Worcester Polytechnic Institute

Major Qualifying Project

Educational Engineering Toy

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Abstract

Educational toys play a huge role in the intellectual development of children. The goal of this project was to design and construct a toy that introduces simple engineering concepts to children between the ages of 8 and 12. This toy utilizes interchangeable four-bar linkages with adjustable link lengths to teach children about simple concepts of coupler curve generation. The linkages are attached to a game board with pins set up to be knocked down as it moves. This can be an effective tool for teachers looking to provide something for students interested in science, math, and/or mechanical engineering. Incorporating a sense of autonomy in learning, along with teamwork and competition, our toy provides students an engaging way to learn about linkages.

Acknowledgments

We would like to express our gratitude to Professor Eben C. Cobb for providing us an opportunity to contribute to education and for guiding us through this Engineering Educational Toy Project. We would also like to thank Barbara Fuhrman and the other staff members in WPI's Mechanical Engineering office for helping us order our parts and materials for our project in an efficient and timely manner.

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Chapter I: Introduction

There is a need for educational aids that will get children excited to learn and keep them engaged. Engineering education can appeal to children with multiple different learning styles due to its creative outcomes and tangible subject matter. (Bagiati & Evangelou, 2015) This project was undertaken to fulfill the need for an educational toy that teaches children about simple engineering mechanisms and linkages. The project is intended for children around the ages 8-12 who either have a strong interest in engineering or those who seek introductory learning of engineering not provided at school. Potential clients or customers could be secondary school teachers who want to bring more engineering into their classrooms, parents who want to teach their children about engineering, or larger toy companies who see potential success with the finished product. The expected outcome of this project is to have a finished, working prototype of our educational toy. The goal is to design and construct a toy that teaches young children about mechanisms through an engaging hands-on approach with elements of teamwork and competition.

Chapter II: Background

An educational toy aids in the development of children, because it gives an opportunity for interaction with physical parts. In the ever-growing market for educational toys, there are only a few products that teach children about mechanisms and linkages. Some currently available toys that teach about mechanisms include Engino's Levers and Linkages Toys ® (shown in Figure 1), LEGO ®, K'NEX ®, and Eitech ®.

Figure 1: Engino's Lever and Linkages Mechanics Toy

These toys all teach children simple engineering concepts and provide an interactive way to do so. However, they do have their shortcomings. One common issue is that they can often be complicated to assemble and use for children or teachers with a lack of hands-on engineering exposure. (Bagiati & Evangelou, 2015) Another problem is that there are not many toys or games that teach and elaborate on one specific engineering linkage. We are aiming for our finished product to be easily assembled and understood while teaching children about a specific linkage. One more issue is that many of the existing toys do not involve some sort of competition, the building block that transforms potential into success. Addressing this issue, our toy will allow children, whether in the classroom or casual setting, to cooperate and compete with others, ultimately enhancing the learning process. Our functional requirements and educational objectives that we followed when designing and constructing our toy are outlined below. The functional requirements are based on our budget for the product, spatial limitations, ease of assembly, as well as restrictions and guidelines from the American Society for Testing and Materials (ASTM F963) manual.

Functional Requirements

- Able to be assembled with everyday tools (Screwdriver/wrench-will be included)
- Able to be assembled and produced at WPI
- Maximum size of a shoebox (Unassembled)
- Maximum size assembled 12”x12”x6” (stationary)
- Maximum operating space of 24”x24”6”
- Maximum weight of 10 lbs.
- For ages 8-12
- Teaches children about a specific mechanism or engineering concept
- Not too expensive to make ($750 budget)
- Adheres to ASTM F963 Safety Standards for toys

Educational Objectives

- Competition
- Allow for many configurations (so that it isn’t boring with repetition)
- Teamwork
- Teaching introductory information about mechanisms (or a specific mechanism)

Chapter III: Design Concepts

When determining the final design for our engineering toy, we started by brainstorming ideas that fulfilled our educational objectives. We wanted to create a product that involves learning while also incorporating elements of teamwork and competition. There were three resultant ideas that we came up with: a walking mechanism toy, a roller coaster toy, and a pin game.

The first design idea, a walking mechanism toy, prompts youth to create different walking mechanisms based on the linkage type chosen. For example, children could create different linkage assemblies depending on whether they wanted a mechanism that consists of Klann, Jansen, Ghassaei, or Plantigrade Linkages. The idea behind this design proposal was to enhance the understanding of linkages through contrast and comparison of different linkage types and each one's effect on the output motion of a walking mechanism. This toy would guide children through the process of making each animal-imitating mechanism, allowing them to learn through a hands-on approach. The toy would also incorporate competition by having children race their respective assemblies to observe which linkage type results in the fastest walking mechanism. We ultimately decided against this idea because of the high cost of manufacturing and the presence of similar toys in the market.

The second idea, a roller coaster toy, involves the use of linkages to create a simulated, miniature "roller-coaster" path on a board. Children could place a stuffed animal or another toy on the end of the coupler and could mount a small camera to it as well. The board would include different objects and scenery to which the toy would interact with on its path around the board. The linkage would be powered by a motor and the children could watch the toy go around the path with the view provided by the camera. There would be different link lengths included so that different paths and path shapes could be generated. We decided that this idea would both cost the most and provide the least opportunity for competition, which were the main factors in deciding against it.

The third idea, a pin game, prompts children to play around with and understand the relationship between a linkage assembly's components and resultant motion of the coupler curve or path generation. The toy would consist of a large game board that is split in half, with a base on each end of the board. Each team would be assigned to a half, where they would have to work together to complete the challenge. Pins would be placed in respective locations on each team's board, and each team would be provided numerous links and connection joints. Using provided information regarding four-bar linkage configurations and resultant output motion, children would construct a four-bar linkage and attach the ground link to the game board base. When the linkage is attached to the game board, the team or person would rotate the crank to see whether the linkage assembly knocks the pins down. The first team or person to knock all the pins wins. We ultimately decided on this idea due to its innovative concept as well as its incorporation of competition and instruction of linkages. Further details regarding how our group ended up choosing the Pin Game are outlined in *Chapter 5: Design Selection* of this report.

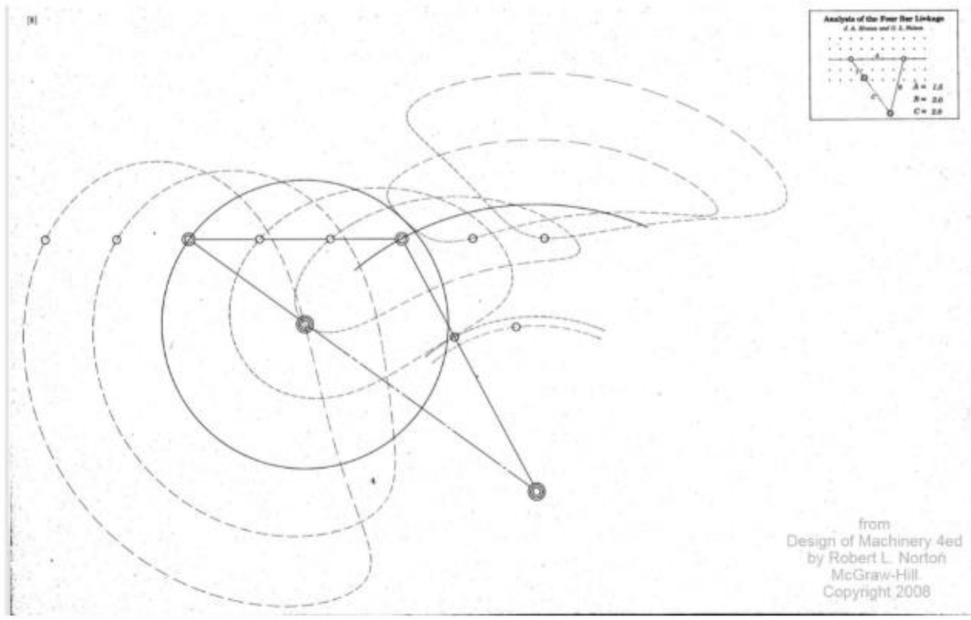
Chapter IV: Synthesis and Analysis

Each initial design that we came up with had both strengths and weaknesses regarding how well it fulfilled our functional requirements. To determine the most effective design for our educational product, we had to compare and analyze each idea.

