3D Design in Art and Engineering: An Interdisciplinary Experiment

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Abstract

As part of an institutional initiative to develop "hybrid" courses at the boundaries of two distinct disciplines, the authors recently created and taught a course that merged studio art and computer-aided engineering. External constraints dictated that the course satisfy Loyola University Maryland's core (general education) fine arts requirement and also serve as an "engineering elective" for engineering students, though the course was open to students from all majors. The theme that tied the disciplines together was the process of design and problem solving. Early lessons and exercises explored the creation of objects in both the physical and digital realms, progressing from sketches and simple extrusions to more complex three-dimensional (3-D) solids and assemblies. Once they had developed basic proficiency with the sculptural techniques and software, and had gained an understanding of visual principles and concepts behind analysis of art, students were asked to design and fabricate an artistic piece comprised of manually-formed and 3-D-printed elements. This final project incorporated both artistic objectives and engineering constraints and reinforced the similarities and differences between the artistic and engineering design processes. As the course unfolded, and again at the end, students were asked to evaluate the extent to which the course goals and learning outcomes were satisfied and to provide suggestions for improving the course the next time it is taught. This paper describes the goals, outcomes, structure, and assignments associated with the course, as well as the challenges, evaluation results, and lessons learned. Although several areas for improvement were identified, both the instructors and the students considered the course to be successful and worthwhile.

Introduction

In light of its heritage and mission, Loyola University Maryland places a strong emphasis on the liberal arts, even as it offers professional programs in many areas, including computer, electrical, materials, and mechanical engineering. Recently, the institution has undertaken an initiative to develop courses at the boundaries of different academic disciplines. The intent is to challenge both students and instructors to explore connections and synergies that might otherwise go unnoticed when the subjects are treated in separate courses. With this in mind, the authors developed and taught—for the first time in Fall 2019—a pilot undergraduate course that merged studio art and computer-aided engineering. This course was intended to meet Loyola's core (general education) requirements in the fine arts area, while also satisfying an "engineering elective" requirement for any engineering students who chose to take the course.

Different approaches for integrating art and engineering in an educational setting have been described by several investigators. Some incorporated modules or projects into existing art or engineering courses [1-4] or labs [5,6]. Others developed new courses that combined the disciplines in particular ways [7-12]. Still others conducted studies outside of courses [13] or modified entire curricula [14]. The aims and methods associated with these efforts were quite varied. For example, Benson and Burnett [2] were concerned with creating a floating art installation that conveyed "the need for convergence in a disparate world." In addition to creating a working installation, a major goal of the project was for students and faculty members in different fields (including art and engineering) and geographic locations to experience collaboration across disciplines. Thus, the students were involved directly in the creation of art. In contrast, Findley and Mirth [9] designed a course that was "created specifically for the purpose of enabling students to explore the interconnected worlds of art and engineering." The course included a variety of activities, but the most significant of these were four writing assignments that asked the students to consider "how function and aesthetic form can contribute to the improvement of an engineered object." The students did not create art as part of this course, but they explored various engineering themes through the study of art. Beams, *et al.* [8] describe an experimental course that replaced (temporarily) a "Design Methodology" course for electrical engineering majors, dubbed the "Leonardo Project." The intent was that "engineers would experience the design process through direct participation in the arts as artists in multiple fields of artistic expression." Individual students worked directly with arts faculty mentors to create an artistic product. Students were required to prepare project plans in a way that emphasized parallels between engineering design and design in the arts. Themes related to science and engineering were preferred but were not mandatory. A public exhibition of student works was held at the end of the course, and it was reported that many of the students appreciated the chance to experience the process of design and creation outside their field.

Ottino [15] offers an interesting perspective on the intersection of art and engineering, noting that "engineers equate art with paintings, photographs, and sculptures, and leave out conceptual art, installations, and much more. Artists equate engineering with technology and not with the human factors and passions that animate it." He goes on to suggest that engineers "and artists can connect through the need to *make* things, rather than *talk* about things. At a high level of abstraction and production the differences between artists, scientists, and engineers blur. They all rely on a singular need, craving or obsessiveness, and an ability to enjoy the process of creation for its own sake."

Clearly, there are a number of approaches we could have taken. Early on, we committed to making the course open to all majors, thinking that this could lead to unexpected interdisciplinary interactions among the students. Because of this, we agreed that meeting the core fine arts requirement (which all undergraduate students must satisfy) would be our primary course focus and that the approach for meeting the engineering elective requirement would be tailored to also support satisfaction of the first (art) requirement. After much consideration, we decided that the engineering content would be centered on computer-aided design (CAD). Ours would be a hybrid course that merged 3-D studio art with 3-D CAD, and the thread that we would use to tie the disciplines together would be the process of design and problem-solving.

Course Description

The catalogue description of our course is given below.

