it will not break	2	16 14 10							
	Item gets stuck inside	a) rod won't rotate b) injure someone	9 9	1) Items are left too close to shaft during operation 2) People other than operators are allowed too close to shaft	1) Move all items away from bar 2) Label Shaft with warning label 3) Encase Mechanism in container	2	Run the system and see if anything gets stuck	3	54 54							
	Diameters do not drop planets to various heights	planets do not have the desired impact	3	1) calculations were inccorect 2) the shaft wasn't made correctly 3)	1) Double check calculations	1	Diameter Meaasurement Test	2	6							
Pulley System / Guides Wire Quietly	Squeaky	a) distracts from show b) Barata is dissatisfied c)	6 5	1) pulleys are low quality 2) wire and pulley wheel material interfere 3)	1) Buy good quality pulleys 2) Calculate for interference	3	Measure noise made by spinning pulleys in a quiet room	1	18 15							
	Pulley Snaps off Grid	a) the planet does not go to correct spot b) planets drop	6	1) pulleys are not safely attached to grid	1) Calculate Load on pulley	2	Load Test of Pulley	3	36							
Carabiner / Connect Wire to Planet	Snaps	a) planets fall b) injure audience or actor c)	8 9	1) connection loop detaches from planet 2) carabiner breaks 3) wire snaps	1) Calculate Load on carabiner	2	Load Test of carabiner	3	48 54							
	Too Visible	a) distracts from show b) Barata is dissatisfied c) there is no surprise or wonder	5 6 5	1) the carabiner is very large 2) carabiner is reflective	1) Pick low visble caribener 2) Use tie that is non-colored 3) Cover carabiner up	5	Visual inspection by cast of production	3	75 90 75							
Planets / Look Aesthetic	Look Bad	a) Audience is dissatisfied b) Barata is dissatisfied	5 5	1) the paint destorts under the heat of the lights 2) the planets are too reflective or not reflective enough 3) Planets were poorly painted/ not creatively made	1) Spray with fire retardent material 2) Be very creative when desiging planets	3	Visual Inspection by cast of play	2	30 30							
	Planet Deforms	a) audience doesn't think they are planets b) Barata is dissatisfied	6 5	1) planet can't withstand heat of lights	1) test planet materials with stage lights	4	Compare to spherical shape	2	48 40							

Appendix G: Indented Bill of Materials (iBOM)

Assembly Level	Part Number	Description					Qty	Cost	Ttl Cost	Source	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	Final Assy								------	
1	110000		Wind Up Rod							------	
2	111000			Support Structure						------	
3	111100				wood 2x4		4	2.97	11.88	Home Depot	96 inch whitewood
3	111200				wood 2x12		2	15.42	30.84	Home Depot	96 inch whitewood
3	111300				Angle Frame Anchor		48	0.68	32.64	Home Depot	item 23-4509
3	111400				Screws		1	7.98	7.98	Home Depot	72 Screws
3	111500				Pillow Block Bearing		4	15.75	63.00	Amazon	2 Pillow Blocks
3	111600				25 1/4-20 Hex Bolt		1	5.92	5.92	McMaster	PN # 92240A552
3	111700				50 Hex Nut		1	2.27	2.27	McMaster	PN # 92673A113
3	111800				25 Washer		2	9.60	19.20	McMaster	PN # 91525A416
2	112000			Shaft						------	
3	112100				1in Diameter wood rod		4	3.98	15.92	Home Depot	48" long (6416U)
3	112200				Discs					------	
4	112210					10in Discs	5	5.50	27.50	Woodpeckers	1/2 in
4	112220					11in Discs	5	6.00	30.00	Woodpeckers	1/2 in
4	112230					12in Discs	5	5.50	27.50	Woodpeckers	1/2 in
4	112240					13in Discs	5	5.50	27.50	Woodpeckers	1/2 in
2	112250					14in Discs	40	2.60	104.00	Woodpeckers	1/8 in
1	120000		Planet Connection							------	
2	121000			Ring Base			40		0.00	custom	scrap wood
2	122000			"Godline" Fishing line			2	13.99	27.98	Amazon	150yd
2	123000			1/16th aircraft cable			2	145.00	290.00	RoseBrand	1000 ft spool
1	130000		Planets							------	
2	131000			38-45 cm Exercise Ball			5	16.99	84.95	Amazon	
2	132000			58-65 cm Exercise Ball			9	21.99	197.91	Amazon	
2	133000			78-85 cm Exercise Ball			5	23.99	119.95	Amazon	
1	140000		Pulleys							------	
2	141000			1 groove			20	8.12	162.40	McMaster	w/ bearing (3742T56)
2	142000			2 groove			10	16.08	160.80	McMaster	w/o bearing (3099T23)
1	150000		Crimps & tool				1	18.99	18.99	Amazon	Glarks 180Pcs 1.2/1.5/2mm
	Total Parts						**190**		**1469.13**		

Appendix H: Design Verification Process

Senior Project DVP&R

Date: 2/3/2020	Team: RSVP Heavenly Bodies/Project Atlas	Sponsor: Dr. Antonio Barata	Description of System: Pulley System Operated manually which will suspend planets, allowing them to be moved vertically up and down by translating rotational motion into translational motion.	DVP&R Engineer: Justin Spitzer & Allison Turnbaugh

TEST PLAN										TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	3	Individual Planet Weight	5lb Max	Justin	CP	10	C	2/24/2020	2/28/2020	N/A	N/A	N/A	
2	4	Operating Volume	35dB ± 5 dB	Jack	FP	1	Sys	4/6/2020	4/10/2020	N/A	N/A	N/A	
3	5	Operating Speed	8ft/s ± 1.5ft/s	Allison	FP	1	Sys	4/6/2020	4/10/2020	N/A	N/A	N/A	
4	6	Heat Resistance	150 °F Min	Braden	CP	10	C	2/24/2020	2/28/2020	N/A	N/A	N/A	
5													
6													
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Appendix I: Purchased Parts

"2 in. x 4 in. x 96 in. Premium Kiln-Dried Whitewood Stud" *Home Depot,* https://www.homedepot.com/p/2-in-x-4-in-x-96-in-Premium-Kiln-Dried-Whitewood-Stud-161640/202091220
"2 in. x 12 in. x 8 ft. Premium #2 and Better Douglas Fir Lumber" *Home Depot,* https://www.homedepot.com/p/2-in-x-12-in-x-8-ft-Premium-2-and-Better-Douglas-Fir-Lumber-707195/202094201
"ZMAX 18-Gauge Galvanized Steel Angle" *Home Depot* https://www.homedepot.com/p/Simpson-Strong-Tie-ZMAX-18-Gauge-Galvanized-Steel-Angle-A21Z/100375047
"2-1/2 in. Construction Screw (1 lb.-Box)" *Home Depot* https://www.homedepot.com/p/Grip-Rite-2-1-2-in-Construction-Screw-1-lb-Box-212GCS1/207200494
"Jeremywell 2 Pieces UCP205-16, 1 Inch Pillow Block Bearing, Solid Base, Self-Alignment, Brand New" *Amazon,* https://www.amazon.com/Jeremywell-Pieces-UCP205-16-Bearing-Self-Alignment/dp/B01IWGLPF2/ref=sr_1_4?keywords=pillow+block+bearing+jeremywell&qid=1581100975&s=industrial&sr=1-4
"18-8 Stainless Steel Hex Head Screw, 1/4"-20 Thread Size, 2-1/2" Long, Fully Threaded" *McMaster-Carr,* https://www.mcmaster.com/92240a552
"18-8 Stainless Steel Hex Nut, 1/4"-20 Thread Size, ASTM F594" *Mcmaster-Carr,* https://www.mcmaster.com/92673A113
"316 Stainless Steel Washer, Oversized, 1/4" Screw Size, 0.281" ID, 0.75" OD" *Mcmaster-Carr,* https://www.mcmaster.com/91525A416
"6416U 1 in. x 1 in. x 48 in. Hardwood Round Dowel" *Home Depot,* https://www.homedepot.com/p/6416U-1-in-x-1-in-x-48-in-Hardwood-Round-Dowel-10001808/203334068
"10" Circle Wooden Cutout, 1/2" Thick" *Woodpeckers Crafts,* https://woodpeckerscrafts.com/10-circle-wooden-cutout-1-4-thick/
"12" Circle Wooden Cutout, 1/2" Thick" *Woodpeckers Crafts,* https://woodpeckerscrafts.com/12-circle-wooden-cutout-1-4-thick/
"13" Circle Wooden Cutout, 1/2" Thick" *Woodpeckers Crafts,* https://woodpeckerscrafts.com/13-circle-wooden-cutout-1-4-thick/
"14" Circle Wooden Cutout, 1/2" Thick" *Woodpeckers Crafts,* https://woodpeckerscrafts.com/14-circle-wooden-cutout-1-4-thick/
"FISHINGSIR GODLINE Braided Fishing Line - Super Power Braid Lines - Abrasion Resistant Superline, 150-1094 Yds, 8-120LB" *Amazon*, https://www.amazon.com/FISHINGSIR-GODLINE-Braided-Fishing-Line/dp/B075VP4ZGL
"URBNFit Exercise Ball (Multiple Sizes) for Fitness, Stability, Balance & Yoga - Workout Guide & Quick Pump Included - Anti Burst Professional Quality Design" *Amazon,* https://www.amazon.com/URBNFit-Exercise-Ball-Stability-Yoga/dp/B010MVAMH2/

Appendix J: Full Drawing Package

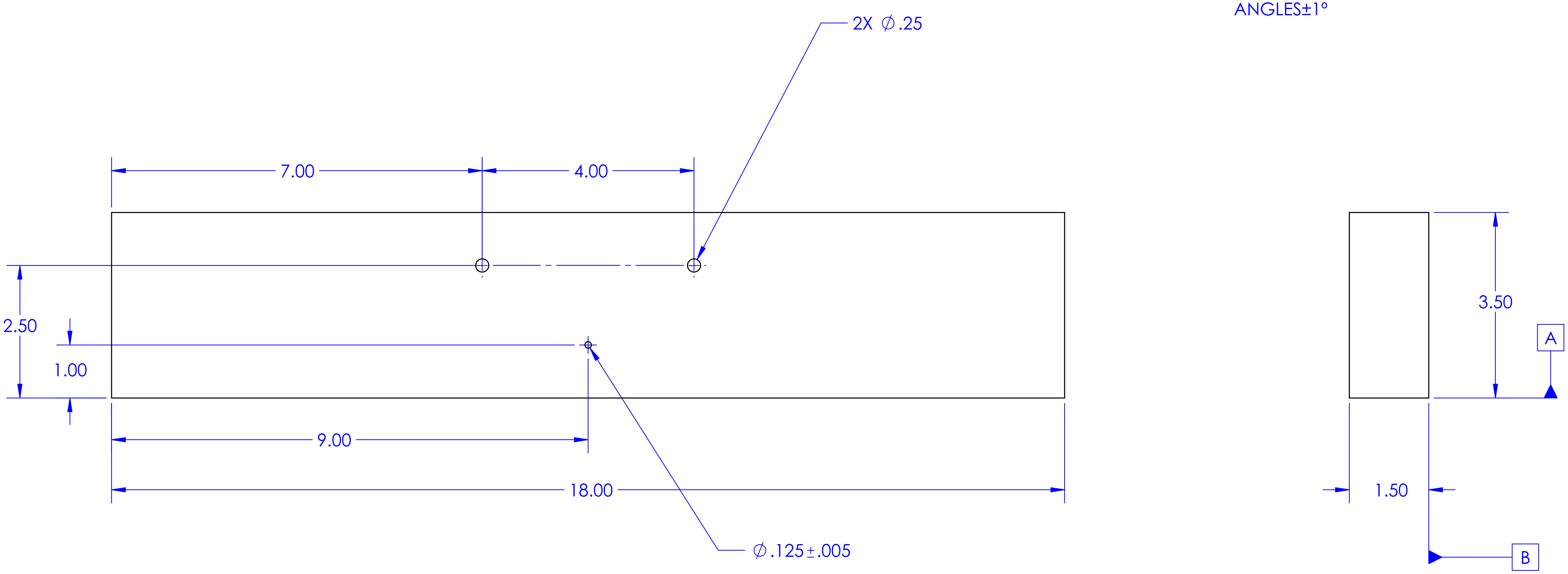
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 111110	Title: LOWER LEG	Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 1	Nxt Asb:	Date: 6/4/2020 / Scale: 1:2	Chkd. By: ME STAFF

UNLESS OTHERWISE SPECIFIED:

