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# Developing Design Thinking in Senior Capstone Bioengineering Student

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## Introduction

Accreditation is important for ensuring that institutions of higher education meet acceptable universal standards for developing graduates. These standards are designed to produce graduates that are ready for work in technical fields. Institutions seeking accreditation from the Engineering Accreditation Commission of ABET must satisfy all General Criteria for Baccalaureate level programs. For instance, evidence of the engineering design process needs to be specifically demonstrated for graduating engineering students based on the revised ABET criteria 3, which requests that programs show that students have the "ability to apply engineering design to produce solutions that meet specified needs..." [1]

The requirements for showing "engineering design" ability has been well defined by the current ABET student outcomes. Engineering design begins with empathy towards the end user by developing quantitative requirements, identification of opportunities, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks and making trade-offs for the purpose of obtaining a high-quality solution under the given circumstances. [1] Therefore, engineering design is an important aspect of today's engineering curriculum.

For a majority of institutions of higher education, the engineering design courses start early in the academic career and are meant to encourage first year students' interest in engineering with fun, hands-on projects that require minimal foundational knowledge. Later in the undergraduate curriculum, senior capstone engineering design courses are meant to give graduating engineering students exposure to real-world open-ended problems that pull information from previous years of education. However, engineering design courses or experiences aimed at mid-career undergraduates, i.e. sophomores and juniors, are uncommon [2]–[4]. The sophomore and junior years contain the greatest concentration of foundational didactic course work (including math and science), which tend be geared towards problem solving using textbook problems that are set, greatly simplified, and have a single solution. Students moving into senior design classes have difficulty with the mental shift from singular, short problems sets to open-ended, long-term capstone projects [2], [5].

The process for addressing open-ended problems involves diverse aspects of Design Thinking. "Design Thinking, which encourages through prototyping the constant deconstruction and rebuilding of objects and ideas that most of us accept as static and fixed, fosters the growth mindset in our students to explore, investigate and try again, for each iteration will lead to even better ideas" [6]. One method of Design Thinking illustrates a multistep process that begins with the formalization of the problem statement and moves through implementation of possible solutions with the needs of the end-user in mind. (Figure 1) The process of problem solving through "Design Thinking" is a skill that can be taught and is truly a valuable commodity. It is increasingly looked for as a key skill set in potential employees by industry and academia alike.

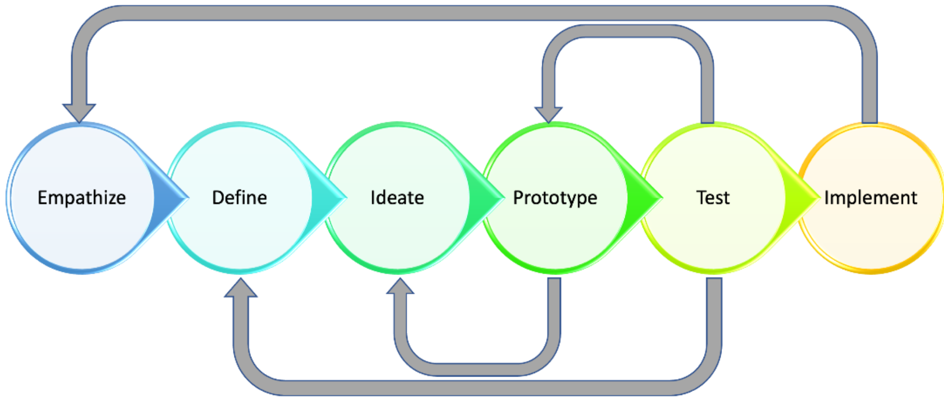


*Figure 1: Design Thinking Process schematic*

Due to this lack of exposure to open-ended problems with real client needs, students in capstone courses tend to skip over problem development/definition and do not explore a variety of potential solutions. Rather, most students sitting in these classes jump into working on a single, usually the most obvious, if not best, solution to the perceived problem. In 2014, Temple University's College of Engineering incorporated the Design Thinking (DT) process to our introductory freshman course and to our senior capstone experience. However, faculty advising in the senior capstone projects still noted that their student teams were not using DT for their projects without explicit reminders. We feel that this 'gap' in reinforcement of the DT process from freshmen to senior year resulted in the lacks seen in our senior team capstone projects. It is expected that engineering students will transfer principles of design thinking they learn in their courses to new situations and problems [7]. Yet, decades of research have demonstrated that promoting transfer is very challenging [8]–[10]. Indeed, even before becoming engineers, many engineering students seem to fail to transfer design thinking principles when confronting open-ended assignments in advanced courses and potentially in their future careers.

*Transfer Theory*

Transfer theory describes the process through which students use prior learning to solve problems in a new situation [10]–[12]. Arguably, transfer of learning to new situations constitutes a core goal of education. Yet decades of research have demonstrated that transfer of problem-solving strategies rarely happens spontaneously, and is hard to teach [7], [13]. Traditional concepts of transfer that aimed to explain its infrequency viewed it as primarily a cognitive process that is based in the learner's recognition that specific problem-solving strategies learned previously are relevant for application to a problem in the new situation [11]. A common distinction in this literature was between "low-road" and "high road" transfer [10]. "Low-road" transfer refers to the relatively automatic application of well-practiced strategies in a new problem perceived to be very similar to the problems practiced previously. "High-road" transfer refers to the reflective, intentional, and effortful application of strategies in a problem that is, at least initially, perceived to be different from the problems practiced previously. It was the latter that was perceived to happen infrequently, as it requires abstraction of strategies from the particular learning context and the effortful search for their relevance to a new problem [10]. Research on improving transfer among engineering students has built on these theories to emphasize the need for teaching fundamental concepts and their relevance for application in new situations for students to achieve "mastery" [11]. Felder and Brent (2016) suggested the need for open-ended projects, like senior capstone, to include a problem-solving structure that incorporated repetition and metacognition (reflection on one's thinking) in order to acquire expertise.