> **SA 226 - Three-Dimensional Design in Art and Engineering (3.00 credits)**
> Students learn the elements of three-dimensional design via interdisciplinary connections between the fields of studio art and engineering. The foundations of visual communication and spatial design are addressed through hands-on creation of artworks and verbal/written analysis of design concepts. Engineering drawing and solid modeling techniques and conventions are also covered within the context of computer-aided design (CAD) software. Students work with a range of studio art media and fabrication techniques throughout the course, including 3D printing. *Fulfills fine arts core requirement. Same course as EG 226.*

In addition to serving as a core fine arts course and an engineering elective, a major learning aim of the course was that the students recognize similarities and differences in the ways that artists and engineers approach their designs. With this in mind, broad course goals and measurable learning outcomes were developed.

Goals and Learning Outcomes

The following *goals* were established for student learning:

1. Learn to use digital and sculptural tools to realize 3-D ideas.
2. Learn effective workflow to draft, plan, measure, and execute 3-D artistic forms.
3. Understand and utilize contemporary 3-D computer-aided modeling and printing techniques.
4. Gain familiarity with contemporary and historical artists working in three-dimensions.
5. Develop critical thinking and problem solving in the research and development of individualized projects.
6. Sharpen oral and written fluency in the discussion and analysis of art.
7. Model the professional activities of an artist in terms of the self-discipline to complete all work in a timely fashion.
8. Recognize and appreciate similarities and differences between the engineering and artistic design processes and connections between the two disciplines.

These goals reflect modifications to the goals associated with a “traditional” core studio arts course (SA 224 Two-Dimensional Design), with specific changes made to reflect (i) 3-D rather than 2-D design and (ii) the integration of CAD and engineering into the course. To support the achievement of these goals, a specific set of measurable *learning outcomes* was created, three of which were adapted from the core studio arts course (a, b, and d):

By the end of the course, students will have demonstrated the ability to

a) create original works of art using a combination of physical and computer technology;
b) engage in critical thinking in class discussions, writing and critiques;
c) effectively build 3-D structures;
d) respond to design challenges which require the application of foundational visual and engineering principles;
e) use CAD software to create 3-D (solid) computer models of objects and assemblies;
f) design an artistic piece (and its means of display) to meet specific artistic goals and other requirements, fabricate their design, and assess the degree to which the design was successful.

Course Format and Approach

Two sections of the course were run at the same time—SA/EG226.01 and SA/EG226.02. The sections met twice per week for 100 minutes per session. Each section was co-listed as both a studio art (SA) course and an engineering (EG) course. Students from any major were free to sign up for either section, and the course counted toward their major and graduation requirements in the same way no matter which section they chose. One classroom was an art studio; the other was a computer-equipped instructional space. After considering various alternatives, the authors decided to "swap" the sections back and forth between the instructors (and classrooms) every other week for the first 10 weeks of the course (*i.e.*, two classes of engineering/CAD instruction, two classes of art instruction, two classes of engineering/CAD instruction, two classes of art instruction…). Over the last four weeks, the frequency of swapping switched to every class period as the students worked on their final projects. This change allowed students to experience a more integrated design process between sculptural materials and CAD while also giving the instructors a chance to test and reflect upon an alternative course format. On three occasions, the two sections met as one—initially at the very beginning of the course, again when the final project was introduced, and lastly when the final project sculptures were displayed and discussed.

Topics within the studio art and engineering/CAD sessions were designed to complement each other. This is shown in detail in Table 1. Early lessons and exercises explored the creation of objects in both the physical and digital realms, progressing from sketches and simple extrusions to more complex 3-D solids and assemblies. Once they developed basic proficiency with the sculptural techniques and CAD software, and gained an understanding of fundamental visual analysis and critical thinking skills, students were asked to design and fabricate an artistic piece comprised of both manually-formed sculptures and 3-D-printed elements. This final project incorporated both artistic objectives and engineering constraints and reinforced the similarities and differences between the artistic and engineering design processes.

Table 1. Order and Duration of Topics within the Studio Art and Engineering/CAD Sessions

Weeks	Studio Art Topics	Engineering/CAD Topics
1 - 2	Artistic design process intro; axonometric projection and perspective sketching	Engineering design process intro; simple 2-D computer-based sketching & extrusion
3 - 4	Gestalt principles and linear extrusion with chip board	Intermediate 2-D computer-based sketching & extrusion
5 - 8	Artistic vocabulary and analysis of art; trip to art museum; discussion with visiting artist; analysis of selected pieces	3-D additive and subtractive computer modeling
9-10	Subtractive modeling and clay sculpting	Computer modeling of assemblies
11-14	Armature and plaster sculpture (integrated with 3D-printed piece)	Design and refinement of 3D-printed piece (integrated with plaster sculpture)

The concept of following a design process for both art and engineering was introduced early. As the course progressed, these processes were revisited in the context of the assignments and projects. At several points, the students were asked to reflect on the differences and similarities in the ways they were approaching their art and engineering tasks.