The Walking Mechanism Toy is an idea with high educational value regarding linkages but fails to fulfill some of our fundamental requirements. The design would require high costs to manufacture due to its many components as well as the inclusion of small motors. The idea was also overly challenging for our target audience of 8-12 year-old children. Also, there were several similar products in the educational toy market. Companies such as LEGO, Engino, and K'NEX all had similar products that involved the concept of step-by-step instructions in assembling parts to create a contraption. Seeking to create an innovative concept that enhances understanding of linkages, we decided not to pursue this idea.

The main reason we decided against the Roller Coaster Toy was due to the lack of opportunity for competitiveness. While students could work together to build the mechanism, we did not see a way to turn it into a game in which groups could compete against one another. Similar to the walking mechanism, this design would also be more expensive since we would need to include numerous small parts, a motor, and a small camera.

The Pin Game has high educational value in that it uses a simple four-bar linkage to teach introductory basics of mechanism synthesis, coupler curves and path generation. Mechanism synthesis is the process that, after identifying a desired motion of a link, a specific mechanism is synthesized and the dimensions of all the linkages are identified. Path generation deals with the tracking of the output of a tracer point. The tracer points output path generates a shape or curve that we refer to a coupler curve. (Norton, 2014) These coupler curves are all described in the Hrones and Nelson atlas which gives ratios for each linkage size to achieve certain path generations. One example curve and path is shown below in Figure 2.



Pg. 8 Hrones and Nelson Atlas

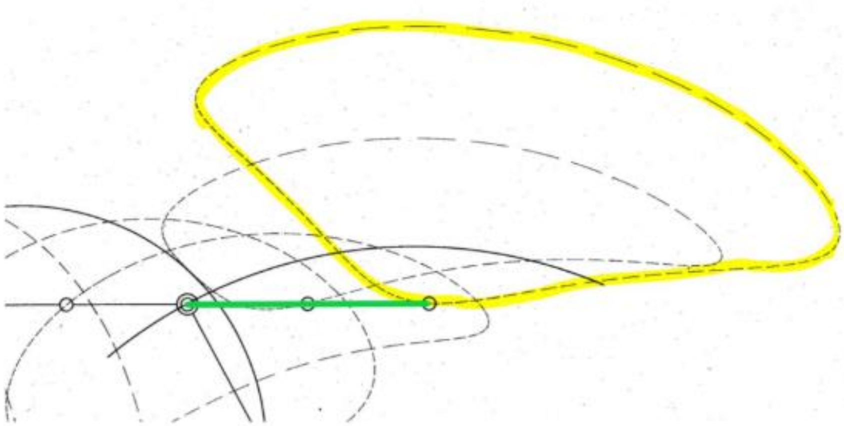


Figure 2: Hrones and Nelson Example Linkage

The pin game also encourages competition with children competing against each other to create the best mechanism to knock down the most pins as possible. Also due to the simplicity of the mechanism, new mechanisms can be easily assembled creating different paths and new ways to play making the constantly changing and making the children think about the best paths to use to win and being able to easily try a lot of different coupler curves.

Chapter V: Design Selection

To select our design, we created a decision matrix that evaluated each design based on the criteria that we set. The criteria they were evaluated on include the cost associated with designing and making the specific design. Competitiveness refers to how much the toys allow for competition between kids and how competition can motivate the children to learn. Fun and engagement refer to how much enjoyment can be had by playing with the respective toy. Educational refers to the educational value of the toy presented regarding engineering concepts and mechanisms. Ease of assembly refers to how easily the toy would be assembled by the students in our target audience. Modularity refers to how much the toys can be changed to promote replay-ability with the students. Finally, they were evaluated on how well they would hold to the toy safety guidelines outlined in ASTM F963 (Appendix F).

Each criterion was then weighed a percentage out of 100% based on their level of importance. The cost was given a weight of 10% based on our decision that although the overall cost of production is important, we would like to focus on making the best product possible rather than the cost to make it. Competitiveness was given a weight of 15% due to the importance of competition in motivating and engaging students in learning. The fun and engagement and educational value both received weights of 30%, because they are most directly related to our goal statement. Ease of Assembly, Modularity, and ASTM Standards all received weights of 5%. We gave each of these categories five percent weight because they are the least important factors to consider but still needed to be included in our matrix to make a proper decision.

Our final decision matrix is shown in Table 1. Each toy was given a score for each from 0 to 5. Zero meaning the toy fails to fulfill any part of the criteria, A score of 1 indicates one or two aspects of criteria fulfilled. A two indicates more than two but less than half aspects of criteria fulfilled. A three approximately half of the criteria fulfilled, a four mostly fulfills criteria And a 5 indicates the toy completely fulfills criteria.

Table 1: Decision Matrix

	Walking Mechanism Toy	**Roller Coaster Toy**	**Pin Game**
Cost (10%)	2 (0.2)	1 (0.1)	3 (0.3)
Competitiveness (15%)	2 (0.3)	0 (0)	4 (0.6)
Fun/Engagement (30%)	4 (1.2)	2 (0.6)	5 (1.5)
Educational (regarding mechanisms) (30%)	5 (1.5)	3 (0.9)	4 (1.2)
Ease of assembly (5%)	1 (0.05)	3(0.15)	3 (0.15)
Modularity (5%)	3 (0.15)	3 (0.15)	3 (0.15)
ASTM F963 Standards (5%)	4 (0.2)	3 (0.15)	4 (0.2)
Total (out of 5)	**3.6**	**2.05**	**4.1**

The scores the toys were given for each criterion and totaled and the toy with the highest score (out of 5) was the toy design that we selected. The Walking mechanism toy received a score of 3.6, and the Roller Coaster toy scored a 2.05. We selected the Pin Game with a score of 4.1 and is highlighted in green on our matrix.

Chapter VI: Detailed Design Description

The game consists of numerous four-bar linkages, a game board, small plastic pins, LEGO connector pins, and a brochure detailing the assembly instructions, rules, and important engineering concepts. Two teams compete against each other to see who can score the most points by knocking down pins with their chosen linkage, which will be elevated above the board once completed. The coupler will have a small connector peg on the end hanging down, which will knock the pins when the players rotate the crank. The crank will have another peg extending upwards with will serve as the handle the children can rotate. Every linkage in this game has a 6-inch ground link that is attached to the game board and is stationary. A CAD model of the game board is shown in Figure 3.

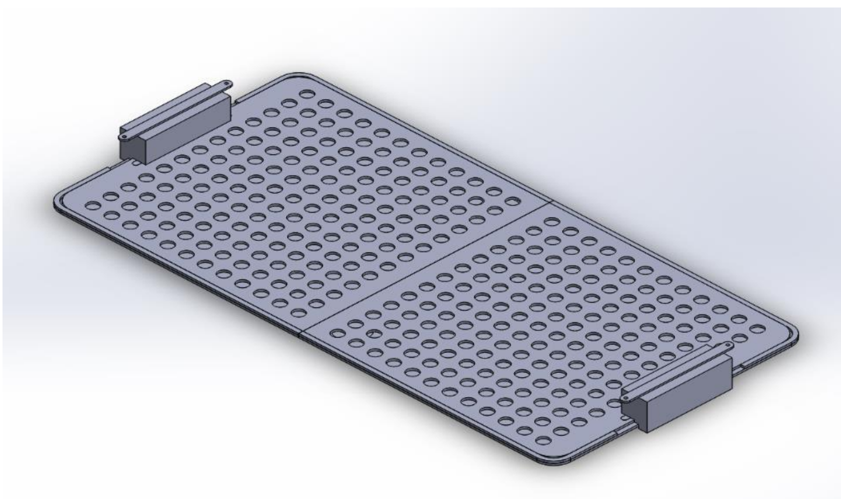
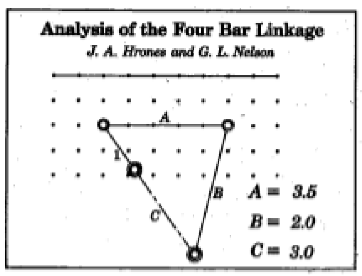
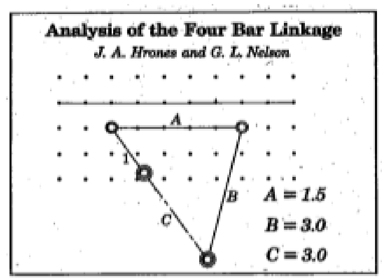


Figure 3: CAD Model of Game Board

Based on an agreed upon arrangement of pins, the teams must choose the best linkage that they think will knock the most pins, scoring the most points. A full set of rules is outlined in Appendix D. Table 2 shows the lengths we chose for two linkages we were able to manufacture at WPI. We chose 6 inches for every ground link in the game and calculated the other lengths based on that dimension. In linkage #1, the crank (labeled with a "1" in the diagram) must be 1/3 the length of the ground link (labeled "C"). The coupler (labeled "A") then must be 3.5 times the length of the crank, and the rocker (labeled "B") must be 2 times the length of the crank. The same steps were followed for linkage #2, keeping the ground link constant at 6 inches and figuring out the other lengths with the associated A, B, and C values in the diagram. Lastly, we found the angle at which the coupler point must extend from the coupler by first choosing the curve we wanted it to produce (highlighted in yellow in Figure 4), then measuring the angle between the line of centers of link 3, and the line between the pin joint that connects link 2 to link 3 and the coupler point of the desired curve. The distance between the pin joint and the coupler point was measured. This defines link 3. Detailed part drawings can be seen in Appendix A, and an exploded-view assembly drawing can be seen in Appendix C.

