AC 2007-849: ASSESSING LEARNING OUTCOMES OF SENIOR MECHANICAL ENGINEERS IN A CAPSTONE DESIGN EXPERIENCE

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1. Introduction

Design is widely considered to be the central or distinguishing activity of engineering. A capstone design course and project (Senior Design) not only provides a meaningful design experience for students, but also creates an opportunity for them to begin the process of becoming engineering professionals. Participation in capstone design projects deepens a student's understanding and promotes the communication and teamwork needed to solve complex problems. Also, enabling students to be part of the intellectual process instills in them a sense of fulfillment and imparts life-long benefits. Capstone design courses are also one of the most effective ways for engineering departments to facilitate to the outcomes of ABET criteria 3a-k. Although capstone design courses have great potential for bringing active learning to the undergraduate level, little is known about the student learning outcomes (what students know and are able to do, i.e. knowledge, skills, attitudes) as a result of these often year-long design projects. There are limited assessment studies that address what students learn from these capstone design projects.

ABET criteria 3a-k challenges engineering institutions to produce graduates with professional as well as technical skills by outlining the desired attributes for graduating engineers. This paper discusses the bodies-of-knowledge and learning outcomes comprising of the countless ways in which students benefit from being involved in senior design projects. Since most of our students follow careers that lead to industry, of particular importance is how these design experiences help to make better *engineers*.

A pilot survey instrument, which included the compilation of over fifty learning outcomes (categorized as either "technical" or "personal and professional" learning outcomes) closely linked to the ABET criteria and other desired skills, was developed and administered to 125 mechanical engineering seniors at Virginia Tech at the end of their first semester capstone experience. This will be repeated at the end of their second semester experience as well. Presented herein are results from the first semester only. Emphasis was placed on assessing knowledge and skills pertaining to but not limited to: (1) problem-solving, (2) writing and communication skills, (3) understanding and applying knowledge, (4) teamwork, (5) confidence gains, (6) organization and management skills, and (7) interest and engagement of project. In better assessing the quality of learning during this capstone design experience, we have classified these technical learning outcomes to the six levels of Bloom's taxonomy, a hierarchy of cognitive learning skills. Lastly, in accompaniment to the student survey instrument intended to assess the extent to which these students are achieving certain learning outcomes desired of engineering graduates, a similar faculty survey instrument was also developed to assess the extend to which faculty expected the students to meet these learning outcomes. The goals guiding this research effort were to: (1) identify and generate a set of student learning outcomes for undergraduate engineering students involved in capstone design, (2) develop two survey instruments, one for the students and one for the faculty advisors, to assess the students' learning outcomes and compare these to how well the faculty felt that the students met these outcomes, and (3) identify the learning outcomes most valued by the students and compare how these outcomes varied across diverse groups of students.

Overall, the data show that the students highly valued the capstone experience. In comparing the average student and faculty ratings for the learning outcomes, we can conclude that for about 70% of them, there was good correlation between the student and faculty ratings. Results also show that male and female students rank their learning outcome gains similarly, but with statistically significant differences in the ratings of these gains. The broader impact of this study is that although the methods herein were developed for mechanical engineering students participating in a capstone design experience, the test instrument can be useful to other engineering disciplines and learning experiences, such as research, coursework and service learning experiences, as well.

2. Development of the Pilot Survey Instruments and Methods

According to ABET, students must be prepared for engineering practice through the curriculum culminating in a major design experience (most often in the senior year) based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints [1]. The Department's capstone course objectives are very closely linked to the ABET criteria "3a through k." During this experience, the senior engineering students are expected to design mechanical and/or thermal systems using engineering, science, and mathematical methodologies including but not limited to, the following:

1. knowledge of and skill with the design process including
   a.) problem recognition and definition
   b.) establishment of design requirements (performance and life-cycle, such as economic, manufacturability, assemblability, usability, aesthetics, quality, serviceability, sustainability, as well as impact in an environmental, societal, and/or global context)
   c.) generation of multiple design concept alternatives
   d.) utilization of decision-based methods and tools to support analysis, evaluation, and selection of design alternatives against multiple and perhaps conflicting requirements
   e.) analysis and verification of the design throughout the various stages of the process, leading to a product that is validated against design requirements
2. Design systems in a team environment where multiple disciplines or ME specialty areas are used.
3. Understand the ethical responsibilities associated with the mechanical engineering profession.
4. Prepare formal written design documentation (e.g. memos and technical reports) and present effective oral presentations.
5. Utilize a variety of sources in researching the field(s) and concepts appropriate to the design and benchmarking (e.g: US Patent and Trademark Office, vendor catalogs, Thomas Register, library, and Internet).
6. Utilize modern engineering and computer tools.

Thus, guiding this research assessment effort and the development of the piloting instrument was ABET's "3a through k" criteria which state that: "engineering programs must demonstrate that their graduates have:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multi-disciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.[1]"

Moreover, according to a recent NAE CASEE report, rigorous literature search revealed that the engineering education community desires four additional student outcomes [2]. Based on this report, an engineering graduate should also be able to demonstrate:

(a) an ability to manage a project, including a familiarity with business, market-related, and financial matters,
(b) a multidisciplinary systems perspective,
(c) an understanding of and appreciation for the diversity of students, faculty, staff, colleagues, and customers, and
(d) a strong work ethic.