Major Course Assignments

As mentioned, the order and content of the assignments were chosen so that there was crossover between the art and CAD/engineering portions of the course, even as the activities remained largely segregated until the final project. The major art assignments were as follows:

- *Visual Analysis Essay* - Tour the nationally-recognized Baltimore Museum of Art and observe many different sculptures from ancient to contemporary periods. Draw three sculptures. Select one piece out of the three and write a visual analysis essay using methods of inquiry and terminology covered in class.
- *Sketching Project* – Create drawings of cityscapes using axonometric (no perspective) projection and linear perspective.
- *Extrusion Project* – Create 2-D geometric shapes on paper and then linearly extrude these shapes (using chip board and glue) to form 3-D objects. Arrange the objects on a foam core sheet in a way that embodies specific Gestalt principles [16]. Paint the objects black, white, or gray.
- *Subtractive Modeling Project* – Create a sculpture from a block of Plastilina clay that is as tall as physically possible and provides the viewer with something of interest from multiple viewing points. Reflect on the use of scale in monuments, architecture and sculpture to impart importance or stature. Plan the sculpture using sketches that utilize verticality as both a technique and concept. Consider the sculpture as a monument to something that doesn't get enough attention in our society. Slice, cut, or carve forms out of the block using clay tools and reassemble them into a vertical sculptural form.

There were out-of-class readings associated with each project, and the second author also devoted class time to instruction regarding the concepts and principles involved. As the students worked on their projects, the instructor circulated around the room, providing guidance and assistance. Significant in-class time was allotted for hands-on work, but the students were expected to come to the studio outside of class, if necessary, to meet project deadlines.

The CAD/engineering assignments in the course were more prescriptive and were designed to help students gain basic proficiency in creating digital 3-D objects using commercially available software (SOLIDWORKS [17]).

- *Guided Exercises* – Reference [18] contains a number of progressively more complex, step-by-step exercises that guide the student through the software features and strategies used in 3-D CAD. Objects to be created included a gasket, a metal grate, a threaded shaft, and an automobile jack stand. A total of 17 such exercises was assigned, of which three were collected at random for grading over the course of the semester.
- *Independent Exercises* – The students were provided with a dimensioned, isometric drawing and asked to develop a 3-D computer model of the pictured object without any specific instructions on how to do so. Three independent exercises were assigned, and they required that the students draw on what they had learned in the guided exercises.

- *Quizzes* - The students were given a dimensioned, isometric drawing and asked to develop a 3-D computer model of the pictured object without step-by-step guidance. In contrast to the independent exercises, the allotted time (*e.g.*, 50 minutes) for quizzes was much less than one class period, and a penalty was assessed for exceeding the limit.

The first author conducted mini-lectures at the beginning of several of the classes to introduce concepts or demonstrate modeling strategies and features. Periodic discussions also focused on where and how CAD modeling could be used in the overall engineering design process, which is shown in Figure 1. As the students worked on the guided and independent exercises, the instructor acted as a coach, offering suggestions and helping them work through difficulties when problems arose. Significant in-class time was allotted for students to complete these exercises, but as with their art projects, the students were expected to come to the computer lab outside of class, if necessary, to meet assignment deadlines.

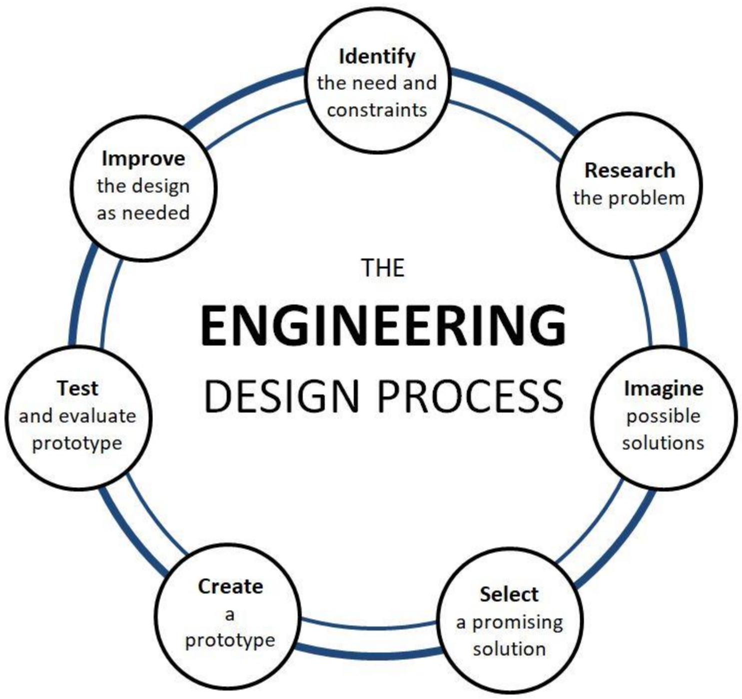

Figure 1. The engineering design process (adapted from [18]).

The course culminated in the following combined art/engineering assignment.

- *Final Project* - Design and construct a 3-D sculpture using plaster over an armature (framework) and incorporate a 3-D printed, digitally designed component. Consider the strengths of a work from the Baltimore Museum of Art (technique, form, concept, *etc*.) and design a form that responds in an interesting way. The sculpture may be painted. Compose a written reflection describing the rationale behind your design and the reasons for the decisions you made.

