Interdisciplinary Mini-mester course on Rapid Prototyping for Product Design

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I am a 4th year Mechanical Engineering student at Georgia Tech; and I love designing and building projects that help make the world a better place. The first project team I was a part of worked on designing a self sustaining fuel source for rural residents in Uttar Pradesh, India who suffer from respiratory related ailments linked to air pollution. In 2018, I took that interest in helping others in a different direction by working with Dr. Amit Jariwala and Thomas Spencer on finding new ways to teach Design for Rapid Prototyping (DFRP) to K-12 and collegiate level students. More recently I have worked with an undergraduate engineering team at Georgia Tech to develop a collegiate Mechanical Engineering lab course to help students identify: design specifications, functional requirements, and process validation tactics for design solutions.

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Abstract

In Fall 2019, Georgia Tech implemented a pilot program offering a selection of five-week long, one-credit hour courses covering a range of unique subjects. These mini-mester courses aim to introduce students to non-traditional classroom material, allowing them to explore topics they are interested in without a major time commitment. The flexibility and versatility of the mini-mester format enable constructive experimentation regarding the curriculum and structure of a course. This paper focuses on the mini-mester course "Rapid Prototyping for Product Design," a hands-on course where students were trained on makerspace equipment and taught various prototyping strategies as a means to validate design solutions.

The course combines lectures, interactive discussions, and workshops to create a comprehensive education on prototyping processes and the use of makerspace resources with the objective of enhancing students' understanding and capability in relation to the design process. These materials and assignments were developed based on published literature in the field of design and prototyping processes for product design. A "masterpiece" assignment required students to fabricate a complex artifact using various manufacturing methods in order to familiarize them with the tools/processes available, as well as develop an appreciation for utilizing multiple processes for an end goal. Additionally, students engaged in an open-ended design project that required them to work in teams and practice the ability to assess and utilize rapid prototyping processes and select the optimal tool/process to fulfill a design purpose. Regular peer feedback sessions were implemented within class discussions to provide students with a role-playing scenario where each team would serve as a "user" for another team to practice critical thinking and learn to empathize with the end-user. This paper presents the lessons learned from the course offering along with guidelines to help readers create a fun and engaging learning experience for novice designers and innovators.

1. Introduction and Background

1.1 Introduction

The Georgia Institute of Technology has recently introduced a pilot program of mini-mester offerings into its curriculum. The program divides the traditional semester into three five-week terms during which students can take one-credit mini-mester courses on a variety of non-traditional classroom topics. This makes students' experience at Georgia Tech more personalizable by enabling them to explore areas of interest outside their main program of study, and gain knowledge across different academic disciplines. The abbreviated mini-mester format allows students to receive an introduction to a subject without the traditional three-hour weekly time commitment over the course of a fifteen-week semester. Additionally, mini-mesters provide a platform for experimentation, where faculty can test new pedagogies and new configurations of course content and structure. As a clarification, the course is not expected to be a part of any ABET accreditation process, or a substitute to any of the existing required courses in engineering.

1.2 Literature on Mini-mesters

Several other universities have developed programs similar to the mini-mester idea, using short-term courses as a way for students to earn credit hours that work flexibly with their schedules, and to diversify the student learning experience. While the structure of these short courses differ from that of the Georgia Tech mini-mester, analyzing their goals and characteristics shows the success the programs have had over time.

The University of Miami offers “Inter-Sessions,” which are five to ten day intensive courses that take place during the winter, spring, and summer breaks. [1] Students receive three credit hours for these courses, and the lectures last from four to eight hours. The courses offered include “Effective Leadership and Motivation,” “Athletic Injuries & Sports First Aid,” and “Arts Leadership.” Similarly, the University of Alabama schedules its “Interim Sessions” during academic breaks. [2] These three-week courses explore a range of topics such as “Emergency Room Nursing,” “Mad Men & American Culture,” and “Introduction to Investing.” Mini-semesters at New Mexico State University are 8-week accelerated courses offered in two sessions during the semester with the same content as the corresponding regular courses. [3] The University of Georgia requires its first-year students to participate in their “Odyssey Program,” which consists of courses that either meet for one hour a week for the entire semester or for two hours a week for half of the semester. [4] The program includes over three hundred different seminars, with 15-18 students per class. With courses such as “3D Printing and Design”, “Coffee Technology”, and “The Art of Asking Questions in Interviews,” the Odyssey Program courses provide students the opportunity to explore topics of interest outside their major.

These short course programs have shown success in giving students more command over their educational experience, and inciting students’ desire to learn. Many of the courses developed were inspired by the interests of faculty members, or from students who saw gaps in their school’s catalog. The Georgia Tech’s mini-mesters have similar goals as these existing programs, aiming to effectively enrich student and faculty experience.

1.3 Literature on Teaching Design and Prototyping

Project-based design courses are an essential aspect of engineering education, as they cultivate student interest and put engineering concepts into practice. There are several benefits to teaching design in an engineering curriculum. Exposing students to real engineering work helps excite and motivate them for what lies ahead. It has been shown that instilling passion and enthusiasm in students early in their careers positively affects their educational experience. [5] Additionally, design courses can incorporate a variety of subjects, thus helping students learn how to integrate information, make connections across disciplines, and develop holistic solutions to complex problems.

Teaching rapid prototyping in conjunction with design can significantly enhance students’ experience with the design process. An exhaustive literature review on teaching design for additive manufacturing within makerspaces is presented in Jariwala et al. [6] Rapid prototyping is a useful tool for design visualization and verification, allowing students to realize their designs in an efficient manner and test their functionality without requiring machine shop fabrication skills.

Structured prototyping methods can promote feelings of control and lead to an increase in creative output, higher levels of motivation, and advancement in the overall quality of design. [7]

With regard to the use of rapid prototyping for design visualization and validation in a design course, it was found that having a physical three-dimensional model that can be seen, touched, and handled allows students to receive meaningful comments from peers, instructors, and potential end-users. [8] The relative speed and facility of the rapid prototyping process enables students to obtain prompt feedback on their designs and make revisions to improve them. This manner of effectively executing iterations of designs is conducive to an active and compelling learning environment.