Based on the research surrounding transfer of knowledge and specifically transfer of design thinking, our program introduced two elective Biodesign courses and offered an internship on team-based design in clinical settings that focused on students in their sophomore and junior years. **We hypothesize that our bioengineering specific interventions have a positive effect on our students' internalization of the DT process as part of their senior capstone projects due to the reinforcement of these concepts with additional interventions.** As these are elective interventions, we felt that participating students would bring their additional experiences to share during their capstone experiences. The resulting evidence of DT use was measured in the final reports that senior students write at the end of their capstone experiences.

**Methods**

Bioengineering students who completed one of two elective courses in Biodesign and/or participated in a Summer Clinical Immersion were considered exposed to the intervention. The Biodesign courses were new electives and we intended them to be open to many students. As such, they did not have extensive pre-requisites (Calculus II, Physics, and our Intro to Engineering course). The students who enrolled in these courses had an interest in design/building devices, the class fit their schedule, or this was the one elective whose pre-requisites they met. The classes were small at first (<10 students) and gradually grew to 10-15 students per semester. This allowed the instructors time to work with each of the students and make sure each was contributing to their group. The Summer Clinical Immersion program hosted between 8-12 students each summer. Students applied to the program with statements of interest, two letters of recommendation and there was a requirement to have a GPA of 2.8. For these applications, students from Under-Represented Minorities (URM, as defined by the NIH) were given priority. In some cases, these URM students were admitted to the summer program with a GPA lower than 2.8.

In our two Biodesign elective courses, students learned about the DT process in depth. They spent time working in groups to develop solutions to biomedical problems using an iterative DT process. Students were given a scaffolded opportunity to work through the DT process on projects prior to their SD capstone. The students were taken through all steps of the process as they worked on class projects, where students identified engineering needs in the medical field, researched them in depth using peer reviewed scientific literature and interviews with medical personnel and patients and/or caregivers. The students developed their Needs Statement and Needs Criteria, getting feedback from their colleagues, instructor and interviewees and then brainstormed potential solutions. Once a solution was identified, supplies were ordered, and students began working on a plan to test their device and confirm their Needs Criteria were met.

Students built their prototypes of their device, testing and optimizing it, as needed. Examples of some of the projects students worked on were various modifications to face masks, improvements for finding veins for injections, and modifications to the nose swap to improve sample collection. Throughout the process students presented their work orally or in written communications with a final presentation and report due at the end of the semester.

One Biodesign course focused on ideation of a problem while the other focused on prototyping and testing, but both have students work on at least one project fully from start to finish using the DT process. In the Summer Clinical Immersion, students spent 6 weeks shadowing surgical rotation teams at [blinded] Hospital for four days a week. The 5$^{th}$ day each week was spent discussing the problems the students identified at the hospital with their engineering professors and classmates. The students learned more about these needs by doing research and talking to medical personnel at the hospital in depth. They then chose one need to expand upon. They developed Needs Statements, Needs Criteria and identified current and potential solutions. Through all three of these interventions the students spent time developing solutions to open-ended problems using a DT approach. These students, as all engineering students in our college are required, also participated in the senior design (SD) capstone course sequence in their final two semesters. Here, they were part of a team tasked with developing, building and testing a device to solve a particular problem. They are meant to use their engineering knowledge to complete this project while using the DT process. All the students who underwent our in-depth interventions were placed on teams with other students who had not been exposed to the DT process since their freshman year introductory courses. The intervention students were expected to use their recent experiences of the DT process for their SD projects and to facilitate transfer of knowledge and strengthen their group's participation in this iterative process.

The final design documents from our SD capstone courses were collected to determine if there was evidence of the students using the design thinking process. These documents were selected from 4 different semesters: Spring 2018 (n = 56), Fall 2019 (n = 32), Fall 2020 (n = 25) and Spring 2021 (n = 41). The SD design documents covered a range of topics related to the engineering disciplines taught in the College of Engineering. The student teams, which are typically made of 3-4 students, could have members from any of the engineering disciplines, although students tended to select SD projects that best matched their major. The SD project topics tended to have a focus in one engineering discipline, for example Bioengineering, but could have elements of other disciplines, such as Mechanical or Electrical engineering. The students in senior design were given a general template for writing their reports that includes executive summary, problem description, design criteria, solution description, testing and results, budget, and future work. Many parts of the final design document were class assignments that students would turn in over the yearlong senior capstone course sequence to get feedback from course coordinators and their project advisors. These individual assignments were revised and then collated into a single, comprehensive final design document.