Table 2: Lengths of Manufactured Links

	Linkage #1	**Linkage #2**
Crank	2 in	2 in
Coupler (A)	7 in	3 in
Rocker (B)	4 in	6 in
Ground (C)	6 in	6 in
Hrones and Nelson Diagram		

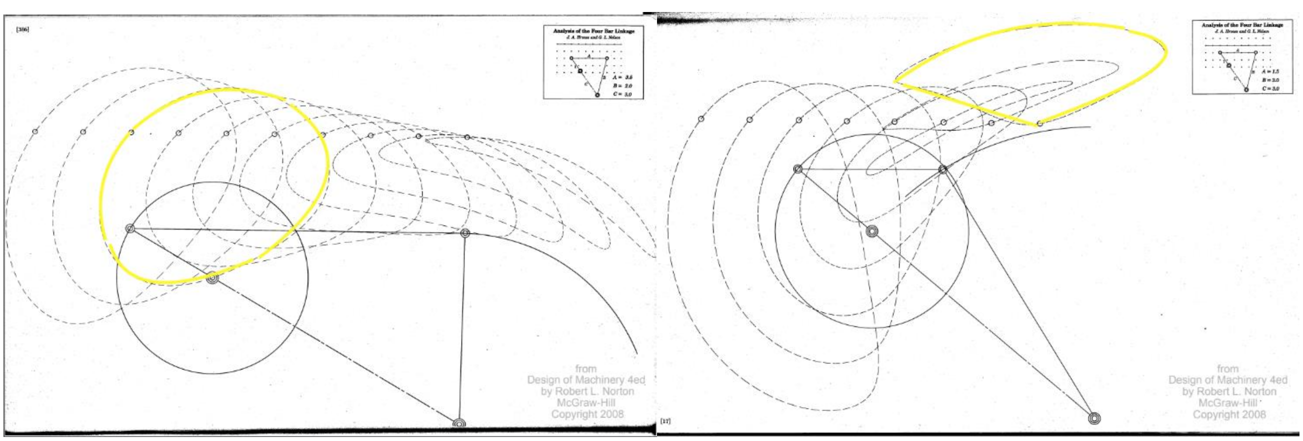


Figure 4: Schematics for Linkage #1 (Left) and Linkage #2 (Right)

Figure 5 shows the parts we purchased from Amazon for this project. To the right is a LEGO connector peg used for the joints, and to the left are the plastic pawns used as the pins. Figure 6 shows the game board (top) and links (bottom) that we laser-cut with acrylic sheets at WPI's Foisie Innovation Studio.

Figure 5: LEGO Connector Peg and Pawns

Figure 6: Laser-Cut Game Board and Links

Chapter VII: Manufacturing

The manufacturing process of our educational toy employed the use of the laser-cutter and 3D-printer. The game board and individual links were made by laser cutting ⅛" thick acrylic sheets, purchased through RoboSource. We decided to use clear and black acrylic sheets to enhance the aesthetic appeal of our game board. The two stands/bases that fit into both ends of the board were 3D-printed with white polylactic acid (PLA). Lastly, we purchased the game pieces and LEGO connector pegs to use as the joints for our mechanism through Amazon.

We first made a 3D model of our game board and two sets of links on SolidWorks to 3D print and create 2D drawings needed for laser cutting. Our game board consists of six parts in total: four parts in total for the bases and two parts for the ground link bases. We made the base of the game board with black acrylic and made the top layer (one with holes) out of clear acrylic. Each layer was split into two parts that interlock with each other, making our board more portable. We also engraved labels onto each part so that children know which pieces fit together. The walls of the board, which are stuck to the bottom base layer, were also laser cut from the black acrylic. The walls were placed to prevent pins from sliding off the game board and getting lost. The last two pieces of the game board are the 3D printed ground link stands, which interlock with the board layers at both ends. We decided to fix a common ground link to the stand to eliminate the need for children to replace the ground link. After assembling the game board, students can then place game pins in the holes on the board, either following a template to show where they should be placed or creating their own arrangement.

All the links that are to be attached to the ground link were made by laser cutting the clear acrylic sheets. We have two different sets of links to get two different coupler curves and made two copies of each set. Each set of links is assembled by connecting the crank and rocker into each end of the stand. The coupler is then added to the linkage, using the LEGO connector pegs as joints at each end. One more LEGO connector peg will be added to the last hole on the coupler to knock the pins down as the linkage moves.

Chapter VIII: Virtual Testing

Testing is a crucial part of the engineering design process that we unfortunately, could not complete due to the COVID-19 pandemic. We originally had plans to test our educational toy with middle school students to determine how effectively the toy stimulated student interest and delivered an introduction to mechanisms and linkages. This testing and evaluation process would have allowed us to iterate more on our toy, getting us closer to creating a product that enhances student understanding of linkages in an exciting way. Here are a few things we intended to do, but could not due to the unusual circumstances:

I. **Assemble the toy and play with it**
   A. This would have been done to ensure all the joints work properly. Playing with the toy would have also ensured the generation of desired coupler curves and proper contact between the knocking arm and plastic game pins.

II. **Refinement**
   A. Any issues with the game board or pieces would be resolved by either remaking the piece. This stage would also be where most if not all of the game's rules would be made and fleshed out to maximize entertainment, learning, and competitiveness.

Chapter IX: Conclusions and Recommendations

Through this Major Qualifying Project, we were able to design and assemble a working educational toy that teaches children about the introductory concepts of linkages such as coupler curve generation. After conducting research on learning motivations and children's behavior, we discovered that students thrive when given control of their learning. Activities that are open-ended to allow the application of their understanding and creativity help children better comprehend content material. This sense of autonomy in learning was a crucial element that we integrated into our toy, along with aspects of teamwork and competition, to make our product both instructional and engaging. The final toy design that we came up with was a game that uses simple four-bar linkages to teach about mechanism synthesis as well as coupler curves and path generation. Based on the configuration of pins on the game board, children are to construct and test various four-bar linkages to determine which one generates the path needed to knock down all the pins. Two teams will simultaneously work on knocking their own pins, with the first team to do so standing victorious. Through an iterative process of building a variety of linkages, children will learn to problem-solve while gradually understanding the concept of how the coupler curve changes according to the length and shape of its parts. Due to the COVID-19 pandemic, we were unable to test our product and make needed improvements. Here are a few recommendations we have compiled to enhance our toy:

I. **Adding more links**
   A. Adding more sets of links will allow for more coupler curve paths. This is crucial when trying to knock over pins in all areas of the board. Having more links will also allow children to use their creativity and knowledge of four-bar linkages to create their own coupler curves.

II. **Split the game board into smaller parts**
   A. This will allow the educational toy to fit into a smaller box, making it easier to carry around. Having more parts to the game board will also provide an opportunity for children to practice their motor skills, matching the correct puzzle pieces together.

III. Complete a Brochure

A. Create an instructional brochure that will teach children how to properly assemble the toys and give simple and easily understood descriptions of engineering concepts like mechanism synthesis and coupler curves. A draft of our brochure included steps for assembly, rules to the game, and a brief description of engineering concepts, but we would have included pictures of our finished product at different stages of assembly.