In addition to communicating design concepts to others, rapid prototyping is also useful in verifying the feasibility of new design objectives. Through creating prototypes, students can examine whether or not their designs operate as intended and might detect problems that would not be apparent without a physical model. Thus, prototypes can be used for functional testing and design validation. [9]

2. Course Design

The course was designed with input from student staff of the Institute's oldest student-run makerspace, undergraduate and graduate research students, as well as recent alumni from the School of Mechanical Engineering. The emphasis on the course design was to make it relevant and engaging for undergraduates from across majors and academic standing. The primary motivation behind the course was to impart the following principles:

1. Design is an iterative process and so failures must be celebrated while learning from and constantly improving the end product.
2. Product design may require more than one prototype and hence one should develop and utilize a prototyping strategy rather than building only one prototype that fulfills all functional requirements.

Figure 1 illustrates the main elements of the course and their relevant components and assignments.

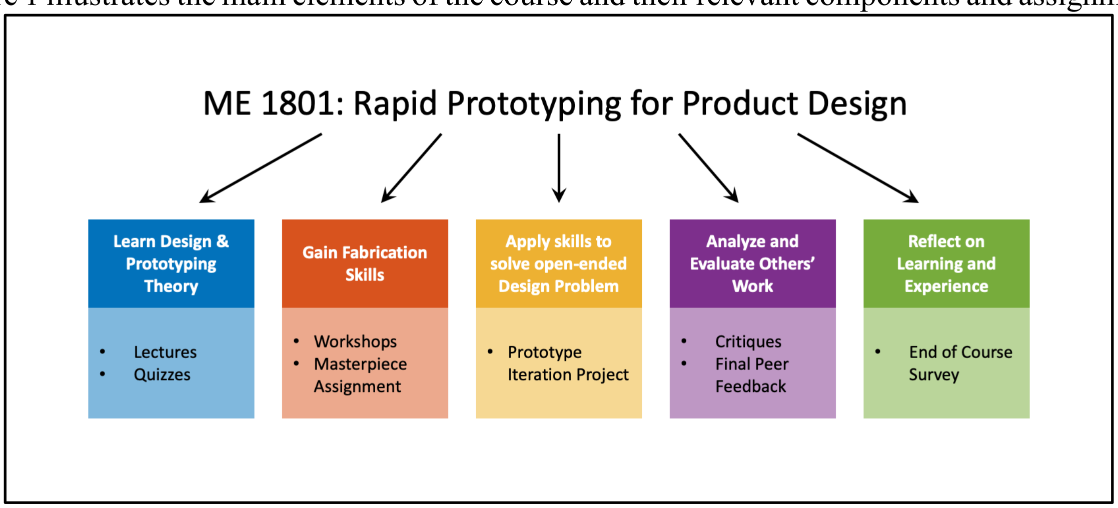

Figure 1: *ME 1801 Course Elements*

2.1 Course Descriptions and Outcomes

The course description is as follows: "*This is a hands-on course where students will learn to utilize prototyping processes as a means to validate design solutions. Students will be introduced to additive manufacturing (AM) processes and common makerspace tools/equipment (like laser cutters, woodshop tools, waterjet, etc.). The course will briefly introduce the concept of hybrid manufacturing in the context of rapid prototyping scoped around tools available within academic makerspaces. Students will design and build prototypes to demonstrate competencies on utilizing prototyping equipment as well as validate specific design requirements*." The corresponding course outcomes are defined below:

1. To enable students to identify design specifications, functional requirements and develop a process to validate design solutions
    - Students will identify relationships between design requirements and develop a validation strategy.
    - Students will demonstrate how prototypes help validate design requirements.
2. To develop in students the ability to identify, evaluate, and safely utilize rapid prototyping processes available in higher education makerspaces
    - Students will gain hands-on skills to utilize fabrication tools/processes.
    - Students will be able to compare and select appropriate prototyping tool/process based on specific design requirements.

2.2 Course Organization

The schedule for the five-week course is shown in Appendix A. A faculty member in the School of Mechanical Engineering was the primary instructor for the course, and the student staff of the makerspace served as the Learning Facilitators (LF). Recent alumni and industry experts were invited to offer special lectures and lead discussions on specific topics in the class. The class had 1.5 hours of lectures scheduled twice per week. Optional evening workshops were offered twice per week based on common availability of students and LFs. The course consisted of a three-pronged approach to teaching:

- Lecture style discussion on concepts like Design for Manufacturing (DFM) and Prototyping strategies
- Workshops where trained LFs provided focused and specific instruction in the safe operation of the prototyping and manufacturing tools
- In-class discussions between teams to practice lecture material through role-playing as "designer" and "user"

2.3 Course Assignments

The course included a number of both team and individual assignments to aid students' learning, provide hands-on experience with the material covered, promote self reflection and evaluation, formulate constructive criticism of others' work, and foster a rich and interactive learning environment. This section describes the main course assignments in detail.

2.3.1 Masterpiece Assignment

To help introduce students to makerspace equipment and demonstrate the practice of employing different processes towards the realization of a project, a "masterpiece" assignment was developed. The masterpiece assignment required students to work in groups of two or three to fabricate a complex artifact using multiple manufacturing methods. Detailed instructions and dimensioned engineering drawings were provided to aid students in this assignment. The masterpiece, shown in Figure 2, is made from aluminum 80/20 rails, aluminum sheets, plywood, and acrylic sheets. A detailed drawing of the masterpiece is shown in Appendix B. Constructing the masterpiece involved the use of various wood and metal machining processes, laser cutting, and 3D printing. A full list of the tools used, along with their functions, can be seen in Table 1. To ensure equal division of work among group members, students were required to fill out a parts checklist, shown in Appendix C, which evaluates the contribution of each group member to each part. Students were strongly encouraged to attend workshops where learning facilitators were present to teach them proper tool usage procedures and provide help and clarification on specific tool functionalities. After creating all the parts, students were also responsible for assembling them into the final artifact.