Based on these fifteen learning outcomes, review of the literature and ABET-related sources, we developed a survey instrument for the students which included (a) about thirty technical learning outcomes closely linked to the ABET criteria, (b) roughly twenty personal and professional learning outcomes pertaining to knowledge, skills, and dispositional gains, (c) several qualitative-based questions about the strengths and weaknesses of the capstone design experience, and (d) general questions about the team, demographics, etc. In this survey instrument, most of the questions were based on the Likert Scaling. More specifically, in assessing the fifty learning outcomes (thirty "technical" and twenty "personal and professional"), the students were asked "how helpful was your senior design project/experience this semester in enabling you to achieve the following skills." These learning outcomes were based on a scale of one (1-Very Unhelpful) to five (5-Very Helpful), as well as having the option to select "I already had this skill." A list of these fifty learning outcomes is included in the Appendix in Table A1. A hardcopy version of the survey was administered to the students at the end of the semester (Fall 2006) and this will be repeated at the end of the second semester as well (Spring 2007). Moreover, a similar instrument was prepared for the faculty advisors, who were asked "how helpful was the senior design project/experience in enabling your students to achieve the following skills" in order to assess the students' learning outcomes.

High-level cognitive learning skills are essential for the creativity of engineering design processes. By using Bloom's taxonomy, a hierarchy of cognitive learning skills, which categorizes particular levels of competence to demonstrated learning skills, we coupled the thirty technical learning outcomes included in our survey instrument to the six Bloom levels. The six

Bloom's taxonomy competence levels are: (1) knowledge, (2) comprehension, (3) application, (4) analysis, (5) synthesis, and (6) evaluation [3]. **Figure 1** illustrates the six Bloom levels and the direction of higher thought processes. This allowed us to classify the ladder of Bloom's learning

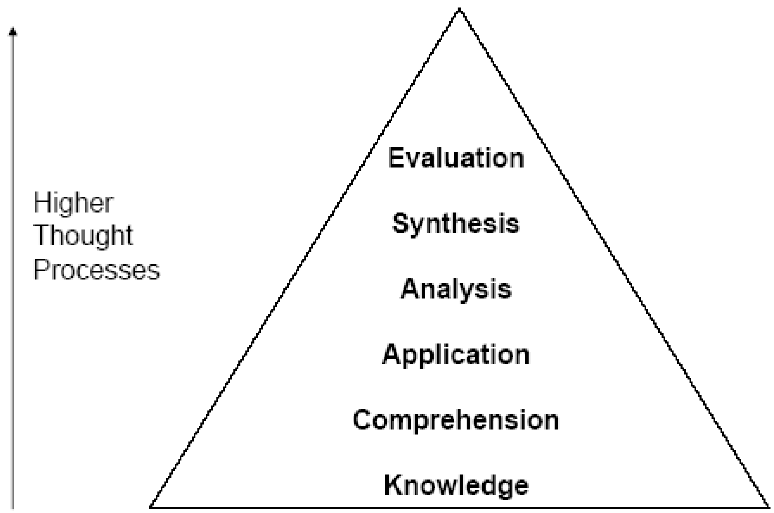

Figure 1: Schematic of the six Bloom cognitive learning skill levels and the direction of higher thought processes.

skills to the desired learning outcomes included in our survey instrument. In many cases, lectures and homework assignments focus exclusively on Bloom level 3 (Application), whereas creativity requires higher thought processes (Bloom levels 4-6: Analysis, Synthesis, Evaluation) [4]. Thus, during this effort, it was important for us not only to assess the students' learning outcomes but also the extent of which these outcomes demonstrated cognitive skills.

3. Background - Students and Design Teams

In this section, student population demographics and some general information about the senior design teams are presented.

3.1 Demographics

Being the seventh largest mechanical engineering department in the nation, in terms of the number of BS graduates each year, the Department of Mechanical Engineering at Virginia Tech offers a wide-range of capstone design projects. During the current academic year of 2006-2007, the graduating class is about 275 students and the number of capstone design teams totals to over thirty. The capstone design projects in the department vary from automotive (such as hybrid electric vehicles, all-terrain Mini Baja, SAE race car) to robotics, fuel cells, and biomedical engineering (such as design of bioreactors, acoustic sensors for biological applications, stents). The total number of participants was 125 students of whom 83% were male students and 17% female. Moreover, the 125 participants of this study corresponded to eleven design teams, which have been categorized as automotive, biomedical, robotics, renewable energy, or education (design of experiments for K-12 education efforts). **Table 1** shows a breakdown of the student population demographics based on gender and race for each of the five design project categories. The two largest groups are the automotive and biomedical design team categories, which account for 50% and 20% of the student participants respectively. Moreover, there were eleven faculty, one from each of the eleven design teams that participated in this study. The lead author serves as faculty advisor to four of these design teams (corresponding to twenty-five students) pertaining to biomedical engineering design projects.

Table 1: Student population based on gender, race and design team subject matter.

