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Student Skills Growth in a Prototyping and Fabrication Course: Increase in Operation and Technique-based Knowledge as a Result of an Apprenticeship Model

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Matthew Wettergreen was appointed director of the department's Master's of Bioengineering Global Medical Innovation program in 2020. He is also an Associate Teaching Professor at the award-winning Oshman Engineering Design Kitchen at Rice University, recruited as the first faculty hire in 2013.

Wettergreen co-developed six of the seven engineering design courses in the design curriculum at the OEDK, including the flagship first-year engineering design and Prototyping and Fabrication course. This practical hands-on course increases student proficiency in the development of prototypes using low fidelity prototyping, iterative design, and advanced manufacturing tools. Dr. Wettergreen's efforts to scaffold prototyping into all of the OEDK's design courses were recognized with Rice's Teaching Award for Excellence in Inquiry-Based Learning. In 2017, four faculty members, including Wettergreen, combined the engineering design courses at the OEDK to create the first engineering design minor in the US, credentialing students for a course of study in engineering design, teamwork, prototyping, and client-based projects.

Wettergreen has over ten years of experience teaching client-based engineering design courses, and a deep interest in engineering education, specifically curriculum that can be employed to build capacity for student development in makerspaces. Building off of this interest, he has taught and mentored faculty in Brazil, Malawi, and Tanzania to launch makerspaces and work with institutions to develop engineering design curriculum. Dr. Wettergreen is the faculty mentor for Rice's Design for America chapter, for which he has been given the Hudspeth Award for excellence in student club mentoring.

Wettergreen is also a designer of consumer products under Data Design Co, and of a number of academic products that improve students prototyping techniques, including a low fidelity prototyping cart and the Laser Cutter Prototyping Library. His design work has been featured on the cover of NASA Tech Briefs and in the pages of the Wall Street Journal, Make Magazine, Atlantic Monthly and Texas Monthly.

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Abstract

The essence of prototyping is solving problems through the creation of physical or digital artifacts. In professional practice, engineers use these artifacts for many purposes: to communicate creative ideas, explore design alternatives, evolve the details of a solution, and achieve functional design solutions. The process of prototyping exists on a spectrum of scope (whole solution versus component of solution) and complexity (simple tools and materials versus manufacturing tools and materials). Years of study, practice, and repetition on machines and software packages are needed to acquire deep expertise in prototyping. Unfortunately, engineering students are expected to produce physical prototypes without the luxury of dedicated training in this skill, as much of their time is occupied by fundamentals and other course content.

There exists a need to upskill engineering students to a point where they can gain momentum on physical and digital prototypes using trial-and-error processes. Prototyping schemas do exist but they are heavily abstract; other methods of instruction use principles to guide action in prototyping. Very few instructional materials exist that are step-by-step or heavily guided by the instructor.

In academic makerspaces, prototyping education is completed through several avenues, including informal workshops, independent self-directed learning, and formal courses. This paper details over five years of results from a course that teaches skills in prototyping and fabrication seeking to increase student confidence towards producing high-resolution prototypes. This course includes modules that instruct students in many useful techniques for producing prototypes: how to build a box with hand tools (3 ways), post-processing and finishing objects, 2D drawing (digital), vector-based cutting, additive and subtractive 3D manufacturing methods, and the application of multiple toolchains/processes to produce objects. The course is designed to be high-touch and to simulate apprenticeship with an expert. All aspects of the

course involve active learning and routine hands-on workshops. This structure enhances the student experience by making the environment practical instead of didactic. Grading is proficiency-based so students have standards of excellence to work towards. Students peer grade each other, which helps them to develop a critical eye for high-quality products as well as to articulate (and receive) feedback on their work. Students detail their progress in the class through a publicly viewable blog that showcases their process, decisions, failures, and triumphs. Through surveys and analyses of work products, we evaluated the learning outcomes of the course and found that a proficiency increase was measured in each of the techniques and tools that were instructed, furthermore, students recognized these proficiency increases.

Introduction

Prototyping is a critical technical skill that engineers use to solve problems and explore design alternatives. As succinctly explained in Ulrich and Eppinger's seminal *Product Design and Development*, "prototypes are used for four purposes: learning, communication, integration, and milestones" [1]. When engineers prototype, they do so physically or digitally through artifacts that communicate design intent, sub-features, or a full solution; as Tom Kelley of IDEO has stated, "A prototype is worth a thousand meetings" [2]. While there is consensus on the importance of the skill of prototyping, there is no one standard for how to upskill students in this area. Complicating the matter are the variety of machines, tools, techniques, and individual areas that must be mastered to produce functional and aesthetically appealing prototypes. Thus, a variety of methods are applied internationally to instruct students in this area: self-directed learning, informal learning, and formal learning.

Self-directed learning methods encompass a range of topics and resources that can be accessed by individuals online or through written text. Instructables.com is one useful repository of tutorials that can help motivated individuals build prototypes and functional devices. Youtube.com hosts millions of videos with educational content. Make Magazine has helped prop up the industry of "making" and provides online references as well as a regular magazine with stories and how-tos. Interested individuals need to have intrinsic motivation and drive to utilize these resources. Self-directed learning methods can be just as effective as more structured ones, but learners may progress more slowly without reinforcement or expert feedback.

Informal learning methods include workshops and in-person tutorials taken by learners in a group setting. These methods are effective, especially in makerspaces, when there is a need to train many people at one time. Instruction offered in an informal learning setting is often short-term (i.e., on the order of hours rather than months), but can include some form of hands-on learning with a feedback cycle from a trained user/expert.

Formal learning methods encompass coursework and classes that educate students and require graded assignments. The formal methods are the most structured and can result in increased student proficiency, but the tradeoff is the limited time during which instructors are available to work with the students. MIT's "How to Make Anything" class is an example of what can be achieved in one course's worth of content with support from faculty and teaching assistants. In this course, students learn the core techniques/tools of prototyping, including CAD, basic electronics, CNC machining, molding and casting, mechanical movements [3].

An effective add-on to any instructional method are apprenticeship models, which offer many attractive benefits for educating students to build prototypes through feedback loops. The cognitive model of situated learning—which apprenticeship falls under—engages experts to train students (novices), often placing them in side-by-side working situations [4]. This format is conducive to the teaching of procedural techniques, such as laboratory methods, shop methods, coding, and culinary processes. Both the presentation of content and the participation by students are necessarily active and social in this educational style [5]. These types of instruction combine explicit and tacit knowledge [6] and in doing so focus on the *practice* of what it is to be an expert in this area, rather than letting novices construct this knowledge independently. By helping students develop in real-time the tacit knowledge necessary to succeed in a skill, career, or position, an expert can cultivate the proper behaviors and skills. A trade-off with apprenticeship models is their commitment to a long-term relationship between the novice and expert, rather than the shorter-term learning models described above.

Course Overview

The Oshman Engineering Design Kitchen (OEDK) facility at Rice University hosts courses as part of the first credentialled engineering design minor in the United States. One of the required courses in the minor is ENGI 210: Prototyping and Fabrication. This course introduces students to a variety of methods for producing and refining physical prototypes. The participants of the course are undergraduate engineering students, most of whom are taking the course as a requirement for the engineering design minor. This course has one section per semester (fall and spring) with an average of 11 students per section. The course objectives include developing advanced prototyping skills, learning prototyping toolchains, gaining a critical eye for giving and receiving feedback, and working in a clean and organized environment. Full course objectives and outcomes are listed in Appendix A.