In an effort to reduce potential bias in scoring, the SD documents were evaluated using an in-house rubric by 4-5 graduate students that had no interactions with these SD teams nor had participated in any role in the courses or programs related to design thinking offered by the college.[14] The graduate students were trained on how to use the rubrics to score sample SD documents prior to working on the main set of documents used in this study. Each rubric was based on a 4-point Likert scale and ranked from 4 (master) to 1 (novice) based on multiple DT concept categories (see Appendix). These categories were defined as problem description, needs statement, design criteria, multiple solutions, prototype creation, component testing, final prototype testing, and context, which stem from different aspects of the Design Thinking Process. The SD design documents were reviewed to determine if these items were mentioned and described based on the defined rubric levels. These rubric criteria were linked to the DT process, where 'empathize' – problem description; 'define' – needs statement and design criteria; 'ideate' – multiple solutions; 'prototype' – prototype solutions, and 'test' – component testing, final prototype testing, and 'implement' – context. Here 'context' is an important step to determine if students can 'close the loop' relate how their final solutions address the initial problem in addition to relating their projects in the greater societal arena.

Students that participated in an elective Biodesign class and/or the Summer Clinical Immersion program had additional training in the Design Thinking Process over what other engineering students experienced in their undergraduate academic careers. It was expected that these students would share this additional knowledge and experience with their SD team members during the senior capstone course sequence, but this was not monitored. SD teams that had at least one student that had participated in these additional courses or programs were considered part of this study's "intervention" group. Teams that did not include a student that participated in additional courses or programs focused on the Design Thinking process were part of the "non-intervention" group.

Intraclass correlation coefficients (ICC) are an established method of evaluating interobserver reliability. [15] ICC values between 0.5 and 0.75 indicate moderate reliability, between 0.75 and 0.9 is good reliability and greater than 0.9 is excellent reliability. The ICC was determined for each category in the rubric. For the semesters scored, the ICCs were shown to be moderately reliable for all categories, except for 'Multiple Solutions' which was shown to have good reliability. (Table 1). Therefore, the presented data were averaged across all scorers. [16]

*Table 1: Interclass correlation values for each category measured for all scorers.*

| | |
|---|---|
| Problem Descriptions | 0.741 |
| Needs Statement | 0.587 |
| Design Criteria | 0.557 |
| Multiple Solutions | 0.882 |
| Prototype Creations | 0.719 |
| Component Testing | 0.694 |
| Final Prototype Testing | 0.525 |
| Context | 0.663 |

To determine if there are differences in the evidence of design thinking process from the SD final design documents, comparisons between student work from teams with an intervention member versus those without interventions members were made using t-tests with an alpha level set at 0.05. Non-parametric testing using the Mann-Whitney U test was also conducted as the sample sizes between groups were different. There was agreement between both statistical test methods used for analysis.

**Results**

To date, 80 students have elected to participate in one or more of the interventions (Summer Clinical Immersion Program or one of two elective Biodesign courses) since their inception starting in Summer 2018. Students could participate in more than one intervention and 79 of these intervention students were Bioengineering majors. The one non-Bioengineering student had transferred from Bioengineering to another engineering discipline just prior to participating in the Summer Clinical Immersion Program. Since the students could elect to participate and the content of this project were part of their normal instructional experience, IRB stated that this project did not need to be reviewed as it was not human subjects research.

For the semesters that were analyzed in this project, 13 out of 151 senior capstone teams contained at least one student that participated in an intervention (spring 2018 = 0/56, Fall 2019 = 5/32, Fall 2020 = 3/25, Spring 2021 = 5/41). Only 1 intervention team from the 13 contained multiple intervention students (2 of 4 students) for the semesters evaluated. This group was lumped with all intervention teams as there were too few multi-student intervention teams to evaluate separately. There were no intervention students in Spring 2018 cohort as these teams were enrolled in the senior capstone before any interventions were started. Spring 2018 data was analyzed to determine a baseline level of DT incorporation into final SD design documents prior to the start of our interventions.

Looking at the data as a whole and summing the rubric scores across the 8 categories for each scorer (maximum score of 32 points), the average of these summed scores shows an increase that plateaued over time (Figure 2). The Spring 2018 scores were significantly lower than all other semesters ($p < 0.001$). The other semesters were not significantly different from each other.

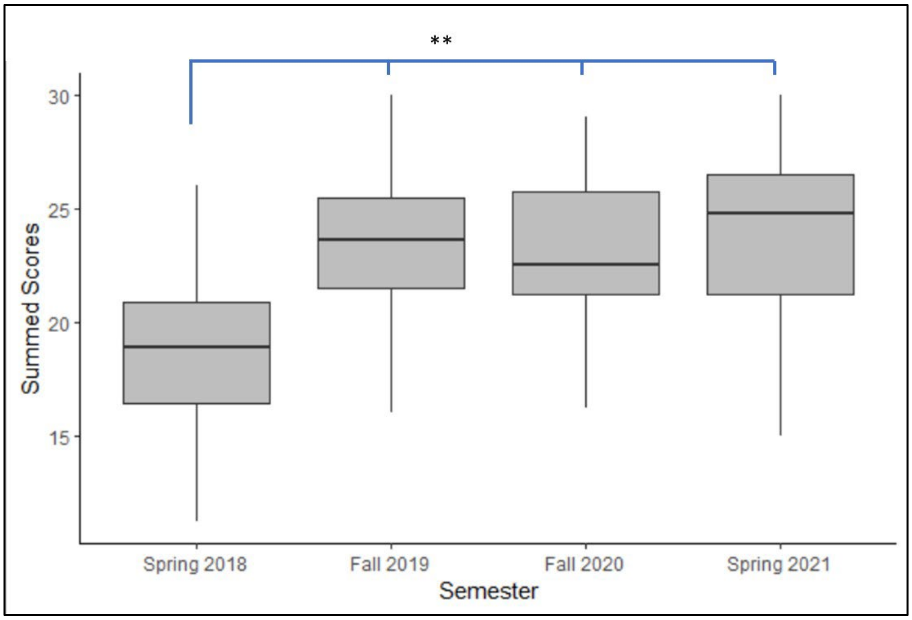


*Figure 2: Average of summed scores for all teams separated by semester. Spring 2018 scores were significantly lower than other semesters. (p < 0.001)*