Student Population *(Total Number of Participants —125)*	**Automotive (50%)**	**Biomedical (20%)**	**Robotics (14%)**	**Renewable Energy (12%)**	**Education-Design Experiments for K-12 Students (4%)**	**Overall**
Gender						
Male	**80%**	**83%**	**94%**	**85%**	**60%**	**83%**
Female	**20%**	**17%**	**6%**	**15%**	**40%**	**17%**
Race						
African American	**0%**	**0%**	**6%**	**0%**	**0%**	**3%**
Asian	**10%**	**8%**	**18%**	**0%**	**0%**	**9%**
Caucasian	**79%**	**71%**	**76%**	**92%**	**100%**	**77%**
Hispanic	**2%**	**17%**	**2%**	**0%**	**0%**	**6%**
Other	**7%**	**4%**	**7%**	**8%**	**0%**	**5%**

3.2 General Details about Design Teams

In better evaluating the students' learning outcomes, it is essential to gather and have a good basis of their team environment and hour commitments. **Table 2** summarizes some of these general team details (team size, number of faculty advisors, number of graduate students involved, etc.) and also includes the average hours per week the students committed to the design project. Overall, the design teams varied in size, there were teams as small as four and teams as large as twenty-seven. The number of faculty advisors also varied from one to three per team. In at least one-quarter of the teams, there were graduate students involved as well. Moreover, the time spent on the project per week varied from two to thirty-two hours, where the average time students spent on their design project was about 10.7 hours/week. Survey results also show that they wished to spend more time on their project – 2.6 hours more per week on average (equivalent to almost 25% more time than what they spent). The average time the students spent with their faculty advisor(s) averaged about 2.3 hours per week. It appears that students were overall satisfied with the amount of time they spent with their advisors, considering that the average time they would prefer to spend was about 2.5 hours per week (only 12 minutes more than the time they spent with the faculty already). Lastly, when the students were asked to rate how challenging their design project was, ratings ranged from 3 to 10 and the average rating was 8.1 (with 10 being the most challenging).

Table 2: General information about the senior design teams.

	Mean	Range
Design team size	14 students	2 to 30 students
Number of faculty advisors in a team	1	1 to 3
Number of graduate students involved in a team	1-2	0 to 4
Time spent on project	10.7 hours per week	2 to 32 hours per week
Time wish to spend on project	13.3 hours per week	0 to 75 hours per week
Time spent with faculty advisors	2.3 hours per week	0 to 6 hours per week
Time preferred to spent with faculty advisors	2.5 hours per week	0 to 6 hours per week
Challenge of design project (student rating) (scale of 1 to 10, with 10 being high)	8.1	3 to 10

4. Results and Discussion

In this section, we present and discuss the results of the student and faculty instruments. As mentioned previously, the fifty learning outcomes included in the survey instrument were classified as either technical learning outcomes or personal and professional learning outcomes. In assessing these learning outcomes (thirty "technical" and twenty "personal and professional"), not only are results pertaining to all 125 participants presented in this section, but also how male and female students rated the learning outcomes.

4.1 Assessment of Overall Learning Outcomes for All Participants

Before we can begin to assess which learning outcomes were most valued by the students, though, it is important to present the skills that the students rated as already having. **Table 3** shows the top five personal and professional learning outcomes as well as the five technical learning outcomes, along with the corresponding percentage of students that rated these learning outcomes/skills as already having. The highest of these outcomes was 'knowing what you want to do after graduation' (12%), followed by an 'improved work ethic' (8%) and 'reaching beyond yourself' (12%).

Considering that these percentages in Table 3 are on the low end and the fact that we would have anticipated a larger percentage of students to select the option of "I already had this skill," it is our speculation that most students overlooked this option, possibly because it was the last one listed. To an extent, most students should have had some experience with each of these skills. Another possibility to explain these lower percentages could be that the students felt strongly about their design experience strengthening their ability to achieve the listed outcomes/skills and thus undervaluing the fact that they had the skill already. In better understanding the reasoning for these results of Table 3, we will form a focus student group, which will not only help us in clarifying these results but also in improving the survey instrument.

Table 3: Top ten (five 'personal and professional' and five 'technical') learning outcomes the students rated as already having and their corresponding percentages.

	Personal and Professional Learning Outcomes	**Percent**
1	Know what you want to do after graduation (get a job, go to graduate school, etc.)	12%
2	Improved work ethic	8%
3	Reach beyond yourself	8%
4	Communicate effectively with others	7%
5	Apply interpersonal skills in managing people	7%
	Technical Learning Outcomes	**Percent**
1	Identify and establish design requirements and constraints	7%
2	Recognize the need to consult an expert from a discipline other than your own when working on a project	7%
3	Recognize the need for life-long learning	6%
4	Design a system, component, or process to meet desired needs	4%
5	Utilization of modern engineering and computer tools	4%

Tables 4 and **5** show a list of the twenty "personal and professional" and thirty "technical" learning outcomes, respectively, sorted in descending order (highest to lowest average rating) based on the student mean rating. The tables also show the faculty advisors' mean rating in addressing how well the students achieved the skill/outcome. Learning outcomes showing statistically significant differences between the student and faculty ratings are shaded and marked with one asterisk, signifying a p-value of less than 0.05, or two, signifying a p-value of less than 0.01. Overall, by comparing these two tables, we observe that the three highest ranked student outcomes are "personal and professional learning outcomes," pertaining to working in teams where knowledge and ideas from many engineering disciplines must be applied (4.59), communicating effectively (4.57), and valuing that students taught and learned from each other (4.48). The three highest ranked "technical learning outcomes" were being able to generate multiple design concept alternatives (4.39), followed by recognizing the need to consult an expert (4.28), and applying basic scientific and engineering principles to analyze the performance of processes and systems (4.24).