The course heavily utilizes active learning, hands-on workshops, in an apprenticeship model. True to an apprenticeship model, instruction is fully integrated with the practice of making and includes three important components of any training system: information, demonstration, and practice [7]. Instruction on each topic in the curriculum begins with a short active learning lecture about a particular method or tool. In these lectures, exemplars produced by the instructor or sampled from prior student work are presented to the students. The class engages in an open discussion about what makes each piece a success or failure. Following this period, the instructor or TA gives a demonstration of how to execute the relevant technique/tool, including methods of operation, and displays of best and worst practices. Students then rehearse the technique/tool in class or a scheduled out-of-class workshop. While students are practicing this new skill during class, the workshop, or in their homework, instructors provide just-in-time feedback to the students to improve their proficiency. Students are advised that this feedback is designed to help them improve their work over the semester, similar to apprentices developing under an expert. This style of teaching is different from more traditional forms of training which include information (possibly lecture), examples of material (perhaps demonstrated examples), and practice time for the individual (worked examples or individual work). In the apprenticeship model, both explicit knowledge and tacit knowledge are shared with students. The explicit knowledge—for example, the steps of a machining technique—is delivered traditionally, such as with lectures or hands-on workshops. The tacit knowledge is delivered through one-on-one mentoring of the student by the instructor mentorship and communication of best practices in real-time as the student evolves and refines prototypes.

Tacit knowledge is a type of information that cannot be easily communicated from person to person. It is the type of knowledge that is acquired over time and practice, exercising a skill, or using a tool. In machining and prototyping, tacit knowledge refers to the ability to anticipate the behavior of materials or to adjust tool usage for optimal results. Examples include being able to feel how much force to apply when using a tool, or identifying defects on a piece of material to a great level of detail. Appendix B is included to provide an example of a workshop during which students receive expert demonstration and supervised practice with feedback. This putting-things-together workshop is conducted on the first day of class and serves the purpose of introducing students to the apprenticeship style of learning including components of lecture, expert demonstration, practice, and feedback.

Through this apprenticeship model, students receive a cycle of information, demonstration, practice, and feedback on their quality of work. This cycle is displayed in Figure 1. The hope is that this cycle of improvement allows students to approach a work product with a more refined level of craftsmanship.

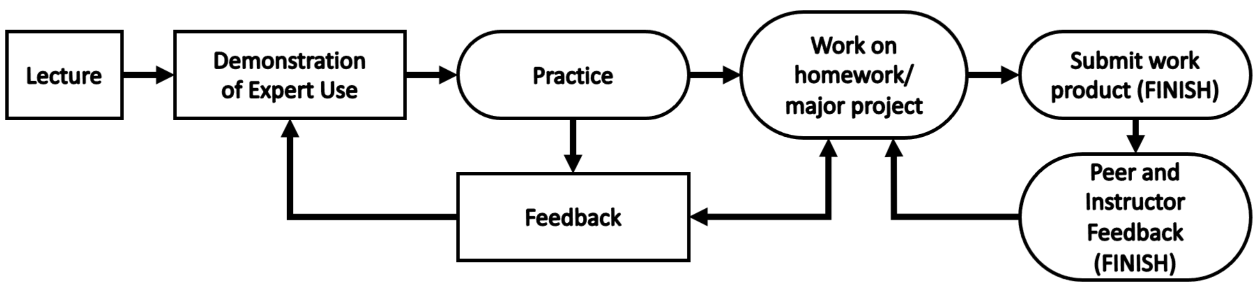

Figure 1. Flow chart representing feedback cycle in apprenticeship model used in ENGI 210.

Homework assignments for each of these topics require students to apply and extend the knowledge gained in the instruction on the topic provided in-class. For most assignments, students produce individual work; in some cases, students are paired together to reap the benefits of the buddy system, but they are still required to produce individual work. Each assignment seems deceptively simple (e.g., build a box) but has been designed to require a great deal of self-directed learning to accomplish the task. A breakdown of the coursework and how it integrates these teaching methods can be found in Table 1. The course is intended to advance student proficiency level beyond their starting state; because students come to the class with a variety of starting skill levels, each assignment has been written to accommodate for this. To provide context for how different proficiency levels are accommodated in the homework, an example homework assignment utilizing the laser cutter has been included in Appendix C.

Apprenticeship is again mirrored in the grading schema, which is proficiency-based. This means that grades reflect the overall knowledge gained by students throughout course activities rather than points earned for correct answers [8]. Each assignment is rubric is mapped to a three-tiered proficiency scale. Key characteristics of work products are listed as statements such as “part is smooth with no burrs or sharp edges.” For each corresponding statement, a mark is made reflecting where students’ work falls on this proficiency scale. These scales transparently telegraph the standards of excellence students should strive to achieve. At the end of each assignment, students assess the work of their peers, identifying aspects of each product that they either like or would want to improve. This process is random and anonymized so students do not immediately know whose work they are evaluating. This is designed to help students develop a critical eye for both giving and

Table 1. Course content: topics, workshop content, and homework. The course has gone through several revisions over the years to streamline content and topics. Thus, more topics are listed here than are covered in one semester; this table reflects the approach for a variety of topics rather than seeking to depict an actual full semester.

Topic	**In-class Workshop**	**Homework Prompt**	**Embedded difficulty students need to overcome**
Digital Documentation	WordPress operation for blogging	Introduce yourself via your first blog post ▞	
Sewing	Sewing machine operation, garment construction, making templates off of your body	Sew a workshop apron ▞	Move from a standard pattern to one that needs to be adapted to the student's body.
Woodworking	Basic joining using clamps, fasteners, and jigs; routing wood	Build a box ▞◐	Joining one corner correctly can be easily accomplished but putting together a box is deceptively complex.
Post-processing and finishing	Wood specific: removing material, surface preparation, surface coating (e.g., painting, sealing) Metal specific: removing material, surface preparation, surface coating (e.g., powder coating)	Attached to "build a box" homework ▞◐ NOTE: following this assignment, all subsequent homework must be properly post-processed and finished	Students are challenged to use "intention" when making their parts; they also have to make two identical versions, which is much more difficult in practice.
2D Drawing	Introduction and usage of Adobe Illustrator for the creation of shapefiles	Produce an accurate drawing of one of the 507 Mechanical Movements▞	Students attempt to shortcut by using the trace function in Illustrator, which doesn't work well when tracing images with exact dimensions.
Laser cutting	Laser cutter operation and usage. Out-of-class: one-on-one workshop with instructor to extend proficiency of machine usage.	Laser cut a personalized box ⊿◐	Proper finger joint tolerances are difficult to execute properly, requiring iteration or planning. A variety of power/ speed combinations need to be controlled.
Plasma cutting	Plasma cutter operation and usage. Out-of-class: one-on-one workshop with instructor to extend proficiency of machine usage.	Plasma cut and post-process a demonstration piece ⊿◐	The plasma cutter is accurate but imprecise, tracing the desired path but with a varying width of kerf and leaving the part edges messy and uneven.
Midterm: P01 - Design and build a complex machine assembly ▞◐			Assembly of parts is difficult and can present challenges to making edges square and parts move smoothly.
3D Printing	Overview of 3D printing methods, identifying methods by sight and feel	3D print a complex mathematical equation ▞◐	Students must construct a mental model of scale and feature size; they need to take into account feature size when scaling appropriately.
CNC Machining	Setup and operation of desktop CNC machine for 2.5D milling	CNC machine a simple object ▞◐	Students need to learn to test a prototype/file quickly instead of working on a file for too long.
Molding and Casting	Use of molding and casting materials for shape transfer (both positive and negative)	Cast/mold a complex structure ▞	The process requires caution and care as well as patience and time management.
P02 – CNC and mold a custom chess piece Project completed in partners ◐			The combination of two techniques to create one workpiece requires careful planning and tolerancing.