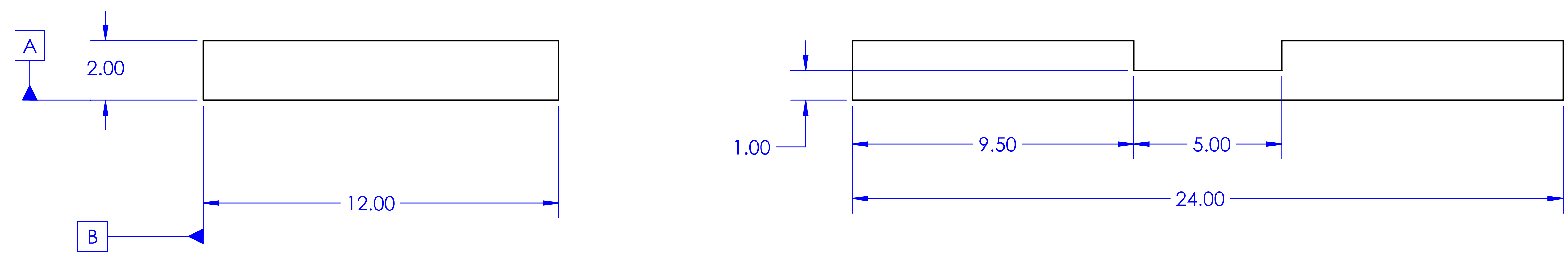
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



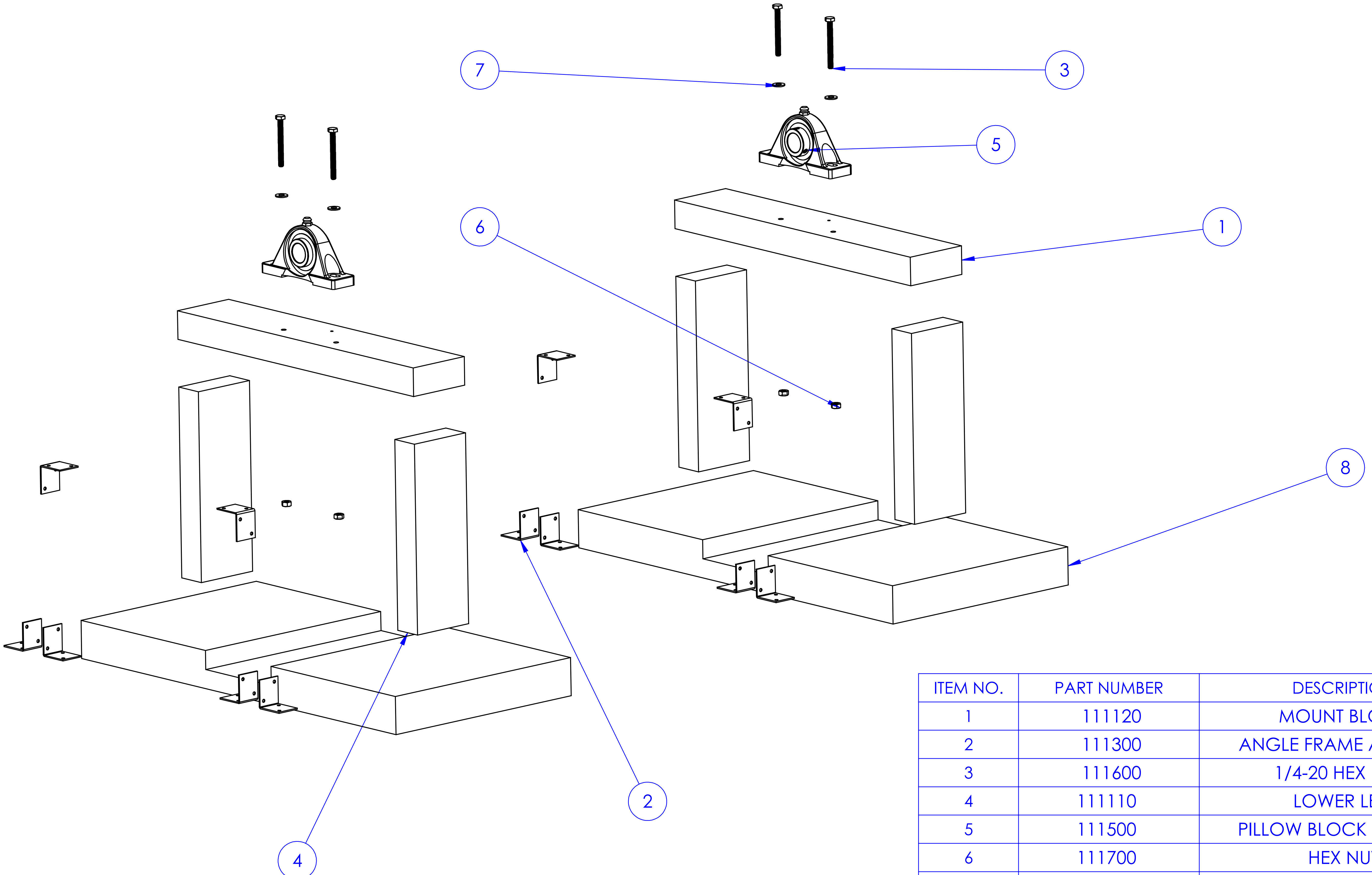
Cal Poly Mechanical Engineering	Lab Section: 03	PN # 111120	Title: MOUNT BLOCK		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 2	Nxt Asb:	Date: 6/4/2020	Scale: 1:2	Chkd. By: ME STAFF

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section: 03	PN# 111210	Title: BASE		Drwn. By: JUSTIN SPITZER
	Dwg. #: 3	Nxt Asb:	Date: 6/4/2020	Scale: 1:4	Chkd. By: ME STAFF

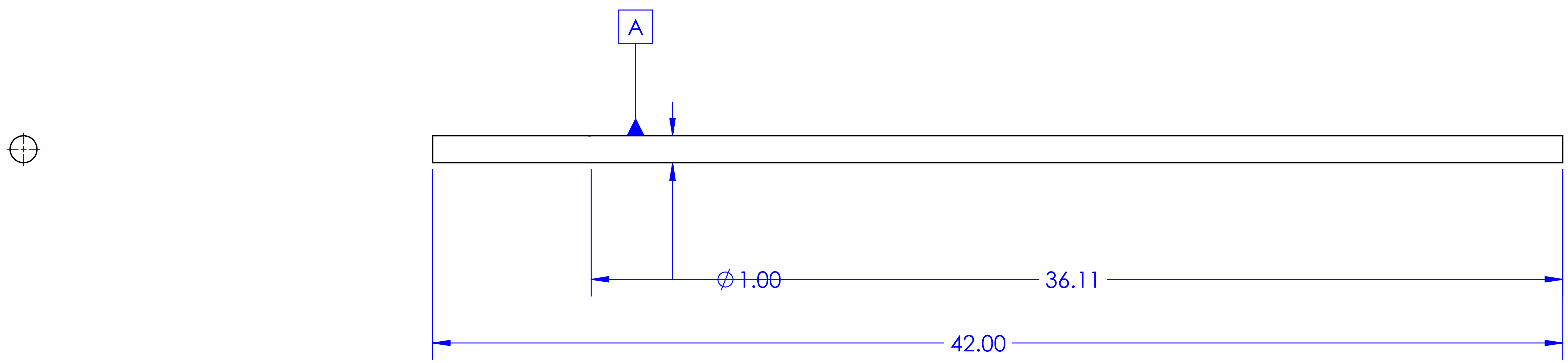


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	111120	MOUNT BLOCK	2
2	111300	ANGLE FRAME ANCHOR	12
3	111600	1/4-20 HEX BOLT	4
4	111110	LOWER LEG	4
5	111500	PILLOW BLOCK BEARING	2
6	111700	HEX NUT	4
7	111800	WASHER	4
8	111210	BASE	2

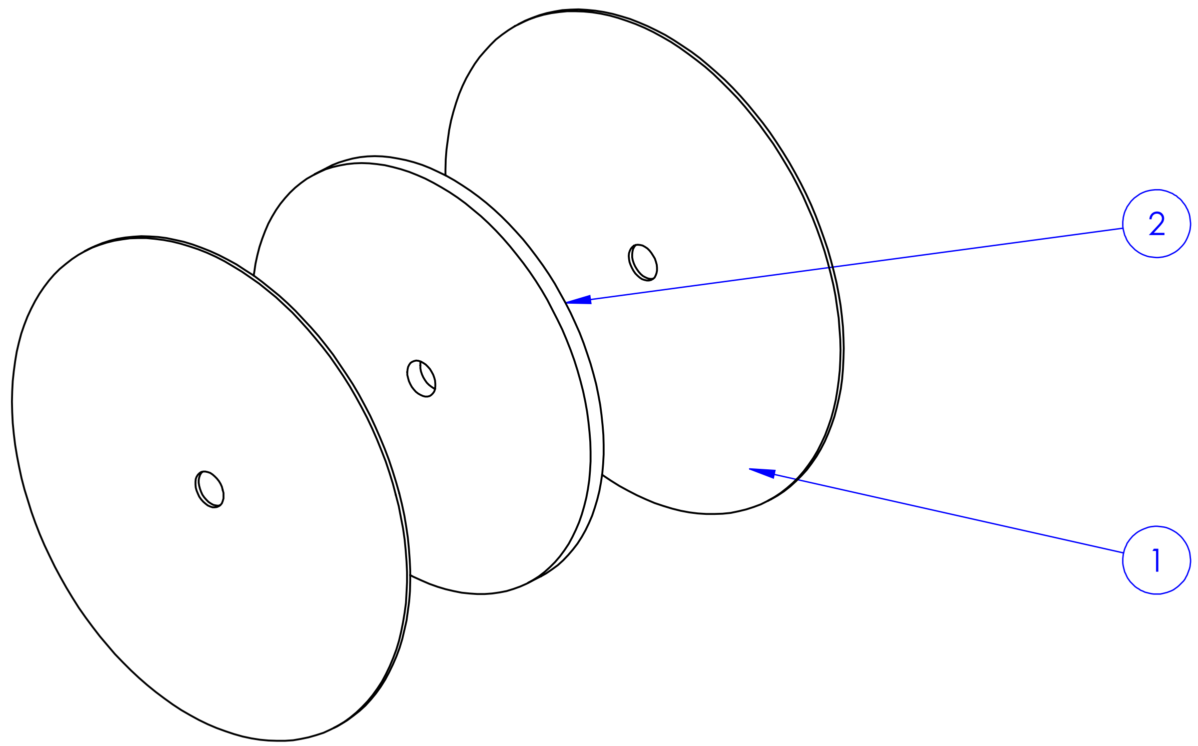
Cal Poly Mechanical Engineering	Lab Section: 03	PN # 111000	Title: SUPPORT STRUCTURE		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 4	Nxt Asb:	Date: 6/4/2020	Scale: 1:5	Chkd. By: ME STAFF

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

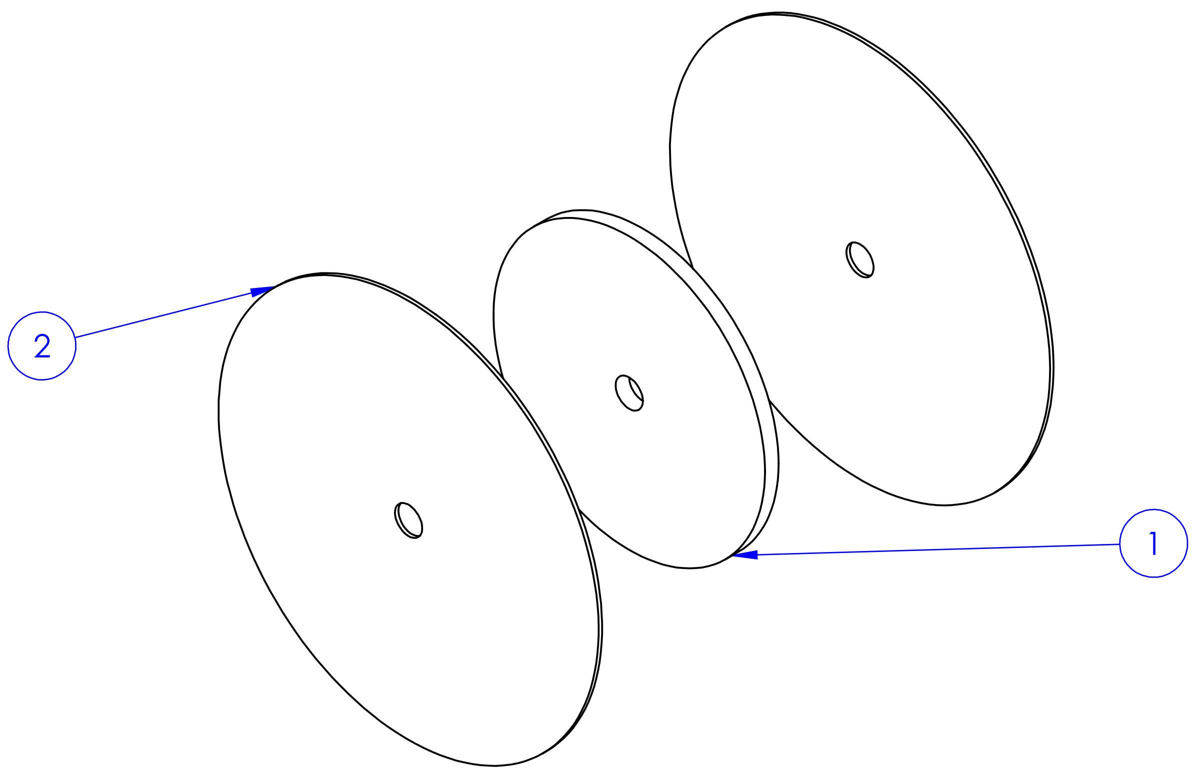


Cal Poly Mechanical Engineering	Lab Section: 03	PN # 112100	Title: 1 INCH WOOD ROD	Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 5	Nxt Asb:	Date: 6/4/2020 / Scale: 1:5	Chkd. By: ME STAFF