The categories were broken out by semester to determine more specifically if the categories changed over time. (Figure 3) Maximum scores were out of 4 for the following analyses. Spring 2018 was scored lower than Fall 2019 for each category. Spring 2018 was significantly lower than Fall 2020 in all categories, except Problem Description and Prototype Creation. Spring 2018 was significantly lower than Fall 2021 in Design Criteria, Prototype Creation, Multiple Solutions, Component Testing and Context. Fall 2019 was significantly lower than Fall 2020 and Spring 2021 in Context. In addition, Fall 2019 was significantly higher than Spring 2021 in Final Prototype Testing. Fall 2020 was significantly lower than Spring 2021 in Prototype Creation. The p values associated with these differences can be seen in Figure 3 (**$p < 0.001$, *$p < 0.003$, or #$p < 0.01$).

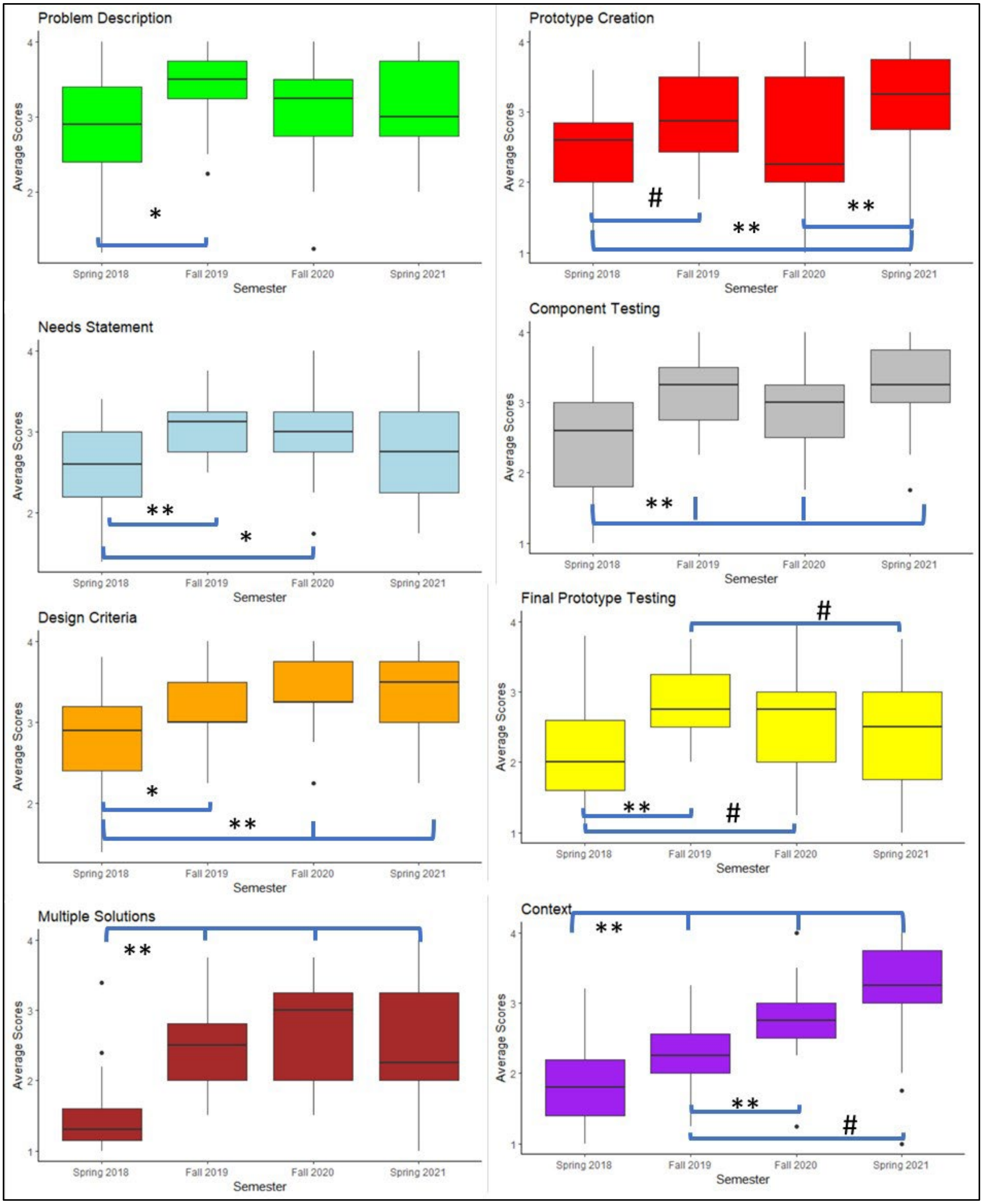


*Figure 3: Averaged scores for all categories shown versus semester. Green – Problem Description; Light Blue – Needs Statement, Orange – Design Criteria, Brown – Multiple Solutions, Red – Prototype Creation, Gray – Component Testing, Yellow – Final Prototype Testing, Purple – Context. **p < 0.001, *p < 0.003, #p < 0.01*

*Intervention vs Non-intervention teams*

Assessment of the individual categories between intervention and non-intervention teams was conducted. The effects of teams with students that participated in an intervention activity versus teams that did not contain an intervention student for all semesters analyzed are shown in Figure 4. Significant differences are shown in most categories, except 'Context'.