▞individual product
⊿ individual product, produced in partners
◐includes peer feedback portion following submission

receiving feedback. A 2016 study found that this style of proficiency-based grading “provides valuable benefits to students, including direct feedback, effective self-assessment, opportunities for improvement, and a focus on learning” [9].

Students write blog posts describing all of their assignments, giving them a platform to publicly display their progress while reflecting on obstacles and breakthroughs. Students are encouraged to use their voice when writing these posts and do not have to follow a technical document format. Grading rubrics reflect that the goal of this documentation is to highlight failure and growth while reporting the start-to-finish process and key conclusions.

Methods

Two strands of data were evaluated for this study: a) quantitative assessment of proficiency gains through a self-reported skills survey and b) coded assessment of homework assignments and major projects. For the former, a skills-focused survey was administered to the students two times during the semester: first at the midpoint, and then at the conclusion of the course. This survey asked students to report their skills in specific techniques and tools on a Likert scale of increasing proficiency from 1 to 5. Data from these surveys were collected from Fall 2014 to Spring 2020. Student data was used only if the complete pre- and post-surveys were both available. A two-tailed t-test was used to evaluate gains in proficiency for students comparing the stated proficiency at the middle of the course to the end of the course.

Student work samples were scored using a 5-point scale separately evaluating *operation* & *technique*. Operation was defined as whether a tool was used correctly, for example, whether the correct power and speed settings were used on a laser cutter to pierce 4mm plywood. Technique was defined as whether the student achieved the intended outcome with the tool/technique, such as applying a plasma cutter correctly to execute a clean and detailed design. A heavy focus was placed on whether the student/s recovered based on an error and produced a final part that met the expectations for the homework assignment. Additionally, students’ willingness to modify their design to make better use of the machine weighed heavily on the technical proficiency score. This scoring system was developed by two independent scorers based on an iterative revision of the rubric after independent scoring sessions and a comparison of the results. Individual cases were used as exemplars for specific levels, allowing for lending robust and consistent descriptions of these levels.

Scoring was completed by the two scorers for the usage of tools that contributed to the major assignments in the class: the midterm and final. For the midterm, they scored the laser cutter, plasma cutter, and then midterm project for both operation and technique. For a separate semester, they scored assignments that contributed to and led up to the final project: 3D printer, CNC mill, molding & casting, and then final project.

This study collected data observationally as part of the course and was thus human subjects exempt. Students gave release for their blog post material to be made public.

Results

ENGI 210 has been run since the Fall 2014 semester; course size has included on average 11 students per semester depending upon local/global natural disasters as well as a popularity of course surfing at Rice University. The course has been taken predominantly by STEM students with >90% of participation comprising engineering students and a small number (~7%) of these natural science students, with the occasional student in architecture or psychology. Almost half of all students have been Mechanical Engineering students, but 20% of the total participants reported as undeclared in their engineering discipline, which based on the trend could increase the total number of mechanical engineers. This course is taken by students of all grade levels, with nearly half of the historical enrollment composed of sophomores and the remaining half divided between freshman, junior, and senior students. Most of the undeclared engineering students were in their first year of study when they took the course. Females have made up 36% of the total participation.

ENGI 210 is the type of hands-on course in which students apply critical prototyping techniques to create physical artifacts. Representative photos sampled from the students' blog posts showcase the types of work products that students made for various assignments. As seen in Figure 2, some of the workpieces showcase a high level of skill while others reflect a state of learning.

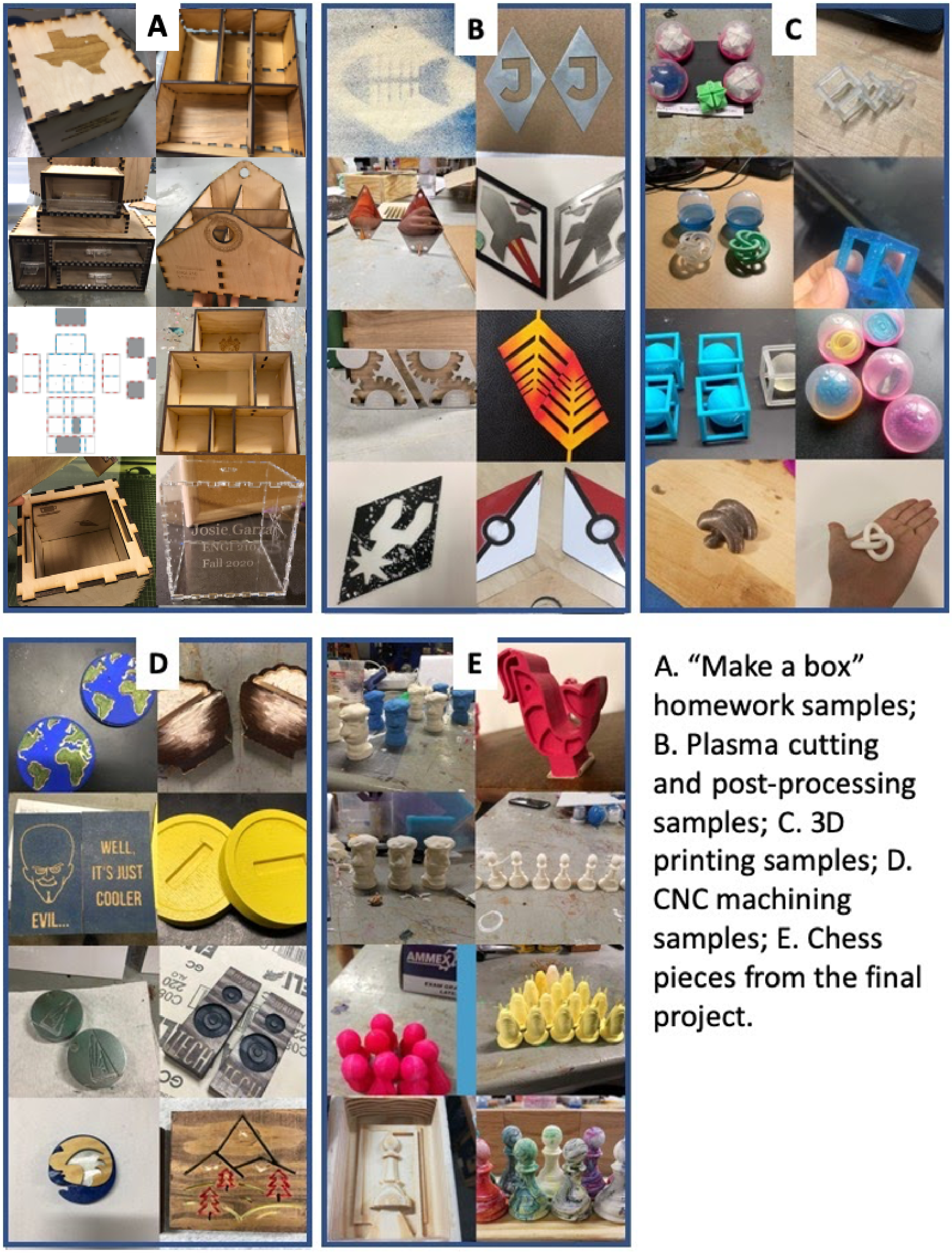

Figure 2. Examples of artifacts created by students for select homework assignments.