IV. Packaging

A. Due to the use of small parts in these educational toys, a choking hazard warning should be placed on the box outlined in the ASTM F963-17 section 5.11.

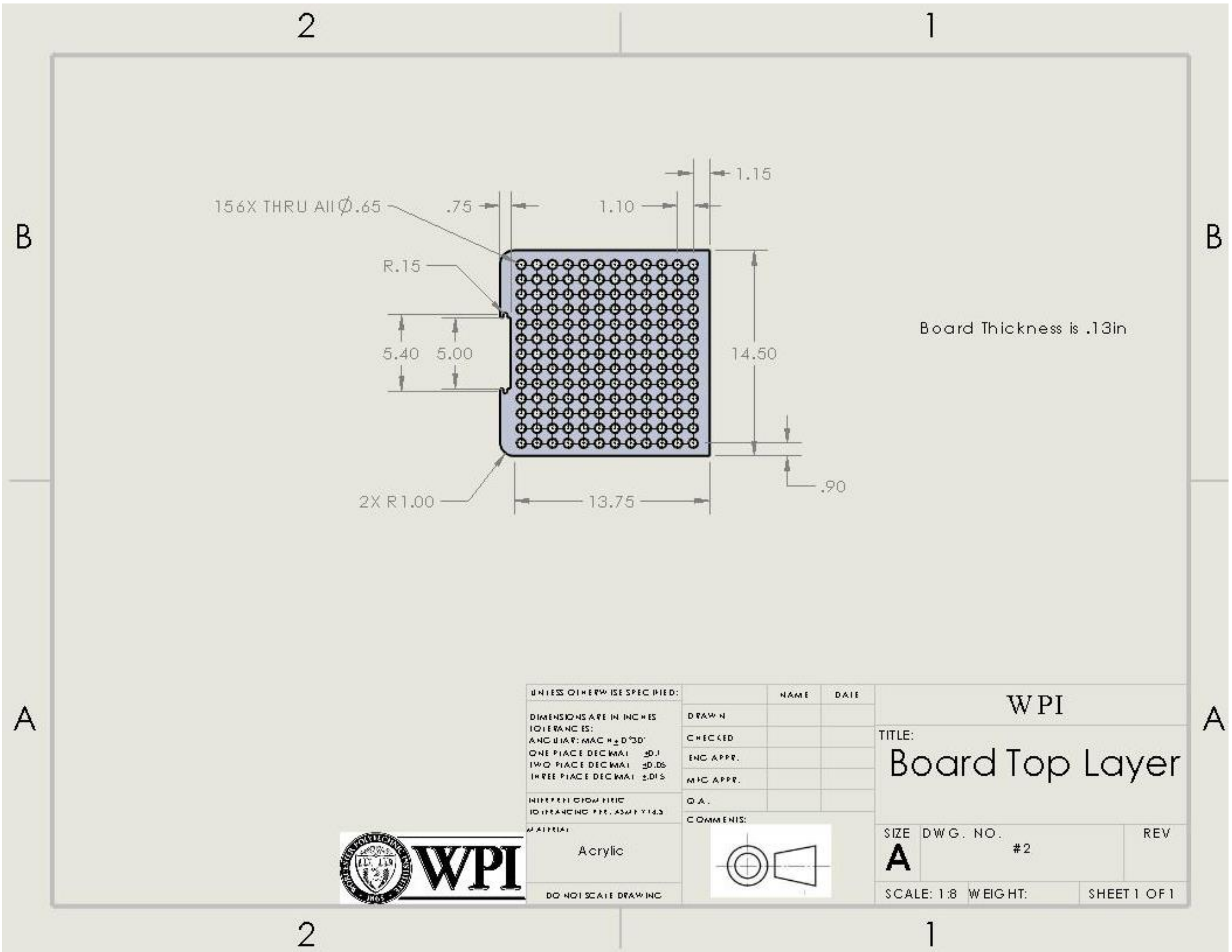
B. Any images or materials on the packaging or inside of it will all follow section 5.16 and not contradict any safety warning located on the packaging of the toy.

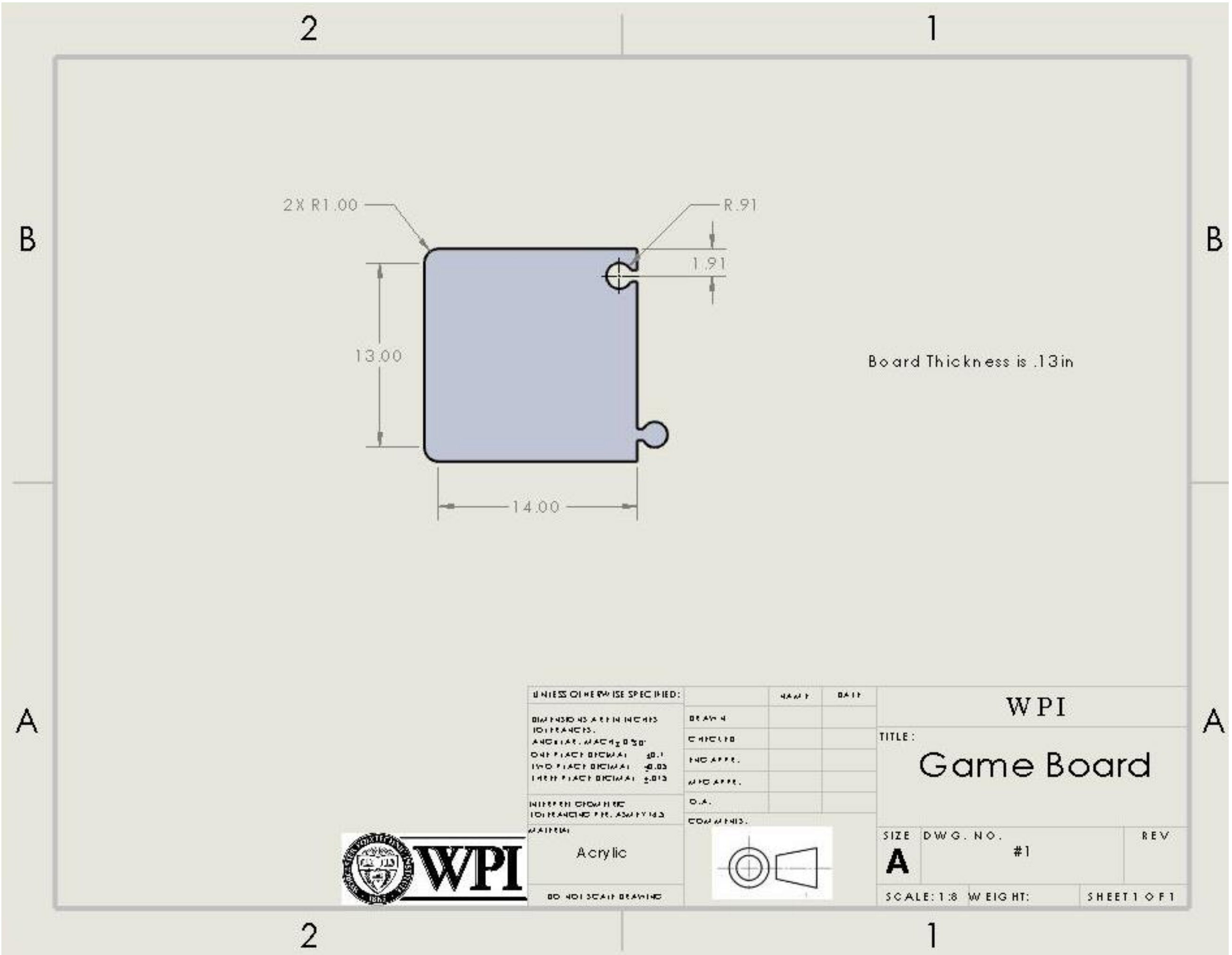
V. Game Rules Refinement

A. The initial rules for the pin game can be found in the appendix. The game with these rules, due to complications with the Covid-19 pandemic, have not been tested. These game rules will need to be tested and refined in order to make sure the game is fair for both teams and the rules maximize fun, teamwork, and competition.