In the class period during which the project was introduced, the two sections and two instructors met as a group to discuss the expectations and the change of class format (*i.e.*, swapping after every class period). Examples of sculptures addressing the core topics of the final project were presented in a lecture format by the second author. The first author also introduced the technical aspects involved in 3-D printing, both in the discipline at large and as it would be used in our course.

Students were given additional guidance about both the artistic aspects and the engineering aspects of the final project. For example, the sculpture was to be an abstraction of the human form. The students were to begin with sketches and consider how the sculpture would look from different angles. The idea that humans exist simultaneously in physical and digital space was to be considered, and the dual nature of the media (plaster and 3-D-printed plastic) provided an opportunity to reflect this reality in abstract form. On the engineering side, more prescriptive criteria were given, as is common for the discipline. The 3-D printed SOLIDWORKS part was required to fit within a 3″ by 3″ by 4″ envelope, and it had to contain certain digitally created features (*e.g.*, a spline, a revolved or lofted boss/base, and a rectangular or circular pattern). It would be fabricated on a MakerGear® M3 printer using PLA plastic—a standard material for 3-D printing.

<u>Student Demographics</u>

Twenty-seven students took the course—14 in one section and 13 in the other. Their demographics are provided in Table 2.

Table 2. Student Demographics for SA/EG226

	Gender		Major			Class Year			
Section	Female	Male	Engr.	Art*	Other	1st	So.	Jr.	Sr.
01	4	10	6	0	8	3	4	2	5
02	7	6	0	0	13	11	2	0	0
Total	11	16	6	0	21	14	6	2	5

* There were no declared art majors in the course, but some of the first-year students were considering it.

As already mentioned, each section received the same amount of instructional time from both authors. However, in the course schedule for registration, the first author was listed as the responsible instructor for Section 01, while the second author was listed for Section 02. It is likely that this is why all of the engineering students signed up for Section 01. Also, because this is a gateway, introductory-level course for the visual arts major, no students would have declared their major in this discipline before taking the course. It is noted, though, that two of the first-year students in the course mentioned that they planned to major or minor in studio art, and approximately eight students expressed interest in taking upper-level courses in studio art.

Performance, Assessment, and Evaluation

Examples of student work for the extrusion project (chip board), the subtractive modeling project (clay), and the final project (plaster and plastic) are shown in Figures 2 through 8. Overall, the students responded seriously to the assignments and produced a rich variety of interesting works.

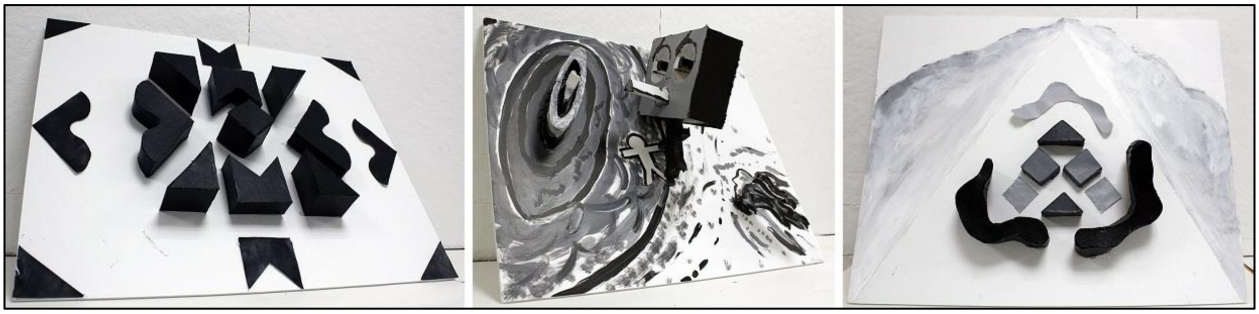

Figure 2. Examples of student work for the extrusion (Gestalt) project.

Figure 3. Examples of student work for the subtractive modeling (tower) project.

Student performance on the subtractive modeling (tower; Plastilina clay) project revealed some differences in the way that engineering students and other students approached the project. Though we are generalizing a bit, some of the engineering students immediately focused on the "make the sculpture as tall as possible" criterion, viewing the exercise as a structural engineering challenge. The non-engineering students seemed to focus more on the theme of their work. An exception might be the center picture in Figure 3. This sculpture reflected the *failure* to achieve height by human means, but in that failure, a more "natural" height was achieved by the tree. This piece was created by a senior in mechanical engineering.

Figure 4. 3-D printed components for the final project.

Figure 5. Integrated final project and CAD object (balloon) for Student A

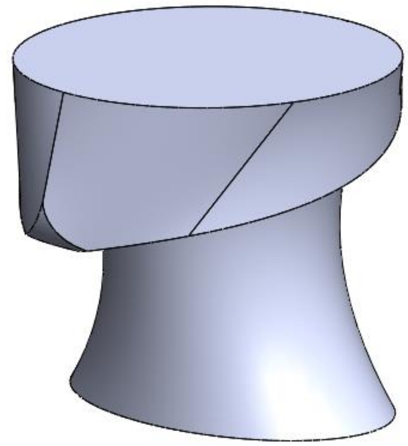

Figure 6. Integrated final project and CAD object for Student B

Figure 7. Integrated final project and CAD object for Student C

The final projects were quite diverse, and we were pleased that the students took the assignment in so many different directions. Three examples are shown in Figures 5, 6, and 7. In each figure, the SOLIDWORKS model of the 3-D-printed component, which had to meet size and feature requirements, is also shown. (The actual PLA components for most of the students in the course are shown together in Figure 4.) The students were free to select what part of their work would be 3-D-printed and how that item would be incorporated into the overall sculpture. This resulted in a variety of choices by the students.