Surveys administered at the start and end of each semester recorded students' impressions of their prototyping proficiency in the techniques/tools used in the course. Nine topics were included in this survey: sketching and drawing; low fidelity prototyping; vector (2D) drawing; laser cutting; plasma cutting; computer-aided design; 3D printing; molding and casting; and finishing. The sample size of collected data for surveys was between n=37-44 (some skills were not taught every semester). As reflected in Figure 3, for each topic, students reported that they ended the class with more proficiency in the topics than when they started. For all of these topics, there was a statistical difference between the two states, with $p < 0.01$. Gains in topics with direct instruction were higher than gains for topics that were required for success but not directly taught. For example, laser cutting and plasma cutting were taught both in class and in accompanying workshops where students worked one-on-one with the instructor to hone their skills. These two skills had greater gains than sketching/drawing and low fidelity prototyping. These latter skills were not presented in class, but they were necessary for success in coursework such as the midterm and the final. Students reported the highest final proficiency in laser cutting and the lowest final proficiency in sketching and drawing.

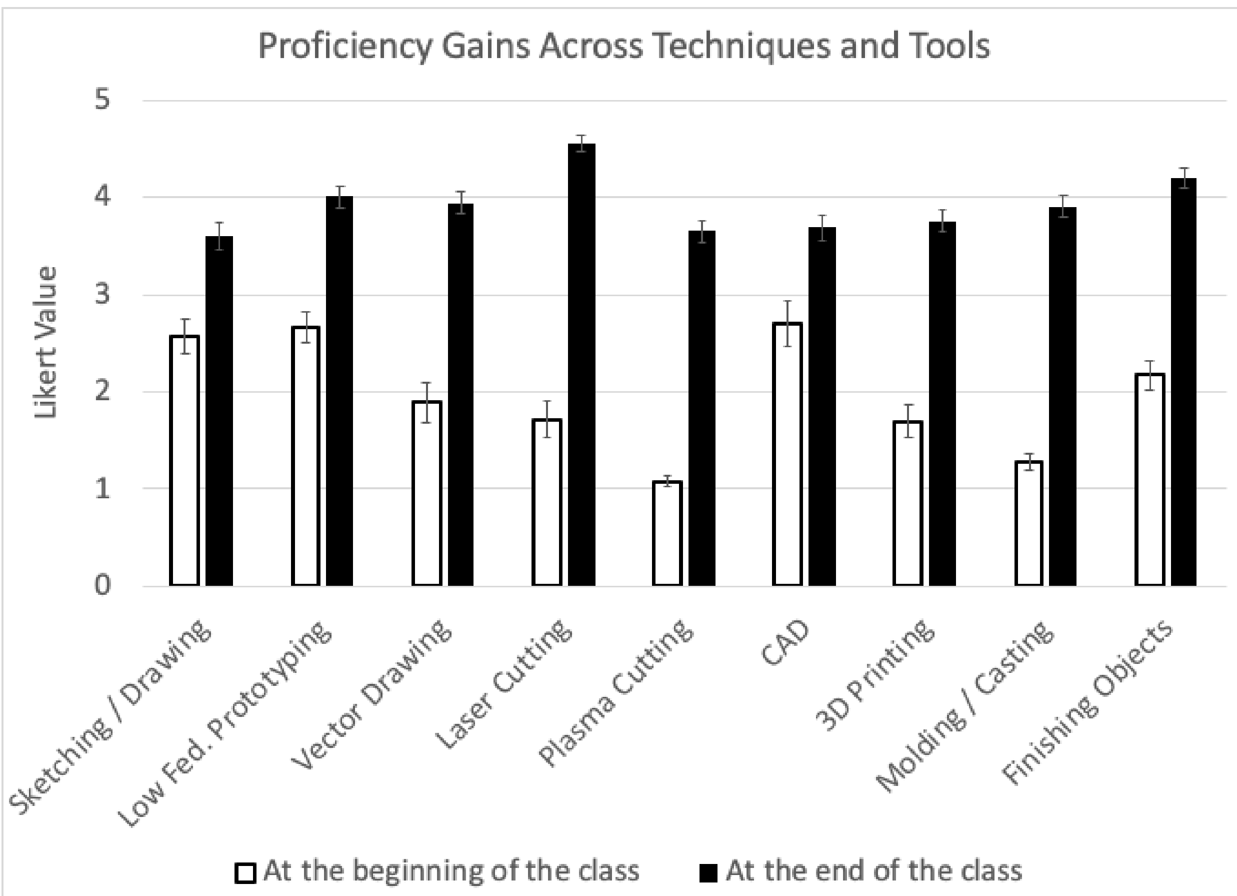

Figure 3. Proficiency gains across for students across techniques and tools. Error bars reflect standard error. Statistically significant gains were found for *each* pair (at the beginning and at the end) at $p < 0.01$.

Quality of Operation and Technique Reflected in Student Homework

Scoring results of student homework are reflected in Tables 2 and 3. One assessment evaluated the 2D manufacturing techniques: the laser cutter homework, the plasma cutter homework, and the midterm project, which used both of those tools. All students attained operation scores of a 2 or above, with ~92% of students scoring a 3 or greater on the laser cutter assignment and ~92% of students scoring a 3 or greater on the plasma cutter assignment. The technique scores for all students had a much wider range, with ~84% of students scoring a 3 or greater on the laser cutter assignment, and ~61% of students scoring a 3 or greater on the plasma cutter assignment. Laser cutter operation scores increased from the homework to the midterm. For the midterm, all technique scores were 3 or higher, while there were some 1s and 2s on the homework technique scores. The lowest technique scores on the midterm came from students who had lower technique scores on their assignments, although some who got low scores on the assignments showed great improvement on the midterm. Essentially, no student's technique got significantly worse from the homework to the midterm; it either stayed the same or improved. Overall, the technique score was higher on the midterms than on the individual assignments, indicating greater comfort and ambition with the tools.