Appendices

A. Part Drawings and Bill of Materials

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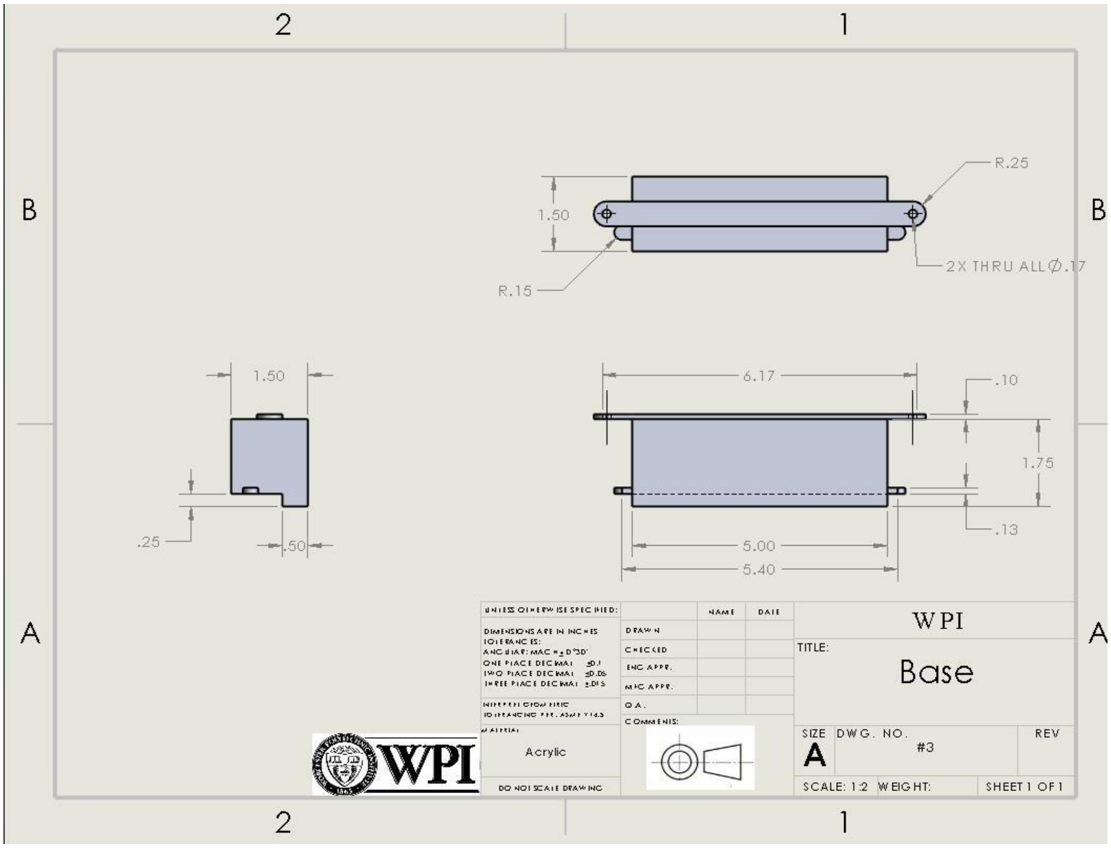
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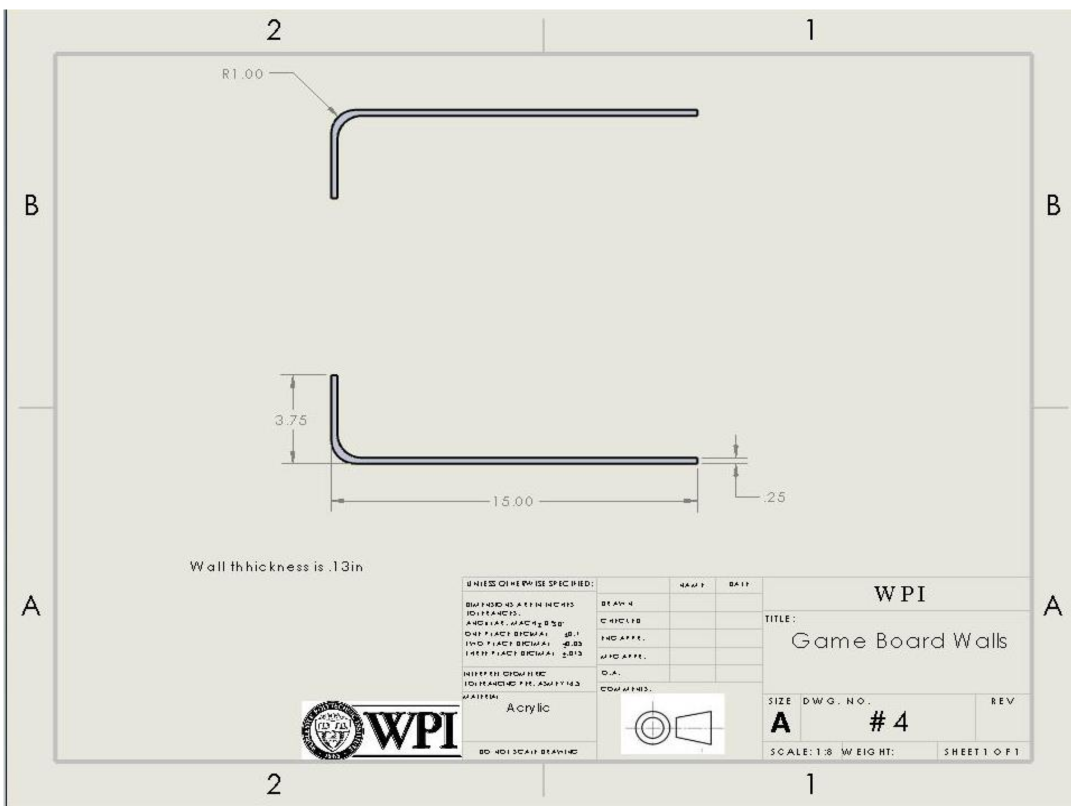
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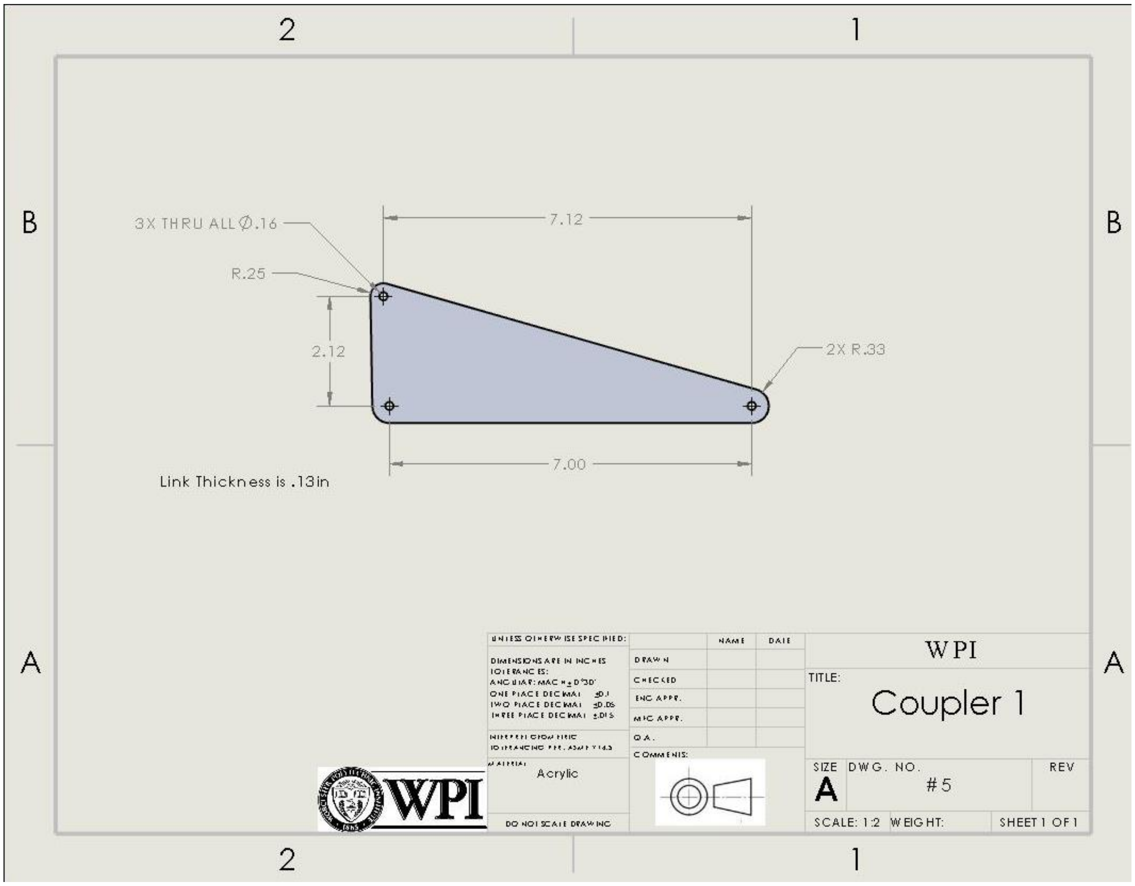