In Figure 5, the 3-D-printed pieces were balloons, mounted above plaster mountains. The two media (plastic and plaster) were thus physically separated. The artist (Student A) provided the following commentary about their piece:

> "It is ironic that humans live within a physical body, but what makes us human is what we carry in our minds and heads. I decided to abstractly apply this idea to my project. The mountainous landscape below the balloons represent[s] our physical, natural bodies. Levitating above these mountains, or bodies, is a digital world, which is our minds. It is as if our physical body carries the weight of our complex or 'digital' mind. Our minds are especially heavy in this generation because of the constant use of social media and technology, as that use greatly affects our minds and how we think. Even though proportionately the rest of our body is bigger than our heads, our heads hold the most weight. Thus it takes the mass of mountains to hold up the digital weight and complexity of our heads, or balloons."

In contrast, the work shown in Figure 6 involved the direct merging of the 3-D-printed piece with the plaster medium in a more abstract format. In fact, this integration was essential to the artist's intent, as Student B describes:

> "While the printed element is there to contrast the other parts, I think the integration of it is what makes it one cohesive piece. By having plaster drip onto the printed part, it showed that while contrasting, the two parts make up one thing. I made the different parts opposite colors to highlight their difference. The blue being a cold color corresponding with the artificial plastic and the warm orange representing the real and natural mask the person has on. However, by adding blue to the orange as the kind of transition color in the middle, it shows how the two are connected and the true inside breaking out."

Finally, in Figure 7, the 3-D-printed object is again integrated into the overall sculpture, but as a mask on a humanlike figure. This represents a kind of middle ground between the approaches taken in Figures 5 and 6. In the words of Student C:

> "Looking at the assignment at hand combining 3-D printing and plaster, I wanted there [to] be a distinction between the natural and the printed. With this idea I chose to make the 3-D printed part a mask on my figure. The mask has random shapes extruded onto it. This is meant [to] represent a glitching face. The mask is black and geometric while the figure is red and gold with organic shapes and the feeling of movement. With my piece I wanted to look at the contrast between these two worlds. In terms of the movement I was trying to convey

with the draping of the cloth I was hoping to extract the feeling of wind [or] someone running."

Faculty Reflections and Evaluations

As mentioned previously, this "hybrid" course was still intended to meet the fine arts core requirement within Loyola's curricular framework. What that meant relative to the art content was that multiple learning goals had to be merged into single assignments due to the reduced time available for art instruction. This produced varied results. For instance, a "traditional" core fine arts course in 2-D design typically includes a visual analysis essay, which has been used for assessment within the studio arts program. The goal is for students to learn to use terminology and critical thinking to assign meaning to a work of art, using visual evidence to back up their claims. In our course, the second author spent much less time going over these techniques in discussions and demonstrations, but surprisingly the students' essays were just as strong as those from the "traditional" course.

On the other hand, in the "traditional" course, the first quarter of the semester is spent building fundamental techniques with specific materials. These assignments include strict parameters with the goal of focusing the students on building a strong core set of skills. In the later 75 percent of the course, they are asked to develop conceptual awareness of their art projects, which include intention statements, reflections, and theoretical texts that form the conceptual territory on which the assignments are based. In our course, this ratio shifted because of the shortened time frame. The foundational art projects took up more than half of the semester, while much of the higher-level conceptually challenging material was integrated into one larger project at the end of the semester. Students were still required to write intention statements and reflections, but the theoretical texts were delivered in a lecture format. An additional level of complexity was introduced in the large final project as it was the first time students were asked to integrate their 3-D modeling techniques from the engineering side with the sculptural techniques from the studio art side. The results of the integrated final project were positive, demonstrating a synthesis of concept, research, technique and expression. This begs the question if more aspects of the first part of the course could benefit from further integration.

Perhaps the biggest challenge in this format is that studio art projects are immensely time consuming by nature. With less time, there is less room for students to experience a wide variety of materials and concepts. In this course we covered three different materials/building techniques, whereas in a "traditional" core studio art course, we would typically cover five or six. Foundational art courses are not only about an introduction to materials; they are based on learning to understand and to be critically aware of how visual communication operates. Through discussions of artwork in class, the second author did find that the level of visual acuity demonstrated by the students was similar to that exhibited by students in the "traditional" core course. This may in part be due to the way we designed the sequence of our sections. The engineering coursework was laid out in a chronology that mirrored the concepts that students learned in the art studio. For instance, when they learned how to draw shapes and extrude them in CAD, they simultaneously learned to cut shapes out of chip board and build three-dimensional relief shapes in the studio.