The second analysis was on 3D manufacturing assignments: the CNC milling, 3D printing, and molding/casting homeworks, and the final project, which employed all three of these techniques. The operation scores for all students was a 2 or above, with ~93% of students scoring a 4 or greater on the CNC machining assignment, ~79% of students scoring a 4 or greater on the 3D printing assignment, and ~79% of students scoring a 4 or greater on the molding and casting assignment. The technique scores for all students had a much wider range, with ~93% of students scoring a 3 or greater on the CNC machining assignment, ~93% of students scoring a 3 or greater on the 3D printing assignment, and ~86% of students scoring a 4 or greater on the molding and casting assignment.

Table 2: Tool operation scores.

Tool	**Homework Operation**	**Midterm/Final Operation**
Laser cutter	4.23	4.77
Plasma cutter	3.85	3.23
CNC mill	4.21	4.40
3D printer	4.21	4.71
Mold/cast	4.15	4.43

Table 3: Technique scores.

Semester	**Assignment Type**	**Technique (Average)**
F18	Homework	3.50
	Midterm Project	4.23
F19	Homework	3.86
	Final Project	4.14

Discussion

Students apply a range of techniques and their own creativity to produce work products in ENGI 210; these objects are beautiful and uniquely represent each students' efforts. Figure 2 shows how students applied laser cutting, plasma cutting, 3D printing, molding and casting, and post-processing to generate physical prototypes. This figure showcases the range of fidelity and refinement found in student prototypes created in this class. For example, in section A some of the boxes have misaligned edges and sharp corners while others are neatly constructed and sanded smooth. Despite a wide variety of starting tool knowledge, time spent on assignments, and creativity applied, all students were able to complete the assignments implementing the required prototyping techniques.

The results of the student skills survey in Figure 3 demonstrate that students believe this course is effective in increasing student proficiency in particular skills. This includes skills that are directly taught (e.g., laser cutting and 3D printing) as well as other skills that are not directly taught but are needed for project success (such as drawing or low-fidelity prototyping). These skill gains are supported by the instructional methods and how the coursework requires students to extend their knowledge and proficiency to complete a task. Further research could extend the understanding of a student's understanding of proficiency gains by surveying them for situations in which they believe they demonstrated proficiency in a skill.

Coded scoring of sample homeworks reflects the growth in operation and technique students applied, thus demonstrating that the work products provide evidence of student proficiency gains. As can be seen in Tables 2 and 3, students increased their applied knowledge of operation and technique between the individual assignments and the midterm; this is analogous to charting student growth through a string of quizzes and then the final exam. Tool operation scores were very high on average for the assignments (most tools had average scores above 4.0 on the 5-point scale), indicating effective teaching methods and good outcomes. Generally, operation scores increased in the midterm and final assignments. For example, all students achieved a 4 or 5 for laser cutter operation on the midterm. This is expected since the laser cutter is relatively easy to learn and gain proficiency in. Plasma cutter operation decreased from the assignment to the midterm because students tend to avoid using the plasma cutter in the midterm project and thus produce lower-fidelity plasma cut objects in the project than in the homework assignment. Technique scores increased on average from the homework assignments to the midterm and final projects. This trend suggests that the experience gained with each tool allowed students to tackle more challenging and complex designs for their projects in the midterm and finals.

Practical skills-based courses such as ENGI 210 often have observable impacts later in a students' academic career; at Rice University ENGI 210 seems to be transferable to follow-on design courses. Anecdotal reports from senior design/capstone professors report that students who have taken the prototyping course create designs of higher quality. Due to the small sample size, this trend is difficult to measure empirically.

Course feedback plays a large role in how the course evolves. Several prompts are provided to encourage students to vocalize their learning about each assignment. For example, all students are asked to comment on the question "if you had to do this again how would you do it differently?" The instructor also discusses with the students the more difficult aspects of the course, and these conversations are used as a proxy to determine whether the module learning objectives have been met. In some cases, these discussions have resulted in new rules being created, the assignment difficulty being adjusted up or down, or the assignment being removed from the course altogether. An example of an assignment that was removed from the course taught students how to use low fidelity materials to build prototypes; students reported that they had sufficient experience in this from a freshman design course.

Exploration of the learning outcomes from this course is ongoing and requires more rigorous codification to gain a greater understanding of the differences between students. One of the goals of having students write blog posts is to lower the barrier of creating worthwhile documentation by removing the limitations of format, length, and style. By encouraging students to write freely and appealing to their intrinsic motivation, we hope that they will write authentical descriptions of their process for others to review. Student process documentation captured by the blogs showcases a snapshot of individual student learning progress at the end of each assignment. In some cases, students document their process, including failure, by displaying photos of incomplete prototypes. In other cases, students elect to show off the final version without much commentary. An adjacent study exploring the evidence of proficiency gains based on the text itself is in progress.

Conclusion

This study evaluated the proficiency gains of students taking a flagship course in prototyping in an undergraduate engineering design curriculum. Students created unique physical artifacts by using the prototyping techniques taught in the class to execute original designs, underscoring the efficacy of this course in bringing students to a functional level of tool proficiency. Student surveys administered at the beginning and end of the course reported their gains in the use of specific techniques or tools. For each technique or tool surveyed, the students self-reported statistically significant proficiency gains ($p < 0.01$). Independent scorers also evaluated assignments from a selection of semesters and found that both operational skill and tool technique improved as students progressed through the course. Thus, this class is effective in increasing students' proficiency in the relevant techniques and tools. An adjacent study exploring student writing samples is ongoing and will provide insight into the student sentiment of the learning opportunities this course affords. The results of this exploration contribute to a body of literature that seeks to understand the most effective methods of instructing students on the creation of physical artifacts, a skill that is critical for engineers both in academic and professional settings.

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Appendix A. Course Objectives and Outcomes for ENGI 210

Students will acquire basic to intermediate-level proficiency in the digital and physical fabrication of objects for engineering design-related projects. Students will train with the instructor and learn by doing with other students. Work will be completed individually and in groups on short projects.

Course Objectives. Students will learn:

1. Advanced prototyping and fabrication skills useful in the construction of physical objects.
2. How to utilize toolchains to string together multiple manufacturing processes to translate an idea into a physical part.
3. A critical eye to objectively discuss the post-processing and finishing of objects.
4. How to maintain a clean and organized environment while working on projects.

Course Outcomes. Students completing this course will be able to:

1. Rapidly prototype, via models or sketching, rough ideas to communicate an integrated project or a functional design block.
2. Create, prepare, or modify a digital file and fabricate an object/part using a laser cutter, plasma cutter, or vinyl cutter.
3. Modify a digital file encoding an object to the correct dimensions, tolerances, and geometry to produce the objects using manufacturing/fabrication techniques.
4. Produce a positive and negative of a designed part using a combination of advanced manufacturing techniques such as 3D printing, CNC Machining, and molding/casting.