In comparing the average student and faculty ratings for the personal and professional learning outcomes, we observe that the biggest discrepancies (which are also statistically significant) pertain to the value the students place on the diversity of the team leading to diverse talents and ways of thinking (15.9%, $p < 0.01$), improved organizational skills (15.5%, $p < 0.01$), 'reaching beyond yourself' (14.6%, $p < 0.01$), operating in the unknown (13.4% difference, $p < 0.01$), and taking initiative and ownership of the project (12.5%, $p < 0.01$). For all these, the faculty advisors rated the outcomes higher. In fact, the students rated just six of the twenty personal and professional outcomes higher than the faculty advisors. Overall, this may imply that the faculty slightly overestimated the students' learning outcomes. A similar observation can be made for the technical learning outcomes (Table 5), which revealed that for about 65% of the learning outcomes, the faculty had a higher rating. In the remaining 35%, rated higher by the students, the highest significant discrepancies between the student and faculty ratings existed for outcomes pertaining to recognizing the need for life-long learning (24% difference, $p < 0.01$), applying technical codes and standards (23% difference, $p < 0.01$), and identifying potential ethical issues and dilemmas (21% difference, $p < 0.05$). For these three outcomes, our speculation is that the faculty underestimated the students' ability to achieve these skills, perhaps because the opportunity to demonstrate these skills never comes during design meetings. Other significant discrepancies, rated higher by the faculty pertained to conveying technical ideas in formal writing and other design documentation (10% difference, $p < 0.01$), designing a system, component, or process to meet desired needs (14% difference, $p < 0.01$), and creating a timeline when managing a project (12% difference, $p < 0.01$) could be because the students overestimated the ability with these skills.

Table 4: List of the twenty personal and professional learning outcomes sorted in descending order (highest to lowest average rating) based on the student mean rating. Learning outcomes showing statistically significant differences between the student and faculty ratings are shaded. [* p-value < 0.05 and ** p-value < 0.01]

	Personal and Professional Learning Outcomes	Student Mean	Faculty Mean	% Diff
1	Work in teams where knowledge and ideas from many engineering disciplines must be applied	4.59	4.70	2.4%
2	Communicate effectively with others	4.57	4.70	2.7%
3	Value that students taught and learned from each other	4.48	4.20	-6.7%
4	Convey ideas verbally and in formal presentations	4.32	4.70	8.2% *
5	Effectively manage conflicts that arise when working on teams	4.22	4.22	0%
6	Apply interpersonal skills in managing people	4.22	4.30	2.0%
7	Set and pursue my own learning goals	4.20	3.70	-13.6% *
8	Take new opportunities for intellectual growth or professional development	4.14	3.90	-6.2%
9	Engage in critical, reliable, and valid self-assessment	4.14	4.10	-0.9%
10	Know what you want to do after graduation (get a job, go to graduate school, etc.)	4.09	3.90	-4.8%
11	Operate in the unknown (open-ended problems)	4.07	4.70	13.4% **
12	Taking initiative and ownership of senior design project	4.03	4.60	12.5% **
13	Recognize intrinsic interest in learning/intellectual curiosity	4.03	4.10	1.8%
14	Increased self-confidence	4.01	4.33	7.5%
15	Increased perseverance	3.97	4.30	7.6%
16	Improved work ethic	3.97	4.00	0.7%
17	Improved organizational skills	3.97	4.70	15.5% **
18	Pursue of post-graduate education	3.90	3.70	-5.5%
19	Value the diversity of the team (students, faculty, customers, etc.) leading to diverse talents and ways of thinking	3.79	4.50	15.9% **
20	Reach beyond yourself	3.41	4.00	14.6% **

From this data, it is not only important to observe the higher rated learning outcomes, but just as important is to identify the learning outcomes that were least rated. In Table 4, the personal and professional learning outcomes least rated by the students were pursuing a post-graduate education, valuing the diversity of the team, and reaching beyond themselves. The reason we believe these outcomes were least rated is because these are skills/attitudes the students already possessed. Concerning the technical learning outcomes, though, we observe outcomes of designing and conducting and experiment as well as identifying and understanding ethical issues to be least rated. Unlike the reasoning for the least rated professional outcomes, the reason for these low-rated technical skills may be that the students did not feel they achieved these outcomes, illustrating that these are outcomes that need to be better addressed in the future.

Table 5: List of the thirty technical learning outcomes sorted in descending order (highest to lowest average rating) based on the student mean rating. Learning outcomes showing statistically significant differences between the student and faculty ratings are shaded. [* p-value < 0.05 and ** p-value < 0.01]