In parsing the results from this course, it is interesting to consider the two sections as case studies. In section 01 (in which 10 of the 14 students were engineers or computer scientists) half of the students were juniors and seniors, while in section 02 (all 13 of whom were non-technical majors) the majority of students were first-year students. Beyond student major, this factor (class year) may have some bearing on the outcomes. For instance, the second author observed that the critiques and discussions with section 01 were quite advanced, even though the majority of these students had little to no experience in art courses. It is possible that their level of inquiry and critical thinking developed as result of Loyola's core curriculum, yielding a certain level of academic maturity.

The students in Section 02, on the other hand, were generally more willing to take risks with their designs. While their conceptual abilities were more basic (perhaps due to this being, in large part, the first semester of their college careers), they were unencumbered by the idea of failure or resistance to improvisation in the act of creation. Some in this group reported an interest in the arts, some with advanced experience with art in high school. While these are generalizations, it is interesting to consider how area of concentration and age/academic experience affect the outcomes.

A further aspect to consider is how teaching a course in two distinct classrooms alters the dynamic. In the studio art instructional space there are four tables, each with four chairs. As students worked, they frequently discussed their projects with their neighbors. This culminated in one table actually designing all of their projects around a central theme of natural growth with a distinct difference between each sculpture. In other scenarios this manifested in a kind of groupthink that was not as beneficial—an effort to satisfy the requirements by following the lead of one student who seemed to have it figured out. At times this also amounted to a subdivision of the sections into cliques. It is worth considering how this spatial format can be used to integrate disciplines and academic levels, to encourage networked knowledge and discourage provincial approaches.

In the CAD/engineering sessions, there were noticeable differences in the aptitudes shown by the students, initially. Because this new course included non-engineers as well as students from all class years, this was not unanticipated, but it manifested in ways that were sometimes unexpected. For example, terms such as concentric and orthogonal were unfamiliar to many of the non-technical-major students. Also, some were unaccustomed to using an origin and a Cartesian coordinate system to locate spatial positions. (They certainly had seen the concept before, but they had not really used it.) This meant that the instructor typically had to provide clarification of the written guided instructions more frequently than in other CAD courses. The non-technical-major students were also less adept at recovering from problems when they incorrectly executed one or more program features.

As a result, when working with section 01 (predominantly engineers or computer scientists), students rarely had to wait for one-on-one assistance as they worked through hands-on assignments. In contrast, multiple students in section 02 (all non-technical majors) often needed help simultaneously, but not on the same element or feature. The instructor also allowed students to consult with their neighbors when they encountered difficulties on the guided exercises, but this was helpful only when their neighbors were more skilled. What this ultimately meant was that the students in section 01 had little difficulty completing most of their CAD assignments in class, while those in section 02 routinely had to come in after class to complete their work. This made it a bit of a challenge to set a level of difficulty and a workload that was appropriate for both sections.

It is possible that in the future, the separate sections of this course will have student populations that are more similar, as a group, but if we continue to open the course to all students, without prerequisites, then some of these challenges will remain. The good news is that, by the end of the course, all 27 students had demonstrated satisfactory proficiency with SOLIDWORKS based on the performance rubric developed by the first author.

One limitation associated with the majority of the CAD/engineering portion of the course was that the assignments in this area, though challenging, did not allow the students to exercise the engineering design process for themselves. The process was presented, and the role of CAD was discussed, but the process itself was not executed until the final project. As the course was being created, we realized that in order to obtain the level of CAD proficiency required for the final project, significant skill-based practice was required. Therefore, the CAD/engineering assignments during the first 11 weeks (prior to the final project) were specifically selected to enable the students to develop the necessary skillset. They were prescriptive, with little room for real creativity. It is possible that another strategy could be adopted, with smaller, project-based assignments accomplishing the same skillset development while also including application of the engineering design process, even in an abbreviated form.

On the positive side, the instructors were very satisfied with both the complexity and diversity of the 3-D-printed objects in the final project. The concepts that the students came up with often stretched what they had learned, and they exhibited both curiosity and tenacity when figuring out how to create digital models of their ideas. An aspect of the final project that achieved mixed results was the inclusion of time for the students to perform one iteration on their 3-D printed objects. Revision is an important part of the engineering design process, and the students were required to first develop and submit a digital prototype, which was then fabricated and returned to them. They were then asked to consider altering the prototype to improve it, relative to the project criteria or their own personal objectives for the sculpture. Some students took this to heart, changing their design to correct deviations from the stated requirements (*e.g.*, errors in size or omission of required features) or to improve the way the object reflected their artistic goals for it. Other students, however, decided that their prototype was fine as-is and performed no refinement. The instructor allowed this, since engineers can make such a choice, but the instructor also believes that some students skipped refinement simply to avoid "extra" work. In the future, consideration will be given to making meaningful refinement a requirement.

One additional observation is warranted. Prior to teaching this course, the two authors had interacted only rarely with faculty members from the other department. Both found this experience to be both educational and enjoyable. Each gained a better understanding of the pedagogies associated with the other's discipline, and the first author, in particular, learned about aspects of artistic design that they previously knew nothing about. Weekly meetings between the instructors provided opportunities to share observations and ideas, and we benefitted from hearing each other's experiences and perspectives. We currently have no specific plans to work together in other ways beyond the continuation of this course, but there is little doubt that such collaborations are now much more likely—collaborations that could result in new learning opportunities for our students and ourselves.