Appendix B. Sample Workshop Session Plan and Sample Homework Assignment

Sample Workshop Session Plan: “Module 2: Putting Things Together”

Materials needed for this module:

Material	**Where it’s located**	**Setup for module**
Safety glasses, PPE	Bins around the building	Students retrieve
Hot glue gun	Prototyping bins upstairs or downstairs	TA sets up and plugs in so they are hot for the beginning of class
Hot glue sticks	Prototyping bins upstairs or downstairs	Students retrieve
Drill	Downstairs building area	Students retrieve
Drill bits	Downstairs building area	TA retrieves before class
Cardboard	Underneath downstairs building table	Students retrieve
Utility knife	Prototyping bins upstairs or downstairs	Students retrieve
C-clamps	Downstairs building area	Students retrieve
Kreg jig	Office or in tool cage	TA retrieves before class
Corner clamps	Downstairs building area	TA retrieves before class
Screws	Fasteners area	Students retrieve
Finished version of corners made with Kreg jig	210 Storage area	TA sets up before class
Finished version of corners made with corner clamps	210 Storage area	TA sets up before class
Complete box made with hot glue	210 Storage area	TA sets up before class
Scrap wood	Underneath downstairs building table	Students retrieve

<u>Sections of Module</u>

1. Discussion of Putting Things Together

2. Learn how to build a box of “indeterminate size” using cardboard and hot glue
3. Learn how to join corners of a box using wood and fasteners
    a. Kreg jig
    b. Corner Clamps
4. Learn how to finish box corners using a router

Skills students will learn
- Rapid construction using cardboard and glue
- Use of a drill
- Joining materials with clamps and fasteners

Section 2: Box of Indeterminate Size
1. Beginning of the lab: TA plugs in the hot glue gun so that they can start warming up.
2. Students: Go to the tool corner to grab cardboard and bring it to the ENGI 210 table.
3. Students: Bring utility knives and hot glue guns to the table.
4. Cut the cardboard such that there are 4 strips and a base to take the place of the bottom of the box.
    a. Instructor demonstrates processes to better understand the design.
5. Hot glue the strips to base similarly to the way it was performed in the demonstration.

- What you can do with a box of “indeterminate size”?
    - Make T connections
    - Use them for molding and casting
    - You can shrink or grow to need
    - You can build a box around an object and grow or shrink as needed
- Time taken: 20 min total
    - Retrieving materials: 5 min.
    - Cutting time: 5 min.
    - Glueing time: 10 min.

Section 3a: Joining Corners of Rigid Material with Kreg jig
1. Before the lab: TA builds or retrieves examples of joined wood.
2. Before the lab: TA sets up corner clamp and Kreg jig.
3. Students: take sample wood from below the building table.
4. Demonstration: how to set up a Kreg jig.
5. Student pairs: join wood with the Kreg jig or corner clamp, then switch, making a box with three sides.

- Notes
    - Don’t use 2x4, they are large and not usually a lot of scrap.
    - Practice using more random sized pieces (thicknesses).
- Detailed description of demonstration of the Kreg jig
    - Measure the dimensions of the wood on the other side of the jig.

    - Adjust the jig such that it is the same length as the width of the wood.
    - Use the accompanying drill bit to drill the holes provided by the jig.
        - This may take multiple passes, and if it gets stuck, blow/take out the accumulated wood pieces in the jig.
    - Take the screw and screw it as far as the hole has allowed.
    - Drill into the wood and screw the wood together into place.
- Time taken: 45 min for both demo and activity time for both Kreg jig and corner clamp

<u>Section 3b: Joining Corners of Rigid Material with Corner Clamps</u>

1. Before the lab: TA builds or retrieves examples of joined wood.
2. Before the lab: TA sets up corner clamp and Kreg jig.
3. Students: take sample wood from below the building table.
4. Demonstration: how to set up a corner clamp.
5. Student pairs: join wood with the Kreg jig or corner clamp, then switch, making a box with three sides.

- Detailed description of demonstration of the corner clamp
    - Attach the corner clamp to the edge of a table with a C-clamp.
    - Drill a hole into the wood using a bit appropriately sized to screw that is to be used.
    - Use a larger bit close to the surface in order to “countersink” screws, or make space for the head of the screw so that the side of the wood is flush and the head sinks.
- Time taken: 45 min for both demo and activity time for both Kreg jig and corner clamp

<u>Section 4: Finishing Corners of Box with Router</u>

1. Before the lab: TA sets up the router with a bit that is ready to cut a piece of wood.
2. Students: bring their wood that they joined in Phase 2 & Phase 3.
3. Demonstration: how to run the router with a bit already in the router.
4. Students: each routes one edge of their three-sided box.

- Notes
    - Due to time constraints of the class period, students only need to know how to operate the machine, not how to change the bit on the router. This should be set up by the TA or the lab techs when the students need to use the machine.
- Detailed description of the demonstration of the use of the router
    - Confirm that the correct bit is in the router.
    - Turn the router on.
    - Take the plane of wood and have an edge run by the router. The edge should be finish with the same profile as the router.
- Time taken: 10 min total
    - Demo time: 5 min.
    - All students route one edge: 5 min.

Appendix C: Sample Homework Assignment for ENGI 210: Prototyping and Fabrication

ENGI 210: Prototyping and Fabrication

Assignment: Laser Cutting
Turn in: 1) Post on our course blog (engi210.blogs.rice.edu), and
2) Bring your physical model to class

In this assignment you will use the laser cutter to produce a box that can be used to display the physical parts produced in ENGI 210.

This assignment is broken into three difficulty levels:

1. Beginner: This assignment level is for students who have not used the laser cutter or are not comfortable using it without instruction or supervision (Turn to page 56).
2. Intermediate to Proficient: These assignment levels are for students who have used the laser cutter before, and are comfortable using it without instruction or supervision (Turn to page 57 or 58).

You may work with partners on this assignment but each person will need to produce one box that they will be individually graded on. With your partner, go through the laser cutter training for the OEDK laser. You will be allowed to use the laser cutter on your own after passing this training so it is important that you write down, remember, or otherwise memorize the steps to operate the machine. You may cut any files while learning the laser cutter: the OEDK logo, the map of Texas, the War Owl, or something of your own preparation.

After you and your partner(s) have operated the machine several times and are comfortable using the laser cutter each of you may begin to work on your own homework.

When cutting your boxes, produce a version that can snap assemble and hold itself together without an adhesive. This will require you to adjust the finger joint tolerances so that it snaps together without damaging the parts.

When working on your homework, etch/cut what you would consider to be a *high quality* example. There should be minimal to no charring, the edges should be clean, and the part should have the correct geometry.

For your homework (Beginner/Intermediate/Proficient):

1. Produce your box based on your level of proficiency:
    a. Beginner: Etch and cut a box, using the provided instructions
    b. Intermediate: Design, etch, and cut your box using uniform compartment sizes
    c. Proficient: Design, etch, and cut a 3D structure that can be used to display your objects
2. Individually, document your laser cutting experience. This may be in the form of pictures of files, drawings, pictures, or videos. Post this to the course blog.
    a. In your blog post, answer this question: How much did this object cost? Clearly document your calculations, including raw materials, labor, and machine time.

Grading will be based on the included rubric.

Peer grading will be conducted for this assignment.

Beginner Level Assignment

Description

For this assignment you will create a box that demonstrates proficient use of a laser cutter to make a part. You will use a box making program online to generate the box file and then *cut* the box yourself on the laser cutter. The box dimensions should be no smaller than 4” on a side. You are free to use whatever box making program online you wish.

There is one physical deliverable to this assignment:

1. Laser etch/cut **one** box created with a box maker program. Etch your name, ENGI 210 (what semester), the date on the side of the box. On another side of the box, etch your college crest appropriately.

