EDUCATION ON AXIOMATIC DESIGN FOR K-12
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Abstract

Axiomatic Design is a solution to the lack of standard design methodology taught to engineers. Design is an important part of many careers and can apply to everyday problems. Students that are taught Axiomatic Design concepts at a young age will have an advantage with design and engineering in their futures. Most curriculum for Axiomatic Design is currently geared towards college students. This project tests curriculum designed for each age group on Axiomatic Design. The results show a need for specialized material geared towards teaching design concepts to students with a variety of attention spans and first languages. It is clear that this project has produced viable and distributable learning materials for Axiomatic Design.
Table of Contents

1. Introduction .......................................................................................................................... 4
   1.1. Objective .......................................................................................................................... 4
   1.2. Rationale .......................................................................................................................... 4
   1.3. State of the Art ................................................................................................................. 4
   1.4. Approach .......................................................................................................................... 5
2. Decompositions and Constraints ......................................................................................... 5
   2.1. Why we used AD to design our education ..................................................................... 5
   2.2. Constraints considered throughout design ...................................................................... 6
   2.3. FRs and DPs for overall design ....................................................................................... 6
   2.4. CEME evaluation (collectively exhaustive, mutually exclusive) ................................... 6
   2.5. Breakdown for activity ..................................................................................................... 7
   2.6. Various DP ideas for activity ........................................................................................... 7
   2.7. Breakdowns for worksheets ............................................................................................. 8
3. Methods .................................................................................................................................. 8
   3.1. Overall idea ....................................................................................................................... 8
   3.2. Targeted to children .......................................................................................................... 8
   3.3. Targeted for teenagers ..................................................................................................... 9
4. Testing of the Final Products ............................................................................................... 10
   4.1. Testing activities on our own ......................................................................................... 10
   4.2. Obtaining materials for the activities ............................................................................. 10
   4.3. Developing and printing 3D models ................................................................................. 11
   4.4. Presenting to Shrewsbury High School .......................................................................... 11
   4.5. Presenting to Worcester State University secondary education students .................. 12
5. Review of data collected ....................................................................................................... 13
   5.1. Review test results from Shrewsbury High school ......................................................... 13
   5.2. Comments from SHS students and SHS engineering teacher .................................... 13
   5.3. Review critique and Google responses from WSU ....................................................... 13
6. Improvements ....................................................................................................................... 14
7. Discussion ............................................................................................................................... 15
8. Concluding Remarks ............................................................................................................ 16
9. Bibliography .......................................................................................................................... 17
Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slides for grades 4-8 (1)</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>Slides for grades 4-8 (2)</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Slides for grades 4-8 (3)</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>Slides for grades 9-12 (1)</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Slides for grades 9-12 (2)</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>Slides for grades 9-12 (3)</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>Slides for grades 9-12 (4)</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Slides for grades 9-12 (5)</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>Grades 9-12 Test</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>Axiom Worksheet</td>
<td>28</td>
</tr>
<tr>
<td>11</td>
<td>Coupling Worksheet P1</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>Coupling Worksheet P2</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>Coupling Worksheet P3</td>
<td>31</td>
</tr>
<tr>
<td>14</td>
<td>Handout for grades 4-8</td>
<td>32</td>
</tr>
<tr>
<td>15</td>
<td>Handout for grades 9-12</td>
<td>33</td>
</tr>
<tr>
<td>16</td>
<td>SHS review test data</td>
<td>34</td>
</tr>
<tr>
<td>17</td>
<td>WSU survey response 1</td>
<td>34</td>
</tr>
<tr>
<td>18</td>
<td>WSU survey response 2</td>
<td>35</td>
</tr>
<tr>
<td>19</td>
<td>WSU survey response 3</td>
<td>35</td>
</tr>
<tr>
<td>20</td>
<td>WSU survey response 4</td>
<td>35</td>
</tr>
<tr>
<td>21</td>
<td>WSU survey response 5</td>
<td>36</td>
</tr>
<tr>
<td>22</td>
<td>First level overall FRs/DPs</td>
<td>36</td>
</tr>
<tr>
<td>23</td>
<td>Decomposition 1</td>
<td>36</td>
</tr>
<tr>
<td>24</td>
<td>Decomposition 2</td>
<td>37</td>
</tr>
<tr>
<td>25</td>
<td>Decomposition 3</td>
<td>37</td>
</tr>
<tr>
<td>26</td>
<td>Axiom Worksheet Decomposition</td>
<td>37</td>
</tr>
<tr>
<td>27</td>
<td>Coupling Worksheet Decomposition</td>
<td>38</td>
</tr>
<tr>
<td>28</td>
<td>Presenting to SHS</td>
<td>38</td>
</tr>
<tr>
<td>29</td>
<td>Mr. Wood and his Class</td>
<td>39</td>
</tr>
<tr>
<td>30</td>
<td>Class paying attention</td>
<td>39</td>
</tr>
<tr>
<td>31</td>
<td>Cara presenting to class</td>
<td>40</td>
</tr>
<tr>
<td>32</td>
<td>Cara doing iPhone example with class</td>
<td>40</td>
</tr>
<tr>
<td>33</td>
<td>SHS students</td>
<td>41</td>
</tr>
<tr>
<td>34</td>
<td>Chair 1 parts</td>
<td>41</td>
</tr>
<tr>
<td>35</td>
<td>Chairs assembled</td>
<td>42</td>
</tr>
<tr>
<td>36</td>
<td>Students doing worksheets</td>
<td>42</td>
</tr>
<tr>
<td>37</td>
<td>Cara helping student with worksheet</td>
<td>43</td>
</tr>
<tr>
<td>38</td>
<td>Students finishing worksheets</td>
<td>43</td>
</tr>
<tr>
<td>39</td>
<td>Chair 1 Assembly</td>
<td>44</td>
</tr>
<tr>
<td>40</td>
<td>Chair 1 parts</td>
<td>44</td>
</tr>
<tr>
<td>41</td>
<td>Both chairs assembled</td>
<td>45</td>
</tr>
<tr>
<td>42</td>
<td>&quot;Level the boxes&quot; demonstration</td>
<td>45</td>
</tr>
</tbody>
</table>
1. Introduction

1.1. Objective

The objective of this project is to axiomatically design educational modules on Axiomatic Design (AD), observe how effective and useful this education is for a variety of audiences when applied, and adapt these modules based on teacher feedback.