	Technical Learning Outcomes (TLO)	Student Mean	Faculty Mean	% Diff	Bloom Level
1	Generate multiple design concept alternatives	4.39	4.40	0.3%	2
2	Recognize the need to consult an expert from a discipline other than your own when working on a project	4.28	4.50	4.8%	4
3	Apply basic scientific and engineering principles to analyze the performance of processes and systems	4.24	4.10	-3.3%	3
4	Recognize the need for life-long learning	4.22	3.40	-24.1% **	4
5	Convey technical ideas in formal writing and other design documentation	4.22	4.70	10.3% **	6
6	Identify and establish design requirements and constraints	4.19	4.40	4.8%	3
7	Use evidence to draw conclusions or make recommendations	4.18	4.00	-4.4%	6
8	Formulate a range of solutions to your engineering design problem	4.17	4.40	5.2%	5
9	Apply engineering tools (e.g., software, lathes, oscilloscopes) in engineering practice	4.17	4.20	0.7%	3
10	Utilization of modern engineering and computer tools	4.16	4.20	1.1%	3
11	Recognize knowledge transfer between senior design project and engineering courses (classroom)	4.14	4.20	1.4%	4
12	Design a system, component, or process to meet desired needs	4.14	4.80	13.8% **	5
13	Identify and define problems for which there are engineering solutions	4.13	4.40	6.1%	1
14	Recognize connections between/within engineering disciplines	4.09	4.40	7.1% *	4
15	Create a timeline when managing a project	4.04	4.60	12.1% **	2
16	Recognize the need for diverse perspectives in solving engineering problems	4.03	4.50	10.5%*	4
17	Analyze and interpret data	4.01	3.90	-2.8%	4
18	Apply engineering skills (e.g., experimentation, machining, programming) in engineering practice	4.00	4.60	13.0% *	3
19	Understand the impact of your engineering design/solution in a societal and global context	3.99	4.00	0.2%	2
20	Use feedback from an experiment to improve solutions to an engineering problem	3.99	4.00	0.2%	6
21	Follow a budget when managing a project	3.96	3.70	-7.0%	3
22	Apply technical codes and standards	3.94	3.20	-23.2% **	3
23	Follow a timeline when managing a project	3.93	4.40	10.6%	3
24	Understand assumptions needed to be made to solve your engineering design problem	3.91	3.90	-0.2%	2
25	Use and reference engineering and scientific textbooks, journal papers, and other documents	3.87	3.40	-13.9%	2
26	Create a budget when managing a project	3.83	3.90	1.7%	2
27	Design an experiment	3.81	3.60	-5.8%	5
28	Conduct (or simulate) an experiment	3.79	3.90	2.7%	3
29	Identify potential ethical issues and dilemmas in your design project	3.75	3.10	-21.1% *	1
30	Understand the ethical responsibility associated with the engineering profession and also your design project	3.56	3.30	-7.9%	2

Overall, for the twenty personal and professional outcomes (Table 4), the average student rating was 4.11 whereas the average faculty rating was 4.27 (4% difference), resulting to a p-value of 0.052 (barely statistically significant). Also, another way to look at this is to observe that seven of the twenty professional outcomes (shaded in Table 4) revealed statistically significant differences. This corresponds to 35% of the professional learning outcomes. For the thirty technical learning outcomes, the average student rating was 4.04 and faculty rating a 4.07 (less than 1% difference and p-value of 0.36). Moreover, just nine of the thirty technical outcomes revealed statistically significant findings (corresponding to 30% of the outcomes). Thus, overall, we can conclude that for about 70% of all the outcomes, there was good correlation between the student and faculty ratings. Also included in Table 5 is the corresponding Bloom level for each of the thirty technical learning outcomes.

4.2 Assessment of Learning Outcomes Based on Gender

Also important to assess in this study are the learning outcomes most valued by male and female students. From the 125 student participants, 17% are female and 83% male. Also, according to Table 1 which includes the percentage of male and female students within each of the five design team subject matter or category, female students vary from 6% to 40% of the team. **Tables 6 and 8** list the top ten rated personal and professional outcomes and top fifteen rated technical outcomes, respectively, for the female and male students. Moreover, **Tables 7 and 9** illustrate the professional and technical outcomes shown to have a statistically significant difference between the male and female students.

Table 6 reveals that there is no significant difference in terms of which personal and professional outcomes are most valued by male and female students. Nine of the ten professional outcomes are common to both groups. What is significantly different in these groups is the rating of the learning outcomes. The female students rated the learning outcomes significantly higher than the male students. In fact, for the twenty personal and professional learning outcomes, the average rating for the female students was 4.37, where as for the male students it was 4.05. This 7% difference is statistically significant ($p < 0.001$). Table 7 shows the eight personal and professional learning outcomes whose rating is significantly different between the male and female students. These eight outcomes pertain to communication and interpersonal skills, taking new opportunities for intellectual growth and recognizing intrinsic interest in intellectual curiosity, operating in the unknown, reaching beyond self, and increased work-ethic and self-confidence. The findings lead to the conclusion that male and female students rank the learning outcome gains similarly, but with statistically significant differences in the ratings of these gains. Is this because female students are gaining more and valuing the experience more or they are simply overestimating these?

Similar to the findings of the personal and professional learning outcomes for the female and male students, the top ranking technical learning outcomes are similar for the two groups. Table 8 shows that twelve of the top fifteen ranked technical learning outcomes (80% of the outcomes) are common to both the female and male students. The significant difference is the rating of these outcomes, which are rated much higher by the female students. In fact, for the thirty technical learning outcomes, the average rating of the female students was 4.26, where as for the male students it was 4.00. This 6.5% difference is statistically significant ($p < 0.001$). Interestingly, the number one ranked technical outcome for both groups was the ability to convey technical ideas in formal writing and other design documentation. Also, noticing the learning outcome not common to both groups in Table 8, it appears that female students value recognizing connections between disciplines, lifelong-learning, and knowledge transfer, whereas male students value applying principles, understanding assumptions, utilizing modern engineering and computer tools. Also interesting is that the skills the female students better value correspond to Bloom level four, cognitive skills at the analysis level, whereas the male students value the skills that correspond to Bloom level two or three, cognitive skills at the comprehension and application levels. Could this imply that female students prefer analysis and male students prefer application?

Table 6: Top ten ranking "personal and professional" learning outcomes for the female and male students. **Outcomes that are common to both groups are shaded.