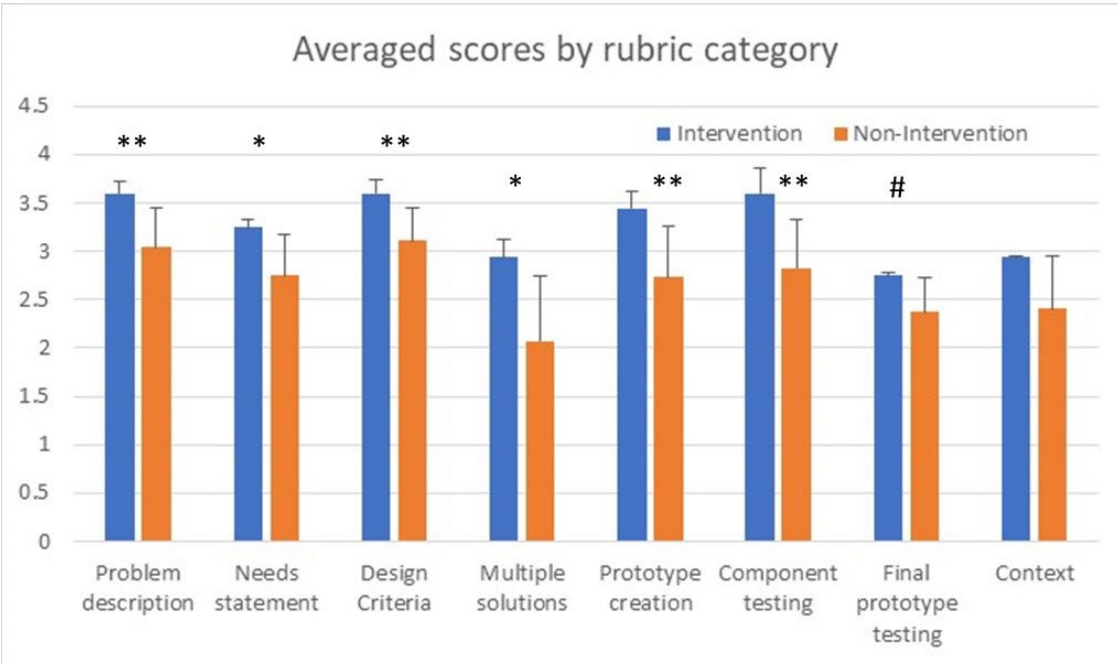


*Figure 4: Comparison of overall averaged mean scores for each category between intervention and non-intervention team reports for all semesters scored (mean (std dev)). ($p< 0.05^{\#}$, $p< 0.01$*, $p<0.001$ **)*

Breaking out the data by semester, the effects of the intervention teams versus those teams without intervention members illustrates significant differences in categories that change over time. (Figure 5) There are no significant differences seen in Spring 2021 teams between the intervention and non-intervention teams although there seems to be a trend of higher scores in the 'Component Testing' category. Significant increases in scores were found in two categories during Fall 2020 in 'Multiple Solutions' and 'Context' ($p<0.05$). In Fall 2019, most categories showed significant increases in scores for teams with intervention students ($p<0.01$* and $p<0.05^{\#}$), except for 'Final Prototype Testing' and 'Context'. In Spring 2018, there were no students that participated in interventions as they had not started until Summer 2018. Thus, no comparisons could be made with regards to our interventions and this semester was considered baseline data (see Figure 2).