1.2. Rationale

Developing education on AD is useful to society in all areas because “The process by which things are designed influences everything,” (Brown, 2005). Design plays a major role in daily life and the general public does not have a structured method of approaching a design, “An axiomatic approach to design allows engineering design to be taught as a science,” (Brown, 2005). Creating presentations on AD that require no prior knowledge would provide a design solution for any audience and their personal applications (Foley, Harardóttir, 2016). “In Axiomatic Design: Advances and Applications, Suh [2001] states that ‘in the past, many engineers have designed their products iteratively, empirically and intuitively, based on years of experience, cleverness or creativity, and involving much trial and error.’ The same is still true for the design of educational courses or curricula. Although many attempts have been made to model the educational process and formalize methods for the design of courses and course materials, most of this work is still very qualitative and heavily based on experience or case studies” (Hopkins, Thomas, Thompson, 2009). [The importance of teaching at a young age…Making educational materials more available and of value to teachers]

1.3. State of the Art

AD is currently used by some engineers, however it is not commonly used or taught in most STEM fields (Park, 2014). Education on AD is currently structured for a student with background in Linear Algebra and process mapping (Foley, Harardóttir, 2016). Design education for young students does not result in an ability to design on their own because “Current programs do not provide sufficient design experiences to students,” (Mills, Treagust, 2003). Education on AD for engineers has been developed by Nam Suh and other professors for a
course at Massachusetts Institute of Technology (MIT) (Suh, Lee, 2005) and by professor Christopher Brown for graduate courses (Brown, 2005).

1.4. Approach

Compared to the MIT course and YouTube videos on the topic, our approach towards AD Education will be adapted to a variety of audiences and age groups (Suh, Lee, 2005). The need for targeted explanations is important because groups with varying backgrounds who are taught AD will have a method to use to develop solutions to many facets of life. “Developing an integrated knowledge of STEM is essential in K-12 education, as it lays the foundation for a learner to learn more, solve problems, and innovate,” (Krajcik, Delen, 2017). Implementing AD is useful in any career path because it gives a general design process for all problem solvers and gives a method of reviewing and choosing designs (Park, 2014). We will use explanations that can be interpreted by the targeted group and examples that are relatable. These educational sessions will be presented to each group, one group of high school students, and one group of middle school students. Each team will be required to design a part or complete problem-solving activities using AD and will give feedback on their experiences. If successful, the education will be simplified and universal enough for grade school students to understand and apply.

2. Decompositions and Constraints

2.1. Why we used AD to design our education

2.1.1. Basics of AD

Axiomatic Design begins with two main axioms which are kept in mind throughout a design process. The first axiom states “maintain the independence of the functional requirements (FR).” This instructs the designer to try and keep each functional requirement affected by design parameters (DP) which don’t affect other functional requirements. The second axiom states “minimize the information content of the design.” This guides the designer to keep the design simple and only as precise as it needs to be. This raises the probability that the design will perform correctly when manufactured, and will be less likely to fail. Two other main acronyms in AD are customer needs (CNs), constraints (CONs), and process variables (PVs). CNs and CONs outline the basic needs of the design, and CNs can be converted to FRs. Once FRs are listed, DPs are assigned to each FR and then DPs are broken down further into more FRs. This process continues until the design is down to basic parts, or becomes obvious. PVs will be used to determine how to produce or manufacture each DP.
2.1.2. Sources on using AD for abstract problems

Although AD is typically used for the design of physical, manufacturable components, the customer need here was the creation of educational modules about AD for use in K-12. Using AD to design an abstract concept is not unheard of. At the Iceland Academy of the Arts (in collaboration with Reykjavik University's Science and Engineering Department), students paired together to create mechanical masterpieces. This combined creativity with structured concepts of AD (Foley, Harardóttir, 2016). This is similar to using AD to develop educational material because we combined our own creative ideas with necessary FRs.

2.2. Constraints considered throughout design

When designing these learning modules for AD, the first major constraint was cost. Any activities created for the modules have to be cheap enough for most classrooms to have the financial resources to execute them. Another constraint was to design the activities to be portable enough to allow for testing on students and educators in presentations. These portable activities also would need to be performed in only a few minutes as they would be featured only during an hour long presentation. The learning materials used for these presentations should be distributable online for teachers to download or share.

2.3. FRs and DPs for overall design

When breaking down our design, our main FR was to provide an AD curriculum and its DP was an educational seminar. There were FRs at the same level with the same idea as they too were “provide an AD curriculum,” but they specified which age group would be targeted. This made each of their DPs a tailored seminar to that age group. The next level of FRs listed what the seminars had to accomplish. The seminars needed to “provide motive for learning” AD, “teach AD basics,” and “test retained knowledge.” Their corresponding DPs and next level FRs can be found in Figure 23. The lower level FR’s slightly differed in number for some age groups, but many were consistent. The difference raised in their DPs which were chosen to be age appropriate and relatable or comprehensible for the target audience.

2.4. CEME evaluation (collectively exhaustive, mutually exclusive)

The overall design for the curriculum was to provide seminar’s targets to 4 different groups. The groups were ages 6-11, ages 12-18, adults without an engineering background, and adults with an engineering background as shown in Figure 22. This grouping seemed to be collectively exhaustive as it seemed to
encompass all groups which would benefit from learning about AD. Any younger persons would likely not be able to retain or understand the discussed content so it seemed unnecessary to incorporate a younger group. However, as the high level FRs are all aimed at providing curriculums about AD, the design is not entirely mutually exclusive. PowerPoints for different age groups share components in the form of examples and information as they are trying to teach the same topics. Demonstrations visualizing the 1st and 2nd axioms were also shared between age groups as they physically represent fundamental AD concepts in a straightforward manner. A large group activity was also given a framework which could work across age groups while modifying the DPs to improve entertainment value.

2.5. Breakdown for activity

In order to expose the students to all the basic topics of AD simultaneously, a large hands-on exercise was designed. The decomposition of this activity can be found in Figure 25. The activity had to assess the students’ understanding of both axioms, FRs, DPs, CNs, and constraints. There was also an FR to assess understanding of PVs, but could be removed for younger ages. In order to allow fast assessment of the students, the object of their design would have a limited number of materials and options to be made with and therefore could be evaluated with a master spreadsheet. The spreadsheet would allow a teacher to quickly determine the coupling of a design and its information content. It would also aid in evaluating fulfilled FRs by listing what specific DPs are intended to bring to the design.