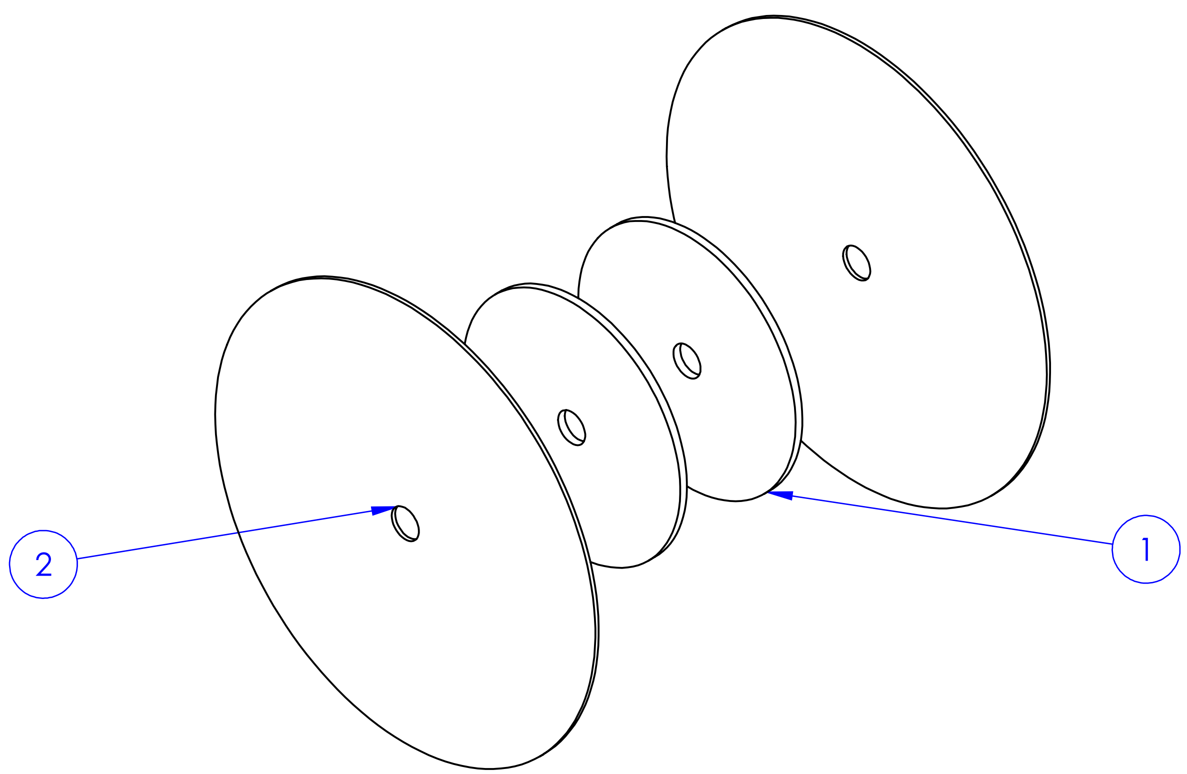
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112220	14 INCH DISC	2
2	112210	12 INCH DISC	1

Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section: 03	PN# 112200	Title: 12 INCH DISK ASSEMBLY		Drwn. By: JUSTIN SPITZER
	Dwg. #: 6	Nxt Asb:	Date: 6/4/2020	Scale: 1:5	Chkd. By: ME STAFF



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112230	10 INCH DISK	1
2	112220	14 INCH DISK	2

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 112300	Title: 10 INCH DISK ASSEMBLY		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 7	Nxt Asb:	Date: 6/4/2020	Scale: 1:5	Chkd. By: ME STAFF

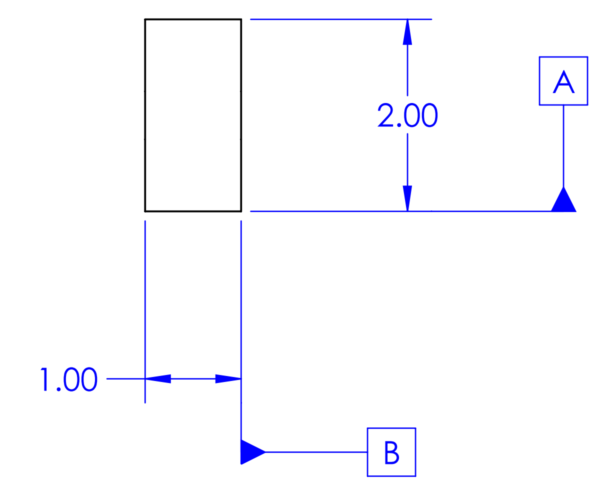


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112240	8 INCH DISK	2
2	112220	14 INCH DISK	2

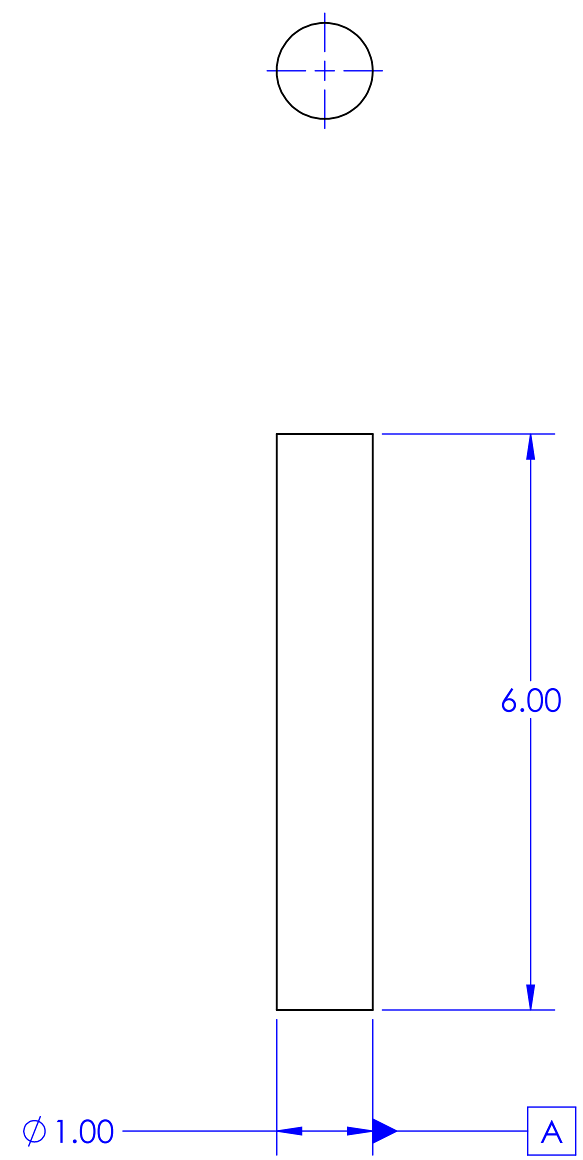
Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section: 03	PN # 112400	Title: 8 INCH DISK ASSEMBLY		Drwn. By: JUSTIN SPITZER
	Dwg. #: 8	Nxt Asb:	Date: 6/4/2020	Scale: 1:5	Chkd. By: ME STAFF

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



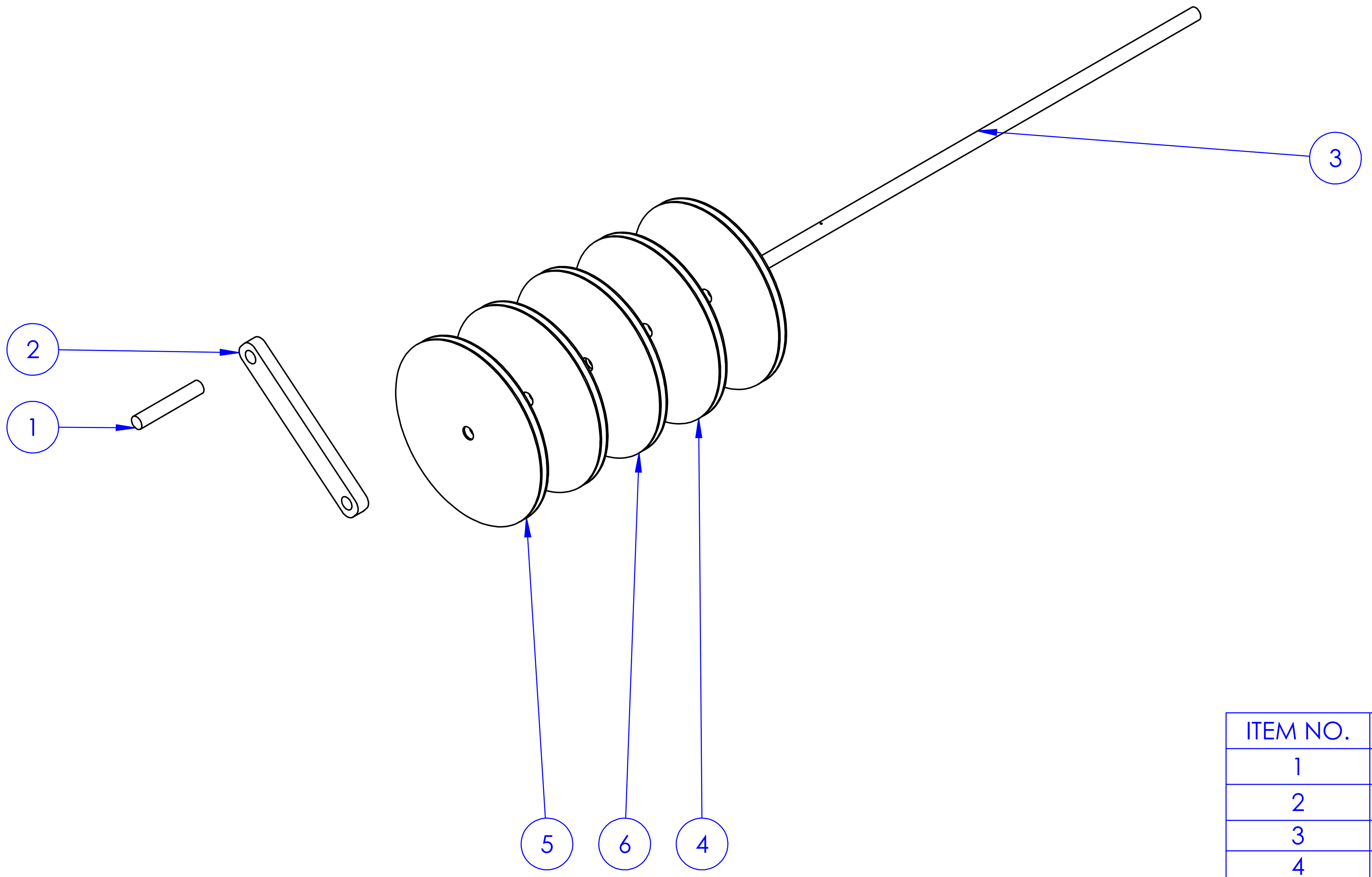
Cal Poly Mechanical Engineering	Lab Section: 03	PN # 112500	Title: CRANK ARM		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 9	Nxt Asb:	Date: 6/4/2020	Scale: 1:2	Chkd. By: ME STAFF



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 112600	Title: HANDLE		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 10	Nxt Asb:	Date: 6/4/2020	Scale: 1:2	Chkd. By: ME STAFF

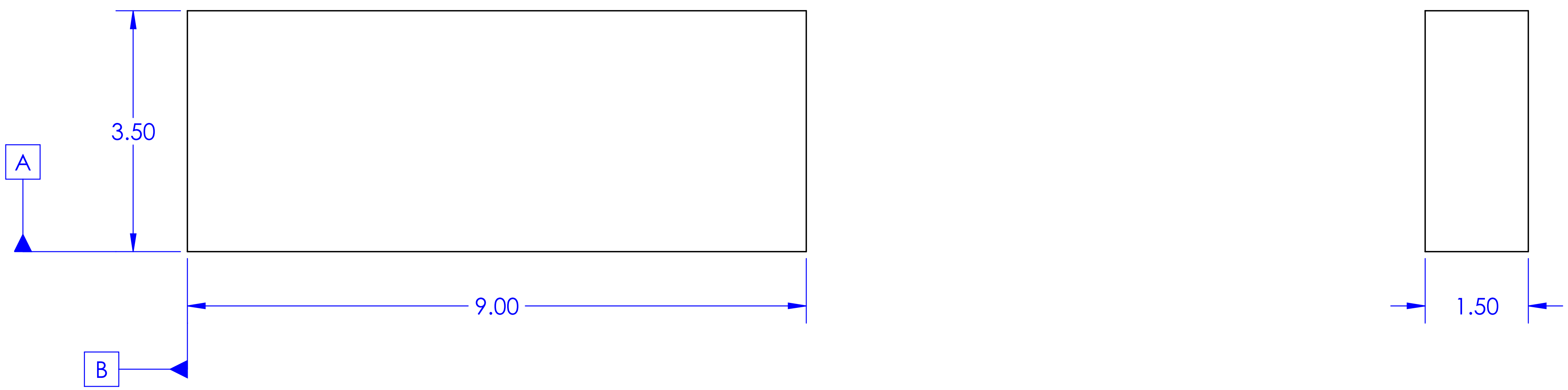


UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112600	GRIP	1
2	112500	CRANK ARM	1
3	112100	1 INCH WOOD ROD	1
4	112300	10 INCH DISK ASSEMBLY	2
5	112200	12 INCH DISK ASSEMBLY	2
6	112400	8 INCH DISK ASSEMBLY	1