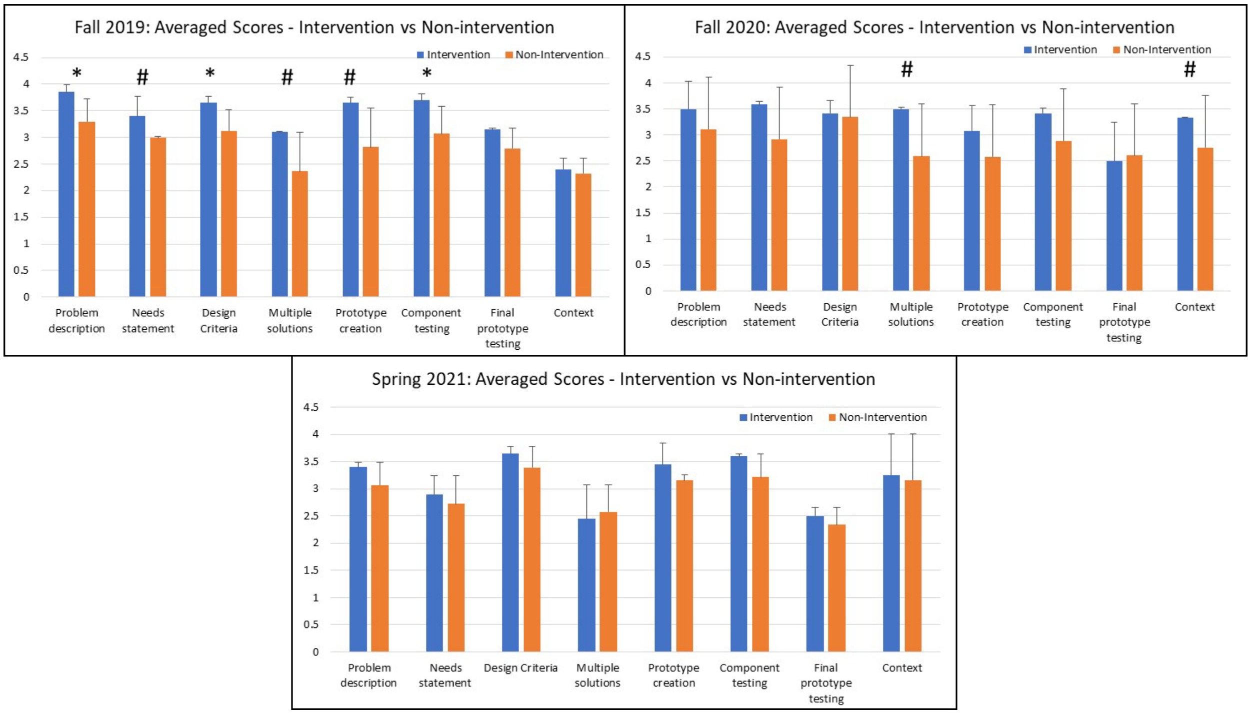


*Figure 5: Comparisons of averaged mean scores for each category between intervention and non-intervention team reports separated by semester with intervention teams (mean (std dev)). Intervention teams are indicated with blue solid bars and non-intervention are indicated with orange solid bars. Significant differences are indicated. (*p<0.01, #p < 0.05)*

Differences between Intervention and Non-intervention teams over the semesters were affected by the power of the analysis. There was 75% power for Fall 2019 and this power dropped for the next two semesters evaluated to 15% and 17% for Fall 2020 and Spring 2021, respectively. Therefore, determining the potential significance of the intervention was adversely affected in the last two semesters. (Figure 5)

Since a majority of students that participated in an intervention were bioengineering majors, a comparison of intervention versus non-intervention teams that were part of bioengineering projects was conducted. Although the project teams could be multidisciplinary, most students chose projects that were within their major discipline. There were 22 BIOE teams that were non-intervention, compared to the 13 teams that had intervention student members. There were significant increases in averaged scores in categories for 'Multiple Solutions' and 'Component Testing' ($p<0.01$). (Figure 6)

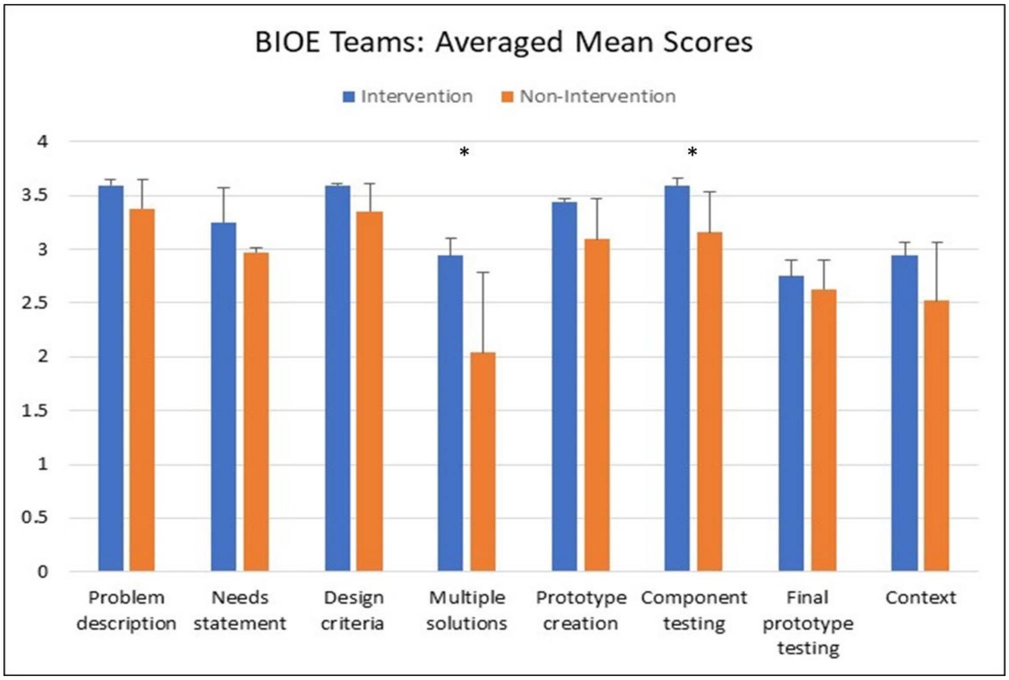


*Figure 6: Comparisons of overall averaged mean scores for each category between intervention and non-intervention team reports in Bioengineering teams (mean (std dev)). P-values are listed for each category (*p<0.01)*

**Discussion**

This study demonstrates the impact of our Design Thinking process captured within the final senior capstone design documents and its impact over the 4 semesters that were evaluated with significant improvements in scores from Spring 2018 to Fall 2019. In addition, teams that had students that participated in the interventions (Biodesign classes and Summer Clinical Immersion Program) received higher scoring in their final design documents across a majority of the categories (except Final Prototype Testing or Context) as opposed to teams without an intervention student. This implies that potential mastery with the use of DT was accomplished with the additional reinforcement. This concept for mastery development has been shown to occur with practice, integration, and application of desired skills. [11] We hypothesized that adding additional opportunities for students to apply DT in a manner similar to their SD capstone experience, such as in our Biodesign courses, students would more likely employ DT in this subsequent class.