2.6. Various DP ideas for activity

The large hands-on activity was design to be a framework which allowed for the object being designed to be interchanged to some other simple object. Some simple objects which could be done easily are gummy bears, bouncy balls, and toy cars. These objects are simple enough to be made across two class periods with a day in-between. It was important to make sure the object of design would be interchangeable in order to maximize the activities usage in classrooms. This means the activity cannot be disallowed because of a rule about candy, or cannot be performed because a lack of equipment or materials. Of course the most struggling school districts probably won’t be able to perform this activity even with the simplest object of design. But such a district would have other problems to worry about. If allowed, gummy bears require gelatin, artificial flavoring, and a microwave, all easily attainable for a modern classroom. If not allowed, non-edibles like a bouncy ball is simple enough to create. A slightly more complex object like a toy car can be simplified by using a preexisting architecture like pinewood derby kits or Legos.
2.7. Breakdowns for worksheets

As the performance in the large hands-on activity hinges on understanding of multiple aspects of AD, there was a need to be able to assess the understanding of each idea independently in order to make adjustments to the curriculums accordingly. A worksheet on axioms had FRs for testing the ability to define AD axioms, ability to create a generic axiom, and also recognize generic axioms. The decomposition of this worksheet can be found in Figure 26. There is also a worksheet on coupling which had FRs for testing the ability to differentiate between the different states of coupling, evaluating a given design’s state of coupling, and recall of what made an example design coupled. The decomposition of this worksheet can be found in Figure 27.

3. Methods

3.1. Overall idea

A short educational module will be designed using AD for each age group including a presentation, group discussion, and hands-on design based activities related to the target audience.

3.2. Targeted to children

A simplified presentation will be used with examples related to a popular and humorous cartoon, followed by a design challenge to create a desktop organizer and a feedback session with worksheets. The large hands-on activity would be performed with an appropriate object of design which would be pre-approved by the school, but still keep the attention of the students. The main idea will be a “Design a Candy” challenge. Worksheets containing simplified language would also be used to test understanding in individual aspects of AD. Examples of these can be found in Figures 9-15.

3.2.1. Decomposition realizations and concluding ideas

As shown in Figure 23, an FR of the curriculum for younger students was to provide a reference of terms for them to use as to not get lost during and after the initial presentation. The goal of this FR was to make the understanding of the AD topics independent of the students’ ability to retain trivial terminology. This worksheet can be found in Figure 14. This worksheet provides definitions of fundamental AD terms, explains the two axioms with basic language, and also provides a flowchart on how to apply AD.
3.2.2. Steps taken to develop the materials

The slideshow presentation used for the younger students was a derivation of the high school presentation as the curriculums are similar. The presentation used simplified definitions and reduced text. It also utilized images that demonstrate core AD concepts. Some of these images were just illustrations of coupling examples like the faucet example found in Suh’s *The Principles of Design*. Other images were created in order to illustrate more complicated topics like the importance of lowering information content without trying to explain the concept of tolerancing and manufacturability. SpongeBob macaroni and cheese was used to show a simple design which is created numerous times with a low failure rate. The DeepDream program was then be used to create a render of a highly detailed and accurate macaroni SpongeBob in order to emphasize the idea of information content.

3.3. Targeted for teenagers

For teenagers, a presentation with relatable iPhone design examples and definitions would be given before hands-on design challenges. One of their challenges could be based on a social problem to show how AD can be applied to any facet of life, and keep AD education goals separate from current STEM education programs. We will not fully develop an encompassing activity for teenagers because they have an attention span for longer presentations and lectures. For hands-on learning, we will gear a 3D printed chair activity towards them as a way to visualize the axioms. One chair is designed with more information content than the other, and is therefore more difficult to put together. This can be seen in Figure 41. We will also include the coupling and axiom worksheets (Figures 10-13) and a “level the boxes” activity (Figure 42). The boxes show coupled, decoupled, and uncoupled designs. Each box needs to be leveled, but some are fully connected, completely separate, or one affects the other with a wrench tool.

3.3.1. Decomposition realizations and concluding ideas

While breaking down the education for teenagers, we noticed the presentation will be a major part of their understanding. This led us to use examples that relate to their everyday lives, and FR and DP lists that they can come up with themselves. We added many break points in the presentation to be sure their attention is held. We added pop quizzes and questions such as “Can you come up with an example of a coupled design?” which tests their understanding and brings out misconceptions even when the students believe they fully understand the material. The
solutions to our FRs became obvious early on, so we were able to create the presentation and adapt it as we received advice and found examples.

3.3.2. Steps taken to develop these materials

Our first step to creating materials is our presentation for teenagers. We used a PowerPoint presentation because it is easy to distribute, access, and present. In this presentation, we include pop quizzes and group discussions to break up the lecture time and gauge the students understanding. We then developed our 3D chair and level the boxes activities. Our chairs appear identical and have the same amount of parts, however one has clear uses for each part and the other has parts that are difficult to interpret. This will be created in SolidWorks and subsequently printed. We will also develop boxes using basic hardware parts. The boxes will each have a level, and they will either be fully coupled, decoupled, or uncoupled based on how they are put together.

4. Testing of the Final Products

4.1. Testing activities on our own

Before testing activities on students, we spent time in their shoes to determine what activities would be effective. One idea for a design challenge stemmed from a DP from the breakdown for younger children. The original idea involved building a Lego desk organizer with various customer needs given. Since this idea would require Legos which are expensive, we tried a similar idea with spaghetti and marshmallows. The premise was to build a house for toy animals that required a certain amount of space. Although this idea was much cheaper, it broke easily which did not allow for more complicated CNs such as a second floor. Testing the 3D printed chairs went well. An important part of this was realizing the tolerances of the printer, and how this affected the ability to snap the pieces together. They were fixable by adding tape on pegs that did not fit snugly into the holes. Testing the “level the boxes” activity went well but was not developed on SolidWorks. It used parts that were easy to find: electrical boxes, levels, hot glue, and a wrench. These made it possible for two boxes to be reassembled for each demonstration.

4.2. Obtaining materials for the activities

Developing ideas for inexpensive activities was a limiting factor in our project. We recognize that our curriculum is targeted to any teacher in any community, who unfortunately do not have the budget for Legos and often spend their own money on learning materials. Spaghetti and marshmallows were not strong enough, so we focused on materials that are stronger while still cost effective. Supplies for the boxes can be found at the hardware store for less than $20.
4.3. Developing and printing 3D models

3D printers are becoming more available in public schools. These act as a way to print specific learning materials that would be expensive to buy or make. Our idea for a 3D printed chair puzzle with different information contents is an easy way to distribute learning materials to teachers with 3D printer access. Testing our 3D model showed that not every 3D printer will produce a perfect result, and teachers may have trouble fixing imperfections if we do not take tolerances into consideration. Our first models came out with too much excess material to put them together. We increased the tolerance of the holes and were able to fit all the pieces together with the new print, but because of this tolerance change, some holes were too loose for the pegs and we needed to add tape to provide a good connection. One last improvement to this could be to form a snap fit piece with the shape of a ball joint.