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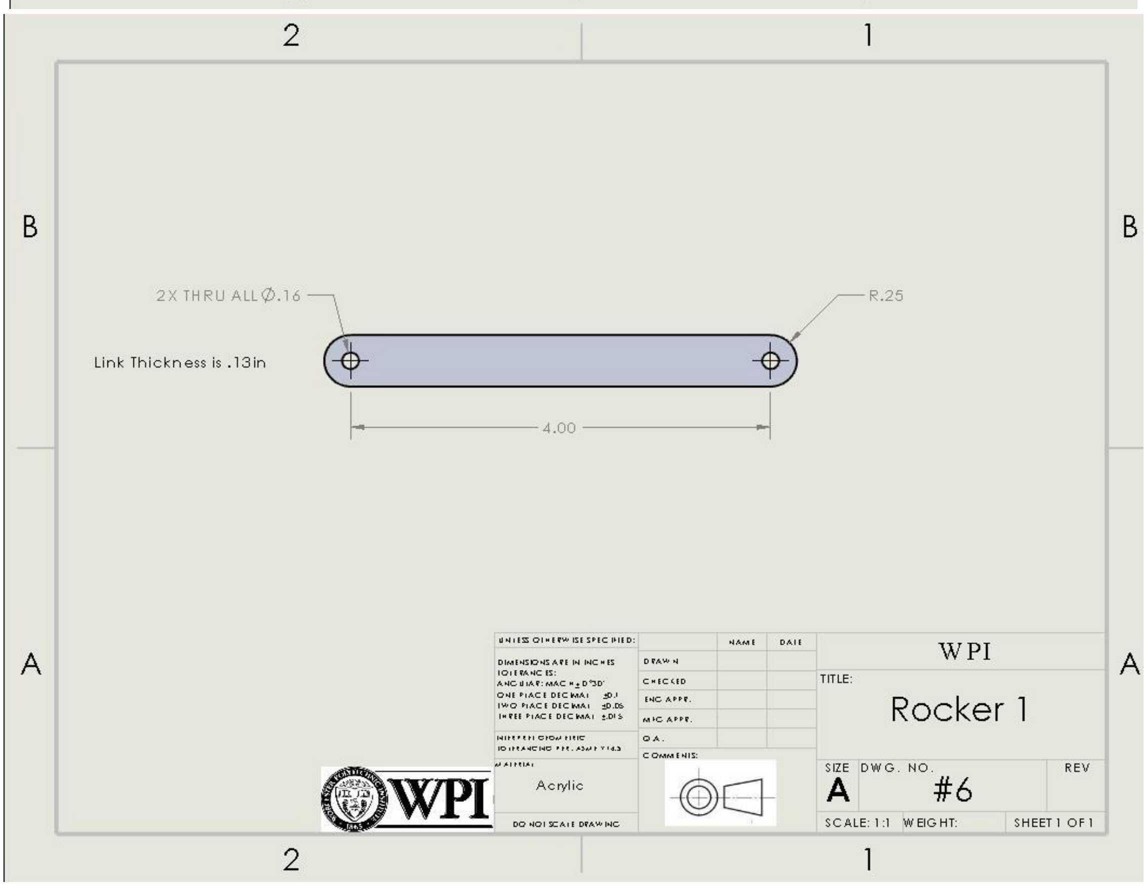
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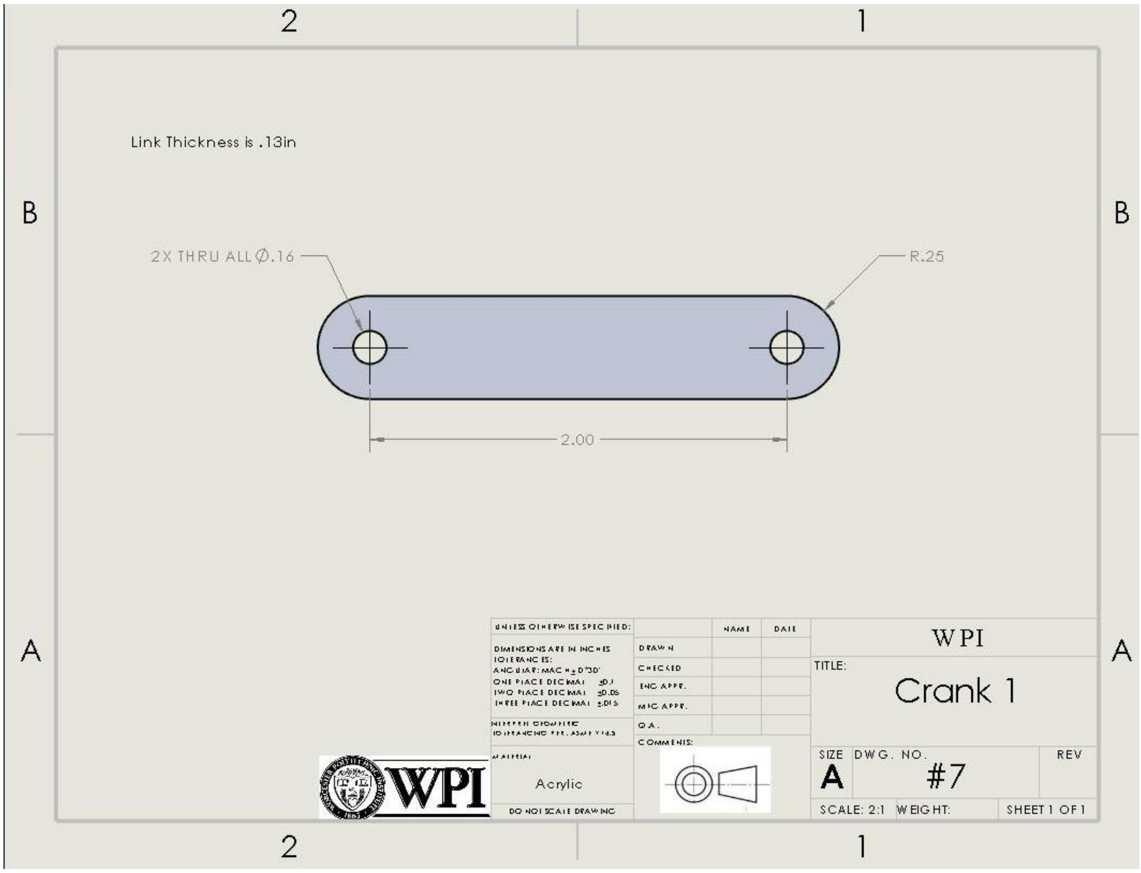
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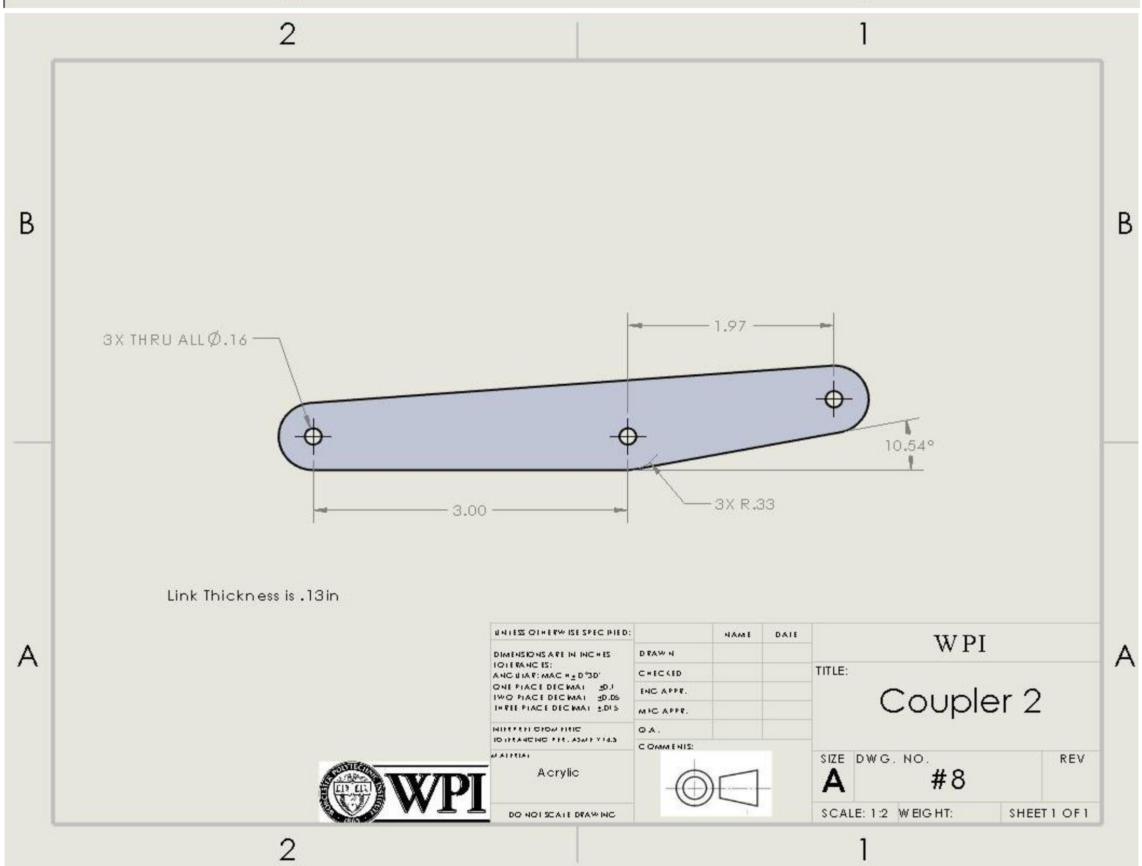