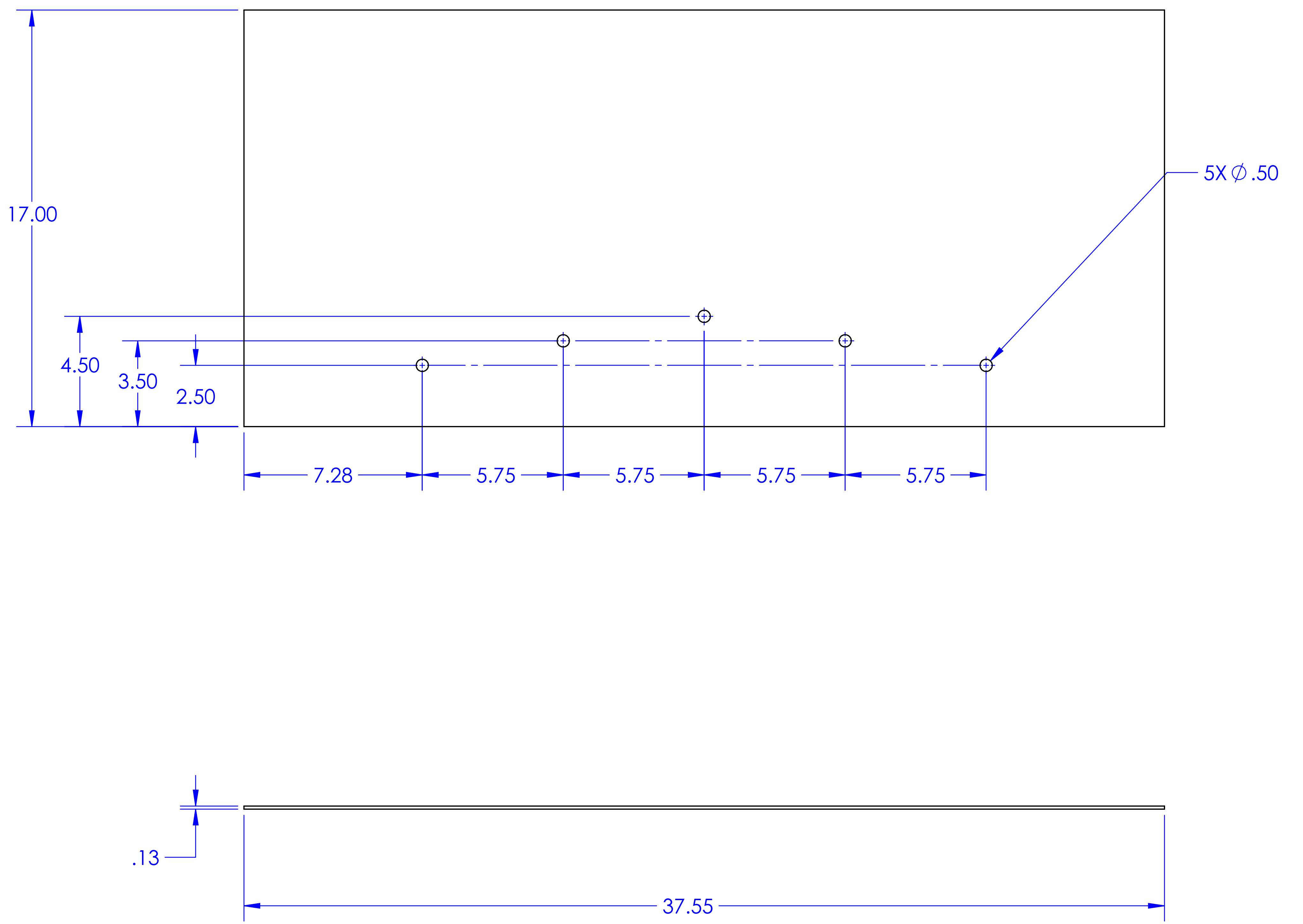
Cal Poly Mechanical Engineering	Lab Section: 03	PN # 112000	Title: SHAFT		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 11	Nxt Asb:	Date: 6/4/2020	Scale: 1:10	Chkd. By: ME STAFF



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

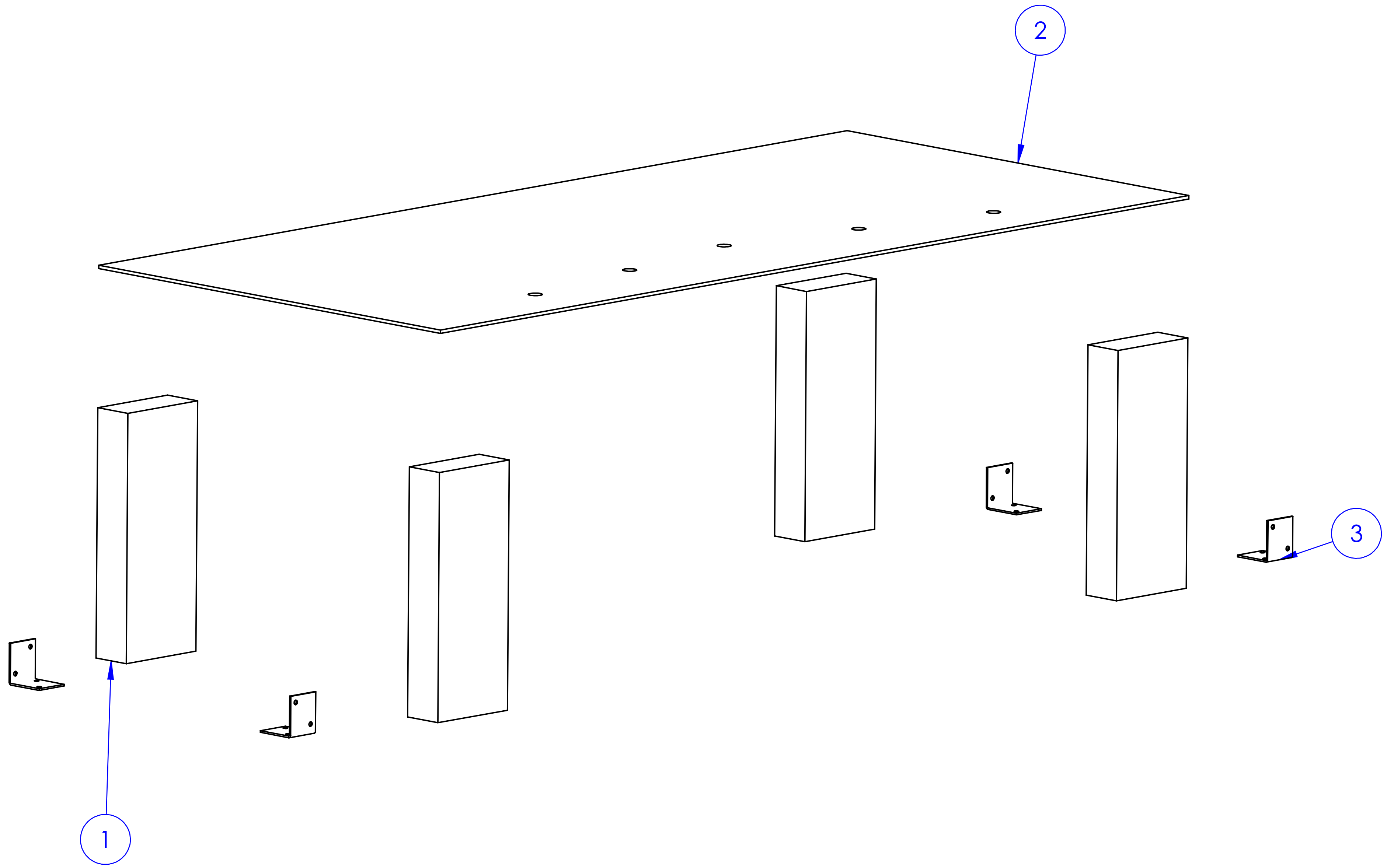
Cal Poly Mechanical Engineering	Lab Section: 03	PN # 113110	Title: UPPER LEG		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 1	Nxt Asb:	Date: 6/4/2020	Scale: 1:2	Chkd. By: ME STAFF



UNLESS OTHERWISE SPECIFIED:

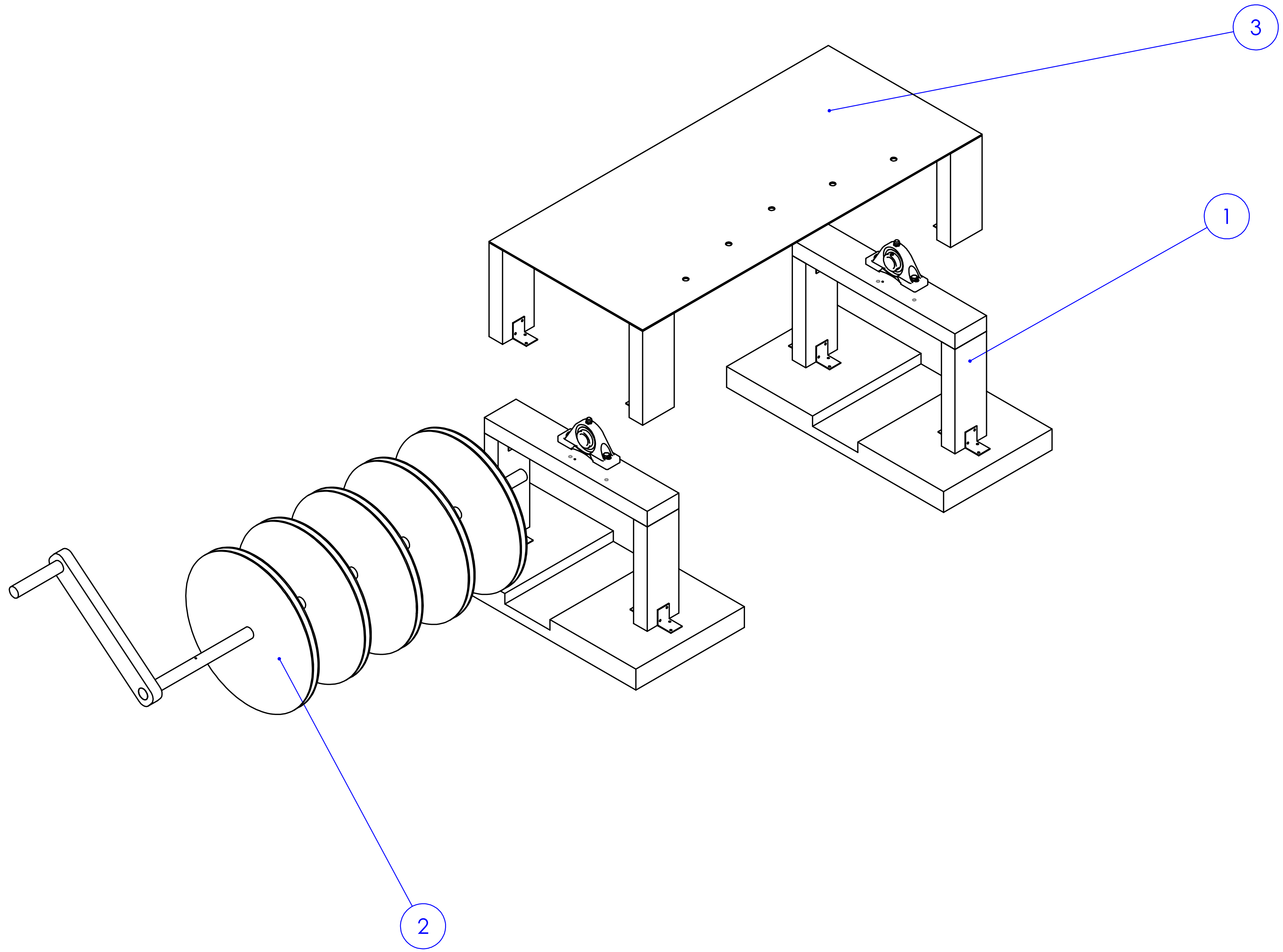
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 113210	Title: CLUE PLATE		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 13	Nxt Asb:	Date: 6/4/2020	Scale: 1:2	Chkd. By: ME STAFF