"Female" Personal and Professional Learning Outcomes	Mean	"Male" Personal and Professional Learning Outcomes	Mean
1. Communicate effectively with others	4.89	**1.** Convey ideas verbally and in formal presentations	4.57
2. Value of students teaching and learning from each other	4.74	**2.** Communicate effectively with others	4.52
3. Convey ideas verbally and in formal presentations	4.68	**3.** Value of students teaching and learning from each other	4.43
4. Operate in the unknown (open-ended problems)	4.58	**4.** Taking initiative and ownership of senior design project	4.28
5. Apply interpersonal skills in managing people	4.53	**5.** Work in teams where knowledge and ideas from many engineering disciplines must be applied	4.19
6. Taking initiative and ownership of senior design project	4.53	**6.** Value the diversity of the team (students, faculty, customers, etc.) leading to diverse talents and ways of thinking	4.17
7. Recognize intrinsic interest in learning/intellectual curiosity	4.53	**7.** Operate in the unknown (open-ended problems)	4.16
8. Take new opportunities for intellectual growth or professional development	4.47	**8.** Apply interpersonal skills in managing people	4.07
9. Work in teams where knowledge and ideas from many engineering disciplines must be applied	4.47	**9.** Recognize intrinsic interest in learning/intellectual curiosity	4.06
10. Value the diversity of the team (students, faculty, customers, etc.) leading to diverse talents and ways of thinking	4.39	**10.** Set and pursue my own learning goals	4.03

Table 9 reveals that the ratings of the fourteen out of the thirty technical learning outcomes, almost half of them, are statistically significant between male and female students. On the top of that list are outcomes such as conducting and designing experiments, identifying and defining problems, using feedback from an experiment, recognizing connections between engineering disciplines and knowledge transfer between project and classroom, recognizing life long learning, etc. So, once again and slightly more pronounced for the technical outcomes than the professional outcomes, male and female students are highly ranking a similar set of technical outcomes, they simply rate them much differently. The female students are rating these outcomes significantly higher than the male students. So, are they overestimating their gains/abilities or simply value the experience more than the male students?

Table 7: List of "personal and professional" learning outcomes shown to have a statistically significant difference between the male and female students. Outcomes ranked based on lowest to highest p-value [* p-value < 0.05 and ** p-value < 0.01].

Personal and Professional Learning Outcomes Statistically Significant Between the Male and Female Students	Female Students	Male Students	% Diff
1. Communicate effectively with others	4.89	4.52	8% **
2. Take new opportunities for intellectual growth or professional development	4.47	4.01	10% **
3. Apply interpersonal skills in managing people	4.53	4.07	10% **
4. Operate in the unknown (open-ended problems)	4.58	4.16	9% **
5. Recognize intrinsic interest in learning/intellectual curiosity	4.53	4.06	10% **
6. Increase self-confidence	4.26	3.80	11% *
7. Improve work ethic	4.28	3.92	8% *
8. Reach beyond yourself	4.32	3.96	8% *

Table 8: Top fifteen ranking "technical" learning outcomes for the female and male students. **Outcomes that are common to both groups are shaded.

"Female" Technical Learning Outcomes	Mean	"Male" Technical Learning Outcomes	Mean
1. Convey technical ideas in formal writing and other design documentation	4.68	**1.** Convey technical ideas in formal writing and other design documentation	4.47
2. Recognize the need to consult an expert from a discipline other than your own when working on a project	4.63	**2.** Generate multiple design concept alternatives	4.34
3. Identify and define problems for which there are engineering solutions	4.63	**3.** Identify and define problems for which there are engineering solutions	4.27
4. Use evidence to draw conclusions or make recommendations	4.53	**4.** Design a system, component, or process to meet desired needs	4.26
5. Formulate a range of solutions to your engineering design problem	4.53	**5.** Identify and establish design requirements and constraints	4.23
6. Recognize the need for diverse perspectives in solving engineering problems	4.53	**6.** Recognize the need for diverse perspectives in solving engineering problems	4.23
7. Create a timeline when managing a project	4.53	**7.** Formulate a range of solutions to your engineering design problem	4.21
8. Recognize connections between/within engineering disciplines	4.47	**8.** Recognize the need to consult an expert from a discipline other than your own when working on a project	4.21
9. Identify and establish design requirements and constraints	4.47	**9.** Create a timeline when managing a project	4.21
10. Design a system, component, or process to meet desired needs	4.42	**10.** Apply basic scientific and engineering principles to analyze the performance of processes and systems	4.20
11. Recognize the need for life-long learning	4.41	**11.** Use evidence to draw conclusions or make recommendations	4.18
12. Recognize knowledge transfer between senior design project and engineering courses (classroom)	4.37	**12.** Understand assumptions needed to be made to solve your engineering design problem	4.16
13. Generate multiple design concept alternatives	4.37	**13.** Utilization of modern engineering and computer tools	4.14
14. Follow a timeline when managing a project	4.32	**14.** Follow a timeline when managing a project	4.11
15. Apply engineering skills (e.g., experimentation, machining, programming) in engineering practice	4.32	**15.** Apply engineering skills (e.g., experimentation, machining, programming) in engineering practice	4.11

Table 9: List of "technical" learning outcomes shown to have a statistically significant difference between the male and female students. List of outcomes is ranked based on lowest to highest p-value [* $p < 0.05$ and ** $p < 0.01$].

Technical Learning Outcomes Statistically Significant Between the Male and Female Students	Female Students	Male Students	% Diff
1. Conduct (or simulate) an experiment	4.05	3.55	12.5% **
2. Recognize connections between/within engineering disciplines	4.47	3.98	11.1% **
3. Design an experiment	4.05	3.57	11.8% **
4. Identify and define problems for which there are engineering solutions	4.63	4.27	7.9% **
5. Use feedback from an experiment to improve solutions to an engineering problem	4.26	3.79	11.1% **
6. Formulate a range of solutions to your engineering design problem	4.53	4.21	7.0% *
7. Recognize the need for life-long learning	4.41	3.97	10.1% *
8. Recognize the need for diverse perspectives in solving engineering problems	4.53	4.23	6.6% *
9. Use evidence to draw conclusions or make recommendations	4.53	4.18	7.7% *
10. Recognize knowledge transfer between senior design project and engineering courses (classroom)	4.37	4.07	6.8% *
11. Understand the impact of your engineering design/solution in a societal and global context	4.32	3.89	9.9% *
12. Create a timeline when managing a project	4.05	3.55	12.5% *
13. Recognize the need to consult an expert from a discipline other than your own when working on a project	4.47	3.98	11.1% *
14. Convey technical ideas in formal writing and other design documentation	4.05	3.57	11.8% *

4.5 Summary of Overall Assessment Results

This section summarizes the average ratings for "personal and professional" and "technical" learning outcomes (**Table 10**) as well as the average ratings of value placed on the capstone design experience (**Table 11**) for the male and female students as well as overall for all the entire student population. From Table 10, we observe that all the ratings for both sets of learning outcomes (professional and technical) are four and above. This observation illustrates that the students value the learning outcomes of the capstone experience. Also, for all student groups, the personal and professional skill gains are ranked higher than the technical outcomes. More specifically, for the personal and professional outcomes, the female students rated these skills higher, with a rating of 4.37, while the male students rated these skills with a mean value of 4.05. This is a statistically significant difference between the male and female students (7.3% difference, $p < 0.01$). Consequently, for the technical learning outcomes, we observed similar trends between the groups. The female students rated these set of skills higher than the male students. As was the case for the professional outcomes, statistical significant differences in the ratings of the outcomes were observed between the male and female students (6.1% difference, $p < 0.01$).

Table 10: Summary of average ratings for "personal and professional" and "technical" learning outcomes for the six student groups and overall. Percent differences shown to have a statistically significant difference between the coupled student groups are depicted with an asterisk [* $p < 0.05$ and ** $p < 0.01$]. The Bloom index is also included.

Student Group	Personal and Professional Learning Outcomes		Technical Learning Outcomes	
All students (overall)	4.11		4.04	
Female Students	4.37	7.3% **	4.26	6.1% **
Male Students	4.05		4.00	

Overall average ratings for the value the various student groups placed on the capstone design experience are shown in Table 11. Overall, the students were satisfied with their senior design project/experience, with an overall rating of 4.3 and above. Similarly, when students were asked if the design experience was a valuable learning event, all the students agreed and gave an overall rating of 4.54. The students gave slightly lower ratings, although still high, to statements pertaining to "the design experience provided me with a new motivation for learning (average rating of 3.84)" and "because of this experience, I am more optimistic about my future" (average rating of 3.72). Taken as a whole, we observe some trends when comparing the male and female students. As was the case in the results of Table 10, the female students rated the experience higher, in terms of the value of the design process, motivation for learning as well as optimism about the future. This is consistent with previous results.

Table 11: Summary of average ratings for the overall value of the capstone design experience for the six student groups and overall.

Overall Value of Capstone Design Experience	Overall	Female Students	Male Students
1. Overall, I am satisfied with my senior design project/experience	4.32	4.37	4.30
2. Overall, the senior design experience is a valuable learning experience	4.54	4.68	4.50
3. This semester's design project has given me a clear picture of the relevance of the engineering design process	4.12	4.37	4.07
4. This senior design experience has provided me with a new motivation for learning	3.84	4.16	3.79
5. Because of this senior design experience, I am more optimistic about my future	3.72	3.84	3.69

5. Conclusions

This paper has presented an extensive amount of data pertinent to the learning outcomes of mechanical engineering seniors involved in their first semester of a capstone design experience. During this effort, student and faculty surveys instruments, which included the compilation of over fifty learning outcomes (categorized as either "technical" or "personal and professional" learning outcomes) closely linked to the ABET criteria and other desired skills, were developed. The student survey instrument intended to assess the extent to which these students are achieving certain learning outcomes desired of engineering graduates, while the faculty survey instrument intended to assess the extend to which faculty expected the students to meet these learning outcomes. The student instrument was administered to 125 mechanical engineering seniors at the end of their first semester capstone experience and this will also be repeated at the end of their second semester experience as well. In better assessing the quality of learning during this capstone design experience, we also classified and coupled the thirty technical learning outcomes to the six levels of Bloom's taxonomy, a hierarchy of cognitive learning skills. In assessing these learning outcomes, we presented results pertaining to not only the entire student population, but also how male and female students rated and valued these learning outcomes. Some of the key findings of this study are addressed in the following paragraphs.

Overall, the results show that students' learning outcomes during this experience were personal and professional skills and gains over the technical outcomes. The highest three ranked personal and professional outcomes pertained to working in teams where knowledge and ideas from many engineering disciplines must be applied, communicating effectively, and valuing that students taught and learned from each other. The three highest ranked "technical learning outcomes" were being able to generate multiple design concept alternatives, recognizing the need to consult an expert, and applying basic scientific and engineering principles to analyze the performance of processes and systems.

In comparing the average student and faculty ratings for the personal and professional learning outcomes, we can conclude that for about 70% of all the outcomes, there was good correlation between the student and faculty ratings. In the personal and professional learning outcomes category, the biggest discrepancies (which are also statistically significant) pertained to the value the students place on the diversity of the team leading to diverse talents and ways of thinking, improved organizational skills, reaching beyond self, operating in the unknown, and taking initiative and ownership of the project. For all these, the faculty advisors rated the outcomes higher. Our speculation is that this implies that the faculty slightly overestimated the students' learning outcomes. A similar observation was made for the technical learning outcomes, which revealed that for about 65% of the learning outcomes, the faculty had a higher rating. In the remaining 35%, rated higher by the students, the highest significant discrepancies between the student and faculty ratings existed for outcomes pertaining to recognizing the need for life-long learning, applying technical codes and standards, and identifying potential ethical issues and dilemmas. For these three outcomes, our speculation is that the faculty underestimated the students' ability to achieve these skills. Other significant discrepancies, rated higher by the faculty pertained to conveying technical ideas in formal writing and other design documentation, designing a system, component, or process to meet desired needs, and creating a timeline when managing a project could be because the students overestimated the ability with these skills.

Also assessed in this study were the learning outcomes most valued by male and female students. Results showed that there is no significant difference in terms of which personal and professional outcomes are most valued by male and female students. What is significantly different in these groups is how these two groups rated the learning outcomes. Similarly, but slightly more pronounced for the technical outcomes, male and female students are highly ranking a similar set of technical outcomes, they simply rate them much differently. Some of the technical outcomes female students value most include recognizing connections between disciplines, lifelong-learning, and knowledge transfer, whereas the male students seem to better value applying principles, understanding assumptions, utilizing modern engineering and computer tools. Also interesting was that the skills the female students better value correspond to Bloom level four, cognitive skills at the analysis level, whereas the male students value the skills that correspond to Bloom level two or three, cognitive skills at the comprehension and application levels. The findings lead to the conclusion that male and female students rank their learning outcome gains similarly, but with statistically significant differences in the ratings of these gains. It is our speculation that female students are valuing the experience more. We do plan to look more into this finding by possibly forming a small focus group.

In summary, the students highly valued the learning outcomes of the capstone experience and also were highly satisfied. The personal and professional skill gains are ranked higher than the technical outcomes. Additionally, for both sets of outcomes (professional and technical outcomes), the female students revealed the highest ratings. The female students also rated the experience higher, in terms of the valuing the design process, being more motivated for learning as well as being more optimistic about the future. Statistical significant differences were observed between the male and female students.

Lastly, some of the broader impacts of this study are that the survey instruments developed herein are as applicable and pertinent to other engineering and non-engineering students as they are to mechanical engineers. Also, this type of assessment instrument can be used not only for students participating in capstone design experiences, but also for other learning experiences, such as research, coursework and service learning.

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APPENDIX

Table A1: List of the twenty personal and professional learning outcomes and thirty technical learning outcomes included in the survey instrument. The corresponding Bloom level is included for each technical learning outcome.

	Personal and Professional Learning Outcomes	
1	Convey ideas verbally and in formal presentations	
2	Communicate effectively with others	
3	Value that students taught and learned from each other	
4	Taking initiative and ownership of senior design project	
5	Work in teams where knowledge and ideas from many engineering disciplines must be applied	
6	Operate in the unknown (open-ended problems)	
7	Value the diversity of the team (students, faculty, customers, etc.) leading to diverse talents and ways of thinking	
8	Apply interpersonal skills in managing people	
9	Recognize intrinsic interest in learning/intellectual curiosity	
10	Take new opportunities for intellectual growth or professional development	
11	Set and pursue my own learning goals	
12	Reach beyond yourself	
13	Engage in critical, reliable, and valid self-assessment	
14	Effectively manage conflicts that arise when working on teams	
15	Improved organizational skills	
16	Increased perseverance	
17	Improved work ethic	
18	Increased self-confidence	
19	Know what you want to do after graduation (get a job, go to graduate school, etc.)	
20	Pursue of post-graduate education	
	Technical Learning Outcomes	**Bloom Level**
1	Use feedback from an experiment to improve solutions to an engineering problem	6
2	Use evidence to draw conclusions or make recommendations	6
3	Convey technical ideas in formal writing and other design documentation	6
4	Design a system, component, or process to meet desired needs	5
5	Design an experiment	5
6	Formulate a range of solutions to your engineering design problem	5
7	Recognize the need for life-long learning	4
8	Analyze and interpret data	4
9	Recognize connections between/within engineering disciplines	4
10	Recognize knowledge transfer between senior design project and engineering courses (classroom)	4
11	Recognize the need for diverse perspectives in solving engineering problems	4
12	Recognize the need to consult an expert from a discipline other than your own when working on a project	4
13	Apply basic scientific and engineering principles to analyze the performance of processes and systems	3
14	Follow a budget when managing a project	3
15	Identify and establish design requirements and constraints	3
16	Conduct (or simulate) an experiment	3
17	Apply engineering tools (e.g., software, lathes, oscilloscopes) in engineering practice	3
18	Utilization of modern engineering and computer tools	3
19	Follow a timeline when managing a project	3
20	Apply engineering skills (e.g., experimentation, machining, programming) in engineering practice	3

21	Apply technical codes and standards	3
22	Generate multiple design concept alternatives	2
23	Create a budget when managing a project	2
24	Create a timeline when managing a project	2
25	Use and reference engineering and scientific textbooks, journal papers, and other documents	2
26	Understand the impact of your engineering design/solution in a societal and global context	2
27	Understand assumptions needed to be made to solve your engineering design problem	2
28	Understand the ethical responsibility associated with the engineering profession and also your design project	2
29	Identify and define problems for which there are engineering solutions	1
30	Identify potential ethical issues and dilemmas in your design project	1