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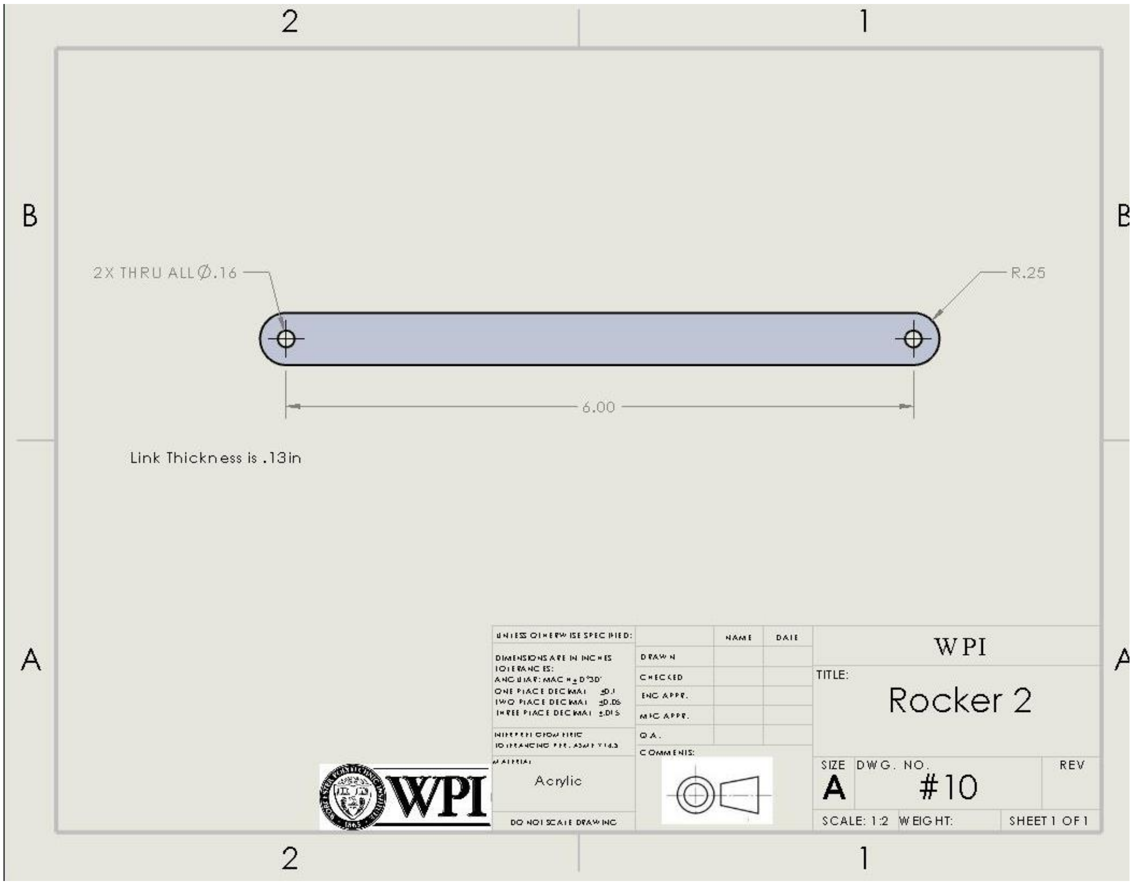
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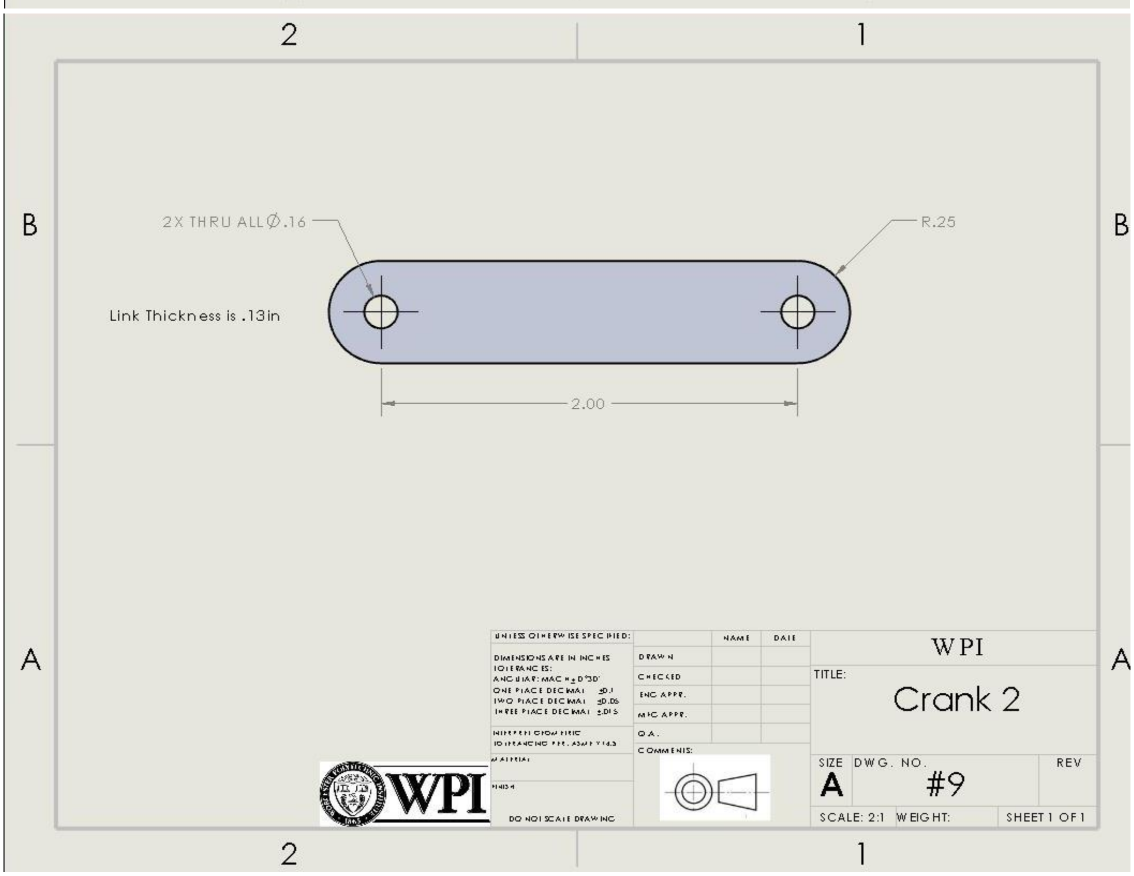
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Table 3: Bill of Materials