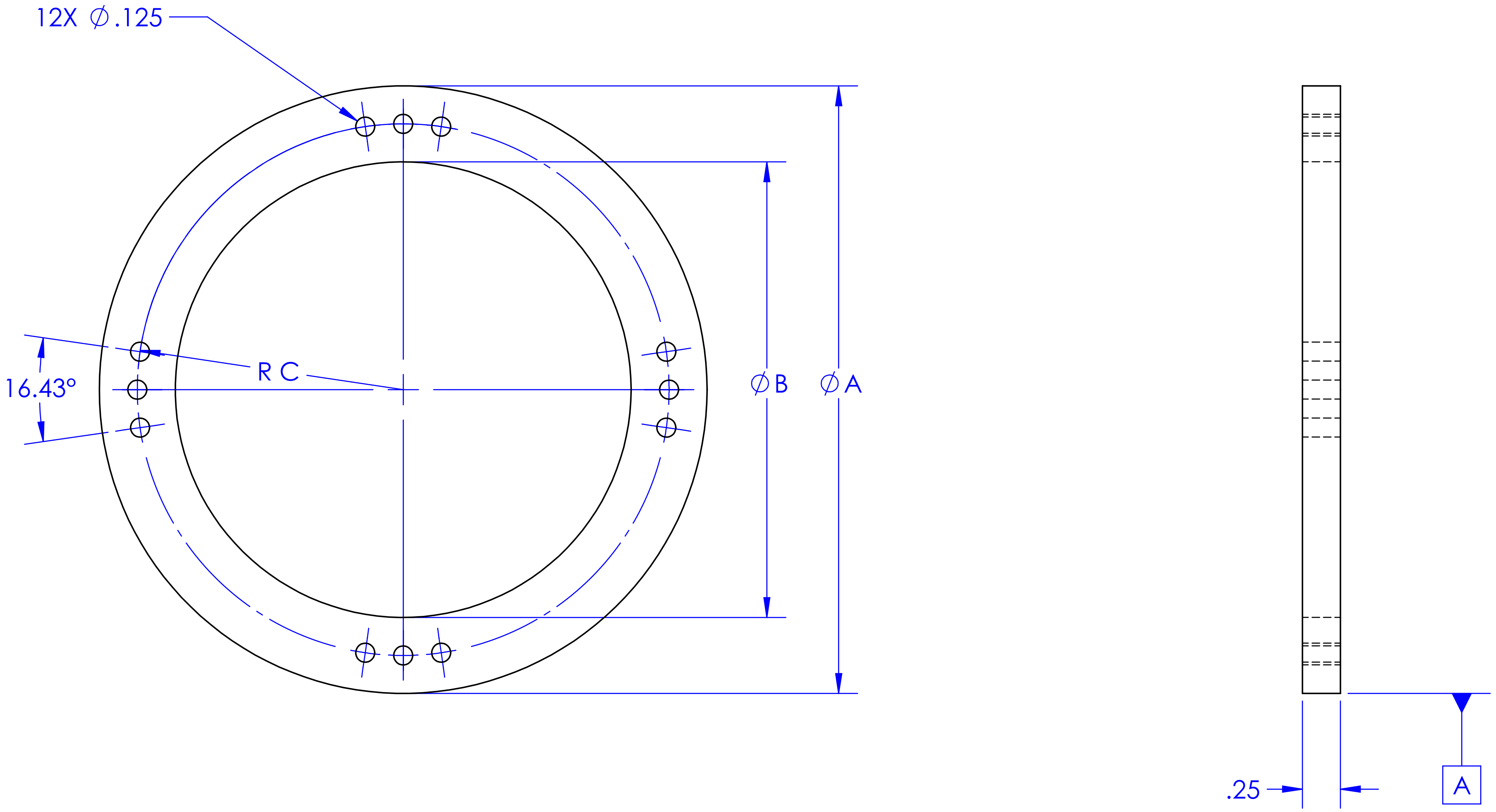
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	113110	UPPER LEGS	4
2	113210	CLUE PLATE	1
3	111300	ANGLE FRAME ANCHOR	4

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 113000	Title: CLUE GUIDE		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 14	Nxt Asb:	Date: 6/4/2020	Scale: 1:5	Chkd. By: ME STAFF



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	111000	SUPPORT STRUCTURE	1
2	112000	SHAFT	1
3	113000	CLUE GUIDE	1

Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section: 03	PN # 110000	Title: WIND UP ROD		Drwn. By: JUSTIN SPITZER
	Dwg. #: 15	Nxt Asb:	Date: 6/4/2020	Scale: 1:10	Chkd. By: ME STAFF

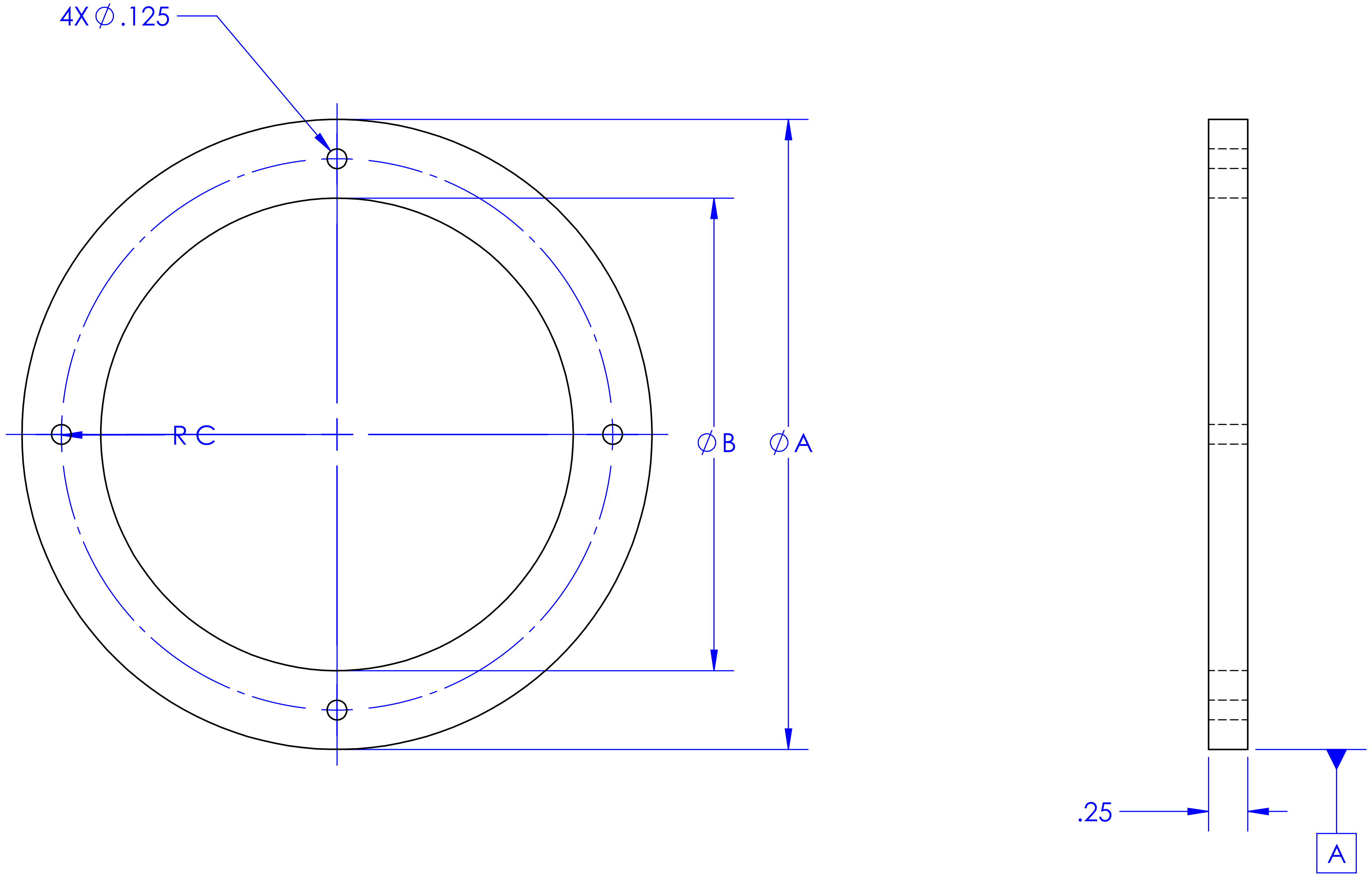


UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

PART NUMBER	/DESCRIPTION	A	B	C
121100	3 Inch Wood Ring	3.00	2.00	1.25
121200	4 Inch Wood Ring	4.00	3.00	1.75
121300	5 Inch Wood Ring	5.00	4.00	2.25

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 121XXX	Title: WOOD RINGS		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 16	Nxt Asb:	Date: 6/4/2020	Scale: 1:1	Chkd. By: ME STAFF



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

PART NUMBER	DESCRIPTION	A	B	C
122100	3 Inch Acrylic Ring	3.00	2.00	1.25
122200	4 Inch Acrylic Ring	4.00	3.00	1.75
122300	5 Inch Acrylic Ring	5.00	4.00	2.25

Cal Poly Mechanical Engineering	Lab Section: 03	PN # 122XXX	Title: ACRYLIC RINGS		Drwn. By: JUSTIN SPITZER
ME 429 - WINTER 2020	Dwg. #: 17	Nxt Asb:	Date: 6/4/2020	Scale: 1:1	Chkd. By: ME STAFF

Appendix K: Instructables

instructables

Planet Prop Suspension System

by rsvpheavenlyengineers

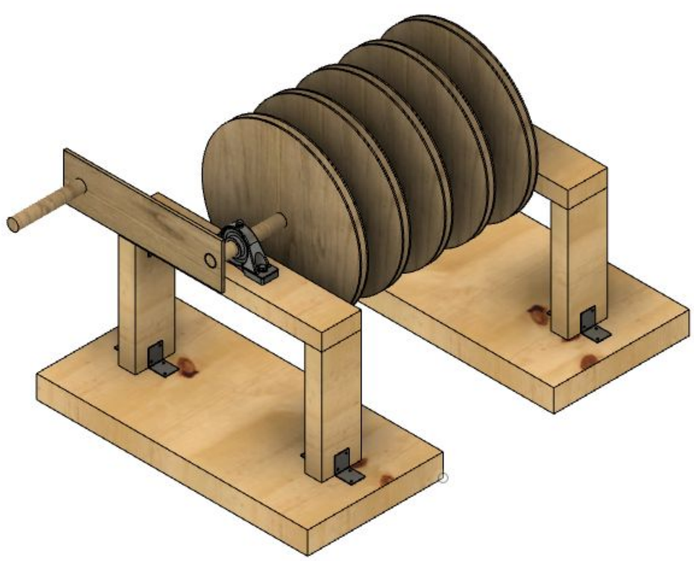
All materials needed for this project are in the images in this section.

For ease of use each step in this instructable is labelled with the respective name shown in the materials list.

Next to each item is the number of each of those items you will need to purchase along with the respective price and website/store to buy from

Items without prices are either assemblies or parts that will be self made from purchased materials

First you must decide how big you want this system to be. This will help to figure out how much material you will need. The number or planets/balls controlled by the system will dictate how many "Wind-up Rods" you will need to build and how much material you need overall. The following procedure describes a system five planets on each wind-up rod; however, the wind-up rod is modular so, it can have less than 5 planets associated with it.



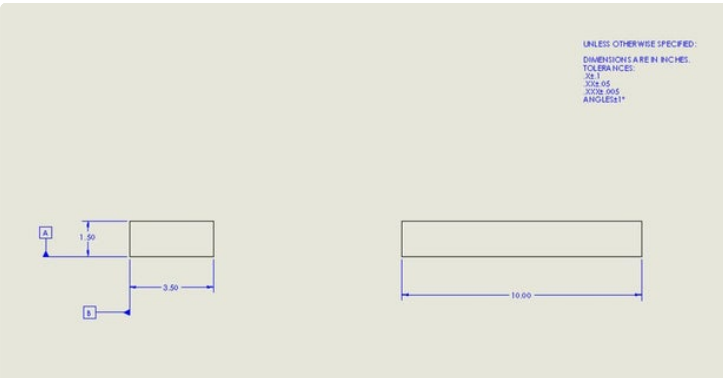
Final Assy				------	
— Wind Up Rod				------	
—— Support Structure				------	
——— wood 2x4	1	2.97	2.97	Home Depot	96 inch whitewood
———— Lower Legs	4	------	------	Self Made	
———— Mount Block	2	------	------	Self Made	
——— wood 2x12	1	15.42	15.42	Home Depot	96 inch whitewood
———— Base	2	------	------	Self Made	
——— Angle Frame Anchor	12	0.68	8.16	Home Depot	item 23-4509
——— Screws	1	7.98	7.98	Home Depot	72 Screws
——— Pillow Block Bearing	1	15.75	15.75	Amazon	2 Pillow Blocks
——— 25 1/4-20 Hex Bolt	1	5.92	5.92	McMaster	PN # 92240A552
——— 50 Hex Nut	1	2.27	2.27	McMaster	PN # 92673A113
——— 25 Washer	1	9.60	9.60	McMaster	PN # 91525A416
—— Shaft		------	------	------	
——— 1 Inch Wood Rod	1	3.98	3.98	Home Depot	48" long (6416U)
——— 12 inch disk assembly		------	------	------	
———— 12in Discs	2	5.50	11.00	Woodpeckers	1/2 in
———— 14in Discs	4	2.60	10.40	Woodpeckers	1/8 in
——— 10 inch disk assembly		------	------		
———— 10in Discs	2	5.50	11.00	Woodpeckers	1/2 in
———— 14in Discs	4	2.60	10.40	Woodpeckers	1/8 in
——— 8 inch disk assembly		------	------		
———— 8in Discs	2	2.25	4.50	Woodpeckers	1/4 in
———— 14in Discs	4	2.60	10.40	Woodpeckers	1/8 in
——— Crank Arm	1	------	------	Self Made	
——— Grip	1	------	------	Self Made	Cut from 48" wood rod
—— Clue Guide					
——— Wood 2x4 (9" cuts)	1	2.97	2.97	Home Depot	96 in whitewood
———— Upper Legs	4	------	------	Self Made	
——— Plywood sheet	1	11.42	11.42	Home Depot	1/10 sheet(cut into 4 pieces)
———— Clue Plate	1	------	------	Self Made	
——— Angle Frame Anchor	4	0.64	2.56	Home Depot	item 23-4509