As seen in Figure 2, the average scores versus semester for categories such as Context and Design Criteria showed steady signs of improvement each semester. However, with other categories such as Multiple Solutions and Component Testing scores plateaued across time. Other categories i.e. Problem Description, Needs Statement, and Final Prototype Testing showed peak scores in Fall 2019. There was a distinctive drop in Prototype Creation scores during Fall 2020, which could be attributed to the hybrid nature of the SD course for that semester due to the on-going pandemic. During this semester, the class met via Zoom and the students coordinated building and testing their devices off campus for the most part, with many teams choosing to build components separately and only bring them together near the end of the semester. Thus, Prototype Creation was hampered by the on-going pandemic, specifically in Fall 2020, as social distancing requirements and lack of available vaccinations kept many students from interacting with each other for their projects. Thus, categories that could more easily be completed in isolation fared better with the scoring than those that required hands-on actions. We hoped that with the opening up of campuses and readily available vaccines, student teams will be more engaged and active with the hands-on components of their SD projects. However, we noted that in later semesters students seemed to favor virtual over in-person team interactions. It has been shown that it is more difficult for there to be knowledge sharing between team members in virtual environments and this could explain the reduced effects of the intervention in later semesters. [17], [18]

The effect of the intervention was explored for Bioengineering teams only as intervention teams all selected Bioengineering projects and a majority of the intervention students were Bioengineering majors. There was the expectation that intervention teams would do significantly better in all rubric categories than non-intervention teams, but that was only true for Multiple Solutions and Component Testing. Interviews with the SD coordinator, who was overseeing the Bioengineering projects, discovered that they prompted all teams to complete the DT process for their SD projects, for example, guiding students to consider multiple solutions rather than simply choosing the simplest, most obvious or a previous team's solution. This would account for many of the similarities in the scores between intervention and non-intervention Bioengineering teams. For the two categories that were scored significantly higher than the others, students that participated in the intervention courses or summer program learned the importance of exploring multiple solutions and not jumping to a single idea right away. This reinforcement of detailing multiple potential solutions supported the need for these solutions to be presented in written work. Students in the Biodesign courses were given a focus on iterative testing on small class projects, which would have supported the improvements in the Component Testing category.

Changes in scores may also be attributed to alterations in instruction and guidance by the SD capstone instructor and SD coordinators based on the review of preliminary results from Spring 2018. The elements of the DT process have always been included in the requirements for the design document, but grading rubrics were revised over time emphasizing particular elements of the DT process in the final reports, such as Multiple Solutions and Context. Improvements in these categories across the semesters are clearly observed. The SD students had access to all grading rubrics for their SD assignments from the start of the semester. Any revisions to these rubrics by semester were also reflective of the effects of the pandemic requiring the restructuring of the SD classes into online or hybrid teaching models.

<u>Limitations</u>

There were some observed limitations in the conducted study. One limitation can be observed in the number of "intervention" teams was small for each semester selected, which affected the power of our analysis at the semester level. This was specifically seen in Fall 2020 and Spring 2021 where the power was less than 17%, which made determining significance in these semesters difficult. However, the number of teams that had intervention students could not be controlled for as we did not know when intervention students would have taken their SD capstone courses. Looking at the overall effect of the intervention on evidence of DT in the SD final design documents showed that there was an increase in scores for a majority of the categories measured. Another observed limitation was revealed in the parameters that the authors had no influence over during the 3 years of this study, which could account for some of the changes observed over time. Examples of this can be observed with the changes in instructors for the SD capstone sequence, changes in the SD coordinators that had close interactions with the student teams, and complications due to the pandemic. The jump in average summed scores seen in Figure 2 from Spring 2018 to Fall 2019 could be accounted for by the instructional changes to the capstone sequence. Interviews with one of the SD coordinators who spanned the timeframe of this study, indicated that the written rubrics were available to students at the start of the semester and the coordinators made verbal statements to teams to emphasize certain aspects of the DT process, which needed to be included in the team's written work. The global pandemic created challenges conducting our SD capstone courses. An example of this is demonstrated in March 2020 where students were sent home due to locks downs and consequently not allowed to enter lab space to complete their projects. This disruption in Spring 2020 is the reason why these data were not included in our analysis. As the pandemic restriction started to lift and our school developed a virtual/hybrid learning process, our study was continued. While students were sent home during parts of subsequent semesters, this allowed for students to purchase materials and build at home (Fall 2020). However, virtual/hybrid courses limited contact and could have unduly influenced group work.