Drawing #	**Drawing Title**	**Quantity**	**Description**	**Material**
1	Game Board	2	Game board base layer	Black acrylic
2	Board Top Layer	2	Game board top layer with holes for pins	Black acrylic
3	Base	2	Stand/ground link for all linkages	White PLA
4	Game Board Walls	4	Walls for game board	Black acrylic
5	Coupler 1	2	Coupler for linkage 1	Clear acrylic
6	Rocker 1	2	Rocker for linkage 1	Clear acrylic
7	Crank 1	2	Crank for linkage 1	Clear acrylic
8	Coupler 2	2	Coupler for linkage 2	Clear acrylic
9	Crank 2	2	Crank for linkage 2	Clear acrylic
10	Rocker 2	2	Rocker for linkage 2	Clear acrylic

B. Bibliography

Bagiati, Aikaterini & Evangelou, Demetra (2015). Engineering curriculum in the preschool classroom: the teacher's experience, *European Early Childhood Education Research Journal*, 23:1, 112-128, Accessed October 9, 2019 from https://doi.org/10.1080/1350293X.2014.991099.

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Hrones, John A. and Nelson, George L. *ANALYSIS of the FOUR-BAR LINKAGE: It's Application to the Synthesis of Mechanisms.* Accessed November 5, 2019 from https://moodlearn.ariel.ac.il/pluginfile.php/813361/mod_resource/content/1/Hrones%20and%20Nelson%20Atlas.pdf.

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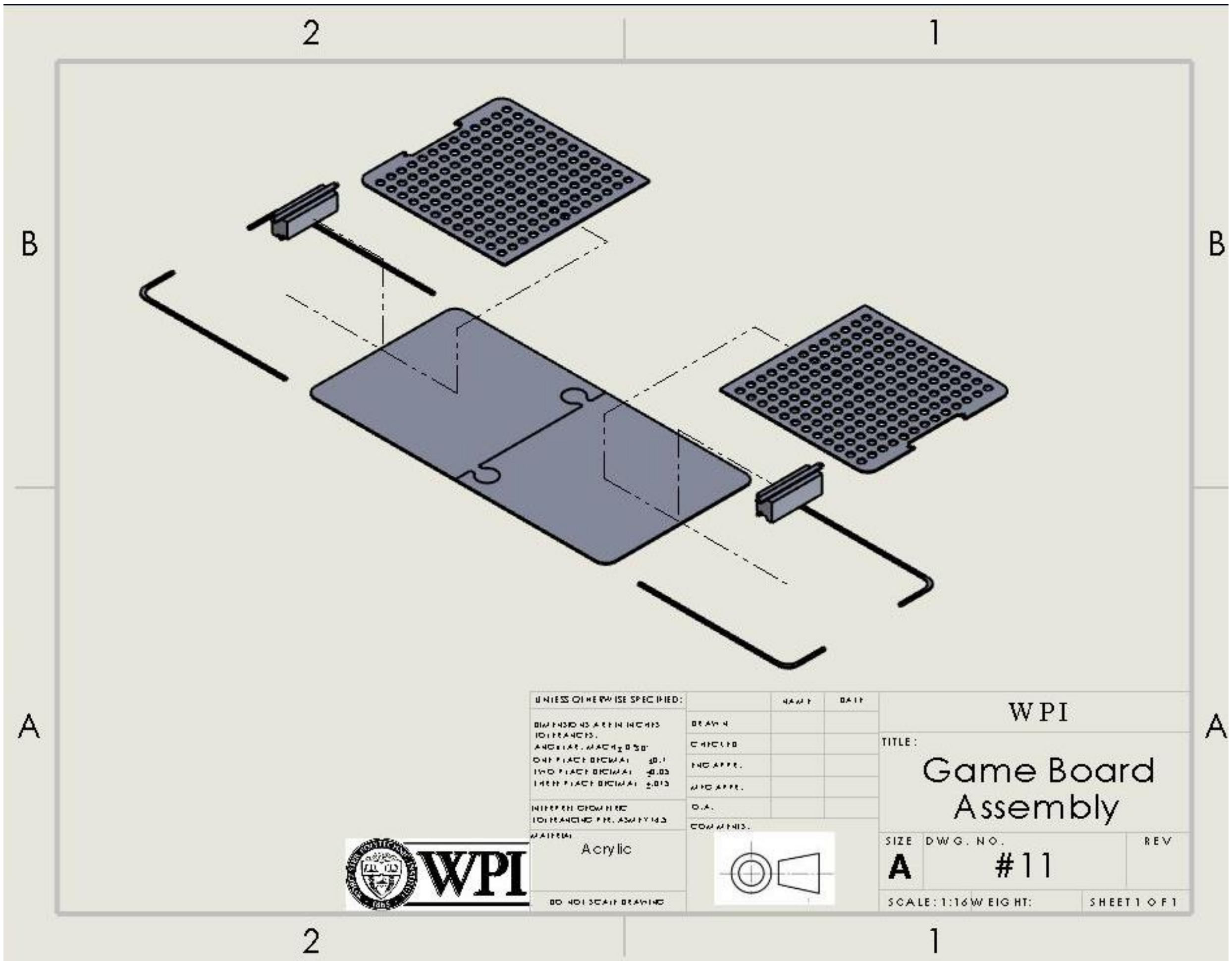
C. Assembly Drawings

Exploded View



D. Pin Game Rules

Two teams of 2 or 3 players each are needed.

1. Assemble the game board as shown in Appendix C.
2. Working with the opposing team, choose an arrangement of any number of pins for each side of the board (all holes do not have to be filled). The point value of each color pin is shown below. Make sure the arrangement is the same for each team.

Table 4: Point Value of each Pin

Color	Point Value
Red	1
Yellow	2
Green	3
Blue	4
White	5
Black	6

3. Each team must select a set of links based on the arrangement of pins that has been chosen. The links are labeled either with an uppercase or lowercase letter. Make sure the letters on all the links in each set match.
4. Both teams should attach their crank and rocker to the ground link, which should be already connected to each end of the board. Then, attach the coupler to the open ends of the crank and rocker with the black connector pegs provided.
5. Make sure your linkage moves freely, with the crank being the only link that makes a full rotation and the ground link being the only link that does not move at all.
6. Attach another connector peg to the last open hole in the coupler. This is what will knock the pins down for each team to score points.
7. When both teams are ready with completed assemblies, rotate the crank 3 full rotations.
8. Each team should then collect all of the pins they knocked, and tally their score based on the chart above. The team with the most points wins the round.
9. A full game consists of 5 rounds. Whichever team wins 3 rounds first wins the game. Between each round, the teams should each choose a new set of links and a new arrangement of pins must be agreed upon.

E. Authorship Page

Justin Carbonneau - Researched and ordered materials for laser cutting and ordered other small parts that were not made at WPI, developed a set of rules for the game, organized bill of materials, and wrote parts of the report (Background, Synthesis and Analysis, Detailed Design Description, and Manufacturing).

Jonathan Han – Developed CAD models of our educational toy, laser-cut and 3D-printed individual parts for assembly, and wrote parts of the report (Abstract, Acknowledgements, Design Concepts, Virtual Testing, and Conclusions and Recommendations).

Michael McCarthy - Researched initial Pin game concepts and educational merits, researched ASTM F963 safety standards for toys, developed the CAD part drawings for the educational toy, and wrote parts of the report (Introduction, Background, Design Concepts, and Design Selections).

F. ASTM F963 Notable Standards

5.11.7 Alternative Labeling Statements for Items Subject to the Requirements of 5.11—Labeling statements on small packages of toys or balloons that have a principal display panel of 15 in.2 or less and that display cautionary statements in three or more languages may appear on a display panel other than the principal display panel if the principal display panel bears the appropriate statement below and bears an arrow or other indicator pointing toward or directing the purchaser's attention to the display panel on the package where the full labeling statement appears.

5.11.7.1 For a toy or game that is or contains a small object, small ball, or marble:

△ SAFETY WARNING

5.16 Promotional Materials—Packaging, literature accompanying toys, and point-of-sale presentations shall not use words, statements, or graphics that are inconsistent in any way with the safety labeling instructions for use or assembly or age grading of the toy.