Assessment by Students

At roughly the mid-point of the course, and again at the end, students were asked to evaluate the extent to which the course goals and learning outcomes had been satisfied and to provide suggestions for improving the course.

For the learning outcomes, the students were asked to "indicate the degree to which you have SHOWN YOU CAN DO these specific things." A five point Likert scale was used (1 - strongly disagree, 2 - disagree, 3 - neutral, 4 - agree, 5 - strongly agree). The average scores from the outcomes portion of the mid-term and end-of-course surveys are shown in Figure 8. We were pleased to observe that by the end of the course, the averages for all six outcomes were above 4, and the averages for four of the outcomes (a, d, e, and f) were above 4.5. This suggested that the students had high confidence that they had demonstrated achievement of these outcomes. In addition, we were encouraged that the scores for five of the six outcomes had increased between mid-term and end-of term. This implies that the assignments continued to build on each other, leading to a stronger and more comprehensive learning experience for the students over time. However, in one case (outcome c, effectively build 3-D structures), a small decrease was observed between the mid-term and end-of-term. While not statistically significant, this drop might have been the result of the subtractive modeling project. Students were asked to construct tall, vertical structures out of clay. In some cases, the structures collapsed, or the students were not able to build them as high as they might have liked while maintaining stability. Truthfully, though, this is conjecture.

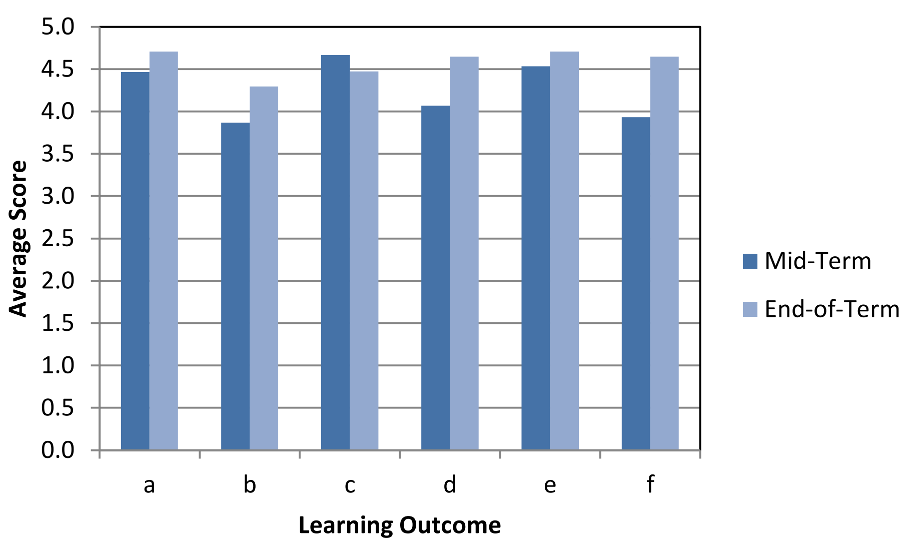

Figure 8. Results of mid-term and end-of-course surveys regarding learning outcomes.

For the course goals, the students were asked to "indicate the degree to which you think these broader goals were met," using the same Likert scale. These results are shown in Figure 9. As with the outcomes, by the end of the course, the averages for all eight goals were above 4 (agree). We were particularly satisfied that the score for goal 8 (recognize and appreciate similarities and differences between the engineering and artistic design processes and connections between the two disciplines) received the highest average score (4.6). When we first decided on the "weekly flipping" format for the course, we were concerned that this could lead to insufficient integration of the subjects. This survey result suggests that the students believe that, to a large extent, this did not occur.

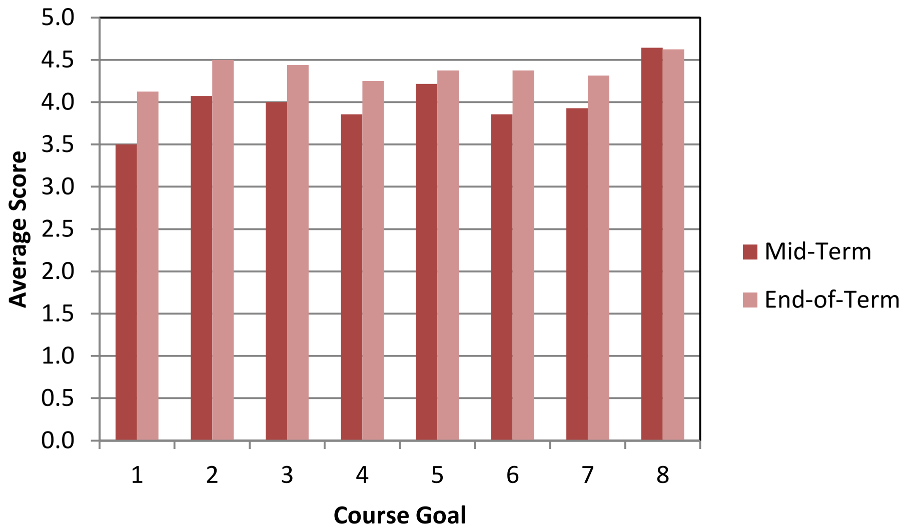

Figure 9. Results of mid-term and end-of-course surveys regarding course goals.