4.4. Presenting to Shrewsbury High School

Paul Wood, an engineering teacher at Shrewsbury High School, allowed us to come to his Principles of Engineering Honors class to present to the students about AD. Overall, this experience proved that the presentation of the data and curriculum is key to the students’ understanding. We presented our slideshow during a 50 minute class section, and the next day we had the students fill out worksheets, do the chair activity, see the coupled box examples, and complete a review quiz. Overall, the students were engaged, the pop quizzes and group discussions proved to hold their attention and interest, and the results from the worksheets and tests showed retained knowledge and understanding. Students were able to explain their answers for the worksheets, and the review quiz sampled in Figure 9 showed an A average for scores and gave thoughtful feedback. Mr. Wood gave us feedback on the presentation because although he was not fully attentive, he was confused about coupling. The presentation of the coupled, decoupled, and uncoupled boxes did not improve his understanding. This could have been because of the way they were presented, because we did not clearly explain that each box needed to be leveled. After discussing it more with him during the worksheets, he was able to understand. This emphasized the need for a strong presenter, or more information in the presentation materials.
4.5. Presenting to Worcester State University secondary education students

Based on the difficulty of finding secondary school class time and our uncertainty of the guided curriculum’s effectiveness, it was decided that a presentation to education majors at Worcester State University focusing on the same age group would be more insightful than visiting a middle school. This way, we would obtain high-level feedback about how to modify the presentation to enhance its educational value. We connected with a professor named Dr. Susan Monaghan for help. The amount of feedback given in person after the presentation signified that an actual presentation would not have gone well. Most of the feedback centered on using less specific vocabulary, not using acronyms so quickly, and using less words in general. They felt the process of AD could be conveyed successfully without the vocabulary being used at all. Another reason for less vocabulary was because of the lower than expected percentage of U.S. students speaking English as a 1st language (typically 50% according to Dr. Monaghan). We did not have the time to fully perform the hands-on activity, but we were able to explain it. They felt it was a good start, except it would require the help of a teacher’s assistant, which is a difficult resource for some schools to have. They also mentioned removing the idea of eating because of sugar and allergy restrictions in classrooms. We had a working version of the information content chair activity which we were able to test on the students. We gave two groups a different version of the chair and in less than 30 seconds, one group was able to assemble the chair without even knowing what it was. The second group was given as much time as they wanted until they were frustrated and gave up. Once the second chair was assembled correctly and they saw the chairs were exactly the same, just differing in complexity of assembly, they felt that they had a better grasp of information content. They advised us that similar activities are exactly the type of hands-on experiences that students would highly benefit from over a wordy PowerPoint. They also recommended that if a PowerPoint is going to be used, it should feature inquiry based learning in the form of guiding questions. A child is more likely to retain a definition if they saw the concept and tried to derive their own meaning before they are given the actual definition. One example would be doing the chair activity before discussing the idea of information content. These methods provoke curiosity in the child that drives them to learn.
5. Review of data collected

5.1. Review test results from Shrewsbury High school

The average test score for the students was an A as shown Figure 16. Overall, this shows the students retained the data they learned and could provide realistic examples showing understanding of the topic. We also asked the students if they would use AD for a project, and why. Most students agreed it was a good method and stated it would be useful to them in developing a design. Few students were still confused by it, and some still prefer “winging it” when it comes to their design.

5.2. Comments from SHS students and SHS engineering teacher

Students from the presentation at SHS were very driven to learn about AD because they immediately accepted the need to learn a design method as future engineers. The class they are taking, Principles of Engineering Honors, requires some engineering background or skills in other sciences, per teacher’s signature. With this in mind, we were not surprised to see an eager audience. During the presentation, students came up with thoughtful ideas of coupled designs. Two ideas that stood out were videogames where a button caused you to jump and move forward at the same time, and a display that is warmed by a heating pad and lit by a warm lamp which affects temperature (decoupled). Students asked questions to ensure they understood, and were able to provide reasons for their answers to the pop quiz sections. During the iPhone example, students were able to come up with FRs and match reasonable DPs to them without prompting. Comments we received about lack of understanding was mostly towards the idea of coupling, especially decoupled designs. They felt that physical examples were necessary and helpful. Mr. Wood, the teacher, was overall happy with the presentation and how engaged his students were. He felt that the session was helpful to them and their future assignments in his class, and a useful tool for their futures in engineering.

5.3. Review critique and Google responses from WSU

WSU provided useful insight and ideas on how younger students would react to the presentation and how to engage them. Most of the students in the WSU class participate in activities with secondary school classrooms geared towards STEM learning. They have seen firsthand that students often struggle with understanding rich vocabulary, yet can learn and apply the concepts. The vocabulary is easier to remember once the students can relate it back to a solidified concept. WSU students provided alternative ideas such as toys that show examples of coupling, toy cars to use as models while discussing them as an
example, and more 3D printed designs as examples. From the google form, we do not have each student fully on board for hypothetically using this AD curriculum in their future classrooms. Students hoped to see less vocabulary, more activities like the chairs, and an activity like designing a candy that is more classroom friendly.

6. Improvements

A crucial change which should to be made in order to improve the curriculum for younger students is the lessening or removal of the curriculum’s dependence on vocabulary. The understanding of the curriculum is coupled to the language it is written in. In order to decouple them, the curriculum cannot rely on PowerPoints as much as it currently does. More activities which causes a student to think abstractly and independent of a spoken language will have to be created.

In order to grab a student’s interest at the beginning of the presentation, hands-on activities should come before any form of PowerPoint or worksheet. This way, students are already coming up with questions and forming a framework of understanding which the rest of the presentation can formalize and reinforce. The current curriculum begins with a PowerPoint which worked with high school students, but younger students will have a more difficult time trying to absorb the same amount of information without having seen a physical manifestation or conceptualization.

The PowerPoints from this curriculum could easily be formatted into worksheets or study guides, and yet not gain any educational value. No matter what form the information from these PowerPoints take, the information should be given to the students in the form of guiding questions. Students should have a basic concept of what they are trying to learn about in an activity before formally being told what the concept is.

In order to decouple the understanding of this curriculum from the language it is written in, there should be more activities and visuals which don’t heavily rely on AD vocabulary. According to the American Community Survey in 2016, about 21% of people aged five years of or older don’t speak English at home, rather some other 1st language. This means that in order to maximize this curriculum’s effectiveness and reception in K-12, it must be able to convey its ideas independent of the students’ language.

Activities need to be designed to be adaptable to differing regulations on food, or perhaps choose a range of foods to be utilized in an activity. Or an activity should not focus on food and can be performed using equipment that schools have deemed safe for use in a classroom.
Activities should use cost-effective materials and be carried out with as few adult hands as possible. This will maximize usage of the curriculum as it can be adapted into even the tightest school budgets.