— Planet Connection				------	
—— Plywood Sheet	1	8.41	8.41	Home Depot	plywood laser cut into 40 rings
——— 3 Inch Wood Ring	2	------	------	Self Made	
——— 4 Inch Wood Ring	2	------	------	Self Made	
——— 5 Inch Wood Ring	1	------	------	Self Made	
—— Acrylic Sheet 18" x 24" x 1/4"	1	29.79	29.79	Home Depot	
——— 3 Inch Acrylic Ring	2	------	------	Self Made	
——— 4 Inch Acrylic Ring	2	------	------	Self Made	
——— 5 Inch Acrylic Ring	1	------	------	Self Made	
—— "Godline" Fishing line	1	13.99	13.99	Amazon	150yd
—— Rope	1	10.00	10.00	Amazon	
— Planets		------	------	------	
—— 38-45 cm Exercise Ball	2	16.99	33.98	Amazon	
—— 58-65 cm Exercise Ball	2	21.99	43.98	Amazon	
—— 78-85 cm Exercise Ball	1	23.99	23.99	Amazon	
— Pulleys		------	------	------	
—— 1 groove	10	8.12	81.20	McMaster	w/ bearing (3742T56)
—— 2 groove	0	16.08	0.00	McMaster	w/o bearing (3099T23)
— Crimps & tool	1	18.99	18.99	Amazon	Glarks 180Pcs 1.2/1.5/2mm
	78		411.03		

Step 1: Cut 2x4 to Length to Make Lower Legs

Make a cut of the 2x4 wood using a table saw or a miter saw.

Cut Each length of wood to 10 inches in length make sure to compensate for the thickness of the saw you are cutting with.



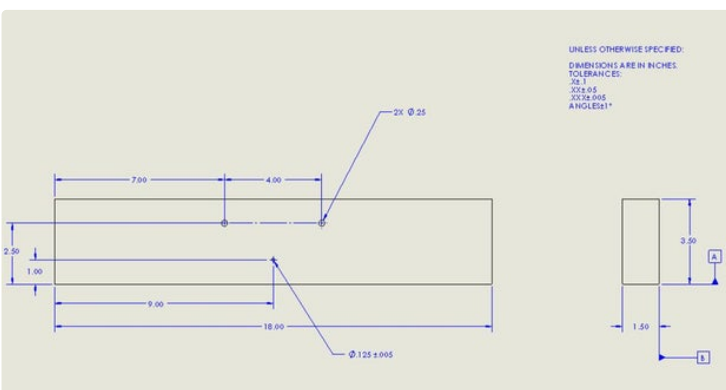
Step 2: Cut 2x4 to Make Mount Block

This cut of wood requires a table saw or miter saw.

Follow the drawing carefully on this step.

Cut the board to a length of 18 inches

Drill two 1/4 inch holes and one 1/8 inch hole at the specified dimensions in the picture.



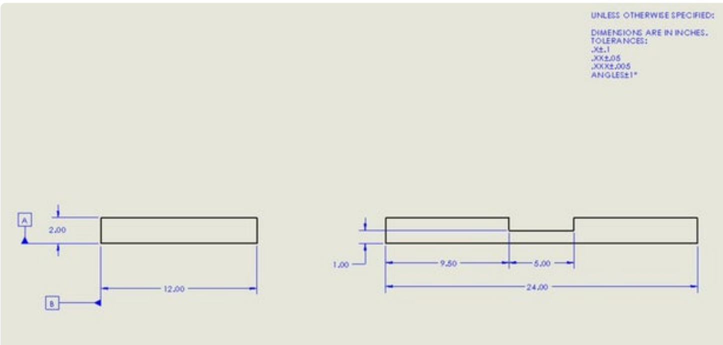
Step 3: Cut 2x12 for the Base

The purpose of this piece of wood is to allow for a weight to rest in the middle of the wood in order for the system to remain grounded during operation.

Cut the 2x12 wood to a length of 24 inches using a table saw or miter saw.

The next cut is more challenging and is optional as weight can be placed anywhere along the 2x4 to keep it down but this cut will provide a groove for the weight.

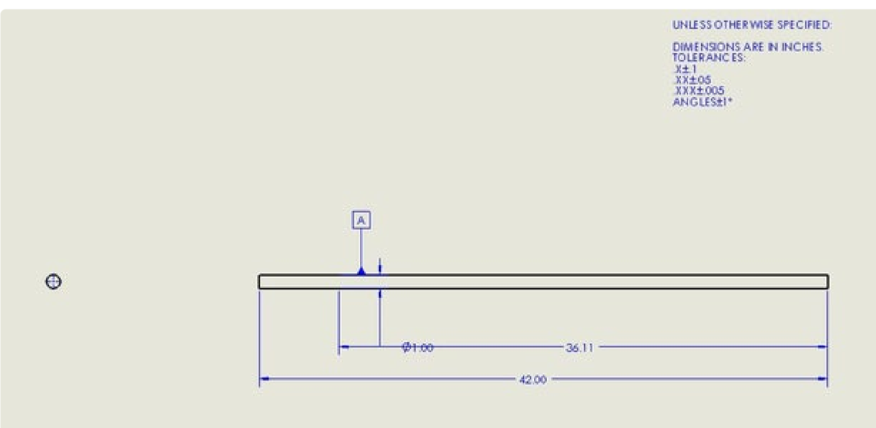
One way to approach the cut is to use a table saw aligned with the middle of the board and make multiple passes with the saw until its width is 5 inches.

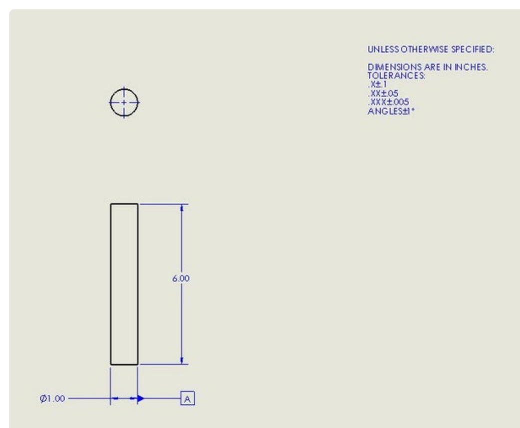


Step 4: Make Cut for Shaft and Handle

Using a miter saw cut the 1 inch dowel rod that is 48 inches long to a length of 42 inches, this will serve as the shaft.

The other 6 inches will be used as the handle for the crank.

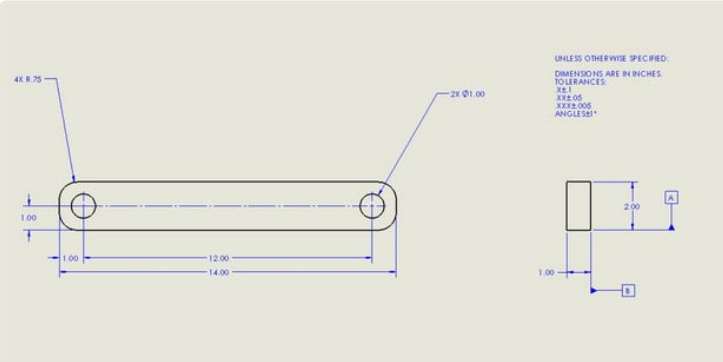




Step 5: Make Crank Arm

Use scrap 2x4 wood left over and a band saw to make the cuts shown in the picture

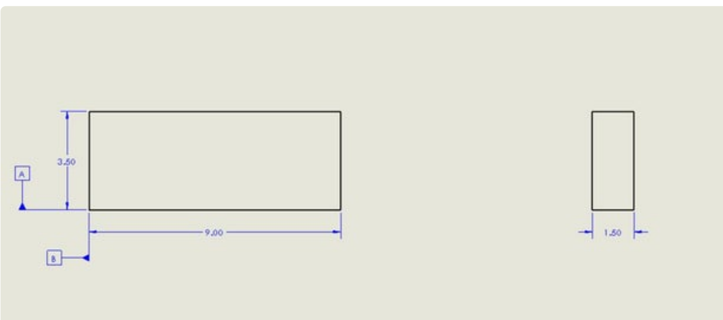
Drill two 1 inch holes as shown and sand as necessary to press fit the shaft and handle in when necessary.



Step 6: (Optional) Cut 2x4 for Upper Legs for the Clue

This cut will be done with a table saw or miter saw.

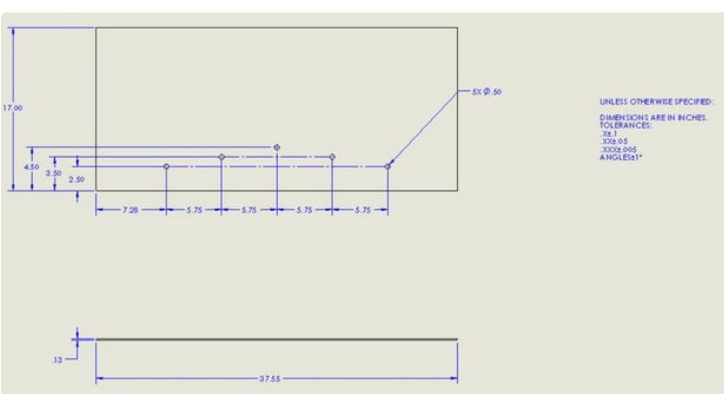
Follow the length of cut in the picture.



Step 7: (Optional) Cut Plywood Sheet Into Clue Plate and Drill Holes

Follow dimensions shown on the image.

Cut plywood sheet with a table saw to length and drill holes at the respective locations



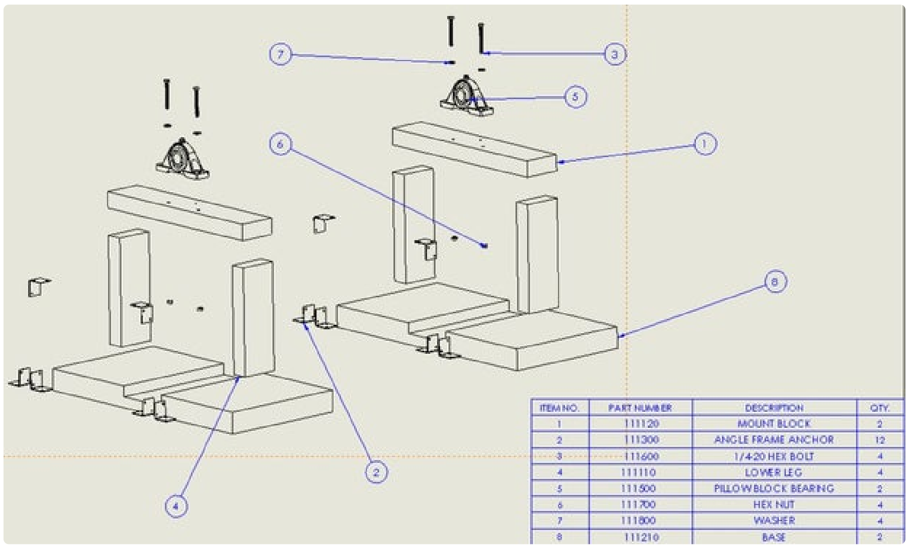
Step 8: Assemble Support Structure

With all materials from the material list underneath support structure use them to combine into the orientation shown in the picture.

1) Place Mount Block upside down and mount each leg to the end with an Angle Frame Anchor and screw in with a power screw

2) Flip Legs and mount onto the Base using screws and Angle Frame Anchor

3) Mount Pillow Block Bearing through the holes on top and secure with bolts washer and nut.