*Future Directions*

The current study illustrated how the required steps for engineering design, as described by ABET, were being evidenced by our senior capstone student work. Traditionally engineering students are introduced to the Design Thinking for the first time their freshman year and assessed during their senior capstone work. The need for reinforcement of the Design Thinking Process through deliberation and practice in classes, whether through curricular and extracurricular programming or instructional emphasis, is necessary during engineering students' sophomore and junior years. We suggest including modules (or entire courses) that provide opportunities for practice on addressing open-ended problems, that involve the use of DT to address them, throughout the curriculum. If hands-on projects that include designing and building of prototypes are difficult to include, the use of models and simulations can be equally effective. As the definition by ABET states "Engineering design is a process of devising a system, component, or process to meet desired needs and specifications within constraints." [1] The main point is to offer students opportunities to work through the entire process (including optimization) frequently in their academic careers while explicitly emphasizing that they are using the DT process and how it is effective for many open-ended situations.

This study showed that there could be two major issues at play in regards of students applying DT in the capstone projects:

1) Students would not naturally apply DT to a new situation (i.e. senior capstone projects) even though they were exposed to this process earlier in their academic careers. (Transfer issue)

OR

2) Students may not automatically share knowledge that they have when put into new teams. (Team dynamics issue)

We assumed that the inclusion of the intervention classes and programming would address point #1. There was some evidence that this may have been the case, but the intervention team numbers were extremely small in this study. One of the Biodesign courses is now required for all Bioengineering students and future work in looking at potential evidence of DT in the final SD design documents will be conducted. As for point #2, more in depth discussions with the teams, via focus groups or surveys, will need to be utilized to determine whether or not intervention students naturally shared knowledge in new team situations.

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**Appendix**

The in-house rubric with category level descriptions is shown in the following table.

| | 1 - Novice | 2 - Apprentice | 3 - Proficient | 4 - Master |
|---|---|---|---|---|
| Problem description | The problem that was to be solved was unclear. | Problem is mentioned, but the motivation for studying this problem is not well defined. | Problem is described with some support as to why the problem needs to be studied. | A compelling problem was described and motivation for the work was well supported. |
| Needs statement | No statement of need was presented. | Needs statement is implied, but not explicitly reported. How it is related to the problem description is up for interpretation. | Needs statement is stated and it is related to the presented problem. Not all aspects of a needs statement are present. | Needs statement is clearly and explicitly defined with all parts and reflects the problem statement. |
| Design Criteria | No design criteria were presented or described. | Design criteria were presented in a surface manner and without detail or relation to problem. The team reported whether or not the criteria were met by their solution. | Design criteria were described with some of the pertanent thresholds defined. The team reported whether or not the criteria were met by their solution. | Design criteria were well described with pertanent thresholds detailed and related to why they were needed to address given problem. The team reported whether or not the criteria were met by their solution. |
| Multiple solutions | No other potential solutions were presented. Final design choice was presented. | Few other potential solutions were aluded to, but not described fully. Final design choice was presented. | Multiple other solutions were described. Final design choice was fully described with some reasonings as to why it was chosen. | Multiple potential solutions were presented. Final design choice was clearly described and and reasons for selection were fully supported. |
| Prototype creation | Prototype was contructed based on final design choice, but it doesn't work or doesn't address the presented problem. The design criteria were not evaluated with this prototype. | Prototype was constructed based on final design choice, but does not work as desired. Some attempts at addressing design criteria are made. | Prototype was constructed based on final design choice, but may not contain all functionality desired. It addresses the problem presented. This prototype was evaluated against the described design criteria and may not meet all criteria selected. | Prototype was constructed based on final design choice and addresses the problem presented. This prototype was evaluated against the described design criteria and the design criteria were met |
| Component Testing | Does not create and implement appropriate testing methods that examine the feasibility of the solution | Some evidence of testing has been presented. The testing is limited in terms of scope and lacks the full interpretation of results that are presented. | Evidence of appropriate testing was created and used to evaluate the feasibility of solution. This evidence includes some use of standards, clear testing protocols, results, statistical analysis of results, and interpretation of these results with application to solution. The testing is somewhat limited, but within the scope of project. | Evidence of appropriate testing was created and used to evaluate the feasibility of solution. This evidence includes use of standards, clear testing protocols, results, statistical analysis of results, and interpretation of these results with application to solution. The testing is exhaustive and complete within the scope of project. |
| Final Prototype testing | No testing of full prototype was presented. The full prototype does not work OR doesn't address presented problem. Design criteria were not evaluated. | The full prototype works somewhat and data/results are presented to support this. There are definite problems and testing/optimization of the final solution needs to be conducted. Not all design criteria were evaluated. | The full prototype works and addresses the proposed problem based on the presented needs statment. Data/results are presented to support this. OR Not all design criteria were met. OR Some needed testing was not conducted/completed. | The full protoype works and completely addresses the proposed problem based on the presented needs statment and design criteria. The testing presented on the final solution was complete. |
| Context | Solution was not placed into context on how it affects or is affected by larger ethical, global, societal, environmental, reglatory, etc. influences | Solution is not placed into context; however some indication of how this solution is affected by ethical, environmental, societal, regulatory, or global issues. | Solution is described in context with some indication of how this solution affects (or how it is affected by) larger ethical, global, societal, environmental, regulatory, etc. influences | Solution is placed into context and is described with regards to its affect (or how it is affected by) larger ethical, global, societal, environmental, regulatory, etc. influences |