7. Discussion

At the start of our project, we had some unrealistic expectations of teaching AD to K-12. We were not familiar with education styles tailored to specific age groups, and education for AD is currently geared towards college level. It seemed easy to simplify the material enough for younger ages to understand, however we quickly learned from research that attention span and learning style must be taken into consideration. Inquiry based learning was the most important recommendation from Dr. Monaghan because young children need to be curious about a topic to motivate them to learn.

Students are learning to read, rather than reading to learn until 5\textsuperscript{th} grade. This creates a challenge for any area of study outside of reading and writing to worm its way into early education. The education system wants to utilize this time in a child’s life as their brain will be forming connections they will use for the rest of their life. It then makes sense that the focus on reading and writing is important as everyone should be able to do both without much thought in order to lead an independent life in modern society. If this AD curriculum were made to be accessible to children in these pivotal mental development years, it could have the potential to improve analytical thinking among Americans if not only improve performance and interest in STEM.

In AD, DPs can become “obvious” when breaking them down becomes more of a redundancy than an aid. When we broke down our educational material, it became too redundant to break our PowerPoint into individual slides and bits of information. Some things were helpful, like adding certain sections or examples, but it was not necessary to break down each slide. It became more necessary to break down parts of our activity, such as what parts and materials we would need for the Design a Candy activity.

Teachers and education majors found the vocab of the AD curriculum to be slightly confusing and would be too wordy for a younger student to pay much attention too. A rule of thumb in education is that a teacher only has a student’s attention for as long as the student’s age. This means that a 5\textsuperscript{th} grader would have only about 10 to 11 minute long attention span. In Kindergarten, a student only has about 5 minutes. This means that even shortened PowerPoints are no match for the limited attention span of a young student. If vocab is minimalized and amount of activities increased, then AD topics will be more effectively communicated and retained.

This project could be continued in many directions. We did not get to explore the full spectrum of ages K-12, as we did not touch on kindergarten/elementary level students. At this age, the most important step would be to remove all vocabulary and focus on challenges that could solidify design concepts into a developing and curious mind. We also did not expand this to non-engineering majors and working engineers that
were never introduced to AD. These groups could all use AD in their current lives and futures.

A video series targeted to younger students would have the benefit of being able to perform demonstrations without having a teacher needing to acquire the materials or learn how to perform them. Limitations would come about if the successors of this project were to only provide videos as the benefits of hands-on experience through activities would be lost.

8. Concluding Remarks

The main challenge of this project was to develop education that suits the needs of today’s classroom and teachers. Necessary materials must be kept to a minimum, taking advantage of computers and 3D printers teachers have access to. Activities and education must cater to a diverse group of students, included English language learners, students with special diets, and special needs.

As we attempt to target this education to younger groups of students, their attention span gets lower and lower with age. Because of this, we must focus more on learning and understanding concepts with breaks in between discussing material to test understanding. Long lectures and PowerPoints with no breaks only hold students' attention for an average of ten minutes.

It is clear that we were successful in teaching high school students AD concepts, and in developing material that could be used for secondary school students. We have measured our success by evaluating grades and comments from both demonstration groups, and although there are areas to improve upon, we have overall reached our goal with this project.

Despite our efforts, our project was not completely successful in the sense that some of our materials need improvement for younger audiences, and the project could always be improved upon. The comments and feedback from WSU showed that we were not completely successful in tailoring our materials to secondary students, so further developments are necessary before the material could be sent to secondary school teachers or used in their classrooms.

Our largest area of improvement is our curriculum for secondary school students. Our presentation should be broken up into even smaller chunks based on the age of the students, and should include time to discuss, small design challenges, and more group activities in those breaks. The activity is the right type of learning tool for them, but it could be done with better synonyms for the vocabulary and needs to be altered for classroom safety and dietary requirements. Using similar materials, the activity could be changed to “design a bouncy ball”. This project should be explored further and altered in future years because STEM classrooms are changing, and there can always be improvements made and more activities developed.
9. Bibliography


9.22. Wettasinghe, C. & Koh, T. 2007, The analysis, comparison, and redesign of curriculum for special education using the principles of axiomatic design, ACM.
10. Appendices
10.1. PowerPoint for Grades 4-8

Axiomatic Design

By Cara Freedman and Spencer Howes
For grades 4-8

What is Design?
Is design based on art or science?
How do you come up with an idea to solve a problem? Using creativity?
Can Axiomatic design solve this challenge to create a general, step-by-step method for design?

What is an Axiom?
An axiom is a statement or rule that is thought to be obviously true.
In other words an axiom is a statement that everyone agrees on in order to discuss something or play a game.
For example, rules in games are self-evident truths which require no proof because they must be accepted in order to play the game correctly.

Axiomatic Design: The basics
- Two main Axioms (rules) are kept in mind throughout the process
  - CWS – what the customer wants
  - CCW – what needs to be avoided
- FRs – what it does
- DPs – what it looks like
- Zigzagging – back and forth creation of FRs and DPs
- PVS – how you make it

The Two Axioms
- The Independence Axiom
  - Actual Definition: Maintain the independence of the functional elements.
  - Meaning: Keep the use of each part separate.
- The Information Axiom
  - Actual Definition: Minimize the information content.
  - Meaning: Keep it simple, silly!

Figure 1 - Slides for grades 4-8 (1)
FRs, CNs, CONs
To begin our design, we must start with the Customer Needs, or CNs. From there, we come up with Functional Requirements (FRs) and Constraints (CONs). Not every FR will come from the list of CNs, most FRs serve purposes that the customer may not have thought of.

Constraints are kept in mind throughout the design process.

POP QUIZ
Which is an example of an axiom?

a. The sky is green
b. The sky is blue
c. How are you?
d. Pass go, collect $200

DPs
Each FR is assigned a Design Parameter, or DP. DPs are a noun (person, place or thing), which suits the need of the FR which is typically a verb (action).

Example
An FR (action) might be to spin, and the corresponding DP (noun) might be a wheel.

Zigzagging
In order to fulfill each FR of a design, the designer must go back and forth between coming up with FRs and coming up with DPs. This is because the first "level" of FRs may be very general, and as DPs are assigned, more specific requirements are discovered.

Example: Zigzagging
If a designer wants to plan their design for a way to get around their city, they may start with their first FR as "To get around the city". That DP could be "A car". It could also be "A bike", or "A train" or maybe a new type of vehicle they want to invent.

Now, he has to come up with more FRs to create more DPs. For example, this car needs "to turn" and "to accelerate" and "to stop". In turn, he can make more DPs to fit these FRs, such as "a wheel", "an engine", or "brakes".

Figure 2 - Slides for grades 4-8 (2)
10.2. PowerPoint for Grades 9-12
Axiomatic Design

By Cara Freedman and Spencer Howes
For grades 9-12

Today’s Plan

Objective:
To learn about Axiomatic design, how to use it, and see examples of this method in action.

Presentation:
This slideshow includes each piece of Axiomatic design, defines the term ‘axiomatic’, and shows how each component works up to a final design.

Why we care:
Honing a step-by-step process to help approach a design or problem is extremely useful in the STEM community, and could be a useful way of thinking in any daily challenge.

About Us

Spencer Howes - Robotics Engineering Student
- From Granby, CT
- Goes to WPI
- Builds Robots
- Uses design at school, work, and home

Cara Freedman - Mechanical Engineering Student
- From Shrewsbury, MA
- Goes to WPI
- Uses design at school, work, and home
- Works on lasers
- Attended Engineering courses at SHS

The Origins of Axiomatic Design

Where it came from:
- Dr. Nan P. Sun
- Past MIT MED Department Chair
- Past Engineering Director at the NSF
- Currently President of KAST
- Honorary doctorate from WPI

Dr. Sun developed the two axioms in the 70’s to improve design and develop Axiomatic Design

Why we care:
Design plays a role in everyone’s life, regardless of career or hobbies.
Axiomatic Design can be applied to engineering, art, various workplaces, personal projects, and even social issues.
Knowledge on Axiomatic Design gives any designer the upper hand in approach and organization.

What is Design?

Is design based on art or science?
Can you design using the Scientific Method? If so, how do you come up with your hypothesis? Using creativity or artistic thinking?
How do we teach design without a science-based structured methodology?
Can Axiomatic design solve this challenge to create a general, step by step method for design?

State of the Art: Engineering Design

Algorithmic Approach
- Assumes:
- Correct process yields good result
- Requires:
- Iteration (trial-and-error)
- Evaluation:
  - by experience

Axiomatic Approach
- Assumes:
  - Two axioms, or “rules”, are true
- Requires:
  - Decompositions (hierarchical structures)
- Evaluation:
  - by test parameters and axioms

Figure 4 - Slides for grades 9-12 (1)
What is an Axiom?

An axiom is a statement or proposition that is regarded as being established, accepted, or self-evidently true.

In other words, an axiom is a statement that all parties agree on in order to form a logical argument.

For example, rules in games are self-evident truths which require no proof as they must be accepted in order to play the game correctly.

POP QUIZ

What is most necessary before the design process?

a. Testing  
 b. Analysis  
 c. Prototypes  
 d. Research

Axiomatic Design: The basics

- Two main Axioms are kept in mind throughout the process
- CNs – what the customer wants
- CONs – what needs to be avoided
- FRs – what it does
- DPs – what it looks like
- Zigzagging – back and forth from FRs and DPs
- PVs – how you make it

The Two Axioms

The Independence Axiom
Definition: Maintain the independence of the functional elements.
Simplification: Keep the use of each part separate.

The Information Axiom
Definition: Minimize the information content.
Simplification: Do not overcomplicate any part of the design.

FRs, CNs, CONs

To begin a design, we must start with the Customer Needs, or CNs.
From there, we develop Functional Requirements (FRs) and Constraints (CON).

Not every FR will come from the list of CNs, most FRs serve purposes that the customer may not have thought of.
Constraints are kept in mind throughout the design process.

POP QUIZ

Which is an example of an axiom?

a. The sky is green  
 b. The sky is blue  
 c. How are you?  
 d. Pass go, collect $200

Figure 5 - Slides for grades 9-12 (2)
**DPs**

Each FR is assigned a Design Parameter, or DP. DPs are typically defined by a noun, which suits the need of the FR, which is typically defined as a verb. For example, an FR might be to rotate, and the corresponding DP might be a spinning motor.

**Zigzagging**

In order to fulfill each FR of a design, one must go back and forth between coming up with FRs and coming up with DPs. This is because the first level of FRs may be more general, and as DPs are assigned, more specific requirements are discovered.

**Example: Zigzagging**

If a designer wants to plan their design for a way to get around their city, they may start with their first FR as “To get around the city.” Their DP could be “A car.” It could also be “A bike” or “A bus” or maybe a new type of vehicle they want to invent.

Now, he has to come up with more FRs to create more DPs. For example, this car needs “to start” and “to accelerate” and “to stop.” In turn, he can make more DPs to fit these FRs, such as “a v1.0,” “an engine” and “a motor.”

**Smartphone Group Example:**

<table>
<thead>
<tr>
<th>FRs</th>
<th>DPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To improve battery life</td>
<td>1. 20 mA battery</td>
</tr>
<tr>
<td>2. To improve functionality</td>
<td>2. 12 MP camera</td>
</tr>
<tr>
<td>3. To improve gaming experience</td>
<td>3. 3 GB RAM</td>
</tr>
<tr>
<td>4. To improve performance</td>
<td>4. 5.7” 1080p Display</td>
</tr>
<tr>
<td>5. To improve battery life</td>
<td>5. Snapdragon 855</td>
</tr>
<tr>
<td>6. To have better camera</td>
<td>6. Dual 12MP camera</td>
</tr>
<tr>
<td>7. To have a better gaming experience</td>
<td>7. Wi-Fi 6x6 MU-MIMO</td>
</tr>
<tr>
<td>8. To have a better battery life</td>
<td>8. 35W fast charging</td>
</tr>
<tr>
<td>9. To have a better gaming experience</td>
<td>9. NFC</td>
</tr>
<tr>
<td>10. To have a better camera</td>
<td>10. GPS</td>
</tr>
<tr>
<td>11. To have a better battery life</td>
<td>11. 4G LTE</td>
</tr>
<tr>
<td>12. To have a better gaming experience</td>
<td>12. IP68 water resistance</td>
</tr>
<tr>
<td>13. To have a better battery life</td>
<td>13. IP68 dust resistance</td>
</tr>
</tbody>
</table>

**PVs**

When developing a design, another key aspect is how each parameter is going to be created. Process Variables (PVs) describe this for each parameter.

In other words, this is how each part of your design will be manufactured.

**POP QUIZ**

Which comes first?

a. Process Variable          b. Functional Requirement
c. Test Parameter           d. Design Parameter

---

Figure 6 - Slides for grades 9-12 (3)
**Faucet-What is Coupling?**

**Uncoupled:**
Water flow and temperature are controlled by DIFFERENT motions; moving the lever side to side changes temperature.

**Coupled:**
Water flow and temperature are controlled by the **SAME** motion; moving the hot lever forward increases flow while increasing heat, AND moving the cold lever forward increases flow while lowering temperature.

---

**Christmas Light Wiring**

"One goes out, they all go out"

When Christmas lights are wired in series, strand failure is coupled with bulb failure.

This means that if anyone one bulb in the strand goes out, they all go out.

Most modern Christmas lights are wired in parallel which uncouples strand failure with bulb failure.

This allows for the strand to continue working even if a bulb is out.

---

**Refrigerator Doors**

**Functional Requirements:**
- FR₁: Allow access to food inside
- FR₂: Minimize energy loss

**Parameters:**
- DP₁: Vertically hung door
- DP₂: Thermally insulated

**Horizontal Door Design Parameters:**
- DP₁: Horizontally hung door
- DP₂: Thermally insulated

---

**Refrigerator Doors Analysis**

**Uncoupled Design**

**Coupled Design**

---

**Discussion:**
Can you come up with an example of a coupled design?

---

**Information Content**

**EXAMPLE:** Mac and Cheese

Why is Spongebob shaped Mac and cheese shaped like this:

Instead of this:

---

*Figure 7 - Slides for grades 9-12 (4)*
Figure 8 - Slides for grades 9-12 (5)

10.3. Grades 9-12 Test
Review Quiz

1. Define axiom in your own words: __________________________________________

2. Select the two axioms in Axiomatic Design:
   a. Maintain Independence
   b. Maintain Political Correctness
   c. Minimize Information Content
   d. Minimize Potential Content
   e. Maximize Potential Content

3. Match the acronym to its definition:
   1. ___ CN  A. What is does
   2. ___ CON  B. Back and Forth
   3. ___ FR  C. What it looks like
   4. ___ DP  D. How you make it
   5. ___ Zigzag  E. What the customer wants
   6. ___ PV  F. What needs to be avoided

4. What are three examples of designs that could be drafted using the Axiomatic Design process? __________________________________________

5. What does it mean when a design is coupled? ________________________________
   ________________________________________________________________

6. Could you see yourself using Axiomatic Design for a project at school? Why or why not? __________________________________________
   ________________________________________________________________

Figure 9 - Grades 9-12 Test

10.4. Worksheets
Name:______________ Date:______________

Axiom Review

1. Circle the two axioms used in Axiomatic Design.
   
   A. Maintain Independence  
   B. Maximize Profit  
   C. Minimize Information  
   D. Minimize Waste  
   E. Maximize Followers
   
2. Write one example of an axiom not used in Axiomatic Design.

________________________________________________________________________

________________________________________________________________________

3. Circle all examples of axioms.

   A. Pass go, collect $200  
   B. The average height of an adult man is 5'9  
   C. There are 27 bones in a human hand  
   D. If a=b and b=c, then a=c  
   E. The sun rises from the east  
   F. Two parallel lines never bisect each other  
   G. Humans lay eggs

Figure 10 - Axiom Worksheet
Design Coupling Review

1. Label each of the following designs with ‘coupled’, ‘uncoupled’, or ‘decoupled’.

![Diagram of two designs]

**FR:** Allow access to food inside
- Design 1: Uncoupled
- Design 2: Decoupled

**FR:** Minimize energy loss
- Design 1: Uncoupled
- Design 2: Coupled

*Figure 11 - Coupling Worksheet P1*
2. Circle the faucet design that is coupled.

3. Fill out the following design tables with X's where DPs and FRs interact. Determine if the designs are coupled, uncoupled, or decoupled.

*Figure 12 - Coupling Worksheet P2*
Figure 13 - Coupling Worksheet P3

10.5. Grades 4-8 Handout
Axiomatic Design
A design method to use on any problem or project

Definitions
Axiom: A truth or rule that can’t be proven wrong
CN: Customer Need: What the “customer” (sometimes yourself) wants the design to do
FR: Functional requirement: What the design (or part of the design) will do
DP: Design Parameter: A part of the design that carries out an FR
PV: Process Variable: How a part is made
Zigzagging: Repeatedly breaking down DPs into FRs and creating a DP for each new FR until the DPs are basic parts
Coupling: Using the same DP to fit multiple FRs

The Axioms Explained
1. Maximize the independence of the functional elements.
   This axiom tells us to avoid coupling our design. The design parameters (or features) should each serve their own function.
2. Minimize the information content.
   Information content can be thought of as restrictions on parts of the design. Less restrictions allow for more options to improve our design

How to Apply
Follow the flow chart on the back side of this page. Apply the axioms and your constraints throughout the design process.

Figure 14 - Handout for grades 4-8

10.6. Grades 9-12 Handout
Axiomatic Design

Definitions
Axiom: A statement or proposition accepted as true and agreed on by all parties in order to form a logical argument
CN: Customer Need: Objectives which the customer wants the design to fulfill (What it should do)
FR: Functional requirement: A specific requirement to fulfill a design objective (What it does)
DP: Design Parameter: A physical embodiment of an FR (How it does it)
PV: Process Variable: A method for the creation of a DP (How it’s made)
Zigzagging: Working back and forth between FRs and DPs
Coupling: Using the same DP to fit multiple FRs

The Axioms Explained
1. Maximize the independence of the functional elements.
   This axiom tells us to avoid coupling our design. The design parameters (or features) should each serve their own function.
2. Minimize the information content.
   Information content can be thought of as restrictions on components of the design. Restricting only when necessary allows us to choose from a wider range of design parameters, allowing more options to optimize our design.

How to Apply

Follow the flow chart on the back side of this page. Apply the axioms and your constraints throughout the design process.

Figure 15 - Handout for grades 9-12

10.7. Shrewsbury High School Test Results
Figure 16 – SHS review test data

10.8. Worcester State University Feedback

Would you consider teaching Axiomatic Design in your classroom?

4 responses

Figure 17 – WSU survey response 1
Why or why not?
4 responses

- A more simplified version without the emphasis on vocabulary.
- It is an interesting way to teach students about the steps it takes and what to consider when making something.
- I think it is very inquiry based and hands on. It allows students to be creative while engaging in science material.
- I chose maybe because it really depends on the grade level I’m working with and what adjustments could be made to make it more understandable for younger grades.

Figure 18 - WSU survey response 2

What types of learning materials would you like to see added to this curriculum?
3 responses

- Relate more to the curriculum and MA standards, show what standards that the lesson is relating to.
- Toy cars when discussing them. Maybe a prototype of a design you have made that is more advanced and can be explained easily to the children.
- I feel that more hands-on materials would be really beneficial for some students, especially young students or ELLs, because they can sometimes learn more from using their hands. Additionally, it would help with the language barrier between some students that their first language isn’t English.

Figure 19 – WSU survey response 3

Do you feel it is important to teach a structured method for design in grades K-12?
4 responses

- Yes, but more in a way without them knowing. For example, begin designing or building something and have them explain why they chose certain decisions or materials.
- Yes, however it should be modified for each grade. Even if you are not calling the lesson exactly what it is to the students, simplifying the process and the vocabulary.
- Yes, many students do not understand how to design and build things. They might think it’s too difficult but by teaching this method it breaks it down to simpler steps for all to understand and follow.
- I feel that it is an important topic to teach students because all their life they will be working with simple machines and constructing objects. But I feel the information content needs to be reduced as much as possible and put in simpler terms for younger students to really benefit from this activity.

Figure 20 – WSU survey response 4
Please leave any additional feedback or ideas for us below.

1 response

For an activity you could have students design and build a car (instead of candy due to allergies, etc.). This car could be raced or tested to make sure it actually has what the customer needs.

Figure 21 – WSU survey response 5

10.9. Acclaro Decompositions

<table>
<thead>
<tr>
<th>0</th>
<th>Provide AD curriculum</th>
<th>Educational seminar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Provide AD curriculum to ages 5-11</td>
<td>Seminar targeted to ages 5-11</td>
</tr>
<tr>
<td>2</td>
<td>Provide AD curriculum to ages 12-18</td>
<td>Seminar targeted to ages 12-18</td>
</tr>
<tr>
<td>3</td>
<td>Provide AD curriculum to ages 10+ without background</td>
<td>Seminar targeted to 10+ without background</td>
</tr>
<tr>
<td>4</td>
<td>Provide AD curriculum to engineers 18+</td>
<td>Seminar targeted to 18+ with engineering background</td>
</tr>
</tbody>
</table>

Figure 22 – First level overall FRs/DPs

<table>
<thead>
<tr>
<th>0</th>
<th>Provide AD curriculum</th>
<th>Educational seminar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Provide AD curriculum to ages 5-11</td>
<td>Seminar targeted to ages 5-11</td>
</tr>
<tr>
<td>1.1</td>
<td>Provide motivation for learning</td>
<td>Examples with Teenage Mutant Ninja Turtles (TMNT)</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Show why I am teaching design</td>
<td>Description of me and my engineering background</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Motivate children to be designers</td>
<td>Relation of engineers/designers to “Inventors”</td>
</tr>
<tr>
<td>1.1.3</td>
<td>Relate AD to age specific lifestyle</td>
<td>Clubhouse design example</td>
</tr>
<tr>
<td>1.1.4</td>
<td>Provide entertainment</td>
<td>Jokes and common character catchphrases</td>
</tr>
<tr>
<td>1.2</td>
<td>Teach AD basics</td>
<td>Powerpoint presentation with handout</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Teach axioms</td>
<td>Axioms reworded with simpler language</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Teach CNs</td>
<td>TMNT example of CN</td>
</tr>
<tr>
<td>1.2.3</td>
<td>Teach FRs</td>
<td>TMNT example of FR</td>
</tr>
<tr>
<td>1.2.4</td>
<td>Teach DPs</td>
<td>TMNT example of DP</td>
</tr>
<tr>
<td>1.2.5</td>
<td>Teach difference between FR and DP</td>
<td>TMNT comparison/constraint example</td>
</tr>
<tr>
<td>1.2.6</td>
<td>Teach zigzagging</td>
<td>TMNT decomposition example</td>
</tr>
<tr>
<td>1.2.7</td>
<td>Provide reference document/ presentation</td>
<td>Handout with condensed slideshow information</td>
</tr>
<tr>
<td>1.3</td>
<td>Test retained knowledge</td>
<td>Fun activities with toys</td>
</tr>
<tr>
<td>1.3.1</td>
<td>Show children can apply AD to a design</td>
<td>Lego desk organizer activity</td>
</tr>
<tr>
<td>1.3.2</td>
<td>Show children know difference between CN, FR, DP</td>
<td>Game Show</td>
</tr>
</tbody>
</table>

Figure 23 - Decomposition 1
Figure 24 - Decomposition 2

- Assess understanding of AD
- Portable, hands-on activity

- Assess ability to recognize coupled design
- DP choices that can solve multiple FRs
- CP choices that are predetermined to be coupled
- Final design that is decoupled or uncoupled

- Assess ability to decouple design
- Assess ability to recognize excess information content
- Provide CPs with arbitrary complexity ratings
- Design’s complexity must be less than a predetermined rating

- Assess understanding of FRs
- Assess understanding of CNs
- Assess understanding of design
- Assess common CNs
- FRs that convert customer language to requirement
- FRs that are necessary that were not taken into account by the customer

- Assess understanding of DPs
- Assess understanding of FRs
- Given CNs that do not include all necessary FRs
- FRs on list that match to CNs
- FRs worded by ‘words’ different than FR worded does’

- Evaluate effectiveness of each DP choice
- Ranking system of effects of each DP

- Assess understanding of CNs
- Assess understanding of CNs
- Given CN cards that do not include all necessary FRs
- FRs on list that match to CNs
- FRs worded by ‘words’ different than FR worded does’

Figure 25 - Decomposition 3

- Develop further understanding of Axioms
- Worksheet on Axioms

- Test ability to define AD axioms
- MC question asking to choose the 2 axioms in AD
- MC question asking to choose the 2 axioms in AD
- Choices of both correct axioms
- Choices of unrelated axioms

- Test ability to come up with a generic axiom
- Question asking for one example of an axiom
- Question asking for one example of an axiom

- Test ability to recognize general axioms
- Question asking to circle axioms

- Axiom Worksheet Decomposition

- Ability to choose real axioms
- Choices including game rules and simple algebraic axioms
- Obvious choices of phrases that are not axioms

- Ability to understand options
- Related pictures with each choice
0. Develop understanding of coupling
1. Ability to differentiate between coupled, decoupled, and uncoupled
2. Ability to regurgitate coupling example from presentation
3. Ability to evaluate design for coupling

Worksheet
Question with three design pictures, match coupled, uncoupled
Some question with two faucet examples
Given 2x2 matrix to fill with x's and o's

Figure 27 - Coupling Worksheet Decomposition

10.10. Photographic Documentation

Figure 28 - Presenting to SHS
Figure 29 - Mr. Wood and his Class

Figure 30 - Class paying attention
Figure 31 - Cara presenting to class

Figure 32 - Cara doing iPhone example with class
Figure 33 - SHS students

Figure 34 - Chair 1 parts
Figure 35 - Chairs assembled

Figure 36 - Students doing worksheets
Figure 37 - Cara helping student with worksheet

Figure 38 - Students finishing worksheets
Figure 39 - Chair 1 Assembly

Figure 40 - Chair 1 parts
Figure 41 - Both chairs assembled

Figure 42 - "Level the boxes" demonstration