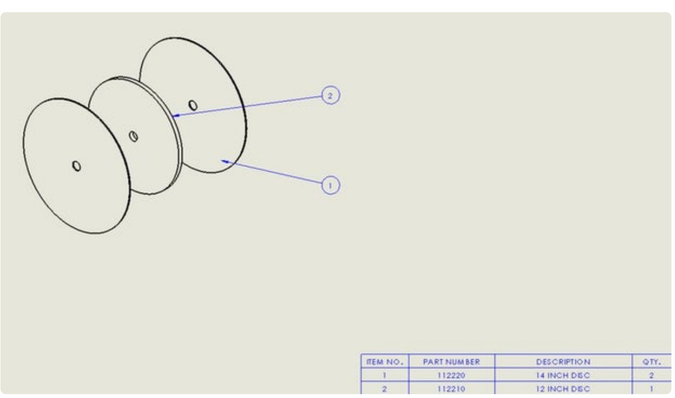


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	111120	MOUNT BLOCK	2
2	111300	ANGLE FRAME ANCHOR	12
3	111600	1/4-20 HEX BOLT	4
4	111110	LOWER LEG	4
5	111500	PILLOW BLOCK BEARING	2
6	111700	HEX NUT	4
7	111800	WASHER	4
8	111210	BASE	2

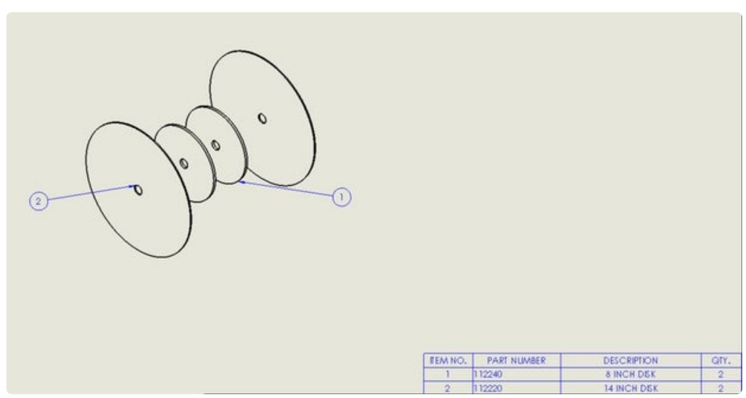
Step 9: Assemble Disks

Using the 14 inch disks on the outside place the 12 inch disk inside and apply wood glue liberally and allow 12 hours to dry.

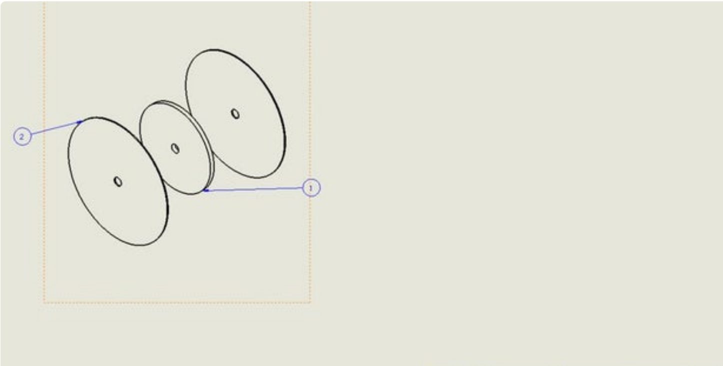
Do this with the 10 inch and 8 inch disks too.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112220	14 INCH DISC	2
2	112210	12 INCH DISC	1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112240	8 INCH DISK	2
2	112220	14 INCH DISK	2



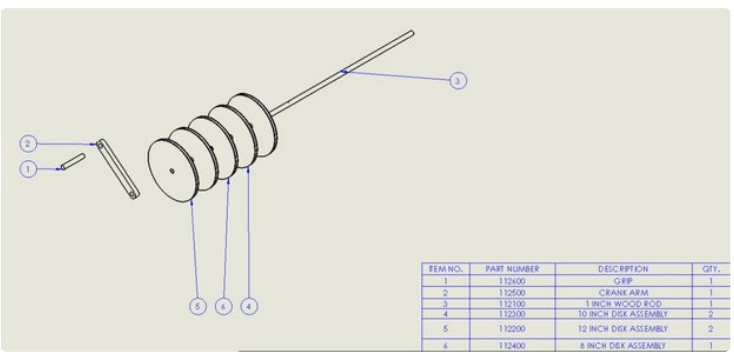
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112230	10 INCH DISK	1
2	112220	14 INCH DISK	2

Step 10: Assemble Shaft

Drill a one inch hole inside of all the dried circular disk assemblies in order to mount with the shaft.

Attach all components as necessary in the orientation shown.

Use sandpaper to sand the wood as needed to press fit the shaft into the wooden disks as necessary.

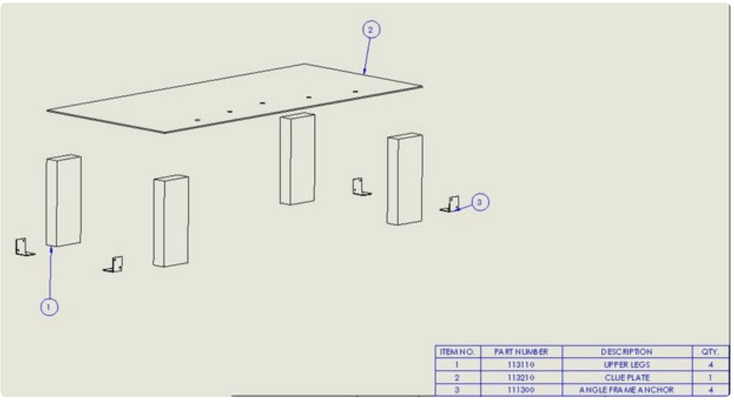


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	112600	GRIP	1
2	112500	CRANK ARM	1
3	112100	1 INCH WOOD ROD	1
4	112300	10 INCH DISK ASSEMBLY	2
5	112200	12 INCH DISK ASSEMBLY	2
6	112400	8 INCH DISK ASSEMBLY	1

Step 11: (Optional) Assemble Clue Guide

Use all the cuts made for the clue guide in the orientation shown and assemble.

Screws and Frame Anchors will be used on this step as well.



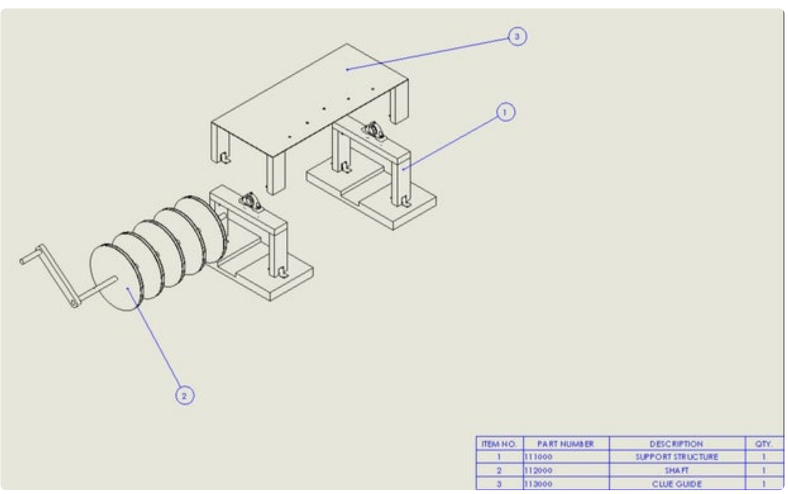
Step 12: Assemble "Wind-up Rod"

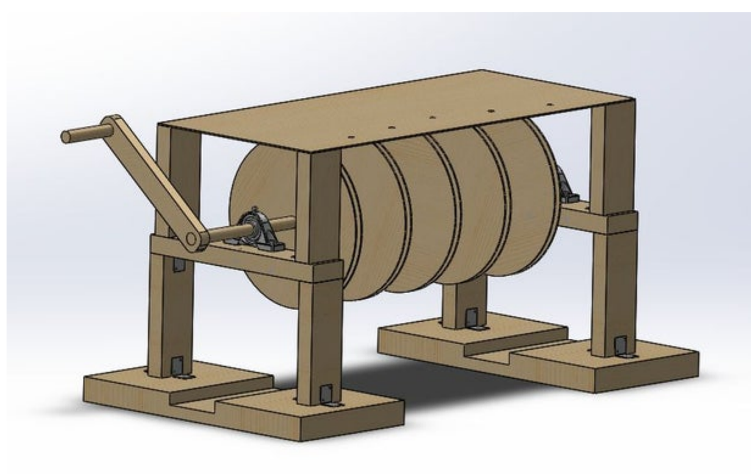
With each sub assembly complete the final assebly can now be finished.

Refer to the picture when assembling.

Mount the shaft inside of the Pillow Block Bearings and tighten with axle wrench.

(Optional) Mount the Clue Guide on the top of the Support Structure once the shaft has been installed.





Step 13: Planet Design

Pick Planet Sizes

In our design we utilized 3 different sizes of planets to give more dimension and make it more interesting. We used exercise balls for the base of our planets. Other options could be using beachballs, paper-mache balls (which can be heavy), or create fiber-glass balls (very time consuming and difficult: not recommended but if you're up to it go for it).

Decorate Planets

GET CREATIVE! You can paint the balls to be whatever you want. You can create stencils for various patterns and use spray paint to get fun consistent patterns on the ball. You can glue on some cotton balls to give it some texture or add some glitter to give it a little shine. If you are making planets you can create Jupiter or Mars or even create your own planet for fun (this is your solar system after all).

Step 14: Connecting Planets

Dual Ring Design/Construction

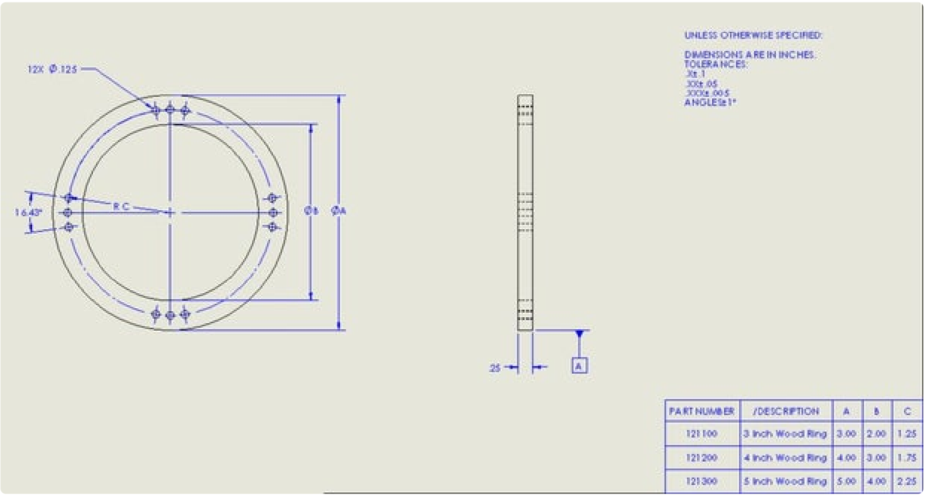
To attach the planets to the rest of the system, we created two rings that would sit on the top and bottom of each ball and allow you to wrap fishing line around and through the rings to act like a cage and keep the ball in place. The size of these rings can be modified depending on the size of the balls you are working with.

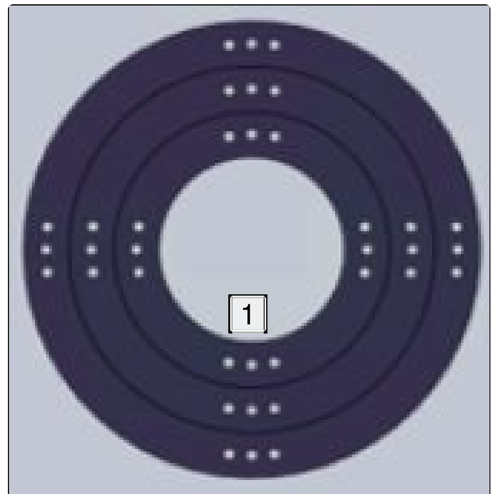
1. **Top Ring:** The top ring has a total of 12 1/8 inch holes spaced in groups of three around the ring. The group of three holes act like a belt or shoelace, letting you feed the string through each and tightening the string without creating slack in any of the other lines.

2. **Bottom Ring:** The bottom ring has 4 1/8 inch holes spaced evenly around the ring.