The response rates for the online surveys were 15/27 at mid-term (56%) and 17/27 at the end of the course (63%).

In open-ended survey questions, the students were also asked to identify aspects of the course that worked well and areas for improvement. In terms of what worked well, the student offered the following observations:

> "I really liked the integration for the final [project]. Making the two parts work together taught me a lot."

> "The balance of art and engineering worked well between each week. The combination of work and assignments from both parts complemented each other."

> "The final project was very fun and interesting. I liked hearing about everyone's piece."

> "I really enjoy[ed] having CAD one week and art the next week."

> "Both professors worked hard to make this class inclusive for people of all skill levels and interests."

The students made several suggestions for improving the course:

> "I would try to combine the projects earlier. I liked that the last project integrated both but it would have been cool to have other projects earlier integrate both. I would also look into finding more artists that push the limits in terms of art and engineering. There are a lot of artists out there that I think could be used to model off of. We could talk about fractals and how that is technically all mathematical but used to do art."

> "Actually work with a 3-D printer, learn how things print, and how the machine works. Start integrating 3-D prints into art earlier."

> "I would suggest having a tutor for the CAD aspect of the class. Since other classes had a tutor at the computer science lab to help them."

> "If there were more in depth projects. I wish we had the opportunity to create more using CAD. If we had more independent projects I think that could have been cool. And if the art class was a bit faster paced so that more projects could have been incorporated."

> "A little less time spent on step by step CAD projects. And teach more techniques about drawing and painting."

Finally, we asked the students whether the course should be offered again, and the responses were quite positive:

> "Yes. I think it's a good way to get people who aren't super into art engaged in a way that interests them. I think it was refreshing."

> "Absolutely. This is a great way to get engineers to think outside the box and a great way for other students to get their hands on CAD software they would never use otherwise."

In fact, every student response to this question was "yes."

Conclusions and Future Plans

The up-front requirements that were imposed on this course created a key challenge: balancing the course material so that we included enough artistic content to guarantee a genuine "core-level" liberal arts experience and also incorporated enough engineering content to justify simultaneous satisfaction of the engineering department's "engineering elective" requirement. We believe that we generally met this challenge, while also integrating the two subjects in an interesting and effective way.

A key component in our approach was laying out the studio art and CAD/engineering topics in a chronology that allowed students to see parallels in the ways that 3-D concepts could be expressed physically and digitally. Conversely, they also experienced differences in the often (but not always) precise and constrained nature of engineering design versus the open-ended and less constrained aspects of artistic design. The final project, which involved the integration of a

3-D-printed, digitally-developed piece with a physically crafted artistic sculpture allowed the students to both synthesize and evaluate what they had learned. Overall, we view this first iteration of the course as successful, and the students' reactions support this conclusion.

That said, there are a number of areas for improvement that we are considering:

- Include smaller assignments/projects that encourage/require integration of art and CAD/engineering earlier in the semester.
- Develop intermediate CAD assignments that also allow students to exercise the engineering design process rather than being too rigid and prescriptive.
- Recruit junior and senior students who already have expertise in SOLIDWORKS as tutors and make them available to students in this course, either during class or after class.
- Require (rather than encourage) refinement of the digital prototype in the final project.
- Develop some team-based assignments to facilitate more cross-disciplinary collaboration among the students—ones that require teams to include students from more than one major.

In closing, we note that one reviewer of this paper suggested framing what we learned in the context of a recent report from the National Academies of Sciences, Engineering, and Medicine: *The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree* [20]. We did not consider this report when we developed the concept or executed the course, but it appears that our course falls under the category "in-course integration" from that study, "when new interdisciplinary courses are developed as part of a larger, unintegrated curriculum." The sixteen recommendations from that report cover a wide range of themes including

- evaluating effectiveness relative to student learning and workforce readiness;
- marshalling institutional resources to support integrative curricular efforts;
- developing pilot programs;
- conducting "controlled, randomized, longitudinal research on integrative higher education programs;"
- exploring how such programs can promote representation of women and minorities in specific areas;
- eliminating roadblocks to integration posed by traditional academic structures and processes (*e.g.*, criteria for tenure and promotion, accreditation, and budgeting);
- professional development of faculty to address pedagogical aspects of interdisciplinary instruction and learning.

Candidly, we are at the beginning of our own exploration of these expansive topics. Our contributions to the broader discussion in this paper are focused on describing our experiences and those of our students to identify approaches that could be helpful to other instructors working in this area. Our relatively small classes limit our ability to identify statistically significant trends from single-semester results. That said, we will continue to reflect on our results in the context of the above as we move ahead. We are looking forward to working with each other again next academic year to improve the foundation that we laid this past fall.

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