Instructions

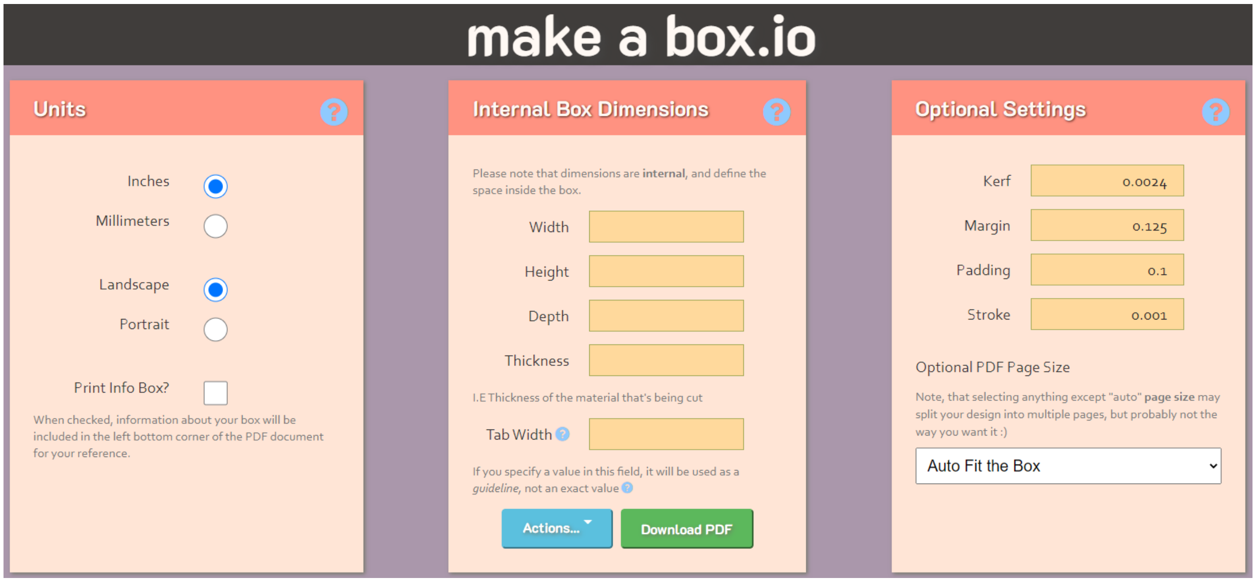
In class, we went through the basics of laser cutting and the steps required to set up a drawing in Illustrator and translate that into a physical 3D design using the laser cutter. In this tutorial we will be going through the steps required to make a simple laser cut box.

Materials:

- plywood
- laser cutter
- Adobe Illustrator

Steps:

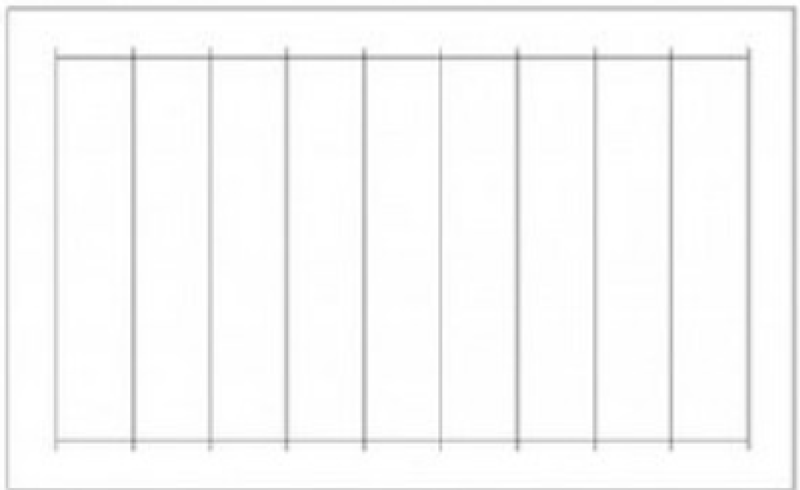
1. As mentioned in class, the laser cutter can be used to create a 3D model of a 2D drawing. For this assignment we will be using a 2D drawing generated by makeabox.io. This website makes it easy to put in desired measurements and quickly get a box design that is almost ready to be laser cut.
2. Once you navigate to makeabox.io there are many inputs needed to produce a box.



3. To begin, we want a box of at least 4”x4”x4”. To make this, we will choose inches as the units, and for the width, height, and depth we will use 4 minus the width of the wood.
    a. If you read carefully at the top, it stated that the measurements input are the internal dimensions of the box. So if we are trying to make a box of exactly 4”x4”x4”, then we will have to subtract the width of the wood from the dimensions that we will use.
4. So, for the dimensions, since the plywood we typically have as stock is ⅛” thick, we will input 3 ⅞” for each of the dimensions.
    a. You will have to specifically measure the dimensions of the wood that you will use. It is best to use the decimal inch measurement using calipers.
5. Next you will specify the dimensions for the thickness of the wood there it asks you to input it. You should already have this measurement on hand.
6. You can then specify the width of the tabs that you would like to use. Generally, it is best to use as few tabs as possible that still result in a good build.
    a. If you use a tab width of 0.25”, then you will have about 8 tabs along just one side. Repeated along every edge and the box gets very difficult to align and put together. It is best to use tabs with width of 0.5” or larger (unless a smaller tab is required). Additionally, you do not want a tab width to be too large, or there will be too few attachment points along an edge i.e. if you box is 5” wide, but each tab is 2”, then there can be a max of two tabs per edge which would produce a very weak joint.
7. The last step before you can successfully generate the file is dealing with the kerf. As mentioned in class, kerf is the material that is cut away (or burned) when manufacturing. In this case, the laser cutter physically burns away wood in order to create the cut of the design. To account for this and in order to create a snap fit box successfully, you will have to determine the proper kerf needed for the box.
    a. Most online box making programs allow you to set the kerf manufally (typically between 0.012” to 0.015”) to achieve snug (also called “press-fit”) fit. Kerf can

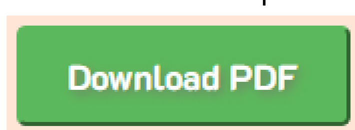
depend on many factors, including laser power, laser speed, maintenance, and quality of the laser. For example, if the laser has not been cleaned for some time or it is misaligned, then the kerf values will change. It is recommended that you test various values for the kerf rather than simply guessing.

b. A best practice for measuring kerf involves downloading **THIS** file, cutting it out and then measuring the resulting kerf.

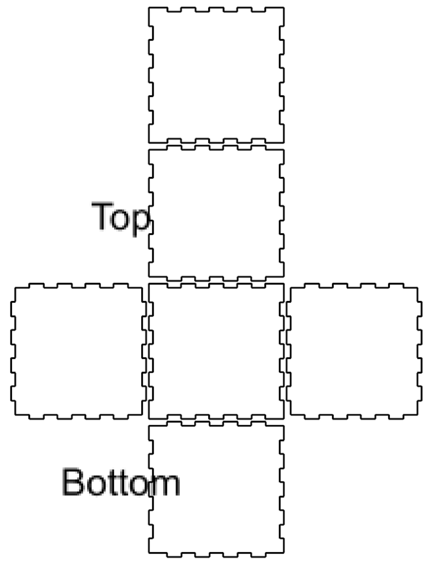


   i. Load the file, then cut it with your best guess setting. When you remove it from the laser cutter, push the rectangles against each other, creating a gap between the last rectangle and the border. Measure this gap with a caliper and divide by 10 to determine the average kerf.