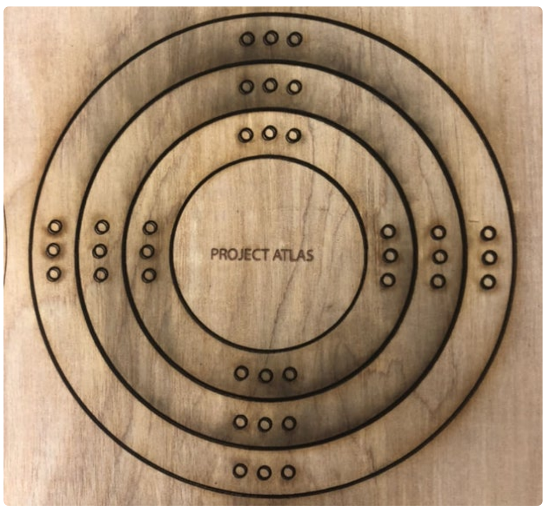
Manufacturing

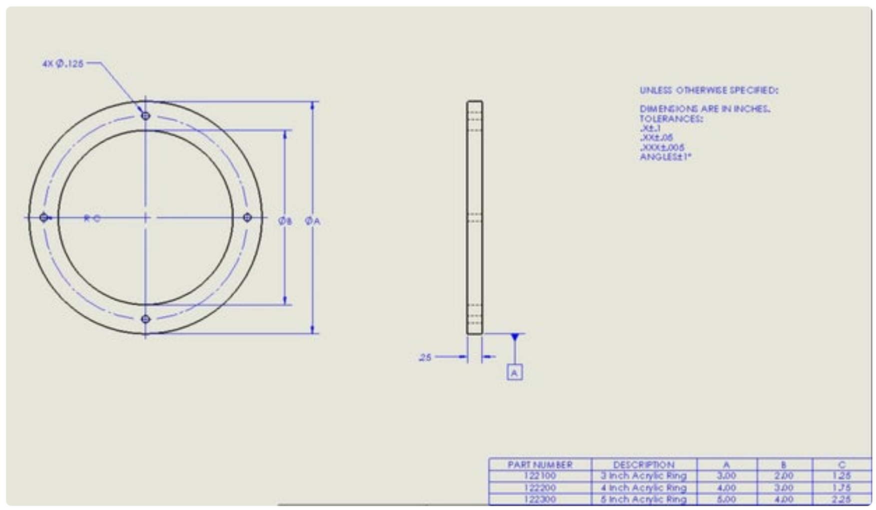
We used a laser cutter to cut the rings out of ½ inch plywood for the top ring and ¼ inch clear acrylic for the bottom rings. Because we needed three different diameter rings, we made the rings concentric to save material. The rings can also be manufactured using a drill, scroll saw, band saw, sander. Start with a square of wood and trace the ring pattern onto the piece of wood. Next, use the band saw to create the outer diameter of the ring. (If, it's not perfect it's okay, no one will really be looking at the rings.) Next, use a drill to drill a 1 inch hole in the center of the ring. Feed the scroll saw blade through the hole you just drilled, then tighten the blade back into place. Use the scroll saw to create the inner diameter of the ring. After taking the ring out of the scroll saw, use a 1/8 inch drill bit to create the holes around the perimeter of the ring. Finally, sand off any rough edges and repeat the process for the rest of the rings.

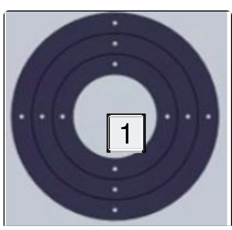




1. Top Ring Design







1. Bottom Ring Design

Step 15: Suspend the System

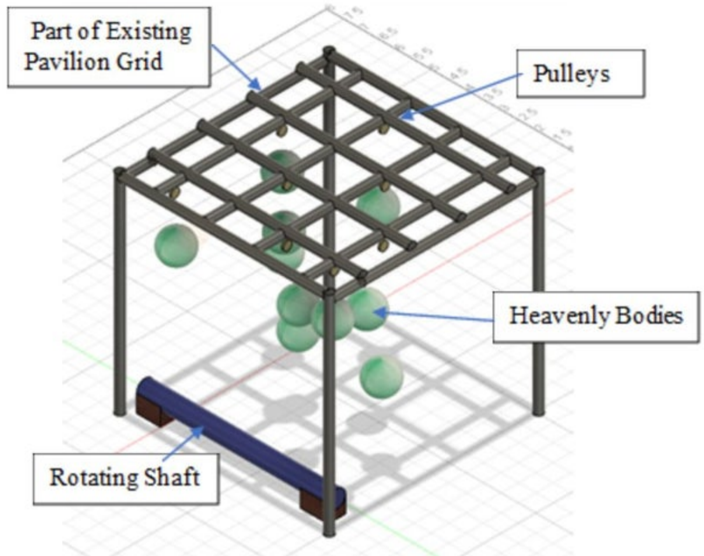
Pulley/Clip attachments and spacing

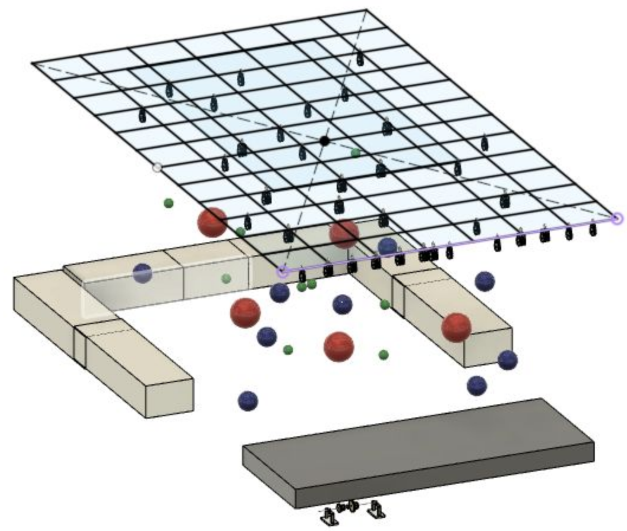
Each planet will have a designated "drop-zone" and you will want these "drop-zones" to be spread out so you can fill the space around you. Directly above each planet will be one pulley and directly above each disc in the Wind-up rod will be another pulley. If there is not a straight line from the disc to the drop-zone you may need another pulley to better guide the string to the planet.

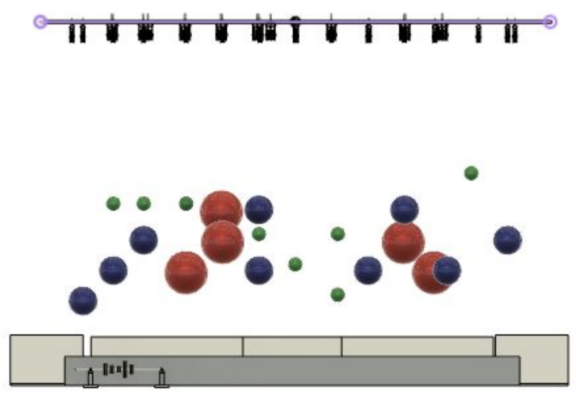
PSA this next part will most-likely be frustrating so have some extra rope on hand and be prepared to redo the process a few times and a few different ways. The easiest way to attach the planet to the rest of the system would be to first place all of your pulleys on your gird structure (we zip tied the pulleys in place).

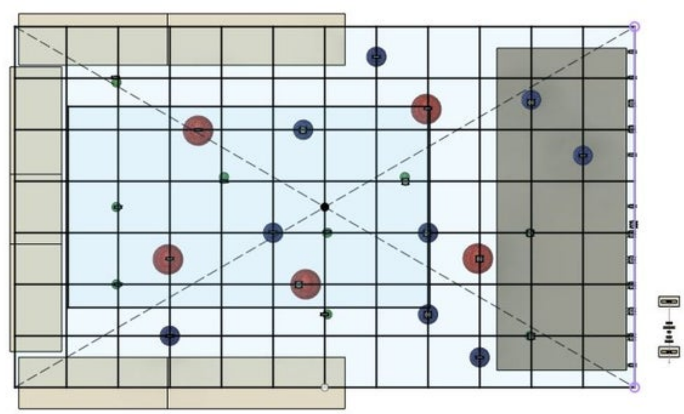
Next feed the string that has already been attached to the wind-up rod through the various pulleys landing at the "drop-zone".

Once the rope is fed through the final pulley string the rope through the loop at the top of the planet and tie it off securely (you can use a crimping tool to crimp the rope around the loop on the planet).





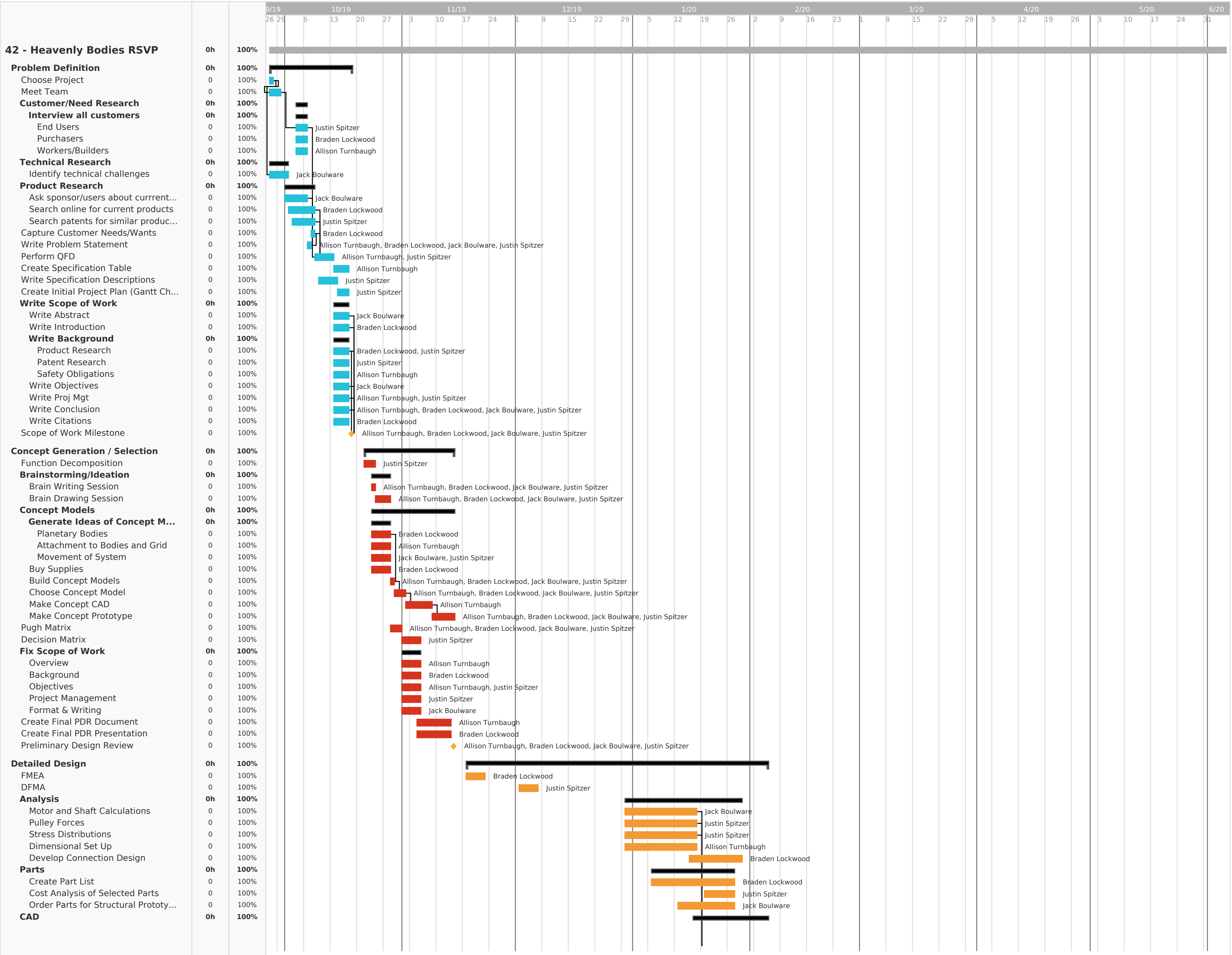




Step 16: Running the System

Slowly crank the arm in both clockwise and counterclockwise direction to become familiar with how each rotation effects the system. Once you know which direction is up and down crank the arm and you've got yourself a solar system!! Be aware of how far your planets are moving so you don't accidentally crash into either your grid system or the floor.

Appendix L: Gantt Chart



Update Previous CAD Model	0	100%
Add Calculated Dimensions into S...	0	100%
BOM	0	100%
Create Part Drawings	0	100%
Assemble Drawing Package	0	100%
Update Hazard/Safety Checklist	0	100%
Prep for PDR	**0h**	**100%**
Grind on Making Report	0	100%
Complete Final Design Section	0	100%
Complete Mfg. Plan Section	0	100%
Complete Design Verification Plan	0	100%
Interim Design Review	0	100%
Critical Design Review	0	100%
Manufacturing/Testing	**0h**	**100%**
Begin Construction of Structural Pr...	0	100%
Confirm Final Design Details	0	100%
Update Bill of Materials to reflect n...	0	100%
Work out Reimbursement	0	100%
Risk Assessment	0	100%
Clean up CDR Document	0	100%
Order All Parts	0	100%
Set Up Planet Heat Testing with Th...	0	100%
Set Up Time for group to meet w/ T...	0	100%
Carry out Heat Testing	0	100%
Begin Construction of 3 other wind ...	0	100%
Laser Cut Rings	0	100%
Mfg. & Test Review	0	100%
No work due to finals/ break	0	100%
Set Up Sound and Speed Test in Pa...	0	100%
Carry Out Full System Speed/Sound...	0	100%
Test Procedures	0	100%
Create Operator's Manual	0	100%
Revised Plan	**0h**	**100%**
Create Step by Step Assembly Guide	0	100%
Redesign a stopping mechanism for...	0	100%
Plan for tests that would be carried...	0	100%
Operation of the System Plan	0	100%
The Finale	**0h**	**100%**
Full System Ready to Go	0	100%
EXPO	0	100%
Clean up/ Clear out Workspaces	0	100%
Finish FDR Report/Print Poster	0	100%