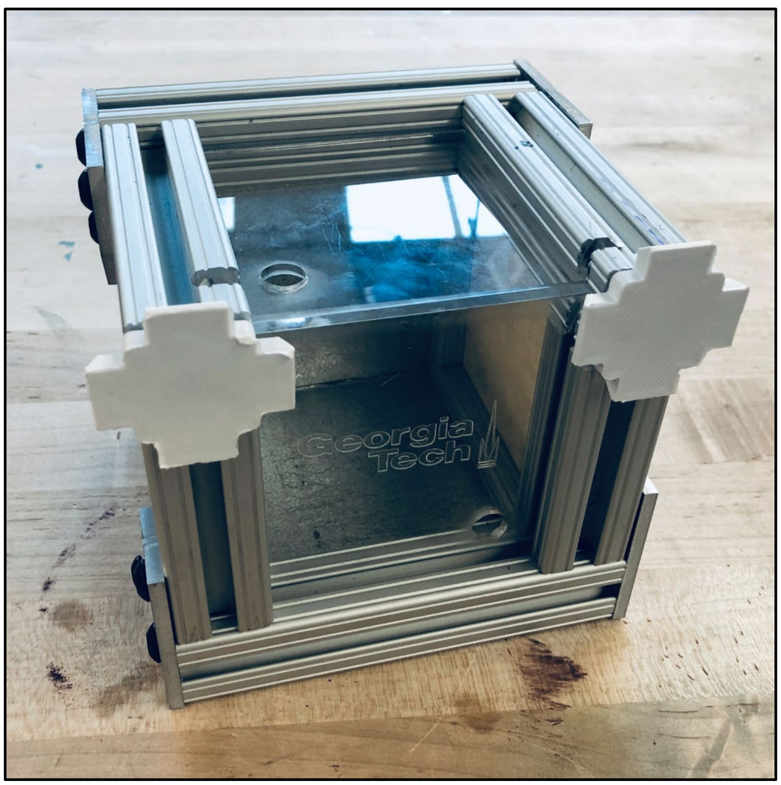

Figure 2: *Photo of the Completed "Masterpiece" Assignment*

Table 1: *Tools Used for Masterpiece Assignment*

	Machine	Purpose
wood	Table Saw	Cut the workpiece from stock
	Band Saw	Cut the wood panels to dimension
	Sanders	Smooth cut edges and faces of wood
	Planer	Decrease the width of the wood
	Drum Sander	Thin the workpiece
metal	Waterjet	Cut the joining plates
	Cold Saw	Cut the rails to dimension
	Sheet Metal Brake	Bend the aluminum sheet
	Beverly Shear	Cut the aluminum sheet to dimension
	Sanders	Deburr the edges of the rails
	Hand Taps	Creat threads in the rails
	Transfer Punch	Produce divot in aluminum sheet
	Drill Press	Make hole in corner plate
	Hand Drill	Make hole in corner plate
	Dremel	Cut slots in rails
other	Laser Cutter	Cut and engrave acrylic panels
	3D Printer	Create end stopper
	Foam Cutter/X-Acto Knife	Cut back foam spacers

The main purpose of the assignment was to familiarize students with the makerspace and help them develop basic skills in fabrication. Additionally, it provided a means for the instructor and learning facilitators to teach process selection in a dynamic, hands-on fashion. In this way, the masterpiece assignment served as an introduction to makerspace tools, and manifested the practice of creating an intricate product with various fabrication processes. Based on the experience from the pilot run, the authors propose to add an emphasis on tolerance stack-ups, Geometric Dimensioning & Tolerances, and constraint-driven material selection in the guidance documents for the masterpiece assignment.

2.3.2 Prototype Iteration Project

The prototype iteration project required students to work in teams of four or five to demonstrate their understanding of the prototyping strategies covered during lecture. In the pre-course survey, students were asked to each come up with two project ideas. Among the suggested projects, five were selected to be used in the course. See Appendix D for a list of all projects used. In order for a project to be selected, it was required to be open-ended enough to provide scope for substantial ideation. Additionally, the background of the problem must be easily understood by students in the class. The projects were assigned to those teams whose members did not propose the assigned project. Teams consisting of members who proposed the project served as a "user" team, which provided weekly feedback to the "designer" team. This split was intentionally made so that students could role-play both as designers and users, and learn first-hand about the challenges of empathizing with the end user, which is a critical aspect of successful design. [10] Teams were formed based on students' individual project interest and common availability for workshops outside of scheduled class times. There was no intentional effort in mixing the engineering students with non-engineering.

Teams designed, built, and documented the iterations of their prototype. Three iterations of the design were developed throughout the course—a low-fi prototype, med-fi prototype, and revised med-fi prototype. With each of these, feedback sessions were incorporated to help teams alter and improve upon their designs. Both “designer” and “user” teams were required to complete a critique form for every weekly meeting. These organized critiques are described in detail in Section 2.3.3. The final project was graded on the following components:

1. Clear identification of end-user
2. Understanding of user needs and specifications
3. Ability to select appropriate prototyping strategy and tools
4. Ability to incorporate user feedback and implement change in the next iteration
5. Clarity in the presentation of the final state and future steps

One example of a prototype iteration project was the design of foldable skis for easy transportation. For this project, the “designer” team created a low-fi proof of concept prototype from laser cut cardboard consisting of three separate segments connected with masking tape hinges. The purpose of this prototype was to demonstrate the direction of the folds and validate the form factor of foldable skis. Feedback from the “user” team identified the problem of preventing the skis from folding unintentionally. Thus, for the med-fi prototype, the “designer” team explored the use of magnets as a folding mechanism. The med-fi prototype, shown in Figure 3, was made from sawed wood with magnets hot glued at the hinges.

Figure 3: *Foldable Skis Med-fi Prototype*

The user feedback for this prototype prompted the “designer” team to consider the forces applied on the skis while in use. Determining the magnets to be insufficient, the “designer” team moved on to create a latch for their revised med-fi prototype. The 3D printed prototype and the refined CAD render for this design are shown in Figure 4. Class observations indicated that the design team realized the importance of focusing on individual aspects and functions of the design, rather than immediately attempting to prototype a product in its entirety.

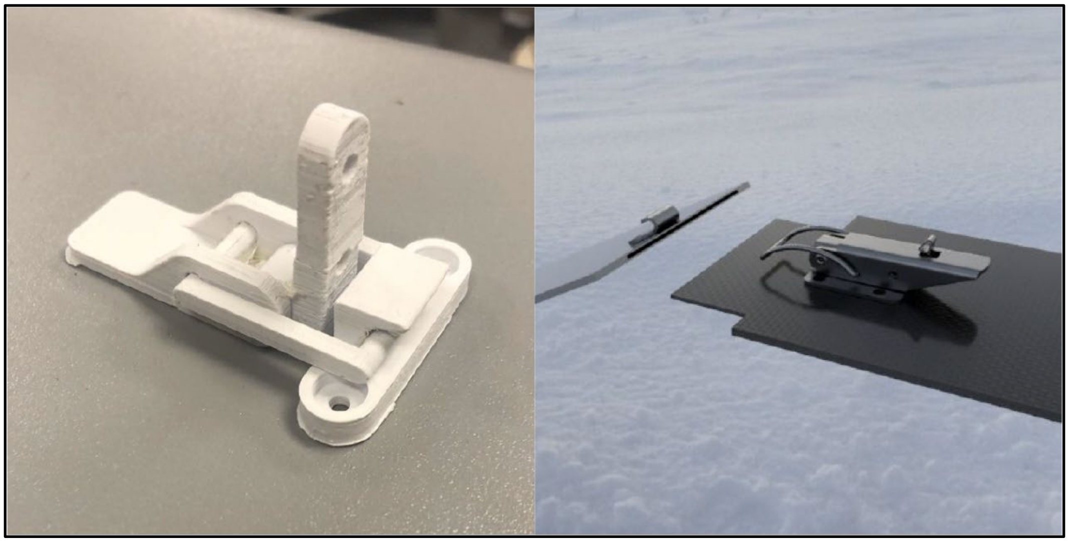

Figure 4: *Foldable Skis Revised Med-fi Prototype*

The team's progress throughout the project is evident in the development of their advancing prototypes, which were critical in communicating the "designer" team's ideas to the "user" team, and helped test certain mechanisms and identify areas for improvement.

Bloom's Revised Taxonomy places creation at the top of its categorization of learning objectives. [11] Hence, the prototype iteration project was added to provide a unique opportunity for students to practice creative judgment, innovation, and hands-on building in a course. While the masterpiece assignment only required students to follow guidelines, the prototype iteration project enabled students to think logically and critically, and directly apply the content covered in class discussions.

2.3.3 Critique Sheets

At weekly intervals during the prototype iteration project, teams were required to fill out critique sheets. The first part of the critique sheet, the designer response, was for the teams to evaluate their own design. This section prompted the teams to reflect on their design process up to date, critically assess their prototype, and define their next steps. The designer response questions are listed below:

1. Why did we create this prototype?
2. Which fabrication processes were used and why?
3. What do you think was successful about the prototype?
4. What aspects of the prototype do you think could be improved?
5. What is your next step?

The second part of the critique sheet guided teams in evaluating the design for which they were the "user." This user input section compelled the "user" team to judge the quality of the "designer" team's prototype, as well as the effectiveness of the fabrication processes employed. The user input section consisted of the following questions:

1. How well did the prototype test the designers' hypothesis?
2. Was the selected fabrication process effective? What other fabrication processes could have been used?
3. What do you think was successful about the prototype?
4. What aspects of the prototype do you think could be improved?
5. What should they do next in your opinion?

The teams' responses to these questions throughout the course reflect the evolution of their own projects as well as their understanding of the projects they were critiquing. For example, one team aimed to maximize the usable storage space in a refrigerator. In the first critique sheet, their answer to question 1 of the designer response was "to test the desirability for two ideas." As the course progressed, their answers became increasingly specific and definitive. By the second critique period, the team had decided to hang bags from the bottoms of refrigerator shelves as a means to save space. They stated that they created the second prototype "to show how food items would fit and how bags could be used." For the final critique sheet, they refined their design to be a bag that would slide out from beneath the shelf for easy access, and they declared the purpose of the third prototype to be "to test the desirability of a pull-out bag under the shelf." The responses of the "user" team for this project showed similar advancement. For the first critique sheet, they simply said that the "designer" team's prototype tested their hypothesis "very well." Their comments on the final critique sheet were significantly more meaningful, commending the prototype's demonstration of the "general form of the shelf" and "how the shelf would work." Both "designer" and "user" teams' responses on the critique sheets showed considerable development over time, indicating their increased learning and engagement with the project.

The critique sheets served to focus and frame the conversation about the project, allowing students to exercise another form of communication in addition to verbal discussion. They emphasized learning through reflection, assisted with executing iterations rather than being fixated with one concept, and encouraged students to be comfortable with failure and view it as an opportunity for continuous improvement. Based on the feedback and student input from the pilot offering of this course, the authors recommend that the questions be reframed to make it easier to apply the class lecture discussions. For example, one question that could be asked is "What prototyping strategy did your team employ in creating the prototype and why?" after the first question "Why did you create this prototype?" Additionally, more time could be allocated for the teams to brainstorm design solutions immediately after receiving feedback in the critique sessions.

2.3.4 Final Peer Feedback

At the end of the course, students were asked to individually give feedback on all other teams' projects. The open-ended format of this assignment allowed students freedom in their commentary, providing an overall well-rounded and insightful evaluation of the designs. Students' assessments generally addressed three main topics—identification of user needs, prototyping strategy, and iteration and implementation of user feedback—all of which are important elements of the course. The vast majority of the final peer feedback was specific in its suggestions for improvement, as well as its commendation of the efforts put in by the teams. The purpose of this assignment was to assess the students' understanding of concepts covered in class and their ability to provide critical yet constructive feedback to their peers. Students were graded based on the quality of the feedback they provided.

3. Student Outcomes

Students were asked to individually describe their overall experiences and opinions of the course once they had completed it. This was meant to provide the course design team with feedback that could be used to improve the course for future semesters. Select examples of student comments are shown in Appendix E.

An overwhelming number of students indicated that their largest takeaway was the knowledge of tools and processes that they learned during the workshops. Many students outside of the mechanical engineering major stated that they would not have had the opportunity to learn about these machines and processes had they not enrolled in this course. Students also indicated that the workshop environment in which they were taught the tools/processes helped to facilitate their learning. More specifically, students mentioned that the low student-to-learning facilitator ratio along with pre-scheduled after-hours access to the makerspace allowed them to feel more comfortable asking questions. These conditions also ensured that they would have easy access to the machines and tools they were required to learn.

As part of the lecture component of this course, students were offered the opportunity to interact with industry professionals whose companies specialized in different aspects of rapid prototyping. Many students indicated that the ability to see the real-life applications of these skills helped them understand the practicality behind what they were being taught and provided them with a greater motivation to learn from the course.

With regard to the criticisms students had, some expressed that they perceived a disconnect between different elements of the course. While the lecture content was closely aligned with the Prototype Iteration Project, some students felt that the higher level concepts about prototyping and design taught in lectures did not seem relevant to the specific applications practiced during workshops for building the masterpiece assignment. Students stated that they would have liked to see an intentional link between the lecture discussions with the workshop tasks. As an improvement, the workshop materials could be revised to clearly cite the content from lecture discussions. It would also be helpful to emphasize the need for selection of appropriate fabrication tools for the intended application during the workshop discussions.

4. Discussion and Next Steps

One of the major successes of the course was its encouragement and facilitation of interdisciplinary education. The mini-mester format is unique in how it enables students to learn about topics in different majors. Among the 21 students enrolled in the course, approximately one quarter were juniors, and the rest were seniors. Half were engineering majors, and half were non-engineering majors. A student from Computer Sciences specified the following response in the post-course survey for the question about the most important takeaway from the course, "*I learned the fundamentals of engineering a solution. I'm CS, so I didn't really know anything about engineering at all coming into this course. I didn't even know what I didn't know. Now, I got to understand the brainstorming process, how to prototype, the different ways to prototype, and how to move on from there. It was exactly what I was looking for when signing up for this course*." Another student responded, "*The two most important takeaways from this course for me are that it is always important to consider multiple viewpoints when considering a solution to a problem rather than go with the first thing that comes to mind. For example, there were people in my project group who had not taken all of the same ME classes that I had, so their experience was very different and led them to look at a problem differently than I did. We were also able to use their experience in various ways that I did not think were going to be possible when the project started.*"

A significant aspect of the course was its industry collaboration. Companies involved with CAD software as well as prototyping service providers sent several unrestricted gifts and resources to support the course and student projects. They also volunteered their time to provide case studies and company agnostic case studies/expert lectures to the class. These industry talks received very strong positive feedback from the students. This demonstrates the practicability of designing customized courses to meet specific industry needs with help from industry partners.

With regards to scheduling, it was favorable for the course to take place during the second mini-mester. This prevented students from enrolling in the course and then dropping it, as students' schedules must be finalized by the end of the first week of the semester. Having a fixed roster enabled the authors to administer the pre-course survey and begin organizing projects and teams prior to the start of the course. In the future, rather than simply dividing the traditional semester into thirds, more flexibility in the timing of mini-mester courses could be beneficial. Ideally, this course would be offered starting a few weeks into the semester—so as to have a definite roster, and for there to be time to conduct the pre-course survey and associated analysis—but not so late such that a high workload has accumulated in other classes.

Students were asked to give feedback on the course immediately after they had completed it, in addition to the standard course instructor opinion survey (CIOS) administered by the institute at the end of each semester. In the immediate feedback, several students criticized the workload of the course. This indicates a need to clarify expectations about the credit hours of mini-mester courses. Since the courses are only one credit, students might be led to believe that they require less effort than a typical three-credit hour course. In reality, mini-mester courses consist of the same amount of work as a regular course, but only last a third as long. Feedback from the CIOS, which occurred several months after the completion of the course, was generally more reflective and substantial.

Additionally, a survey was administered after the completion of the course, in which students were asked to rate their agreement to several statements regarding the mini-mester course. Table 2 shows some of these statements and their average ratings, where the numbers 0-3 correspond to “strongly disagree,” “disagree,” “agree,” and “strongly agree.”

Table 2: *Post-course Survey Results*

Statement	Average Rating
This mini-mester added value to my education.	2.47/3
This mini-mester provided me the opportunity to explore curriculum outside of my standard major courses.	2.31/3
I recommend this specific mini-mester to other students.	2.35/3

In Figure 5, the course assignments and components are related to Bloom’s Taxonomy, demonstrating a comprehensive embodiment of educational learning objectives. Overall, the course was successful in introducing students to various prototyping processes as a means to validate design solutions. Students gained hands-on experience with fabrication tools/processes, and learned how to evaluate them with respect to a certain functional need. Additionally, students learned to use prototyping methods to solve design problems, incorporate user feedback, and iterate their designs in a meaningful manner.

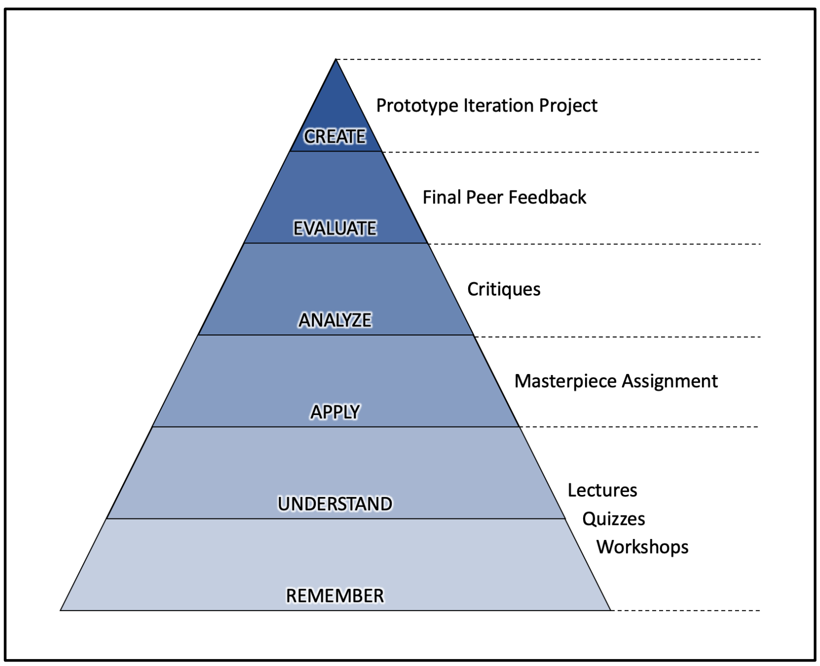

Figure 5: *Course Elements in Relation to Bloom's Taxonomy*

Acknowledgment: This material is based upon work supported by the Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921.

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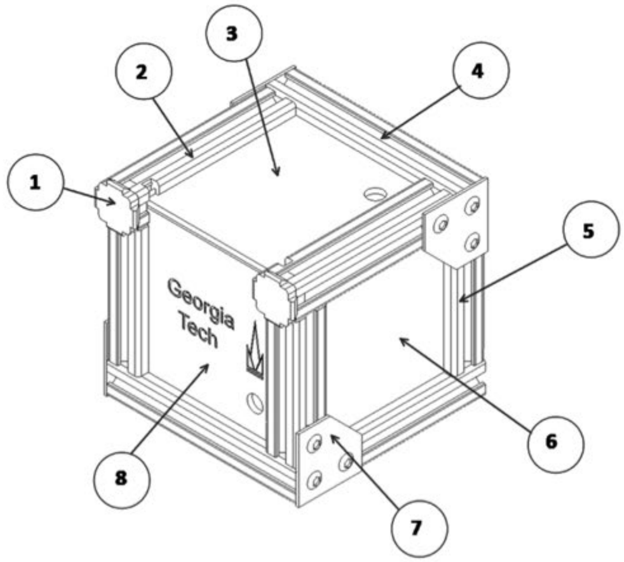
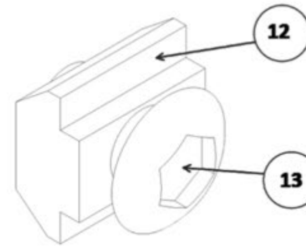
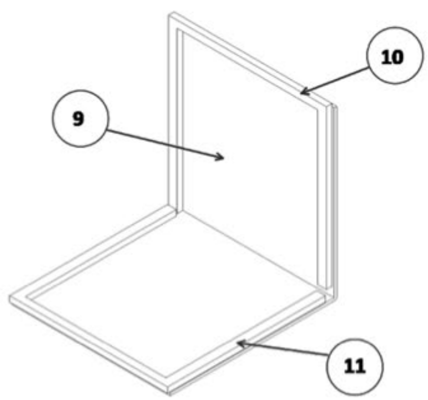
Appendix A: Course Schedule

Schedule for 5 Week Mini-Mester Course - Rapid Prototyping for Product Design				
Week #	**Date**	**Topic**	**Type**	**Deliverable**
1	Lecture Session #1	Overview of Design Process	Lecture	Introduce Yourself Quiz
		Problem Identification and Project Selection	Lecture	
		Concept Generation Exercise	Group Activity	
		Critiquing Session - how to provide constructive feedback	Interactive Discussion	
	Lecture Session #2	Industry Invited Talk on Design Process of a well-known product	Lecture	
	Learning Facilitator Office Hours	CAD Software	Workshop	
	Learning Facilitator Office Hours	Makerspace Tour and Shop Safety	Workshop	
2	Lecture Session #3	Types of Prototypes	Lecture	Hand-sketches of project concepts
		Overview of Prototyping Processes	Lecture	
		Group Presentation of projects to class	Interactive Discussion	
	Lecture Session #4	Design Analysis, Verification and Validation	Lecture	Bring low-fi prototype to class
		Share-n-Learn Session (Low-Fi Prototype)	Interactive Discussion	
	Learning Facilitator Office Hours	Wood Shop	Workshop	
	Learning Facilitator Office Hours	Laser Cutter	Workshop	
3	Lecture Session #5	Additive and Hybrid Manufacturing	Lecture	
	Lecture Session #6	Industry Invited Talk on Prototpying Case Studies	Lecture	
		Share-n-Learn Session (Med-Fi Prototype)	Interactive Discussion	Bring med-fi prototype to class
	Learning Facilitator Office Hours	3D Printing Basic	Workshop	
	Learning Facilitator Office Hours	3D Printing Advanced	Workshop	
4	Lecture Session #7	HOLIDAY - Fall Break	-	
	Lecture Session #8	Share-n-Learn Session (Revised Med-Fi Prototype)	Interactive Discussion	Bring rev. med-fi prototype to class
	Learning Facilitator Office Hours	Metal Shop Tools	Workshop	
	Learning Facilitator Office Hours	Waterjet	Workshop	
5	Lecture Session #9	Industry Invited Talk on Prototype to Production	Interactive Discussion	
	Lecture Session #10	Final Presentation	Interactive Discussion	All prototypes and final presentations
	Learning Facilitator Office Hours	Electronics (Optional; extra-credit)	Workshop	
	Learning Facilitator Office Hours	CNC/CAM (Optional, extra-credit)	Workshop	

Appendix B: Masterpiece Drawing







Item	Quantity	Part
1	2	Stopper
2	4	4 in Rail
3	1	Top Panel
4	2	5 in Rail
5	4	3 in Rail
6	2	Side Panel
7	4	Joining Plate
8	1	Front Panel
9	1	Bottom & Back Panel
10	1	Back Spacer
11	1	Bottom Spacer
12	12	T-Nut
13	16	Bolt

Appendix C: Masterpiece Assignment Parts Checklist

Parts Checklist

Group Name: ______
Student #1 Name: ______________________________
Student #2 Name: ______________________________
Student #3 Name: ______________________________

Below you will find a chart with all the items included in your masterpiece. Score yourself and your partner on a scale from 1-10 on how much you contributed to each part. If you only have one partner ignore student #3.

ITEM	TOTAL QTY	PART	Student #1	Student #2	Student #3
1	2	Stopper			
2	4	4 in. Rail			
3	1	Top Panel			
4	2	5 in. Rail			
5	4	3 in. Rail			
6	2	Side Panel			
7	4	Joining Plate			
8	1	Front Panel			
9	1	Bottom & Back Panel			
10	1	Back Spacer			
11	1	Bottom Spacer			
12	12	T-Nut			
13	16	Bolt			
	Assembly of the box				

Appendix D: Prototype Iteration Projects

1. Foldable Skis: skis that fold for easy transportation.
2. Bike Brake Aligner: device to keep bike brakes aligned with the wheel frame. See Figure D1 for final 3D printed prototype.
3. Improved Grocery Basket: redesign of traditional grocery basket to be more easy and comfortable to hold. See Figure D2 for final cloth-and-fastener prototype.
4. Cup Holder Insert: removable, washable sleeve for car cup holders. See Figure D3 for final silicone molded prototype.
5. Adjustable Mini-fridge: mini-fridge shelf redesign to maximize usable space. See Figure D4 for final wood, acrylic, and fabric prototype.

Figure D1: *Brake Aligner Revised Med-fi Prototype*

Figure D2: *Improved Grocery Basket Revised Med-fi Prototype*

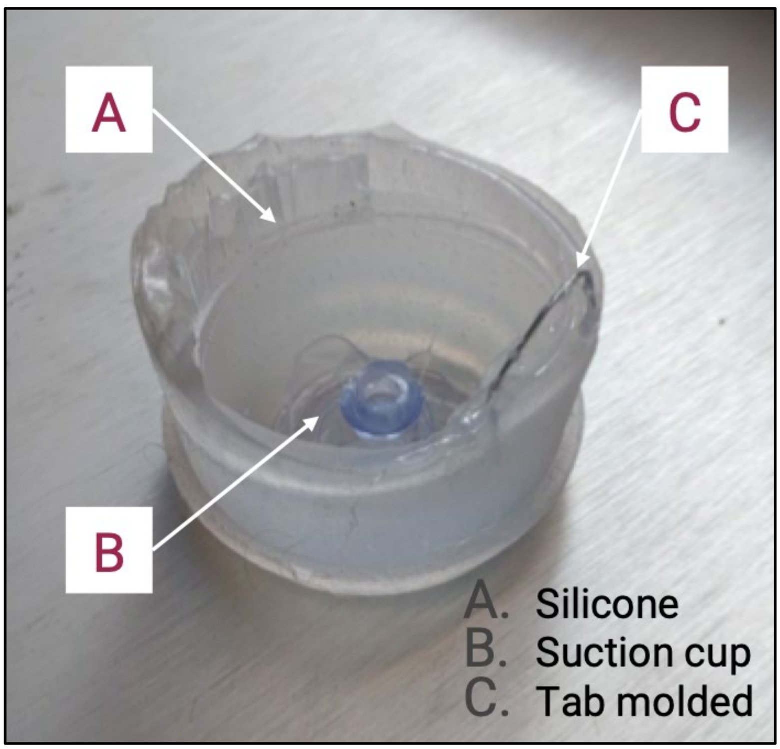


Figure D3: *Cup Holder Insert Revised Med-fi Prototype*

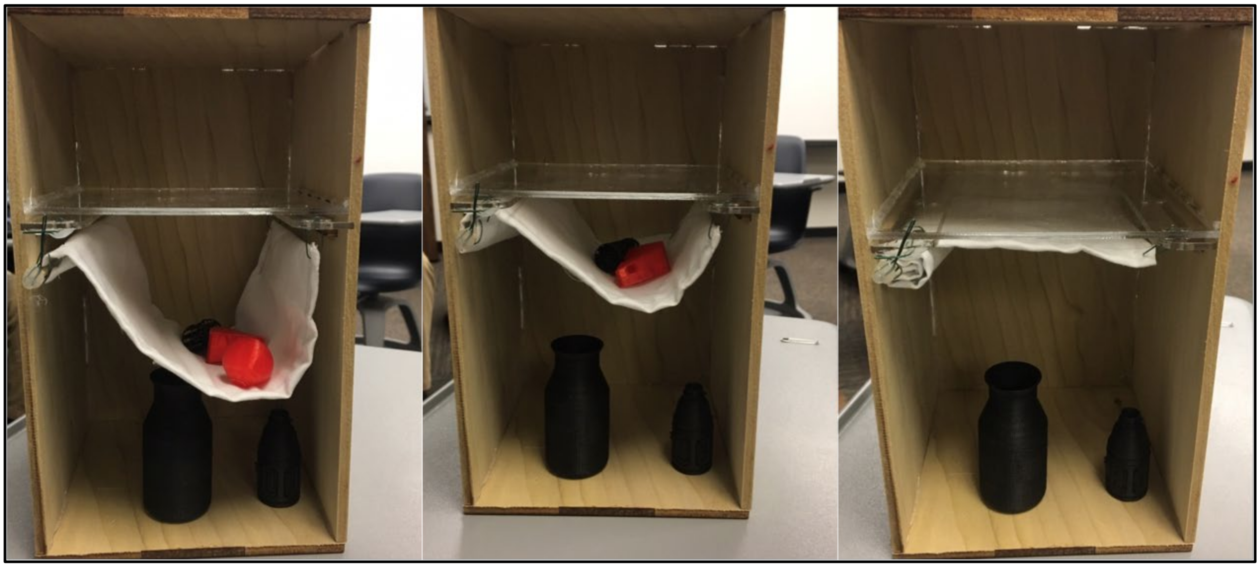


Figure D4: *Adjustable Mini-fridge Revised Med-fi Prototype*

Appendix E: Post-course Student Feedback

Workload

- *"I think this course should be during the first mini-mester when there is less going on."*
- *"Did not expect to spend so much time outside of class completing assignments, but was able to finish everything on time."*
- *"More work than was justifiable."*
- *"Through the masterpiece assignment, I have learned a lot of useful manufacturing skills. Also, I think 5 weeks were appropriate for two projects: masterpiece and prototype."*

Satisfaction/Best Aspect

- *"Fun, hands-on work gave good technical experience"*
- *"The hands-on experience. One guest speaker was exceptional."*
- *"The depth and breadth of prototyping we had the chance to explore over such a short period of time! I absolutely loved the concepts behind the class."*
- *"I really liked the hands-on aspect. Both of the projects were really cool and I enjoyed getting to work on them."*
- *"I liked getting hands-on experience in the Invention Studio"*
- *"Really liked the workshop assignments and felt like they offered good exposure to the machines available in the Invention Studio Felt like a good intro to the maker space for someone who was not an ME major"*

Scheduling

- *"I think this class should have blocked out the times for the Invention Studio workshops. Even if we didn't get credit for them, I think this would be very helpful in making sure that there aren't any conflicts and that students can attend each workshop to learn how to use the Invention Studio tools."*
- *"If class time was a little longer, there would be more time for groups to plan their next iteration. This was the biggest problem in my group, since workshop was the only time we could all meet to do that, and then we had to work on the box assignment separately at another time."*

Reflection on Learning

a. Prototyping Process:

- *"One of the biggest takeaways I've gotten from the class is to not only test early and fail early, but to give up on ideas early. Sometimes I've been told to always have a drive to pursue an idea if I believe in it, but the very nature of iterative prototyping for a possible product is that you ditch the ideas that fail and pivot to find a new solution. The lesson isn't necessarily that I have to be taking the idea completely out of my mind, but more to do with how to learn from failed iterations of an idea and move forward with it."*
- *"Create something rather than spend all your time making the perfect thing."*
- *"Prototype selectively. I learned to test one idea and one aspect at a time. Doing this in parallel can make the process much faster and more informative, but I learned the key is for each iteration to test one thing. The idea of doing a works-like and looks-like prototype was new to me and helpful in focusing my own projects."*

- *"There's no need for every prototype to be a working model, or even a complete model. There are many strategies to break things down, whether it's testing a small part or trying multiple concepts roughly."*
- *"The first major takeaway I had from this class was that prototypes are made for a purpose. Before this course, I thought that a prototype was just a prerequisite to a final product. I thought the design process was to define the problem -> make a prototype or 2 -> make the finished process. What I learned in this class was that prototypes shouldn't test everything at once. Prototypes should be very quick to make and have a very clear validation goal in mind."*
- *"I think from now on I will consider whether I'm prototyping for desirability, feasibility or viability in the future."*
- *"The strategy of Subsystem Isolation is extremely useful—a prototype doesn't have to do EVERYTHING, it has to just fully do one thing. A divide-and-conquer approach allows an engineer to ensure 100% functionality (or similar) to a function before unifying the entire product. If three systems have a 95% success rate, then the overall product only has about an 85% success rate—which is why it's important to refine each individual system as much as possible."*
- *"The importance of working quickly. Not rushing, but moving forward with ideas, critiquing and making changes at a fast pace in order to settle on the best design."*
- *"I think learning about low-fi prototyping was most important because usually when I think of prototyping, I think of something that looks nice and polished, but now I understand that making some quick designs with cardboard and tape can be even more effective for exploring and refining initial ideas."*

b. Equipment Proficiency/Familiarization with Makerspaces

- *"I got really comfortable with the machines in the Invention Studio. I mean I even got comfortable just GOING to the Invention Studio; that's the most important. With that, I can continue to learn on my own now that the intimidation is gone."*
- *"I am thrilled that I now know how to use machines in the Invention Studio and feel comfortable working in this space. The skills I acquired during this course will apply to my BME design courses. I feel that I will be a step ahead of my peers in that I already know how to utilize these machines and differentiate between what can and should be used."*
- *"Learning how to use the equipment in the Invention Studio. For the best 4.5 years, I've been too intimidated to go in and ask how to do something and I'm so glad this class showed me so much. I now feel confident to go to the Invention Studio and know what equipment to use to get certain things done and how to use those pieces of equipment."*
- *"Even though I'd taken <a sophomore level design course>, I learned about the machines more in depth in this class, particularly with the Masterpiece assignment. Now I know about the 3D printers, CNC Machining, and circuit board designing (and components!) that are available."*

c. Teamwork and Collaboration

- *"The most important thing to keep in mind for any engineering project is teamwork-everyone on a team has their own strengths and weaknesses, and it's of utmost importance for a team leader to identify these strengths and delegate roles and* *responsibilities accordingly. When each member can shine in their particular area of expertise, the entire team benefits."*

d. Inspiration from Industry Talks
   - *"Just because you study one thing in your undergraduate and graduate career, there's absolutely no guarantee that you're going to focus on that for the rest of your life if you don't want to. I think about <invited speaker> and how he built a robotic fish in graduate school, but then worked as an Imagineer at Disney before going to iRobot to help create the Roomba. Yes, they are all related in the sense that it takes a robotic background, but he studied biomechanics and now helps companies with manufacturing. It's about how you apply the skills you are taught in college rather than the actual knowledge that is taught."*