8. Use this value for the kerf on your online box maker. Download the PDF and you should be able to open this file in Illustrator for further processing.



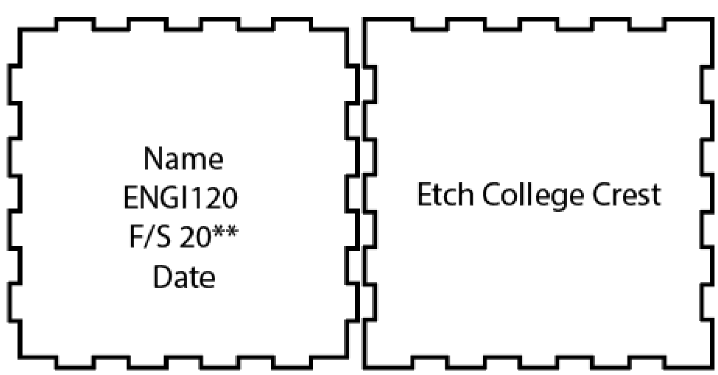
9. With the file in Illustrator, you will need to combine the separate squares into shapes using the shape building tool.



a. When you first import the file, every line on the page is independent. This means that when you laser cut, the laser cutter will cut every single line one at a time and that is very inefficient. To remedy this problem, use the shape builder tool to create 6 different shapes. The shortcut to do this is done by pressing **Ctrl A**, then **Shift M.** This will select all, and then activate the hotkey for the shape building setting.

b. Once you have done that, click inside of each square and this will shape build the new squares. Now, the laser cutter will cut 6 objects rather than 100 lines.

10. You should now add the text that will be etched onto the box. To do this press on the **Text** icon and click on where you want the text to appear. This can be moved around and aligned to any of the sides. Additionally, you need to import your college crest and place it on one side of the box.



11. Once this file is ready, it can now be cut on the laser cutter. You will now need the laser cutter manual located at the laser cutting computer to finish the rest of the laser cutter processing.

a. At the laser cutter, it is best practice to always draw a small 0.25”x0.25” square in the top left corner of your artboard and cut it out on the laser cutter. This is a good first initial cut to test to see whether your cutting settings are set correctly and give you the desired cut. At this point you should be testing to see if you cut too long which would char the edges, or if you did not cut long enough with enough power which will not cut through. This will help speed up your testing and give you a good finished product.

12. You will have 6 sides of a box after using the laser cutter which can now be snap-fit together. Do not use glue to connect the sides.

Intermediate Level Assignment

Description

For this assignment you will create a flat box with multiple compartments that will be used to display your work from this course. You will *design* and then *cut* the box yourself. Included with this assignment is a .pdf of the dimensions of the box compartments that you will need to take into account. The depth of the box should be no less than 3” (interior compartment). Feel free to exercise as much creativity as you are comfortable with while still completing the assignment functionally. This will essentially involve making a structure with cubby holes of the required sizes.

There is one physical deliverable to this assignment:

1. Laser etch/cut **one** box with multiple compartments (as indicated in the attached pdf). Etch your name, the class, the date somewhere on the box. On another side of the box, etch your college crest appropriately.

Proficient Level Assignment

Description

For this assignment you will create a structure that will be used to display your work from this course. You can design this structure in any way, shape, or form that you think will display your projects well. Included with this assignment is a .pdf of the dimensions of the box compartments that you can choose to take into account, or you may elect to display them in a new unique way. Feel free to exercise as much creativity as you are comfortable with while still completing the assignment functionally. You may choose to create your structure in 2D, or choose to make a 3D structure where your projects can be displayed. An example of this would be a Ferris Wheel that can display all of the assignments. This is very open ended, and extreme creativity is encouraged.

There is one physical deliverable to this assignment:

2. Laser etch/cut **one** structure with multiple compartments or platforms. Etch your name, the class, the date somewhere on the structure.

ENGI 210 Homework: Laser Cutter

Name:

	Low	Average	High	Points
Operation of the laser cutter	The incorrect power / speed settings were used; the kerf was set incorrectly; finger joint settings were inefficient or poorly chosen; part was designed with the wrong material thickness in mind; the part is incorrectly sized.	The power / speed settings could be improved; the kerf could be improved; finger joint settings need adjusting; material thickness and joint overlap could be improved; the part size could be improved.	The correct power / speed settings were used; the correct kerf settings were used; finger joint settings were specifically selected based on the box size; joint overlap is correct based on material thickness; the part is the correct size.	/10
Technique demonstrated while using the laser cutter	Part's aesthetics are unsuccessful or made without consideration; no additional design elements are included; no creative intention or it is buried; part does not complete the attempted assignment	Part was made with consideration to aesthetics but it could be improved; any additional design flair needs refinement; unclear of the creative intention or the creative intention does not shine through; part reasonably completes the assignment.	Part was successfully made with consideration to aesthetics; Part has some additional design flair (unique features); part was created with clear intention; evidence that part was created with a particular design goal instead of simply completing the assignment.	/10
Documentation	Process has not been documented. No images/files or low quality media. Failures, challenges, or missteps are not discussed. Insufficient description of final work product and cost estimate.	Process has been documented but some steps are omitted or vague. Photos, files, or rich media could be improved. Sufficient final description of final work and cost estimate.	Process has been documented transparently. Photos of work are included. Failures are exposed and written about. Final work product is explained and can be understood by a reader. Cost estimate is insightful.	/5
			TOTAL	

Comments:

ENGI 210 Homework: Laser Cutter – Peer Grading Instructions: Inspect the box. Circle or underline the corresponding statements. Write in any comments that are not covered by the assignment rubric. Comments may take the form of suggestions, or constructive criticism.
Submission number:

	Low	**Average**	**High**
Operation of the laser cutter	The incorrect power / speed settings were used; the kerf was set incorrectly; finger joint settings were inefficient or poorly chosen; part was designed with the wrong material thickness in mind; the part is incorrectly sized.	The power / speed settings could be improved; the kerf could be improved; finger joint settings need adjusting; material thickness and joint overlap could be improved; the part size could be improved.	The correct power / speed settings were used; the correct kerf settings were used; finger joint settings were specifically selected based on the box size; joint overlap is correct based on material thickness; the part is the correct size.
Technique demonstrated while using the laser cutter	Part's aesthetics are unsuccessful or made without consideration; no additional design elements are included; no creative intention or it is buried; part does not complete the attempted assignment	Part was made with consideration to aesthetics but it could be improved; any additional design flair needs refinement; unclear of the creative intention or the creative intention does not shine through; part reasonably completes the assignment.	Part was successfully made with consideration to aesthetics; Part has some additional design flair (unique features); part was created with clear intention; evidence that part was created with a particular design goal instead of simply completing the assignment.

Comments: